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U.S. Department of the Interior
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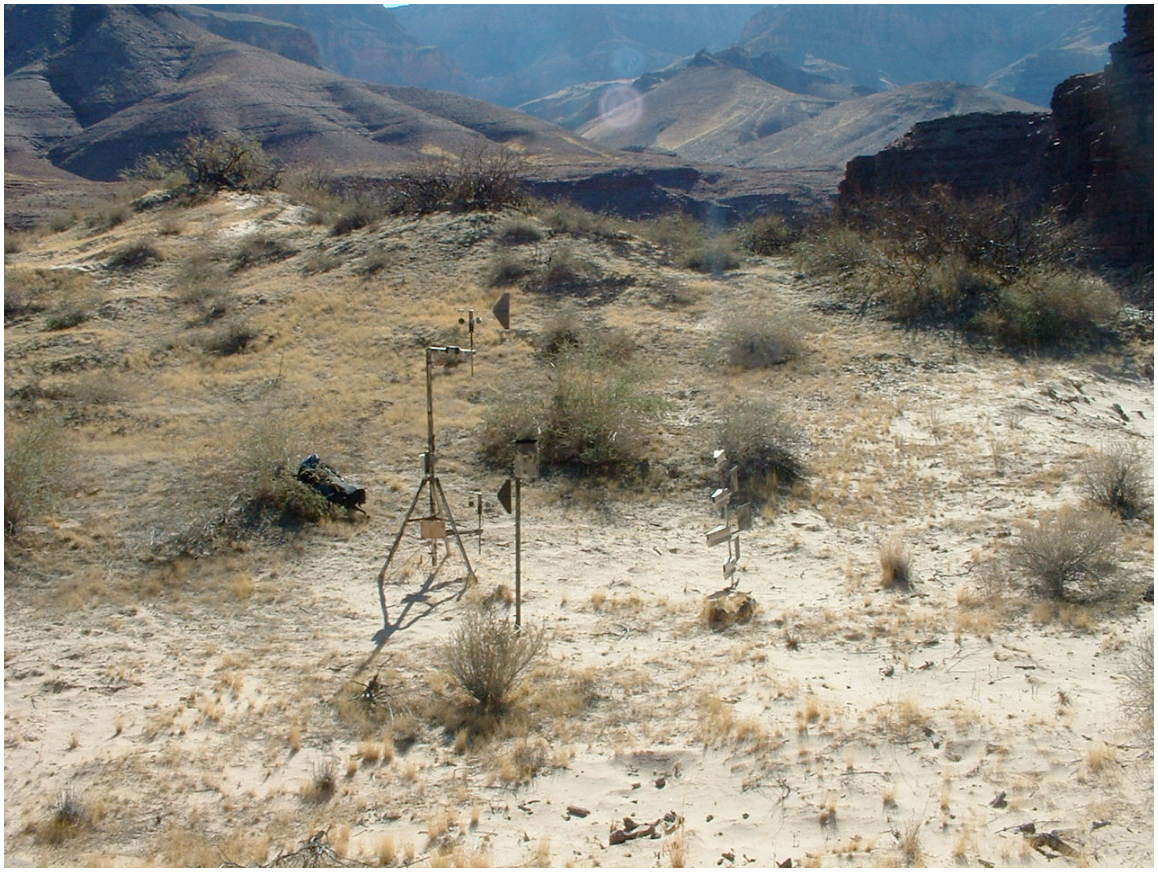
Open-File Report 2006-1188



Measurements of Wind, Aeolian Sand Transport, and Precipitation in the Colorado River Corridor, Grand Canyon, Arizona: January 2005 to January 2006

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For more information on USGS science in Grand Canyon, Arizona through the Grand Canyon Monitoring and Research Center: http://www.gcmrc.gov

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ADDITIONAL DIGITAL INFORMATION

For an online PDF version of this report, including supplemental data files, please see: http://pubs.usgs.gov/of/2006/1188/

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REPORT REFERENCE

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ABSTRACT

This report presents measurements of aeolian sediment-transport rates, wind speed and direction, and precipitation records from six locations that contain aeolian deposits in the Colorado River corridor through Grand Canyon, Grand Canyon National Park, Arizona. Aeolian deposits, many of which contain and preserve archaeological material, are an important part of the Grand Canyon ecosystem. This report contains data collected between January 2005 and January 2006, and is the second in a series; the first contained data that were collected between November 2003 and December 2004 (Draut and Rubin, 2005; http://pubs.usgs.gov/of/2005/1309/).

Analysis of data collected in 2005 shows great spatial and seasonal variation in wind and precipitation patterns. Total annual rainfall can vary by more than a factor of two over distances ~ 10 km. Western Grand Canyon received substantially more precipitation than the eastern canyon during the abnormally wet winter of 2005. Great spatial variability in precipitation indicates that future sedimentary and geomorphic studies would benefit substantially from continued or expanded data collection at multiple locations along the river corridor, because rainfall records collected by NPS at Phantom Ranch (near river-mile 88) cannot be assumed to apply to other areas of the canyon.

Wind velocities and sand transport in 2005 were greatest during May and June, with maximum winds locally as high as ~25 m s^{-1}, and transport rates locally >100 g cm^{-1} d^{-1}. This represents a later peak in seasonal aeolian sand transport compared to the previous year, in which transport rates were greatest in April and May 2004. Dominant wind direction varies with location, but during the spring windy season the greatest transport potential was directed upstream in Marble Canyon (eastern Grand Canyon). At all locations, rates of sand transport during the spring windy season were 5–15 times higher than at other times of year.

This information has been used to evaluate the potential for aeolian reworking of new fluvial sand deposits, and restoration of higher-elevation

aeolian deposits, following the 60-hour controlled flood release from Glen Canyon Dam in November 2004. Substantial deposition of new sand occurred at all study sites during this high-flow experiment, but most of the new sediment was eroded by high flow fluctuations between January and March 2005. Comparison of aeolian sand transport in the spring windy seasons of the pre- and post-flood years indicates that, where some of the flood-deposited sand remained by spring, aeolian sand transport was significantly higher than during the pre-flood spring. Gully incision in an aeolian dune field was observed to be partially ameliorated by deposition of wind-blown sand derived from a nearby 2004 flood deposit. These results imply that sediment-rich controlled floods can renew sand deposition in aeolian dune fields above the flood-stage elevation. The potential for restoration of archaeological sites in aeolian deposits can be maximized by using dam operations that maximize the open sand area on fluvial sandbars during spring, when aeolian sediment transport is greatest.

INTRODUCTION

A network of weather stations was operated by the U.S. Geological Survey (USGS) in the Colorado River corridor in Grand Canyon, Grand Canyon National Park, Arizona, between November 2003 and January 2006. Wind, precipitation, and aeolian sand-transport data collected at these stations constitute the only continuous weather record from the river corridor during this time interval with the exception of temperature and rainfall measurements made at Phantom Ranch (river-mile 88) by the National Park Service (NPS). The data presented in this report allow resolution of seasonal and regional variability in wind intensity and direction, and resultant aeolian sediment transport, as well as precipitation patterns. This report contains data collected between January 2005 and January 2006. In January 2006, data collection ceased and all equipment was removed upon expiration of the NPS research and collecting permit (GRCA-2003-SCI-0101).

High-resolution records from these instrument stations can be used to identify rainfall events that cause gully incision and to predict aeolian sediment redistribution, thus aiding other sedimentary and geomorphic studies of sediment deposits in the river corridor. The condition of fluvial and aeolian deposits in the river corridor is of particular concern to scientists and recreational visitors to Grand Canyon National Park, in light of the depletion of sediment deposits since 1963 attributed to sediment-supply limiting effects of Glen Canyon Dam (Beus and others, 1985; Schmidt and Graf, 1987; Kearsley and others, 1994; Kaplinski and others, 1995; Topping and others, 2000a, b; Rubin and Topping, 2001; Rubin and others, 2002; Schmidt and others, 2004). The operation of these stations was timed to include one full year of data before and more than one full year of data collected after the November 2004 high-flow release of 1,160 m^3 s^{-1} (41,000 ft^3 s^{-1}) from Glen Canyon Dam. The results have been used to analyze aeolian redistribution of new sediment deposited by that flood. These records are therefore important for assessing the potential of controlled flooding to replenish aeolian sediment deposits above the flood-stage elevation. Many of these aeolian deposits contain and provide a protective cover for archaeological resources, a valuable cultural component of the Grand Canyon river corridor (for example, Thompson and Potochnik, 2000; Draut and others, 2005; Fairley, 2005).

Study Sites:

The six study sites where weather stations were established for this project are shown in figure 1. Locations in the river corridor are commonly referred to by distance in miles downstream of Lees Ferry, Arizona; this report follows that convention while using metric units for other measurements. Each of three sites located in eastern Grand Canyon, at 24.5 mile, Malgosa (river-mile 57.9), and Palisades (river-mile 66.1), was equipped with two weather stations between November 2003 and January 2006. One instrument station operated at each of three additional sites: Comanche (river-mile 68.0) in eastern Grand

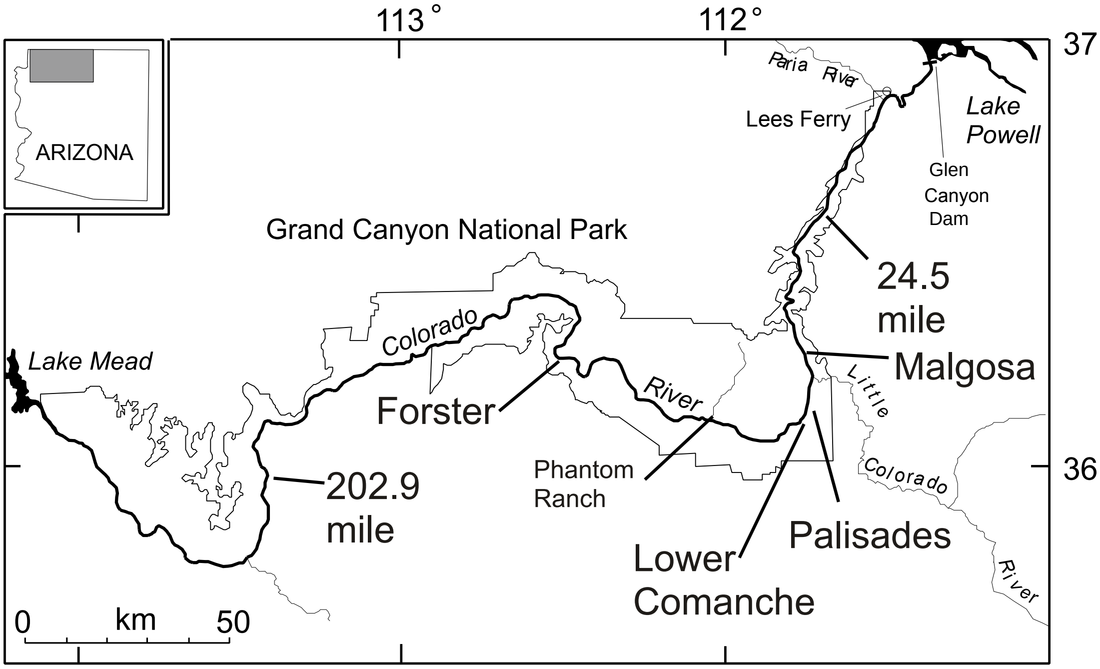

***FIGURE 1**. Location map showing the Colorado River through Grand Canyon, with weather-station sites indicated. Six stations, active since November 2003, collect data at three sites: two stations each at 24.5 mile, Malgosa, and Palisades. One station collects data at each of three additional sites: Comanche, Forster, and 202.9 mile; these three have been in operation since April 2004. The National Park Service (NPS) operates a weather station at Phantom Ranch, near river-mile 88, that measures daily rainfall and temperature.*

Canyon, and Forster (river-mile 123.0), and 202.9 mile in western Grand Canyon, between April 2004 and January 2006. River miles are those given by the internet map server operated by the Grand Canyon Monitoring and Research Center (http://www.gcmrc.gov/products/ims/ims.htm).

In order to generate data relevant to the monitoring of archaeological resources, the weather stations were deployed in areas of the river corridor known to contain culturally significant areas but far enough from any archaeological site so that neither the installation of equipment nor maintenance visits by scientists would damage the sites. All study sites have experienced a reduction in open sand area since Glen Canyon Dam was constructed (based on analysis of aerial photographs), but were also determined to have experienced new deposition during the 1996 high-flow experiment (Webb and others, 1999). These criteria were intended to allow monitoring of the effects of similar high-flow experiments in the event that any occurred during the two-year duration of the weather-station project; the timing of the November 2004 flood experiment did allow for its effects to be studied as part of this project. Finally, study sites were chosen away from high-visitation areas such as camping beaches, to limit visitor interaction with the equipment.

24.5 mile:

Two instrument stations operated at 24.5 mile, at the downstream end of a small debris fan on river left (the left bank of the river when viewed facing downstream) from 11/14/03, to 1/12/06. One of these, named Station 24.5 L (for "lower"), was located near the river just above the 1,270 $m^3 s^{-1}$ (45,000 $ft^3 s^{-1}$) stage elevation at the lower end of a small aeolian dune field. The portion of the dune field between the two weather stations undergoes active aeolian sand transport, while an area of approximately equal size to the north (upstream) of the active dunes contains relatively inactive, deflated aeolian dunes that have a thin cover of cryptogamic crust. A moderate amount of vegetation (tamarisk shrubs and grasses) is present between this weather station and the river. The second station, 24.5 U ("upper") was situated 95 m uphill of 24.5 L, at the upper, northeastern end of the dune field, ~20 m away from the cliff wall that forms the upper-elevation boundary of the dune field. In December 2004, immediately following the 1,160 $m^3 s^{-1}$ (41,000 $ft^3 s^{-1}$) high-flow experiment, an automated camera station was established at 24.5 mile that was intended to photograph daily the river-level sandbar below station 24.5 L. The camera station operated intermittently until March 2005 but power-supply problems limited the number of photographs that were taken.

Malgosa:

Two weather stations were installed in a very active aeolian dune field at the downstream side of the debris fan at the mouth of Malgosa Canyon (a small tributary drainage that joins the Colorado River on river right, near river-mile 57.9) on 11/17/03, and operated there until 1/14/06. Station Mal L was located near river level approximately at the 1,160 $m^3 s^{-1}$ (41,000 $ft^3 s^{-1}$) stage elevation, at the low-elevation, downstream (southern) end of the dune field. Vegetation that grew noticeably during the 26-month study interval is present between Station Mal L and the river. Station Mal U was located 50 m uphill from Mal L at the top (north, upstream end) of the dune field, approximately 3 m (vertically) below the dune crest; the position of the dune crest shifts on time scales of weeks due to active sand transport at this site. The dune field between the two instrument stations has sparse vegetation and no cryptogamic crust.

Palisades:

Two weather stations operated on river left in the Palisades area (near Palisades Creek, river-mile 66.1) from 11/18/03, to 1/14/06. Station Pal L was located on a relict fluvial cobble-boulder deposit immediately above the river (~ 2 m above the 566 $m^3 s^{-1}$ [20,000 $ft^3 s^{-1}$] stage). Boulders and a moderate amount of vegetation (small shrubs) surrounded this instrument site. Station Pal U

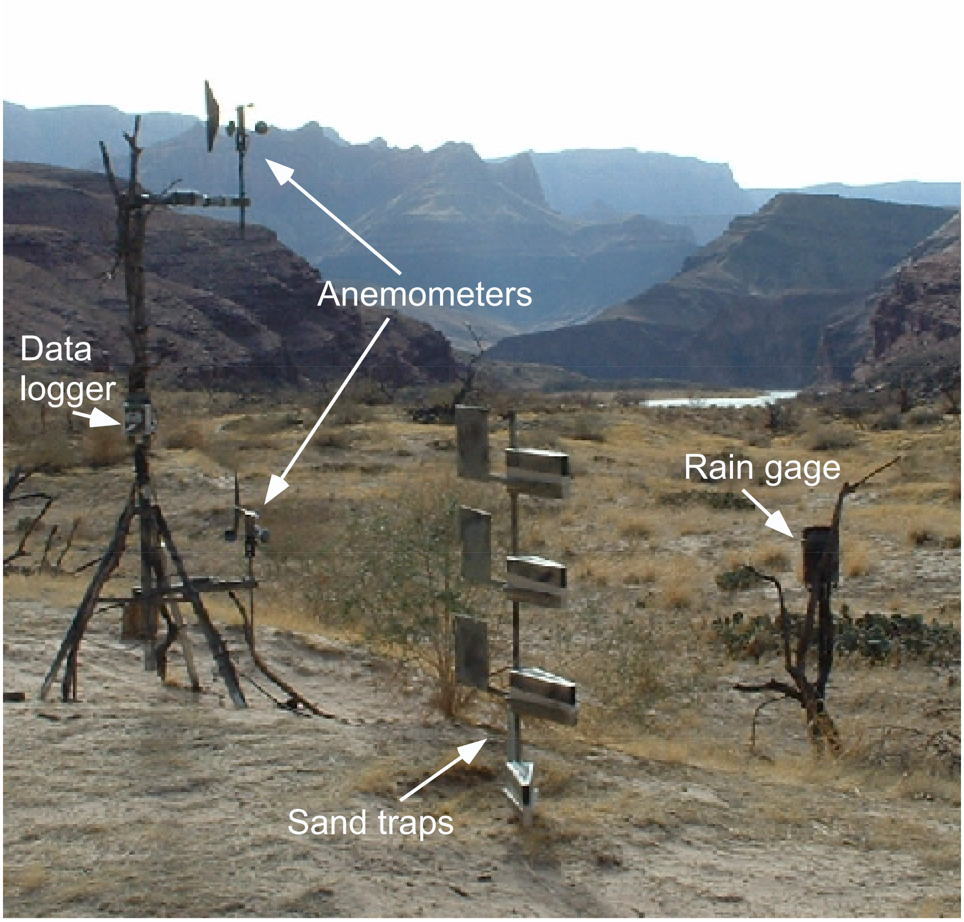

FIGURE 2. *Photograph of one instrument station, deployed at Palisades (Station Pal U). Four sand traps are shown on a vertical pole at the center of the photo. A tripod with two anemometers (at heights 2.0 m and 0.5 m above ground level) is at left; the data logger is also attached to this tripod. On the right is a tipping-bucket rain gauge. Equipment was camouflaged with spray paint and dead branches to reduce visual impact to canyon visitors.*

(shown in fig. 2) was located ~ 100 m northeast of Pal L in a large aeolian coppice-dune field that is relatively inactive, with grasses, occasional mesquite trees, and well developed cryptogamic crust covering most dunes.

Comanche:

One weather station was deployed on river left downstream of Comanche Creek on 4/20/04 (Station Com; river-mile 68.0), which remained in operation continuously until 1/16/06. This station was located in an aeolian dune field that is relatively inactive, with grass and cryptogamic-crust cover; a zone of dense vegetation dominated by mesquite trees separates this dune field from the river.

Forster:

One weather station was deployed on river left in an active aeolian dune field at the mouth of Forster Canyon (river-mile 123.0) on 4/23/04. This station was removed on 1/27/06. The orientation of sand shadows and dune forms indicated that the dominant aeolian sand transport was likely to be directed up the Forster drainage, perpendicular to the trend of the river, an unusual situation that prompted further study; this dominant north wind direction was later confirmed by the anemometer data collected. Sparse vegetation and occasional cryptogamic crust occur in this dune field.

202.9 mile:

One weather station was deployed on river right at mile 202.9 (Station 202.9) on 4/28/04, and remained in operation until 1/29/06. This site includes an aeolian dune field near river level that is covered by trees and abundant willow, arrowweed, acacia, and some rabbit-brush shrubs. Interpretation of aerial photographs indicates that the heavy vegetation cover has grown on the dune field and on a large river-level sand bar just downstream of the dune field during the post-dam era; vegetation now covers a large area of previously open sand. Immediately upstream from the instrument site, an aeolian dune field at higher elevation has experienced erosion by deflation and gully incision. Equipment installed at 202.9 mile included an anemometer and rain gauge but no sand traps. This site was instrumented to identify the sand source for the eroding, higher-elevation dune field by documenting the dominant wind direction that causes sand transport; identifying the net transport direction can indicate to what degree vegetation encroachment downstream of the site may have affected the condition of the upper sand-dune field by limiting aeolian transport from nearby sand sources.

METHODS

Technical specifications of instruments used during this study are discussed briefly below, and were discussed thoroughly by Draut and Rubin (2005). Digital measurements of wind and rainfall were recorded on data loggers from which data were downloaded at regular intervals (typically 4–8 weeks). Mean wind velocity, maximum gust velocity, and wind direction were measured at each station with a 4-minute sampling interval and recorded as 4-minute averages. Aeolian sand flux was monitored using sand traps that were emptied during each maintenance visit. Measurements of sand transport are therefore based on cumulative values that represent the interval between maintenance visits to the study sites.

Anemometers:

Wind velocity, maximum gust velocity, and wind direction were measured using ‘spinning cup’ anemometers manufactured by Onset Computer Company of Bourne, Massachusetts. These anemometers measure wind speed with a resolution of 0.19 m s^{-1}. Gust speed is recorded as the maximum three-second wind recorded during each logging interval. Wind direction, measured as vector components with a resolution of 1.4° and an accuracy range of ±5°, is accumulated every three seconds during each logging interval, and recorded as an average direction calculated from the sum of the vector components. These anemometers have a 2° blind window between 358° and 0° in which no readings can be made.

Rain Gauges:

Rainfall was monitored using Onset 'tipping-bucket' rain gauges. The use of two rain gauges at three of the study sites (24.5 mile, Malgosa, and Palisades) allowed resolution of local precipitation events that often varied greatly in intensity over short distances. The Onset rain gauge has a resolution of 0.2 mm and operate with an accuracy of ±1 percent at rainfall rates of up to 20 mm/hour.

Data Loggers:

Anemometers and rain gauges at each instrument station were connected to a HOBO® MicroStation weather station (data logger) manufactured by Onset. This four-channel logger has a time accuracy of 0–2 seconds for the first data point, and ±5 seconds per week for subsequent data points when operating conditions are maintained at ~25°C. Because the logging interval used in this study is substantially longer (4 minutes) than the accuracy envelope for time, any drift in the logger's time accuracy is not considered significant.

Sand Traps:

A variety of sand traps have been developed for use in aeolian transport studies (for example, Goossens and others, 2000, 2001; Zobeck and others, 2003). Optimal trap design includes the ability of traps to perform isokinetically and to have a high, well-calibrated efficiency range (Nickling and McKenna Neuman, 1997). The galvanized metal traps used in this study, a wedge-shaped passive-sampling design known as the Big Spring Number Eight (BSNE; Fryrear, 1986) perform well in both respects (Stout and Fryrear, 1989) and have vanes that turn the traps to face the incident wind direction. BSNE traps have a sampling orifice that is 0.05 m tall and 0.02 m wide; air flow enters the trap through this orifice and exits through a 60-mesh screen in the upper surface of the trap. Sand is retained in the lower half of the trap after falling through a wider (18-mesh) screen. The BSNE design efficiency has been calibrated by multiple wind-tunnel and field studies using a range of grain sizes for sand and dust over a wide range of wind velocities (Fryrear, 1986; Shao and others, 1993; Goossens and Offer, 2000; Goossens and others, 2000, 2001). These calibrations suggest an efficiency range of 70–130 percent for the range of grain sizes and velocities measured at these study sites (a truly isokinetic sand trap would have a trapping efficiency of 100%; trapping efficiency is above or below 100% if the sand-trap design directs air flow into the trap or away from it, respectively).

Field Deployment:

An example of one instrument station (at Palisades) is shown in figure 2. Tripods were deployed with two anemometers and one rain gauge at Stations 24.5 L, 24.5 U, Pal L, Pal U, and Com. At those stations, anemometer heights were set at 2.0 and 0.5 m (with the exception of Station Pal L, where the lower anemometer was set at 1.0 m to reduce interference with boulders). Station Mal U included three anemometers, at heights of 2.0, 1.0, and 0.3 m. Each of the remaining stations (Mal L, For, and 202.9 mile) used one anemometer at a height of 2.0 m and one rain gauge. The directional reading of each anemometer was re-calibrated at each maintenance visit using a compass. Instrument tripods were equipped with a copper-plated grounding rod and copper grounding wire clamped to the metal tripod, to reduce instrument damage in the event of a lightning strike.

An array of BSNE sand traps was set up ~ 3 to 5 m from each instrument tripod (with the exception of the 202.9 mile station, at which no sand traps were used) to collect wind-blown sand. Four BSNE traps were mounted on a vertical pole. Sand trap heights were set at 1.0, 0.7, 0.4, and 0.1 m. Station Pal L used only three traps, because very little sand transport occurred near its location in a boulder field; heights of sand traps at Pal L were 1.0, 0.5, and 0.25 m.

To minimize visual impacts to canyon visitors, instruments were made as inconspicuous as possible using paint and vegetation camouflage. At most sites, vegetation along the river level also provided some screening. Tripods were labeled with signs that explained their function in order to educate any visitors that encountered the equipment.

Sediment Collection and Analysis:

The total mass of sand collected from each trap during each maintenance visit was weighed. Mass-transport rates were calculated for each interval between downloads by integration from 0 to 1 m of a curve fit to the mass-vs.-height data. Because the great majority of aeolian sediment transport takes place near the ground surface, the amount of sediment transport represented by the lowermost 1 m will generally account for over 99 percent of the actual transport (Zobeck and Fryrear, 1986; Vories and Fryrear, 1991; Sterk and Raats, 1996; Zobeck and others, 2003). The curve-fitting procedure uses a five-parameter combined power-law and exponential function that has been shown to model vertical aeolian mass flux more accurately than either power-law (Zobeck and Fryrear, 1986; Fryrear and others, 1991) or exponential (Vories and Fryrear, 1991) fits alone (Sterk and Raats, 1996). The actual mass flux is considered to span an efficiency range of 70–130% for the BSNE traps with the grain size at the various study locations and the wind speeds measured (Goossens and others, 2000). This efficiency range was used as the basis for estimating the error on the sand-transport data. It therefore constitutes a very conservative treatment of the data but this error approximation is the best available given that these are bulk sand-transport data (the exact correspondence between wind speed and local sand transport is unknown).

Grain-size analyses were completed for representative samples of sand at the location of each instrument tripod at the time of initial deployment. Sediment samples were analyzed using a Beckman Coulter LS 100Q laser particle-size analyzer linked to a LS variable-speed fluid module. Median grain size (d_{50}) for these 'grab samples' from each of the study sites is shown in table 1. The particle-size data allowed estimation of the critical threshold of motion at these sites; that is, the wind velocity needed to mobilize and transport sand grains of a certain size. Using the formulation developed by Bagnold (1941), the critical threshold of motion for sand of the grain sizes collected at these study sites is approximately 2 m s^{-1}.

Data Processing:

Data downloaded from the data loggers (wind speed, gust speed, wind direction, and rainfall) were exported from Onset Boxcar™ software into Microsoft Excel spreadsheets and then into Mathworks™ MATLAB software for subsequent manipulation and analysis. The first four and last four data points of each data set were deleted because these typically corresponded to the times during which maintenance activities were conducted on the stations, which may have affected data quality.

In analyzing the wind data, it is useful to consider not only wind velocity but the potential for aeolian sediment transport that can result from a given wind velocity. We used a proxy variable to represent the potential for sediment transport due to wind velocity. This variable, Qp, is calculated for data points in which wind velocity (u) exceeds the critical threshold of motion (u_{crit}), and is defined as the difference between the measured wind velocity and the critical threshold of motion (taken to be 2 m s^{-1}), raised to the third power:

$$Qp = \left(u - u_{crit}\right)^3$$

This relationship between wind velocity and potential for sediment transport follows the convention used to develop aeolian sediment-transport models such

Station	d_{50} (microns)
24.5 L	198.8
24.5 U	214.6
Mal L	204
Mal U	312.9
Pal L	boulders
Pal U	156.7
Com	150.1
For	225.7
202.9 mile	210.3

Table 1. *Median grain size, d_{50}, for sand at the locations of the nine weather stations, measured by Coulter laser particle-size analysis. Station Pal L was located in a cobble/boulder bar; the others are on sand deposits.*

as those of Kawamura (1951) and Lettau and Lettau (1977), but substitutes wind velocity for shear velocity (u_*). The variable *Qp* has units of $m^3 s^{-3}$; while these units do not directly translate to a mass flux, comparing spatial and temporal variations in the relative magnitude of *Qp* values yields information about the potential for sediment redistribution by wind. For data points in which wind velocity is less than u_{crit}, we have set *Qp* equal to zero, indicating that no sediment transport would occur.

RESULTS

Files containing complete records from these instrument stations in Microsoft Excel™ spreadsheet format are available to be downloaded at http://pubs.usgs.gov/of/2006/1188/. An example of a high-resolution wind-velocity record for one month (four-minute averages of wind velocity) is shown in figure 3. This record was collected during September, 2005, at Station Mal U. At this resolution, it is apparent that wind direction can change radically over very short time intervals. Wind direction often varies on a diurnal cycle (fig. 3), with the direction in this record coming from the south (directed upstream) most consistently in the afternoon. Wind velocity is typically highest in the afternoon. Because sediment transport would occur only with wind >2 $m s^{-1}$, the greatest potential for transport in the record shown in figure 3 would also be directed upstream (wind blowing from the south).

Diurnally averaged wind conditions are reported for each individual station and are discussed in more detail below. Vector sums indicating the magnitude and direction of potential sediment transport (*Qp*) are listed by month for each weather station in table 2.

Precipitation data for calendar-year 2005 are summarized in figure 4 and in tables 3 and 4. Table 4 also includes the available data from days in January 2006 when stations recorded data before they were dismantled. These data include the latter part of the unusually wet winter of 2004–2005, during which

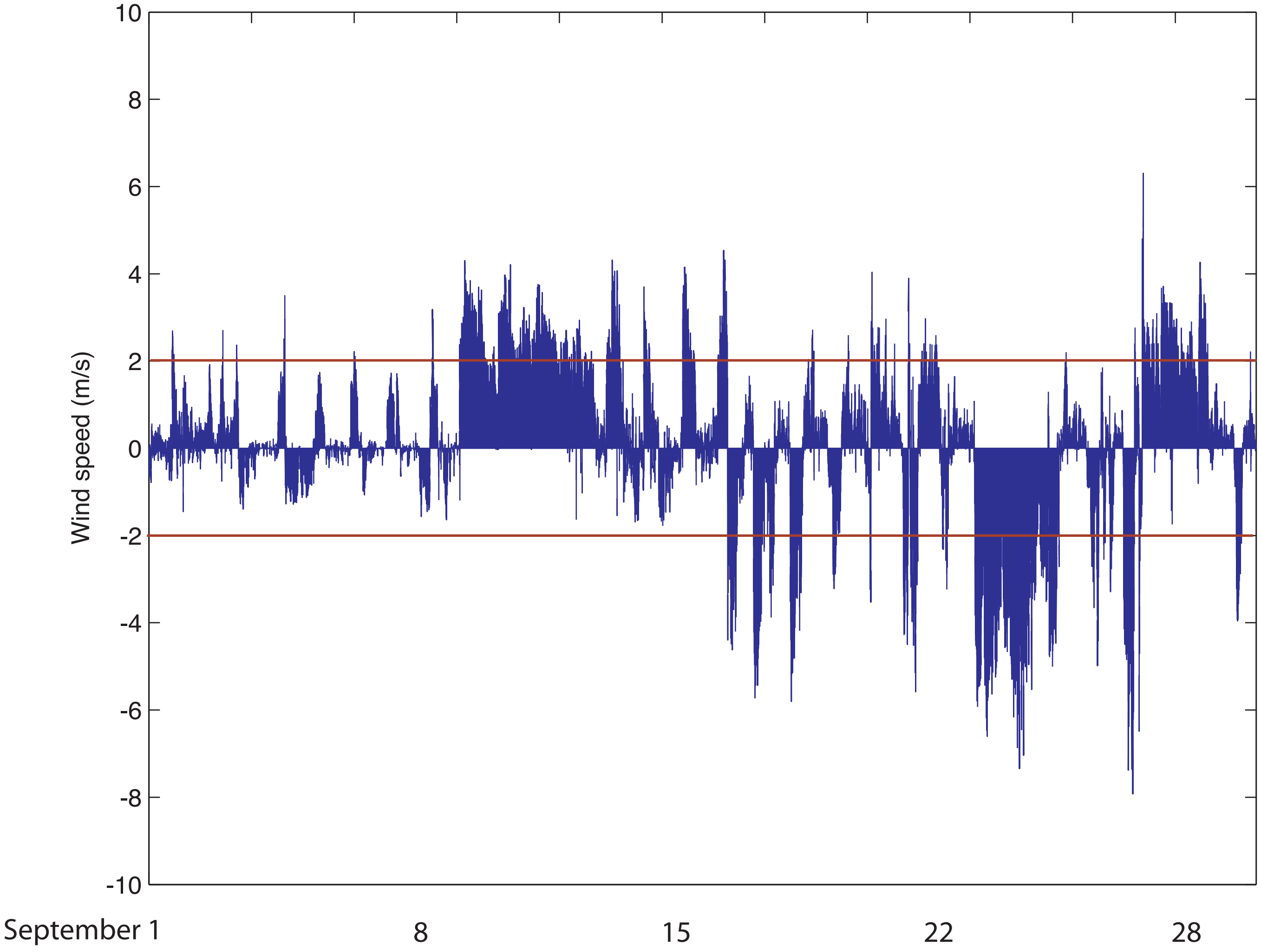

FIGURE 3. *Example of high-resolution wind-speed data for one month at one weather station; data were collected during September 2005 at the upper of the two stations at Malgosa, river-mile 57.9 (Station Mal U). Data represent wind speed averaged over four-minute intervals, sampled every four minutes. Line lengths represent magnitude of wind speed for each data point; orientation of the lines indicates the direction from which the wind blew. At Malgosa, the trend of the main canyon is approximately north-south, such that the dominant wind directions (upstream and downstream) are readily apparent. Wind speeds in this record tended to increase during the afternoons; wind direction often varied diurnally and could change radically over very short time intervals. The critical threshold of motion for sand of grain size ~300 m (at this site the median grain size,* d_{50}*, is 313* μ*) is approximately 2 m* s^{-1}*; wind velocities capable of transporting sand must exceed this (red horizontal lines). For September 2005, the direction of dominant transport at this site was from the southeast (from 140 degrees; tab. 2a), directed upstream.*

Station	Jan-05	Feb-05	Mar-05	Apr-05	May-05	Jun-05	Jul-05	Aug-05	Sep-05	Oct-05	Nov-05	Dec-05
24.5 L	171, 180	11, 124	496, 212	2294, 245	934, 233	1050, 220	224, 236	58, 203	584, 222	428, 221	316, 148	86, 154
24.5 U	454, 222	111, 222	2063, 247	8272, 256	4645, 248	6456, 209	2004, 206	1358, 199	3124, 211	3104, 220	715, 177	360, 182
Mal L	3312, 157	756, 171	5509, 150	18265, 149	14475, 151	9972, 163	1124, 175	132, 184	N/A	N/A	N/A	N/A
Mal U	24934, 149	6396, 141	66558, 169	164250, 172	124640, 169	141770, 137	51587, 139	7349, 124	76466, 140	57697, 160	11746, 152	18169, 158
Pal L	8556, 165	1089, 22	12495, 180	18044, 181	5653, 180	6498, 183	2735, 203	1315, 290	2376, 181	2268, 178	858, 148	10828, 174
Pal U	34221, 141	4564, 64	45218, 150	N/A	N/A	N/A	N/A	N/A	N/A	21738, 117	14467, 100	44043, 131
Com	724, 161	344, 18	957, 130	3616, 147	1794, 139	2677, 178	349, 181	663, 26	1280, 179	1235, 164	654, 58	2035, 167
For	9837, 15	603, 11	29244, 10	N/A	N/A	N/A	N/A	N/A	N/A	22460, 27	3534, 37	34148, 40
202.9	N/A	821, 352	468, 343	685, 189	641, 184	703, 181	129, 209	800, 349	488, 182	97, 208	437, 335	309, 306

Table 2a

Station	Jan-05	Feb-05	Mar-05	Apr-05	May-05	Jun-05	Jul-05	Aug-05	Sep-05	Oct-05	Nov-05	Dec-05
24.5 L	1, 51	12, 99	452, 227	2165, 245	909, 235	760, 222	161, 248	14, 41	554, 223	428, 221	316, 148	55, 176
24.5 U	10, 238	21, 177	1956, 252	7734, 256	4414, 249	5304, 211	1567, 209	658, 204	2964, 212	3080, 220	715, 177	298, 192
Mal L	38, 134	312, 161	3745, 148	17165, 149	14415, 151	9564, 162	1142, 175	233, 166	N/A	N/A	N/A	N/A
Mal U	1650, 338	1643, 125	41584, 169	126550, 170	119660, 169	128110, 137	51654, 139	6586, 135	75186, 140	54425, 160	11746, 152	17427, 160
Pal L	988, 43	809, 18	6207, 182	16757, 180	5619, 180	5427, 180	2700, 200	665, 244	2410, 181	2224, 177	799, 143	9499, 173
Pal U	2183, 55	2992, 55	22003, 152	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Com	29, 99	195, 19	500, 140	3437, 145	1814, 139	2009, 180	457, 184	47, 143	590, 175	1246, 164	672, 57	2035, 167
For	2, 172	518, 11	6800, 8	N/A	N/A	N/A	N/A	N/A	N/A	20580, 27	3536, 37	31757, 41
202.9	N/A	330, 353	381, 345	626, 189	397, 184	N/A	N/A	N/A	N/A	97, 208	423, 333	313, 307

Table 2b

TABLE 2. *Vector sums of the sediment-transport proxy variable, Qp, by month for each weather station. Vector sums were calculated using wind velocity and direction measurements from the 2.0-m anemometer at each station, and are reported as the magnitude of Qp (in* $m^3\ s^{-3}$*) followed by the direction from which this net transport would occur, in degrees. (a) vector sums for all months at all stations where complete months of data were available. These calculations were made irrespective of rain events. (b) vector sums re-calculated using wind data only from time when sand is assumed to have been dry enough to transport sand. These calculations (in part b) omit wind data collected within 48 hours of a rainfall event.*

	24.5 L	24.5 U	Mal L	Mal U	Pal L	Pal U	Com	For	202.9
Jan-05	29.0	28.0	62.8	62.8	21.4	20.6	23.6	51.4	54.4
Feb-05	30.4	28.2	50.8	52.8	25.8	25.2	25.6	70.0	85.6
Mar-05	7.0	6.6	7.0	7.2	6.2	5.8	5.8	17.8	11.6
Apr-05	18.2	17.0	14.0	13.4	19.6	N/A	20.6	N/A	26.8
May-05	5.6	5.0	4.4	3.8	3.4	N/A	3.4	N/A	3.2*
Jun-05	13.6	12.8	12.2	12.0	14.2	N/A	17.6	14.4*	N/A
Jul-05	10.2	9.8	27.0	26.0	7.8	N/A	7.0	10.2*	N/A
Aug-05	52.8	49.4	69.6	72.0	21.2	N/A	20.2	N/A	N/A
Sep-05	2.8	2.8	0.8	3.8	4.0	N/A	2.6	0.6*	N/A
Oct-05	18.8	16.4	N/A	14.6	7.4	N/A	11.4	24.2	19.4
Nov-05	0.0	0.0	N/A	0.0	0.4	N/A	0.2	0.4	4.0
Dec-05	0.8	0.8	N/A	0.4	1.8	N/A	0.0	0.4	0.8
Total	**189.2**	**176.8**	**248.6***	**268.8**	**133.2**	**51.6***	**138.0**	**164.2***	**202.6***

TABLE 3. *Total rainfall, in mm, received each month at each of the weather stations from January through December 2005.*
An asterisk (*) indicates an incomplete record. N/A indicates that no working rain gage operated at that station for that month.
For comparison, the rain gauge operated by NPS at Phantom Ranch (near river-mile 88) recorded ~330 mm of rain in 2005 (K. Redmond, Desert Research Institute, personal communication, 2006).

TABLE 4. *Total rainfall, in mm, received daily at each of the weather stations. N/A indicates that there was no working rain gauge at that station for that day.*

	24.5 L	24.5 U	Mal L	Mal U	Pal L	Pal U	Com	For	202.9	Year Day
1/1/05	0	0	0	0	0	0	0	0	0	1
1/2/05	0	0	0	0	0	0	0	0	0	2
1/3/05	10.6	9.8	13.0	13.4	9.4	9.4	7.8	5.4	0	3
1/4/05	2.4	2.4	3.2	3.4	1.4	1.4	1.8	7.0	0	4
1/5/05	0	0	0	0	0	0	0	0	0	5
1/6/05	0	0	0.2	0.2	0	0	0	2.4	0	6
1/7/05	0.4	0.4	2.6	2.2	2.6	2.6	3.0	7.0	0	7
1/8/05	0.2	0.2	11.4	10.8	1.8	1.8	2.6	1.4	0	8
1/9/05	0	0	3.2	3.4	0.4	0.4	0.2	5.0	12.8	9
1/10/05	0.2	0.2	1.8	1.8	1.0	0.8	1.4	2.8	8.8	10
1/11/05	0.6	0.6	15.2	14.2	1.6	1.4	2.0	6.0	5.0	11
1/12/05	0	0	0	0	0	0	0	0	0	12
1/13/05	0	0	0	0	0	0	0	0	0	13
1/14/05	0	0	0	0	0	0	0	0	0	14
1/15/05	0	0	0	0	0	0	0	0	0	15
1/16/05	0	0	0	0	0	0	0	0	0	16
1/17/05	0	0	0	0	0	0	0	0	0	17
1/18/05	0	0	0	0	0	0	0	0	0	18
1/19/05	0	0	0	0	0	0	0	0	0	19
1/20/05	0	0	0	0	0	0	0	0	0	20
1/21/05	0	0	0	0	0	0	0	0	0	21
1/22/05	0	0	0	0	0	0	0	0	0	22
1/23/05	0	0	0	0	0	0	0	0	0	23
1/24/05	0	0	0	0	0	0	0	0	0	24
1/25/05	0	0	0	0	0	0	0	0	0	25
1/26/05	10.6	10.2	8.8	9.4	1.2	1.0	1.6	8.4	6.2	26
1/27/05	3.0	3.2	0.4	0.6	0.6	0.4	1.0	2.0	4.2	27
1/28/05	0	0	0	0	0	0	0	0	1.8	28
1/29/05	0.8	0.8	3.0	3.4	1.2	1.4	2.0	4.0	15.6	29
1/30/05	0.2	0.2	0	0	0.2	0	0	0	0	30
1/31/05	0	0	0	0	0	0	0	0	0	31
2/1/05	0	0	0	0	0	0	0	0	0	32
2/2/05	0	0	0	0	0	0	0	0	0	33
2/3/05	0	0	0	0	0	0	0	0	0	34
2/4/05	0	0	0	0	0	0	0	0	0	35
2/5/05	0	0	0	0	0	0	0	0	0	36
2/6/05	0	0	0	0	0	0	0	2.0	5.4	37

2/7/05	0.2	0.2	3.4	3.4	2.4	2.2	2.2	8.4	3.2	38
2/8/05	0	0	0	0	0.8	0.8	1.4	0.2	0	39
2/9/05	0	0	0	0	0	0	0	0	0	40
2/10/05	0	0	0	0	0	0	0	0	0	41
2/11/05	12.0	11.0	26.8	29.4	7.0	6.2	6.0	18.8	24.6	42
2/12/05	1.8	1.6	1.2	1.0	1.8	1.8	2.8	6.4	6.8	43
2/13/05	0	0	0	0	0	0	0	0.2	0	44
2/14/05	0	0	0	0	0	0	0	0	0	45
2/15/05	0.8	0.8	0.8	0.8	0.6	0.4	0.4	2.2	3.2	46
2/16/05	0.6	0.6	1.6	1.6	0.8	1.0	0.4	5.2	0.4	47
2/17/05	0	0	0	0	0	0	0	0.4	0.8	48
2/18/05	3.0	2.8	3.0	3.0	1.8	1.8	2.0	14.4	12.2	49
2/19/05	0.2	0.2	0.6	0.6	0.2	0.2	0	1.4	3.6	50
2/20/05	0	0	0.6	0.8	0	0	0	1.0	0.2	51
2/21/05	0.6	0.6	0.8	1.0	0.2	0.2	0.2	2.8	0.8	52
2/22/05	1.6	1.6	5.4	4.8	5.8	6.4	6.0	1.0	12.8	53
2/23/05	5.6	5.2	4.0	3.6	2.4	2.4	1.8	4.8	0	54
2/24/05	4.0	3.6	2.4	2.6	1.2	1.0	0.8	0	0.6	55
2/25/05	0	0	0.2	0.2	0	0.2	0	0	0	56
2/26/05	0	0	0	0	0.6	0.4	1.6	0	0.4	57
2/27/05	0	0	0	0	0	0	0	0	0	58
2/28/05	0	0	0	0	0.2	0.2	0	0.8	10.6	59
3/1/05	0	0	0	0	0	0	0	0	0.2	60
3/2/05	0	0	0	0	0	0	0	0	0	61
3/3/05	0	0	2.2	2.4	1.8	1.8	1.4	3.2	4.2	62
3/4/05	0	0	0	0	0	0	0	0	0.2	63
3/5/05	1.2	1.0	2.2	2.2	0.8	0.8	0.4	0	0.2	64
3/6/05	0.4	0.6	0	0	0	0	0.2	0	0	65
3/7/05	0	0	0	0	0	0	0	0	0	66
3/8/05	0	0	0	0	0	0	0	0	0	67
3/9/05	0	0	0	0	0	0	0	0	0	68
3/10/05	0	0	0	0	0	0	0	0	0	69
3/11/05	0	0	0	0	0	0	0	0	0	70
3/12/05	0	0	0	0	0	0	0	0	0	71
3/13/05	0	0	0	0	0	0	0	0	0	72
3/14/05	0	0	0	0	0	0	0	0	0	73
3/15/05	0	0	0	0	0	0	0	0	0	74
3/16/05	0	0	0	0	0	0	0	0	0	75
3/17/05	0	0	0	0	0	0	0	0	0	76
3/18/05	0	0	0	0	0	0	0	0	0	77
3/19/05	0	0	0.2	0.2	1.0	1.0	0.6	1.8	0.4	78
3/20/05	0	0	0.2	0	0.2	0	0.2	0	0	79
3/21/05	0	0	0	0	0	0	0.2	0	0	80

3/22/05	0	0	0	0	0	0	0	0	1.0	81
3/23/05	0	0	0.2	0.2	0.6	0.6	0.6	1.8	4.2	82
3/24/05	0	0	0	0	0	0	0	0	0	83
3/25/05	0.8	0.8	0.4	0.6	0.2	0.2	0.8	0.6	0.6	84
3/26/05	0	0	0	0	0	0	0	0	0	85
3/27/05	0	0	0	0	0	0	0	0	0	86
3/28/05	3.4	3.0	1.4	1.4	0.6	0.4	0.4	4.6	0.6	87
3/29/05	0.2	0.2	0	0	0.6	0.8	0.6	1.6	0	88
3/30/05	1.0	1.0	0.2	0.2	0.4	0.2	0.4	4.2	0	89
3/31/05	0	0	0	0	0	0	0	0	0	90
4/1/05	0	0	0	0	0	0	0	0	0	91
4/2/05	0	0	0	0	0	N/A	0	0	0	92
4/3/05	0	0	0	0	0	N/A	0	N/A	0	93
4/4/05	0	0	0	0	0	N/A	0	N/A	0	94
4/5/05	0	0	0	0	0	N/A	0	N/A	0	95
4/6/05	0	0	0	0	0	N/A	0	N/A	0	96
4/7/05	0	0	0	0	0	N/A	0	N/A	0	97
4/8/05	0	0	0	0	0	N/A	0	N/A	0	98
4/9/05	3.0	2.6	0.4	0.4	1.6	N/A	2.0	N/A	0	99
4/10/05	0	0.2	0	0	0	N/A	0	N/A	0	100
4/11/05	0	0	0	0	0	N/A	0	N/A	0	101
4/12/05	0	0	0	0	0	N/A	0	N/A	0	102
4/13/05	0	0	0	0	0	N/A	0	N/A	0	103
4/14/05	0	0	0	0	0	N/A	0	N/A	0	104
4/15/05	0	0	0	0	0	N/A	0	N/A	0	105
4/16/05	0	0	0	0	0	N/A	0	N/A	0	106
4/17/05	0	0	0	0	0	N/A	0	N/A	0	107
4/18/05	0	0	0	0	0	N/A	0	N/A	0	108
4/19/05	0	0	0	0	0	N/A	0	N/A	0	109
4/20/05	0	0	0	0	0	N/A	0	N/A	0	110
4/21/05	0	0	0	0	0	N/A	0	N/A	0	111
4/22/05	0	0	0	0	0	N/A	0	N/A	0	112
4/23/05	1.4	1.2	0.2	0.2	0	N/A	0.2	N/A	10.2	113
4/24/05	13.4	12.4	12.0	11.2	13.8	N/A	14.6	N/A	5.8	114
4/25/05	0	0	0	0.4	1.4	N/A	1.6	N/A	0	115
4/26/05	0	0	0	0	0	N/A	0	N/A	5.0	116
4/27/05	0	0	0.2	0.2	0	N/A	0	N/A	1.6	117
4/28/05	0.4	0.6	1.2	0.8	2.8	N/A	2.2	N/A	4.2	118
4/29/05	0	0	0	0.2	0	N/A	0	N/A	0	119
4/30/05	0	0	0	0	0	N/A	0	N/A	0	120
5/1/05	0	0	0	0	0	N/A	0	N/A	0	121
5/2/05	3.2	2.8	2.4	2.0	2.2	N/A	2.4	N/A	0.4	122
5/3/05	1.2	1.2	0.4	0.2	0	N/A	0	N/A	0	123

5/4/05	0	0	0	0	0	N/A	0	N/A	0	124
5/5/05	0	0	0	0	0	N/A	0	N/A	0	125
5/6/05	1.0	0.8	1.6	1.6	1.2	N/A	1.0	N/A	2.0	126
5/7/05	0	0	0	0	0	N/A	0	N/A	0	127
5/8/05	0	0	0	0	0	N/A	0	N/A	0	128
5/9/05	0	0	0	0	0	N/A	0	N/A	0	129
5/10/05	0	0	0	0	0	N/A	0	N/A	0	130
5/11/05	0	0	0	0	0	N/A	0	N/A	0	131
5/12/05	0	0	0	0	0	N/A	0	N/A	0	132
5/13/05	0	0	0	0	0	N/A	0	N/A	0	133
5/14/05	0	0	0	0	0	N/A	0	N/A	0.8	134
5/15/05	0	0	0	0	0	N/A	0	N/A	0	135
5/16/05	0	0	0	0	0	N/A	0	N/A	0	136
5/17/05	0	0	0	0	0	N/A	0	N/A	0	137
5/18/05	0	0	0	0	0	N/A	0	N/A	0	138
5/19/05	0	0	0	0	0	N/A	0	N/A	0	139
5/20/05	0	0	0	0	0	N/A	0	N/A	0	140
5/21/05	0	0	0	0	0	N/A	0	N/A	0	141
5/22/05	0	0	0	0	0	N/A	0	N/A	0	142
5/23/05	0	0	0	0	0	N/A	0	N/A	0	143
5/24/05	0	0	0	0	0	N/A	0	N/A	0	144
5/25/05	0	0	0	0	0	N/A	0	N/A	0	145
5/26/05	0	0	0	0	0	N/A	0	N/A	0	146
5/27/05	0.2	0.2	0	0	0	N/A	0	N/A	0	147
5/28/05	0	0	0	0	0	N/A	0	N/A	0	148
5/29/05	0	0	0	0	0	N/A	0	N/A	0	149
5/30/05	0	0	0	0	0	N/A	0	N/A	0	150
5/31/05	0	0	0	0	0	N/A	0	N/A	0	151
6/1/05	0	0	0	0	0	N/A	0	N/A	0	152
6/2/05	0	0	0	0	0	N/A	0	N/A	0	153
6/3/05	0	0	0	0	0	N/A	0	0	0	154
6/4/05	0	0	0	0	0	N/A	0	0	0	155
6/5/05	0	0	0	0	0	N/A	0	0	0	156
6/6/05	0	0	0	0	0	N/A	0	0	0	157
6/7/05	0	0	0	0	0	N/A	0	0	0	158
6/8/05	0	0	0	0	0	N/A	0	0	0	159
6/9/05	0.2	0.2	2.2	2.2	1.2	N/A	1.2	0	0	160
6/10/05	0	0	0	0	0	N/A	0	0	N/A	161
6/11/05	11.4	10.6	7.8	7.8	1.4	N/A	1.8	14.4	N/A	162
6/12/05	0	0	0	0	0	N/A	0	0	N/A	163
6/13/05	0	0	0	0	0	N/A	0	0	N/A	164
6/14/05	0	0	0	0	0	N/A	0	N/A	N/A	165
6/15/05	0	0	0	0	0	N/A	0	N/A	N/A	166

6/16/05	0	0	0	0	0	N/A	0	N/A	N/A	167
6/17/05	0	0	0	0	0	N/A	0	N/A	N/A	168
6/18/05	0	0	0	0	0	N/A	0	N/A	N/A	169
6/19/05	0	0	0	0	0	N/A	0	N/A	N/A	170
6/20/05	0	0	0	0	0	N/A	0	N/A	N/A	171
6/21/05	0.6	0.6	0	0	1.8	N/A	1.8	N/A	N/A	172
6/22/05	0	0	0	0	0.4	N/A	0	N/A	N/A	173
6/23/05	1.0	1.0	1.2	1.2	7.0	N/A	10.2	N/A	N/A	174
6/24/05	0.4	0.4	0	0	1.4	N/A	1.8	N/A	N/A	175
6/25/05	0	0	1.0	0.8	0.6	N/A	0.6	N/A	N/A	176
6/26/05	0	0	0	0	0	N/A	0	N/A	N/A	177
6/27/05	0	0	0	0	0	N/A	0	N/A	N/A	178
6/28/05	0	0	0	0	0.4	N/A	0.2	N/A	N/A	179
6/29/05	0	0	0	0	0	N/A	0	N/A	N/A	180
6/30/05	0	0	0	0	0	N/A	0	N/A	N/A	181
7/1/05	0	0	0	0	0	N/A	0	N/A	N/A	182
7/2/05	0	0	0	0	0	N/A	0	N/A	N/A	183
7/3/05	0	0	0	0	0	N/A	0	N/A	N/A	184
7/4/05	0	0	0	0	0	N/A	0	N/A	N/A	185
7/5/05	0	0	0	0	0	N/A	0	N/A	N/A	186
7/6/05	0	0	0	0	0	N/A	0	N/A	N/A	187
7/7/05	0	0	0	0	0	N/A	0	N/A	N/A	188
7/8/05	0	0	0	0	0	N/A	0	N/A	N/A	189
7/9/05	0	0	0	0	0	N/A	0	N/A	N/A	190
7/10/05	0	0	0	0	0	N/A	0	N/A	N/A	191
7/11/05	0	0	0	0	0	N/A	0	N/A	N/A	192
7/12/05	0	0	0	0	0	N/A	0	N/A	N/A	193
7/13/05	0	0	0	0	0	N/A	0	N/A	N/A	194
7/14/05	0	0	0	0	0	N/A	0	N/A	N/A	195
7/15/05	0	0	0	0	0	N/A	0	N/A	N/A	196
7/16/05	0.8	1.0	0	0	0	N/A	0	N/A	N/A	197
7/17/05	0	0	0	0	0	N/A	0	N/A	N/A	198
7/18/05	0	0	0	0	0	N/A	0	N/A	N/A	199
7/19/05	0	0	0	0	0	N/A	0	N/A	N/A	200
7/20/05	0	0	0	0	0	N/A	0	N/A	N/A	201
7/21/05	0	0	0	0	0	N/A	0	N/A	N/A	202
7/22/05	0	0	0	0	0	N/A	0	N/A	N/A	203
7/23/05	0	0	0	0	0	N/A	0	N/A	N/A	204
7/24/05	0	0	0	0	0	N/A	0	0	N/A	205
7/25/05	6.8	6.0	6.6	6.2	5.0	N/A	1.0	10.2	N/A	206
7/26/05	0	0	9.0	8.2	1.2	N/A	5.8	0	N/A	207
7/27/05	0	0	0	0	0	N/A	0	0	N/A	208
7/28/05	0	0	0	0	0	N/A	0	0	N/A	209

7/29/05	0	0	0	0	0	N/A	0	0	N/A	210
7/30/05	0	0	0	0	0	N/A	0	N/A	N/A	211
7/31/05	2.6	2.8	11.4	11.6	1.6	N/A	0.2	N/A	N/A	212
8/1/05	3.4	2.8	4.4	4.4	3.2	N/A	2.6	N/A	N/A	213
8/2/05	0	0	1.4	1.0	1.6	N/A	2.8	N/A	N/A	214
8/3/05	0	0	0	0	0	N/A	0	N/A	N/A	215
8/4/05	0	0	0.2	0.2	0	N/A	2.2	N/A	N/A	216
8/5/05	0	0	0	0	0.4	N/A	0	N/A	N/A	217
8/6/05	0	0	0	0	0	N/A	0	N/A	N/A	218
8/7/05	0	0	0	0	0	N/A	0	N/A	N/A	219
8/8/05	11.2	12.6	8.0	6.8	0	N/A	0.6	N/A	N/A	220
8/9/05	0	0	0	0	0	N/A	0	N/A	N/A	221
8/10/05	9.6	8.4	24.8	26.4	0.6	N/A	1.0	N/A	N/A	222
8/11/05	15.6	13.2	1.0	1.0	1.6	N/A	0.8	N/A	N/A	223
8/12/05	0	0	0	0	0	N/A	0	N/A	N/A	224
8/13/05	8.0	7.8	21.8	23.0	0	N/A	0	N/A	N/A	225
8/14/05	0	0	2.0	2.2	0	N/A	1.2	N/A	N/A	226
8/15/05	0	0	0	0	0	N/A	0	N/A	N/A	227
8/16/05	0.4	0.4	0	0	0	N/A	0	N/A	N/A	228
8/17/05	0	0	0	0	0	N/A	0	N/A	N/A	229
8/18/05	0	0	0	0	5.2	N/A	1.8	N/A	N/A	230
8/19/05	4.6	4.2	1.6	1.8	8.6	N/A	7.0	N/A	N/A	231
8/20/05	0	0	0	0	0	N/A	0	N/A	N/A	232
8/21/05	0	0	0	0	0	N/A	0	N/A	N/A	233
8/22/05	0	0	0	0	0	N/A	0	N/A	N/A	234
8/23/05	0	0	4.4	5.2	0	N/A	0.2	N/A	N/A	235
8/24/05	0	0	0	0	0	N/A	0	N/A	N/A	236
8/25/05	0	0	0	0	0	N/A	0	N/A	N/A	237
8/26/05	0	0	0	0	0	N/A	0	N/A	N/A	238
8/27/05	0	0	0	0	0	N/A	0	N/A	N/A	239
8/28/05	0	0	0	0	0	N/A	0	N/A	N/A	240
8/29/05	0	0	0	0	0	N/A	0	N/A	N/A	241
8/30/05	0	0	0	0	0	N/A	0	N/A	N/A	242
8/31/05	0	0	0	0	0	N/A	0	N/A	N/A	243
9/1/05	0	0	0	0	0	N/A	0	N/A	N/A	244
9/2/05	0	0	0	0	0	N/A	0.4	N/A	N/A	245
9/3/05	1.4	1.2	0.4	0.4	3.4	N/A	1.2	N/A	N/A	246
9/4/05	1.4	1.6	0.4	0.4	0	N/A	0	N/A	N/A	247
9/5/05	0	0	0	0	0	N/A	0	N/A	N/A	248
9/6/05	0	0	0	0	0	N/A	0	N/A	N/A	249
9/7/05	0	0	0	0	0	N/A	0	N/A	N/A	250
9/8/05	0	0	0	0	0	N/A	0.4	N/A	N/A	251
9/9/05	0	0	0	0	0	N/A	0	N/A	N/A	252

9/10/05	0	0	0	0	0	N/A	0	N/A	N/A	253
9/11/05	0	0	0	0	0	N/A	0	N/A	N/A	254
9/12/05	0	0	0	0	0	N/A	0	N/A	N/A	255
9/13/05	0	0	0	0	0	N/A	0	N/A	N/A	256
9/14/05	0	0	0	0	0	N/A	0	N/A	N/A	257
9/15/05	0	0	0	0	0	N/A	0	N/A	N/A	258
9/16/05	0	0	0	0	0	N/A	0	N/A	N/A	259
9/17/05	0	0	0	0	0	N/A	0	N/A	N/A	260
9/18/05	0	0	0	0	0	N/A	0	N/A	N/A	261
9/19/05	0	0	N/A	0	0	N/A	0	N/A	N/A	262
9/20/05	0	0	N/A	0.6	0	N/A	0	0.6	N/A	263
9/21/05	0	0	N/A	0	0	N/A	0	0	N/A	264
9/22/05	0	0	N/A	0	0	N/A	0	0	0	265
9/23/05	0	0	N/A	0	0	N/A	0	0	0	266
9/24/05	0	0	N/A	0	0	N/A	0	0	0	267
9/25/05	0	0	N/A	0	0	N/A	0	0	0	268
9/26/05	0	0	N/A	0	0	N/A	0	0	0	269
9/27/05	0	0	N/A	2.4	0.6	N/A	5.6	0	0	270
9/28/05	0	0	N/A	0	0	N/A	5.8	0	0	271
9/29/05	0	0	N/A	0	0	N/A	0	0	0	272
9/30/05	0	0	N/A	0	0	N/A	0	0	0	273
10/1/05	0	0	N/A	0	0	N/A	0	0	0	274
10/2/05	0	0	N/A	0	0	N/A	0	0	0	275
10/3/05	0	0	N/A	0	0	N/A	0	0	0	276
10/4/05	0	0	N/A	0	0	N/A	0	0	0	277
10/5/05	0	0	N/A	0	0	N/A	0	0	0	278
10/6/05	0	0	N/A	0	0	N/A	0	0	0	279
10/7/05	0	0	N/A	0	0	N/A	0	0	0	280
10/8/05	0	0	N/A	0	0	N/A	0	0	0	281
10/9/05	0	0	N/A	0	0	N/A	0	0	0	282
10/10/05	0	0	N/A	0	0	N/A	0	0	0	283
10/11/05	0	0	N/A	0	0	N/A	0	0	0	284
10/12/05	0	0	N/A	0	0	N/A	0	0	0	285
10/13/05	0	0	N/A	0	0	N/A	0	0	0	286
10/14/05	0	0	N/A	0	0	N/A	0	0	0	287
10/15/05	1.6	1.4	N/A	1.8	2.4	N/A	5.6	1.4	0	288
10/16/05	0	0	N/A	0	0	N/A	0	0.2	0	289
10/17/05	0	0	N/A	0	0	N/A	0	0.6	1.4	290
10/18/05	17.2	15.0	N/A	11.8	4.6	N/A	5.8	20.2	18.0	291
10/19/05	0	0	N/A	0	0	N/A	0	0.2	0	292
10/20/05	0	0	N/A	0	0	N/A	0	0	0	293
10/21/05	0	0	N/A	0	0	N/A	0	0	0	294
10/22/05	0	0	N/A	0	0	N/A	0	0	0	295

10/23/05	0	0	N/A	0	0	N/A	0	0	0	296
10/24/05	0	0	N/A	0	0	N/A	0	0	0	297
10/25/05	0	0	N/A	0.2	0.4	N/A	0	1.0	0	298
10/26/05	0	0	N/A	0	0	N/A	0	0	0	299
10/27/05	0	0	N/A	0	0	N/A	0	0	0	300
10/28/05	0	0	N/A	0.8	0	N/A	0	0.6	0	301
10/29/05	0	0	N/A	0	0	N/A	0	0	0	302
10/30/05	0	0	N/A	0	0	N/A	0	0	0	303
10/31/05	0	0	N/A	0	0	N/A	0	0	0	304
11/1/05	0	0	N/A	0	0	N/A	0	0	0	305
11/2/05	0	0	N/A	0	0	N/A	0	0	0	306
11/3/05	0	0	N/A	0	0	N/A	0	0	0	307
11/4/05	0	0	N/A	0	0	N/A	0	0	0	308
11/5/05	0	0	N/A	0	0	N/A	0	0	0	309
11/6/05	0	0	N/A	0	0	N/A	0	0	0	310
11/7/05	0	0	N/A	0	0	N/A	0	0	0	311
11/8/05	0	0	N/A	0	0	N/A	0	0	0	312
11/9/05	0	0	N/A	0	0	N/A	0	0	0	313
11/10/05	0	0	N/A	0	0	N/A	0	0	0	314
11/11/05	0	0	N/A	0	0.4	N/A	0.2	0.4	4.0	315
11/12/05	0	0	N/A	0	0	N/A	0	0	0	316
11/13/05	0	0	N/A	0	0	N/A	0	0	0	317
11/14/05	0	0	N/A	0	0	N/A	0	0	0	318
11/15/05	0	0	N/A	0	0	N/A	0	0	0	319
11/16/05	0	0	N/A	0	0	N/A	0	0	0	320
11/17/05	0	0	N/A	0	0	N/A	0	0	0	321
11/18/05	0	0	N/A	0	0	N/A	0	0	0	322
11/19/05	0	0	N/A	0	0	N/A	0	0	0	323
11/20/05	0	0	N/A	0	0	N/A	0	0	0	324
11/21/05	0	0	N/A	0	0	N/A	0	0	0	325
11/22/05	0	0	N/A	0	0	N/A	0	0	0	326
11/23/05	0	0	N/A	0	0	N/A	0	0	0	327
11/24/05	0	0	N/A	0	0	N/A	0	0	0	328
11/25/05	0	0	N/A	0	0	N/A	0	0	0	329
11/26/05	0	0	N/A	0	0	N/A	0	0	0	330
11/27/05	0	0	N/A	0	0	N/A	0	0	0	331
11/28/05	0	0	N/A	0	0	N/A	0	0	0	332
11/29/05	0	0	N/A	0	0	N/A	0	0	0	333
11/30/05	0	0	N/A	0	0	N/A	0	0	0	334
12/1/05	0	0	N/A	0	0	N/A	0	0	0	335
12/2/05	0	0	N/A	0.2	1.6	N/A	0	0	0	336
12/3/05	0	0	N/A	0	0	N/A	0	0	0	337
12/4/05	0	0	N/A	0	0	N/A	0	0	0	338

12/5/05	0	0	N/A	0	0	N/A	0	0	0	339
12/6/05	0	0	N/A	0	0	N/A	0	0	0	340
12/7/05	0	0	N/A	0	0	N/A	0	0	0	341
12/8/05	0	0	N/A	0	0	N/A	0	0	0	342
12/9/05	0	0	N/A	0	0	N/A	0	0	0	343
12/10/05	0	0	N/A	0	0	N/A	0	0	0	344
12/11/05	0	0	N/A	0	0	N/A	0	0	0	345
12/12/05	0	0	N/A	0	0	N/A	0	0	0	346
12/13/05	0	0	N/A	0	0	N/A	0	0	0	347
12/14/05	0	0	N/A	0	0	N/A	0	0	0	348
12/15/05	0	0	N/A	0	0	N/A	0	0	0	349
12/16/05	0	0	N/A	0	0	N/A	0	0	0	350
12/17/05	0	0	N/A	0	0	N/A	0	0	0	351
12/18/05	0	0	N/A	0	0	N/A	0	0	0	352
12/19/05	0	0	N/A	0	0	N/A	0	0	0	353
12/20/05	0	0	N/A	0	0	N/A	0	0	0	354
12/21/05	0	0	N/A	0	0	N/A	0	0	0	355
12/22/05	0	0	N/A	0	0	N/A	0	0	0	356
12/23/05	0	0	N/A	0	0	N/A	0	0	0	357
12/24/05	0	0	N/A	0	0	N/A	0	0	0	358
12/25/05	0	0	N/A	0	0	N/A	0	0	0	359
12/26/05	0	0	N/A	0	0	N/A	0	0	0	360
12/27/05	0	0	N/A	0	0	N/A	0	0	0	361
12/28/05	0	0	N/A	0	0	N/A	0	0	0	362
12/29/05	0	0	N/A	0	0	N/A	0	0	0	363
12/30/05	0	0	N/A	0	0	N/A	0	0	0	364
12/31/05	0.8	0.8	N/A	0.2	0.2	N/A	0	0.4	0.8	365
1/1/06	0	0	N/A	0.2	0	N/A	0	0	0	1
1/2/06	0	0	N/A	0	0	N/A	0	0	0	2
1/3/06	0	0	N/A	0.2	0	N/A	0.2	0	0	3
1/4/06	0	0	N/A	0	0	N/A	0	0	0	4
1/5/06	0	0	N/A	0	0	N/A	0	0	0	5
1/6/06	0	0	N/A	0	0	N/A	0	0	0	6
1/7/06	0	0	N/A	0	0	N/A	0	0	0	7
1/8/06	0	0	N/A	0	0	N/A	0	0	0	8
1/9/06	0	0	N/A	0	0	N/A	0	0	0	9
1/10/06	0	0	N/A	0	0	N/A	0	0	0	10
1/11/06	0	0	N/A	0	0	N/A	0	0	0	11
1/12/06	N/A	N/A	N/A	0	0	N/A	0	0	0	12
1/13/06	N/A	N/A	N/A	0	0	N/A	0	0	0	13
1/14/06	N/A	N/A	N/A	0	0	N/A	0	0	0	14
1/15/06	N/A	N/A	N/A	N/A	N/A	N/A	0	0.2	0	15
1/16/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0	16

1/17/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0	17
1/18/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0	18
1/19/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0	19
1/20/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0	20
1/21/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0	21
1/22/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0	22
1/23/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0	23
1/24/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0	24
1/25/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1.6	0.6	25
1/26/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0	26
1/27/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	27
1/28/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	28
1/29/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	29

precipitation reached near record levels in northern Arizona, as well as the exceptionally dry fall and early winter of 2005. The month in this reporting interval with the greatest total rainfall was August 2005; within that month, the highest total monthly rainfall was recorded at Malgosa (72.0 mm, Station Mal U; tab. 3). The highest daily total rainfall was also recorded at Malgosa, where 29.4 mm of rain fell on 2/11/05 (Station Mal U; tab. 4).

Total rainfall varies substantially with location throughout the river corridor (tab. 3), and the same event may induce precipitation with great spatial variability (tab. 4). It is common for daily rainfall amounts at the upper and lower rain gauges at a single location to differ by several tenths of millimeters (for example, records from 1/3/05 at 24.5 mile or 1/26/05 at Malgosa; tab. 4). The two rain gauges at one location may also record daily rainfall totals that differ by as much as several mm (for example, on 8/10/05 at Malgosa, where rainfall was 24.8 mm and 26.4 mm at Stations Mal L and Mal U, respectively; tab. 4). Several strong but spatially isolated summer storms were recorded. One such event occurred on 8/13/05, on which day 24.5 mile received 7.8–8.0 mm of rain while Malgosa received 21.8–23.0 mm and Palisades and Comanche received no precipitation at all (tab. 4). For comparison with the data collected during this study, the rain gauge operated by NPS at Phantom Ranch (near river-mile 88) recorded 330 mm of precipitation during calendar-year 2005 (K. Redmond, Western Regional Climate Center, Desert Research Institute, personal communication, 2006).

24.5 mile:

The record reported for Station 24.5 L began at the start of 1/1/05 (as the station was already operating) and continued until 1209 hours on 1/12/06 with no interruptions other than routine maintenance. Sand-transport rates, diurnally averaged wind velocity, diurnal measurements of maximum gust speed, and total daily rainfall for Station 24.5 L from January 2005–January 2006 are shown in figure 5. All data collected previously at this station (Draut and Rubin, 2005) are also shown in figure 5 for comparison. Sediment-transport potential by direction for January through December 2005 is summarized in the rose diagram in figure

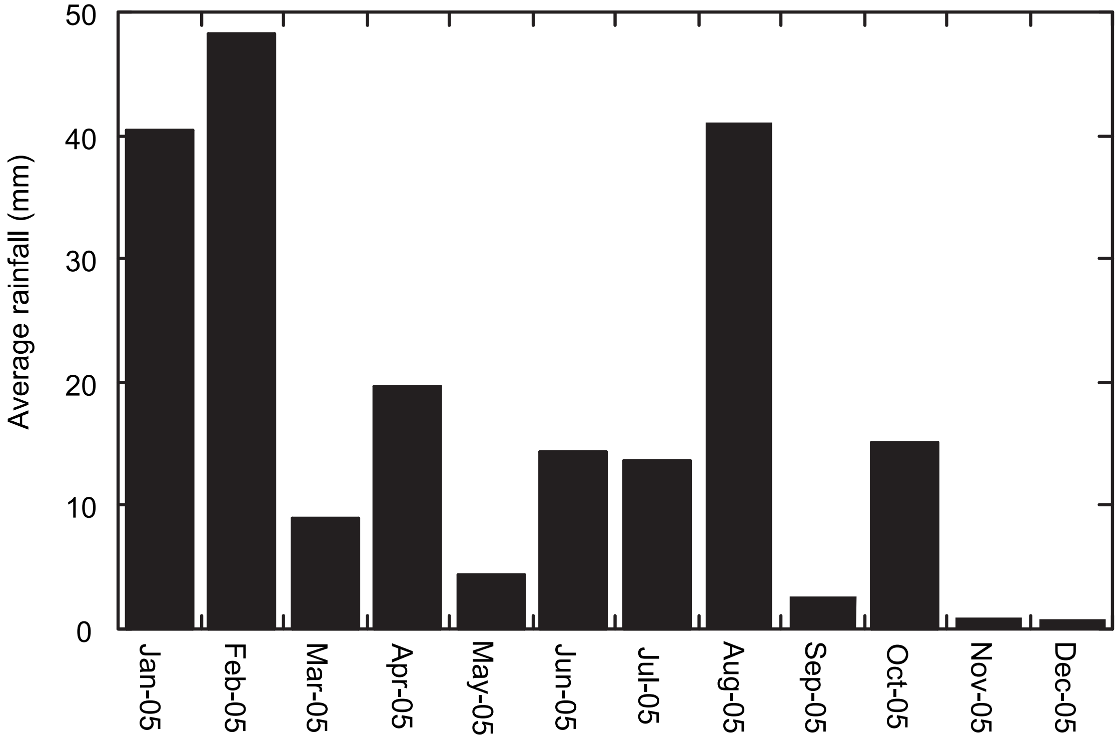

FIGURE 4. *Average monthly rainfall in the Colorado River corridor in Grand Canyon. Values are calculated for January through December 2005 using all available complete months of data from stations with functioning rain gauges (mean values were used to represent 24.5 mile, Malgosa, and Palisades, each of which had two instrument stations).*

6. A vector sum of the data for calendar-year 2005 at this station yields a net *Qp* magnitude of 5,974 m^3 s^{-3} from a direction of 244 degrees. For the previous complete calendar year, 2004, net *Qp* magnitude and direction at Station 24.5 L were 7,350 m^3 s^{-3} and 244 degrees, respectively (Draut and Rubin, 2005).

The record at Station 24.5 U began at the start of 1/1/05 (already operating) and continued until 1248 hours on 1/12/06 with no interruptions other than routine maintenance. Sand-transport, wind, and precipitation data for Station 24.5 U during calendar-year 2005 are shown in figure 7, along with all previously reported data from this station (Draut and Rubin, 2005) for comparison. Sediment transport measured at Station 24.5 U from data collected on 11/15/05 has been underestimated by an unknown amount, and that collected on 1/12/06 correspondingly overestimated, due to complications related to a mouse having contaminated the lowermost sand trap at this site some time between the September and November 2005 maintenance visits. Potential sediment transport at Station 24.5 U is summarized in figure 8 (for comparison purposes, figs. 6a and 8a are plotted on the same scale). A vector sum of the data for calendar-year 2005 at Station 24.5 U yields a net *Qp* magnitude of 23,607 m^3 s^{-3} from a direction of 244 degrees. During calendar-year 2004, the same calculation yielded a net *Qp* magnitude of 35,800 m^3 s^{-3} from a direction of 229 degrees (Draut and Rubin, 2005).

Rates of sediment transport measured at Station 24.5 U were consistently higher than those measured at Station 24.5 L, by a factor of two to four during most of the year; this agrees with higher wind velocities measured at Station 24.5 U, which resulted in greater potential for sediment transport (fig. 8), and also with patterns at this location observed between November 2003 and December 2004 (Draut and Rubin, 2005). Net aeolian sediment transport is directed upstream with respect to the river, and is oriented such that sand is mobilized from a river-level sand bar near Station 24.5 L and transported uphill along the dune field within which Station 24.5 U is located (fig. 6). The higher transport rates at Station 24.5 U compared to those measured at Station 24.5 L indicate that the net flux of sand is out of the dune field, and that the dune field underwent net loss

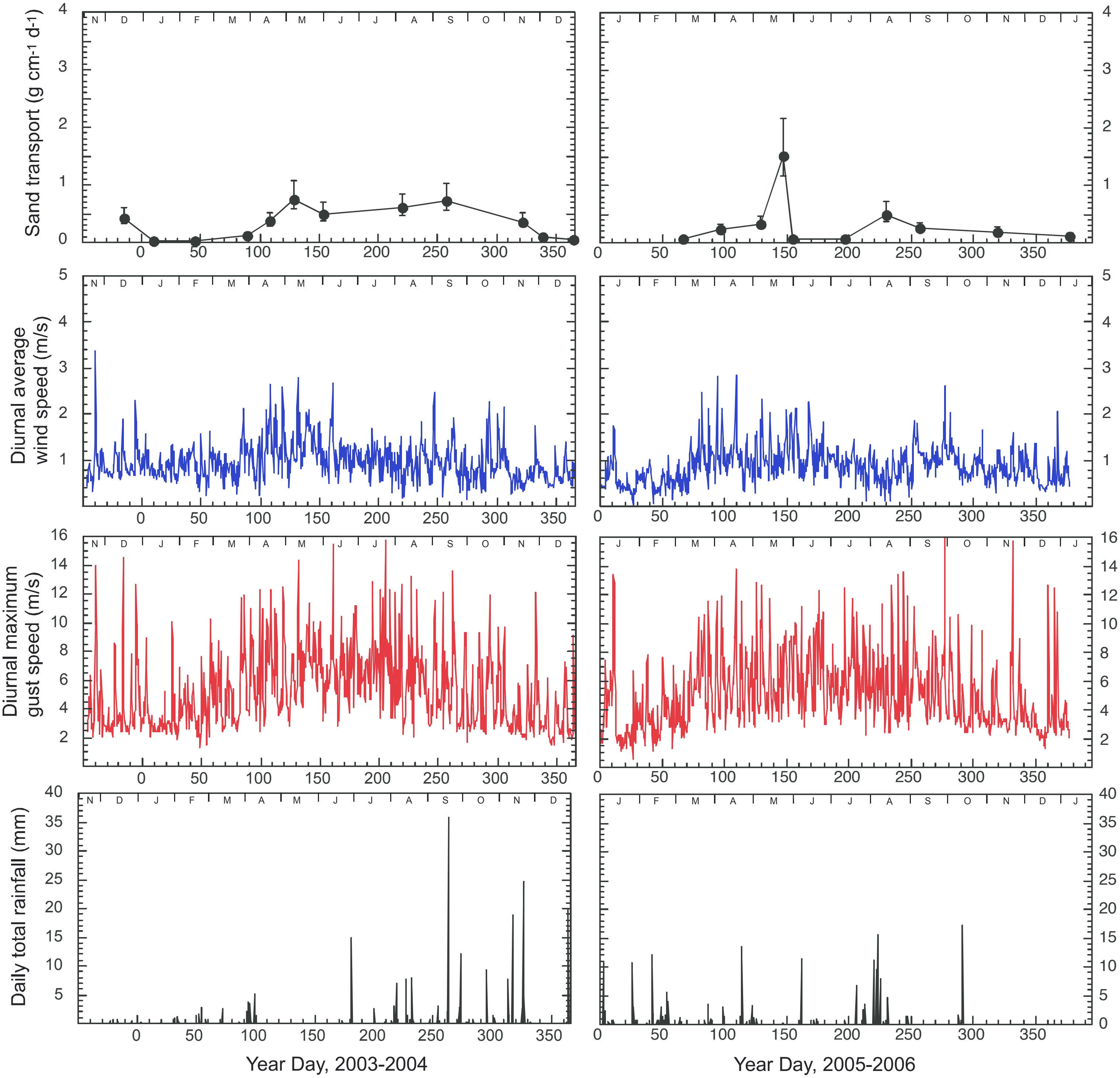

FIGURE 5. *Sand-transport, wind, and precipitation data for the lower of the two stations deployed at 24.5 mile (Station 24.5 L). This record began at the start of 1/1/05 (as the station was already operating) and continued until 1209 hours on 1/12/06 with no interruptions other than routine maintenance. For this and all other stations, sand-transport data are reported as grams per day transported between the ground surface and a height of 1 m (the elevation of the uppermost sand trap), normalized to a width of 1 cm to yield g cm^{-1} d^{-1}; sand mass collected from the four traps at each visit has been integrated over 1 m and divided by the number of days since the traps had last been emptied, to obtain these values. Wind data from the upper (2.0 m) anemometer only are presented as diurnal averaged wind speed and diurnal maximum gust speed using daytime (0600–1800 hrs) and nighttime (1800–0600 hrs) averages of the data points collected at four-minute intervals. Rainfall is shown as daily totals summed over 24-hour periods for each day of the year. Data from 2003–2004 (Draut and Rubin, 2005) are shown for comparison.*

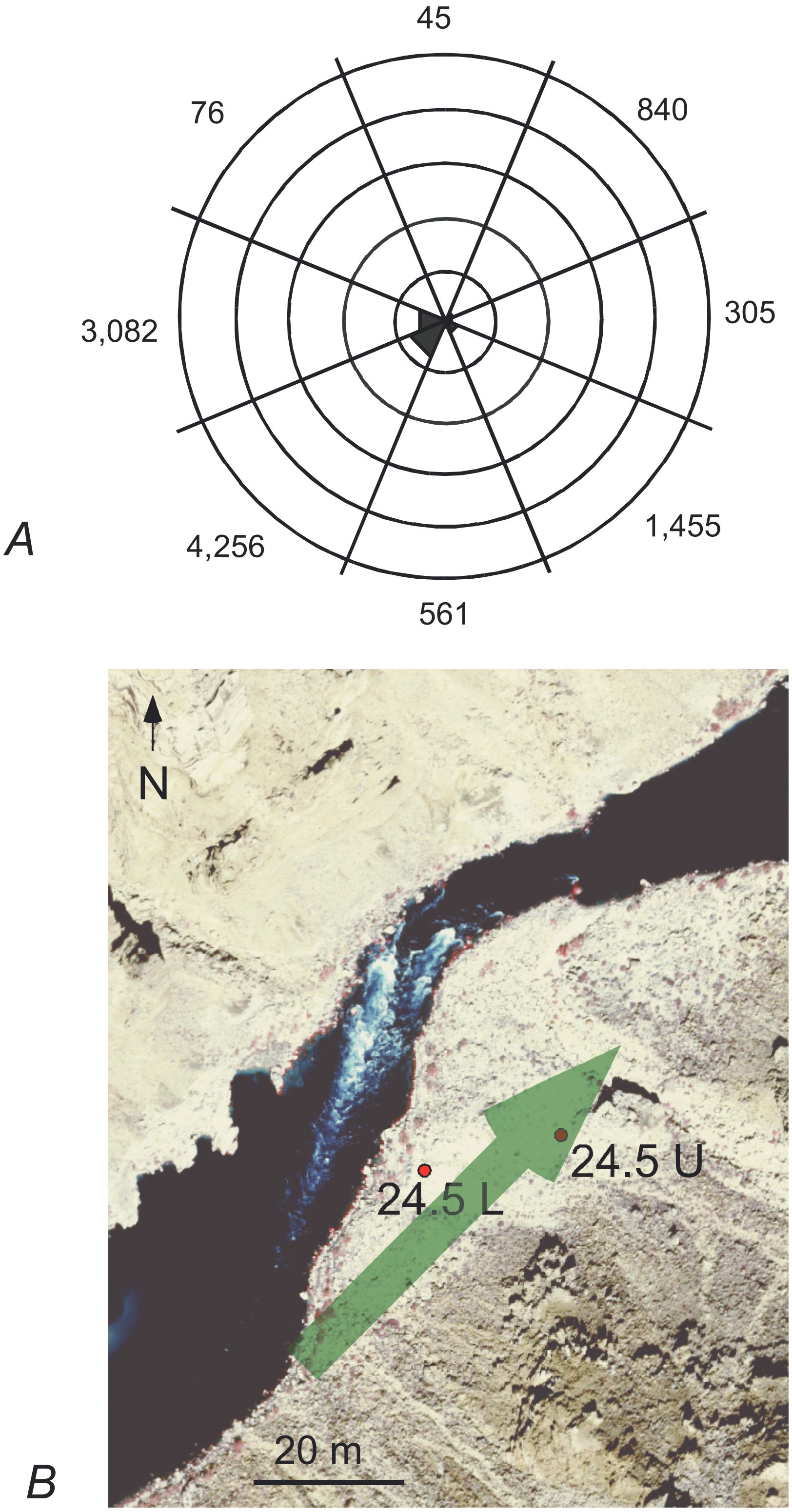

FIGURE 6. *Potential sand transport calculated from wind data for calendar-year 2005 at Station 24.5 L. A) The rose diagram shows the total magnitude of the sediment-transport proxy variable Qp for each of eight directional half-quadrants, indicating total potential for aeolian sediment transport from each sector. A vector sum of the data for 2005 at this station yields a net Qp magnitude of 5,974* $m^3 s^{-3}$ *from a direction of 244 degrees. B) aerial photograph of the 24.5-mile area. Locations of weather stations 24.5 L and 24.5 U are indicated. The green arrow shows the net transport direction, from 244 degrees.*

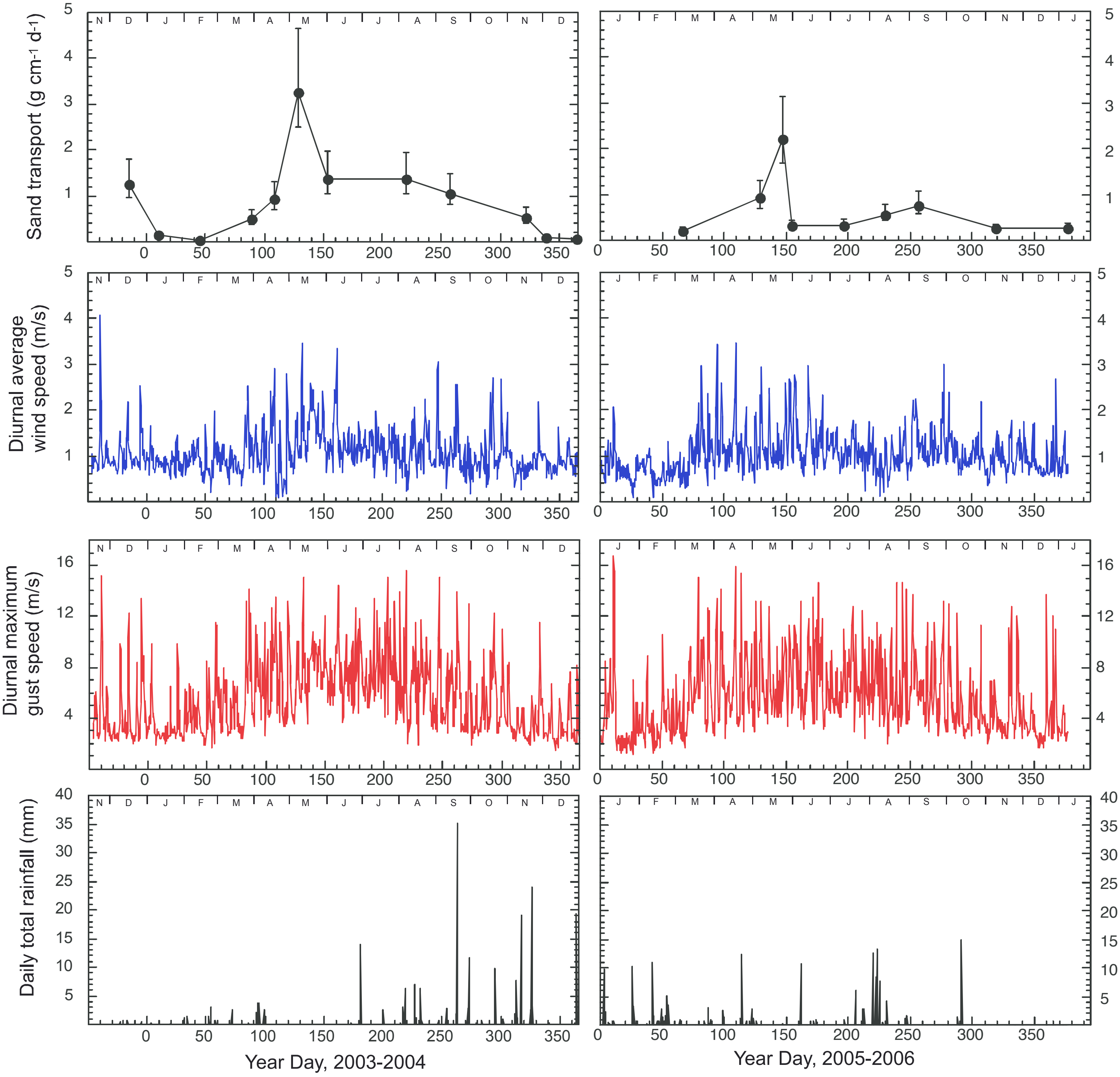

FIGURE 7. *Sand-transport, wind, and precipitation data for the upper of the two stations deployed at 24.5 mile (Station 24.5 U). This record began at the start of 1/1/05 and continued until 1248 hours on 1/12/06 with no interruptions other than routine maintenance. Measurements of sand transport made from data collected on 11/15/05 were underestimated by an unknown amount, and those made from samples collected on 1/12/06 were correspondingly overestimated, because a mouse had contaminated the lowermost (0.1 m) sand trap at this site. Data from 2003–2004 (Draut and Rubin, 2005) are shown for comparison.*

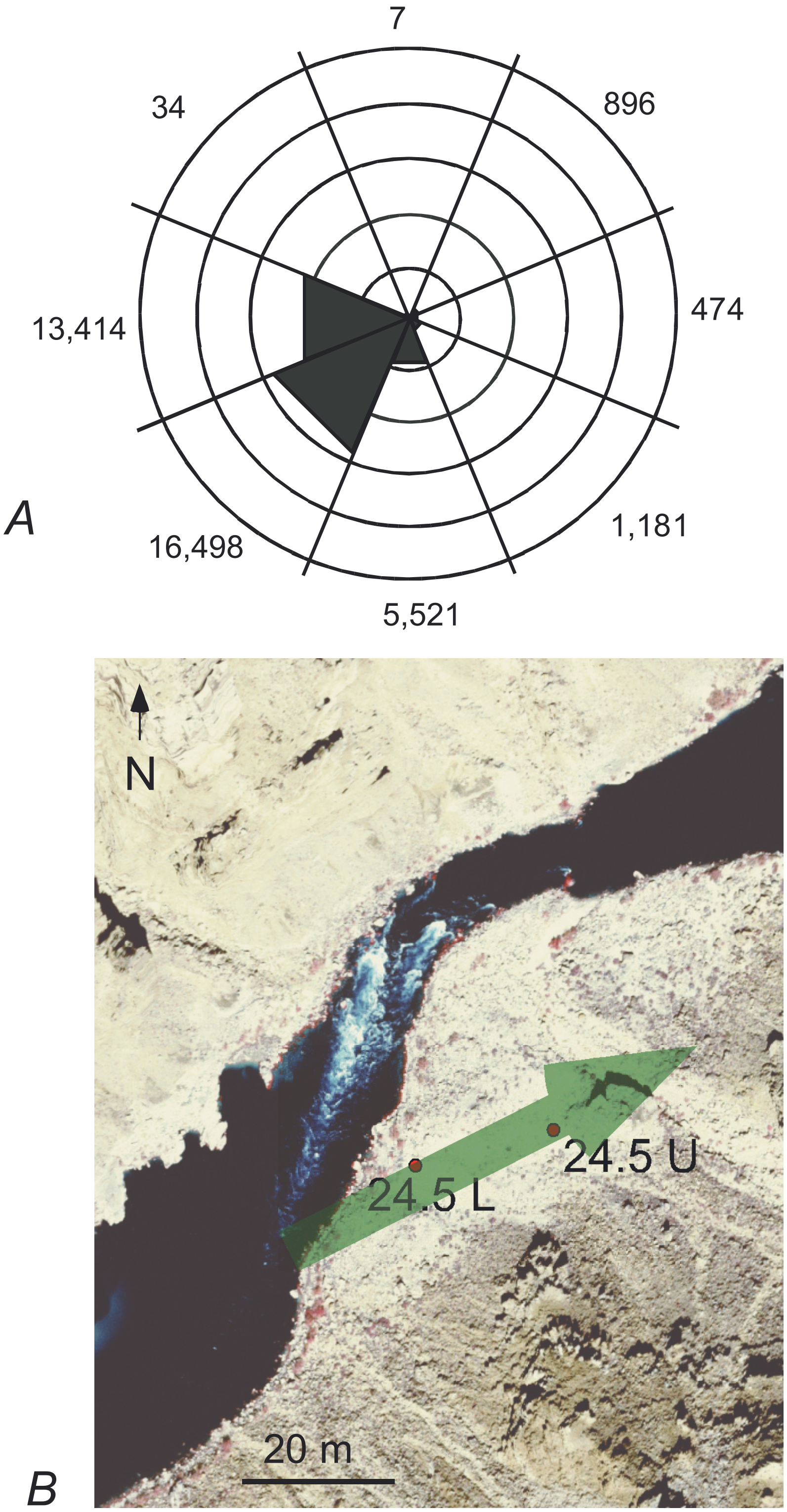

FIGURE 8. Potential sand transport calculated from wind data for calendar-year 2005 at Station 24.5 U. A) The rose diagram shows the total magnitude of the sediment-transport proxy variable Qp for each of eight half-quadrants, indicating total potential for aeolian sediment transport from each sector. A vector sum of the data for calendar-year 2005 at Station 24.5 U yields a net Qp magnitude of 23,607 $m^3 s^{-3}$ from a direction of 244 degrees. B) aerial photograph of the 24.5-mile area. Locations of weather stations 24.5 L and 24.5 U are indicated. The green arrow shows the net transport direction, from 244 degrees.

of sand during the interval studied. Aeolian sand-transport rates at Station 24.5 L during the spring windy season of 2005 were approximately twice as high as those measured during the spring windy season in 2004 (fig. 5). In contrast, sand-transport rates in the upper dune field, Station 24.5 U, were, within error, no different during the 2005 windy season than in 2004 (fig. 7).

Malgosa:

The record for Station Mal L during this reporting interval began at the start of 1/1/05 and ended at 1058 hours on 9/19/05 when the data logger ceased to function, with no apparent cause. The most recent maintenance work before the logger failed, which was performed on 9/16/05, showed no problems and at that time the logger battery power was high (85 percent). Because no maintenance visits were made to this station between 9/16/05 and when the stations at Malgosa were dismantled on 1/14/06 (although the sand traps were emptied on 11/16/05 by members of a river trip who were not equipped to download data electronically), the failed data logger could not be replaced. The available sand-transport, wind, and precipitation data for Station Mal L during 2005 are shown in figure 9; potential sediment transport by direction is summarized in figure 10. Calculating a vector sum of the available data from 2005, ending on 9/19/05, gives a *Qp* magnitude of 56,148 m^3 s^{-3} from a direction of 154 degrees. A vector sum of the data for calendar-year 2004 at this station (excluding time during which the station was inactive between 11/17/04 and 12/9/04) yielded a net *Qp* magnitude of 107,000 m^3 s^{-3} from a direction of 132 degrees (Draut and Rubin, 2005).

The record at Station Mal U began at the start of 1/1/05, and continued until 1007 hours on 1/14/06 with no interruptions other than routine maintenance. Sand-transport, wind, and precipitation data for Station Mal U are shown in figure 11; potential sediment transport by direction is summarized in figure 12 (figs. 10a and 12a are plotted at the same scale). Sand-transport measurements collected in January 2005 and January 2006 are shown on figure 11 as minimum estimates because in each case one of the sand traps had been deployed

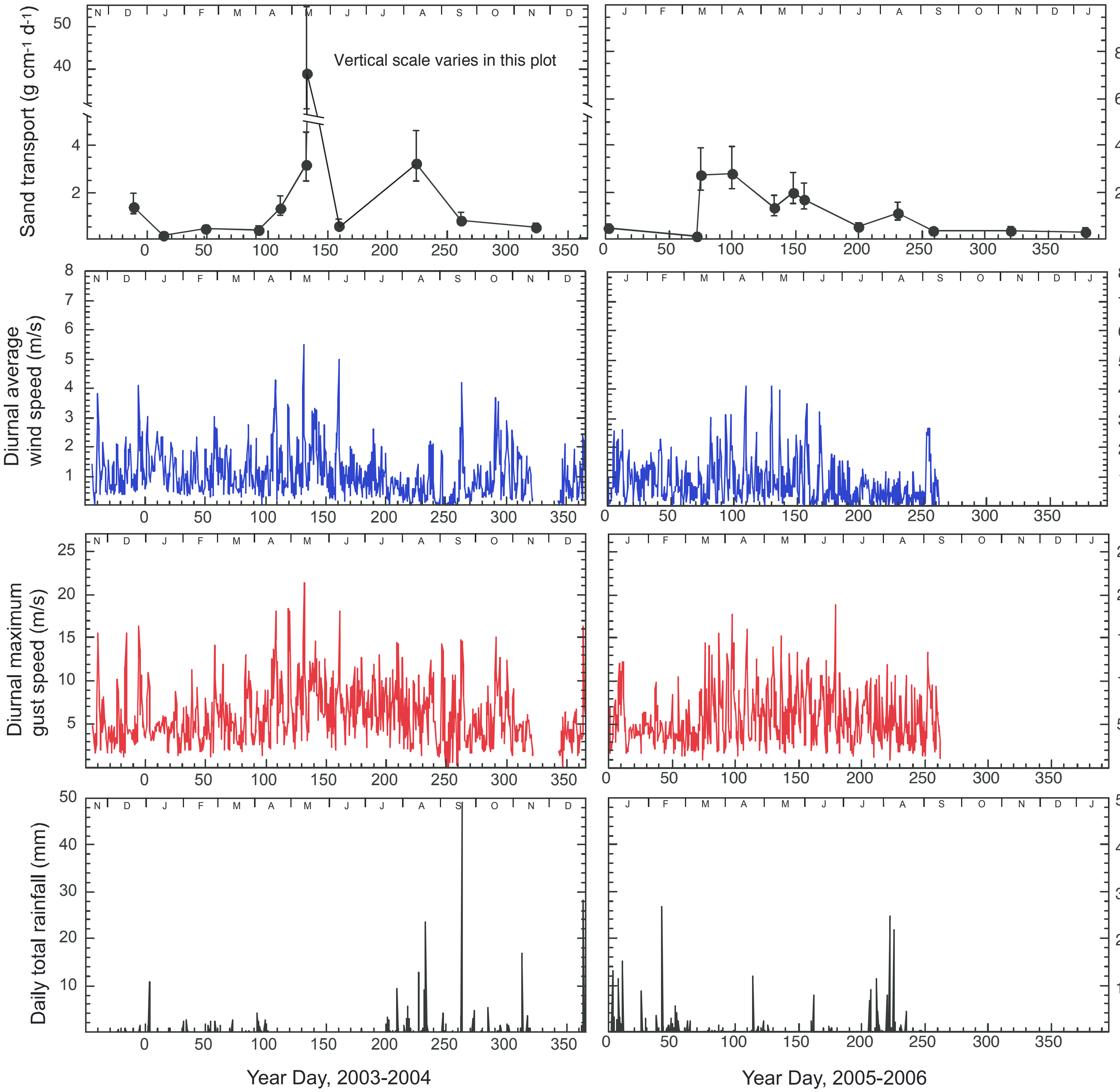

FIGURE 9. Sand-transport, wind, and precipitation data for the lower of the two stations deployed at Malgosa, at river-mile 57.9 (Station Mal L). This record began at the start of 1/1/05 and ended at 1058 hours on 9/19/05 when the data logger ceased to function. Data from 2003–2004 (Draut and Rubin, 2005) are shown for comparison.

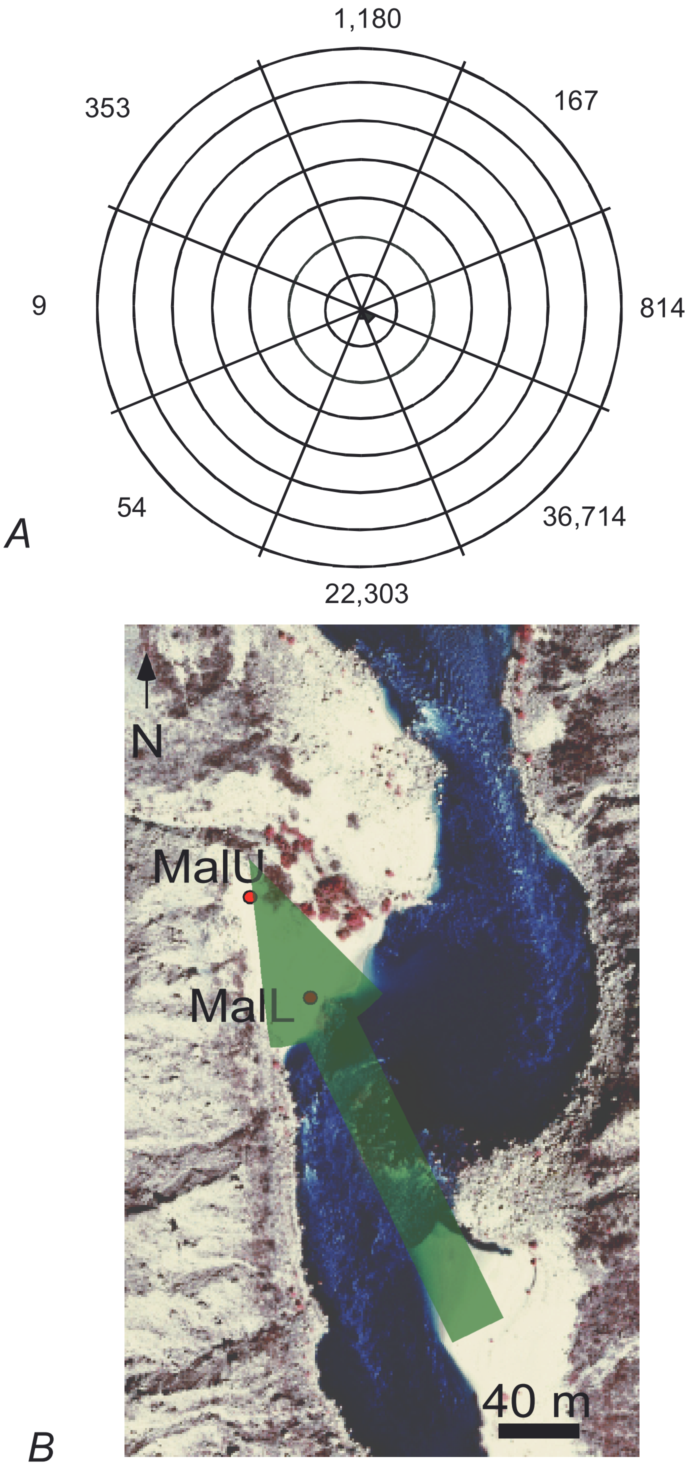

FIGURE 10. *Potential sand transport calculated from wind data for calendar-year 2005 at Station Mal L. A) The rose diagram shows the total magnitude of the sediment-transport proxy variable Qp for each of eight half-quadrants, indicating total potential for aeolian sediment transport from each sector (data from 1/1/05 until 9/19/05 only). A vector sum of the data for calendar-year 2005 at this station, ending when the data logger failed on 9/19/05, yields a net Qp magnitude of 56,148* $m^3 s^{-3}$ *from a direction of 154 degrees. B) aerial photograph of the Malgosa (river-mile 57.9) area. Locations of weather stations Mal L and Mal U are indicated. The green arrow shows the net transport direction, from 154 degrees.*

incorrectly, allowing some of the sand to spill out. Calculating a vector sum of the sediment-transport proxy data for Station Mal U in 2005 gives a *Qp* magnitude of 725,880 m^3 s^{-3} from a direction of 156 degrees. For comparison, a vector sum of the data for calendar-year 2004 at this same station yielded a *Qp* magnitude of 757,000 m^3 s^{-3} from a direction of 143 degrees (Draut and Rubin, 2005).

Rates of aeolian sediment transport measured at Station Mal U, near the dune crest, were higher than those at Station Mal L (near river level) by one to two orders of magnitude during most of the year. The greatest difference in sand transport between these two stations was recorded during late summer and fall, when transport rates at Station Mal U were over 240 times greater than those at Station Mal L. Based on the vector-sum calculations, sediment transport at Malgosa was apparently dominated by southeast (upstream-directed) winds that mobilized sand from the river-level sandbar near Station Mal L and transported it up the dune toward Station Mal U (fig. 12). A second source of sand at this location is a lower-elevation sandbar on river right ~120 m away from the dune station in which the weather stations were located; this dune field is directly upwind of the Malgosa dune field and likely serves as a sediment source to the Malgosa dunes during the spring windy season, when wind-blown sand has been observed to cross the river.

Comparison of sand transport at the Malgosa stations between 2004 and 2005 indicates little difference in spring-windy-season transport (figs. 9 and 11), with the exception of an interval in May 2004 during which exceptionally high transport rates were recorded because the sand traps were emptied several times during two very windy days (Draut and Rubin, 2005). In general, transport rates at Station Mal L showed no significant difference between 2004 and 2005. At Station Mal U, 2005 sand-transport rates were generally comparable to those measured in 2004; however, high winds accompanied by dry conditions in late December 2005 and early January 2006 produced substantially higher aeolian transport than was measured during the same, wetter, time frame in 2004 (fig. 11). It is not known why a comparable increase in sand transport is not apparent in data from late December 2005 and early January 2006 at Station Mal L; wind

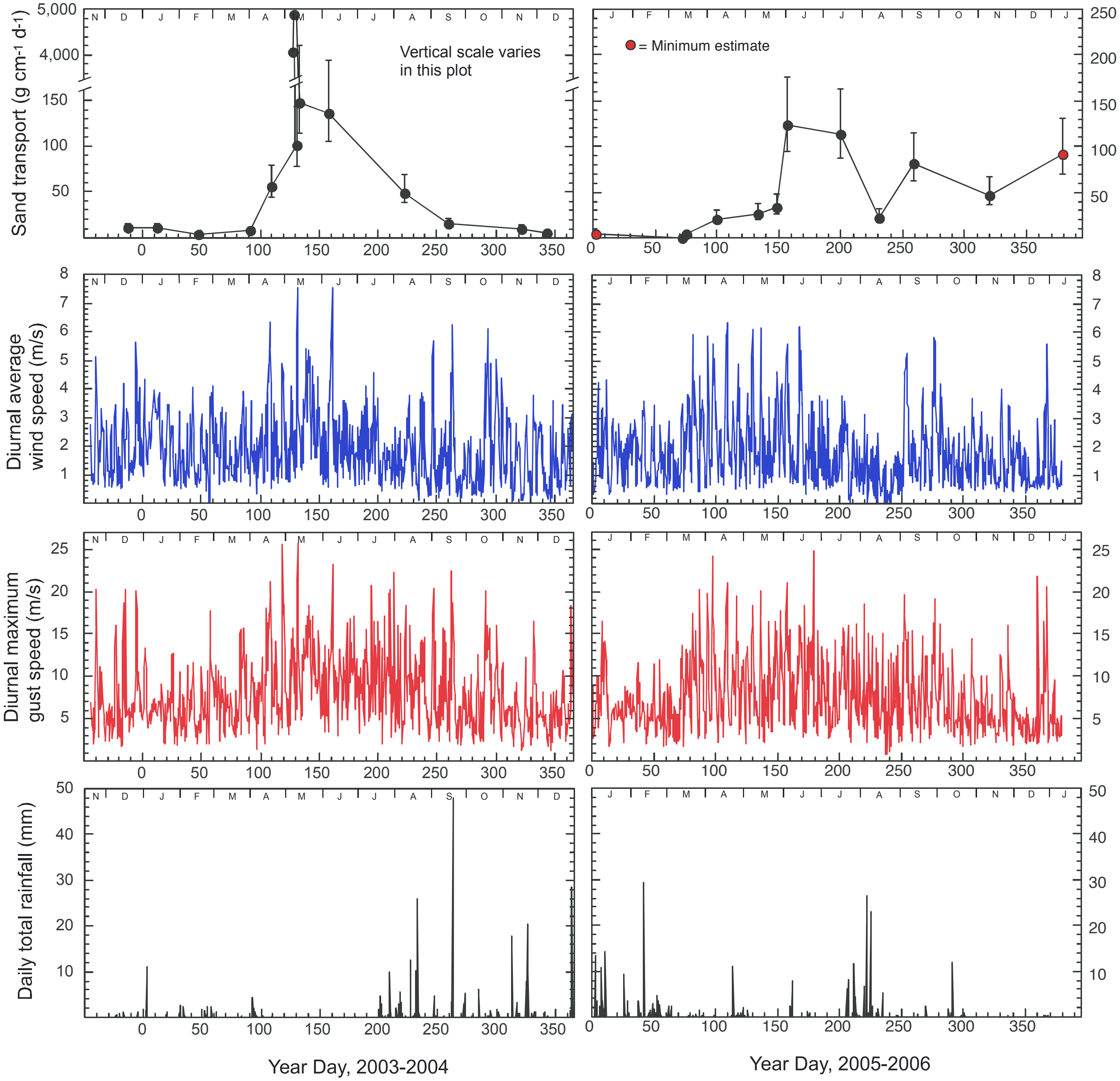

FIGURE 11. *Sand-transport, wind, and precipitation data for the upper of the two stations deployed at Malgosa (Station Mal U). This record began at the start of 1/1/05, and continued uninterrupted until 1007 hours on 1/14/06 with no interruptions other than routine maintenance. Sand-transport calculations made from samples collected in January 2005 and January 2006, shown with red circles, are minimum transport estimates only, because one or more of the sand traps was deployed incorrectly. Data from 2003–2004 (Draut and Rubin, 2005) are shown for comparison.*

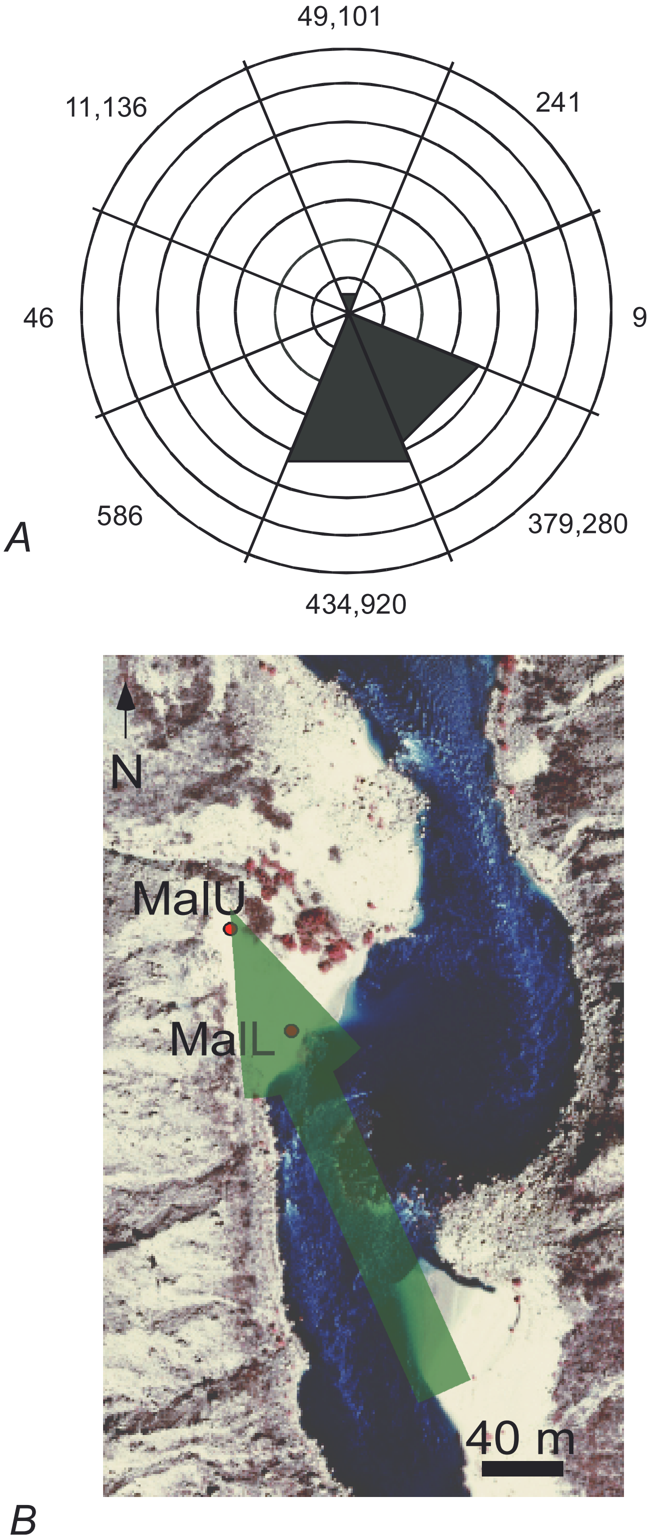

FIGURE 12. *Potential sand transport calculated from wind data for calendar-year 2005 at Station Mal U. A) The rose diagram shows the total magnitude of the sediment-transport proxy variable Qp for each of eight half-quadrants, indicating total potential for aeolian sediment transport from each sector. A vector sum of the data for calendar-year 2005 at this station yields a net Qp magnitude of 725,880* m^3 s^{-3} *from a direction of 156 degrees. B) aerial photograph of the Malgosa (river-mile 57.9) area. Locations of weather stations Mal L and Mal U are indicated. The green arrow shows the net transport direction, from 156 degrees.*

velocity from that time was not recorded at Station Mal L because the data logger was not functioning.

Palisades:

The record for Station Pal L began at the start of 1/1/05 and continued until 1213 hours on 1/14/06 with no interruptions other than routine maintenance. Sand-transport, wind, and precipitation data for Station Pal L are shown in figure 13; potential sediment transport by direction is summarized in figure 14. A vector sum of the data for calendar-year 2005 at this station yields a net *Qp* magnitude of 68,171 $m^3 s^{-3}$ from a direction of 179 degrees. A comparable calculation for the 2004 data at this station yielded a *Qp* magnitude of 38,800 $m^3 s^{-3}$ from a direction of 149 degrees (Draut and Rubin, 2005).

The record for Station Pal U began at the start of 1/1/05, and continued normally until the afternoon of 4/2/05. At that time, both wind and rainfall records began to show consistently unreasonable values (such as rainfall > 700 mm per four-minute sampling interval and wind speeds > 45 m s^{-1}) that continued for the next nine days, after which time the data logger ceased to record any data. Discussion of the suspect data with technical-support personnel from Onset Computer Corporation resulted in no explanation for its occurrence. The station was next visited for maintenance on 5/30/05, at which time the data logger and upper (2.0 m) anemometer were replaced. During that visit it was determined that the rain gauge was not able to function normally even while connected to the new data logger, and was removed. No new rain gauge was installed at Station Pal U after that time. In the supplemental data files that accompany this report, the nine days of suspect data (4/2/05 to 4/11/05) have been removed and the records truncated with the last reliable data point at 1307 hours on 4/2/05. After replacement of the data logger on 5/30/05, the logger was incorrectly programmed to record data every four hours instead of every four minutes. This programming error resulted in reporting of diurnally averaged wind speeds that are lower than those in the normal (four-minute sampling interval) data record where noted in figure 15. The logger was programmed correctly (to record at

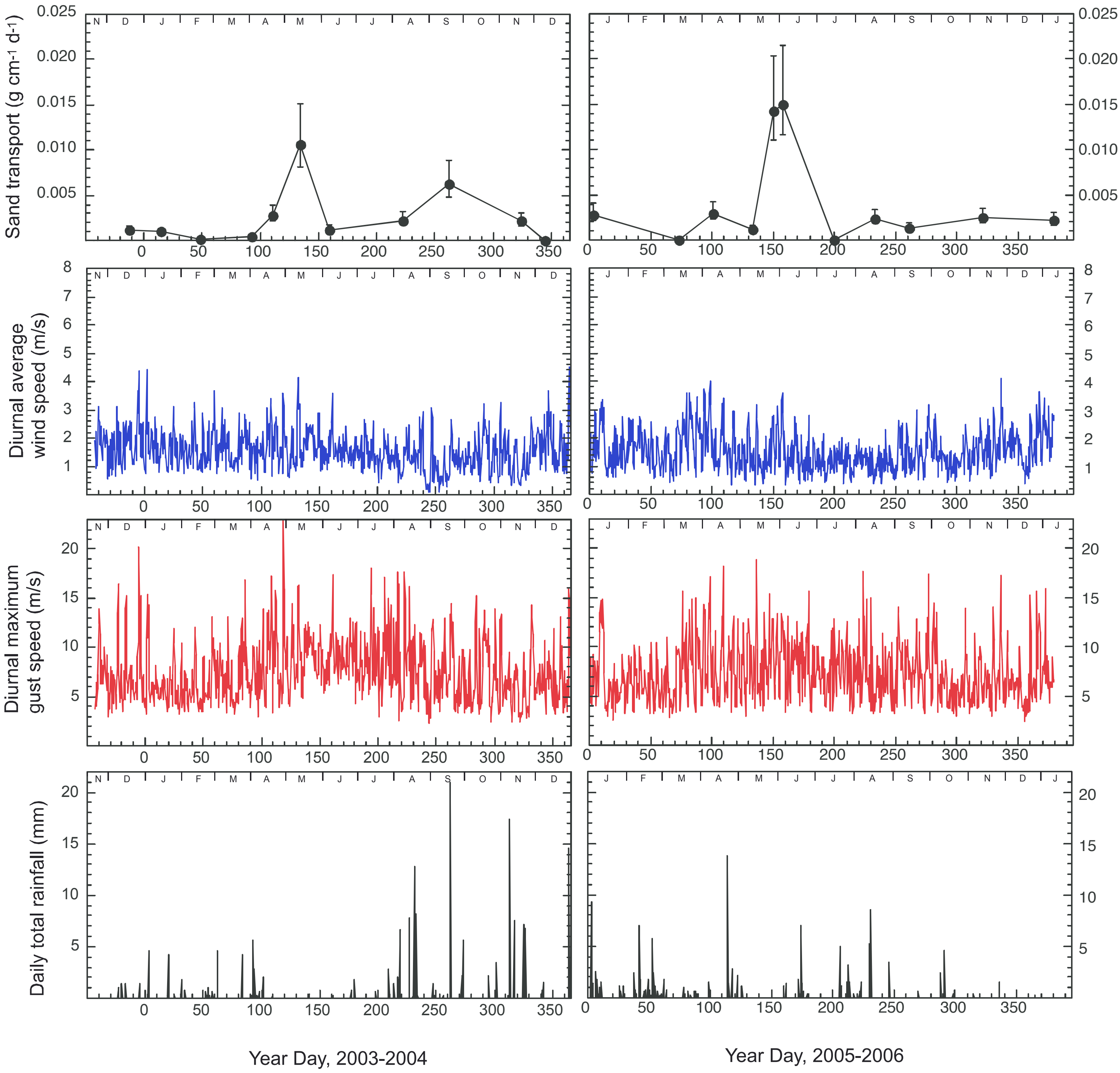

__FIGURE 13.__ Sand-transport, wind, and precipitation data for the lower of the two stations deployed at Palisades, river-mile 66.1 (Station Pal L). This record began at the start of 1/1/05 and continued until 1213 hours on 1/14/06 with no interruptions other than routine maintenance. Data from 2003–2004 (Draut and Rubin, 2005) are shown for comparison.

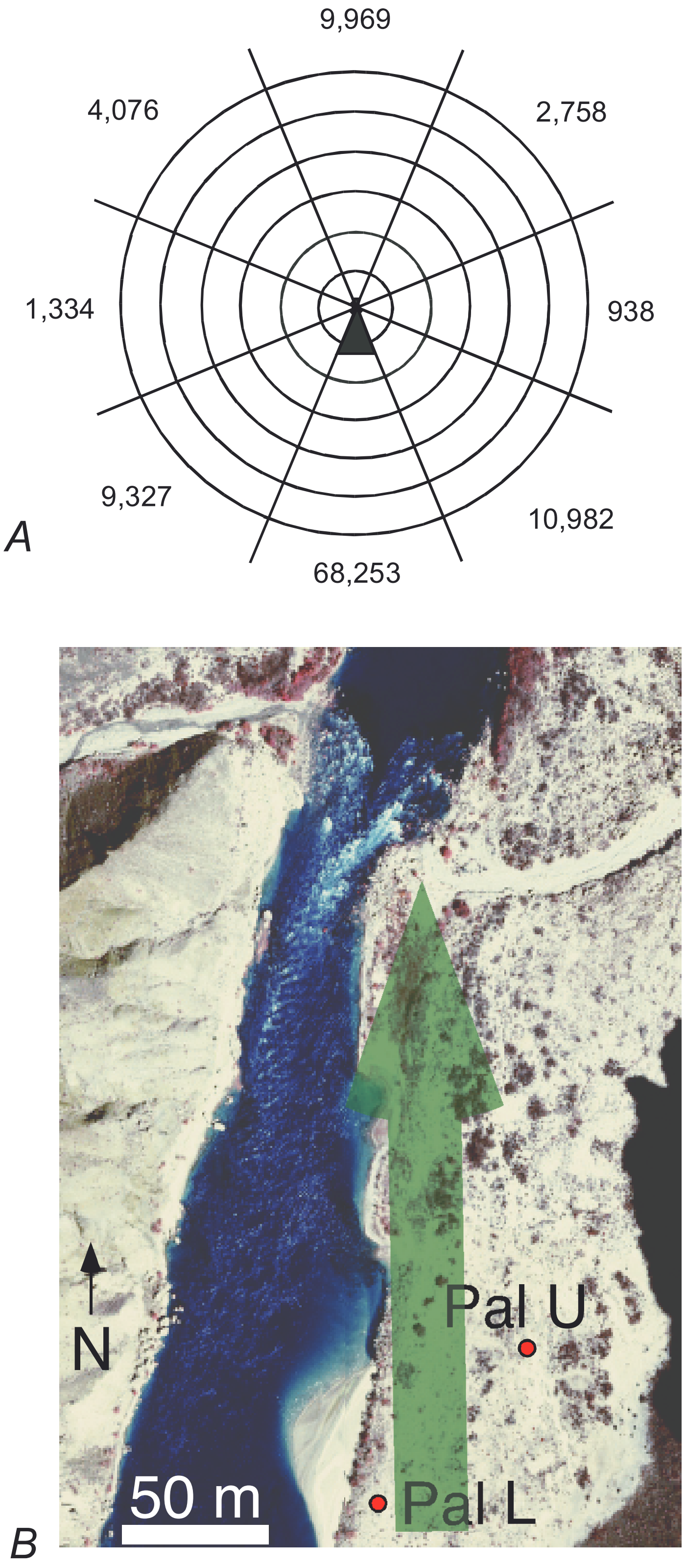

FIGURE 14. *Potential sand transport calculated from wind data for calendar-year 2005 at Station Pal L. A) The rose diagram shows the total magnitude of the sediment-transport proxy variable Qp for each of eight half-quadrants, indicating total potential for aeolian sediment transport from each sector. A vector sum of the data for 2005 at this station yields a net Qp magnitude of 68,171* m^3 s^{-3} *from a direction of 179 degrees. B) aerial photograph of the Palisades area. Locations of weather stations Pal L and Pal U are indicated. The green arrow shows the net transport direction, from 179 degrees.*

four-minute intervals) on 9/18/05, after which time data collection proceeded normally but without a functioning rain gauge until the station was disabled at 1316 hours on 1/14/06.

Sand-transport, wind, and the available precipitation data for Station Pal U are shown in figure 15; potential sediment transport by direction is summarized in figure 16. The rose diagram in figure 16 includes data only from times when the logger at this site collected data at four-minute intervals, and thus excludes June, July, August, and early September 2005. For the time frame used, the net *Qp* value for this site has a magnitude of 154,890 $m^3 s^{-3}$ from a direction of 132 degrees. A vector sum of the data for 2004 at this station (which included almost the whole year except for station inactivity between 11/19/04 and 11/21/04) yielded a net *Qp* magnitude of 467,000 $m^3 s^{-3}$ from a direction of 155 degrees (Draut and Rubin, 2005).

The dominant aeolian sand-transport direction at Palisades is oriented toward the north-northwest, directed upstream. This indicates that sand in the aeolian dune field would not likely be derived from the sandbar near Station Pal L (an ephemeral fluvial sand deposit that was present throughout 2005). Rates of sand transport measured at Station Pal U, in a relatively inactive dune field, were typically two orders of magnitude higher than those on the cobble-boulder bar at Station Pal L. Transport rates at Station Pal L during the spring windy season of 2005 may have been slightly higher than for the comparable season in 2004 (fig. 13), but the wide error margin generated by our conservative treatment of these data implies no statistically significant difference. Transport rates at Station Pal U were comparable during the 2004 and 2005 spring windy seasons (fig. 15). As at the upper Malgosa dune crest, the Palisades dune field apparently also experienced increased aeolian sand transport during late December and early January compared with the previous four months, associated with dry, windy weather.

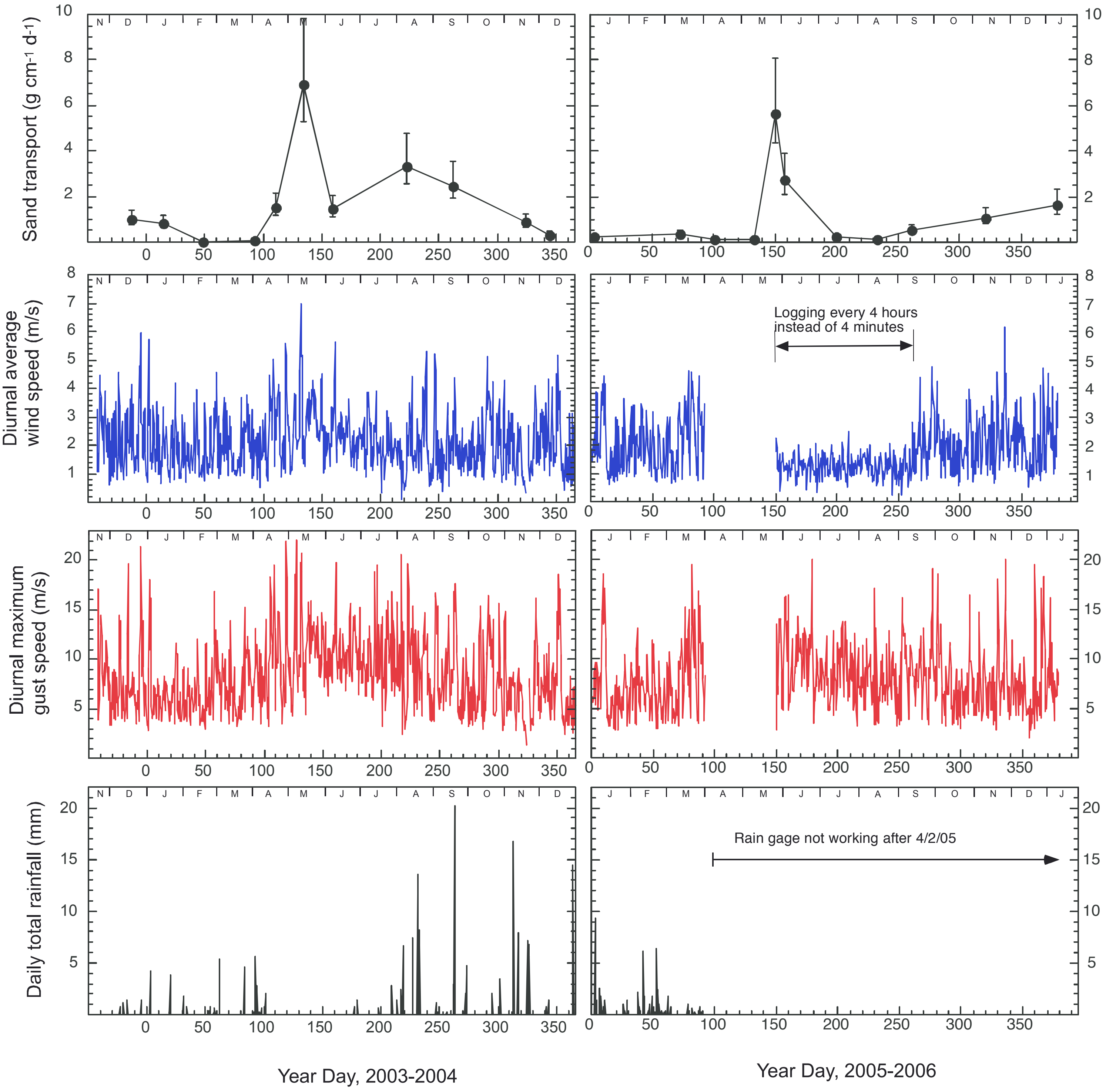

FIGURE 15. *Sand-transport, wind, and precipitation data for the upper of the two stations deployed at Palisades, river-mile 66.1 (Station Pal U). This record began at the start of 1/1/05, and continued normally until the afternoon of 4/2/05 when the data logger began to malfunction. Operation resumed on 5/30/05 but with the logger incorrectly programmed to record data every four hours instead of every four minutes. The logger was reprogrammed correctly (to record at four-minute intervals) on 9/18/05, after which data collection proceeded normally but without a functioning rain gauge until the station was disabled at 1316 hours on 1/14/06. Data from 2003–2004 (Draut and Rubin, 2005) are shown for comparison.*

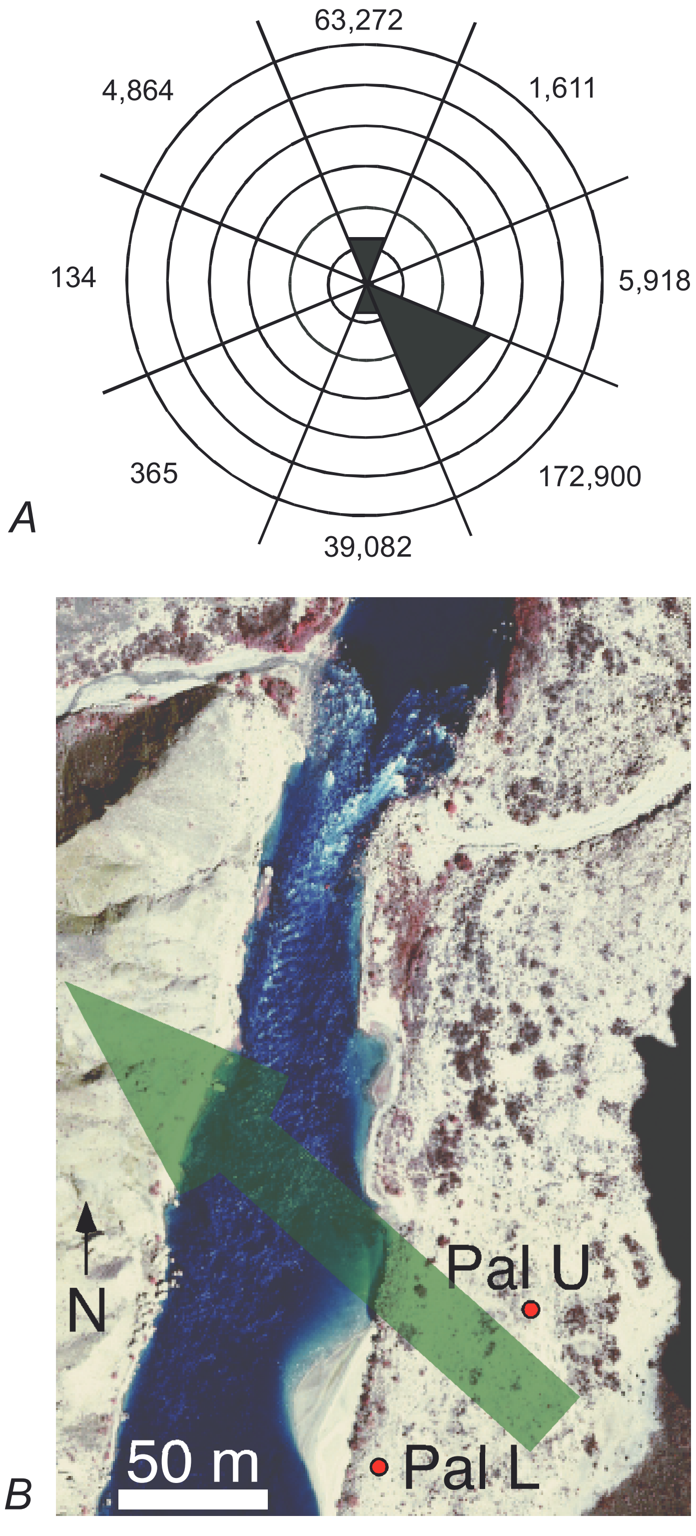

__FIGURE 16.__ Potential sand transport calculated from wind data for calendar-year 2005 at Station Pal U. A) The rose diagram shows the total magnitude of the sediment-transport proxy variable Qp for each of eight half-quadrants, indicating total potential for aeolian sediment transport from each sector. Only those data collected while the logger used a four-minute sampling interval are included in this plot (1/1/05 to 4/2/05, and 9/18/05 to 1/14/06). A vector sum of the data for this same time frame yields a net Qp magnitude of 154,890 m^3 s^{-3} from a direction of 132 degrees. B) aerial photograph of the Palisades area. Locations of weather stations Pal L and Pal U are indicated. The green arrow shows the net transport direction, from 132 degrees.

Comanche:

The record at Station Com began at the start of 1/1/05, and continued until the station was disabled at 1254 hours on 1/16/06 with no interruptions other than routine maintenance. Sand-transport, wind, and precipitation data for this site are shown in figure 17; potential sediment transport by direction is summarized in figure 18. A vector sum of the data for calendar-year 2005 at this station gives a net *Qp* magnitude of 13,308 $m^3 s^{-3}$ from a direction of 153 degrees. For comparison, a vector sum of the available data for 2004 at this station (which began on 4/20/04, when this station was first deployed) yields a net *Qp* magnitude of 10,200 $m^3 s^{-3}$ from a direction of 98 degrees (Draut and Rubin, 2005). Net sand transport is therefore apparently directed upstream and from the southeast in this part of the Comanche dune field, although the 2005 data indicate a more southerly dominant wind direction compared with the east-south-easterly net wind measured in 2004. Dry, windy weather in late December 2005 and early January 2006 caused a slight increase in aeolian sand transport at Comanche compared to the previous few months, as was the case at the upper Malgosa and Palisades instrument stations (Mal U and Pal U).

Forster:

The record for the weather station at the mouth of Forster Canyon began at the start of 1/1/05 but experienced multiple interruptions throughout the year, caused by data-logger malfunctions. The station was active and functioned normally between 1/1/05 and 4/3/05, between 6/2/05 and 6/14/05, between 7/24/05 and 7/30/05, and between 9/20/05 and when it was intentionally disabled at 1657 hours on 1/27/06. Sand-transport, wind, and precipitation data for Station For are shown in figure 19; potential sediment transport by direction is summarized in figure 20. The two extensive intervals of normal operation during calendar-year 2005 (1/1/05 to 4/3/05, and 9/20/05 to 12/31/05) were used to calculate a vector sum for the sediment-transport proxy variable; this generated a net *Qp* magnitude of 101,070 $m^3 s^{-3}$ from a direction of 26 degrees. For comparison, a vector sum of available data for 2004 at this station (which began

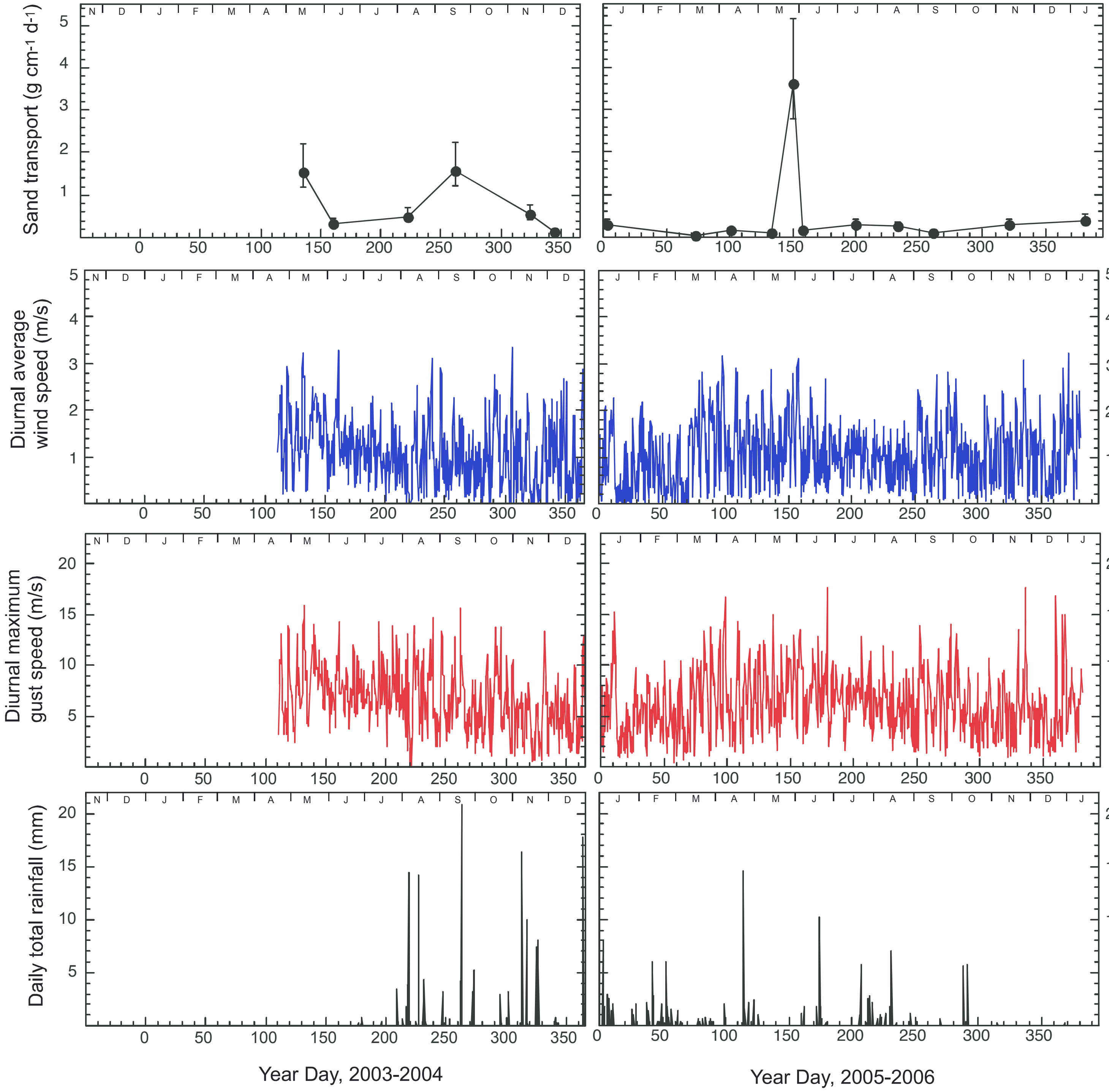

FIGURE 17. *Sand-transport, wind, and precipitation data for the station deployed at Comanche, river-mile 68.0 (Station Com). This record began at the start of 1/1/05, and continued until the station was disabled at 1254 hours on 1/16/06 with no interruptions other than routine maintenance. Data from 2004 (Draut and Rubin, 2005) are shown for comparison.*

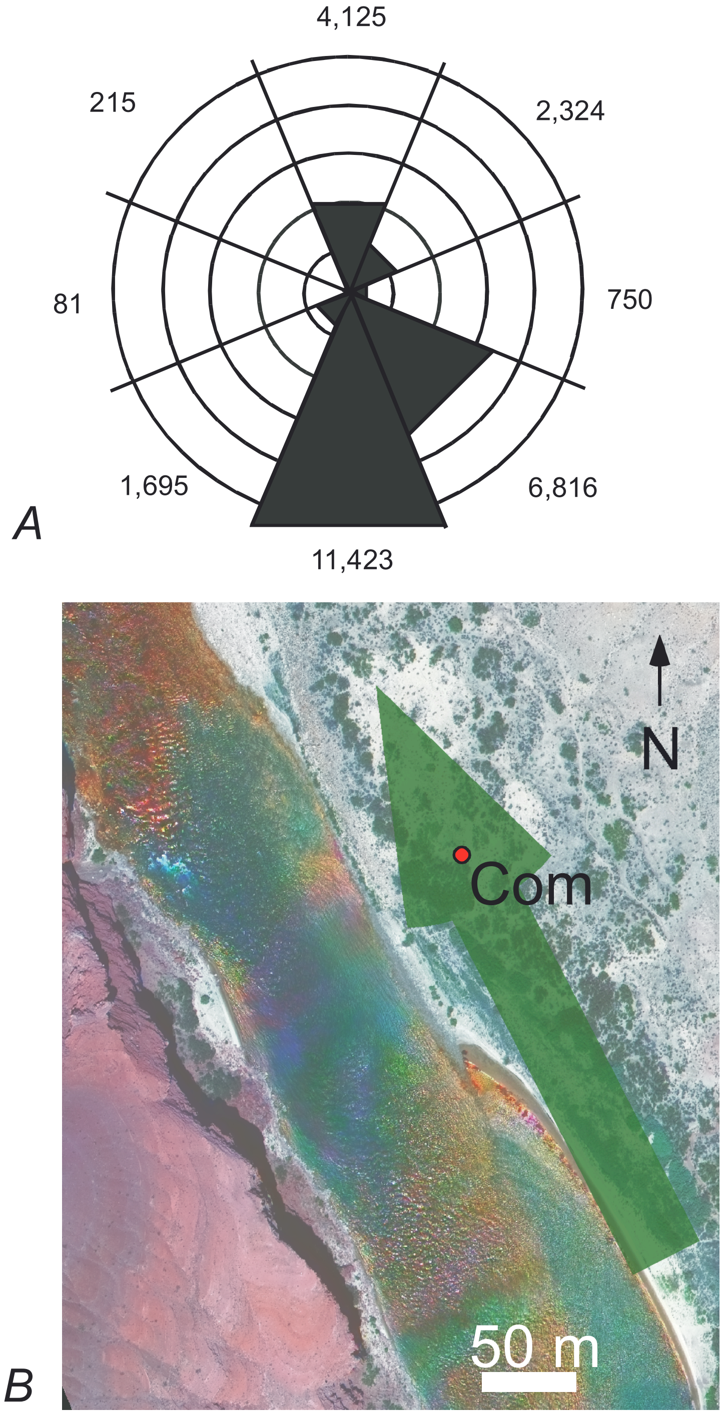

FIGURE 18. *Potential sand transport calculated from wind data for calendar-year 2005 at the Comanche weather station. A) The rose diagram shows the total magnitude of the sediment-transport proxy variable Qp for each of eight half-quadrants, indicating total potential for aeolian sediment transport from each sector. A vector sum of the available data from this station for calendar-year 2005 yields a net Qp magnitude of 13,308* $m^3\ s^{-3}$ *from a direction of 153 degrees. B) aerial photograph of the Comanche area. The location of the weather station (Com) is indicated. The green arrow shows the net transport direction, from 153 degrees.*

on 4/23/04 and excluded station inactivity between 10/21/04 and 11/23/04) yielded a net *Qp* magnitude of 219,000 m^3 s^{-3} from a direction of 21 degrees (Draut and Rubin, 2005).

Sand-trap data collected on several of the maintenance visits, shown with red circles on figure 19, are minimum estimates of transport rate because the lowermost trap had completely filled with sand between maintenance visits. The dominant wind direction at this site is from the north-northeast. Wind with this orientation transports abundant quantities of sand approximately parallel to the axis of Forster Canyon, which is perpendicular to the Colorado River (fig. 20).

202.9 mile:

The record at 202.9 mile for this reporting period began at 0938 hours on 1/9/05 (the station had ceased to function on 11/26/04 and was re-launched on 1/9/05). The logger recorded data normally from the anemometer, with no interruptions other than routine maintenance, until the station was disabled at 1237 hours on 1/29/06. However, the rain gauge failed on 6/10/05 when an animal chewed through the protective plastic conduit covering the cable and then through the cable itself. The rain gauge was removed for repairs in July 2005 and was replaced, with reinforced aluminum conduit around its cable, on 9/22/05. Wind and available precipitation data for this site are shown in figure 21. Although sand traps were not used at this site, potential sediment transport was calculated and is summarized by direction in figure 22. Wind direction at 202.9 mile can vary substantially (fig. 22). Upstream- and downstream-directed winds nearly balanced each other, and so the net wind (and potential sand-transport) direction was determined by a northwesterly component; a vector sum of the 2005 wind data yielded a net *Qp* magnitude of 1,286 m^3 s^{-3} from a direction of 283 degrees. A vector sum from data collected between April and November 2004 (Draut and Rubin, 2005) indicated net potential transport oriented upstream, with a net *Qp* magnitude of 2,160 m^3 s^{-3} from a direction of 194 degrees.

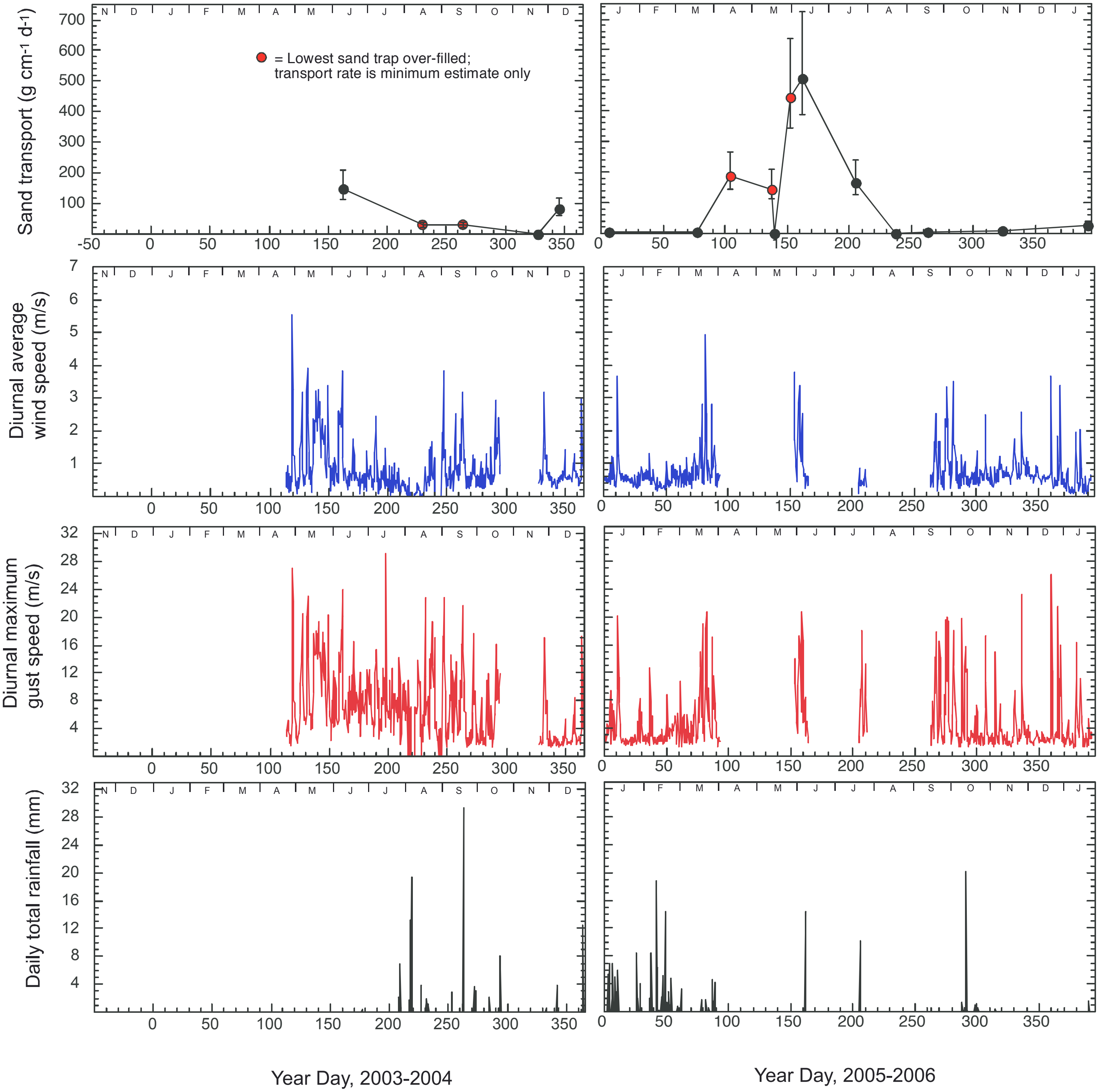

FIGURE 19. *Sand-transport, wind, and precipitation data for the station deployed at Forster, river-mile 123.0 (Station For). This record began at the start of 1/1/05 but experienced multiple interruptions throughout the year, caused by data-logger malfunctions. The station functioned normally between 1/1/05 and 4/3/05, between 6/2/05 and 6/14/05, between 7/24/05 and 7/30/05, and between 9/20/05 and when it was intentionally disabled at 1657 hours on 1/27/06. Sand-trap data shown with red circles are minimum estimates of transport rate only, because the lowermost trap was found completely filled with sand on the date of those maintenance visits. Data from 2004 (Draut and Rubin, 2005) are shown for comparison.*

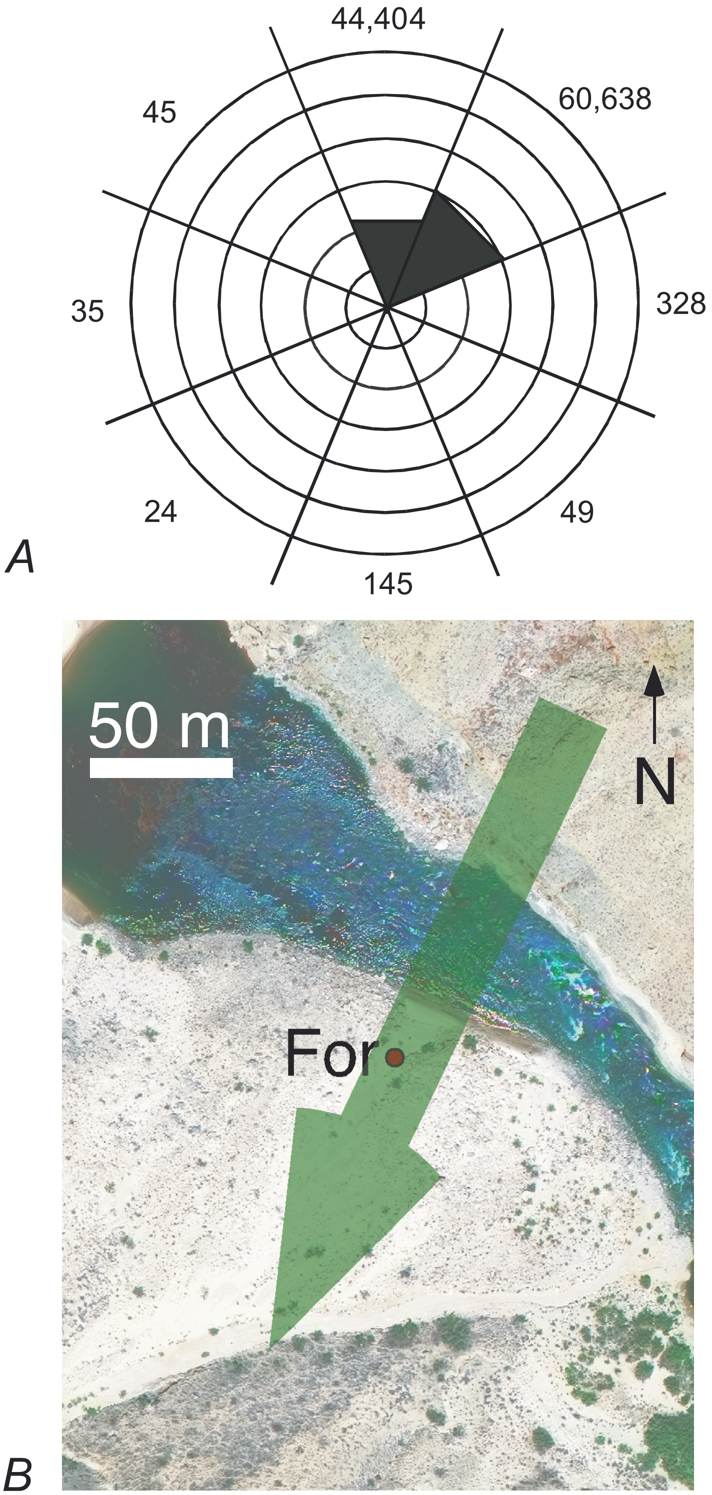

Figure 20. *Potential sand transport calculated from wind data for calendar-year 2004 at the Forster weather station. A) The rose diagram shows the total magnitude of the sediment-transport proxy variable Qp for each of eight half-quadrants, indicating total potential for aeolian sediment transport from each sector. The two extensive intervals of normal operation during 2005 (1/1/05 to 4/3/05, and 9/20/05 to 12/31/05) were used to calculate a vector sum for Qp; this generated a net magnitude of 101,070* m^3 s^{-3} *from a direction of 26 degrees. B) aerial photograph of the Forster area. The location of the weather station (For) is indicated. The green arrow shows the net transport direction, from 26 degrees (directed up the Forster Canyon tributary).*

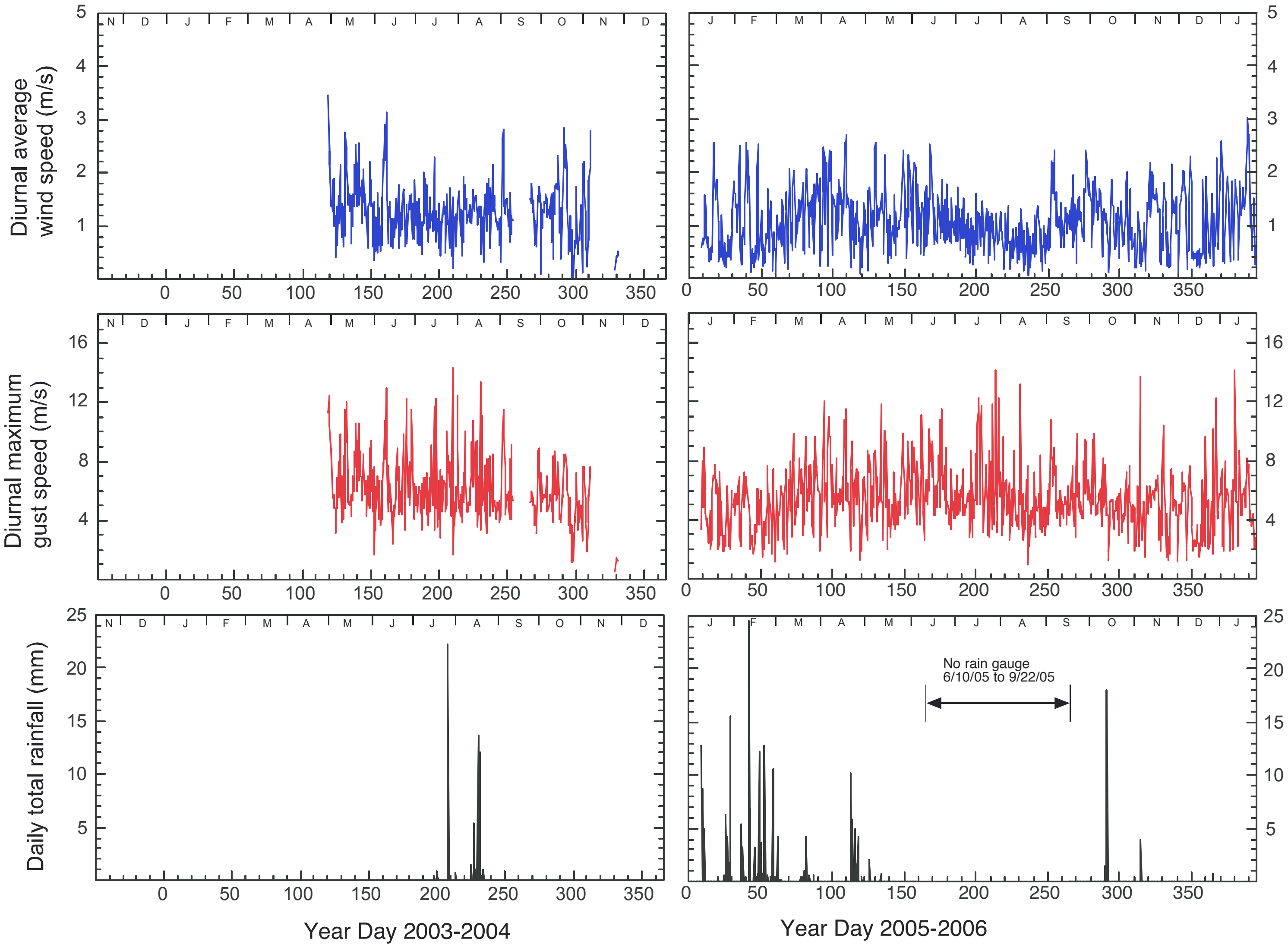

FIGURE 21. *Wind and precipitation data for the station deployed at river-mile 202.9 (sand traps were not used at this station). The record for this reporting period began at 0938 hours on 1/9/05. The logger recorded data normally from the anemometer, with no interruptions other than routine maintenance, until the station was disabled at 1237 hours on 1/29/06. However, the rain gauge at this station was not in operation between 6/10/05 and 9/22/05. Data from 2004 (Draut and Rubin, 2005) are shown for comparison.*

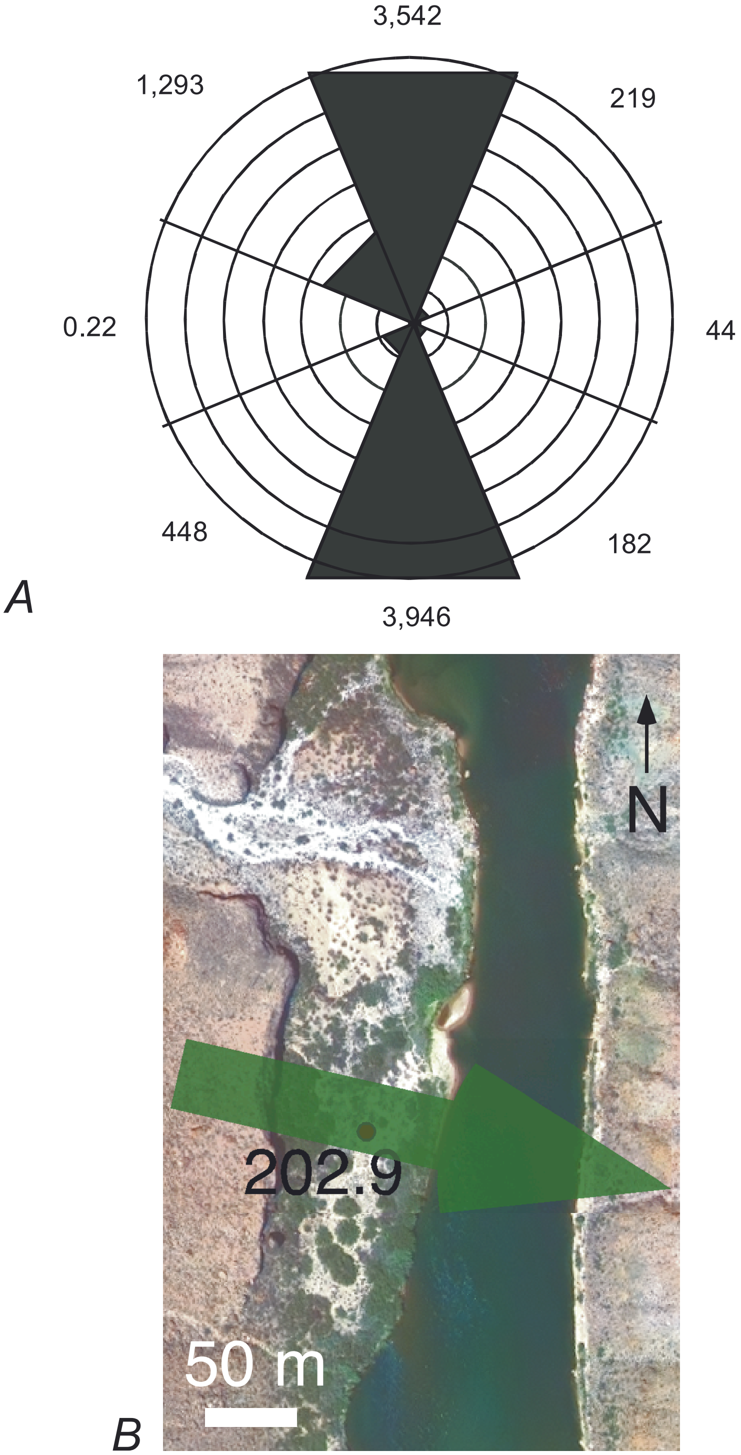

FIGURE 22. *Potential sand transport calculated from wind data for calendar-year 2005 at the 202.9-mile weather station. a) The rose diagram shows the total magnitude of the sediment-transport proxy variable Qp for each of eight half-quadrants, indicating total potential for aeolian sediment transport from each sector. A vector sum of the 2005 data at this station yields a net Qp magnitude of 1,286* $m^3 s^{-3}$ *from a direction of 283 degrees. b) aerial photograph of the 202.9-mile area taken in 2002; the location of the weather station (202.9) is indicated. The green arrow shows the net transport direction, from 283 degrees.*

DISCUSSION

Wind, Aeolian Sand-Transport, and Precipitation Patterns:

For the interval from December 2004 through February 2005, northern Arizona experienced precipitation levels that the National Climatic Data Center defined as “greatly above normal”. Precipitation for the rest of 2005 was considered in the normal range for this region; the combination of an unusually wet winter with subsequent normal conditions resulted in total annual precipitation in 2005 that was considered above normal in Arizona (the 81st wettest year out of 111 years on record; National Climatic Data Center, http://www.ncdc.noaa.gov/). Of the unusually wet winter months, February 2005 was particularly notable. During that month, western Grand Canyon received far more precipitation than eastern Grand Canyon and Marble Canyon—rain gauges at Forster and 202.9 mile recorded 70.0 and 85.6 mm of monthly rainfall, respectively. Much of this rain fell on February 11 and 12, as part of a major storm system that also caused floods and rock slides in other parts of the state. High rainfall in winter 2005 recorded in the western canyon was consistent with extremely high rainfall in the Las Vegas, Nevada, area ~150 km away, which, between December 2004 and February 2005, broke records by receiving more than twice the normal rainfall for those winter months (National Climatic Data Center). Winter precipitation totals in the western canyon were higher than total *annual* precipitation totals at several sites farther east (tab. 3); Forster and 202.9 mile each received more rain during January–March 2005 alone (139.2 and 151.6 mm, respectively) than either Palisades or Comanche received from January–December 2005 (133.2 and 138.0 mm, respectively).

The greatest precipitation amounts measured during this study were recorded at Malgosa, where Station Mal U received an annual total of 268.8 mm during 2005 (tab. 3). This represents an annual rainfall that is 202 percent higher than was measured at the next-closest site, Palisades, located only eight river-miles downstream of Malgosa (approximately 12 km straight-line distance). Such a discrepancy between precipitation patterns at these two locations (and between Malgosa and other sites) was also apparent in the 2003–2004 data set (Draut and Rubin, 2005) and is not the result of one or a few unusual events that skew the totals, but is instead a fairly consistent pattern. Compared to the other study sites in Marble Canyon and eastern Grand Canyon (24.5 mile, Palisades, and Comanche) in 2005, precipitation at Malgosa was greater by a factor of 1.7–3.1 during the abnormally wet January and February, approximately equal from March through June, greater by a factor of 1.3–3.7 during the summer monsoon season of July through September, and, from October through December, was similar to 24.5 mile but greater than Palisades and Comanche by up to a factor of two.

The marked differences between rainfall at Malgosa and the other sites are attributed to local topography, but this interpretation is not well constrained. The Malgosa Creek tributary, which joins the Colorado River from the west near river-mile 57.9, trends northeast and drains the eastern side of the Walhalla Plateau, located southeast of the main Kaibab Monocline. At Palisades, drainages enter the Colorado River (near river-mile 66) from both the east and west. The drainage on river right (west), Lava Creek, drains the Chuar Valley on the east side of Walhalla Plateau but is oriented west-northwest instead of northeast. The total relief and area of the Lava-Chuar Creek drainage basin are both much greater than those of Malgosa Creek. It is possible that the differences in tributary orientation and drainage-basin geometry are sufficient to cause differences in the movement of local weather systems, perhaps creating a funneling effect for eastward-moving storms at Malgosa that could account for the significant difference in rainfall recorded near river level at the two sites.

Above-normal precipitation throughout the canyon in the winter of 2005 resulted in unusually abundant vegetation growth in the spring of 2005. It was qualitatively observed that dune fields, including those that served as study sites for this project, had thicker live grass cover in March and April 2005 than at any other time during the study duration. Because vegetation reduces the ability of sediment to be entrained by wind (Ash and Wasson, 1983; Buckley, 1987), the unusually high productivity of vegetation in 2005 likely reduced the amount of aeolian sand transport in the spring windy season, although the magnitude of this effect was not quantified.

At all study locations, the most common incidence of high wind velocities, and greatest potential for sediment transport (as well as actual measured sand-transport rates), occurred during the spring windy season. This general pattern was similar to that measured during 2004 (Draut and Rubin, 2005). The highest rates of aeolian sand transport during 2005 were measured in May and June, when maximum winds were locally as high as ~25 m s^{-1}, and sand-transport rates locally >100 g cm^{-1} d^{-1}. The timing of the 2005 seasonal sediment-transport peak was thus somewhat later than in the previous year, during which aeolian sand-transport rates were greatest in April and May 2004. Part of the difference in the observed timing of the sediment-transport peak may have been caused by differences in the schedule on which the sand traps were emptied, as maintenance visits could not easily be timed to occur on specific days given the remote locations of the study sites. However, in both 2004 and 2005, sand-trap samples were collected in mid-April, mid-May, and early June, so the timing of sample collection from year to year was consistent enough that real differences in the timing of peak sand transport were apparently resolved.

High wind velocities were also recorded at times of year other than in the spring windy season. In late December 2005 and early January 2006, for instance, several days of winds were recorded with velocities that matched or exceeded velocities that tend to occur in the spring windy season (>20 m s^{-1} at Malgosa; consistently >10 m s^{-1} at the other locations). Winds of this magnitude occurred on 12/26/05, 12/31/05, and 1/2/06 throughout the canyon, but only on the night of 12/31/05 were they accompanied by any precipitation, and then only minimal amounts (less than 1 mm at every station; tab. 4). At several of the weather stations (Mal U, Pal U, and Com), the few winter days of dry, windy conditions contributed to aeolian sand-transport rates that were the highest measured in 2005 outside of the spring windy season.

When high winds are accompanied by rain, wind generally cannot induce sediment transport because the sand is too wet to be mobilized; such a situation is common during summer and fall monsoon storms, which may bring significant quantities of rain and high winds but are not typically associated with much aeolian sand movement. A comparison of general sediment-transport potential (*Qp* vector sums, tab. 2a) with that during only dry conditions (tab. 2b) reveals that although much of the wind data have been removed in order to calculate dry-sand transport potential in table 2b, the magnitudes of the dry *Qp* vectors do not necessarily decrease when wind that occurred only during dry-sand conditions is considered. In some instances (for example, data from October and November, 2005, at Comanche; tab. 2b) removing wind data associated with rainy weather results in higher *Qp* values because winds opposing the dominant transport direction have been filtered out of the calculation, leaving more net transport in the dominant transport direction.

Data from the three study sites at which two weather stations operated (24.5 mile, Malgosa, and Palisades) indicate that wind velocities and aeolian sand-transport rates are uniformly higher at the higher-elevation station in each case (Stations 24.5 U, Mal U, and Pal U) compared to those measured at river level (Stations 24.5 L, Mal L, and Pal L). This is likely caused in part by vegetation near the river, which reduces wind velocity and, consequently, the potential for aeolian sediment entrainment (Olson, 1958; Bressolier and Thomas, 1977; Ash and Wasson, 1983; Wasson and Nanninga, 1986; Buckley, 1987; Bauer and others, 1996). Wind can also attain higher velocity at higher elevation given the reduced interaction of air flow with boundaries such as the canyon walls, as the canyon widens upward. This is not a universal rule, however, because local topography can cause major local variations in wind speed and direction.

Variations in sand-transport rates between sites are related not only to variable wind strength but also to other local factors that affect the sand-entrainment potential. Sand transport may be lower at low-elevation sites near the river because residual moisture in sandbars along the river-channel margin limits entrainment of sand there by wind. Aeolian sediment transport is reduced significantly by the presence of interstitial moisture (Sarre, 1988, 1989; McKenna Neuman and Nickling, 1989; Namikas and Sherman, 1995; Wiggs and others, 2004). In Grand Canyon, sandbars inundated by daily fluctuating flows often do not dry thoroughly before they are inundated again the following day.

Site-Specific Aeolian Sediment-Transport Processes:

The highest rates of sediment transport measured during this study, at Malgosa and Forster, occur in “active” dune fields. In a sand-dune environment that commonly undergoes active aeolian sediment transport, dune crests and sand shadows are well defined, with little vegetation and little or no cryptogamic crust. Data throughout the 2003–2006 study interval have shown that, at these sites, sand-transport rates of tens of grams per centimeter per day (g cm^{-1} d^{-1}) were common and that much higher rates (hundreds to thousands of g cm^{-1} d^{-1}) were possible during the spring windy season. In contrast, less-active aeolian dune fields (those that have substantial vegetation cover and cryptogamic crust, such as Palisades near the Pal U weather station, and Comanche) had sediment-transport rates that were at least an order of magnitude less than those measured at Forster and Malgosa (0.1–1 g cm^{-1} d^{-1} during the non-windy season and 1–10 g cm^{-1} d^{-1} during the windy season).

These differences in wind-blown sand transport between active and less active dune fields are consistent with the findings of previous studies that have demonstrated lower transport rates over dune surfaces on which cryptogamic crust is present (Leys and Eldridge, 1998; Belknap, 2001; Goossens, 2004). The dune field at 24.5 mile, which has both active and relatively inactive geomorphic zones, had transport rates more similar to those of Palisades and Comanche (order 1 g cm^{-1} d^{-1}) than to the very active Malgosa and Forster sites. With the lowest transport rates of any sites, Station Pal L, located on a relict fluvial cobble-boulder bar, typically recorded sediment-transport rates on the order of 0.01 g cm^{-1} d^{-1}. Such low transport rates at that location are apparently a function of a low supply of available sand, and cannot be accounted for by lower wind speeds at Station Pal L as compared to those at Station Pal U. At all stations, rates of sand transport during the spring windy season were 5–15 times higher than at other times of year.

Net aeolian sand-transport directions are locally variable; at 24.5 mile, Malgosa, and Forster, the calculated transport directions indicate net motion of sand from fluvial sandbars toward aeolian dune fields located further from the river. At those three locations, any increase in fluvial sandbar area (such as would occur following a sediment-rich controlled flood of the Colorado River) is expected to increase sand transport to the adjacent aeolian dune fields. However, at Palisades and Comanche the calculated dominant transport direction is oriented such that new fluvial sand deposits left by floods on the order of 1,270 m^3 s^{-1} (45,000 ft^3 s^{-1}) will probably not act as major sand sources for adjacent dune fields; instead, at those two sites the net transport from river-level sandbars is directed upstream and toward the river, where wind-blown sand would become entrained in the water. (Note that much larger, pre-dam floods >4,810 m^3 s^{-1} [170,000 ft^3 s^{-1}] left extensive fluvial deposits in the Palisades area from which the aeolian dune field apparently formed; Draut and others, 2005).

At 202.9 mile, data collected between April and December 2004 indicated that the dominant sand transport would be directed north (from downstream; Draut and Rubin, 2005). Those initial data supported the idea that the large sandbar downstream of the weather station at that site, on the surface of which vegetation has encroached substantially since the mid-1960s, formerly provided a sand source to the dune field on the debris fan upstream of the weather station. This in turn implied that reduced sand-entrainment potential from the newly vegetated sandbar had affected or could affect the condition of the aeolian deposits downwind (upstream) of this sandbar. Wind conditions at 202.9 mile in 2005, however, indicated a more complex situation. Although upstream and downstream winds nearly balanced each other at that site in 2005, a tertiary component from the northwest yielded a vector sum showing net sediment transport toward the river (fig. 22). Thus the longer-term record now available from this site seems to suggest that although loss of the potential sand source (the now-vegetated sandbar) downstream of this site may affect the condition of that dune field, the availability of sand from other sources could also affect aeolian deposition and erosion processes there.

Effects of the November 2004 High-Flow Experiment:

The data collected at the weather stations provide information about the potential for aeolian redistribution of sand from fluvial sandbars. This information can therefore be used to evaluate transport to and restorative deposition on aeolian dune fields that protect archaeological sites, following the formation of new fluvial deposits after a controlled flood of the Colorado River. Sandbar restoration was the primary goal of the high-flow experiment conducted in November 2004. The November 2004 controlled flood release from Glen Canyon Dam, a 60-hour steady flow of 1,160 $m^3 s^{-1}$ (41,000 $ft^3 s^{-1}$) on November 22 and 23, was the second experiment of its kind. The first, conducted in March 1996 under conditions of sediment depletion in the Colorado River channel, resulted in a temporary increase in surface area and volume of higher-elevation parts of sandbars in Grand Canyon (Rubin and others, 1998, 2002; Hazel and others, 1999; Topping and others, 2006).

In order to ensure a greater supply of sand in the upstream reach than was available in 1996, the 2004 high-flow experiment took place after substantial quantities of sand had recently been supplied to upper Marble Canyon by the Paria River and other tributaries, and after an interval of lower dam releases to minimize export of this sediment. Conditions during the 2004 controlled flood therefore represented suspended-sediment enrichment in the river channel relative to conditions during the 1996 flood (Topping and others, 2006).

The duration of this study included one year of pre-flood data spanning each season, and, for comparison, slightly more than a year of post-flood data. The sites studied for this aeolian-transport research were chosen in part because they had experienced new fluvial sand deposition during the 1996 high-flow experiment. Therefore, it was predicted that similar deposition would occur at these locations during the November 2004 high flow. Based on results from the year of pre-flood data (2003–2004), the greatest potential for redistribution of new, flood-deposited sediment was predicted to occur during the spring windy season when wind-blown sand-transport rates were expected to be up to an order of magnitude greater than during the non-windy season.

Surveys conducted before and after the November 2004 flood indicated that the area and volume of sandbars in Marble Canyon upstream river-mile ~40 were, in general, significantly greater than before this flood, and that approximately half of the surveyed sand deposits were much larger than they had been immediately after the 1996 controlled flood (Hazel and others, 2005; Topping and others, 2006). Downstream from river-mile ~40, localized deposition and erosion were documented (Topping and others, 2006). The study sites at 24.5 mile, Malgosa, Palisades, and Comanche were photographed immediately before the flood experiment began, one to two weeks after the flood, and a third time in March 2005. At all study sites, both upstream and downstream of river-mile 40 (including Forster, and 202.9 mile, which could not be photographed on the same schedule as the first four sites) this flood experiment resulted in substantial new sand deposition (figs. 23–28).

Because the fluvial sandbars at these study sites are the source areas from which wind transports sediment to aeolian deposits, the substantial deposition in those areas during a sediment-rich Colorado River flood implies that such floods have excellent potential for restoring aeolian deposits (and thus enhancing the preservation of any associated archaeological sites). However, though the November 2004 flood brought substantial new sand to many sandbars (and also promoted aeolian sand entrainment by decreasing the roughness of the land surface by depositing sand cover on vegetation, rocks, and driftwood), much of that sand was removed by high daily flow fluctuations that ranged from 142 to 566 $m^3 s^{-1}$ (5,000 to 20,000 $ft^3 s^{-1}$) for the three months between January and March 2005, before the spring windy season began (figs. 23–28). The most dramatic changes were observed at Malgosa, where a new sand deposit 1.5 m thick and more than 10 m wide formed during the flood but was eroded almost entirely over the following four months. By May 2005, the appearance of the sandbar at Malgosa was virtually indistinguishable from its state before the flood (fig. 26). Sites located a short distance downstream of the Little Colorado River (LCR), such as Palisades and Comanche, 7.4 and 10.4 km below the LCR confluence, respectively, showed less pronounced loss of sand during the January–March high flow fluctuations than that observed at 24.5 mile and Malgosa. This was presumably because flooding from the LCR in February 2005 (~70 $m^3 s^{-1}$ [2,500 $ft^3 s^{-1}$]) possibly provided additional sand to these areas (figs. 27 and 28).

At sites where the flood deposits were entirely removed before the 2005 windy season began, windy-season aeolian sand-transport rates in 2005 were comparable to or lower than those measured during the 2004 windy season, given similar wind conditions. As discussed above, unusually thick grass cover in spring 2005 may have reduced aeolian entrainment and transport of sand compared to the previous spring. A clear exception to this pattern occurred at 24.5 mile, where about half of the flood-deposited sand remained at the start of the windy season in spring 2005 (figs. 23 and 24). Aeolian sand-transport rates at the low-elevation instrument station there (Station 24.5 L, near the river) during the spring 2005 windy season were approximately double those measured in spring 2004. This is interpreted to be a result of the increased area of available sand upwind and decreased roughness of the land surface where the 2004 flood sediment was still present; the sand traps at Station 24.5 L were located only ~15 m from the landward edge of the 2004 flood deposit. However, no similar increase in sand flux relative to the previous year was measured at the upper-elevation station in the dune field at 24.5 mile (Station 24.5 U; fig. 7).

The dominant wind direction at 24.5 mile transports sand from the area of the lower station toward the upper station. Because wind conditions at the upper and lower stations at 24.5 mile varied in a manner similar to each other compared with those measured the previous year, the data in figures 5 and 7 suggest that, although the influence of the new flood sediment was felt at the lower station, its effects had not yet propagated to the upper part of the dune field. In many areas of the river corridor, new sand would need to reach the highest parts of aeolian dune fields in order to benefit archaeologically significant locations. Because the sand flux measured at the upper station at 24.5 mile exceeded that at the lower station even with the new flood deposit present, the net flux of sand into this dune field was still negative, indicating deflation of its land surface. Assuming wind conditions similar to those measured in 2005, the sediment flux at the lower station would need to be ~50 percent higher than that measured in 2005 to equal the sand flux at the upper station; such a situation would indicate that the dune field was stable, with no net gain or loss of sediment. It is possible that, if the sandbar near the lower station at 24.5 mile had still been as large during the spring 2005 windy season as it was immediately after the November 2004 flood (figs. 23 and 24), the sand flux into the dune field (measured at the lower station, 24.5 L) might have balanced or exceeded that measured at the upper station, resulting in net sediment gain in the dune field.

Despite the loss of flood-deposited sand at 24.5 mile during high fluctuating flows after the flood, the restorative capability of aeolian sand derived from the flood deposit could still be observed at this site more than a year after the flood experiment. In January 2006, a new gully was observed that had recently begun to incise into the aeolian dune field at 24.5 mile. The lower end of this feature, to a visible length of at least 5 m, had filled with wind-blown sand (fig. 25). Based on the orientation of the gully and of wind ripples on the surface of the sand, it was clear that the sediment that had filled the lower part of this gully was derived from the November 2004 flood deposit. This inference is consistent with the dominant wind direction recorded at 24.5 mile over the preceding 27 months. The ability of gullies to act as natural traps for wind-blown

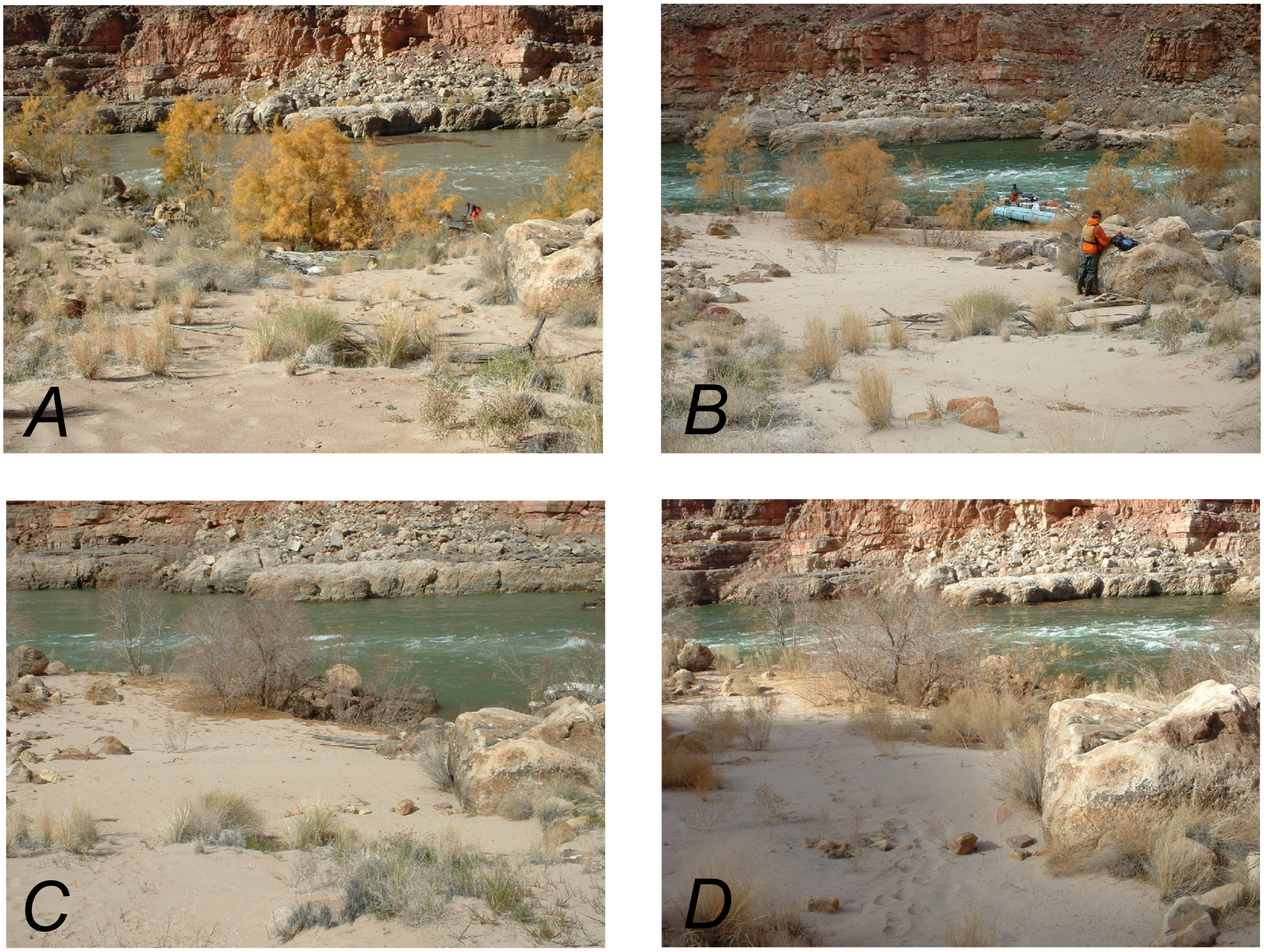

FIGURE 23. *Photographs taken at 24.5 mile showing the response of this area to the November 2004 high flow and subsequent fluctuating flows. Photographs were taken near weather station 24.5 L, (A) immediately before the November 2004 flood experiment, on 11/17/04, at a discharge of 226* $m^3\ s^{-1}$ *(8,000* $ft^3\ s^{-1}$*). (B) The area as it looked shortly after the flood, on 12/4/04, at a discharge of 226* $m^3\ s^{-1}$ *(8,000* $ft^3\ s^{-1}$*). New sand deposited by the flood covered vegetation, driftwood, and rocks to a thickness of up to ~ 1 m. (C) Photograph taken on 3/8/05, at a discharge of approximately 226* $m^3\ s^{-1}$ *(8,000* $ft^3\ s^{-1}$*), after two months of daily flow fluctuations during which discharge ranged between 142 and 566* $m^3\ s^{-1}$ *(5,000–20,000* $ft^3\ s^{-1}$*). The edge of the flood deposit had eroded substantially by March 2005. (D) The same area on 1/12/06 appeared similar to its state the previous spring.*

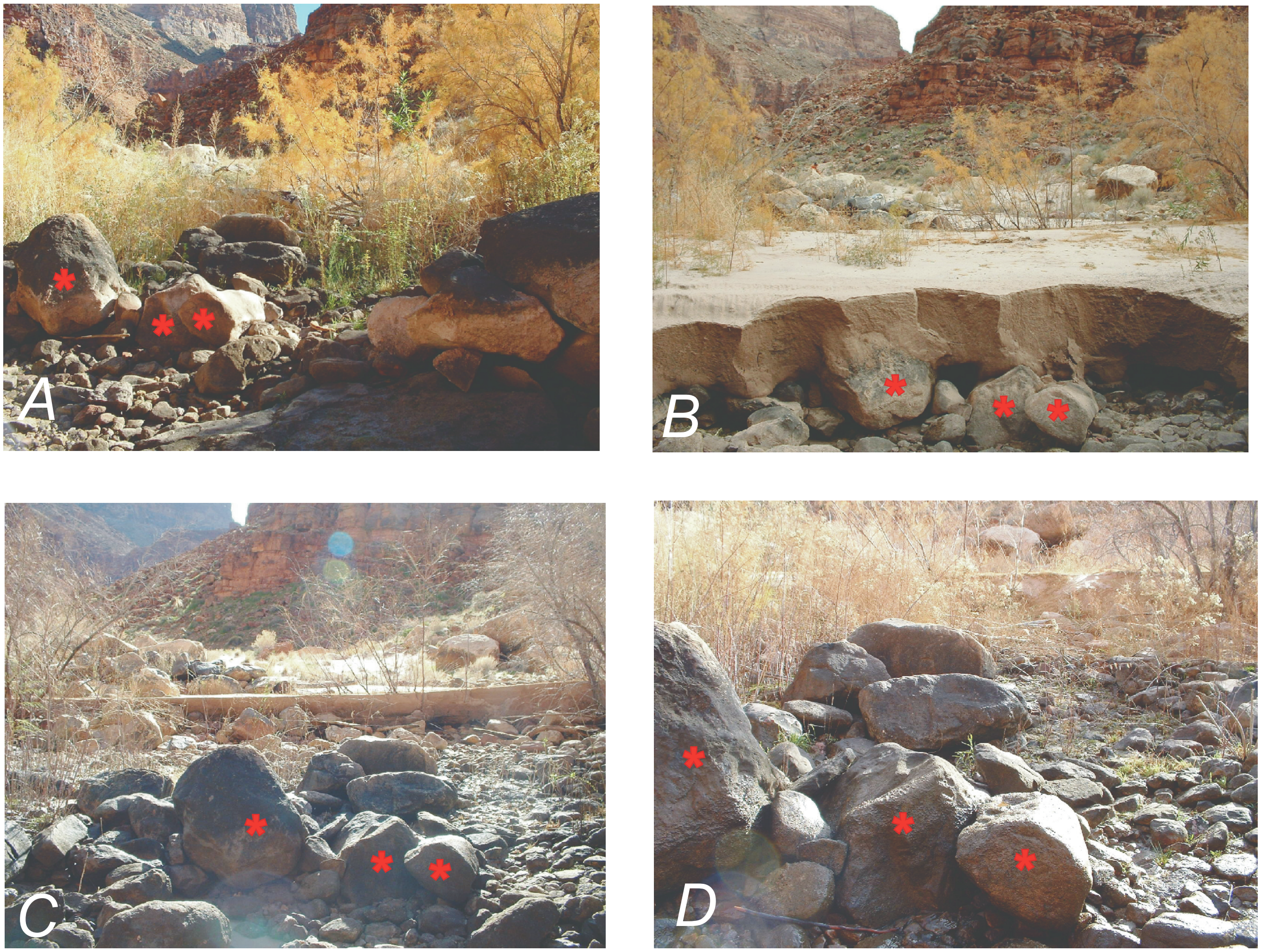

FIGURE 24. *Photographs of the same flood deposit at 24.5 mile that appears in figure 23, but shown from river level. Red asterisks mark three rocks that appear in each photograph for reference. A) The area immediately before the November 2004 flood experiment, on 11/17/04, at a discharge of 226 m^3 s^{-1} (8,000 ft^3 s^{-1}). B) The new flood sand as of 12/4/04, at a discharge of 226 m^3 s^{-1} (8,000 ft^3 s^{-1}), covered rocks, vegetation, and driftwood. C) Photograph taken on 3/8/05, at a discharge of approximately 226 m^3 s^{-1} (8,000 ft^3 s^{-1}), shows approximately 10 m of recession of the edge of the flood sand that occurred during two months of daily flow fluctuations between 142 and 566 m^3 s^{-1} (5,000–20,000 ft^3 s^{-1}). D) The same are on 1/12/06. The edge of the flood-sand cut bank is visible in the background of the photograph but is partially obscured by foliage.*

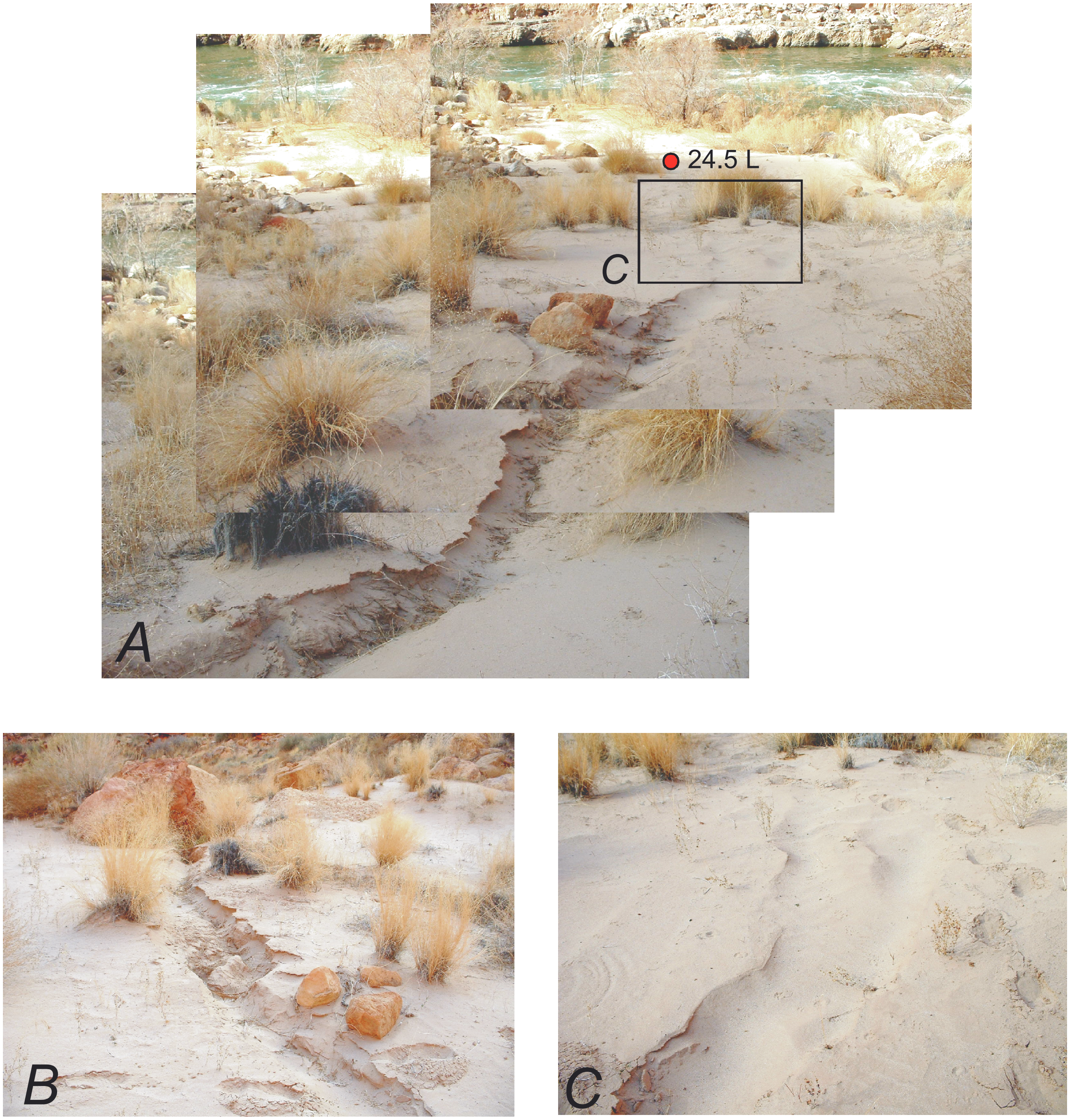

__FIGURE 25.__ Photographs taken on 1/12/06 of a small gully that had incised into the aeolian dune field at 24.5 mile. This gully, which had not been observed on previous maintenance visits to the site, was approximately 10 m long, 25 cm wide, and up to 25 cm deep. Its terminus, to a length of about 3 m, had been filled by wind-blown sand. Based on the orientation of the gully and wind ripples on the surface of the sand, the sediment that had filled the lower part of this gully had been derived from the November 2004 flood deposit. This inference is consistent with the documented predominant wind direction at 24.5 mile. A) Photomosaic of the gully, facing upwind and downgully, with perspective slightly different in each of the three photographs in the mosaic. The former location of the 24.5 L weather station, which had just been dismantled, is shown by the red circle. The area shown in part (C) is indicated by the box. B) Head of the gully, which appeared to have formed by drainage of rainwater around the sandstone boulder in the background. C) Terminus of the gully, filled by aeolian sand.

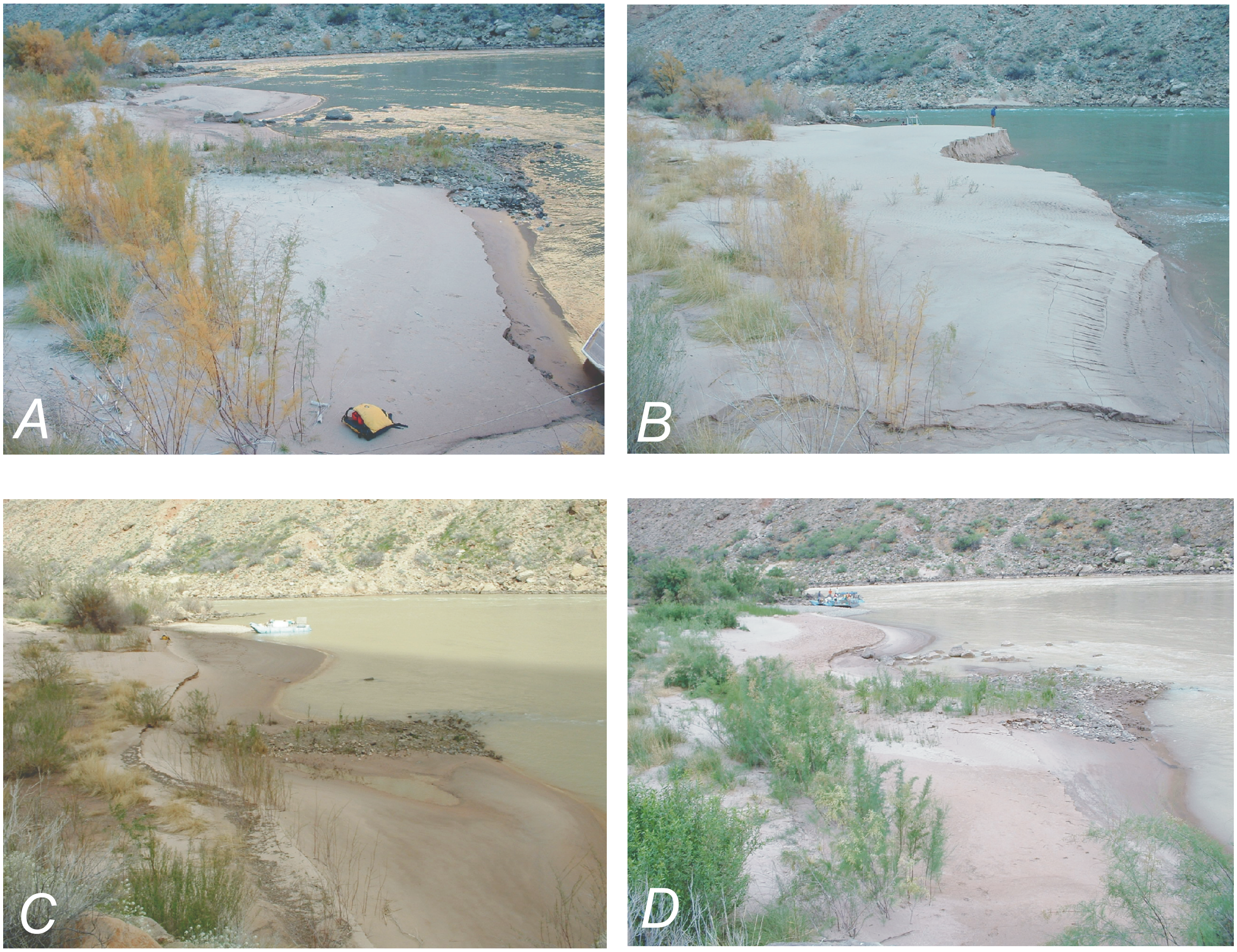

FIGURE 26. *Photographs taken at Malgosa showing the effects of the November 2004 flood and subsequent fluctuating flows. The area pictured is on river right near weather station Mal L. The pre-flood photo (A) was taken on 11/17/04, at a discharge of 226* $m^3\ s^{-1}$ *(8,000* $ft^3\ s^{-1}$*). The post-flood photo (B) was taken on 12/9/04, at a discharge of ~226* $m^3\ s^{-1}$ *(8,000* $ft^3\ s^{-1}$*). New sand deposited at this location during the flood flow was approximately 2 m thick (a person standing on top of the deposit is visible for scale in the background of B). C) After several months of 142–566* $m^3\ s^{-1}$ *(5,000–20,000* $ft^3\ s^{-1}$*) daily flow fluctuations, this photo from 3/13/05, shows that the flood deposit had eroded substantially, exposing many of the rocks in the center of the beach that were exposed before the flood. The 3/8/05 photo in (C) was taken during a discharge of ~ 226* $m^3\ s^{-1}$ *(8,000* $ft^3\ s^{-1}$*). D) Photograph taken on 5/28/05 at a steady discharge of ~ 226* $m^3\ s^{-1}$ *(8,000* $ft^3\ s^{-1}$*). By May, the flood deposit had been almost entirely removed, and the sandbar in (D) appears nearly identical to its pre-flood state.*


A
B
C
D
E
F

FIGURE 27. *Photographs taken at Palisades showing the effects of the November 2004 flood and subsequent fluctuating flows. This location is on river left near weather station Pal L. The pre-flood photo (A) was taken on 11/19/04, at a discharge of 226* $m^3\ s^{-1}$ *(8,000* $ft^3\ s^{-1}$*). The first post-flood photo (B) was taken on 12/10/04, at a discharge of ~283* $m^3\ s^{-1}$ *(10,000* $ft^3\ s^{-1}$*). Even at slightly higher discharge, it is apparent in (B) that a large subaerial sand deposit was left by the flood flow. C) Photo taken after several months of 142–566* $m^3\ s^{-1}$ *(5,000–20,000* $ft^3\ s^{-1}$*) daily flow fluctuations. This picture was taken on 3/16/05, at a discharge of ~425* $m^3\ s^{-1}$ *(15,000* $ft^3\ s^{-1}$*). Sediment that was deposited on this sandbar by the November flood experiment had been reworked by high daily flow fluctuations between January and March, 2005, but its persistence in this location four miles downstream of the Little Colorado River (LCR) confluence throughout the rest of the year indicated that substantial additional sand may have been deposited here during sediment-laden floods of the LCR in February, 2005. D) The fourth photograph was taken on 5/30/05, at a discharge of steady 226* $m^3\ s^{-1}$ *(8,000* $ft^3\ s^{-1}$*). E) The fifth photograph was taken on 9/18/05 at a discharge of approximately 226* $m^3\ s^{-1}$ *(8,000* $ft^3\ s^{-1}$*). F) The final photograph, taken on 1/15/06 at a discharge of 340* $m^3\ s^{-1}$ *(12,000* $ft^3\ s^{-1}$*), shows that a subaerial sandbar was still present at this site more than one year after the high-flow experiment.*

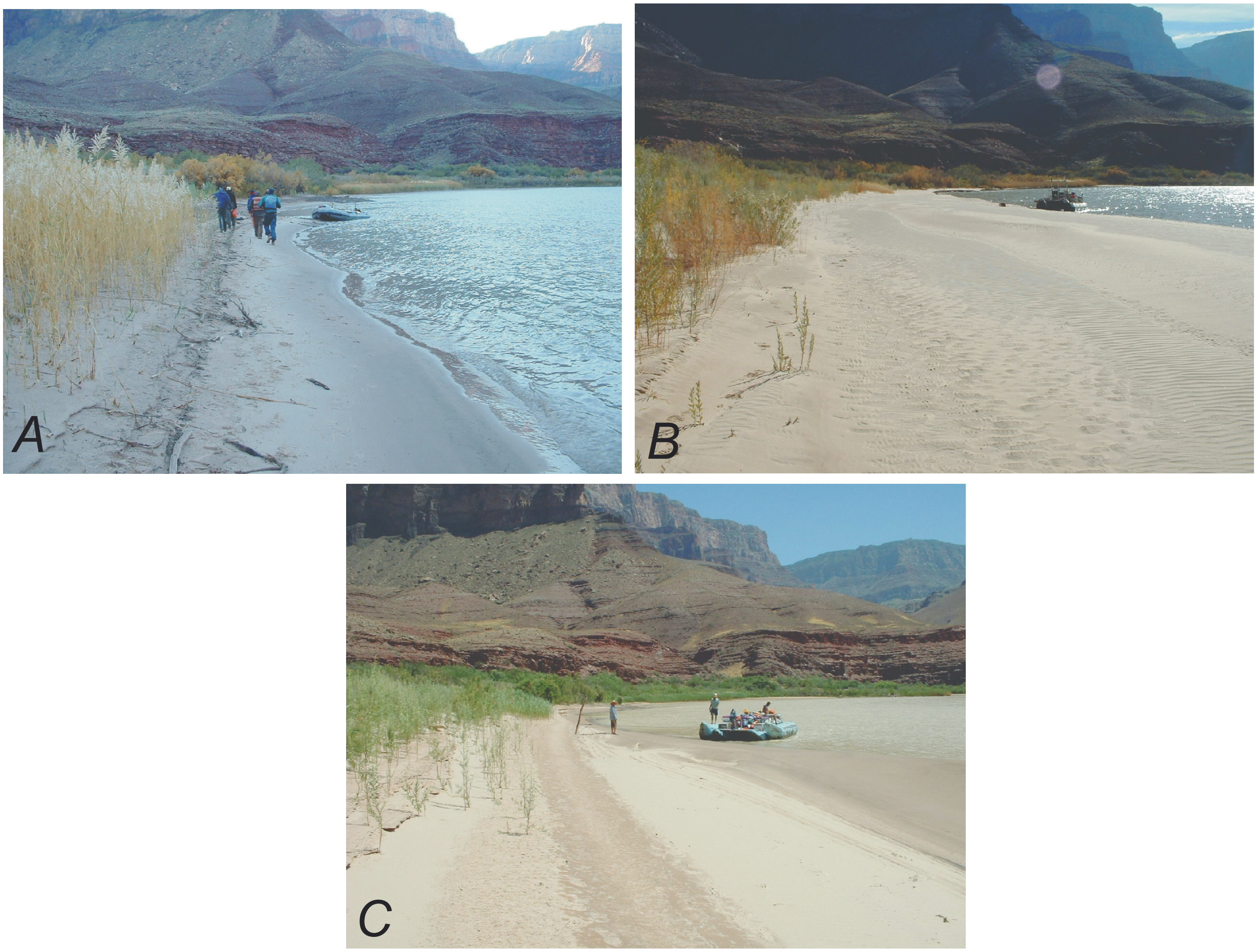

FIGURE 28. *Photographs taken at Comanche showing the effects of the November 2004 flood and subsequent fluctuating flows. This location is on river left and is the closest beach to the location where Station Com was set up. The pre-flood photo (A) was taken on 11/18/04, at a discharge of 226* $m^3\ s^{-1}$ *(8,000* $ft^3\ s^{-1}$*). The post-flood photo (B) was taken on 12/10/04 at a discharge of ~255* $m^3\ s^{-1}$ *(9,000* $ft^3\ s^{-1}$*). Even at slightly higher discharge compared with (A), it is apparent in (b) that sand deposited by the high flow had substantially widened the beach. (C) Photo taken on 5/30/05, about six weeks after the end of high daily flow fluctations. This picture was taken at a discharge of steady 226* $m^3\ s^{-1}$ *(8,000* $ft^3\ s^{-1}$*). The beach had narrowed substantially compared to its state in December 2004 but was still noticeably wider than it had been before the flood. As at Palisades, it is possible that additional sand introduced to this area by Little Colorado River floods in February 2005 helped maintain open sand area at this site longer than would have occurred without that input.*

sand, as illustrated with this example from 24.5 mile (fig. 25), could contribute to slowing or cessation of erosional processes that affect the integrity and preservation of archaeological sites in aeolian deposits (for example, Thompson and Potochnik, 2000).

Apart from 24.5 mile, the only other study location at which a substantial new fluvial deposit persisted after the flood was at Palisades, near the river-level Station Pal L. Sediment-transport rates were very low at this station (fig. 13) due to its location within a boulder field; however, a low-elevation fluvial sandbar was present throughout 2005, adjacent to the boulder deposit, that had not been present immediately prior to the November 2004 high-flow experiment (fig. 27). It is probable that the high flow fluctuations eroded some of the November 2004 flood sediment away from this sandbar between January and March 2005. This sandbar remained fairly large and exposed throughout 2005, however (fig. 27), suggesting that flooding of the Little Colorado River in February 2005, combined with daily dam releases peaking at 566 $m^3 s^{-1}$ (20,000 $ft^3 s^{-1}$), probably deposited additional sand at this location. This sandbar may have served as an additional source of aeolian sediment to the Palisades area during 2005, but the wide error margin on the sand-transport data from Station Pal L (fig. 13) prevents this from being determined conclusively. As shown in figs. 14 and 16, also, the dominant southwesterly wind direction in this area implies that even the presence of this major new sandbar after the 2004 flood likely did not provide much new sediment to the large, relatively inactive aeolian dune field on river left at Palisades.

Recommended Future Directions:

The 27 months of data discussed in this report and by Draut and Rubin (2005) span a variety of conditions and weather patterns but still are likely not complete enough to represent long-term climate in the Grand Canyon region. A longer weather-monitoring program would allow weather patterns and potential sand-transport measurements to be refined with greater accuracy. To represent weather conditions at high spatial resolution over the entire river corridor in Grand Canyon, many stations would be required. To achieve some spatial representation of weather variability in the canyon, a minimum of five to six stations are recommended between Marble Canyon and Diamond Creek (river-mile 226). Although the stations used in this study monitored weather that was directly relevant to archaeological sites (that is, aeolian sand transport and precipitation), longer-term weather monitoring could utilize additional equipment to measure air temperature, relative humidity, barometric pressure, and other variables to generate a broader-scale record of climate in the Colorado River corridor.

Recording climatic data in the river corridor is only one step, however, in resolving the complex geomorphic processes that affect the condition of aeolian deposits, and, by extension, many archaeological sites. The information gathered and presented in this report, and in other publications (Draut and others, 2005; in review; Draut and Rubin, 2005; in review), forms the basis for a wide array of detailed modeling studies that could be undertaken in the future. It is becoming increasingly clear that aeolian transport and deposition of sediment can and do affect the condition of archaeological sites in the river corridor, and that the availability of sediment from open-sand areas on fluvial sandbars is an integral component in these processes. Two further, related, research initiatives are suggested to address these issues: (1) a detailed aerodynamic modeling study of one or more locations that would involve numerical representation of air flow, including dynamic interactions with obstacles, slope, and irregular spatial boundaries, and (2) deployment of recording sand traps (not commercially available) that would allow unprecedented temporal resolution of sediment-transport response to specific, short-duration wind conditions. Future research in these two linked directions would undoubtedly lead to a better understanding of the aeolian-transport system that affects natural and cultural resources in Grand Canyon.

CONCLUSIONS

Data collected at nine weather stations in the Colorado River corridor, Grand Canyon, between January 2005 and January 2006 reveal considerable spatial and seasonal variation in wind and precipitation patterns. Over this interval, total annual rainfall varied by more than a factor of two over distances of ~10 km. During the unusually wet winter months of 2005, western Grand Canyon received approximately twice as much rain as the average of eastern Grand and Marble Canyon sites studied. The degree of measured spatial variation in precipitation indicates that future sedimentary and geomorphic studies in the canyon would benefit substantially from continued or expanded data collection at multiple locations along the river corridor, because rainfall records collected by NPS at Phantom Ranch cannot be assumed to be valid for other areas of the canyon.

Wind velocities and sand-transport rates were greatest during May and June 2005. During that spring windy season, maximum winds exceeded 25 m s^{-1}, and aeolian transport rates in active dune fields exceeded 100 g cm^{-1} d^{-1}. The timing of windy-season aeolian sand transport represents a somewhat later peak than was measured the previous year, when the most transport occurred during April and May 2004. At all weather stations, rates of sand transport during the 2005 spring windy season were 5–15 times higher than at other times of year. Dominant wind direction during strong winds varied with location, but during the spring windy season the greatest transport potential was directed upstream in Marble Canyon and eastern Grand Canyon.

These records have been used to evaluate the potential for aeolian reworking of new fluvial sand deposits, and renewed deposition on higher-elevation aeolian deposits, following the November 2004 high-flow experiment. Although this flood deposited substantial quantities of new sand at all six study locations, high flow fluctuations between January and March 2005 removed much of the new sediment. At sites where essentially none of the flood-deposited sediment remained by the time the 2005 spring windy season began, aeolian transport rates then were comparable to or lower than those in spring 2004. At the one studied location (24.5 mile) where substantial fluvial sand from the 2004 flood remained by spring and where the wind direction was oriented to bring sand from river level landward into aeolian dunes, sand transport rates near the river in spring 2005 were significantly higher than in spring 2004. At the same site, gully incision in the dune field was partially ameliorated by deposition of wind-blown sand derived from the 2004 flood deposit. Together these findings imply that (1) sediment-rich controlled floods can be used to restore sand deposition in aeolian dune fields above the flood-stage elevation, (2) that the restoration potential for cultural sites in aeolian deposits can be maximized by using dam operations (floods and post-flood flows) that maximize the open, dry sand area on fluvial sandbars during spring, when aeolian sediment transport is greatest, and (3) that to provide the greatest benefit to aeolian deposits and associated archaeological sites, flows that follow sandbar-building floods would need to be managed to retain and maximize high-elevation, open, dry, sandbar area.

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