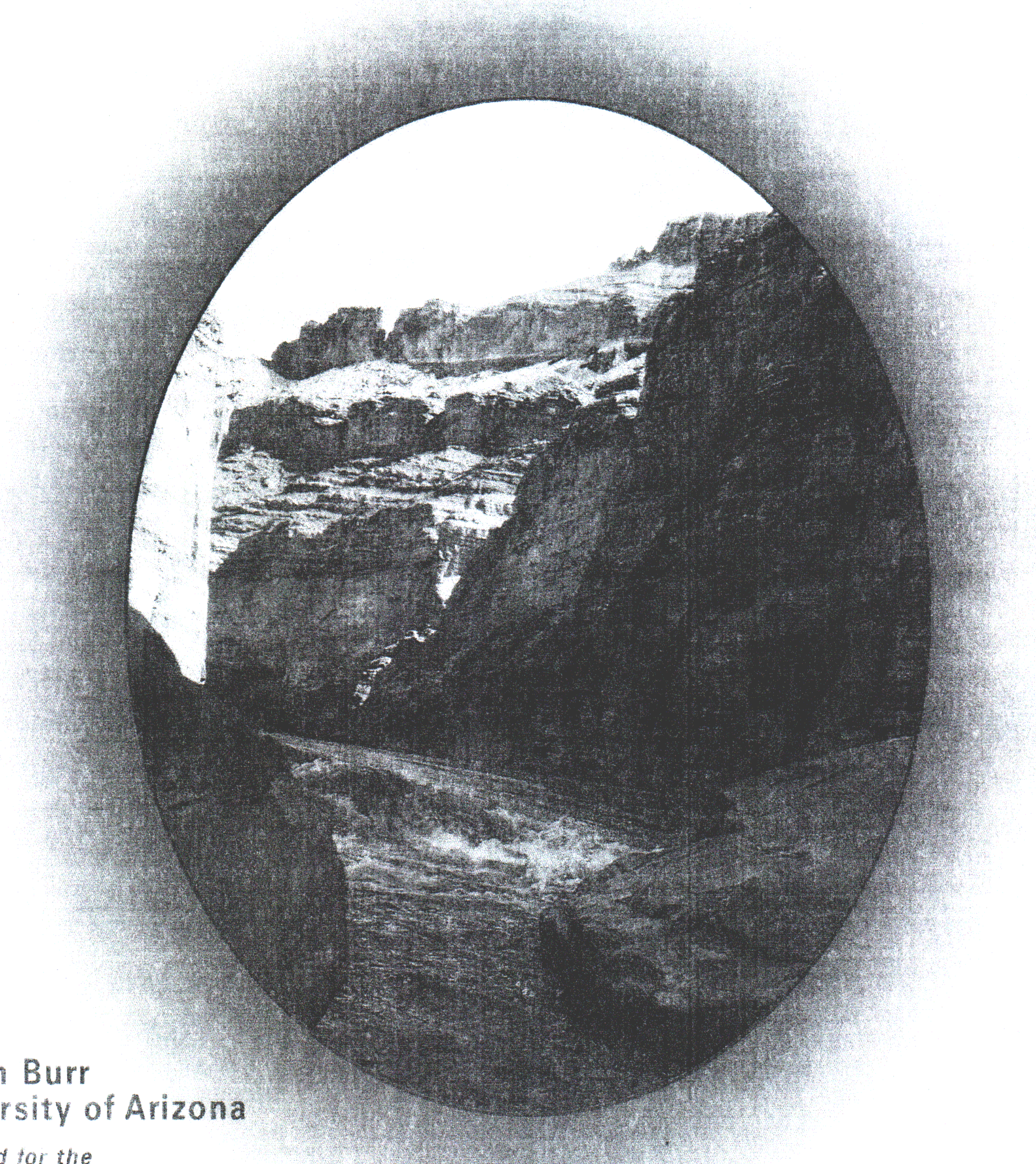
Turbidity in the Colorado River Through Grand Canyon National Park, July 1998 to July 1999



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Prepared for the
U.S. GEOLOGICAL SURVEY
in cooperation with the
GRAND CANYON MONITORING AND RESEARCH CENTER

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ABSTRACT

Turbidity in the Colorado River through Grand Canyon is of interest because of its effects on the aquatic ecosystem and because of its potential correlation with suspended sediment concentration. Since June 1998, turbidimeters have been in operation at three streamflow gaging stations on the Colorado River in the Grand Canyon: at Lees Ferry (09380000), above the Little Colorado River near Desert View (09383100), and near Grand Canyon (09402500). The data collected between July 1998 and July 1999 have various sources of error. The primary source of error appears to be data clipping caused by improper instrument configuration, specifically the connection between the turbidity probe and the data logger. The data also show significant scatter, which may be due to sand and bubbles interfering with the probe. A second data logger used at each site in parallel with the current logger would provide verification of the data collected and allow an assessment of various logger settings to increase the quality of data collected. The installation of a stilling well or similar device may help to determine the cause of the erratic readings by reducing the amount of sand and bubbles around the probe.

Introduction

Turbidity refers to the optical condition of water characterized by lack of light penetration, the visual opacity of the water, its "muddiness" or "cloudiness." The turbidity of the Colorado River is legendary. Early settlers purportedly quipped that the river was "too thin to plow, too thick to drink" (Beverage and Culbertson, 1964). Even its name—"the river colored red"—evokes the Colorado's unusual optical properties. Turbidity is caused by suspended sediments which reduce the transmission of light through absorption or scattering. The turbidity of the Colorado River in Grand Canyon has been significantly reduced by the trapping of sediments behind the Glen Canyon Dam. The amount of reduction is unknown, because no pre-dam turbidity measurements were taken, but the river now runs generally clear from the dam to the first tributary.

The dam has also produced other significant changes in the river. Before the dam, the river water temperature fluctuated from near freezing during the winter to more than 26 degrees Celsius by late summer (Bureau of Reclamation, 1995). Now, the inlet to the dam's eight penstocks, at 230 feet below full pool level and 465 feet above bedrock, is located in Lake Powell's hypolimnion. Consequently, post-dam river water temperatures have remained between 7 and 16 degrees Celsius (Rote et al., 1997). The magnitude and frequency of flooding in the canyon has also been reduced. Historic records indicate that annual peak discharges during the spring runoff were commonly 80,000 cubic feet per second (ft^3/sec), with higher maxima; low flows during the fall often reached 3,000 ft^3/sec (Rote et al., 1997). In contrast, dam-controlled discharges, determined primarily by irrigation, flood control, and power production requirements, are restricted to flows between 5,000 ft^3/sec and 25,000 ft^3/sec by the Bureau of Reclamation Record of Decision (1996).

It is reasonable to hypothesize that these significant changes caused by the dam have had significant effects downstream, and this hypothesis is substantiated by downstream changes. But determining cause and corresponding effect in these circumstances is difficult because of the multiple changes produced by the dam. Accurate measurement of the magnitude and character of each of the three changes caused by the dam (turbidity, temperature, and discharge) is the first step in untangling the dam's complex effects. Decades of temperature data, collected on a routine basis at the four gaging stations and the dam in the Grand Canyon, are available in the U.S. Geological Survey (USGS) surface water database. Historical discharge data likewise are available, and ongoing paleohydrological studies on the Colorado Plateau are extending this record. In contrast, turbidity sensors were installed in the Grand Canyon only in the spring of 1998 as the initiation of routine, automatic turbidity data collection. This report discusses these sensors and the data collected by the sensors from July 1, 1998 to July 15, 1999.

The Ichthyological Impetus for Turbidity Assessment

One of the more significant changes in the post-dam Colorado River is the decline or disappearance of indigenous fish. Historical accounts (several such sources are given by Minckley, 1991) indicate an abundance of fish large enough to be caught by early explorers and settlers for food. These fish were not only numerous but unusual, 93 percent endemic by one estimate (Carlson and Muth, 1989). Today, of the eight native species that remain, four—the humpback chub, the bonytail, the Colorado squawfish, and the razorback sucker—are listed or proposed as endangered (U.S. Fish and Wildlife Service, 1989, 1990). Although this change in native ichthyofauna could be due to any of the several post-dam changes in the river, reduced turbidity may be reasonably hypothesized as a primary causal or contributing factor, especially in conjunction with introduced trout. For example, trout are generally adapted to clear-running rivers, whereas native Colorado fish have reduced eyes, possibly to avoid abrasion in a sediment-laden river (Minckley, 1991, p. 128), so that a reduction in turbidity may favor the trout. Radiotelemetry studies show that humpback chub are inactive when the river is clear, and very active when the river is turbid, whereas the rainbow trout display an inverse activity schedule. This indicates that the humpbacks rely on turbidity for predator avoidance (Richard A. Valdez, Senior Aquatic Ecologist, Southwest Conservation Association, personal communication, 1999), so that again, a reduction in turbidity favors the trout.

Changes in a river's turbidity not only affect the fish directly but also indirectly through changes in the food base of the aquatic ecosystem. As turbidity decreases, the effective depth at which photosynthesis can occur increases, and as turbidity increases, the effective depth at which photosynthesis can occur decreases. This, in turn, changes the type of biomass production from heterotrophic to autotrophic (or vice versa). In the Colorado River through Grand Canyon, pre-dam primary algal production is thought to have been heterotrophic, limited by the low light penetration. The clarity of post-dam water allows algae, primarily *Cladophora glomerata*, and associated organisms such as *Gammarus*, midges, and diatoms to flourish as autotrophic producers (Carothers et al., 1981, as referenced in Grand Canyon Environmental Studies, 1988, p B7-B8). Blinn and Cole (1991) found a significant change in macroinvertebrate species composition between pre and post-dam conditions in the Colorado River through Grand Canyon. Haden (1997) found a significant difference in macroinvertebrate species composition between the Colorado River through Cataract Canyon, upstream of the Glen Canyon Dam, and the Colorado River through Grand Canyon. These results showing changes in biomass production have implications for the relative viability of fish species, which may depend on biomass production of a particular type or quantity for food, cover, or other needs.

In sum, extant research indicates a strong connection between turbidity and aquatic life in the Colorado River, but few in-depth studies have been published that specify the mechanisms by which turbidity, directly or indirectly, affects the native fish in the Colorado River through Grand Canyon. Accurate turbidity measurements would encourage and facilitate this research.

Interest in Turbidity as a Proxy for Suspended Sediment Concentration

In addition to its significance in the biological system, turbidity is of interest in geomorphic and land use studies. Sediment load is widely used to estimate erosion from a landscape and to characterize movement of nutrients and pollutants in a river, and its determination typically requires sampling and return to a laboratory for analysis. Turbidity, however, can be measured in-situ with a probe and a data logger, and the data downloaded via satellite. Turbidity is the result of the interaction of suspended sediment and solar radiation. Incoming radiation striking the water surface may be specularly (like a mirror) reflected at the surface of the water, absorbed by subsurface particles, or backscattered by subsurface particles (Curran and Novo, 1988). Clear water transmits light away from the viewer and thus appears translucent and dark. Water containing suspended sediment backscatters light and thus apears lighter (depending on the color of the sediments), more opaque and turbid. Because of the causal connection between suspended sediment and turbidity, attempts have been made to use turbidity measurements as easier, proxy measurements for suspended sediment concentration. This potential is especially attractive for remote rivers, such as the Colorado through Grand Canyon, for rivers of unpredictable discharge, such as glacial meltwater streams, or in areas lacking laboratory facilities. Success along these lines has been mixed, primarily because of the non-unique relation between the mass and the optical properties of sediments. (See the Appendix for further discussion.) To begin an assessment of the possibility of correlating turbidity and suspended sediment in the Colorado River through Grand Canyon, accurate turbidity data are necessary.

Colorado Plateau rivers have some of the highest suspended sediment loads measured in the United States. The Paria River at Lee's Ferry, Arizona, had a mean daily concentration of 41.1 percent on August 27, 1952, while other, similarly high levels were recorded in the Little Colorado River, and the Rios Puerco and Salida in New Mexico (Beverage and Culbertson, 1964). Water and sediment records from 1951 to 1962 for the Green River (a tributary to the Colorado River in southern Utah) indicate that most of the suspended sediment in these rivers is from lowland arid regions (Andrews, 1986). The specific geologic sources of the sediments in the Colorado River, however, are not known, although they may result from the erosion of the clay-, silt- and sand-rich strata on the Plateau (Potter and Drake, 1989). The geologic history of the Colorado Plateau is well-chronicled by Hintze (1988); the history of the Mesozoic and Cenozoic formations was compiled by Morales (1990), on which the following generalized summary of the southern Colorado Plateau is based.

Geologic History of the Colorado Plateau

The strata of the southern Colorado Plateau record interspersed periods of marine transgressions, and uplift and erosion. From the late Pre-Cambrian through the Devonian eras, what is now western Utah comprised the continental margin, accumulating thick sandstone, limestone and shale deposits. Uplift begun during the Mississippian period produced northwest-southeast trending basins, such as the Paradox Basin in eastern Utah and the Oquirrah Basin near Salt Lake. Thick sedimentary deposits accumulated in these basins, and in the Four Corners area to the south, a prime example of which is the bright, iron-bearing sandstones of the Cutler Group known as "red beds" from the Permian period. Marine transgression was continuing during this time, so that the Pennsylvanian rocks—the Paradox evaporites and the Honacker Trail formations—are shallow marine in origin. Uplift ceased in the early-mid Triassic and a transitional environment of shallow coastline, deltas, floodplains, and tidal flats deposited the Moenkopi Formation (mudstone) and Shinarump Member (conglomerate). By the late Triassic, more red sandstones—the freshwater shales, silt- and sandstones of the Chinle Formation, and the eolian Wingate Sandstone—were being laid down. In the early Jurassic, the Kayenta

Formation (sand- and siltstone) was deposited in a predominately fluvial environment, followed by the whitish Navajo Sandstone of eolian origin, famous for its textbook cross-bedding. During the mid-Jurassic, limestones and mudstones of the Carmel Formation were deposited in a shallow marine environment, after which the Entrada Sandstone was laid down, mostly by wind. The late Jurassic saw the deposition of the thick, maroon, fluvial Morrison Formation (mud- and sandstones). The major action during the Cretaceous was the Sevier orogeny rising in the west and the opening of the Mancos seaway to the east. The result was eastward flowing rivers, which deposited the sandstones and conglomerates, and a shallow marine environment to the east in which was laid down the Mancos (or Tropic) Shale. During the Paleogene, the Laramide orogeny was followed by a stratovolcano phase that emplaced laccoliths such as the Abajo Mountains in eastern Utah. Sandstone and freshwater lacustrine deposition continued during this period, the results of which bear a variety of names throughout the region, such as the Kaiparowits and Wasatch Formations. Quaternary deposits on the Colorado Plateau generally consist of basalt flows followed by alluvium.

Thus, many of the strata on what is now the Colorado Plateau are continental, medium- to fine-grained material deposited near sea level. This deposition occurred in two broad phases, the first as debris from the ancestral Rocky Mountains was transported first westward to the continental margin in central Utah, and later as material from the Sevier orogeny flowed eastward to the Mancos seaway. A complex of interior basins, maintained by tectonic movement, and a predominately arid climate may have prevented drainages from integrating so that these Paleo- and Mesozoic deposits were retained in the regions (Potter and Drake, 1989). During the late Cretaceous and early Tertiary, the large tectonic uplift of the Colorado Plateau, which left these strata essentially undeformed amid the convulsions of the Larmide orogeny, increased the gradient of the plateau-draining rivers. During the late Tertiary, the subduction of the east Pacific rift beneath the western margin of North America produced tension which opened up the Gulf of California (Coney, 1983), invigorating the ancestral Colorado River and establishing it in its present course (Lucchitta, 1990). These events set in motion a tremendous erosional period, as rivers cut canyons in the plateau sedimentary strata and basement rocks, and carried the ensuing sediments to the Gulf of California. The present day high turbidity of the Colorado River and its tributaries may be the latest or last expression of this erosion, or it may signify a separate erosional phase. More data on current uplift and erosion rates--which is informed by suspended sediment measurements, which may be informed in turn by turbidity measurements--would help to answer this question

Methods of Turbidity Measurement

The measurement of turbidity was originated by the oceanography and limnology community. The first systematic method to measure light penetration was the Secchi disk, invented by Professor P.A. Secchi and Commander A. Cialdi during a scientific voyage aboard the SS L'Immacolata Concezione (Cialdi, 1866, in Tyler, 1968). In Cialdi's report, Secchi notes many of the factors that affect the visibility of the disk, including the size and whiteness of the disk, the amount of surface refraction or reflection, the altitude of the sun, the ship's shadow underwater, the clearness of the sky, the color of the water and the height of the observer. Given this long and accurate list of factors, it is understandable that the Secchi disk has never really been standardized. The disk's physical properties, such as the reflectance of the paint, are not universally promulgated, and a precise method of use is not universally adhered to (Tyler, 1968). Nonetheless, its simplicity and low cost ensure its continued use as a method of assessing relative turbidity, and attempts have been made to correlate Secchi disk measurements with other, more sophisticated visiblity parameters (e.g., Tyler, 1968, Preisendorfer, 1986). Common use, as reflected in limnology texts (e.g., Wetzel, 1975, pp. 62-64), specifies that the disk, weighted and painted black and white, be lowered from the shaded side of a vessel until it disappears and then raised until it reappears; this depth of reappearance is the Secchi disk transparency.

Another method of turbidity measurement that uses the same principle as the Secchi disk is the platinum wire method (Welch, 1948). The instrument is a straight platinum wire that projects at a right angle from the end of an aluminum scale. The scale is lowered into the water until the platinum wire disappears, at which depth the turbidity value in parts per million is read off the scale. The USGS produced probably the most widely used form of this instrument. Like the Secchi disk, the platinum wire method was subject both to the vagaries of the environment under which the measurements were made, and to the visual acuity of the measurer (Welch, 1948).

Laboratory techniques were also developed for measuring turbidity. The most basic of these used standard mixtures of known turbidity, composed of silica and water, for comparison with the sample of interest; when an object appeared equally distinct as observed through the sample and the standard, the sample had the same turbidity (in milligrams of silica per liter) as the standard (Welch, 1948). Certain rules of thumb improved the accuracy of this technique—"[E]xperience seems to show that there is some advantage if the object observed is a series of black lines ruled on white paper, if the light used is electric, and if the light illuminates both sample and standard from above. . . "—but it retained significant sources of variability. A similar technique, using standards composed of a polymer called Formazine, is used to calibrate turbidimeters in the field.

Laboratory turbidimeters were developed which, although continuing to rely on the judgment/eyesight of the observer, did standardize the conditions of the measurement. The Jackson turbidimeter used a candle vertically aligned below a graduated cylinder into which the water sample was gradually poured. When, in a darkened room, the candle became invisible through the column of water, the turbidity was read off the graduated cylinder in parts per million (Welch, 1948), often referred to as Jackson turbidity units (JTU's). Because of its veiwing geometry, the Jackson turbidimeter was insensitive to turbidities lower than about 25 JTU's. Transmitted light (the light that would be seen through the column of sample being measured) is difficult to assess at low concentrations because few particles interfere with direct transmission. One solution to this is to measure light scattered at an angle, which is more sensitive at low concentrations, and compare it with transmitted light. In the Hellige turbidimeter, light from a bulb was reflected off two different surfaces so that it illuminated the column of sample laterally (producing a diffuse "Tyndall effect") and vertically from the bottom (producing a bright spot) (Welch, 1948). The slit through which the vertical illumination passed was adjusted so that the bright illumination and the Tyndall illumination blended together. The number read off the adjustment dial was then used in a table or curve to ascertain the turbidity in milligrams per liter (Welch, 1948; Brown and Ritter, 1971). Although applicable in low turbidity situations, Hellige-type turbidimeters still relied upon user judgment.

More objective turbidimeters marked a large advance in the standardization of turbidity and water quality measurement. These turbidimeters use a photosensitive cell to detect the amount of light received from a light source of known output, and are of two types. Spectrophotometers, in which the photosensitive cell is situated in-line with the beam, measure the amount of light absorbed by the suspended material. Because a polymer suspension called

Formazin is stipulated by the American Public Health Association for use in spectrophotometer calibration, turbidity from these instruments is reported in Formazin turbidity units (FTU's). Owing to the instrument geometry, spectrophotometers are less sensitive to low turbidity. Nephelometers, in which the photosensitive cell is situated at ninety degrees to the beam, measure the amount of light scattered by the suspended material. The better sensitivity of nephelometers to a range in turbidity and their greater precision have led to their establishment as the standard method for measuring turbidity by the American Public Health Association, the American Water Works Association, and the Water Pollution Control Federation (APHA, 1989), the U.S. Environmental Protection Agency (EPA) Method 180.1, and the International Organisation for Standardisation (ISO) 7027. Although also calibrated with Formazin, turbidity measurements from these instruments are reported in nephelometeric turbidity units (NTU's), so as not to be confused with spectrometric measurements. Absorptometric determination of turbidity, as by spectophotometer, is not approved by the organizations named above and is generally only used for relative measurements.

A third method of measuring turbidity uses the ratio of scattered to transmitted light in order to cancel out sample color, stray light, and other environmental variables that would affect both the scattered and transmitted light. To date, this technology is not available in field instrumentation but ratioing laboratory instruments are available (e.g. the Hach Ratio 2000 Turbidimeter, described at www.hach.com/Spec/SR2000.htm, accessed June 1999). Continued development of field turbidimeters may be expected to include these features in the near future.

Measurement of Turbidity in the Colorado River through Grand Canyon National Park

Turbidity in the Colorado River in Grand Canyon has been measured systematically by the USGS on at least two occasions. On the first occasion, measurements were made as part of a sediment transport study at streamflow-gaging station 09404120, Colorado River above National Canyon near Supai, Arizona (Figure 1), between December 1990 and July 1991. Secchi disk measurements were made up to four times daily at the "cable rock" opposite the gage. These appear to have been intended as rough or relative turbidity measurements; no correlation between Secchi depths and nephelometric values was established. Consequently these measurements are not comparable to electronic measurements presently being collected electronically. In addition, depth-integrated water samples for turbidity analysis were collected with varying frequency depending on stage (generally about twice a day) from the suspended sediment centroid (John R. Gray, Hydrologist, USGS, personal communication, 1999). These samples were analyzed by the USGS National Water Quality Laboratory and the resultant turbidity values in NTU's are stored in the USGS surface water database. The usefulness of these laboratory data (Figure 2) is limited by their small number and the lack of simultaneous data for suspended sediment concentrations.

Turbidity is currently being measured at three USGS streamflow-gaging stations on the Colorado River through Grand Canyon. In April, 1998, an Analite 190/10/30-G turbidity probe was installed at streamflow-gaging station 09380000, Colorado River at Lees Ferry (Figure 1). The probe, which measures 32 mm in diameter and 200 mm in length, is attached to a programmable Sutron 8200 DCP data logger, which controls the acquisition and transmission of the data. A nephelometer, the probe has a range of 0—400 NTU's. The body of the probe is encased in a metal pipe and attached to the short end of an adjustable, L-shaped bracket. The bracket is attached to the downstream side of the Lees Ferry gaging-station enclosure, so that the probe projects approximately one-half foot out from behind the enclosure into the flow (James J. Wellman, Hydrologic Technician, USGS, personal communication, 1999). In general, the bracket is adjusted so that the probe sits a few feet below the water surface at a discharge of 8,000 ft^3/s (Gregory G.. Fisk, personal communication, 1999). The probe is oriented horizontally (in accordance with instructions), and almost perpendicularly to the flow as judged to be optimal for minimizing algal build-up (James J. Wellman, personal communication, 1999).

In June, 1998, an Analite 195/10/30-G model probe with a data collection platform (DCP) was installed at gaging station 09383100, Colorado River above the Little Colorado River near Desert View (Figure 1). This probe is similar to the 190 model, the primary difference being a greater range of NTU's (0—1,000), and the addition of a wiper designed to remove biofouling or sedimentary build-up before each turbidity reading is taken (Analite, 1990). Secured by cable at 1 to 2 feet off the channel bottom, this probe also sits just below the water surface at 8,000 ft^3/sec (Gregory G. Fisk, personal communication, 1999). The probe above the Little Colorado River sits in a small eddy and is situated horizontally and angled slightly downstream (Frank Schaffner, Hydrologic Technician, USGS, personal communication, 1999).

A probe also was installed in June 1998 at streamflow-gaging station 09402500, Colorado River near Grand Canyon, Arizona (Figure 1). This probe was originally an ABS model and had the advantage of durability in a sandy environment, but produced very erratic readings, apparently because of greater biofouling. After G*ammarus* was observed on the probe during the summer, the ABS model was replaced with an Analite 195 probe with wiper on October 19, 1998. (Gregory G. Fisk, personal communication, 1999). The Analite probe was originally situated horizontally, because of the belief that vertically situated probes would produce erroneously high readings due to the signal bouncing off the streambed. This turned out to be misinformation, as the infrared light beam does not penetrate more than a few centimeters (Gregory G. Fisk, personal communication, 1999). This probe is currently situated about 2 to 3 feet from shore and fastened to the steel frame of the gaging station.

At each of these three gaging stations, turbidity is sensed once hourly by the probes and recorded by the programmable data loggers, which transmit the data to the USGS databases every 4 hours via satellite. With the exception of a few weeks in the fall of 1998 when the ABS probe at the Grand Canyon gage failed, these probes have been collecting data continually since their installation. The resultant data are stored in the USGS surface water database.

Data Analysis

Lees Ferry: This data set (Figure 3) is characterized by marked cycles over time, a series of apparent "ramping up" episodes. The turbidity values increase from near zero to some peak value, the maximum and most common of which is 324.67 NTU's, before dropping to zero. The cycle then begins again, repeating approximately every fifteen to twenty-five days. Because of its cyclic nature, evocative of an organism's life cycle, and the probe's location in the autotrophic water below Glen Canyon Dam, these Lees Ferry data were hypothesized to be affected by biofouling. With further investigation, however, this hypothesis was rejected.[1] Leslie

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[1] Specifically, the hypothesis was for increasing growth on or colonization of the probe by algae or benthic invertebrates causing increasingly high readings, until some sudden event—such as a probe cleaning visit, or natural mass dieoff of the colonizing organism—removed them, restoring the readings to near zero. No natural algal or benthic invertebrate lifecycle, however, is known to operate at that periodicity (W. Matter, Associate Professor, University of Arizona, personal communication, 1999). Neither are the episodes of probe cleaning recorded in the USGS water quality data base as remarks frequent enough to account for all the sudden drops in turbidity; however, not all probe cleanings to this gage are recorded in the field notes (Nancy J. Hornewer, Hydrologist, USGS, personal communication, 1999). Finally, this hypothesis requires that complete coverage of the probe by biomass consistently produce a reading of 324.67

Graham of McVan Instruments in Australia suggested that this "data clipping" was caused by improper analog to digital conversion in the data logger, which truncates the probe's analog voltage reading during its conversion to or storage as a digital value prior to transmission every 4 hours. This is a more pausible explanation, given that the same data ceilings occur at the other two probe sites, which are situated in more heterotrophic waters and so should be less susceptible, though not immune, to biofouling. This cause is substantiated by Gregory G. Fisk (personal communication, 1999); however, an understanding of the connections or configurations caused the clipping has not yet been articulated. The "step up" toward the end of the data set is an artifact of setting the offset in the data logger to 20 NTU's (i.e. a probe voltage of zero will be stored in the data logger as 20 NTU's.) This adjustment has been implemented to remove negative turbidity values (Gregory G. Fisk, personal communication, 1999) and may be insignificant for gross determinations of turbidity. An offset of this magnitude, however, especially at a low turbidity site like Lees Ferry, will bias the data so that they are not comparable to any other data, and will preclude their use in any low-turbidity research. The occurrence of negative turbidity values, may be symptomatic of some error in instrument configuration.

Above the Little Colorado River: This data set (Figure 4) also shows data clipping, at value 327.67 NTU's, from approximately June 21 to December 17, 1998. Afterwards, a period of consistently low values occurs until early March, 1999. Then, the data points increase in both value and scatter until mid-April. Afterwards, they again become consistently low, ending with a large spike.

While the ceiling of 327.67 NTU's continues to be a puzzle, an additional issue with this data set is the large degree of scatter during the winter and early spring. This may be the result of the high percentage of sand in the Colorado River, for which the Analite probes are not designed. The last three months of data appear to be the most realistic, inasmuch as the generally low turbidity values correspond to generally low flows from the Paria River, the single largest sediment source between the Glen Canyon Dam and the Little Colorado River; and the spike in turbidity appears to correspond to a flood on the Paria around July 15, 1999 (Figure 6).

NTU's, which is not likely, given expected variations in thickness and areal extent of the biomass on the probe.

Grand Canyon: The artificial ceiling in this data set (Figure 5) is considerably lower than in the other two, and the majority of the data look realistic. The period of zero valued data in September and October 1998, is due to failure of the ABS probe. The Analite model was installed after this time.

Discussion

The data described above raise several issues:

Artificial data ceilings: All three data sets exhibit, to a greater or lesser degree, an artificial ceiling at 324.67 or 327.67 NTU's. The artificial data celing persists in the data from the Lees Ferry site until June 1999, and in the data from the Little Colorado River site until mid-December 1998. The problem is believed to be or have been an improper data-storage configuration, although it is unclear how the problem was fixed at each of these sites. At the Grand Canyon gage, an initial ceiling of 327.67 NTU's lasted only a few weeks; the timing coincidence suggests that this problem was somehow fixed with the installation of the new Analite probe. After an extended period of realistic looking data, a new ceiling around 3,447 NTU's occurred in late July 1999 beyond the dates covered by this report. The new ceiling is not as rigid or precise as the previous ceilings, varying between 3,446 NTU's and 3,448 NTU's. The consistency of one part per 3,447, however, seems high enough to be suspicious. No explanation is offered in this report for this new development.

The artificial ceilings in the data could arise from probe malfunction, data logger malfunction, or the interaction between the two. The probes are sealed and guaranteed before shipment and tested in the field with turbidity standards, which indicated measurement accuracy; this is taken to indicate that the probes are not the source of the artificial data ceilings. As a result, an investigation of the transmission of data from the probes to and through the data loggers is warranted. This could be accomplished by using an additional data logger in parallel with the Sutron for some period of time. Although other methods of independent turbidity assessment are possible, the investigation requires that turbidity be measured during a wide range of conditions and as close to the probe site as possible without causing interference. These criteria are probably best met by a second off-line data logger connected in parallel to the (same) probe. Readings from this off-line data logger could be compared later with values transmitted by the Sutron DCP. No differences in the data sets would indicate that the problem is with another part of the system (most likely the probe) and not the data loggers. Discrepancies in the data set would indicate the problem was in the data transmission to or storage in the data logger. The nature of the discrepancies would probably indicate the specific malfunction of the data logger and/or might be useful information for correcting data from the Colorado River above the Little Colorado River and Colorado River near Grand Canyon sites. (The Lees Ferry data set, because of prior editing (Gregory G. Fisk, personal communication, 1999), cannot be corrected in this manner.)

Uncorrelated turbidity spikes: Related to the issue of determination of data validity is the correlation between main stem turbidity and tributary discharge. Most sediment downstream of the dam is introduced by the Paria and the Little Colorado Rivers. Consequently, it is hypothesized that turbidity at the gaging station of the Colorado River above the Little Colorado River should correlate with the discharge from the Paria River, and that the turbidity of the Colorado River at the gaging station near Grand Canyon should correlate with discharge from either the Paria River or Little Colorado River or both. This working hypothesis is used to assess qualitatively the validity of the data. To date, however, the turbidity data do not show these correlations. Large discharges on the Paria or Little Colorado Rivers often did not produce turbidity spikes downstream in the Colorado River, and turbidity spikes in the Colorado River often were not preceded by floods on the Paria River or Little Colorado River. (See Figures 4 through 6 for the following discussion)

During the approximate year of data covered by this report, the Paria River had high discharges on July 24, September 5 and 12, and October 22, 1998, and July 15, 1999. Only the most recent of these floods correlates with a turbidity spike on the Colorado River above the Little Colorado River. Even if the turbidity values of 327.67 NTU's from the Colorado River above the Little Colorado River are assumed to be spikes of turbidity truncated by instrument problems, these spikes begin at least a few days *before* any putative causative peak discharge on the Paria River. So the large discharges on the Paria River do not appear to have caused turbidity spikes on the Colorado River.

The converse is also true. If the artificial ceiling at 327.67 NTU's on the Colorado River above the Little Colorado River is hypothesized to mask turbidity spikes, then these turbidity spikes began on July 1, July 22, August 18, September 1, October 15, and November 8, 1998. These hypothetically truncated spikes, however, are not preceded by large discharges from the

Paria River, so that turbidity spikes on the Colorado do not appear to have been caused by large discharges on the Paria. The large Paria discharge and the Colorado River turbidity spikes are not necessarily unrelated. For example the rain that eventually causes a large discharge on the Paria could be sensed first at the gage above the Little Colorado River as over the rim run-off, which might explain the seeming temporal inversion in some cases. Nevertheless, the simple hypothesis of cause and effect relation between Paria River discharge and turbidity in the Grand Canyon above the Little Colorado River is not substantiated by this data set.

Turbidity at the Grand Canyon gage should be most affected by discharge from the Little Colorado River and to a lesser extent by discharge from the Paria River. The Little Colorado River had large daily discharges on July 24, August 3, September 5, September 11, October 29, and November 2, 1998, and April 20 and July 3, 1999. The main stem had possible truncated turbidity spikes on July 8 and July 22, and visible spikes on October 23, November 12, December 2, 1998 and January 12, April 22, and July 13, 1999. Except for the April 22 event, the putative cause and effect relation between discharge and turbidity is not borne out by this data set.

Scatter: The data set from above the Little Colorado River shows one area of widely scattered readings, beginning February 2 and lasting to April 1, 1999. While such erratic readings might reflect genuine variations in turbidity related to sediment, its unique occurrence in the data to date indicates another cause, such as bubbles or sand particles on the probe. This type of scatter may be corrected for by either physical or electronic means. Physically, the sand (and perhaps the bubbles) may be settled out of the sampled water by use of a stilling well. The Analite probe instructions stipulate that "the . . . probes are not suitable in situations where they may be abraded by large particles such as sand. Under these circumstances the readings become erratic in any event due to the large particles. Measuring turbidity under these circumstances would require a stilling well to allow sand to settle away from the probe tip" (Analite, 1998). The use of an inexpensive stilling well at the Little Colorado River gage may resolve the problem. If the use of a stilling well did eliminate the scatter, it would remain to be determined whether such data, absent the effects of sand, provide the desired information. As discussed in the introduction, the turbidity of the Colorado River through Grand Canyon is of interest as a measure of light penetration and as an indirect measure of sediment transport. A single method of turbidity measurement may not accurately reflect both of these phenomena. McVan

Instruments limits turbidity to “the effects of particles that are singularly not visible to the human eye” (Leslie Graham, McVan Instruments, personal communication, 1999); this would eliminate the effect of sand from turbidity. Hydrologists, however, are certainly, perhaps especially, interested in the amount of sand in transport through Grand Canyon, and biologists, depending on their area of interest, may also need to know the total (i.e. sand-inclusive) turbidity. If the effect of sand is determined to be of interest, another option is to investigate alternative instruments designed for such environments. (The U.S. Geological Survey Hydrologic Instrumentation Facility (HIF) conducts instrument reviews which may be helpful in selecting a more appropriate turbidimeter if necessary.)

Scatter may also be removed electronically (Leslie Graham, personal communication, 1999). A sufficiently sophisticated data logger may be programmed to remove the spikes from the data, leaving the underlying signal; this would produce the most accurate data. Another option is to average the data over a certain time period or number of readings. Because this does not actually remove the spikes, the result will be higher than the true baseline turbidity. Collecting data off-line as suggested above for the purpose of instrument validation would serve a second important purpose in this regard, namely, determination of the best frequency at which to sample turbidity. Because sediment concentration is highly variable, turbidity is assumed to be likewise variable. Although this assumption is not always substantiated (Adams and Delisio, 1991), insufficiently frequent sampling is cited as the greatest source of error in the estimation of stream sediment load from turbidity (Gippel, 1995). Perhaps as a consequence, explanation of the establishment of sampling frequency for turbidity is somewhat vague in the literature. For example, Jansson (1992) first sampled every 3 minutes but ultimately changed to every 5 minutes. Six samples were taken within 10 seconds and averaged in order to even out great variations (Jansson, 1992). Although this is apparently assumed by the author to have achieved the desired effect, no quantitative support is provided to substantiate these decisions. Sampling at different intervals from a continuous or short (e.g. 1 minute) interval record should indicating the optimal sampling frequency. Although this procedure would be initially more work intensive, the knowledge gained from it would reduce unnecessary data collection as well as improve data validity.

Calibration: A final point of information with regard to these data is the calibration of the data logger to the probe, which was accomplished using turbidity standards of zero, 100, 400 and 900

NTU's (Nancy J. Hornewer, personal communication, 1999). For the sites above the Little Colorado River and at Grand Canyon, a single line fit over the entire range of the probes (0-1,000 NTU's) was deemed not sufficiently accurate. Because the river tends to have low turbidity on average, the data logger offset was increased and the slope adjusted to fit the lower range more accurately than the upper range (Nancy J. Hornewer, personal communication, 1999). Although this modification improves the accuracy of most of the data, it increases the uncertainty of the data pertaining to the larger events, which may have the most effect on sediment transport. A graph of the calibration data with an offset of zero and a linear curve is presented in Figure 7.

Conclusion

The turbidity data from the Grand Canyon to date are not an accurate representation of the turbidity in the Colorado River, and the degree of error is unknown. The error is primarily caused by data clipping due to instrument configuration, with additional, less apparent error introduced by scatter due to sand and bubble spikes, some probably smaller known error from the probe-data logger calibration, and unknown error caused by the long intervals between instantaneous sampling. Although some of the clipping seems to have been rectified, most of these error sources remain. Recommended actions include:1) offline, continuous or short interval logging of the turbidity probe data using a parallel, second data logger, to confirm the correct operation of the primary Sutron data logger; 2) analysis of this continuous or short interval data in order to determine the best frequency at which to collect representative data; 3) determination of the cause of erratic readings, through devices such as a stilling well; 4) implementation of a method for the removal of erratic readings compatible with the goals for which the turbidity data collection is designed; and 5) quantification of the uncertainty introduced at each site by the probe-data logger calibration.

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Appendix: The relation between suspended sediment and turbidity

Research indicates that the relation between suspended sediment and turbidity is complex. Brown and Ritter (1971, p. 60-66), for example, collected turbidity and suspended sediment concentration data from the Eel River basin, California, that showed a similar logarithmic relation for each station in the basin. The scatter was significant, however, and there appeared to be a chronological trend, such that regression line slopes steepened over time. Perhaps more importantly, the correlation was not valid for the drainage basin immediately to the south, which has similar geology and climate.

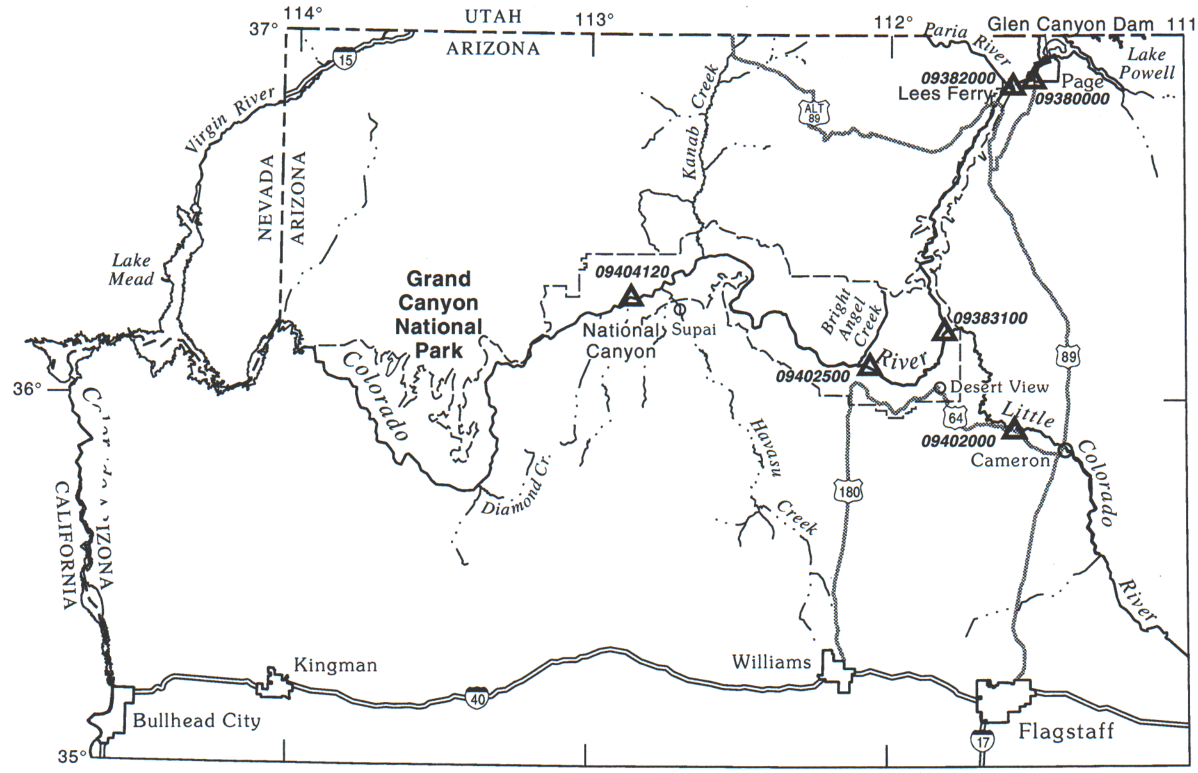
In another California study, Bolda and Meyers (1997, p.53) attributed a lack of correspondence between variation in turbidity and suspended sediment to the sandy, loamy soils eroded in the watershed, which, owing to their high weight and reflectivity, would increase the concentration without increasing the turbidity. This assessment agrees with Brown and Ritter's (1971, p.64) observation that "turbidity is higher at a given concentration for a water and sediment mixture which contains only silt and clay than for a mixture containing mostly sand." An important point to note is that there is not universal agreement on whether sand contributes to turbidity. McVan Instruments, for example, the purveyors of the Analite probes currently in use by the USGS in the Grand Canyon, takes the position that turbidity is that reduction in light transmittance caused only by autosuspended particles. Sand, which settles out in still water, is not considered to be a contributing factor, and is not adequately measured by their instruments (Leslie Graham, personal communication, 1999). This is an important point to clarify before attempting to establish a turbidity-suspended sediment correlation in such a sand-rich river as the Colorado.

Fluvial phenomena are often characterized by hysteresis, and the relation between suspended sediment and turbidity is not an exception. Gilvear and Petts (1985) found an "anticlockwise" hysteresis during a reservoir release-- i.e. turbidity values from the rising limb of the hydrograph were much less than values for the falling limb for the same suspended sediment concentration--but a clockwise hysteresis during a tributary flood. Hysteresis is not the only complicating factor. In deriving sediment rating curves for a small humid catchment in England, Walling (1977) used rating relations differentiated by hydrograph limb, to account for hysteresis effects, and by season. Despite this subsetting, errors were as high as +30 percent for annual loads, and +900 to –90 percent for monthly loads.

Part of the difficulty in establishing an adequate relation between suspended sediment and turbidity may be due to the sampling frequencies used in such research. Frequencies required for accurate assessment generally are assumed to be quite high--Gilvear and Petts (1985), for example, recommended sampling every 5 minutes or less in a small Welsh stream--often higher than practical for sustained monitoring. Thomas and Lewis (1993, 1995) and Lewis (1996) discuss two different random sampling techniques, which retain randomness, yet concentrate sampling during high flows so as to reduce the overall sampling requirements. Both techniques would require a data logger that can be programmed to trigger sampling at the necessary time. The selection at list time (SALT) technique uses an "auxiliary variable" related to discharge in combination with random numbers to increase random sampling during higher flows. Time-stratified sampling divides the hydrograph into periods, or strata, in each of which samples are collected randomly. The advantage of these methods is their statistical tractability: each provides unbiased data and valid estimators of sample variance (Thomas and Lewis, 1993). Their variances can be quite different, however, and the theoretical promise of each of these methods is not always borne out. It is difficult to select the appropriate auxiliary variable for SALT, and time-stratified sampling does not perform well with large variations in sediment flux (Thomas and Lewis, 1993). Essentially, it must be decided whether precise measurements are more important for small floods or large floods. Further discussion is outside the scope of this paper, but the reader is referred to the cited literature for more information on these promising techniques.

Improved sampling techniques give hope for better correlation between suspended sediment concentration and turbidity, and certainly in some cases an adequate correlation can be found. Even with some scatter in the turbidity-sediment correlation, a continual estimate of suspended solids concentration, which is possible using turbidity measurements, is more accurate than infrequent sampling, which induces the greatest source of error in sediment load estimation (Gippel, 1995).

At the present time, the correlation of turbidity with suspended sediment concentration remains an elusive goal, primarily because of the non-unique relation between the mass and the optical properties of sediment. A correlation curve must be established for each river, and if possible for each season and hydrograph limb, which requires a significant period of both turbidity and suspended sediment data collection. The result of such an effort must still be considered suspect in the event of discharges outside the range of those from which the calibration was derived, so that data for the flows contributing the largest amount of sediment would be subject to the greatest uncertainty. Even in the large, slow-moving upper Mississippi River, a usable correlation between turbidity and suspended sediment was not attained (Adams and Delisio, 1991). The establishment of such a correlation in the Colorado River should be undertaken with care and patience.



Base from U.S. Geological Survey digital data, 1:100,000, 1980
Lambert Conformal Conic projection
Standard parallels 29°30' and 45°30', central meridian -96°00'

0 50 MILES
0 50 KILOMETERS

EXPLANATION

STREAMFLOW-GAGING STATIONS

09380000—*Colorado River at Lees Ferry*
09382000—*Paria River at Lees Ferry*
09383100—*Colorado River above the Little Colorado River, near Desert View*
09402000—*Little Colorado River near Cameron*
09402500—*Colorado River near Grand Canyon*
09402000—*Colorado River above National Canyon, near Supai*

LOCATIONS OF STREAMFLOW-GAGING STATIONS IN GRAND CANYON NATIONAL PARK, ARIZONA, WHERE TURBIDITY IS MEASURED

Figure 1

TURBIDITY IN THE COLORADO RIVER ABOVE NATIONAL CANYON, NEAR SUPAI, ARIZONA (09404120)

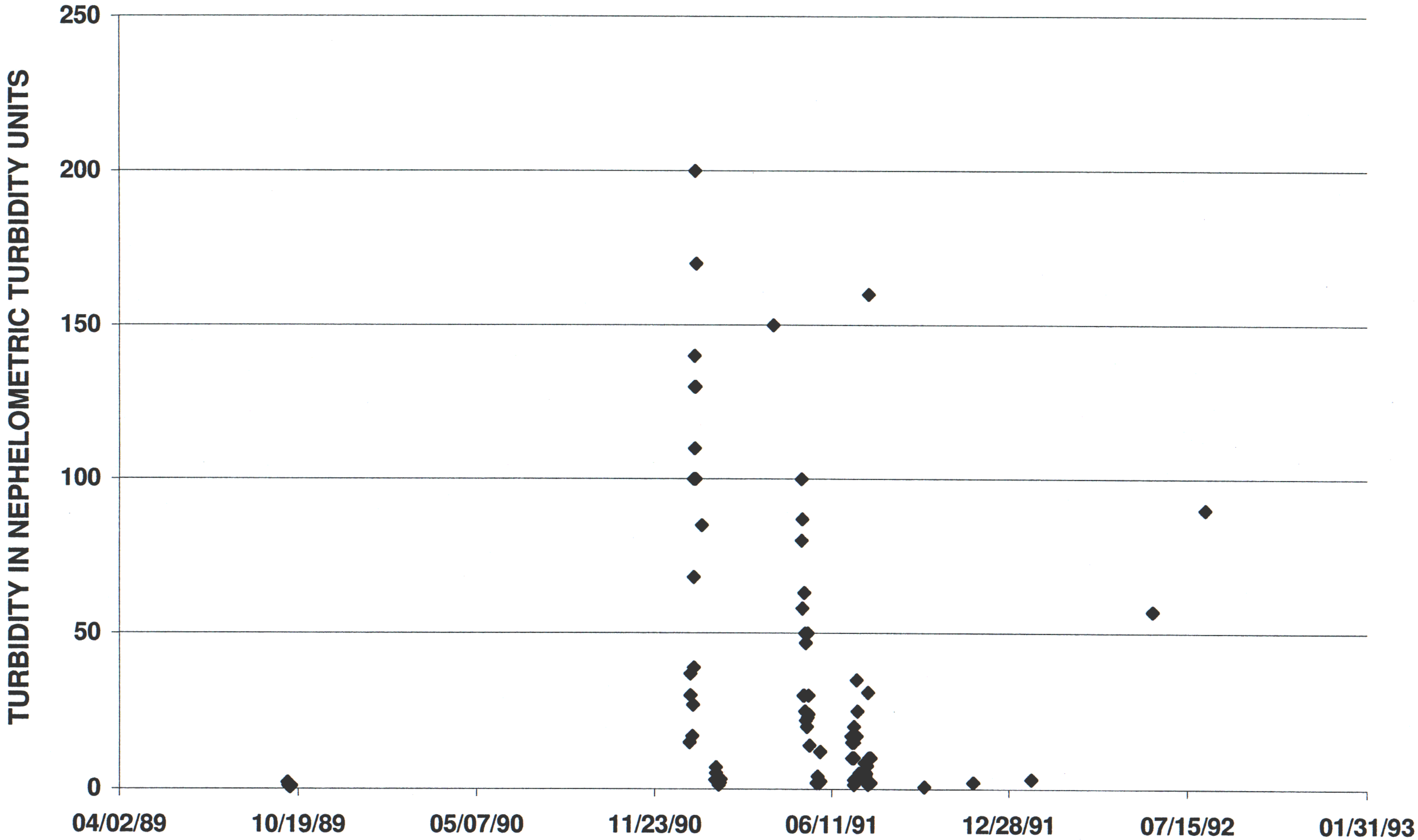


Figure 2

TURBIDITY IN THE COLORADO RIVER AT LEES FERRY, ARIZONA
(09380000)

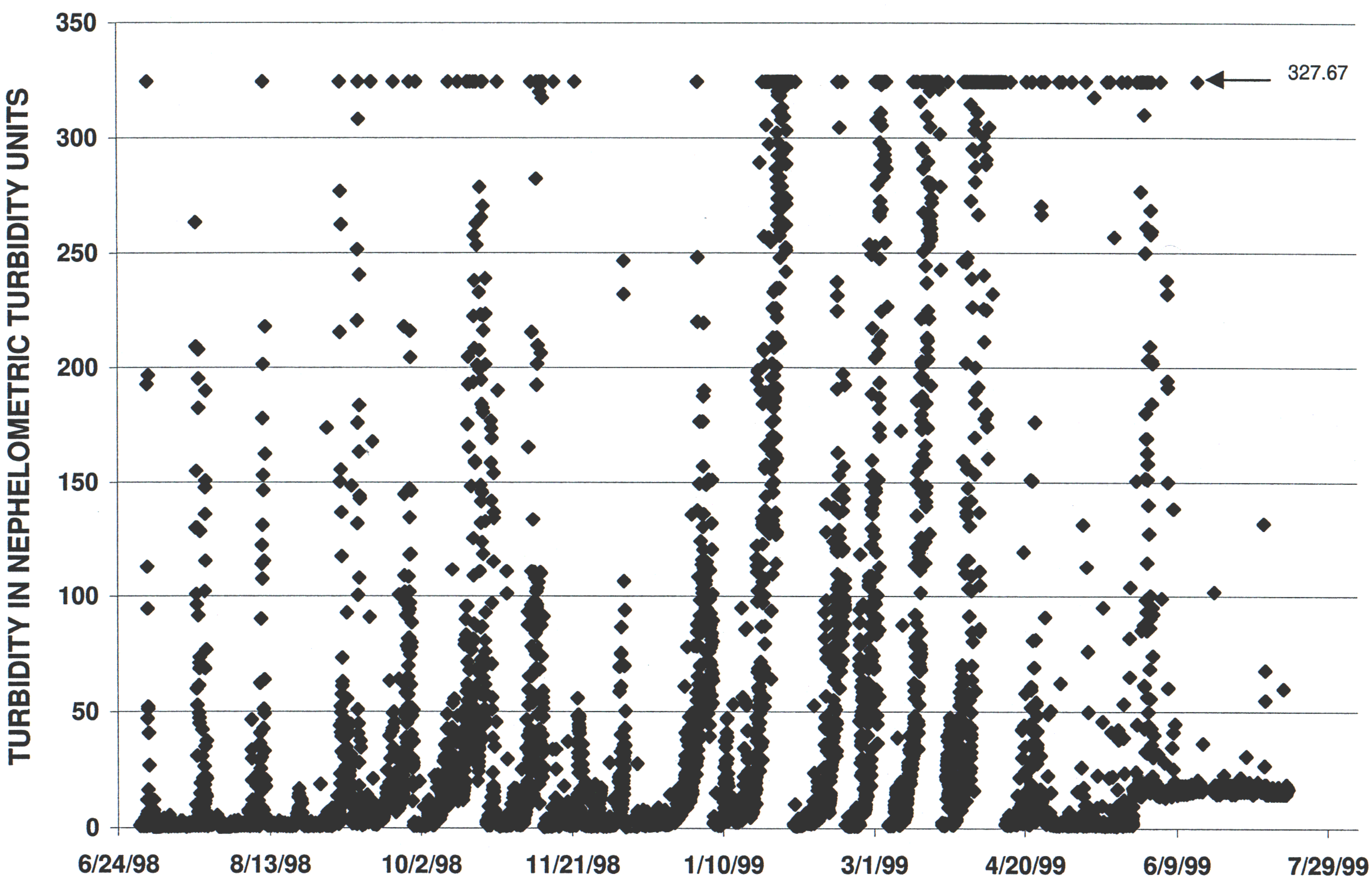


Figure 3

TURBIDITY IN THE COLORADO RIVER ABOVE THE LITTLE COLORADO RIVER, NEAR DESERT VIEW, ARIZONA (09383100)

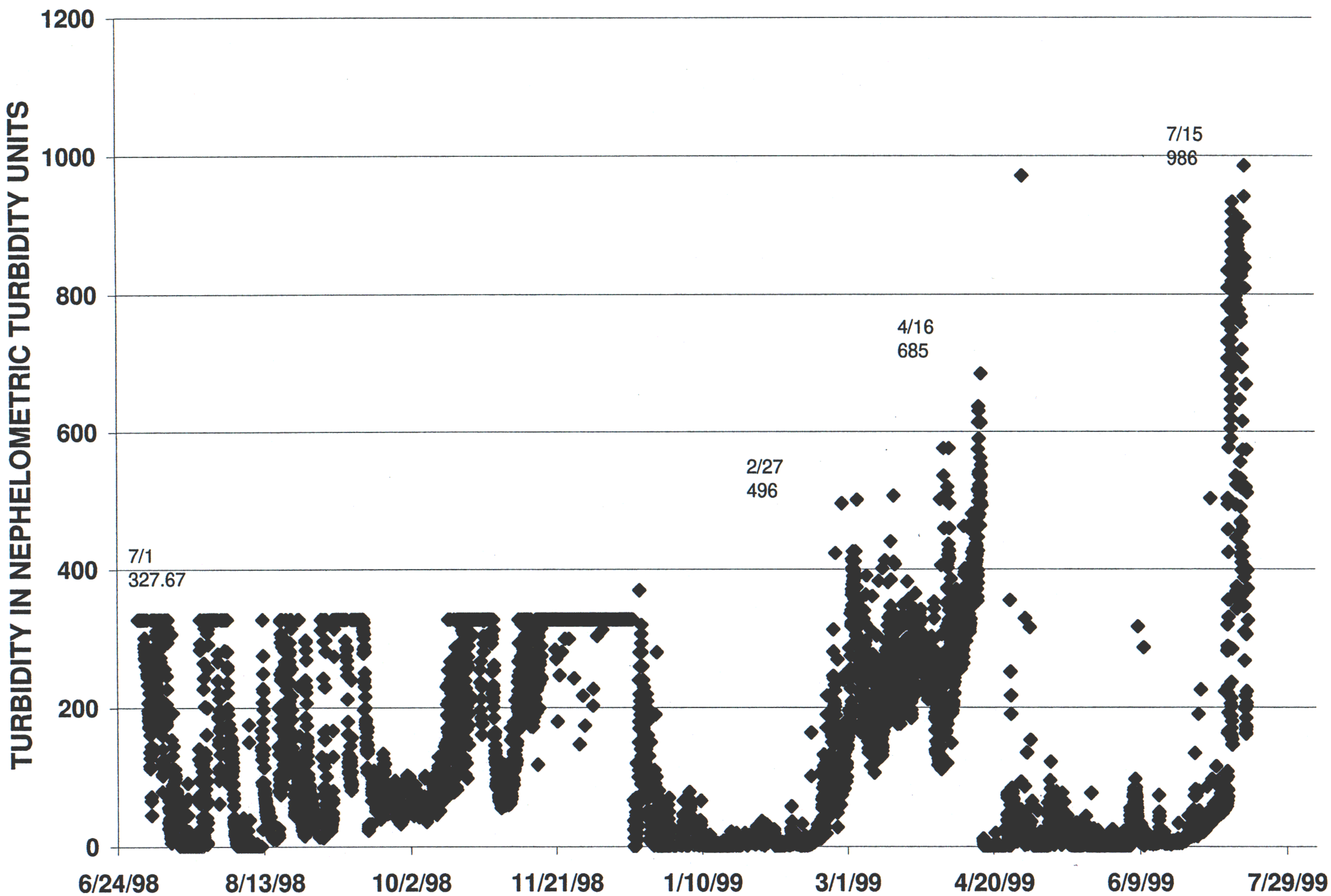


Figure 4

TURBIDITY IN THE COLORADO RIVER NEAR GRAND CANYON, ARIZONA (09402500)

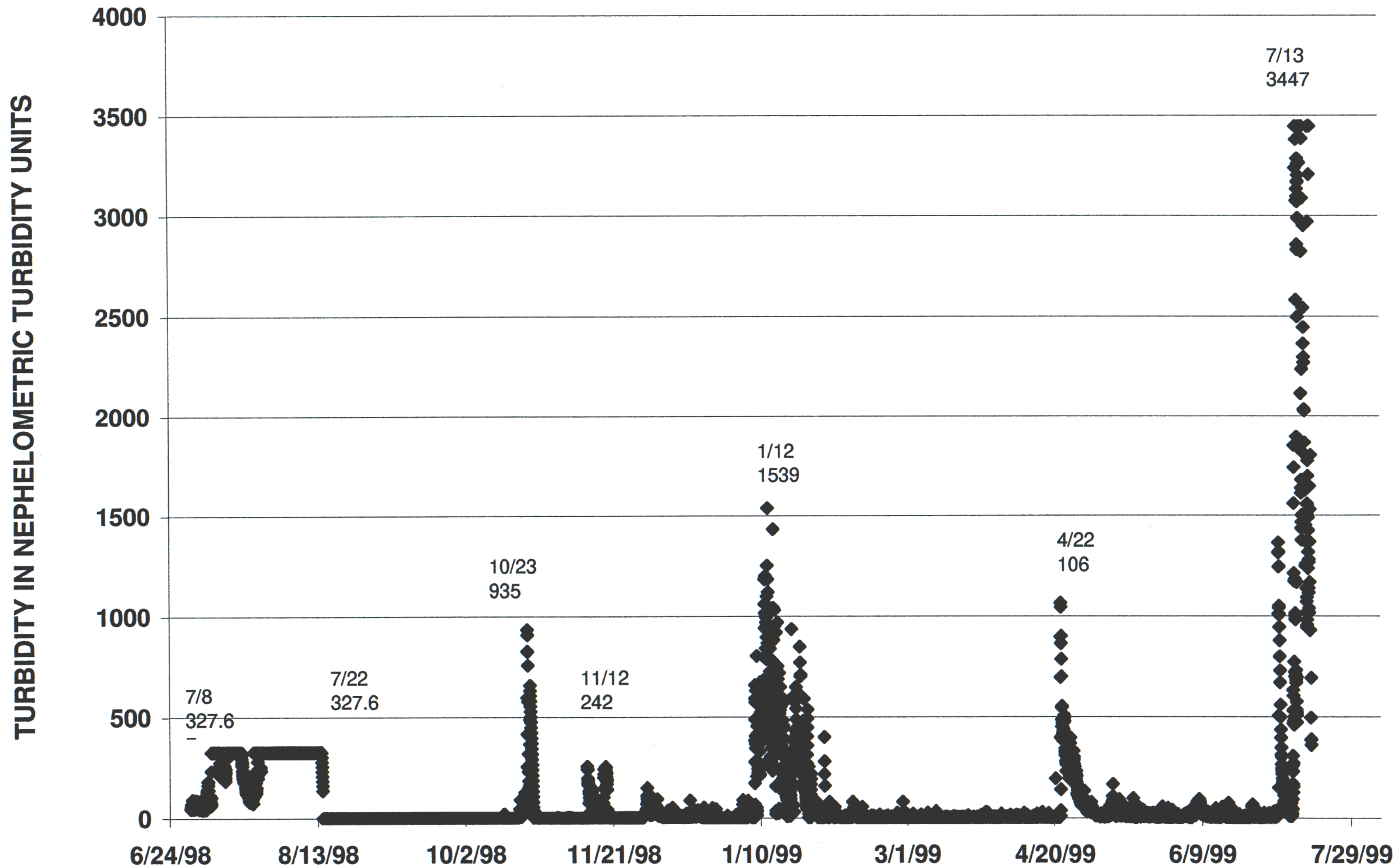


Figure 5

DAILY DISCHARGES OF THE PARIA RIVER AT LEES FERRY, ARIZONA (09382000) AND OF THE LITTLE COLORADO RIVER NEAR CAMERON, ARIZONA (09402000)

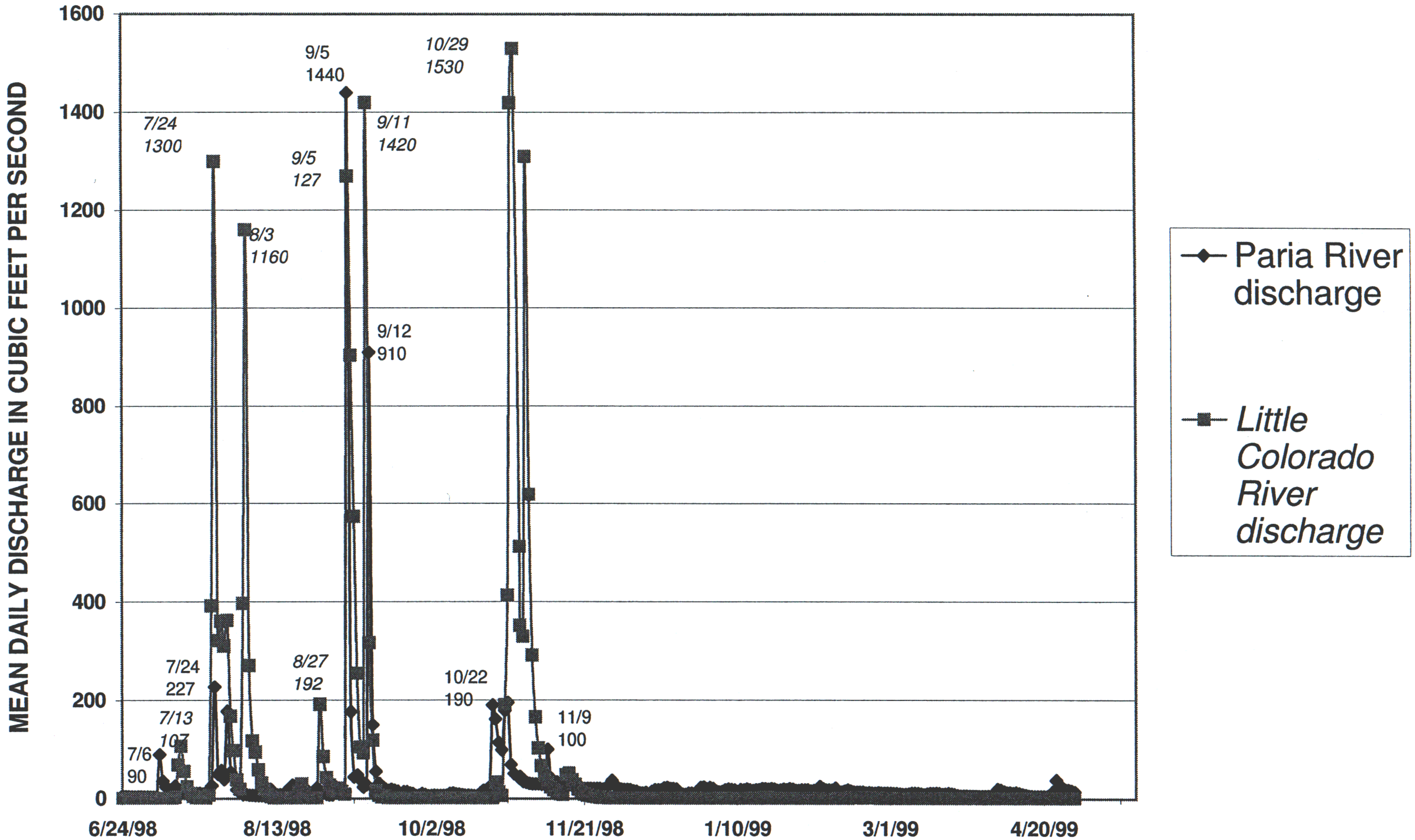


Figure 6

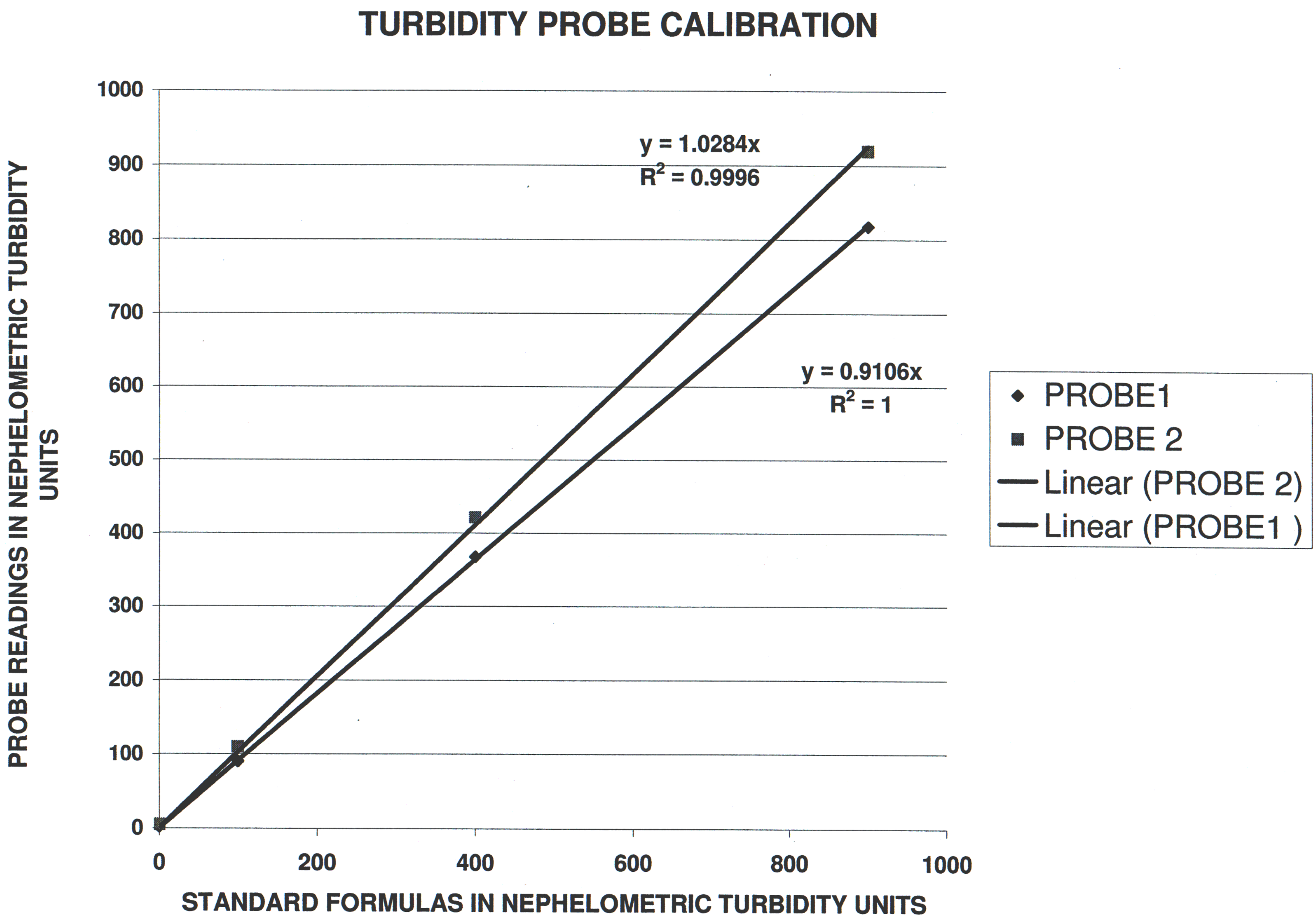

TURBIDITY PROBE CALIBRATION
y = 1.0284x
R2 = 0.9996
y = 0.9106x
R2 = 1
PROBE READINGS IN NEPHELOMETRIC TURBIDITY UNITS
STANDARD FORMULAS IN NEPHELOMETRIC TURBIDITY UNITS
0
100
200
300
400
500
600
700
800
900
1000
0
200
400
600
800
1000
PROBE1
PROBE 2
Linear (PROBE 2)
Linear (PROBE1)

Figure 7