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FACTORS INFLUENCING BENTHIC ALGAL STANDING MASS IN THE COLORADO RIVER: LIGHT, DRIFT AND VELOCITY

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INTRODUCTION:

Availability of light has been demonstrated as being one of the most fundamental factors determining benthic production in Glen and Grand Canyons (Usher and Blinn 1990, Hardwick *et al.* 1992; Blinn and Cole, 1991, Shannon *et al.* 1994, Shaver 1995). Benthic production has been recognized for its overall trophic role and linkage as the aquatic foodbase to native and non-native fishes (Angradi 1994). Solar radiation and it's vertical distribution, as well as spectral composition is regulated by the inherent optical properties of that water medium, and these properties determine the absorptive and scattering characteristics exhibited. The solar beam and diffuse scattering from skylight contributes directly to the vertical distribution of down-dwelling irradiance, though its relative proportional quantity contributed, will vary according to angle of incidence in crossing through the air-water interface (Kirk 1977,1984, 1994; Morris et al. 1995). Upon surface penetration this irradiant field measurably diminishes exponentially as a function of depth. Therefore, dissolved and particulate components comprising these waters determine the behavioral characteristics of the underwater light regime.

Suspended matter exists in all natural water bodies of nominal concentrations and are often responsible for diminishing water clarity (Maffione 1998). Suspended sediment loads are the primary determinant of underwater light characteristics in the Colorado River (Yard *et al* 1993; Shannon *et al.* 1996). The longitudinal distribution of light availability is spatially and temporally limited in the Colorado River by suspended loads. These loads are regulated by processes such as transport capacity, channel morphometry, sediment availability and tributary inputs (Steven et al. 1997; Schmidt and Graf 1990; Schmidt and Rubin 1995). However, light attenuation does not appear to be correlated to total suspended loads due to their low concentrations. Glen Canyon (RKM 0.0 to RKM 25.0) spatially accounts for only 7% of the overall area available for primary production, yet accounts for at least 75% of the total gross primary production occurring in the entire system (Angradi and Kubly 1993).

Results from this research are to be used in developing predictive relationships for primary production in this aquatic system (Krause-Jensen and Sand-Jensen 1998). Conceptualizing and developing predictive models that are reliable and empirically based have direct applications to managing this aquatic food base (Smith et al. 1989). Modeling availability of photosynthetically active radiation, 400 to 700 nm (PAR), provides both predictive and simulative capabilities for improving management of potential aquatic primary production in this large regulated river system. Therefore, understanding the availability and interaction of PAR and its functional role in primary production in this ecosystem is

essential for developing the predictive relationships necessary for a primary production model.

RESEARCH OBJECTIVES

The findings from our research will provide the remaining empirical relationships that are necessary for refining, validating and completing this primary production model by developing a better understanding of the ecological role and life history requirements of *Cladophora glomerata*. Our research findings will further complement our model development by addressing the monitoring and research objectives listed below:

Objective 1. *Monitor underwater light attenuation (K_d) for spatial and intra-seasonal variability and continue to collect validation data for the primary production model.*

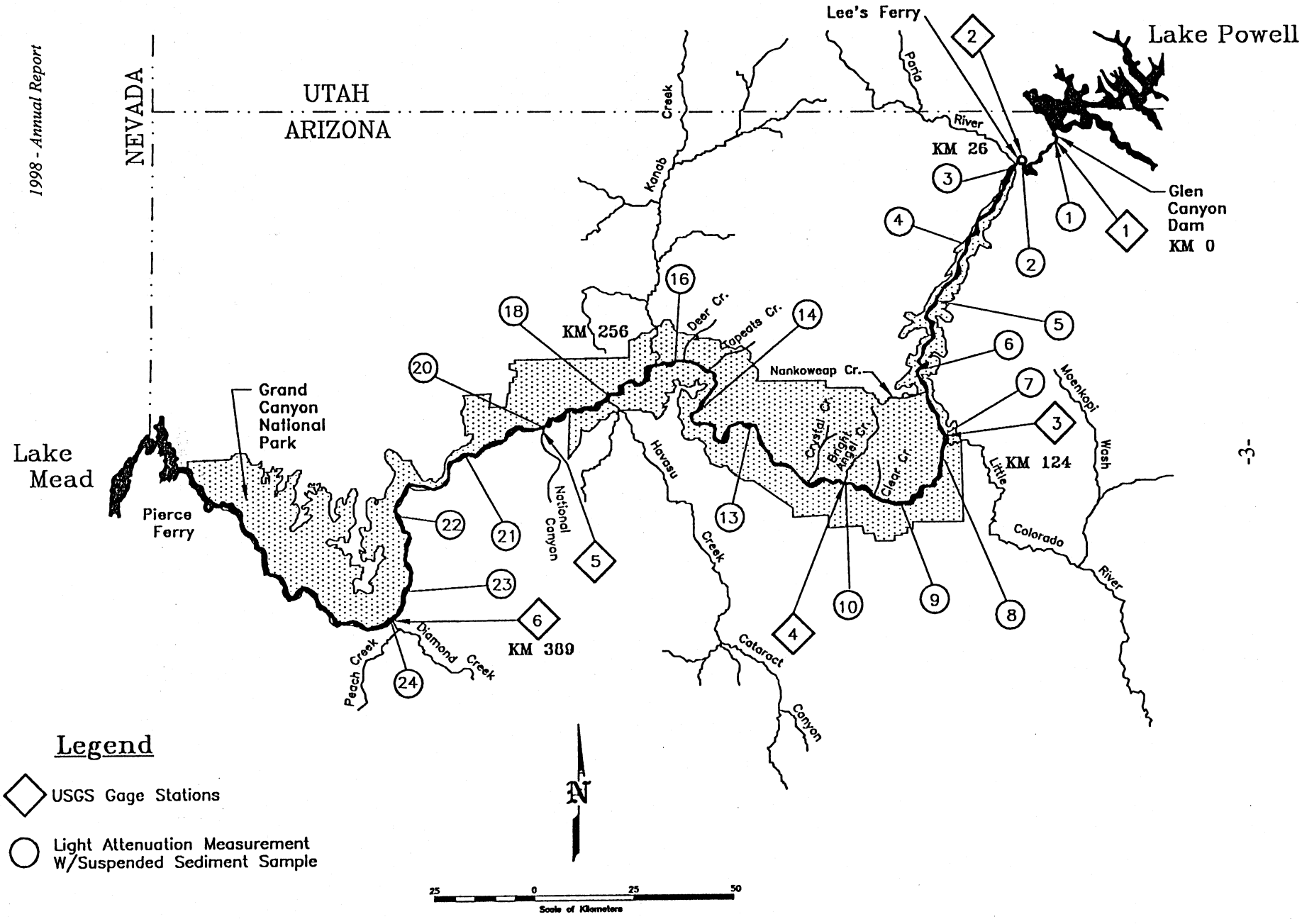
Objective 2. *Determine the net photosynthetic and respiration rates for Cladophora glomerata at varying irradiance, depths, temperatures and suspended sediment loads.*

Objective 3. *Determine if net loss and loss rates to Cladophora glomerata differs as a function standing masses and varying flow velocities.*

This report identifies the progress to date made toward completing the study objectives as stated in the proposal entitled "Factors Influencing Benthic Standing Mass in the Colorado River: Light, Drift and Velocity." Additionally, it provides some preliminary analyses and discussion on some of the data. Note, that research objectives 2 and 3, are scheduled to be addressed the following 1999 field season.

STUDY AREA

The Colorado River is the dominant river system in the Southwest, and is one of the most thoroughly regulated large rivers in the United States (Hirsch *et al.* 1990). More than 40 large flow regulation structures affect the river's 2,250 km course between the Rocky Mountain headwaters and its complete diversion before the Gulf of California (Stevens et al. 1997). In northern Arizona, the Colorado River is approximately an eighth order stream, and flows 472 km from Glen Canyon Dam to Lake Mead through the deeply incised Grand Canyon (Fig. 1). The Colorado River in the Grand Canyon flows through low-elevation Great Basin, Sonoran and Mojave desert shrublands and


NEVADA
UTAH
ARIZONA
Lake Powell
Lee's Ferry
Paria
River
KM 26
Glen Canyon Dam KM 0
Kanab
Creek
Deer Cr.
Kapeats Cr.
KM 256
Nankoweap Cr.
Crystal Cr.
Bright Angel Cr.
Clear Cr.
Havasu
Creek
National Canyon
Grand Canyon National Park
Lake Mead
Pierce Ferry
Peach Creek
Diamond Creek
KM 389
Cataract
Canyon
Little
Colorado
River
Meenkopi
Wash
KM 124
Legend
USGS Gage Stations
Light Attenuation Measurement W/Suspended Sediment Sample
N
25
0
25
50
Scale of Kilometers

grasslands, and receives a highly variable annual precipitation (Sellers and Hill 1974). The study area encompasses a river distance of 389 km from Glen Canyon Dam (36°52'03"N, 111°35'40"W) to Diamond Creek (35°46'0"N, 113°22'30"W), just upstream from Lake Mead, draining more than 106,000 km^2 of upland grasslands and forests. River site locations are based on distances (river kilometer, RKM) downstream from Glen Canyon Dam. We stratified are sampling effort into two geographical regions to address the specific research and monitoring objectives. The second region encompasses the entire Colorado River including Glen Canyon, Marble Canyon (RKM 25 to RKM 125), Central Grand Canyon (RKM 125 to RKM 259) and Western Grand Canyon (RKM 259 to RKM 389). Studies conducted in this region are associated with monitoring activities to collect model verification data.

SAMPLING METHODS:

Field Collection Methods

Irradiance was measured using underwater spherical sensors (LI-193SA) and terrestrial quanta sensors (LI-190SA) measuring scalar and incidental solar irradiance respectively. Profiles of irradimetric measurements were made at varying depth intervals. Measurements were made either at 0.5 m interval during high clarity conditions or adjusted to a reduced interval 0.1 m during periods of high suspended loads. Typically, three profiles are made for every sampling period specific to a site and time of measurement.. Each sensor measured within the spectral region (400-700 nm) with equal sensitivity. All irradiant measurements (irradiant units, 6.02×10^{-17} quanta/photon) and the specific depths were recorded using a data logger (LI-COR 1000). Initially single profiles were measured at hour intervals during the pre- and post test period (August 23-24, 1997 and September 6-7, 1997) encompassing the Labor Day 8,000 cfs test flow. This sampling protocol was adjusted and made more robust with three replicate profiles measured at hour intervals and a single profile at a half-hour intervals (December 17 - 18, 1997, March 21-22, 1998, May 22 - 31, 1998, June 19 - 20, 1998, August 16 - 23, 1998, and September 19 - 20, 1998). The sampling protocol modification was for analytical purposes to conduct pairwise comparisons with independent variables being collected simultaneously.

Three replicate samples were collected using a depth integrated sampler. The sample constituents were collected and analyzed for total suspended particulates (TSP), particulate organic matter (POM), particulate inorganic matter (PIM) and dissolved organic carbon (DOC). Samples were collected concurrently during irradiametric measurements using a D-77 sampler (Army Corp. Engineers) and

concurrently during irradiametric measurements using a D-77 sampler (Army Corp. Engineers) and bridge boom (Scientific Int., Inc). All field collected samples were returned for analysis to Northern Arizona University, Department of Biological Sciences. Refer to Table 1 and 2, for sample information (Appendix A).

Sampling Schedule

Quarterly sampling efforts were conducted seasonally to coincide with the solar equinoxes (Fall and Spring) and solstices (Winter and Summer) in the Glen Canyon/Lees Ferry reach. These sampling efforts were conducted simultaneously at three sites, Site 0 (GCD-draft tubes), Site 1 (GCD-Turbine Outflow, RKM 0.0) and Site 2 (Lees Ferry, RKM 25.2) . All irradiant measurements and sample parameters were made on hour intervals for a continuous 24 h period. The sampling effort was initiated at 1800 and completed the following day at 1800. Additionally, PAR was also measured on a ½ h basis to increase the temporal robustness for determining the apparent optics for each sampling site (Sites 1 and 2).

Also, two down river trips were conducted as light/sediment validation trips. These sampling trips were used for collecting additional irradiant data and light attenuating parameters under a wide range of optical conditions. These trips were scheduled to coincide with two distinctly different optical conditions, one with relatively high water clarity (May 22 - 31, 1998) and the other turbid periods (August 16 - 23, 1998) associated with sediment discharges from tributaries. The purpose of these trips were to collect independent data on suspended wash loads for correlating, testing and determining confidence intervals for established suspended sediment light attenuation relationships presently used in the GCMRC Conceptual Model (Korman et al. 1998). Two additional validation trips are scheduled for the next 1999 field season.

Light Attenuation Analyses

Irradiant measurements were log transformed and attenuation coefficients were calculated for each measured profile. All light attenuation coefficients (K_o or K_d) have been regressed using a natural log transformation of irradiance to depth (m) using the expression, $I_z = I_o e^{-Ktz}$, where I_o and I_z are the values of downward irradiance at the surface and at depth *z* (m) in the water column. Therefore, K_t (m^{-1}) based on a natural logarithm is the light attenuation coefficient, where *t* represents coefficients derived from either scalar (K_o) or cosine corrected irradiance (K_d). The derived coefficients, K, provide a useful index for characterizing the apparent optical properties of the water, and secondly

provide a functional mathematical expression for estimating depth specific irradiance.

Attenuation coefficients for each profile were calculated using two types of methods. The first method, the standard regression using natural log transformed data of scalar irradiance. The other method, a ratio method using a natural log transformation of the proportion of measured underwater irradiance to incidental irradiance. Measurements of underwater irradiance decreases as a function of depth. Under variable solar intensities due to atmospheric conditions or solar flux the linearity (r^2) of the calculated regression are less accurate using the standard method for calculating attenuation coefficients. Irradiant measurements are effected by variation in ambient albedo that occurs above the water surface. This will simultaneously influence subsurface irradiance readings made at a specific depth. Since light travels the speed of light the ratio of subsurface irradiance to surface incidence is solely a function of depth and not environmental variation. Therefore, to adjust for this environmental variation attenuation coefficients are regressed by the log transformation of the above ratio method. Qualitative criteria were established to evaluate the accuracy of the irradiance collected in the field. All of the attenuation coefficients (Ko) used in the preliminary analyses were derived using the ratio method. However, alternate attenuation coefficients using the standard method were substituted if the coefficient of determination (r^2) was less than .90, or if regression calculations were questionable due to sensor interference, set-up and/or data entry errors. Refer to Table 3 (Appendix A), identifies the profile criteria for each calculated attenuation coefficient.

DOC Analyses

Dissolved organic carbon (DOC) analyses are to be performed at Northern Arizona University, Geochemical Laboratory. Three independent DOC samples are collected concurrently with total suspended samples using an integrated sampler (D-77 sampler). Each sample is withdrawn from sampler using a 60 ml syringe and filtered through a 0.7 μm filter (Whatman GF/F glass fiber filters), preserved by acidification to pH 2 with H_2SO_4 and stored in a 60 ml amber bottle. DOC concentrations are measured using a UV oxidation process (Dohrman Model DC 180 low-level TOC analyzer). The analyses for DOC are incomplete to date due to a series of instrumentation problems preventing the work completion. For this reason, we are unable to evaluate how this parameter might be related to light attenuation. Projected completion dates are identified in Table 2 (Appendix A).

Suspended Particulate Analyses

The integrated water samples (0.5 L) were analyzed for the total suspended particulates (TSP) by a

filtration process using 1.5μm filters (Whatman 934-AH glass fiber filters), dried, weighed and ashed for particulate organic matter (POM) and particulate inorganic matter (PIM) determination. At present, most of the particulate analyses are complete to date, refer to Table 2 (Appendix A).

Suspended Sediment - Light Attenuation Analyses

Additional data are necessary before these types of analyses are performed. Two additional data collection trips are scheduled for the 1999 field season. Refer to Table 3., Appendix A for specific dates.

Experimental Light Attenuation Chamber

The primary purpose of these experiments are to determine if the optical characteristics of the water (i.e., light attenuation coefficients) were effected by changes in dissolved organic carbon concentrations. This entailed using the methods described below. Six circular steel experimental tanks (1.2192 m x 0.762 m) with a volumetric capacity of 5.6775 m^{-3} were lined each with clear polyvinyl plastic. One control (initial light attenuation) and two experimental treatments (EU's) one with algae and one without algae were established at the onset of the experiment. All experiment tanks (treatments and control) were filled simultaneously filled with filtered river water (375 l) removing coarse particulates. 120 benthic algal samples consisting of *Cladophora glomerata* and associated epiphytes were collected locally, translocated and randomly selected (n = 40) for each EU replicate. Both treatments consisting of three replicates each were suspended as a triad unit in the river with a recirculating pump and incubated under natural light conditions with moderate flow and low temperatures (10 - 14°C) for a 48 h period.

Total amount of irradiance (μmol s^{-1} m^{-2}) was measured remotely during the entire treatment. At the initiation of the experiment, and again on completion the inoculum (375 l) from each control and treatment replicate were pumped into a vertical light attenuation chamber (PVC Sched-40, 5 m x 0.3048 m) where three irradiant profiles were measured at 0.25 m depth intervals using a cosine corrected sensor (QA-190, LI-Cor). Interior walls of chamber were washed with DI water prior to each measurement. A halogen lamp (Sylvania, Metalarc M1000/U) emitting in the red spectral band was used as the artificial light source. Direct vertical light beam was suspended directly over the chamber approximately 0.5 m above the water surface measuring between 2100-2000 μmol s^{-1} m^{-2}. Replicate samples of DOC, TSP, POM and PIM were collected for each experimental unit upon treatment initiation, completion and following light attenuation measurements. The initial light attenuation and light attenuation parameters served as the control for baseline comparisons between control and

treatment groups. Light attenuation coefficients were calculated using the previously described method. Post treatment, EU algal samples were removed, desiccated and analyzed for AFSM determination for calculating total DOC generation per algal area treatment time.

1998 RESEARCH - PRELIMINARY RESULTS

Recognize that these analyses are preliminary and are based on a data set that are only partially complete. For this reason, some of the data have not been analyzed and included in this summary. The analyses have been approached in a sequential fashion. First, the independent variables considered potentially responsible for regulating the apparent optical properties of the water were evaluated. These variables are referred to as light attenuation parameters and consist of total suspended sediment (TSS), particulate organic matter (POM) and particulate inorganic matter (PIM), and dissolved organic carbon (DOC).

Suspended Particulates

ANOVA were performed to evaluate mean concentrations (TSS, POM and PIM) for each site and sampling period. Refer to Table 1 and 2, (Appendix A), for the tabulated values collected and processed since August 1997. Therefore, statistical analyses discussed in this section are preliminary and do not reflect the entire data set collected for all sampling periods. Certain collected data remains to be processed, compiled and analyzed. These data include samples collected during the Light/Sediment Validation Trips (August 16 - 23, 1998) and the samples collected during the Fall-equinox Sampling (June 20 - 21, 1998 and September 19 - 20, 1998). Differences in total suspended sediment (TSS) concentrations measured between sites and sampling periods were not found to be significant ($F_{.95, 13, 546} = 0.74$, $p = 0.7283$). Refer to Fig 1 - 15 (Appendix B), showing the variation of the sample concentrations collected during each of the sampling periods for each site. There appears to be greater intra-site variability than between sites and sampling periods. The exception to this was the observed high turbidity event measured at Lees Ferry (Site 2) during the early morning to mid-day period on September 7, 1997 ($F_{.95, 3, 570} = 2.22$, $p = 0.0078$), (Fig 12).

Concentrations of particulate inorganic matter (PIM) were found not to be significantly different ($F_{.95, 13, 546} = 0.73$, $p = 0.7342$) spatially (sites) or temporally (seasonality), primarily due to the variance being greater within a site than between sites (Fig 30 - 43., Appendix B). The exception to this pattern was the sediment discharge event previously discussed ($F_{.95, 13, 546} = 2.01$, $p < 0.0186$).

The suspended component, consisting of particulate organic matter (POM) were found sometimes to be significantly different between sites and seasons ($F_{.95, 8, 552} = 17.38$, $p < 0.0001$), (Fig 16 - 29, Appendix B). Additionally, the organic contribution was significant during periods of high turbidity, as observed on September 7, 1997 ($F_{.95, 8, 576} = 30.47$, $p < 0.0001$). Partial F-tests verified that there were both spatial and temporal differences in organic concentrations. The overall trend was for an increase in organic matter with distance downstream from Glen Canyon Dam. Additionally, seasonality was found to be significantly different in POM concentrations, however, there does not appear to be a consistent temporal pattern. Refer to Fig 53 - 54 (Appendix B), graphically demonstrates concentration differences between sites and sampling periods. The source of incoming organic matter from the Lake Powell reservoir (Site 0), indicates that during Winter Solstice (1997) there was a significant difference in POM concentrations. Though differences in POM are significant, there are no apparent temporal patterns. Typically, Site 0 (Glen Canyon Dam) measures low levels of organics directly from the reservoir. These concentrations are generally not significantly different from other sampling periods (exception December).

Light Attenuation Coefficients

Light attenuation coefficients (K_O) were calculated for the entire duration of visible light at ½ hour intervals and graphically represented as a time series plot for each site and sampling period, (Fig 44 - 52., Appendix B). Unfortunately, some portions of the time series were lost due to data logger storage problems, therefore we do not have a complete measure of light attenuation for the entire photic period at specific sites and sampling periods. This problem has reoccurred and is noticeable in the graphs for the August 23-24 period (Sites 1 and 2), and December 17-18 (Site 2) period. The greatest water clarity occurs during the solar noon period. Since K_O measured during the early morning and evening periods are extremely high and systematic, diel variability therefore may not be a function of light attenuating parameters (Kirk 1994; 1984). Instead it is thought that this light behavior is partially due to the solar altitude and declination. Kirk (1984) identifies that reflectant loss should only account for approximately 3-5% of the total light available for this time period. For this reason, only coefficients based on irradiant values collected between 0800 and 1400, 4 h ± from solar zenith were used analytically for estimating a mean daily K_O. This procedure prevents comparative distortions between inter- and intra- site variability due to refraction (Kirk 1994; Morris et al. 1995). The results using mean daily K_O, indicate that significant main factor effects between sites, time and calendar day, as well as interactions exists between these same factors (site*time, site*calendar day, and time*calendar day).

Refer to Table 4. (Appendix A), and graph that demonstrate these interactions (Fig 55., Appendix B).

There are significant spatial and temporal differences in K_O which are attributed to strong main factor effects between K_O and the interactions with site, time of day and season ($F_{.95, 80, 42} = 8.09$, $p < 0.0001$) . Note, that there is a reinforcement interaction between sites and season (calendar day) indicating that there is an increase in light attenuation as a function of distance downstream from Glen Canyon Dam. The main factor effects in light attenuation indicate that Site 1 (Glen Canyon Dam) are considerably less than Site 2. The significance associated with the interaction effect between time of day and site indicates that light attenuation is variable within a site and between sites as function of the time of day. Note, that at some sites there is a distinct systematic pattern. It is most noticeable further down stream at Site 2.

The seasonal-site interaction has the strongest effect with the greatest temporal variability in light attenuation. This observation appears to be explained by seasonal differences related to the limnology of the reservoir. This appears to govern the optical characteristics (light attenuation parameters) that influence the observed variability in light attenuation. Additionally, solar declination (e.g., light refraction between the surface interface and travel length through the water medium) also appears to influence the light behavioral phenomena.

The strongest main factor effect is seasonality. Mean daily K_O for all sites were significantly higher in the winter (Site 1 - 0.415, and Site 2 - 0.489), and conversely so in the summer (Site 1 - 0.321 , and Site 2 - 0.363). Note, that increasing light attenuation had reversed by March 22, 1998 (Fig. 48 - 50, Appendix B). This implies a very systematic annual pattern that is sinusoidal in shape. Also, inter-site variation were found to be significantly different in light attenuation for all seasons (exception - Spring equinox). Site 2, was significant and consistently higher in K_O then the Glen Canyon Dam site (Site 1). These observations are indicative of other secondary effects responsible for increasing light attenuation in the river over a distance downstream of 25 km. Since DOC analyses are incomplete we can only speculate that increases in light attenuation downstream are related to primary production an the additive increase of extracellular DOC due to photosynthesis. However, as a precautionary note these seasonal trends in light attenuation are incomplete and will need to verified using the entire data set. Refer to Fig 44 - 52., (Appendix B), that include a total time series of light attenuation coefficients plotted for each site on a diel and seasonal basis. Certain time series were lost due to data logger storage problems. So, for this reason there are incomplete measurements of light attenuation for sampling periods at specific sites. This problem has reoccurred and is noticeable in the graphs for the August 23-24 period (sites 1 and 2), December 17-18 (Site 2) and March 20-21 (Site 2) period.

Labor Day Response

Observations were made prior to and following special release flows scheduled during the Labor Day weekend (August 30 - September 1, 1997). The light attenuation response to this flow event was found to be significantly different for Site 2. On August 24th, Site 2, demonstrated significantly higher K_O than Site 1, measured on August 23rd. Following the test flow experiment an opposite inter and intra-site K_O pattern occurred. Fig 55. (Appendix B), graphically demonstrates the disordinal interaction that occurred between August 23-24 and September 6-7 ($F_{.95, 10, 316} = 19.95$, $p < 0.0001$) for both of the study sites. Under normal conditions we expected to observe Site 2 having an equivalent K_O or higher K_O. Instead Site 2, showed a significant reduction in K_O following the experiment. As expected, K_O measured at Site 2 (September 7) was found to be significantly less than previously observed at this site. This was the expected response if there was going to be a measurable effect as a result of the Labor Day weekend (steady 8,000 cfs flows) flow reduction. Water transparency was significantly clearer at this site in the early afternoon than previously measured and significantly clearer than observations made upstream at Site 1. Yet, there was no significant difference observed for Site 1 prior to and following the experimental flow.

Unfortunately, we cannot be sure if our observations were related to the Labor Day event or the duration of a high sediment load event. On September 7, 1997 we observed very high suspended loads during the early morning to mid-day period. Turbidity extended from 0600 to 1330 (18 hr exclusion of PAR), with suspended loads ranging from 331.8 to 0.2 mg/L. Following this episodic event, K_O values became significantly reduced. The mean daily K_O for the non-turbid period was $0.3115 \pm .031$sd. This was found to be significantly lower than other mean daily attenuation coefficients measured at the Lees Ferry (Site 2) or at the Glen Canyon Dam (Site 1). Secondly, note that within a 21 day period water clarity conditions for Site 2 had significantly regressed. For this reason, the results are inconclusive on the causative nature of this increased light clarity. However, the observed pattern for light attenuation still remains supportive of our primary research hypothesis that light transparency levels in the Glen Canyon reach are inversely correlated to primary production.

Experimental Light Attenuation Chamber

The preliminary results from the 48 h treatments show that there was a significant reduction in coefficients for diffuse light attenuation (K_d) in the treatment exposed only to natural light conditions without the algal inoculum ($K_d = 1.581 \pm 0.08$). Additionally, we observed an increase in K_d for the

algal inoculum was 1.762 ± 0.09, but was found not to be significantly different than for the control (K_d = 1.735 ± 0.06)., Refer to Fig 57. (Appendix B), for graphic representation. The mean AFSM for all algal treatments was 106.53 g m^{-2} ± 5.46, and the 40 cobbles accounted for a mean substrate area of 1.3 m^2 per treatment Total DOC generation per algal area treatment time has not determined to date. The implications of this photoreactive response are discussed later.

DISCUSSION

Seasonal variability in benthic production has been attributed to releases from Glen Canyon Dam, which are determined by both management actions and the physical/chemical characteristics of the reservoir, such as discharges, fluctuations, penstock depth, inflows, seasonal stratification, advective currents and planktonic production (Shannon et al. 1994; Blinn and Cole 1991, Hardwick *et al.* 1992; Hueftle and Vernieu 1998). It has always been assumed that the high clarity conditions found in Glen Canyon remain fairly constant, and yet relatively little research has been done to confirm this premise. Some of our preliminary light data indicate otherwise. A substantial decrease in the availability of PAR has occurred since instituting the interim flow regime.

During 1991, diffuse attenuation coefficients, K_d (0.06 - 0.08) measured for Lake Powell were at the lower end of the optical range for oligotrophic lakes and oceans with a euphotic zone extending approximately 70 m or deeper (Hart and Sherman 1996; Kirk 1994; Vincent et al. 1998, Morris et al. 1995). Yet, during the research period (1991-1992), light attenuation characteristics for the hypolimnetic releases in the river were found to considerably higher. In Glen Canyon, the average attenuation coefficient (K_O) was 0.238 ± SE 0.009, indicating that surficial lake measurements are not equivalent to the optical characteristics of the river. This is partly due to physical (stratification) and chemical processes that are occurring in the hypolimnion (Hueftle and Vernieu 1998; Hart and Sherman).

Observed temporal shifts in light attenuation for the Lake Powell reservoir have been found only to be seasonal and not diel in pattern (Hart and Sherman 1996). Therefore, the Glen Canyon section should remain, presumably stable on a daily basis because of the proximity of the tailwater section to Glen Canyon Dam. However, our irradiametric analysis, indicates a diel shift in Ko, with increasing attenuation occurring as a function of time. Since initiating these studies observed K_O values are more elevated. For this reason, the overall decrease in observed underwater light availability since the early 90's, as well as the daily variability in light attenuation for the tailwater section becomes problematic.

Since, the implementation of interim flows standing mass of benthic productivity has increased.

The euphotic zone represents 1% of available solar irradiance. So, if the average summer mean daily K_O was 0.322 in Glen Canyon, the euphotic zone would extend 14 m. However, if the mean winter K_O increased to 0.489 the zone would be equivalent to a depth of 9.5 m. If we explain the underwater light field in relationship to PAR, the maximum light penetration becomes considerably less in the winter period when one considers compensation points (*C. glomerata*, 30-50 $\mu mol\ s^{-1}\ m^{-2}$), seasonal variability in solar intensities (summer - maximum 2000 $\mu mol\ s^{-1}\ m^{-2}$; whereas winter - maximum 1200 $\mu mol\ s^{-1}\ m^{-2}$) and duration (summer - 13.5 h and winter 9.5 h). This adjusted depth would be equivalent to 7 m and the maximum penetration would occur only briefly during the solar zenith. Note that in 1991-92, the average attenuation coefficient (K_O) was 0.238, equivalent to a euphotic zone 19 m in depth. Changes to the optical properties of water has an exponential influence on the underwater light field. Therefore, physiological responses by aquatic alga and macrophytes to these varying K_O (annually, seasonally and daily) has considerable ecological implications on the structure and production of the benthic community (Moorhead et al. 1997; Steinman et al. 1990).

Inter-site Variability - Lentic waters typically have high concentrations of DOC, which contain a high proportion of humic substances (i.e., fulvic and humic acid) that are intensely photoreactive to ultraviolet radiation (UVR), (Wetzel et al. 1995; Vincent et al. 1998; Morris et al. 1995). The source of these substances are allochthonous in origin (Thurman 1983). It has been shown that the concentrations of these photoreactive are directly related to the overall concentration of DOC (Amon and Benner 1996; Duarte et al. 1998). Typically, large rivers in mid-latitudes have DOC concentrations ranging from 2 - 6 mg/L which consist of 60 to 80% humic substances. The photolytic reductions or molecular alterations of these humic substances can results from exposures to UV irradiance and natural sunlight (PAR), (Manny et al. 1971; Stewart and Wetzel 1981; Wetzel et al. 1995). Unfortunately, little information is available about the type and fate of these molecular compounds. Though certain studies have shown that an oxidative reduction in DOC results in CO_2 generation and atmospheric loss (Morris et al. 1995; Wetzel et al. 1995; Neale et al. 1998).

Preliminary results from our experiments using a vertical light attenuation chamber indicate that exposure to natural sunlight, inclusive of the entire spectral band (i.e, UVR and PAR) can significantly alter attenuation coefficients (Ibelings and Maberly 1998). And thereby, increasing the degree of water transparency. This phenomena has been observed for numerous lakes in the Antarctic (Vincent et al. 1998; Morris et al. 1995). Secondly, the results from the algal inoculum indicate that the photoreactive

loss occurring simultaneously in the alternate treatment are mediated by algal production. At this point in time we can only speculate that this light attenuation response is related to DOC concentrations as a result of extracellular loss due to photosynthesis. We intend on repeating this experiment two more times, as well as completing the DOC analyses. Hopefully these additional experiments will shed light on this rather interesting topic of algal mediated response to light attenuation.

Diel Variation - Since light attenuates exponentially, the transformed slope of attenuation (attenuation coefficient) provides a colligative and useful metric to characterize the apparent optical properties (AOP) of the water medium (Kirk 1984). The AOP is behaviorally more variable because it is a measure of the irradiant distribution within the underwater light field and not the natural or inherent optical properties of the water (Priesendorfer 1986; Kirk 1983; 1984). Yet, attenuation coefficients (K) are relatively insensitive to atmospheric fluxes or time of day as long as the light attenuating particles in the water remain stable (Kirk 1984 , 1994).

Waters having a high concentration of seston are associated with scattering by the organic and inorganic particulates (Vincent et al. 1998). The typical diel pattern for light attenuation shows a shift in coefficients during the day length period. The attenuating qualities of the water are variable and appear to form a concave shape during the Summer solstice and Fall-Spring Equinox. Typically the greatest clarity occurs approximately mid-day (solar noon) period. However, for the winter period, the diel pattern shifts to more of a convex shape. These patterns are consistent for both sites, but are more pronounced at the Lees Ferry Site (2) than at the Dam Site (1). We do not feel this diel variability is related to primary production, but rather the behavior of light. It has been observed that in systems lacking suspended particulates in large enough concentration typically absorb light rather than scatter light (Kirk 1994). This is especially the case for systems that are dominated by dissolved humic substances rather than a larger pariticulate fraction. There appears to be supportive evidence that this is the case in the Glen Canyon reach which has very reduced sediment loads. For a given site, intra-variability in suspended loads consisting of either the total suspended sediment, and the inorganic and organic fraction were found not to be systematically correlated to time. Concentrations of these potential attenuating parameters, TSS, PIM, and POM (excluding DOC) are so reduced they show no significant pattern with K.

If waters are dominated by optical properties that absorb light we should have increased attenuation as a function of both refraction and reflection when the source of light departs from the solar zenith. The solar altitude is very important in determining changes in the underwater flux of PAR (Kirk 1984,

1994). This is related to the optical properties of the water as they relate to either refraction/reflection. Otherwise, light attenuating parameters must become less during the mid-day period. This has not been observed and does not appear to be likely. In comparison, diel variability in light attenuation coefficients for the downstream reaches of Grand Canyon do not occur. Variability in K_0's for this region are explained by differences in suspended sediment loads an underwater light field dominated by light scattering, rather then a one dominated by factors of absorptance.

Turbid Flow Events - Turbidity events are infrequently observed in the Glen Canyon reach, however these sediment inputs may occur more often than previously thought. This is partially due to the climatic patterns associated with late summer monsoons that promote episodic flow events from ungaged tributaries. Thunderstorms and rain showers typically develop during the late afternoons and evenings and for this reason sediment inputs go unobserved or measured. We were very fortunate to observe a number of these episodic events on August 23, 31st and September 6, 1997. The runoff flowed into the river from the high cliffs and small catchments, yet the suspension of fines were quickly evacuated and not readily apparent by next morning. The mass transport rates within this reach are between 6 and 10 hours. The length of the Glen Canyon section is very short, encompassing a distance of 25 km. There are a number of drainages in this section, they include Honey Draw (RM - 13), Ferry Swale (RM - 11.5 and 11.35), Nine Mile Draw (RM - 9.8), Water Holes Canyon (RM - 4.1), Cave Canyon (RM - 3.0) and Fall Creek (RM -2.6). Most of these have very small catchment areas. The largest drainage is Water Holes Canyon. Unfortunately, information regarding catchment area appear to be unknown for these drainages. Also, the temporal nature (frequency and duration) of these sediment inputs appear not to be limiting to PAR, however, other questions regarding nutrient inputs, scouring and deposition from these events may effect primary production in this reach. The frequency and duration of these events and the characteristics of the catchments should be further explored.

Predictive Relationship - There appears to be strong correlated patterns with the observed optical responses in Glen Canyon and specific water quality parameters associated with Lake Powell Reservoir (Hueftle and Vernieu 1998; Weideman and Bannister 1985; Thurman 1983). This limnological data has been collected as part to the GCMRC Lake Powell Water Quality Program. In addition, I will attempt to determine experimentally if changes in salinity or pH are responsible for this observed response. However, whether or not we are able to prove a causal relationship among some of these water quality parameters these parameters appear to have some colligative value for predicting the

underwater characteristics that are present in the Glen Canyon/Lees Ferry reach.

Validation Trip (May 21 - 31) - Fig 56, indicates the degree of light attenuation encountered longitudinally as measured from Glen Canyon Dam to Diamond Creek during the Validation trip (High-clarity light trip), scheduled May 22 - 31, 1998. Note, the progressive increase in attenuation as a function of distance downstream is equivalent spatially to previous observations made for similar data collected between 1991, 1992 and 1994. The site variability observed may be related to variation in discharge during sampling period and the channel morphometry for specific geomorphic reaches. The period of observation was during a period of high clarity, yet only a few days had passed since the LCR winter runoff had ceased to baseflow. Therefore, some of the elevated attenuation coefficients may be related to this antecedent period where the suspended fines had not been evacuated out of the system. Since sediment samples have not been analyzed to date, no attempts were made to correlate sediment concentrations to light attenuation.

1999 RESEARCH PLANS

Table 4, summarizes the remaining experimental and monitoring work for 1999. The two primary areas that remain are:

Primary Production Irradiant/Temperature Curves

These experiments have not been conducted to date. We are in the process of completing the fabrication and construction of these experimental light chambers used for measuring dissolved oxygen generation under varying underwater light regimes. We are planning to conduct a pilot test on the equipments effectiveness as of October 17-18, 1998

Experimental Drift Chambers

These experiments are scheduled for being conducted as planned for the summer of 1999. The methods to be used are as described in the original proposal.

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APPENDIX A

TABLE 1., PROGRESS REPORT

Sampling Period (1997 - 1998)

Date	Site	Constituents	Site	Constituents	Site	Constituents
August 23, 1997	Site 0	(TSP, POM, PIM, DOC)	Site 1	(TSP, POM, PIM, DOC, KO)		
August 24, 1997	Site 0	(TSP, POM, PIM, DOC)			Site 2	(TSP, POM, PIM, DOC, KO)
September 6, 1997	Site 0	(TSP, POM, PIM, DOC)	Site 1	(TSP, POM, PIM, DOC, KO)		
September 7, 1997	Site 0	(TSP, POM, PIM, DOC)			Site 2	(TSP, POM, PIM, DOC, KO)
September 28, 1997	Site 2	(KO)				
Dec, 21- 22, 1997	Site 0	(TSP, POM, PIM, DOC)	Site 1	(TSP, POM, PIM, DOC, KO)	Site 2	(TSP, POM, PIM, DOC, KO)
March 21-22, 1997	Site 0	(TSP, POM, PIM, DOC)	Site 1	(TSP, POM, PIM, DOC, KO)	Site 2	(TSP, POM, PIM, DOC, KO)
May 22 - 31, 1998		57 Sampling events, (Includes 19 historical sites, 40 intra-sites, and 2 historical sites with daily multiple replicates) (TSP, POM, PIM, DOC, KO)				
June 20 -21, 1998	Site 0	(TSP, POM, PIM, DOC)	Site 1	(TSP, POM, PIM, DOC, KO)	Site 2	(TSP, POM, PIM, DOC, KO)
July 23, 1998					Site 2	(KO)
August 16 - 23, 1998		57 Sampling events, (Includes 19 historical sites, 40 intra-sites, and 2 historical sites with daily multiple replicates) (TSP, POM, PIM, DOC, KO				
Sept 19-20, 1998	Site 0	(TSP, POM, PIM, DOC)	Site 1	(TSP, POM, PIM, DOC, KO)	Site 2	(TSP, POM, PIM, DOC, KO)

TABLE 2., ANALYTICAL WORK COMPLETED TO DATE

Glen Canyon Reach

Site 0	Date	Suspended Constituents	Dissolved Organic Carbon	Light Attenuation
	August 23, 1997	45 Samples Completed	48 Samples Partially Complete	Not Applicable
	August 24, 1997	45 Samples Completed	48 Samples Partially Complete	Not Applicable
	September 6, 1997	45 Samples Completed	48 Samples Partially Complete	Not Applicable
	September 7, 1997	45 Samples Completed	48 Samples Partially Complete	Not Applicable
	December 17-18, 1997	75 Samples Completed	87 Samples Not Analyzed	Not Applicable
	March 21-22, 1998	75 Samples Complete	87 Samples Not Analyzed	Not Applicable
	June 19-20, 1998	75 Samples Complete	87 Samples Not Analyzed	Not Applicable
	September 19-20, 1998	75 Samples Not Analyzed	87 Samples Not Analyzed	Not Applicable

Site 1	Date	Suspended Constituents	Dissolved Organic Carbon	Light Attenuation
	August 23, 1997	45 Samples Completed	48 Samples Partially Complete	22 Profiles Completed
	September 6, 1997	45 Samples Completed	48 Samples Partially Complete	52 Profiles Completed
	December 17-18, 1997	75 Samples Completed	87 Not Analyzed	50 Profiles Completed
	March 21-22, 1998	75 Samples Complete	87 Not Analyzed	59 Profiles Completed
	June 19-20, 1998	75 Samples Complete	87 Samples Not Analyzed	67 Profiles Completed
	September 19-20, 1998	75 Samples Not Analyzed	87 Samples Not Analyzed	60 Profiles Completed

Site 2	Date	Suspended Constituents	Dissolved Organic Carbon	Light Attenuation
	August 24, 1997	45 Samples Completed	48 Samples Partially Complete	27 Profiles Completed
	September 7, 1997	45 Samples Completed	48 Samples Partially Complete	56 Profiles Completed
	September 28, 1997	No Samples	No Samples	25 Profiles Completed
	December 17-18, 1997	75 Samples Completed	87 Samples Not Analyzed	31 Profiles Completed
	March 21-22, 1997	75 Samples Complete	87 Samples Not Analyzed	63 Profiles Completed
	June 19-20, 1998	75 Samples Complete	87 Samples Not Analyzed	58 Profiles Completed
	July ??, 1998	No Samples	No Samples	48 Profiles Completed
	September 19-20, 1998	75 Samples Not Analyzed	87 Samples Not Analyzed	60 Profiles Completed

Validation Trips

High Clarity Light Trip				
	May 22 - 31, 1998	171 Samples	48 Samples Not Analyzed	171 Profiles Completed
High Turbidity Light Trip				
	August 16 - 23, 1998	Samples Partially Analyzed	No Samples	Partially Analyzed

TABLE 3., PROFILE CRITERIA FOR ATTENUATION COEFFICIENTS

PROFILE CRITERIA	DEFINITION OF CRITERIA FOR QUALIFYING ATTENUATION COEFFICIENTS
0	Direct beam, solar flux between the minimum and maximum measurements of ambient incidence (μE) are less than 5%.
1	Direct beam, solar flux between the minimum and maximum measurements of ambient incidence (μE) are greater than 5% and less than 10%
2	Direct beam, solar flux between the minimum and maximum measurements of ambient incidence (μE) are greater than 10%.
3	Indirect beam, source of incidence is skylight (absence of clouds or diffuse overcast).
4	Indirect beam, source of incidence is skylight (presence of clouds or diffuse overcast).
5	Indirect beam, source of incidence is skylight (presence of clouds and precipitation).
6	Data entry error
7	Instrumentation set-up error
8	Interference of terrestrial quanta sensor (LI-190SA).
9	Deployment angle
10	Debris interference

TABLE 4., TUKEYS STUDENTIZED RANGE (HSD) TEST FOR KO

Alpha= 0.05 df= 246 MSE= 0.001076, Critical Value of Studentized Range= 4.426, Minimum Significant Difference= 0.0308

WARNING: Cell sizes are not equal. Harmonic Mean of cell sizes= 22.22577

Mean attenuation coefficients with the same letter are not significantly different.

Tukey Grouping		Mean	N	J_DAY	Site	Date
	A	0.488825	24	352.2	2	December 18, 1997
	B	0.416642	43	446.2	2	March 22, 1998
	B					
	B	0.415365	37	352.1	1	December 18, 1997
	B					
	B	0.404400	41	446.1	1	March 22, 1998
	B					
C	B	0.392757	23	271	2	September 28, 1997
C						
C	D	0.362724	21	236	2	August 24, 1997
	D					
E	D	0.345502	43	249	1	September 6, 1997
E						
E	F	0.321282	11	235	1	August 23, 1997
	F					
	F	0.311592	12	250	2	September 7, 1997

TABLE 5., SUMMARY OF REMAINING EXPERIMENTAL WORK FOR 1999

<u>Experimental Light Attenuation Chamber</u>	
October 9-12, 1998	Lees Ferry, Marble Canyon, AZ
December 19-21, 1998	Lees Ferry, Marble Canyon, AZ
<u>DOC Salinity Experiments</u>	
November 7-9, 1998	Glen Canyon Dam, Page, AZ
November 15-16, 1998	Glen Canyon Dam, Page, AZ
November 22-23, 1998	Glen Canyon Dam, Page, AZ
November 29-30, 1998	Glen Canyon Dam, Page, AZ
<u>Primary Production Chamber Experiments</u>	
October 17-19, 1998	Lees Ferry, Marble Canyon, AZ
February 12-14, 1999	Lees Ferry, Marble Canyon, AZ
March 12-14, 1999	Lees Ferry, Marble Canyon, AZ
April 12-14, 1999	Lees Ferry, Marble Canyon, AZ
June 11-21, 1999	Lees Ferry, Marble Canyon, AZ
June 25-28, 1999	Lees Ferry, Marble Canyon, AZ
<u>Winter Solstice Sampling</u>	
December 19-21, 1998	Site 0, Site 1 and Site 2
<u>Light/Sediment Validation Trips</u>	
May 16-23, 1999	Glen and Grand canyons
August 15-22, 1999	Glen and Grand canyons
<u>Algal Drift Experiments</u>	
July 8-13, 1999	Glen Canyon Dam, Page, AZ
July 18-21, 1999	Glen Canyon Dam, Page, AZ
August 7-10, 1999	Glen Canyon Dam, Page, AZ

APPENDIX B

Fig 1

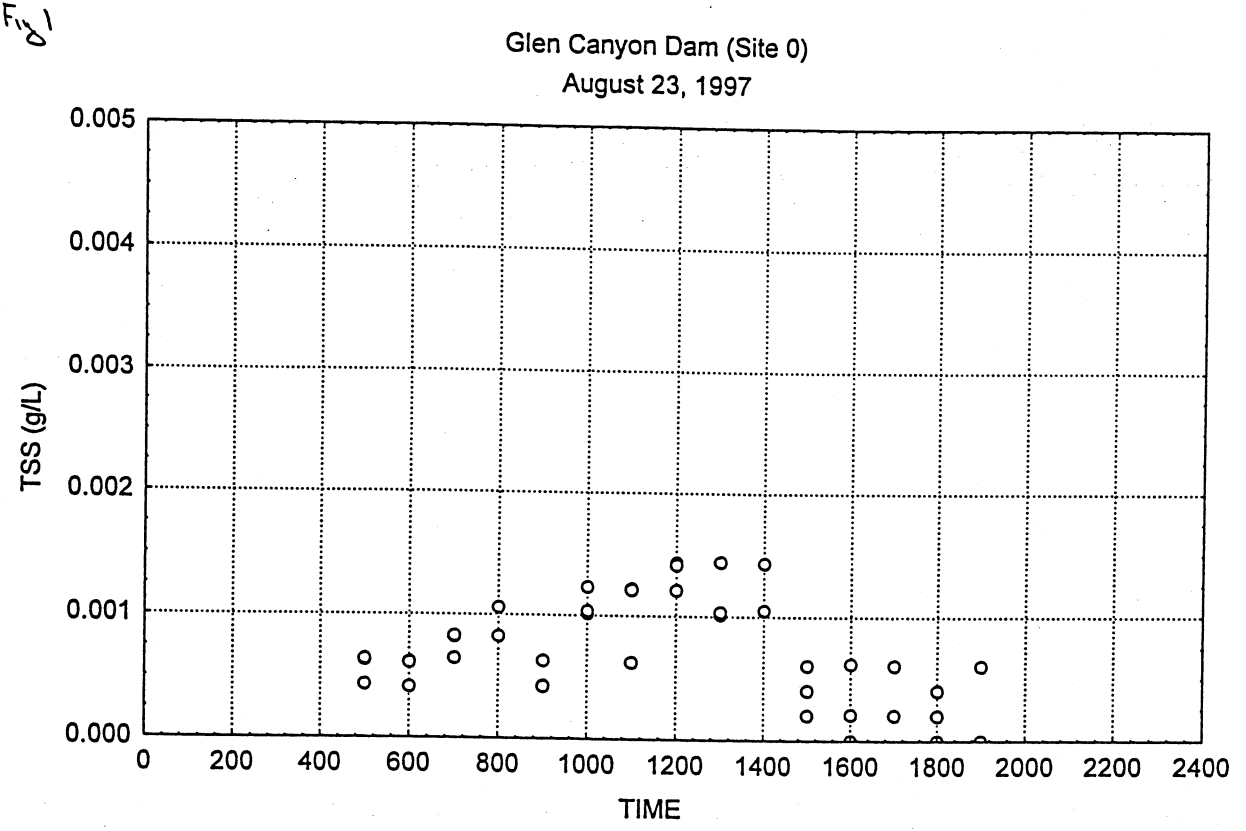
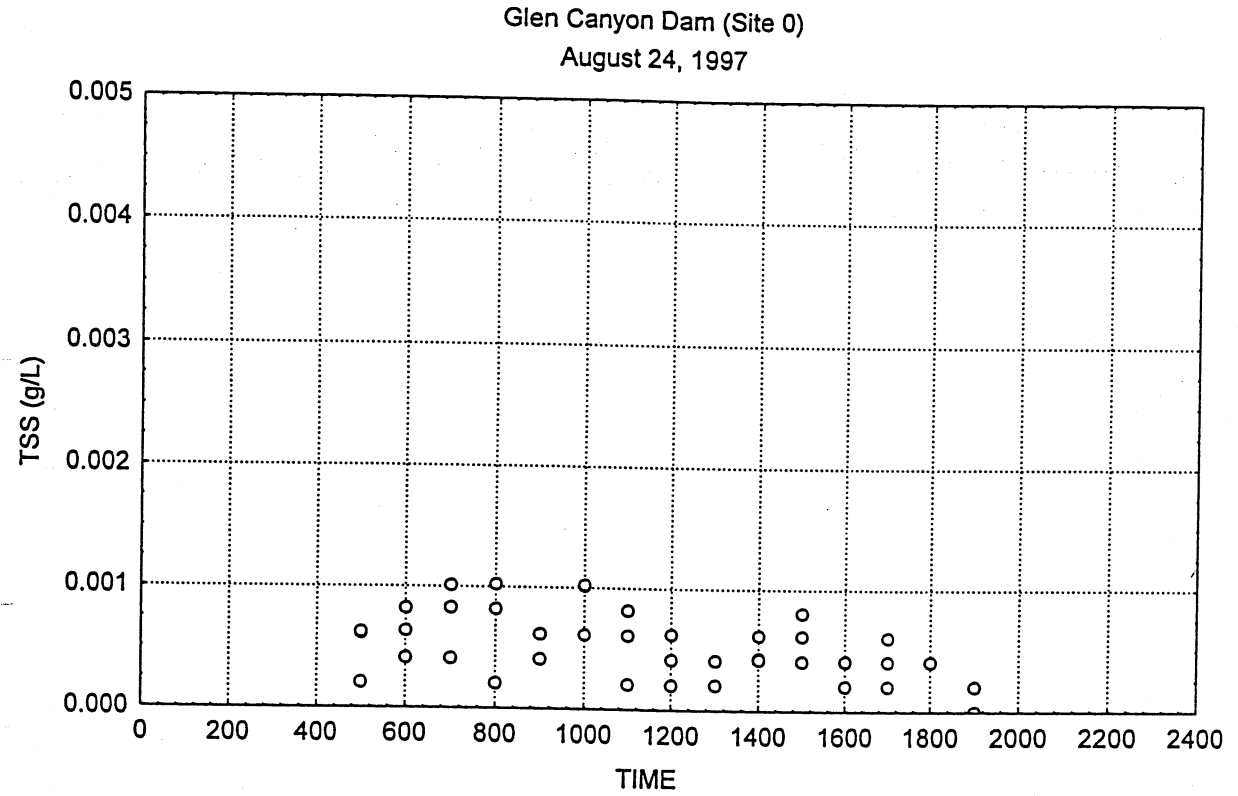

Glen Canyon Dam (Site 0)
August 23, 1997
TSS (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 2.


Glen Canyon Dam (Site 0)
August 24, 1997
TSS (g/L)
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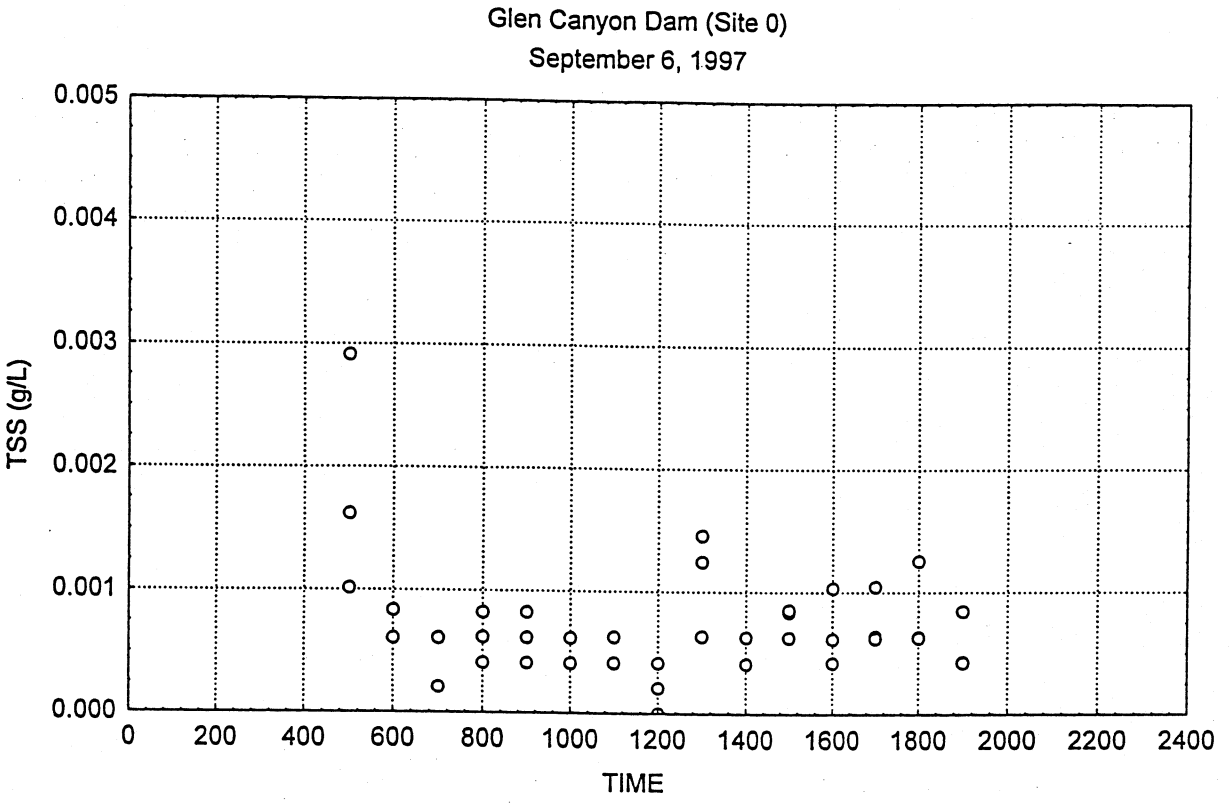
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 3


Glen Canyon Dam (Site 0)
September 6, 1997
TSS (g/L)
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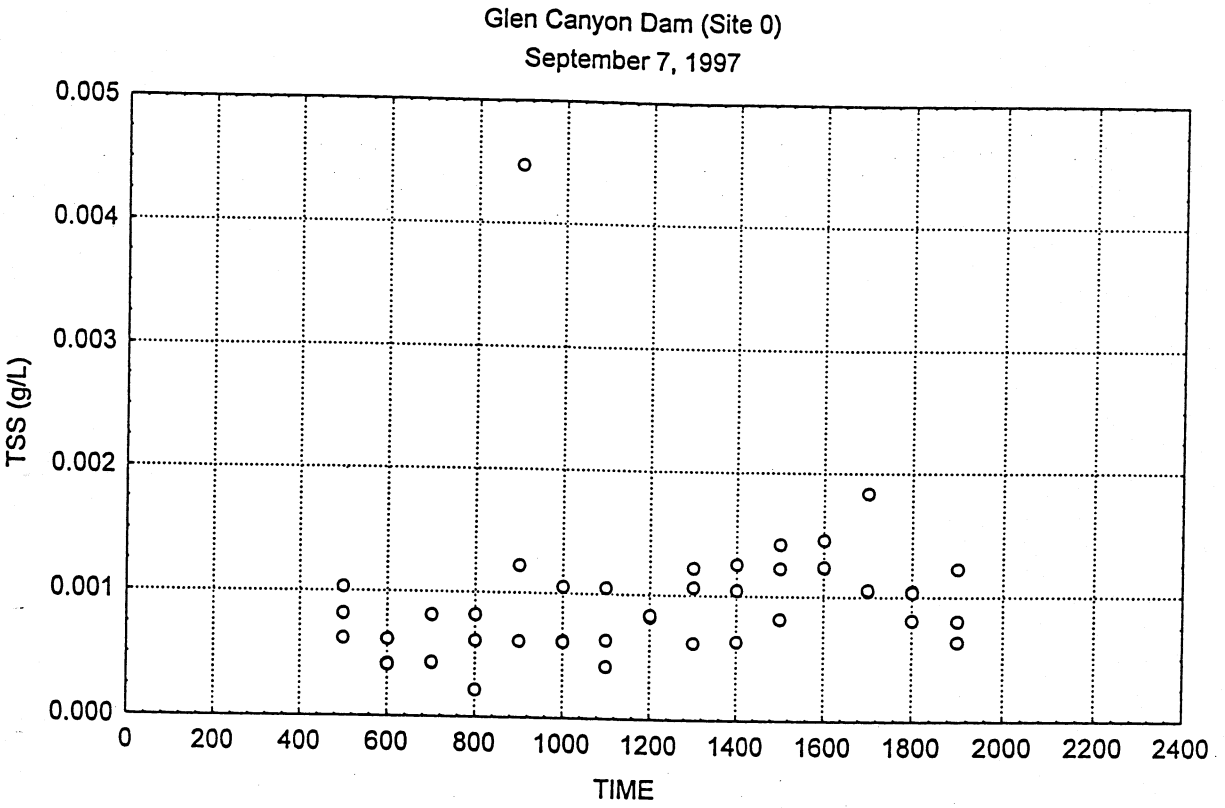
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 4


Glen Canyon Dam (Site 0)
September 7, 1997
TSS (g/L)
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0.004
0.003
0.002
0.001
0.000
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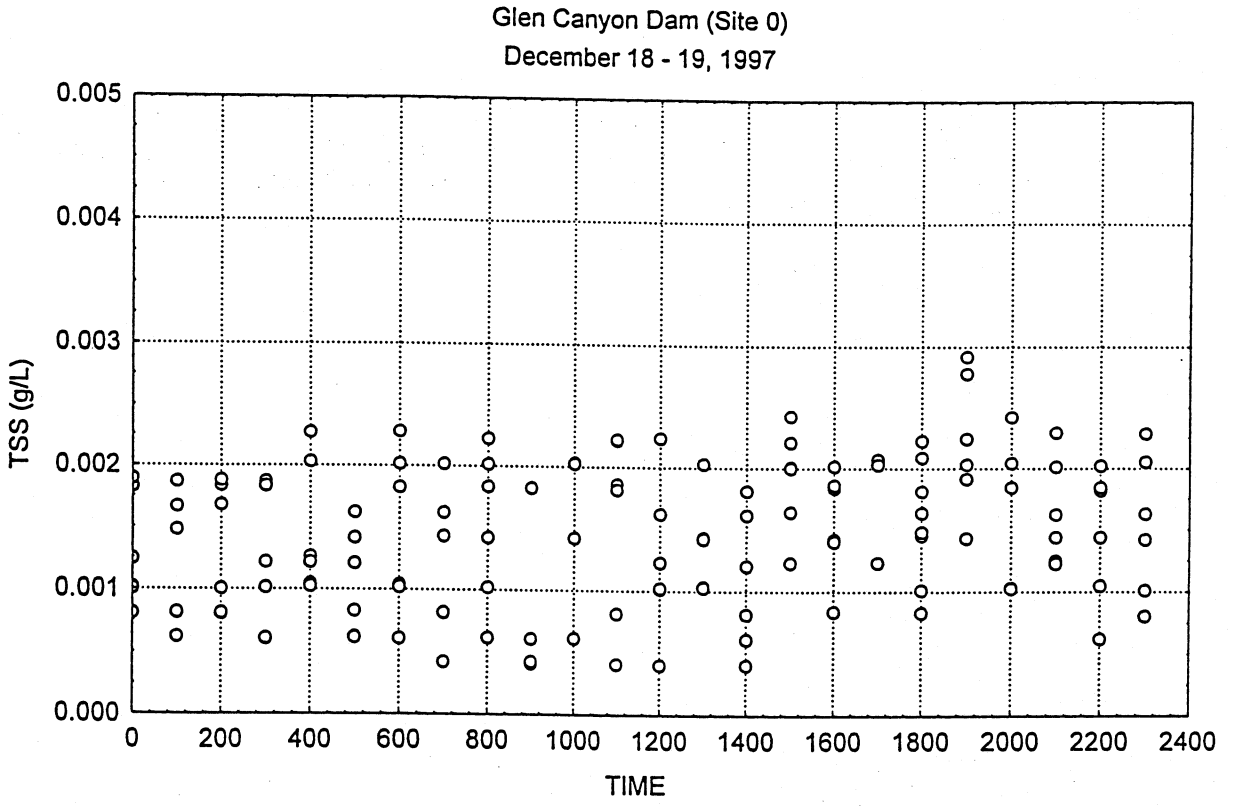
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 5


Glen Canyon Dam (Site 0)
December 18 - 19, 1997
TSS (g/L)
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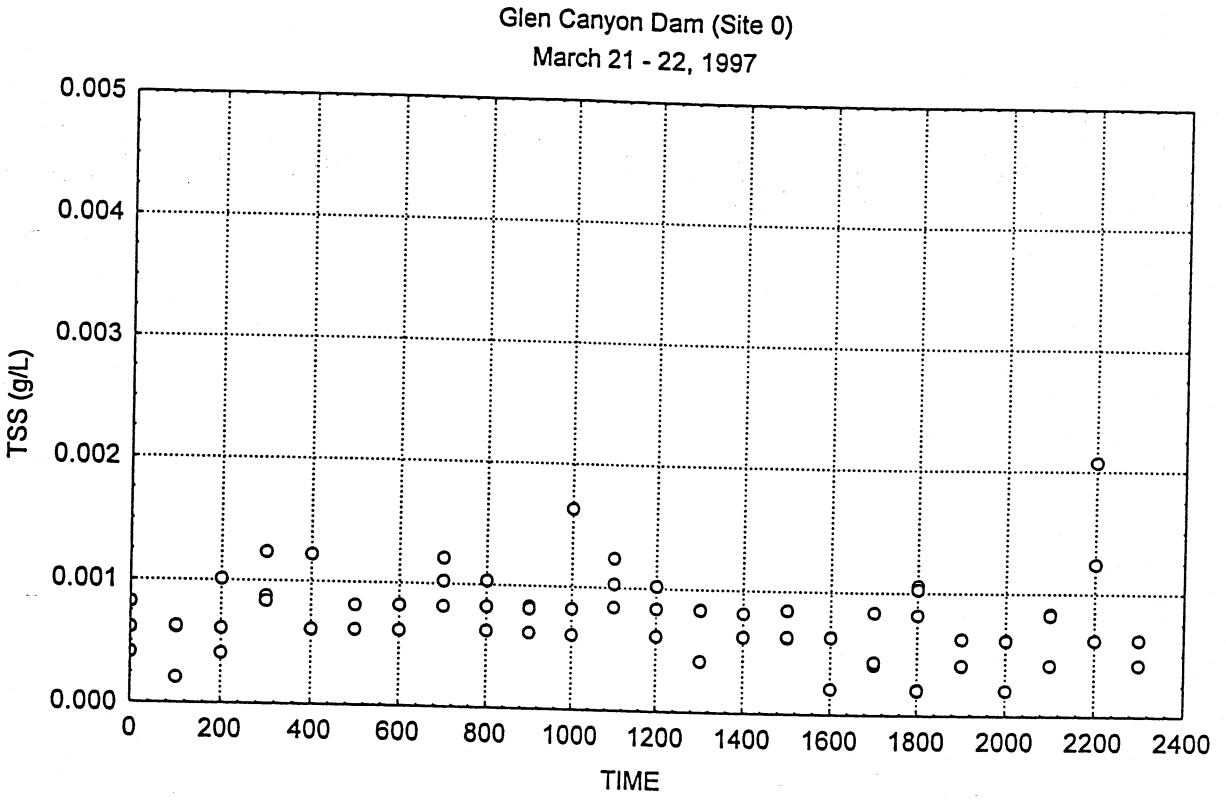
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 6


Glen Canyon Dam (Site 0)
March 21 - 22, 1997
TSS (g/L)
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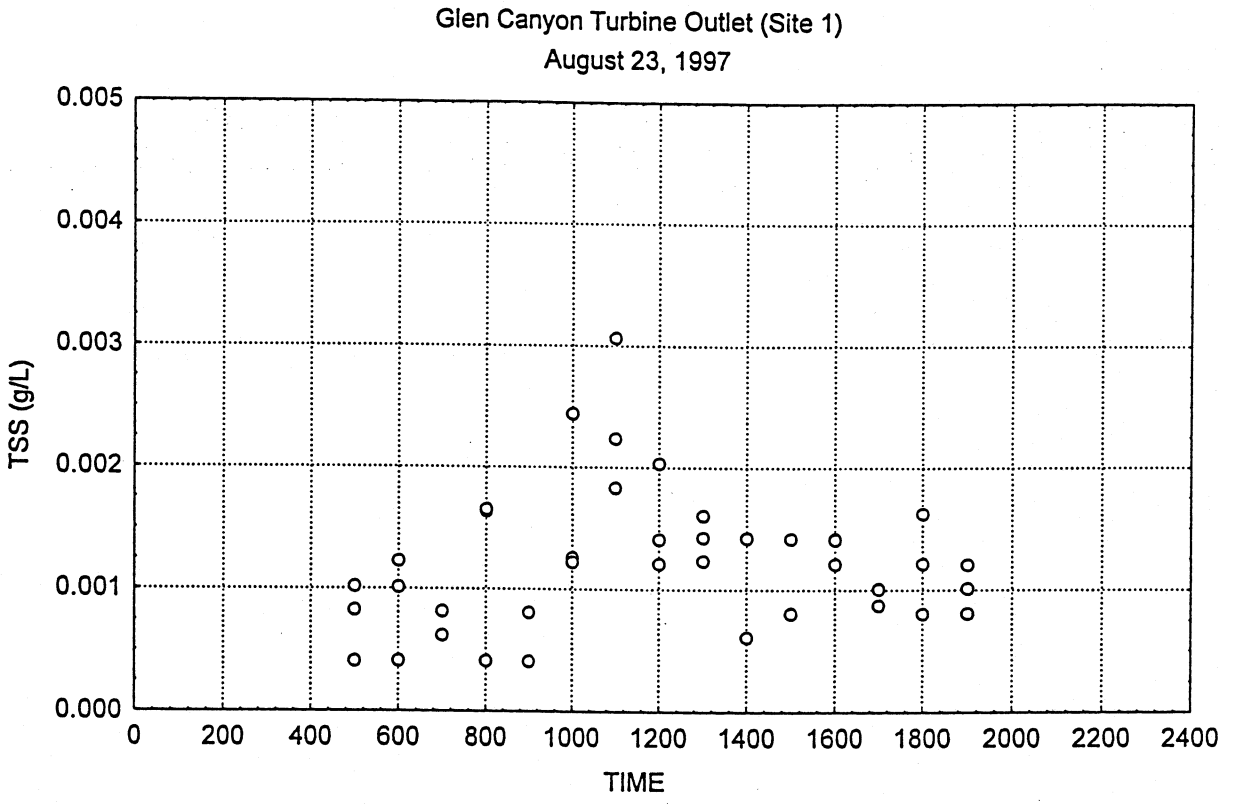
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 7


Glen Canyon Turbine Outlet (Site 1)
August 23, 1997
TSS (g/L)
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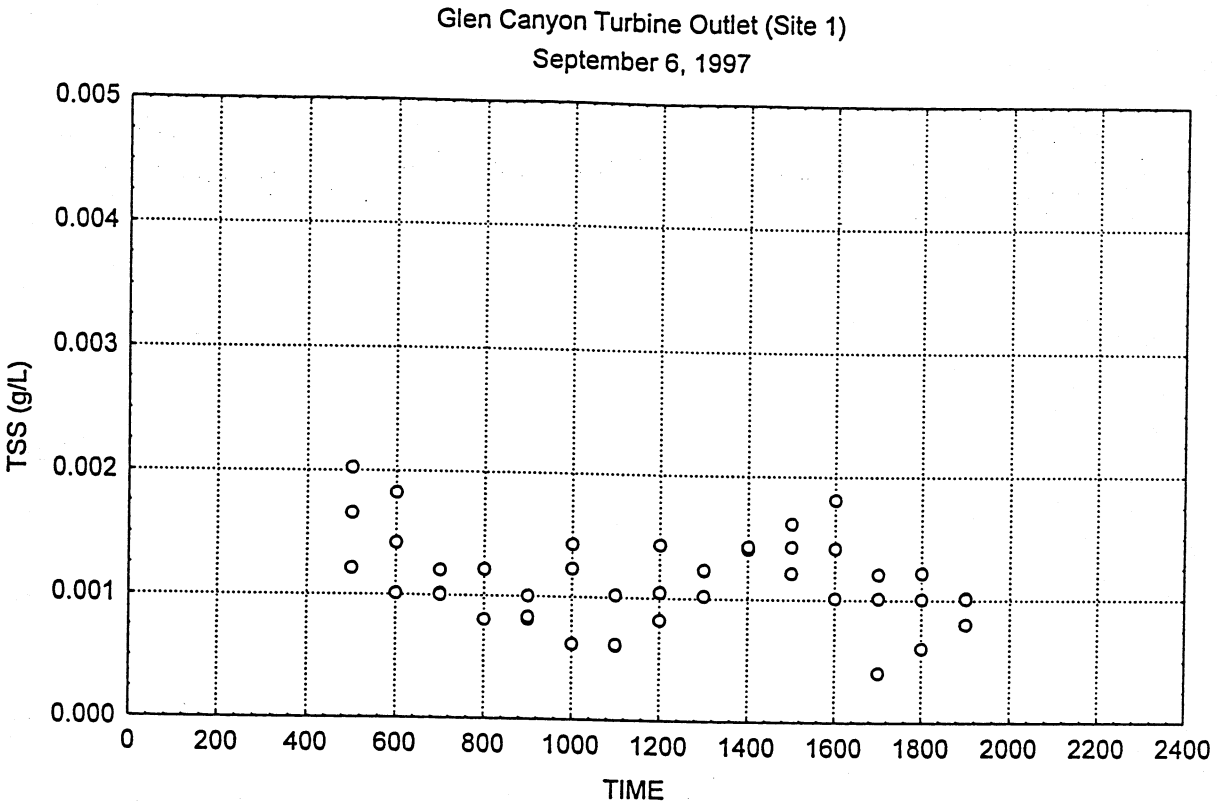
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 8


Glen Canyon Turbine Outlet (Site 1)
September 6, 1997
TSS (g/L)
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0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

fig 9

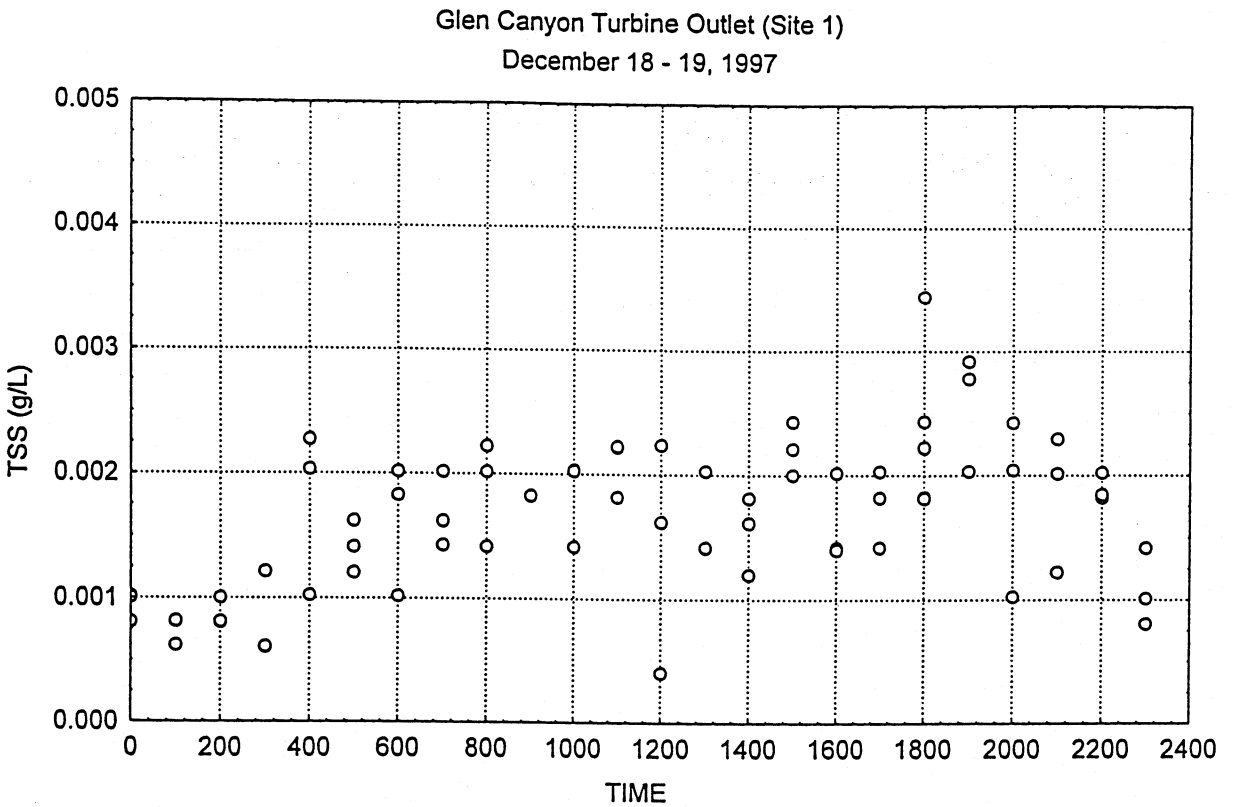

Glen Canyon Turbine Outlet (Site 1)
December 18 - 19, 1997
TSS (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 10

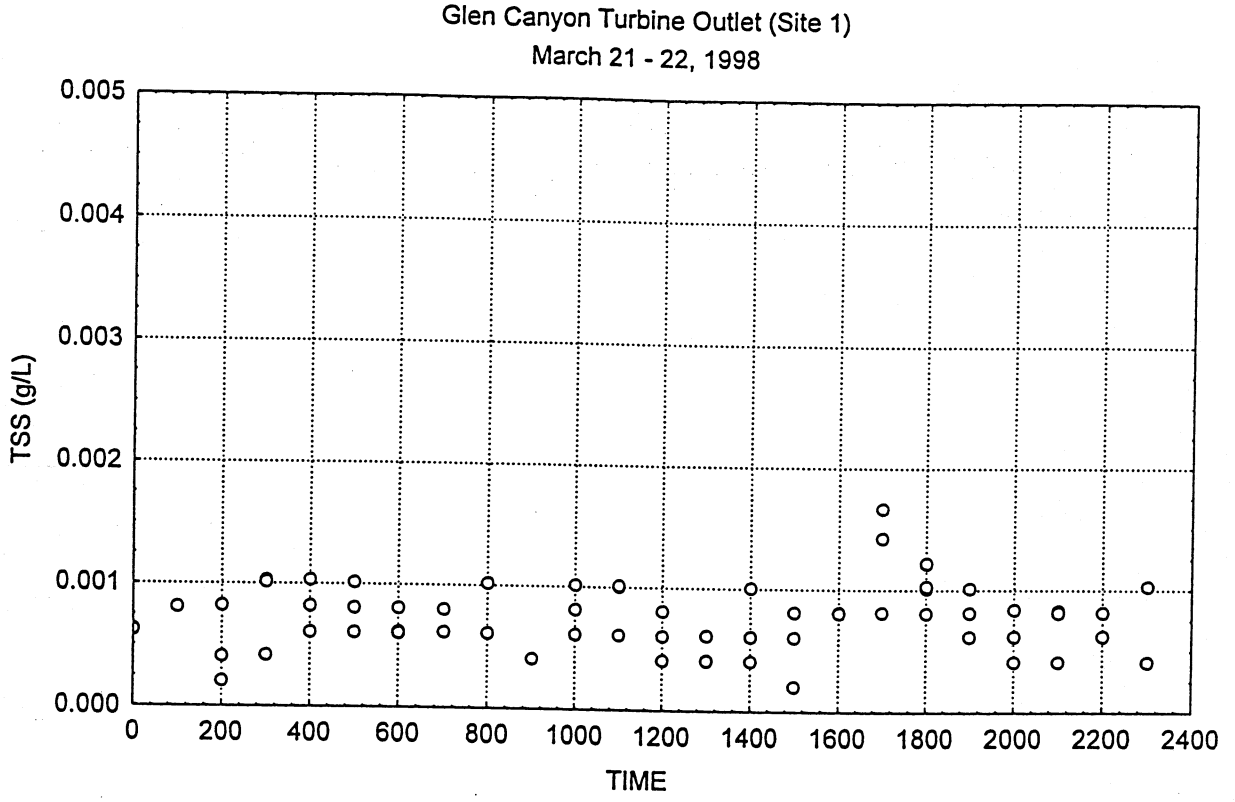

Glen Canyon Turbine Outlet (Site 1)
March 21 - 22, 1998
TSS (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 11

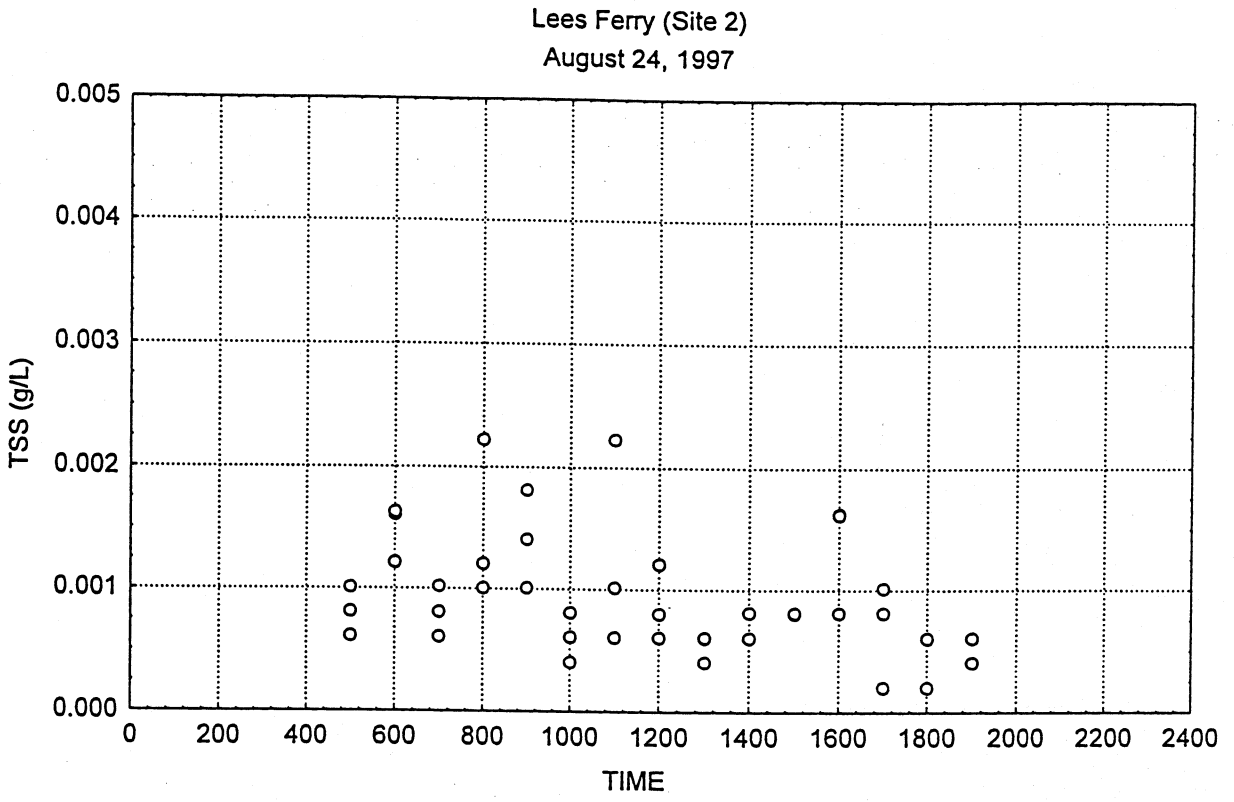

Lees Ferry (Site 2)
August 24, 1997
TSS (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 12

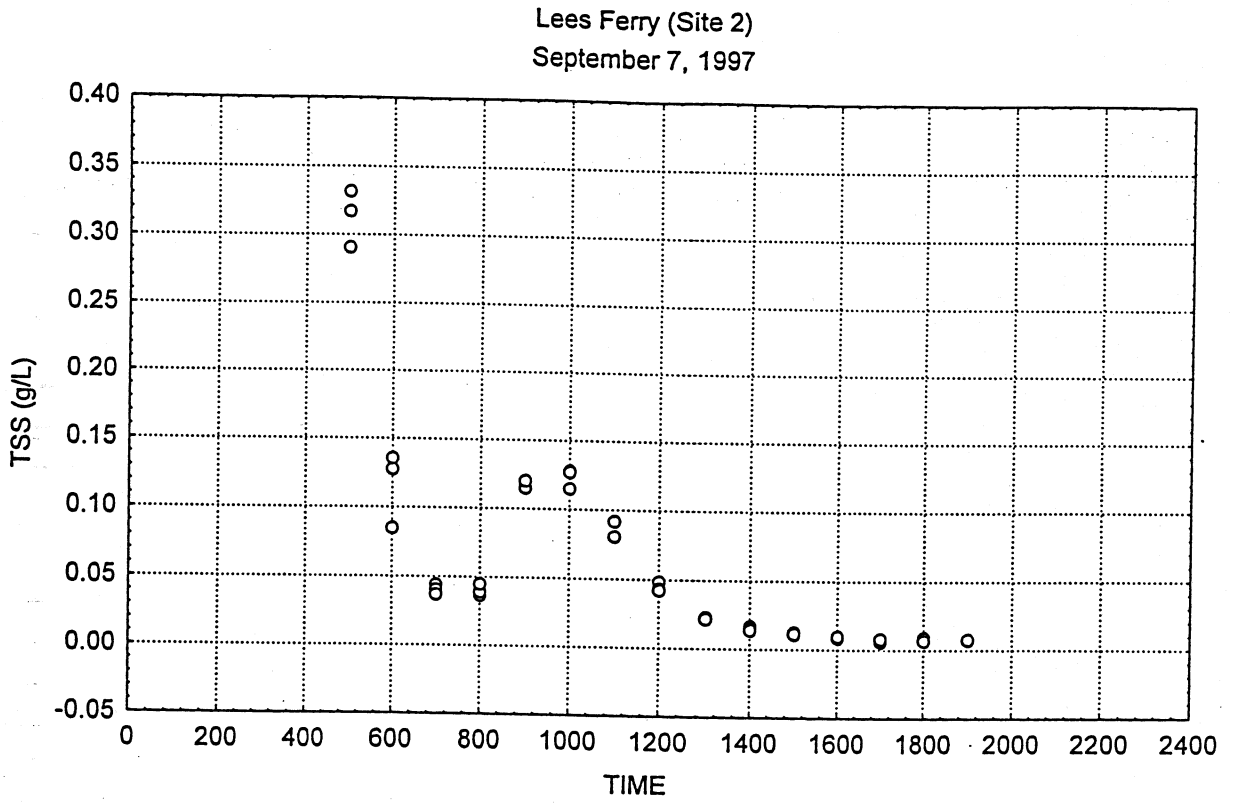

Lees Ferry (Site 2)
September 7, 1997
TSS (g/L)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 13

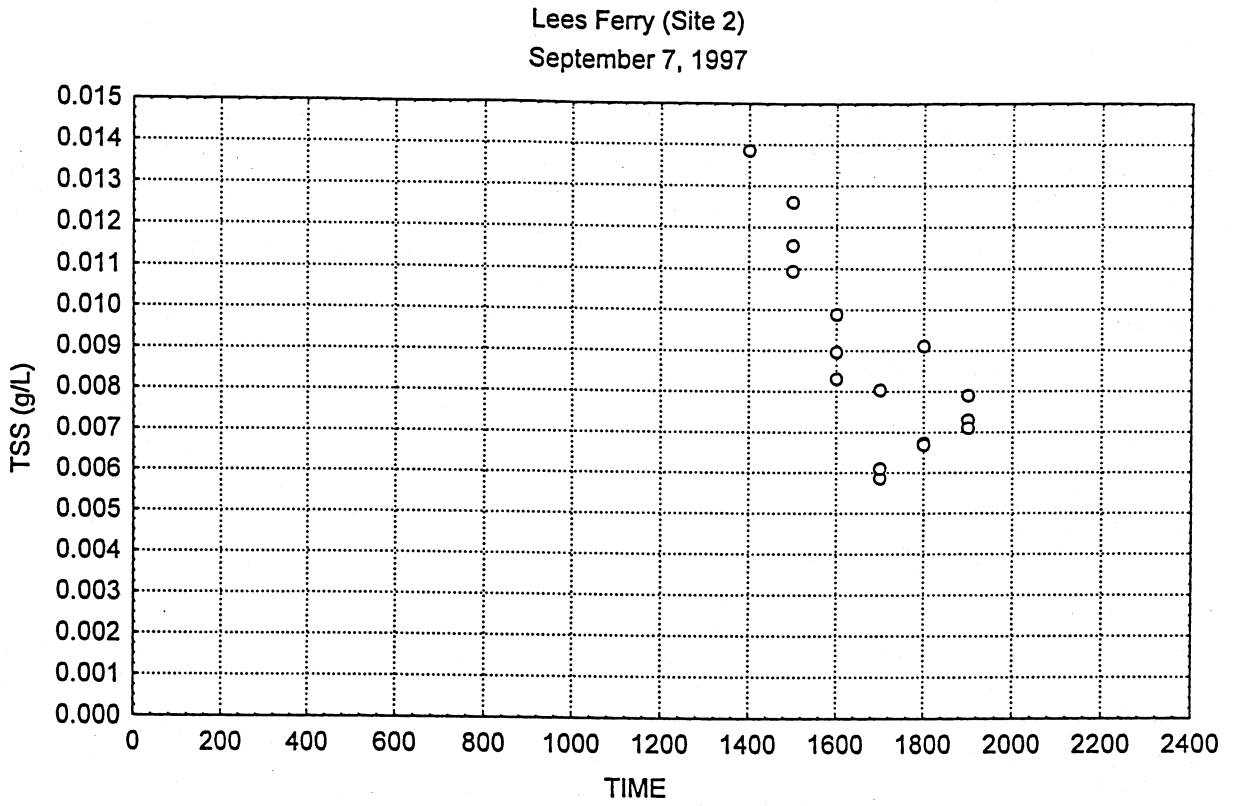

Lees Ferry (Site 2)
September 7, 1997
TSS (g/L)
0.015
0.014
0.013
0.012
0.011
0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 14

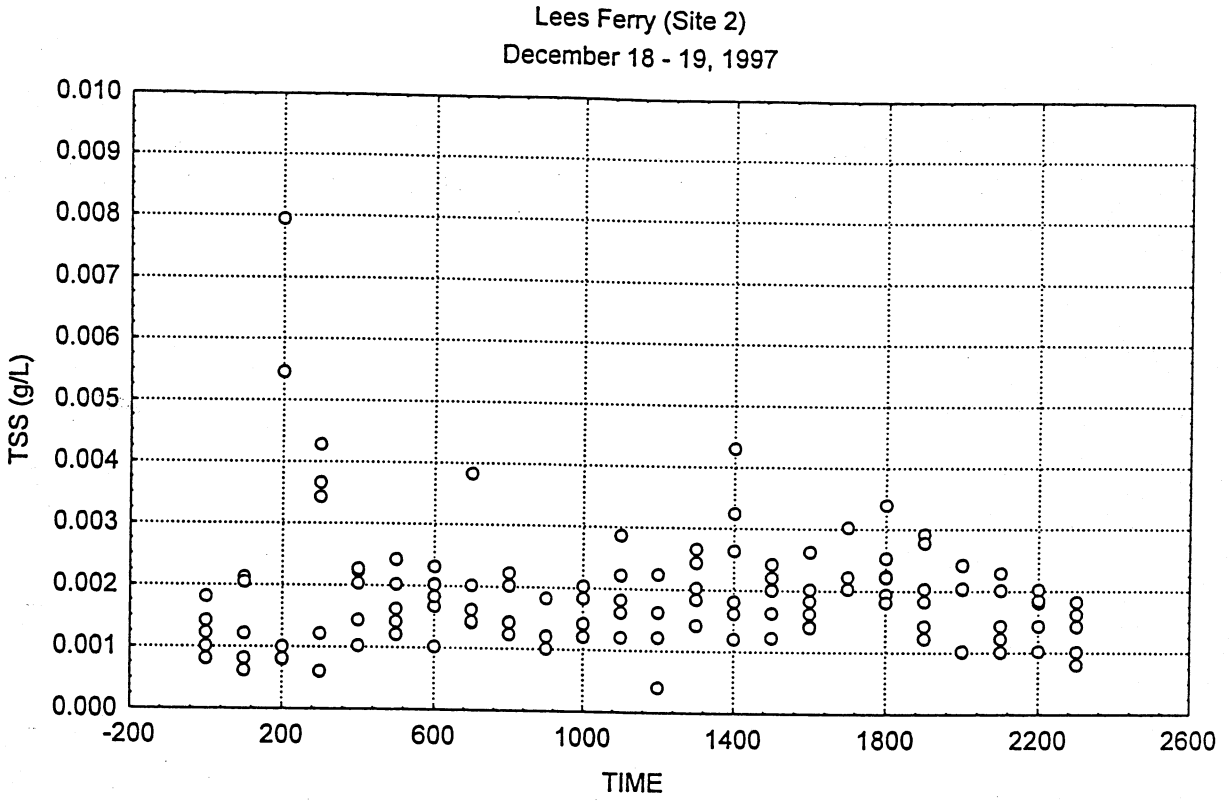

Lees Ferry (Site 2)
December 18 - 19, 1997
TSS (g/L)
0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
-200
200
600
1000
1400
1800
2200
2600
TIME

Fig 15

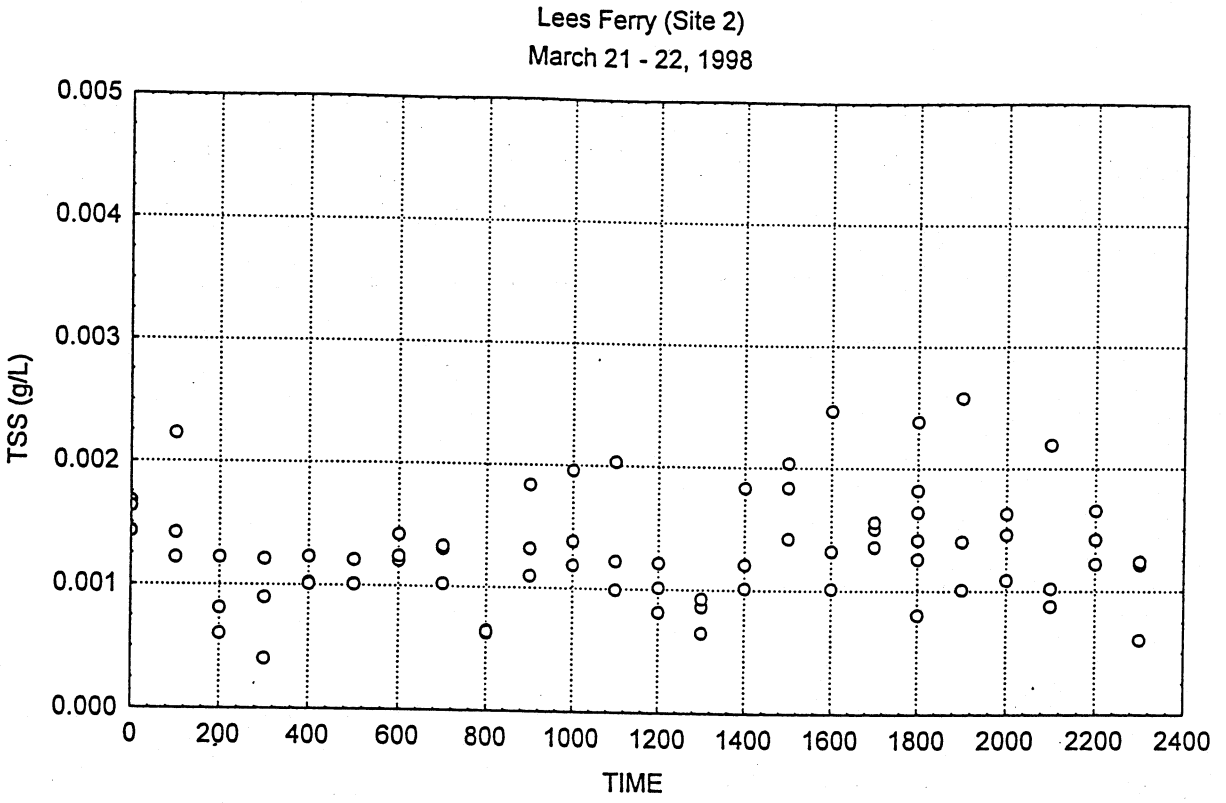

Lees Ferry (Site 2)
March 21 - 22, 1998
TSS (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 16

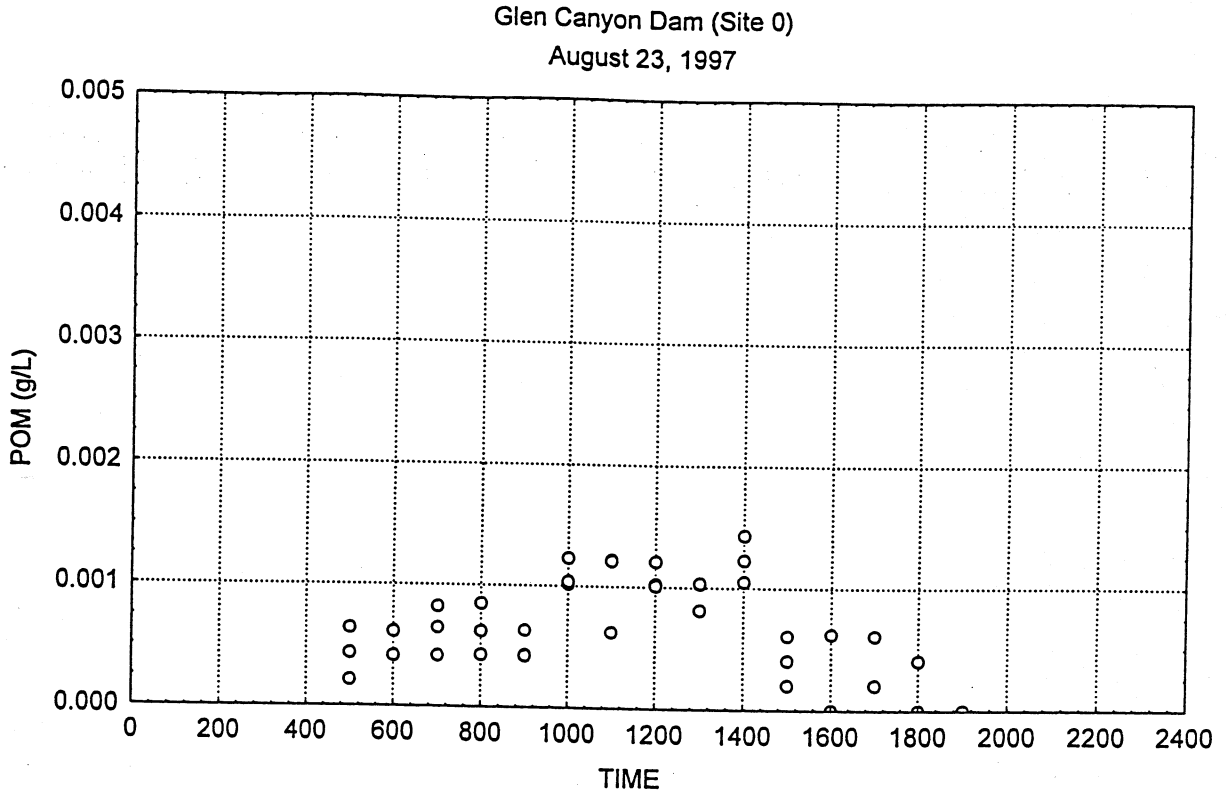

Glen Canyon Dam (Site 0)
August 23, 1997
POM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 17

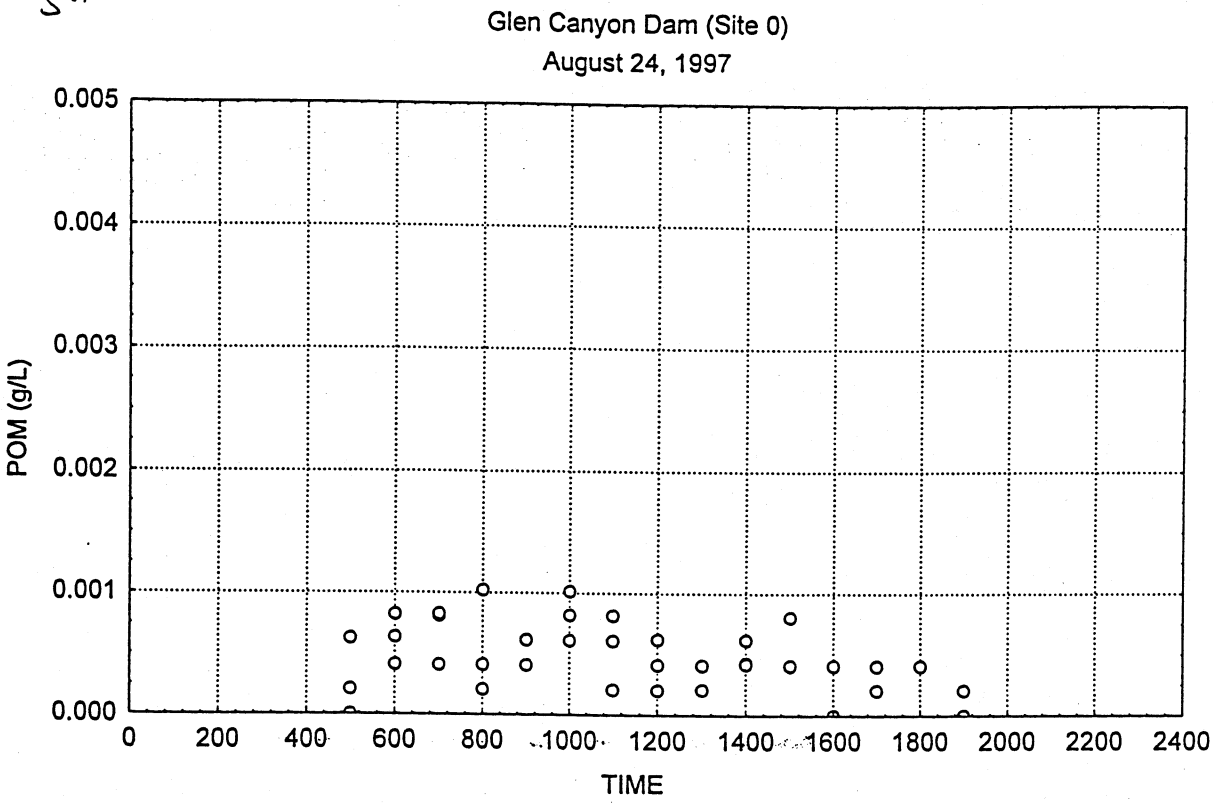

Glen Canyon Dam (Site 0)
August 24, 1997
POM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 18

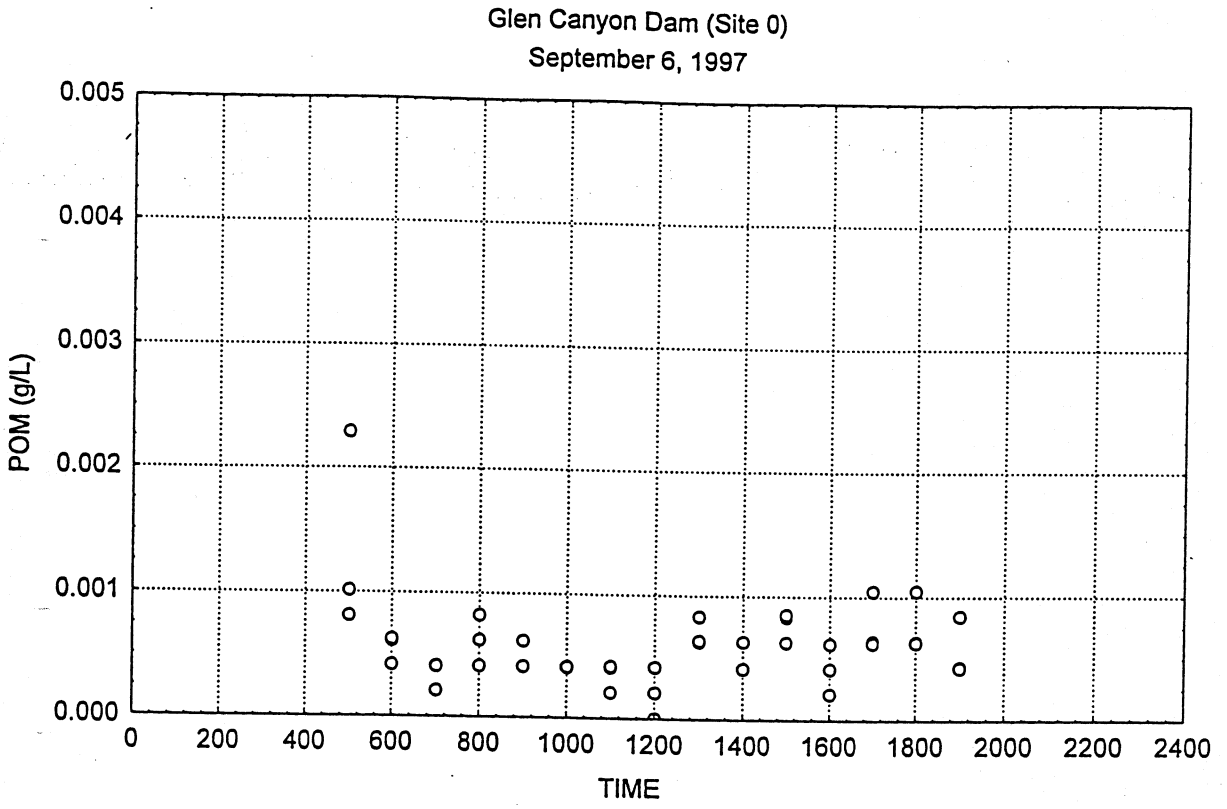

Glen Canyon Dam (Site 0)
September 6, 1997
POM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 19

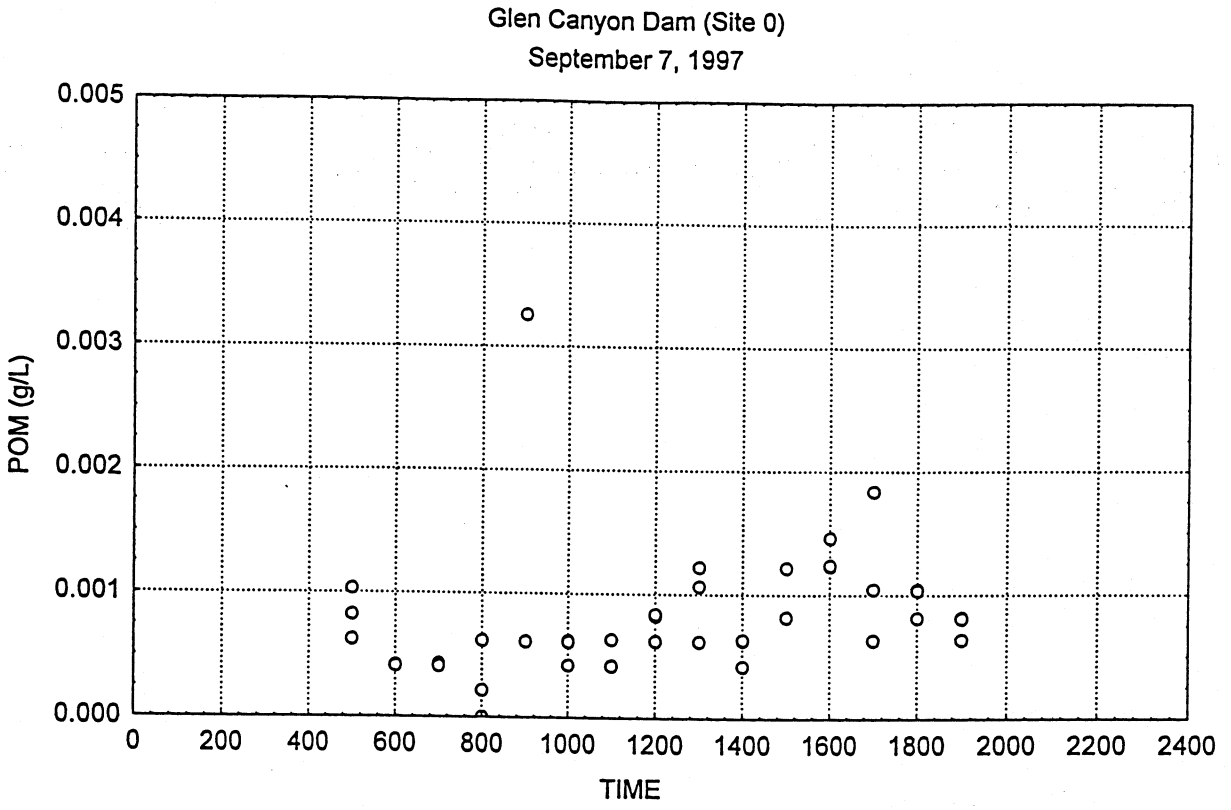

Glen Canyon Dam (Site 0)
September 7, 1997
POM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 20

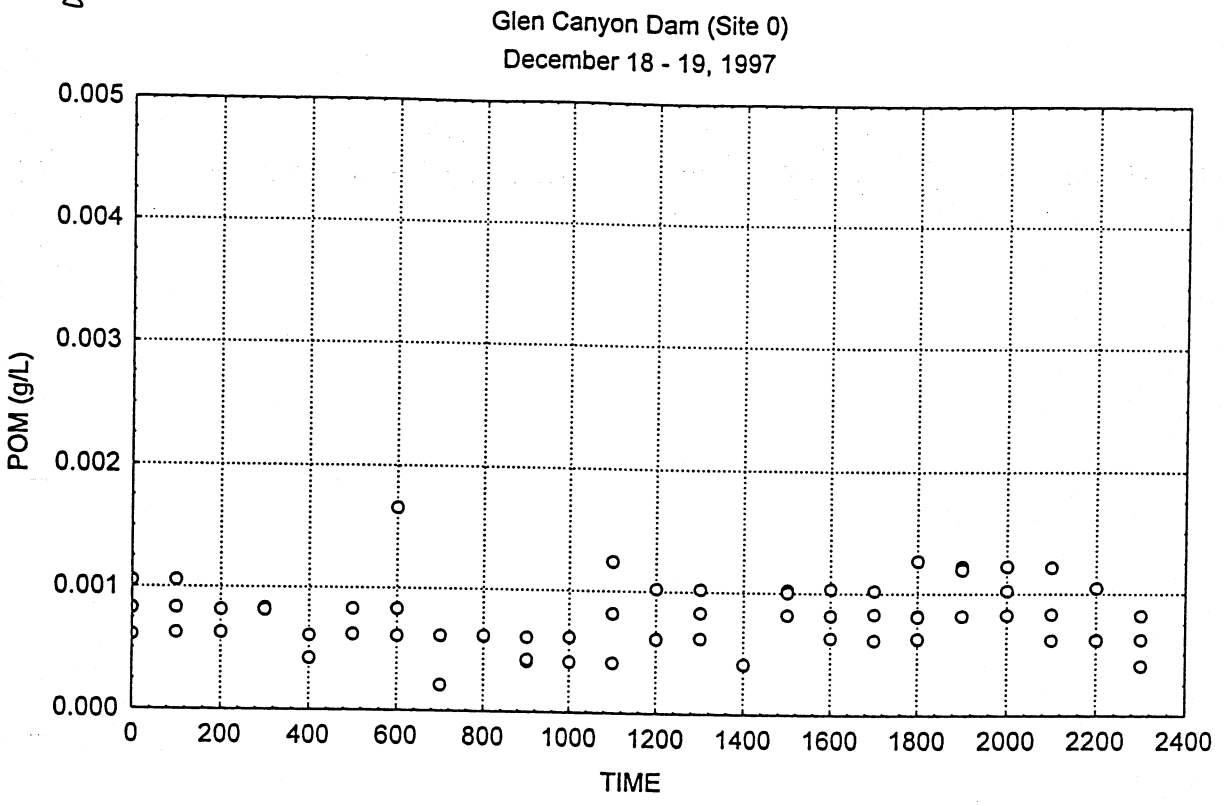

Glen Canyon Dam (Site 0)
December 18 - 19, 1997
POM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 21

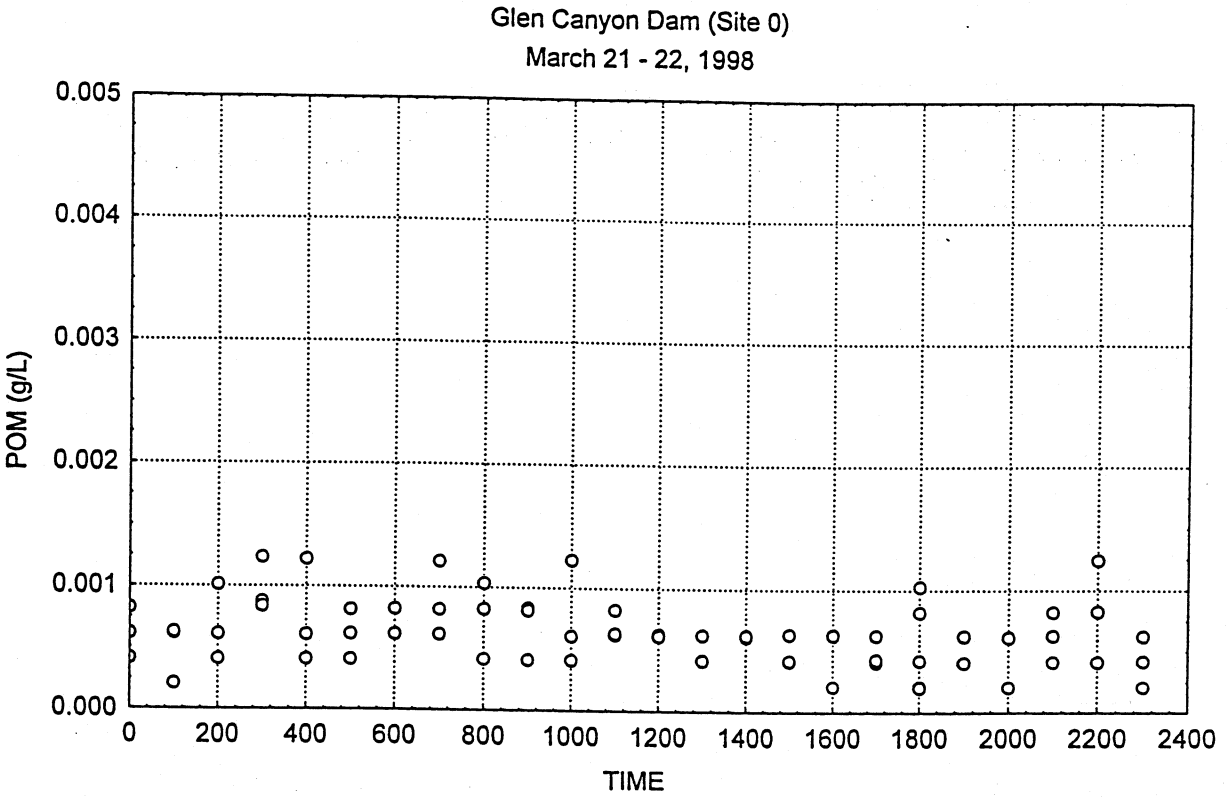

Glen Canyon Dam (Site 0)
March 21 - 22, 1998
POM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 22

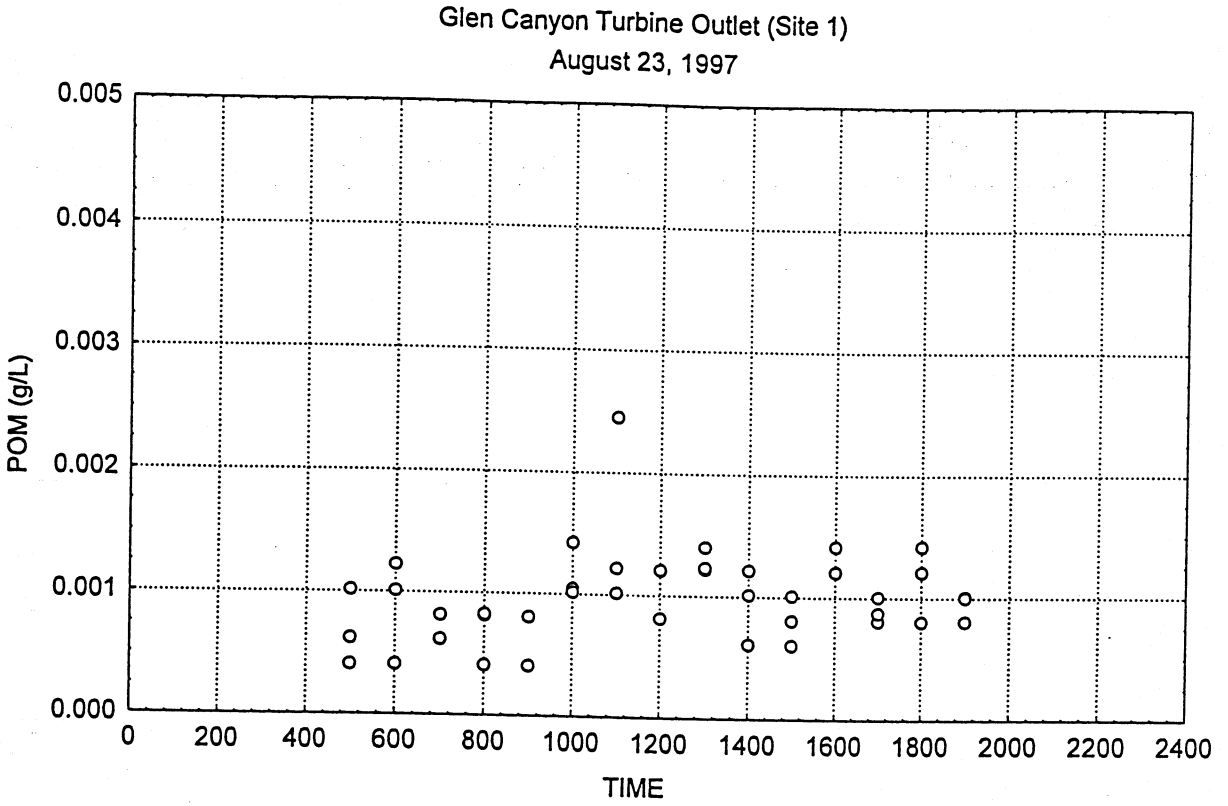

Glen Canyon Turbine Outlet (Site 1)
August 23, 1997
POM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 23

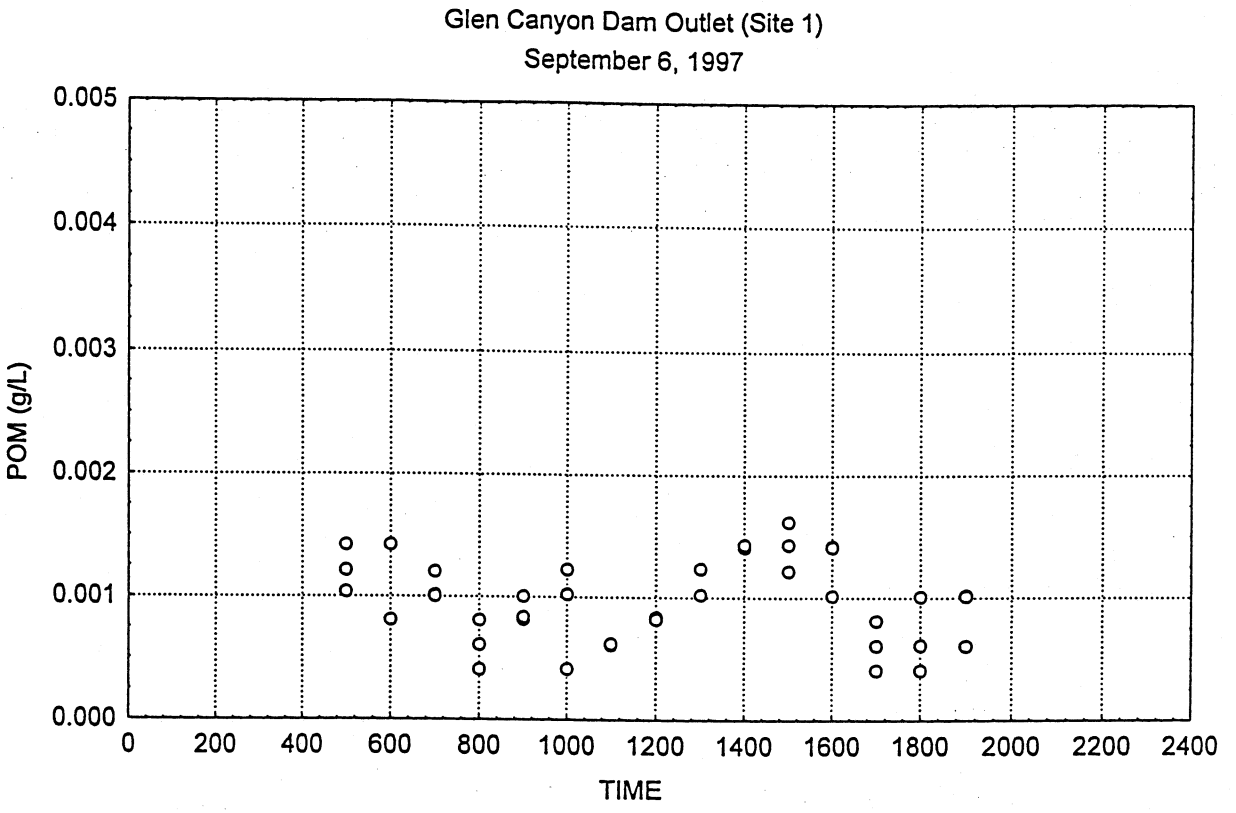

Glen Canyon Dam Outlet (Site 1)
September 6, 1997
POM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 24

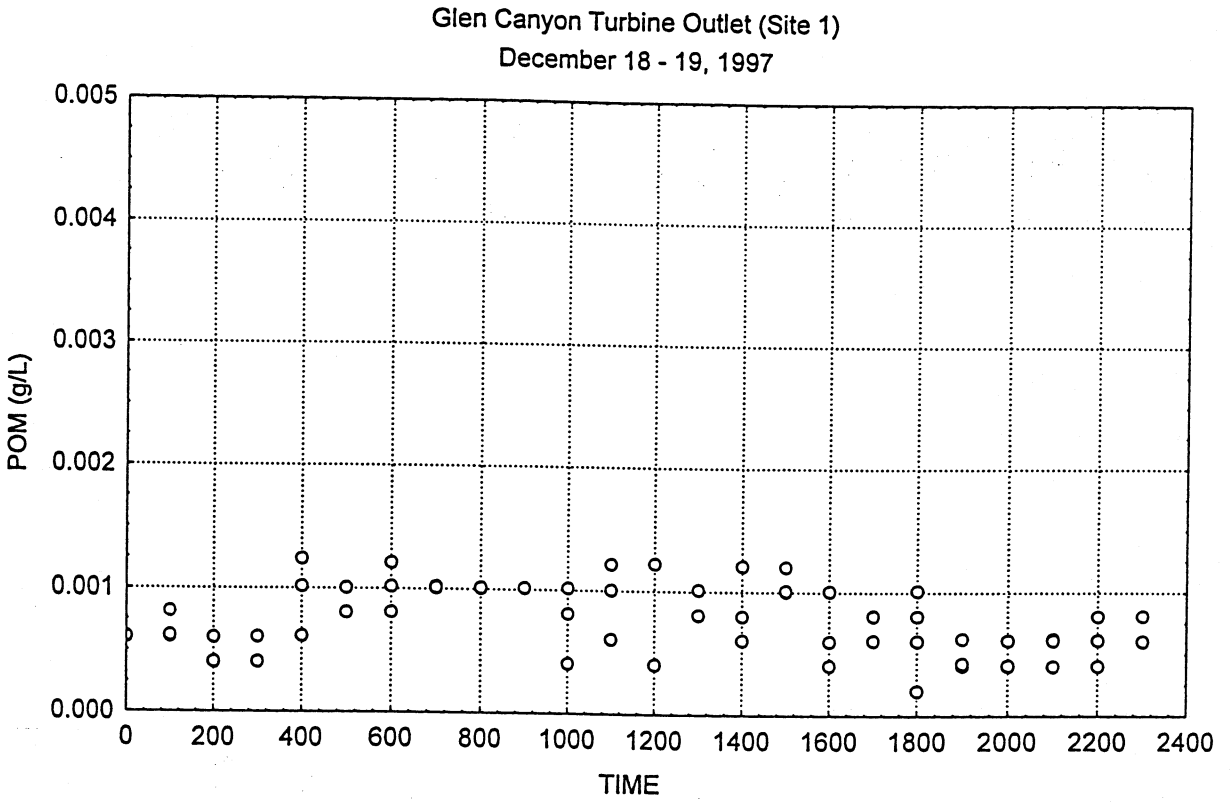

Glen Canyon Turbine Outlet (Site 1)
December 18 - 19, 1997
POM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 25

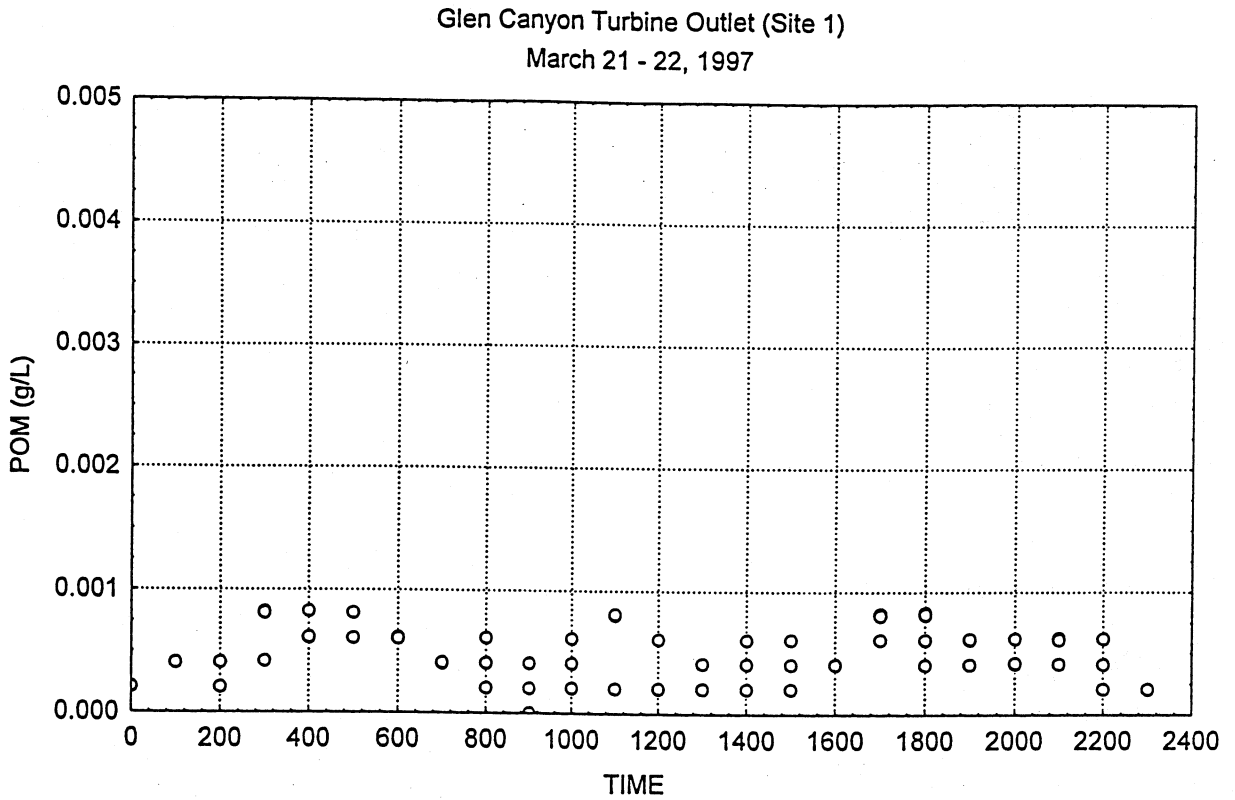

Glen Canyon Turbine Outlet (Site 1)
March 21 - 22, 1997
POM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 26

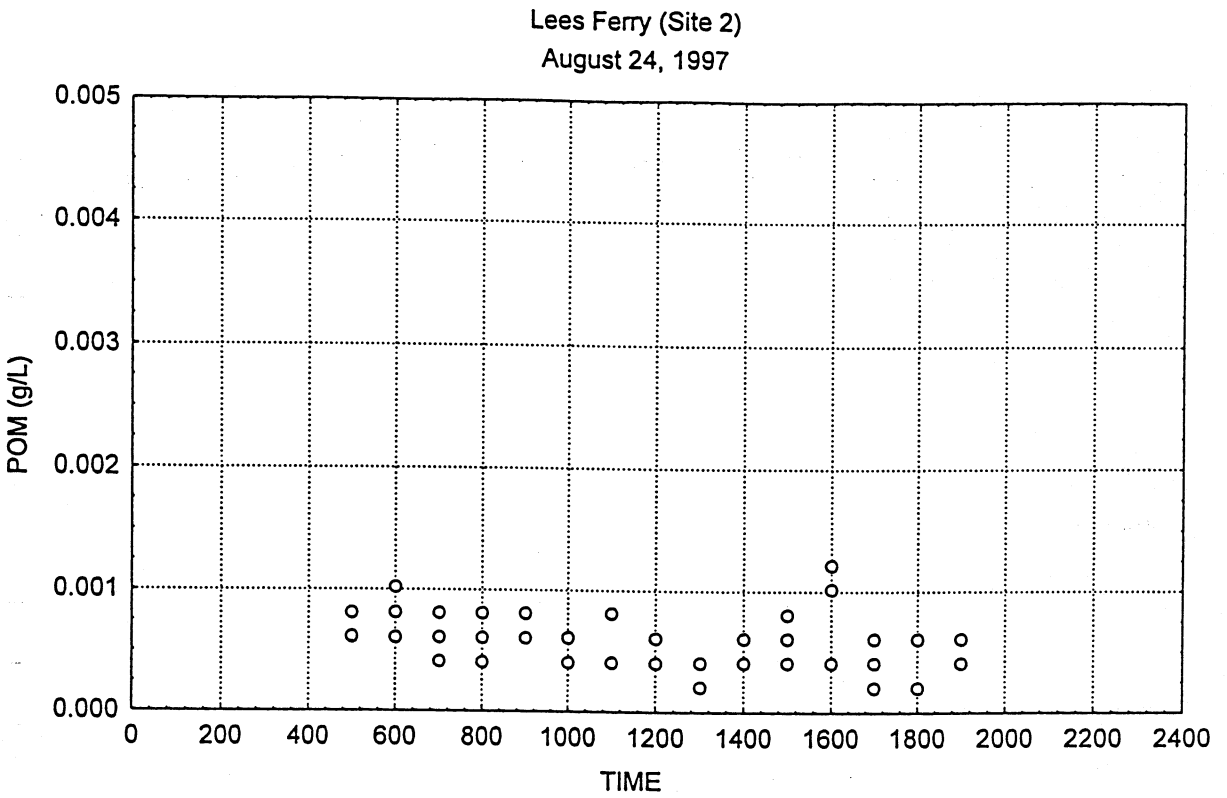

Lees Ferry (Site 2)
August 24, 1997
POM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 27

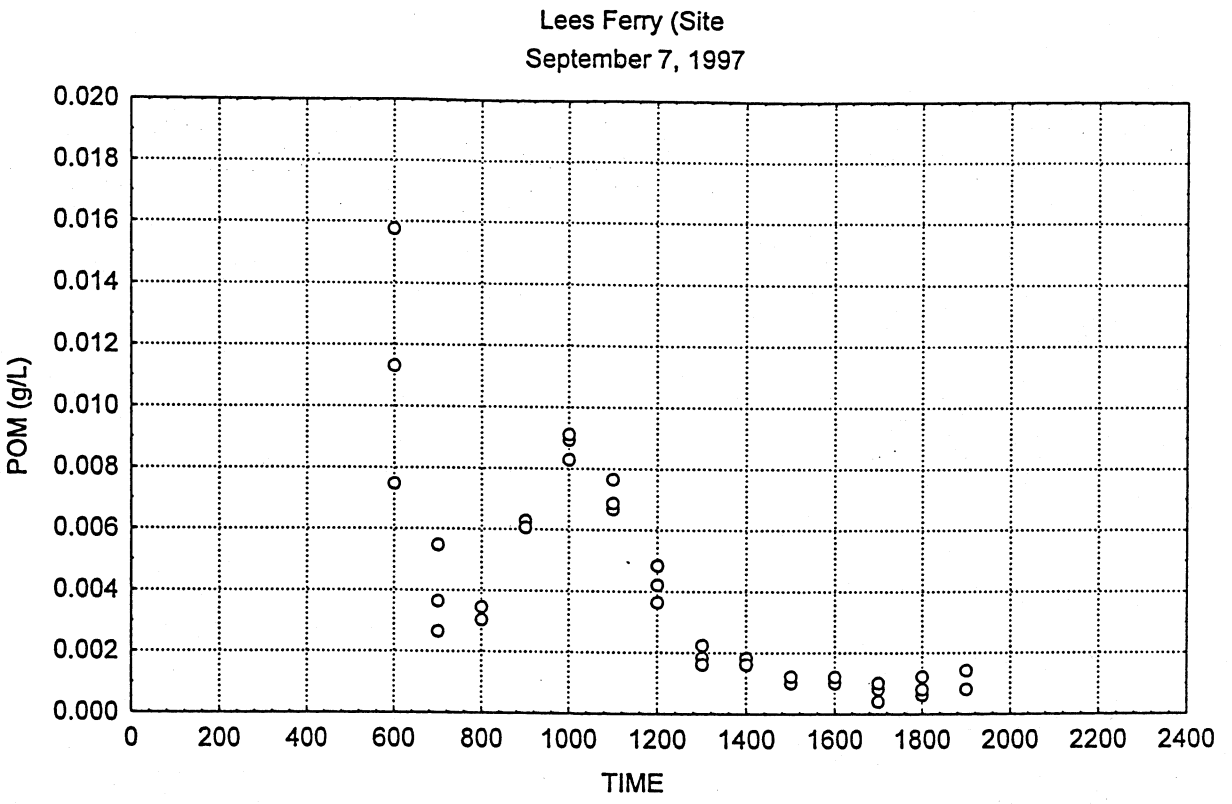

Lees Ferry (Site
September 7, 1997
POM (g/L)
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 28

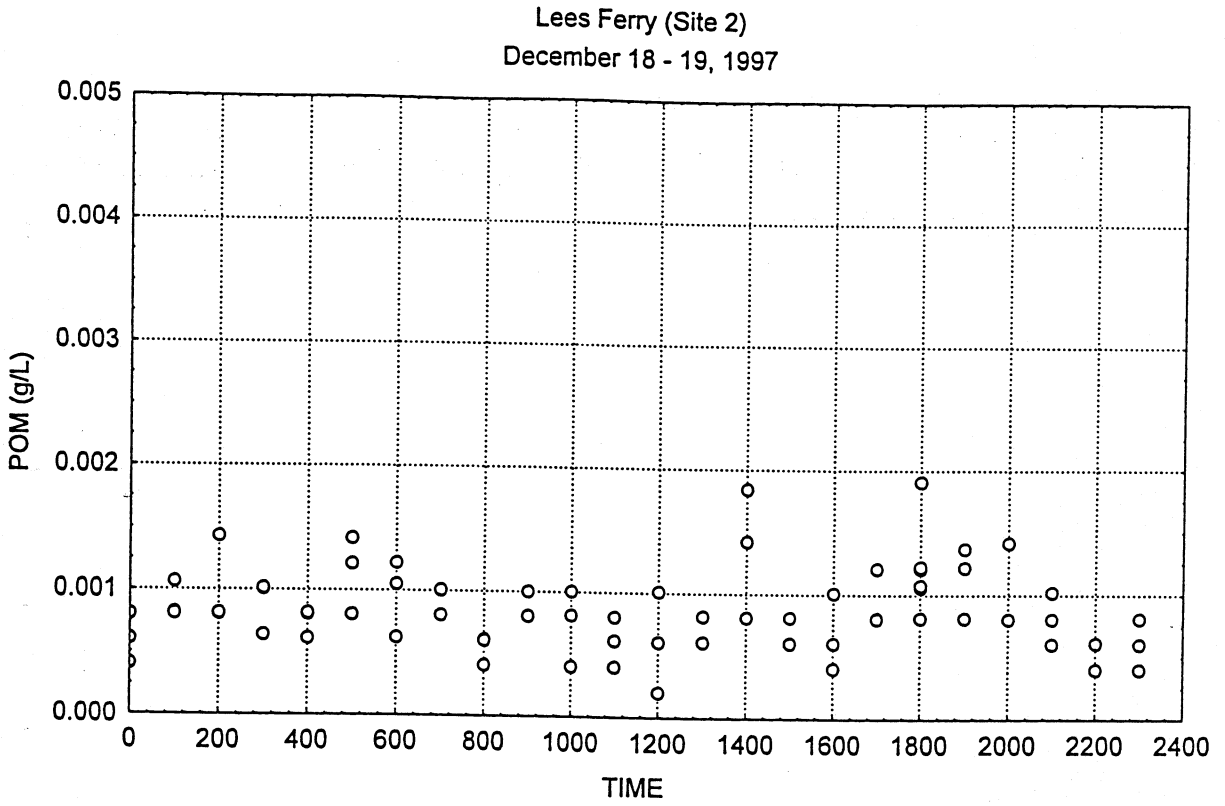

Lees Ferry (Site 2)
December 18 - 19, 1997
POM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 29

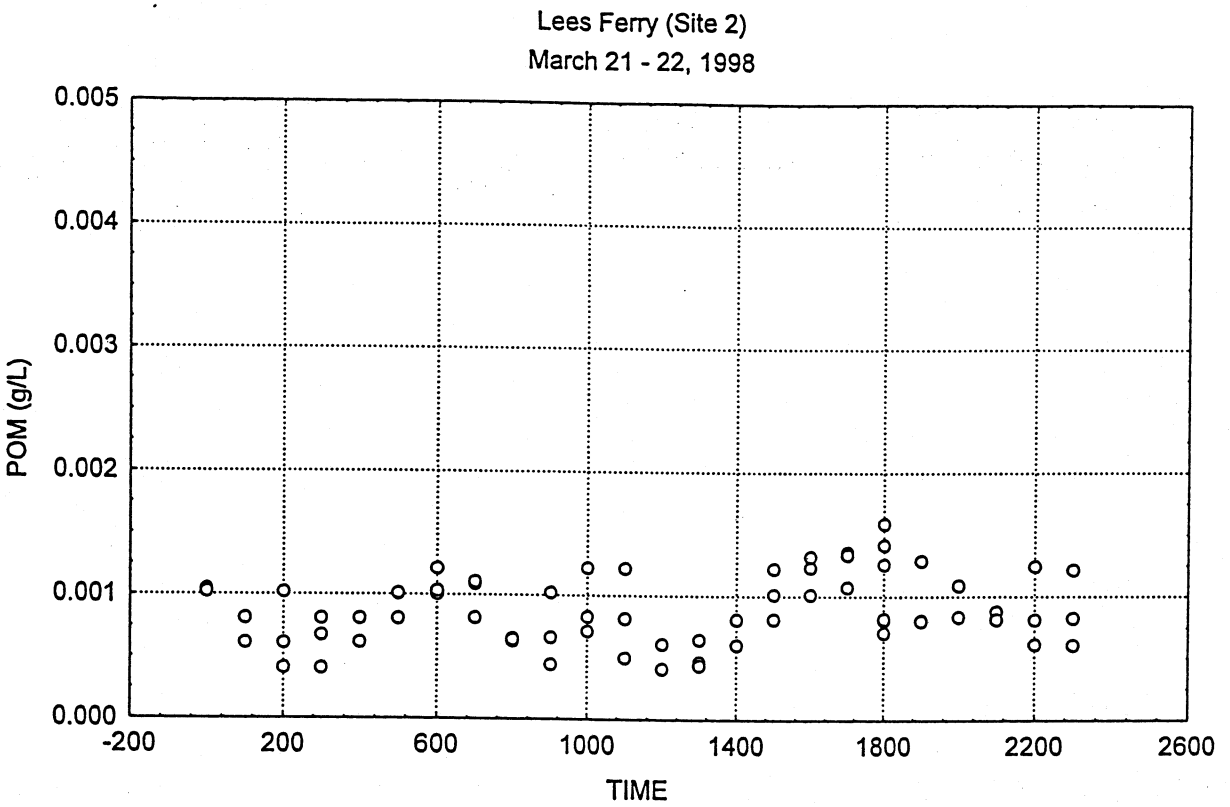

Lees Ferry (Site 2)
March 21 - 22, 1998
POM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
-200
200
600
1000
1400
1800
2200
2600
TIME

Fig 30

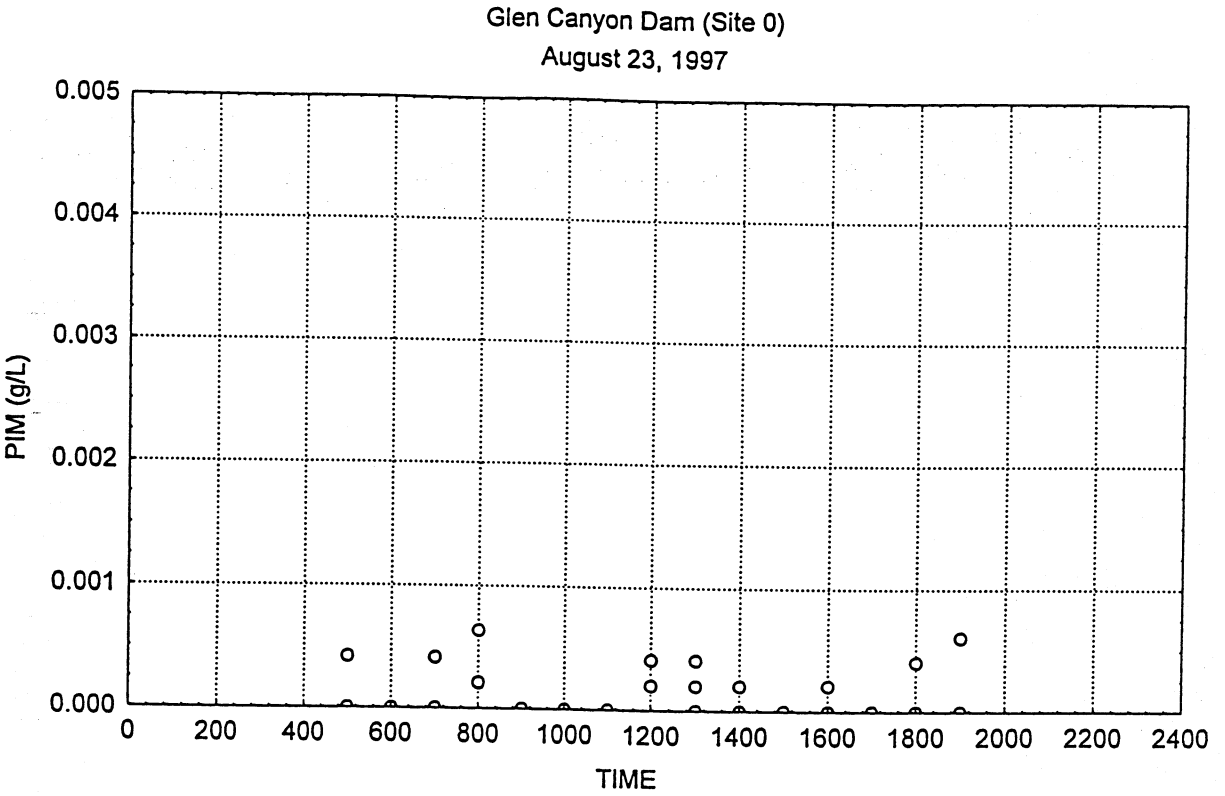

Glen Canyon Dam (Site 0)
August 23, 1997
PIM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 31

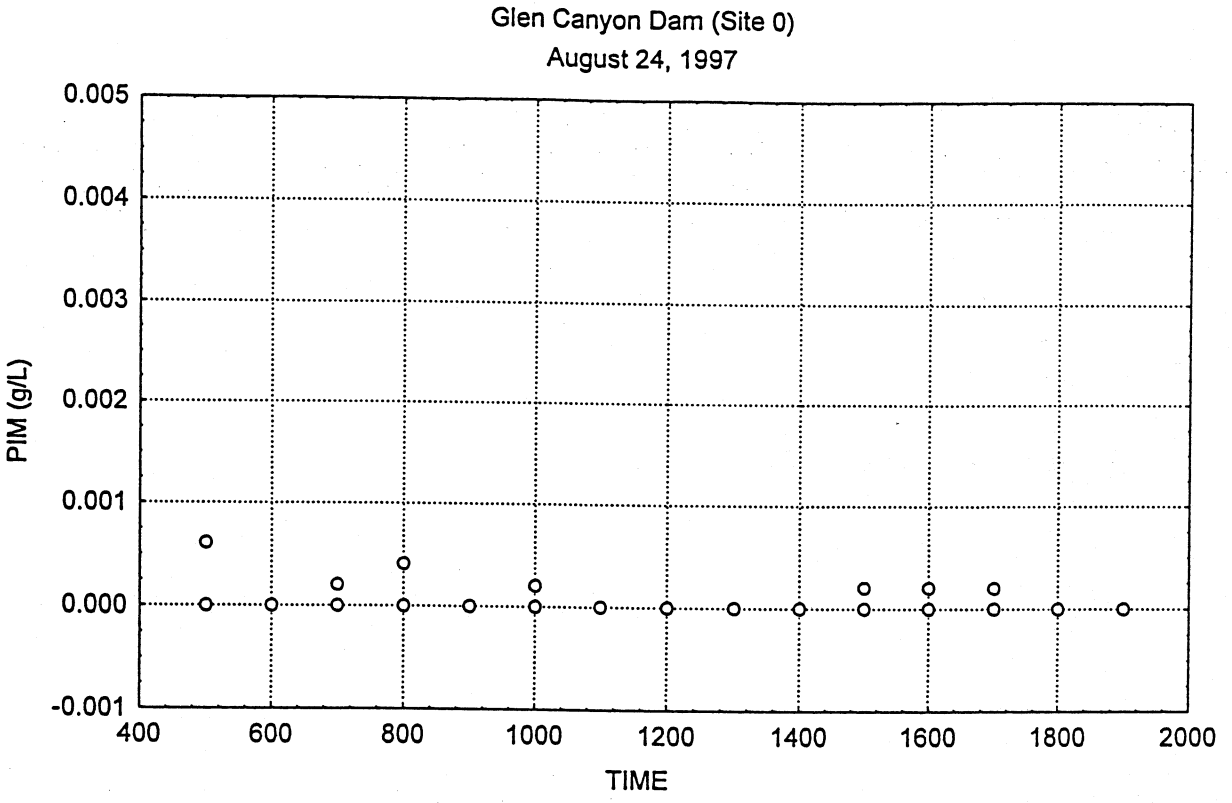

Glen Canyon Dam (Site 0)
August 24, 1997
PIM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
-0.001
400
600
800
1000
1200
1400
1600
1800
2000
TIME

Fig 32

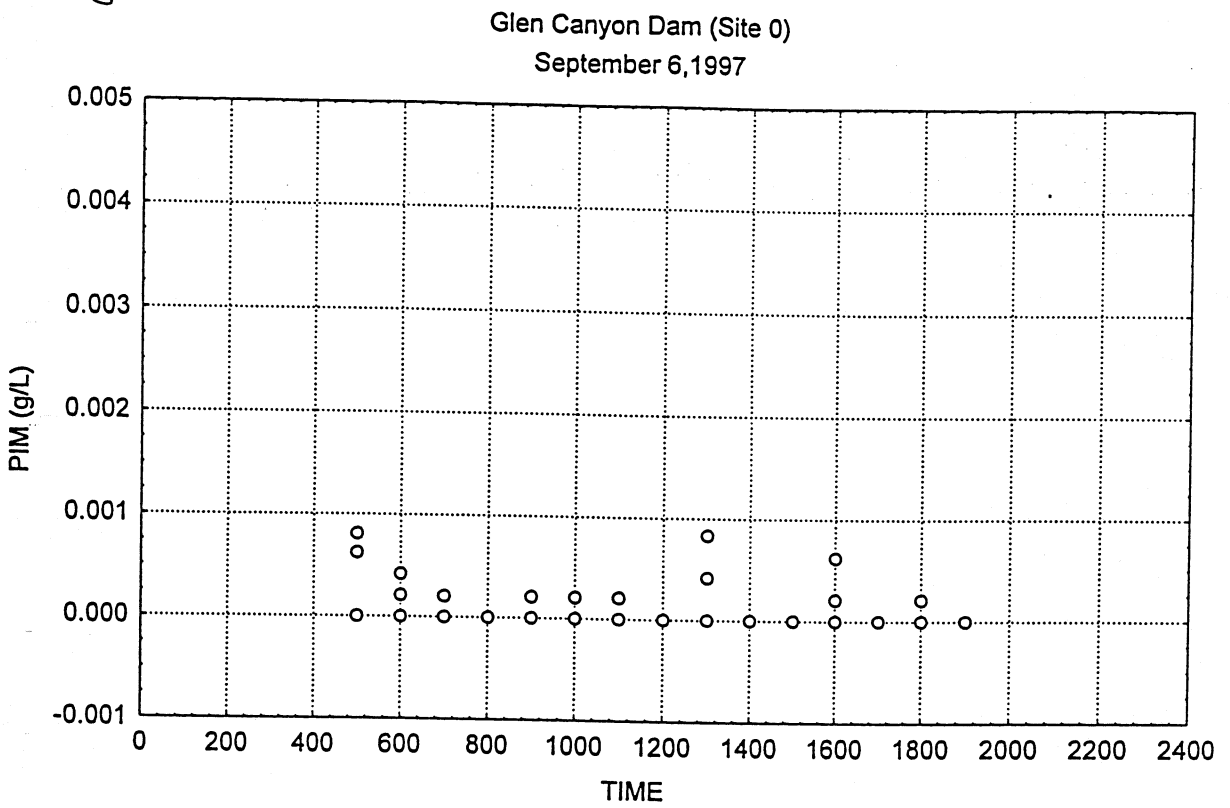

Glen Canyon Dam (Site 0)
September 6,1997
PIM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
-0.001
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 33

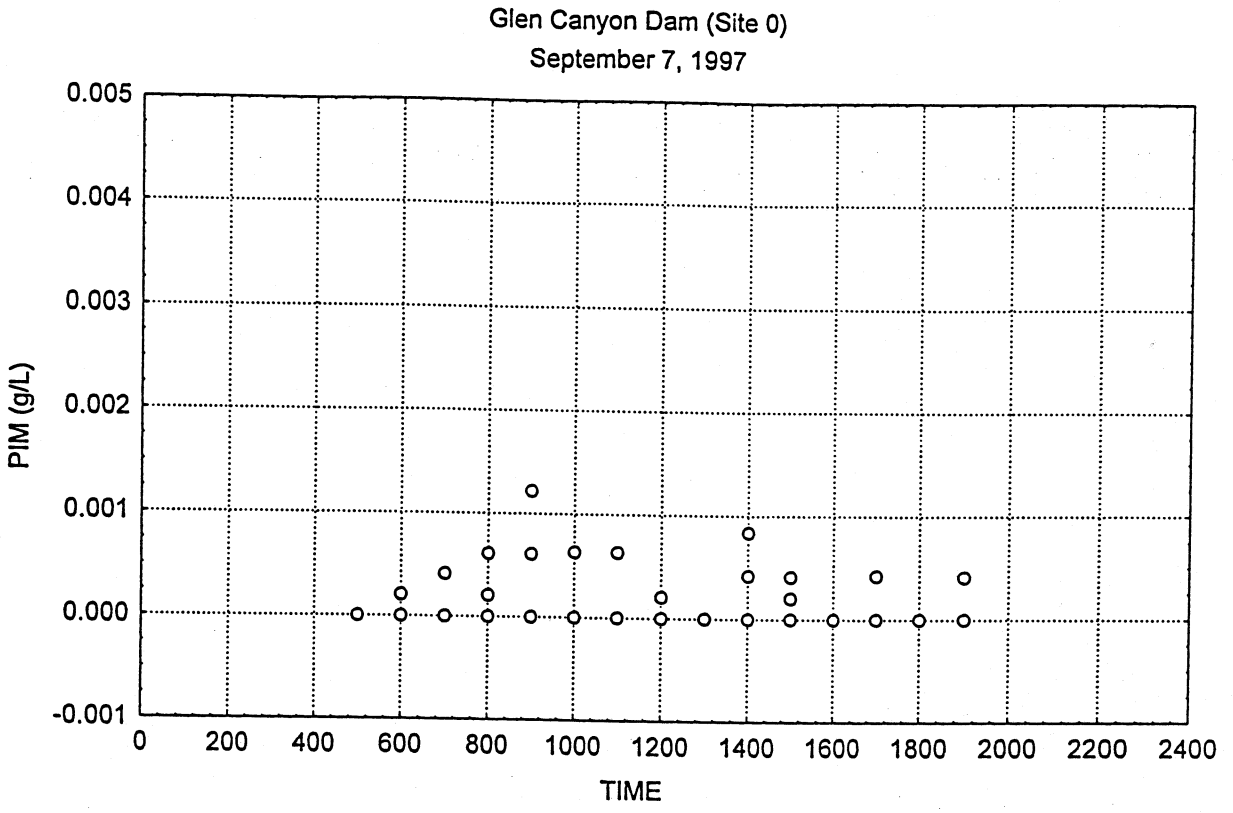

Glen Canyon Dam (Site 0)
September 7, 1997
PIM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
-0.001
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 34

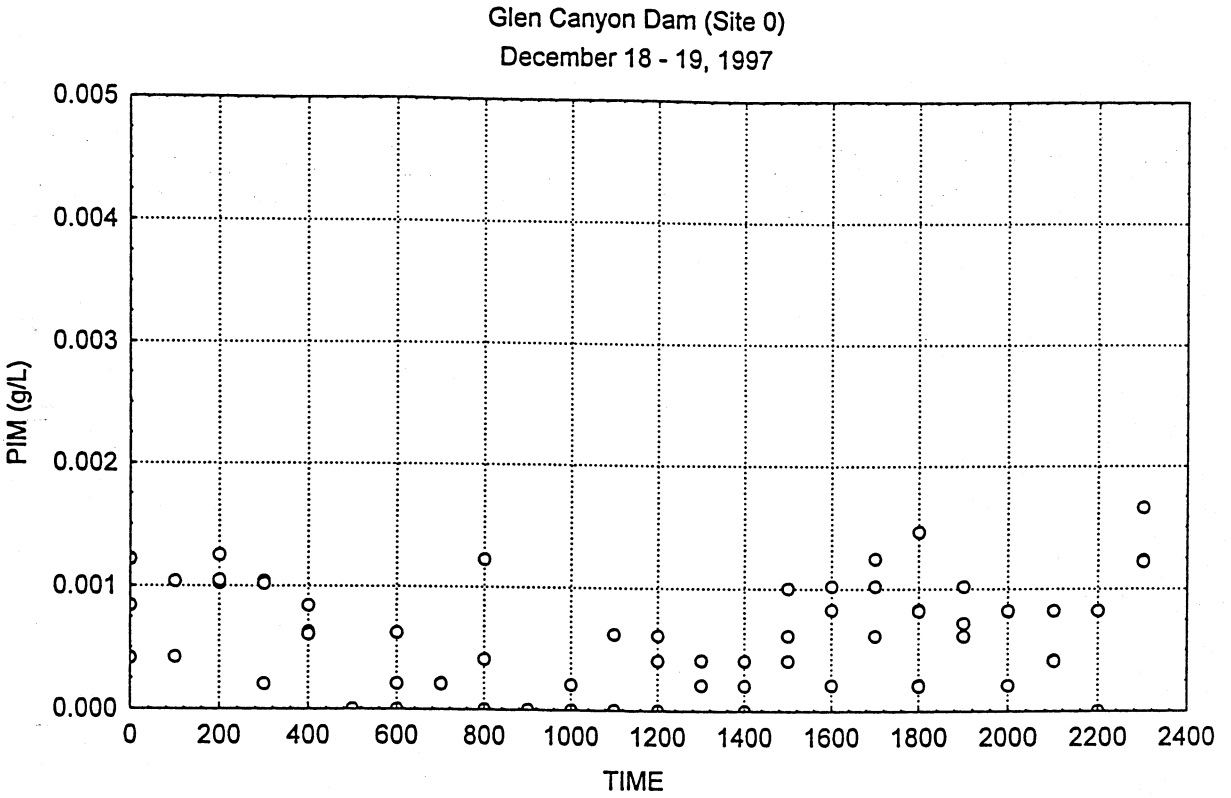

Glen Canyon Dam (Site 0)
December 18 - 19, 1997
PIM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 35

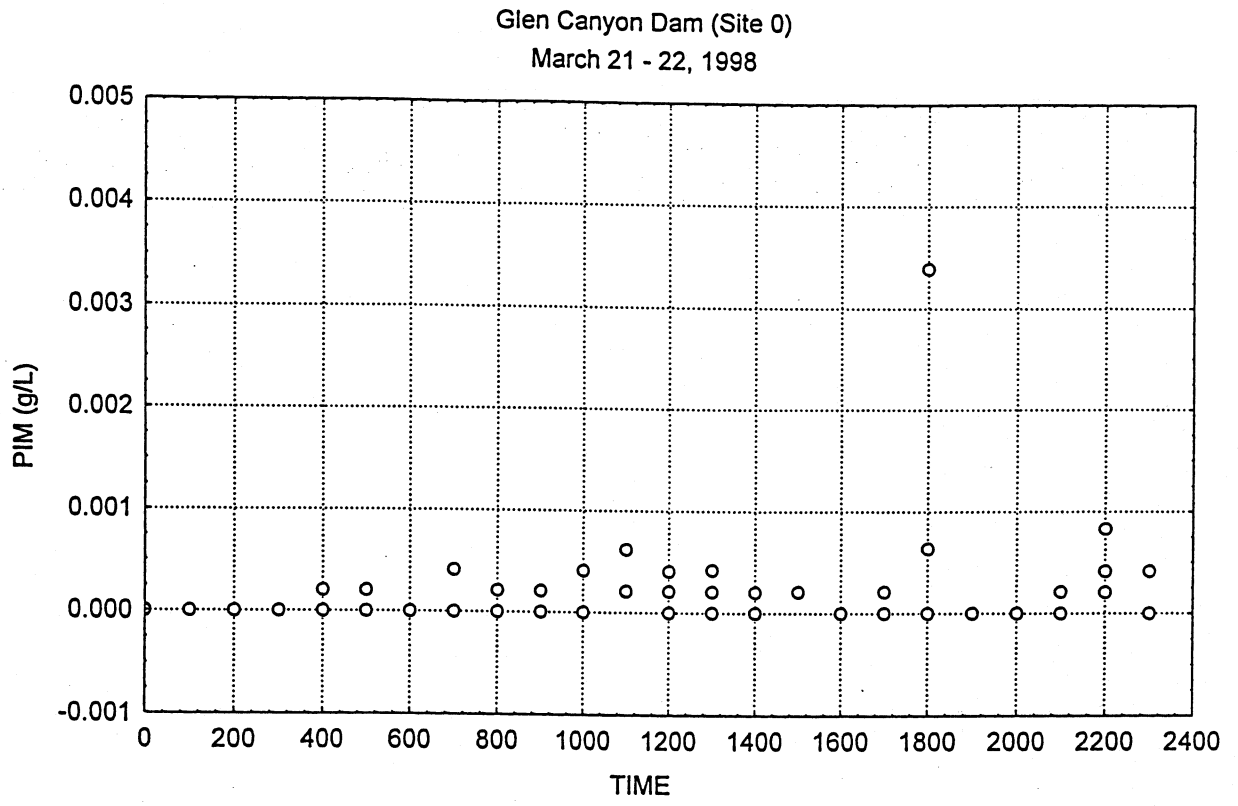

Glen Canyon Dam (Site 0)
March 21 - 22, 1998
PIM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
-0.001
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 36

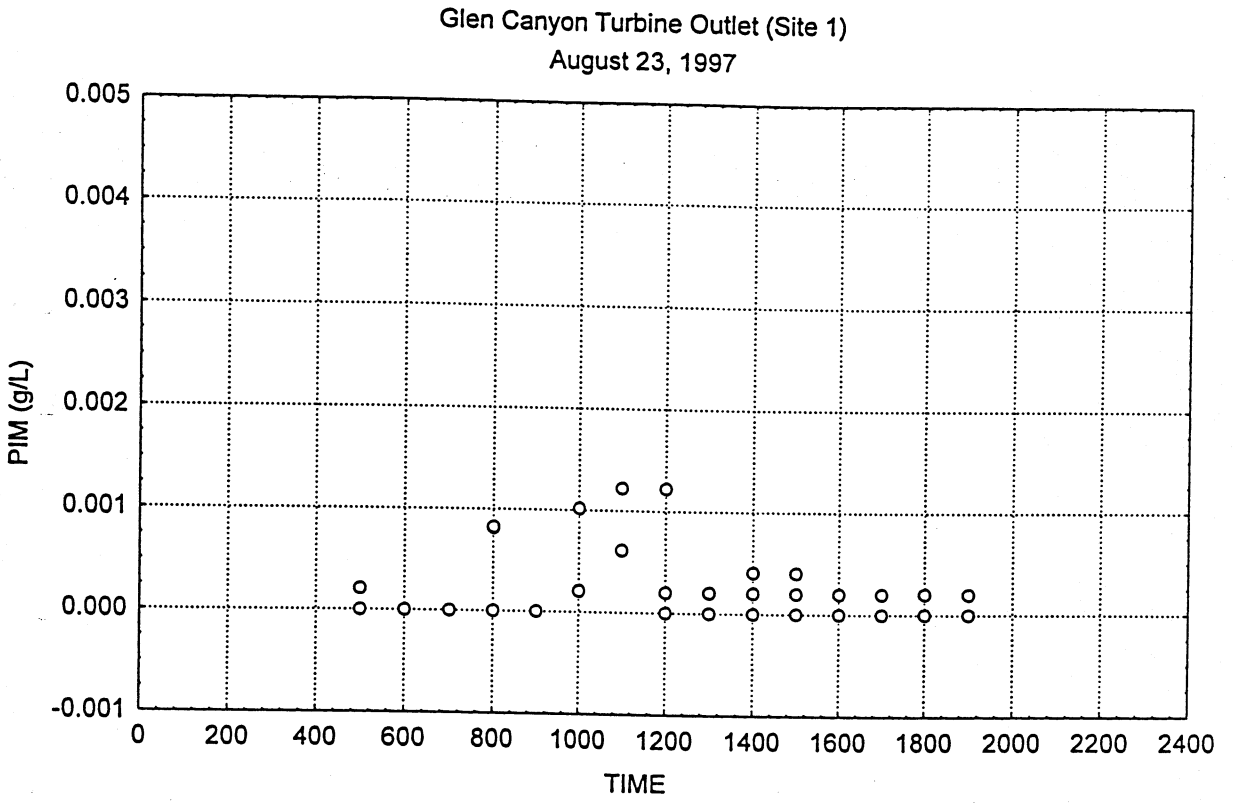

Glen Canyon Turbine Outlet (Site 1)
August 23, 1997
PIM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
-0.001
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 37

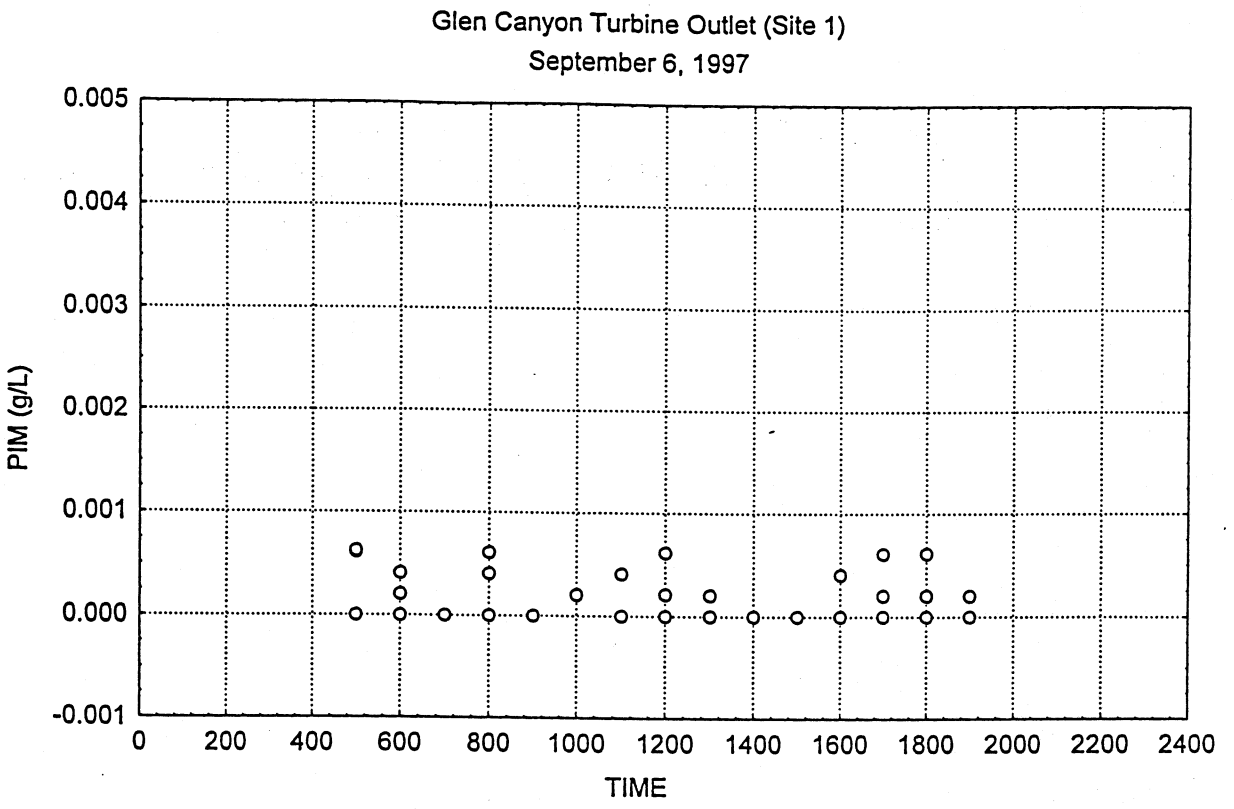

Glen Canyon Turbine Outlet (Site 1)
September 6, 1997
PIM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
-0.001
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 38

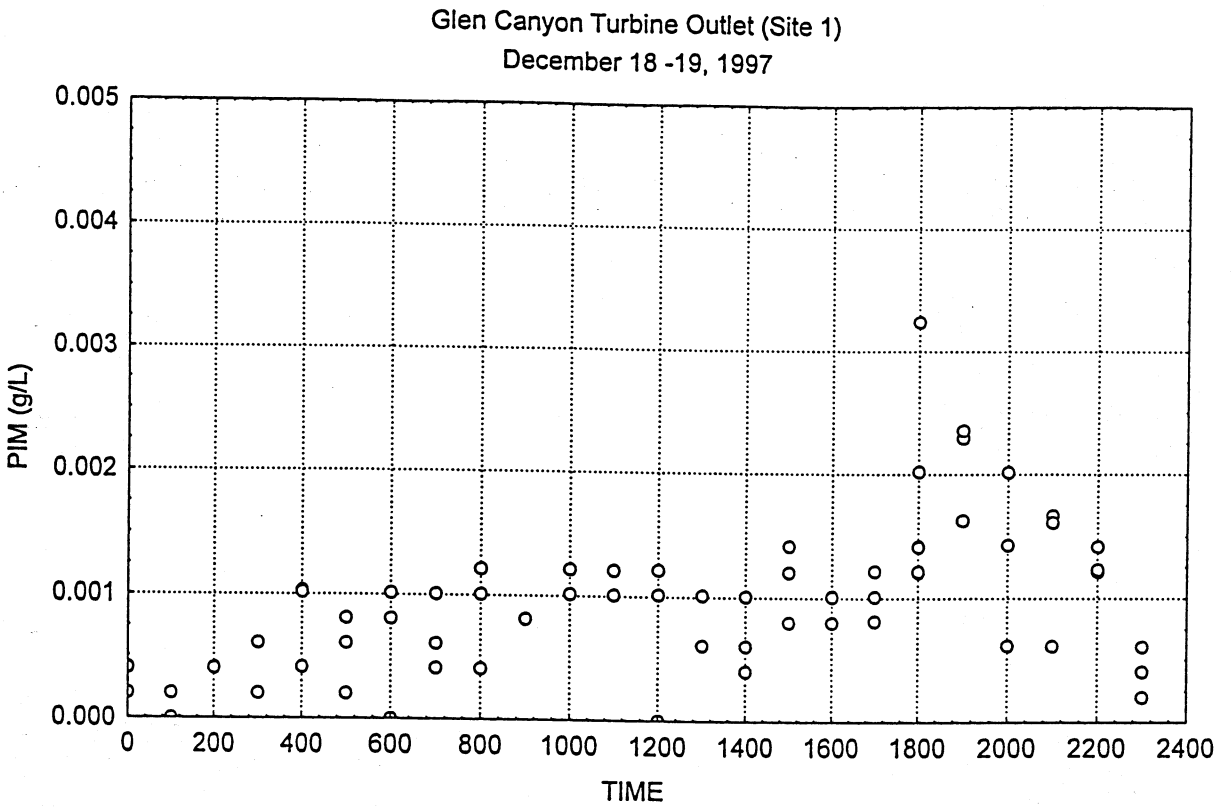

Glen Canyon Turbine Outlet (Site 1)
December 18 -19, 1997
PIM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 39

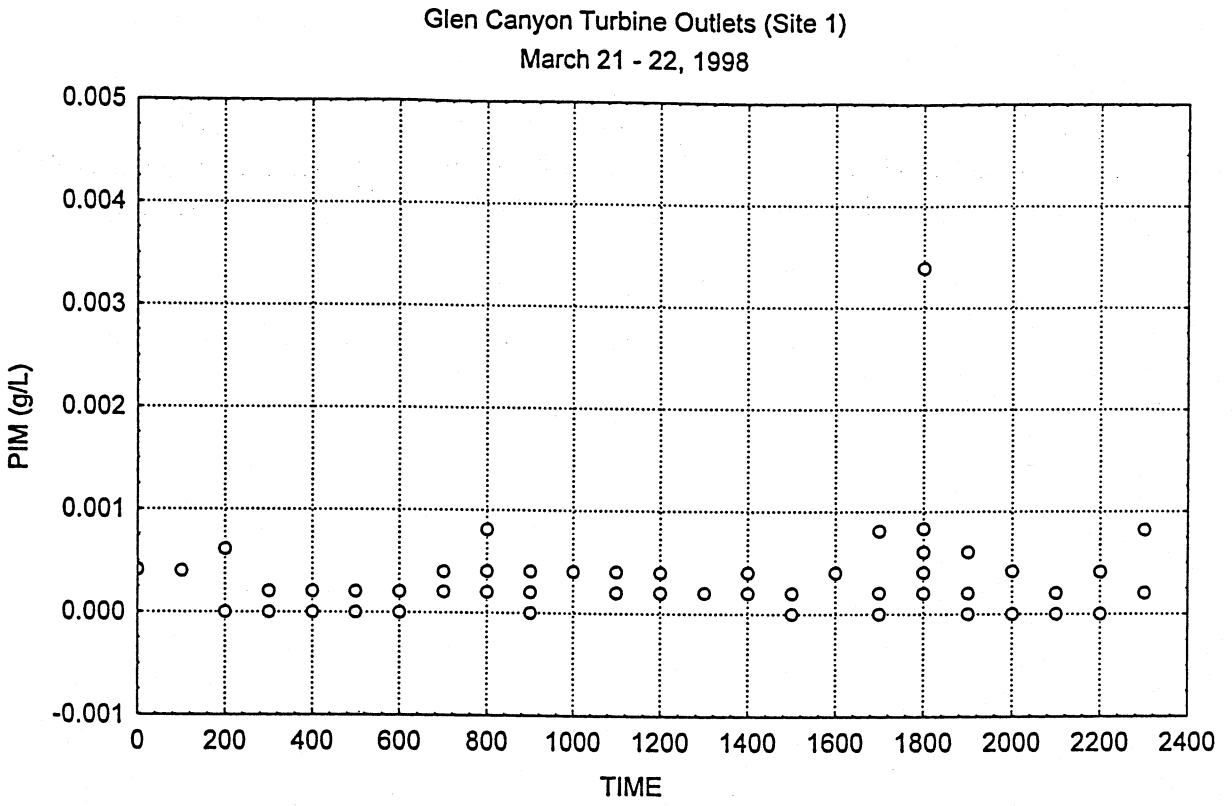

Glen Canyon Turbine Outlets (Site 1)
March 21 - 22, 1998
PIM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
-0.001
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 40

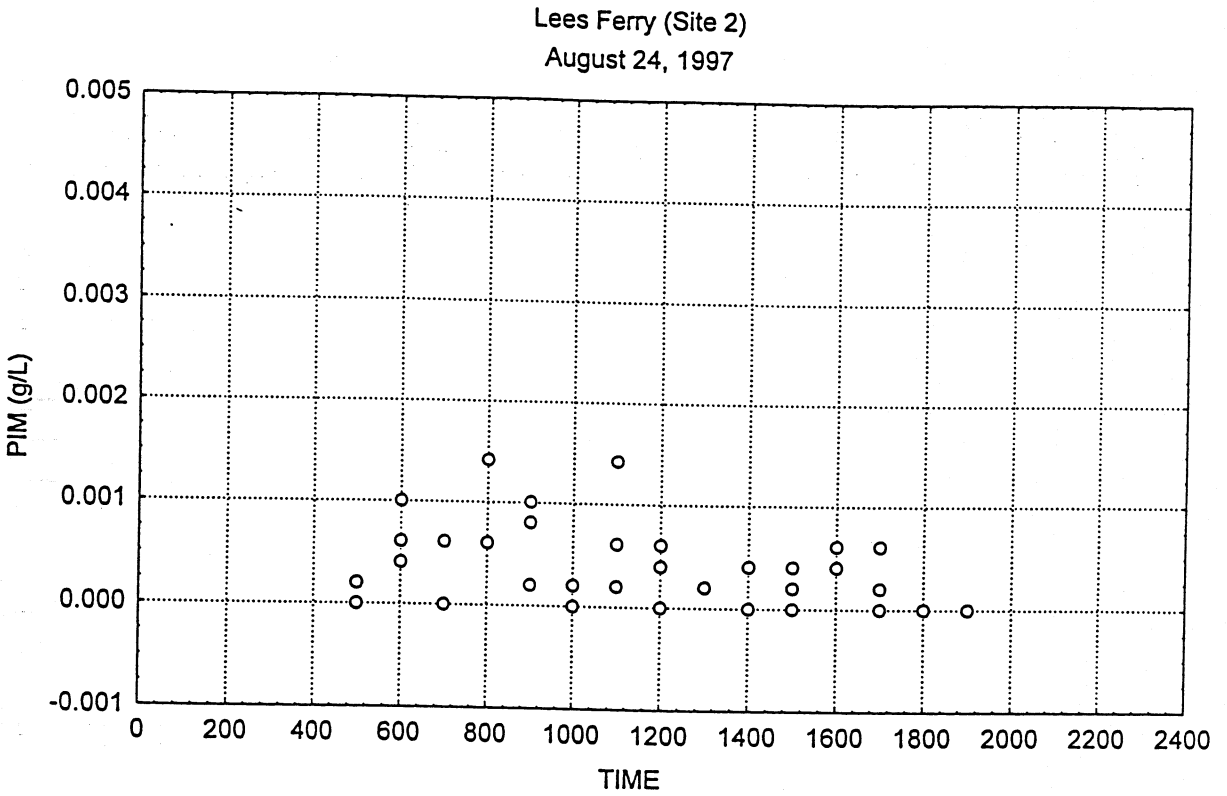

Lees Ferry (Site 2)
August 24, 1997
PIM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
-0.001
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 41

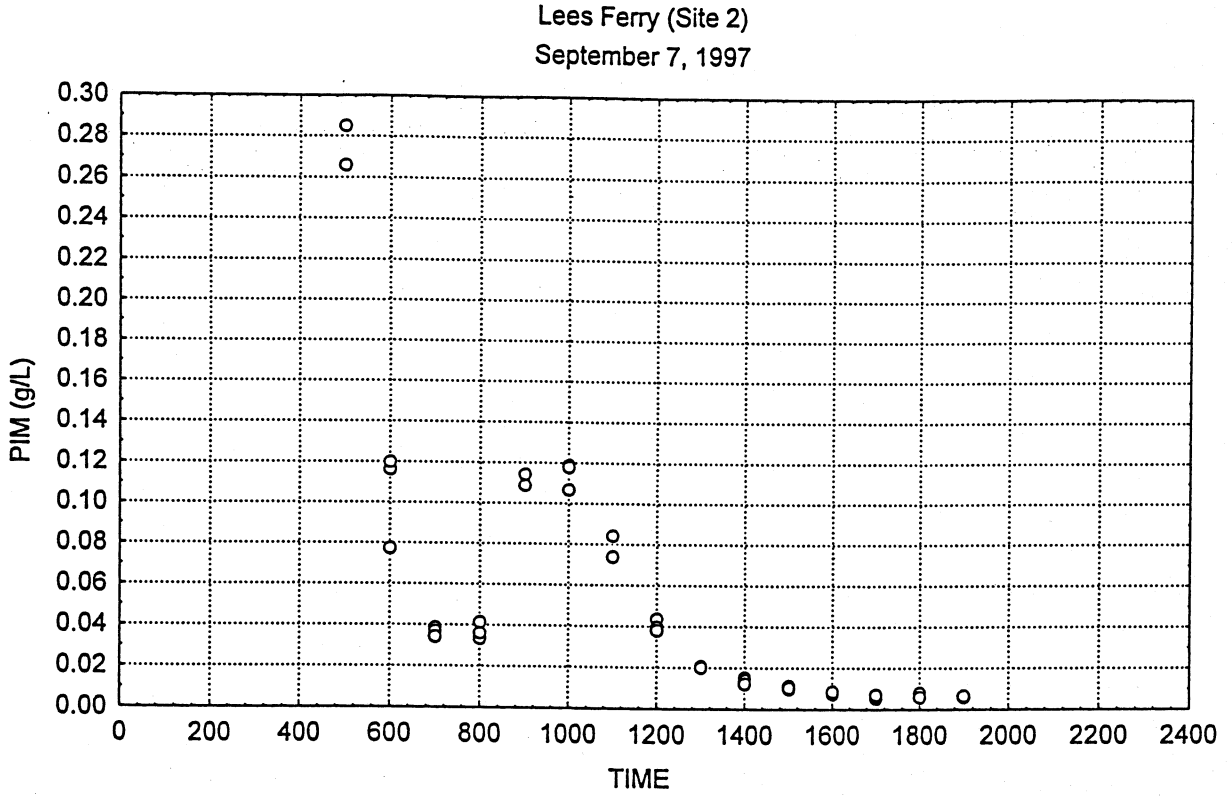

Lees Ferry (Site 2)
September 7, 1997
PIM (g/L)
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 42

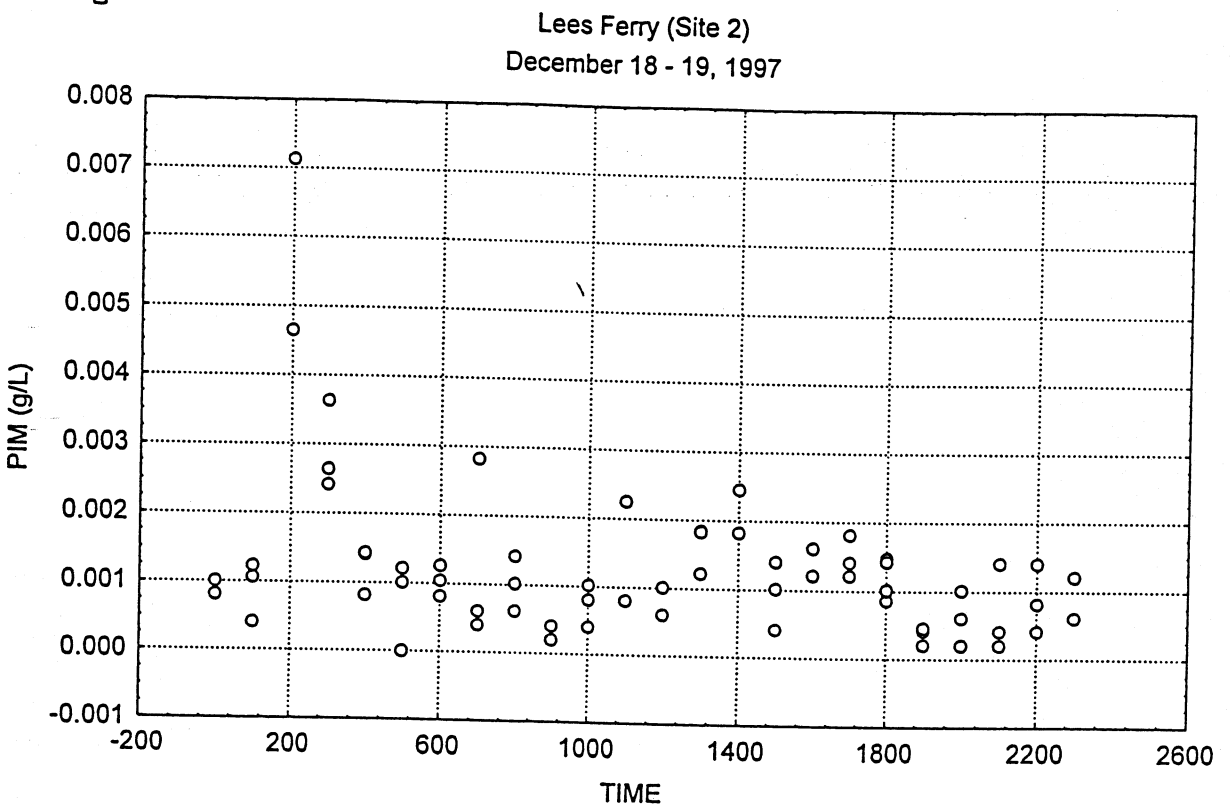

Lees Ferry (Site 2)
December 18 - 19, 1997
PIM (g/L)
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
-0.001
-200
200
600
1000
1400
1800
2200
2600
TIME

Fig 43

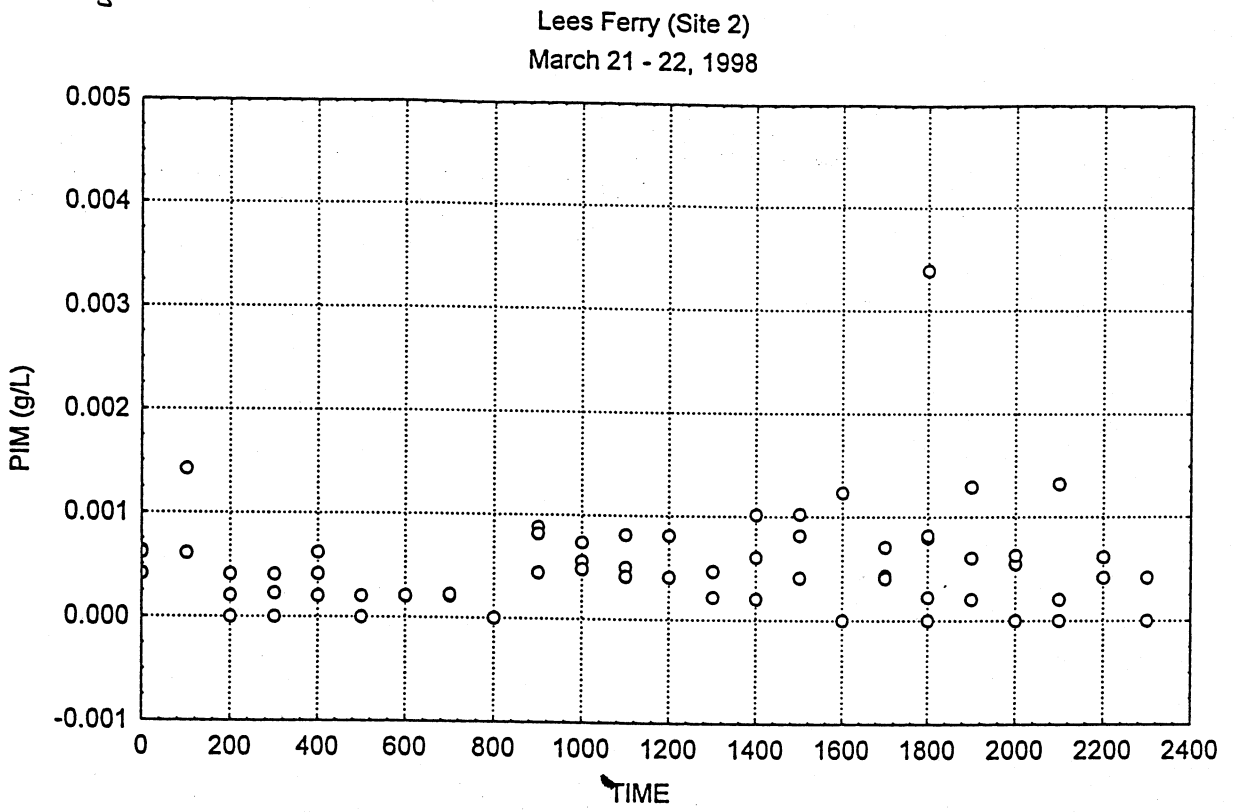

Lees Ferry (Site 2)
March 21 - 22, 1998
PIM (g/L)
0.005
0.004
0.003
0.002
0.001
0.000
-0.001
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TIME

Fig 44

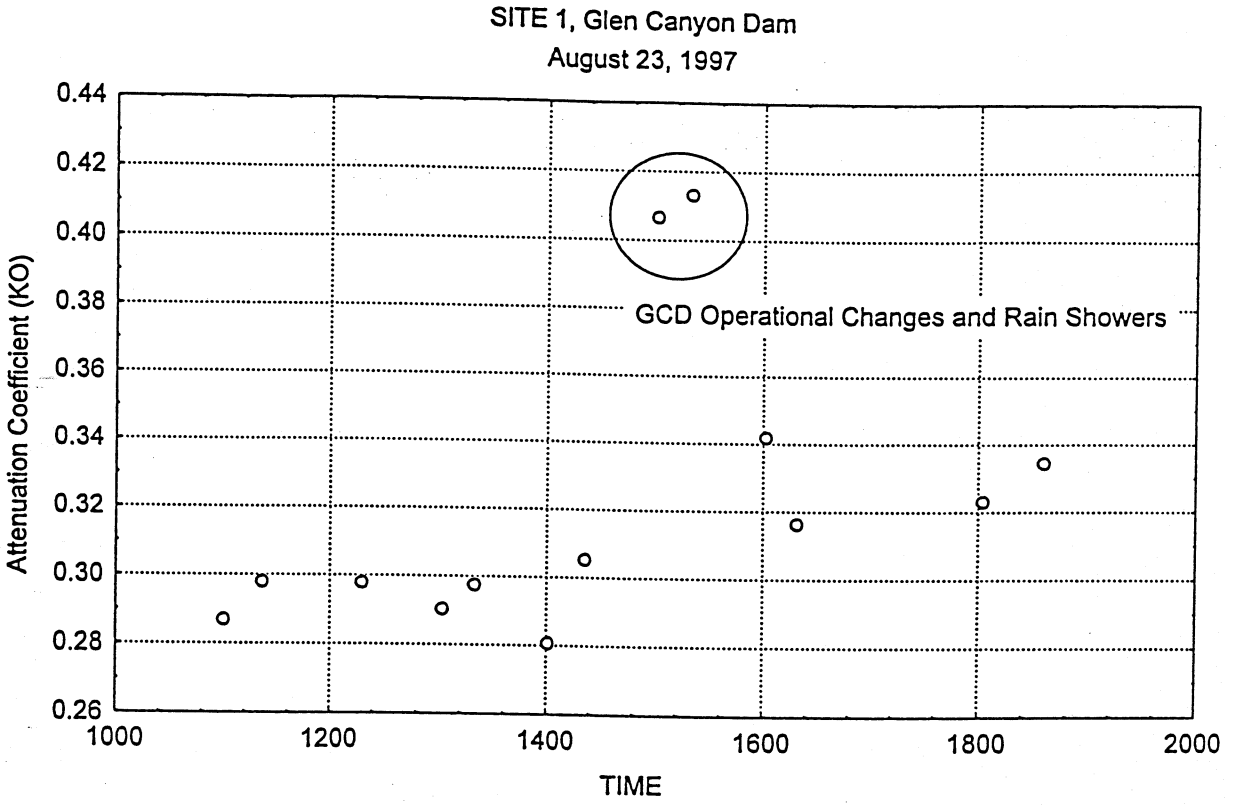

SITE 1, Glen Canyon Dam
August 23, 1997
Attenuation Coefficient (KO)
0.44
0.42
0.40
0.38
0.36
0.34
0.32
0.30
0.28
0.26
1000
1200
1400
1600
1800
2000
TIME
GCD Operational Changes and Rain Showers

Fig 45

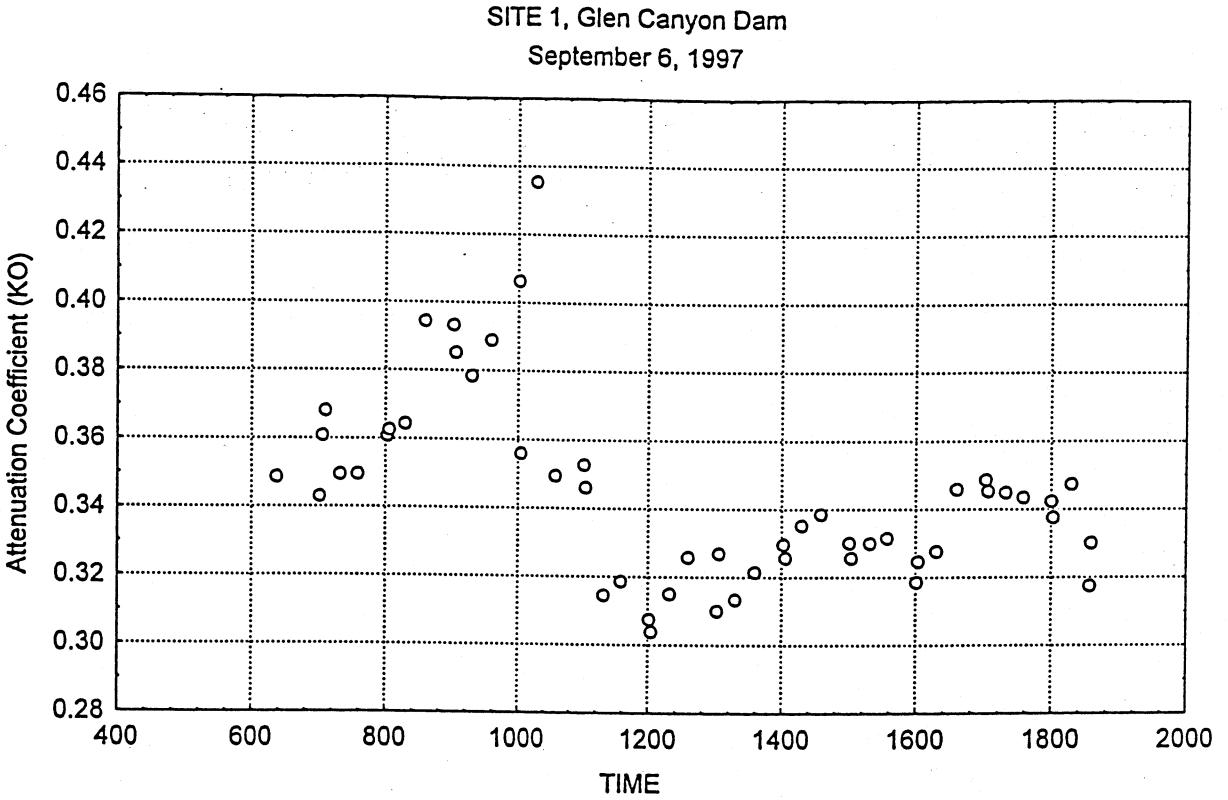

SITE 1, Glen Canyon Dam
September 6, 1997
Attenuation Coefficient (KO)
0.46
0.44
0.42
0.40
0.38
0.36
0.34
0.32
0.30
0.28
400
600
800
1000
1200
1400
1600
1800
2000
TIME

Fig 46

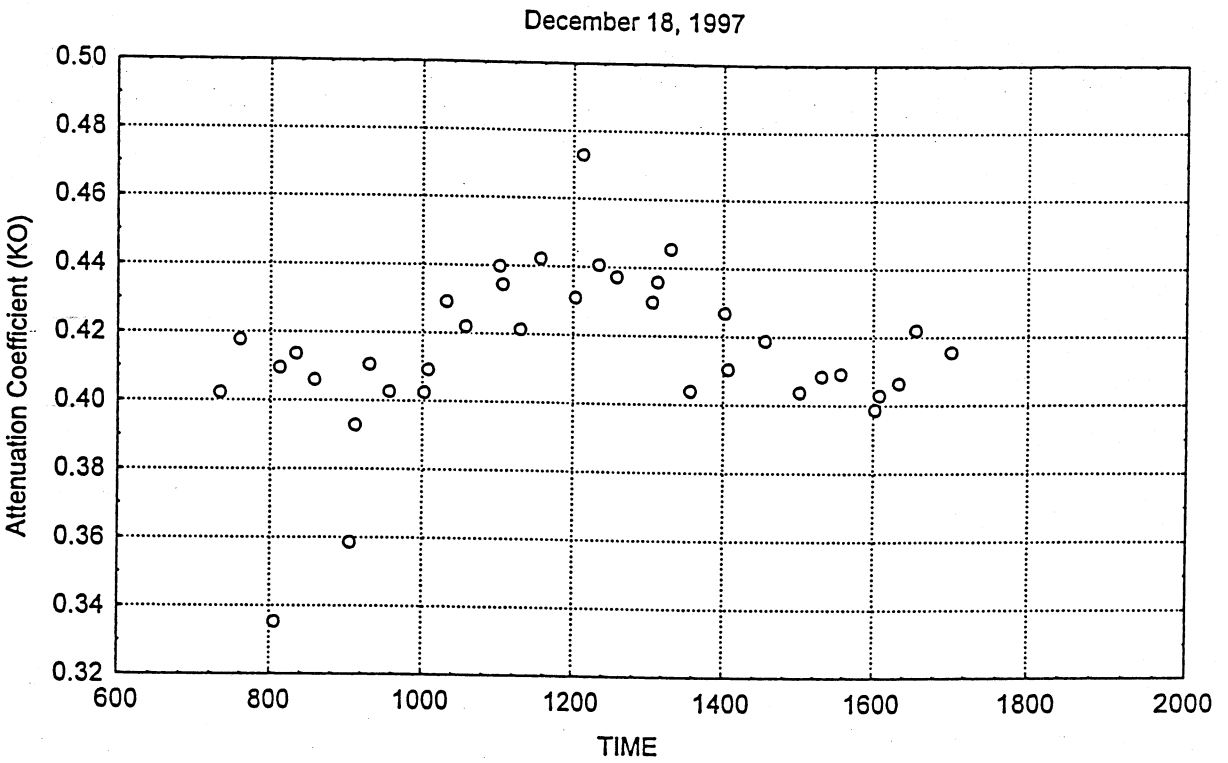

SITE 1, Glen Canyon Dam
December 18, 1997
Attenuation Coefficient (KO)
0.50
0.48
0.46
0.44
0.42
0.40
0.38
0.36
0.34
0.32
600
800
1000
1200
1400
1600
1800
2000
TIME

Fig 47

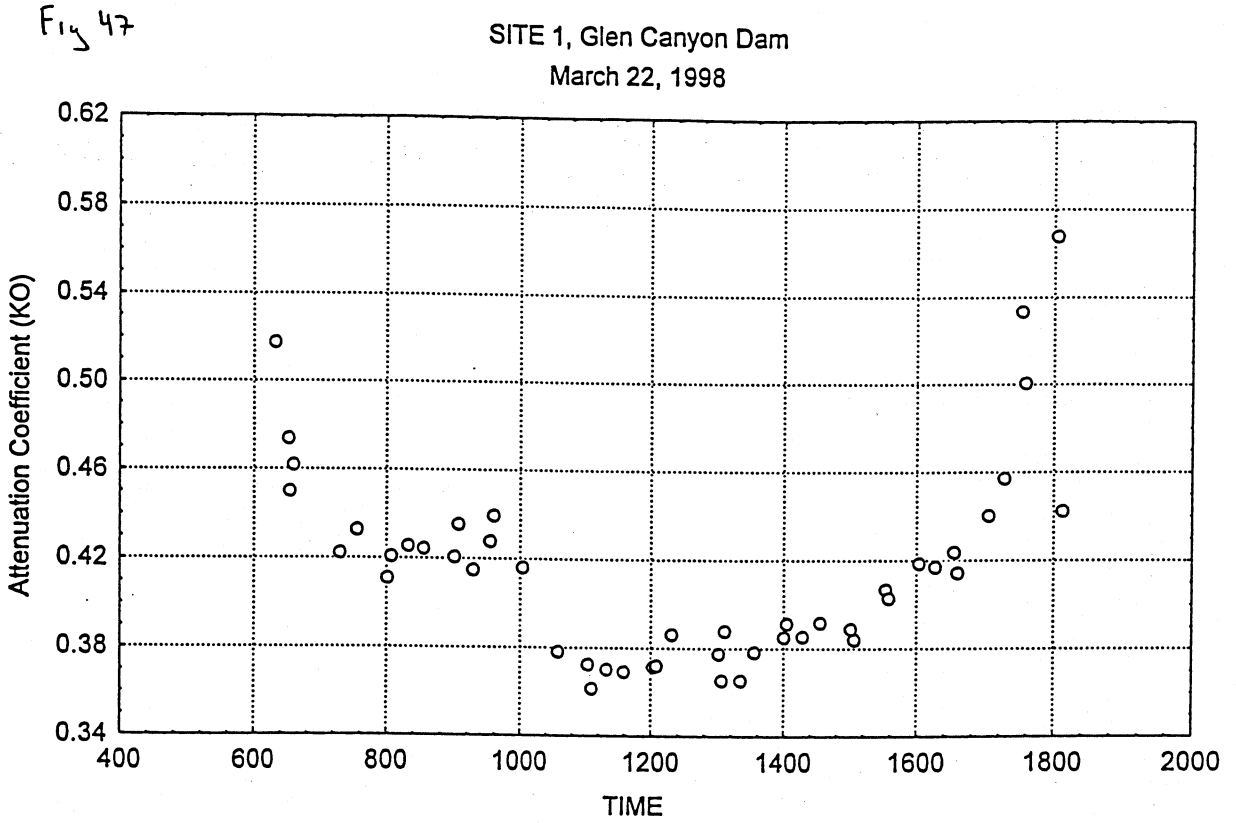

SITE 1, Glen Canyon Dam
March 22, 1998
Attenuation Coefficient (KO)
0.62
0.58
0.54
0.50
0.46
0.42
0.38
0.34
400
600
800
1000
1200
1400
1600
1800
2000
TIME

Fig 48

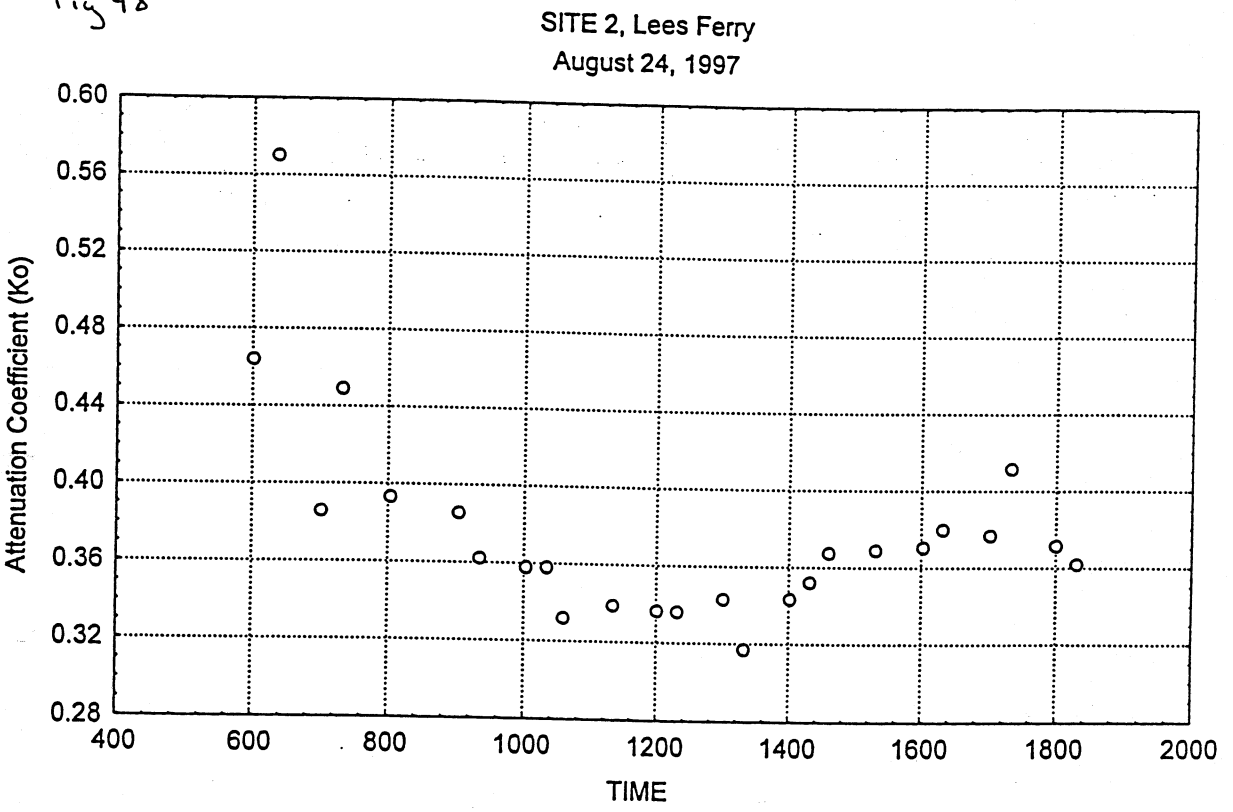

SITE 2, Lees Ferry
August 24, 1997
Attenuation Coefficient (Ko)
0.60
0.56
0.52
0.48
0.44
0.40
0.36
0.32
0.28
400
600
800
1000
1200
1400
1600
1800
2000
TIME

Fig 49

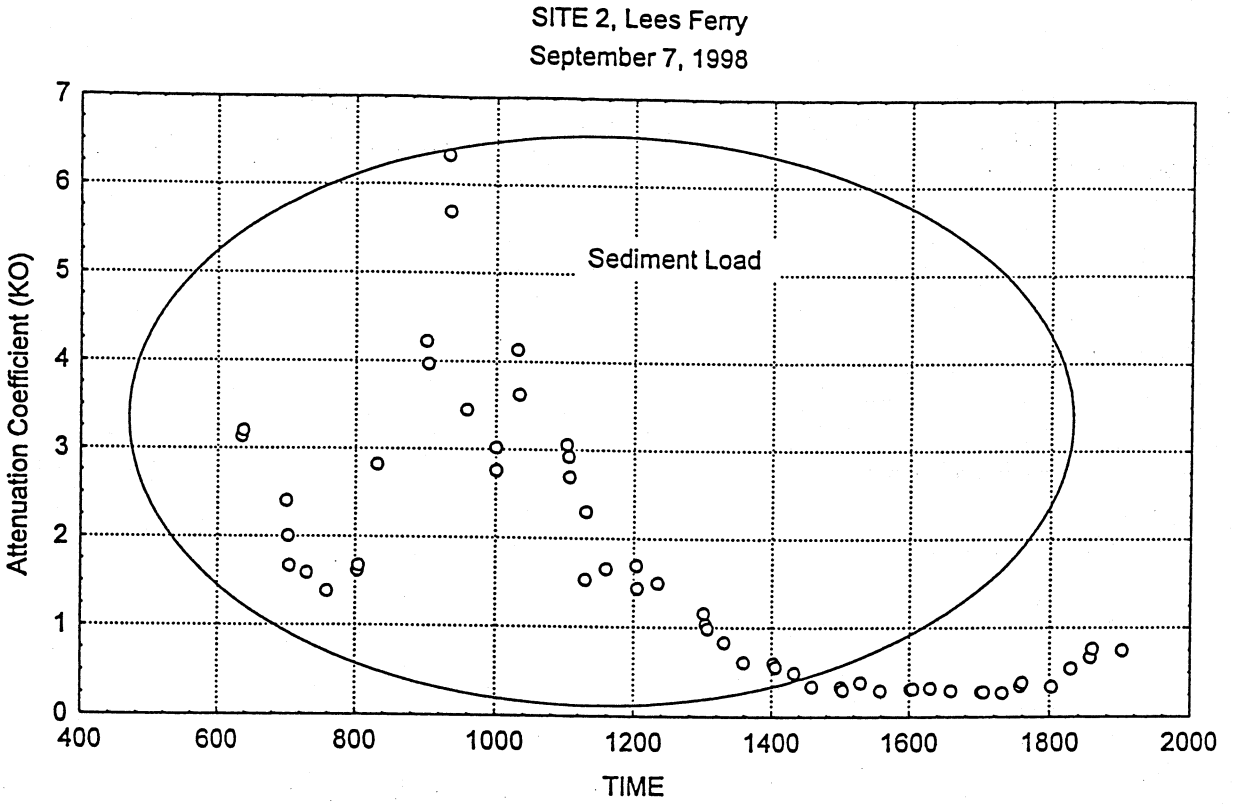

SITE 2, Lees Ferry
September 7, 1998
Sediment Load
Attenuation Coefficient (KO)
TIME
0
1
2
3
4
5
6
7
400
600
800
1000
1200
1400
1600
1800
2000

Fig 50

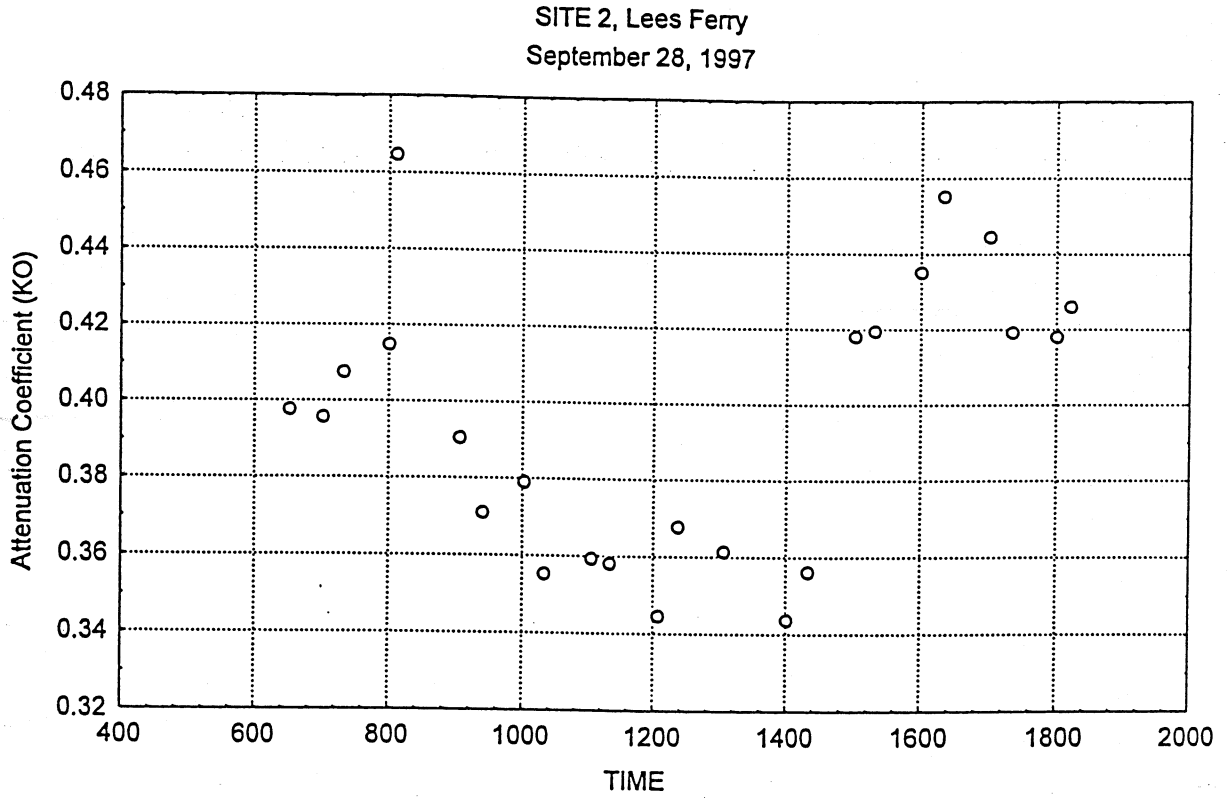

SITE 2, Lees Ferry
September 28, 1997
Attenuation Coefficient (KO)
0.48
0.46
0.44
0.42
0.40
0.38
0.36
0.34
0.32
400
600
800
1000
1200
1400
1600
1800
2000
TIME

Fig 51

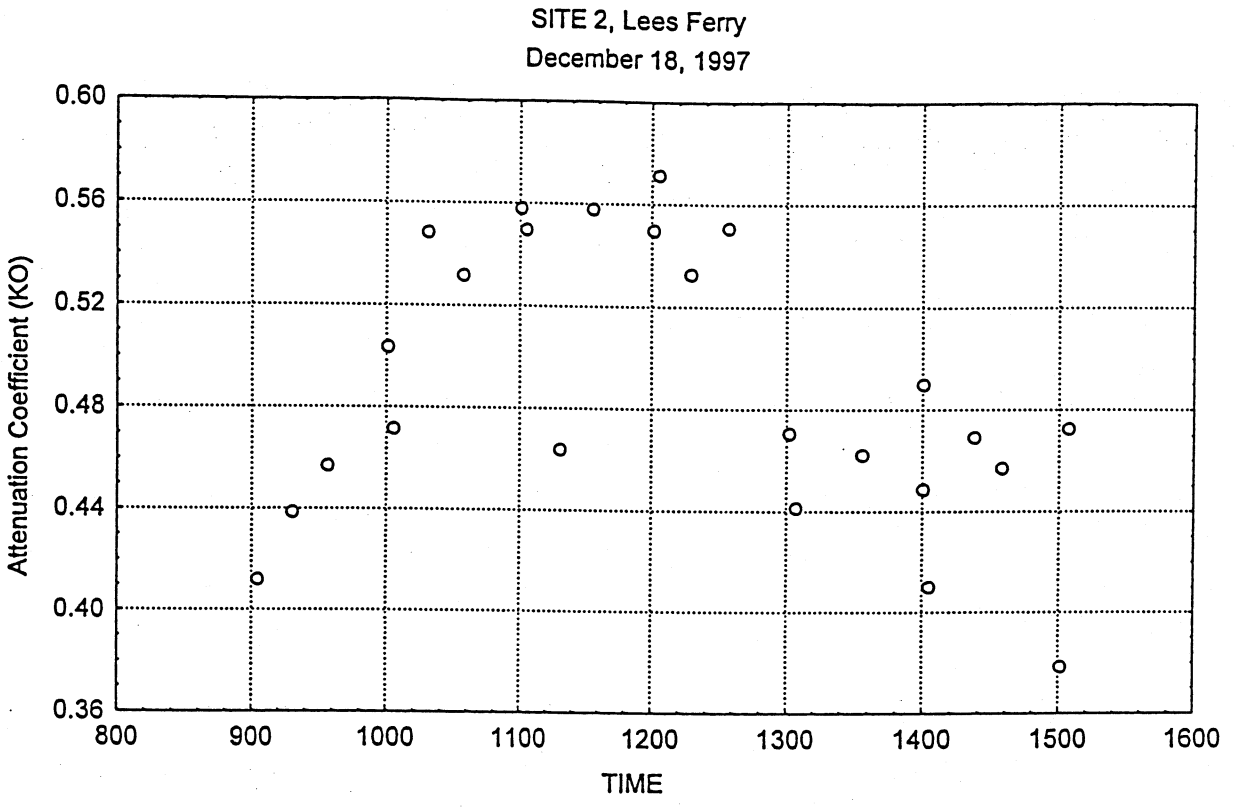

SITE 2, Lees Ferry
December 18, 1997
Attenuation Coefficient (KO)
0.60
0.56
0.52
0.48
0.44
0.40
0.36
800
900
1000
1100
1200
1300
1400
1500
1600
TIME

Fig 52

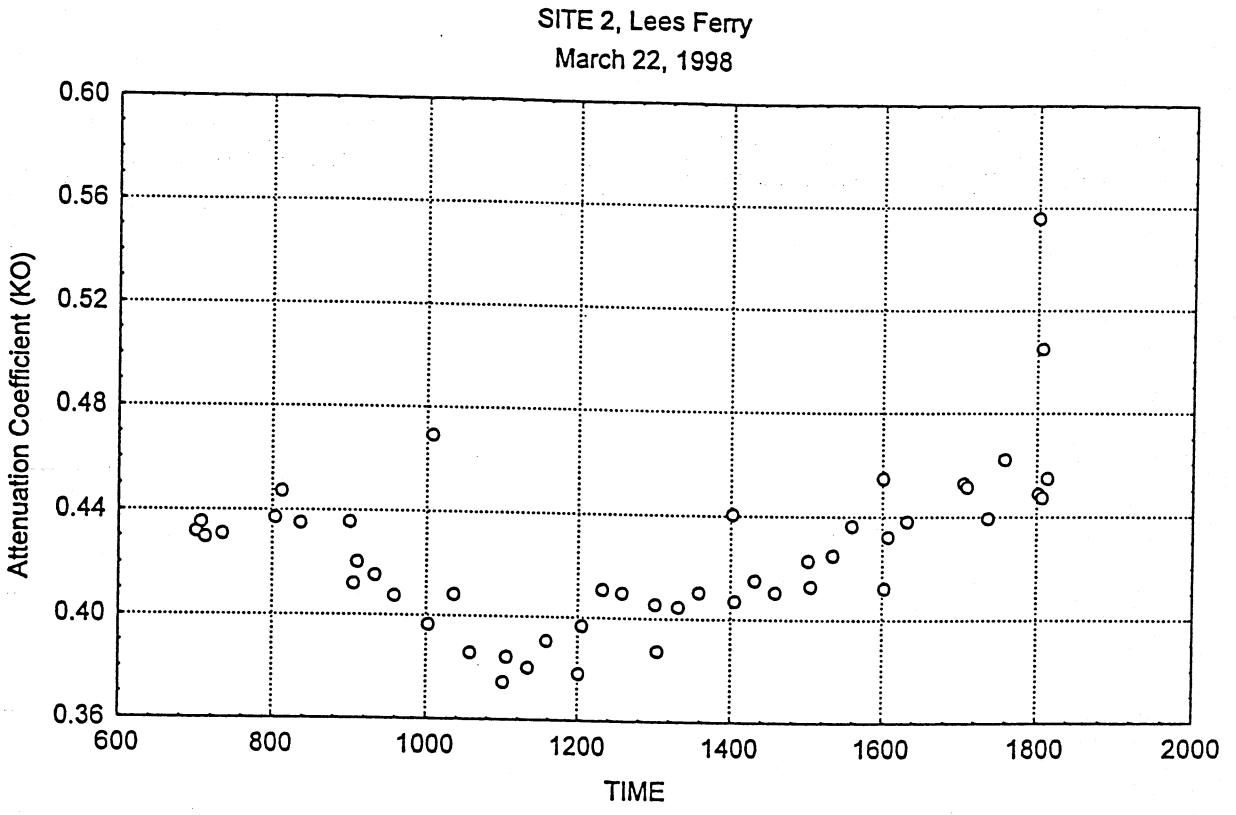

SITE 2, Lees Ferry
March 22, 1998
Attenuation Coefficient (KO)
0.60
0.56
0.52
0.48
0.44
0.40
0.36
600
800
1000
1200
1400
1600
1800
2000
TIME

Fig 53

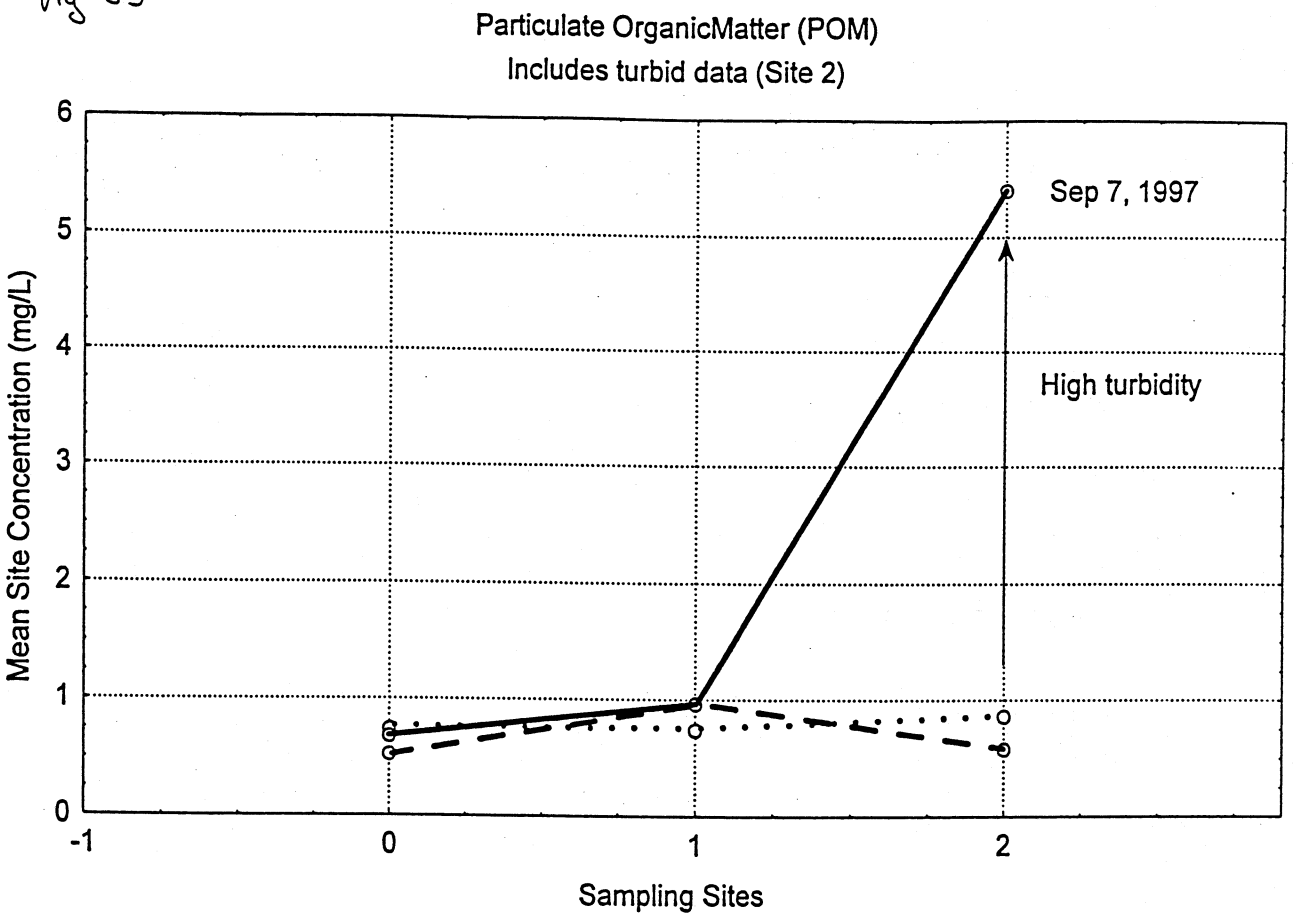

Particulate OrganicMatter (POM)
Includes turbid data (Site 2)
Mean Site Concentration (mg/L)
6
5
4
3
2
1
0
-1
0
1
2
Sampling Sites
Sep 7, 1997
High turbidity

Fig 54

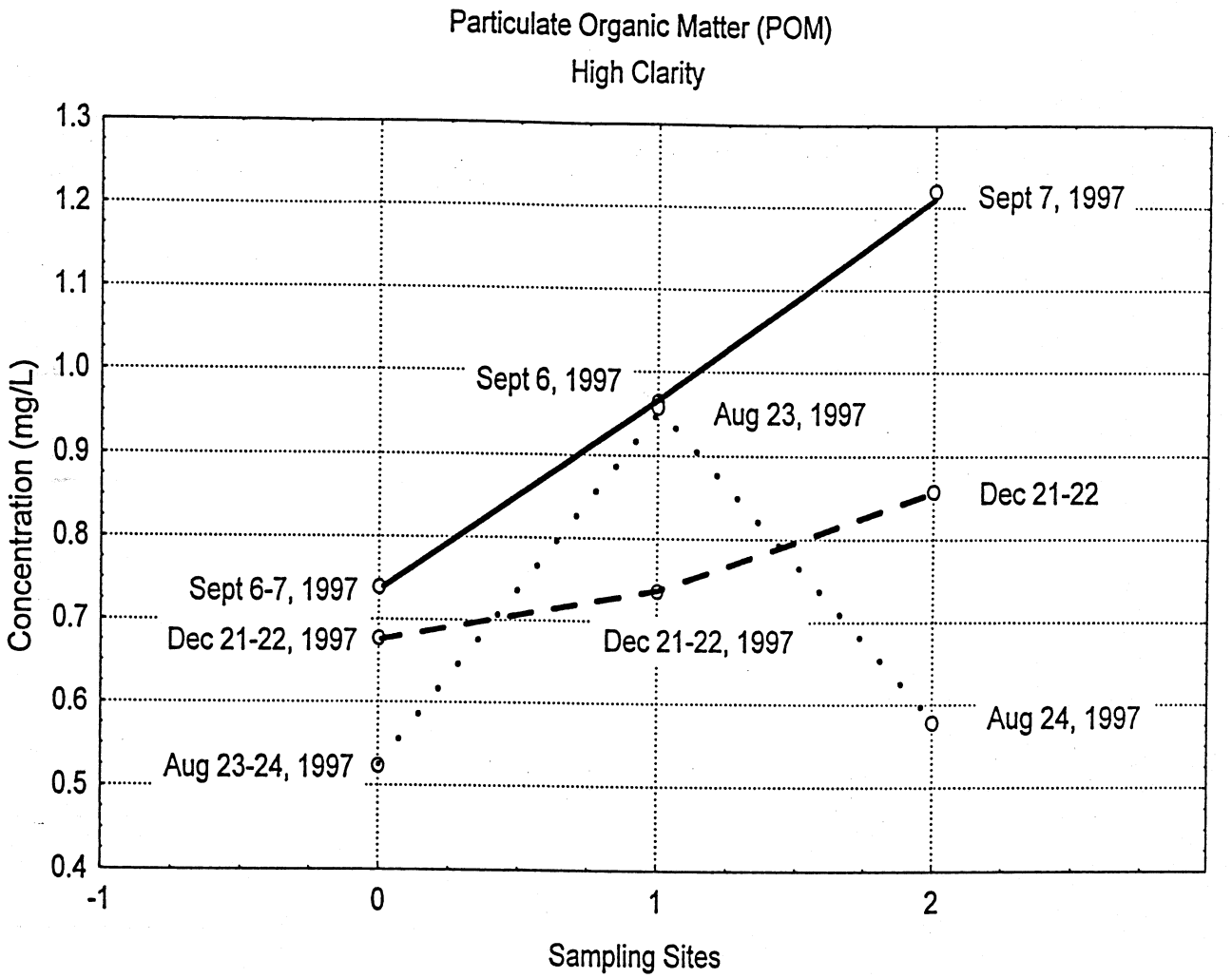

Particulate Organic Matter (POM)
High Clarity
Concentration (mg/L)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
-1
0
1
2
Sampling Sites
Sept 7, 1997
Sept 6, 1997
Aug 23, 1997
Dec 21-22
Sept 6-7, 1997
Dec 21-22, 1997
Dec 21-22, 1997
Aug 24, 1997
Aug 23-24, 1997

Fig 55

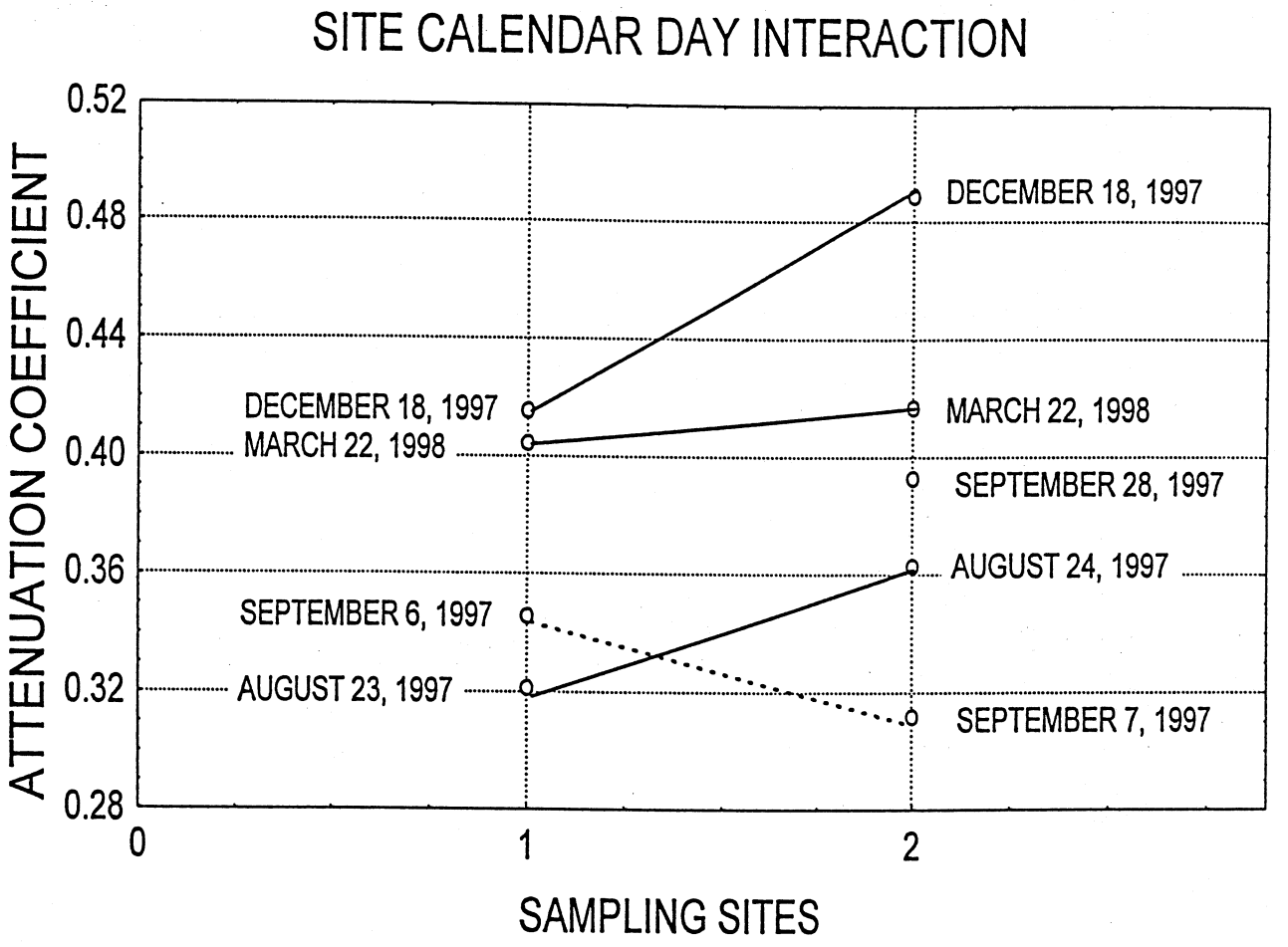

SITE CALENDAR DAY INTERACTION
ATTENUATION COEFFICIENT
0.52
0.48
0.44
0.40
0.36
0.32
0.28
0
1
2
SAMPLING SITES
DECEMBER 18, 1997
DECEMBER 18, 1997
MARCH 22, 1998
MARCH 22, 1998
SEPTEMBER 28, 1997
AUGUST 24, 1997
SEPTEMBER 6, 1997
AUGUST 23, 1997
SEPTEMBER 7, 1997

Fig 56

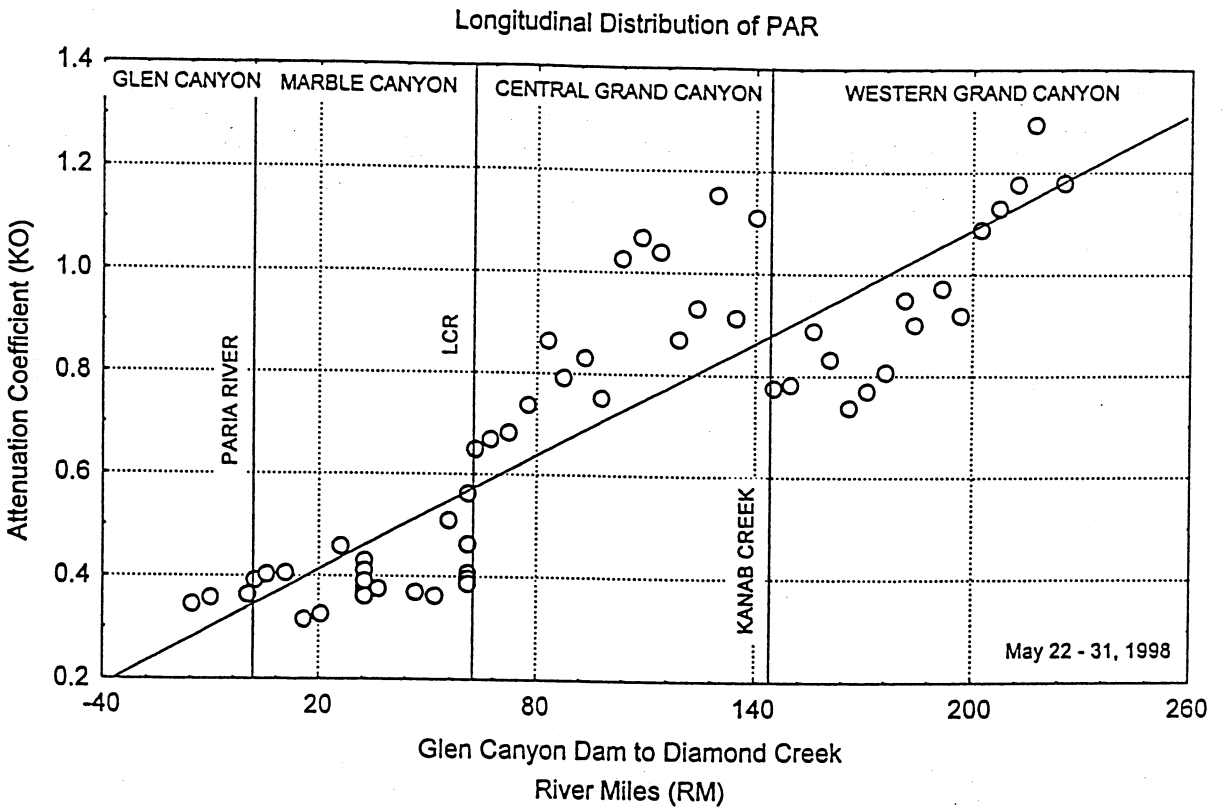
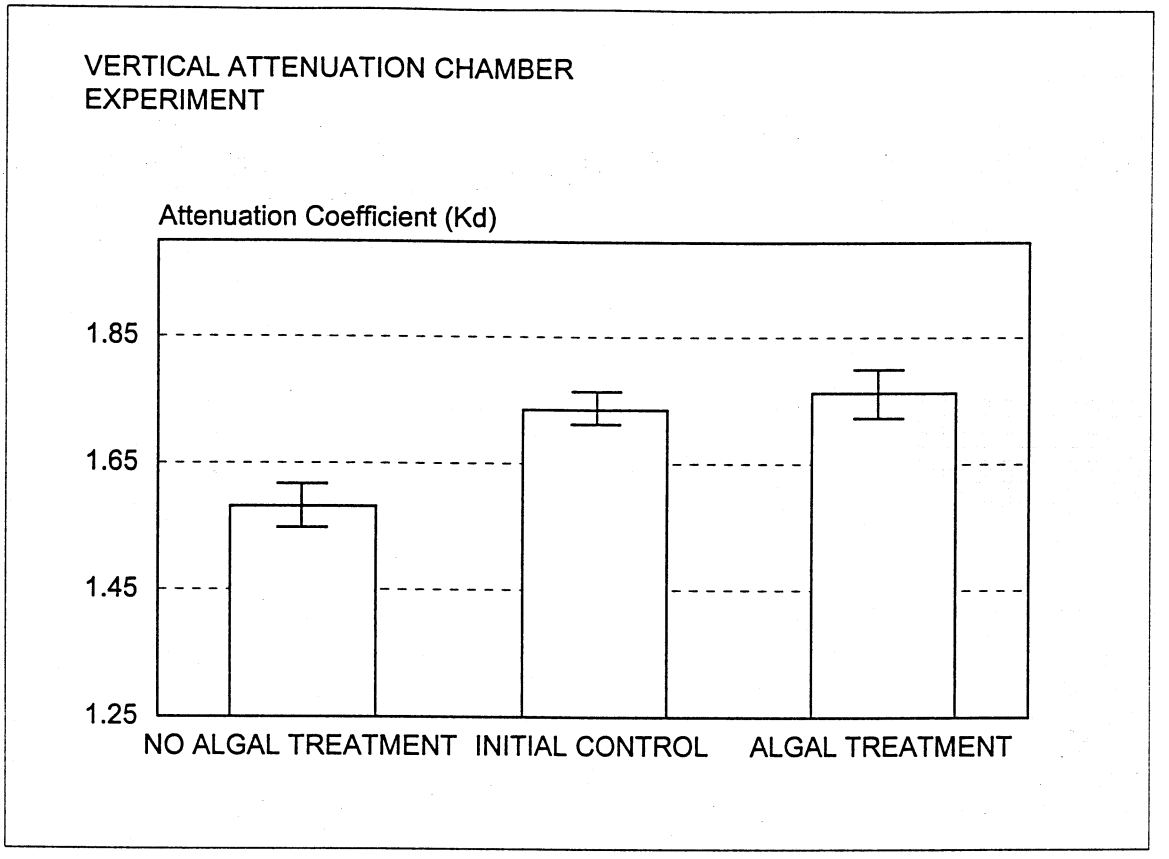

Longitudinal Distribution of PAR
GLEN CANYON
MARBLE CANYON
CENTRAL GRAND CANYON
WESTERN GRAND CANYON
PARIA RIVER
LCR
KANAB CREEK
May 22 - 31, 1998
Attenuation Coefficient (KO)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
-40
20
80
140
200
260
Glen Canyon Dam to Diamond Creek
River Miles (RM)

Fig 57


VERTICAL ATTENUATION CHAMBER
EXPERIMENT
Attenuation Coefficient (Kd)
1.85
1.65
1.45
1.25
NO ALGAL TREATMENT
INITIAL CONTROL
ALGAL TREATMENT