Near-shore Clarity at Lake Tahoe: Status and Causes of Reduction

Kendrick Taylor[1]
Rick Susfalk[1]
Margaret Shanafield[1]
Geoff Schladow[2]

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Prepared by:

[1]Division of Hydrologic Sciences, Desert Research Institute, University and Community College System of Nevada

[2]Department of Civil and Environmental Engineering, University of California, Davis

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Cover photos clockwise from top left: Example of near-shore clarity; view from the boat on a winter day; some of the instruments and sampling equipment used in this study; Margaret Shanafield uses a c-βeta instrument to measure how the attenuation of light changes with depth; a scanning electron microscope image of Lake Tahoe diatoms that are 10 micrometers in diameter; winter landscape; the research vessel Mount Rose with the water sampling probe on the bow.

TAHOE REGIONAL PLANNING AGENCY

DRI Desert Research Institute

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SUMMARY

Lake Tahoe is known for the exceptional clarity of its water, which is most obvious near the shore. Water clarity near the shore will respond faster and in a more localized way to management actions than the clarity in the middle of the lake. The neighborhood-scale response of near-shore clarity, which is different than the basin-scale response of mid-lake clarity, allows the location of problem areas to be identified. The fast and small spatial-scale response of near-shore clarity makes it well suited for guiding and evaluating management actions.

The clarity of the near-shore zone cannot be determined with a Secchi disk because the disk will frequently be visible when it is on the bottom. This project used an instrumented boat to measure turbidity and chlorophyll in the near-shore zone, allowing investigation of the spatial and temporal variability of near-shore clarity. Particle samples were also collected at selected locations to determine if the particles were primarily organic or mineral material.

Of the 114 km of shoreline, 1.5 km had extremely elevated turbidity, 4 km had moderately elevated turbidity, and 9 km had slightly elevated turbidity. There was an obvious association between elevated near-shore turbidity and some developed areas. The areas with the most elevated turbidity were offshore of the Upper Truckee River outlet, Al Tahoe, and Bijou Creek. The highest turbidities were observed during periods of low-elevation snowmelt and spring runoff, and were always associated with an abundance of mineral particles. With the possible exception of Tahoe Keys, reducing the ability of surface water to mobilize sediment in the areas with elevated near-shore turbidity would be an effective way to reduce the near-shore clarity problem. The situation offshore of the Tahoe Keys Marina was difficult to clarify because it is close to the outlet of the Upper Truckee River. Summer thunderstorms influenced near-shore clarity to a minor degree, but much less than snowmelt.

The near-shore areas are monitored by the Tahoe Regional Planning Agency (TRPA) littoral zone turbidity monitoring program. As currently implemented, the TRPA littoral zone monitoring program is not well suited for identifying changes in littoral zone turbidity, or detecting areas with elevated turbidity. A near-shore zone monitoring program utilizing an array of buoys that make continuous measurements of light transmission is recommended as a replacement for the current littoral zone monitoring program. This approach would allow long-term trends in near-shore water quality to be determined for specific locations and could be an important element of an adaptive management process.

The near-shore zone is subject to the TRPA littoral zone turbidity threshold (TRPA water quality threshold 1). The current threshold is difficult to apply because it is ambiguously written. The current threshold allows large reductions in near-shore clarity before conditions are not in compliance with the threshold. It is recommended that a new threshold be developed that provides for a greater level of protection in undeveloped areas than in developed areas, allows for a tightly defined increase in turbidity during infrequent storm events, and sets a threshold value that is consistent with the public's expectations.

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INTRODUCTION

Lake Tahoe is a mountain lake on the border of California and Nevada. Lake Tahoe's large surface area (33 km by 17 km), moderately high elevation (1,887 m), and great depth (498 m) make it unique among lakes in the United States. The lake is known for the clarity of its water. There are many ways to measure water clarity. The most common method at Lake Tahoe is to use a 20-cm diameter white disk, known as a Secchi disk. The greatest depth at which a Secchi disk is visible is known as the Secchi depth and is a quantitative measure of the clarity of the water. Currently, the annual average Secchi depth is approximately 23 m and it has been increasing during the last five years, but there has been a long-term decline during the last 34 years. Maintaining the clarity is important for aesthetic, economic, public health, and environmental reasons. Lake Tahoe is designated as an "Outstanding National Resources Water" by the Environmental Protection Agency which requires that states prohibit uses that alter the essential character of the water and that water quality be maintained at current levels (TRPA, 2002). This designation is recognized by California. Nevada has a less protective requirement (TRPA, 2002).

The portion of a lake deep enough that light does not reach the bottom is the called the pelagic zone. The Secchi depth can be measured in the pelagic zone. The portion of a lake where enough light reaches the bottom for macrophytes (rooted plants) and periphyton (attached algae) to grow is commonly called the littoral zone. The Secchi depth cannot be measured in most of the littoral zone because the disk will still be visible when it is on the bottom. At Lake Tahoe, the littoral zone frequently extends to depths greater than 40 m, and can be 20 m to several kilometers wide. The Tahoe Regional Planning Agency (TRPA) defines the littoral zone as the portion of the lake that is less than 100 m deep. From the perspective of a person onshore, the clarity of the water near the shore is more obvious than in the pelagic zone where Secchi depth is measured.

In this report, the near-shore zone is defined as starting where the water is 1 m deep and extending offshore 100 m or until the water is at least 30 m deep, whichever distance offshore is greater (Figure 1). We exclude areas less than 1 m deep where resuspension of bottom sediment by small waves can have a large influence on clarity. There is no widely accepted definition for the near-shore zone, and different reports may use a different definition. We extend the near-shore zone to water that is at least 30 m deep because this is slightly more than the maximum depth at which an object on the bottom might be visible. We require the near-shore zone to be at least 100 m wide to avoid having an extremely narrow near-shore zone in places where deep water is close to shore.

The near-shore zone is more affected by disturbances onshore than the deep portion of the lake. This occurs because the material causing the adverse effect will have the greatest concentration when it passes through the near-shore zone and has not yet been diluted by mixing with cleaner lake water. The near-shore zone responds to local restoration activities faster than the center of the lake because it is more influenced by local changes than the center of the lake. Except for atmospheric deposition, all the clarity reducing materials such as nutrients and particles that enter the lake pass through the near-shore zone, making the near-shore zone a good place to search for undesirable inflows to the lake. Reduced water clarity is most obvious in the near-shore zone because this is where most people come close enough to the lake to observe the clarity of the water.

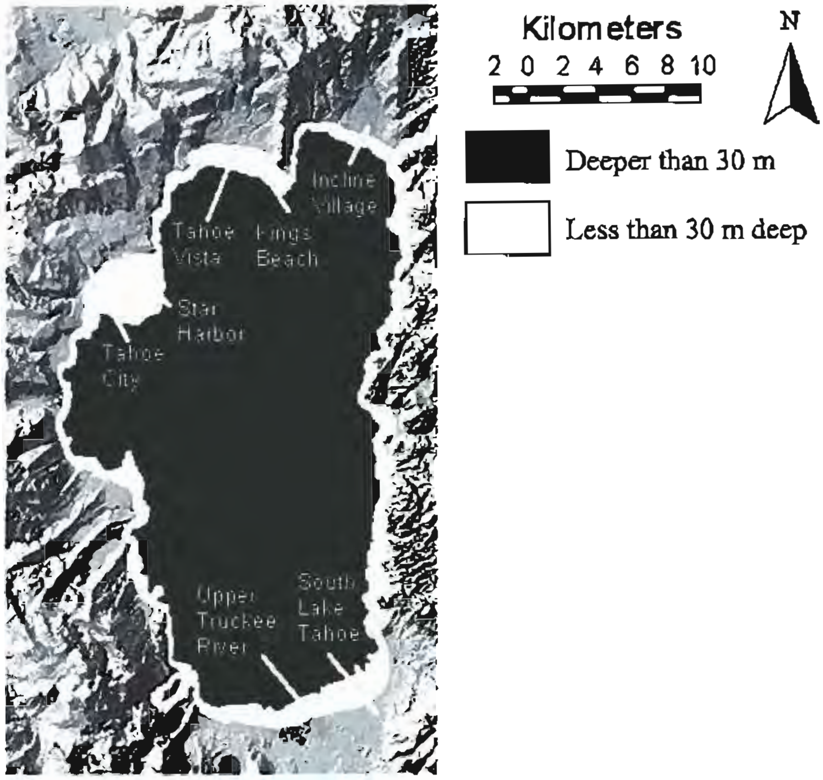


Figure 1. Place-names and shallow water areas at Lake Tahoe.

OPTICAL PROPERTIES OF WATER IN RELATION TO LAKE TAHOE

The optical properties of water are broadly separated into two categories: apparent and inherent. Apparent optical properties are dependent on natural lighting and are also influenced by factors such as the angle of the sun above the horizon, cloud cover, and water surface conditions such as waves. Inherent optical properties only depend on the water, and are not influenced by changes in the natural lighting or surface conditions.

Several apparent optical properties have been used in studies at Lake Tahoe. The Secchi depth is particularly useful because it is directly related to how deep into the water an observer can see and it is easy to comprehend. For a Secchi depth measurement to be valid it must be taken within two hours of solar noon, during calm surface conditions, on a cloud-free day, and on the shady side of a boat. Secchi depth cannot be measured in most of the near-shore zone because in clear shallow water the Secchi disk is still visible when it is on the bottom. The Tahoe Research Group at the University of California, Davis, has been monitoring the mid-lake clarity of Lake Tahoe using a Secchi disk for 34 years. There has been a long-term decline in mid-lake clarity as measured by the Secchi depth during the last 34 years.

Another apparent optical property occasionally discussed at Tahoe is vertical light extinction, which is a measure of the rate natural light decreases with depth. This property depends on the inherent optical properties of the water, the angle of the sun above the horizon, cloud cover, and wave conditions on the surface. A profile of the amount of light versus depth has to be measured to determine the vertical light extinction. For best results, this profile should consist of at least eight measurements, with the deepest measurement at about the Secchi depth. If the water depth is less than about 30 percent of the Secchi depth, the accuracy of the measurement is significantly decreased because there is not enough attenuation in the short water column. This is a time-consuming measurement that cannot be made from a moving boat or when there is significant wave action, and it is difficult to do by remote operation on a buoy. An accurate measurement is also not possible in clear shallow water such as in water 3 m deep on the east and west shores of Lake Tahoe.

A remote sensing approach to measure an apparent optical property is under development by Simon Hook at the National Aeronautics and Space Administration. He is experimenting with a satellite method to identify the maximum water depth in different areas around the lake at which the lake bottom can be detected with optical satellite remote sensing. (i.e., in one area the satellite might detect the bottom in water that is 4 m deep, and in another area it might detect the bottom in water that is 10 m deep.) This method is adversely influenced by changes in bottom conditions, sun angle, clouds, and surface conditions. The method is difficult to use because it requires perfect weather conditions on the rare occasions when the satellite has been instructed to acquire an image and is passing overhead. It also does not work well in areas where there is an abrupt increase in water depth near the shore. The method is not suitable for long-term use because there is no assurance that measurements with a similar response will be made in the future. Optical oceanographic remote sensing methods will not work in the near-shore zone because the optical properties observed by the sensors are a combination of the properties of the water and the lake bottom. In oceanographic work, the characteristics of the bottom do not influence the measurements. A remote sensing method that could frequently and quickly determine the clarity of the entire near-shore zone without the need for expensive field operations would be helpful; however, no such method exists.

Light attenuation is an inherent optical property that characterizes how much light is attenuated, or reduced, when light travels through water. Light attenuation is caused by two inherent optical properties of water: absorption and scattering of light. Absorption occurs when particles and dissolved material in the water absorb light. The amount of light that is absorbed is different for different colors of light. Scattering occurs when particles in water scatter light in a direction that is different from the incoming light. The amount of light that is scattered and the angle at which it is scattered is different for different colors of light and different particle sizes and composition. Unlike vertical light extinction, light attenuation does not use the sun for a light source and is not influenced by the angle of the sun above the horizon, clouds, or surface conditions. Light attenuation is measured on a discreet water sample, not over a range of depths like vertical light extinction. Light attenuation can be measured at any depth, whereas vertical light extinction can only be measured above the Secchi depth.

Coffee is an example of a fluid with high absorption and low scattering. Light passing through coffee is attenuated because the organic compounds in the coffee absorb light, but is not significantly attenuated by scattering because there are few particles to scatter the light. Water with a reflective white powder like chalk dust is an example of a fluid with low absorption and high scattering. Light passing through this water is attenuated because the chalk particles scatter the light, but there is not much light absorption because the chalk reflects the light. Water with coal dust is an example of a fluid with high absorption and scattering. Light passing through this water is attenuated because the dark coal dust absorbs and scatters the light. In Lake Tahoe, light scattering and absorption are caused by mineral and organic particles. Absorption also occurs from dissolved organic material (i.e., naturally occurring tannins) and anthropogenic compounds that inadvertently enter the lake (i.e., detergents, fuel oil, oily road residue).

Light transmission is an inherent optical property that is a measure of the percentage of light that remains after the light has traveled a specified distance through water. For example, if 70 percent of the original light remains after passing though 1 meter of water, the light transmission is 0.7 per meter. Light attenuation and transmission are related to each other by a simple equation. Light transmission is different for different colors of light because light absorption and scattering, which are the processes responsible for the attenuation of the light, are different for different colors of light. The white light we see on the surface contains the full spectrum of colors. Light with a short wavelength (near the blue end of the spectrum) has a greater light transmission than long wavelength light (near the red end of the spectrum). Underwater objects appear blue because as white light passes through water the red end of the spectrum is attenuated and only blue light is left to illuminate underwater objects.

Light transmission is measured with a transmissometer, which consists of a light source that emits a narrow beam of light into a water sample. The ratio of the intensity of the light before it passes through the water to the intensity of the light after it passes through a known distance of water is used to calculate the light transmission. The distance the light travels through the water is typically less than 30 cm. The water sample can be pumped into a sample cell, or the measurement can be taken in the lake without a sample container. Transmissometers are routinely deployed on ocean buoys where they operate unattended for several months at a time. Mechanical shutters or chemical coatings are used to keep the optics clear of biofouling.

There are instruments for measuring light scattering, absorption, attenuation, and transmission. These instruments have an internal light source and are not influenced by the natural lighting or surface water conditions. Different instruments will measure different values for scattering or attenuation depending on the color of the light and geometry of the light path. When comparing measurements made with different instruments it is important that the color of the light and scattering angle used by the instruments be the same.

Turbidity measurements are a specific class of scattering measurements. High turbidity water is murky and low-turbidity water is clear. If done in accordance with EPA method 180.1, turbidity measurements must use white light (e.g., a light source that contains many colors of light such as a tungsten light bulb as opposed to a colored light emitting diode) and the scattered light must be measured at 90° to the incoming light beam. If the measurement is done with the EPA GLI Method 2, a light source of 860 nm is used and the scattered light is measured at 90 ° to the incoming light beam. Turbidity is expressed in nephelometric turbidity units (NTU), which are based on an empirical relationship to standard concentrations of formazin (a white powder) in water. This reliance on an empirical standard causes problems. The design of some turbidity instruments is more sensitive to the color of the water than others. Hence, particle-free water containing tannin can have two different turbidity values, both of which are correct. Turbidity is not commonly used in ocean optics research because the resulting measurements are so dependent on the design of the instrument. Many instruments sold as turbidity meters, particularly instruments for *in-situ* measurements, are not compliant with EPA regulations because they use another color of light and/or use a scattering angle other than 90°. Turbidity measurements, like light transmission, scattering and absorption measurements, are made on a discrete water sample and are not measured over a column of water like vertical light extinction or Secchi depth. Turbidity values observed at Lake Tahoe during this project ranged from 0.1 NTU in the middle of the lake to 20 NTU near the outlet of the Upper Truckee River after a storm. For comparison, filtered distilled water typically has a turbidity of 0.02 NTU and the EPA standard for drinking water is 0.5 NTU. This project utilized turbidity measurements because turbidity is used by the Tahoe Regional Planning Agency (TRPA) and Nevada and California State agencies as an environmental criteria in the shallow waters of Lake Tahoe.

The relationship between turbidity, light transmission and Secchi depth depends on the type and stratification of particles and dissolved material in the water. Preliminary measurements were made to illustrate the general relationships between these parameters for Lake Tahoe (Figure 2). The Secchi depth versus turbidity relationship is extremely nonlinear (Figure 2A). It is difficult to measure the small change in turbidity associated with a change in Secchi depth from 10 to 15 m. Light transmission and Secchi depth have a more linear relationship (Figure 2B). Light transmission is a better indicator of changes in the clarity of the

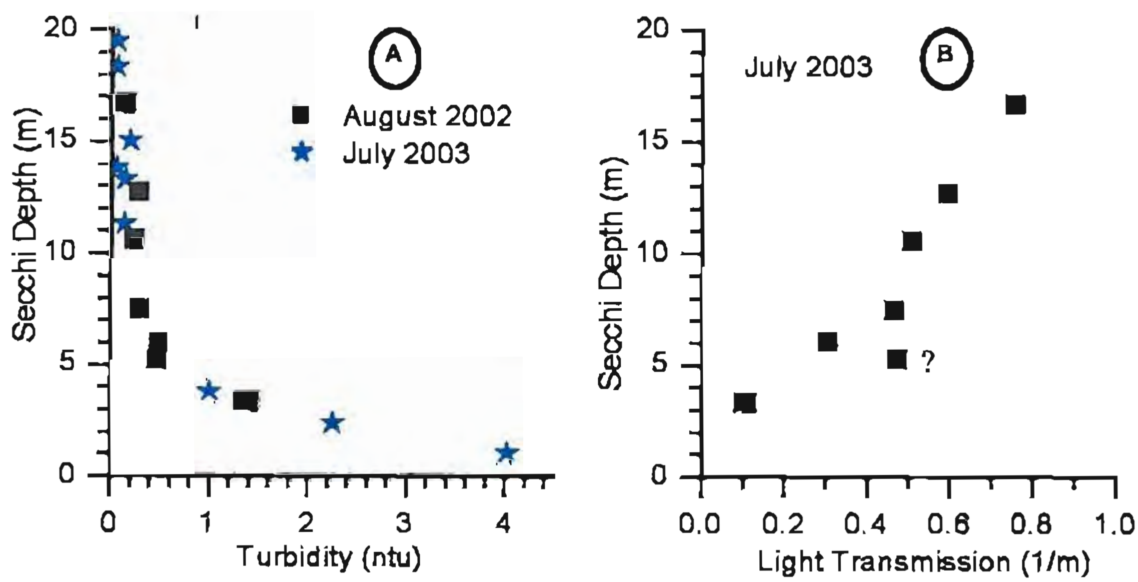


Figure 2. Relationships observed between Secchi depth, light transmission and turbidity at Lake Tahoe. The relationship between Secchi depth and turbidity (A), and between Secchi depth and light transmission at 488 nm (B) are shown. The turbidity and light transmission are measured on water taken from ~0.5 m below the surface. Secchi depth is dependent on the water clarity over the entire Secchi depth. These preliminary relationships are only based on a few days of measurements and should not be used to infer specific quantitative relationships. The measurements were made along a transect from inside Tahoe Keys Marina to Emerald Bay. Changes in the stratification of the optical characteristics of the water will influence these relationships. The measurement with a light transmission of 0.5 1/m and a Secchi depth of 6 m seems inconsistent with the other measurements and may be an error.

clear portions of the lake than turbidity because unlike turbidity, the change in light transmission associated with a change in Secchi depth clarity from 10 to 15 m is relatively easy to measure. However, the exact relationship between light transmission and Secchi depth will depend on stratification of the water column. The relationships presented in Figure 2 are a general example of how the properties are related and should not be used for quantitative purposes due to the preliminary nature and low replications of the data.

The turbidity near the shore is strongly controlled by the concentration of particles in the water. The flux of particles passing through the near-shore zone into the deeper portion of the lake is a function of both the particle concentration in the water and the velocity of the water. Turbidity is a poor indicator of the flux of particles from the near-shore to mid-lake because it does not account for the influence of the water velocity. For example, consider two streams that have the same high flux of particles into the lake. But, offshore of the first stream there is shallow water that mixes slowly with the deep water, and offshore of the second stream there is deep water and a lake current that quickly mixes the near-shore water with deep water. The water offshore of the first stream has greater turbidity than the water offshore of the second stream that is diluted by clean water from the middle of the lake. High turbidity values indicate there is a source of high turbidity water entering the lake, but near-shore water currents will move the high turbidity water and can make it difficult to identify the exact location of the source. Turbidity is also a poor indicator of where nutrients enter the lake. When nutrients first enter the lake, they will not influence the turbidity. By the time the nutrients have been in the lake long enough to stimulate algae growth and have an influence on turbidity, near-shore currents will have carried the nutrients far from where they entered the lake. Turbidity is not a good indicator of near-shore biological activity because it is influenced by organic and mineral particles. Measurements of periphyton (attached algae) are a better indicator of biological activity and are made by the Tahoe Research Group. However, periphyton is a poor indicator of near-shore clarity, which is largely controlled by the concentration of mineral particles, not algae. Turbidity and the other optical properties discussed above are good indicators of water clarity and are most useful for addressing the aesthetic aspects of near-shore water quality.

Another inherent optical property used in this study was fluorescence. Fluorescence occurs when water is illuminated with light of one color and the water emits, or fluoresces, light of a different color. This occurs because some dissolved compounds absorb light energy at one wavelength and use the energy to emit light at a different wavelength. Fluorescence can be used to measure the concentration of chlorophyll or tannin in the water. To determine the chlorophyll concentration in a water sample, the sample is illuminated with blue light and the amount of red light that is emitted, which is proportional to the amount of chlorophyll in the water, is measured. The relationship between the amount of fluorescence and the chlorophyll concentration partially depends on the algal species that contains the chlorophyll. This project used the voltage output of the chlorophyll fluorometer as a quantitative measure of the relative chlorophyll concentration. No attempt was made to quantify the concentration of chlorophyll in terms of an absolute measurement such as milligrams of chlorophyll/liter. This allowed the resources required to make an absolute chlorophyll measurement to be used more effectively elsewhere in the project.

INSTRUMENTATION AND METHODS USED IN THIS STUDY

Optical Instrumentation and Methods

The central piece of equipment used in this study was the Research Vessel "Mount Rose." The Mount Rose is a 6.5-m aluminum boat specifically built for research at Lake Tahoe. It has a jet drive, as opposed to a conventional propeller, which allows it to operate in water only 70 cm deep. It has enhanced electrical and safety systems and a weather tight cabin to allow operations in poor weather conditions. A bow-mounted water sampling probe was pushed in front of the boat in water that was not affected by the boat's presence. The sampling probe contained a water temperature sensor as well as a pump to transfer lake water to the instruments onboard the boat. The sample inlet on the probe was 10 to 50 cm below the water surface depending on the boat speed, depth to bottom, and wave conditions. Water was pumped into the cabin, where it passed through a chlorophyll fluorometer, two turbidity sensors, a flow meter, and occasionally a light transmissometer. A custom data acquisition system collected the data from the sensors and location information from a global positioning system (GPS), saved the information, and displayed it as a color-coded moving map on a display.

The two turbidity sensors were a Hach 2000 and a Hach 2100. These instruments follow EPA method 180.1, which uses a white light source and a scattering angle of 90°. The instruments were not sensitive to the presence of tannins in the water because they measured the ratio of the scattered light to the transmitted light. The Hach 2000 was configured to measure between 0 and 2 NTU, and the Hach 2100 was configured to measure between 0 and 4 NTU. The Hach 2000 was used as the primary instrument until January 2002. Using this instrument, it was possible to determine if the turbidity was greater than 2 NTU, but it could not be determined how much greater. After January 2002, the Hach 2000 was still used as the primary instrument for water with a turbidity of 0 to 2 NTU, and the Hach 2100 was used to record the turbidity of water with a turbidity of 2 to 4 NTU. The Hach 2100 also had a panel display capable of displaying readings up to 4000 NTU. The reading from the panel was occasionally manually recorded when the sample had a turbidity greater than the 4 NTU limit of the automated recording system. A Wetlabs Wetstar was used for the chlorophyll fluorometer. A Wetlabs C-star (488 nm) was used for the transmissometer. The transmissometer was only used on a few surveys. The data acquisitions system continuously compared the two turbidity measurements and monitored water flow through the instruments. If the turbidity sensors did not agree, or the water flow was too low, the data were not recorded and the operator was notified. The ability of the system to display data in real time, and to continuously check the turbidity measurements and flow, was essential for efficient field operations and to have confidence in the data.

This system allowed us to efficiently measure turbidity, relative chlorophyll concentration, temperature, and light transmission. Measurements could be made when the boat was moving 35 km/hour if other boats and the boat wake were not a concern. Typical operating speeds were between 10 km/hour and 25 km/hour and a set of measurements was made about every 10 m. An instrument that measured light attenuation as a function of depth was also used in this study. This instrument, a c-βeta made by Hobilabs, required that the boat was not moving when the measurement was made.

Particle Analysis Methods

Particle samples were collected to determine the composition and size of the particles. In a general sense, particles can have an inorganic origin (i.e., minerals, soil and rock), or an organic origin (living algae, bacteria, or parts of dead algae). Two methods were used to determine the origin of the particles: 1) scanning electron microscope and energy dispersive spectrometry measurements of the particles, and 2) measurements of the optical properties of the water.

In the first method, a scanning electron microscope was used to determine if the particles in a water sample were organic or inorganic in origin. Water samples from selected locations were passed through a 0.1-micron filter. The filter was examined with a scanning electron microscope (Figure 3). Particles larger than approximately 5 microns across that had an inorganic origin could be identified in the scanning electron microscope images by their angular rock and mineral-like morphology. Particles larger than approximately 5 microns that had an organic origin could be identified because they had intricate structures characteristic of biological material. Particles smaller than 2 microns could not be classified by appearance because they were too small to have a visible morphology indicative of either inorganic or organic material. A comparison of images from sections of the filter through which water was passed (Figure 3) and through which water was not passed showed there was a large amount of

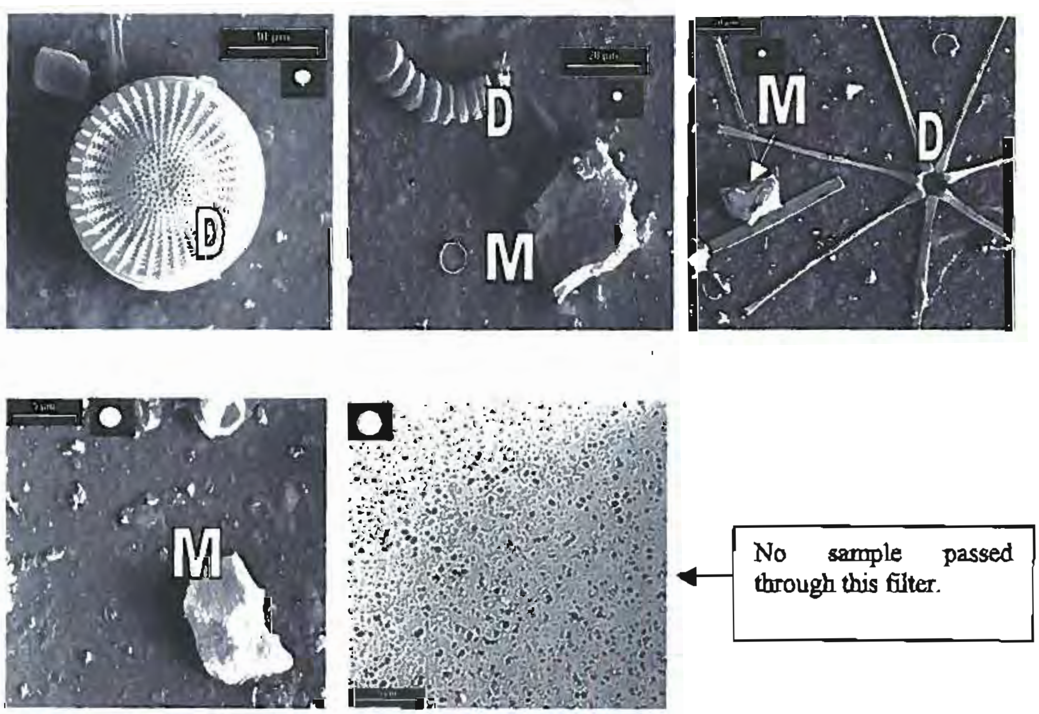


Figure 3. Scanning electron microscope images of particles in a water sample from Sand Harbor collected on January 10, 2002. The scale is different in each image, but the white circle in the black square is 2 micron in all the images. This is the size of a large clay particle. Diatoms are indicated by "D." Mineral particles are indicated by "M." The filter on the lower right had no sample passed through it and the holes in the filter can be seen. Notice that the filters that the sample did pass through have a coating of sub-micron particles.

material smaller than 1 micron. Sub-micron particles are more effective at scattering light than larger particles because the size of the small particles is closer to the wavelength of light and scattering occurs by refraction, not by reflection as with larger particles. From a water clarity perspective, the origin of the sub-micron particles is therefore of greater interest. This prevents using particle morphology to directly determine the origin of the particles that are the most responsible for the reduction in water clarity.

Energy dispersive spectrometry was used to determine the major elemental composition of the submicron particles. This method used x-ray emissions to determine the relative abundance of different elements in a particular area of the filter. Initially, to evaluate this analysis method, we used energy dispersive spectrometry to determine the relative abundance of silica, carbon, and metals (aluminum, iron, and calcium) in particles that were large enough to determine the origin by visual inspection in the scanning electron microscope images. Mineral particles contained silica and metals, diatoms consisted of silica with no metals, and organic particles contained carbon with no metals or silica. A convenient way to represent this information is with a ternary diagram (Figure 4).

After using large particles of known origin to define the fields in the ternary diagram, the energy dispersive spectroscopy method was applied to the sub-micron particles that are known to have the greatest influence on clarity. The sub-micron particles were too small to be classified by their appearance in scanning electron microscope images (Figure 5a). The energy dispersive spectroscopy system was adjusted to measure areas on the filter that only had sub-micron particles. This allowed the elemental composition of thousands of sub-micron particles to be determined at once. The origin of the particles was determined by noting in which field (diatom, mineral, or organic) on the ternary diagram the measurement plotted. Areas of the filter that had a mix of organic and mineral particles plot between the two fields. Points close to but not inside the mineral field have mostly mineral particles. Points close to but not inside the organic field have mostly organic particles. At least three locations were measured on each filter. Figure 5b is an example of the analysis approach, the data in Figure 5b and data from other samples sites are discussed later in the report.

A second way to estimate if the turbidity in a water sample is caused by mineral or organic particles is to use optical measurement of the water, in particular measurements of turbidity and chlorophyll. In pure water, both the turbidity and chlorophyll concentrations will be low (Figure 6a). If mineral particles are added to pure water, the turbidity will increase but the chlorophyll concentration will remain the same (Figure 6a). If algae are added to pure water, both the turbidity and chlorophyll concentrations will increase (Figure 6a). The turbidity/chlorophyll ratio was used to determine if the particles were primarily mineral material or organic (Figure 6b, 6c). This ratio could be determined at every location turbidity and chlorophyll were measured, not just at discreet locations where water samples were collected for the energy dispersive spectrometry measurements. Maps of the ratios are presented later in the report and discussed in conjunction with maps of turbidity.

Particle Size

Samples were collected to determine the particle size distribution. This was not part of the scope of work of this project and is part of a separate project that is underway by Geoffrey Schladow at the University of California, Davis. Preliminary results on the particle size work are presented in Appendix A. Further results will be part of a later report by Schladow.

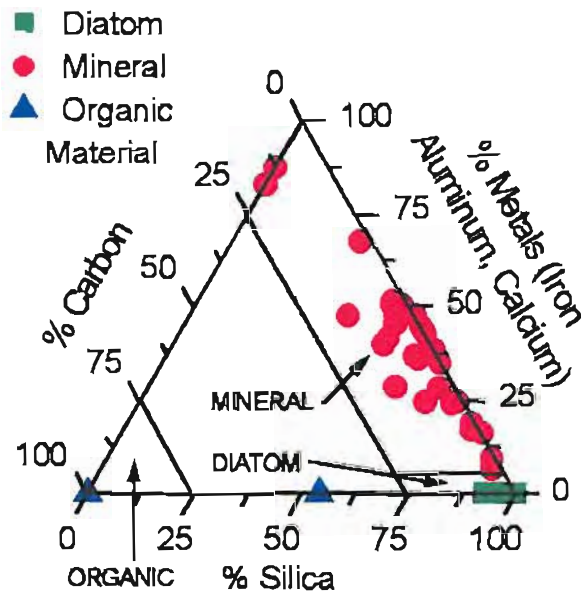


Figure 4. Relative elemental composition of diatom, mineral, and organic particles of identifiable morphology. Particle origin was visually assessed from the scanning electron microscope images. Samples from six sites along the south shore were used to make this plot. The three sides of the triangle are plot axes corresponding to the percentage of silica (bottom axis), carbon (left axis), or metals (iron + aluminum + calcium, shown on the right axis) in the particle. The three percentages are normalized to add up to 100%. There are other elements in the particles but they are not relevant to this analysis. Diatoms, which are 100% silica, plot in the lower right of the triangle (green squares). Organic material, which is 100% carbon, plots in the lower left of the triangle (blue triangles). There are 10 samples that plot on top of each other in the lower left corner; one anomalous organic sample also contained silica. Minerals, which contain both silica and metals, plot along the right side of the triangle. The triangle has been divided into fields that show regions where mineral, organic and diatom particles plot on the triangle. The boundaries for these areas are subjective, but they provide a rough indication of the origin of the particle.

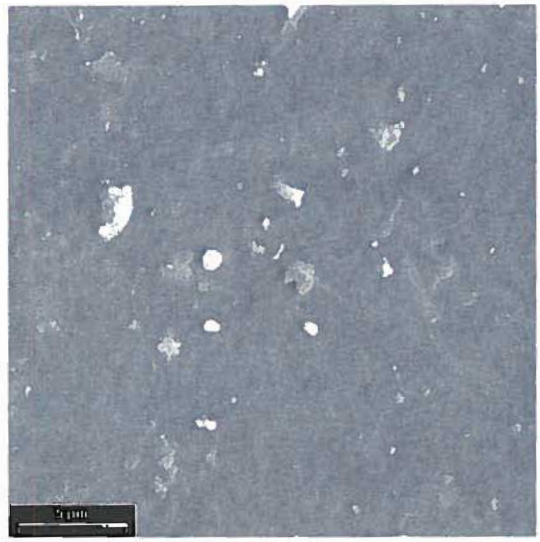


Figure 5a. Scanning electron microscope image of a portion of a filter collected off the Upper Truckee River that does not contain large particles. Most of the surface of the filter has this appearance. The filter is coated with a layer of sub-micron particles that cannot be identified by morphology. The entire area of this image was investigated with energy dispersive spectroscopy to make one composite measurement of the elemental composition of all the particles that form the layer of material covering this portion the filter. Each such measurement is represented by a single symbol on the ternary diagrams, and is representative of the elemental composition of all the particles the area shown in this image.

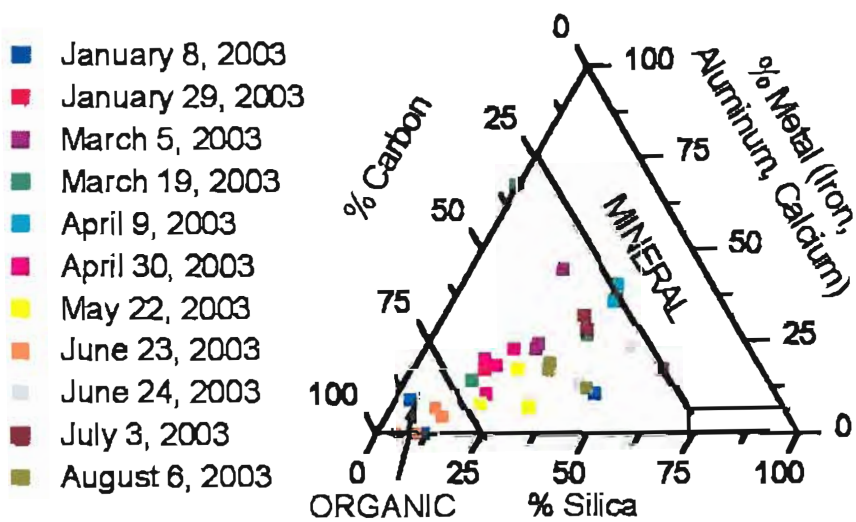


Figure 5b. Elemental composition of particles collected off the Upper Truckee River during different seasons. The elemental composition of the particles, as determined by energy dispersive spectroscopy, differs with season. In summer, the particles plot in the organic portion of the plot. In winter, spring, or after a summer precipitation event, the particles plot closer to the mineral portion of the plot, indicating the particles are a mix of minerals and organic material. This method was used to determine the origin of the small particles that are the primary cause of the reduction in water clarity.

Figure 6a. Effect of clay and algae on turbidity. Pure water has low turbidity and chlorophyll. As clay is added to pure water, the turbidity increases and chlorophyll concentration stays the same. This is indicated by movement along the brown arrow. As algae is added to pure water, the chlorophyll concentration and turbidity both increase. This is indicated by movement along the green arrow.

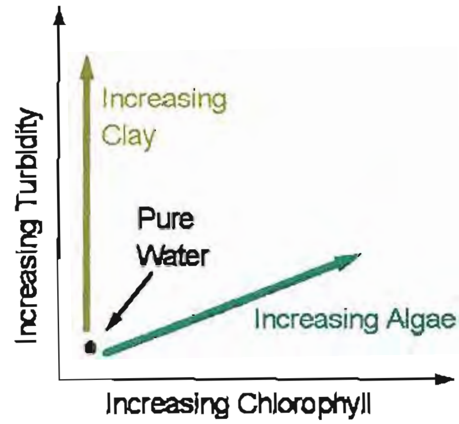


Figure 6b. Relationship of turbidity and relative chlorophyll content of all samples collected offshore of South Lake Tahoe. The red points show the range in values observed in the lake during all seasons in 2002 and 2003. Chlorophyll measurements are expressed as raw fluorometer voltages. The ratio of turbidity to the chlorophyll fluorometer voltage can be used as a relative indication of composition of the particles. The black lines show different ratios. The ratios are also a function of the equipment that is used and cannot be compared to ratios measured with other equipment.

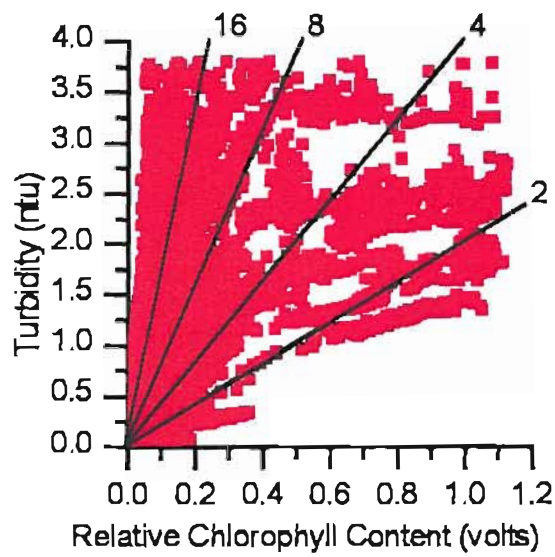
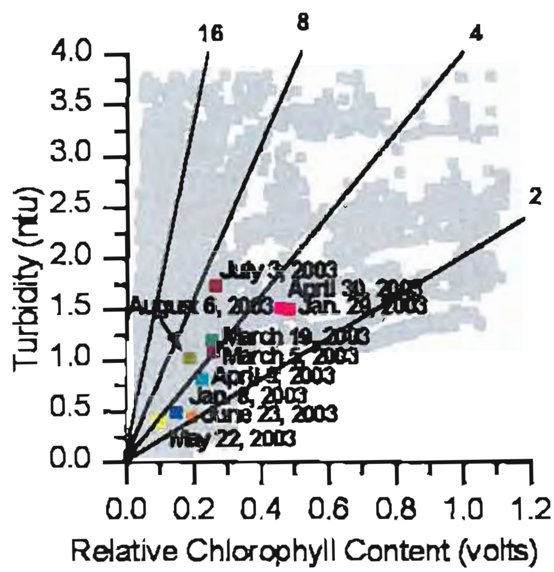


Figure 6c. Comparison of turbidity, chlorophyll, and energy dispersive spectroscopy measurements. The colored points are measurements made off the outlet of the Upper Truckee River and correspond to the energy dispersive spectroscopy measurements shown in Figure 5. The turbidity/chlorophyll ratio, indicated by the black lines, is an indicator of the origin of the particles. The energy dispersive spectroscopy measurements show that samples with a ratio greater than 16 have mostly mineral particles, and samples with a ratio less than 2 have mostly organic particles. Samples with intermediate ratios are a mix of organic and mineral particles.



IDENTIFICATION OF AREAS WITH PERSISTENTLY ELEVATED TURBIDITY

Overview

Identifying areas with elevated turbidity is a good way to determine where high concentrations of particles are entering the lake. However, rapid dilution by near-shore currents may prevent some sources of particles from being detected, and inflows with high particle concentrations that plunge into deep water cannot be detected by surface measurements. Identifying areas with elevated turbidity is also a good way to identify sections of the near-shore that do not have the aesthetic appeal of high-clarity water. It is desirable to identify areas of elevated turbidity to: 1) direct restoration efforts to areas with the largest problems; 2) identify areas of high particle loading not associated with obvious inflows; and 3) identify areas that may be near the TRPA water quality threshold for the littoral zone. Turbidity greater than 0.25 NTU, which is about twice the turbidity common in the middle of the lake, is considered to be elevated in this report. These areas are shown in green, yellow, or red in the turbidity maps.

Presentation of Data

A two-phase approach was used to identify areas with persistently elevated turbidity. First, surveys around the whole lakeshore that were conducted prior to this project were reviewed to identify areas that occasionally had elevated turbidity. Second, repeated detailed surveys were conducted as part of this project in areas the whole lakeshore surveys had identified as occasionally having elevated turbidity.

The whole lakeshore surveys conducted prior to this project (Figure 7) typically consisted of a single measurement transect as close to the shore as practical (20 to 300 m) while keeping a safe distance from obstacles. Additional transects were occasionally measured at varying distances offshore in areas of special interest. The surveys showed that undeveloped near-shore areas had low turbidity, and some developed areas had elevated turbidity. These surveys were used to identify portions of the near-shore with a clarity problem (yellow, orange, or red areas in Figure 7) that were studied in the second phase with more detailed surveys. The large scale of the maps in Figure 7 masks the full level of detail in these data. Maps with greater detail are shown in Figures 9 to 16. Only during the most recent whole lakeshore survey (May 2003) were transects measured at increasing distances offshore until turbidity values typical of mid-lake values were observed. Turbidity values typical of mid-lake values were observed just a few meters offshore in some places (e.g., off Rubicon Point), but in other places and times were not observed until 6 km offshore (e.g., the outlet of the Upper Truckee during spring runoff).

Detailed surveys where conducted in areas the whole lakeshore surveys identified as occasionally having elevated turbidity. The detailed surveys used multiple transects at various distances offshore to determine the spatial extent of the elevated turbidity areas. Transects were as close as 50 m apart in areas where the spatial variability was high, but were up to 500 m apart where the spatial variability was low. These surveys were conducted between September 2001 and August 2003 offshore of South Lake Tahoe, Incline Village, Kings Beach, Tahoe Vista, and Tahoe City. The surveys made prior to September 2001 were made during calm periods when there had been no precipitation and only light winds for several days preceding the surveys. After September 2001, the measurements were made during calm periods and 1 to 5 days after storms that resulted in precipitation or high winds. Turbidity maps for all the surveys that the Desert Research Institute has conducted (August 2000 through August 2003) are presented in Figures 9 to 16. To facilitate visual comparison between the maps, they all have the same spatial and turbidity scales. Figure 8 is an overview map that provides an index for the other maps.

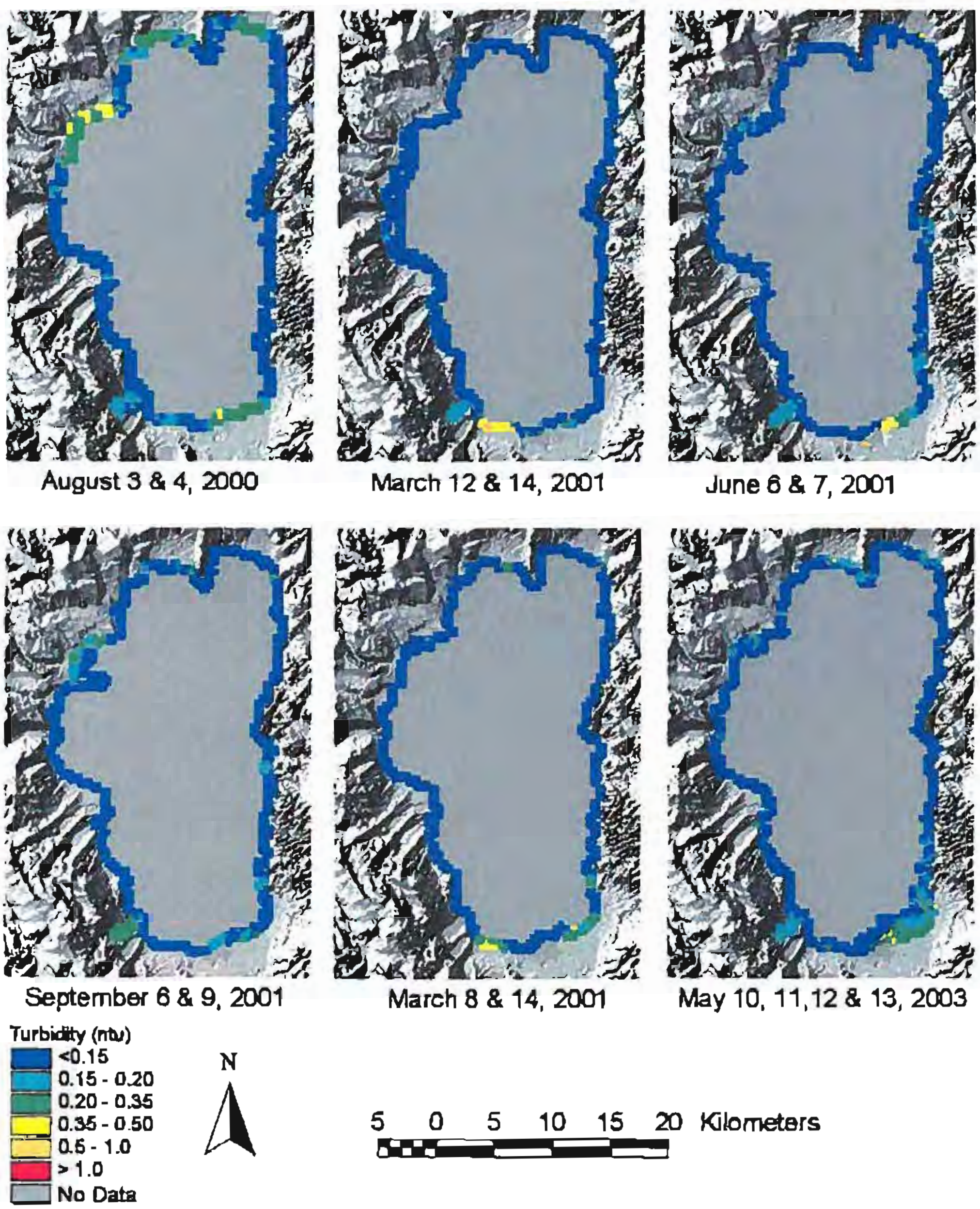


Figure 7. Whole lakeshore turbidity surveys conducted during several different seasons. Green areas have significantly elevated turbidity. The yellow, orange, and red areas have progressively greater turbidity. There is a strong correlation between developed areas and elevated turbidity. These surveys do not extend inside Tahoe Keys. Only during the most recent whole lakeshore survey (May 2003) were sufficient transects made at varying distances offshore to determine the lake-ward extent of areas with elevated turbidity.

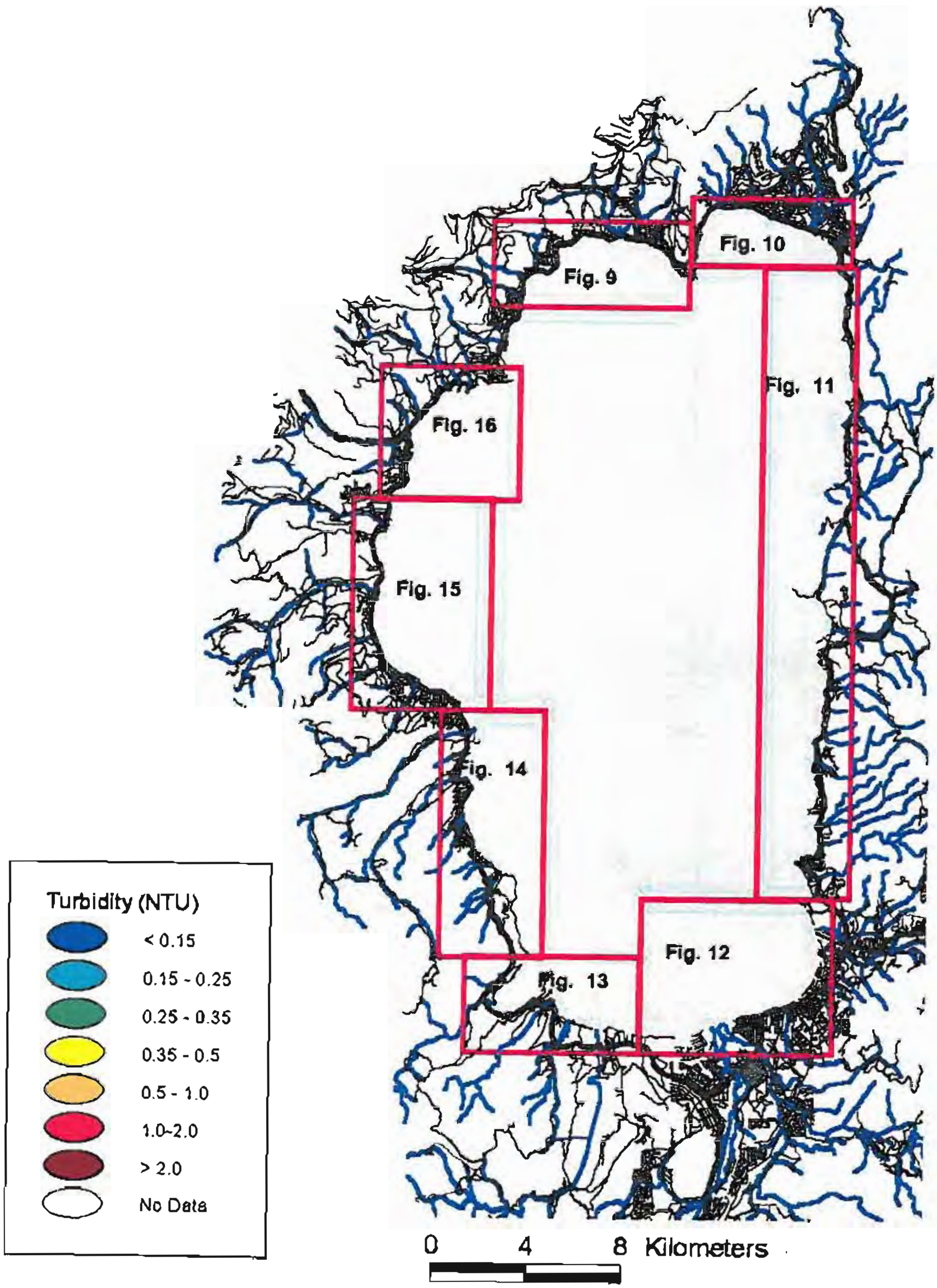


Figure 8. Overview map showing location of Figures 9 to 16. The turbidity color scale is used for Figures 9 to 16.

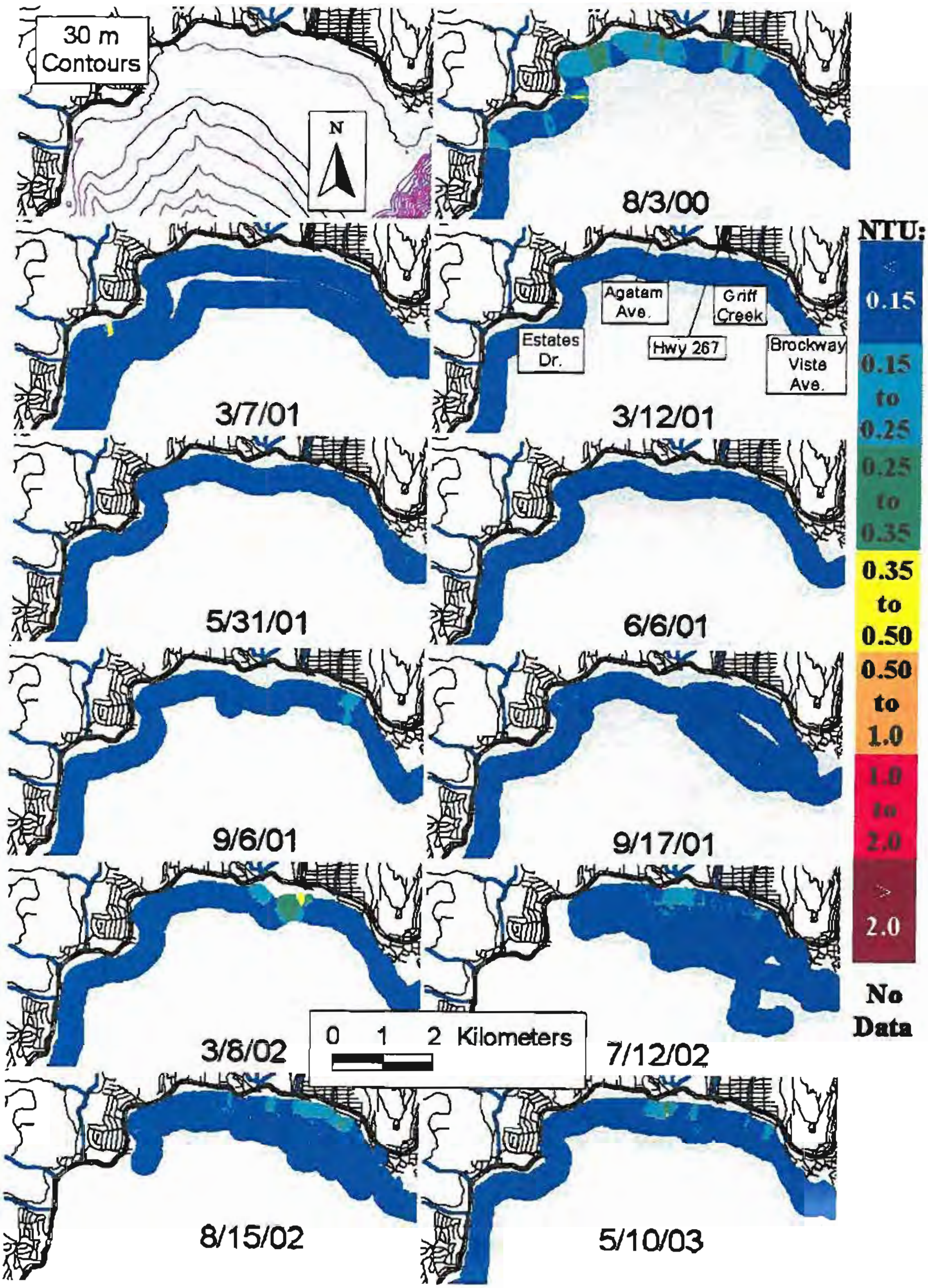


Figure 9. Turbidity surveys offshore of Kings Beach and Tahoe Vista.

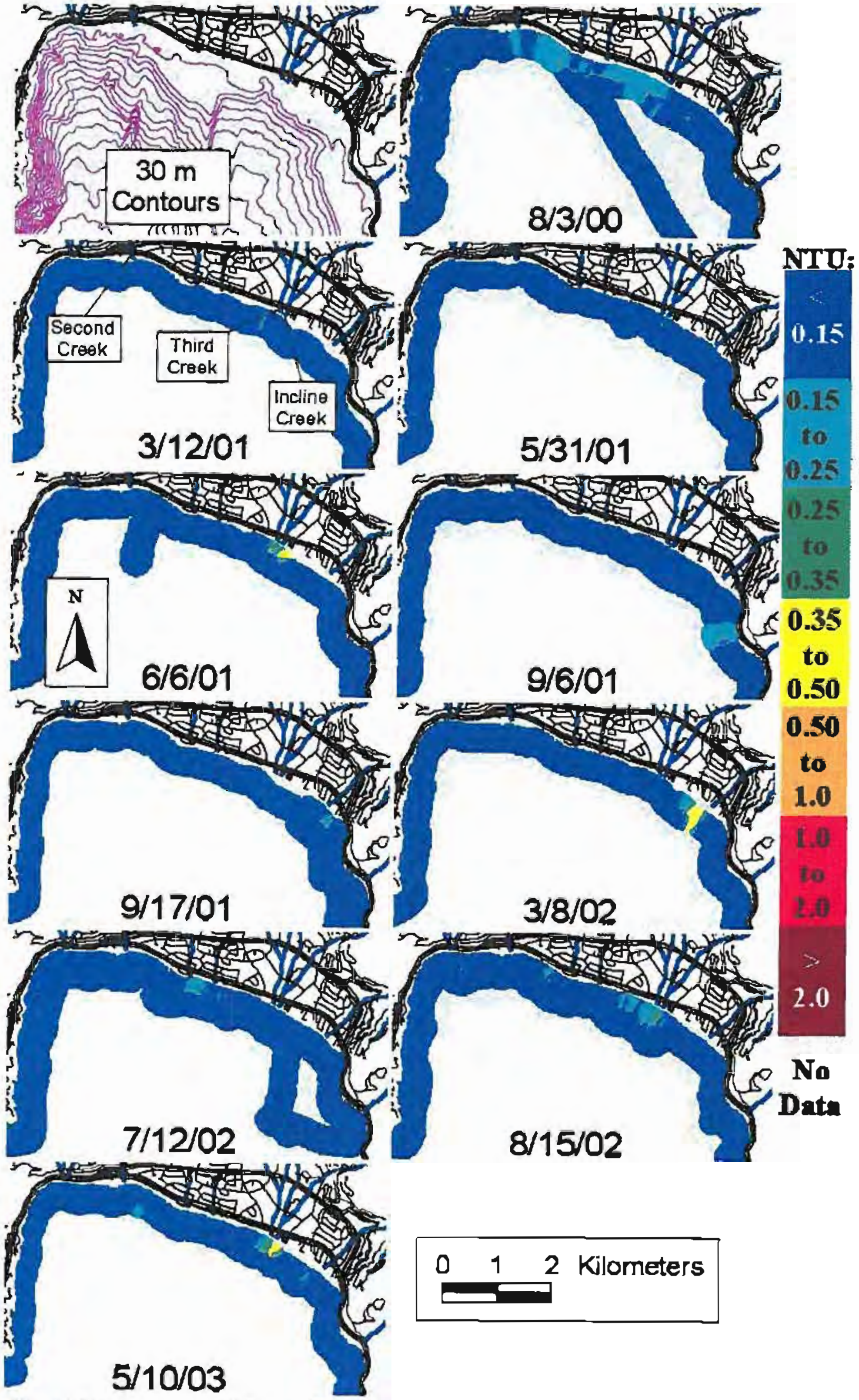


Figure 10. Turbidity surveys offshore of Incline Village.

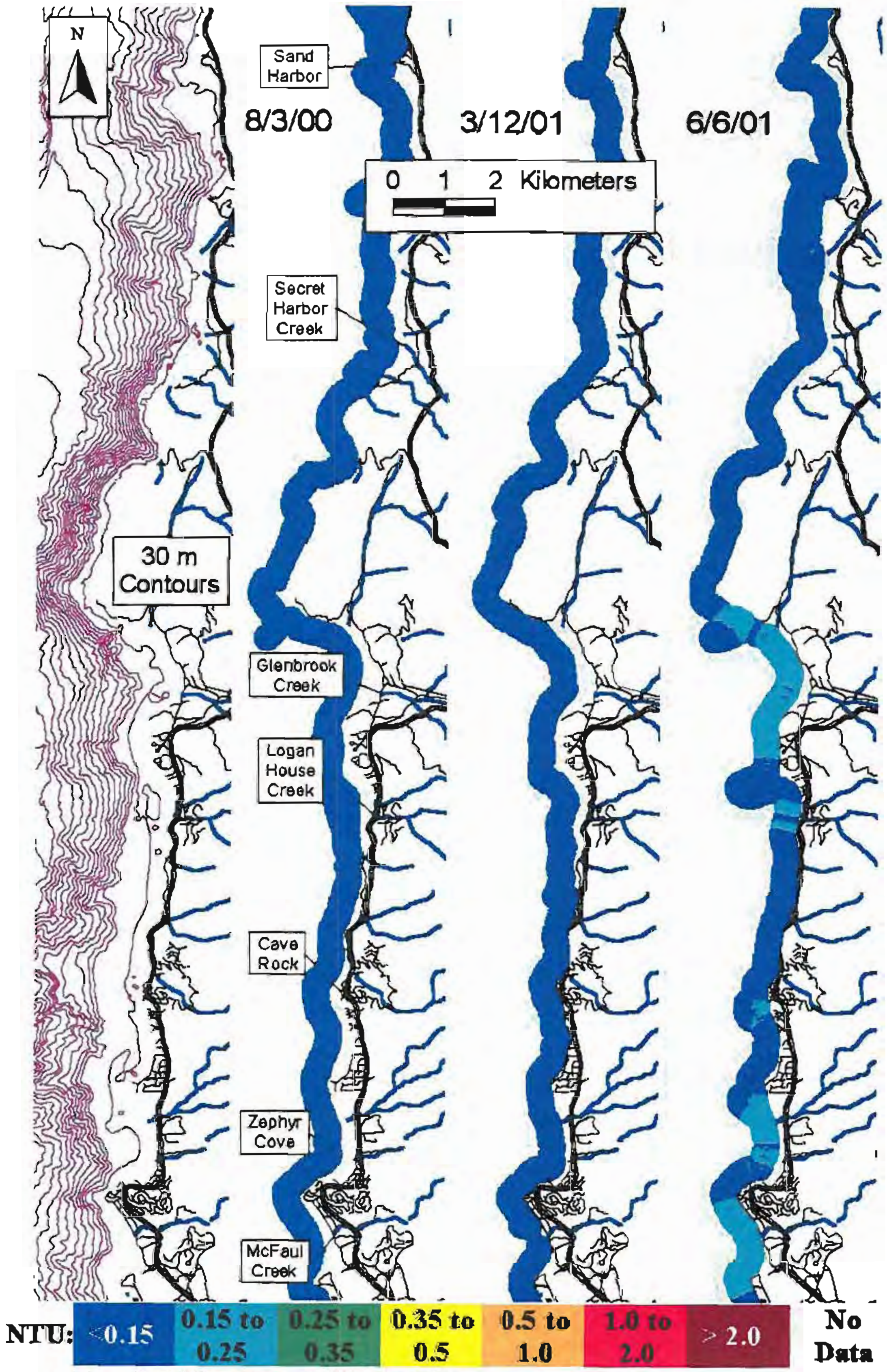


Figure 11. Turbidity surveys off the east shore.

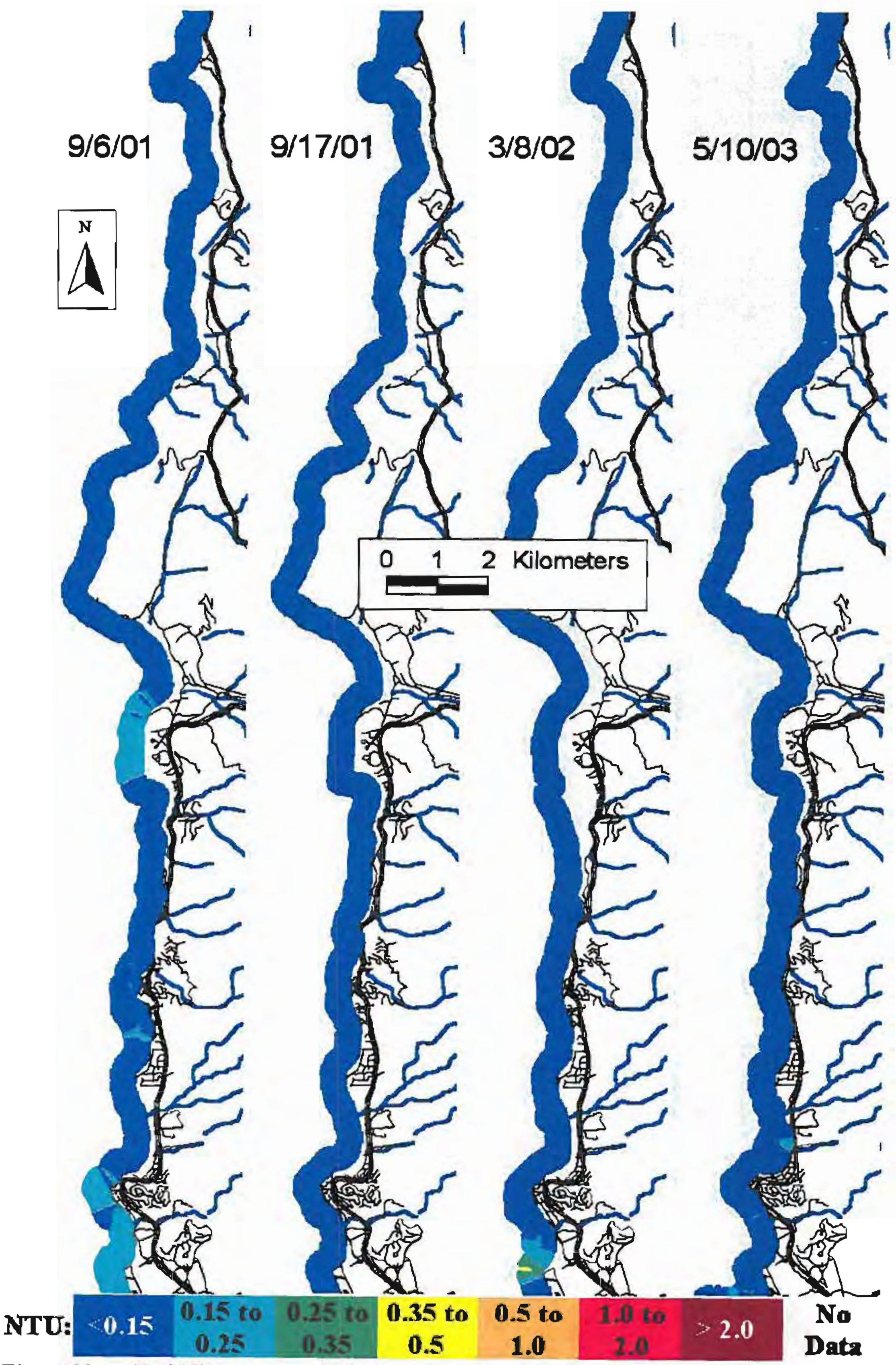


Figure 11. Turbidity surveys off the east shore (continued).

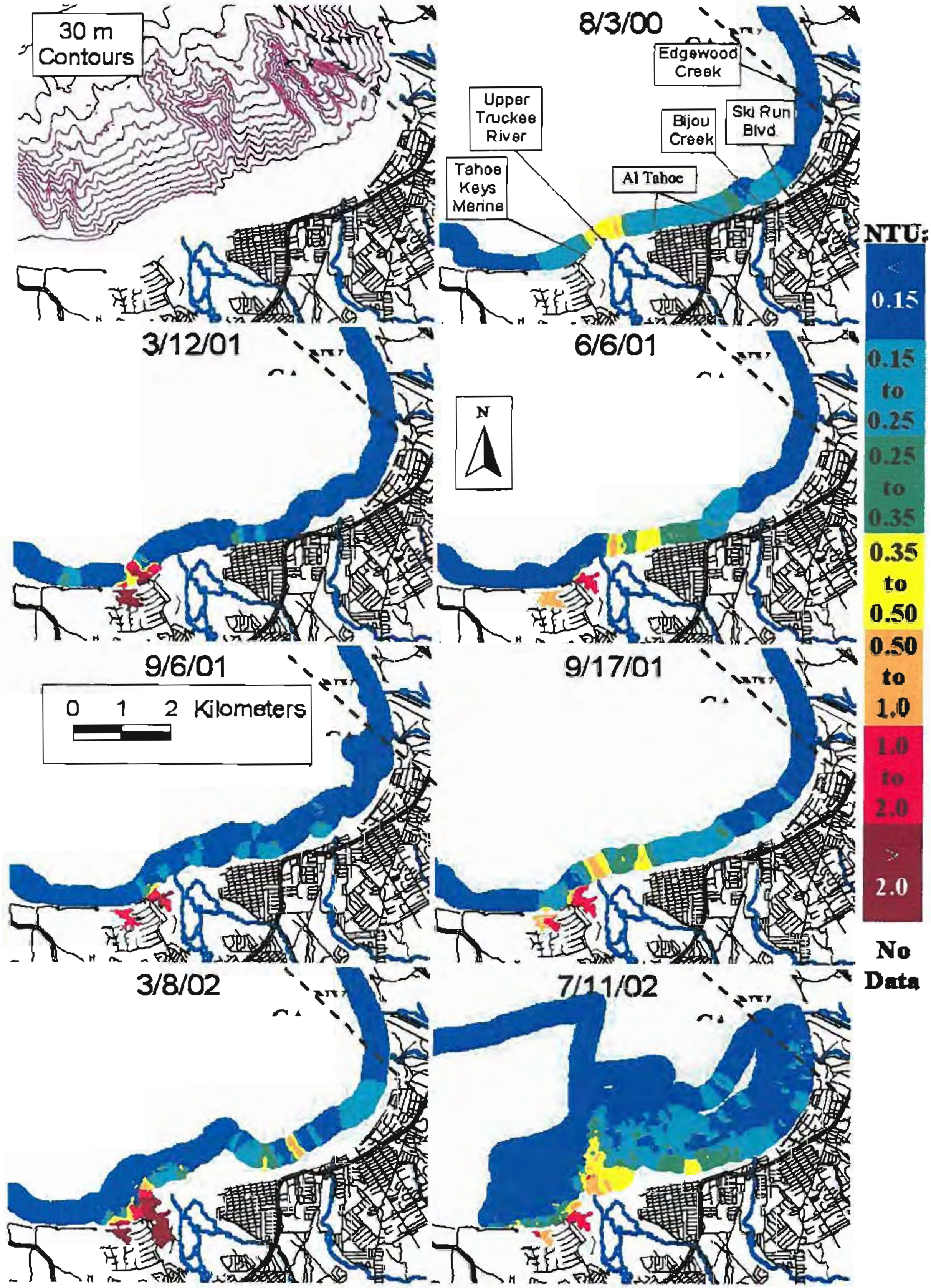


Figure 12. Turbidity surveys off the southeast shore.

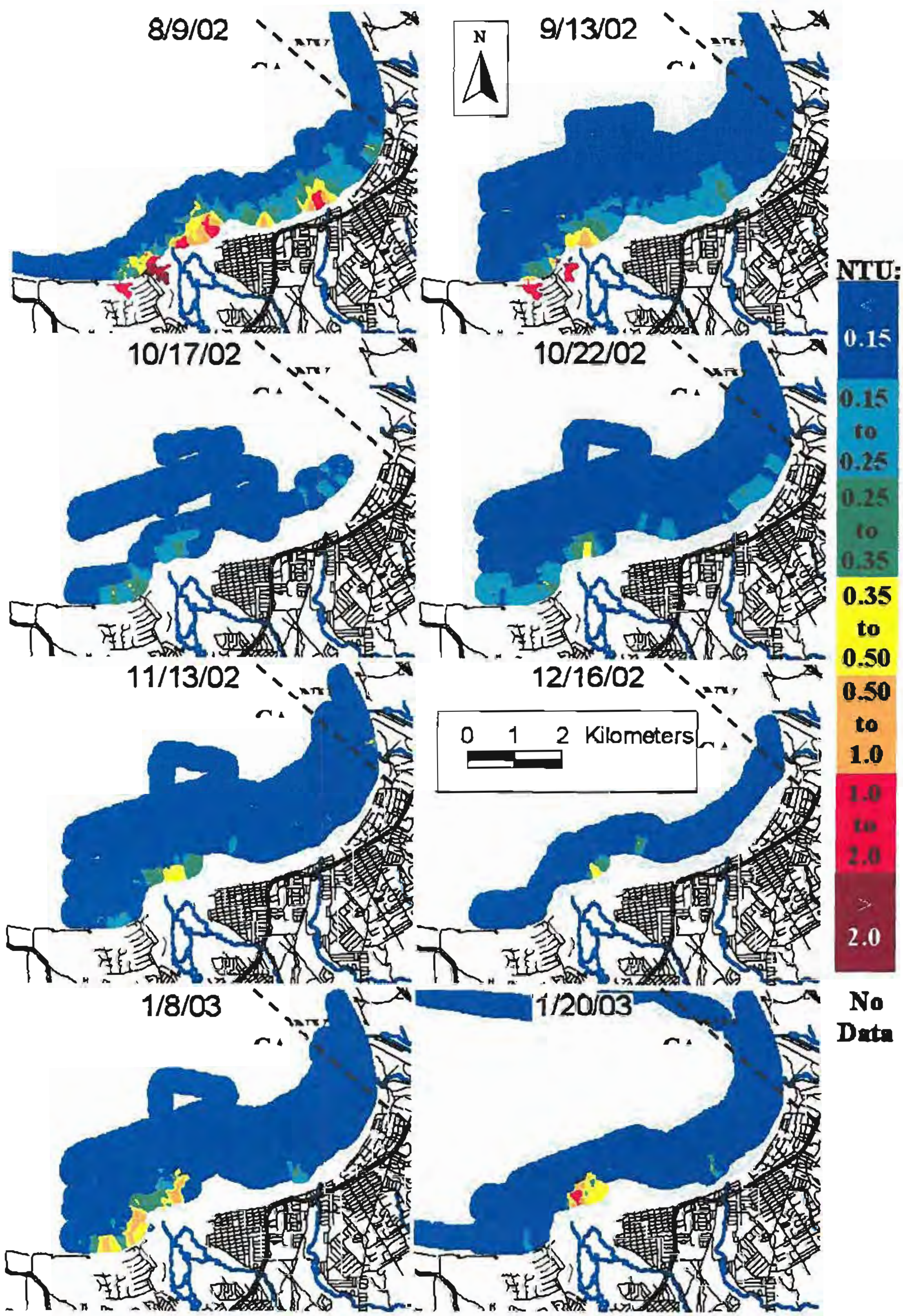


Figure 12. Turbidity surveys off the southeast shore (continued).

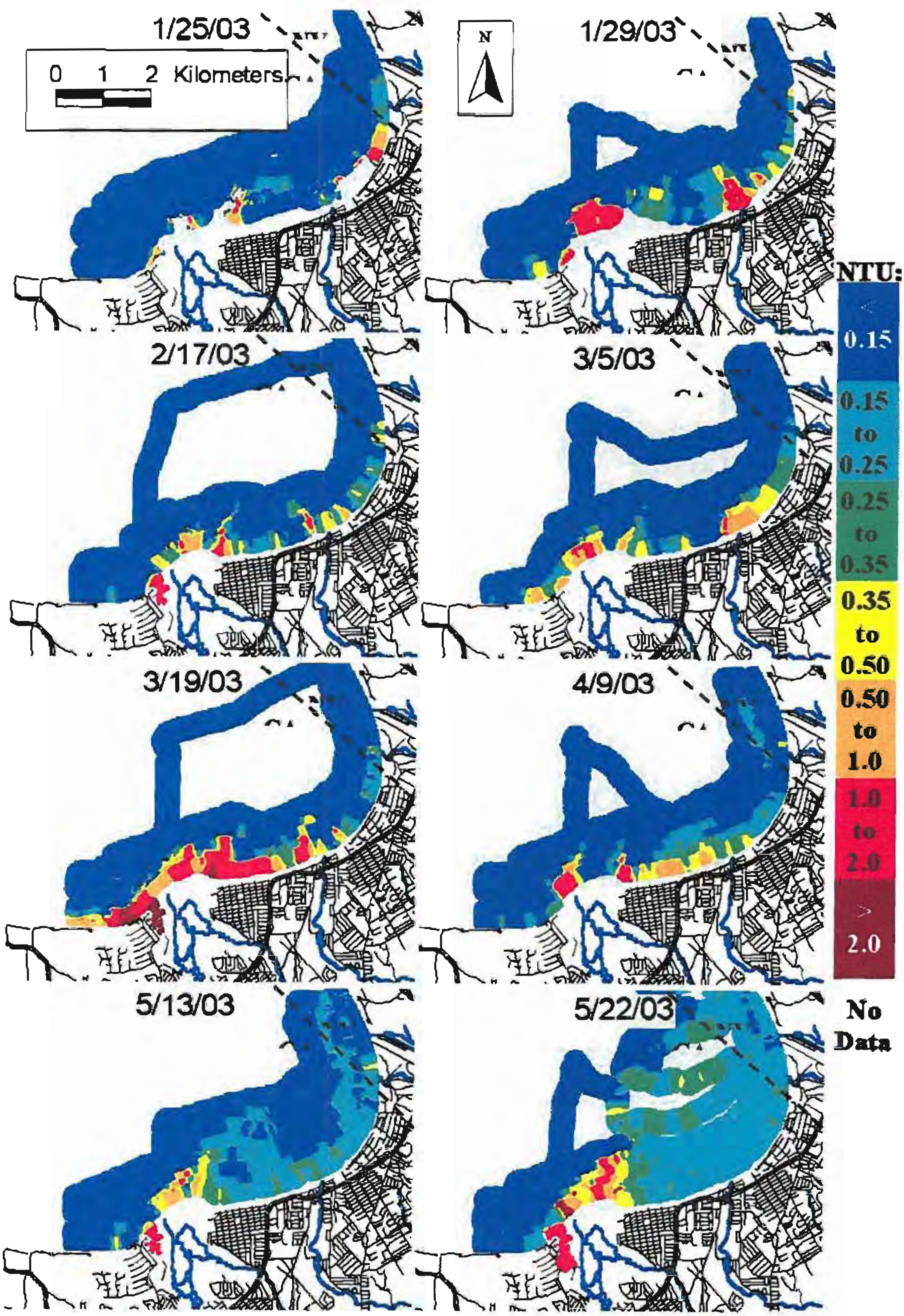


Figure 12. Turbidity surveys off the southeast shore (continued).

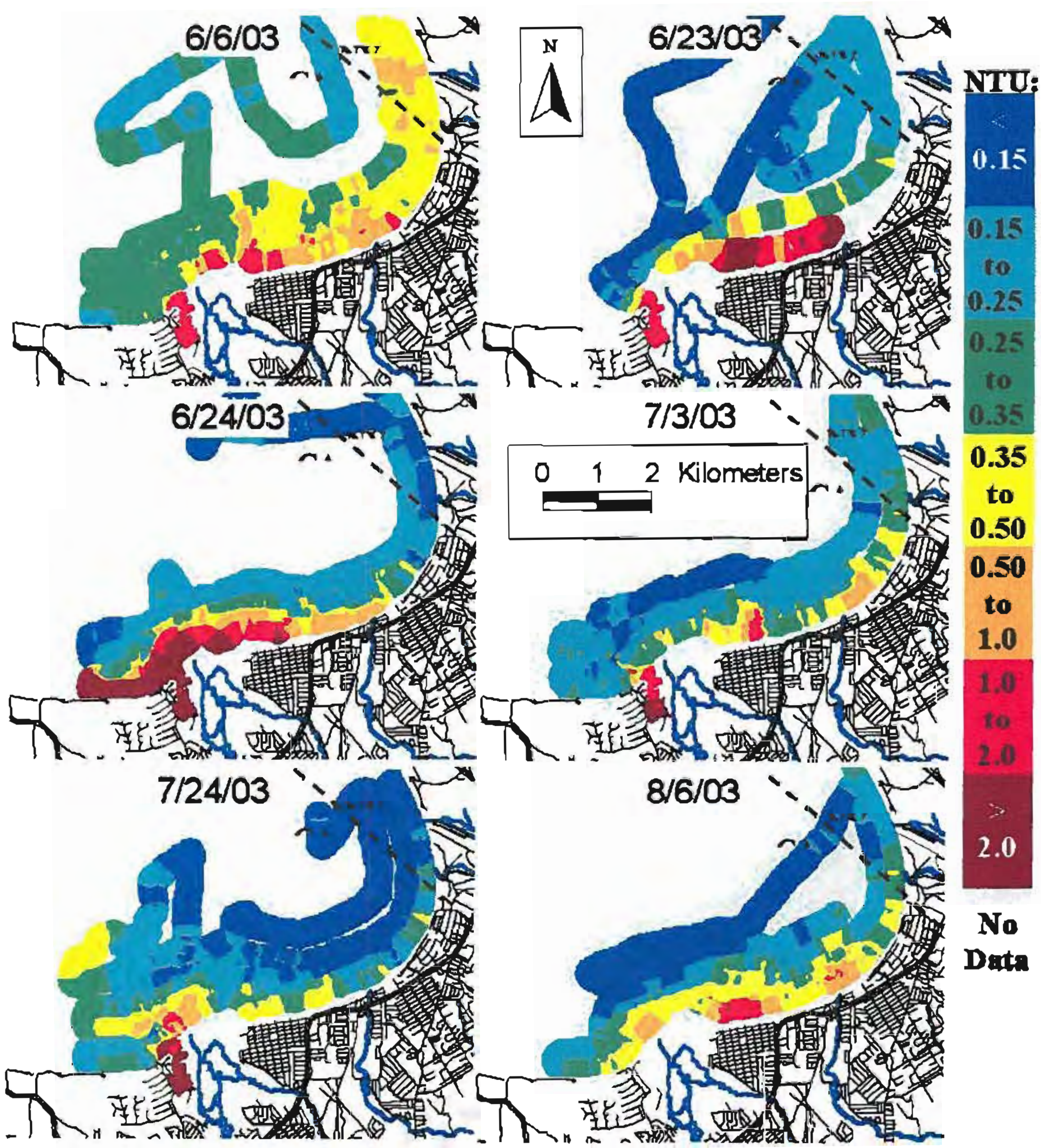


Figure 12. Turbidity surveys off the southeast shore (continued).

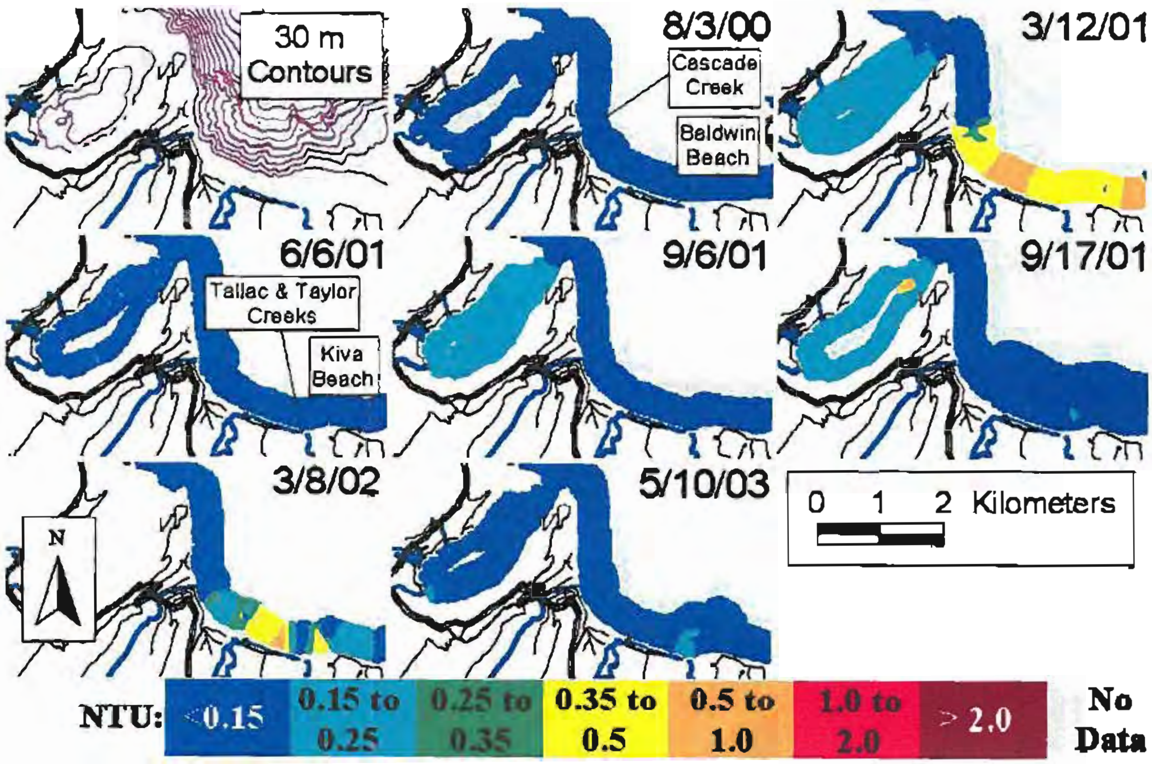


Figure 13. Turbidity surveys off the southwest shore.

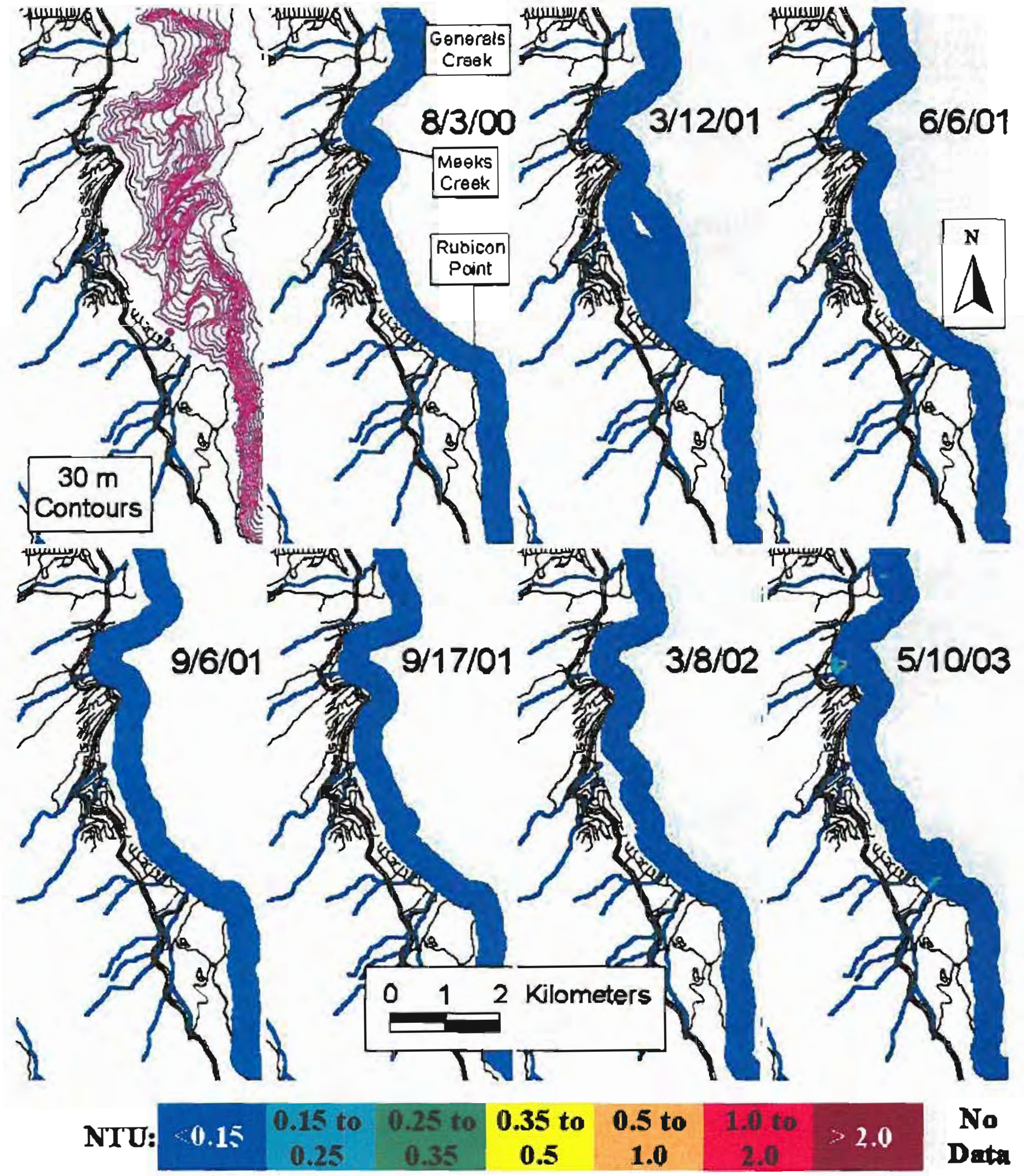


Figure 14. Turbidity surveys offshore of the Rubicon Point area.

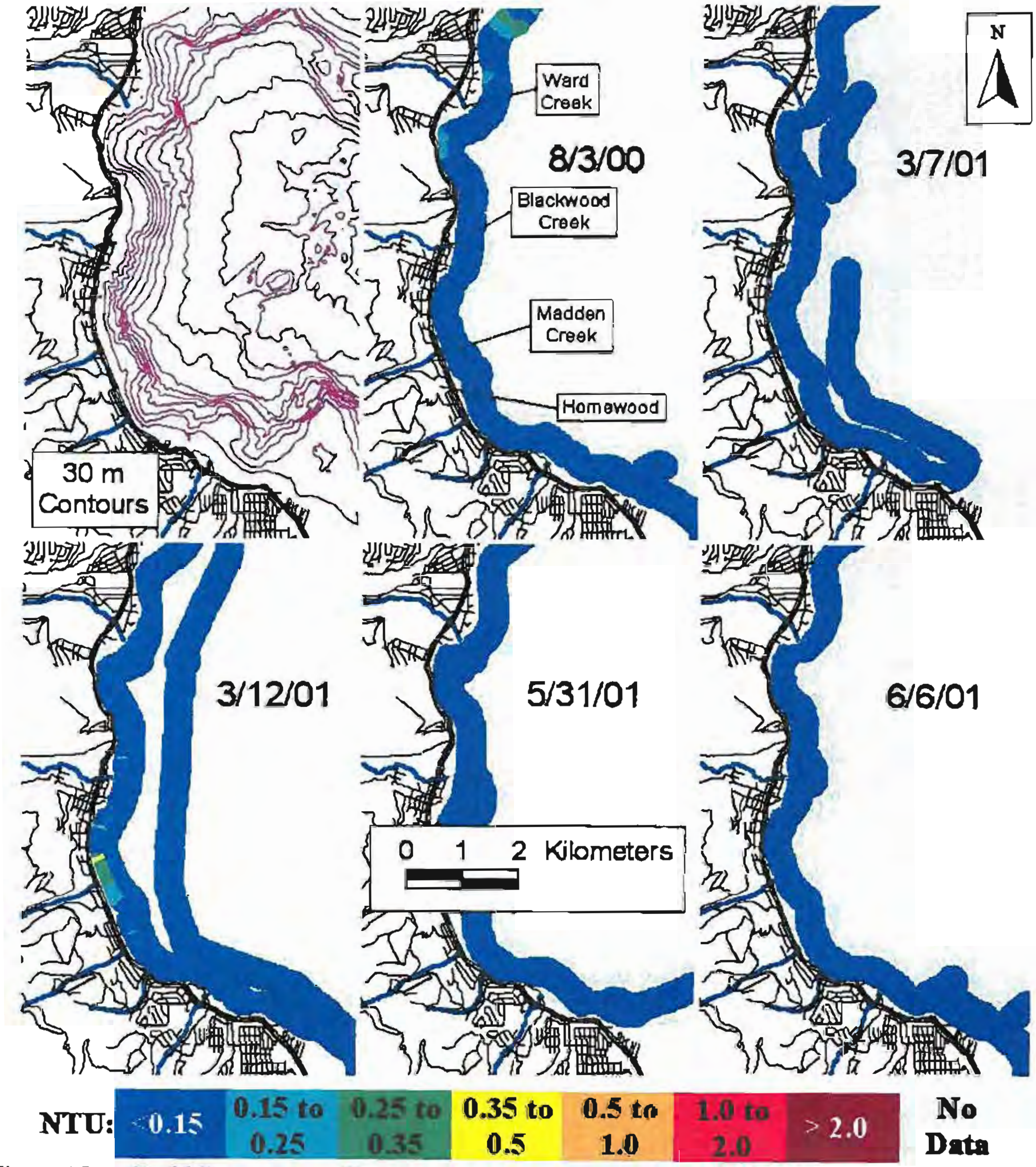


Figure 15. Turbidity surveys off the Blackwood Creek area.

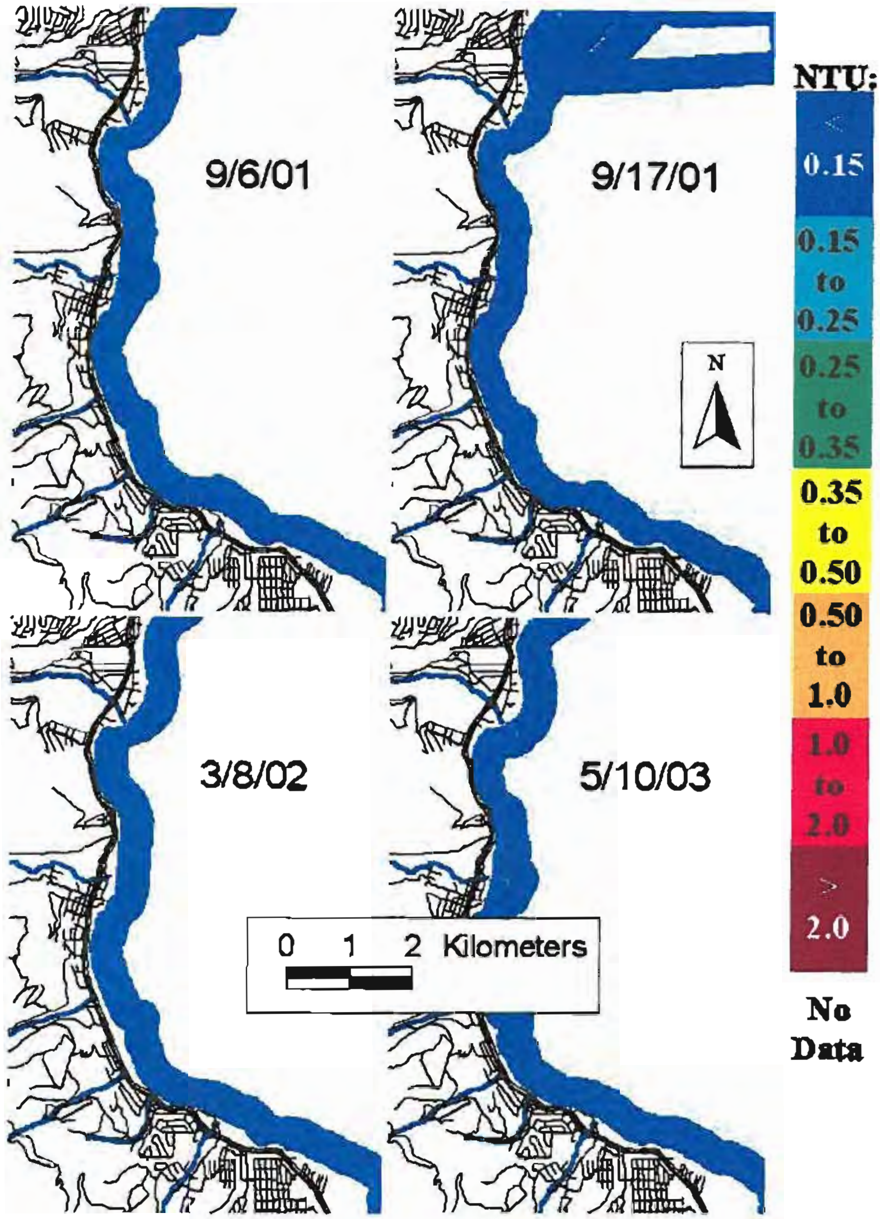


Figure 15. Turbidity surveys off the Blackwood Creek area (continued).

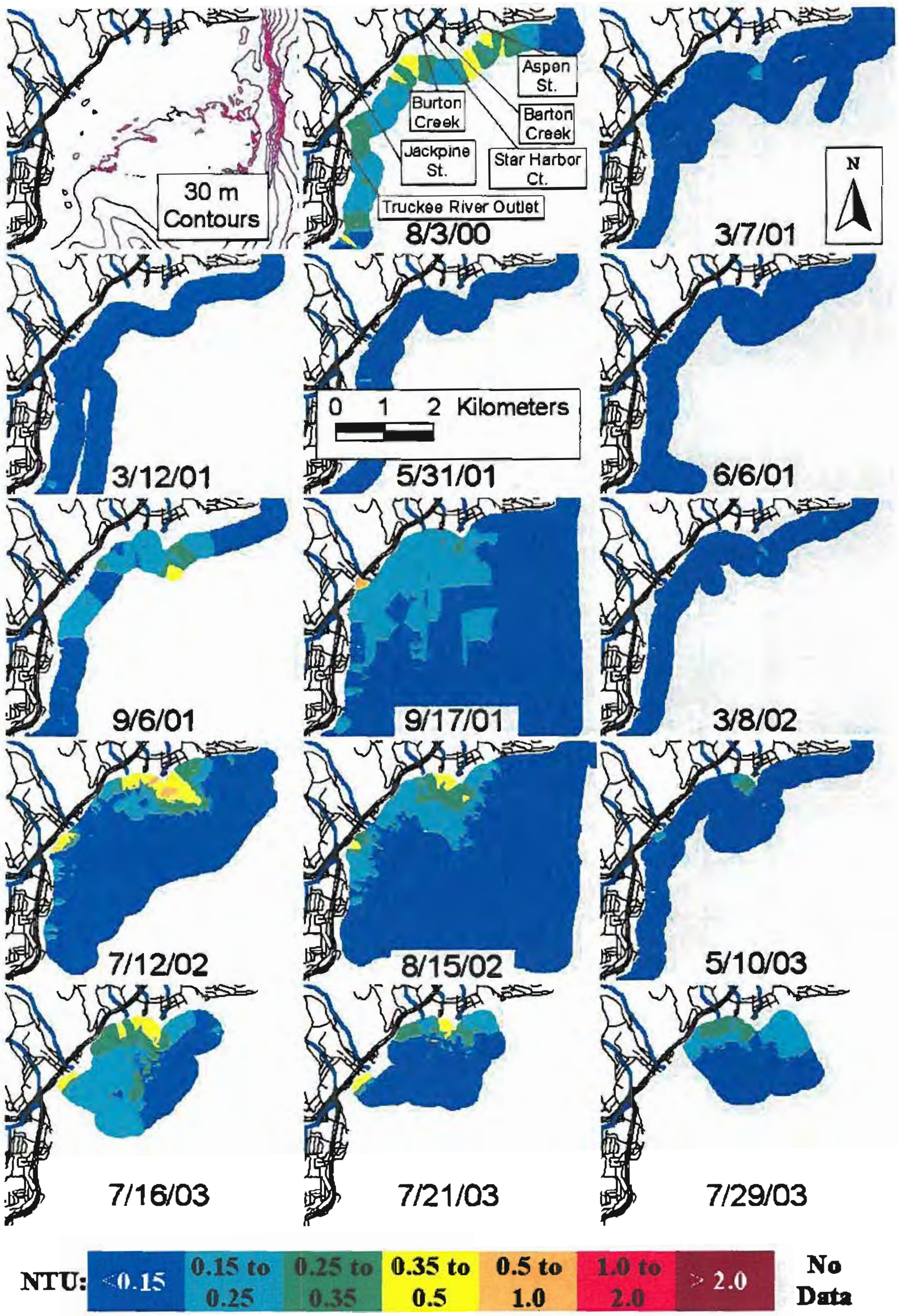


Figure 16. Turbidity surveys offshore of Tahoe City and Lake Forest.

Discussion of Areas with Persistently Elevated Turbidity

Three attributes were used to classify the magnitude of elevated turbidity in specific areas: 1) the average turbidity that was observed in the area; 2) the size of the area that was commonly observed to have a turbidity greater than 0.25 NTU; and 3) the percentage of surveys in which the turbidity was greater than 0.25 NTU. The value of 0.25 NTU was selected as a threshold because the reduction in clarity was always visually obvious to the field crew who were familiar with Lake Tahoe. A single composite quantitative indicator to express the magnitude of the elevated turbidity was not developed because surveys were not conducted frequently enough to determine the three characteristics in a statistically rigorous manner. Areas of elevated turbidity were qualitatively grouped into three categories based on the guidelines below. The definitions of the categories are subjective and a different set of definitions could be developed that uses different attributes or places a different emphasis on the attributes described above. There are also issues related to the spatial extent of some areas; somewhat subjective decisions had to be made if two adjacent areas should be considered separately or considered to be one larger area. The categories do not correspond to any regulatory standard or threshold and are related to the aesthetic aspects of clarity in a specific area. The term "frequently" implies something occurs more than 50 percent of the time.

Slightly Elevated: Areas where the average turbidity was less than 0.4 NTU and the maximum observed turbidity was less than 1.5 NTU. On the infrequent occasions when the turbidity was elevated, these areas generally had turbidity less than 0.8 NTU. A casual observer would infrequently notice the elevated turbidity.

Moderately Elevated: Areas where the average turbidity was greater than 0.4 NTU and the maximum observed turbidity was greater than 1.5 NTU. A casual observer would frequently notice the elevated turbidity.

Extremely Elevated: Areas where the average turbidity was 1.0 NTU or greater, and the average area of elevated turbidity was greater than 0.5 km^2. Even a nonobservant person would consistently notice the elevated turbidity.

Characteristics and locations of the areas with elevated turbidity are listed in Table 1.

Extremely Elevated Areas

Upper Truckee River (south shore, California, Figure 12)

The highest turbidity water in the lake was at the outlet of the Upper Truckee River. Elevated turbidity was noted in 23 out of 23 surveys, and commonly extended 0.8 km to the east, 0.5 m to the west, and 1.2 km offshore. The highest turbidity value measured (20 NTU) occurred in this area on June 24, 2003. It is possible the West Al Tahoe area, listed immediately below, should be considered part of this area, but shallow water prevented measurements that might demonstrate a connection between the two areas. This area and the other south shore areas are discussed in greater detail in the next section of this report

Table 1. Characteristics of areas with elevated turbidity.

Site	Location	State	Degree of elevated turbidity	Average values observed: Temporal average of maximum turbidity (NTU)[1]	Average values observed: Average area >0.25 NTU (km^2)[2]	Maximum values observed[3]: Turbidity (NTU)	Maximum values observed[3]: Area >0.25 NTU (km^2)	Number of observations: With turbidity >0.25 NTU[4]	Number of observations: Total[5]
Upper Truckee River	South Shore	CA	Extreme	1.0	0.7	20	3.3	23	23
West Al Tahoe	South Shore	CA	Moderate	0.7	0.3	4.1	1.2	17	22
East Al Tahoe	South Shore	CA	Moderate	0.7	0.4	3.1	1.6	16	20
Bijou Creek	South Shore	CA	Moderate	0.7	0.2	3.9	0.6	16	18
Tahoe Keys[6]	South Shore	CA	Moderate	1.1	0.2	4.1	0.8	19	22
Ski Run Marina	South Shore	CA	Moderate	0.5	0.2	1.9	0.6	11	16
Lake Forest	Lake Forest	CA	Slight	0.3	0.4	0.9	0.8	9	14
Edgewood Creek	South Shore	NV	Slight	0.3	0.2	1.1	0.4	7	23
Third & Incline Creeks	Incline Village	NV	Slight	0.2	0.1	0.9	0.1	3	11
Tahoe City	Tahoe City	CA	Slight	0.3	0.1	0.9	0.1	6	14
Kings Beach	Kings Beach	CA	Slight	0.2	0.1	0.6	0.2	3	10
Cascade Ck. to Kiva Beach	Southwest	CA	Slight	0.2	0.7	1.0	1.1	2	7
Emerald Bay	Southwest	CA	Slight	0.2	0	0.2	0	0	6

[1] Temporal average of the spatially averaged turbidity along the shore.

[2] Temporal average of the area having a turbidity greater than 0.25 NTU observed at each site.

[3] Maximum values observed during this study. The maximum value, which extends over small areas, cannot be observed in the figures used in this report.

[4] Number of surveys during which a turbidity greater than 0.25 NTU was observed during this study.

[5] Number of surveys made at the site that were included in the analysis. For south shore sites, only data from the intensive surveys (July 11, 2002 to August 6, 2003) was included, as an effort was made to approach as close to shore as possible. Sites from the intensive survey were discarded if adequate data was not available. Analysis at other sites around the lake included all available data.

[6] Does not include the interior of the Tahoe Keys Marina.

West Al Tahoe (south shore, California, Figure 12)

On the west side of Al Tahoe there was an area that had persistently elevated turbidity (July 6, 2001; September 17, 2001; January 25, 2003; February 17, 2003; March 19, 2003; April 9, 2003; June 6, 2003; June 23, 2003). Elevated turbidity frequently extended along 200 m of shoreline and there were no obvious surface water or storm drain discharges in this area. This area is 1 km from the outlet of the Upper Truckee River in the direction that wind-driven currents frequently push the plume from the Upper Truckee River. The high turbidity water likely flowed along the shore from the Upper Truckee River to this area, but it was too shallow for us to document this. Additional studies using an instrumented kayak or jet ski in shallow water that could not be accessed with the research vessel Mount Rose would improve our understanding of this situation.

Moderately Elevated Areas

East Al Tahoe (south shore, California, Figure 12)

On the east side of Al Tahoe there was frequently an area of elevated turbidity that was spatially distinct from the high turbidity area on the west side of Al Tahoe (July 11, 2002; August 8, 2002; September 9, 2002; March 5 2003; April 9, 2003; July 3, 2003; July 23, 2003). This area frequently extended along 200 m of shoreline. There are large urban storm water outlets in this area that may have been the cause of the high turbidity in this area during periods of high urban runoff, however monitoring of the these culverts suggests they have small and infrequent discharges. Additional studies are required to confidently understand the relative significance of urban runoff, wave resuspension of bottom sediments, and outflow from the Upper Truckee on the near-shore clarity in this area.

Bijou Creek (south shore, California, Figure 12)

Bijou Creek introduced water with a very high turbidity to the lake particularly during low-elevation snowmelt and precipitation events that produce urban runoff. The area adversely influenced by Bijou Creek frequently extended along 600 m of shoreline and 700 m offshore.

Tahoe Keys (south shore, California, Figure 12)

The high turbidity water in the two bays of Tahoe Keys can only enter the lake by exchange though the entrance channels. This is a highly time-dependent and seasonally varying process. Inflows from the Upper Truckee River, 250 m to the east of the Tahoe Keys Marina, complicated the assessment of how much of the turbidity off Tahoe Keys was elevated by outflow from Tahoe Keys and how much of it was elevated by the outflow of the Upper Truckee River. During time periods when lake currents where pushing the outflow of the Upper Truckee away from Tahoe Keys, or when the influence of the Upper Truckee on near-shore turbidity was small, the lake was only moderately affected by outflow from the Tahoe Keys and boat traffic resuspension (e.g., March 12, 2001; June 6, 2001; July 11, 2002; August 9, 2002; May 13, 2003). However, as this study was primarily based on measurements taken at a depth of 0.5 m, nothing can be said about exchange occurring below this depth. Additional studies with measurements at multiple depths, and using an instrumented kayak to allow measurements in water less than 0.7 m would improve our understanding of this situation.

Ski Run Marina (south shore, California, Figure 12)

Ski Run Marina is adjacent to a large area of water less than 0.5 m deep and is the homeport of a paddle wheeler that stirs up bottom sediment. The area of elevated turbidity off of Ski Run Marina typically extended 100 m to the west, 200 m to the east, and 400 m offshore. The water quality seemed to be occasionally influenced by Bijou Creek, 500 m to the west. During periods of urban runoff, water flowed through a series of retention ponds, into the marina, and out into the lake. This flushed the low-quality water in the marina into the lake along with the urban storm water.

Slightly Elevated Areas

Lake Forest (Lake Forest, California, Figure 16)

The area of elevated turbidity extended approximately 1.2 km along the shore from Star Harbor Court to Aspen Street, and extended 700 m offshore. Several ephemeral streams discharged into the lake during the spring, but they were not a likely source in late summer. This area did have a shallow area that became an island at low lake levels, which may have been a source of resuspended particles. More studies are needed to understand the causes of clarity loss in this area.

Third and Incline Creeks (Incline Village, Nevada, Figure 10)

Elevated turbidity was observed only during times when the creeks had elevated discharge (e.g., snowmelt or after precipitation). The spatial extent of elevated turbidity was always observed to be within 20 m of the outlet. Between 1989 and 1997, the average combined suspended sediment inflow into Lake Tahoe from Incline and Third creeks was about 60 % of the sediment inflow from the Upper Truckee River (Rowe et. al, 2002). Despite the large suspended sediment load from Incline and Third creeks the increase in near-shore turbidity off Incline and Third Creeks is insignificant compared to the near-shore turbidity increase off the Upper Truckee River. It is likely the near-shore turbidity off Incline and Third Creeks is low because a rapid increase in the depth of the lake just off the stream outlets allows stream inflows to rapidly mix with cleaner lake water.

Tahoe City (Tahoe City, California, Figure 16)

Elevated turbidity was occasionally observed around Tahoe City. There is a small ephemeral stream next to the Safeway that is primarily urban runoff and which has been observed to have high turbidity by the Lake Tahoe Environmental Education Collation snapshot day monitoring program. This area has extensive commercial development both onshore and in the lake. Large areas of shallow water, and outflow to the Truckee River, also complicated the hydrology of this area.

Kings Beach and Tahoe Vista (north shore, California, Figure 9)

Elevated turbidity levels were low (<0.4 NTU) and not persistent. The location of the area with elevated turbidity was variable, possibly because there was not a strong source of high turbidity inflows and water currents moved the plume around in the lake, or because there were multiple small sources in this area. The cause of elevated turbidity in this area is not known. It does not seem to be associated with abnormally high algae content suggestive of high nutrients, but more studies will be required to identify the cause of elevated turbidity in this area.

Cascade Creek to Kiva Beach, California (southwest shore, Figure 13)

The area between Cascade Creek and Kiva Beach exhibited slightly elevated turbidity only on rare occasions. We do not have enough measurements in this area to comment on the possible causes.

Emerald Bay (southwest shore, California, Figure 13)

Emerald Bay consistently exhibited a slightly elevated turbidity of approximately 0.2 NTU with particles that were predominately organic material. This could be caused by surface inflows and limited mixing with the lake. Comparison studies between Emerald Bay and Cascade Lake (which has similar land use around it) would help to address that issue.

Edgewood Creek (southeast shore, California, Figure 12)

At Edgewood Creek, plumes of water with elevated turbidity were infrequently observed extending several meters into the lake and extending about 50 m along the shore before being dispersed by mixing with cleaner lake water. The 2002 Gondola fire that occurred in part of the Edgewood Creek watershed did not result in significantly increased turbidity offshore of Edgewood Creek. It appeared the turbidity was occasionally elevated in this area by eastward movement of high turbidity water from the Ski Run Marina and Bijou Creek area (March 5, 2003; July 3, 2003; Figures 9-13 and 19-21).

Noteworthy areas that did not have elevated turbidity

The areas offshore of Ward and Blackwood creeks (Figure 15) were not observed to have elevated turbidity. Average yearly suspended sediment inflows into Lake Tahoe from Ward and Blackwood creeks between 1989 and 1997 were 33 % and 63 %, respectively, of the suspended sediment inflow from the Upper Truckee River (Rowe et. al, 2002). The absence of elevated turbidity off Ward and Blackwood creeks is likely due to the rapid increase in the depth of the lake at the stream outlets that allow the stream inflows to rapidly mix with cleaner lake water.

INFLUENCES ON NEAR-SHORE CLARITY ALONG THE SOUTH SHORE

Overview

The near-shore zone responds quickly to seasonal and storm influences because it does not have the large volume of water that dampens changes in clarity like the deeper portions of the lake. The near-shore zone also receives concentrated and localized inflows, as well as sediment resuspension from the bottom, that will have a strong influence on water clarity. A major goal of this project was to determine how near-shore clarity is influenced by seasonal changes and different types of storms and other hydrologic events (e.g., fall during calm conditions, fall rain, mid-winter during calm conditions, rain on snow, low elevation snow melt, early spring run off, late spring run off, early summer, summer rain, mid-summer). This is of interest because it helps determine when and where clarity-reducing material enters the lake.

In this study, spatial turbidity surveys were repeatedly conducted off the southeast shore to provide an indication of the spatial and temporal distribution of particles in the water. Near-shore turbidity is not necessarily related to the flux of particles into the lake in a given area. For example, an area could have low turbidity because there is a low flux of particles to the lake, or it could have low turbidity because there is a large near-shore current that dilutes a turbid inflow with cleaner water. However, high turbidity is proof of an elevated concentration of particles in that area.

At any time, and particularly during storms, there are large differences in wind direction and speed across the study area. Precipitation during a single storm is also not uniformly distributed across the study area. Only the general characteristics of each storm are reported because there is not enough information to describe the spatial patterns of precipitation and wind in detail.

Presentation of Data

Repeated spatial surveys of turbidity and chlorophyll were made in the South Shore area to determine how near-shore clarity in different areas was influenced by seasonal changes and different types of storms. The size of the study area was selected such that it could be surveyed during a long field day. The southeast portion of the lake (Figures 17a and 17b) was selected as the study area because it contains a wide range of land uses and was known to have elevated turbidity. Heavily developed commercial areas include the Stateline, Nevada casinos, and the Bijou Creek and Ski Run commercial areas. There is a golf course along Edgewood Creek and Bijou Creek. The largest surface inflow to the lake occurs from the Upper Truckee River. Undeveloped areas include Nevada and Pope beaches. Residential areas include the older Al Tahoe area, and the more upscale area between Ski Run Marina and Edgewood Creek. Tahoe Keys consists of two large artificial bays formed by dredging a portion of the Truckee Marsh. There is a shallow shelf off most of the study area (Figure 17a) that has a sharp drop off. The shallow water off the Upper Truckee River outlet and Al Tahoe forced us to stay approximately 200 m offshore in these areas. Surveys were made repeatedly during a one-year period during calm periods and shortly after storms (Table 2). The surveys

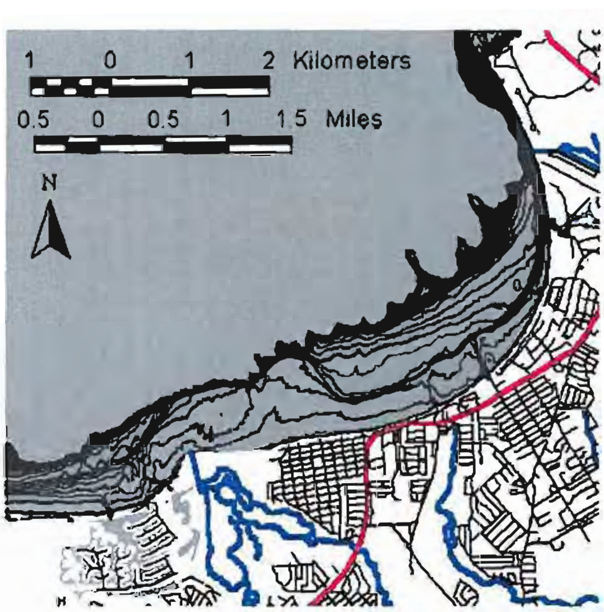


Figure 17a. Map of study area showing 1.5 meter water depth contours to a depth of 30 meters.

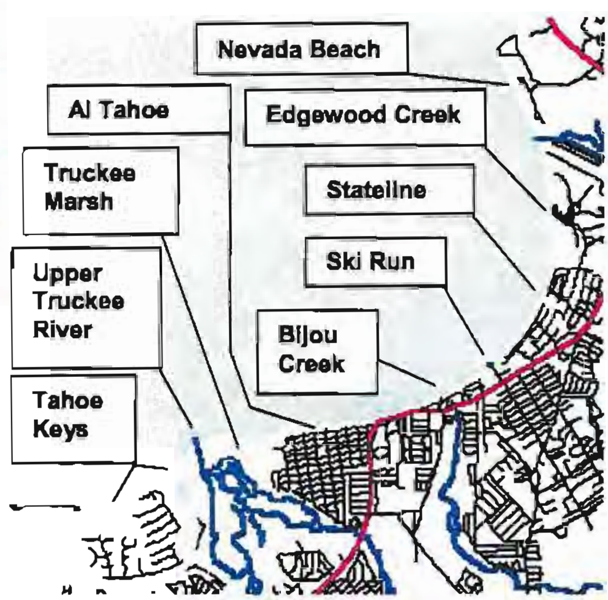


Figure 17b. Map of study area showing place names.

consisted of multiple transects at different distances offshore. As much as practicable, transects were at the same locations in all the surveys. However, variations in the location of the transects, particularly the ones further from shore, occurred due to weather conditions and boat traffic. Surface inflow and precipitation records are shown in Figures 18a and 18b. The surveys are shown in Figures 19-1 to 19-23 as maps of turbidity and maps of the turbidity/chlorophyll ratio. These turbidity maps are the same as shown in Figure 12 and are reproduced here to facilitate comparison with the ratio maps. The ratio maps provide a qualitative indication of if the particles are predominantly organic or mineral material.

Table 2. Dates and conditions when spatial surveys were done at South Lake Tahoe.

Date	Preceding Hydrologic Conditions	Comments	Fig #
July 11, 2002	Calm, mid-summer	Low turbidity	19-1
August 9, 2002	Calm, mid-summer	Low turbidity	19-2
September 13, 2002	Calm, late summer	Low turbidity	19-3
October 17, 2002	Calm, fall	Low turbidity	19-4
October 22, 2002	Calm, fall	Low turbidity	19-5
November 13, 2002	After first winter storm, 2 inch snow onshore, small increase in discharge from Upper Truckee	Not much change after storm	19-6
December 18, 2002	During major winter storm, marina frozen, increase in discharge from Upper Truckee	Decrease in turbidity	19-7
January 8, 2003	After major winter storm, some melting	Moderate turbidity	19-8
January 20, 2003	Calm, winter, melting snow on shore	Moderate turbidity	19-9
January 25, 2003	Two days after rain on lakeshore	High turbidity	19-10
January 29, 2003	Calm, all snow melted	High turbidity	19-11
February 17, 2003	After storm, 10 cm of snow at lake level	Moderate turbidity	19-12
March 5, 2003	Calm, winter	Moderate turbidity	19-13
March 19, 2003	Two days after lake level rain	Large, high turbidity areas	19-14
April 9, 2003	Snow at lake level, then wind, snow melted when survey made	High turbidity	19-15
May 13, 2003	Beginning of Upper Truckee runoff	Moderate turbidity	19-16
May 22, 2003	During Upper Truckee runoff	Extensive high turbidity areas spreading across the south shore	19-17
June 6, 2003	During Upper Truckee runoff	Extensive high turbidity	19-18
June 23, 2003	After Upper Truckee runoff, calm before summer rain	High turbidity near Upper Truckee	19-19
June 24, 2003	After half inch of rain	Maximum turbidity of 20 NTU off Upper Truckee River	19-20
July 3, 2003	Calm, summer	Moderate turbidity	19-21
July 24, 2003	Immediately after several summer thundershowers	Moderate turbidity	19-22
August 6, 2003	A week after several summer thundershowers	Moderate turbidity	19-23

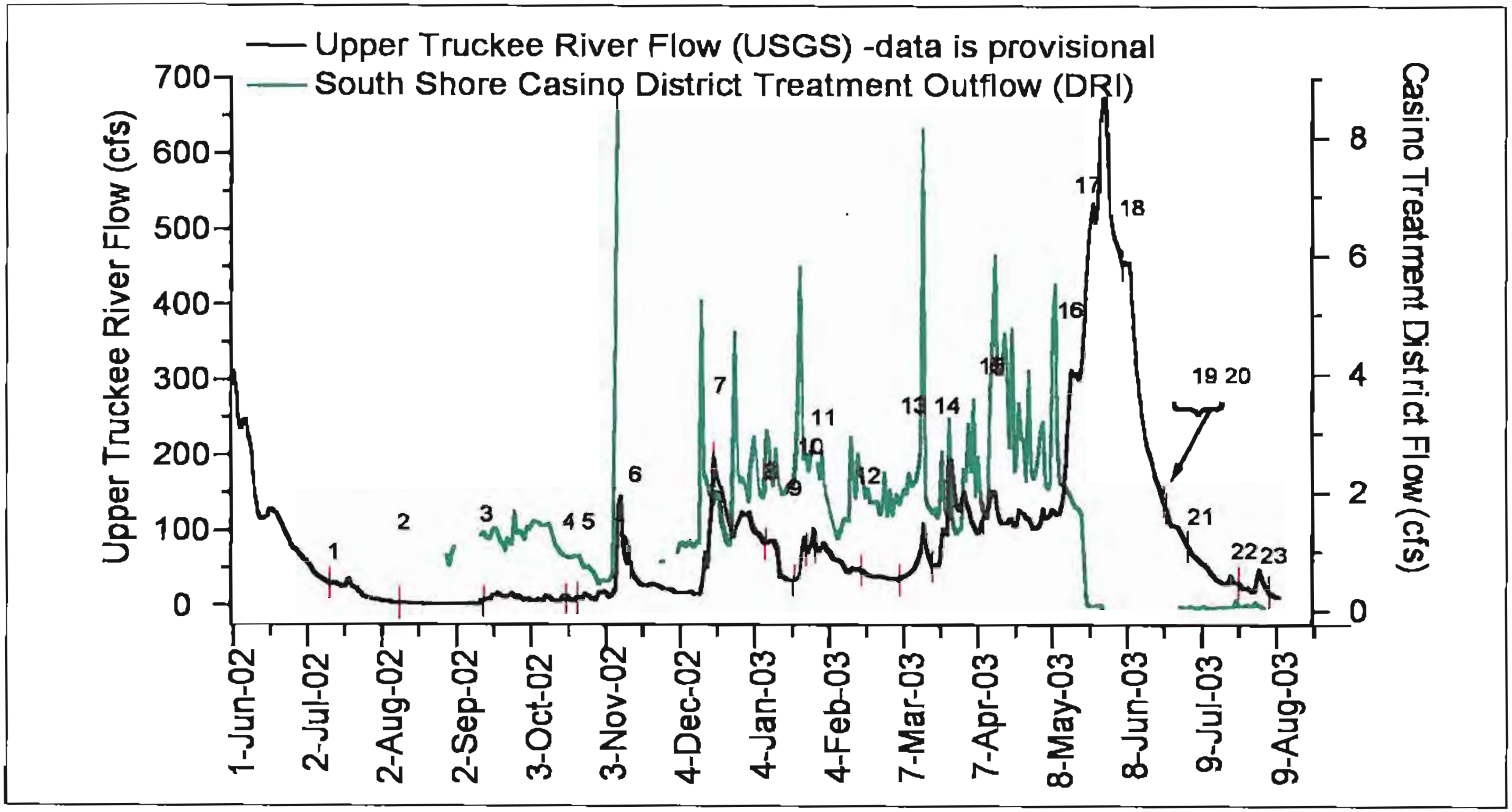


Figure 18a. Timing and magnitude of surface water inflows to Lake Tahoe. The data for the Upper Truckee River (black) are provisional data from the U.S. Geological Survey. Also shown are urban storm drain inflows from the State Line Casino District (green). These can be used as a general indication of urban storm drain inflows. These data were collected by Todd Mihevc (DRI) after August 28, 2002. The red lines are dates when spatial surveys were conducted off South Shore. The numbers by the red lines correspond to the number of the figure that shows the survey. For example, the red line labeled "2" on August 9. 2002, corresponds to the survey shown in Figure 19-2.

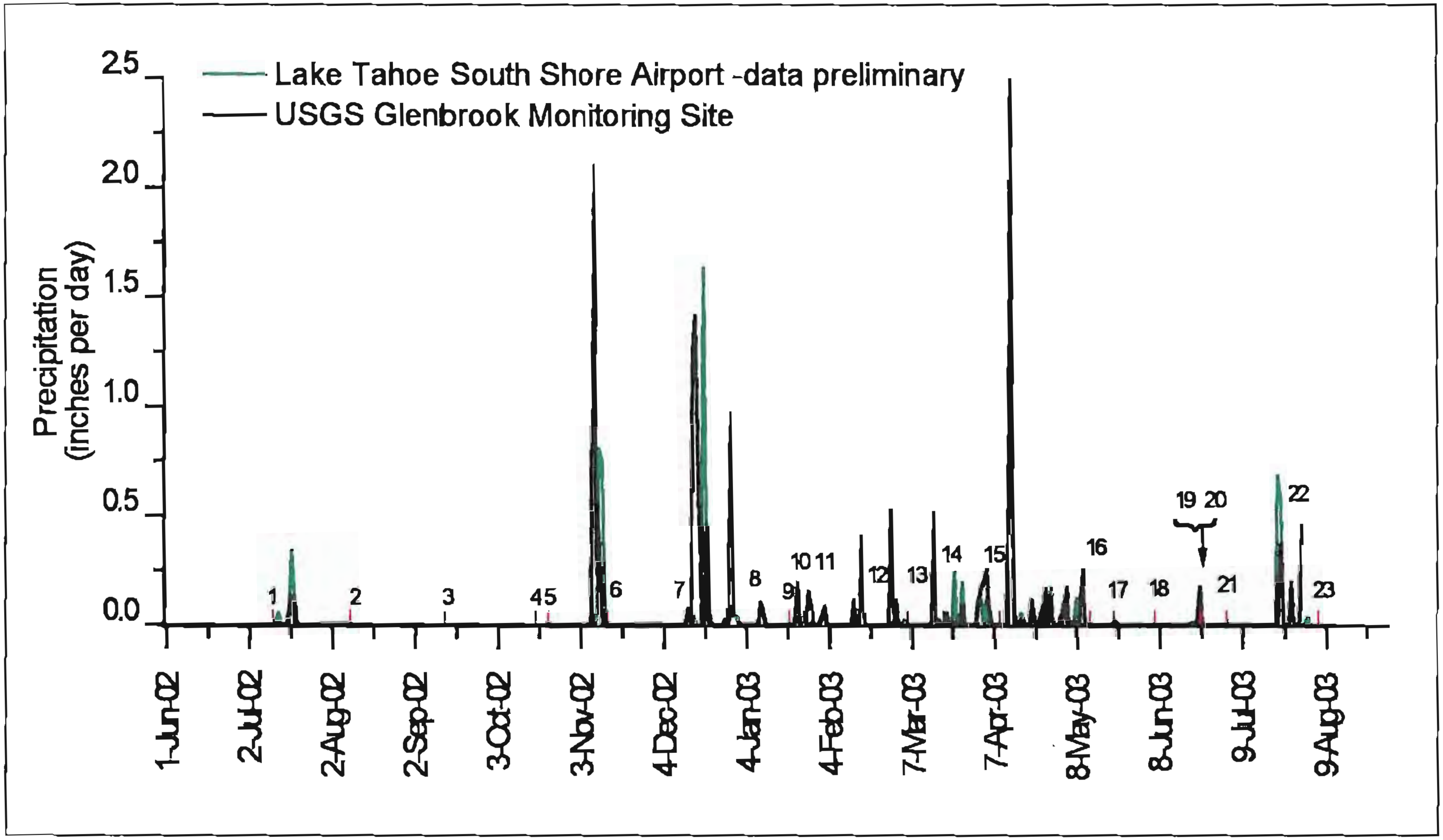


Figure 18b. Timing and magnitude of precipitation measured at the South Lake Tahoe airport and the Glenbrook fire station. Both records rely on manual reporting that may not record all precipitation events and are influenced by large spatial variability in precipitation.

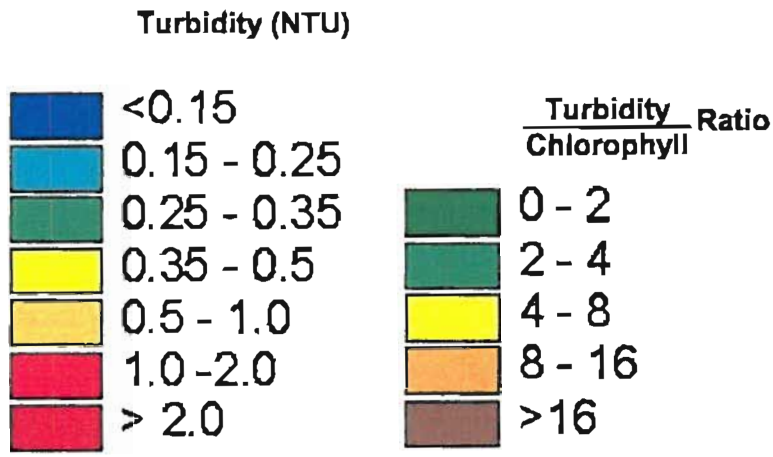


Figure 19-0. Color scales for maps in Figures 19-1 to 19-23. The units of the turbidity/chlorophyll scale are NTU/volts. These units are only meaningful for the instrumentation used in this study and can only be used as a relative indication of the origin of the particles. The greater the ratio value, the greater the percentage of mineral particles and the lower the percentage of organic particles. The map scale and location are the same as in Figure 17, which also shows the bathymetry and some place-names. The second part of the figure number corresponds to the number on the red lines in Figure 18 (e.g., Figure 19-2 occurred at the time of the red line labeled "2" in Figure 18.

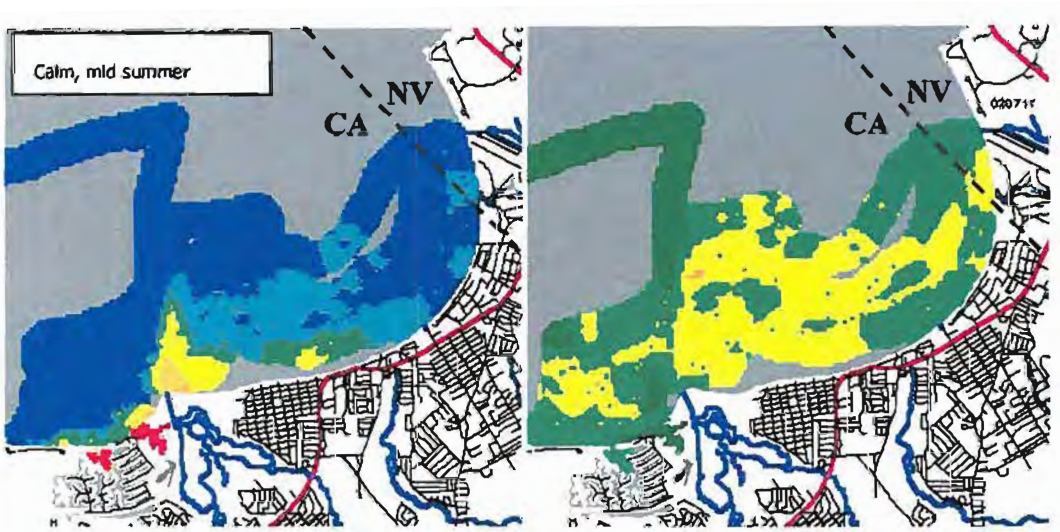


Figure 19-1. Turbidity and particle characterization maps for July 11, 2002.

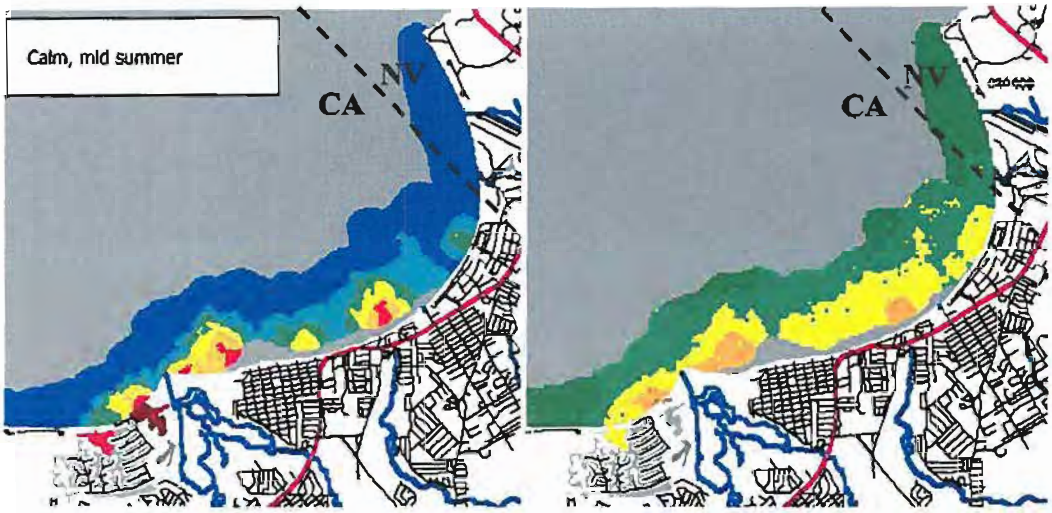


Figure 19-2. Turbidity and particle characterization maps for August 9, 2002.

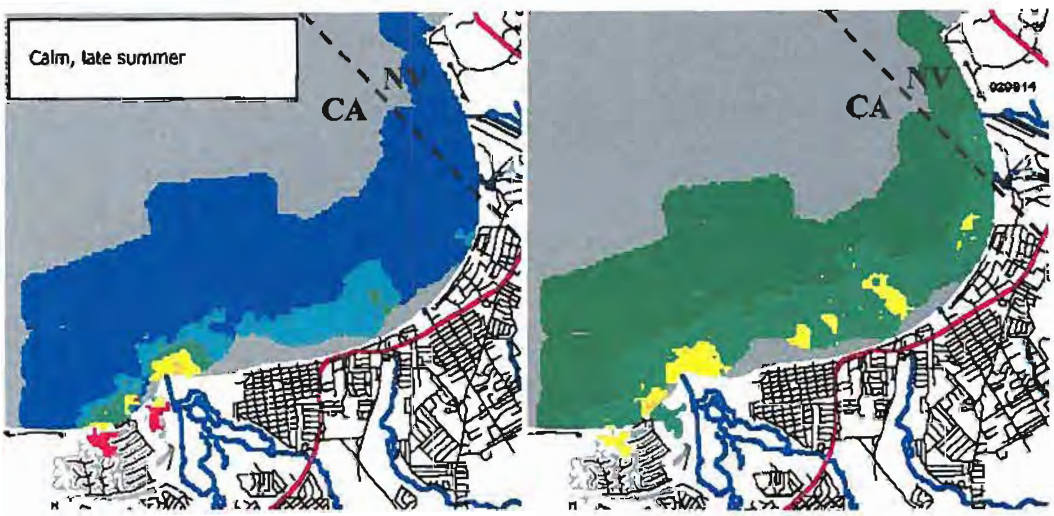


Figure 19-3. Turbidity and particle characterization maps for September 13, 2002.

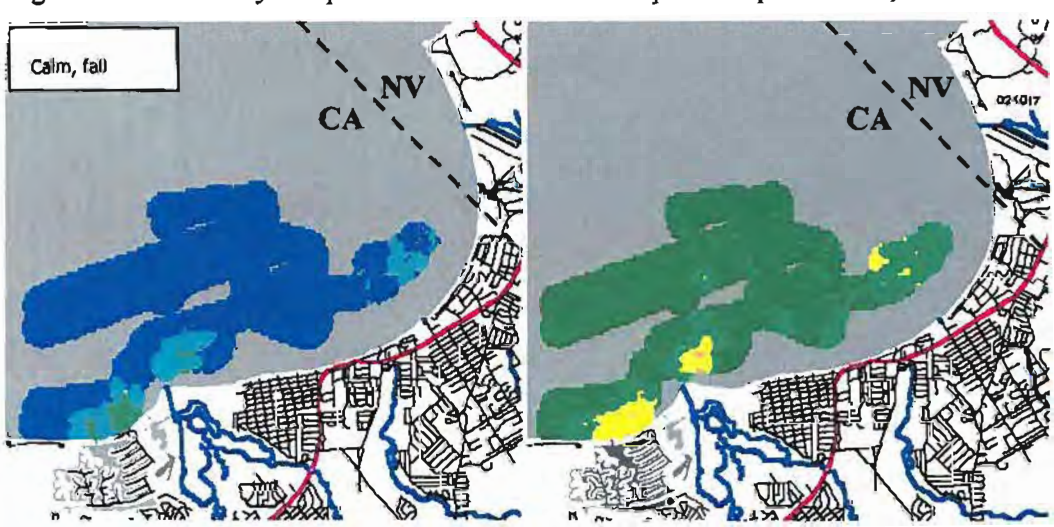


Figure 19-4. Turbidity and particle characterization maps for October 17, 2002.

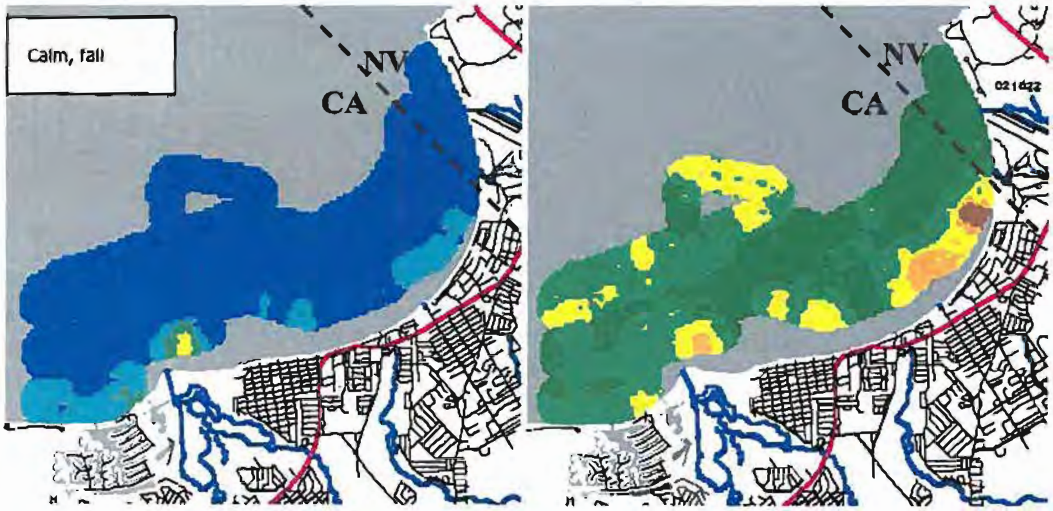


Figure 19-5. Turbidity and particle characterization maps for October 22, 2002.

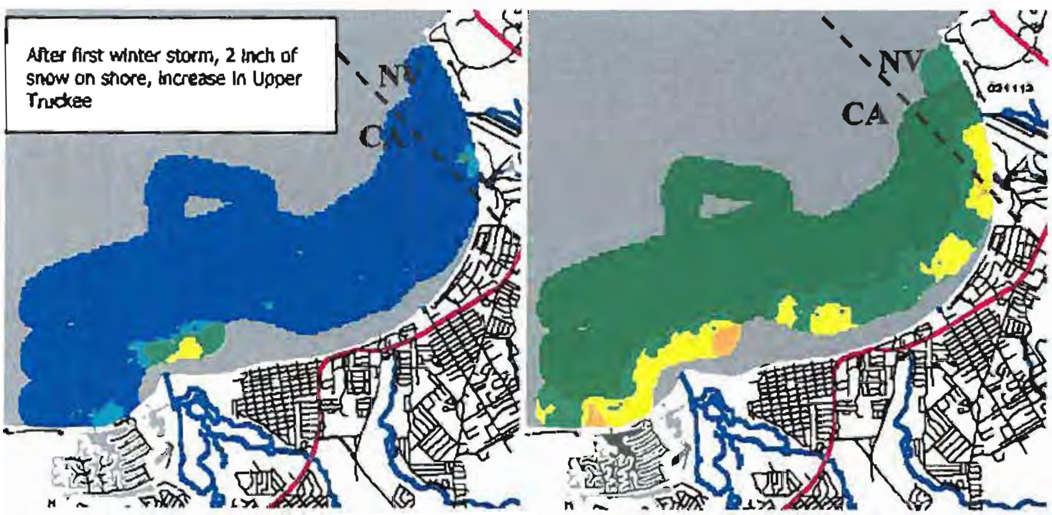


Figure 19-6. Turbidity and particle characterization maps for November 13, 2002.

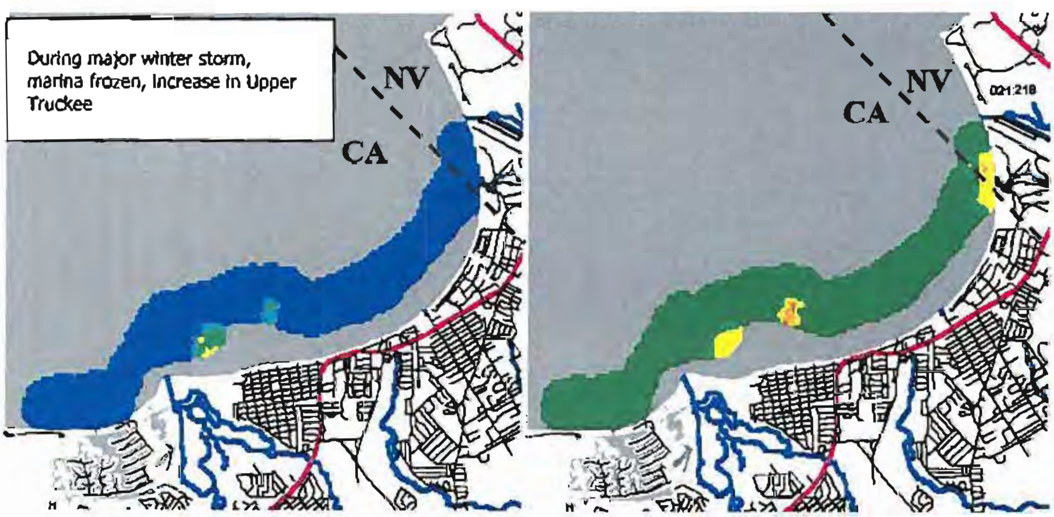


Figure 19-7. Turbidity and particle characterization maps for December 16, 2002.

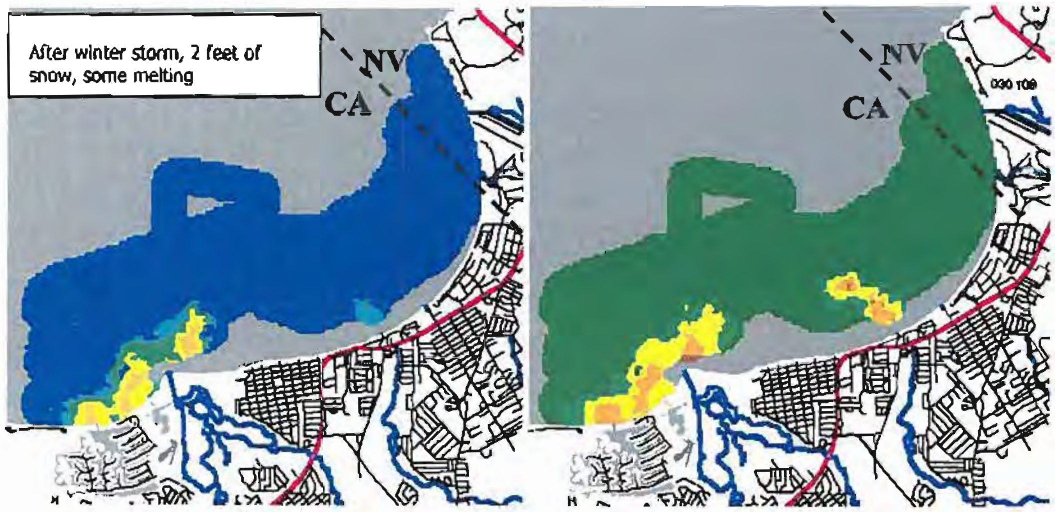


Figure 19-8. Turbidity and particle characterization maps for January 8, 2003.

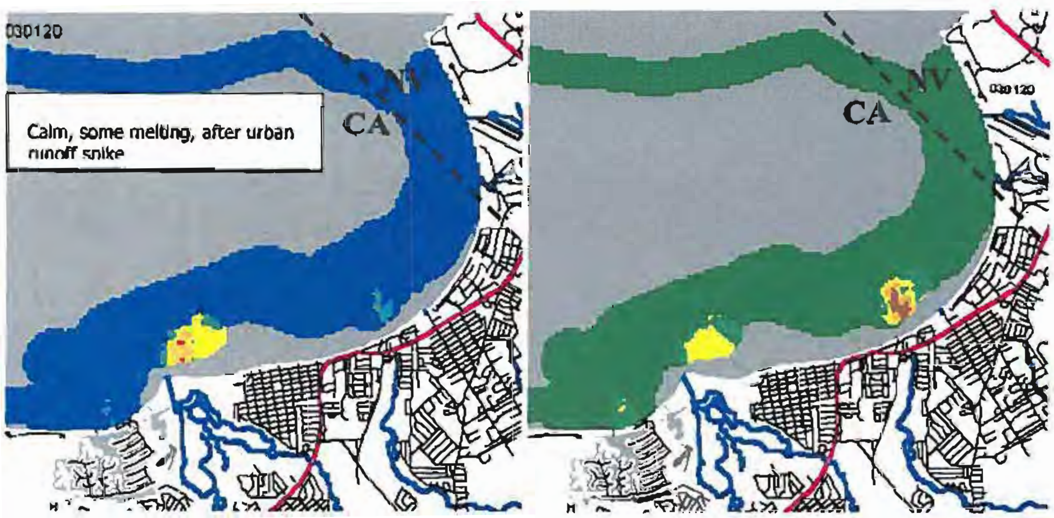


Figure 19-9. Turbidity and particle characterization maps for January 20, 2003.

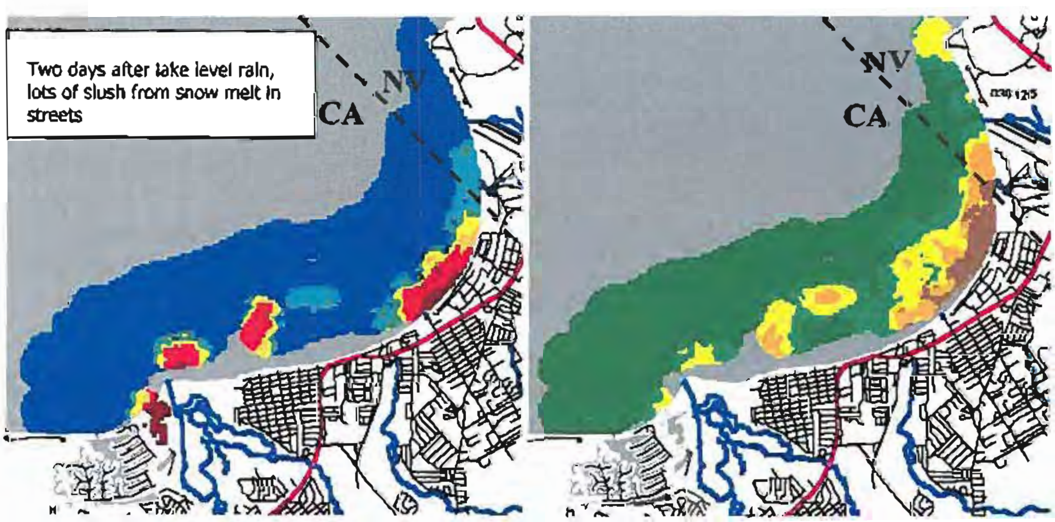


Figure 19-10. Turbidity and particle characterization maps for January 25, 2003.

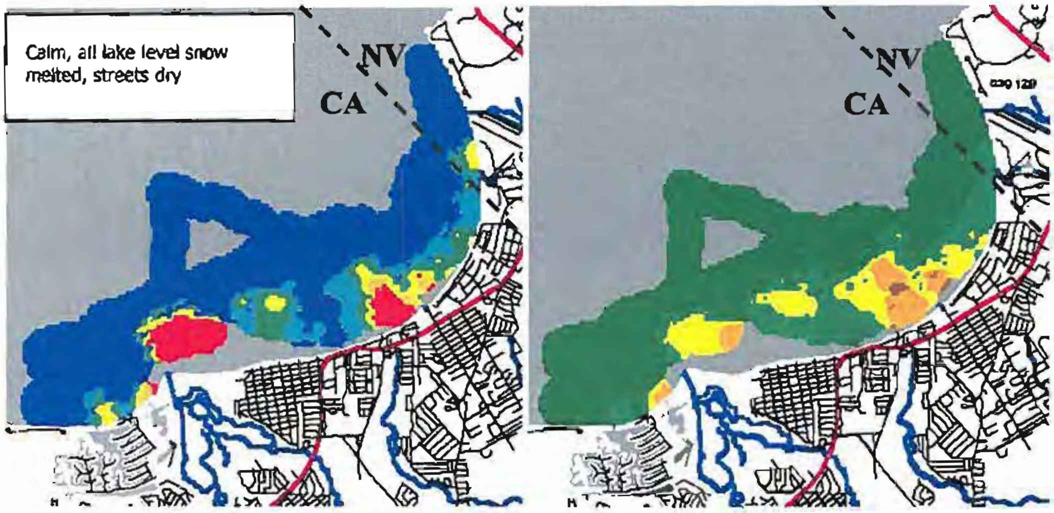


Figure 19-11. Turbidity and particle characterization maps for January 29, 2003.

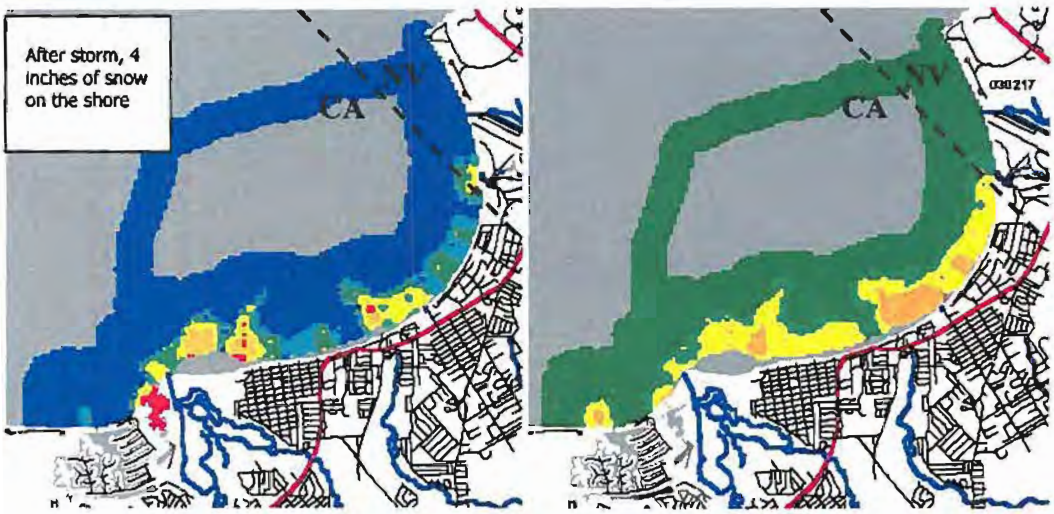


Figure 19-12. Turbidity and particle characterization maps for February 17, 2003.

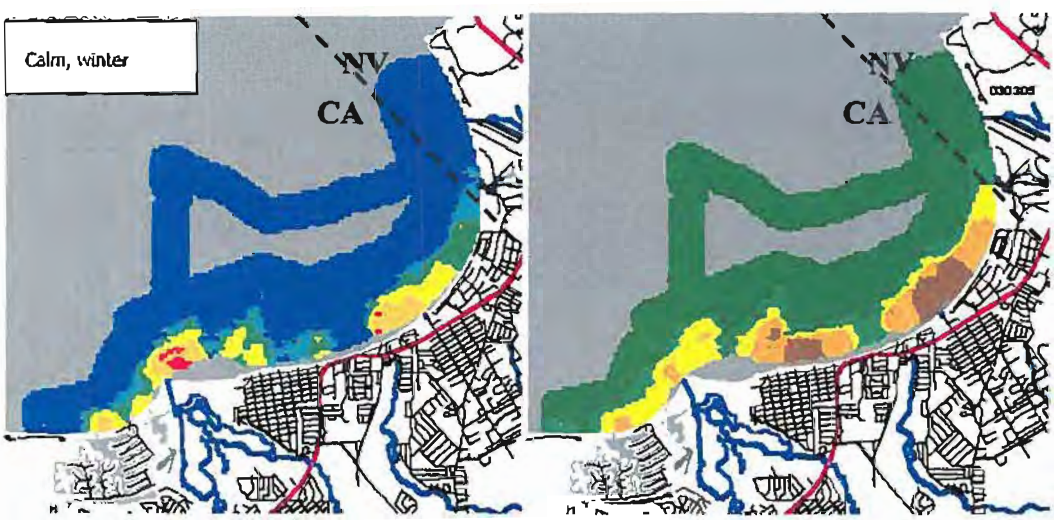


Figure 19-13. Turbidity and particle characterization maps for March 5, 2003.

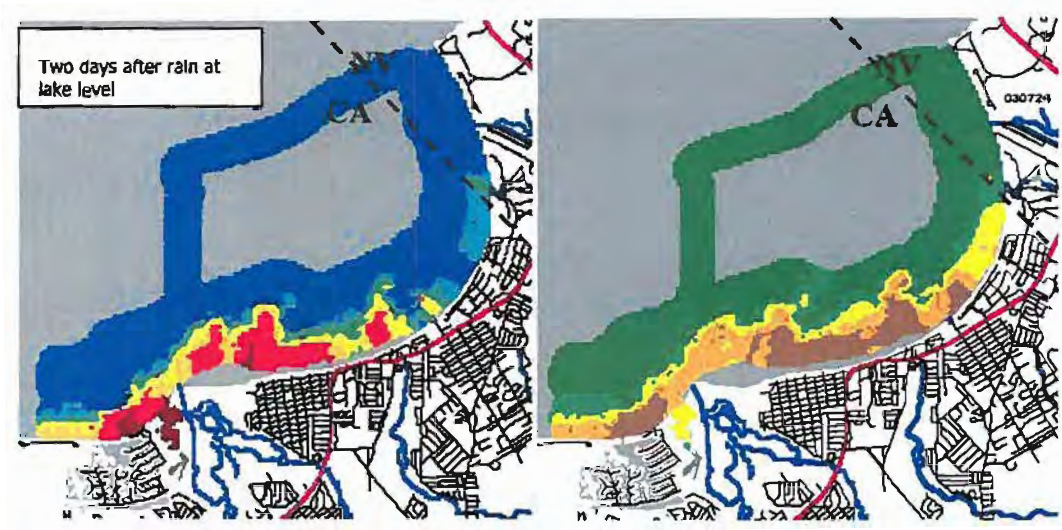


Figure 19-14. Turbidity and particle characterization maps for March 19, 2003.

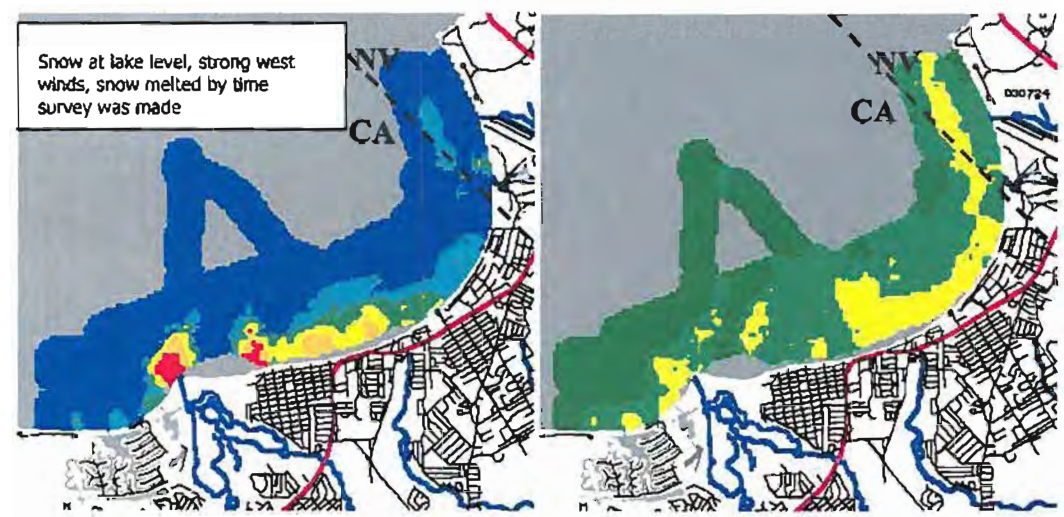


Figure 19-15. Turbidity and particle characterization maps for April 9, 2003.

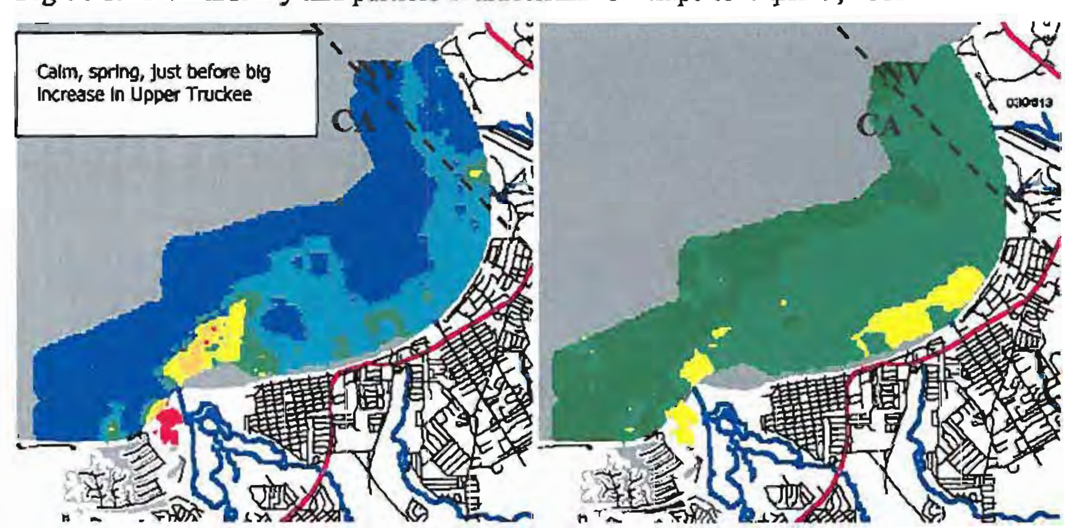


Figure 19-16. Turbidity and particle characterization maps for May 13, 2003.

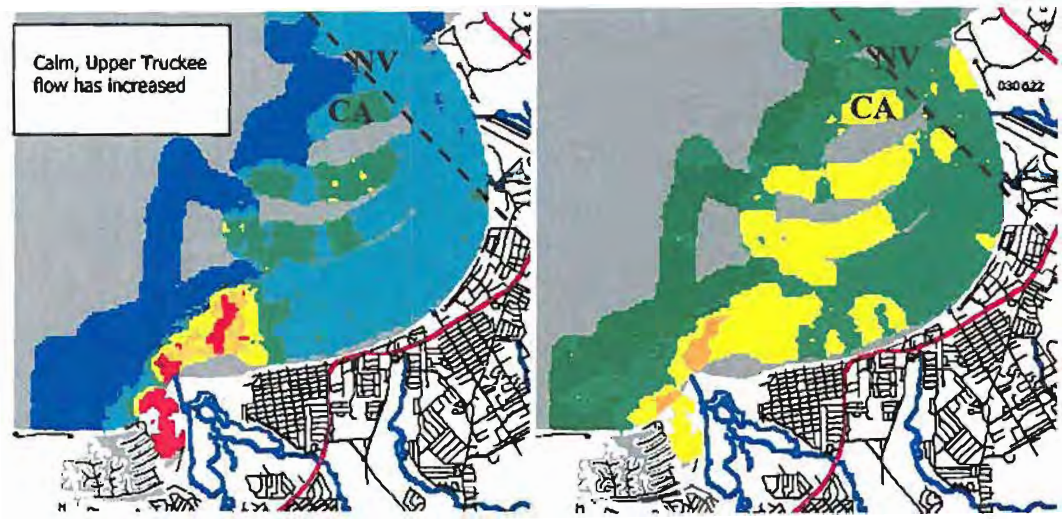


Figure 19-17. Turbidity and particle characterization maps for May 22, 2003.

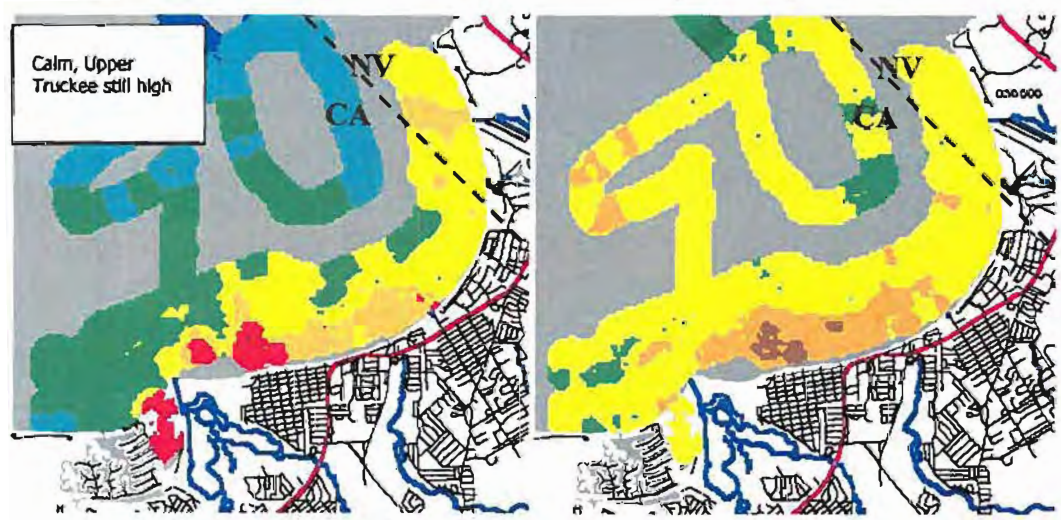


Figure 19-18. Turbidity and particle characterization maps for June 6, 2003.

Figure 19-19. Turbidity and particle characterization maps for June 23, 2003.

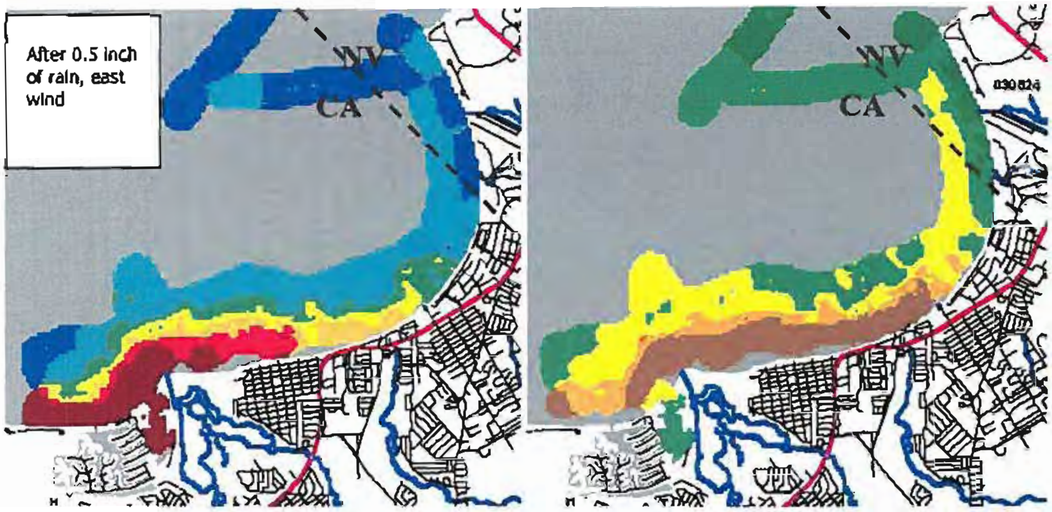


Figure 19-20. Turbidity and particle characterization maps for June 24, 2003.

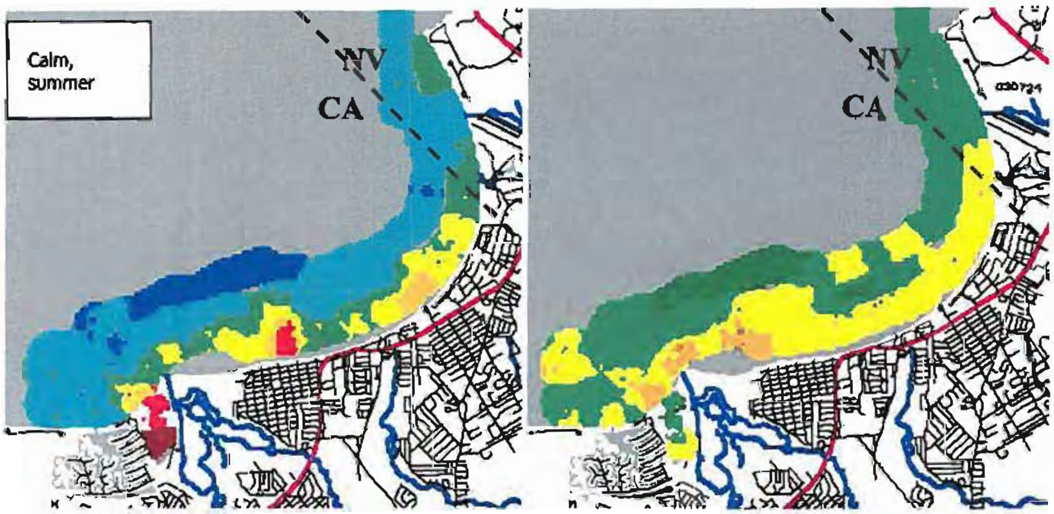


Figure 19-21. Turbidity and particle characterization maps for July 3, 2003.

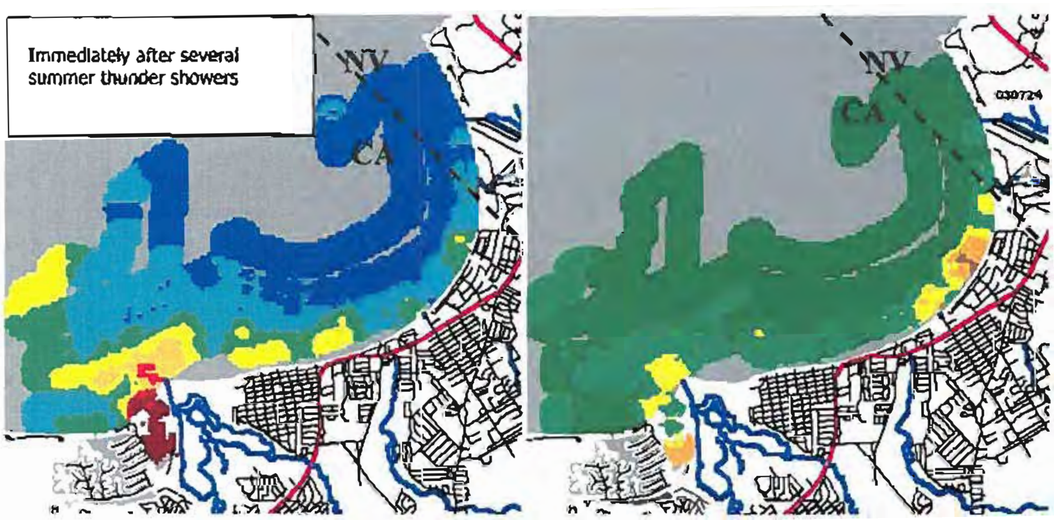


Figure 19-22. Turbidity and particle characterization maps for July 24, 2003.

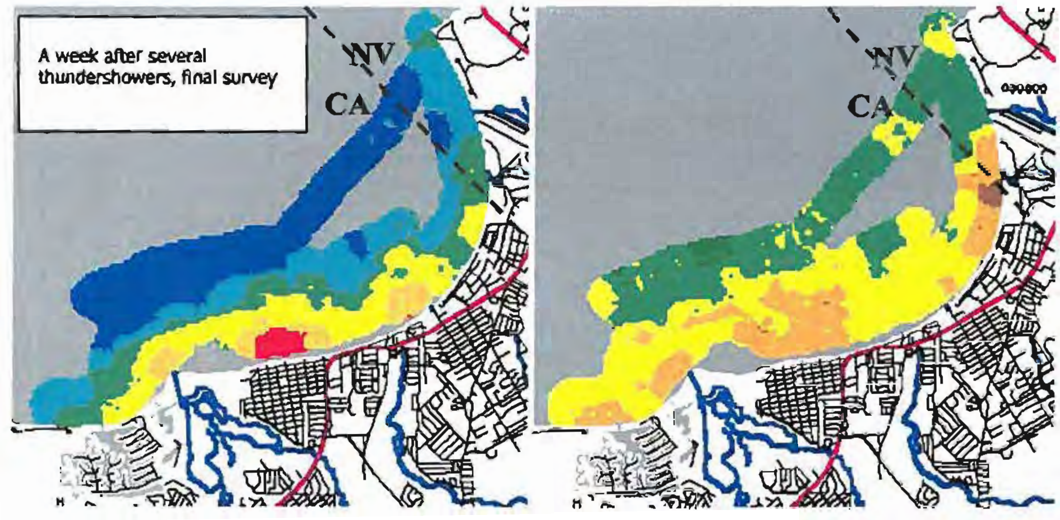


Figure 19-23. Turbidity and particle characterization maps for August 6, 2003.

In addition to the spatial surveys shown in Figure 19, particle samples were also collected and analyzed with energy dispersive spectroscopy. The results for the sub-micron particles that are primarily responsible for the reduction of clarity are shown in Figure 20a through Figure 20d. These particles were too small to use the scanning electron microscope imagery to determine the morphology of the particles.

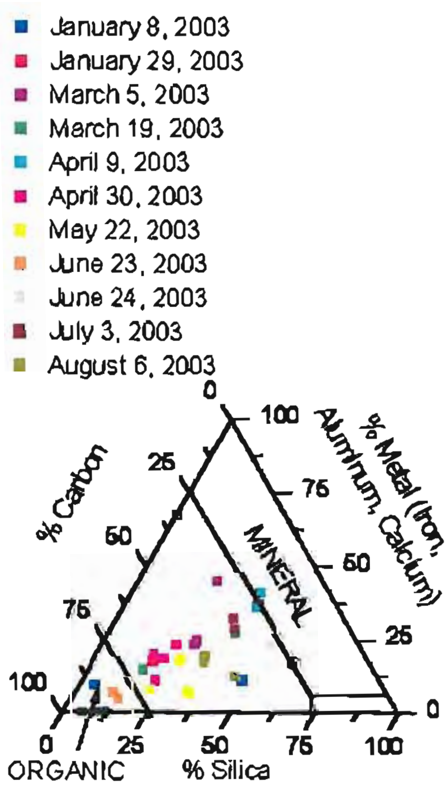


Figure 20a. Composition of particle samples from ~200 m off the Upper Truckee River. See the method section and the caption of Figure 4 for an explanation of these ternary diagrams.

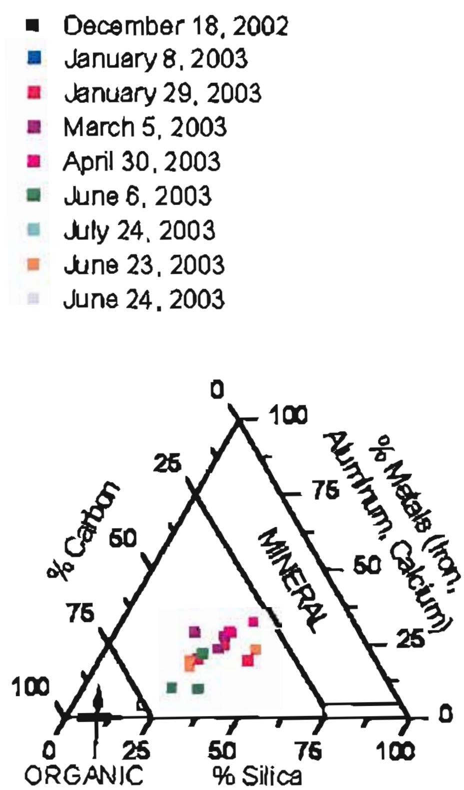


Figure 20b. Composition of particle samples from ~70 m off Bijou Creek.

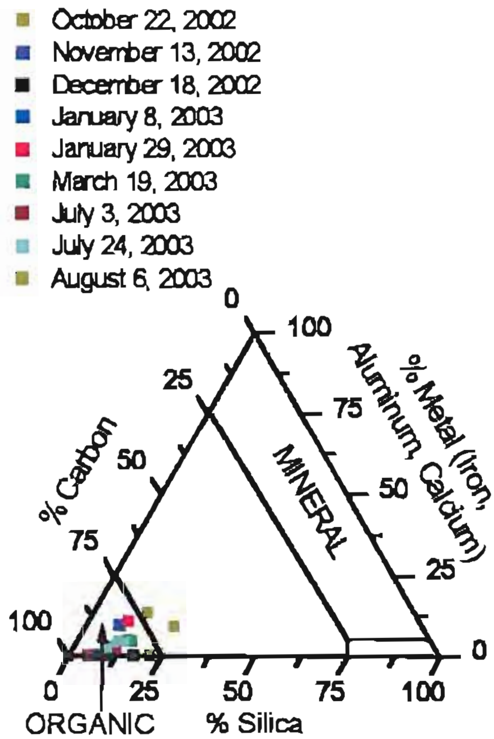


Figure 20c. Composition of particle samples from approximately 20 m off Edgewood Creek.

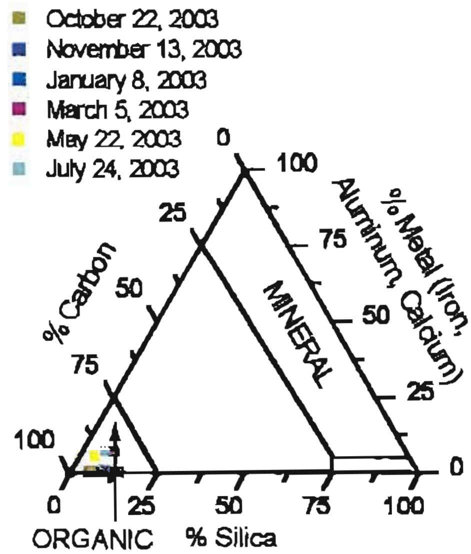


Figure 20d. Composition of particle samples from 3,000 m off the Upper Truckee River.

Discussion of South Shore Data from a Geographical Perspective

The turbidity, and hence clarity, of near-shore waters along South Lake Tahoe varies greatly depending on location and time. Near-shore turbidity values comparable to mid-lake values of 0.1 NTU were frequently observed just offshore of undeveloped areas. Near-shore turbidity values as high as 20 NTU, with an estimated Secchi depth clarity of approximately 0.2 m, were also observed at the outlet of the Upper Truckee after a summer storm.

There was a large seasonal influence on near-shore turbidity. During the fall and early winter, areas with moderate to high turbidity (yellow, orange, red in Figure 19) typically only extended 50 to 100 m into the lake. Surface inflows to the lake are small at this time and the elevated turbidity never extended past the edge of the shallow shelf where the water depth exceeds 8 m. During fall and winter, the spatial pattern of turbidity was relatively consistent (Figures 19-3 to 19-9). With the onset of winter storms the spatial pattern of turbidity became more variable in response to surface water inflows (Figures 19-10 to 19-15). During the spring melt, the spatial extent and magnitude of elevated turbidity areas increased dramatically (Figures 19-16 to 19-19) in response to large surface inflows.

Relatively undeveloped areas of the study area included Pope Beach on the west end of the study area and Nevada Beach in the northeast corner of study area. These areas never had an elevated turbidity except on March 19 and June 24, 2003 (Figures 19-14, 19-20) when east winds pushed high turbidity water from the Upper Truckee area to Pope Beach. These areas were always dominated by organic particles except for Pope Beach on March 19 and June 24, 2003, when mineral particles dominated.

Streams with extensive development in their watersheds included the Upper Truckee River and Bijou Creek. At Bijou Creek, runoff from several large parking areas drains into the creek without treatment. These waterways were always associated with elevated near-shore turbidity. The lake-ward extent of the high turbidity plume from the Upper Truckee during the winter seemed limited to the edge of the shallow shelf (Figures 19-10, 19-11, and 19-12). Apparently, the interaction of the near-shore and deeper water in this area was hydrodynamically controlled by the position of the shelf break. This was not the case in the summer when warm surface water mixed less readily with the colder water several meters below (Figures 19-1, 19-17, and 19-18). The extent of high turbidity plumes along the shore seemed to be controlled by near-shore currents that are in turn strongly influenced by winds. A good example of this occurred on June 23, 2003 and June 24, 2003, when first a west wind pushed the high turbidity plume to the east (Figure 19-19), and then a day later an east wind pushed the high turbidity plume to the west (Figure 19-20). The particles in these areas were a mix of minerals and organic material (Figure 20a and 20b), with a greater percentage of minerals during the high turbidity time periods.

The turbidity in these areas frequently exceeded 1 NTU and on several occasions exceeded 3 NTU. The highest turbidity values observed were off the Upper Truckee River on June 24, 2003, and ranged from 5 to 20 NTU. Bijou Creek and the Upper Truckee River were the dominant influence on near-shore clarity in the southeast portion of the lake. This was particularly apparent for the Upper Truckee during spring runoff (Figures 19-17, and 19-18). Based on the whole lake spatial surveys (Figure 7), there were no other features elsewhere in the lake that had a comparable influence on near-shore clarity.

Edgewood Creek is a natural creek and outflow for urban storm water. The creek and storm water pass through a pond on Park Cattle company land and a series of retention basins in the Edgewood Golf Course before entering the lake. Portions of the Edgewood Golf Course are immediately adjacent to the shore. Most of the Gondola wildfire (673 acres) occurred in the headwaters of Edgewood Creek in July 2002. The water depth drops off sharply at the outlet of Edgewood creek and measurements were occasionally made within 5 to 10 m of the outlet. On several occasions a thin plume of high turbidity water was observed that originated from the creek and moved along the shore or into the lake. This plume was visually observed to be less then a few meters wide and dissipated after moving approximately 50 m from the outlet of the creek. The turbidity of this water could not be determined because it was within a few meters of shore or was a thin band. The turbidity 10 m from shore was only slightly elevated on rare occasions, despite the disturbance caused by the Gondola fire. The high turbidity stream water was rarely detected by the instruments when the boat was at a typical survey distance of ~20 m offshore and was generally only detectable when the survey crew made an effort to search for it. The lack of high near-shore turbidity associated with the Gondola fire may be related to the effectiveness of the retention basins or due to rapid near-shore mixing.

Elevated levels of chlorophyll were never observed adjacent to the Edgewood Golf Course despite the abundance of fertilized turf immediately adjacent to the lake. Given that the time scale for algal growth is on the order of days, and that the near-shore surface water can move many hundreds of meters in a day (see section on the exchange between near-shore and mid-lake waters), this result is not surprising. The particles off Edgewood Creek were mostly organic (Figure 20c). It appeared the turbidity was occasionally elevated in this area by eastward movement of high turbidity water from the Ski Run Marina and Bijou Creek area (March 5, 2003; July 3, 2003; Figures 9-13 and 19-21).

Ski Run Marina is a small artificial bay and the homeport for a paddle wheel tour boat. Urban runoff is collected in a series of retention basins before discharging into the marina. The near-shore turbidity was frequently elevated in this area but typically to a lesser degree than around Bijou Creek. The retention basins discharged water directly into Lake Tahoe on three occasions preceding near-shore surveys (R. Wigart, personal communication). The first event occurred over a three-day period, having peak discharges of 0.6 to 0.7 cfs on November 8, 2002 and November 11, 2002; the first and last days of the event. Water discharged during the first peak on November 8, 2002 was more sediment laden (TSS of 81 mg L^{-1}) than the latter peak (November 11, 2002; TSS of 9 mg L^{-1}). However, near-shore turbidity was not found to be elevated off of Ski Run during the November 13, 2002 survey (Figure 19-6). The lack of elevated turbidity in the near-shore zone may be due to fact that this survey was conducted further offshore than most of the subsequent surveys, and/or to the 5 day delay between the onset of the storm and the near-shore survey.

The second discharge of the retention basin into Ski Run Marina occurred over a three-hour period during extensive lake level snowmelt on January 23, 2003. Near-shore turbidity measured two days later on January 25 (Figure 19-10) was uncharacteristically high in the area, and was attributed to a source of mineral particles within the Ski Run Marina area. The third discharge of the retention basin occurred over a five-hour period during lake level rain on March 15, 2003. Near-shore turbidity measured four days later on March 19, 2003 (Figure 19-14) was only slightly elevated near Ski Run. Elevated near-shore turbidity was also observed offshore of Ski Run when there was no outflow from the detention basins (e.g. February 17, 2003; April 9, 2003; July 3, 2003; August 6, 2003). Several of these particular elevated turbidity events observed offshore of Ski Run appeared to be from Bijou Creek to the west. Bijou Creek, which does not have retention basins between the urban inflows and discharge into the lake, was generally a much larger and more persistent source of high turbidity water to the lake than Ski Run Marina.

The Tahoe Keys development consists of two bays. The east bay is a commercial marina with year-round operations. The west bay is used by property owners and receives less use, particularly in winter. The water in the bays had high turbidity, commonly in excess of 2 NTU, and was dominated by organic particles. Both bays are connected to the lake by channels that are about 20 m wide and either 80 m or 150 m long. The direct influence of Tahoe Keys on the near-shore zone appeared to be minor, although as mentioned previously these measurements only sampled the water 0.5 m below the surface. Numerous trips in and out of the Keys demonstrated that low-quality surface water from the Keys did not extend more than a few tens to a hundred meters into the lake. The situation was complicated by the outflow of the Upper Truckee River just 500 m east of the entrance to the Tahoe Keys, and shallow water that prevented making measurements within about 100 m of the shore between the outlet of the Upper Truckee and the entrance to the east bay of Tahoe Keys. Surveys made on August 9, 2002; January 29, 2003; February 17, 2003; April 9, 2003; and May 13, 2003 (Figures 19-2, 19-11, 19-13, 19-15, and 19-16) are examples of separate high turbidity plumes from the Upper Truckee River and Tahoe Keys, with the plume from the Upper Truckee

River being much larger then the one from Tahoe Keys. The interaction between the water in Tahoe Keys and the rest of the lake may be controlled by convective flow driven by the temperature difference between the waters in the lake and the Tahoe Keys. This might result in a two-layer exchange flow, which could not be detected by this study because measurements were only made at one depth. To fully characterize the relationship of high turbidity plumes from the Upper Truckee River and Tahoe Keys will require surveys with an ability to operate in water less than 70 cm deep and measurements at multiple depths around the entrances to Tahoe Keys.

The Al Tahoe area is an older residential area. Runoff is collected by storm drains that flow directly into the lake without treatment. Two elevated-turbidity areas were frequently observed in the Al Tahoe area (e.g., August 9, 2002; March 9, 2003; Figures 19-2, 19-15). On the east edge, a high turbidity feature commonly occurred where State Highway 50 leaves the lakeshore and heads south. There is a large storm-water outfall there. On the west side of Al Tahoe, there was frequently a plume of high turbidity water that appeared on the survey maps as a separate plume from the Upper Truckee plume. This plume may be caused by high turbidity water from the Upper Truckee that moved along the lakeshore in water that is too shallow to survey with the present instrument arrangement. However, resuspension of bottom sediments in the large shallow areas off Al Tahoe cannot be ruled out. The particles in this area were mostly minerals.

The spatial surveys commonly included a single transect through a point 3 km off the outlet of the Upper Truckee in water more than 200 m deep. This served as a background location and the turbidity of this location was always less than 0.14 NTU except on July 6, 2003, after peak runoff from the Upper Truckee. The particles at this site were always mostly organic material (Figure 20d), but there was a minor and brief increase in the concentration of mineral particles during spring runoff (Figure 19-18).

The spatial surveys illustrate the difficulty of using in-lake measurements to determine the flux of material to the lake. Measurements within tens of meters of a stream outlet have a large spatial and temporal variability due to slight shifts in lake currents and temperatures. It is not appropriate to compare measurements taken a meter away from a stream inflow with measurements taken tens of meters away. When the turbid stream inflow is rapidly diluted by cleaner lake water there is not a significant reduction in near-shore clarity and the inflow is difficult to detect. From a near-shore perspective thin bands of high turbidity water that are rapidly diluted by clean lake water are not an aesthetic concern; however, in such situations the inflow is still contributing to the decline of mid-lake clarity. Examples of this situation are Edgewood, Blackwood and Ward Creeks. A different situation occurs when there is shallow water off the stream outlet and high turbidity stream inflows mix more slowly with cleaner lake water. In such situations the inflow has a large detrimental influence on both near-shore and mid-lake clarity. Examples of this are Bijou Creek and the Upper Truckee River. Establishing a clarity standard for the mid-lake does not protect the aesthetic values of the near-shore zone, and establishing a clarity standard for the near-shore zone would not be sufficient to protect the aesthetic value of the mid-lake. Near-shore water quality measurements do not determine the flux of material into the lake and are not a substitute for directly monitoring streams and culverts. Near-shore clarity measurements can be used as a direct and unbiased measure of the effectiveness of management actions on near-shore clarity in specific areas.

Discussion of South Shore Data from a Meteorological Perspective

Near-shore turbidity increased during periods of increased high stream and urban inflows. During the late summer and early fall, when the only significant surface inflow was from the Upper Truckee, the near-shore zone turbidity was very low, occasionally even as low as mid-lake levels. During these times, the particles were primarily organic material except off the Upper Truckee and Bijou Creek (i.e., October 17 and 22, 2002; November 13, 2002; December 18, 2002; Figures 19-4, 19-5, 19-6, and 19-7).

Summer storms had an immediate influence on near-shore turbidity. A storm on June 20, 2003, at the tail end of the Upper Truckee runoff in which 1 centimeter of rain fell at Al Tahoe, had a significant influence off developed areas but negligible influence in lightly developed areas. For example, compare the pre-storm survey of June 23, 2003 (Figure 19-19) to the post-storm survey of June 24, 2003 (Figure 19-20). This is consistent with a previous set of turbidity surveys along the east shore from the Thunderbird Lodge to the south end of Incline Village that showed negligible change in turbidity along undeveloped areas after an intense August thunderstorm (1.5 cm of rain fell in 15 minutes and caused extensive mobilization of material), which was quickly absorbed by the forest and did not reach the lake.

Cold winter storms with lake level snow (but not lake level rain) did not have an immediate influence on near-shore turbidity (i.e., November 13, 2002; December 18, 2002; Figures 19-5, and 19-6), despite wave action that might have resuspended bottom sediments. The lack of an immediate effect of cold winter storms occurs because the precipitation is in the form of snow and does not immediately drain to the lake. When lake level snow melted (i.e., January 25, 2003; January 29, 2003; Figures 19-10, and 19-11), near-shore turbidity increased in areas with urban drainage to the lake, but not in undeveloped areas.

Wind and surface currents strongly influence the spread of near-shore turbidity plumes. The wind was most frequently from the southwest, which commonly spread high turbidity water to the east. For example, there was a west-to-east flow of high turbidity water along the south shore during spring (March 19, 2003; May 22, 2003; June 6, 2003; Figures 19-14, 19-17, and 19-18). Between June 23 and June 24, 2003 (Figures 19-18, 19-19), the wind direction shifted from the west to the east, and the direction of the plume from the Upper Truckee River responded by also shifting direction.

During calm periods in the fall and winter, the lake-ward extent of the high turbidity areas appeared more constrained by the temperature controlled plunge dynamics of the streams and bathymetrically controlled mixing along the offshore drop-off than by winds (September 13, 2002; October 17 and 22, 2003; November 13, 2002; December 18, 2002; January 8 and 20, 2003; Figures 19-3, 19-4, 19-5, 19-6, 19-7, 19-8, and 19-9). During this time, the surface water inflows were colder than the lake and they readily sank at the edge of the shallow shelf.

During late spring and summer, the lake-ward extent of high turbidity plumes appeared to be more related to the rate of inflow preceding the survey than bathymetry (July 11, 2002; August 9, 2002 May 22, 2003; and June 6, 2003; Figures 19-1, 19-2, 19-17, and 19-18). During these times, surface inflows were warmer than the surface water of the lake and hence were likely to disperse horizontally instead of sinking.

Discussion of the Influence of Water Temperature on South Shore Turbidity

Although temperature measurements were not part of the scope of work for this project, some measurements were made and they are useful to review. Most surveys made after October 2002 included a measurement of water temperature approximately 0.5 m below the surface. During winter, the Upper Truckee inflow was colder than the surface of the lake, and formed a plume of cold, turbid water where it entered the lake (January 8, 2003; Figure 21). The cold, turbid winter inflows plunged below the surface because they were denser than the lake surface water. During spring, the Upper Truckee was warmer than the surface of the lake, and formed a plume of warm, turbid water when it entered the lake (June 6, 2003; Figure 21). The warm, turbid spring inflows did not mix readily with the deeper water because the light, warm water floated on top of the colder, deeper water. The relative temperature difference between the inflowing water and the lake surface waters seemed to have a large influence on the spatial extent of the high turbidity plumes. In January, the high turbidity areas off the south shore did not extend past the shallow shelf where the high turbidity inflows were diluted by the deeper water. In spring and summer, the high turbidity areas extended past the shelf because they were spreading in a surface layer that floated on top of the colder water below. This high turbidity surface layer was observed in vertical profiles of turbidity (Figure 22).

However, it needs to be kept in mind that the stream inflows are not constant in either flow or temperature. During the course of a day, stream temperatures can vary by 6^{0} C and the flow may vary by as much as 50 percent. As a result, the depth and location of where the stream water plunges deeper into the lake can vary during a day.

Discussion of Resuspension of Bottom Sediments

It is tempting to attribute the increased turbidity near the shore to shallow water that facilitates resuspension of bottom sediment. Comparison of the bathymetry (Figure 17a) and survey results (Figures 19-2, 19-10, 19-11, 19-13, 19-14, and 19-16) shows this was not always the situation. For example, there were commonly high turbidity plumes in the shallow areas off Bijou Creek and Al Tahoe, but not in the similarly shallow area between them. During other periods, it was not possible to determine the role of shallow areas because of the large spatial extent of high turbidity areas.

If wave action was stirring up bottom material the turbidity would be high immediately after periods of high winds. Wind speed data at the South Lake Tahoe airport is compared to the spatial surveys made during this project in Figure 23. The turbidity surveys in January 2003 were collected during a variety of conditions including: after lake-level snow, after rain, and after a calm period. Wind speeds were low during this entire time. Despite the low wind during this time period (Figure 23) the surveys on January 20, 25, and 29 (Figures 19-9, 19-10, 19-11) show progressive increases in the size of the turbidity plumes at the Upper Truckee River and Bijou Creek. At the same time lake level snowmelt was causing stream flow and urban run off to increase. The increases in turbidity during January were caused by increases in runoff, not by resuspension of bottom sediment by wave action. In another example, the surveys made on November 13, 2003 (Figure 19-6) and December 16, 2003 (Figure 19-7) occurred immediately after windy periods (Figure 23), yet near-shore turbidity was not elevated. Although wave action does increase turbidity in water less than a meter deep, it does not seem responsible for the elevated turbidity that was observed in these surveys where the water depth was deeper than about a meter.

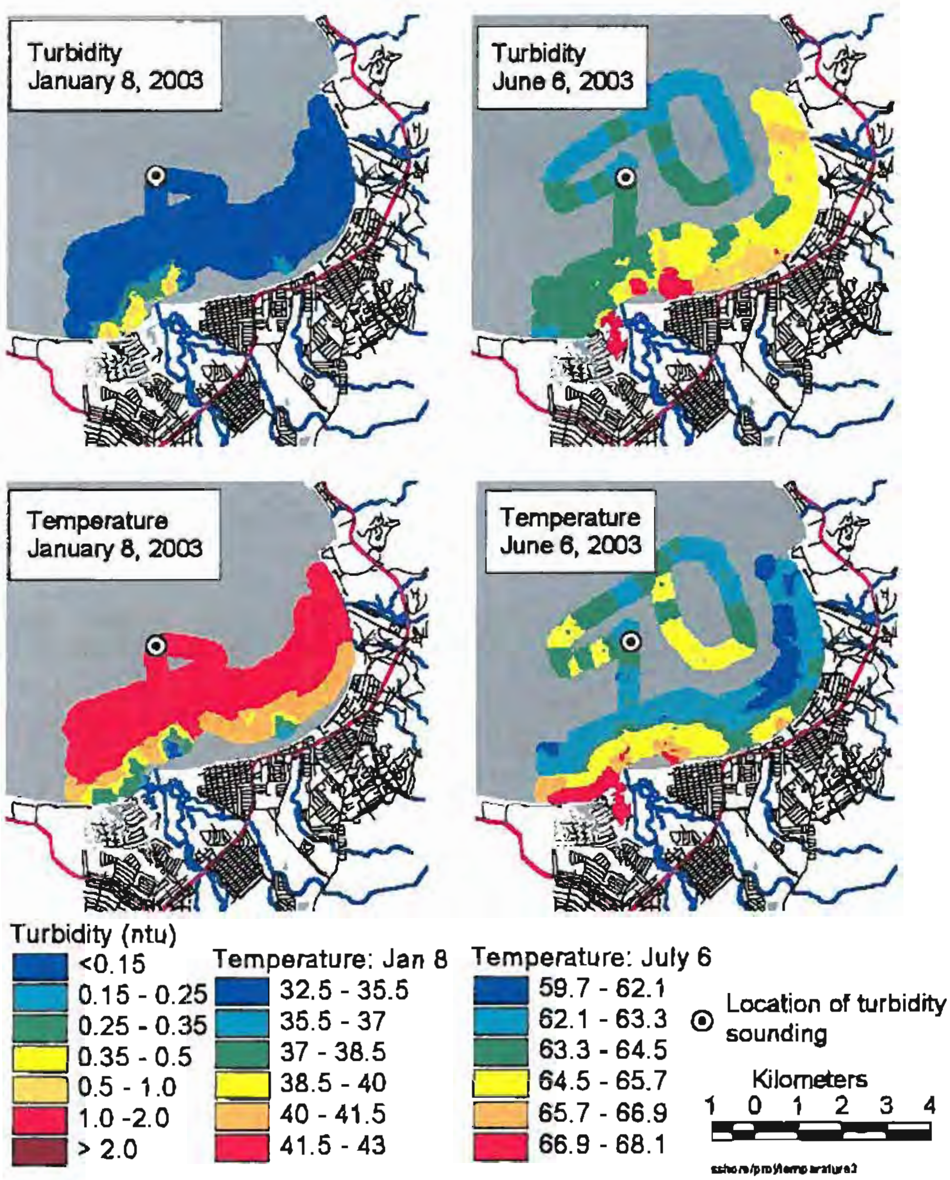


Figure 21. Turbidity and temperature surveys measured on January 8, 2003 and June 6, 2003. The turbidity scale is the same for both surveys. The temperature scale is different for the two surveys so the temperature variation in each survey will be displayed by a full spectrum of colors. In January, the water at the outlet of the Upper Truckee River and Bijou Creek was colder than further offshore, and the high turbidity areas were associated with cold water. In July, the water at the outlet of the Upper Truckee River and Bijou Creek was warmer than that further offshore, and the high turbidity areas were associated with warm water. In January, the areas with elevated turbidity did not extend past the shallow shelf (Figure 17a). During July, areas with elevated turbidity extended many kilometers offshore. The target symbols show the location of the turbidity soundings shown in Figure 22.

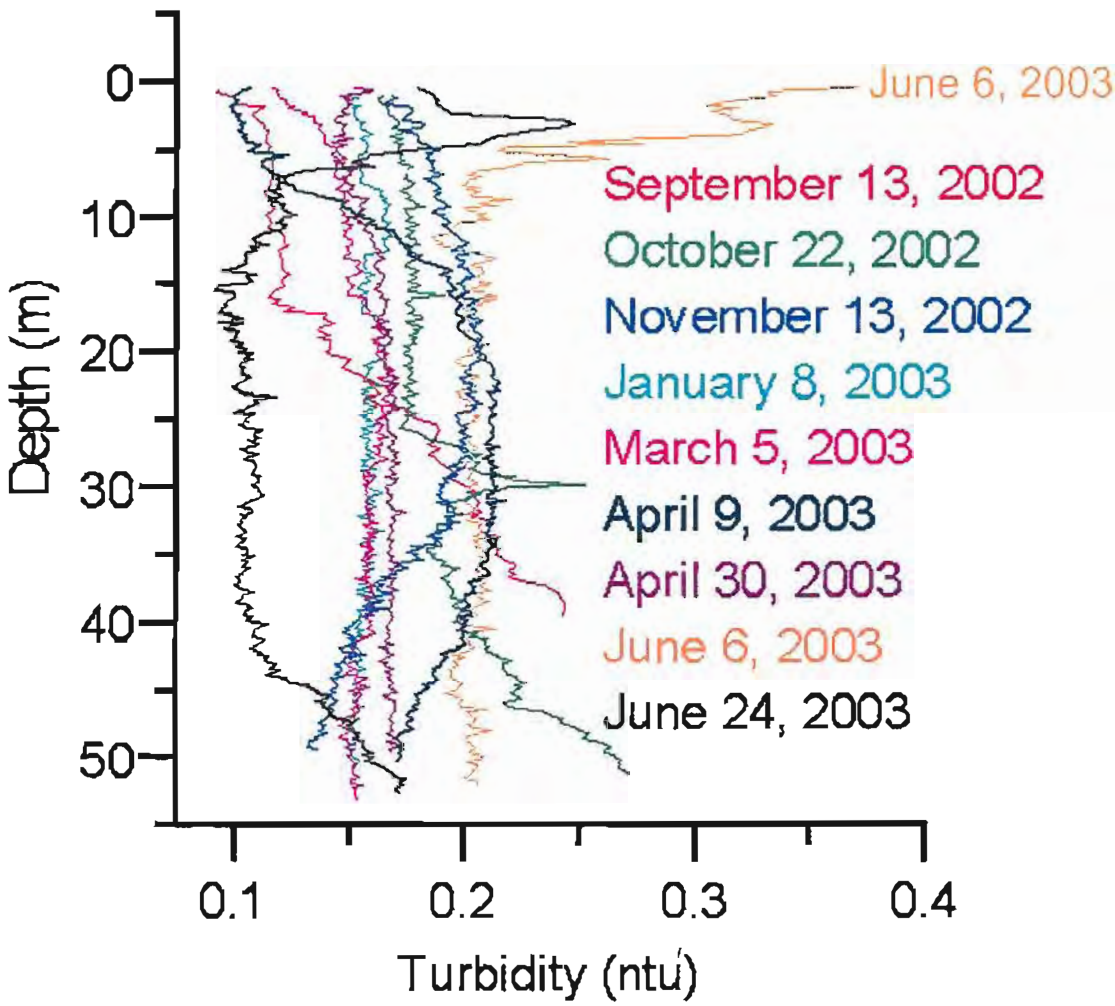


Figure 22. Vertical turbidity profiles measured at the target symbol in Figure 12, 3 km off the outlet of the Upper Truckee River. During winter the shallow turbidity did not vary much with depth, although there was considerable variation at depth. In summer, the greatest variations were in the surface layer. Note the large change in surface turbidity during summer by comparing June 6 and June 24. The high turbidity in both these profiles is attributable to the Upper Truckee River outflow. These profiles were obtained by measuring the light attenuation with a c-βeta and converting the measurement to turbidity using a rough empirical relationship. They should not be directly compared to the spatial survey measurements that were made with turbidity instruments, which have a greater degree of quality assurance.

To fully determine the significance of resuspension on near-shore high turbidity will require a study specifically designed for that task. A resuspension study could be conducted by using approximately six instrumented buoys that continuously measure turbidity. The buoys would be placed along two transects perpendicular to shore. The buoys would be placed

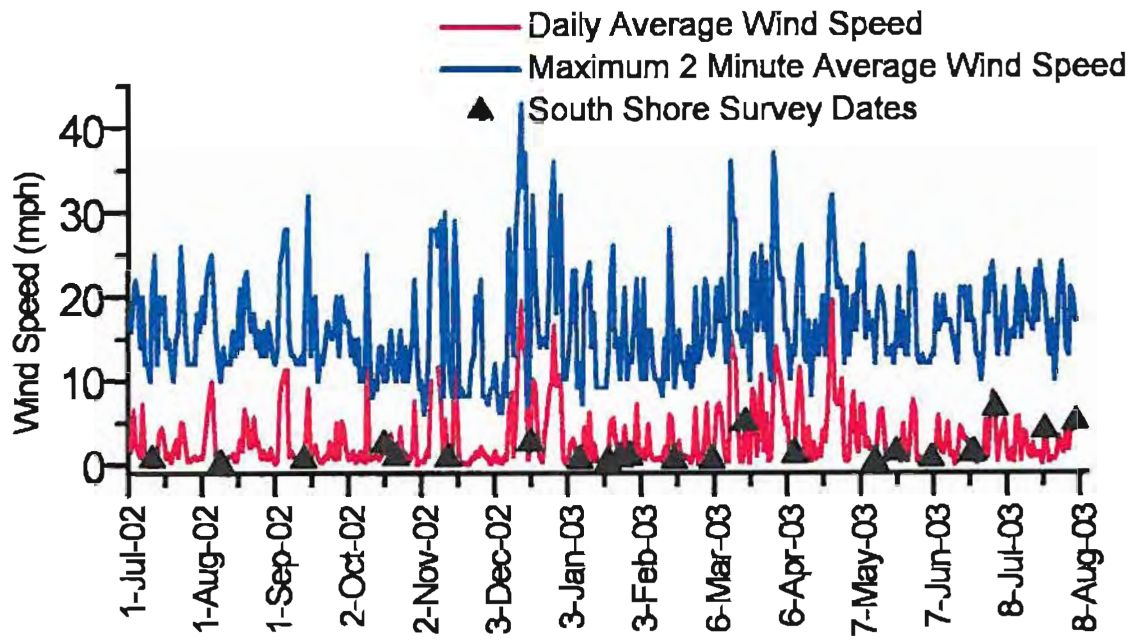


Figure 23. Daily average wind speed and maximum 2-minute average wind speed at the South Lake Tahoe Airport during the period July 1, 2002 to July 31, 2003.

in water from 0.5 m to approximately 10 m deep. Instruments to continuously record wave heights, wind speed, wind direction, and adjacent stream flows would also be necessary. This system would then have to be operated for about six months during a stormy time of the year. The resulting records could be examined for time periods when there were large waves, but no change in stream flows. This condition commonly occurs before storms, or during storms that are either dry or very cold so that the precipitation is in the form of snow that does not run off. By studying the response of near-shore turbidity during and after periods of large waves that are not associated with changes in stream flows, the influence of wave driven resuspension of bottom sediments might be determined. It will be necessary to continuously monitor the conditions, as opposed to infrequent spatial surveys, to significantly advance our understanding of the importance of resuspension on near-shore clarity in shallow areas.

Summary Discussion on South Shore Surveys

With the possible exception of the frequent high turbidity areas off Al Tahoe, all the high turbidity areas had a clear and obvious association with surface water inflows. The high turbidity areas off Al Tahoe were likely associated with surface inflows from the obvious storm water drains associated with this neighborhood and outflow from the Upper Truckee. We were unable to determine the relative significance of these two sources because of the difficulty of making measurements in the shallow water in this area. There was a clear spatial correlation between developed areas with drainage directly to streams or storm drains and high near-shore turbidity. Time periods of high surface water inflows, particularly in association with lake level snow melt and the main spring runoff, caused the largest decreases in near-shore clarity. Reduction of near-shore clarity could usually be associated with a specific inflow to the lake, indicating that reductions in near-shore clarity is a watershed scale problem, as opposed to a basin-wide or regional problem. Near-shore clarity problems were not observed in lightly or undeveloped areas. It is likely that near-shore clarity is a neighborhood scale problem because near-shore clarity problems are always associated with mineral particles entering the lake from developed areas.

In all locations and times that near-shore turbidity was moderately elevated (greater than 0.35 NTU), the particles were predominantly mineral material. The only exception was inside Tahoe Keys, where organic material was always dominant. Organic material was a secondary issue for near-shore clarity, except perhaps for the areas distant from developed areas such as Bliss State Park and the east shore from Sand Harbor to Deadman Point, which may be more influenced by the general decline of mid-lake clarity than activities along the adjoining shore. However, the particles were always predominantly organic 3 km offshore, except during spring runoff, when large inflows of mineral particles from the Upper Truckee spread offshore many kilometers (May 22, 2003, June 6, 2003; Figures 9-17, and 19-18).

EXCHANGE BETWEEN NEAR-SHORE AND MID-LAKE WATERS

Preliminary experiments were made in July 2003 to determine the rate at which water passes through near-shore high turbidity areas. Surface water velocity measurements were made with a "drifter," consisting of a subsurface drogue and a surface buoy that holds the drogue at a fixed depth. Water currents drag the large subsurface drogue (~1 m^2 area) along, and wind forces have a negligible influence on the movement of the drifter due to the small surface area of the buoy (~0.1 m^2) above the water. The movement of the drifter is similar to the movement of the water at the depth of the drogue. The drifter is released and allowed to drift freely for about an hour, after which the direction and distance of movement is determined by GPS measurements.

Typically, seven to 10 drifters with drogues at depth of 1 to 8 meters were released within a 30-minute time period and allowed to drift freely for approximately one hour. This was repeated two to four times a day. Drifter measurements were made at the outlet of the Upper Truckee River and near Star Harbor during one day each week in July 2003. The near-shore currents in the top two meters of the lake had essentially the same average velocity off the outlet of the Upper Truckee (150 m/hour) and offshore of Star Harbor (140 m/hour). The fastest drifter speed off the Upper Truckee was 840 m/hour and occurred with a drogue depth of 2 m. At Star Harbor, the greatest drifter speed was only 390 m/hour, with a drogue depth of 2 m. The differences between the two sites could be due to a number of factors, including stream flow magnitude, wind speed, and ambient lake circulation currents. Considering the water velocity and the size of areas with elevated turbidity, the high turbidity water in the near-shore zone mixed daily with mid-lake water even during the summer non-storm conditions when these measurements were made.

The rapid mixing of near-shore and mid-lake water precludes the use of near-shore turbidity measurements to identify the location of nutrient rich ground water inflows. It takes several days for biological activity to convert nutrients to the biological material that influences turbidity. During these several days the nutrients will have moved kilometers away from where the nutrients entered the lake. Hence, the influence of an inflow of nutrients on near-shore clarity is delayed in time and separated from the time and location of the inflow. Nutrient rich ground water inflows may adversely influence the overall clarity of the near-shore and mid-lake, but they will not have a localized effect.

THOUGHTS ON A MONITORING PLAN AND AN ENVIRONMENTAL THRESHOLD FOR NEAR-SHORE CLARITY

Background

The near-shore zone is where the aesthetic appeal of Tahoe's water clarity is most apparent. The local community and visitors consider the ongoing reduction of near-shore clarity to be a concern for aesthetic, environmental, and economic reasons. The near-shore zone is also the portion of the lake that responds the fastest to changes in land use. The results of the extensive restoration efforts that are underway will have a significant influence on near-shore clarity many years before they will have a comparable influence on mid-lake clarity.

It is important to have a monitoring program that can detect changes in near-shore clarity so the effect of management decisions can be determined. The monitoring program must be designed to have sufficient spatial and temporal coverage to be meaningful, have sufficient quality assurance so that long-term trends can be determined, and have a reasonable cost. The monitoring program should measure an inherent optical property of the lake water that is closely related to clarity. (Inherent optical properties are not influenced by the angle of the sun above the horizon, cloud cover, and waves.) Secchi depth clarity cannot be used in a near-shore monitoring program because it is too time consuming to meet the spatial and temporal sampling requirements, and it is not an inherent optical property. Periphyton (attached algae) is not an appropriate indicator of clarity, either, because it is largely controlled by the concentration of mineral particles, not algae.

California recognizes Lake Tahoe as an "Outstanding National Resource Water" which under federal rules requires water quality to be maintained and protected such that there is no long-term reduction in water quality (TRPA, 2002). Nevada requirements are to maintain water quality higher than required to support beneficial uses, which include recreation and water supply. The TRPA has established environmental thresholds for a wide variety of environmental indicators including water and air quality, traffic, and scenic values. The current TRPA environmental indictor that is applicable to the near-shore zone is the littoral zone turbidity indicator. This shallow water threshold calls for the turbidity in the littoral zone to be less than 1 NTU except for areas "directly influenced by stream discharge" where turbidity should be less than 3 NTU (TRPA, 2002). The state of California uses the same criteria for Lake Tahoe as TRPA, and Nevada uses a 3 NTU limit for shallow water at Lake Tahoe. Exactly how large an area is considered to be influenced by a stream is not defined. Figure 24 shows how the lack of a clear definition of the areas that are "directly influenced by stream discharge" leads to ambiguity. The threshold uses turbidity as an indication of clarity. Depending on the type of turbidity instrumentation used, the measurement may not be affected by clarity reducing dissolved organic material such as tannin. A turbidity of 1 NTU roughly corresponds to a Secchi depth of 3 to 6 m (Figure 2). Currently, the typical Secchi depth off Bliss State Park is 14 to 18 m. The TRPA littoral zone indicator permits the near-shore Secchi depth in undeveloped areas like Bliss and Sand Harbor state parks, or at the water intakes for municipal water systems, to be less than 6 m, maybe even less than 3 m, before non-compliance occurs. An obvious reduction of clarity off developed areas, and an extreme reduction of clarity off undeveloped areas and over municipal water system intakes could occur before clarity becomes noncompliant with the TRPA littoral zone indictor and the California and Nevada water quality standards.

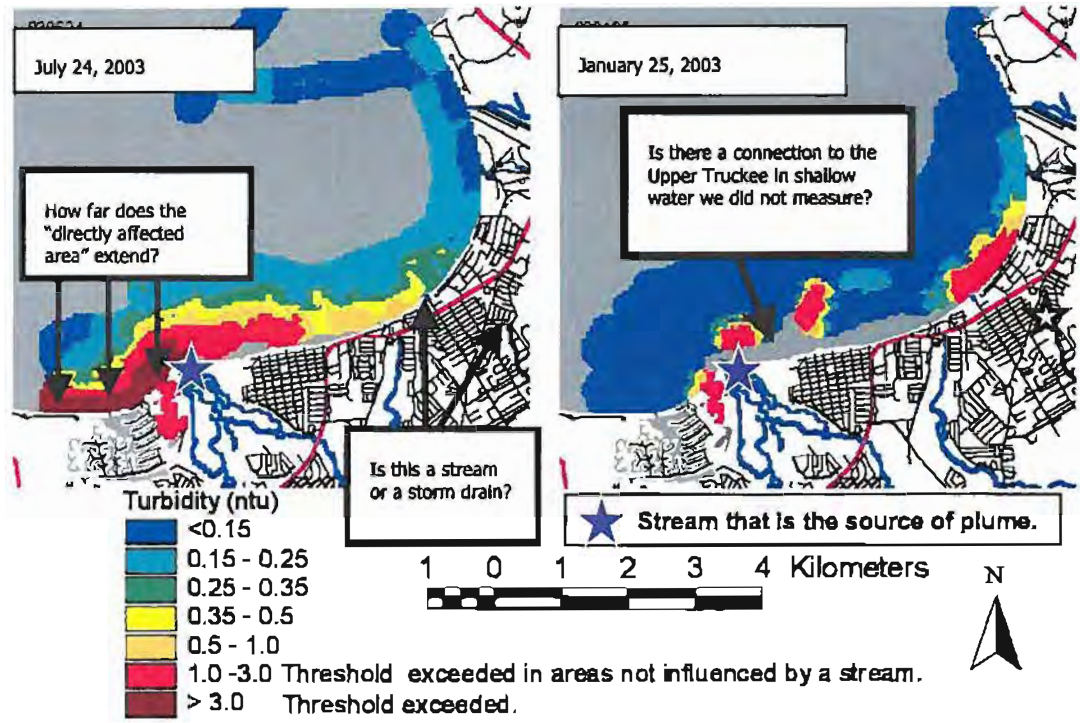


Figure 24. Illustration of the problem created by the ambiguous wording in the current littoral zone threshold. This threshold has a 1 NTU standard for areas not directly influenced by stream discharge and a 3 NTU standard for areas directly influenced by stream discharge. The threshold does not specifically define what "directly influenced by stream discharge" means. In this figure, the areas in light red were between 1 and 3 NTU. Portions of the light red areas not considered to be directly influenced by stream discharge were in violation of the threshold, but portions of the light red areas that are considered to be directly influenced by stream discharge were not in violation of the threshold. The dark red areas were greater than 3 NTU and were in violation of the threshold regardless of the influence of stream discharge. Most people are likely to consider the area just off the Upper Truckee River to be influenced by stream discharge. But other locations are less clear, for example: 1) the light red area off Al Tahoe on January 25, 2003 (which may be connected to the Upper Truckee River by a shallow turbid plume in water that is to shallow too be measured with our current system); 2) the 1.8-km-long plume of high turbidity that flows west from the Upper Truckee River on July 24; 3) the 1.1-km plume that flows east from Ski Run Marina on January 25; and 4) should the Ski Run Marina area even be considered to have a steam? (A small stream not shown on this GIS layer flows occasionally through a series of detention basins and enters the lake via a culvert that flows into the marina and then into the lake. Is this a stream or a storm drain?) It can also be argued that the entire lake is directly influenced by stream discharge because there is daily mixing between the near-shore and mid-lake. The current ambiguous definition of areas that have a 1 NTU threshold and areas that have a 3 NTU threshold offers endless opportunity for debate.

The current TRPA monitoring program for littoral zone turbidity consists of measuring turbidity four to five times a year during calm conditions. The measurements are made at nine locations around the lake in water that is 25 m deep. Elevated turbidity values will not be observed at the TRPA monitoring sites because the 25 m depth provides ample opportunity for dilution by cleaner mid-lake water. These measurements are not indicative of the portion of the lake where the clarity is apparent to an observer on shore. The operational requirement that measurements be made during calm weather also biases the results. The lead author observed TRPA turbidity measurement procedures and has concerns about how the measurements are made. The current program was as well designed as possible when it was first implemented. However, the improvements in instrumentation and our understanding of near-shore clarity developed during this project should be incorporated in the littoral zone monitoring program. TRPA has recently been made aware of these issues and is considering changing the monitoring plan and environmental threshold for the near-shore zone in conjunction with the development of permissible total maximum daily loads (TMDLs) and the 2007 Regional Plan Update.

The existing regulatory criteria for the littoral zone are not consistent with the no degradation requirement of California's recognition of Lake Tahoe as an "Outstanding National Resource Water". The TRPA littoral zone monitoring program in water that is 25 m deep prevents the detection of degradation near the shore where the majority of the public observes the water clarity and enters the water, and there is no way to determine if the clarity near the shore is increasing or decreasing. The TRPA littoral zone indicator (WQ-1), Nevada's 3 NTU criteria, and California's 1 and 3 NTU criteria, are not consistent with the communities expectations for clarity, and are inconsistent with the use of the littoral zone for unfiltered municipal water supply.

Suggested Approach for a Near-shore Clarity Monitoring Plan

A good near-shore clarity monitoring program and environmental indicator should be based on an inherent optical property (i.e., a property that is not dependent on the natural lighting or surface conditions) that is closely related to clarity. The measurement should be capable of being made from a moving boat so spatial surveys can be conducted. The measurement should also be capable of being made on a moored buoy so that continuous measurements can be made at a fixed location with only infrequent visits by field personnel. To assure that long-term records can be developed, the instrumentation should be available from several manufacturers, be common enough that instruments with a similar response will be available several decades in the future, and quality assurance and calibration procedures should be easy to document and frequently apply.

Many instruments marketed as "turbidity sensors" do not have an optical path geometry compliant with established EPA protocols. Instruments that are not compliant with EPA regulations are not suitable for long-term monitoring because instruments made by different manufacturers do not have a consistent response to different types of particles. This will cause problems when it inevitably becomes necessary to replace the instruments in a long-term monitoring program. The non EPA-compliant turbidity instruments are frequently difficult to calibrate because typically they do not make their measurements in a closed sample cell, hence they require a large volume of calibration solution. The primary EPA turbidity standards are based on formazin, which is a carcinogen, so large volumes of turbidity calibration solutions are not desirable. We are not aware of any commercially available EPA-compliant turbidity instrument that has demonstrated the sensitivity and base line stability required to measure the small changes in the exceptionally low turbidity water of Lake Tahoe without maintenance for several weeks. The manufactures we have spoken with are reluctant to comment on the ability of their instruments to meet these challenging requirements. The only way to be sure a particular turbidity instrument will be suitable for a long-term deployment with minimal maintenance is to test it.

Light scattering measurements are also not recommended as the primary method in a long-term monitoring plan. We have not identified an instrument that can measure the low level of light scattering that occurs in the clean water of Lake Tahoe with an acceptable signal to noise ratio. Light scattering instruments from two leading manufacturers of ocean optical instruments (Wetlabs and Hobilabs) were evaluated and both had an unacceptable level of measurement noise in the clear water of Lake Tahoe. Although long-term averaging of measurements might reduce the noise level to an acceptable level, this is not a desirable approach because it reduces the sensitivity to small changes. Light scattering instruments typically have to be calibrated once a year by the manufacturer, a process that takes the instrument out of use for several weeks. These instruments also cannot be used in shallow water and are not practical to deploy from a moving boat.

The most promising optical property to use for monitoring near-shore optical properties is light transmission. The same measurement sensor can be deployed on a moving boat or a buoy. The sensor is available from at least two manufacturers. Light transmission is such a fundamental property that instruments with a similar response to current instruments will be available in the future. The instruments are routinely deployed unattended for several months in oceanographic studies where mechanical shutters or chemical systems are used to protect the optics from biofouling. The ability to operate for several months without manually cleaning the optics greatly reduces the cost of monitoring efforts compared to instruments that must be cleaned by a field person every week or two. The light transmission sensor can be calibrated with pure water in few hours by someone with a general science background, which contrasts with the carcinogenic standards used for turbidity sensor, and the delays and typical $500 cost of having the manufacturer calibrate a scattering senor. Initial results show light transmission is nearly linearly related to clarity (Figure 2b). Light transmission is sensitive to reductions in clarity caused by light absorption from dissolved organic material, light absorption by particles, and light scattering by particles. A comparison of spatial surveys of the south shore area made with turbidity and light attenuation instruments is shown in Figure 25. The similar results obtained from both methods during this particular survey illustrate how light attenuation measurements can provide similar information as turbidity measurements. An exception to this is when the concentration of dissolved organic matter in the water is elevated, which was not the case during this particular survey. The light transmission method is more suitable for long-term monitoring than turbidity measurements for the reasons explained above (e.g., greater sensitivity to clarity changes in water with a Secchi depth clarity greater than 10 m; responsiveness to dissolved organic material; simpler calibration, field, and quality assurance procedures; ability to be deployed for extended periods without attention from field personnel; a consistent response between instruments regardless of the types of particles; and the likelihood of there being suitable replacement instruments many decades from now).

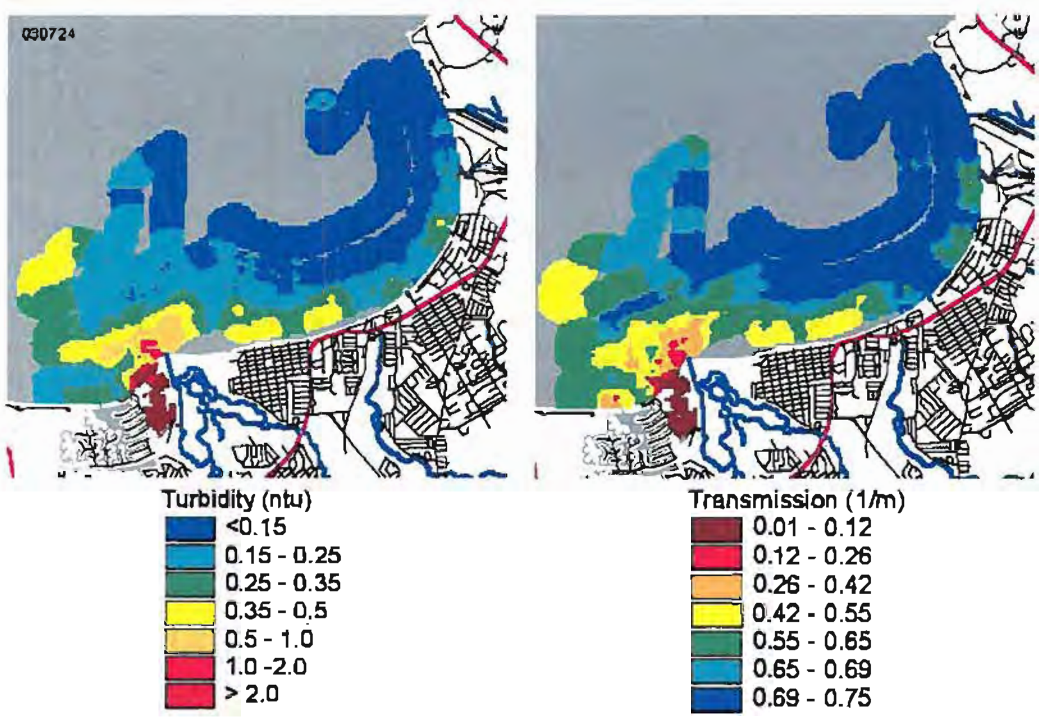


Figure 25. Comparison of turbidity and light transmission surveys from July 24, 2003. The two measurements show the same general pattern. Minor differences in the two surveys are partially due to differences in the two methods and due to the limited number of colors used in this plot. Transmission is influenced by both light scattering and absorption, while turbidity is only influenced by light scattering. Selection of a slightly different color scale may alter the shape of minor details. Although the two methods led to a similar result during this survey, the transmission measurement is more suitable for long-term monitoring for its sensitivity to light absorption by dissolved organic matter, simpler calibration and field procedures, and other reasons detailed in the text.

It is unrealistic to suggest that an optical property of the near-shore, such as light transmission, be continuously measured throughout the entire near-shore zone. Spatial surveys such as those in Figure 19 are useful for determining the spatial extent of light transmission on a given day, but they cannot define long-term trends because they cannot be made frequently enough to fully sample the range of temporal variations. Likewise, continuous measurements at a fixed location can be used for detection of long-term trends, but they must be located in meaningful places. A combination of infrequent spatial surveys combined with continuous measurements at fixed locations is a practical and effective approach. The infrequent spatial surveys can be used to select optimal locations for continuous measurements and to identify new problem areas that might develop. The spatial surveys would ideally be done after storms so that small problems areas could be identified, but even if they were done during calm periods areas with a persistent problem would be detected. Selecting the location for a continuous monitoring station is complicated by changes in the surface level of the lake and the large near-shore gradient in turbidity. If a monitoring site is at a fixed location, the water depth at the site will be different in different years. An instrument that is in three meters of water one year may be in one meter of water a few years later. This will cause problems because the resuspension ofbottom sediment in the shallow water that occurs some years will adversely influence the measurements. Likewise, placing the instrument in water deep enough that changes in lake level are not significant will place some instruments so far offshore they will not be measuring near-shore conditions. The authors suggest placing the monitoring sites in water two to four meters deep and moving the site closer or further from shore when the lake level changes. This avoids placing the instruments in very shallow water where resuspension of sediment by waves would adversely influence the measurement, but still keeps the instruments as close to shore as practical. The instruments would have to be robust enough to minimize damage by intentional tampering (this is routinely done with weather stations), and be marked with surface buoys so boaters could avoid them. The surface buoys could be "camouflaged" by making them look like the thousands of other mooring buoys around the lake. At some sites the instrument buoys could be attached to existing buoys that could still be used for their current purpose (e.g. swim area and channel markers, some boat moorings). Other sites would require permitting new buoys, but the buoys would only be deployed for part of the year and they would not need the large moorings that are required to secure a boat. Deploying another 20 buoys does not seem unreasonable when one considers the hundreds of illegal buoys that are currently on the lake.

The deployment of continuous recording instruments is complicated by electrical power requirements requiring large batteries, and the biological fouling of the optics. In practice, measurements are not made continuously, but instead are made several times a day. For convenience, we refer to measurements made several times a day as continuous measurements because they are frequent enough to record the temporal variability. Making measurements several times a day reduces the power requirements and allows mechanical shutters or chemicals to protect the optics from biological fouling when measurements are not being made. Given a fixed amount of resources, there is a tradeoff between the number of sites that can be monitored with continuous instruments and the length of time the instruments can be deployed. One option is to have only a few sites that operate year round. Another option is to have many sites that only operate a short time each year. It is the authors' current opinion that sites should be monitored for at least eight weeks during the summer (July and August) and eight weeks during the winter (January 15 to March 15) in order to collect data that accurately represents near-shore clarity. This allows determination of a summer and a winter trend. Monitoring sites for shorter time periods is likely to result in a poor determination of actual conditions because a single abnormal event can bias the results. Monitoring for longer time periods is desirable, but in the authors' current opinion, resources would be better spent on increasing the number of monitoring locations until there are about twenty monitoring locations, rather than increasing the time each location is monitored to longer than eight weeks.

Three levels of near-shore zone monitoring programs are suggested in Table 3. The startup program does not have a full range of sampling sites and relies on the spatial surveys that have already been completed to select sampling sites. This level of effort is considered inadequate for long-term monitoring because it does not monitor enough sites, and there is no way to determine if changes in the near-shore zone are such that monitoring sites remain in appropriate locations. The startup program is provided as an example of an intermediate goal for a near-shore monitoring program. It provides enough information about existing conditions that informed decisions could be made when a new environmental threshold is established for the near-shore zone. The basic monitoring program is adequate to address large-scale changes in near-shore clarity, but it has too few monitoring sites to assess the effectiveness of all the planned restoration efforts. It does monitor the areas of greatest concern. The full monitoring program has sufficient coverage that it can be used by land managers to assess the effectiveness of anticipated restoration efforts, and it can identify new problem areas that may develop over time. Full lakeshore spatial surveys should be conducted periodically (i.e., Table 3) to determine if problems have developed in new areas. Although the full lakeshore surveys would be conducted infrequently, they would still identify new problem areas that are large and persistent.

Table 3. Suggested monitoring plans for the near-shore zone.

Monitoring task	Startup program	Basic program	Full program
Number of Whole Lakeshore Spatial Surveys Per Year	None	1 per year alternating between a summer and a winter survey	1 during summer 2 during winter
Locations for Continuous Monitoring Sites			
State Line, South Shore	No	Yes	Yes
Nevada Beach	No	No	Yes
Cave Rock State Park	No	No	Yes
Sand Harbor State Park	Yes	Yes	Yes
Incline Village/Third & Incline Creeks	Yes	Yes	Yes
Incline Village/Burnt Cedar Beach	No	Yes	Yes
Kings Beach	No	Yes	Yes
Tahoe Vista	No	Yes	Yes
Star Harbor	Yes	Yes	Yes
Tahoe City	No	Yes	Yes
Sugar Pine Point, State Park	No	No	Yes
Rubicon Point	Yes	Yes	Yes
Emerald Bay	No	No	Yes
Tahoe Keys (~50 m off East Marina Entrance)	No	No	Yes
Upper Truckee River	Yes	Yes	Yes
Al Tahoe West	No	Yes	Yes
Al Tahoe East	No	No	Yes
Bijou Creek	Yes	Yes	Yes
Ski Run Marina	No	Yes	Yes
An unspecified location	No	No	Yes
Number of continuous monitoring sites	6	13	20

The monitoring program suggested here focuses on the clarity of the near-shore zone. Depending on the location and hydrologic conditions, near-shore clarity is controlled by the presence of mineral or organic particles. Chlorophyll fluorometers could also be deployed on the buoys to monitor the chlorophyll concentrations in the near-shore. Water samples would have to be collected every few weeks to convert the fluorometer readings to measurements of chlorophyll expressed in absolute units such as mg of chlorophyll/liter of water. This would allow summer and winter trends of chlorophyll concentration to be determined for specific areas. This could be used to determine if efforts to decrease nutrients are really reducing the algae in the near-shore zone. For best results this should be combined with a periphyton (attached algae) monitoring program.

The costs of the proposed monitoring programs depends on a variety of factors that cannot be determined at this time (e.g., how frequently the optics have to be cleaned, how much cost saving will occur when a larger number of sites are monitored, what other measurements will be made at the sites, will the spatial surveys be conducted and if so will other efforts share in the upkeep of the spatial survey system, what level of analysis and reporting will be required, and what organization is performing the work). A rough estimate is that each instrumented buoy will cost $8,000 to $15,000. An annual cost of $9,000 to $16,000 per buoy would cover the operations (e.g., calibration before deployment, instrument deployment, in lake instrument maintenance, instrument removal, checking the calibration after the deployment, reporting the results, and post deployment maintenance, repair and depreciation.) The cost for the first buoy will be at least twice the range reported above because there will be development costs associated with the program regardless of the number of sites or buoys. The costs will fall into the ranges above after a year or two of experience has been gained and the instrument design has been finalized. The cost of the mooring may be nonexistent (e.g., attaching the instrument buoy to a swim marker buoy at Sand Harbor) or large (e.g., the cost of salary time used to obtain permission for a new buoy in a sensitive area). The cost to replicate the spatial survey equipment and boat used in this study would be between $130,000 and $250,000 depending on the skill and efficiency of the organization. The cost to conduct a single whole lakeshore survey would be between $15,000 and $30,000 depending on the level of detail in the survey, reporting requirements, the frequency of the surveys, and the organization.

Suggested Approach for a Near-shore Clarity Threshold

An environmental threshold for near-shore clarity should be consistent with the public's expectations for lake clarity, but also has to take into consideration natural temporal and spatial variations in near-shore clarity, and be consistent with the high level of environmental protection typical of other TRPA environmental thresholds.

The authors recommend light transmission be considered for use as the optical property on which the near-shore clarity threshold is based. This property has the advantages over turbidity of being more sensitive to small changes in clarity in the high clarity water typical of undeveloped areas, is relatively simple to make from a moving boat or an unattended buoy, has relatively easy calibration and quality assurance procedures, has a more stable base line value, and is more likely to provide a record that can be quantitatively compared to measurements in the distant future. The authors suspect measurements of light transmission must be made at least four times a day and for at least eight weeks to determine meaningful statistics that can be used to compare measurements in different years. When only a few measurements are made each day, shutters can be used to protect the instrument's optics from biological material reducing the need to clean the instrument as often. More frequent measurements are desirable, but the shutters are much less effective when they are frequently opened. More frequent measurements would incur greater costs to manually clean the optics every few weeks. It is recommended that measurements be made during the summer (July and August) and during the winter (January 15 to March 15) so that both winter and summer trends can be determined. Field trials will be necessary to determine the most efficient way to deploy the instruments and collect useful data.

The authors recommend the near-shore clarity threshold contain three elements. The first element is the minimum percent light transmission per meter that is considered desirable. The second element of the near-shore clarity threshold should be the percentage of time that light transmission is required to be greater than the minimum desirable value. To illustrate this concept consider a person that goes to the lakeshore every day to see if a particular underwater rock can be seen from the shore. The person knows that natural events can decrease near-shore clarity for short time periods and that developing the infrastructure to mitigate the adverse effects of development under extreme hydrologic conditions requires an unrealistic amount of resources. The person may consider near-shore clarity to be acceptable (i.e., compliant with the near-shore clarity threshold) as long as the underwater rock can be seen on 95 percent of their visits. If the light transmission is such that the underwater rock cannot be seen 95 percent or more of the time, then the near-shore clarity would be considered to be unacceptable (i.e., not in compliance with the near-shore clarity threshold). In this example, the near-shore clarity could be very poor 4.9 percent of the time and the threshold would still not be considered exceeded. This allows compliance with the near-shore clarity threshold during natural clarity-degrading events that are exceptionally rare and of short duration.

The third element of the near-shore clarity threshold should be to incorporate the concept that some portions of the lake should have a greater level of protection than other areas. In the same way that an advertisement sign is considered acceptable in the Stateline, Nevada casino district, but is not considered acceptable at Bliss State Park, there should be an expectation for greater near-shore clarity off Bliss State Park than off the casino district. Also, some portions of the near-shore zone may naturally have a lower clarity due to stream inflows that mix slowly with clear deep water, shoreline erosion, or resuspension of bottom material in shallow water. This concept leads to the idea of having three threshold levels for near-shore clarity. One level might be for areas with extensive commercial development near the lakeshore with shallow water that limits near-shore mixing (e.g., Bijou Center). A second level might be for moderately developed areas (e.g., Al Tahoe) or areas where natural conditions increase the turbidity (e.g., Upper Truckee River). A third level might be for areas that are undeveloped (e.g., Bliss State Park). This allows a high level of protection for relatively pristine areas (e.g., Bliss State Park) without setting an unreasonable standard for areas that have extensive commercial development and a small amount of near-shore mixing, (e.g., Bijou Center). This approach recognizes there are environmental consequences associated with development and to a specified extent, as rigorously defined by the different threshold levels for the different areas, some environmental consequences are considered acceptable. In order to establish what the threshold levels should be for the different areas it will be necessary to have a better understanding of the current conditions, the natural influences on near-shore clarity in specific areas, the biological issues associated with specific areas, and the public's expectations. When this information is available, regulatory agencies could make well-informed decisions regarding what threshold levels are appropriate for specific areas.

The near-shore threshold concept proposed here should not be confused with the establishment of an allowable total maximum daily load for individual sources. The near-shore monitoring and threshold proposed here only address the issue of near-shore clarity. Near-shore clarity is not a useful indication of the flux of particles and nutrients to the lake because of temporal and spatial changes in the rate of exchange between near-shore and mid-lake water. A similar situation exists with mid-lake clarity where the Secchi depth is used to quantify mid-lake clarity, but is not considered to be related in a simple way to the influx of nutrients and particles to the lake. The mid-lake and near-shore clarity can be used to measure the effectiveness of management decisions on clarity, the visibly observable property that Lake Tahoe is famous for, but they are not a measure of the loading to the lake.

Direct measurements of the outflow of streams, culverts, groundwater and atmospheric inputs are required to determine the loading to the lake and to measure the effectiveness of management action on controlling the loading to the lake. Measuring the loading to the lake does not determine the effect of management actions on water clarity, because the relationship between clarity and loading is non-linear and spatially and temporally variable. From the public's perspective, direct casual observation of the near-shore and mid-lake clarity is the criteria that is used to judge the effectiveness of management actions; and reported reductions in the loading to the lake are of secondary interest. It is necessary to monitor the near-shore and mid-lake clarity to determine how much effect the regulatory efforts that reduce loading have on clarity. Existing models and models under development cannot quantify the effect of load reductions on near-shore clarity. Such models will require long-term records of near-shore clarity before they are developed. Even if such models were available a large segment of the public would judge the effectiveness of management actions based on their own direct observation of clarity instead of the reported results of a computer model. The only way to determine the effectiveness of management actions on mid-lake and near-shore clarity is to have effective clarity monitoring programs. Such a program exists for mid-lake clarity, but not for near-shore clarity where the clarity of the lake is most frequently observed.

The authors suggest a near-shore monitoring program be established similar to the full program proposed above. The data could be used to determine long-term clarity trends for specific areas. This would allow the effect of management actions on the clarity of the lake to be rigorously determined. If this is not done there is no way to quantify how management actions have influenced near-shore clarity and the effectiveness of management actions on near-shore clarity will be evaluated by informally developed public perception. This monitoring program would allow the adoption of an environmental threshold like the one proposed above. It would allow compliance with the near-shore clarity threshold to be determined independently for summer and winter seasons, for specific areas, and do so in a rigorously defensible way into the foreseeable future.

SUMMARY OF MAJOR RESULTS

Near-shore turbidity is a good measure of near-shore clarity and is relevant to discussions of the aesthetic appearance of the water near the shore. Near-shore turbidity can identify some large sources of particle inflows to the lake. However, near-shore turbidity cannot identify all large sources of particle inflows to the lake because rapid dilution of the inflow water by cleaner lake water keeps the near-shore turbidity low in some areas despite a large inflow of particles. Establishing a clarity standard for the mid-lake does not protect the aesthetic values of the near-shore zone, and establishing a tighter clarity standard for just the near-shore zone would not protect the aesthetic value of the mid-lake. Near-shore water quality measurements do not determine the flux of material into the lake and are not a substitute for directly monitoring streams and culverts.

Near-shore clarity measurements can be used as a direct and unbiased measure of the effectiveness of management actions on near-shore clarity in specific areas. It is not appropriate to rely only on monitoring of streams and culverts to measure the effectiveness of management actions on near-shore clarity. Stream and culvert monitoring can determine if management actions have been successful in reducing the flux of undesirable material to the lake, but it cannot determine what effect the management actions have had on the near-shore clarity that is observed by the public. There is no model that can relate particle flux to near-shore clarity and such a model is unlikely to be developed in the foreseeable future. Even if such a model were developed, near-shore clarity measurements would be required to calibrate and test the model before it was useful. Near-shore clarity should be used as a measure of the effectiveness of management actions and for public education in the same way that mid-lake clarity is used. Near-shore clarity will respond more quickly to management actions than mid-lake clarity allowing a more timely approach to adaptive management. Near-shore clarity is more relevant to the public than mid-lake clarity because the concern or pride associated with near-shore clarity is focused on specific areas instead of the entire basin. By focusing the clarity issue on neighborhood scale areas many people will feel a greater responsibility then when the clarity issue is presented as a basin wide issue.

Near-shore turbidity is not a good way to monitor biological activity in the near-shore, other metrics such as periphyton and continuous *in-situ* chlorophyll measurements should be used for that application. Light transmission should be considered as an alternative to turbidity for long-term monitoring of near-shore clarity.

Of the 114 km of shoreline, only 5.5 km had a turbidity sufficiently elevated to be frequently detected by a casual observer onshore. Most areas with frequently elevated turbidity can be linked to an obvious point source of high turbidity water such as a stream or culvert. More detailed studies in water that was too shallow to measure with the equipment used in this project would likely link all the areas with frequently elevated turbidity to a point source of high turbidity water. There were many places that infrequently had slightly elevated near-shore turbidity for which we were unable to identify a cause. It is unclear if these areas were caused by the weak point sources that existed in these areas, diffuse inflows, or another process such as upwelling.

All the areas with significantly elevated near-shore turbidity were associated with developed areas. However, not all developed areas had high near-shore turbidity. Inflows from the upper Truckee River and its tributary, Trout Creek, and Bijou Creek are the major cause of reduced clarity in the near-shore zone, and at times adversely influenced the entire southeast shore from Pope Beach to Edgewood Creek.

Near-shore turbidity is greatly elevated during periods when there are large surface water inflows to the lake such as during spring melt, rain at lake level, or snow melt at lake level. The clarity off undeveloped areas is not as adversely influenced by water inflows to the lake as developed areas. Summer thunderstorms influenced near-shore clarity to a minor degree, but much less then snowmelt.

There was a good temporal and spatial association between highly elevated near-shore turbidity and an abundance of mineral particles. This indicates light scattering by mineral particles is more responsible than organic material for the highly elevated turbidity that occurs off some developed areas. However, in near-shore areas with low turbidity, most of the particles were organic material, indicating the lake-wide increase in algae is more of a factor than mineral particles on near-shore clarity in undeveloped areas. The role of colored dissolved organic material such as tannin was not studied as part of this project. Visual observations suggest that tannins were a major cause of near-shore clarity loss near the outlets of some creeks during the spring. The significance of tannins in reducing near-shore clarity, the extent to which this is a natural occurrence, and the extent to which human activities have increased or decreased the inflow of tannins are unknown.

RECOMMENDATIONS

Near-shore clarity is poor in many areas along the California side of the south shore and is slightly reduced around other developed areas. Management actions should target inflows occurring at all locations because they all contribute to the decline of mid-lake clarity. However, to improve near-shore clarity some management actions must specifically address near-shore clarity problems. This means having stricter regulations to reduce particle inflows from areas where near-shore currents do not rapidly dilute inflows with cleaner lake water. Applying a spatially uniform set of regulations driven by basin scale mid-lake clarity concerns will not solve the spatially variable local scale near-shore clarity problems.

The relationship between stream and culvert inflows and near-shore turbidity should be investigated so that there is a better understanding of how proposed management actions will influence near-shore clarity.

The Upper Truckee River and its tributary, Trout Creek, and Bijou Creek are the largest cause of elevated near-shore turbidity. Multiple spatial surveys should be made on these waterways to identify the specific segments that contribute the most mineral particles to the lake. This will allow management actions to target sections of the Upper Truckee River and Trout and Bijou creeks that have the greatest adverse impact on near-shore clarity.

The existing littoral zone monitoring program has many flaws that prevent it from identifying areas in violation of the littoral zone turbidity threshold, and it does not produce data that can be used to document trends in littoral zone clarity. Despite the high public awareness of near-shore clarity and the ability of near-shore clarity to be a scientifically rigorous and publicly visible measure of the success of management actions, the level of support for littoral zone monitoring is negligible. A new littoral or near-shore zone monitoring program should be developed that includes independent measures of water clarity and biological activity. This should start with a pilot program to fully develop the field and data analysis methods before committing to a new monitoring approach.

The current littoral zone water quality threshold provides a level of protection that is considerably below the high standards of other TRPA thresholds, and is inconsistent with the federal designation of Lake Tahoe as an Outstanding National Resource Water and public expectations. For example, with the current littoral zone turbidity threshold it would be acceptable for the water off Bliss and Sand Harbor state parks to have a turbidity of 1 NTU, corresponding to a Secchi depth clarity of 3-6 m. This is considerably worse than the current clarity of more than 18 m in these areas. The littoral zone water quality standards should be modified. This should be done by first collecting data so that existing conditions can be determined and taken into consideration when a new threshold is established.

The Al Tahoe and Star Harbor areas have moderately elevated near-shore turbidity and there was not a clear reason for this. Further studies to understand the cause of near-shore clarity loss in these areas would be beneficial.

Dissolved organic material (e.g., tannin), algae, and mineral particles all influence near-shore and mid-lake clarity. Improving our understanding of the relative contribution of these three classes of clarity reducing materials would increase the confidence in predictions of near-shore and mid-lake clarity.

The interaction of stream inflows, near-shore water, and mid-lake water is poorly understood. Currently, it is not possible to rigorously determine the effect of high turbidity near-shore waters on mid-lake clarity. Improving our understanding of how streams, near-shore waters, and mid-lake waters mix, would improve our confidence in predictions of mid-lake clarity.

The significance of resuspension of bottom sediments on clarity in shallow near-shore areas is poorly understood. Further studies to understand this would help determine how much of the clarity reduction in shallow areas is due to development and how much is due to natural conditions. This information would be useful when decisions are made about what level of near-shore clarity is acceptable in different areas.

ACKNOWLEDGEMENTS

This work was funded by the Lahontan District of the California Water Quality Control Board, the Nevada Division of State Lands using funds from the sale of vehicle license plates with a Lake Tahoe design, the Tahoe Regional Planning Agency, and the Desert Research Institute of the University and Community College System of Nevada. We greatly appreciate the assistance of Dick Horton with the Tahoe Keys Marina, who provided us with a boat slip while we worked along the south shore, and Rick Keller with Sand Harbor State Park, for logistics assistance while we worked along the north shore. Without their help we would not have accomplished as much as we did. John Reuter with the University of California at Davis provided great advice during the course of the project and while reviewing this report. Rick Susfalk and Margaret Shanafield participated in the fieldwork and report preparation. Susfalk developed the section on areas with persistent high turbidity. Shanafield developed the section on the exchange of near-shore and mid-lake waters. Geoff Schladow is responsible for the section on particle size (appendix A) and the measurements of particle size were made by Gandhi dePaz and Andrew Funk. Ken Taylor was the project director and except for the particle size work, he developed the instrumentation and methods for data collection, processing, and analysis. Taylor was the lead author.

CONTACT INFORMATION

For more information about this project, please contact the lead author: Kendrick Taylor, Desert Research Institute, University and Community College System of Nevada, Reno, Nevada. Phone 775.673.7375, Email: kendrick@dri.edu. This report is available on-line at http://tahoenearshore.dri.edu.

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TRPA (2002) 2001 Threshold Evaluation Report, chapter 3, page 3 (http:www.trpa.org/documents/Threshold_Eval_2001/3-WQ%20FINAL.pdf)

APPENDIX A: PARTICLE SIZE DISTRIBUTION

Particle size and concentration has a strong influence on water clarity. This project collected water samples under a variety of conditions to support a project by the University of California. Preliminary results are presented here. A future report by Geoffrey Schladow will integrate this information with other data sets and provide an expanded interpretation.

A subset of water samples was analyzed for its particle size distribution and particle-number concentration using an LS-200 Liquid Sampler and LiQuilaz-S05-HF sensor manufactured by Particle Measuring Systems Inc (Boulder, Colorado). The system, based on the measurement of light scatter, allows for the simultaneous measurement of particle size and concentration in up to 15 user-selected size ranges. In this work, the boundaries of the measured size ranges were: 0.5, 0.63, 0.794, 1.0, 1.414, 2.0, 2.828, 4.0, 4.757, 5.657, 6.727, 8.0, 11.31, 16.0, and 20 μm. Three 10-ml subsamples were measured from each sample. NANOpure™ blanks were analyzed prior, during, and at the end of the measurement to ensure quality control. Periodically, the accuracy of the LiQuilaz was checked using solutions of NANOpure™ water and latex beads of known diameter.

Table A1 shows the subset of samples that were analyzed for particle size distribution. The dates sampled and the locations are indicated. Figure A1 shows a typical particle size distribution for surface water (0 cm depth) at the Tahoe Research Groups Midlake sampling station. Particle concentrations tend to be a little higher in summer (after spring snowmelt) and lower in winter, when deep mixing is occurring. The overall range of particle concentrations in each size range would rarely change by more than a factor of two. The exponent (slope) of the line when plotted on a log-log axis is –3.5.

Figure A2 shows the particle size distributions for all samples taken just offshore of the outlet of the Truckee River. In all cases, the finest particles are present at this site in concentrations four to 10 times higher than at mid-lake. All these sampling dates had turbidity described as either moderate or high. The notable exceptions to this were May 22, 2003 during the Upper Truckee River runoff (See Figure 19-17) and July 24, 2003, after a half inch of rain and when the maximum turbidity off the Upper Truckee River was observed. Both of these distributions show enrichment of the coarser particle fractions (indicated by the flatter slopes). Interestingly, these high turbidity events were not associated with any measurable change in the finest particle concentrations (less than 1 micron), but purely with increases in the larger particle concentrations.

Table A1. Samples that were analyzed for particle size distribution.

Site Id and Date	Site Description
020711A 7/11/02	100 m off Upper Truckee
020711B 7/11/02	2,000 m off Upper Truckee
020712A 7/12/02	500 m off Incline Creek
020712B 7/12/02	20 m off Incline Creek
020716A 7/16/02	300 m off Kings Beach
020716B 7/16/02	40 m off Kings Beach
020718A 7/18/02	50 m off Star Harbor
020722-1 7/22/02	Center of lake-north
020722-3 7/22/02	Center of lake-south
020722-4 7/22/02	100 m off Upper Truckee
020722-5 7/22/02	50 m off Star Harbor
020722-6 7/22/02	50 m off Incline Creek
020722-7 7/22/02	50 m off Rubicon Point
020722-8 7/22/02	Inside Tahoe Keys Marina
020722-9 7/22/02	50 m off Tahoe City
UT2 021021 10/21/02	300 m off Upper Truckee
UT4 021022 10/22/02	3,000 m off Upper Truckee
BC2 021022 10/22/02	100 m off Bijou Creek
EW1 11/13/02	10 m off Edgewood Creek
BC2 11/13/02	100 m off Bijou Creek
UT2 11/13/02	300 m off Upper Truckee
UT4 11/13/02	3,000 m off Upper Truckee
EW112/18/02	50 m off Edgewood Creek
BC2 12/18/02	100 m off Bijou Creek
UT2 12/18/02	300 m off Upper Truckee
EW1 1/8/03	10 m off Edgewood Creek
BC2 1/8/03	100 m off Bijou Creek
UT2 1/8/03	300 m off Upper Truckee
UT4 1/8/03	3,000 m off Upper Truckee
EW1 1/29/03	10 m of Edgewood Creek
BC2 1/29/03	100 m Bijou Creek
UT2 1/29/03	300 m off Upper Truckee
UT4 1/29/03	3,000 m off Upper Truckee
030129A 1/29/03	100 m off Upper Truckee
030129B 1/29/03	50 m off Bijou Creek
030129C 1/29/03	40 m off Ski Run Marina
Tahoe Keys 4/30/03	Inside Tahoe Keys Marina
UT1 4/30/03	50 m off Upper Truckee
UT4 4/30/03	3,000 m off Upper Truckee
BC2 4/30/03	300 m off Bijou Creek
UT1 5/22/03	100 m off Upper Truckee
UT4 5/22/03	3,000 m off Upper Truckee
UT1 6/23/03	100 m off Upper Truckee
UT1 6/24/03	100 m off Upper Truckee
AIT 6/23/03	100 m off Al Tahoe
BC1 6/23/03	50 m off Bijou Creek
BC1 7/24/03	50 m off Bijou Creek
EW1 7/24/03	10 m off Edgewood Creek
UT1 7/24/03	100 m off Upper Truckee
UT4 7/24/03	3,000 m off Upper Truckee

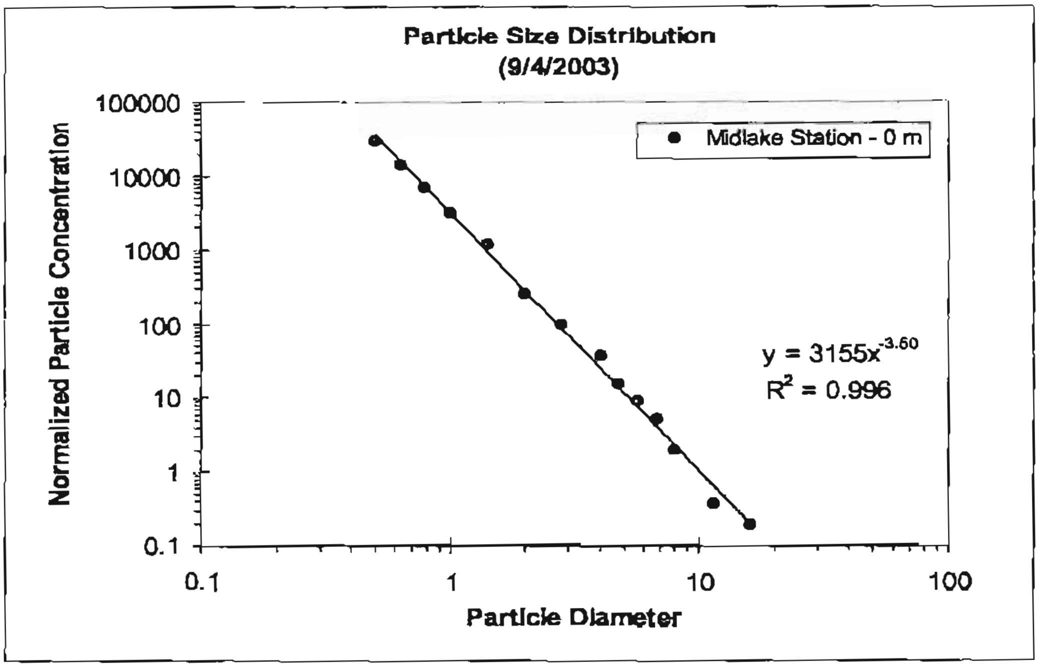

Figure A1. Particle size distribution for surface water at the Midlake Station, September 4, 2003.

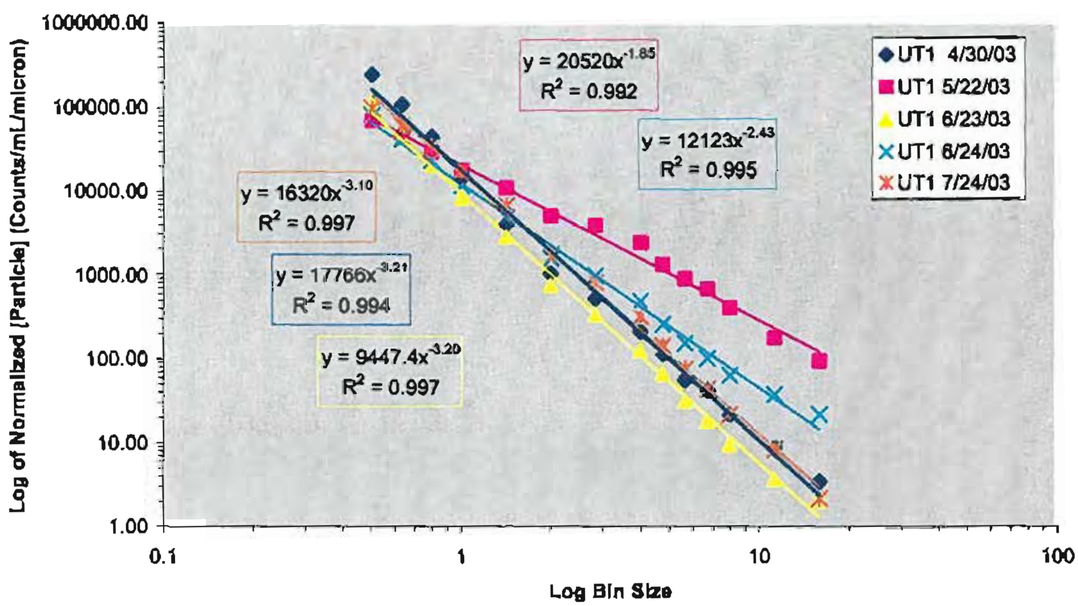

Figure A2. Particle size distribution curves for the mouth of Upper Truckee River.

Figure A3 shows particle size distributions for a site 300 m offshore of the outlet of the Upper Truckee River. The same two dates that had an enrichment of coarse particles near the shore were also enriched in coarse particles 300 m offshore, although dilution with lake water had apparently reduced this somewhat. The high turbidity day of January 19, 2003 (Figure19-11) had high concentrations of particles across all size ranges. The December 18, 2003 storm produced an increase in the finer particles and a decrease in the coarser particles, to yield an unusual distribution.

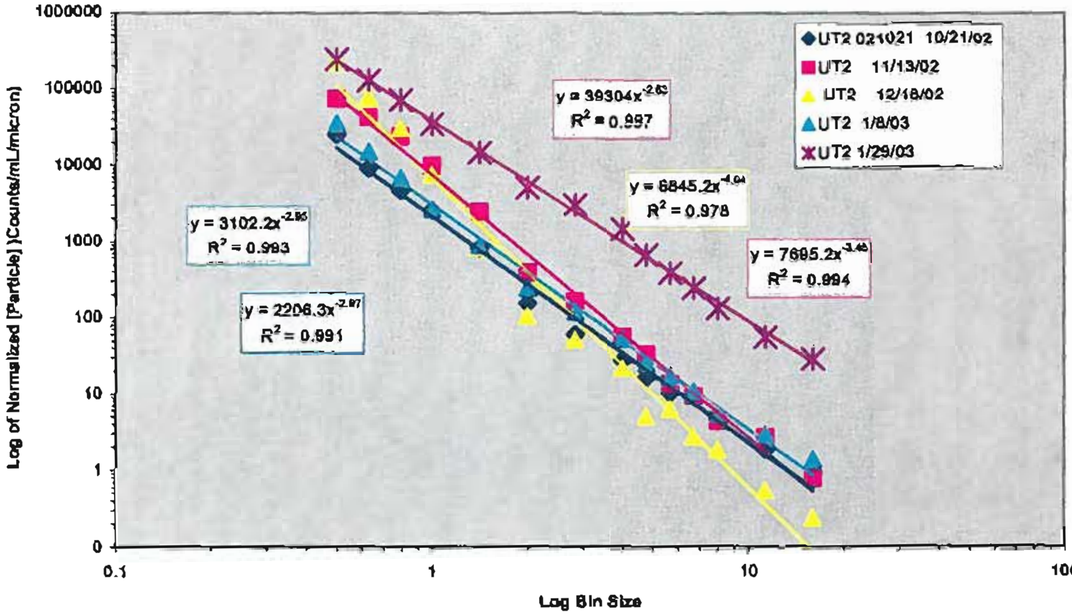

Figure A3. Particle size distribution curves 300 m off the mouth of Upper Truckee River.

Figure A4, for a site 3,000 m off the Upper Truckee River, has similar particle size distributions to the Midlake station, with the exception that there is more variability, i.e., the distributions do not conform as closely to a hyperbolic function fit. This suggests that there is still some influence of the near-shore and in particular the Upper Truckee River.

Bijou Creek has been associated with elevated near-shore turbidity. The two particle size distributions shown in Figure A5 are during two such events. During the higher-turbidity event of June 23, 2003, the slope of the distribution was distinctly flatter than for mid-lake waters. In Figure A6, the two particle size distributions with the highest concentrations have particle concentrations two orders of magnitude higher than lake background, although the slope of the distribution is similar to that at Midlake.

Three particle size distribution curves stand out in Figure A7 for Edgewood Creek. On November 13, 2002, after the first winter storm, there was little change in turbidity (Figure19-6). However, the particle size distribution was markedly affected with significant enrichment of the coarser sediment fractions. On January 29, 2003, when high turbidity was observed (Figure19-11), the particle size distribution is elevated across all size ranges. On July 24, 2003, summer thundershowers produced moderate turbidity levels (Figure19-22). The particle size distribution curve is seen to be elevated across all size ranges, although significantly less than on January 29, 2003.

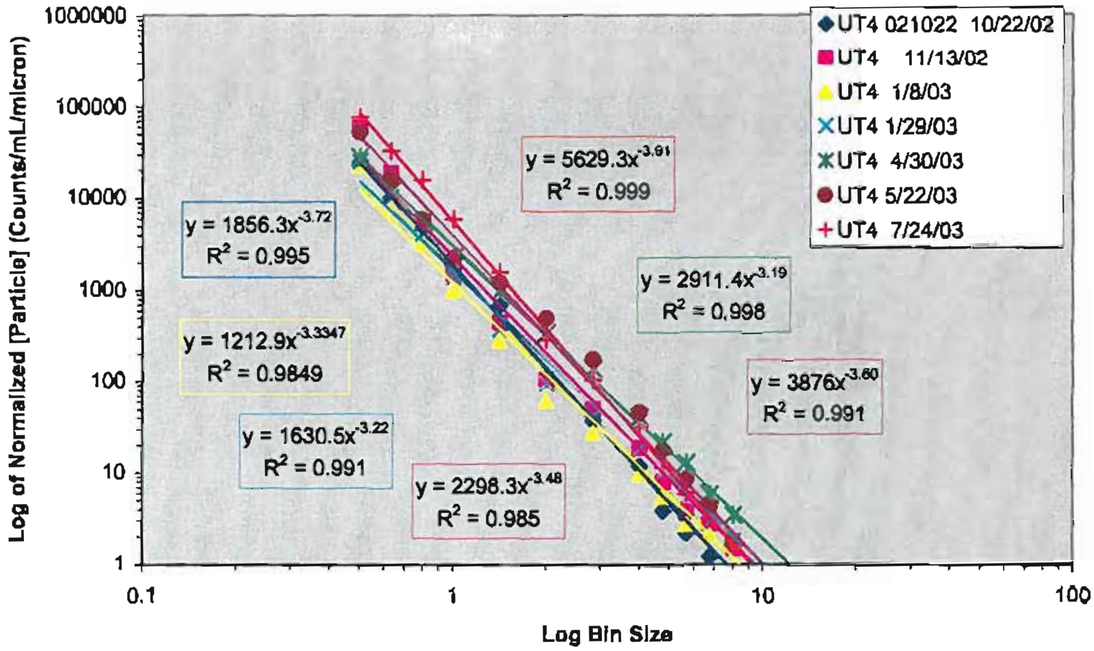

Figure A4. Particle size distribution curves 3,000 m off the mouth of Upper Truckee River.

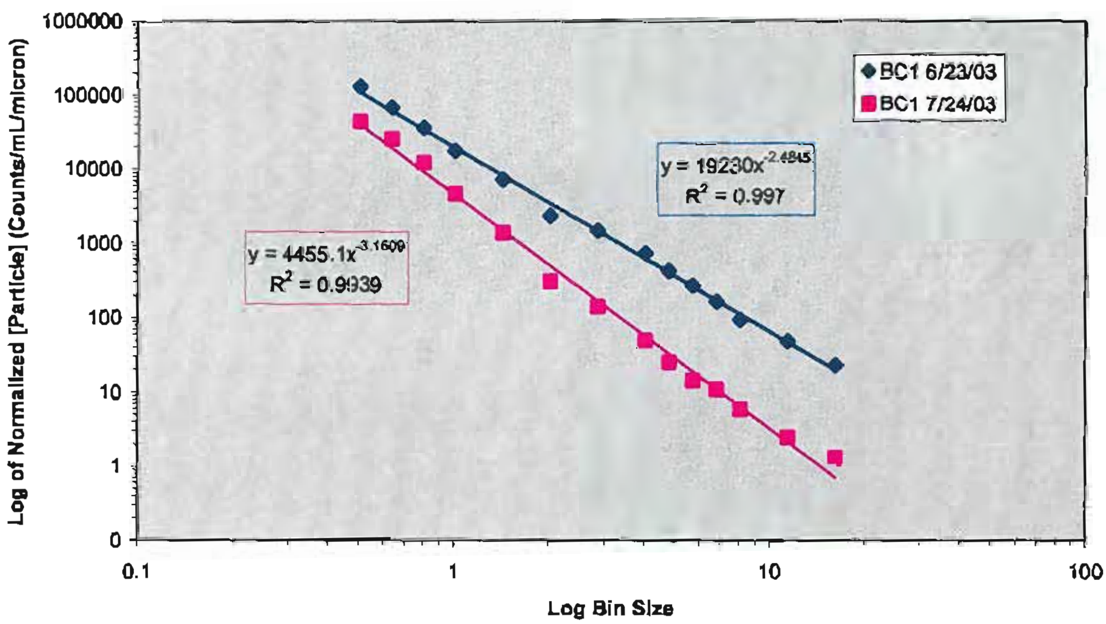

Figure A5. Particle size distribution curves at mouth of Bijou Creek.

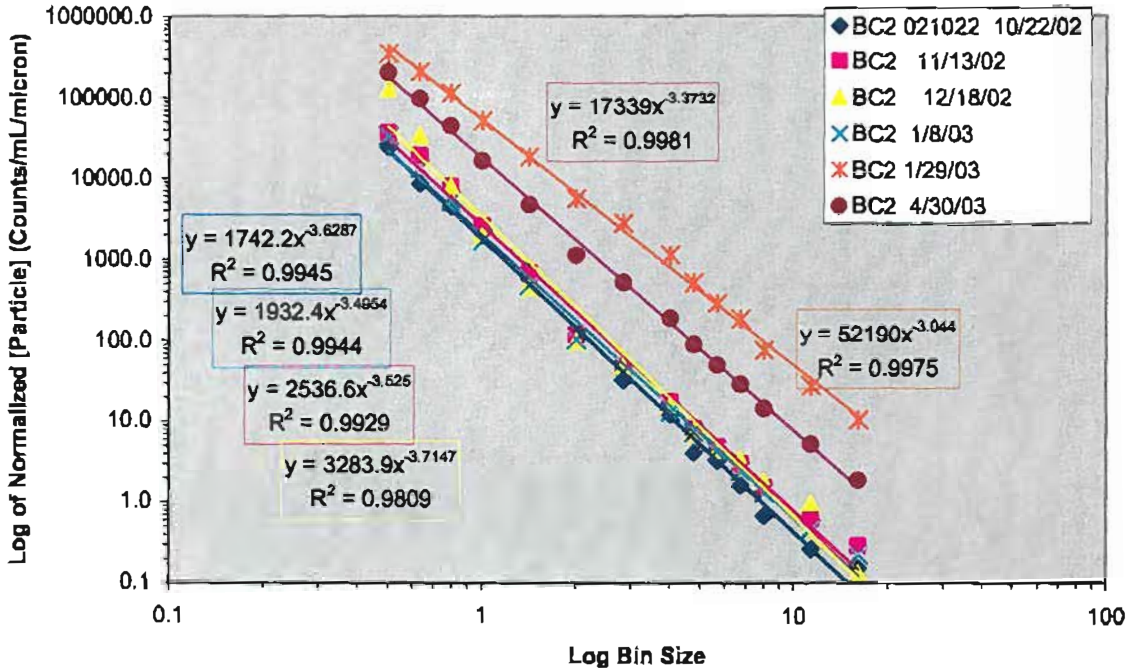

Figure A6. Particle size distribution curves 300 m off Bijou Creek

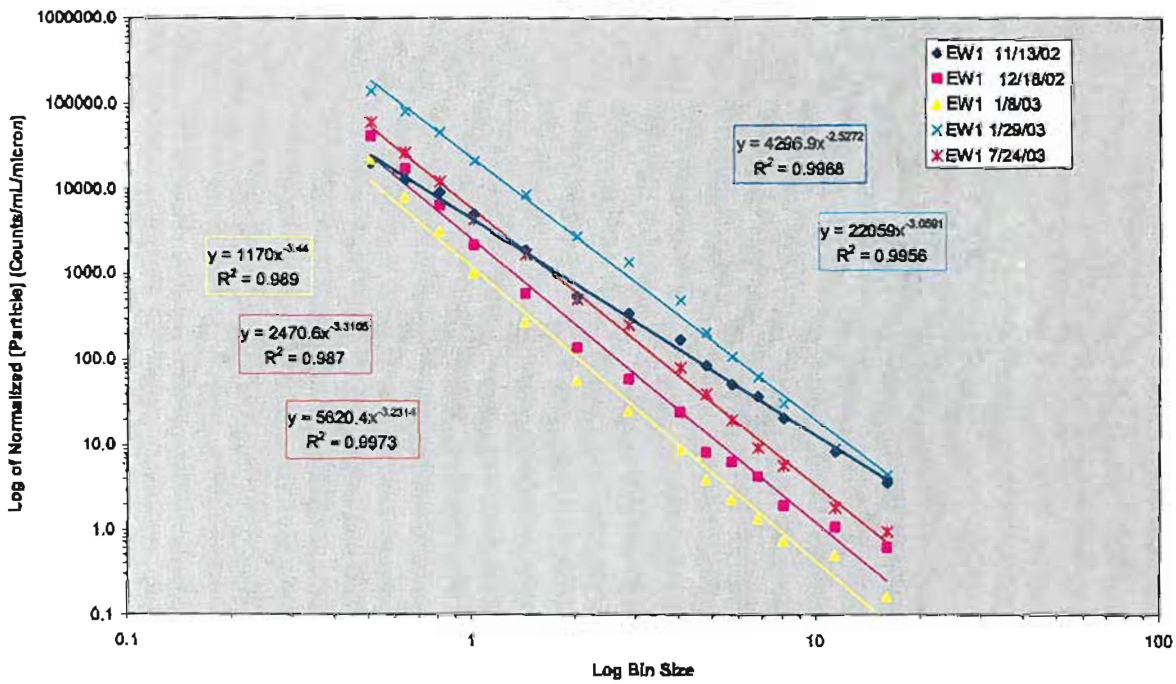

Figure A7. Particle size distribution curves at mouth of Edgewood Creek.

In Figure A8, the particle size distribution curves for Tahoe Keys are presented. The slope and magnitude of the concentrations are very similar to those at the mouth of the Truckee River on the same day (Figure A2).

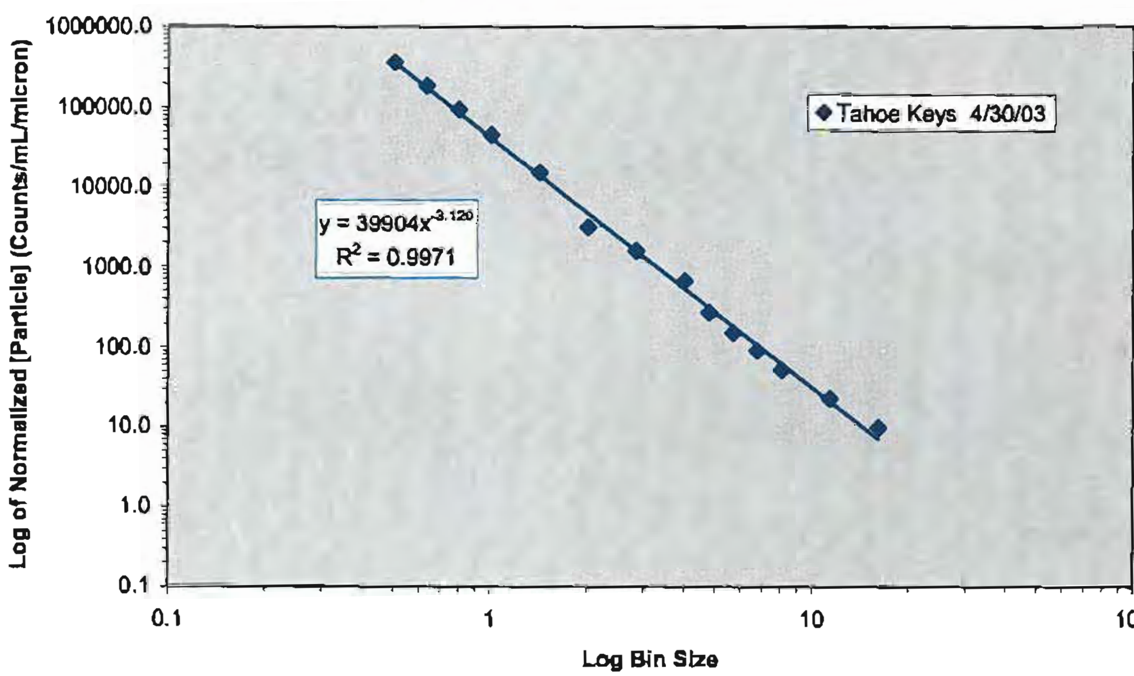

Figure A8. Particle size distribution curve for Tahoe Keys.

In Figures A9 to A11, the distribution of fine, medium, and coarse particles for the various near-shore sites are shown. Fine-particle concentration represents the summation of all particles in the range 0.5 to 2.8 µm. Medium particles are those between 2.8 and 8.0 µm, while coarse particles are those in the range 8 to 20 µm.

Summary Discussion on Particle Size

The particle size distribution analysis clearly showed that high turbidity events were associated with increases in concentration of particles, particularly in the fine (0.5 to 2.8 micron) and medium (2.8 to 8.0 micron) size ranges. These order of magnitude increases were variable, in that different near-shore regions and different storms yielded different results. The decrease in slope of the particle size distributions during these high turbidity events also set these events apart. While mid-lake slopes were typically in the range -3.0 to -3.5, high turbidity regions were sometimes as low as -1.8. Analyses to date show that the Lake Tahoe Interagency Monitoring Program streams do not display slopes as low as this. Recent analysis of the Snapshot Day stream samples (Schladow and Rabidoux, 2003) did show that under "normal" conditions (i.e., pre-spring snowmelt), Bijou Creek has one of the highest particle concentration of all the streams in the basin.

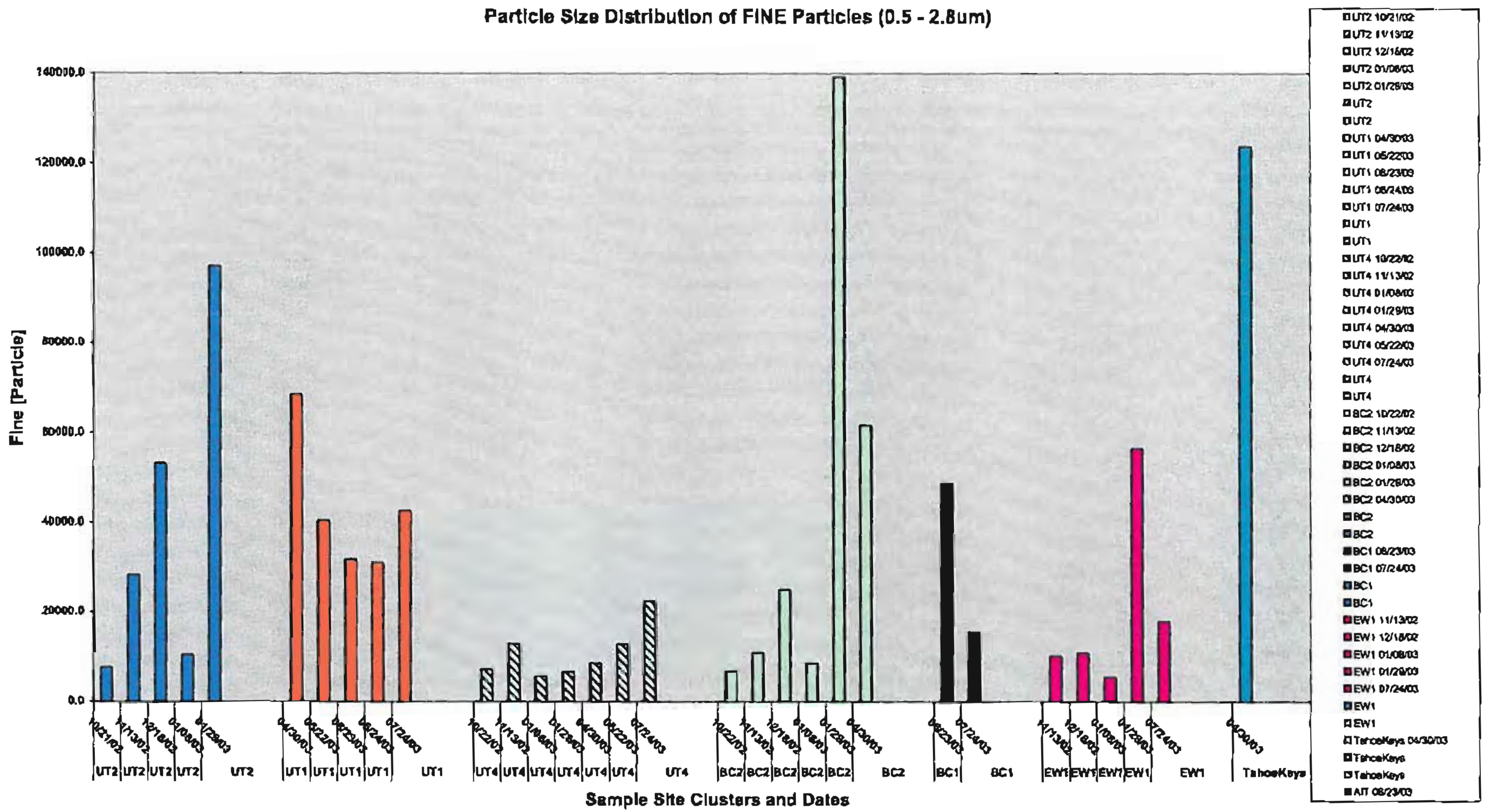

Figure A9. Fine-particle distribution.

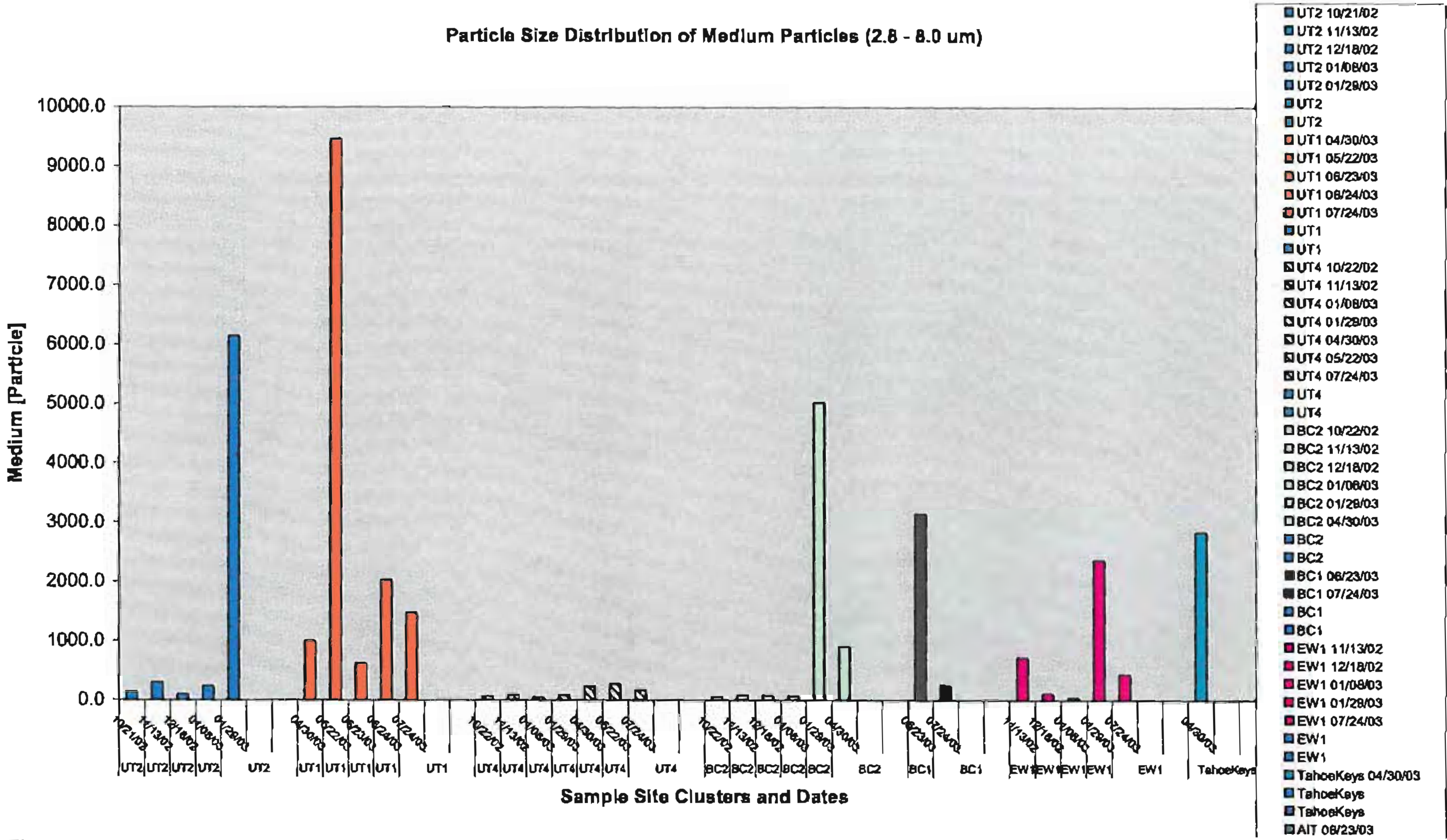

Figure A10. Medium-particle distribution.

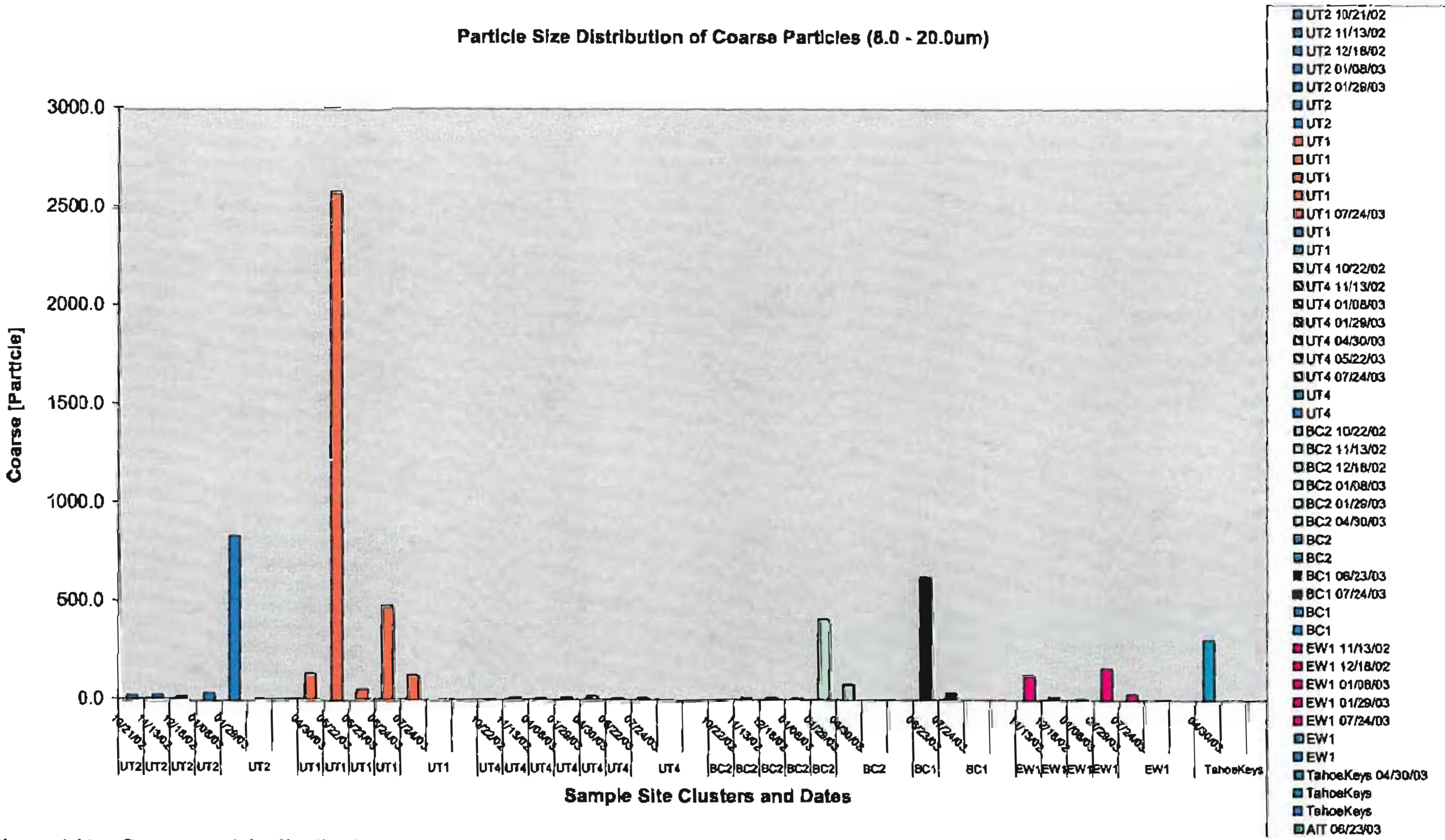

Figure A11. Coarse-particle distribution.