Linking On-Shore and Near-Shore Processes: Near-Shore Water Quality Monitoring Buoy at Lake Tahoe

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ABSTRACT

Snapshot surveys have historically been used at Lake Tahoe to assess near-shore water clarity (Taylor *et al.*, 2003). Although they can provide data along the entire lake perimeter, snapshot surveys are not well suited for quantifying longer-term trends because of the lack of data between individual surveys. The objective of this project was to address several practical questions pertaining to the construction, operation, and maintenance of an autonomously deployed near-shore buoy capable of providing continuous water clarity measurements.

The buoy was deployed 40 m off of Third Creek between April and October of 2008. Sensors included two turbidimeters, a light transmissometer, a water temperature sensor, a wind speed and direction sensor, and associated supporting electronics. Biofouling of the sensor's optics was the greatest concern in limiting the length of autonomous deployment. For turbidity, the integrated wiper system was successful at eliminating biofouling concerns. For light transmission, simple anti-biofouling techniques were moderately successful at inhibiting biofouling, requiring routine cleaning approximately twice a month. Additional approaches that could be used to increase this cleaning interval were discussed.

The degradation of near-shore water clarity generally reflected elevated sediment loads of the adjacent creeks, however, wind and lake currents were capable of pushing turbid plumes away from the buoy. Turbidity measured within the adjacent creeks was diluted by a factor of three-to-one, or more, compared to that measured at the buoy. The Third Creek watershed exceeded current near-shore thresholds (3 NTU) during four percent of the 3451 hours that the buoy was deployed. Near-shore water temperatures were also influenced by the input of creek water during some occasions, but prevailing air temperatures and wind-driven mixing with colder waters were also controlling factors.

Relative to light transmission, turbidity was not as responsive to the degradation of water near optically clear background conditions. Based on their poor performance at ultra-low turbidity levels, it was concluded that turbidimeters should only be used to assess obvious clarity-degrading events (e.g. >1 NTU), such as for compliance monitoring. The light transmissometer was more suitable for long-term monitoring of near-shore conditions as it measured both scattering and absorption processes and was sensitive to small clarity changes under background conditions.

These results were used to assess where current Lake Tahoe near-shore water quality standards are deficient, providing basin managers with six points to consider when discussing future threshold updates. A cost-effective near-shore monitoring plan was suggested, comprised of shorter-term compliance monitoring using turbidimeter-based systems and longer-term threshold monitoring using transmissometer-based systems. This binary approach takes advantage of the strengths of each sensor technology to address the different objectives of short- and long-term monitoring programs. Continuous measurements from buoy-based systems would provide a new level of detail that previous near-shore snapshot surveys were not capable of, including the definition of long-term trends and a mechanism to support compliance and the implementation of more realistic thresholds that permit threshold exceedance during unusual or infrequent events.

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1.0 INTRODUCTION AND OBJECTIVES

Lake Tahoe is a unique environment that has been designated an "Outstanding National Water Resource" by the US Environmental Protection Agency due to its ecological assets, its scenic characteristics, and the recreational opportunities that it provides. Of particular concern to resource management agencies is the fact that optical clarity of Lake Tahoe has decreased significantly during the last four decades. This is largely the result of an accumulation of fine sediment particles in the lake from watershed runoff and atmospheric deposition (Byron and Goldman, 1986; Goldman *et al.*, 1993; Jassby *et al.*, 1999) and increased algal growth from greater nutrient inputs. Historically, research has been directed towards quantifying and understanding the sources of sediment and nutrient loads from watersheds, as well as the impacts that these pollutants have on mid-lake clarity. However, the processes that link on-shore nutrient and sediment sources with mid-lake clarity through the near-shore zone are not yet well understood (Reuter and Miller, 2001).

The clarity of water in Lake Tahoe's near-shore zone is an important issue as: 1) it is the near-shore zone where most residents and visitors come close enough to the lake to observe its clarity; 2) all clarity reducing materials (i.e. nutrients and sediments), except for those entering by atmospheric deposition, must pass through the near-shore zone; and 3) the concentration of clarity-degrading constituents are greatest in the near-shore zone before subsequent dilution and mixing with cleaner mid-lake water. Additionally, the near-shore zone tends to respond quickly to changes in on-shore processes and disturbances, suggesting that it is the logical place to assess the impacts of localized events (e.g. variable stream flows, urban runoff events, BMP implementation, watershed restoration activities).

Previous investigations of near-shore water clarity have shown a distinct association between elevated near-shore turbidity and some developed areas (Taylor *et al.*, 2003). This work quantified near-shore turbidity on both basin-wide and local (e.g. South Lake Tahoe) scales by utilizing lake perimeter surveys of turbidity and chlorophyll fluorescence. Near-shore turbidity was principally elevated during runoff associated with low-elevation snowmelt and precipitation events. In addition, the Tahoe Regional Planning Agency (TRPA) monitored water clarity through its Littoral Zone Turbidity Monitoring Program at several sites around the lake. This program, however, is not well suited for identifying trends in the near-shore zone as samples are taken offshore in 30-m deep water that may not necessarily reflect near-shore conditions. Both monitoring approaches provide a "snapshot" of near-shore conditions when trained personnel are out on the lake taking measurements. Neither has been successful in quantifying long-term trends because they only collected data several times throughout the year.

We have proposed an alternative approach utilizing an unattended buoy-based system. This approach provides the ability to collect near-continuous water clarity data at specific locations to observe short- and long-term trends. Among other uses, this data could be used to: 1) support the development and/or monitoring of near-shore clarity thresholds; 2) assess the impact that restoration activities and/or BMPs have on water quality entering the lake; 3) provide data on how water-based activities such as marina dredging and/or boating impact the near-shore, either for research efforts or compliance, and 4) improve our understanding of the importance of the near-shore zone through the development of mechanistic links between on-shore, near-shore, and mid-lake processes.

The main objective of this pilot project was to address several practical questions pertaining to the construction, operation, and maintenance of a near-shore water clarity buoy. Specifically:

- What commercial options are available, and how do they compare with a customized buoy constructed specifically for Lake Tahoe's near-shore zone?
- What operational procedures and strategies lead to a cost-effective deployment in support of launching additional monitoring buoys?
- How does bio-fouling impact the length of autonomous deployment?
- How do in-situ turbidity and light transmittance measurements compare?
- How well can the buoy assess changes to water-clarity from on-shore activities?
- How can a buoy system be used to support and monitor near-shore clarity thresholds?

These questions were addressed through the construction and operation of a near-shore buoy in Lake Tahoe's near-shore zone between April and October of 2008.

2.0 NEAR-SHORE MONITORING BUOY

The first consideration of the project was to decide on a buoy/flotation platform. The majority of commercial buoy systems are sold for marine use and were too large for use in Lake Tahoe's near-shore zone as they were cost-prohibitive, would attract too much attention, and would cause an unsightly visual impact from shore. Three smaller integrated-buoy systems from WETLabs, Hach Environmental, and YSI were available as multi-parameter probe (sondes) that could be suspended off a buoy (see Section 2.4). However, only the YSI solution included a pre-fabricated buoy. We decided that a custom-built near-shore buoy had several benefits:

1) Sensor types. There was little or no opportunity to choose the sensors that were included in the multi-parameter sondes. For example, none of these systems included a light transmissometer, a sensor that has previously been shown to be suitable for water clarity measurements in Lake Tahoe (Taylor *et al.*, 2003). We also envisioned adding wind speed and directions sensors to the buoy. These additional sensors would have required the addition of a second data logging system, as the vendor proprietary data logging systems running each of the multi-parameter probes were not capable of interfacing with all of the additional sensors.
2) Specification of the model and manufacturer of the on-board sensors. Where possible, we wanted to use the same sensor manufacturers and models that had been used for previous and ongoing research in the Lake Tahoe Basin. The use of the alternative sensors included on the multi-parameter probes (particularly turbidity) would have needed to be individually evaluated for their use in Lake Tahoe. Lastly, the investigators already had most of the required sensors on-hand, thereby significantly reducing the cost required to purchase new equipment.
3) Expandable data logging and telemetry systems. The use of an expandable data logging system provided us with the ability to add telemetry that provided real-time

access to the data as well as the ability to reprogram the buoy from the shoreline or office. The data loggers contained in the multi-parameter probes were much less flexible regarding the ability to make operational changes. In addition, remote telemetry was not a standard option on any of the commercial systems.

2.1. Buoy Construction, Sensors, and Electronics

The buoy platform was based on a closed cell Softlite ionomer foam float (Gilman Corporation). An equipment cage for mounting the water clarity sensors was mounted underneath the float while an electronics compartment was mounted on top of the float (Figure 1). The cage and electronic compartment were constructed from aluminum alloy 6061 and welded together with a mig welder.

Figure 1. Structural portion of the buoy without sensors or sensor mounts.

The following sensors and equipment were installed on the buoy:

Light Transmissometer. Light transmittance is an optical property that characterizes how much light is attenuated, or reduced, as it travels through water (Zaneveld and Pegan, 2003). Attenuation is caused by two inherent optical properties of water: the absorption and scattering of light. Absorption occurs when particles and dissolved material in the water absorb light. Scattering occurs when particles in water deflect light in a direction that is different from the incoming light. Transmissometers are a preferred "clarity" measurement as they are not influenced by changes in the natural lighting or surface conditions such as with Secchi depths. But, similar to Secchi depths, transmissometer readings are influenced by the presence of tannins and/or other dissolved organic carbon species present in the water. Additionally, transmissometers do not suffer from the instrumentation issues that plague turbidimeters (discussed later). Light transmittance is reported as the percentage of light that remains after the light has traveled a specified distance through water. A WETLabs C-star Light Transmissometer was installed on the buoy.

Turbidimeter. Turbidity measurements are a specific class of scattering measurements, and are unable to quantify the absorption of light by dissolved organic carbon such as tannins. Turbidity is expressed in nephelometric turbidity units (NTU) relative to the concentration of the formazin polymer. If done in accordance with EPA method 180.1, turbidity measurements must use white light (e.g., comprised of many colors of light) and the scattered light must be measured at 90° to the incoming light beam. The EPA method is not used in submersible, battery-powered turbidimeters. Instead, these instruments typically use a single-color infrared diode (IRD) and measure scattering at greater angles, such as 140 to 160°. Model-specific differences in how turbidity is quantified result in differing sensitivities in several factors including the color of water, presence of infrared-absorbing dissolved matter, particle size, particle shape, and sediment concentration and composition. Therefore, caution must be utilized when comparing turbidity between two different meters, especially between bench top units that follow EPA 180.1 and submersible turbidimeters (Lewis *et al*, 2007). The inclusion of the turbidity measurement provided a direct comparison to in-stream turbidity measurements as well as being consistent with regulatory agencies that have historically used turbidity measurements in the shallow waters of Lake Tahoe. As will be discussed in Section 5.1, turbidity measurements are not necessarily well suited for Lake Tahoe clarity measurements due to their poor performance at the low turbidity levels characteristic of Lake Tahoe. Two submersible DTS-12 turbidimeters (FTS Incorporated, Victoria, Canada) were installed on the buoy. This data was compared against turbidity data collected by existing in-situ DTS-12 sensors located in Rosewood and Third creeks above their confluence near Lakeshore Blvd. The DTS-12 sensors also measure water temperature.

Chlorophyll Fluorescence. Fluorescence is an inherent optical property of water that occurs when water is illuminated with light of one color and then emits, or fluoresces, light of a different color. Fluorescence can be used to measure the concentration of chlorophyll in the water. To determine the relative 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. Fluorescence was measured using a WETLabs Chlorophyll Fluorescence WETSTAR. However, the internal cuvette was shattered early on in the project during a storm, submerging the internal electronics and destroying the sensor. The damaged sensor was not replaced due to its cost.

Wind Speed and Direction. An ultrasonic WindSonic (Gill Instruments) wind speed and direction sensor was installed on the top of the buoy. A solid-state electronic compass was also installed to measure the direction that the buoy faced in order to provide meaningful wind direction data. Wind speed and direction data were measured on a 60 second interval and recorded on a 5-minute averaged interval (Figure 2). The high sample rate was used to average the effects that the side-to-side movement of the buoy might have on wind speed during storm events. However, a tilt sensor was not installed to verify this behavior. The buoy exhibited a preference to point towards the SSW during wind events.

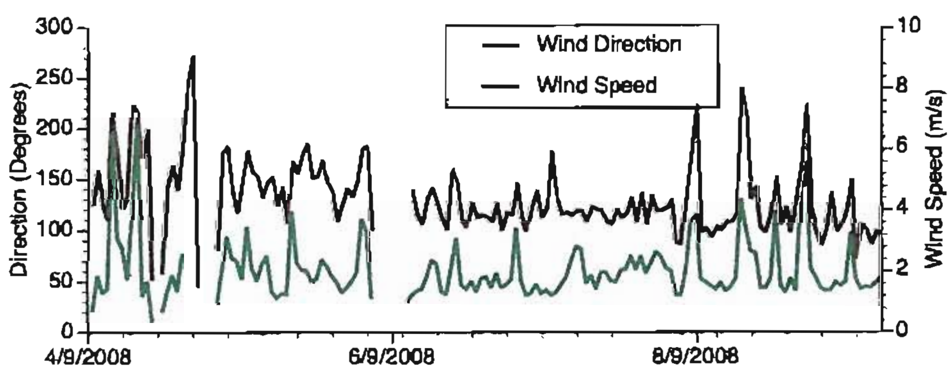

Figure 2. Average daily wind speed and direction measured at the buoy. Direction is reported as true north.

Global Positioning Satellite (GPS) Receiver. A Garmin GPS16-HVS was installed in order to provide the latitude and longitude coordinates of the buoy. This was included so the buoys location could be determined through telemetry if it broke free of its moorings.

Water Temperature. Water temperate was measured at 20, 40, 69 cm underneath the float. The middle sensor was a CS-108 (Campbell Scientific) thermistor-based temperature sensor. The shallowest and deepest sensors were integrated within the DTS-12 turbidity sensor.

Data Logging and Telemetry. A CR10x (Campbell Scientific, Logan, UT) was used to operate the buoy and record data. The buoy was outfitted with a 900 Mhz RF400 (Campbell Scientific) radio, and a Raven cellular modem for telemetry. The 900 Mhz radio was used primarily for shore-to-buoy communications during maintenance whereas the cellular modem was used for the automated transfer of data back to DRI's severs six times a day. The datalogger program used to control buoy functions was occasionally modified while deployed to either conduct experiments, improve operations, and/or to improve the quality of data that was being collected.

Figures 3 and 4 show the buoy during initial testing and how it was observed from shore.

Figure 3. Buoy in the water during initial testing in May 2008. Equipment on the top of the buoy includes (from left to right): ultrasonic wind speed and direction sensor, 900 Mhz radio telemetry antenna, GPS antenna, solar panel, and cellular telemetry antenna.

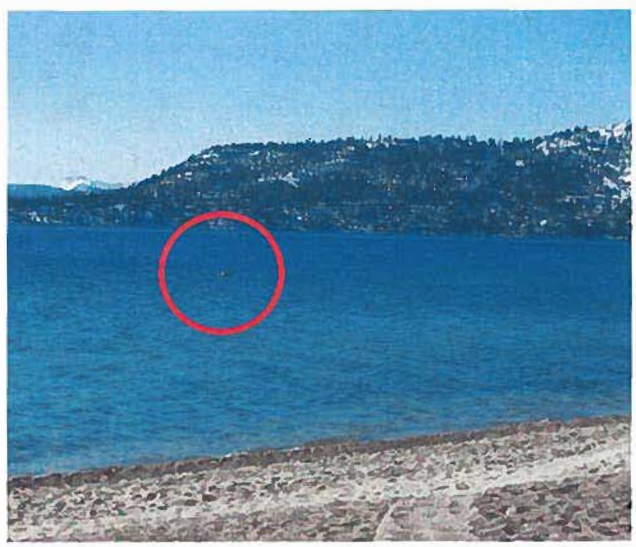

Figure 4. DRI near-shore buoy as viewed from the beach.

2.2 Assembly, Biofouling, and Power Considerations

The water clarity sensors were installed on the buoy either as an "external" sensor that measured the bulk water column or as an "internal" sensor that required water to be passed through a cuvette or internal chamber. The turbidimeters and water temperature sensor were external, while light transmissometer and chlorophyll fluorescence sensors were internal (Figure 5). Water was pushed through the internal sensors by a pump that was driven by a relay operated by the data logging system. Ten-foot lengths of coiled copper tubing were placed on each side of the sensors' sample line to reduce biofouling.

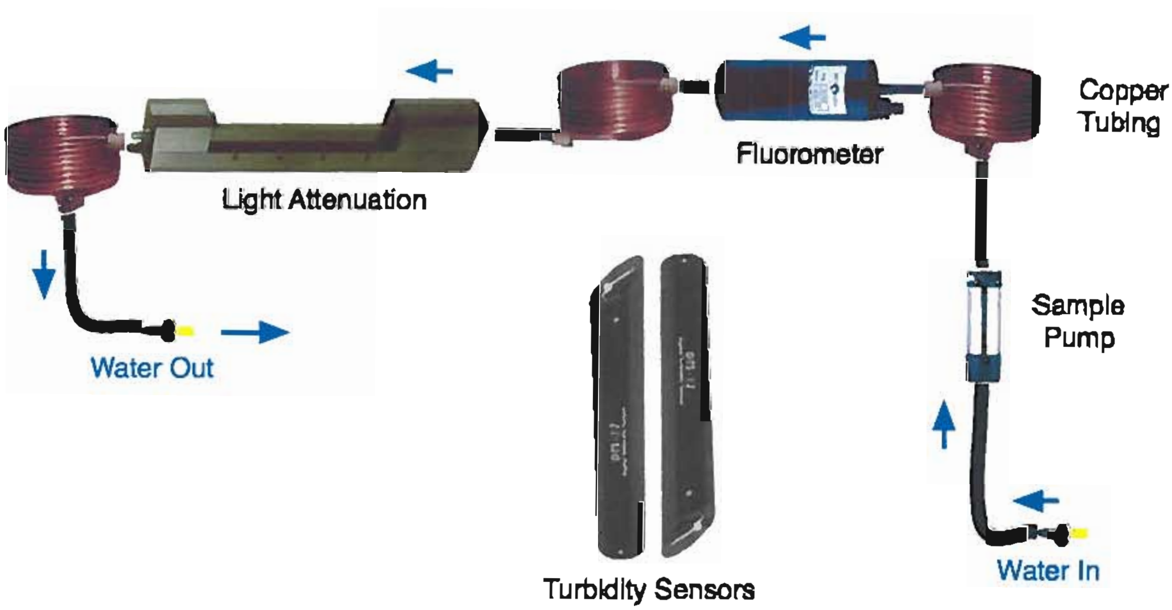

Figure 5. Schematic of water quality sensors on the buoy. Turbidity and water temperature (not shown) sensors were open to the lake whereas all others were part of a closed system requiring a pump to push water through the system.

2.2.1. Anti-Biofouling Approaches and Biofouling Quantification

Over time, the colonization of biological organisms naturally obscured the sensors' optics and degraded sensor data. The minimization of biofouling was critical to improve the cost-efficiency of buoy deployment as it reduced the number of costly trips needed to physically clean the sensors' optics. Several anti-biofouling approaches exist, including the use of tributyl tin waxes and aerosol sprays, antifungal agents, cayenne pepper, silicon compounds, halide tablets, Alconox, and copper paints and tubing (Manov *et al.*, 2004). However, not all approaches can be used with each type of sensor and some are prohibited in Lake Tahoe.

The simplest approach taken to minimize biofouling was to add several feet of copper tubing to both sides of the sample water line (Figure 5). Copper is a biocide that inhibits biofouling. Copper tubing has been used successfully in the oceanography community to extend measurement capabilities from 10 days to over 60 days in coastal waters with no sign of biofouling (Manov *et al.*, 2004). However, the ability of copper tubing to act as an anti-biofouling device in freshwater is unknown due to the lack of salts compared to the corrosive nature present in salt-water marine environments. We extended the length of copper tubing from several inches to ten-foot lengths and utilized tubing at the inlet, between the transmissometer and fluorometer, and at the outlet of the system.

2.2.1. Power Constraints

One of the largest constraints for long-term deployment of the buoy was the potential to run out of battery power. Due to the relatively small size of the buoy, large-capacity battery systems could not be used to supply power. In addition, the cold year-round water temperatures resulted in a reduced battery capacity. In order to provide a sufficient power source for the sensors, logger, and telemetry systems, a 10-Watt unbreakable solar panel was secured to the top surface of the equipment housing. However, we still anticipated a potential need to conserve power by minimizing nighttime operations. The largest power draw on the system was the sampling pump, followed by the telemetry systems.

Initial battery performance was poor, as evidenced by the initial downward slope in battery voltage prior to April 23 (Figure 6). Additionally, the solar panel cable broke causing the steep decline in battery power in late April. After several adjustments and the repair of the solar panel cable, battery capacity was sufficient to run all buoy systems for the remainder of the pilot study. At peak power expenditure, the pump system was activated for two minutes as frequently as every 15-minutes. Turbidity was measured as frequently as every five-minutes with no adverse power drain. The largest positive factor contributing to sufficient power supplies was abundant summer sunshine, which fully recharged the battery every day. When there were a series of cloudy days in late August and early September, power reserves became depleted. Based on this event and operating conditions, we estimate that the buoy had an approximately 8-day power reserve with 5-minute measurements intervals for turbidity and 60-minute measurement intervals for the light transmissometer. These operating conditions would not have been sustainable if buoy operations were extended into the winter season. We believe that wintertime operation of the buoy would have been feasible if the telemetry subsystem was only powered for one-hour per day and pumping operations were limited to between 8 and 12 times per day.

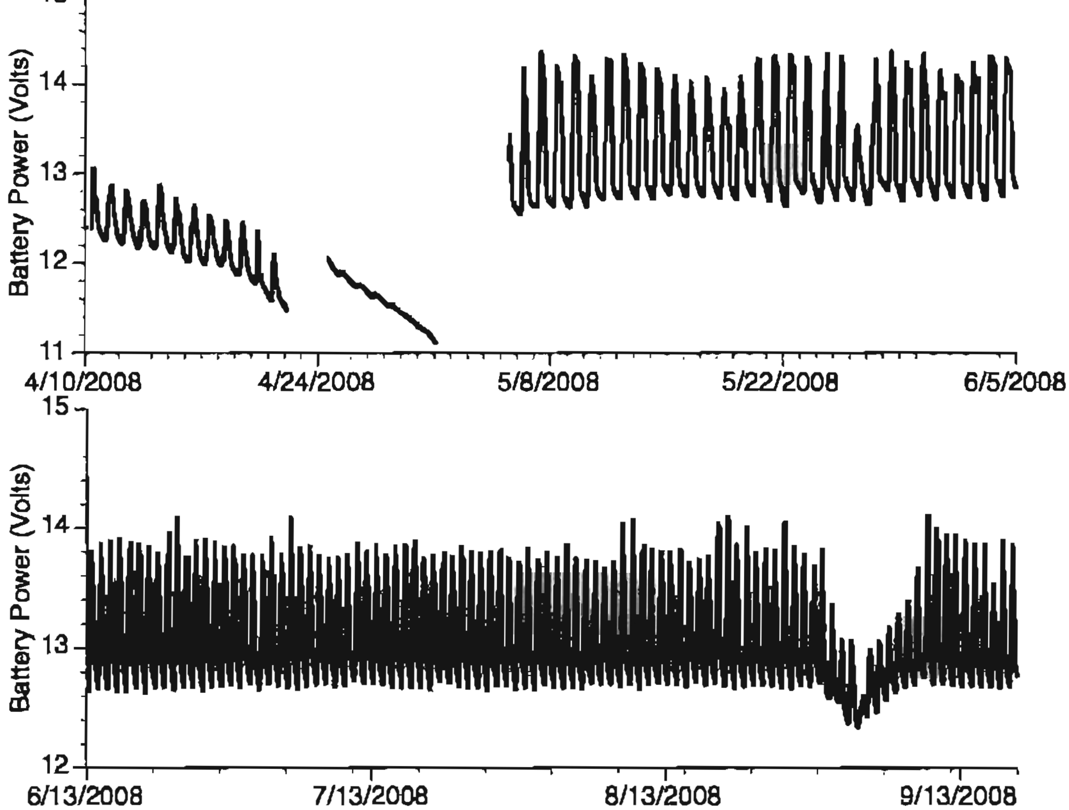

Figure 6. Average hourly battery voltage. The drop in battery voltage in early September was due to a series of cloudy days. The minimum operational voltage was considered as 12 volts as operation of lead-acid below that level will damage the battery.

2.3 Cost of Buoy and Comparison with Commercial Systems.

The total cost of construction and operation of the near-shore buoy for nine months was estimated to be $47,019 (Table 1). The sensor package and supporting electronics comprised 55% of the total cost, while buoy fabrication and operations only contributed 14% ($6671) and 21% ($9,814), respectively. These costs represent what a new buoy would cost including all parts and labor, but do not include data handling and storage, data workup, analysis, project management and report writing. These costs were not reported due to the significant cost savings that would occur with the launch and operation of multiple buoys. In addition, the cost of building additional buoys of similar design would be lower as the design and testing phases would not need to be repeated.

Table 1. Total cost of building and maintaining the DRI near-shore water quality buoy for nine months.

Description	Cost
Infrastructure (Aluminum struts, brackets, buoy float, welding supplies, hardware, anchors, rope, chain, and copper tubing)	$2,067
Construction Time (Planning, welding and assembly)	$4,604
Total: Buoy Infrastructure	**$6,671**
Equipment (Water quality sensors and data logger)	$12,084*
Electronics (GPS, wind speed/direction, compass, telemetry equipment, battery, solar panel)	$7,394
Electronics Time (Interfacing sensors and programming data logger)	$5,543
Testing (Laboratory and in-lake testing of float and pump system)	$718
Total: Sensors, Electronics & Assembly	**$25,739**
Groundwork (Meeting with property owners, discussion with local, state, and federal agencies regarding need for permitting, permitting, etc.)	$1,875
Installation (Anchoring system; time, vehicles, and equipment for installation)	$2,920
Maintenance (Time and motor pool for recovery and deployment for routine and non-routine maintenance)	$9,814
Total: Installation and Maintenance	**$14,609**
Grand Total:	$47,019

*Data logger and the water sensors were provided by DRI at no-cost for this project but were included in this budget.

A direct cost comparison between the DRI buoy and other commercial buoy platforms was difficult as each system provided options and sensors that were not available on the other platforms. For comparison purposes, the cost of a basic system that included a floating platform and turbidity, fluorescence, and water temperature measurements was estimated (Tables 2 and 3). Light transmission was not included since it would have to be a custom addition for any platform. Cost estimates for the WETLab and Hach Environmental buoy platform may be conservative, as the buoy float, enclosure, and equipment cage are not offered as a pre-fabricated package from these manufacturers. Only the YSI system has an option for a pre-fabricated buoy designed for their multi-parameter probes. However, it was three times more expensive than our custom-built buoy platform. Compared to the commercial solutions, a near-shore buoy built by DRI to these basic specifications would be cost-equivalent to the solution sold by Hach Environmental, and only 28 to 35% the cost of the WETLabs and YSI systems.

Table 2. Cost-comparison of commercial buoy systems with the DRI near-shore buoy system. Price quotes were provided to DRI in December 2008 and represent similarly equipped systems (turbidity, fluorescence, temperature, buoy platform) ready for deployment. Table 3 lists the specifics for each commercial system.

	WETLabs	YSI	Hach	DRI*
Sensors:	$23,900	$12,075	$14,130	$11,513
Buoy:	$4,000	$13,025	$4,000	$4369
Total:	**$27,900**	**$25,100**	**$18,130**	**$18,184**

*The DRI buoy system included several capabilities that the other systems did not have. To provide a meaningful comparison, the following were removed from the cost of the DRI system: C-Star Transmissometer, costs associated with GPS, telemetry, wind speed/direction sensor, and 50% of the cost of the electronics time to integrate these sensors and 50% of the time needed to plan buoy construction.

Table 3. Specifics of each commercial buoy system. Prices for floats and/or cage and mooring equipment were estimated if they were not supplied from the manufacturer.

	Description
Vendor:	WETLabs (http://www.wetlabs.com/)
Sensors:	**WQM Self-contained Sonde:** Temperature, conductivity, depth (pressure), dissolved oxygen, chlorophyll fluorescence, and turbidity (0 – 25 NTU). Includes software and communications cables.
Buoy:	Gilman buoy float, equipment cage (not specified), and moorings (not specified).
Vendor:	YSI (https://www.ysi.com/)
Sensors:	**YSI—6600V2-02 Multi-parameter Sonde:** Includes logger, Fluorescence Chlorophyll, Conductivity, Temperature, and Turbidity Probe.
Buoy:	**YSI—EMM67 Buoy:** Includes integral solar panels, electronics mounting bracket, submersible battery pack, mooring system.
Vendor:	Hach Environmental (http://www.hydrolab.com)
Sensors:	**Environmental—Hydrolab DS5X Sonde:** Includes data logger, software, temperature, turbidity, Chlorophyll, conductivity, PAR.
Buoy:	Not specified.

3.0 DEPLOYMENT

3.1 Location

The buoy was located 40 m offshore of Third Creek in Incline Village, NV (39.23870, -119.94777 WGS84). It was specifically placed at the outlet of a watershed in order to test its capabilities during summer background conditions as well as during sediment-producing hydrologic events. Although Third Creek has not historically been the largest contributor of suspended sediment to the lake, the creek was ranked as the number one source of sediment on a yield basis (mass per watershed area) of the USGS/LTIMP monitored streams (Rowe *et al*, 2002). The Third Creek watershed was also chosen because of concurrent real-time turbidity monitoring in both Third and Rosewood creeks by the investigators.

This study location, however, had several negative issues. The first issue revolved around the unusually high boat traffic in the immediate vicinity due to the adjacent Incline Beach boat ramp to the east. Boats were also frequently observed to be beached between the mouth of Third Creek and the boat ramp. To avoid these boating activities, the buoy was placed further offshore and more towards the west than we would have preferred. The second issue was potential disturbance of the buoy by curious swimmers as the buoy was located just outside of the Incline Beach swim zone. Consideration was given to this issue during buoy construction so that the buoy would easily tip and prevent swimmers from physically climbing on board. Finally, Incline Creek, located immediately to the east of the boat ramp, was another potential source of sediments that may have affected water quality measurements. Although continuous turbidity was measured upstream of the creek's mouth, sediment discharged from Incline Creek was never observed to reach the buoy. Incline Creek was a smaller, lower-elevation drainage that responded to hydrologic events with a different timing and smaller magnitude than Third Creek.

3.2 Water Clarity Measurements

Water clarity was assessed using both a light transmissometer and a turbidimeter. The transmissometer measured both the absorption and scattering of visible light in the blue wavelength as light traveled through a straight line (0°) in the water. Units were reported as the percentage of light that remains after absorption and scattering. Therefore, light transmission decreased as water clarity became degraded. Previous work by Taylor *et al.* (2003) has indicated that there is a straightforward relationship between light transmission and clarity as measured by Secchi depth (Figure 7).

Turbidity, in contrast, only measured light scattering at some specific angle from the incident beam. The submersible turbidity sensor used in this study measured scattering between 140-160° from an infrared light source. Turbidity was reported in nephelometric turbidity units (NTU) requiring calibration to formazin, a man-made polymer of known particle size and shape. Turbidity increased as water clarity became degraded. The relationship between turbidity and Secchi depth was previously found to be non-linear (Figure 7). Furthermore, turbidity was found to be relatively insensitive to the initial degradation of excellent water clarity (turbidity <1 NTU) that was observed by Secchi depth (and light transmission). Turbidity continues to be used as a near-shore water clarity surrogate at Lake Tahoe despite this insensitivity and the difficulty of obtaining repeatable measurements with values of less than 1-2 NTU, due to the increased importance of sample handling and cuvette conditions that can significantly bias readings (Sadar, 1998). The continued use of turbidity stems from the specification of the measurement in current near-shore thresholds from the states of California and Nevada, and the TRPA. These near-shore thresholds are expected to be revised starting in 2009.

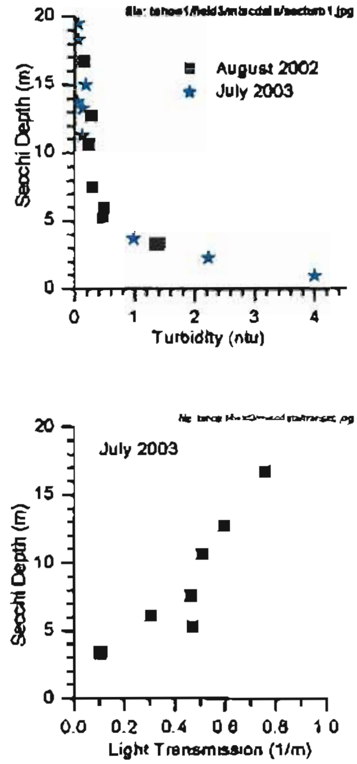

Figure 7. Observed relationships between Secchi depth and turbidity (top) and Secchi depth and light transmission (bottom). From Taylor *et al.*, 2003. See caption in original source for more information regarding the data used in these figures.

3.2.1. Turbidity versus Light Transmittance

Turbidity and light transmission data were compared in Figure 8. However, data obtained from these optical instruments was less reliable during windy conditions because of the presence of entrained air bubbles and algae that became dislodged by wave action. Data were omitted from this comparison during windy conditions (> 2 m/s) and when the reported variance in the instantaneous transmission and turbidity measurements were high. An exponential model was used to reasonably describe the remaining data, however, the bulk of this relationship was defined by clarity-degrading snowmelt events in April and

May. Summer rainstorms did not contribute to the overall shape of this model due to the absence of intense or long-lasting precipitation events during deployment. Smaller rainstorms may not have mobilized sufficient quantities of sediment to be observable 40 m offshore. Positioning the buoy closer to the creek would have increased its sensitivity to smaller events.

Intra-seasonal trends between turbidity and light transmission were also noted, particularly during background conditions when turbidity was low and light transmission was high. Three different relationships were observed during late summer (Figure 9), for example. The overall slopes of the data collected during the first two periods (7/23-8/5 in blue and 8/15-8/30 in red) were similar, but were offset from each other by approximately 0.2 NTU. For the third period (9/1-9/19 in green), changes in light transmission readings were not mirrored by changes in turbidity suggesting that water clarity during this period was dominated by absorption rather than scattering processes. These observations were explained by two factors. First, the response of the turbidimeter varied due to a change in water or particle composition rather than sediment concentration (Conner and De Visser, 1992; Kineke and Sternberg, 1982; Bunt *et al.*, 1999). For example, the shape or composition of particles in the water may have had a reduced preference for backscattering infrared wavelengths between 120 and 160 degrees. This behavior was an artifact of turbidimeter technology and can not be corrected. The second factor was that the concentration of dissolved organic carbon (e.g. tannins) might have shifted over time. This could be assessed in future studies with the addition of a submersible dissolved organic carbon sensor.

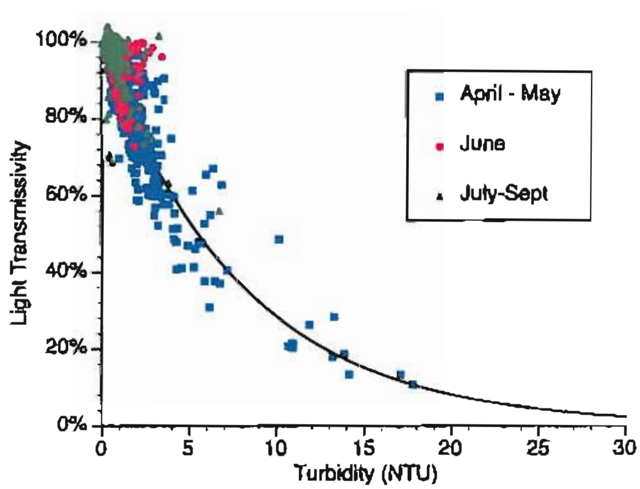

Figure 8. Hourly turbidity average compared against light transmissivity by season. Data for this graph are a subset where wind speed < 2 m/s and variance was < 1000 (if reported). Variance of light transmissivity did not begin until August. Overall regression (n=2335): Cstar = 1.04236 * $e^{(-0.125782*TU)}$; $R^2 = 0.86$.

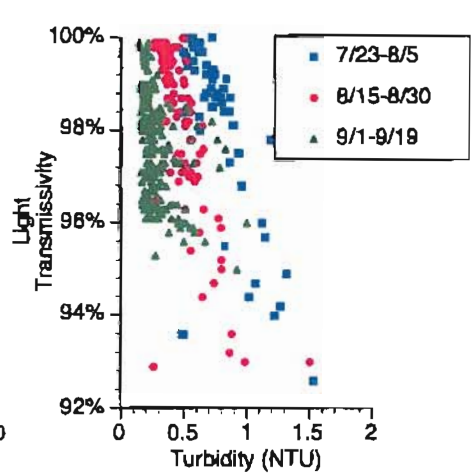

Figure 9. Light transmission for three selected periods during summer background conditions. Only data meeting criteria listed in Figure 8 are included.

The diminished importance of scattering could result from calmer lake conditions, as indicated by an average wind speed of 1.7 m/s compared to 2.2 m/s during each of the earlier periods. There was also a significant storm event between the second and third periods characterized by sustained winds from four to 9 m/s over a 31-hour period. This event appeared to have little direct affect on the water clarity measured at the buoy, indicating that any resuspension of sediments was not observed 40 m offshore. Indirectly, increased mixing resulting from the wave action may have altered the composition of suspended particles, thereby resulting in the significant shift in the relationship between turbidity and light transmission observed in the third period. Regardless of the cause, water clarity assessed by light transmission was more sensitive to changes in the water column than turbidity during background conditions.

Over the deployment season, turbidity and light transmission both mirrored changes in water clarity (Figure 10). However, there were several events when the turbidimeters indicated degraded water clarity that was either partly or not at all observed by the light transmissometer. Examples include data collected on 6/22, 6/29-30, and 8/8-9. This last event, in particular, was interesting because there was only a 4% reduction in light

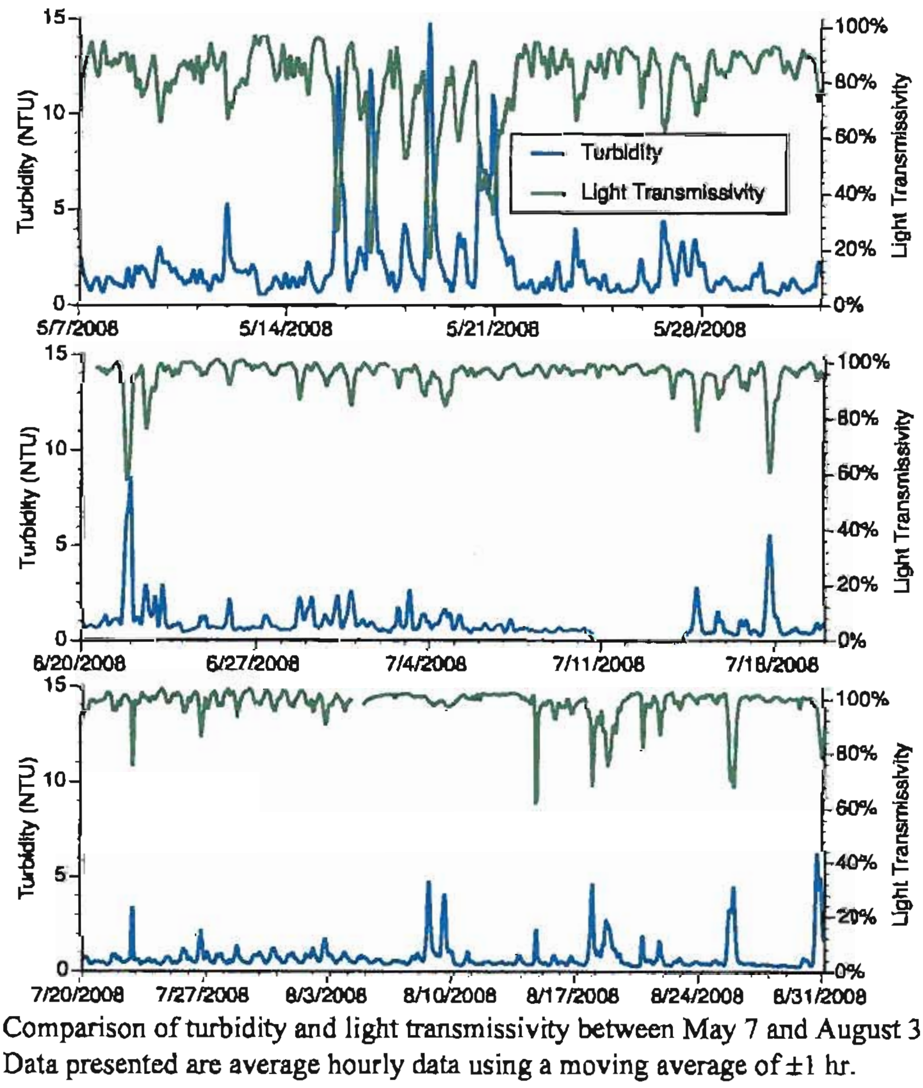

Figure 10. Comparison of turbidity and light transmissivity between May 7 and August 31, 2008. Data presented are average hourly data using a moving average of ±1 hr.

transmission that was coupled with a 4-5 NTU increase in turbidity. The most probable cause was the partial obstruction of the turbidimeter's optical path by detritus or algae hanging off the buoy frame. The sensor's wiping mechanism only clears material that is within 0.75 cm of the turbidimeter's face. This could be corrected by increasing the distance between the sensor and any points of attachment such as the buoy frame.

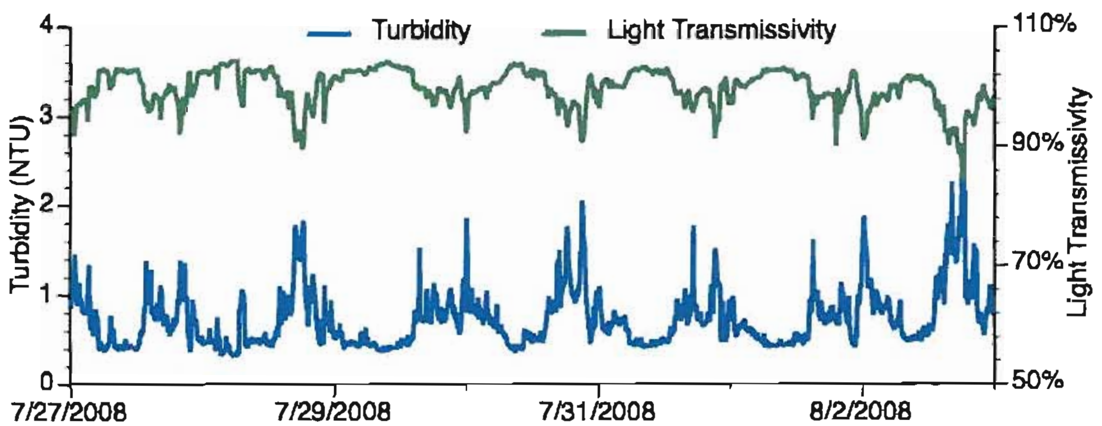

Figure 11. Comparison of turbidity and light transmissivity between July 27 and August 3, 2008. Data are instantaneous data from the sensors.

3.3 Impact of On-shore activities on Near-shore Water Clarity and Temperature

Water clarity measured at the buoy changed in response to sediment loads entering the lake from Third and Rosewood creeks. Daily *minimum* turbidity levels during snowmelt were approximately 0.4 – 0.5 NTU, or about twice that of background measurements (0.26 NTU) conducted in late summer. *Average* daily values of greater than 5 NTU were not uncommon, with *instantaneous* measurements of up to approximately 10 NTU.

Suspended sediment loads from Third Creek played a greater role in the degradation of near-shore clarity than Rosewood Creek, despite the latter contributing water that had turbidity levels that were two to three times greater than the former (Panel A in Figures 12 and 13). This was a product of the larger Third Creek watershed and its greater suspended sediment load and discharge volume (Panel B). Average daily discharge during the period of study for Third Creek was 5.7 cfs whereas it was only 0.7 cfs at Rosewood Creek. The seasonal dominance by Third Creek was also a result of the earlier 2008 snowmelt season for Rosewood Creek, which occurred in March prior to the start installation of the buoy. Despite its lower flows, Rosewood Creek can deliver a significant short-term sediment load during some hydrologic events (Susfalk *et al.*, 2009).

The response of the buoy sensors to sediment loading from the creeks was variable. In some cases, turbidity and light transmission responded immediately, whereas in other cases there was a temporal delay before degraded water clarity was observed at the buoy. For example, there was no delay during Event 1 (Figure 12) but there was an approximately 24-hour delay for both pulses comprising Event 2. Sediment loads from the creeks during Event 3 were not as readily observed at the buoy as they were during Event 1. Much of this response was a result of the buoy's placement 40 m offshore (see Section 3.1). The impact of creek-derived suspended sediment on near-shore clarity would be expected to be lower the further away the buoy was located from the source; the lake has a large volume of

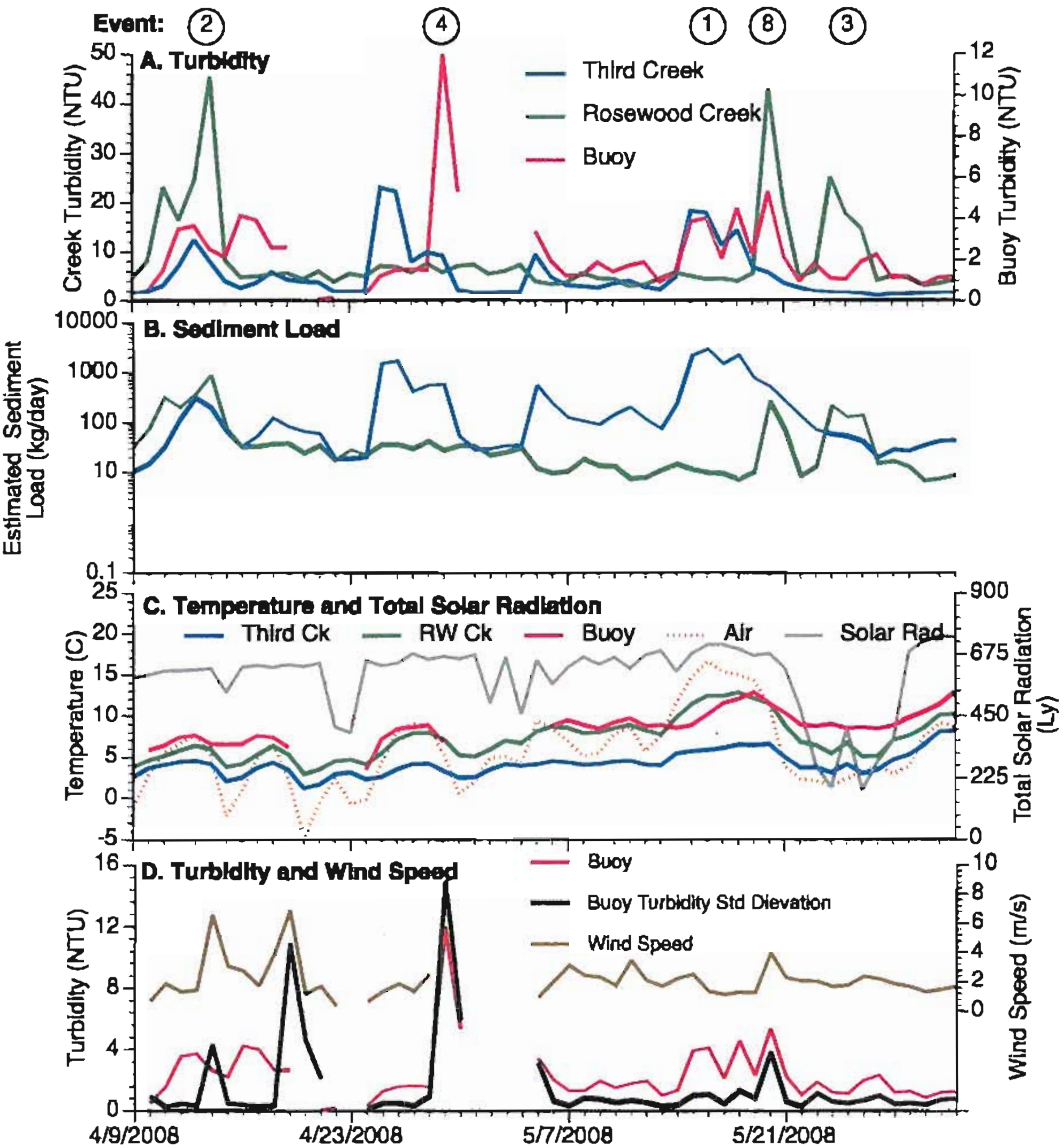

Figure 12. Turbidity, sediment load, water temperature, and wind speed comparison during Spring 2008. All values are reported as daily averages. Event numbers are discussed in the text and are in the order with which they are discussed. For turbidity (Graph A), note that buoy turbidity is presented on the second y-axis that was scaled up by a factor of 4.2 to facilitate comparisons. Average daily suspended sediment concentration (SSC) was estimated using turbidity as a surrogate based on regressions between instantaneous in-situ turbidity and SSC. Sediment load was subsequently calculated by multiplying average daily discharge and estimated average daily SSC. Sediment loads calculated in this fashion are only considered estimates to be used for a rough comparison between the two creeks. (Third Creek flow data provided by the USGS. Air temperature measurements were taken at the DRI Incline Creek Meteorological Station near the base of the Diamond Peak Ski Area).

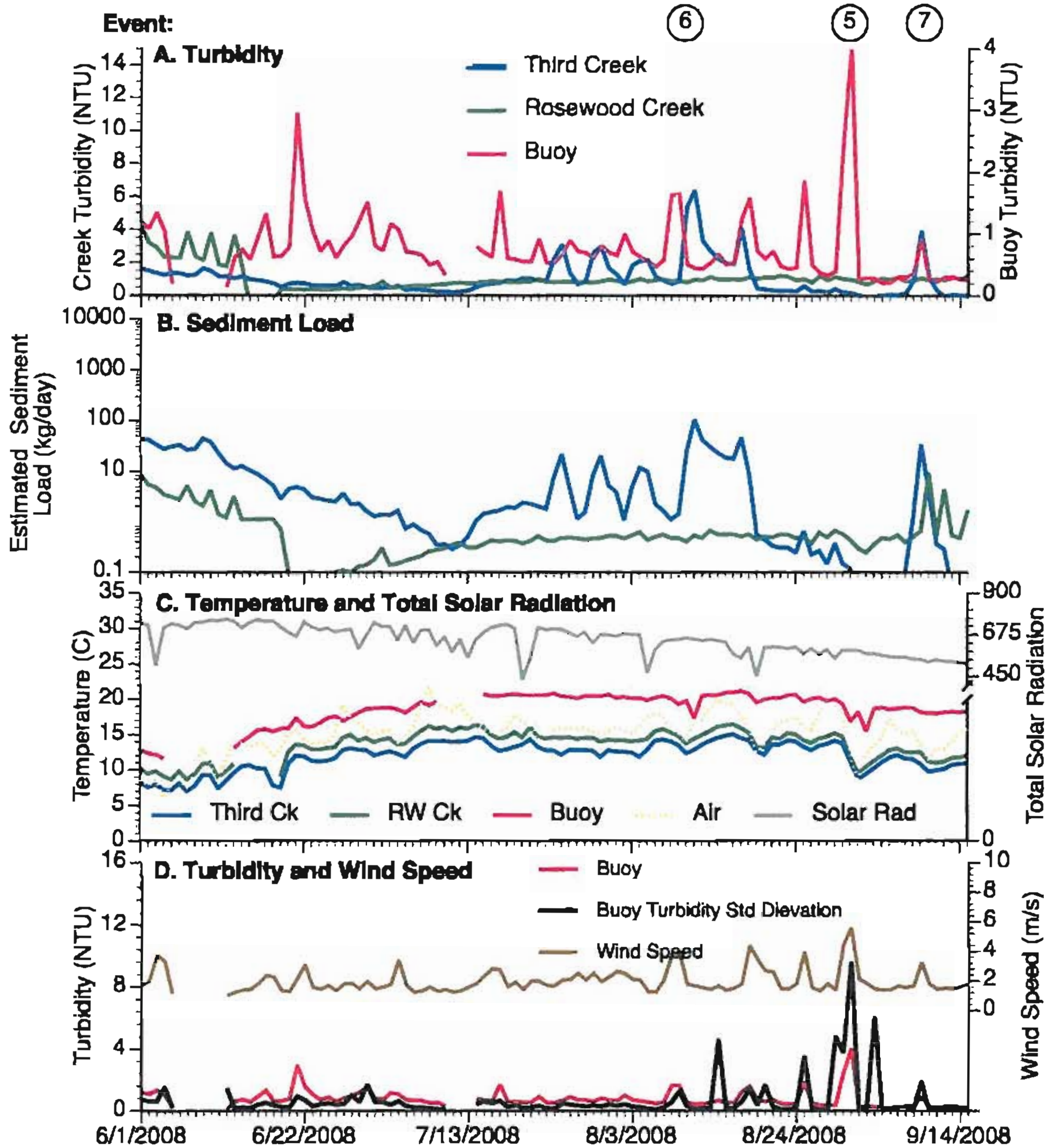

Figure 13. Turbidity, sediment load, water temperature, and wind speed comparison during Summer 2008. All values are reported as daily averages. For turbidity (Graph A), note that buoy turbidity is presented on the second y-axis that was scaled up by a factor of 3.8 to facilitate comparisons. See Figure 12 for other notes.

cleaner water to mix with and currents could affect the direction of the turbidity plume. For example, wind and lake currents were observed to push the turbidity plume to the southeast and away from the buoy on 4/25/08 (Figure 14). At its highest, turbidity measured at the buoy was only 31% of that measured in either of the creeks indicating at least a three-to-one dilution with cleaner lake water. To improve the sensitivity of a buoy-based system, we suggest placing it closer and in front of the outfall that is under study.

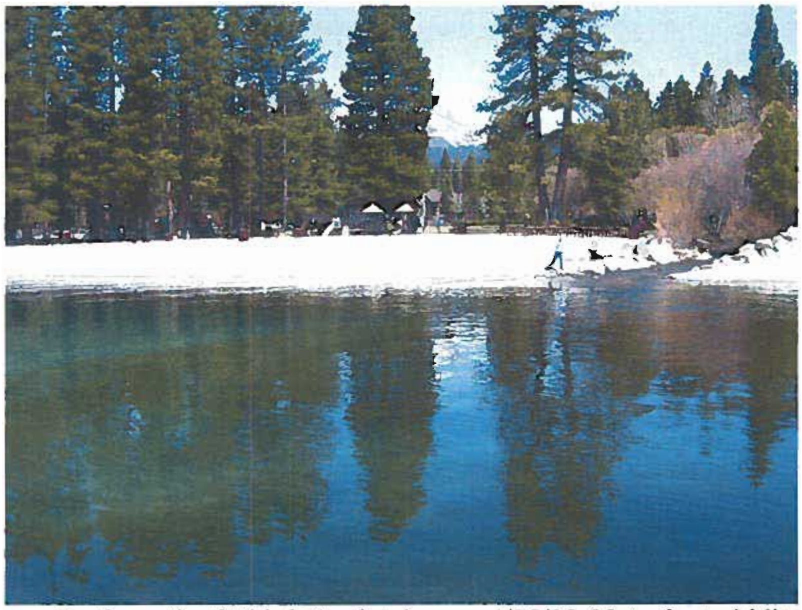

Figure 14. Photograph of mouth of Third Creek taken on 4/25/08. Note the turbidity plume from the creek being pushed towards the southeast (right).

Some turbidity peaks were not real, and were an artifact of buoy movement during wind events. This was evaluated using the variance term reported by the DTS-12 turbidimeter. Each turbidity reading reported by the sensor was comprised of an estimated average of 100 readings taken over 10 seconds. Examples of artificially high readings included Event 4 (Figure 12) and Event 5 (Figure 13) where the standard deviation of instantaneous turbidity was large while winds were elevated (Panel D). Although the standard deviation of instantaneous readings was important in judging the quality of the turbidity reading, it could not be used as the only quality threshold. Large standard deviations did not always indicate wind events or unusual turbidity values. In order to improve instantaneous turbidity readings, we utilized the best easy systematic (BES) estimator of turbidity rather than a straight arithmetic mean. The 100 turbidity readings were ranked from highest to lowest, and then the BES was reported as the average of the 25^{th}, 51^{st}, 52^{nd}, and 75^{th} value. This approach was chosen as it reduced the impact of spurious high and low readings but also provided some weight to values on either side of the mean.

Water temperatures within the near-shore zone were much less variable than that measured in the creeks (Panel C in Figures 12 and 13) due to the near-shore zone having considerably more thermal mass and being buffered by waters outside of the near-shore zone. In summer, the water temperature of the creeks was about 5 degrees Celsius colder than near-shore waters. As a result, increased discharge during Event 6 dropped near-shore temperatures by three degrees. Event 6 was unusual as there was no associated cold front or drop in solar radiation that could have contributed to the drop in temperature. We believe that this event was due to the intentional de-watering of Incline Lake in the upper Third Creek watershed. However, not all declines in near-shore water temperature were the result of higher creek discharges. Event 7 in late August and early September was primarily a wind event and cold front that dropped the average daily air temperature by 10 degrees Celsius. Precipitation did not occur and creek discharge remained unchanged. In this case, we hypothesize that the sustained, high-speed winds increased vertical and lateral mixing within the near-shore zone and promoted the movement of colder water from the deeper part of the lake into the near-shore zone.

The impact of wind events on near-shore water temperatures also occurred during spring, but was less important because of the colder near-shore temperatures at this time of year. During Event 2 for example, average near-shore water temperatures dropped by 1.3 °C during the initial windy day, and remained static during the associated short-lived cold front. In contrast, a smaller wind event in late May (Event 8, Figure 12) dropped near-shore water temperature over 2 °C on the 19^{th} and 20^{th} while another 2 °C drop occurred on the 21^{st} and 22^{nd} due to the extended colder air-temperatures.

Air temperatures also contributed to the complexity of near-shore water temperatures during the spring when the difference between near-shore and creek water temperatures were small (Panel C in Figure 12). During Event 1 for example, near-shore water temperatures increased nearly five degrees in response to an 11 °C increase in average air temperature and not the elevated discharge of 4 °C colder water from Third Creek. Cold water discharged by the creek into the near-shore zone would be expected to sink until it reached a depth where the lake water had similar temperatures. This depth appeared to be deeper than 68 cm, the depth of the lowest water temperature reading. However, suspended sediment inputs from the creek did not follow the same pattern and increased turbidity at the buoy to 4 NTU.

3.2.1. Biofouling of Turbidity Sensors

There was good agreement between the replicate submersible turbidity sensors during routine operation. The sensors were located next to each other, but were pointed in opposite directions so that they observed water clarity at depths that were 30 cm apart. This lack of differentiation during routine operation indicated that this top layer of water was well mixed and/or that any differences in turbidity with depth were not large enough to be registered by the turbidity sensors. During early season power tests when the sensor's wiping mechanism was only activated once a day, the up-facing turbidity sensor had a greater likelihood of fouling compared to the down-facing sensor. Initiating a wiping sequence prior to every turbidity measurement eliminated this difference.

Four tests to investigate biofouling and the impact of the sensor's wiping mechanism were conducted in July and August. After manual cleaning of the sensor, the wiping mechanism of the down-facing sensor was disabled while wiping mechanism of the up-facing was engaged prior to each 5-minute turbidity measurement (Figure 15). Biofouling of the non-wiped turbidity sensor's optics during the first test was noticeable after six hours and maintained a linear increase until 1.5 days. This was equivalent to a biofouling rate of 0.3 NTU day^{-1}. For short periods of time, linear increases in turbidity can be corrected during the data workup if the initial turbidity and turbidity after a cleaning wipe are known. However, biofouling was distinctly non-linear after 2.5 days and exhibited a roughly increasing sinusoidal trend that prohibited any further attempt at correction. After 9 days of biofouling buildup, the wiping mechanism was sufficient to restore the sensor to the same condition as the second turbidity sensor that was wiped prior to every measurement.

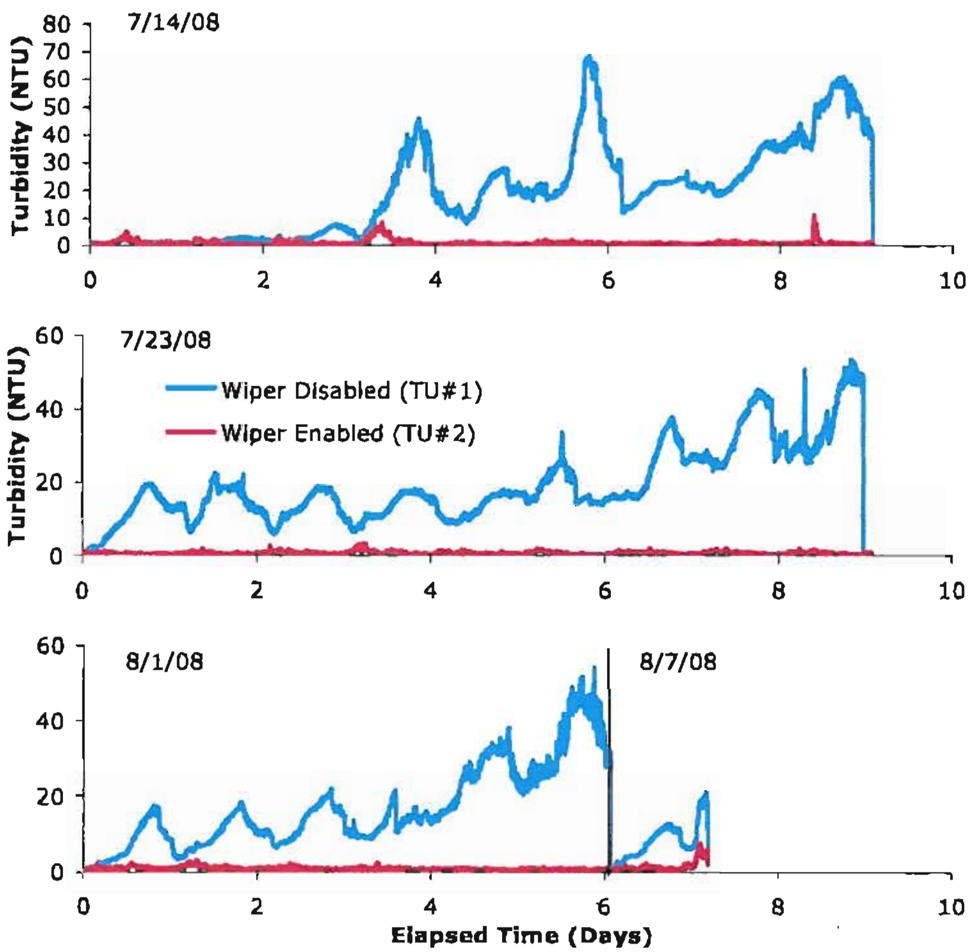

Figure 15. Turbidity during four biofouling tests. The dates when the tests were started are denoted in each panel. The wiping mechanism of the up-facing turbidity sensor (blue) was disabled while that of the down-facing turbidity sensor (red) was activated prior to every measurement.

During the remaining biofouling tests, the un-wiped turbidity sensor became fouled within hours, ranging between 8 and 21 NTU day^{-1}. Fouling resulted in a linear increase in turbidity during the first 10 to 13 hours before becoming non-linear. Changes in the biofouling rates were not related to light intensity, but may have been correlated with exposure to warmer water temperatures (Figure 16). However, a number of other unmeasured parameters could also be responsible. Biofouling was observed to increase at night when light intensity and water temperatures were lower (Figure 17). Variance between the 100 readings taken for an individual turbidity measurement was not abnormal on a biofouled sensor, indicating that it could not be used to assess the presence of biofouling. These results indicate the necessity to wipe the turbidimeter's optical window prior to every reading.

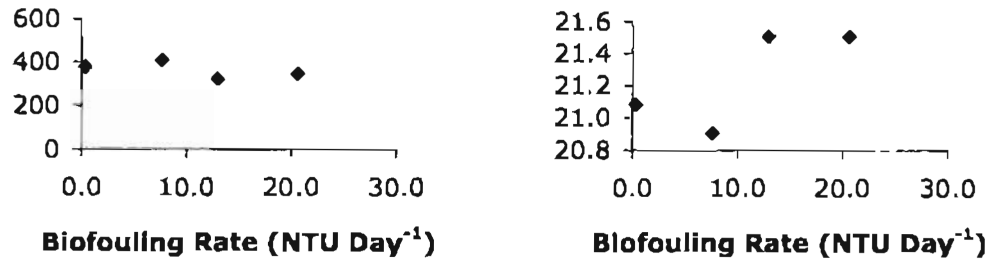

Figure 16. Biofouling rate versus light intensity (Left) and average water temperature (Right). Light intensity was measured 2.8 km onshore at the DRI Incline Creek meteorological station (http://www.wrcc.dri.edu/weather/incc.html). Water temperature was measured at the buoy.

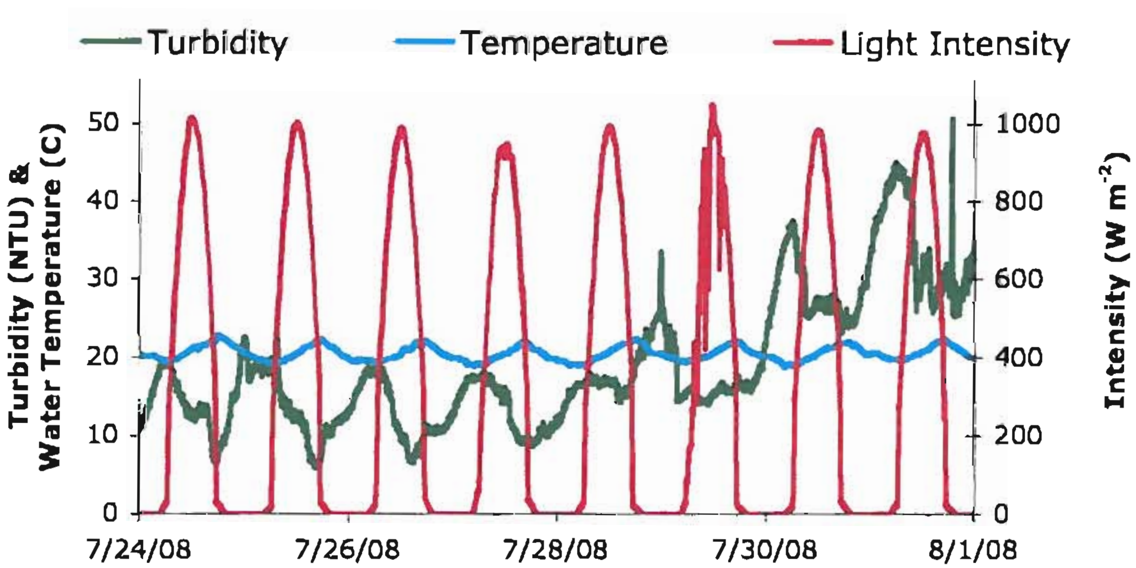

Figure 17. Comparison of turbidity, water temperature, and light intensity during the second biofouling experiment.

3.2.2. Biofouling of the Light Transmissometer

The light transmissometer was more susceptible to biofouling as there was no automated way to physically clean the sensor's optics. To reduce potential biofouling, the sensor was deployed in the "internal" mode where water was pumped through the sensor's opaque cuvette. This type of deployment maintained the sensor's optics in darkness and provided the ability to control the timing and amount of water that passed into the system. Five feet of copper tubing was added to the inlet and outlet of each "internal" sensor. Copper acts as biocide and the use of copper tubing has successfully reduced biofouling and increased deployment times in oceanographic applications (Chavez *et al.*, 2000; Manov *et al.*, 2003). However, the use of copper tubing to reduce biofouling in fresh water that lacks the salts and corrosive nature of the salt-water marine environment was previously untested.

This approach was partially successful. Although biofouling of the transmissometer occurred 7 to 11 days after physical cleaning, it was considerably longer than the few hours it took the unwiped turbidimeter to become biofouled in the mid-summer. The rate of biofouling remained consistent for several weeks, providing the ability to apply a linear correction to the dataset and estimate unfouled light transmission values in post-processing. The 11-day period was achieved by reducing the sampling interval from 15 to 60 minutes as well as a complete replacement of the tubing system. Lengthening the time between measurements increased the length of time that water was exposed to the copper tubing in sample lines, while the replacement of the tubing provided clean copper surfaces. If the same approach is followed in the future, we suggest switching out the tubing system every month, or when needed. The physical replacement of the tubing system was less time consuming than trying to clean the tubing in the field. This also provided an opportunity to bring the tubing back to the laboratory where it could be cleaned more thoroughly, including the flushing of an abrasive through the copper tubing to expose fresh surfaces that promote anti-biofouling activity.

Based on the springtime deployment, biofouling is not expected to be an issue during winter deployments. Although only simple approaches to reduce biofouling were taken during this study, several alternatives do exist. Given the success of the turbidimeter wiper, one alternative is to build a device to physically wipe the transmissometer's optics. The primary benefit to this approach is the conversion from a closed system to an open system by removing the transmissometer's cell and tubing. Energy requirements would be reduced, as the sample pump would be replaced with a more energy efficient wiping system. We believe that this approach should be investigated first as it has a high likelihood of succeeding and poses the least environmental risk. Some development time would be needed to construct a wiping system as no commercial solutions exist for this sensor. A second approach is to accelerate the reactivity of the copper tubing through the use of salt solutions or electrical current that would be intermittently applied. A third solution would be to reduce the amount of tubing to the smallest length possible and coating the inside of the tubing and cells with recently developed anti-biofouling paints that do not contain tin, copper, or pesticides.

4.0 SPATIAL SURVEYS

Two whole-lakeshore surveys and a survey off of South Lake Tahoe were conducted. The whole lake surveys took place on April 25-26, 2008 (Figures 18A-D) and August 12-13, 2008 (Figures 19A-E), and South Lake Tahoe survey on September 15, 2008 (Figure 20). Continuous measurements included turbidity (Hach 2100), light transmission, water temperature, and relative chlorophyll. See Taylor, *et al.* (2003) for a description of the sensors and the procedures used to collect data aboard the Research Vessel Mt. Rose.

Background near-shore turbidity values in April (Figure 18A) were less than 0.15 NTU and were typical of previous whole-lakeshore surveys (Taylor *et al.*, 2003). However, by August background values were elevated to 0.21 NTU (FigureJ2A) and remained slightly elevated at 0.17 NTU on September 15 (Figure 20). We hypothesize that this lake-wide elevated turbidity was deposited as particulate matter from the smoke plumes of several fires that occurred during the summer of 2008 (http://www.inciweb.org). To the north, three fires burned in the Plumas National Forest that started in June, July, and

September. These three fires combined to burn 109,000 acres. To the west, the American River Complex burned 21,000 acres in the Tahoe National Forest starting in June. Visibility conditions in the Lake Tahoe basin were poor enough at times that it was difficult to observe the far shore of the lake. This trend in background turbidity was also observed in transmissometer data as a 10% loss in background light transmission between April (Figure 18B) and August (Figure 19B). In August, average light transmission was 8% lower in waters off the western shore (north of Emerald Bay to Dollar Point) than off the eastern shore (Edgewood Creek to Third Creek). By September (Figure 20), light transmission values off of South Lake Tahoe had nearly returned to spring levels.

During the September survey (Figure 20), near-shore clarity off of Al Tahoe subdivision in the South Lake Tahoe area was surprisingly degraded. There were no precipitation events within the last three weeks that could have contributed to this degradation. We believe that the most likely cause was due to resuspension from wave action, especially during the low lake levels this period. Two weeks prior (8/31-9/1), daytime winds were sustained between 14-16 km/hr with wind gusts between 30-50 km/hr. Daytime winds remained somewhat elevated, and ranged from 16- 25 km/hr during the three days prior to the survey. The slightly warmer water temperatures (Panel C in Figure 20) that corresponded with the elevated turbidity plume suggest mixing with the shallower water of the ultra near-shore zone. The ultra near-shore zone is not included as part of the spatial survey as it was too shallow to safely operate the boat.

Water temperatures in the near-shore zone were variable. In April, water temperatures ranged from 5.5 to 11.1 °C (Figure 18C). Colder surface water inflows from some creeks such as Ward Creek (Point A in Figure 18C) and Third and Incline creeks (Point B) appeared to locally lower near-shore water temperatures. Near-shore temperatures varied from 19 to 23 °C in August (Figure 19C), and from 18 to 21 °C off the South Lake Tahoe in September (Figure 20. Average water temperature off the western shore of the lake was 0.6 °C (April) and 0.8 °C (August) lower than off the eastern shore due to the greater prevalence of shallower waters off the eastern shore.

Light transmission and turbidity were compared against each other (Figures J1D and J2D) utilizing:

$$\text{Comparison Ratio} = \frac{100 - \text{Light Transmission (in \%)}}{\text{Turbidity}}$$

Lower ratio values indicated that light transmission and turbidity readings were most similar while larger ratio values indicted a divergence in the readings of the two sensors. The least agreement between the sensors occurred in South Lake Tahoe in April (Figure 18D) and along the western shore in August (Figure 19D). These differences were likely the result of turbidimeter sensitivity to the size, shape, and composition of particles in the water at a given location, as well as the inability of the turbidimeter to measure light absorption, as previously discussed.

A second index ratio was used to assess the importance of chlorophyll-containing organics, such as algae, to water clarity. This was calculated by dividing the relative chlorophyll value by turbidity (Figures 19E and 20). Lower ratios indicated a greater importance of mineral material while a higher ratio indicated a greater importance of chlorophyll-containing organic matter. As has been observed in past studies (Taylor *et al.*, 2003), mineral particles dominated areas with degraded water clarity, but were less important in areas having background water clarity.

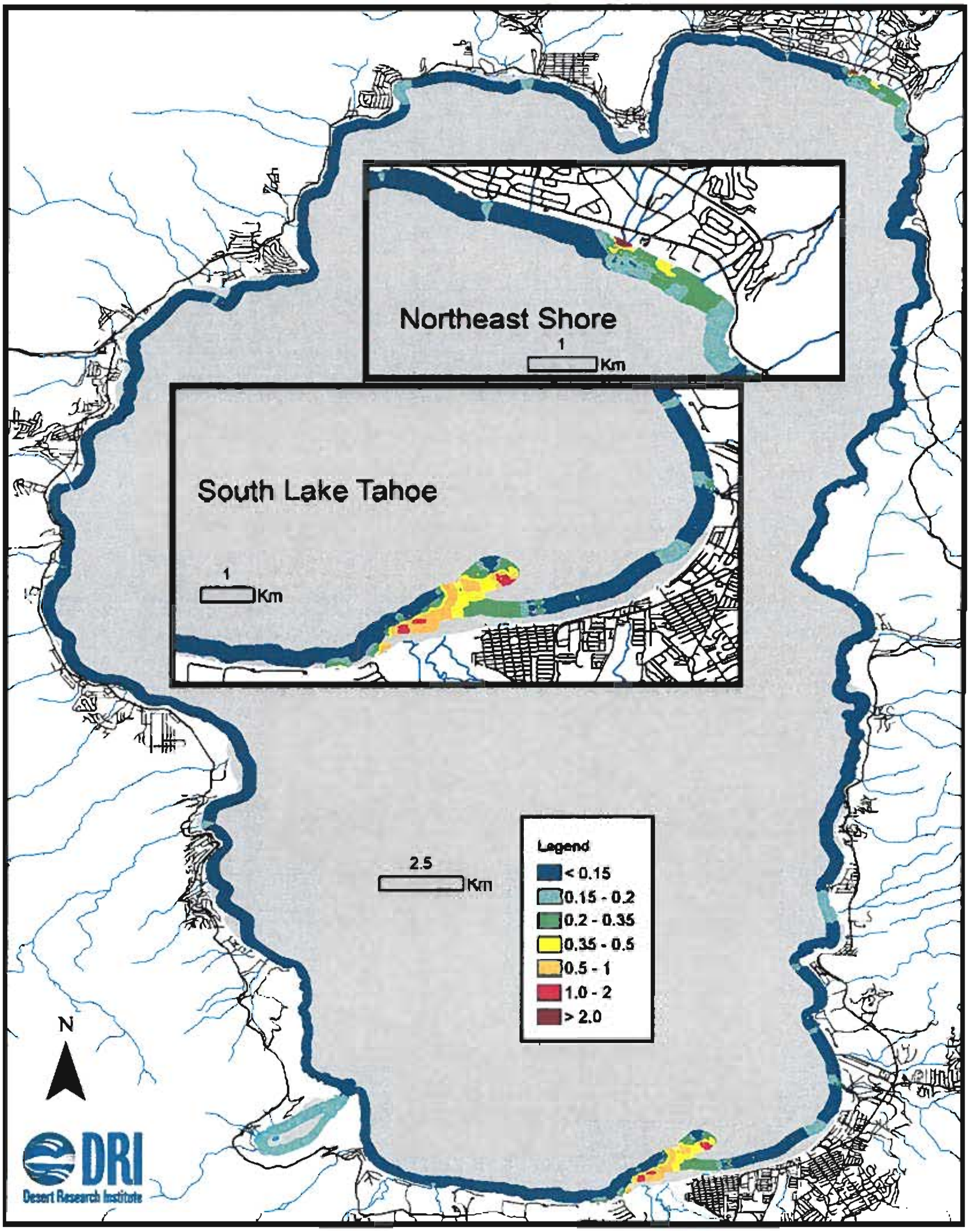

Figure 18-A. Turbidity (Hach 2000) observed during the April 25-26, 2008 whole-lakeshore survey. Units are in NTU.

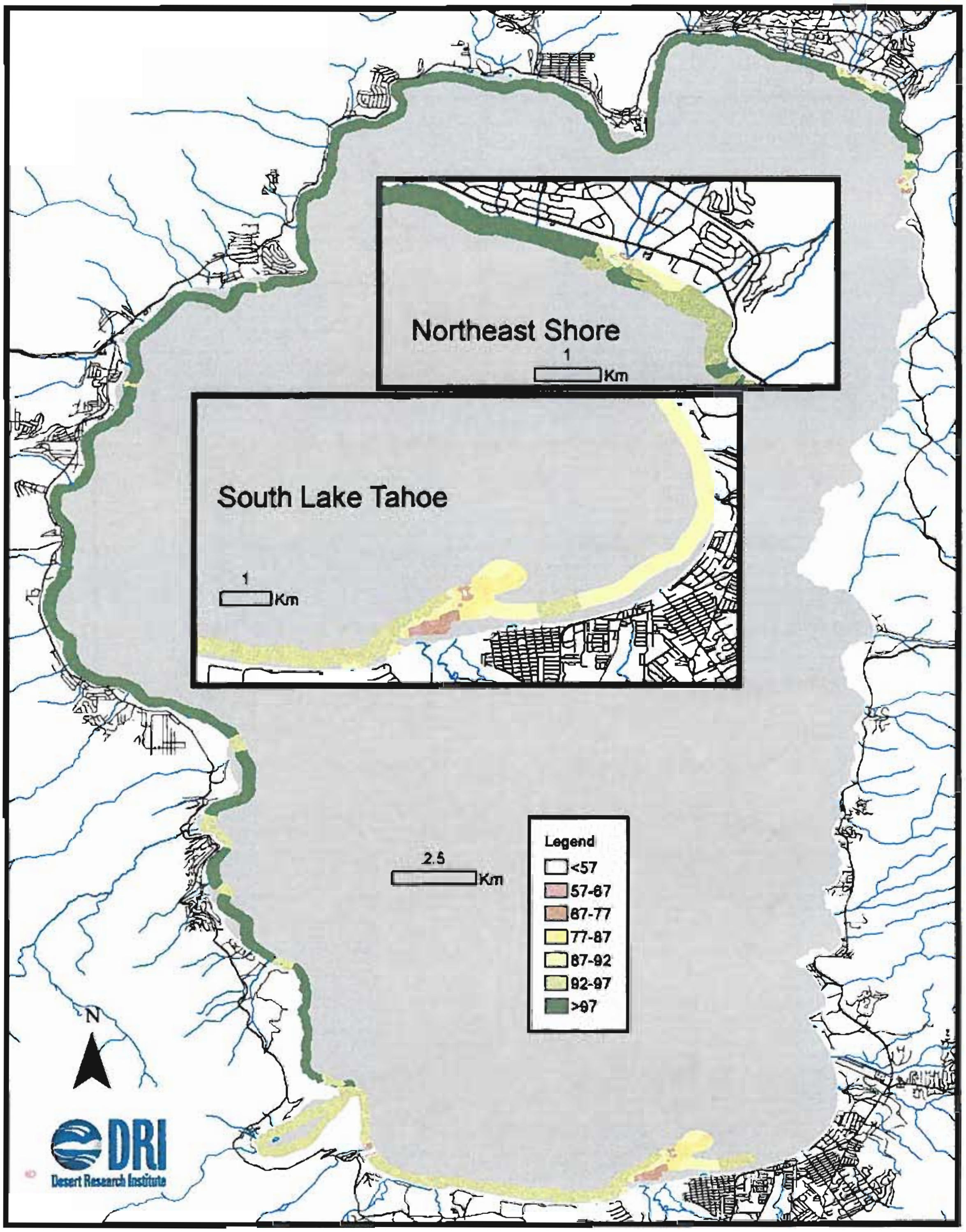

Figure 18-B. Light transmission observed during the April 25-26, 2008 whole-lakeshore survey. Units are in percent.

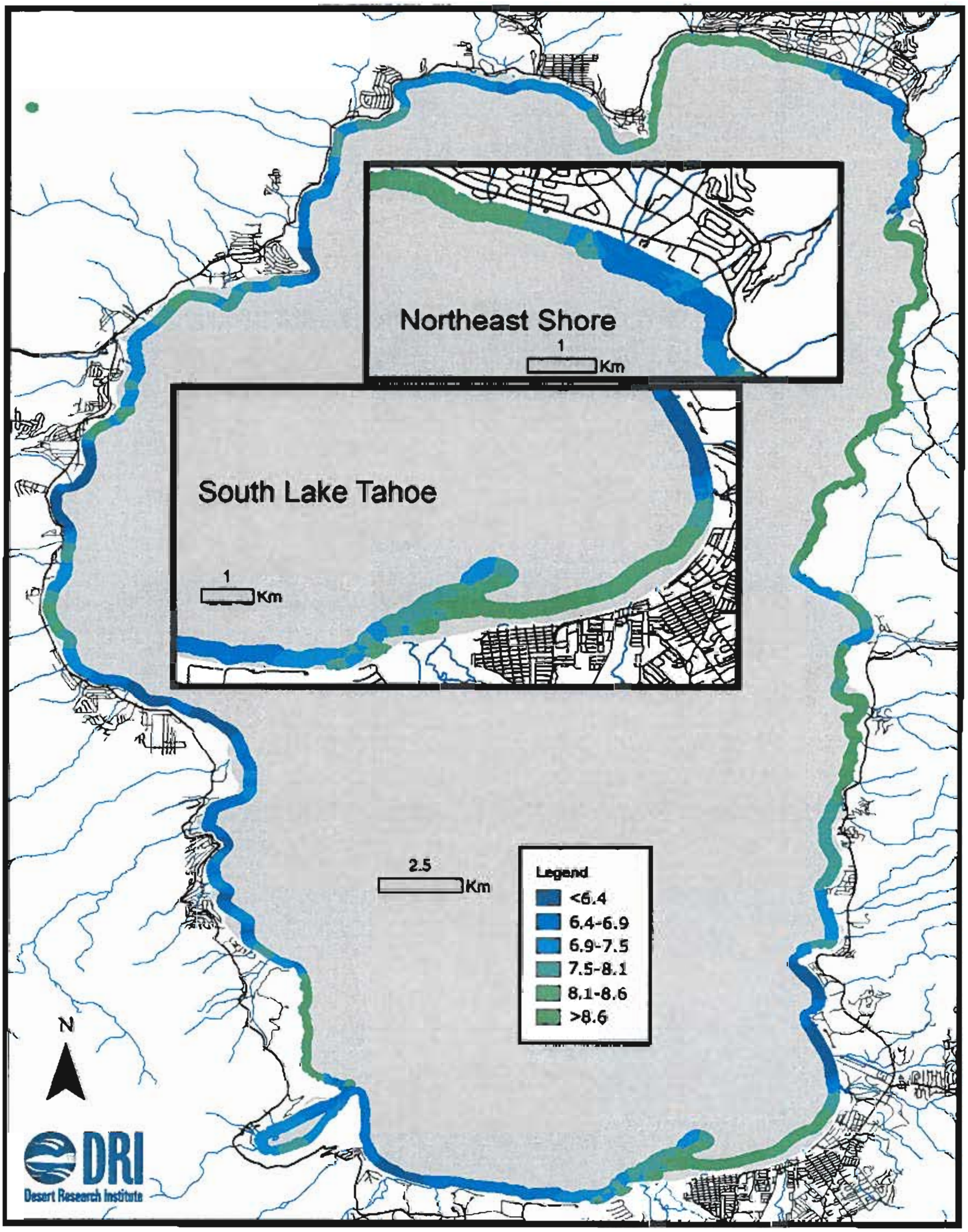

Figure 18-C. Water temperature observed during the April 25-26, 2008 whole-lakeshore survey. Units are in degrees C.

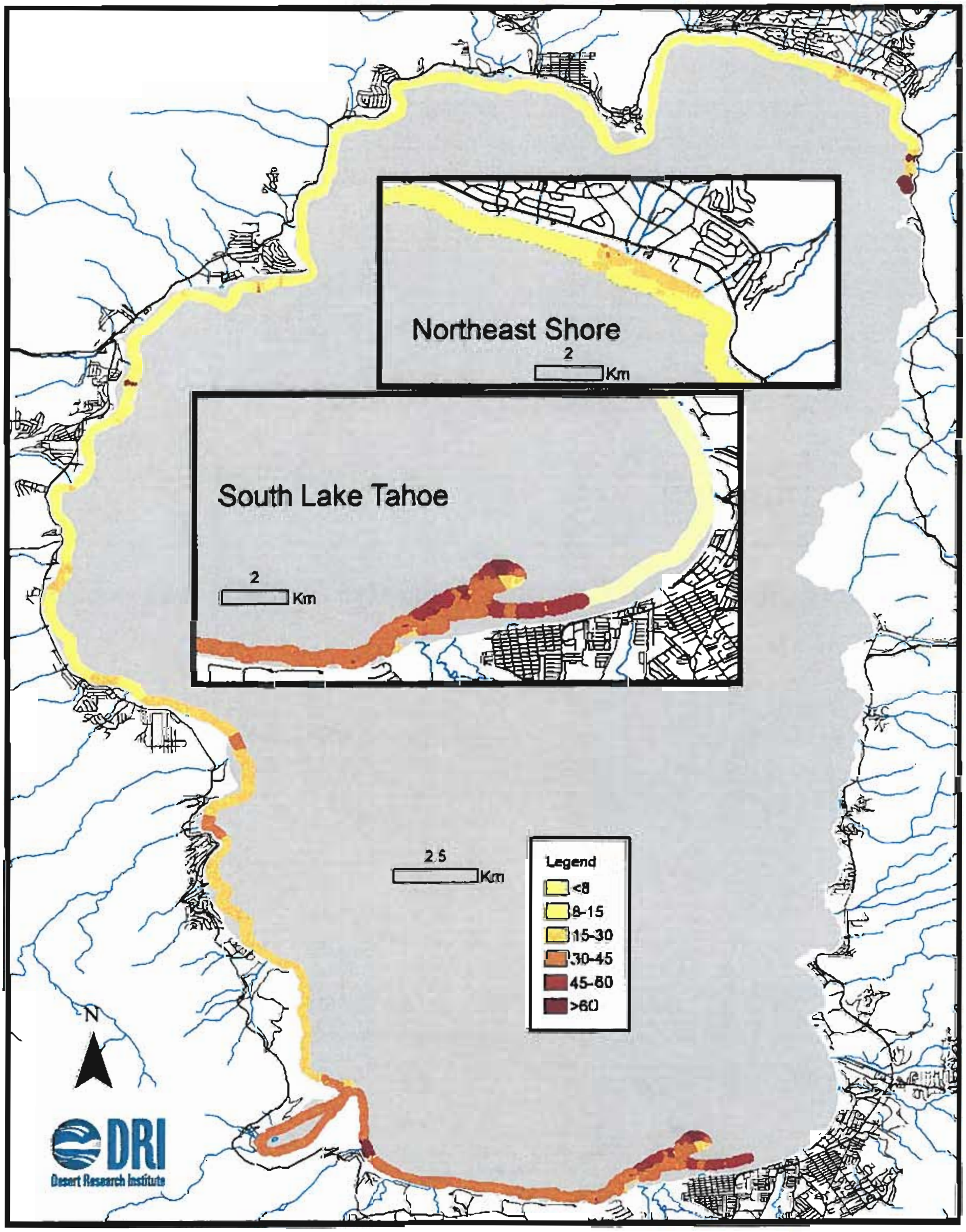

Figure 18-D. Ratio of light transmission to turbidity observed during the April 25-26, 2008 whole-lakeshore survey. The ratio was calculated as (100-Light Transmission)/Turbidity. Lower numbers indicate similar readings between sensors whereas higher numbers represent divergence between sensors.

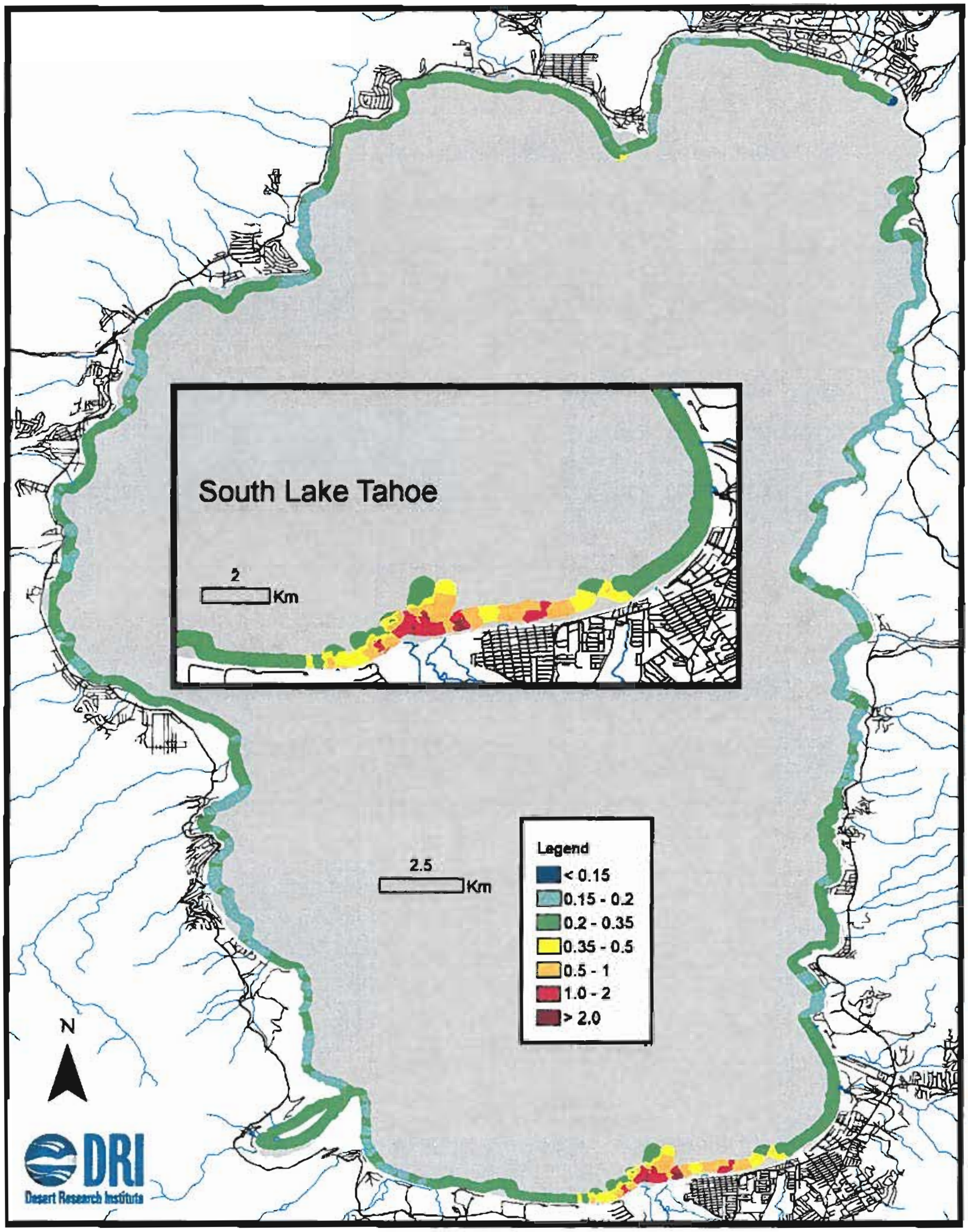

Figure 19-A. Turbidity (Hach 2000) observed during the August 12-13, 2008 whole-lakeshore survey. Units are in NTU.

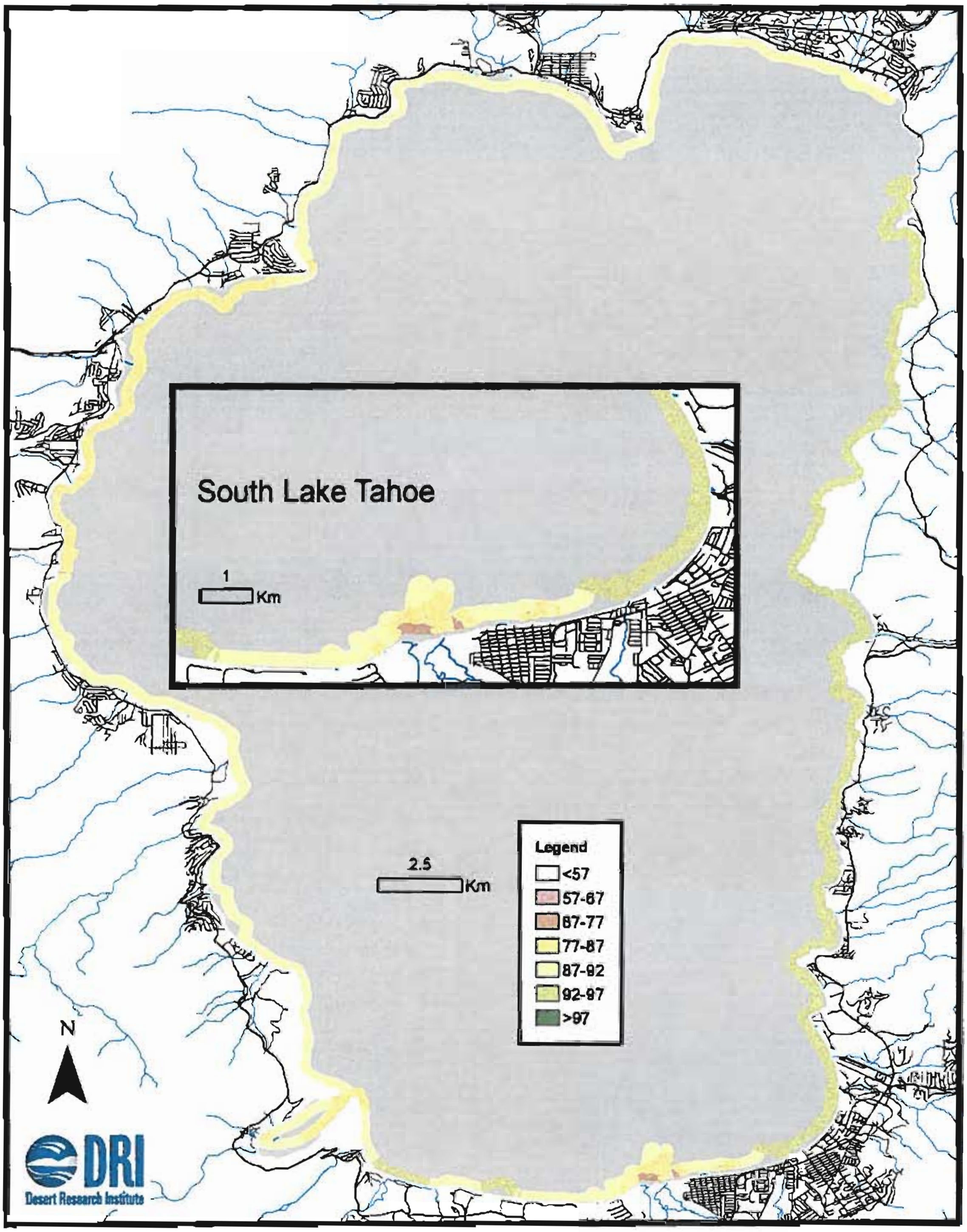

Figure 19-B. Light transmission observed during the August 12-13, 2008 whole-lakeshore survey. Units are in percent.

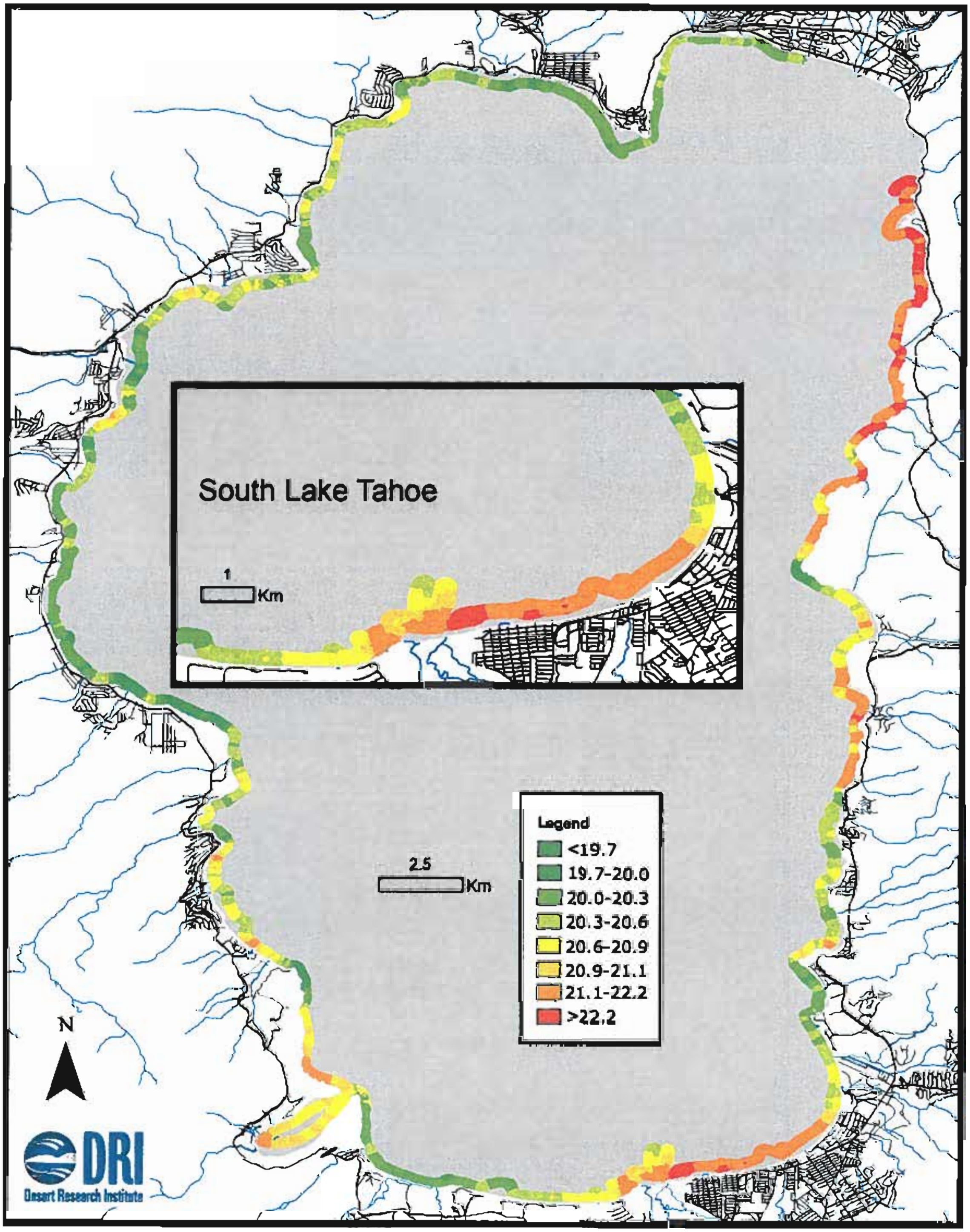

Figure 19-C. Water temperature observed during the August 12-13, 2008 whole-lakeshore survey. Units are in degrees C.

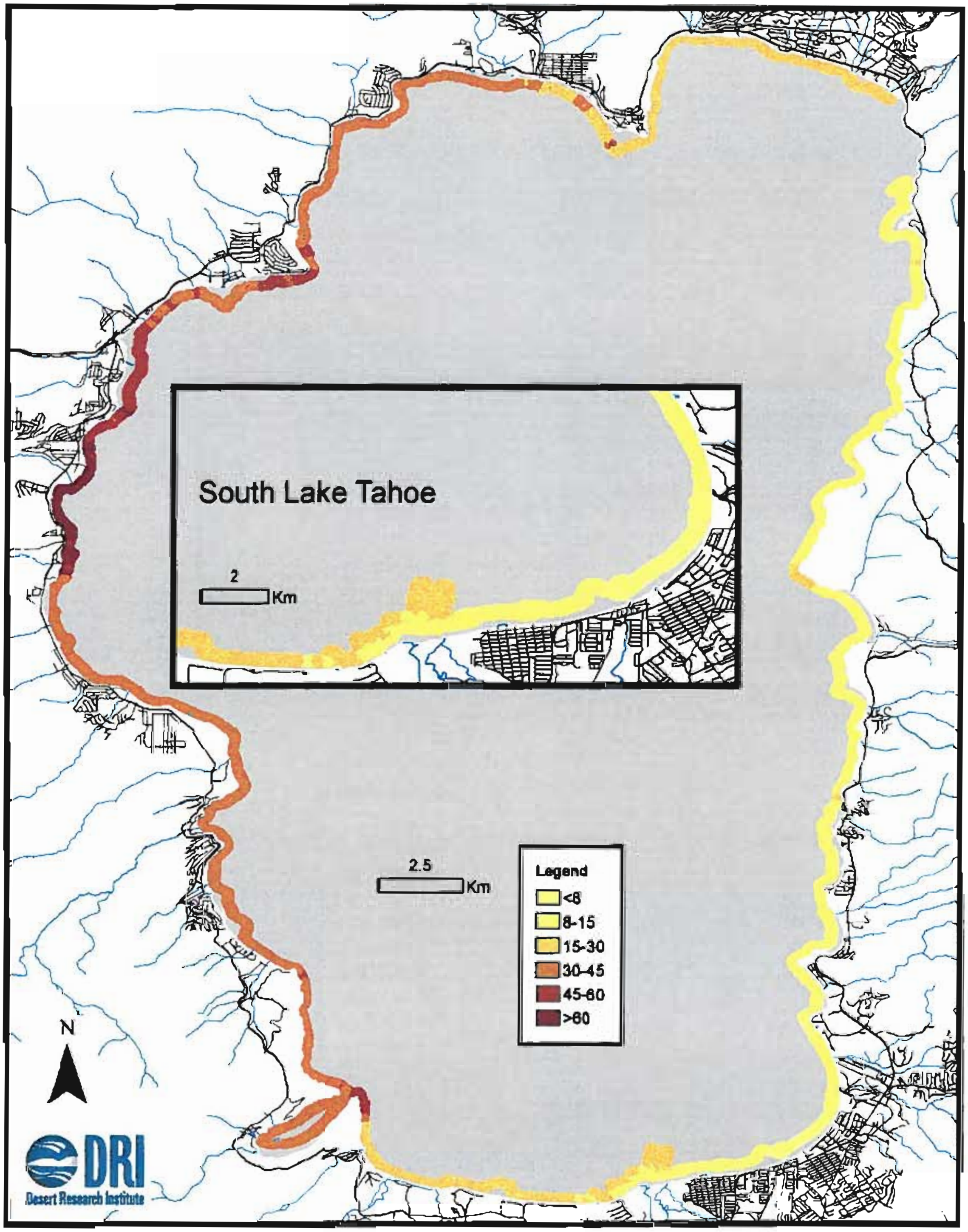

Figure 19-D. Ratio of light transmission to turbidity observed during the August 12-13, 2008 whole-lakeshore survey. The ratio was calculated as (100-Light Transmission)/Turbidity. Lower numbers indicate similar readings between sensors whereas higher numbers represent divergence between sensors

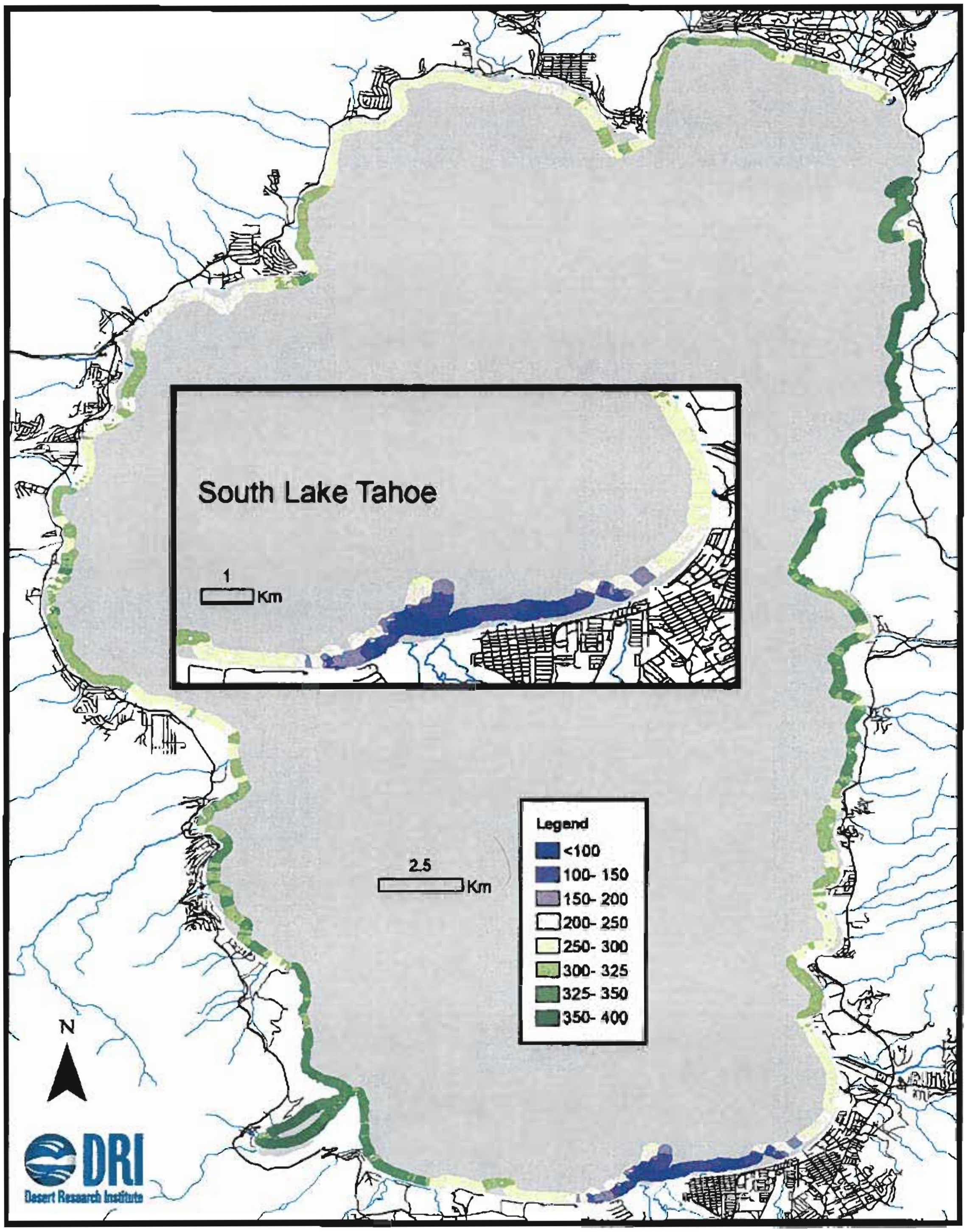

Figure 19-E. Ratio of relative chlorophyll to turbidity observed during the August 12-13, 2008 whole-lakeshore survey. Units are in percent/turbidity. This relative ratio was an indicator of the overall mineral or biologic composition of the water sample. Lower numbers indicate domination by mineral particles while lower higher numbers reflect domination by organisms containing chlorophyll.

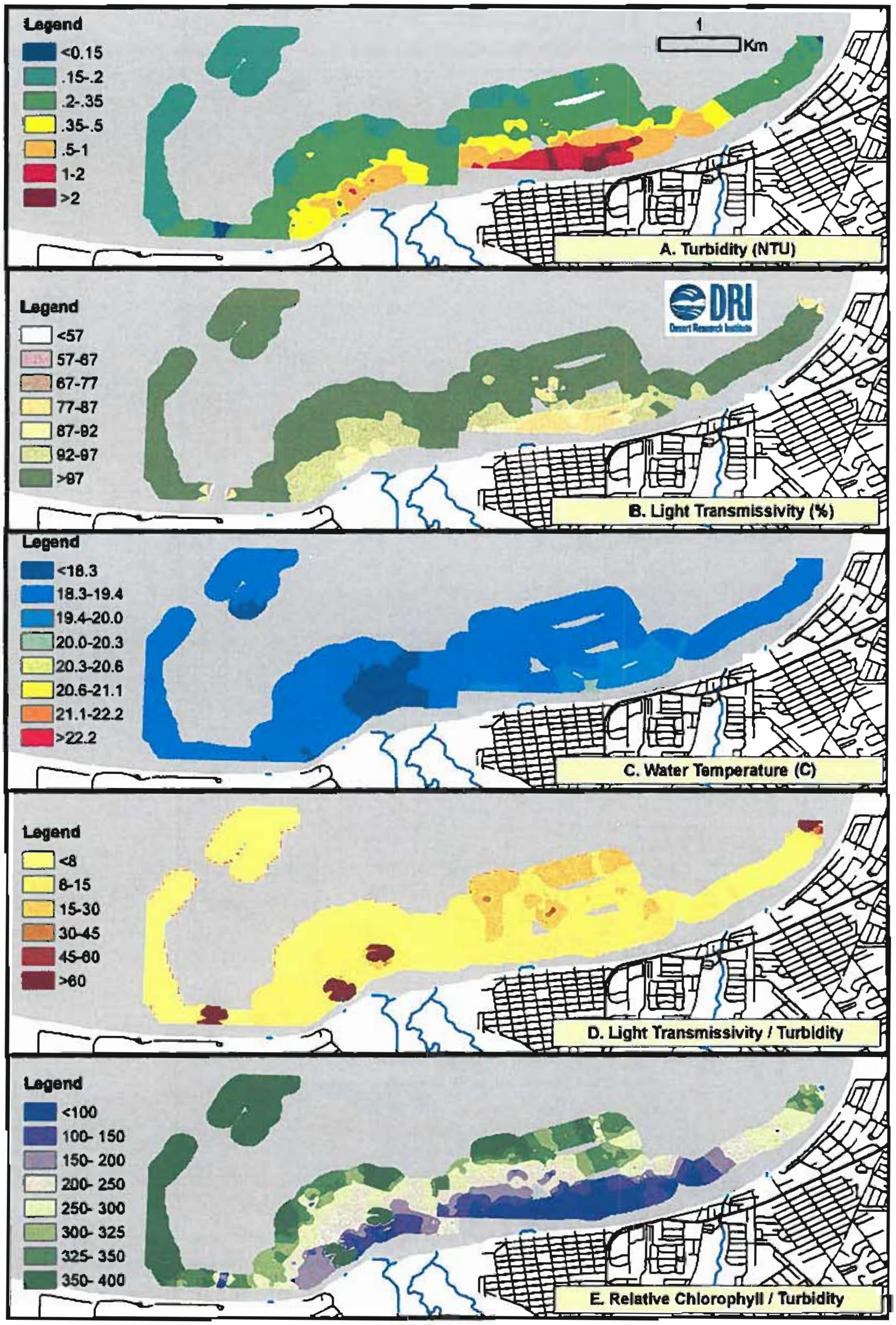

Figure 20. Near-shore clarity data collected off of South Lake Tahoe on September 15, 2008. See previous figure legends for a description of each panel.

5.0 DISCUSSION

5.1 Use of Turbidity for Water Clarity Measurements

Near-shore water clarity declined in response to the delivery of suspended sediments mobilized by snowmelt and rain events from adjacent creeks. This decline was measured as increased turbidity and as decreased light transmission. Both clarity-measuring optical techniques were successful at quantifying these event-induced clarity reductions. However, we have several concerns about the continued use of turbidity to assess seasonal and long-term changes that require measurements during times when water clarity was excellent.

First, turbidity was not very sensitive during background conditions when the number of suspended particles in the water column was low. Under these conditions, other clarity-reducing factors such as absorption from dissolved organic matter (e.g. tannins) can have a greater relative importance to overall water clarity. Turbidimeters only measure scattering and do not measure absorption. This was observed in Figure 9 where the relationship between turbidity and light transmission moved to the left and became steeper as the summer progressed. This behavior would be expected as absorption processes played a greater role in water clarity due to the reduction in scattering processes later in the season.

Turbidity was shown to have a curvilinear relationship with both Secchi depth and light transmission (Figure 7). The particularly steep slope of the curvilinear relationship under good water clarity conditions indicates that a significant change in near-shore water clarity can occur before being registered by the turbidimeters. For example, a small 0.2 NTU change, equivalent to the sensors reported accuracy, can result in up to a 5% change in light transmission. Light transmission was a better measure of water clarity as it measures both light adsorption and scattering within a visible wavelength and has a more linear relationship with Secchi depth (Figure 7).

Second, repeatable turbidity measurements were difficult to achieve at low turbidity values. Even with the best bench-top turbidimeters and trained laboratory personnel, accurate and repeatable turbidity measurements are difficult to achieve at < 2 NTU because turbidimeters exhibit poor sensitivity at the bottom of their detection range. Factors such as water color, impurities, sample preparation and the optical condition of the cuvette effect the final turbidity value to a greater degree as turbidity values drop (Sadar, 1998). In contrast, light transmission is more sensitive because it is measuring at the top of its detection range under optically clear conditions.

Submersible turbidimeters were expected to exhibit lower accuracy and repeatability at low turbidity values because of the trade offs necessary to operate on low-voltage power sources and the need to harden the sensor's electronics and optics to survive the direct exposure to environmental conditions. An approach to improve reproducibility taken by the DTS-12 turbidimeter was to conduct 100 readings in 10 seconds and to report the best easy systematic (BES) indicator in addition to the arithmetic mean. As previously discussed in Section 3.3, the BES was preferred as it eliminated spurious high and low readings but did give some weight to readings on either side of the mean. To test the reproducibility, 288 sequential readings were taken every 5-minutes over a 24-hour period during calm, late summer background conditions. Sensor readings ranged from 0.18 NTU to 0.41 NTU, a change of approximately ± 65% of the mean value of 0.26 NTU (Figure 21). As a result, the

5-minute turbidity data were very noisy during background periods, leading to the use of either average hourly or average daily data in previous graphs that masked this inherent variability. The variability in light transmission during this same time period was lower, with values ranging from 96.7 to 98.1%. Light transmission data were less noisy and easier to interpret because small changes in clarity resulted in more discernible differences in light transmission compared to turbidity. For example, a change of only 1% in light transmission represented 1% of a full-scale reading, whereas a doubling of turbidity from 0.26 0.52 NTU represented only a 0.05% change of the sensor's full-scale reading.

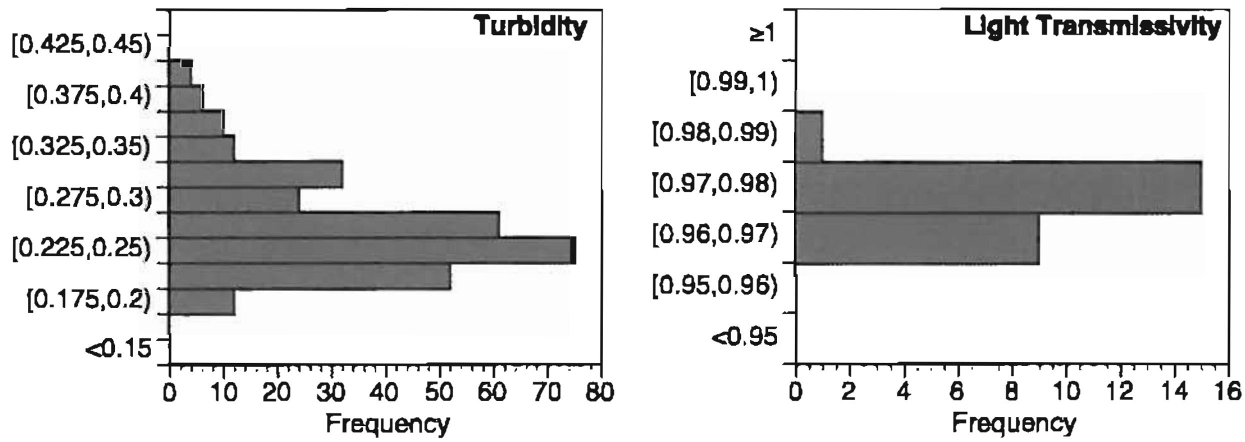

Figure 21. Turbidity and light transmissivity measured during summer background conditions on 9/14/08. Turbidity was measured on 5-minute intervals resulting in 288 readings with an average of 0.26 NTU, a standard deviation of 0.05 NTU, a minimum of 0.18 NTU and a maximum of 0.41 NTU. Light transmissivity was measured on 1-hour intervals resulting in 24 readings with an average of 97.1%, a standard deviation of 0.3%, a minimum of 96.7% and a maximum of 98.1%.

Third, turbidity of the same water sample can be different depending on the model of turbidimeter and the sensitivities that each model has to particle shape, size, and/or composition. As a test, three different EPA method 180.1 compliant laboratory-grade turbidimeters used aboard the RV Mount Rose were compared during the whole-lakeshore survey conducted on 4/25/08. The overall shape of the histograms from each site were similar, however the South Lake location had a greater number of intermediate turbidity values where the Incline Village site had a greater number of higher turbidity values (Figure 22).

Figure 23 compares turbidity values obtained from a Hach 2000 with either a Hach 2100AN or a HF Scientific MictoTol4. Although the Hach 2000 and the Hach 2100AN produced similar results in the South Lake Tahoe area (Figure 23 Panel 1), the Hach 2100AN produced results that were lower and skewed to the left in the Incline Village area (Panel 2). In contrast, the MicroTol4 reported turbidity values consistently 0.03 NTU higher, but with a significant skew to the right compared to those from the Hach 2000 at both sites (Panels 3-4). These results highlighted the fact that meter-specific sensitivities affected how each meter reported turbidity despite all three meters being EPA 180.1 compliant.

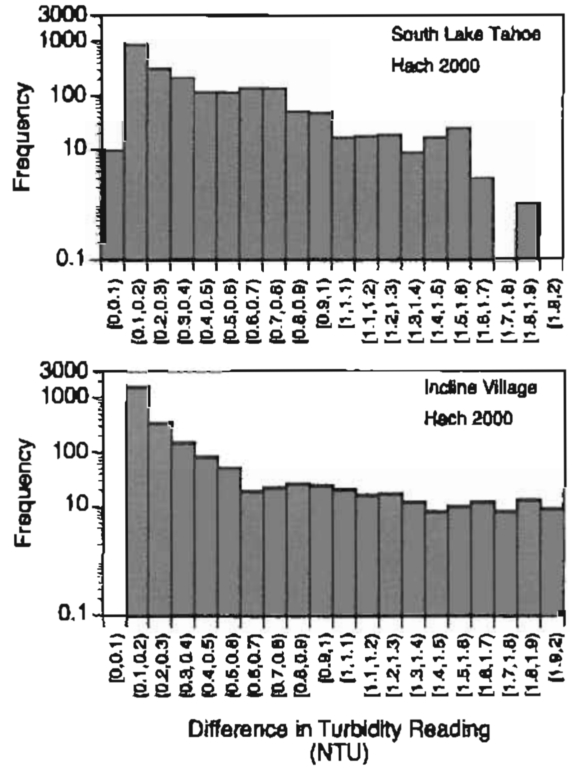

Figure 22. Histograms of turbidity data collected off of South Lake Tahoe and Incline Village on 4/25/08.

The comparison of turbidity readings between meters of different types (EPA method 180.1 white light versus infrared) is challenging because of light source differences and the angle of scatter that they measure. The relationship between any two given turbidimeters will also change depending on the type of sediment that is being observed (Lewis *et al.*, 2007). A comparison of the submersible DTS-12 turbidimeter and the bench top Hach 2100AN for a variety of non-lake sites are presented in Table 4. Although these comparisons were conducted at higher turbidity ranges than found in Lake Tahoe's near-shore zone, they indicate the variability in the relationship between sites. For all urban runoff and river sites, slopes varied from 0.663 to 1.62. Intercepts for Bijou, Regan Beach, and Ace Court urban runoff sites were similar, but those at the Harold Vault and Carson River were significantly different resulting from differences in range and minimum turbidity values in the population of observed samples.

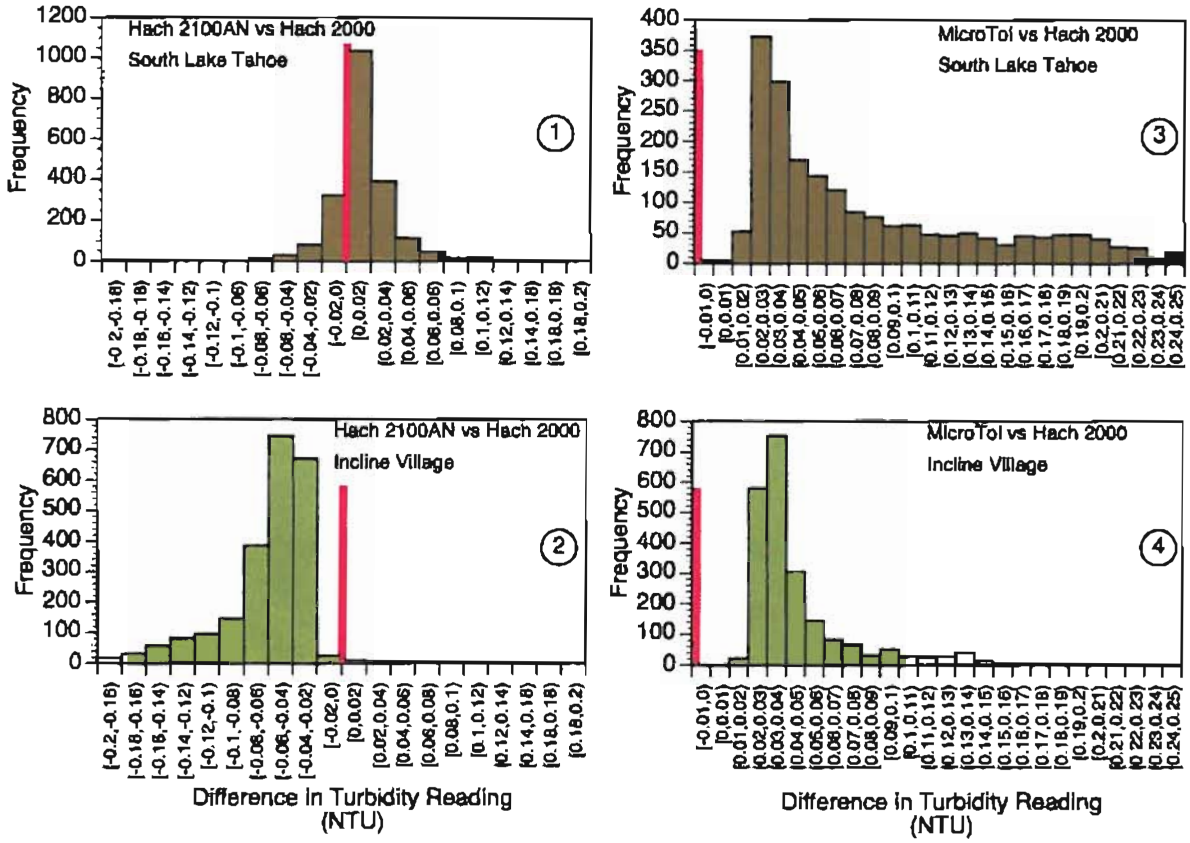

Figure 23. Relative difference (in NTU) between three turbidity meters used to measure water clarity during a whole-lakeshore survey on April 25, 2008. Panels 1 and 2 compare the Hach 2100AN against the Hach 2000 and Panels 3 and 4 compare the MicroTol 4 with the Hach 2000. Data are presented for the South Lake Tahoe area between the Upper Truckee River and Ski Run Blvd (Panels 1 and 3) or for the North Lake Tahoe off of Incline Village (Panels 2 and 4). The red vertical line represents no difference in readings between the two sensors.

Table 4. Comparison of turbidity sensors. Sensors included a submersible FTS DTS-12 (DTS12), a bench top Hach 2100AN (Hach) and a portable Hach2000P (Hach2000P). For the urban runoff sites at Lake Tahoe, in-situ measurements with the DTS-12 were compared with discrete samples taken by an automatic sampler. For the river site, in-situ measurements were compared with manually collected depth-width integrated samples. For the lab study, multiple sediment samples were artificially mixed to provide a direct comparison between sensors (see Lewis *et al*, 2007).

Type	Site	Relationship	R^2 or avg error	n	NTU Range	Source:
Urban Runoff	Bijou	DTS12 = 0.663 x Hach + 35.179	0.88	43	99-1200	Susfalk, unpublished
Urban Runoff	Regan Beach	DTS12 = 1.622 x Hach + 36.379	0.98	9	80-382	Susfalk, unpublished
Urban Runoff	Ace Court	DTS12 = 1.111 x Hach +35.166	0.97	14	34-1200	Susfalk, unpublished
Urban Runoff	Harold Vault	DTS12 = 0.974 x Hach + 117.65	0.91	12	36-1200	Susfalk, unpublished
River	Carson River	DTS12 = 1.360 x Hach + 3.0411	0.84	13	10-44	Susfalk et al, 2008
Lab Study	Multiple	DTS12 = 0.930 x $(Hach)^{2.0323}$	11%	--	25-1200	Lewis et al, 2007
Lab Study	Multiple	Hach2000P = -0.00025 x $(Hach)^2$ + 0.822 x Hach + 3.3057	5%	--	25-1200	Lewis et al, 2007

Lewis *et al.* (2007) compared various turbidimeters directly under a laboratory setting using a variety of watershed sediments. On average, the DTS-12 predicted Hach 2100AN turbidity values with a mean error of 11% and a maximum error of 65%. In comparison, the Hach 2000P, a portable turbidimeter commonly used in the Tahoe basin, predicted Hach 2100AN values with a mean error of 5% and a maximum error of 21%. They concluded that sediment properties had a greater effect on turbidimeter comparisons when meters of different types (white light versus infrared) were compared. Comparison of different turbidimeters must be done on a site-by-site basis to account for the meters' sensitivities to site specific sediment and water characteristics.

5.2 Management and Threshold Implications

Public perception of Lake Tahoe's overall water quality and visual appeal is heavily influenced by the clarity of water in the near-shore zone. Therefore, management of the near-shore zone needs to be consistent with the expectations of the local community and visitors regarding aesthetic, environmental, and economic factors. Current near-shore thresholds are:

> **California** – (1) Turbidity must not exceed 3 NTU at any point of the lake too shallow to determine a reliable extinction coefficient. In addition, turbidity shall not exceed 1 NTU in shallow waters not directly influenced by stream discharges.
> (2) Waters shall be free of changes in turbidity that cause nuisance or adversely affect the water for beneficial uses. Increases in turbidity shall not exceed natural levels by more than 10 percent.
>
> **Nevada** - Turbidity must not exceed 3 NTU at any point of the lake too shallow to determine a reliable extinction coefficient.
>
> **TRPA**- Decrease sediment load as required to attain turbidity values not to exceed 3 NTU in littoral Lake Tahoe. In addition, turbidity shall not exceed 1 NTU in shallow waters of Lake Tahoe not directly influenced by stream discharge.

Near-shore clarity thresholds were not addressed under the Pathway 2007 Evaluation Report in order to provide additional time for near-shore projects like this one to be completed, with the expectation that a discussion on revised thresholds would begin in 2009.

5.2.1 Issues that need to be addressed with current thresholds and monitoring programs:

Based on the results from buoy and whole-lakeshore surveys, we have identified several issues that need to be addressed when near-shore clarity thresholds are revised:

1. Link the definition of the near-shore zone to threshold objectives: Currently, there is no consistent definition of what areas comprise the near-shore zone. One identifier that is commonly used is the littoral zone, defined as areas that are shallow enough to permit sufficient light to reach the bottom to promote the growth of macrophytes (rooted plants) and periphyton (attached algae). For Lake Tahoe, the littoral zone is generally considered to be in water less than 30 m deep. However, special emphasis has been given to the very shallow littoral zone, where pollutants enter the lake and

where water clarity degradation appears to visitors and residents to easily occlude visibility of the lake bottom.

Common practice has been to equate characteristics of the shallow near-shore zone with the deeper littoral zone. Historically, TRPA's littoral zone monitoring has consisted of measuring turbidity at nine locations on the 25-meter bathymetric contour four to five times a year. However, the choice of the 25-meter contour is not consistent with the community's expectations of near-shore water clarity as there is ample opportunity for the dilution of pollutants by cleaner mid-lake water that prevents the detection of degradation near the shore where the majority of the public observes the water clarity. This disconnect between where pollutants enter the lake and monitoring at the 25-meter contour virtually assures that the elevated turbidity levels used in the current thresholds will not be observed at the current TRPA monitoring sites.

Consideration must be given to the actual definition of the near-shore zone when thresholds are revised, based on the desire to either manage pollutant loads in the shallow near-shore zone or in the deeper littoral zone. A suggested definition of the near-shore that could be used is the area of the littoral zone where decline in water quality is easily visible from shore. Operationally, the near-shore could be defined to a shallow water depth (e.g. 5-10 m) and/or a prescribed distance from shore (e.g. 100 m). The exact definition, however, needs to be determined by the desired management objectives.

2. Better definition of the monitoring/sampling approach: Another current ambiguity relates to the temporal frequency and regularity of near-shore water quality sampling. The current TRPA littoral monitoring and past research (e.g. Taylor *et al.*, 2003) have relied on a snapshot approach where near-shore quality was only assessed during specific surveys. A snapshot approach makes it very difficult to perform any trend analysis over time. Results from the buoy (Figure 10) clearly show more complex changes in near-shore clarity on a daily and seasonal time scale then previously suggested by snapshot studies. Additionally, the timing of snapshot surveys is not clearly defined relative to precipitation, wind, or snowmelt events that can affect near-shore clarity. A snapshot survey taken immediately after one of these events will result in the observation of a greater reduction in near-shore clarity. The collection of data only during very calm conditions, such as typical of TRPA's littoral sampling, will bias the data and not properly reflect near-shore conditions. If snapshot surveys are conducted in support of a revised near-shore threshold, then the approach and timing of monitoring activities needs to be better elucidated. The supplemental use of a buoy-based system for continuous monitoring would help alleviate these issues and can provide needed context for snapshot surveys.

3. Eliminate or better define "influenced by stream discharges" terminology: Currently, both the California and TRPA thresholds permit a greater degradation of water clarity in areas influenced by streams. However, easy or straightforward delineation of such areas is nearly impossible, since what is considered to be a stream and/or how large of an area is to be considered affected by a stream are undefined. Taylor *et al.* (2003) provide an example of the complexity of this in the South Lake Tahoe area (Figure 24). To complicate matters, stream-affected areas can also change on a

daily basis due to wind and lake currents (as observed by the buoy), and with stream discharge. Revised thresholds should either abandon this terminology or provide defensible guidance on what constitutes a stream, and how the stream-affected areas should be determined.

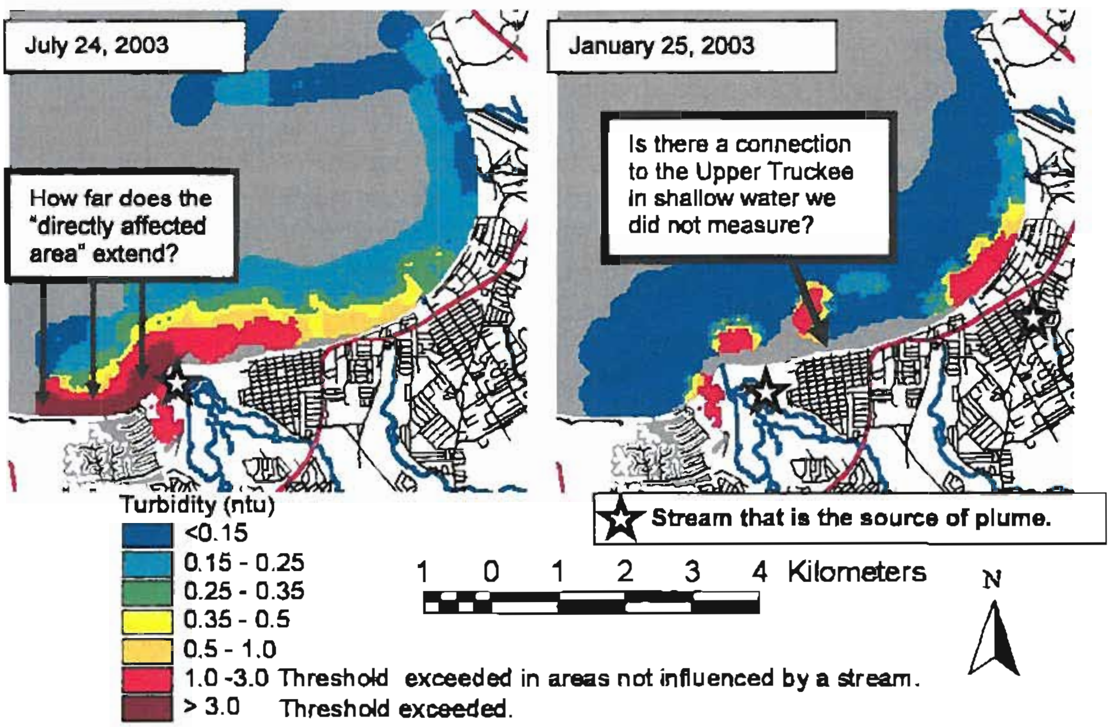

Figure 24. These surveys illustrate the problem created by the ambiguous wording in the current littoral zone threshold that has a 1 NTU threshold for areas not "directly influenced by stream discharge" and a 3 NTU threshold for areas "directly influenced by stream discharge." The threshold does not 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. From Taylor *et al*, 2003.

4. Near-shore water clarity reflects local factors: Water within the near-shore zone reflects on-shore and environmental factors in its immediate vicinity, as it has not yet undergone mixing with cleaner lake waters. Taylor *et al.* (2003) found that areas of decreased water quality were associated with areas of greater on-shore urbanization. We suggest that revised thresholds continue to recognize local factors, such as urbanization, in place of or in addition to areas influenced by stream discharges. Recognition of urban influences separately from pristine areas would provide greater protection for the more pristine areas around the lake. For example, current thresholds permit degradation in water clarity of up to 1 NTU at places like Bliss and Sand Harbor State Parks that would drop clarity from the current 14-18 m down to 3-6 m (Taylor *et al*, 2003). A regional approach, compared to the current stream influenced approach, would be more realistic for the South Lake Tahoe area where it has been difficult to separate pollutant loads from the two-dozen or so urban runoff culverts from the Upper Truckee River. This, however, does not prevent more localized thresholds for specific problem areas (for example, for Bijou Creek). The localization of thresholds could also include a temporal component, permitting exceedance for a greater period of time off-shore from urban areas, but more restrictive near pristine areas. Regardless of form, local factors such as land use, bathymetry, and near-shore currents should be accounted for when developing regional threshold values for different zones around the lake.

5. Relative turbidity thresholds may be difficult to measure: The current California near-shore standard does not permit turbidity to exceed natural levels by more than 10 percent. Although the theoretical accuracy for the turbidimeters used in this study was 2%, those accuracy values were determined under perfect laboratory conditions over a NTU range considerably higher than observed in the near-shore zone. As previously discussed, sample collection, handling, and the optical condition of the turbidity cuvette will impact readings of less than 2 NTU. For the submersible turbidimeter, natural variability during summer background conditions was considerably higher than this threshold, up to ±65% of the mean for 288 turbidity readings taken over a 24-hour period (Figure 21). Therefore, if turbidity continues to be used as part of a revised near-shore threshold, we believe absolute turbidity levels are much more meaningful and defensible than the use of relative (% difference) levels. Due to these issues, the use of a single grab sample for turbidity during background conditions should be avoided. Instead, we suggest the collection of numerous grab samples from the same area, or hundreds of turbidity measurements from a submersible sensor in order to develop a statistical mean and variance.

6. Use indicators that address threshold objectives: The use of turbidity or light transmission as an indicator for near-shore clarity should be dependent on the objectives of the revised threshold. From an on-shore perspective, where the near-shore is treated as an extension of on-shore activities, the use of turbidity as a near-shore zone indicator is consistent with its on-shore/in-stream use. However, the use of turbidity should be limited only to the shallow littoral zone and for purposes where the knowledge of elevated turbidity levels are required. For optimal comparison between sites, we suggest the standardization to a single turbidimeter model. From a lake perspective where the near-shore is considered as an extension of the mid-lake, light transmission is a better indicator because its results appear to

be more consistent with those of Secchi depth as it measures both absorption and scattering processes. As previously discussed, turbidity should be avoided as an indictor if knowledge of background or long-term conditions are desired. Therefore, if monitoring programs like the TRPA's littoral zone monitoring program continues, we suggest moving the sites from the deeper littoral zone into the shallower near-shore zone and the conversion of data collection from turbidity to light transmission.

5.3 Suggested Approach for Near-shore Water Clarity Monitoring

We propose a three-pronged approach for monitoring near-shore clarity: 1) infrequent spatial surveys conducted by boat to assess whole-lakeshore near-shore conditions; 2) the use of inexpensive buoys to assess short-term, inter-seasonal trends, that can be used for compliance monitoring, and; 3) long-term monitoring suited to track trends during both summer and winter.

5.3.1. Spatial Surveys

Spatial surveys, such as those discussed in Section 4.0, are useful for determining the spatial extent of near-shore water clarity during a given day. Therefore, they can be extremely useful in placing the results obtained from fixed-position stations (see section 5.3.2) in the context of local, regional, or lake-wide conditions. Spatial surveys can also be localized in order to gain a better understanding of spatial distribution of degraded water quality from specific point sources. These localized surveys would be conducted only when additional information is needed for scientific (e.g. modeling efforts) and/or management purposes during selected events when the fixed-position buoy stations detect degraded water clarity.

Whole-lakeshore spatial surveys have previously been used to inform seasonal trends in near-shore water clarity. However, they are poorly suited to this task, as they cannot be conducted frequently enough to fully sample the range of temporal variation. The need for these lake-wide spatial surveys will be reduced if fixed-position buoys are installed that can assess both the short- and long-term changes in near-shore water clarity. We propose conducting only two whole-lakeshore surveys per year, during calm conditions in the summer and winter of each year. These remaining surveys would provide lake-wide data to assess the conditions of the near-shore zone through long-term comparisons as well as to identify new problem areas that might develop that could be used to select optimal locations for buoy-based fixed-position stations.

5.3.2. Short-term monitoring

Objectives for short-term monitoring include threshold and compliance monitoring, and for studies on the potential importance of resuspension or the fate of on-shore pollutants as they disperse in the near-shore zone. Depending on location, the buoy approach could be used offshore from designated streams, outfalls, and/or marinas to observe near-shore conditions, or even closer to specific outfalls where on-shore measurements are difficult to obtain. This latter approach, for example, could be used at Bijou Creek and the Upper Truckee River. Bijou Creek is a major urban runoff pathway in the City of South Lake Tahoe, where monitoring is only feasible when lake levels are low. A buoy-based system would eliminate this precondition, although the buoy position may need to be moved in response to lake level changes.

The Upper Truckee River (UTR) delivers the largest sediment and nutrient loads of all the watersheds within the Lake Tahoe basin. The closest routine monitoring station to the lake is just below Highway 50. This site is 2.9 km above the mouth of the river and does not reflect how water quantity and quality changes as the UTR progresses through wetlands, restoration projects, and the confluence with Trout Creek prior to discharging into the lake. The authors have recently installed a submersible turbidity sensor 100 m above the mouth of the UTR. However, slow water velocities at this location have made monitoring difficult due to freezing of the top layers of the river in winter. The use of a buoy-based system at the mouth would alleviate these issues and provide the best indication of its river's impact to the near-shore zone. Furthermore, the use of several buoys arrayed around the mouth of the river and/or along a transect to the east off-shore of Al Tahoe subdivision could be used to better assess how specific sources (e.g. UTR, urban runoff outfalls, resuspension) degrade water clarity. A buoy-based approach may be necessary in South Lake Tahoe, especially in areas that are too shallow to conduct boat-based spatial surveys.

However, turbidity should only be used as a surrogate for near-shore clarity in areas where sufficient degradation is of concern. Based on data presented here and in Taylor *et al.* (2003), this would include most monitoring needed for compliance, as well as the monitoring of discharge to the lake from urban runoff outfalls and of the larger creeks. The use of turbidity has several benefits that make it attractive over light transmission including an integrated wiper on the turbidimeter that eliminates biofouling, and the ability to monitor the bulk water column, foregoing the need for a pumping system. As a result, a turbidity-based system would be smaller, require less power to operate, and be less expensive to build and maintain compared to the light transmissometer-based buoy. In the long run, however, we believe that light transmission should be used whenever possible so that all data collected around the lake would be directly comparable to a long-term dataset based on light transmissivity measurements (Section 5.3.3.).

We estimate that the base model turbidity buoy would cost $6,200 (unburdened dollars) to build. This would include a submersible turbidimeter, data logger, and battery attached to a buoy float that is considerably smaller than the one used in this study. As the turbidimeter accounts for just over half the buoy cost, total costs could be significantly reduced if existing DTS-12 turbidimeters were used. In this base configuration, we anticipate the need to replace battery packs and off-load data every month. The use of larger battery pack and/or a solar panel will increase the time needed between visits. The addition of a solar panel would be $300 and cellular telemetry would add approximately $1700 with 1 year of cellular service. An alternative for telemetry is to use the existing DRI radio telemetry network at the lake. Although initial equipment costs would be about $500 greater per buoy compared to cellular telemetry, the yearly cellular fees of more than $400 would be eliminated. Onboard wind speed and direction (a $2400 upgrade) could be replaced with a pitch and roll sensor that starts at $100 based on the quality of the sensor. Depending on circumstances, a fully submersible system that has no surface expression could also be installed. This system, for example, would utilize a submersible enclosure, such as a Caretta Vault (DRI/Rapid Creek Research), to house the electronics in place of the buoy float. Anticipated cost for a single system is approximately $7000. The costs discussed above will be higher for the first unit due to initial planning and design that must be carried out. Costs would be expected to be slightly lower if several units were built at one time.

For compliance monitoring, these short-term turbidity-based buoys could be deployed for a month or more, as needed, and be repositioned, as needed. Collecting data 24 hours at a time and then repositioning the buoy for another 24 hours would permit monitoring at a greater number of locations. In this fashion, a fleet of 5 buoys could collect data from 25 locations around the lake over a single seven-day period.

5.3.3. Long-term monitoring

When the degradation of water clarity is expected to be low and/or the knowledge of how background conditions change over time are of interest, then an indicator other than turbidity is needed. Light transmissiometers are the instrument of choice as they are easier to calibrate, measure both absorption and scattering, are sensitive to small changes in water clarity, and appear to be more directly relatable to Secchi depth than turbidimeters. Transmissiometers are commonly used by the oceanographic community where they are deployed unattended for several months (with mechanical shutters or chemical systems to protect against biofouling).

As a starting point, we suggest the use of four to six long-term monitoring buoys deployed year-around. The four to six monitoring sites should be selected utilizing results from previous spatial surveys and they should be representative of pristine locations such as off of Rubicon Point and Sand Harbor as well as off urbanized areas. Long-term buoys should be located further off-shore than short-term buoys to minimize resuspension and direct anthropogenic influences, but remain in water from four to ten meters deep.

If year-around deployment is not feasible, an alternative is to conduct discreet deployments in the summer and winter, each of not less than eight weeks in duration. A multi-week window is necessary to quantify prevailing conditions, conduct at least 25 days of light transmission measurements, and provide extra time in case of perturbation by wind or precipitation events.

Based on our experience, we would not expect to see a sizeable cost-savings through limiting deployment lengths as the cost to deploy and maintain the buoy was low relative to equipment and construction costs.. Routine maintenance can be conducted inexpensively from a kayak or canoe while the previously discussed alternative anti-biofouling methods are investigated. Telemetry is necessary so that the progress and the rate of biofouling can be monitored and the number of maintenance trips reduced.

The simplest and most inexpensive long-term buoy would contain only a transmissometer, water temperature, a pitch/roll sensor, solar panel, and telemetry. We estimate the cost of this buoy to range from $9,500 to $15,000 depending on the design and the specific anti-biofouling approaches used. This represents the minimum level required to obtain data for long-term trend analysis. As the protoytope buoy has already been constructed, the costs to redeploy it as the first long-term near-shore water clarity buoy would be minimal.

Depending on specific objectives, other sensors could be added to the buoy to obtain more information. The addition of a turbidimeter would provide a direct comparison with data collected by the short-term buoys as well as providing a secondary water clarity measurement useful in corroborating trends observed in the transmissometer data. The addition of a dissolved organic carbon sensor would address the current ambiguity regarding how compounds such as tannins affect near-shore water clarity. The addition of a chlorophyll fluorometer would provide the ability to detect trends in chlorophyll-containing organisms such as algae and could be used to determine if efforts to decrease nutrient input to the near-shore zone have an impact on the algae community. In order to be relevant to other on-going investigations regarding algae and periphyton dynamics in the near-shore zone, manual water samples would have to be collected every few weeks to convert the relative fluorometer readings to absolute chlorophyll measurements. Furthermore, we suggest that the buoy could also support an artificial substrate that could be used to assess periphyton growth rates.

6.0 SUMMARY AND RECOMMENDATIONS

Over the last seven years, near-shore clarity has been assessed using a "snapshot" approach. Although these surveys provided the near-shore clarity conditions the day they were taken, they have not been suitable for long-term trend analysis because of a lack of data between surveys. To address this shortcoming a near-shore water clarity buoy was constructed and tested in Lake Tahoe between April and September 2008. The main objective of this pilot project was to address several practical questions pertaining to the construction, operation, and maintenance of a near-shore water clarity buoy. Specifically:

1. *What commercial options are available, and how do they compare with a customized buoy constructed specifically for Lake Tahoe's near-shore zone?*

   A customized buoy provided more flexibility than commercial options, including the ability to have specific sensor types, specific sensor models, and an expandable logging and telemetry system. Some sensors, like light transmissometers, are not available in multi-parameter sondes and therefore require customized installation. Although the buoy actually constructed for this project had a greater number of sensors, a comparison of reference systems having similar specifications revealed that the *a la carte* approach and custom fabrication was equivalent to the least expensive commercial option.

2. *What operational procedures and strategies lead to a cost-effective deployment in support of launching additional monitoring buoys?*

   On-board power consumption was not found to be an issue during the summer. However, operation during winter would have required increased battery capacity and/or a reduction in power consumption obtainable through altering the frequency of monitoring and telemetry connections. Routine maintenance and sensor cleaning were easily accomplished by a combination of wading and canoeing. Use of a larger motorboat was sometimes necessary for launching, retrieving, or conducting non-routine maintenance.

3. *How does bio-fouling impact the length of autonomous deployment?*

   Biofouling did not appear to impair turbidity readings as long as the sensor's wiping mechanism was activated prior to each measurement. If the wiping mechanism was not activated, significant biofouling occurred within hours during the summer. Biofouling of the light transmissometer occurred between 7 to 11 days after manual cleaning, and resulted in a predictable linear decrease in light transmission values for an additional two weeks. Therefore, transmissometers deployed on a buoy will require manual cleaning every 2-3 weeks during the summer until acceptable anti-biofouling techniques can be successfully implemented. Biofouling of either sensor was not significant during the colder water temperatures of April and May. Although only simple methods of anti-biofouling were tried during this project, several alternatives exist that could be tested during future deployments.

4. How do in-situ turbidity and light transmittance measurements compare?

These sensors tended to mirror each other and indicated that near-shore clarity was much more variable than previously suggested by snapshot surveys. However, turbidity was not as responsive to small changes in near-shore waters where clarity is not degraded. Over the observed range, turbidity and light transmission had a curvilinear relationship that was difficult to interpret. Turbidity should only be used in situations where one is interested in the degradation of near-shore clarity from particle sources, such as urban runoff or dredging operations. The use of turbidity in this situation is consistent with the concept of the near-shore zone as a localized integrator of on-shore activities.

Light transmission is preferred in situations where high clarity background conditions are of interest. Transmissometers provide stable readings under non-degraded background conditions, are sensitive to small changes in water clarity, and measure both absorption and scattering. Furthermore, the relationship between light transmission and Secchi depth appears to be fairly linear and is therefore more consistent with mid-lake clarity monitoring methods.

5. How well can the buoy assess changes to water-clarity from on-shore activities?

Water clarity measured at the buoy 40 m offshore generally, but not always, reflected elevated turbidity events in the creeks. The mixing with cleaner near-shore water resulted in at least a three-to-one dilution between creek turbidity and that measured at the buoy. Wind and lake currents were observed to direct the turbid water plume away from the buoy on several occasions. During the deployment, turbidity exceeded 5 NTU 4% of the time, exceeded 3 NTU 8% of the time, and exceeded 1 NTU 33% of the time. The most degraded near-shore clarity during snowmelt occurred on May 18 with a turbidity over 15 NTU and a light transmission less than 20%. Although turbidity values in Third Creek were lower than those in Rosewood Creek, near-shore clarity was more responsive to the greater sediment loads delivered by Third Creek and its significantly greater discharge. Near-shore water temperatures reflected inputs of creek water under some occasions, but were also controlled by air temperature and wind-driven mixing with colder waters.

6. How can a buoy system be used to support and monitor near-shore clarity thresholds?

A buoy-based system provides the ability to continuously monitor near-shore water clarity, a deficiency existing in near-shore monitoring programs. A temporally explicit data set provides the opportunity for trend analysis, including approaches such as exceedance curves. Existing near-shore thresholds are static and do not provide exemptions to account for usual or infrequent events – the State of Nevada permits turbidity in the near-shore zone up to 3 NTU, for example. During the 3451 hours the buoy was deployed, the Third Creek watershed exceeded this threshold for 360 hours, or four percent of the time. However, the State of Nevada commonly allows thresholds for conventional pollutants to be exceeded 10 percent of the time before they are considered impaired and included on the 303(d) List (Nevada Division of Environmental Protection, 2009). If this 10% factor were applied to the current threshold, then the Third Creek watershed would have remained in compliance. Therefore, the buoy approach provides a mechanism to implement a more realistic threshold based on actual data that can be localized to different regions of the lake (e.g. pristine versus urbanized, Upper Truckee River versus urban runoff outfalls).

A buoy-based near-shore monitoring system will be able to provide data to basin managers that can be used for future re-calibrations of the water quality model used by the Lake Tahoe TMDL. Programs like RSWMP will benefit from this monitoring system; by supporting or not supporting anticipated lake effects resulting from some RSWMP identified urban runoff sources and impacts. Lastly, data from the buoy system will continue to be used to advance our general scientific understanding of the various factors that affect water quality as they propagate out into the lake.

6.1 Recommendations

Specific recommendations in constructing and operation a near-shore buoy include:

- Buoy stability needs to be measured either through pitch and roll sensors or wind speed (and direction) sensors. Wind speed was important in assessing when the data may have been compromised due to wave action driven by elevated winds. Unexplained spikes and an increase in the variance of instantaneous turbidity readings were correlated with elevated wind events.
- Water temperature needs to be measured. Wind events cause mixing that can affect the types of particles suspended in the water column. Changes in water temperature provided evidence that significant mixing had occurred.
- The location of the buoy should be closer to shore, located in approximately two to four meters of water. Short-term buoys could be located even closer, and with multiple buoys to assess spatial changes, as well.
- Submersible turbidity sensors must include a wiper to eliminate biofouling.

Based on these results and those from Taylor *et al.* (2003), we suggested several issues that need to be addressed when near-shore thresholds are revised:

- The definition of the "near-shore" zone needs to codified and linked to the threshold objectives.
- The monitoring/sampling approach needs to be better defined to remove current ambiguity.

- The phrase "influenced by stream discharges" in the current threshold either needs to be eliminated or better defined.
- Thresholds need to better account for the localized factors that impact near-shore clarity.
- If turbidity thresholds are defined, they should be absolute rather than relative (percent change) due to the insensitivity of turbidimeters.
- Indicators (e.g. turbidity, transmission) should be specified based on threshold objectives.
- Transmissometer data should be considered, also.

A cost-effective approach was suggested for near-shore clarity monitoring comprised of:

- Short-term measurements utilizing relatively inexpensive turbidity-based buoys. The objective would be to address the degradation of near-shore clarity from specific sources during specific events. Compliance monitoring would utilize this approach.
- Long-term measurements utilizing light attenuation measurements from a buoy. The objective would be to assess intra-seasonal changes in near-shore water clarity during background conditions to inform on long-term changes to clarity.
- Seasonal whole-lakeshore spatial surveys that can identify new areas of potential concern.
- Localized lakeshore spatial surveys that would provide context for buoy-based measurements.

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