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Historic Shoreline Change at Lake Tahoe From 1938 to 1998 and its Impact on Sediment and Nutrient Loading

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ABSTRACT

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The goal of this study was to estimate sediment and nutrient loading into Lake Tahoe from shore zone erosion over the last 60 years. We first developed a GIS database of georectified aerial photographs from 1938 to 1998 to track shoreline changes over the last 60 years. The study was augmented by field studies and collection of sediment samples for nutrient analyses. Approximately 80 samples were collected and analyzed for phosphorus and nitrogen content. Using the GIS database, surface areas of both eroding and accreting shoreline segments were calculated. For segments undergoing erosion, the areas were converted to volumetric estimates by estimating their thickness from 1918–1919 U.S. Bureau of Reclamation topographic maps with 1 and 5 foot contour intervals. Approximately 429,000 metric tons (MT) of sediment has been eroded into the lake from shore zone sources since 1938, equating to about 7150 MT per year. Using the nutrient concentrations from this study, approximately 117 MT of phosphorus and 110 MT of nitrogen have also been washed into the lake during the same time period. These values equate to about 2 MT per year of phosphorus and about 1.8 MT per year of nitrogen and are considered to be accurate within a factor of two. Although the nutrient loading values are still relatively small compared to other sources, the amount of sediment washed into the lake each year from shore zone erosion ranks second only to stream loading. Therefore, shore zone erosion is important to the sediment and, to a lesser extent, nutrient budget of Lake Tahoe.

ADDITIONAL INDEX WORDS: *Lake Tahoe, shoreline erosion, phosphorus, nitrogen, nutrient loading.*

INTRODUCTION

Lake Tahoe is known for its beauty and exceptionally clear waters. However, the lake has been decreasing in clarity, as measured by secchi disk, at the rate of about 0.3 m per year since 1968 (JASSBY *et al.,* 1999). The primary causes for this decrease are thought to be the introduction of sediment and nutrients, primarily phosphorus and nitrogen, into the lake. Five sources of these nutrients have been identified that include atmospheric deposition, stream loading, direct runoff, ground water, and shore zone erosion (MURPHY and KNOPP, 2000). Fine sediment is also discharged to the lake from all of these sources except for ground water. The goal of this study is to delineate the mass of sediment and nutrients introduced into Lake Tahoe over the last 60 years from shore zone erosion and to compare these values to the other identified sources.

The shore zone surrounding oligotrophic Lake Tahoe is a very dynamic environment where sediment is eroded, transported, and deposited on an annual basis. Waves in the nearshore area also help to redistribute sediment delivered to the lake by inflowing streams. However, the extent of shoreline erosion, littoral sediment movement, and its effect on the water quality of Lake Tahoe is relatively unknown. Here, we report the results of a detailed study that incorporates georectified air photos into a GIS database, combined with field observations and nutrient sampling, to determine the amount and processes of sediment, phosphorus, and nitrogen input into the lake from shore zone sources. Mass estimates derived from this study are then compared to other sources to determine the relative magnitude of nutrient and sediment input from the shore zone.

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The Physical Setting of Lake Tahoe

The geologic history of the Lake Tahoe basin provides an important context for studying the shore zone system of this high elevation lake. In particular, the Quaternary history of the basin can be directly correlated to the material characteristics, processes, and rates of change found on different lengths of shoreline around the lake. Lake levels have naturally fluctuated at Lake Tahoe, depositing nearshore beach and other lacustrine deposits at higher levels than today. These deposits and their material properties need to be considered when studying shore zone change at Lake Tahoe.

The general geology of the basin is shown in Figure 1 which portrays the distribution of rocks and sediments in the basin. The geologic map shows a variety of different geologic units

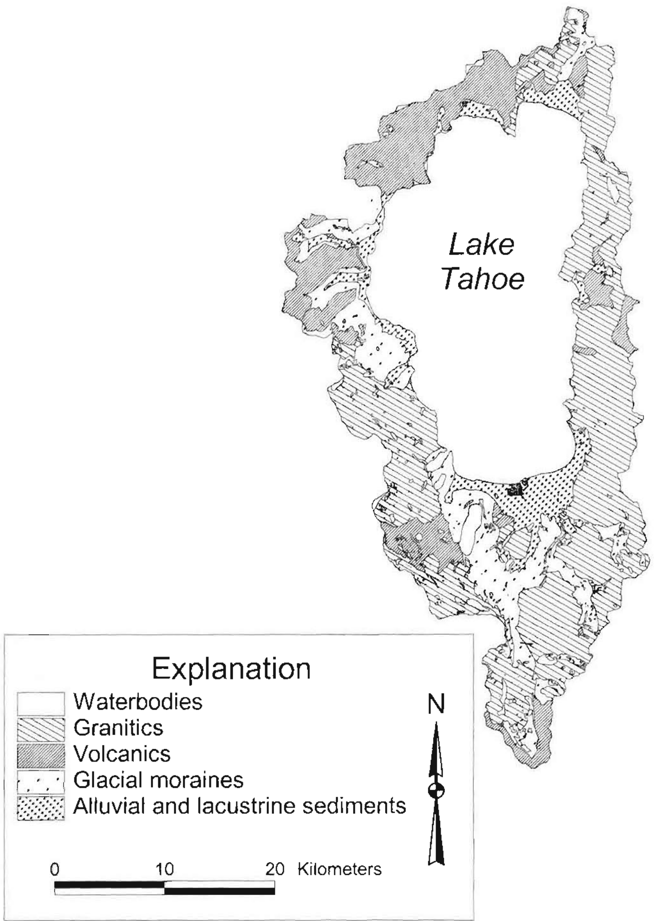

Figure 1. Simplified geologic map of the Lake Tahoe basin showing the distribution of rock types and sediment lithologies. Map adapted from TRPA dataset.

near lake level, each of which probably responds to wave action in different ways. Along the east shore of the lake, granitic bedrock dominates except for a few small pocket beaches such as Sand Harbor, Glenbrook Bay, and Zephyr Cove. The southern shore is largely composed of glacial outwash deposits into which young lake deposits are inset (Figure 1). At the shore, the outwash appears to be graded to levels higher than the current lake level of 1899 m, which means that either there has been significant shore erosion since the outwash was deposited or that the outwash was deposited when lake levels were higher. The west shore of the lake is dominated by glacial moraines, outwash, and lake deposits, although granitic bedrock does crop out near Rubicon Point. The north shore of the lake is largely comprised of volcanic rocks with some granitics around Stateline Point and abundant areas of alluvial and lake deposits near the shore (Figure 1).

Previous Work

Although there is substantial anecdotal evidence for shoreline erosion at Lake Tahoe, few detailed studies quantifying the rates of erosion and the conditions under which it occurred exist. A notable exception is the work of BUDLONG (1971) who studied processes and rates of shore erosion in the area of the then newly built Tahoe Keys development. In this work he documented that rapid erosion occurred immediately east of the Keys East channel because of the interruption of longshore drift from the east by a pair of jetties "protecting" the entrance to the channel. During a single ten-month period (6/01/69–3/31/70), the shoreline retreated up to 16 m over an alongshore distance of about 150 m. In this case, longshore drift was from the east, driven by east winds during the winter months. BUDLONG (1971) also surmised that tree-clearing activities along the shore in this area by Tahoe Keys personnel contributed substantially to the magnitude of shore retreat by eliminating the root-binding effects of the vegetation.

Studies by ORME (1971, 1972) do not specifically quantify shoreline erosion, but they do provide useful information about the shore zone system of Lake Tahoe and factors affecting shoreline erosion. ORME (1971) presents an excellent discussion of the shore zone system at Lake Tahoe, the natural processes occurring along the shore, and how human activities have altered the shore zone system and may continue to do so in the future. A significant contribution of this report is that it served as the basis for constructing a shore zone plan for Lake Tahoe (ORME, 1972) that was officially adopted by the Tahoe Regional Planning Agency (TRPA) in 1976 (TRPA STAFF, 1999). Another significant contribution of

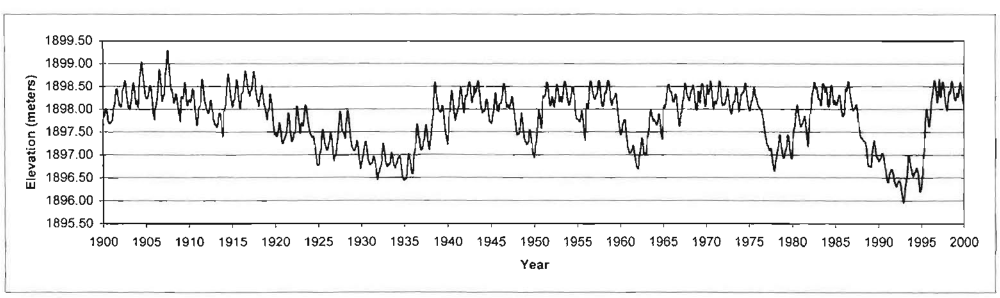

Figure 2. Graph of lake-level fluctuations at Lake Tahoe from 1900 to 2000. In the early part of the 20th century, lake level regularly exceeded the current legal maximum limit of 1898.65 m and likely caused changes to the shore zone. Shore zone erosion likely occurs when the lake is at high levels.

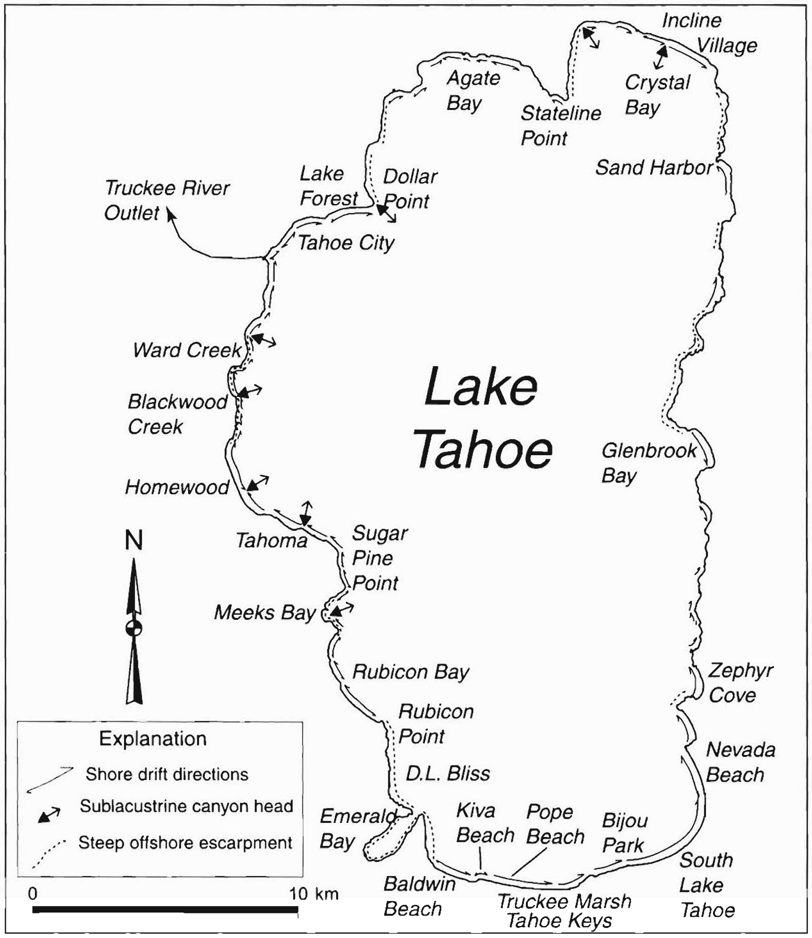

Figure 3. Map of Lake Tahoe showing shore drift directions, locations of sublacustrine canyon heads, steep offshore escarpments, and locations mentioned in text. Lakeward-facing barbs show dominant drift directions and shoreward facing barbs show subordinate directions. Both the sublacustrine canyon heads and steep offshore escarpments are probably barriers to littoral drift. Data used to construct this figure are from ORME (1971), OSBORNE et al. (1985), and observations made during the course of this study.

ORME (1971) is the delineation of currents and littoral drift patterns at the lake. Although the map of shore drift directions is somewhat generalized, it provided a starting place for the refinements of OSBORNE *et al.* (1985) and observations made during the course of the present study (Figure 3).

OSBORNE *et al.* (1985) provide a comprehensive view of the lithologies, grain shapes and size distributions, sediment sources and sinks, and shore drift patterns of the littoral zone of Lake Tahoe. This study represents the synthesis of three masters' theses that include the studies of WALDRON (1982), EDELMAN (1984), and GAYNOR (1984). The major conclusions of these studies, with respect to shore zone erosion, are that: 1) the principal sediment source for the major sand beaches at Lake Tahoe is the shore erosion of young lacustrine and glacio-fluvial outwash; 2) the major sediment source for the gravel and cobble beaches is the erosion of upland areas and possible nearshore erosion of older lakebed deposits, moraines, and volcanic rocks; 3) sand is primarily delivered to the smaller pocket beaches by weathering of local granodiorite bedrock and boulders; 4) the maximum depth of fair-weather sand transport is about 3 m, and about 9 to 10 m under storm conditions; and 5) littoral sand transport is restricted to many small, well-defined drift cells separated by closely-spaced topographic barriers (Figure 3).

REUTER and MILLER (2000) report the results of a preliminary study to determine the mass of sediment and nutrients introduced into the lake from shore zone erosion. In that study, they assumed that 55% of the Tahoe shore was eroding at a given rate and then applied nutrient (P and N) concentrations and a density factor to determine an order-of-magnitude estimate of the mass of sediment, nitrogen, and phosphorus introduced into the lake each year from shore zone erosion. The results of REUTER and MILLER (2000) indicate that approximately 450 to 900 MT (metric tons) of sediment, 0.3 to 0.6 MT of phosphorus, and 0.5 to 1.0 MT of nitrogen are introduced into the lake each year from this source. These values serve as a direct comparison to the estimates derived from the present study.

Table 1. *Information about aerial photographs used in this study.*

Year and Photo	Scale	Agency	Location	Water Surface Elevation
1938				
BPB14-69	1:20,000	USFS	Glenbrook Bay	1898.18 m
BPB14-75	1:20,000	USFS	Zephyr Cove	1898.18 m
1939				1898.18 m
CDJ14-51	1:20,000	USFS	Sunnyside/Tahoe City	1898.18 m
CDJ14-53	1:20,000	USFS	Sunnyside/Ward Creek	1898.18 m
CDJ14-55	1:20,000	USFS	Idlewild/Blackwood Creek	1898.18 m
CDJ14-70	1:20,000	USFS	Meeks Bay/Rubicon Bay	1898.18 m
CDJ14-72	1:20,000	USFS	Sugar Pine Point	1898.18 m
CDJ14-72revised	1:20,000	USFS	Sugar Pine Point	1898.18 m
CDJ14-74	1:20,000	USFS	Homewood/Sugar Pine Point	1898.18 m
CDJ14-79	1:20,000	USFS	Tahoe City	1898.18 m
CDJ15-52	1:20,000	USFS	Dollar Point	1898.18 m
CDJ15-54	1:20,000	USFS	Carnelian Bay	1898.18 m
CDJ15-56	1:20,000	USFS	Carnelian Bay/Agate Tay	1898.18 m
CDJ16-44	1:20,000	USFS	Agate Bay/Stateline Point	1898.18 m
CDJ16-48	1:20,000	USFS	Stateline Point/Crystal Bay	1898.18 m
CDJ16-112	1:20,000	USFS	Crystal Bay/Incline Village	1898.18 m
CDJ17-15	1:20,000	USFS	Sand Harbor	1898.18 m
1940				
CNL23-2	1:20,000	USFS	Rubicon Bay	1898.36 m
CNL23-3	1:20,000	USFS	Rubicon Point	1898.36 m
CNL23-4	1:20,000	USFS	Emerald Bay	1898.36 m
CNL23-5	1:20,000	USFS	Emerald Bay	1898.36 m
CNL23-68	1:20,000	USFS	Baldwin Beach	1898.36 m
CNL23-74	1:20,000	USFS	Camp Richardson/Truckee Marsh	1898.36 m
CNL23-137	1:20,000	USFS	Truckee Marsh/South Lake Tahoe	1898.36 m
CNL23-140	1:20,000	USFS	Nevada Beach/Marla Bay	1898.36 m
CNL23-141	1:20,000	USFS	Nevada Beach	1898.36 m
1952				
ABM3k-63	1:20,000	USFS	Carnelian Bay/Agate Bay	1898.52 m
ABM3k-103	1:20,000	USFS	Agate Bay/Stateline Point	1898.52 m
DSC6k-121	1:20,000	USFS	Sugar Pine Point	1898.55 m
DSC6k-177	1:20,000	USFS	South Lake Tahoe	1898.55 m
DSC6k-178	1:20,000	USFS	South Lake Tahoe/Nevada Beach	1898.55 m
1963				
EME-8-69	1:20,000	DRI	Bijou Park	1897.86 m
EME-8-70	1:20,000	DRI	Bijou Park/Edgewood	1897.86 m
EME-8-71	1:20,000	DRI	Edgewood/Nevada Beach	1897.86 m
1992				
DOQ	1:12,000	USGS	Entire basin	1896.25 m
1995				
TAH-12N-170	1:8,000	TRPA	Dollar Point	1897.95 m
TAH-11N-139	1:8,000	TRPA	Lake Forest	1897.95 m
TAH-10N-138	1:8,000	TRPA	Lake Forest	1897.95 m
TAH-9N-109	1:8,000	TRPA	Tahoe City	1897.95 m
TAH-8N-220	1:8,000	TRPA	Tahoe City/Tahoe Tavern	1897.95 m
TAH-8N-219	1:8,000	TRPA	Sunnyside	1897.95 m
TAH-8N-218	1:8,000	TRPA	Sunnyside	1897.95 m
TAH-8N-217	1:8,000	TRPA	Sunnyside/Ward Creek	1897.95 m
TAH-8N-215	1:8,000	TRPA	Ward Creek/Kaspian	1897.95 m
TAH-8N-213	1:8,000	TRPA	Kaspian/Blackwood Creek	1897.95 m
TAH-8N-211	1:8,000	TRPA	Tahoe Pines/Homewood	1897.95 m
TAH-8N-209	1:8,000	TRPA	Homewood	1897.95 m
TAH-9S-125	1:8,000	TRPA	Chambers Lodge//Tahoma	1897.95 m
TAH-10S-122	1:8,000	TRPA	Tahoma/Sugar Pine Point	1897.95 m
TAH-11S-54	1:8,000	TRPA	Sugar Pine Point	1897.95 m
TAH-11S-56	1:8,000	TRPA	Meeks Bay	1897.95 m
TAH-11S-58	1:8,000	TRPA	Rubicon Bay	1897.95 m
TAH-11S-60	1:8,000	TRPA	Rubicon Bay	1897.95 m
TAH-12s-47	1:8,000	TRPA	Emerald Bay	1897.95 m
TAH-12s-49	1:8,000	TRPA	Emerald Point	1897.95 m
TAH-12s-50	1:8,000	TRPA	D.L. Bliss State Park	1897.95 m
TAH-13s-2	1:8,000	TRPA	Emerald Point/Eagle Point	1897.95 m
TAH-13s-4	1:8,000	TRPA	Baldwin Beach-west side	1897.95 m

Table 1. *Continued.*

Year and Photo	Scale	Agency	Location	Water Surface Elevation
TAH-14s-209	1:8,000	TRPA	Baldwin Beach	1897.96 m
TAH-15s-154	1:8,000	TRPA	Baldwin Beach/Kiva Beach	1897.96 m
TAH-16s-153	1:8,000	TRPA	Pope Beach	1897.96 m
TAH-17s-72	1:8,000	TRPA	Pope Beach/Tahoe Keys	1897.96 m
TAH-18s-71	1:8,000	TRPA	Tahoe Keys/Upper Truckee River	1897.96 m
TAH-19s-207	1:8,000	TRPA	Truckee Marsh/South Lake Tahoe	1897.96 m
TAH-20s-205	1:8,000	TRPA	S. Lake Tahoe	1897.96 m
TAH-21s-144	1:8,000	TRPA	Nevada Beach	1897.96 m
TAH-21s-146	1:8,000	TRPA	Stateline/Edgewood Golf Course	1897.96 m
TAH-21s-148	1:8,000	TRPA	South Lake Tahoe	1897.96 m
1998				
DOQ	1:12,000	USGS	Entire basin	1898.50 m

METHODS

This study combined a GIS analysis using georectified historical aerial photographs with fieldwork consisting of confirming the air photo interpretations, documenting physical conditions along the shore, and collecting samples for nutrient analyses. Each of these efforts is outlined in the following sections.

Aerial Photograph Acquisition

Historical aerial photographs and mosaicked digital orthophotographic quadrangles (DOQs) spanning 60 years were acquired from the U.S. Geological Survey (USGS), U.S. Forest Service (USFS), and Tahoe Regional Planning Agency (TRPA). Table 1 indicates the dates the photographs were taken, the geographic location, photographic scale, and re-

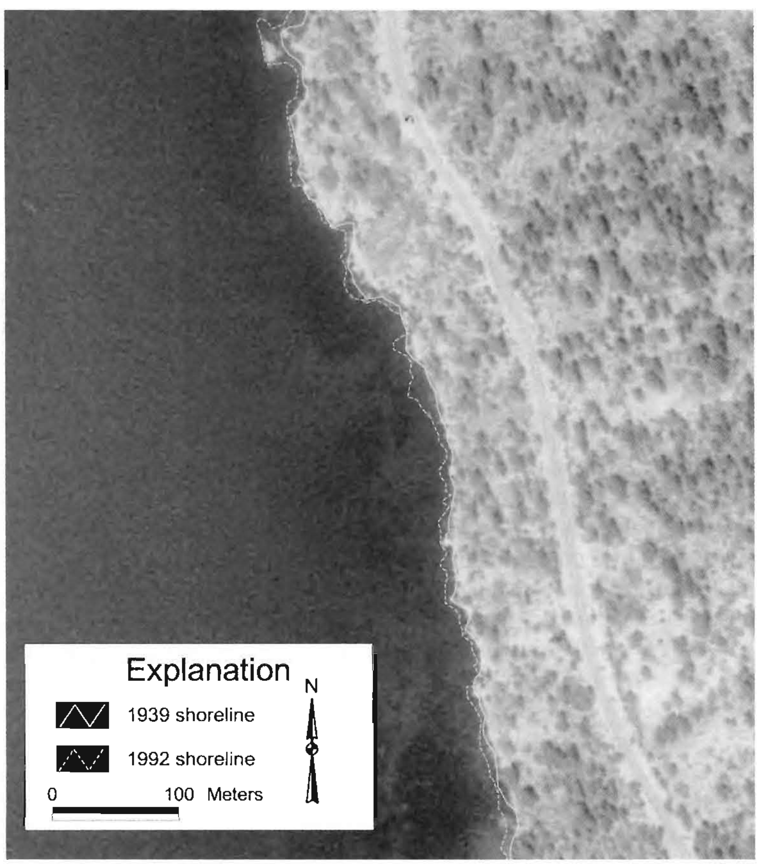

Figure 4. Shorelines from 1939 and 1992 superimposed on a 1998 image of the east shore of Lake Tahoe north of Sand Harbor. This section of the shore has apparently been stable over the last 60 years. In 1998 lake level was at 1898.5 m, in 1939 at 1898.0 m, and in 1992 lake level was at 1896.25 m. Note how the superimposed shorelines essentially form contour lines on this stable bedrock shore, with their spacing dependent on local slope.

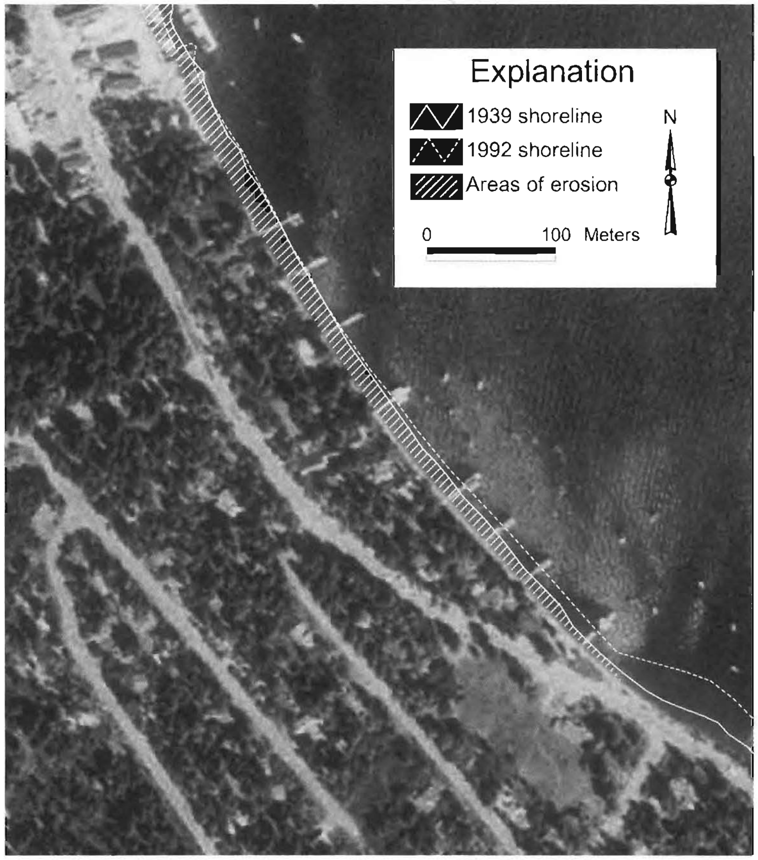

Figure 5. Shorelines from 1939 and 1992 superimposed on a 1998 image of the Homewood area. In this case, erosion is indicated because the 1939 shoreline (1898.0 m) is coincident with the 1992 shoreline (1896.25 m) along part of its length.

sponsible agency. Photographic scales ranged from 1:8,000 to 1:20,000. A scale of 1:20,000 is considered the smallest usable for shoreline mapping (MOORE, 2000). The color and black and white photographic prints were scanned and digitized using a flat bed scanner. Scan rates varied between 300 dots per inch (dpi) and 600 dpi, depending on the scale and quality of the photographic prints. Using the scan rate, print dimensions, and digital image dimensions (in picture elements or pixels), the nominal ground resolutions of the aerial photographs were calculated; for the 1:20,000 scale prints, the ground resolution was 2 meters, for the 1:8,000 scale photographs from 1995, the ground resolution was 1 meter. The ground resolution for the two DOQs was also one meter.

Image Processing Methods

The multi-date, multi-scale aerial photographs of the Lake Tahoe basin were rectified to the one meter DOQs in a standard polynomial based image-to-map rectification process using ENVI image processing software. Initial attempts to orthorectify the historical photographs proved unsuccessful, as the camera parameters required to build interior orientation were not available for the older photographs (fiducial marks and focal length are required to establish the relationship between the camera model, the aerial photos, Ground Control Points (GCPs), and a Digital Elevation Model (DEM) (THIELER and DANFORTH, 1994). We also attempted to rectify the aerial photographs using a Delaunay triangulation warping method, which fits triangles to irregularly spaced GCPs and interpolates new values. This method was unsuccessful, however, because it required control points on all sides of the feature of interest, in this case the shoreline, and selecting control points in the lake was not possible.

The image-to-map rectification process involved the selection of ground control points common to both the scanned aerial photography and the USGS DOQs. Several rule bases were developed for the point selection process in order to minimize potential errors that can accumulate and contribute to inaccurate shoreline interpretation results. Favorable control points selected included anthropogenic and natural features that were distinct and common to both data sets (road intersections, buildings, trees, and near shore boulders). Care was taken to be cognizant of shadowing effects in the photography and DOQs when selecting GCPs, as these sometimes distorted the precise location of a feature. To avoid the introduction of spatial errors due to lens distortion and camera tilt, control points were preferentially selected in the center of each unrectified photograph. Along steep shores, control points were only selected near the shore zone to avoid errors related to

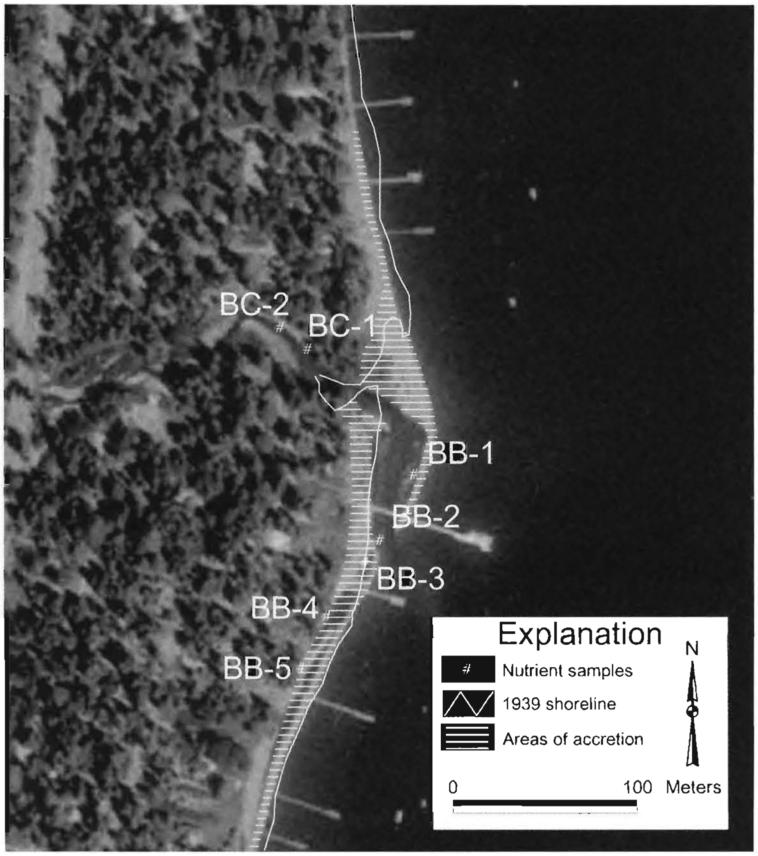

Figure 6. The shoreline from 1939 (1898.0 m) superimposed on a 1998 image (lake level = 1898.5 m) of the mouth of Blackwood Creek. Note that the shore has built lakeward even though lake level in 1939 was about one half meter below that in 1998.

topographic relief displacement. Selecting control points at elevations significantly higher than lake level introduces significant errors into the rectification process. This was evident when selecting control points on photos taken over the Emerald Bay region; greater errors were observed for points selected at higher elevations along Highway 89 than those located near the shore.

A minimum of ten GCPs were selected for each scanned photograph. Older photographs presented greater challenges in the process, as there were often few common features found between the historical aerial photography and the more recent DOQs. The Root Mean Square Error (RMSE), the average error that describes the difference between the predicted and observed control point locations in an input image relative to the DOQs, was between 2.0 to 2.25 image picture elements (pixels or cells) for each of the rectified photographs. That is, for each of the photo images rectified, the RMSE for all control points in that image was approximately 2.1 pixels. In ground distance, a RMSE of 1.0 for the 1:20,000 scale photographs was two meters. For the 1:8,000 scale 1995 photographs, the RMSE ground distance was one meter per image pixel. Several iterations were often required in the GCP selection process to arrive at a satisfactory RMS level for all the photographs. Once the GCPs were selected, a first-degree polynomial warping algorithm was implemented, with a nearest neighbor resampling method. The uncorrected images were warped and resampled to the DOQs, cast into a UTM coordinate system (Zone 10) based on the NAD27 datum.

Based on the calculated RMSE observed in the rectification process, the observed spatial error in ground distance over an entire photograph was ± four meters (RMSE of 2.1). In actuality, however, that error term is much less for the feature of interest, the shore zone, where the error is closer to ± two meters for the 1:20,000 scale photography, and even less (± one meter) for the 1995 imagery (RMSE of 1.0 in both cases). This estimate is based on an examination of the errors for individual control points along the immediate shore zone, where the RMSE was sometimes found to be below 1.0. This occurred because most of the control points in each image were selected near the shorezone, ensuring a better polynomial fit of the rectification model in that portion of the image. The RMSE for the control points selected further away from the shorezone were located on slopes, where the change in elevation contributed to the distortion found in the image, and thus increased the overall RMSE for the entire photo image. These numbers all exceed the National Mapping Ac-

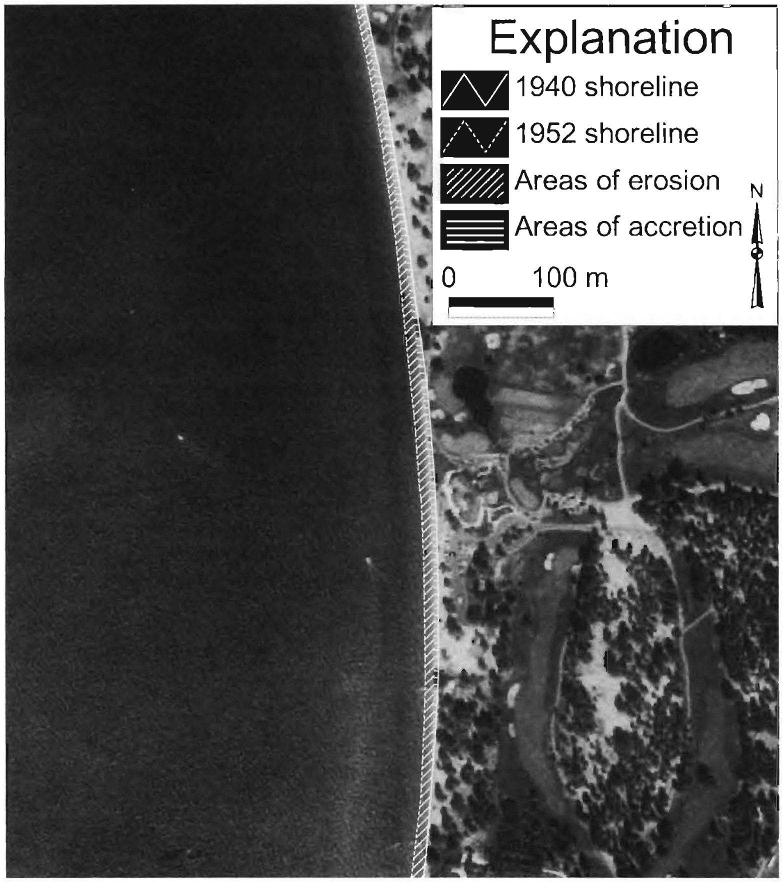

Figure 7. Shorelines from 1940 (1898.36 m) and 1952 (1896.25 m) superimposed on a 1998 image (lake level = 1898.5 m) from Edgewood Golf Course along the southeast shore of Lake Tahoe. In this case, there was accretion from 1940 to 1952 and then erosion from 1952 to 1998.

curacy Standards defined by the USGS in 1941 (10.2 meters for 1:20,000 scale data; 8.0 meters for 1:8,000 scale).

Delineating the Shoreline

The first challenge in mapping the former position of the shoreline is to define a consistent and obvious shoreline feature, one that can be recognized on multiple generations of aerial photographs of varying quality. The line between wet sediment and dry sediment is the most commonly used proxy for shoreline position because it approximates the mean high water line (DOLAN *et al.,* 1980; MOORE, 2000). However, most studies using this proxy have been conducted on open marine coasts, where the lateral position of the high water line varies considerably depending on tidal range, beach slope, wave energy, and other parameters (DOLAN *et al.,* 1980). Fortunately, Lake Tahoe does not have tides and is not affected by large waves that would affect the shoreline position shown on an air photo. Therefore, the linear interface between the water and shore was selected to represent the shoreline position in this study. Other markers, such as debris lines, crests of barriers, and bases of wave cut scarps may be visible in the field but are often difficult to discern on aerial photographs and may have different relationships to still water level. In contrast, the shore-water interface is readily discernible on all photographs used in this study, but presents other challenges.

The lateral position of the shore-water interface through time is affected by a number of parameters including wave runup, wave setup, seiches, human activities, variations in lake level, and shoreline erosion/accretion. Lateral changes in the position of the shoreline due to wave runup, wave setup, and seiches are not significant in this study because none of the photos appear to have been acquired when strong winds were affecting the lake. Human activities, such as infilling portions of the lakeshore or constructing seawalls or other revetments, are commonly discernable from aerial photographs and represent permanent alterations.

After georectifying the air photos and importing them into a GIS database (ESRI ArcView 3.2), the shore-water interface was mapped at a scale of 1:3,000 as a separate theme for each age of photo. At this scale, one millimeter equals three meters on the ground, which is close to the resolution of the georectification process. Where adjacent photographs of the same age and water level overlapped, the photo that most closely matched the two orthophotoquad bases (1992 and 1998) was used to map the shoreline. The "goodness of fit" was deter-

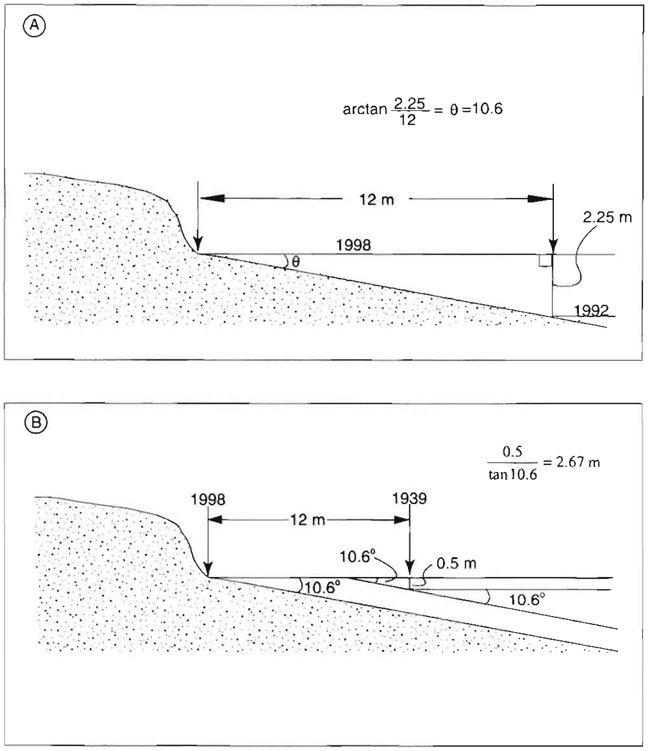

Figure 8. Schematic diagram that shows an example of how the amount of shoreline erosion is calculated from air photos that reflect different lake levels. Figure 8a shows how the overall slope is calculated from the 1992 and 1998 DOQ's. Figure 8b shows how this slope is used to estimate where the 1939 shoreline would project if lake level was the same as when the 1998 image was taken. In this case, about 9 m of apparent erosion has occurred because, given a slope of 10.6 degrees, the projected 1939 lake level would only move up the beach about 2.67 m but the 1998 shoreline is 12 m away. The approximately 9 m of difference between these figures represents erosion.

mined by how closely common ground features, such as roads, buildings, boulders, and other features, matched the base images for each of the rectified photos. Almost the entire shoreline was mapped from 1938, 1939, and 1940 images (Table 1). Additional areas of the shoreline were also mapped from 1952, 1963, and 1995 images and 1992 and 1998 DOQs.

Over the last 60 years, the most significant factor affecting the lateral position of the shore-water interface is lake-level fluctuations, which cause this marker to migrate tens of meters with relatively minor changes in lake level. This effect, of course, depends on the slope of the shore, which is particularly pronounced on the gently sloping offshore areas at the south end of the lake and near the outlet. In areas where the shore is relatively steep, as along much of the east shore, this effect is relatively minor. Over the last 100 years, the surface of Lake Tahoe has fluctuated from an historic high of 1899.29 m in July 1907 to an historic low of 1895.96 m on November 30, 1992 (Figure 2). These fluctuations are largely controlled by the rate of inflow into the basin relative to the volume of water released by the dam, which only controls the upper two meters or so of lake level, and the volume of water evaporated from the surface of the lake. Since 1935, when the Truckee River Agreement went into effect, the upper legal limit of Lake Tahoe has been defined as 1898.65 m. Table 1 presents lake levels measured for particular days that aerial photographs were flown from 1938 to 1998. Surface water elevations range from a low of 1896.25 m on August 26, 1992 to a high of 1898.55 m on August 14, 1952, a difference of 2.3 m. Over the last 10 years, Lake Tahoe has undergone the most dramatic lake-level changes in recorded history, fluctuating between its historic lowstand (1895.96 m) in late 1992 to a level about 9 cm above the legal limit of 1898.65 in early January, 1997. The net result of lake-level fluctuations is an apparent migration of the shoreline.

Superimposed on the yearly lake-level fluctuations are real changes to the Lake Tahoe shoreline, in terms of both accretion and erosion. The challenge is to devise a methodology using multiple generations of aerial photographs taken on days with different lake levels to discern changes to the high shoreline position. Although most shoreline change likely happens when the lake is at or near its legal limit, the photographs were taken over a range of lake levels. Therefore, the following technique was developed to estimate the position of the shore through time by correcting for different water levels.

This technique is based on the assumption that on a stable, sloping shore the shore-water interface will migrate laterally in a predictable way depending on water level. This is essentially a process of inundation, but may not perfectly apply to shores composed of unconsolidated sediment where subsequent wave action can regrade the shoreline causing a shift in the shoreline planform. At Lake Tahoe, this assumption is reasonably valid but may not apply to other bodies of water. Figure 4 portrays the relationship between different lake levels impinging on a stable shoreline. In this image, all of the projected shorelines are essentially parallel and the distance between them is proportional to the difference in lake levels and the slope of the shore. The addition or subtraction of sediment along the shore is reflected in an apparent change in the shoreline position for a given water level with respect to the other projected shorelines.

Four different situations were encountered when mapping the shoreline from 1938 to the present. The most common situation is represented by Figure 4 where there has been no change and the shorelines plot primarily in a regular and parallel manner. The three other conditions are erosion, accretion, and oscillation and are represented by Figures 5, 6, and 7, respectively. In each of these situations, the nearshore slope and simple trigonometry is used to estimate the amount of shoreline change that has occurred. In this study, we assume that the shape of the nearshore profile has remained relatively constant through time although it may have shifted in space (HANDS, 1983).

The shoreline positions observed in the 1940 and 1952 photographs should plot in nearly identical positions to the 1998 shoreline because water level was nearly identical (Table 1). If the 1940 or 1952 shorelines plot lakeward of the 1998 shoreline, then erosion must have occurred. If the 1940 or 1952 shorelines plot landward of the 1998 shoreline, then that particular location along the shore must have accreted.

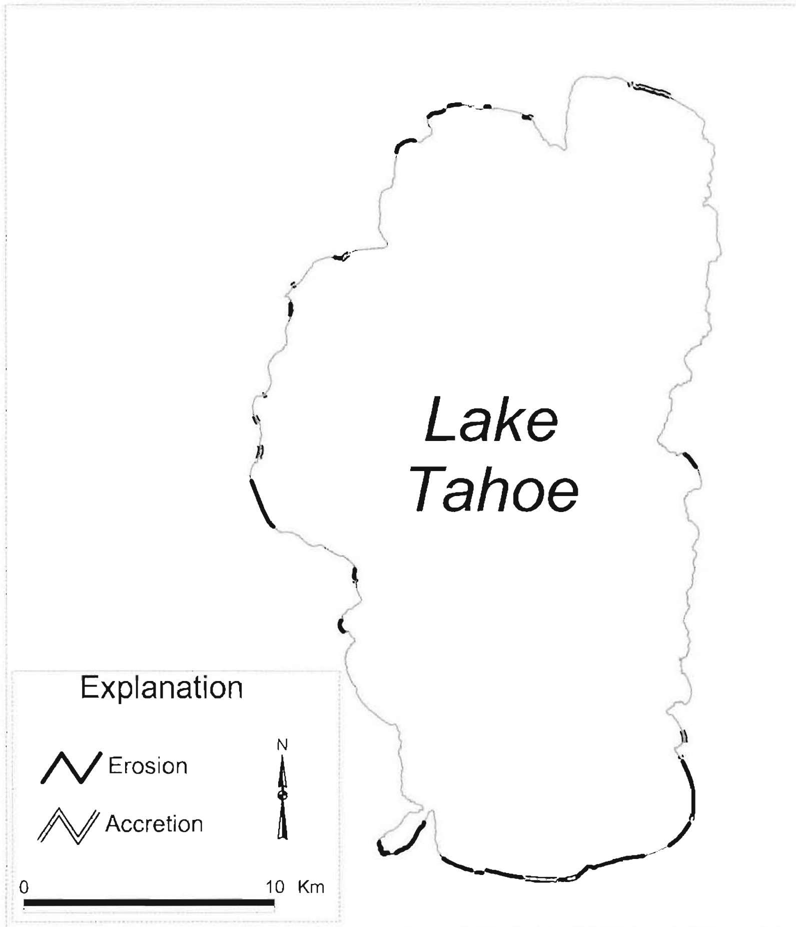

Figure 9. Map of Lake Tahoe that shows areas that have undergone erosion and accretion since 1938. Most of the areas undergoing erosion are located in embayments backed by unconsolidated lacustrine and/or alluvial deposits. See Figure 1 for comparison.

This also holds true for the lower water level 1938 and 1939 shorelines; if they plot landward of the 1998 shoreline, then shoreline accretion has taken place (Figure 6). However, when the 1938 and 1939 shorelines plot lakeward of the 1998 shoreline, change may still have occurred but is more difficult to document.

The first step in documenting change using the 1938 and 1939 photos is to calculate the nearshore slope at a particular location. Because we have no historical profile data we used the average slope at a location as a proxy for the profile. The average slope is measured by using the 1992 and 1998 images combined with simple trigonometry (Figure 8a). Assuming a constant slope through time, the 1938 or 1939 shorelines can be projected to reflect a lake level equal to that of 1998 (Figure 8b). In other words, 0.5 m of water is added to the 1939 lake level to estimate where that shoreline would plot if the water level were the same as in 1998. If the 1998 shoreline plots significantly landward of the projected 1939 shoreline, then erosion must have occurred. When calculating volumes of eroded sediment, we only considered the volume of eroded subaerial bluff or beach material.

The fourth situation is represented by shoreline positions that have apparently oscillated through time (Figure 7). In this case, comparing the 1940 shoreline position to that of 1998 indicates that accretion has taken place. However, comparing the 1952 shoreline position with 1998 indicates that the shore has eroded. We interpret these changing shoreline positions through time to represent a dynamic situation where from 1940 to 1952 the shoreline was accreting, but from 1952 to 1998 the shoreline eroded back to near the 1940 position. Therefore, although both erosion and accretion have taken place along this shore over the last 60 years, shore zone processes have resulted in net erosion.

Nutrient Sampling and Analysis

Grab samples of shore zone sediments were taken at multiple locations around the lake to analyze nutrient content (Table 2). Grain size was characterized in the field and compared to analyses performed by OSBORNE *et al.* (1985). Typically, samples for this study were taken from the beach, sediments exposed in wave-cut scarps, and in the backshore area. Grab samples were collected from a depth of about 10 cm on beaches and backshore areas, but at depths of up to 3 m from exposed sediments in wave-cut exposures.

Samples were analyzed for total phosphorus and total Kjeldahl nitrogen at the Division of Hydrological Sciences analytical chemistry laboratory at the Desert Research Institute. Total phosphorus and total Kjeldahl nitrogen analytical procedures were used as a conservative measure of nutrient content because it is not likely that additional nutrients could be extracted from the samples by lake water. Therefore, the nutrient content of the samples should be thought of as a maximum estimate and are directly comparable to nutrient flux rates reported by REUTER and MILLER (2000). Additionally, several analyses were performed on 1:1 soil-water extracts.

RESULTS

Both erosion and accretion have occurred along the shore of Lake Tahoe over the last 60 years. Figure 9 presents a map delineating the areas where change has occurred. Twenty-two areas along the shore have undergone erosion, the largest of which encompasses an area of about 32,000 m^2 (Table 3). The total surface area of the eroded shore zone equates to about 190,600 m^2. By contrast, twenty areas have undergone accretion, comprising a total area of about 56,500 m^2. In order to calculate the volume of sediment and nutrients introduced into the lake by erosion, the thickness of each area had to be estimated. Large-scale (1:2400) U.S. Bureau of Reclamation topographic maps with one and five foot contours dating from 1918 and 1919 were used to calculate the thickness of discrete sediment packages eroded into the lake. These packages typically were one to two meters thick but ranged up to six meters thick along parts of the south shore of Tahoe. The total volume of the eroded shore zone material equates to about 286,000 m^3 (Table 3). To convert this volume of sediment into a mass, a density of 1.5 g/cm^3 was assumed because this value represents typical soil densities found in the Lake Tahoe basin (RODGERS, 1974). From Table 3, the total mass of sediment eroded into Lake Tahoe from the shore zone since 1938 amounts to about 429,000,000 kilograms or approximately 429,000 metric tons. If averaged over the sixty year study period, about 7150 metric tons of sediment have been washed into the lake each year from shore zone erosion. The areas that have undergone accretion are not included as sediment sinks in this budget.

The phosphorus and nitrogen content of the sampled sediment have wide ranges, but generally the sediment around the lake is higher in phosphorus than nitrogen (Table 2). A notable exception is at Lake Forest (samples LF-1 through LF-6; Table 2) where nitrogen is unusually high. However, samples LF-3 through LF-6 were collected from a single vertical exposure through a gravelly silt or clay loam. Samples GB-5 and GB-6 from Glenbrook are also relatively high in nutrients, but these came from a seep emanating from a wave-cut scarp below a large grassy area. Several stream samples were also collected adjacent to their respective beaches and include samples from Third Creek at Incline Village (SB-7 and SB-8) and from Blackwood Creek (BC-1 and BC-2) along the west shore. Both of these drainages are supplying sediment that is apparently much higher in nitrogen than the beaches upon which they divulge.

Although all sediment samples were analyzed for total phosphorus and nitrogen by digestion procedures, several duplicate samples were also analyzed with a 1:1 soil-water extract procedure. These samples include UT-3 Soil ext., LF-6 Soil ext., SB-11 Soil ext., KB-3 Soil ext., and NV-4 Soil ext. (Table 2). All of the samples analyzed by the soil water extract procedure show similar values of nutrients, but yield nutrient concentrations at least an order of magnitude less than their duplicates where the sediment was first digested and then analyzed.

Because all tasks in this study proceeded concurrently, not all locations that have experienced erosion were sampled for nutrient content. Where sample locations coincide with areas of erosion, average nutrient concentrations were used to calculate the mass of phosphorus and nitrogen contained within a particular package of sediment. Along eroded reaches of shore where no sample data exists, the average nutrient concentrations of similar geologic materials were used.

In terms of nutrient loading, a total of about 117 metric tons of phosphorus and 110 metric tons of nitrogen have been introduced into the lake during the period 1938 to 1998 from shoreline erosion (Table 3). If averaged over the 60 years, these volumes equate to about 2 metric tons per year of phosphorus and about 1.8 metric tons per year of nitrogen.

Sources of Error

Several sources of error could affect the estimates of the mass of sediment and nutrients delivered into Lake Tahoe from shore zone erosion. These sources include errors introduced by data sources, measurement methods, analytical uncertainty, and natural variability in the concentration of nutrients in shore zone sediments. Each of these sources will be discussed in turn in an attempt to quantify the precision of the estimates.

The first source of error is associated with the area and volumetric calculations of the amount of shore zone erosion. The precision of the aerial photograph rectification procedure is about ± 2 m. Using this error, the total eroded shore zone area could be as low 112,000 m^2 or as high as 272,600 m^2, a difference of about $\pm 43\%$ from the observed value of 190,600 m^2. Converting this area to a volume required the interpretation of one and five foot contour intervals. We assume that thickness values are within 25% of the true value.

The value used for the density of eroded sediment was 1.5 g/cm^3 because this is near the average density for soils exposed near the shoreline of Lake Tahoe (RODGERS, 1974). The standard deviation for the density of the soils analyzed by RODGERS (1974) is about $\pm 13\%$.

The error associated with the nutrient concentrations may stem from analytical error as well as natural variability. Because most of the shore zone sediment eroded at Lake Tahoe is composed of alluvial and lacustrine deposits (Figure 1), we use the standard deviation of phosphorus and nitrogen concentrations associated with these deposits, which are 68% and 95%, respectively.

Table 2. *Nutrient sample data. All location data is referenced to UTM Zone 10, NAD 27.*

Sample Name	Sample Date	Easting	Northing	TPO4 (mgP/kg)	TKN (mgN/kg)
SB-1	17-May-00	763682	4347495	212	18
SB-2	17-May-00	763681	4347521	316	229
SB-3	17-May-00	763637	4347520	192	22
SB-4	17-May-00	763610	4347540	264	25
SB-5	17-May-00	763580	4347562	656	31
SB-6	17-May-00	763575	4347559	224	18
SB-7	17-May-00	763598	4347635	452	338
SB-8	17-May-00	763619	4347653	444	108
SB-9	17-May-00	763544	4347581	172	22
SB-10	17-May-00	763499	4347606	740	37
SB-11	17-May-00	763474	4347624	756	97
SB-12	17-May-00	763449	4347637	1800	16
SB-13	17-May-00	763396	4347657	960	37
SB-14	17-May-00	763409	4347669	572	171
SB-15	17-May-00	763450	4347671	408	216
KB-1	17-May-00	757082	4346895	4	33
KB-2	17-May-00	757021	4346930	92	76
KB-3	17-May-00	756940	4346962	55	35
KB-4	17-May-00	756920	4346986	40	67
KB-5	17-May-00	756882	4346986	47	32
KB-6	17-May-00	756832	4347008	54	39
KB-7	17-May-00	756788	4347005	100	18
KB-8	17-May-00	756763	4347011	58	15
KB-9	17-May-00	756751	4347038	16	67
KB-10	17-May-00	756687	4347046	55	39
SPP-1	18-May-00	749888	4326641	320	20
SPP-2	18-May-00	749927	4326294	168	20
SPP-3	18-May-00	749947	4326252	148	274
SPP-4	18-May-00	749955	4326256	328	218
SPP-5	18-May-00	749955	4326256	272	32
SPP-6	18-May-00	749998	4326140	784	926
SPP-7	18-May-00	750030	4326073	79	4330
SPP-8	18-May-00	750026	4326079	584	628
SPP-9A	4-Aug-00	749805	4326977	299	297
SPP-9B	4-Aug-00	749805	4326977	205	219
SPP-9C	4-Aug-00	749805	4326977	172	83
SPP-9D	4-Aug-00	749805	4326977	477	50
SPP-10A	4-Aug-00	749809	4327071	484	167
SPP-10B	4-Aug-00	749809	4327071	445	62
SPP-10C	4-Aug-00	749809	4327071	171	203
BB-1	18-May-00	745806	4332280	648	58
BB-2	18-May-00	745784	4332237	576	41
BB-3	18-May-00	745774	4332222	740	56
BB-4	18-May-00	745749	4332187	624	51
BB-5	18-May-00	745732	4332153	636	67
LF-1	17-May-00	749414	4340749	729	1320
LF-2	17-May-00	749342	4340675	328	61
LF-3	17-May-00	749291	4340628	1410	1950
LF-4	17-May-00	749197	4340634	388	1360
LF-5	17-May-00	749197	4340634	542	1520
LF-6	17-May-00	749197	4340634	254	1360
NV-1	3-May-00	763884	4318954	80	18
NV-2	3-May-00	763904	4318962	88	112
NV-3	3-May-00	763930	4318969	168	136
NV-4	3-May-00	763962	4318989	172	321
NV-5	3-May-00	763995	4318992	164	363
NV-6	3-May-00	764034	4319003	128	265
CL-1	18-May-00	747392	4328651	380	42
CL-2	18-May-00	747427	4328625	416	43
CL-3	18-May-00	747454	4328595	324	145
TV-1	17-May-00	754976	4347261	72	50
TV-2	17-May-00	754925	4347267	64	486
UT-1	17-May-00	759883	4314321	132	41
UT-2	17-May-00	759900	4314321	192	31
UT-3	17-May-00	759910	4314321	130	35

Table 2. *Continued.*

Sample Name	Sample Date	Easting	Northing	TPO4 (mgP/kg)	TKN (mgN/kg)
BC-1	18-May-00	745737	4332362	467	185
BC-2	18-May-00	745719	4332376	506	139
ZC-1	6-Jun-00	764212	4322331	84	24
ZC-2	6-Jun-00	764224	4322331	552	315
ZC-3	6-Jun-00	764250	4322254	122	11
ZC-4	6-Jun-00	764268	4322250	285	258
ZC-5	6-Jun-00	764281	4322180	90	12
ZC-6	6-Jun-00	764293	4322169	330	199
ZC-7	6-Jun-00	764298	4322118	62	11
ZC-8	6-Jun-00	764308	4322120	114	240
GB-1	6-Jun-00	764768	4330898	196	36
GB-2	6-Jun-00	764749	4331014	132	21
GB-3	6-Jun-00	764744	4331079	189	32
GB-4	6-Jun-00	764726	4331157	266	25
GB-5	6-Jun-00	764722	4331197	690	1270
GB-6	6-Jun-00	764713	4331225	502	814
UT-3 Soil ext.	17-May-00	759910	4314321	0.06	1.2
LF-6 Soil ext.	17-May-00	749197	4340634	0.23	4.2
SB-11 Soil ext.	17-May-00	763474	4347624	0.44	1.6
KB-3 Soil ext.	17-May-00	756940	4346962	0.02	0.6
NV-4 Soil ext.	17-May-00	749197	4340634	0.13	1.9

To arrive at the total error from all sources for these calculations, we summed the fractional errors from each of the sources (TAYLOR, 1997). In other words, if we were to compute the error just for the mass of sediment introduced into the lake from shoreline erosion, it would be about ±80%. However, by adding in the fractional uncertainties associated with the nutrient measurements, the overall uncertainties increase to about ±150% for phosphorus and about ±176% for nitrogen loading.

DISCUSSION

Shore zone change around Lake Tahoe is discontinuous in space and appears to be well correlated with the type of geologic materials found along the shore (Figures 1 and 9). Virtually no significant change was found along shores primarily composed of bedrock, either granitic or volcanic. Instead, the areas where both erosion and deposition have occurred are almost all composed of alluvium or older lacustrine deposits. An exception is along the south eastern shore of Emerald Bay where there appears to be significant shore erosion in glacial till. This assessment is largely in agreement with the studies of ORME (1971, 1972) and with the assessment of disturbance potential outlined in the Lake Tahoe Shore Zone Ordinance Amendments (TRPA STAFF, 1999), all of which indicate that the areas subject to the largest disturbance potential or erosion are those consisting of glacial moraines, alluvium, colluvium, and outwash materials. Contrary to the studies of ENGSTROM (1978), shoreline stability has apparently more to do with the composition of shoreline materials than it has to do with prevailing winds and the amount of fetch, although these parameters are certainly important.

Observations made during the course of this study also confirm the conclusions of OSBORNE *et al.* (1985) who conclusively demonstrated that most of the material found along the beaches of Lake Tahoe is locally derived from erosion of backshore areas and that littoral transport tends to occur in relatively small, isolated cells. Evidence for littoral drift was also seen in this study where areas of erosion were adjacent to small areas of accretion, suggesting a redistribution of material along the shore.

The quantitative results of this study only document net shoreline change over the last 60 years, but additional observations suggest similar longer-term trends. Almost all of the areas of significant shoreline erosion occur within bays or reentrants along the shore backed by relatively erodible sediment. The shape of these bays suggest that over the long term, hundreds to thousands of years, net erosion has taken place, causing the bays to enlarge relative to more stable portions of the shore (Figure 9). On much shorter time scales, obvious erosional features (shoreline scarps, fallen trees, *etc.*) observed in the field do not always reflect longer term (decadal) conditions because, overall, many of these areas have changed relatively little over the last 60 years. In places like Kiva Beach and Sugar Pine Point (See Figure 3), fresh evidence of erosion is matched by a noticeable change over the last 60 years. Along many lower elevation parts of the shore, including Baldwin Beach, parts of Sugar Pine Point, and Nevada Beach, relatively young beach barriers are located inland from the shore that rise only a small vertical distance (1–2 m) above current maximum lake level. It is unknown if these features date from the early part of the 20th century when lake levels regularly exceeded the legal limit of 1898.65 m, but if so, their development and positions provide insight into the effects of higher lake levels on Lake Tahoe.

Field observations also confirmed that seawalls or other types of revetments now protect some of the areas with documented erosion. Therefore, these areas are no longer able to contribute sediment and nutrients to the lake, provided these structures remain in functional working order. Their effect on offshore and alongshore erosion is relatively un-

Table 3. *Locations of eroded shorezones and sediment and nutrient calculations for those areas.*

Location	Material Type	Area (m^ 2)	Thickness	Volume (m^ 3)	Mass (kg)	P (mg/kg)	N (mg/kg)	Tot P (MT)	Tot N (MT)
Nevada Beach-Stateline	old granitic beach sand	21,898	1	21,898	32,847,000	280	330	9.20	10.84
Stateline	old granitic beach sand	361	1	361	541,500	280	330	0.15	0.18
Bijou Park	old granitic beach sand	11,644	1	11,644	17,466,000	280	330	4.89	5.76
Al Tahoe-Regan Beach	old granitic beach sand	11,275	6	67,650	101,475,000	280	330	28.41	33.49
Upper Truckee River	granitic beach sand	31,643	1	31,643	47,464,500	150	35	7.12	1.66
Tahoe Keys	old granitic beach sand	1,234	1	1,234	1,851,000	280	330	0.52	0.61
Kiva Beach-Camp Richardson	old granitic beach sand	10,272	2	20,544	30,816,000	280	330	8.63	10.17
Baldwin Beach	old granitic beach sand	13,600	1	13,600	20,400,000	280	330	5.71	6.73
SE shore of Emerald Bay	glacial till	15,544	2	31,088	46,632,000	315	120	14.69	5.60
Emerald Bay-Vikingsholm	glacial till	8,304	1	8,304	12,456,000	315	120	3.92	1.49
Meeks Bay	old granitic beach sand	6,996	1	6,996	10,494,000	280	330	2.94	3.46
Sugar Pine Point	old granitic beach sand	4,008	3	12,024	18,036,000	280	330	5.05	5.95
Homewood	volcanic beach sand	18,813	1	18,813	28,219,500	320	230	9.03	6.49
Tahoe Tavern	volcanic beach sand	9,545	1	9,545	14,317,500	320	230	4.58	3.29
Lake Forest	gravelly silt	1,962	1	1,962	2,943,000	395	1415	1.16	4.16
Carnelian Bay	volcanic beach sand	8,160	1	8,160	12,240,000	320	230	3.92	2.82
Agate Bay	volcanic beach sand	4,562	2	9,124	13,686,000	320	230	4.38	3.15
Tahoe Vista	volcanic beach sand	3,449	1	3,449	5,173,500	68	270	0.35	1.40
Brockway	old granitic beach sand	1,190	1	1,190	1,785,000	280	330	0.50	0.59
Kings Beach-west side	volcanic beach sand	728	1	728	1,092,000	50	40	0.05	0.04
Kings Beach-east side	volcanic beach sand	903	2	1,806	2,709,000	50	40	0.14	0.11
Glenbrook	old granitic beach sand	4,471	1	4,471	6,706,500	280	330	1.88	2.21
	TOTALS =	190,562		286,234	429,351,000	TOTALS (MT) =	117		110

Table 4. *Yearly sources for nitrogen and phosphorous for Lake Tahoe in metric tons.*

Nutrient Inputs	Total N (MT)	Total P (MT)
Atmospheric deposition*	233.9 (56%)	12.4 (26%)
Stream loading*	81.6 (20%)	13.3 (28%)
Direct runoff*	41.8 (10%)	15.5 (33%)
Groundwater*	60 (14%)	4 (9%)
Shorezone erosion#,**	1.8 (<1%)	2 (4%)

Source comparison:
* Lake Tahoe Watershed Assessment (MURPHY and KNOPP, 2000).
\# Estimates from the Watershed Assessment for yearly contributions of nitrogen and phosphorous are 0.75 and 0.45 metric tons, respectively.
** From this study.

known, however, and should be investigated. In terms of stability analyses, the data collected and utilized for this study have been for a basin-wide look at shoreline change. The results of this study were not intended to be used for local studies of shoreline stability but may form a valuable framework within which to conduct more detailed stability studies.

CONCLUSIONS

The results of this study indicate that a total of 429,000 MT of sediment, 117 MT of phosphorus, and 110 MT of nitrogen have been introduced into the lake from shore zone erosion over the last 60 years. These values indicate that, on average, about 7150 MT per year of sediment, 2 MT per year of phosphorus, and 1.8 MT per year of nitrogen are being introduced into Lake Tahoe by shore zone erosion. These values represent long-term averages and probably vary considerably from year to year depending on lake level, frequency of storms, intensity of storms, and other factors. Based on the errors associated with these estimates, we consider these estimates accurate to within a factor of two.

The Lake Tahoe Watershed Assessment (MURPHY and KNOPP, 2000) identified five sources of phosphorus and nitrogen for Lake Tahoe including atmospheric deposition, stream loading, direct runoff, groundwater, and shore zone erosion. In the assessment, shoreline erosion is thought to account for about 0.45 and 0.75 metric tons of phosphorus and nitrogen per year, respectively. The results of this study indicate that the loading due to shore zone erosion is appreciably higher for phosphorus (~4%) but still relatively small (<1%) for nitrogen (Table 4). It must be emphasized, however, that these percentages are normalized so that if any of the other sources are scaled back, the relative importance of shore zone erosion to nutrient loading becomes greater and needs to be reconsidered when more firm estimates for each of the other sources of nutrients is better known.

Although the amount of phosphorus and nitrogen loading from shore zone erosion ranks last with respect to the other four nutrient sources, sediment loading from shore zone erosion probably ranks second. All of the other sources, except ground water, contribute fine sediment to the lake. Annual sediment input from stream loading is estimated to be a minimum of about 11,300 MT/yr (REUTER and MILLER, 2000). Firm estimates of the mass of sediment introduced from atmospheric deposition (dust) and direct runoff are lacking, but the average input from shore zone erosion (~ 7150 MT/yr) probably greatly exceeds these other two sources. Thus, shore zone erosion is an important component of the sediment and, to a lesser extent, nutrient budget for Lake Tahoe.

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