Revised Draft Environmental Impact Statement/
Environmental Impact Report

Truckee River Operating Agreement

Sedimentation and Erosion Appendix

California and Nevada

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United States Department of the Interior
Bureau of Reclamation
Fish and Wildlife Service
Bureau of Indian Affairs

State of California
Department of Water Resources

Sedimentation and Erosion Appendix

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SEDIMENTATION AND EROSION APPENDIX

This appendix consists of four parts: (1) a summary table of the effects of the alternatives on sedimentation and erosion, (2) discussion of erosion at Lake Tahoe, (3) discussion of stream channel erosion and sediment transport, and (4) discussion of Truckee River delta formation at Pyramid Lake.

I. SUMMARY OF EFFECTS OF ALTERNATIVES ON SEDIMENTATION AND EROSION

Table SED-A.1 summarizes the effects of the alternatives on sedimentation and erosion.

Table SED-A.1—Summary of effects on sedimentation and erosion

Indicator	No Action	LWSA	TROA
Shoreline erosion at Lake Tahoe	No manmade induced degradation of any water quality parameters	Same as No Action	Same as No Action
Stream channel erosion and sediment transport capacity change	Truckee River from Donner Creek to the Little Truckee River confluence: Same as under current conditions. Little Truckee River from Stampede Dam to Boca Reservoir: potentially more erosion but since located downstream from dam little effect is expected Spice and Lockwood reaches. Potential for more deposition exists. Spice does not seem to have large sediment source upstream. Lockwood could see more deposition because Steamboat Creek, a large sediment source is located within this reach	Truckee River from Donner Creek to the Little Truckee River confluence: Same as under current conditions. Little Truckee River from Stampede Dam to Boca Reservoir: Same as No Action Spice and Lockwood reaches: Same as No Action.	Truckee River from Donner Creek to the Little Truckee River confluence: Same as under current conditions. Little Truckee River from Stampede Dam to Boca Reservoir: potentially more deposition but since located downstream from dam little effect is expected Spice and Lockwood reaches: Some deposition could occur in Spice reach, but large sediment source not available upstream. No effect in Lockwood reach.

Table SED-A.1—Summary of effects on sedimentation and erosion

Indicator	No Action	LWSA	TROA
Stream channel erosion and sediment transport capacity change (continued)	Nixon reach: Less erosion and some deposition but no large sediment source located upstream that enters this reach	Nixon reach: Same as No Action.	Nixon reach: No effect
Truckee River delta formation at Pyramid Lake	No effect.	No effect.	No effect.

II. SHORELINE EROSION AT LAKE TAHOE

Lake Tahoe has a surface area of 192 square miles (120,000 acres), and its watershed area is 314 square miles. The lake has an average water depth of 1027 feet, a maximum depth of 1646 feet, and 72 miles of shoreline. The Federal Clean Water Act of 1972 designated Lake Tahoe as an "Outstanding Natural Resource." As such, no man-induced degradation of its water quality is allowed. The California State Water Resources Control Board also adopted Resolution 68-16 that establishes a nondegradation policy for the protection of water quality, where waters are designated as high quality water, including Lake Tahoe (SWRCB, 1994). Lake Tahoe is identified as impaired under the Clean Water Act for nitrogen, phosphorus, and sedimentation/siltation. Total maximum daily load limits are being studied to identify load limits for the lake. It is considered an oligotrophic (low productivity) lake; that is, it still has relatively low concentrations of nitrogen and phosphorus.

The geologic history and setting directly relates to the shorezone of the lake and effects of shorezone erosion. The general geology of the shorezone has a wide range of geologic formations (Adams, 2003). The eastern shorezone is predominantly granite bedrock and is not erodible. The southern zone is composed of glacial outwash deposits and lake deposits. The western shore is composed of glacial moraine material, outwash and lake deposits. The northern shore is composed of Tertiary volcanic rocks and alluvial and lake deposits.

Lake Tahoe shoreline erosion is directly related to the material properties of the shorezone, wave activity, and fluctuating water levels (Adams and Minor, 2002). More specifically, shorezone erosion is typically caused by waves breaking at the bases of easily eroded bluffs when lake level is high. Both the direct impact of waves on the bluffs and the onrush of wave swash up the beach are capable of erosion and sediment transport. When lake level is low, wave energy is expended on the beaches and does not impact long-term shore erosion.

Ken Adams of the Desert Research Institute performed studies of Lake Tahoe including a background review of existing references. In addition he tried to establish some estimate of shoreline erosion by using Geographical Information System analysis of maps to determine the shoreline change based on several aerial photos between 1939 and the present time.

To further study Lake Tahoe, Adams (2003) also estimated shoreline angles at 90 locations to determine the maximum elevation for historical shoreline erosion or potential new erosion. Shoreline angles are either abrupt changes in slope found at the top of the beach or the crest of beach ridges. These locations and elevations are shown in table SED-A.2. Lake Tahoe fluctuates between elevation 6223 and 6229.1 feet. The potential for shoreline erosion would only occur when lake levels are high. To estimate the potential for shoreline erosion, Adams (2003) looked at shoreline angles as compared to a potential range of wave conditions. Adams also set up wave-recording stations at three locations: Incline Village, Meeks Bay and the Thunderbird Lodge. These stations recorded data for more than 1 year, and the recorded data was analyzed according to technical standards.

Until recently, existing quantitative wave information for Lake Tahoe was quite sparse. Orme (1971) reported that waves could reach up to 2 to 3meters, but waves of this height were not observed. Instead, this range in heights was probably derived from maximum fetch distances and theoretical considerations using the wave growth formulae suggested by the U.S. Army Corps of Engineers (CERC, 1984). Engstrom (1978) also used the wave hindcasting procedures outlined in the Shore Protection Manual (CERC, 1984) combined with wind data reported by TRPA for Tahoe City (Agency, 1971) to hindcast waves at Lake Tahoe. Again, because winds specified by both velocity and duration were not available, this meant that the wind data is not as accurate as it could be.

Very little quantitative data exist for winds in the basin and the effects of the wind on shoreline erosion. The Western Regional Climate Center at DRI archived climate data at from the South Lake Tahoe airport from 1992. These data are limited because winds are only measured in the daytime and far from lake. Other data were collected at the South Lake Tahoe airport from 1965 to 1967. These data were limited to only daylight hours. Air Resource Specialists, Inc. (ARS) has been collecting wind data from at least three different sites at Lake Tahoe. These include sites at D.L. Bliss State Park in the southwest part of the basin, Thunderbird Lodge on the northeast shore, and South Lake Tahoe Boulevard at South Shore. Other researchers have tried to tie wind data to wave propagation but this was difficult with limited data and duration of winds.

Adams (2003) suggested that wave energy is the main force behind shoreline erosion. To date, it has not been determined whether large infrequent storms or frequent daily storm events with small waves provide the majority of the shore erosion. For extreme events, Adams (2003) explored the idea of an extreme wind event as defined by the Tahoe Regional Planning Agency (TRPA) Code. This wind was a wind of 80 miles per hour for 1 hour, because of the fetch-limited conditions at Lake Tahoe. Using TRPA's definition of an extreme wind event in comparison to small waves generated on a daily basis, Adams determined the amount of energy associated with the extreme wind event vs. the amount of energy associated with the small waves that occur on a daily basis for a year. His conclusion was that there was greater energy associated with the small frequent waves that occur on a daily basis.

Lake Tahoe is subject to seiches, which are periodic oscillations of a body of water whose period is determined by the resonant characteristics of the basin. Seiches can temporarily raise water levels along a shore. The importance of seiches to shorezone erosion is that they

Table SED-A.2

Lake Tahoe. SL angle = shoreline angle. Normalized height is the height of the feature minus the legal high limit of Lake Tahoe (6229.1 ft). Coordinate system is UTM Zone 10, NAD 27.

	Easting	Northing	Feature	Height of featu	normalized height (ft)
1	749818	4325595	beach ridge	6229.88	1.73
2	749692	4327507	SL angle	6229.72	1.57
3	749729	4327475	SL angle	6229.06	0.91
4	749765	4327442	SL angle	6228.08	-0.07
5	749834	4327167	SL angle	6228.57	0.42
6	749836	4327140	SL angle	6227.75	-0.40
7	749819	4327096	SL angle	6228.40	0.26
8	749821	4327056	SL angle	6227.09	-1.05
9	749815	4326989	SL angle	6227.26	-0.89
10	749810	4326951	SL angle	6227.58	-0.56
11	749809	4326922	SL angle	6229.22	1.08
12	749810	4326874	SL angle	6229.22	1.08
13	749957	4326279	SL angle	6228.73	0.59
14	749981	4326228	SL angle	6228.73	0.59
15	750001	4326195	SL angle	6228.90	0.75
16	750013	4326153	SL angle	6228.73	0.59
17	750034	4326096	SL angle	6229.22	1.08
18	750073	4326030	SL angle	6229.22	1.08
19	750095	4326006	SL angle	6229.22	1.08
20	749926	4325665	SL angle	6228.90	0.75
21	753637	4314771	SL angle	6227.75	-0.39
22	753793	4314630	beach ridge	6230.37	2.24
23	753975	4314530	beach ridge	6229.06	0.92
24	754320	4314359	beach ridge	6230.21	2.07
25	754809	4314188	beach ridge	6229.72	1.58
26	754946	4314156	beach ridge	6229.39	1.25
27	755380	4314218	SL angle	6227.91	-0.22
28	755651	4314171	SL angle	6228.90	0.76
29	755806	4314131	SL angle	6229.22	1.09
30	756148	4314042	SL angle	6229.06	0.92
31	756383	4314003	SL angle	6228.57	0.43
32	759651	4314232	SL angle	6228.73	0.60
33	759996	4314378	SL angle	6227.91	-0.22
34	760363	4314440	beach ridge	6228.73	0.60
35	760578	4314526	beach ridge	6228.57	0.43
36	760687	4314541	beach ridge	6229.39	1.25
37	760902	4314633	SL angle	6226.44	-1.70
38	761200	4314707	SL angle	6227.58	-0.55
39	761833	4314795	SL angle	6228.08	-0.06
40	762209	4314854	SL angle	6228.24	0.10
41	762699	4315017	SL angle	6228.24	0.10
42	762796	4315054	SL angle	6228.08	-0.06
43	764234	4318118	beach ridge	6229.72	1.57
44	764378	4316957	SL angle	6229.06	0.91
45	764010	4315990	SL angle	6228.73	0.59
46	763710	4319290	SL angle	6228.73	0.59
47	745841	4333076	SL angle	6228.76	0.60
48	745431	4331603	SL angle	6228.27	0.11
49	745378	4331073	SL angle	6228.60	0.44
50	745666	4330290	SL angle	6228.44	0.27
51	745920	4329647	SL angle	6229.75	1.59
52	746441	4328952	SL angle	6228.76	0.60
53	746631	4328787	SL angle	6228.76	0.60
54	749259	4327770	SL angle	6228.27	0.11
55	749693	4327516	SL angle	6229.42	1.26
56	746000	4334744	beach ridge	6229.26	1.09
57	746273	4335259	SL angle	6227.94	-0.22
58	746273	4335413	SL angle	6228.11	-0.05
59	746200	4336210	SL angle	6228.93	0.77
60	746656	4336629	SL angle	6228.44	0.27
61	746949	4337495	SL angle	6228.27	0.11
62	747133	4338565	SL angle	6228.27	0.11
63	748166	4340504	SL angle	6228.44	0.27
64	749458	4323365	SL angle	6228.57	0.41
65	749726	4322339	SL angle	6228.90	0.74
66	751248	4320567	SL angle	6227.91	-0.24
67	750243	4321404	SL angle	6228.57	0.41
68	764477	4327693	SL angle	6228.54	0.37
69	764529	4327899	SL angle	6228.21	0.04
70	764574	4328969	SL angle	6228.37	0.21
71	764376	4329197	SL angle	6228.21	0.04
72	764222	4325661	SL angle	6228.54	0.37
73	749161	4340634	SL angle	6227.81	-0.33
74	749436	4340744	SL angle	6228.80	0.65
75	749774	4340910	SL angle	6227.81	-0.33
76	750360	4341034	SL angle	6228.96	0.81
77	750923	4341830	SL angle	6227.98	-0.17
78	751657	4345319	SL angle	6228.47	0.32
79	752272	4345755	beach ridge	6231.09	2.95
80	754565	4347239	SL angle	6228.73	0.57
81	754952	4347210	SL angle	6228.90	0.74
82	756345	4347036	SL angle	6228.57	0.41
83	758514	4345579	SL angle	6229.55	1.39
84	761495	4348327	SL angle	6229.22	1.07
85	764297	4322109	SL angle	6228.70	0.54
86	764262	4322179	SL angle	6228.37	0.21
87	764247	4322214	SL angle	6228.37	0.21
88	764221	4322240	SL angle	6228.37	0.21
89	764205	4322375	SL angle	6228.37	0.21
90	764082	4322615	SL angle	6229.03	0.87

can temporarily raise water level along a shore, allowing waves to travel further inland and increasing shoreline erosion. Budlong (1971) personally observed seiches ranging in amplitude from 0.4 to 0.8 foot. On a moderately sloping beach along the south shore, the lateral distance in wave runup appeared to change by as much as several feet with a seiche of about 0.4 foot (Budlong, 1971).

Adams (2003) describes the studies of Budlong (1971) who studied processes and rates of shore erosion. In this work, rapid erosion occurred immediately west of the Keys East channel because of the effect of a pair of jetties protecting the channel. During a single 10-month period (6/01/69 – 3/31/70), the shoreline retreated up to 52 feet over a distance of about 492 ft. In this case, Budlong surmised that the reason for this extensive retreat was due to the extensive willow clearing activities by Tahoe Keys personnel had contributed to the rapid shoreline retreat.

Orme (1971) describes the natural processes of Lake Tahoe. Orme's work was also the basis of the TRPA shorezone plan that was finalized in 1976. Orme (1972) stated that eroding shorelines comprise 16.3 percent of the Lake Tahoe shoreline. Orme (1971) also described the currents and littoral drift patterns of the lake. Adams (2003) made refinement to Orme description of currents and littoral drift.

Monthly water elevations at Lake Tahoe under current conditions, No Action, LWSA, and TROA are shown in table SED-A.3 for median hydrologic conditions and very wet hydrologic conditions. With the use of this data and the stochastic model formulated by Adams (2003), a determination was made that none of the alternatives had a significant effect on shoreline erosion and did not cause any degradation of long term water quality. This study is explained in the following paragraphs.

Lake Tahoe typically fluctuates between its maximum lake elevation of 1898.65 (6229.1 feet) and its natural rim elevation of about 1896.8 meters (6223 feet) (figure 1), although sometimes the lake drops below its natural rim, as at present (December 2003). It is reasonable to assume that shorezone erosion only occurs when lake level is high.

The question then becomes: At what lake surface elevation does shorezone erosion potentially become significant? To address this question, we use the observations of the elevations of the shoreline angles and compare it to the estimates of different wave heights added on to the water surface elevations projected for different alternatives at median and very wet conditions (table SED-A.3).

Ken Adams (2003) addressed the question of whether TROA or any other alternative would potentially have a greater effect on shorezone erosion and at what elevations would erosion occur. He used the assessment that he performed of shoreline elevation and angles (table SED-A.2), and compared elevations of wave run above the lake water surface elevation observed for the shoreline angle. If the lake elevation plus the maximum wave height was greater than the shoreline angle elevation, then erosion could potentially occur.

Table SED-A.3.—Median hydrologic conditions

Median Conditions												
Current	6226.98	6226.98	6226.96	6227.31	6227.32	6227.37	6227.42	6228.07	6228.55	6228.34	6227.98	6227.57
No Action	6226.99	6226.94	6226.91	6227.21	6227.25	6227.34	6227.40	6228.07	6228.49	6228.30	6227.94	6227.52
Difference	0.01	-0.04	-0.05	-0.10	-0.07	-0.03	-0.02	0.00	-0.06	-0.03	-0.04	-0.05
Current	6226.98	6226.98	6226.96	6227.31	6227.32	6227.37	6227.42	6228.07	6228.55	6228.34	6227.98	6227.57
LWSA	6226.98	6226.94	6226.91	6227.21	6227.25	6227.33	6227.40	6228.07	6228.48	6228.30	6227.94	6227.52
Difference	0.00	-0.04	-0.05	-0.10	-0.07	-0.04	-0.02	0.00	-0.07	-0.03	-0.04	-0.05
Current	6226.98	6226.98	6226.96	6227.31	6227.32	6227.37	6227.42	6228.07	6228.55	6228.34	6227.98	6227.57
TROA	6227.16	6227.15	6227.12	6227.31	6227.39	6227.41	6227.52	6228.11	6228.52	6228.33	6227.96	6227.61
Difference	0.18	0.17	0.16	0.00	0.07	0.04	0.11	0.04	-0.02	-0.01	-0.02	0.04
No Action	6226.99	6226.94	6226.91	6227.21	6227.25	6227.34	6227.40	6228.07	6228.49	6228.30	6227.94	6227.52
LWSA	6226.98	6226.94	6226.91	6227.21	6227.25	6227.33	6227.40	6228.07	6228.48	6228.30	6227.94	6227.52
Difference	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00
No Action	6226.99	6226.94	6226.91	6227.21	6227.25	6227.34	6227.40	6228.07	6228.49	6228.30	6227.94	6227.52
TROA	6227.16	6227.15	6227.12	6227.31	6227.39	6227.41	6227.52	6228.11	6228.52	6228.33	6227.96	6227.61
Difference	0.17	0.21	0.21	0.10	0.14	0.07	0.12	0.04	0.03	0.03	0.02	0.09
Very wet conditions												
Current	6228.40	6228.22	6228.30	6228.41	6228.49	6228.65	6228.75	6229.00	6229.00	6229.00	6228.78	6228.50
No Action	6228.37	6228.30	6228.34	6228.44	6228.49	6228.65	6228.75	6229.00	6229.00	6229.00	6228.79	6228.51
Difference	-0.03	0.09	0.04	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Current	6228.40	6228.22	6228.30	6228.41	6228.49	6228.65	6228.75	6229.00	6229.00	6229.00	6228.78	6228.50
LWSA	6228.37	6228.30	6228.34	6228.44	6228.49	6228.65	6228.75	6229.00	6229.00	6229.00	6228.79	6228.51
Difference	-0.03	0.09	0.04	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Current	6228.40	6228.22	6228.30	6228.41	6228.49	6228.65	6228.75	6229.00	6229.00	6229.00	6228.78	6228.50
TROA	6228.36	6228.28	6228.34	6228.45	6228.51	6228.69	6228.75	6229.00	6229.00	6229.00	6228.77	6228.50
Difference	-0.04	0.06	0.04	0.04	0.02	0.04	0.00	0.00	0.00	0.00	-0.01	0.00
No Action	6228.37	6228.30	6228.34	6228.44	6228.49	6228.65	6228.75	6229.00	6229.00	6229.00	6228.79	6228.51
LWSA	6228.37	6228.30	6228.34	6228.44	6228.49	6228.65	6228.75	6229.00	6229.00	6229.00	6228.79	6228.51
Difference	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
No Action	6228.37	6228.30	6228.34	6228.44	6228.49	6228.65	6228.75	6229.00	6229.00	6229.00	6228.79	6228.51
TROA	6228.36	6228.28	6228.34	6228.45	6228.51	6228.69	6228.75	6229.00	6229.00	6229.00	6228.77	6228.50
Difference	-0.01	-0.02	0.00	0.01	0.02	0.04	0.00	0.00	0.00	0.00	-0.02	-0.01

Ken Adams (2003) compared the predicted water levels from the operations model to this shoreline angle elevation plus maximum wave runup. He considered three potential wave heights that he determined from the wave data he has analyzed: 1.45, 3.3 and 4.9 feet with periods ranging from 3 to 5 seconds. He also determined that 6227 feet would be the cutoff elevation below which no shoreline erosion would likely occur. He determined this by comparing the small, medium and large waves and the shoreline angle elevations. With the waves of 4.9 feet with a period of 5 seconds, approximately 4 of the 90 sites he identified were affected. Therefore, 6227.0 feet was considered as the cutoff elevation.

Adams (2003) also made some other assumptions to determine the effects of TROA. He assumed that the lake would never exceed the maximum water elevation, which is set at 6229.1 feet. Also, the natural rim of the lake is at elevation 6223 feet, so waves have only been acting on the shoreline elevation of 6229 feet for a portion of the last 120 years. Therefore, TROA or any other water management alternative would not affect the maximum water elevation of the lake, and, thus, should have no impact on the total long term erosion of the lake. In his analysis as well as the analysis that was used for the revised DEIS/EIR, comparisons were made between model runs as follows: current conditions vs. No Action,

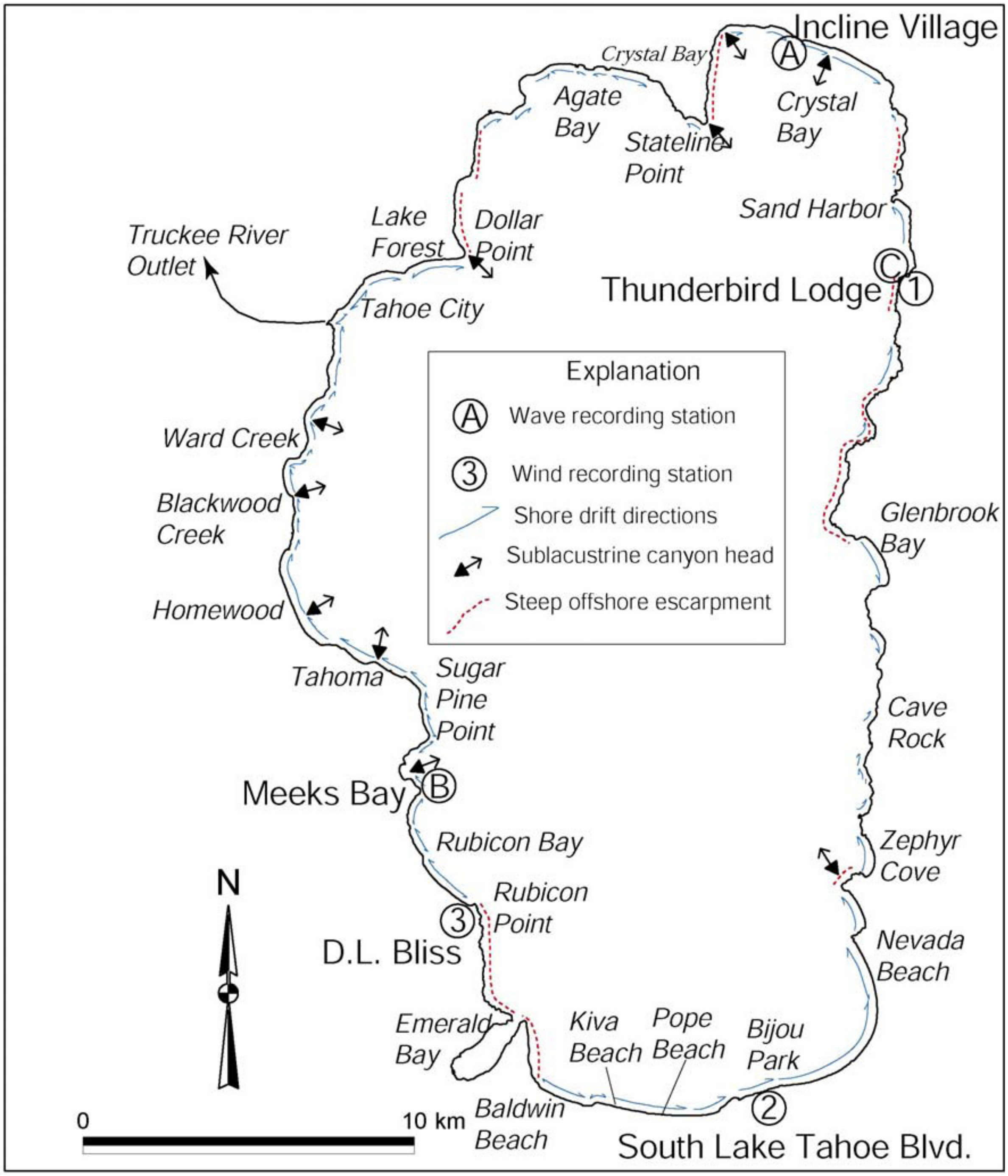
Incline Village
Crystal Bay
Agate Bay
Stateline Point
Crystal Bay
Sand Harbor
Lake Forest
Dollar Point
Truckee River Outlet
Thunderbird Lodge
Tahoe City
Explanation
Wave recording station
Wind recording station
Shore drift directions
Sublacustrine canyon head
Steep offshore escarpment
Ward Creek
Blackwood Creek
Glenbrook Bay
Homewood
Tahoma
Sugar Pine Point
Cave Rock
Meeks Bay
Rubicon Bay
Zephyr Cove
N
Rubicon Point
D.L. Bliss
Nevada Beach
Emerald Bay
Kiva Beach
Pope Beach
Bijou Park
0
10 km
Baldwin Beach
South Lake Tahoe Blvd.

Figure 1

current conditions vs. LWSA, current conditions vs. TROA, No Action vs. LWSA, and No Action vs. TROA. These comparisons were made for two frequencies: the 5 percent exceedence monthly elevations and the median or 50 percent exceedence monthly elevations.

In assessing the difference in monthly elevations between the alternatives, Ken Adams assessed the likelihood of TROA versus the other alternatives having a greater effect on shoreline erosion. In instances where the difference was negative or zero, there would be no difference in shore erosion. In comparing current conditions to No Action and current conditions to LWSA, and No Action to LWSA, either very little positive difference or no difference in water surface elevations was noted. This indicates no potential differences in erosion for either the median or very wet hydrologic conditions. However, in comparing current conditions to No Action in very wet hydrologic conditions, No Action was greater than current conditions for two different months for a range in elevations that were 0.04 to 0.09 foot. In comparing TROA to No Action and current conditions, the water surface elevations for TROA were greater in many months, and ranged from a low value of .02 foot to a maximum of .021 foot.

Adams (2003) evaluated whether or not the magnitude of lake-level change between TROA and the other alternatives would affect shorezone erosion by using the observed values of the elevations of the shoreline angles, the wave runup and a statistical method to check for significance. The basic stochastic model evaluated the probability of the shoreline angles being reached by different size waves, which included 90 shoreline locations (table SED-A.2). Given two different lake levels, for two different alternatives, an estimate would be completed of the difference in the number of shoreline angles that would be reached for the two different lake levels.

The basic procedure was to evaluate the probability of the shoreline angles being reached by runup from different sizes of waves under several lake-level scenarios. Given a lake level, Adams estimated the proportion of the 90 shoreline segments where the waves reach the shoreline angle. Further, given two lake levels from two different management options and wave parameters, Adams (2003) estimated the difference in the proportion of segments for which the waves reach the shoreline angle for each of the lake levels. Using stochastic techniques, Adams tests how many beach segments were affected by a given lake level plus an assumed wave height and then statistical techniques were used to determine if the results were significant.

The results of the stochastic analysis by Adams (2003) are as follows. For the 5 percent exceedence conditions or very wet hydrologic conditions, there were no significant differences in the proportions of (potentially) eroded shoreline segments for any lake levels and wave characteristics. For the 50 percent exceedence values or median hydrologic conditions with moderate –sized waves, (H=1.5 ft. and `5 sec.), one lake level comparison yielded a significant difference in the proportions of impacted shoreline angles under two lake level scenarios. Lake levels during the month of June under the No Action vs. TROA comparison would be increased from 6228.56 to 6228.59 feet, a difference of 0.03 foot. The sample proportion of not impacted shoreline angles under the No Action lake level (LL1) is 0.7444, but under TROA (LL2) the sample proportion is 0.7 (Adams, 2003). The observed difference of 0.0444 has a p-value of 0.03 and is therefore significant. For the largest waves

(H = 7 ft, t= 5 sec), three of the lake level comparisons yielded significant differences in the proportions of impacted shoreline angles under the two lake-level scenarios. These data are summarized in the following table (Adams, 2003).

Comparisons yielding significant differences in proportions of impacted shoreline angles under two lake levels (from Adams, 2003)

Comparison	Month	LL1	LL2	Lake-level difference	Proportion not impacted for LL1	Proportion not impacted for LL2	Difference	P-value
Current conditions vs. TROA	Oct.	6227.11	6227.23	0.012	0.9556	0.9111	0.0444	0.0455
No Action vs. TROA	Oct.	6227.07	6227.23	0.016	0.9556	0.9111	0.0444	0.0455
No Action vs. TROA	Feb.	6227.32	6227.47	0.015	0.9000	0.8444	0.0556	0.0253

For the 5 percent exceedence values (wet hydrologic conditions), there is no significant increase in erosion potential for any of the lake-level scenario comparisons (Adams, 2003). This means that when lake-levels are at their highest, implementing TROA would not affect shorezone erosion at Lake Tahoe.

For the 50 percent exceedence values (median hydrologic conditions), there are three discrete lake-level comparisons that produce significant differences in proportions of impacted shoreline angles under the two lake level scenarios (Adams, 2003). In each case, TROA levels would be higher by about 1.6 to 2 inches. Under TROA, approximately 84 to 91 percent of the measured shoreline angles and beach ridges would not be impacted in these comparisons. Under current conditions or No Action lake levels, from 90 to 96 percent of the sites would not be impacted. There is certainly a statistical difference in the number of sites impacted under the three comparisons. However, what effect it would have on shore zone erosion potential is not entirely clear, but is suspected to be minimal. Adams (2003), therefore, concludes that implementing TROA would have minor effects to the shorezone erosion at Lake Tahoe.

Effects on shoreline erosion at Lake Tahoe under No Action, LWSA, or TROA would cause no manmade degradation of its water quality. Effects would not meet the threshold of significance under any of the alternatives. No increased shoreline erosion is expected, and the maximum water surface elevation that the lake is currently operated at would not be exceeded.

III. STREAM CHANNEL EROSION AND SEDIMENT TRANSPORT

Comparisons are made between all of the alternatives for both median hydrologic conditions and very wet hydrologic conditions on a monthly basis. For stream channel erosion and sediment transport, an effect was considered significant if it would cause widespread and measurable channel erosion or deposition. Based on professional judgment, widespread and measurable channel erosion is expected to occur when sediment transport capacity change is more than 10 percent greater than under current conditions on an annual basis, and the streambed is not already armored. Widespread and measurable channel deposition is expected when sediment transport capacity change is more than 10 percent less than under current conditions on an annual basis and there is a substantial upstream source of river or tributary sediment. For example, a channel downstream from a dam would not have an upstream source of sediment and the bed material sediments would be armored (not erodible). A decrease in sediment transport capacity change for a river downstream from a dam would not result in deposition without a large source of tributary sediment.

A. Erosion on Truckee River: Donner Creek to Little Truckee River Confluence

Monthly streamflows and changes in sediment transport capacity for the Truckee River downstream from Donner Creek to Little Truckee River confluence are summarized in Table SED-A.4. For current conditions vs. TROA, sediment transport capacity change is exceeded in the months of June-August in median hydrologic conditions. Also, for No Action vs. TROA, sediment transport capacity change exceeds the threshold change for the months of May-July. In very wet hydrologic conditions, sediment capacity change is exceeded for current conditions vs. No Action in October and for No Action vs. TROA in May. The estimated sediment capacity change does not meet the threshold of significance for any of the alternatives as compared to current conditions on an annual basis. Little change is sediment transport capacity on an annual basis is expected.

Table SED-A.4.—Monthly flows and change in sediment transport capacity on the Truckee River between Donner Creek and the Little Truckee River in **median** hydrologic conditions

Month	Current conditions (cfs)	No Action (cfs)	Range in sediment transport capacity change (percent)	
October	260	270	8	12
November	193	194	1	2
December	274	270	-3	-4
January	285	286	1	1
February	254	256	2	2
March	331	324	-4	-6
April	623	602	-7	-10
May	778	762	-4	-6
June	518	517	0	-1
July	173	174	1	2
August	110	112	4	6
September	223	226	3	4
Weighted average			-3	-5

Table SED-A.4.—Monthly flows and change in sediment transport capacity on the Truckee River between Donner Creek and the Little Truckee River in **median** hydrologic conditions (continued)

Month	Current conditions (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	260	202	-40	-53
November	193	165	-27	-38
December	274	220	-36	-48
January	285	236	-31	-43
February	254	240	-11	-16
March	331	307	-14	-20
April	623	621	-1	-1
May	778	805	7	11
June	518	551	13	20
July	173	218	59	100
August	110	116	11	17
September	223	137	-62	-77
Weighted average			-3	3

Month	Current conditions (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	260	271	9	13
November	193	194	1	2
December	274	270	-3	-4
January	285	286	1	1
February	254	255	1	1
March	331	324	-4	-6
April	623	603	-6	-9
May	778	763	-4	-6
June	518	516	-1	-1
July	173	174	1	2
August	110	112	4	6
September	223	228	5	7
Weighted Average			-3	-5

Table SED-A.4.—Monthly flows and change in sediment transport capacity on the Truckee River between Donner Creek and the Little Truckee River in **median** hydrologic conditions (continued)

Month	No Action (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	270	202	-44	-58
November	194	165	-28	-38
December	270	220	-34	-46
January	286	236	-32	-44
February	256	240	-12	-18
March	324	307	-10	-15
April	602	621	6	10
May	762	805	12	18
June	517	551	14	21
July	174	218	57	97
August	112	116	7	11
September	226	137	-63	-78
Weighted average			0	9

Month	No Action (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	270	271	1	1
November	194	194	0	0
December	270	270	0	0
January	286	286	0	0
February	256	255	-1	-1
March	324	324	0	0
April	602	603	0	0
May	762	763	0	0
June	517	516	0	-1
July	174	174	0	0
August	112	112	0	0
September	226	228	2	3
Weighted average			0	0

Table SED-A.4.—Monthly flows and change in sediment transport capacity on the Truckee River between Donner Creek and the Little Truckee River in **very wet** hydrologic conditions

Month	Current conditions (cfs)	No Action (cfs)	Range in sediment transport capacity change (percent)	
October	349	367	11	16
November	474	455	-8	-12
December	1087	1077	-2	-3
January	1342	1329	-2	-3
February	1723	1716	-1	-1
March	1779	1747	-4	-5
April	2193	2187	-1	-1
May	2148	2111	-3	-5
June	1572	1571	0	0
July	1122	1119	-1	-1
August	463	463	0	0
September	481	475	-2	-4
Weighted average			-2	-3

Month	Current conditions (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	349	325	-13	-19
November	474	434	-16	-23
December	1087	1091	1	1
January	1342	1373	5	7
February	1723	1723	0	0
March	1779	1800	2	4
April	2193	2188	0	-1
May	2148	2243	9	14
June	1572	1623	7	10
July	1122	1080	-7	-11
August	463	402	-25	-35
September	481	352	-46	-61
Weighted average			2	4

Table SED-A.4.—Monthly flows and change in sediment transport capacity on the Truckee River between Donner Creek and the Little Truckee River in **very wet** hydrologic conditions (continued)

Month	Current conditions (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	349	367	11	16
November	474	455	-8	-12
December	1087	1077	-2	-3
January	1342	1328	-2	-3
February	1723	1716	-1	-1
March	1779	1739	-4	-7
April	2193	2188	0	-1
May	2148	2111	-3	-5
June	1572	1571	0	0
July	1122	1119	-1	-1
August	463	463	0	0
September	481	476	-2	-3
Weighted average			-2	-3

Month	No Action (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	367	325	-22	-31
November	455	434	-9	-13
December	1077	1091	3	4
January	1329	1373	7	10
February	1716	1723	1	1
March	1747	1800	6	9
April	2187	2188	0	0
May	2111	2243	13	20
June	1571	1623	7	10
July	1119	1080	-7	-10
August	463	402	-25	-35
September	475	352	-45	-59
Weighted average			4	7

Table SED-A.4.—Monthly flows and change in sediment transport capacity on the Truckee River between Donner Creek and the Little Truckee River in **very wet** hydrologic conditions (continued)

Month	No Action (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	367	367	0	0
November	455	455	0	0
December	1077	1077	0	0
January	1328	1329	0	0
February	1716	1716	0	0
March	1739	1747	1	1
April	2188	2187	0	0
May	2111	2111	0	0
June	1571	1571	0	0
July	1119	1119	0	0
August	463	463	0	0
September	476	475	0	-1

B. Erosion on Little Truckee River: Stampede Dam to Boca Reservoir

Comparisons are made between all of the alternatives for both median hydrologic conditions and very wet hydrologic conditions on a monthly basis for the Little Truckee River: Stampede Dam to Boca Reservoir in table SED-A.5. For current conditions vs. No Action, sediment transport capacity change is greater than 10 percent in the months of December and May in median hydrologic conditions. Also for current conditions vs. TROA, sediment transport capacity change is greater than current conditions in October. For No Action vs. TROA, sediment transport capacity change is greater in August, September, and October. In very wet hydrologic conditions, sediment capacity change is greater for current conditions vs. No Action in October and December and for current conditions vs. TROA in October, December, August, and September. For No Action vs. TROA, sediment transport capacity change is greater in February, April, August, and September. Annual sediment capacity change is more than 10 percent greater under No Action and LWSA; thus, more erosion and sediment transport likely could occur in this reach, but because this reach is located downstream from a dam and the river is armored, very little change in sediment transport is expected. Annual sediment capacity change is only 11 percent greater under TROA than under current conditions in very wet hydrologic conditions, and annual sediment transport capacity change is much less in median hydrologic conditions; therefore, erosion and sediment transport in this reach under TROA would be about the same as under current conditions. This reach is downstream from Stampede Reservoir, and as such, is probably armored, and no significant erosion or sediment transport is expected.

Table SED-A.5.—Monthly flows and change in sediment transport capacity on the Little Truckee River between Stampede Dam and Boca Reservoir in **median** hydrologic conditions

Month	Current conditions (cfs)	No Action (cfs)	Range in sediment transport capacity change (percent)	
October	94	100	13	20
November	46	47	4	7
December	51	56	21	32
January	65	64	-3	-5
February	90	94	9	14
March	161	159	-2	-4
April	284	292	6	9
May	330	358	18	28
June	264	265	1	1
July	144	138	-8	-12
August	94	75	-36	-49
September	42	30	-49	-64
Weighted average			6	13

Month	Current conditions (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	94	177	255	568
November	46	45	-4	-6
December	51	46	-19	-27
January	65	46	-50	-65
February	90	72	-36	-49
March	161	142	-22	-31
April	284	233	-33	-45
May	330	314	-9	-14
June	264	225	-27	-38
July	144	122	-28	-39
August	94	85	-18	-26
September	42	57	84	150
Weighted average			-15	-24

Table SED-A.5.—Monthly flows and change in sediment transport capacity on the Little Truckee River between Stampede Dam and Boca Reservoir in **median** hydrologic conditions (continued)

Month	Current conditions (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	94	100	13	20
November	46	48	9	14
December	51	56	21	32
January	65	64	-3	-5
February	90	94	9	14
March	161	159	-2	-4
April	284	293	6	10
May	330	359	18	29
June	264	265	1	1
July	144	138	-8	-12
August	94	74	-38	-51
September	42	30	-49	-64
Weighted average			6	14

Month	No Action (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	100	177	213	455
November	47	45	-8	-12
December	56	46	-33	-45
January	64	46	-48	-63
February	94	72	-41	-55
March	159	142	-20	-29
April	292	233	-36	-49
May	358	314	-23	-33
June	265	225	-28	-39
July	138	122	-22	-31
August	75	85	28	46
September	30	57	261	586
Weighted average			-20	-33

Table SED-A.5.—Monthly flows and change in sediment transport capacity on the Little Truckee River between Stampede Dam and Boca Reservoir in **median** hydrologic conditions (continued)

Month	Current conditions (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	100	100	0	0
November	47	48	4	7
December	56	56	0	0
January	64	64	0	0
February	94	94	0	0
March	159	159	0	0
April	292	293	1	1
May	358	359	1	1
June	265	265	0	0
July	138	138	0	0
August	75	74	-3	-4
September	30	30	0	0
Weighted average			0	1

Table SED-A.5.—Monthly flows and change in sediment transport capacity on the Little Truckee River between Stampede Dam and Boca Reservoir in **very wet** hydrologic conditions

Month	Current conditions (cfs)	No Action (cfs)	Range in sediment transport capacity change (percent)	
October	328	373	29	47
November	151	151	0	0
December	173	182	11	16
January	201	201	0	0
February	212	212	0	0
March	413	428	7	11
April	669	689	6	9
May	1115	1109	-1	-2
June	643	644	0	0
July	304	286	-11	-17
August	187	172	-15	-22
September	107	89	-31	-42
Weighted average			2	1

Table SED-A.5.—Monthly flows and change in sediment transport capacity on the Little Truckee River between Stampede Dam and Boca Reservoir in **very wet** hydrologic conditions (continued)

Month	Current conditions (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	328	388	40	66
November	151	155	5	8
December	173	197	30	48
January	201	199	-2	-3
February	212	233	21	33
March	413	442	15	23
April	669	778	35	57
May	1115	1145	5	8
June	643	565	-23	-32
July	304	227	-44	-58
August	187	199	13	21
September	107	221	327	781
Weighted average			8	11

Month	Current conditions (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	328	373	29	47
November	151	151	0	0
December	173	184	13	20
January	201	201	0	0
February	212	212	0	0
March	413	428	7	11
April	669	689	6	9
May	1115	1104	-2	-3
June	643	645	1	1
July	304	286	-11	-17
August	187	171	-16	-24
September	107	89	-31	-42
Weighted average			1	0

Table SED-A.5.—Monthly flows and change in sediment transport capacity on the Little Truckee River between Stampede Dam and Boca Reservoir in **very wet** hydrologic conditions (continued)

Month	No Action (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	373	388	8	13
November	151	155	5	8
December	182	197	17	27
January	201	199	-2	-3
February	212	233	21	33
March	428	442	7	10
April	689	778	28	44
May	1109	1145	7	10
June	644	565	-23	-32
July	286	227	-37	-50
August	172	199	34	55
September	89	221	517	1431
Weighted average			7	10

Month	No Action (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	373	373	0	0
November	151	151	0	0
December	182	184	2	3
January	201	201	0	0
February	212	212	0	0
March	428	428	0	0
April	689	689	0	0
May	1109	1104	-1	-1
June	644	645	0	0
July	286	286	0	0
August	172	171	-1	-2
September	89	89	0	0
Weighted average			0	-1

C. Erosion on Truckee River Reno-Sparks to McCarran Blvd (Spice)

Comparisons are made between all of the alternatives for both median hydrologic conditions and very wet hydrologic conditions on a monthly basis for Truckee River from Reno-Sparks to McCarran Boulevard in table SED-A.6. For current conditions vs. No Action, sediment transport capacity change is greater than 10 percent in October in median hydrologic conditions. Also for current conditions vs. TROA, sediment transport capacity change does not exceed the threshold change in median hydrologic conditions. For No Action vs. TROA, sediment transport capacity change exceeds the threshold change in April, May, June, and August. In very wet hydrologic conditions, sediment capacity change is exceeded for current conditions vs. No Action in October, and for current conditions vs. TROA in October and September. For No Action vs. TROA sediment transport capacity exceeds the threshold change in February, April, August, and September. For the cases in which the sediment capacity change of TROA exceeds No Action or current conditions, the environmental effect may not be as great as predicted.

More sediment deposition could occur in this reach under No Action and LWSA than under current conditions, but because a source of sediment likely does not exist upstream, significant deposition also is not likely. Less erosion and sediment transport likely would occur in this reach under TROA than under current conditions in this reach.

Table SED-A.6.—Monthly flows and change in sediment transport capacity on the Truckee River from Reno-Sparks to McCarran Blvd Reno in **median** hydrologic conditions

Month	Current conditions (cfs)	No Action (cfs)	Range in sediment transport capacity change (percent)	
October	372	394	12	19
November	397	328	-32	-44
December	400	322	-35	-48
January	401	330	-32	-44
February	445	372	-30	-42
March	550	483	-23	-32
April	790	696	-22	-32
May	1062	980	-15	-21
June	774	726	-12	-17
July	347	325	-12	-18
August	304	282	-14	-20
September	275	280	4	6
Weighted average			-18	-25

Table SED-A.6.—Monthly flows and change in sediment transport capacity on the Truckee River from Reno-Sparks to McCarran Blvd Reno in **median** hydrologic conditions (continued)

Month	Current conditions (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	372	386	8	12
November	397	222	-69	-83
December	400	278	-52	-66
January	401	297	-45	-59
February	445	366	-32	-44
March	550	488	-21	-30
April	790	776	-4	-5
May	1062	1062	0	0
June	774	780	2	2
July	347	340	-4	-6
August	304	300	-3	-4
September	275	275	0	0
Weighted average			-11	-9

Month	Current conditions (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	372	394	12	19
November	397	326	-33	-45
December	400	320	-36	-49
January	401	326	-34	-46
February	445	368	-32	-43
March	550	479	-24	-34
April	790	694	-23	-32
May	1062	979	-15	-22
June	774	724	-13	-18
July	347	325	-12	-18
August	304	281	-15	-21
September	275	280	4	6
Weighted average			-18	-25

Table SED-A.6.—Monthly flows and change in sediment transport capacity on the Truckee River from Reno-Sparks to McCarran Blvd Reno in **median** hydrologic conditions (continued)

Month	No Action (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	394	386	-4	-6
November	328	222	-54	-69
December	322	278	-25	-36
January	330	297	-19	-27
February	372	366	-3	-5
March	483	488	2	3
April	696	776	24	39
May	980	1062	17	27
June	726	780	15	24
July	325	340	9	14
August	282	300	13	20
September	280	275	-4	-5
Weighted average			9	21

Month	No Action (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	394	394	0	0
November	328	326	-1	-2
December	322	320	-1	-2
January	330	326	-2	-4
February	372	368	-2	-3
March	483	479	-2	-2
April	696	694	-1	-1
May	980	979	0	0
June	726	724	-1	-1
July	325	325	0	0
August	282	281	-1	-1
September	280	280	0	0
Weighted Average			-1	-1

Table SED-A.6.—Monthly flows and change in sediment transport capacity on the Truckee River near Reno in **very wet** hydrologic conditions

Month	Current conditions (cfs)	No Action (cfs)	Range in sediment transport capacity change (percent)	
October	647	690	14	21
November	776	693	-20	-29
December	1550	1460	-11	-16
January	1895	1779	-12	-17
February	2198	2101	-9	-13
March	2522	2431	-7	-10
April	3273	3111	-10	-14
May	3914	3816	-5	-7
June	2398	2349	-4	-6
July	1475	1468	-1	-1
August	402	402	0	0
September	337	347	6	0
Weighted average			-7	-10

Month	Current conditions (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	647	699	17	26
November	776	712	-16	-23
December	1550	1514	-5	-7
January	1895	1849	-5	-7
February	2198	2111	-8	-11
March	2522	2505	-1	-2
April	3273	3326	3	5
May	3914	3956	2	3
June	2398	2470	6	9
July	1475	1476	0	0
August	402	407	3	4
September	337	361	15	23
Weighted average			1	2

Table SED-A.6.—Monthly flows and change in sediment transport capacity on the Truckee River near Reno in **very wet** hydrologic conditions (continued)

Month	Current conditions (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	647	690	14	21
November	776	690	-21	-30
December	1550	1456	-12	-17
January	1895	1774	-12	-18
February	2198	2096	-9	-13
March	2522	2417	-8	-12
April	3273	3098	-10	-15
May	3914	3812	-5	-8
June	2398	2348	-4	-6
July	1475	1467	-1	-2
August	402	401	0	-1
September	337	347	6	9
Weighted average			-7	-11

Month	No Action (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	690	699	3	4
November	693	712	6	8
December	1460	1514	8	12
January	1779	1849	8	12
February	2101	2111	1	1
March	2431	2505	6	9
April	3111	3326	14	22
May	3816	3956	7	11
June	2349	2470	11	16
July	1468	1476	1	2
August	402	407	3	4
September	347	361	8	13
Weighted average			8	13

Table SED-A.6.—Monthly flows and change in sediment transport capacity on the Truckee River near Reno in **very wet** hydrologic conditions (continued)

Month	No Action (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	690	690	0	0
November	693	690	-1	-1
December	1460	1456	-1	-1
January	1779	1774	-1	-1
February	2101	2096	0	-1
March	2431	2417	-1	-2
April	3111	3098	-1	-1
May	3816	3812	0	0
June	2349	2348	0	0
July	1468	1467	0	0
August	402	401	0	-1
September	347	347	0	0
Weighted average			0	-1

D. Erosion on Truckee River: McCarran Boulevard to Derby Diversion Dam (Lockwood)

Comparisons are made between all of the alternatives for both median hydrologic conditions and very wet hydrologic conditions on a monthly basis for the Truckee River: McCarran Boulevard to Derby Diversion Dam (Lockwood) in table SED-A.7. The minimum threshold set for an impact for sediment transport capacity is a positive change of 10 percent. For current conditions vs. No Action, sediment transport capacity change is greater than 10 percent in October in median hydrologic conditions. Also for current conditions vs. TROA, sediment transport capacity change does not exceed the threshold change in median hydrologic conditions. For No Action vs. TROA, sediment transport capacity change exceeds the threshold change for May, June, July, and September. In very wet hydrologic conditions, sediment capacity change is exceeded for current conditions vs. No Action in October, August, and September and for current conditions vs. TROA in October, June, July, and September. For No Action vs. TROA, sediment transport capacity is greater in April and June.

In median hydrologic conditions, monthly sediment capacity change is less in every month than under current conditions. Thus, much less sediment transport likely would occur in this reach under No Action or LWSA than under current conditions, and significant deposition is possible. Steamboat Creek is a potential source of sediment within this reach. More sediment transport could occur in this reach under TROA than under No Action, but because sediment transport capacity under TROA is almost the same or less than under current conditions, no significant erosion or sediment transport is expected in this reach.

Table SED-A.7.—Monthly flows and change in sediment transport capacity on the Truckee River between McCarran Blvd to Derby Diversion Dam (Lockwood) under **median** hydrologic conditions

Month	Current conditions (cfs)	No Action (cfs)	Range in sediment transport capacity change (percent)	
October	434	460	12	19
November	508	476	-12	-18
December	509	476	-13	-18
January	539	516	-8	-12
February	620	596	-8	-11
March	716	688	-8	-11
April	884	823	-13	-19
May	1142	1054	-15	-21
June	835	784	-12	-17
July	405	374	-15	-21
August	370	338	-17	-24
September	339	337	-1	-2
Weighted average			-11	-17

Month	Current conditions (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	434	452	8	13
November	508	377	-45	-59
December	509	433	-28	-38
January	539	474	-23	-32
February	620	579	-13	-19
March	716	702	-4	-6
April	884	910	6	9
May	1142	1152	2	3
June	835	846	3	4
July	405	391	-7	-10
August	370	360	-5	-8
September	339	330	-5	-8
Weighted average			-5	-3

Table SED-A.7.—Monthly flows and change in sediment transport capacity on the Truckee River between McCarran Blvd to Derby Diversion Dam (Lockwood) under **median** hydrologic conditions (continued)

Month	Current Conditions (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	434	460	12	19
November	508	478	-11	-17
December	509	478	-12	-17
January	539	519	-7	-11
February	620	598	-7	-10
March	716	691	-7	-10
April	884	825	-13	-19
May	1142	1054	-15	-21
June	835	785	-12	-17
July	405	374	-15	-21
August	370	339	-16	-23
September	339	338	-1	-1
Weighted average		614	-11	-17

Month	No Action (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
November	460	452	-3	-5
December	478	377	-38	-51
January	478	433	-18	-26
February	519	474	-17	-24
March	598	579	-6	-9
April	691	702	3	5
May	825	910	22	34
June	1054	1152	19	31
July	785	846	16	25
August	374	391	9	14
September	339	360	13	20
	338	330	-5	-7
Weighted average			7	17

Table SED-A.7.—Monthly flows and change in sediment transport capacity on the Truckee River between McCarran Blvd to Derby Diversion Dam (Lockwood) under **median** hydrologic conditions (continued)

Month	No Action (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
November	460	460	0	0
December	478	476	-1	-1
January	478	476	-1	-1
February	519	516	-1	-2
March	598	596	-1	-1
April	691	688	-1	-1
May	825	823	0	-1
June	1054	1054	0	0
July	785	784	0	0
August	374	374	0	0
September	339	338	-1	-1
	338	337	-1	-1
Weighted average			0	-1

Table SED-A.7.—Monthly flows and change in sediment transport capacity on the Truckee River between McCarran Blvd. and Derby Diversion Dam in **very wet** hydrologic conditions

Month	Current conditions (cfs)	No Action (cfs)	Range in sediment transport capacity change (percent)	
October	745	775	8	13
November	930	902	-6	-9
December	1726	1717	-1	-2
January	2098	2054	-4	-6
February	2408	2394	-1	-2
March	2723	2697	-2	-3
April	3410	3308	-6	-9
May	3976	3891	-4	-6
June	2493	2448	-4	-5
July	1556	1547	-1	-2
August	461	454	-3	-4
September	402	408	3	5
Weighted average			-3	-6

Table SED-A.7.—Monthly flows and change in sediment transport capacity on the Truckee River between McCarran Blvd. and Derby Diversion Dam in **very wet** hydrologic conditions (continued)

Month	Current conditions (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	745	768	6	10
November	930	915	-3	-5
December	1726	1772	5	8
January	2098	2123	2	4
February	2408	2403	0	-1
March	2723	2770	3	5
April	3410	3478	4	6
May	3976	4032	3	4
June	2493	2550	5	7
July	1556	1548	-1	-2
August	461	457	-2	-3
September	402	416	7	11
Weighted average			3	5

Month	Current Conditions (cfs)	LWSA	Range in sediment transport capacity change (percent)	
October	745	775	8	13
November	930	899	-7	-10
December	1726	1714	-1	-2
January	2098	2051	-4	-7
February	2408	2391	-1	-2
March	2723	2685	-3	-4
April	3410	3298	-6	-10
May	3976	3888	-4	-6
June	2493	2447	-4	-5
July	1556	1545	-1	-2
August	461	454	-3	-4
September	402	408	3	5
Weighted average			-4	-6

Table SED-A.7.—Monthly flows and change in sediment transport capacity on the Truckee River between McCarran Blvd. and Derby Diversion Dam in **very wet** hydrologic conditions (continued)

Month	No Action (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	775	768	-2	-3
November	902	915	3	4
December	1717	1772	7	10
January	2054	2123	7	10
February	2394	2403	1	1
March	2697	2770	5	8
April	3308	3478	11	16
May	3891	4032	7	11
June	2448	2550	9	13
July	1547	1548	0	0
August	454	457	1	2
September	408	416	4	6
Weighted average			7	11

Month	No Action (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	775	775	0	0
November	902	899	-1	-1
December	1717	1714	0	-1
January	2054	2051	0	0
February	2394	2391	0	0
March	2697	2685	-1	-1
April	3308	3298	-1	-1
May	3891	3888	0	0
June	2448	2447	0	0
July	1547	1545	0	0
August	454	454	0	0
September	408	408	0	0
Weighted average			0	-1

E. Erosion on the Lower Truckee River between Derby Diversion Dam and Pyramid Lake

Comparisons are made between all of the alternatives for both median hydrologic conditions and very wet hydrologic conditions on the Truckee River between Derby Diversion Dam and Pyramid Lake on a monthly basis in table SED-A.8. For current conditions vs. No Action, sediment transport capacity change is greater than 10 percent in October, August, and September in median hydrologic conditions. Also for current conditions vs. TROA, sediment transport capacity change is greater than 10 percent for October, June, July, and September. For No Action vs. TROA, sediment transport capacity change is greater for April and June. In very wet hydrologic conditions, sediment capacity change is greater for current conditions vs. No Action in September. For No Action vs. TROA, sediment transport capacity change is greater than 10 percent in April and June. The results suggest that almost the same sediment transport likely would occur in this reach under TROA and current conditions.

Table SED-A.8.—Monthly flows and change in sediment transport capacity on the Truckee River between Derby Diversion Dam and Pyramid Lake in **median** hydrologic conditions

Month	Current conditions (cfs)	No Action (cfs)	Range in sediment transport capacity change (percent)	
October	396	429	17	27
November	486	455	-12	-18
December	493	448	-17	-25
January	533	497	-13	-19
February	613	590	-7	-11
March	715	674	-11	-16
April	821	745	-18	-25
May	1012	1000	-2	-4
June	667	657	-3	-4
July	300	300	0	0
August	200	264	74	130
September	246	291	40	66
Weighted average			-6	-11

Table SED-A.8.—Monthly flows and change in sediment transport capacity on the Truckee River between Derby Diversion Dam and Pyramid Lake in **median** hydrologic conditions (continued)

Month	Current conditions (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	396	432	19	30
November	486	308	-60	-75
December	493	328	-56	-71
January	533	424	-37	-50
February	613	561	-16	-23
March	715	688	-7	-11
April	821	833	3	4
May	1012	1041	6	9
June	667	748	26	41
July	300	300	0	0
August	200	262	72	125
September	246	284	33	54
Weighted average			-5	-2

Month	Current conditions (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	396	429	17	27
November	486	453	-13	-19
December	493	445	-19	-26
January	533	494	-14	-20
February	613	587	-8	-12
March	715	671	-12	-17
April	821	743	-18	-26
May	1012	1000	-2	-4
June	667	658	-3	-4
July	300	300	0	0
August	200	265	76	133
September	246	291	40	66
Weighted average			-7	-11

Table SED-A.8.—Monthly flows and change in sediment transport capacity on the Truckee River between Derby Diversion Dam and Pyramid Lake in **median** hydrologic conditions (continued)

	No Action (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	429	432	1	2
November	455	308	-54	-69
December	448	328	-46	-61
January	497	424	-27	-38
February	590	561	-10	-14
March	674	688	4	6
April	745	833	25	40
May	1000	1041	8	13
June	657	748	30	48
July	300	300	0	0
August	264	262	-2	-2
September	291	284	-5	-7
Weighted average			2	9

Month	No Action (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	429	429	0	0
November	455	453	-1	-1
December	448	445	-1	-2
January	497	494	-1	-2
February	590	587	-1	-2
March	674	671	-1	-1
April	745	743	-1	-1
May	1000	1000	0	0
June	657	658	0	0
July	300	300	0	0
August	264	265	1	1
September	291	291	0	0
Weighted average			0	-1

Table SED-A.8.—Monthly flows and change in sediment transport capacity on the Truckee River between Derby Diversion Dam and Pyramid Lake in **very wet** hydrologic conditions

Month	Current conditions (cfs)	No Action (cfs)	Range in sediment transport capacity change (percent)	
October	732	752	6	8
November	911	867	-9	-14
December	1774	1748	-3	-4
January	2145	2086	-5	-8
February	2453	2438	-1	-2
March	2748	2708	-3	-4
April	3396	3302	-5	-8
May	3904	3850	-3	-4
June	2419	2389	-2	-4
July	1443	1464	3	4
August	300	300	0	0
September	300	342	30	48
Weighted average			-3	-5

Month	Current conditions (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	732	749	5	7
November	911	877	-7	-11
December	1774	1803	3	5
January	2145	2156	1	2
February	2453	2455	0	0
March	2748	2770	2	2
April	3396	3468	4	6
May	3904	3992	5	7
June	2419	2493	6	9
July	1443	1467	3	5
August	300	300	0	0
September	300	305	3	5
Weighted average			3	5

Table SED-A.8.—Monthly flows and change in sediment transport capacity on the Truckee River between Derby Diversion Dam and Pyramid Lake in **very wet** hydrologic conditions (continued)

Month	Current conditions (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	732	752	6	8
November	911	864	-10	-15
December	1774	1745	-3	-5
January	2145	2083	-6	-8
February	2453	2435	-1	-2
March	2748	2696	-4	-6
April	3396	3296	-6	-9
May	3904	3847	-3	-4
June	2419	2389	-2	-4
July	1443	1463	3	4
August	300	300	0	0
September	300	342	30	48
Weighted average			-3	-5

Month	No Action (cfs)	TROA (cfs)	Range in sediment transport capacity change (percent)	
October	752	749	-1	-1
November	867	877	2	4
December	1748	1803	6	10
January	2086	2156	7	10
February	2438	2455	1	2
March	2708	2770	5	7
April	3302	3468	10	16
May	3850	3992	8	11
June	2389	2493	9	14
July	1464	1467	0	1
August	300	300	0	0
September	342	305	-20	-29
Weighted average			7	11

Table SED-A.8.—Monthly flows and change in sediment transport capacity on the Truckee River between Derby Diversion Dam and Pyramid Lake in **very wet** hydrologic conditions (continued)

Month	No Action (cfs)	LWSA (cfs)	Range in sediment transport capacity change (percent)	
October	752	752	0	0
November	867	864	-1	-1
December	1748	1745	0	-1
January	2086	2083	0	0
February	2438	2435	0	0
March	2708	2696	-1	-1
April	3302	3296	0	-1
May	3850	3847	0	0
June	2389	2389	0	0
July	1464	1463	0	0
August	300	300	0	0
September	342	342	0	0
Weighted average			0	0

IV. TRUCKEE RIVER DELTA FORMATION AT PYRAMID LAKE

Predicted model elevation change by alternative is shown in table SED-A.9 for Pyramid Lake. The threshold for consideration of an environmental impact at Pyramid Lake is no more than a 0.5 foot reduction in elevation by alternative on a monthly basis, when a comparison is made between the alternative and current conditions or No Action. A comparison of current conditions to No Action in median, very wet, and very dry hydrologic conditions indicates very little difference in elevation change between any of the modeling scenarios. A comparison of LWSA to current conditions shows no impact for any elevation change on a monthly basis for any modeling scenario. On a positive basis, LWSA shows a greater positive elevation change in the months of March through May. A comparison of TROA to current conditions in median, very wet, and very dry hydrologic conditions shows that none of the monthly elevation changes between TROA and current conditions decrease as much as 0.2 foot. Therefore, no impacts would be associated with TROA for the Truckee River delta. A comparison of No Action and LWSA shows very little difference in elevation changes by month for each modeling scenario. As a positive impact, LWSA shows more positive elevation change in the months of March through June. A comparison of No Action to TROA shows very little difference in elevation changes by month for each modeling scenario.

Sediment capacity changes by alternative for inflow to Pyramid Lake also can be identified with no environmental impacts. The change in annual sediment transport capacity under the all of the alternatives does not exceed the average threshold change of 10 percent when compared to either current conditions or No Action. Therefore, the potential for erosion for this reach is no greater than under either current conditions or No Action.

Table SED-A.9.—Water elevation differences at Pyramid Lake in very wet, median, and very dry hydrologic conditions

Month	Current			No Action			LWSA			TROA		
	Median	90%	10%	Median	90%	10%	Median	90%	10%	Median	90%	10%
Oct.	-0.16	-0.38	0.00	-0.16	-0.39	0	-0.165	-0.39	0.08	-0.2	-0.37	0
Nov.	-0.15	-.371	0.09	-0.15	-0.335	0.151	-0.15	-0.331	0.17	-0.16	-0.361	0.087
Dec.	-0.08	-.312	0.41	-0.08	-0.321	0.399	-0.08	-0.311	0.6355	-0.12	-0.32	0.495
Jan.	0.08	-0.16	0.77	0.08	-0.175	0.741	0.075	-0.175	1.045	0	-0.17	0.783
Feb.	0.16	-0.087	0.87	0.16	-0.15	0.801	0.16	-0.087	0.9615	0.15	-0.15	0.853
March	0.24	-0.08	0.90	0.225	-0.087	0.832	0.22	-0.08	1.1825	0.195	-0.087	0.93
April	0.23	-0.08	1.03	0.195	-0.08	0.945	0.17	-0.08	1.3125	0.23	-0.08	1.006
May	0.38	-0.071	1.35	0.38	-0.07	1.347	0.39	-0.07	1.9795	0.39	-0.07	1.361
June	0.08	-0.232	0.62	0.08	-0.221	0.566	0.08	-0.221	0.8925	0.08	-0.221	0.641
July	-0.31	-0.514	0.00	-0.31	-0.522	-0.072	-0.31	-0.524	0.247	-0.305	-0.514	0
Aug.	-0.43	-0.58	-0.29	-0.4	-0.56	-0.304	-0.41	-0.56	-0.2175	-0.4	-0.55	-0.259
Sept.	-0.39	-.551	-0.24	-0.38	-0.513	-0.23	-0.38	-0.52	-0.16	-0.38	-0.541	-0.54

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Shorezone Erosion at Lake Tahoe: Historical Aspects, Processes, and Stochastic Modeling

FINAL REPORT FOR THE
U.S. BUREAU OF RECLAMATION
and
TAHOE REGIONAL PLANNING AGENCY

March 31, 2004

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Desert Research Institute

Table of Contents

Chapter 1
Introduction and Background

Introduction

This report summarizes results and interpretations of Lake Tahoe shorezone studies begun by the Desert Research Institute (DRI) in spring 2000. These studies were originally undertaken to quantify the amount of shorezone erosion since 1940 and to derive estimates of how much sediment and nutrients were introduced into the lake from this source. The studies gradually evolved to include monitoring and characterizing wave activity at the lake, quantifying particle size distributions of shorezone sediments eroded into the lake, and investigating processes of shorezone erosion. Most recently, we have developed stochastic models that predict where and how much shorezone erosion will occur given a set of controlling parameters and a separate modeling approach to assess the effects of different lake-level management schemes on shorezone erosion. In this report, the emphasis is on lateral changes to the shore position and not vertical changes to beach areas. The report is arranged into the following chapters:

- Chapter 1 provides background on previous Lake Tahoe studies that are relevant to shorezone erosion including the physical setting, climate, wave activity, water quality, and shorezone system.
- Chapter 2 includes information on development of the modern shorezone system at Lake Tahoe, the effects of shorezone protective structures on nearshore processes in general, and the possible effects of these types of structures at Lake Tahoe in particular.
- Chapter 3 discusses development of a technique to document the amount of historic shorezone erosion at Lake Tahoe since about 1940 when the earliest aerial photographs were made. This chapter also includes information about particle-size distributions of shorezone sediments. Chapter 3 was published in its present form, except for the particle-size data, in the *Journal of Coastal Research* (Adams and Minor, 2002).
- Chapter 4 presents instrumental wave monitoring procedures, data reduction techniques, and results documenting the wave climate at Lake Tahoe. Also discussed are relationships among wind, waves, and the amount of wave energy impacting a shore from different wave events.
- Chapter 5 presents results of an effort to develop a series of statistical models to predict where shorezone erosion will occur and how much material will be eroded, given a set of governing parameters. The approach uses data from Chapter 3 to develop statistical models but also incorporates field data and analytical modeling of wave run up processes.
- Chapter 6 presents results of a statistical analysis to assess the effects of different lake-level management scenarios on shorezone erosion. In particular, we address the question of whether or not the Truckee River Operating Agreement (TROA), if implemented, would significantly affect shorezone erosion.

Background

Physical Setting of Lake Tahoe

The geologic history of the Lake Tahoe basin provides an important context for studying the shorezone system of this high elevation lake. In particular, the Quaternary (0 to 2,000,000 years ago) 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 shorezone change at Lake Tahoe. Therefore, this section includes a brief discussion of the early geologic development of the Lake Tahoe basin and focuses on the more recent history when glaciers repeatedly advanced and receded and lake levels rose and fell for reasons that are not as yet entirely understood. This section is based on existing literature and from observations made during the course of this study.

Lake Tahoe sits astride the crest of the Sierra Nevada in a large tectonic graben still bounded by active faults. This graben is the westernmost expression of Basin and Range extension at this latitude and is bounded on the east side by the Carson Range and on the west by the Sierra Nevada crest (Gardner et al., 2000). Although faults are more difficult to discern on land in the Tahoe basin, young fault scarps traversing the floor of the lake demonstrate that this basin is still tectonically active (Gardner et al., 1999; Kent et al., 2000). The majority of exposed bedrock in the basin consists of granitic rocks, but the north end is filled with a large pile of Tertiary and Pleistocene volcanic rocks. Scattered metamorphic rocks, particularly around Mt. Tallac, also exist in the basin (Burnett, 1971).

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

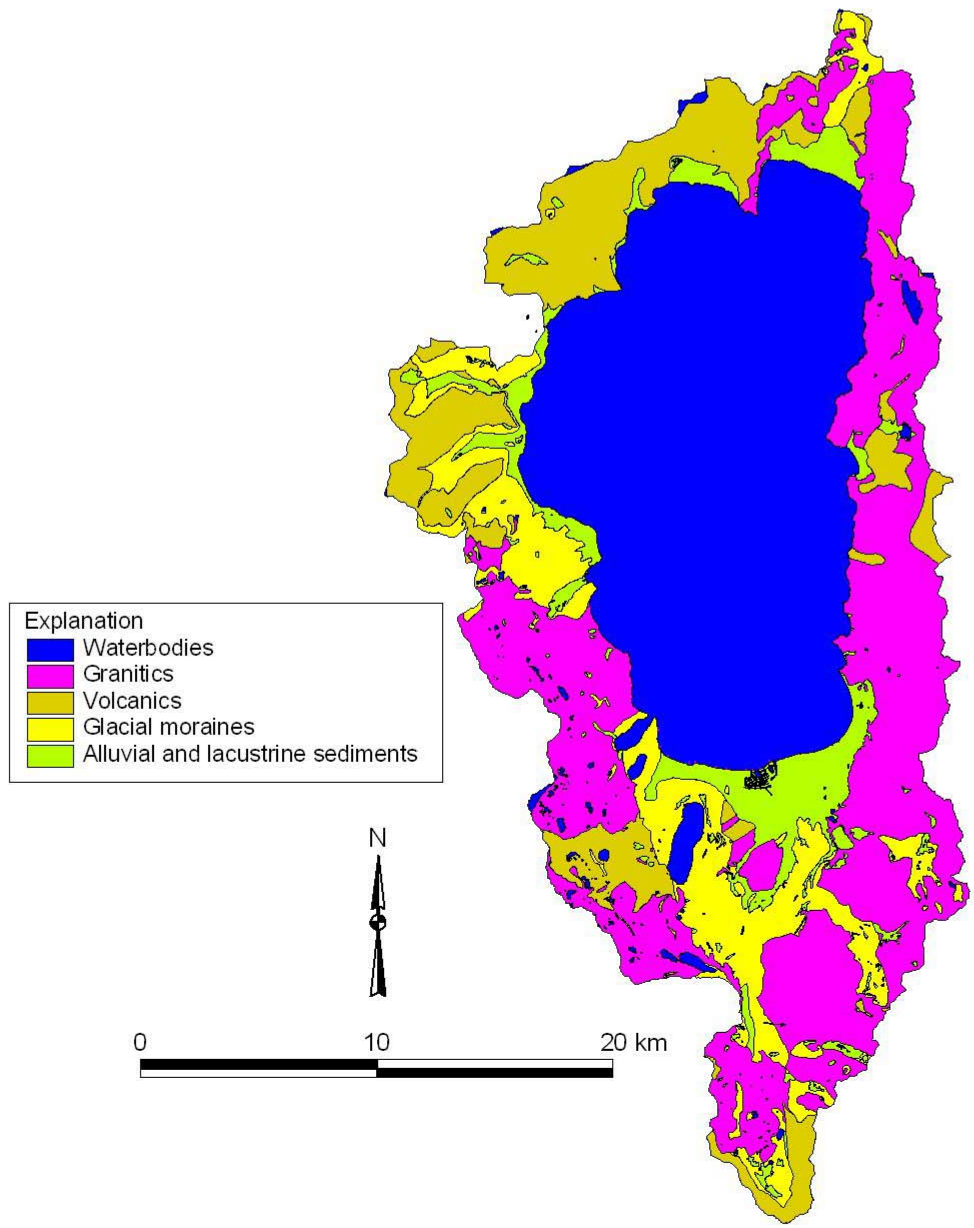

Figure 1-1. Simplified geologic map of the Lake Tahoe basin showing the distribution of rocks and sediment.

Glacial deposits adjacent to the lake generally date from one of three major glacial episodes that include—from oldest to youngest—the Donner Lake, Tahoe, and Tioga glaciations. The Donner Lake glaciation has been difficult to date but may be as old as 400,000 to 600,000 years (Birkeland, 1964). Till and moraines of Tahoe age have not been directly dated in the basin but correlative deposits along the eastern side of the Sierra Nevada near Yosemite date from about 70,000 years ago, 140,000 years ago, or from both times (Bursik and Gillespie, 1993; Phillips et al., 1990). The Tioga glaciation was the last major glaciation and reached its maximum advance around 20,000 years ago, although large expanses of ice still may have been present as late as about 14,000 years ago (James et al., 2002).

The abundance of lake deposits cropping out near the shore of Lake Tahoe indicates that lake level, at times, has been much higher than the current level of 1899 m. Periodic ice dams just downstream from the lake outlet may have been one cause of these higher lake levels. Birkeland (1964) presents evidence that all three of the major glacial episodes may have dammed Lake Tahoe and caused higher than present lake levels. During Donner Lake time, most of the Truckee River Canyon was filled with ice flowing east from the Sierran crest. Lake deposits and benches found at elevations up to 2073 m may relate to this damming episode (Birkeland, 1964). In Tahoe time, ice from Squaw Creek blocked the Truckee River and caused Lake Tahoe to rise to about 1926 m before the dam broke. The sudden release of more than 14 cubic kilometers of water caused a catastrophic flood that coursed down the river and eventually ended up in Lake Lahontan, a large pluvial lake that at times occupied much of northwestern Nevada (Morrison, 1991). Birkeland (1964) thought that ice damming was negligible in Tioga time, even though his mapping clearly shows that Tioga ice blocked the Truckee River to an elevation of about 1902 m, or approximately 5 m above the natural outlet. The volume of water ponded by a dam at 1902 m equates to about 3 cubic kilometers, enough for a large flood event.

During the middle Holocene (4,000 to 7,000 years ago), lake level at Tahoe may have fallen below the natural rim for an extended period. Lindstrom (1990) presents evidence that rising waters between 4,000 and 5,000 years ago drowned currently submerged trees along the southern shore of Tahoe. The implication is that Tahoe did not spill for an extended period, allowing forests to colonize areas adjacent to the lower lake level. When climate became effectively wetter around 4000 years ago, Lake Tahoe again rose to its rim and drowned these trees. Davis et al. (1976) reviewed physical evidence for lower lake levels during this same time period. In particular, the major drainages of the upper Truckee River, Trout Creek, and Taylor Creek were graded to base levels much lower than present and deeply dissected into the glacial outwash plains along the south shore. When water level began to rise at the end of the middle Holocene, these drainages were backfilled and beach barriers developed at the lake-marsh interfaces. According to this model, much of the material filling the marshes around Lake Tahoe dates from the last few thousand years.

In the early part of the 20th century, lake levels commonly exceeded the now legally mandated maximum elevation of 1896.65 m (6229.1 ft) (Fig. 1-2). The highest historic level was in 1907 when the lake rose above 1899.29 m (6231.19 ft). Shoreline erosion undoubtedly occurred during these high water periods, but the aerial photography used in our study (Chapter 3) does not extend far enough back in time to capture the effects of these periods.

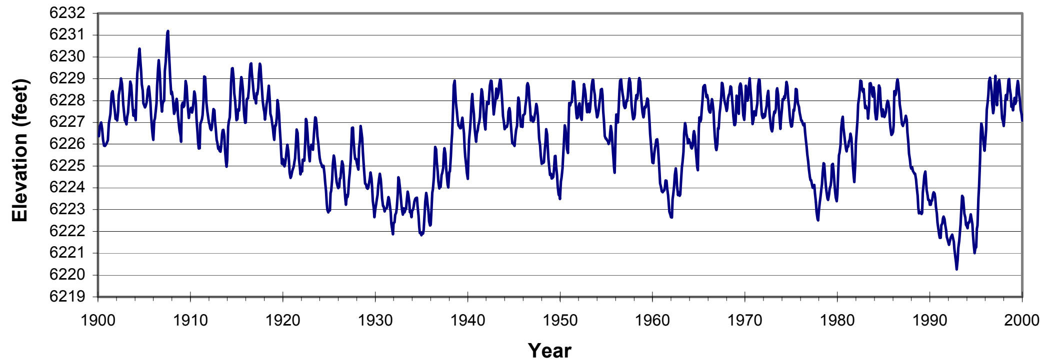

Figure 1-2. Lake levels at Lake Tahoe from 1900 to 2000.

Climate

The climate of Lake Tahoe is strongly influenced by topography and moist Pacific air masses traversing the area from the eastern Pacific Ocean (TRPA Staff, 1971). Elevations range from about 1898.65 m (maximum lake level) to more than 2750 m along both the Sierra crest to the west of the basin and the Carson Range bounding the east side of the lake. Even at the scale of the basin, a strong climatic gradient exists where average annual precipitation ranges up to 125 cm on the western side of the basin but only about 60 cm of precipitation falls along the east shore of the lake. Precipitation falls primarily in the winter months (November through March) as snow from Pacific frontal systems. Annual snowfall around the basin also reflects the climatic gradient. Tahoe City in the northwest part of the basin receives an average annual snowfall of 480 cm, whereas Glenbrook on the east shore and Stateline at the south shore only receive 243 and 161 cm of snowfall, respectively (data from Western Regional Climate Center, Desert Research Institute). Although abundant snow falls on the basin, winter temperatures are relatively mild with daytime high temperatures during January averaging between 2 and 4^{o} C at the lower elevations (TRPA Staff, 1971). Because of its large size and heat capacity, the lake actually has an ameliorating effect on winter temperatures—areas further from the lake are usually colder than areas along the lakeshore. Of course, elevation also plays an important role in controlling local temperature gradients. Summer temperatures around the lake are also mild, with highs commonly in the 21 to 27^{o} C range.

The climate of the Lake Tahoe basin has a strong controlling influence on its hydrology. Most of the annual precipitation is stored as a thick snowpack during the winter months and is released during spring snowmelt. This can be seen in the lake-level record (Fig. 1-2) that shows levels increasing each spring to an annual maximum in early summer, which then generally declines until the next snowmelt season. The timing of these high-water periods has important ramifications for shoreline erosion because it is likely that the most severe erosion occurs when strong winds blow across the lake when the water level is high.

Winds, Waves, Seiches, and Shoreline Erosion

Until recently, limited quantitative data was collected on concerning winds in the basin and how they affect wave generation, seiching, and shoreline erosion. The Western Regional Climate Center (WRCC) at DRI archived wind data from the South Lake Tahoe airport beginning in 1992, but this data is limited for wave growth studies because the site is far from the lakeshore and winds were only recorded during daylight hours. For the years prior to 1992, wind data is available for only sporadic periods. Wind velocity and direction were reported from the South Lake Tahoe airport from 1965 through 1967 (TRPA Staff, 1971), but again these statistics are for winds occurring only during daylight hours. Wind statistics also were reported by the U.S. Coast Guard Station at Tahoe City for the period January 1967 to September 1969 (TRPA Staff, 1971). Unfortunately, wind observations during this period were recorded just twice daily, once in the morning and once in the afternoon, so the duration of wind events is not known. Both Orme (1971) and Engstrom (1978) used wind statistics for Tahoe City to infer wave conditions, but both authors were hampered in their analyses by the lack of wind duration information which is critical for wave growth formulae.

More recently, Air Resource Specialists, Inc. (ARS) has been collecting wind data from at least three different sites near Lake Tahoe. These include D.L. Bliss State Park in the southwestern part of the basin, Thunderbird Lodge on the northeastern shore, and South Lake Tahoe Boulevard at South Shore. Data from these sites is discussed more thoroughly in Chapters 4 and 5.

Two other studies concerning wind conditions at Lake Tahoe are worthy of note. First, a study by Mulberg (1984) delineated seasonal wind patterns. The original report, however, has proved difficult to obtain. The only usable information is a series of figures reproduced in a guidebook article by Moory and Osborne (1984). These figures show winds in all seasons primarily from the south and southwest. From the regular wind flow patterns shown in the figures, however, it seems that local topographic effects were not considered in this study. In this same guidebook article (Moory and Osborne, 1984), a reference is made to wind data from eight locations along the shore of Lake Tahoe. Unfortunately, it is unclear whether this data was ever published; attempts to acquire the data have been fruitless.

Existing quantitative wave information for Lake Tahoe is also sparse. Orme (1971) reported that waves could reach up to 2 – 3 m in height, but waves of this magnitude were not observed. Instead, this range probably was derived from maximum fetch distances and theoretical considerations using the wave growth formulae suggested by the U.S. Army Corps of Engineers (CERC, 1984). Engstrom (1978) also used wave hindcasting procedures outlined in the Shore Protection Manual (CERC, 1984) combined with wind data reported by the Tahoe Regional Planning Agency (TRPA) for Tahoe City (TRPA Staff, 1971) to hindcast waves at Lake Tahoe. Again, because winds specified by both velocity and duration were lacking from the TRPA data set, Engstrom's (1978) analysis is considered preliminary.

Lake Tahoe, like virtually all inland water bodies, is subject to seiches, which are defined as periodic oscillations of a body of water the period of which is determined by resonant characteristics of the containing basin as controlled by its physical dimensions (McGarr and Vorhis, 1968). This means that each basin has a fundamental period of oscillation controlled by the size of the basin, regardless of the magnitude of the initial impulse. A seiche can be created in any number of ways including changes in atmospheric pressure over one part of the water body or by wind stress that causes the water surface to slope and pile-up at the downwind side of the lake (Carter, 1988). When the wind subsides, the water surface oscillates at a period determined by the dimensions of the basin. At a lake shore, occurrence of a seiche would appear as a sudden rise or fall in the water level. The importance of seiches to shorezone erosion is that they can temporarily raise water level along parts of a shore, allowing waves to penetrate further inland and cause accelerated erosion.

LeConte (1884) was the first to discuss the occurrence of seiches at Lake Tahoe, although they were not actually observed by him. Interviews with residents at the time suggested that sudden lake-level changes occasionally had occurred. LeConte (1884) estimated that the fundamental period of a seiche occurring at Lake Tahoe would be about 17 minutes in the north-south direction and about 10 minutes in the east-west direction. The maximum amplitude is currently unknown.

Budlong (1971) discusses the potential for seiches at Lake Tahoe and cites personal observations of seiches ranging in amplitude from 13 to 23 cm. Dramatic photographs documenting these relatively sudden changes in water level emphasize the potential importance of this phenomenon to shorezone erosion (Budlong, 1971). On a moderately sloping beach along the south shore, lateral distance in wave runup appeared to change by as much as several meters with a seiche of about 13 cm (Budlong, 1971).

Although there is substantial anecdotal evidence for shorezone erosion at Lake Tahoe, few detailed studies exist quantifying the rates of erosion and the conditions under which it occurred. A notable exception is the previously mentioned work of Budlong (1971) who studied processes and rates of shorezone erosion in the area of the then newly built Tahoe Keys development. In this work, he documented that rapid erosion occurred immediately west 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 a distance of about 150 m. In this case, longshore drift was from the east, driven by easterly winds during the winter months. Budlong (1971) also surmised that willow-clearing activities along the shore by Tahoe Keys personnel substantially contributed to the magnitude of shore retreat by eliminating the root-binding effects of the vegetation.

Studies by Orme (1971, 1972) do not specifically quantify shorezone erosion, but they do provide useful information about the shorezone system of Lake Tahoe and factors affecting erosion. Orme (1971) presents an excellent discussion of the shorezone system at Lake Tahoe, the natural processes occurring along the shore, and how human activities have altered the shorezone system and may continue to do so in the future. A significant contribution of 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 (Fig. 1-3). A second significant contribution of this early report is that it served as the basis for constructing a shorezone plan for Lake Tahoe (Orme, 1972) that was officially adopted by TRPA in 1976 (TRPA Staff, 1999). Orme (1972) stated that eroding shorelines comprise 16.3% of the Lake Tahoe shoreline and wave-cut escarpments ranging in height from 0.5 to 18 m backed eroding shorelines.

Osborne et al. (1985) provide a comprehensive review 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 master theses that include the studies of Waldron (1982), Edelman (1984), and Gaynor (1984). The major conclusions of Osborne et al. (1985), with respect to shorezone erosion, are that 1) the principal sediment source for the major sand beaches at Lake Tahoe is the backshore erosion of young lacustrine and fluvio-glacial outwash; 2) the major sediment source for the gravel and cobble beaches is also erosion of backshore areas and possibly 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 (Fig. 1-3).

Reuter and Miller (2000) report the results of a preliminary study to determine the mass of sediment and nutrients introduced into the lake from shorezone erosion. In this study, the authors 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 shorezone erosion. The results 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 (Reuter and Miller, 2000). These values will serve as a direct comparison to the estimates derived from the present study.

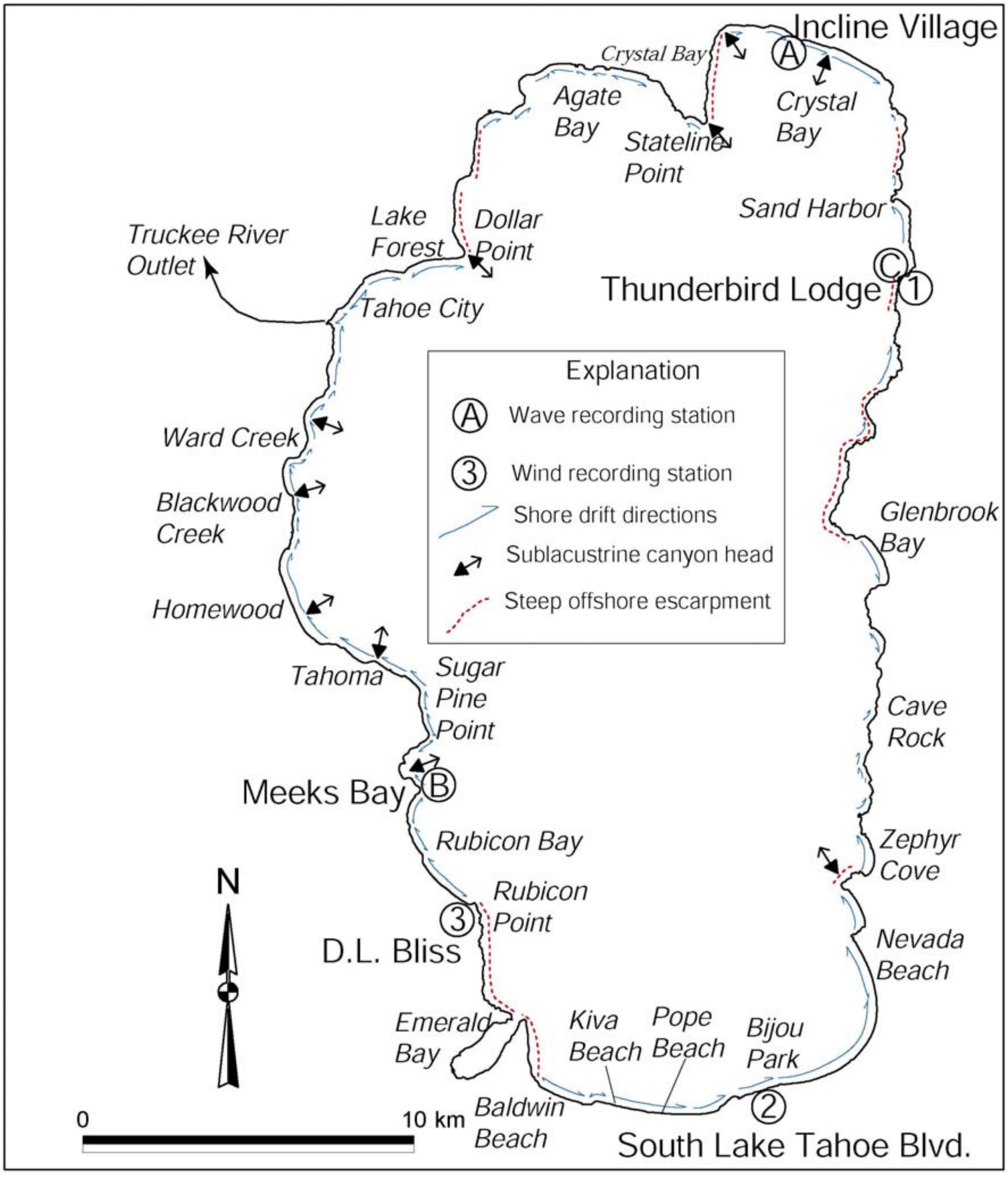

Figure 1-3. Map of Lake Tahoe showing dominant shore drift directions, locations of sublacustrine canyon heads, steep offshore escarpments, wave recording stations, wind recording stations, and locations mentioned in the report. Both the sublacustrine canyon heads and steep offshore escarpments are probably 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.

Water Quality

Since the 1960s, hundreds of scientific papers and reports have been written about the Lake Tahoe watershed and its water quality. Up until recently, however, a comprehensive review and synthesis did not exist. The Lake Tahoe Watershed Assessment (Murphy and Knopp, 2000) fulfills this role by presenting the "state of the science" in what is known about environmental conditions, air quality, aquatic resources, water quality, limnology, biological integrity, and socioeconomic issues within the basin. In particular, one of the stated goals (Aquatic resources, water quality, and limnology of Lake Tahoe and its upland watershed; Reuter and Miller, 2000) is to provide "a comprehensive review of past studies with the focus of assessing both upland and lake water quality." The authors of this chapter succeed admirably at this task by reviewing and synthesizing approximately 450 reports, published papers, and other documents; a repeat of the information here would be redundant. Several publications were not included in the review, however, and warrant mention here.

Nolan and Hill (1991) derived suspended sediment budgets for four tributaries to Lake Tahoe during a four-year period (1984-87) and concluded that bed and bank erosion were the major sources of sediment during the period of study. They found that differences in climate, geology, basin physiography, and land use controlled the differences in sediment production from each of the study drainages. Two of the major implications from this study are that the hillslopes appear to be relatively disconnected from the fluvial systems and that land use changes within each of the drainages could lead to increased suspended sediment delivery to the lake.

Kilroy et al. (1997) provide an important synopsis of past United States Geological Survey (USGS) monitoring activities in the Tahoe basin and include tables and maps of all monitoring stations, their periods of record, and what constituents were analyzed. This document provides a valuable starting place for anyone implementing a water quality monitoring program in the Lake Tahoe basin.

Rowe and Allander (2000) studied the interactions between surface and groundwater for the Upper Truckee River and Trout Creek for the period July through December 1996. One of the major conclusions from this study is that in the upper sections of the watersheds, groundwater flow is generally toward the streams while in the lower reaches, groundwater flow generally parallels both the Upper Truckee and Trout Creek. Another important point is that during the latter part of their study period (November 1996), the groundwater level beneath the lower reaches of the drainages was at about the same elevation as the surface of Lake Tahoe implying that there was minimal groundwater flow directly into the lake. It is unknown how fluctuations in lake level affect groundwater levels.

Chapter 2
Lake Tahoe Shorezone

Development of the Modern Shorezone System

Shorezone erosion at Lake Tahoe is a direct consequence of wave energy acting upon the shore. Although most winds at the lake blow from the south, long-term shorezone erosion is not entirely dependent on the direction and magnitude of prevailing winds. Instead, shorezone erosion during the last 60 years appears to have been largely dependent on the type of geologic materials found along the shore (Fig. 1-1) (Adams and Minor, 2002). The areas that appear to be most susceptible to erosion generally are composed of unconsolidated alluvial and lacustrine sediments, but shores composed of Tertiary volcanics at the north end of the lake also display evidence of recent wave erosion. Not coincidently, shorezone areas composed of unconsolidated sediment are also where the highest concentration of shorezone protective structures is found. In particular, the south and west shores of Lake Tahoe appear to have the most of protective structures, although specific data on exactly how much of the shoreline is protected is not available. Orme (1972) estimated that approximately 16.3% of the shoreline was eroding while Reuter and Miller (2000) assumed that about 55% of the shoreline was eroding. Based on the geologic materials found along the shore and observations made during the course of this study, we conclude that about 67% of the natural Tahoe shoreline is capable of erosion or has eroded since lake level was raised in the late 1800s. This estimate does not account for the percentage of shorezone protected by revetments or other structures. The only type of shore that appears relatively immune from shorezone erosion is that composed of granitic rocks, which make up much of the east shore and the area between Emerald Bay and Rubicon Point (Fig. 1-1).

Another major factor that controls shorezone erosion is spatial-temporal relationships between water level and wave energy. At Lake Tahoe, the largest erosive events occur when strong winds blow and lake level is at or near its maximum level of 1898.65 m (6229.1 ft). Because of dam operations at Lake Tahoe, lake level typically fluctuates between about 1898 m (6227 ft) and 1898.65 m (6229.1 ft) (Fig. 1-2) but occasionally drops lower due to subnormal snowpack. High water or full pool is generally reached around May or June and remains there only a brief time before lake level steadily declines until a low water level of about 1898 m (6227 ft) is reached in late fall or early winter. The strongest winds commonly occur in late fall and winter when large frontal systems move across the area from the eastern Pacific and lake level is not at full pool. An exception occurred in January 1997 when strong easterly winds combined with an abnormally high lake level (~1898.79 m) produced widespread and severe erosion on the western shore of the lake. Interestingly, the severe erosion suffered in 1997 along many parts of the shore does not necessarily reflect long-term trends (Adams and Minor, 2002). This may be due to the relative rarity of strong easterly winds blowing across a higher than typical lake level.

Prior to installation of the first dam at Tahoe City in the late 1880s, the natural spill point of the lake was at about 1896.8 m (6223 ft). The shorezone system that formed around the lake at this elevation was probably in relative equilibrium because lake level likely was unable to rise much above the spill point. The spill point is not composed of bedrock but of light-colored, dense clay covered with patches of sand and gravel. Although this seems like an unstable condition for a lake's overflow point, the cohesive clay actually provides a relatively stable lip.

The shorezone presently forming at the 1898.65 m (6229 ft) level, however, is probably not in equilibrium around much of Lake Tahoe because the lake surface has not been at this elevation for much time since the first dam was installed. What this means is that shorezone erosion around the lake probably proceeded rapidly after the dam was first installed and has decreased through time as more and more waves have impacted the shorezone in the ensuing 120 years. Although we are only able to quantify shorezone erosion back to about 1938 (date of the earliest aerial photographs), it is likely that much erosion occurred between when the first dam was installed and 1938.

After the dam was installed, the lake rose several times to levels above 1898.65 m (6229.1 ft) in the early part of the 20th century (Fig. 1-2). On five separate occasions, lake level exceeded the current maximum for periods of up to several months at a time. In terms of shorezone erosion, the two most important high water periods probably occurred in 1904 and again in 1907 when lake level was above the current maximum beginning in March and lasting through the summer months. The effect of these early high lake periods is not exactly known, but it is likely that they caused widespread erosion around the lake. Evidence of these early high water periods may be found at Baldwin Beach (Fig. 2-1) and Nevada Beach (Fig. 2-2) where young beach features are found about 1 m above the modern shore.

Higher than natural lake levels since the upper limit was leally established in 1935 are causing the shorezone system of Lake Tahoe to seek a new equilibrium condition. Along much of the eastern shore and other rocky areas, bedrock and boulders are sufficiently resistant to change that the higher lake level has had limited impact (Fig. 2-3). Along many other parts of the shore, however, large wave-cut escarpments, overhanging banks, and other signs of active shore erosion are present (Figs. 2-4 to 2-6). This suggests that in many places the shorezone is not yet in equilibrium. Given current management of the Lake Tahoe dam, shorezone erosion will continue but may decrease through time as more areas along the shore reach equilibrium. Continuing erosion represents a direct threat to many properties and structures along the shore and will result in the introduction of sediment and nutrients into Lake Tahoe for the foreseeable future.

Figure 2-1. Vertical aerial photograph of Baldwin Beach (August 19, 1995) showing a series of beach ridges inland from the modern beach ridge. The older, slightly higher beach ridge crests are marked by red lines, and the extent of these older beach deposits are outlined in yellow. The modern ridge is marked by a blue line. The older beach ridges may have formed in the early 20th century when lake levels reached above 1899.23 m (6231 ft). See Fig. 1-2.

Figure 2-2. Aerial photograph of Nevada Beach (August 25, 1963) showing large beach platform that may have formed in early part of the 20th century when lake levels exceeded 1898.65 m (6229.1 ft). The yellow line marks marks the landward limit of this feature. Note the change in vegetation.

Figure 2-3. Armored shore along the east side of Lake Tahoe. This type of shorezone is relatively resistant to erosion from waves.

Figure 2-4. Fresh wave-cut escarpment in unconsolidated sediments. The shoreline angle is the abrupt break in slope at the top of the beach and at the base of the escarpment.

Figure 2-5. Two views of a wave-cut escarpment at Lake Forest on the northern shore of Lake Tahoe. In the photograph to the left, taken on May 17, 2000, lake level is near maximum and wave activity can directly impact the backshore area. In the photograph below, taken at the same place on August 28, 2003, lake level is much lower. The shore has undergone erosion here since May, 2000, as evidenced by the blocks of sediment at the base of the small escarpment. This erosion probably occurred from undercutting by wave activity when water level was high.

Figure 2-6. Photograph of actively eroding shoreline at Sugar Pine Point on the western shore of Lake Tahoe. Note how the trees are being undercut, causing them to lean and eventually fall into the lake.

Shorezone Protective Structures and Their Effects on Coastal Processes

Shorezone protective structures are almost invariably designed and built to do one thing, protect the backshore area directly behind the structure from further erosion. They are not designed to protect the beach in front of the structure, nor are they designed to protect areas of the shore on either side of the structure. We make a distinction between static, vertical, impermeable structures and sloping, dynamic structures. Vertical seawalls and sheet pile structures are examples of the former and permeable structures composed of boulders, cobbles, and gravel are examples of the latter. In addition to the references cited within the text below, the following discussion is also based on the works of McDougal et al. (1987), Weggel (1988), Bruun (1988), Wood (1988), Kraus (1988), Komar and McDougal (1988), Griggs and Fulton-Bennett (1988), Griggs and Tait (1988), Plant and Griggs (1992), Lorang (1992), and Kraus and McDougal (1996).

The debate over whether or not seawalls or other types of "hard" engineering solutions negatively affect beaches has been vigorous during the last 20 years. At this time, there does not appear to be a clear consensus on how structures affect beach processes, probably because of the wide range of parameters that control how a particular beach system responds to changes in one or more of these parameters. However, much of the controversy about the harmful effects of sea walls on beaches could be due to practitioners failing to distinguish between "passive" and "active" erosion. Pilkey and Wright (1988) referred to passive erosion as being "…due to tendencies which existed before the wall was in place," and active erosion as being "…due to the interaction of the wall with local coastal processes." In other words, active erosion is when the wall or other type of revetment directly increases erosion in front of, or to either side of, the structure.

Seawalls and other types of static revetments can negatively interact with coastal processes in several ways, including reducing sediment supply, inhibiting storm response and recovery, shoreface steepening, and narrowing of the surf zone (Pilkey and Wright, 1988). Constructing seawalls at the base of eroding bluffs immediately cuts off this source of beach sand. Considering that Osborne et al. (1985) documented that much of the beach sand at Lake Tahoe is derived from eroding backshore areas, elimination of this source of sediment likely has had negative effects on many of the lake's beaches. It must be borne in mind, however, that this effect will occur regardless of the type of structure.

When steep storm waves impact a shore, they commonly move sand offshore causing a narrowing and steepening of the beach (Komar, 1998). Along the western coast of the U.S., this process commonly occurs during the winter months. During subsequent summer months, long-period swell arriving from far distant parts of the Pacific Ocean gradually move the sand back toward shore causing a widening and flattening of the beach, thus completing the yearly cycle (Komar, 1998). Because swell does not exist at Lake Tahoe, relatively steep storm waves are the most geomorphically effective waves that impact the Lake Tahoe shoreline. Sand transport during these periods is dominantly directed either alongshore or offshore. Once sand is moved offshore, it may be lost to the shore system. Without continued renewal from eroding bluffs or alongshore sources, protective beaches are reduced. During calmer periods, the presence of ripples oriented parallel to the shore may be evidence that, at times, there is a net shoreward movement of sand-sized sediment. At present, however, the relative magnitude of onshore versus offshore sand transport is not known.

Another way that shorezone protective structures may impact the beach is by reflecting wave energy back toward the lake which causes scour in front of the structure (Pilkey and Wright, 1988). The degree to which this occurs may be dependent on where the structure is placed relative to water level and the wave run up zone. If a structure is placed above the wave run up zone, then its presence is likely to have little influence on beach dynamics. If the structure is placed within the active swash zone, however, it can cause wave reflection and net offshore sediment transport. Because sloping dynamic revetments absorb some of the wave energy through kinetic motions of individual particles, there may not be as much wave energy reflectance and consequent beach scour (Komar, 1998). The permeable nature of dynamic revetments also tends to reduce the amount of backwash that may reduce scour in front of the structure.

Shorezone Protective Structures at Lake Tahoe

To examine the specific effects of protective structures on shorezone processes at Lake Tahoe, we compared detailed topographic-bathymetric maps of individual parcels that had shorezone protective structures installed to detailed basin-wide bathymetry. Basin-wide bathymetry was obtained with a LIDAR-equipped airplane in July 2000. For this phase of the study, TRPA supplied twelve project files, each with topographic-bathymetric maps with one or two foot contours. Three of these were deemed unsuitable for our objectives because they were pier replacement or pier modification projects. Of the remaining project files, most structures were classified as sloping, dynamic revetments and only one was considered to be a vertical, static revetment.

Project topographic maps were scanned in order to begin a rectification process using ENVI image processing software. Once the image was digitized, an attempt was made to rectify the project maps to 1992 and 1998 digital orthophoto quadrangles (DOQs). The rectification technique used was similar to that applied in an earlier phase of this study to rectify aerial photographs around the perimeter of Lake Tahoe (see Chapter 3 and Adams and Minor, 2002). Whereas an aerial photograph might cover several square miles and have many roads, buildings, and natural features to select as common ground control points[1], topographic maps of the revetment projects were much smaller. A typical project map shows one or two small buildings, often within a dense canopy of trees, immediately inland from a short stretch of shore. Consequently, rectification posed a significant challenge because common ground control points were exceedingly difficult to identify. In effect, virtually all of the project maps did not have enough common ground control points to accurately rectify them to the DOQs. An exception is the Fleur de Lac topographic map that possessed enough common ground control points to be rectified and imported into ArcView geographic information system (GIS) software where contour lines were traced as a separate theme.

Although LIDAR shallow-water bathymetry data were collected on July 16 and 17, 2000, DRI did not receive the first dataset (10 x 10 x 0.15 m) until January 20, 2001 and the second, more detailed (4 x 4 x 0.15 m) dataset until May 31, 2001. Resolution of the original bathymetric data was 4 x 4 x 0.15 m, which means that each pixel was 4 m on a side and had a vertical resolution of 15 cm. The original data was resampled to 10 x 10 x 0.15 m (herein referred to as coarse bathymetric data) and then released to DRI. In the resampling process, the heights of all objects in a given pixel are averaged and recorded to the nearest 15 cm. Although the vertical resolution is still 15 cm after resampling, this is an average height for the pixel and much information is lost.

The coarse bathymetric data was merged with deep-water bathymetry (Gardner et al., 1999) to yield an impressive view of the bed of Lake Tahoe. Many features can be seen in the shallow areas around the lake that were never seen before (e.g., submerged shorelines, abrasion platforms, and large scale bed forms). Contour lines derived from the

[1] Common ground control points are features that can be identified on both the base DOQ and the image or map that is being rectified.

coarse bathymetric data delineate large-scale features along the shore but are not sufficiently detailed to look at near-shore changes at the parcel level.

The fine bathymetric data (4 x 4 x 0.15 cm) represents a six-fold increase in resolution over the coarse data because of the much smaller 4 x 4 m cell size. Elevation averaging still occurred within the 16 m^2 cells of the fine data, however. The high quality and resolution of the LIDAR bathymetric data must be emphasized because this represents a significant advance over all other readily available topographic or bathymetric sources of data. Limitations discussed below are more a function of the proposed application than of the data itself.

To evaluate these limitations, a comparison was made between a project contour map from Fleur De Lac Estates at Tahoe Pines (1 foot contours; September, 1997) and contours derived from the fine bathymetric data (Figs. 2-7 and 2-8). This part of the shore consists of two breakwaters that nearly enclose a marina or lagoon and have been in place since at least 1939. From site drawings and other information gleaned from the project file and various aerial photographs, vertical shorezone protective structures are also located to the north and south of the breakwaters. Contours derived from the LIDAR 4 x 4 x 0.15 m bathymetry data are shown in Fig. 2-7. Although the higher-resolution data offers a significant improvement over the lower-resolution data, the high-resolution data still does not appear to be appropriate for comparison to project contour maps. Note how resolution of the data affects the creation of the contour lines and the mismatch between the "0" contour line and the shore (Fig. 2-7) Data gaps are also clearly evident where the data grid does not coincide with the shoreline.

As can be seen from Fig. 2-8, project-file and LIDAR contours are not at all coincident. In places, the two sets of contour lines are nearly orthogonal to one another. This situation can mean one of two things. Either there has been a large amount of change in near-shore bathymetry or one or the other data sets is inaccurate or too coarse to make the comparison. Because the project contours appear sufficiently detailed and fit the shore geometry very well, we conclude that this data is reasonably accurate. In contrast, contour lines generated from the LIDAR data do not perfectly follow the shoreline and many are not continuous. The discontinuous nature of many of the contour lines appears largely due to edge effects, where the contours are inadvertently controlled by the edge of the grid. Edge effects are particularly prominent around some of the piers where contours close around data gaps (Figs. 2-7 and 2-8). The LIDAR data is accurate, but does not appear to be able to provide high enough resolution to make these types of comparisons at the parcel level.

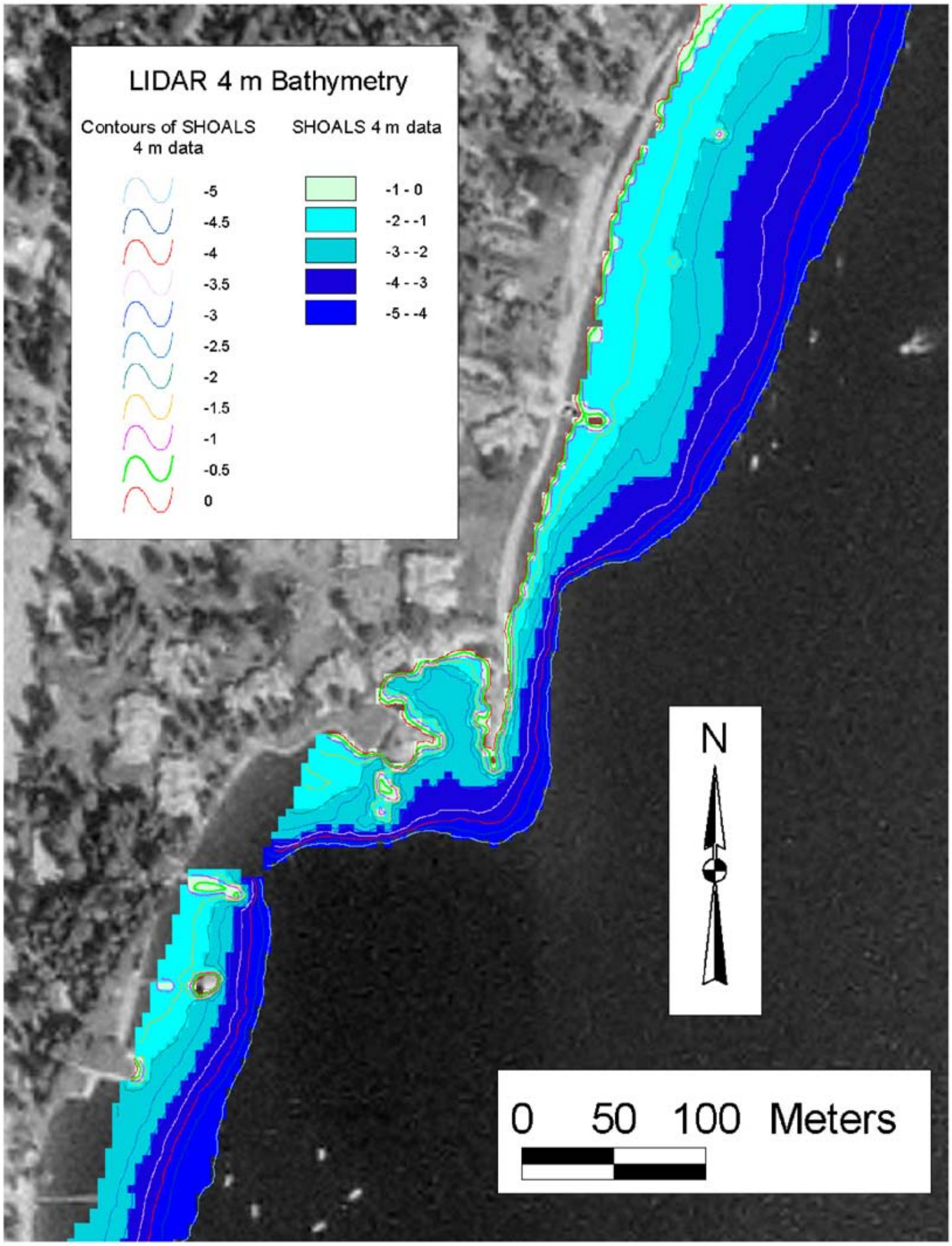

Figure 2-7. Map of the Fleur de Lac site with shallow-water bathymetry and 0.5 m contours superimposed on the 1998 DOQ.

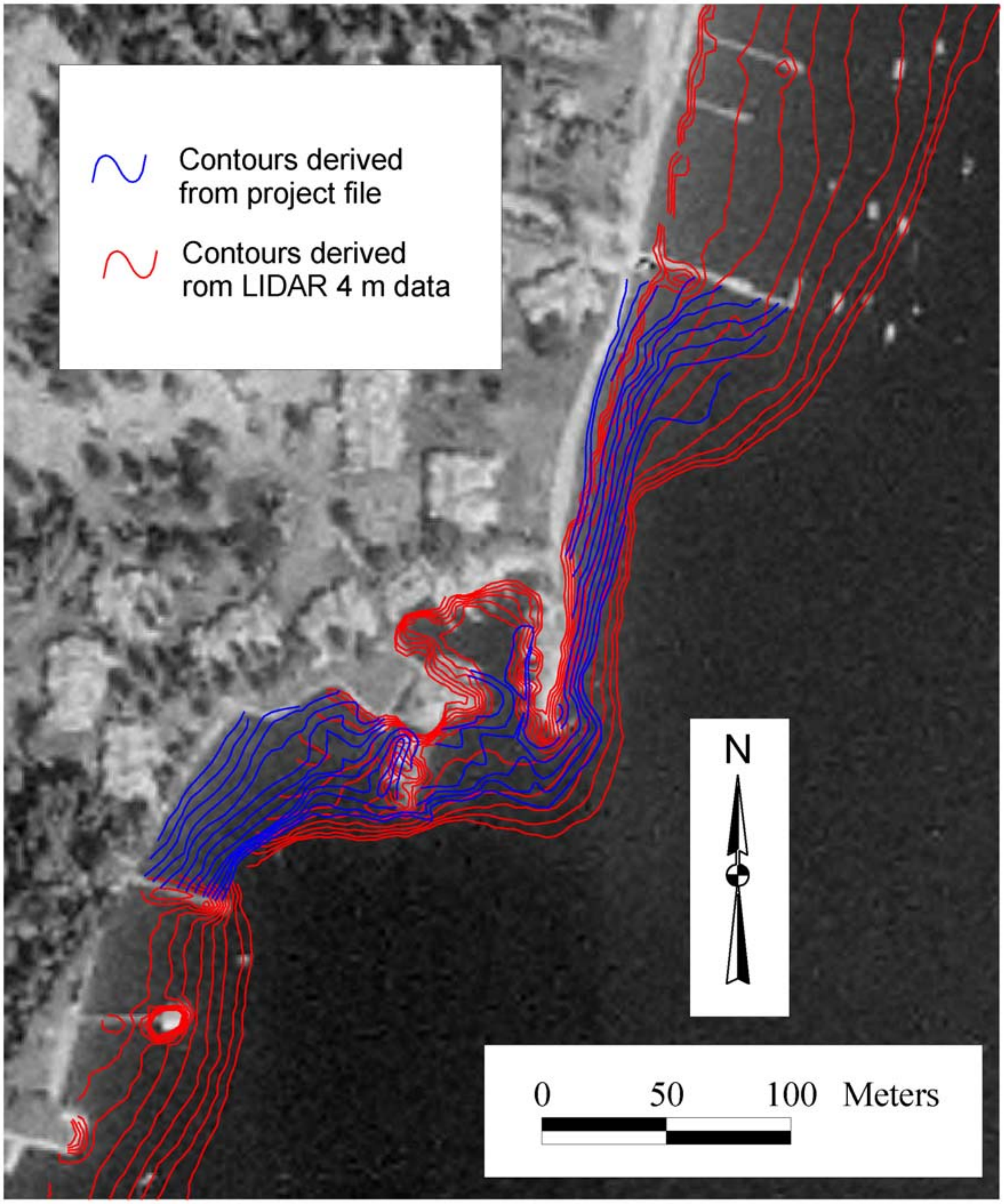

Figure 2-8. Map of the Fleur de Lac area showing a comparison between contours derived from project files and contours derived from LIDAR data. Note how in some places the contour lines are nearly orthogonal.

From this exercise, we conclude that assessing bathymetric change by comparing project contour maps to high precision LIDAR bathymetry is not feasible. The hypotheses proposed in the DRI/TRPA Shorezone Erosion Study Phase II proposal dated November 1, 2000 are, therefore, not testable by this means. These hypotheses stated that vertical, impermeable, static revetments cause significantly elevated rates of erosion in the foreshore and that dynamic, permeable, sloping revetments slow shorezone erosion and have insignificant impacts on foreshore bathymetry.

Although the above hypotheses could not be tested, general recommendations concerning shorezone protective structures can be made based on a literature survey and observations made during the course of this study. The main concern with vertical, static revetments is that they may reflect wave energy back toward the lake, thus causing accelerated erosion in front of the structure. Whether or not this occurs depends on several factors including the position of the vertical revetment relative to wave run-up and the particle size distribution of sediments in front of the structure. A vertical wall placed outside of the maximum run-up zone clearly will have no effect on beach processes, whereas a wall placed well within the surf zone will reflect some of the wave energy and may adversely affect beach processes (Weggel, 1988). The degree to which beach processes are affected depends on the wave climate at the site and the particle size distribution of the foreshore in front of the wall. If the foreshore is armored with gravel, cobbles, or boulders, probably little change will be induced by wave reflection. If the foreshore is composed of sand, however, then wave reflection may cause significant scour.

Sloping, dynamic revetments absorb some wave energy through movement of particles within the revetment (Komar, 1998). Because of the sloping design, additional energy is expended as waves break and run-up the structure. Both of these processes absorb wave energy and decrease reflected wave energy. Scour due to backwash is also reduced because some of the run-up percolates into the structure, thereby decreasing the amount of water in the backwash. All of these features mimic natural processes on a coarse gravel beach, which makes them less likely to adversely affect beach processes in the vicinity.

We recommend against rigid implementation of a blanket policy uniformly applied to all lake front properties. A more reasonable approach would be to treat each project individually, taking into consideration site-specific factors including foreshore particle size distributions, height of total swash elevation relative to the location of the revetment, composition of the backshore, beach gradient, and the local wave climate. Generally, sloping dynamic revetments are less likely to have adverse affects on shorezone processes than do seawalls, but they may not be appropriate for every situation. Because total swash elevation is so important to shorezone erosion and wave interactions with revetments, the manner in which it is calculated should conform to the most recent and defensible research of this process (Komar, 1998). Examples using this procedure to calculate the height of wave run-up are presented in Chapter 4.

Chapter 3
Historic Shorezone Erosion and its Impact on Sediment and Nutrient Loading

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This chapter reports the results of a detailed study that incorporates georectified air photographs into a GIS database to track shoreline changes over a 60-year period. These results were then combined with field observations and nutrient sampling to determine the amount and processes of sediment, phosphorus, and nitrogen input into Lake Tahoe from shorezone sources. We compared mass estimates derived from this study to other sources to determine the relative magnitude of nutrient and sediment input from the shorezone. In addition, we used particle-size data for sediment samples from around the lake to estimate total masses of sand, silt, and clay introduced into the lake from shorezone sources from 1938 to 1998. Most of this chapter was published independently, except for the particle-size data, in the *Journal of Coastal Research* in 2002 (Adams and Minor, 2002).

Methods

Aerial Photograph Acquisition

Historical aerial photographs and mosaicked 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 3-1 indicates the dates the photographs were taken, the geographic location, photographic scale, and responsible 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. Resolution varied between 300 dots per inch (dpi) and 600 dpi, depending on the scale and quality of the photographic prints. Using the resolution, 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 m; for the 1:8,000 scale photographs from 1995, the ground resolution was 1 m; 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 1 m 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 photographs, 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

Table 3-1**.** 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 Bay	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

Table 3-1 (**c**ont.)

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
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

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 that proved to be successful involved 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 photographs and DOQs when selecting GCPs, as these sometimes distorted the precise location of a feature. To avoid 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 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 photographs 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 was 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 images and the more recent DOQs. 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 photographic 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 2m. For the 1:8,000 scale 1995 photographs, the RMSE ground distance was 1m per image pixel. Several iterations were required in many of the GCP selection processes 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 and cast into a Universal Transverse Mercator (UTM) coordinate system (Zone 10) based on the 1927 North American Datum (NAD27).

Based on the calculated RMSE observed in the rectification process, the observed spatial error in ground distance over an entire photograph was +/- 4.0 m (RMSE of 2.1). In actuality, however, that error term is much less for the feature of interest, the shorezone, where the error is closer to +/- 2 m for the 1:20,000 scale photography, and even less (+/- 1 m) 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 shorezone, 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 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 overall RMSE for the entire image. These tolerances all exceed the National Mapping Accuracy Standards defined by the USGS in 1941 (10.2 m for 1:20,000 scale data; 8.0 m for 1:8,000 scale).

Delineating the Shoreline

The first challenge in mapping the former position of a 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). Most studies using this proxy have been conducted on open marine coasts, however, 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 in an aerial photograph. Therefore, we selected the linear interface between the water and shore to