Mapping fish habitats in Lake Tahoe for planning and management

Metz, Joshua, Martin Herold, and J.Shane Romsos

Abstract

High-spatial resolution multi-spectral imagery was used to map near-shore submerged substrate in Lake Tahoe. The goals of this project included determining the capability of IKONOS imagery for effectively discriminating different submerged substrate types around the lake near-shore zone, producing digital substrate maps and correlating them with observed fish habitat use data to derive fish habitat maps, improving the spatial extent and detail of existing fish habitat data using a consistent and repeatable method, and considering how best to incorporate new data into the planning and management process of the Tahoe Regional Planning Agency (TRPA). Four substrate types (boulder, mixed, sand, aquatic plants) and three fish habitat types (spawning, feed/cover, marginal) could be inferred in sufficient accuracy. A consistent method for future mapping efforts was developed for use in environmental monitoring. Finally, potential fish density distributions based on the substrate map and water depth/bathymetry information, were derived by linking the remote sensing measurements with in-situ fish observations.

Introduction

The near-shore zone environment in Lake Tahoe and other recreational lakes is the interface between human activities and the lake environment. As such, it is an area of heavy impact from shore and lake-based recreation. Predicted population growth in California and Nevada is expected to increase the demand for shore-zone access. In Lake Tahoe the near-shore zone is also utilized by native non-game fish species as feed and cover and breeding habitat (Byron et al. 1989, Beauchamp et al. 1991, Beauchamp et al. 1994). In accordance with a directive to protect Lake Tahoe's environmental quality, the Tahoe Regional Planning Agency (TRPA) is concerned with ensuring the long-term persistence of fish species occurring in the lake, while simultaneously establishing effective policies to maintain high quality recreational experiences for the regions visitors. As a result of these conflicting demands for space, focus has been drawn to the shallow near-shore zone as an area in need of continued attention and monitoring.

The Tahoe Regional Planning Agency is the regulatory agency charged with creating and enforcing environmental quality standards for the Lake Tahoe Basin in accordance with state and federal law. The TRPA was created from a bi-state compact between California and Nevada, which was ratified by the US Congress in 1969. Environmental quality standards or thresholds were created in the early 1980's along with ordinances designed to achieve them. The TRPA Regional Plan of 1987 contains the guiding policies currently in effect. Regional plan review and update is required by law every 5-years. The 1996 Threshold Evaluation (TRPA 1996) adopted three threshold standards and associated indicators for fisheries that established criteria for measuring environmental quality in the lakes and streams of the Tahoe Basin. The first standard, F-1 Lake Habitat, aims to establish 5,948 acres of excellent lake fish habitat around the entirety of Lake Tahoe. Physical disturbance of rocky substrate on the lake-bed was set as the indicator of degradation of lake fish habitat. It is noted in the most recent report on compliance with environmental thresholds that the TRPA has not been in compliance on this standard since its inception (TRPA 2002), largely because no standardized measuring and monitoring approach has been available.

In terms of near-shore lake fish habitat, the agency currently relies on a geographic information system (GIS) data layer that was created in 1989 by combining field observation data with an existing administrative boundaries layer. A comprehensive time-constrained field survey of the near-shore zone of Lake Tahoe was completed by the Tahoe Research Group (Byron et al. 1989). The survey provided spatially referenced data that described changes in the lake-bed substrate around the lake. A new GIS data layer was created when the boundaries between different substrates were combined with an existing GIS layer of near-shore administrative boundaries (TRPA Tolerance Districts). This new data layer provided a mechanism for spatially stratifying the near-shore (< 10m depth) environment into zones of different substrate type and fish habitat quality. Since 1989 when the first fish habitat GIS layer was created new techniques and technology became available that offered the promise of increased mapping precision and extent within reasonable cost constraints. It is within this context that the TRPA decided to explore the use of high resolution, multi-spectral satellite imagery provided by the IKONOS platform as a means to improve the quality and repeatability of near-shore zone substrate mapping.

Remote sensing in water presents numerous challenges, mostly related to the complex physical interactions between water and light. Simply described, shorter wavelengths of visible light (~450nm) penetrate deepest into the water column (~10m), while longer wavelengths (~500 – 750nm) are more rapidly absorbed (Jensen 2000). This causes a reduced utility of the visible light spectrum to describe differences in surface features as measured by remote sensing devices. The IKONOS platform measures reflected visible light in 4 multi-spectral bands (Figure 2), because the 3 longer wavelength bands are rapidly absorbed in water there is a greater reliance on the shorter (blue) wavelengths to measure sub-surface features. The shorter wavelength band has a lower reflectance signal which inherently reduces its sensitivity at the sensor, thus presenting a challenge for discriminating fine detail variation under-water. These factors notwithstanding, remote sensing, and IKONOS data specifically is increasingly popular as a tool for mapping reef substrates (Hochberg and Atkinson In Press, Mumby and Edwards 2002, Mumby et al. 1998), aquatic vegetation (Sawaya et al. 2003, Mumby et al. 1998), and for use as a tool in local scale resource planning and monitoring (Sawaya et al. 2003). Research continues into the potential use and applications for a variety of remote sensing platforms in aquatic resources management. This project extends that line of inquiry into lake-bed substrate mapping and linking field observations with remote sensing data products.

There were three objectives of the current project based on the information needs of the TRPA that included:

1. Exploring the utility of IKONOS imagery for mapping submerged and dry shore-zone substrates and pier structures,
2. Developing data products and methods to inform the F-1 Lake Fish Habitat component of the TRPA Environmental Thresholds,

3. Developing links between remotely sensed spatial data, field observations of fish-substrate relationships, and the regional planning and regulatory process.

Data and Methods

Processing and analysis of the IKONOS data was focused on four different mapping products: 1) near-shore lake substrate types, 2) dry shore substrates, 3) fish habitat and fish distributions, and 4) shore-zone structures (piers). Figure 1 shows the general flowchart of the data processing and analysis integrating remote sensing digital image processing, field work, and GIS using standard available methods.

The project relied heavily on the GIS database available from TRPA and data products from related agencies and researchers (e.g. USGS SHOALS bathymetry, 1989 fish habitat map). The processing and analysis of the remote sensing and field data applied in this project are now described in more detail.

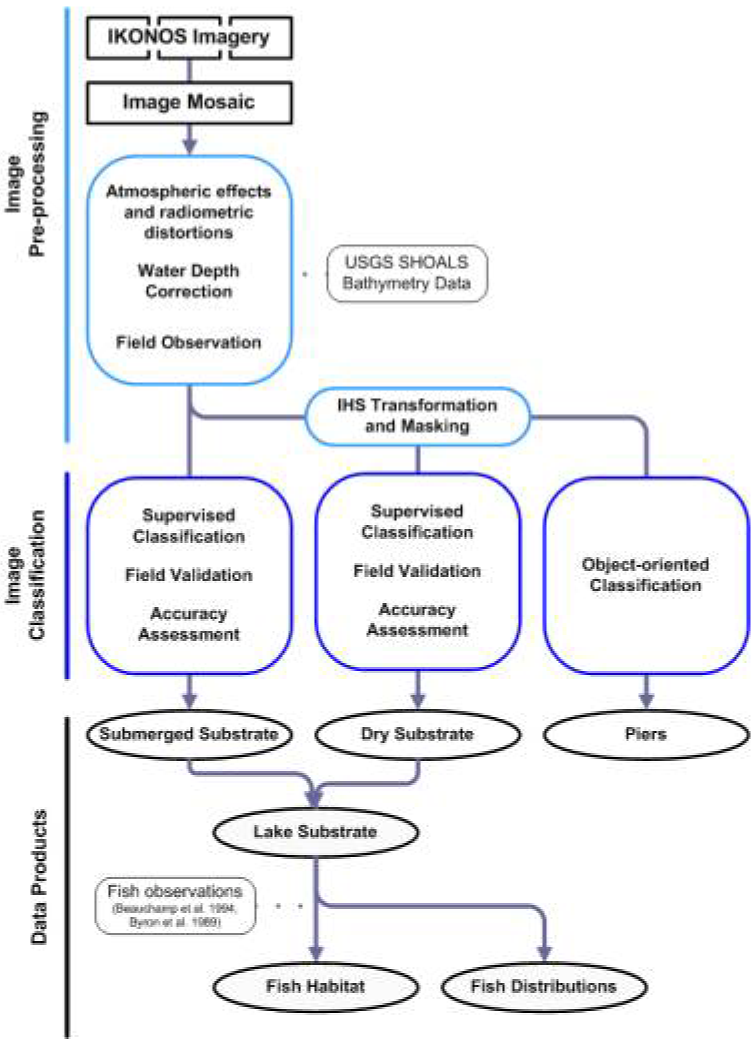


Figure 1. Image processing and classification process of IKONOS imagery for the Lake Tahoe substrate and fish habitat mapping project.

Remote sensing data and processing

Mapping was based on an IKONOS satellite data mosaic of 9 individual scenes acquired 07/19/02 (Figure 2). The IKONOS data had a high level of geometric preprocessing from the data provided and the mosaic was created without any further geo-rectification. There were specific radiometric distortions resulting from atmospheric scattering and wind (waves on lake etc.). This issue was resolved by discriminating the lake in different mapping regions that were analyzed individually (Fig. 2).

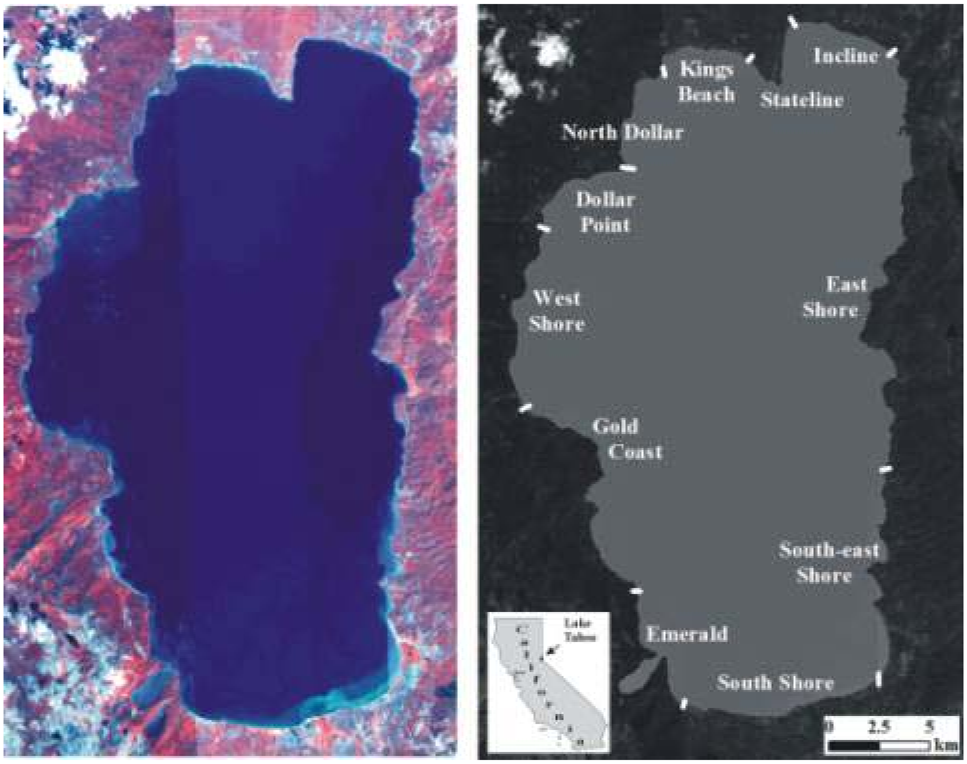


Fig. 2: IKONOS image mosaic (left, channels 4/2/1 as RGB) and mapping regions (right)

In terms of radiometric pre-processing, the following formulas can be used to transform 11 bit IKONOS DN values to at sensor Radiance:

$$L_{\lambda}(Wm^{-2}sr^{-1}\mu m^{-1}) = \frac{10 \cdot DN \cdot BW(\mu m)}{CalCoef_{\lambda}}$$

L_λ = At sensor Radiance of given pixel
DN = Digital number from original IKONOS data
$CalCoef_\lambda$ = Calibration coefficient
BW = Bandwidth of specific IKONOS Band

The required information is presented in Table 1.

Table 1: IKONOS sensor calibration parameters and water column correction results

IKONOS band	Center wavelength (µm)	Bandwidth (µm)	$CalCoef_\lambda$	Radiance opt. deep water: L_{si}	Water atten. coeff.: g	R^2 (radiance / depth)
1 - Blue	0.4801	0.0713	728	0.224	0.122	0.65
2 - Green	0.5507	0.0886	727	0.189	0.191	0.92
3 - Red	0.6648	0.0658	949	0.044	0.171	0.71
4 - NIR	0.805	0.0955	843	0.043	0.093	0.65

For the mapping of submerged substrate types a water column correction was applied to normalize the influence of water depth on the signal. First, the path radiance (atmospheric scattering) and external reflection from water surface (signal from optically thick water) were removed:

$$L_P = L_i - L_{si}$$

L_i = At sensor Radiance of given pixel (L_λ)
L_{si} = Mean Radiance of optically deep water – 2 Std. deviations (from large deep water sample area)
L_P = Corrected Radiance of given pixel

The intensity of light decays exponentially with increasing depth (absorption, Beer-Lamberts Law). To linearize the relationship for estimation of attenuation coefficient use:

$$L_{Plin} = \log(L_P)$$

L_{Plin} = Linearized radiance

The absorption by the water column, hence the relationship between corrected remote sensing signal (L_P) and the sea bottom signal (L_B) can be described by a Beer-Lambert law:

$$L_P = L_B e^{(-2kZ)}$$

k = Water attenuation coefficient (The factor 2 represents the downwelling and upwelling light components and assumes that both coefficients are equal)
Z = Water depth

Using linearized radiance the equation becomes:

$$\log(L_P) = L_{Plin} = \log(L_B) - gZ$$

g = Water attenuation coefficient for both downwelling and upwelling light (2k=g)

Given this linear equation it is possible to estimate the attenuation coefficient g from an empirical relationship, hence the slope between water depth Z (independent variable, taken from SHOALS bathymetry data) and linearized radiance L_{Plin} (dependent variable) with g being the slope of the empirical line (Bierwirth et al. 1993). The attenuation coefficient and the R-squared values for the relationship are shown in Table 1. The results of the water column correction are presented in Figure 3. The example indicates the improved lake bottom substrate information and the constraints of the study by the extent of the SHOALS bathymetry data.

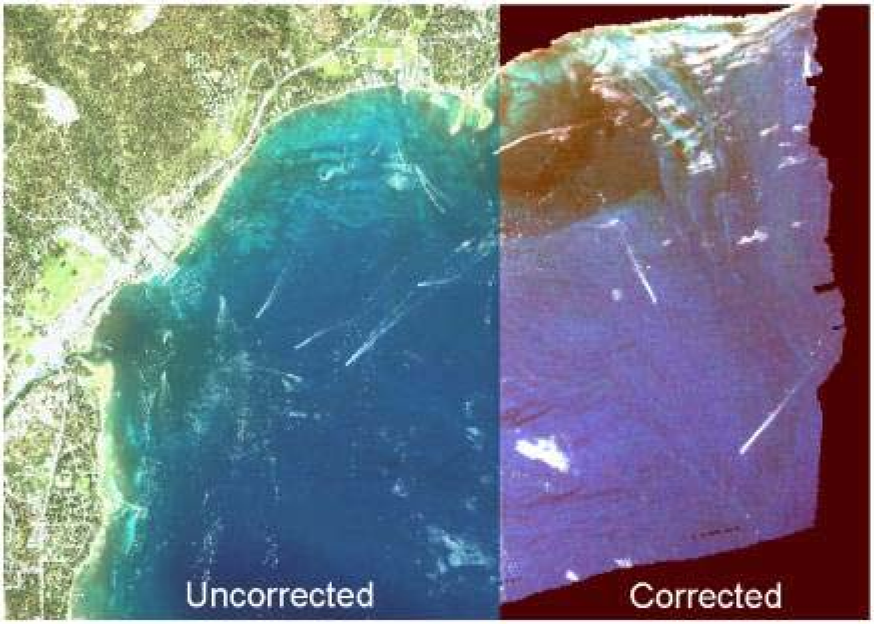


Fig. 3: Results of the water column correction for the Dollar point area.

The mapping of the high and dry shoreline and the piers required high spatial-resolution data that were provided by a merge between the panchromatic (1 m spatial resolution) and the multispectral data (4 m spatial resolution). The image merge used a standard IHS approach available in most image processing software systems (Jensen, 1996). The result of the resolution merge was a multispectral image of IKONOS channels 2,3,4 in 1 m spatial resolution (Fig. 4).

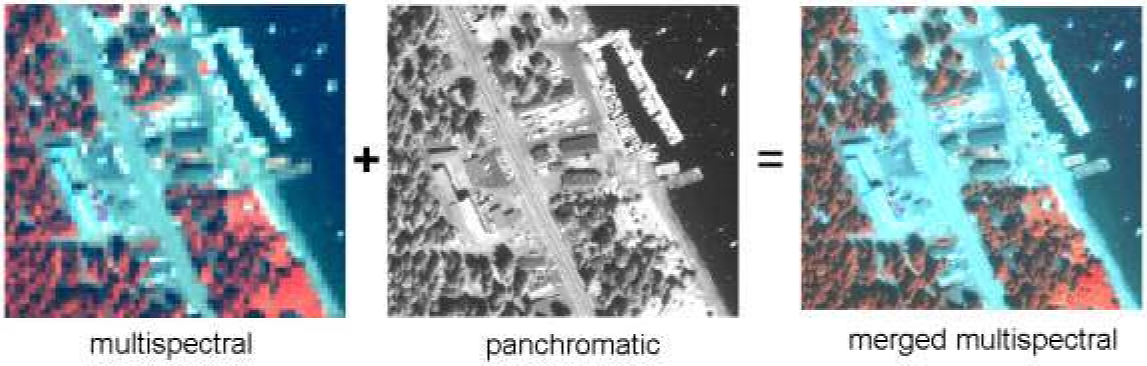


Fig. 4: Results of the panchromatic/multispectral IKONOS resolution merge

The spectral image classification for the submerged substrates was based on the water column corrected image data in 4m spatial resolution, constrained by the spatial extent of the USGS SHOALS bathymetry data with a maximum water depth of 20 feet. Deeper waters were excluded from the analysis since no sufficient signal was available for image classification. An unsupervised classification with visual reclassification was performed for each mapping region (Fig. 2). A similar approach was used for classifying the high and dry shoreline based on the merged multi-spectral data. Prior to the shore-zone classifications the non-vegetated, high and dry shore-zone was digitized from the image data to focus the analysis on this area. Although the mapping has been completed on the 1 m – data, the high and dry mapping product was degraded to 4m when merged back with the submerged substrate classification results. A 5x5 majority filter was used to smooth the final mapping product.

The mapping of the shore-zone structures (piers) used the merged multi-spectral data. Identifying the piers required an object-oriented, segmentation based approach using the eCognition software system (Baatz et al., 2001). eCognition was used to segment the image and classify the shore-zone based on the spectral and spatial characteristics of the piers such as linear shape, pier size, and other geometric properties.

Field data and observations

Three field mapping campaigns were conducted during this project. The first two campaigns (May and August 2003) mainly focused on the submerged substrate types and were performed during periods of similar lake levels as during the IKONOS data acquisition. The field mapping included boat surveys of substrate types using GPS, GIS, Secchi desk, and bathyscopes. The May 2003 field visit was mainly used for the training of the image classification. In August 2003, the boat survey was guided by predetermined stratified-randomly selected points for a robust and rigorous accuracy assessment of the classification results. A third field mapping campaign was conducted in April 2004 for accuracy assessment for mapping the high and dry shoreline mapping and piers.

Results

Lake substrate mapping

The substrate map shown in Fig. 5 contains the results from the submerged substrate image classifications and the high and dry shoreline image classifications (Table 2). The map shows the dominance of sand in the south and south-east shore. Boulders are dominant on the east shore and near Stateline point. Mixed rocky substrates appear for the rest of the lake with unique characteristics for the Dollar point area. Pure gravel substrates appear only for the high and dry shore-zone on the west shore.

Table 2: Substrates types and their area distribution and characteristics

Substrate type	**Area (acr.)**	**Area (%)**
Sand	8824.4	60.8
Cobble (south shore)	6.4	0.0
Small and large boulder (east and southeast shore, Stateline)	733.9	5.1
Sand/cobble/small boulder (Incline, Kings beach, west shore)	1656.2	11.4
Gravel/cobble/small boulder/bedrock (only Dollar point)	204.6	1.4
Cobble/small boulder/bedrock (only Dollar point)	2809.7	19.4
Periphyton (on south shore sands)	88.8	0.6
Gravel (high and dry west shore)	95.5	0.7
Gravel/cobble/small boulder (high and dry west and south shore)	95.3	0.7
Total	14514.8	100.0

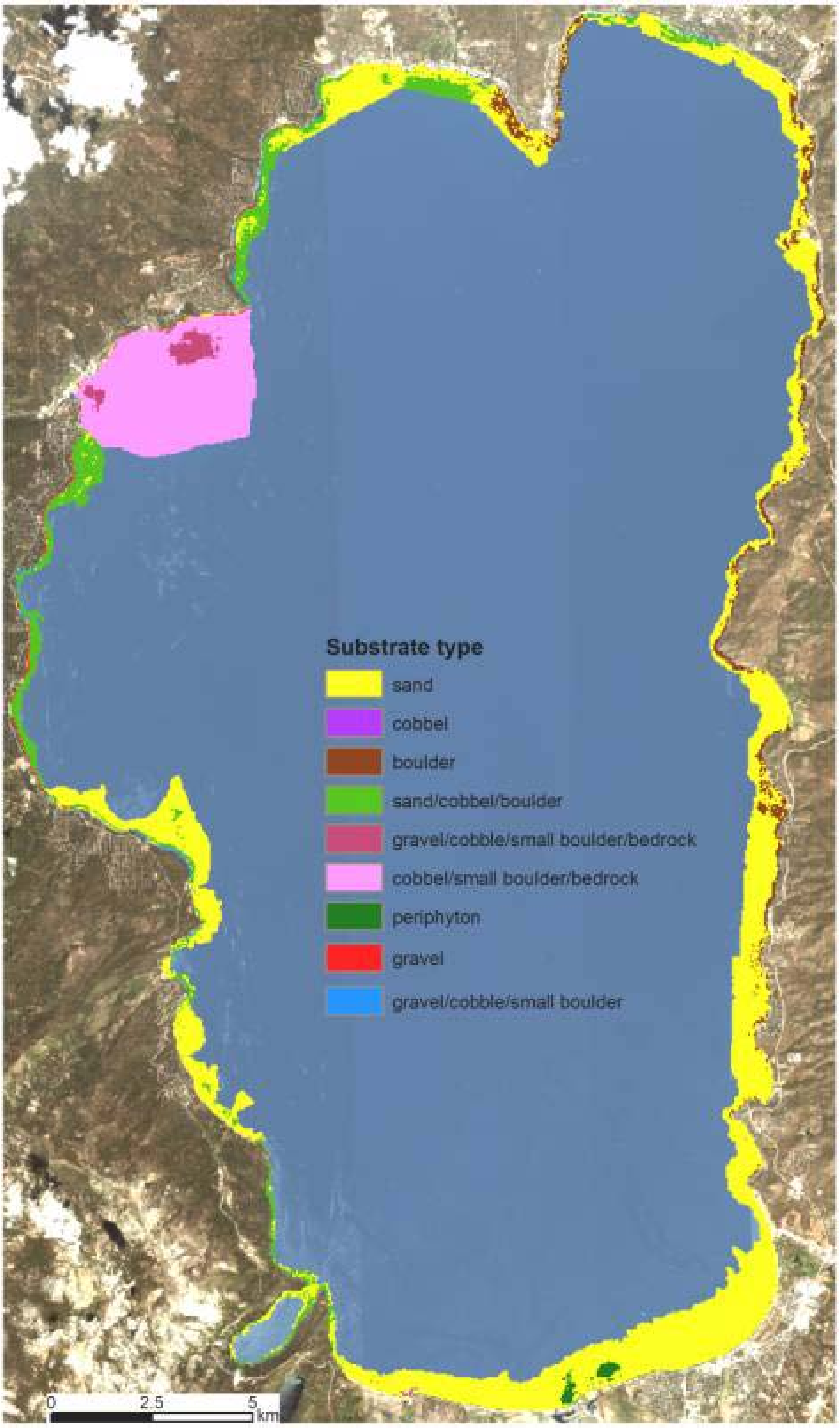


Fig. 5: Near shore lake substrate map derived from IKONOS data

Table 3: Error matrix for the submerged lake substrate types (top) and the high and dry substrate types (bottom).

Submerged substrate mapping:

Reference Data									
Classified Data	1) Sand	2) Cobble	3) Boulder	4) C/B/S	5) Gra/C/B	6) C/B/Bed	7) Periph	Total	Users acc.
1) sand	78	2	7	9	0	0	4	100	78.0%
2) cobble	0	5	0	0	0	0	0	5	100.0%
3) small and large boulder	2	0	27	5	0	0	0	34	79.4%
4) cobble/sand/boulder	3	0	2	82	0	0	0	87	94.3%
5) gravel/Cobble/bedrock	0	0	0	0	4	1	0	5	80.0%
6) cobble/Boulder/Bedrock	2	0	0	4	4	67	0	77	87.0%
7) periphyton	0	0	0	0	0	0	14	14	100.0%
Total	85	7	36	100	8	68	18	322	
Producers acc.	91.8%	71.4%	75.0%	82.0%	50.0%	98.5%	77.8%		
Overall Accuracy = 86.02%									
Overall Kappa = 0.82									

High and dry substrate mapping:

Reference Data								
Classified Data	1) sand	2) gravel	3) bould	4) gr/c/b	5) gr veg	6) wet s	Total	Users acc.
1) sand	22	3	1	0	0	0	26	84.6%
2) gravel	0	11	0	3	0	0	14	78.5%
3) small and large boulder	4	0	13	1	0	0	18	72.2%
4) gravel/cobble/small boulder	2	4	1	7	0	0	14	50.0%
5) green vegetation	0	0	0	0	13	0	13	100.0%
6) wet shoreline	0	0	0	0	0	15	15	100.0%
Total	28	18	15	11	13	15	81	
Producers acc.	78.5%	61.1%	86.6%	63.6%	100.0%	100.0%		
Overall Accuracy = 81.0%								
Overall Kappa = 0.77								

The accuracy of the submerged lake substrate types are presented in Table 3. The error matrix is based on 322 locations distributed randomly and visited during the field campaigns covering the seven substrate classes identified. The results of the accuracy assessment (86 % overall accuracy) shows the good mapping results derived from the IKONOS data. There is some confusion between specific classes but all categories are mapped with sufficient accuracy. The accuracy assessment for the high and dry is shown in Table 3 and also reveals the successful application of IKONOS data in mapping near-shore environments.

Fish habitat and fish distributions

The translation of the substrate map into fish habitat categories and spatial fish distributions was based on intensive knowledge and long-term fish surveys (Byron et al., 1989, Beauchamp et al. 1991, 1994). They show that substrate type is an important variable determining the spatial characteristics of fish habitats given the three habitat categories of “spawning”, “feed and cover”, and “marginal” (Byron et al., 1989). Sand substrates characterize marginal fish habitats, gravels are essential for spawning grounds and rocky substrates (cobble, boulder etc.) represent feed and cover habitats. In this manner, the substrate map was transformed into a fish habitat map (Fig. 6). Marginal fish habitats are most common for Lake Tahoe (Table 4). Feed and cover habitats appear everywhere except the south shore. However their distribution is quite heterogeneous in the east shore, north shore, and south-west shore reflecting the highly variable configuration of boulders and sand substrates. Spawning grounds are very limited in spatial extent and only appear for specific shore-zones on the west shore.

Table 4: Area distributions of fish habitat types for Lake Tahoe

	Area (acr.)	Area (%)
marginal	8913.2	61.4
feed and cover	5506.2	37.9
spawning	95.5	0.7
TOTAL	14514.9	100.0

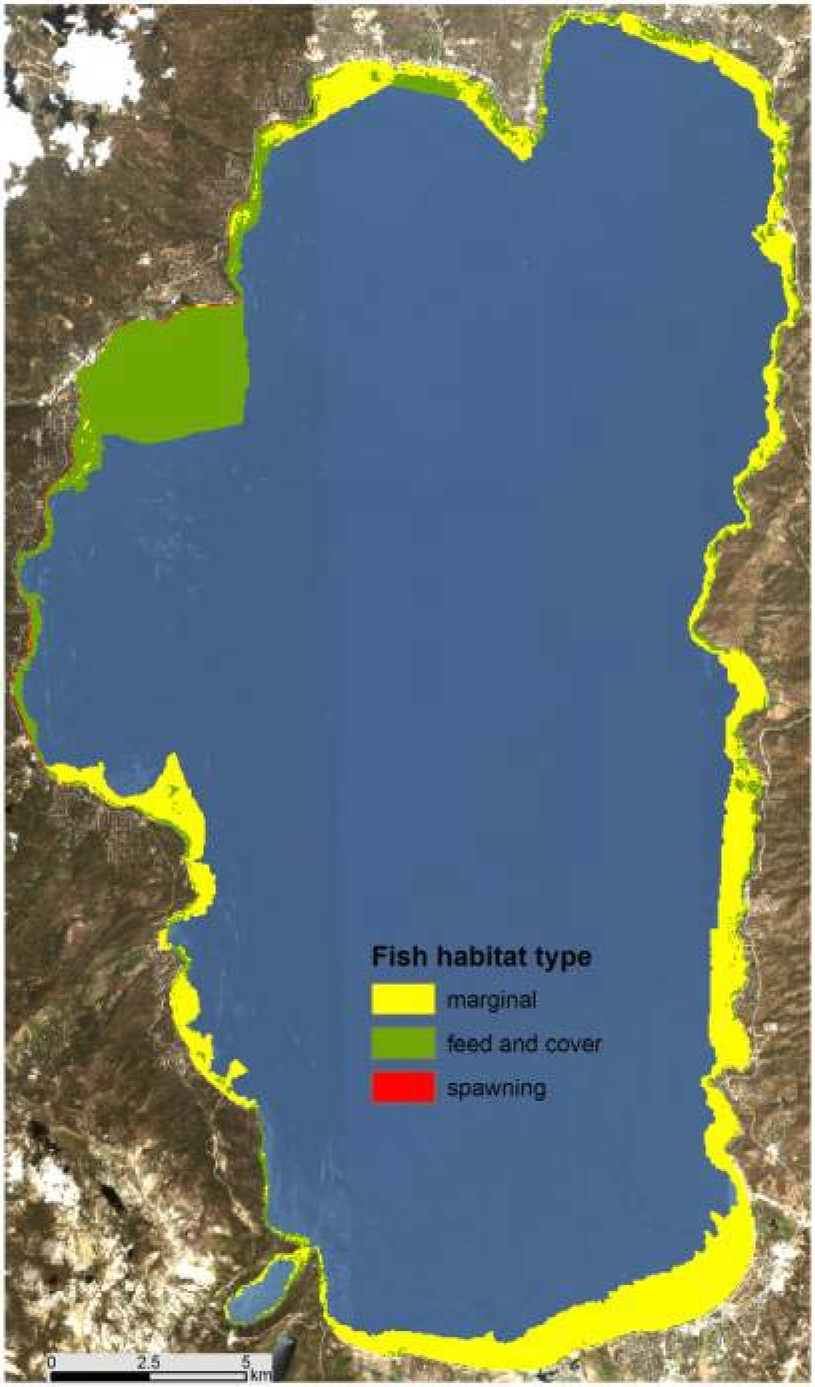
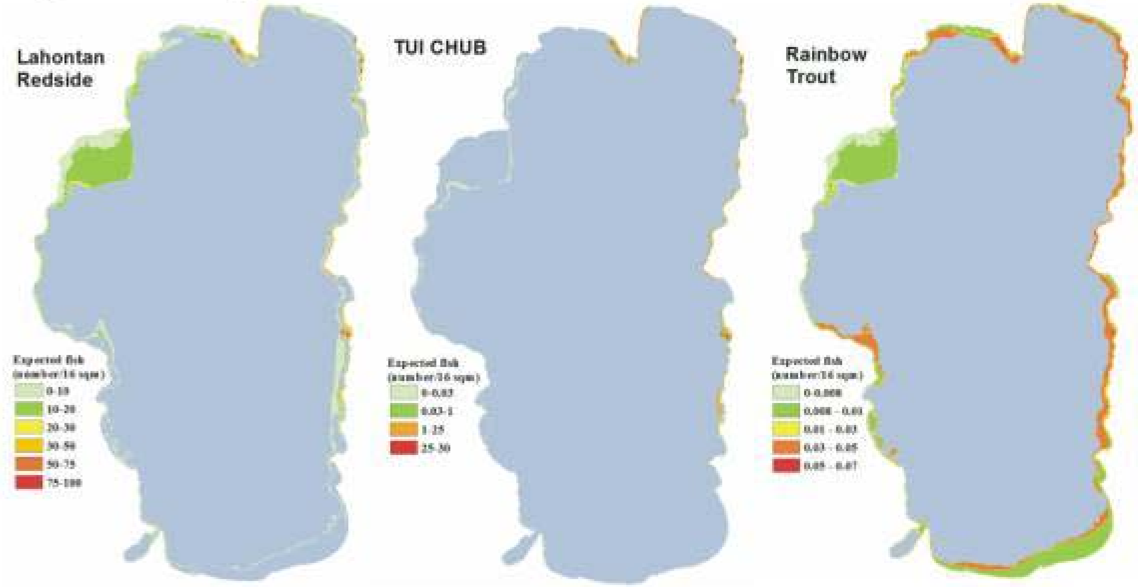


Fig. 6: Fish habitat map of Lake Tahoe derived from IKONOS data.

The work of Beauchamp et al. (1991, 1994) has established relationships between substrate type and water depth and expected fish distributions in Lake Tahoe from field surveys. This information was used along with the substrate map and the SHOALS bathymetry dataset to derive expected fish distributions for the lake. The analysis focused mainly on non-game native fish (Fig.7).

Spatial fish dynamics



Temporal fish dynamics

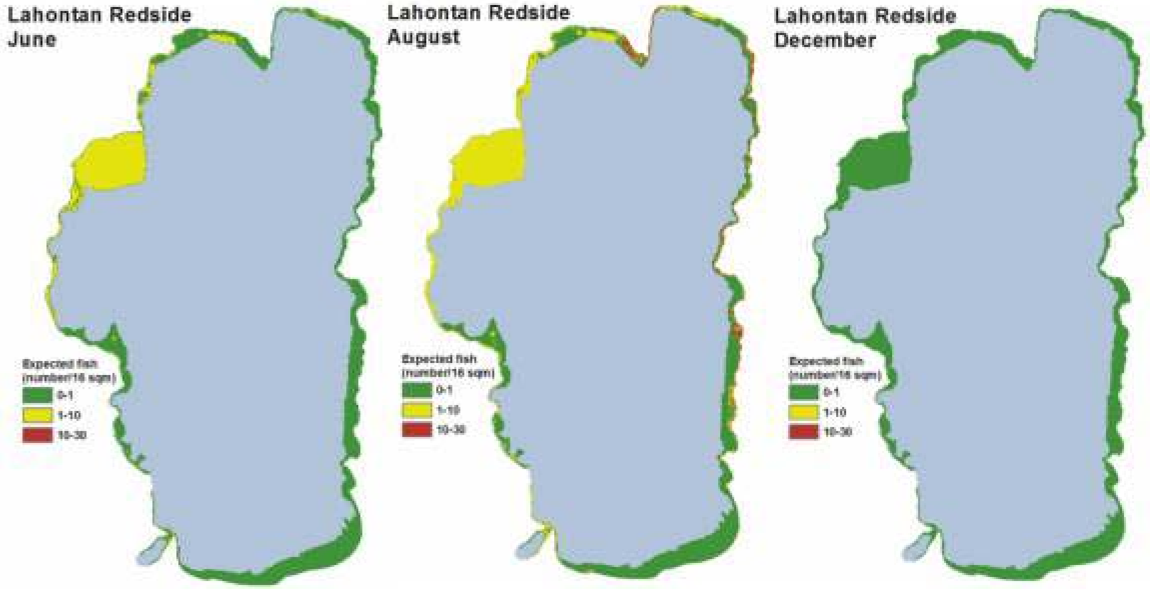


Fig. 7: Spatio-temporal fish distributions of Lake Tahoe.

The maps of Fig. 7 show the specific preferences for different types of fish. The Lahontan Redsides are most commonly found near boulders and in deeper waters for cobble/small boulder mix substrates. Tui Chub is spatially focused on small and large boulder substrates on the east shore and near Stateline point. Both the Lahontan Redside and the Tui Chub avoid areas that have been identified as marginal fish habitats. The Rainbow Trout is a game fish and basically occurs in deeper water in all parts of the lake, even for areas of marginal fish habitats. Interesting spatial-temporal fish dynamics are shown in Fig.7 for the Lahontan Redside. The fish stay offshore in the winter months and then first appear in cobble/small boulder substrates in spring/early summer. In the summer the highest distributions are found near small and large boulders.

Shoreline structure mapping

The result of mapping piers and manmade shoreline structures is indicated in Fig. 8. It shows a subset of the pier outlines mapped from IKONOS using the eCognition software. The classifications resulted in 91 % producer accuracy and 83 % user accuracy which shows the successful application of the mapping approach.

Fig. 8: Results of mapping piers (shown in red) from IKONOS data for the Dollar point area.

The pier locations are a good indicator of the human influences on the near shore Lake Tahoe environment. One of the most sensitive zones is the spawning grounds that are spatially limited as indicated by the fish habitat map. Further research that addresses the influence of human activity in the seasonal spawning habitat of lake fishes could leverage the investments made in the development of this particular dataset. In addition, repeat image classification focused on near-shore pier structures could be implemented as part of a long term monitoring strategy.

Discussion

The work presented in this report is the first standardized approach to measuring the extent and condition shore-zone lake fish habitat since 1989. As noted in TRPA (2002), the lack of standardized monitoring of lake fish habitat has prevented quantitative assessment of progress towards attainment of the F-1 Fish Habitat threshold. The new techniques and datasets resulting from the current work provide a means for initiating a quantitative monitoring and regulatory strategy for attainment of the F-1 fisheries threshold standards. Repeated image classification of IKONOS data at 5-year intervals would provide a lake-scale view substrate change over-time.

It is important to note that though the resolution of the IKONOS data (4m multi-spectral) is relatively fine compared with other satellite-based remote sensing instruments, the resolution is still relatively coarse for performing project-by-project oversight and evaluation. As a result, the practice of site visits and inspection prior to the approval of any projects that affect the lake shore-zone should be continued. If the effort was made to treat the site visits as data collection opportunities, using GPS technology, a substantial database of more site-specific conditions at shorter time intervals could be developed. Such as database used in combination with the regular 5-year interval “whole lake” IKONOS based assessments would provide a substantial boost to the current monitoring activities in support of the F-1 fisheries threshold standard.

The integration of published field observation data with remote sensing data products to derive new information about potential aquatic species distributions is relatively novel. These results demonstrate the utility of comprehensive mapping coverage provided by the IKONOS data products for visualizing the relationships between aquatic habitats and potential species distributions. They highlight how strategic thinking in the utilization of remote sensing and derived data products can yield new tools for environmental planning and management. Specific to the fish distributions shown in this report, such data supported visualizations could be used to evaluate alternative regulatory policies that focused on fish species survival, such as evaluating the effects of a seasonal use limitation adjacent to critical spawning areas.

As technologies continue to evolve there will be opportunities to leverage these new tools for improved environmental management. This project has demonstrated potentially new and useful tools and methods for monitoring and evaluating specific environmental indicators important to the Tahoe Regional Planning Agency. In general the results suggest a framework for linking the TRPA environmental thresholds with specific monitoring techniques when they are drafted. Developing clearly defined measuring approaches for each specific environmental threshold would likely improve timely evaluation, reduce the cost of monitoring, and increase their legal defensibility.

Acknowledgements

Tahoe Regional Planning Agency – Long Range Planning Division, Prof. Frank Davis, UCSB Biogeography Lab, UCSB Remote Sensing Research Unit, Brandt Allen, Prof. Dave Beauchamp, UC Davis Tahoe Research Group, TRPA Fisheries Technical Advisory Group.

Bibliography

Baatz, M. , M. Heynen, P. Hofmann, I. Lingenfelder, M. Mimier, A. Schape, M. Weber and G. Willhauck. 2001. eCognition User Guide 2.0 : Object Oriented Image Analysis. Definiens Imaging GmbH, Trappentreustrasse 1, 80339 München, Germany.

Beauchamp, D.A., W.A. Wurtsbaugh, B. Allen, P. Budy, R. Richards, and J. Reuter. 1991. Lake Tahoe fish community structure investigation: phase II report. University of California, Institute of Ecology Publication 38, Davis.

Beauchamp, D.A., E.R. Byron, W.A. Wurtsbaugh. 1994. Summer habitat use by littoral-zone fishes in Lake Tahoe and the effects of shoreline structures. North American Journal of Fisheries Management, 14: 385-394.

Bierwirth, P.N., T.J. Lee, and R.V. Brune.1993. Shallow sea-floor mapping reflectance and water depth derived by unmixing multispectral imagery. Photogrammetric Engineering and Remote Sensing, 59(3):331-338.

Byron, E.R., B. Allen., W. Wurtsbaugh, and K. Kuzis. 1989. Final Report: Littoral structure and its effects on the fish community of Lake Tahoe. Institute of Ecology, Division of Env. Stud., Univ. Cal., Davis.

Geovine Consulting. 2003. Project Summary and Progress Report: Mapping near-shore submerged substrates in Lake Tahoe, California. Submitted to the Tahoe Regional Planning Agency.

Hochberg, E.J. and M.J. Atkinson. 2004. Capabilities of remote sensors to classify coral, algae, and sand as pure and mixed spectra. Remote Sensing of Environment, *Article in Press*.

Jensen, J. 1996. Introductory digital image processing: a remote sensing perspective. 2nd Edition. Prentice-Hall, NJ.

Jensen, J. 2000. Remote sensing of the environment: an earth resource perspective. Prentice-Hall, NJ.

Mumby, P.J. and A.J. Edwards. 2002. Mapping marine environments with IKONOS imagery: enhanced spatial resolution can deliver greater thematic accuracy. Remote Sensing of the Environment, 82: 248-257.

Mumby, P.J., E.P. Green, C.D. Clark, and A.J. Edwards. 1998. Digital analysis of multi-spectral airborne imagery of coral reefs. Coral Reefs, 17: 59-69.

Sawaya, K.E., L.G. Olmanson, N.J. Heinert, P.L. Brezonik, and M.E. Bauer. 2003. Extending satellite remote sensing to local scales: land and water resource monitoring using high resolution imagery. Remote Sensing of Environment, 88(2): 144-156.

TRPA. 1986. Regional plan for the Lake Tahoe Basin: goals and policies. Tahoe Regional Planning Agency, Zephyr Cove, NV.

TRPA. 1999. Lake Tahoe Shore-zone Ordinance Amendments, Draft EIS. Tahoe Regional Planning Agency, Zephyr Cove, NV.

TRPA. 2002. 2001 TRPA Threshold Evaluation Draft. Tahoe Regional Planning Agency, Zephyr Cove, NV.

Author Information

Joshua Metz
Graduate Researcher
Biogeography Laboratory
Donald Bren School of Environmental Science and Management
University of California, Santa Barbara
2400 Bren Hall
Santa Barbara, California 93106
Email: jmetz@bren.ucsb.edu
Phone: (805) 893-7044

Martin Herold
Remote Sensing Research Unit
Department of Geography
University of California, Santa Barbara
Ellison Hall 1629
Santa Barbara, California 93106
Email: mherold@geog.ucsb.edu
Phone: (805) 893-4196

J. Shane Romsos
Forest Wildlife Biologist
Lake Tahoe Basin Management Unit
USDA Forest Service
35 College Dr.
South Lake Tahoe, CA 96150
Email: sromsos@fs.fed.us
Phone: (530) 543-2600