Division of Hydrologic Sciences Annual Technical Report FY 2005

Introduction

Research Program

Quantifying Potential Economic Impacts of Water Quality Modeling Uncertainty for the Lower Truckee River, Nevada

Basic Information

Title:	Quantifying Potential Economic Impacts of Water Quality Modeling Uncertainty for the Lower Truckee River, Nevada
Project Number:	2003NV41B
Start Date:	3/1/2003
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	02
Research Category:	Climate and Hydrologic Processes
Focus Category:	Water Quality, Economics, Models
Descriptors:	None
Principal Investigators:	Alan McKay, John J. Warwick

Publication

1. McKay, W. A., Warwick, J.J., Kish, S., Fritsen, C., and Bartlett, J., 2003. Modeling linkages between groundwater, surface water and periphyton-driven oxygen dynamics in the lower Truckee River, Nevada, Fall Meeting of the American Geophysical Union, San Francisco, California, December 8-12.
2. Bartlett, J.A. and Warwick, J.J., 2005. Assessing the Impacts of Nutrient Load Uncertainties on Predicted Truckee River Water Quality, Fall Meeting of the American Geophysical Union, San Francisco, California, December 5-9.
3. Kish, S.M., Bartlett, J., Warwick, J.J., McKay, A., and Fritsen, C., In Press. "A long-term dynamic modeling approach to quantifying attached algal growth and associated impacts on dissolved oxygen in the lower Truckee River, Nevada, Journal of Environmental Engineering, ASCE.

Project Identification

USGS water quality modeling - Truckee River, Nevada.
PI: Alan McKay

Problem and Research Objectives

Because dissolved oxygen (DO) is essential to aquatic life, it is important that DO concentrations do not drop too low. Periphyton, or algae attached to the substrate, produces oxygen via photosynthesis and uses up oxygen during cellular respiration, and the result is diel swings in dissolved oxygen concentrations. Periphyton growth is controlled largely by nutrient (nitrogen and phosphorous) availability, meaning that nutrient concentrations indirectly impact DO concentrations by influencing the amount of periphyton biomass. This study aims to refine an existing water quality model to more accurately predict the concentrations of a suite of water quality constituents, including dissolved oxygen, on the lower Truckee River, Nevada. Using this refined model, several hypothetical scenarios are modeled to determine how changes to nutrient loads impact daily minimum DO concentrations. Uncertainty analysis is then used to assess the influence of model boundary condition uncertainty on model predictions.

Methodology

All water quality modeling in this study are computer simulations using a modified version of the U.S. Environmental Protection Agency's Water Quality Analysis Simulation Program, Version 5 (WASP5). While there are too many model inputs and parameters to list, they include a flow balance derived from USGS stream gages, water quality data provided by the Truckee Meadows Water Reclamation Facility (TMWRF), and rate coefficients provided by previous studies on the Truckee River. Hypothetical scenarios are modeled by adjustment of flows and nutrient loads. Uncertainty analysis is employed to quantify the impacts of boundary condition uncertainty on model predictions. More specifically, this analysis will be done using Monte Carlo techniques, and the quantification will be achieved by developing probabilistic confidence intervals around model predictions.

Principal Findings and Significance

<u>Work Completed to Date</u>

This study began with the refinement of an existing long-term, dynamic water quality model for the lower Truckee River. Changes were made in order to reduce error between model predictions and observed data. Predictions from the refined model and observed data both show the Truckee River failing to meet the minimum dissolved oxygen standard prescribed by the Nevada Department of Environmental Protection. Hypothetical scenarios were then modeled to predict the impacts of nutrient removal on periphyton biomass and DO concentrations. A model simulating the removal of a permit discharge excursion from TMWRF and a separate model simulating removal of agriculture nutrient loads both predicted that the dissolved oxygen standard would not be met at all locations in the modeled reach at all times in the model domain. It was eventually determined that the inability of the river to meet the DO standard was a result of low flows. A final scenario set a minimum upstream flow, which was increased until the dissolved oxygen standard was met at all locations at all times. These results suggest that simply decreasing nutrient loads, be it through the removal of the discharge permit excursion or via the removal of agricultural nutrient loads, would still not cause the prescribed dissolved oxygen standard to be met at all times. Instead, these findings indicate that a minimum flow must be maintained in order for the Truckee River to continuously meet the standard.

A Monte Carlo approach was employed using the developed model to perform uncertainty analysis. Calculations indicate that the upstream organic nitrogen boundary condition is the model's most important boundary condition, so uncertainty analysis first focused on determining how uncertainty in upstream organic nitrogen concentrations affects model predictions of other constituents, particularly dissolved oxygen. Another significant source of model uncertainty is the effect of irrigation ditch returns, as nutrient loads from these largely unmonitored ditches are not well known. Additional uncertainty analysis focused on these ditch returns to determine their influence on predicted concentrations of constituents in the river. As mentioned previously, uncertainty analysis will result in confidence intervals around model predictions. Large confidence intervals show a great deal of uncertainty in model predictions and might indicate that more data is required in order to properly model water quality in the lower Truckee River. Small confidence intervals, on the other hand, indicate more certainty in model predictions and might suggest that additional or more frequent sampling is not necessary. The final analyses indicated that uncertainty due to unknown ditch return loading was small, while

Outreach/Publications

Conference Presentations

McKay, W. A., Warwick, J.J., Kish, S., Fritsen, C., and Bartlett, J., 2003. "Modeling linkages between groundwater, surface water and periphyton-driven oxygen dynamics in the lower Truckee River, Nevada," Fall Meeting of the American Geophysical Union, San Francisco, California, December 8-12.

Bartlett, J.A. and Warwick, J.J., 2005. "Assessing the Impacts of Nutrient Load Uncertainties on Predicted Truckee River Water Quality," Fall Meeting of the American Geophysical Union, San Francisco, California, December 5-9.

Peer Reviewed Journal Publications

Kish, S.M., Bartlett, J., Warwick, J.J., McKay, A., and Fritsen, C., In Press. "A long-term dynamic modeling approach to quantifying attached algal growth and associated impacts on dissolved oxygen in the lower Truckee River, Nevada," *Journal of Environmental Engineering, ASCE*.

Small Scale Variability of Soil Ped Hydraulic Properties: Potential Impact on Soil Recharge and Ecosystems

Basic Information

Title:	Small Scale Variability of Soil Ped Hydraulic Properties: Potential Impact on Soil Recharge and Ecosystems
Project Number:	2004NV65B
Start Date:	3/1/2004
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	Nevada 01
Research Category:	Not Applicable
Focus Category:	Hydrology, Geomorphological Processes, Drought
Descriptors:	None
Principal Investigators:	Michael Young, Eric McDonald

Publication

1. Meadows, D.G., M.H. Young, E.V. McDonald. 2005. The mechanism of infiltration on desert pavements as a function of surface age. Soil Science Society of America 69th Annual Meeting, Salt Lake City, UT, Nov. 6-10, 2005.
2. Meadows, D.G., M.H. Young, E.V. McDonald. 2005. Hydraulic property determination of vesiculated soil peds in desert pavement environments. W-188 Soil Physics Research Group Meeting. Las Vegas, NV, Jan. 3-5, 2005.
3. Meadows, D.G., M.H. Young, E.V. McDonald. 2004. Hydraulic properties of individual soil peds, Mojave Desert, CA. Soil Science Society of America 68th Annual Meeting, Seattle, WA, Oct. 31-Nov. 4, 2004.
4. Young, M.H., D.G. Meadows, D. Gimenez, R.J. Heck, T.R. Elliot. 2004. Dynamic behavior of pore morphology using CT scanning preliminary results. Soil Science Society of America 68th Annual Meeting, Seattle, WA, Oct. 31-Nov. 4, 2004.
5. Prim, P.S., D.G. Meadows, M.H. Young. 2004. Determination of interped flow and surface sealing through infiltration experiments on a 100 kA desert pavement. Geological Society of America Annual Meeting, Denver, CO, Nov. 7-10, 2004.
6. Meadows, D.G., M.H. Young, E.V. McDonald. 2005. A laboratory method for determining the unsaturated hydraulic properties of soil peds. Soil Sci. Soc. Am. J. 69:807-815.

7. Meadows, D.G., M.H. Young, E.V. McDonald. 2006. Influence of Surface Age on Hydraulic Properties and Infiltration in Desert Pavement Environments. Catena. Submitted.

Synopsis

Final Report

Problem and research objectives

Spatial variability of soil properties has significant impacts on desert ecosystems that are highly water limited. Coupling that observation with the fact that the southwestern United States has been experiencing significant drought conditions for the past several years, we are left with the need to better understand how water moves through the upper soil surface, into the deeper horizons, and potentially downward to the water table. Many soil surfaces in the desert southwestern United States are covered with highly structured desert pavement environments. The evolution of the hydraulic properties that results from pedologic development over time has implications for the mechanisms, frequency, and depth of recharge events, and how those events could influence plant ecosystems, deeper soil recharge, and potential recharge to groundwater supplies.

Methodology

In this study, we compared the hydraulic properties derived from tension infiltrometer experiments conducted in the field, with the average hydraulic properties of individual soil peds that comprised the area underneath the infiltrometer. This approach facilitated investigation of the interped cracks that separated the individual soil peds on the soil surface because the field infiltrometer method samples ped and interped areas, and the laboratory method samples only the peds themselves. Therefore, the method provides a means to quantify the potential water flow through these preferential flow pathways. The laboratory method for determining the hydraulic properties of individual soil peds is novel and is based on traditional evaporation experiments. Experiments were conducted on three different-aged desert pavement surfaces in the Mojave Desert.

We also conducted experiments where dyed water was applied to four different-aged surfaces under saturated conditions. Following the experiments, the soil was excavated in 2-cm depth increments. Digital images were taken at each depth. The images were then analyzed in a GIS program to calculate the area of dye-stained soil.

Principal findings and significance

We developed a new laboratory method for determining the hydraulic properties of individual soil peds (Meadows et al., 2005). We show:

- K_s and α are significantly higher for the peds on the younger Qf5 surface, most likely a result of reduced pedologic development compared to the older Qf3 and Qf2 surfaces.
- Although the Qf2 and Qf5 surfaces are approximately similar in age, the Qf2 exhibits properties more similar to an older surface (i.e., a Qf3). This may be explained by the fact that the original pavement mantling the Qf2 deposit was stripped away from erosion

and a new pavement re-formed on the site. Thus, the present, re-formed pavement may have been formed on remnant structure from the original pavement.

- Large interped variability exists in the hydraulic properties at the scale that we sampled (tens of cm).
- The oldest surface exhibited the largest variability in hydraulic properties, particularly in K_s. The reason for this difference in variability is uncertain, but probably relates to the disparate lengths of time that the peds have existed at the surface and thus exposed to shrink-swell activity and other pedogenic processes.
- Infiltration into the soil is dominated by the interped cracks on the older surfaces when conditions are near saturation. These interped cracks are preferential flow paths and may increase deep percolation and potential recharge.
- On the young, unstructured surface, water moves rapidly through the soil matrix. Thus, a transition in the primary mechanism of infiltration occurs from a matrix dominated to a preferential flow dominated system.
- The steady-state infiltration rates of the bulk soil are fairly constant once peds are developed (≥10 ka). However, the fact that the steady-state infiltration rates are constant, yet the ped conductivity decreases from the Qf5, may indicate an increase in preferential flow to compensate for the decrease in ped conductivity.
- On well-developed pavements, infiltration appears to occur along ped faces. Water then diffuses toward the ped interiors.
- The total crack length is greater for the Qf3 and Qf2 surfaces. The increase in the preferential flow paths may also explain the constant steady-state infiltration rates.
- The 20 cm diameter tension disc infiltrometer is capable of capturing the ped variability on the surface that exhibits the most ped-to-ped variability (i.e., Qf3).

Information Transfer Activities

Papers:

Meadows, D.G., M.H. Young, E.V. McDonald. 2006. Influence of Surface Age on Hydraulic Properties and Infiltration in Desert Pavement Environments. Catena. *Submitted*.

Meadows, D.G., M.H. Young, E.V. McDonald. 2005. A laboratory method for determining the unsaturated hydraulic properties of soil peds. Soil Sci. Soc. Am. J. 69:807-815.

Presentations:

Meadows, D.G., M.H. Young, E.V. McDonald. 2005. The mechanism of infiltration on desert pavements as a function of surface age. Soil Science Society of America 69th Annual Meeting, Salt Lake City, UT, Nov. 6-10, 2005.

Meadows, D.G., M.H. Young, E.V. McDonald. 2005. Hydraulic property determination of vesiculated soil peds in desert pavement environments. W-188 Soil Physics Research Group Meeting. Las Vegas, NV, Jan. 3-5, 2005.

Meadows, D.G., M.H. Young, E.V. McDonald. 2004. Hydraulic properties of individual soil peds, Mojave Desert, CA. Soil Science Society of America 68th Annual Meeting, Seattle, WA, Oct. 31-Nov. 4, 2004.

Young, M.H., D.G. Meadows, D. Gimenez, R.J. Heck, T.R. Elliot. 2004. Dynamic behavior of pore morphology using CT scanning preliminary results. Soil Science Society of America 68th Annual Meeting, Seattle, WA, Oct. 31-Nov. 4, 2004.

Prim, P.S., D.G. Meadows, M.H. Young. 2004. Determination of interped flow and surface sealing through infiltration experiments on a 100 kA desert pavement. Geological Society of America Annual Meeting, Denver, CO, Nov. 7-10, 2004.

Student Support

This grant largely funded the research endeavors (time, instruments and travel) during completion of Darren Meadows' Ph.D. degree. In addition, the grant funded Pamela Prim, an undergraduate student at University of Nevada Las Vegas (UNLV), Department of Geosciences, who helped with the laboratory and field work. Pamela presented a poster at the Geological Society of America meeting in 2004. Another UNLV student who is working on his M.S. degree, Todd Arrowood, was also funded on this project to help with laboratory and field experiments.

Wash Load and Fractional Suspended Load Transport in Lake Tahoe Tributaries

Basic Information

Title:	Wash Load and Fractional Suspended Load Transport in Lake Tahoe Tributaries
Project Number:	2005NV78B
Start Date:	3/1/2005
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	Nevada 02
Research Category:	Climate and Hydrologic Processes
Focus Category:	Sediments, Surface Water, Non Point Pollution
Descriptors:	None
Principal Investigators:	Guohong Jennifer Duan

Publication

1. Rotter, S. and Duan, J.G. (2005). Fine-sized sediment load prediction by Artificial Newton Network approach. Lake Tahoe Science Consortium 2005, June.
2. Rotter, S. (2006) Predicting fine-sized sediment load in Lake Tahoe tributaries. ASCE EWRI 2006 World Water Congress.
3. Rotter, S. and Duan, J. G. (2006) Statistical properties of fine sediment time-series from Lake Tahoe tributaries, Submitted to Lake Thaoe Basin 3rd Biennial Conference.

Final Report

Quantify Wash Load and Fractional Suspended Load Transport in Lake Tahoe Tributaries

Project Objective

The objective of the project is to quantify fine sediment load from 10 primary streams directly discharging into Lake Tahoe. Integrated sediment samples were collected at the Long Term Interagency Monitoring Program (LTIMP) stations. DRI Soil Lab has analyzed fine particles of silt and clay from the measured suspended load. The project is in collaboration with USGS Carson City office. USGS scientists are Nancy Alevax, Bob Burrow, and Tim Rowe.

This funded research project is important to the LTIMP program. It provides additional data of fine-grained sediment by size fractions at ten primary LTIMP sites, develops statistical and analytical methods to predict fine-grained sediment load, and establishes foundations for DRI and USGS continue their collaboration in strengthening LTIMP program in Lake Tahoe.

Study Site

Due to the focus on Lake Tahoe as the terminal point for suspended sediment transport in all of the tributaries to the lake, the sampling sites of greatest concern are those in the closest proximity to the lake on any individual tributary. The study chose ten primary LTIMP sites, which located at Third Creek near Crystal Bay, Incline Creek near Crystal Bay, Glenbrook Creek at Glenbrook, Edgewood Creek at Stateline, Trout Creek at South Lake Tahoe, Upper Truckee River at South Lake Tahoe, General Creek near Meeks Bay, Blackwood Creek near Tahoe City, Ward Creek at Hwy 89 near Tahoe Pines. The ten tributaries that are monitored each have a gauging site located near their entrance to the lake with several of the streams having additional sites further upstream. The eight additional sites located higher within the watersheds are of less importance to this study because we are most concerned with the final output to the lake from any one tributary. Thus, the ten gauging stations located closest to the lake provide the most relevant data and are the only LTIMP sites used for this study.

Preliminary Result

Measurements were taken weekly or bi-weekly depending on high or low flows since May 2005. At each site, we measured air and water temperature, and collected water samples. These samples were analyzed using DRI Saturn Laser Digitizer for turbidity, suspended sediment concentration, and conductivity. Preliminary conclusions from samples collected from May 2005 to Jan. 2006 are summarized as follows.

1) Over 96% of suspended sediments is finer than $62.5\,\mu m$, and over 82% of suspended sediment is less than $31\mu m$ at the ten streams. The averaged D_{50} for the ten streams is $25.85\mu m$. This result clearly indicated that fine particles less than $62.5\,\mu m$ are the majority of sediment load to the lake.
2) The highest sediment concentration (503 mg/L) was measured at the Glenbrook Creek. Sediment concentrations at Logan House and Edgewood Creek are around 100mg/L. Other Creeks including Blackwood, General, Upper Truckee, Incline, Ward, Third, Trout Creek has SSC varying from 30 to 90 mg/L.
3) Suspended sediment concentration (SSC) does not directly relate to flow discharge. Streams (e.g. Third Creek, Upper Truckee) having high values of SSC associate with low discharges. However, the total fine sediment volume closely correlates with flow

discharge. High flows carry more fine sediment load to the lake because flow discharge is high.

In summary, fine sediment load is the primary suspended sediment load discharging directly into the lake. The contributions from different streams vary depending on climate and watershed characteristics. High suspended sediment concentration does not always associate with high sediment load volume.

Current Research Activity

Since we have not completed data collection for an entire season, field data collection is currently on-going. More sediment samples are analyzed at DRI soil laboratory. SSC showed no direct correlation with flow discharge, so that we are employing statistical method to analyze these field data. Currently, we are generating time-series of discharge, SSC, sediment percentages by size fraction for data collected from May 2005 to June 2006. Statistical characteristics (e.g. mean, variance, skewness) are calculated for these time-series. Correlations between time-series for the same variable (e.g. discharge) at different watersheds or time-series of different variables for the same watershed will be analyzed.

Training Accomplishment

Funding one MS student, Shane Rotter, from the Hydrologic Sciences Program at the University of Nevada, who has successfully defended his proposal, and expected to graduate in Dec 2006.

Publications

Rotter, S. and Duan, J.G. (2005). "Fine-sized sediment load prediction by Artificial Newton Network approach." *Lake Tahoe Science Consortium 2005,* June.

Rotter, S. (2006) "Predicting fine-sized sediment load in Lake Tahoe tributaries." *ASCE EWRI 2006 World Water Congress.*

Rotter, S. and Duan, J. G. (2006) "Statistical properties of fine sediment time-series from Lake Tahoe tributaries", Submitted to Lake Thaoe Basin 3rd Biennial Conference.

Aggregating Hydraulic Property Measurements to Large Scales and Potential Applications on Water Budget Studies in Arid and Semi-Arid Environment

Basic Information

Title:	Aggregating Hydraulic Property Measurements to Large Scales and Potential Applications on Water Budget Studies in Arid and Semi-Arid Environment
Project Number:	2005NV83B
Start Date:	3/1/2005
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	Nevada 01
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Water Supply, Methods
Descriptors:	None
Principal Investigators:	Jianting Julian Zhu

Publication

1. Zhu, J., Mohanty, B. P., and Das, N. N., Effective Soil Hydraulic Properties at the Landscape Scale and Beyond, 18th World Congress of Soil Science, July 9-15, 2006, Philadelphia, Pennsylvania, submitted.
2. Zhu, J., Sun, D., and Young, M. H., Aggregating Hydraulic Property Measurements to Large Scale Hydrologic Processes, Western Pacific Geophysics Meeting, July 24 27, Beijing, China, submitted.
3. Zhu, J., Young, M. H., and van Genuchten, M. Th., Upscaling Schemes for Hydraulic Functions at the Landscape Scale, AGU Joint Assembly, Baltimore, Maryland, May 23 26, 2006.
4. Zhu, J., and Young, M. H., Upscaling Relationships of Hydraulic Functions for Flux and Moisture in Heterogeneous Soils, W1188 Multistate Research Project Annual Meeting, January 2 4, Las Vegas, USA.
5. Zhu, J., Young, M. H., Correspondence of Hydraulic Functions and Its Implication on Upscaling for Large Scale Flux and Surface Soil Moisture in Heterogeneous Soils, AGU Fall Meeting, San Francisco, USA, December 5 9, 2005.
6. Mohanty, B. P., and Zhu, J., Effective Land Surface Hydraulic Parameters for Horizontally and Vertically Heterogeneous Soil, 5th International Scientific Conference on the Global Energy and

Water Cycle, Orange County, California, June 20 24, 2005.
7. Mohanty, B. P., and Zhu, J., Soil hydraulic parameters for heterogeneous landscapes, Invited, AGU 2005 Joint Assembly, New Orleans, Louisiana, May 23-27, 2005.
8. Zhu J., Young, M. H., van Genuchten, M. Th., Upscaling Schemes for Gardner and van Genuchten Hydraulic Functions for Heterogeneous Soils, Vadose Zone Journal, submitted, 2006a.
9. Zhu, J., Mohanty, B. P., and Das, N. N., On the Effective Averaging Schemes of Hydraulic Properties at the Landscape Scale, Vadose Zone Journal, 5, 308-316, 2006b.
10. Zhu, J., and Mohanty, B. P., Effective Scaling Factor for Transient Infiltration in Heterogeneous Soils, Journal of Hydrology, 319, 96-108, 2006a.
11. Zhu, J., Mohanty, B. P., Effective Soil Hydraulic Parameters for Land-atmosphere Interaction, Journal of Hydrometeorology, submitted, 2006b.

Synopsis

Final Report

<u>Title</u>**:** Aggregating Hydraulic Property Measurements to Large Scales and Potential Applications on Water Budget Studies in Arid and Semi-Arid Environment

Investigators: Jianting Zhu

Problem and research objectives:

Groundwater is the main source of water supply in much of Nevada and the Great Basin. The vadose zone determines the partitioning of precipitation over surface runoff and infiltration and the partitioning of infiltrated water over evapotranspiration and the recharge of groundwater. In order to quantify flow and transport in the vadose zone, the hydraulic properties of the vadose zone soils have to be specified. The soil hydraulic properties include the relationships of unsaturated hydraulic conductivity versus capillary pressure head and capillary pressure head versus water content (water retention). Simulations of unsaturated flow and solute transport in soil typically use closed-form functional relationships to represent hydraulic properties.

While there are many point scale field measurements of hydraulic properties available from across various locations of arid and semi-arid western United States, how they can be used in large scale water budget analysis and other environmental applications remains an outstanding issue. Hydraulic property data are often characterized using various forms of functions. Conditions for which alternative forms of the hydraulic functions give the same or similar hydrologic responses for a given hydrologic scenario are essential in many applications, such as soil-vegetation-atmosphere transfer (SVAT) schemes in general circulation models (GCMs). Therefore, our ongoing research project tries to answer two major questions: (1) If the optimal p-norm value (the best averaging scheme) is known for parameters of one hydraulic function to produces the ensemble flux and surface soil moisture content for a certain heterogeneous field, what should the corresponding p-norm be for other hydraulic functions to also produce the ensemble flux and surface soil moisture? and (2) What should be the effective/average hydraulic properties for the entire pixel (a grid cell in large scale hydro-climate models or a footprint of a remote sensor) for a typical soil textural combination in a real field condition, if the soil hydraulic properties can be measured or estimated at point scales?

Methodology:

Using the actual field hydraulic property measurements by researchers at the Desert Research Institute in Nevada from across various locations of arid and semi-arid western United States, we try to develop conceptual guidelines of how to scale up these hydraulic property data to large scale and establish scaling relationships when different hydraulic property models are used to simulate a variety of large scale hydrologic processes.

The soil hydraulic functions consist of the soil water retention function which defines the water content as a function of the suction head, and the hydraulic conductivity function which relates the hydraulic conductivity with the water content or suction head. The hydraulic functions used by Gardner and Russo are given by,

$$S_e = \left[e^{-0.5\alpha_G h}\left(1+0.5\alpha_G h\right)\right]^{0.8} \quad [1]$$

$$K = K_{SG} e^{-\alpha_G h} \quad [2]$$

van Genuchten combined an S-shaped soil water retention function with the statistical pore-size distribution model to obtain the following functions,

$$S_e = \frac{1}{\left[1+\left(\alpha_{vG} h\right)^n\right]^m} \quad [3]$$

$$K = \frac{K_{SvG}\left\{1-\left(\alpha_{vG} h\right)^{mn}\left[1+\left(\alpha_{vG} h\right)^n\right]^{-m}\right\}^2}{\left[1+\left(\alpha_{vG} h\right)^n\right]^{0.5m}} \quad [4]$$

In [1] – [4], $S_e = (\theta-\theta_r)/(\theta_s-\theta_r)$ is effective saturation, θ is the volumetric water content, θ_r is the residual volumetric water content, θ_s is the saturated volumetric water content, h is the suction head (a positive quantity), K is the hydraulic conductivity, K_s is the saturated hydraulic conductivity; α, m and n are empirical hydraulic shape parameters, and m=1-1/n, while the subscripts G and vG refer to Gardner and van Genuchten model parameters.

Using either the field-measured data sets or the re-generated data, we calculate the effective hydraulic parameters using the two critical criteria (i.e., preservation of the surface flux and the surface moisture content). For the Gardner-Russo model, the effective hydraulic parameters α_{Geff} and K_{sGeff} for α and K_s are calculated as follows,

$$\left[e^{-0.5\alpha_{Geff} h_0}\left(1+0.5\alpha_{Geff} h_0\right)\right]^{0.8} = \overline{\left[e^{-0.5\alpha_G h}\left(1+0.5\alpha_G h\right)\right]^{0.8}} \quad [5]$$

$$K_{sGeff}\frac{1-e^{\alpha_{Geff}(z_0-h_0)}}{e^{\alpha_{Geff}}-1} = \overline{q_G} \quad [6]$$

respectively. For the van Genuchten model, the effective hydraulic parameters α_{vGeff} and K_{svGeff} are obtained with

$$\left[1+\left(\alpha_{vGeff} h_0\right)^n\right]^{-m} = \overline{\left[1+\left(\alpha_{vG} h_0\right)^n\right]^{-m}} \quad [7]$$

$$q_{vG}\left(K_{sGeff}, \alpha_{Geff}, n, m, h_0\right) = \overline{q_{vG}} \quad [8]$$

where $\overline{q}$ is the ensemble steady-state flux (either evaporation or infiltration) across the land surface. The right-hand sides of Eqs. [5] - [8] are the mean (ensemble) quantities for the effective degree of saturation at the land surface (Eqs. [5] and [7]) and the flux across the land surface (Eqs. [6] and [8]), while the left-hand side quantities are those based on a single set of effective parameter values. We hence use the effective hydraulic parameters to predict the mean flux exchange between the subsurface and the atmosphere and to preserve the mean effective degree of saturation at the land surface. The effective degree of saturation was used because it reflects (and preserves) the prevailing effective moisture content important for many global water cycle applications, as well as for other large-scale problems.

The p-norm or p-order power average $\hat{\xi}(p)$ for a set of any N random parameter values ξ_i is given by,

$$\hat{\xi}(p) = \left[(1/N) \sum_{i=1}^{N} \xi_i^p \right]^{1/p} \quad [9]$$

Based on these effective parameter values and the original input parameters that were used to obtain the effective parameter values, we calculate the corresponding *p*-norms for the hydraulic parameters iteratively using the following equations,

$$K_{sGeff} = \left[(1/N) \sum_{i=1}^{N} K_{sGi}^{p_{K_sG}} \right]^{1/p_{K_sG}} \quad [10]$$

$$\alpha_{Geff} = \left[(1/N) \sum_{i=1}^{N} \alpha_{Gi}^{p_{\alpha G}} \right]^{1/p_{\alpha G}} \quad [11]$$

$$K_{svGeff} = \left[(1/N) \sum_{i=1}^{N} K_{svGi}^{p_{K_svG}} \right]^{1/p_{K_svG}} \quad [12]$$

$$\alpha_{vGeff} = \left[(1/N) \sum_{i=1}^{N} \alpha_{vGi}^{p_{\alpha vG}} \right]^{1/p_{\alpha vG}} \quad [13]$$

where p_{K_sG} is the *p*-norm for the Gardner K_s, $p_{\alpha G}$ for the Gardner α, p_{K_svG} for the van Genuchten K_s, and $p_{\alpha vG}$ for the van Genuchten α. By calculating the *p*-norm values for both Gardner and van Genuchten models for various environmental conditions, such as surface pressure and water table depth, we can establish scaling relationships between Gardner and van Genuchten hydraulic property functions.

Principal findings and significance:

The main findings of Zhu et al. [2006a] can be summarized as follows. For the steady-state flow problem considered in this project, the degree of site characterization (84 measured points) is generally enough to be used in upscaling the flux across the land surface boundary and the surface effective degree of saturation (the latter being closely related to surface soil moisture content). More heterogeneous sites, however, may require more measurements. The upscaling schemes are better defined, and with less variability, in terms of *p*-norms than when effective parameter values were used. For the α parameters, the *p*-norm relationships between the Gardner and van Genuchten models are typically similar for a variety of scenarios considered in this project, but the *p*-norms may diverge more for different levels of variability in the input hydraulic parameters and other hydrologic conditions. The correlation between hydraulic parameters within the model is important for determining *p*-norm relationships between Gardner and van Genuchten models. In general, *p*-norms (or the optimal averaging schemes) are less well defined for the Gardner model than for the van Genuchten model, and may in fact be more difficult to use compared to the van Genuchten model in the upscaling context when the water table is relatively deep such as for many arid and semi-arid conditions. For deep water table depths (at least equivalent to 10 m), *p*-norms for van Genuchten parameters are relatively constant, while *p*-norms for Gardner parameters vary significantly as flow scenarios shift from evaporation toward infiltration. As the water table becomes shallower, *p*-norms for the van Genuchten model become less well defined and more sensitive to changes in the surface pressure head. Auto-correlations in hydraulic parameters appear to have a very insignificant impact in relating upscaling schemes between the Garner and van Genuchten models.

The study of Zhu and Mohanty [2006a] demonstrate that for a large range of hydraulic properties from silty clay to sand with large uncertainties in the Miller-Miller scaling factor, the saturated water content, and the surface ponding depth, relatively small range of *p*-norm values has been found. Among the three, variability of the Miller-Miller scaling factor has the most significant effect on the ensemble flux behavior. The correlation among the Miller-Miller scaling factor, the saturated water content and the surface ponding depth increases the effects of soil heterogeneity. The main findings of Zhu and Mohanty [2006b] indicate that vertically heterogeneous variably-saturated porous medium does not discharge as much moisture flux as the equivalent homogeneous medium of arithmetic mean values for the hydraulic parameters. Zhu et al. [2006b] show that hydraulic parameter distribution skewness is also important in determining the upscaled effective parameters in addition to the mean and variance. Negative skewness enhances heterogeneity effects, which make the effective parameter values deviate more significantly from the arithmetic mean. In the case of negative skewness, a few small hydraulic parameter values make the heterogeneous soil more permeable (with larger flux), which hence causes the effective heterogeneous system to deviate more from the homogeneous formation with arithmetic mean parameters.

Information Transfer Activities

a) Conference Presentations:

Zhu, J., Mohanty, B. P., and Das, N. N., Effective Soil Hydraulic Properties at the Landscape Scale and Beyond, 18th World Congress of Soil Science, July 9-15, 2006, Philadelphia, Pennsylvania, submitted.

Zhu, J., Sun, D., and Young, M. H., Aggregating Hydraulic Property Measurements to Large Scale Hydrologic Processes, Western Pacific Geophysics Meeting, July 24 – 27, Beijing, China, submitted.

Zhu, J., Young, M. H., and van Genuchten, M. Th., Upscaling Schemes for Hydraulic Functions at the Landscape Scale, AGU Joint Assembly, Baltimore, Maryland, May 23 – 26, 2006.

Zhu, J., and Young, M. H., Upscaling Relationships of Hydraulic Functions for Flux and Moisture in Heterogeneous Soils, W1188 Multistate Research Project Annual Meeting, January 2 – 4, Las Vegas, USA.

Zhu, J., Young, M. H., Correspondence of Hydraulic Functions and Its Implication on Upscaling for Large Scale Flux and Surface Soil Moisture in Heterogeneous Soils**,** AGU Fall Meeting, San Francisco, USA, December 5 – 9, 2005.

Mohanty, B. P., and Zhu, J., Effective Land Surface Hydraulic Parameters for Horizontally and Vertically Heterogeneous Soil, 5th International Scientific Conference on the Global Energy and Water Cycle, Orange County, California, June 20 – 24, 2005.

Mohanty, B. P., and Zhu, J., Soil hydraulic parameters for heterogeneous landscapes, Invited, AGU 2005 Joint Assembly, New Orleans, Louisiana, May 23-27, 2005.

b) Journal Publications

Zhu J., Young, M. H., van Genuchten, M. Th., Upscaling Schemes for Gardner and van Genuchten Hydraulic Functions for Heterogeneous Soils, Vadose Zone Journal, submitted, 2006a.

Zhu, J., Mohanty, B. P., and Das, N. N., On the Effective Averaging Schemes of Hydraulic Properties at the Landscape Scale, Vadose Zone Journal, 5, 308-316, 2006b.

Zhu, J., and Mohanty, B. P., Effective Scaling Factor for Transient Infiltration in Heterogeneous Soils, Journal of Hydrology, 319, 96-108, 2006a.
Zhu, J., Mohanty, B. P., Effective Soil Hydraulic Parameters for Land-atmosphere Interaction, Journal of Hydrometeorology, submitted, 2006b.

Training Accomplishments: Funding one Master student at UNLV for one term (Michelle Harris)

Notable Awards and Achievements: PI has received a DOE grant "A New Method to Estimate Soil Hydraulic Parameter Uncertainty and Heterogeneity Using Bayesian Updating and Neural Network Methods" and NSF-EPSCoR proposal development award "Soil Hydraulic Property Upscaling and Soil Moisture and Flux Dynamics at Various Spatial and Temporal Scales".

Award No. 05HQAG0069 Water Resources of the Basin and Range Carbonate Aquifer System in White Pine County, Nevada, and Adjacent Areas in Nevada and Utah

Basic Information

Title:	Award No. 05HQAG0069 Water Resources of the Basin and Range Carbonate Aquifer System in White Pine County, Nevada, and Adjacent Areas in Nevada and Utah
Project Number:	2005NV125S
Start Date:	6/1/2005
End Date:	5/31/2008
Funding Source:	Supplemental
Congressional District:	Nevada 2
Research Category:	Not Applicable
Focus Category:	Water Quantity, Groundwater, Hydrogeochemistry
Descriptors:	
Principal Investigators:	James Thomas

Publication

Water Resources of the Basin and Range Carbonate Aquifer System in White Pine County, Nevada, and Adjacent Areas in Nevada and Utah

The U.S. Geological Survey proposes a cooperative study with Desert Research Institute to evaluate geohydrologic characteristics of ground-water flow systems in selected basins in White Pine County, Nevada, and adjacent basins in Lincoln County, Nevada, and Utah. The main objectives of the proposed study are to evaluate the following geohydrologic characteristics within the study area:

(1) the extent, thickness, and hydrologic properties of aquifers,
(2) the volume and quality of water stored in aquifers,
(3) the delineation of subsurface geologic structures controlling ground-water flow,
(4) determining ground-water flow direction and gradients,
(5) the distribution of recharge and discharge areas, and
(6) determining representative rates of recharge and discharge.

Geologic, hydrologic, and supplemental geochemical information will be integrated to determine basin and, if possible, regional ground-water budgets. All geohydrologic data will by synthesized and evaluated to develop a three-dimensional conceptual model of the ground-water flow system in the proposed study area.

Information Transfer Activities: The research team has traveled to several communities, within the study area, to deliver progress reports to local residents. Topics of discussion include status of the various projects, identification and discussion of relevant findings, and question and answer sessions with the audience.

Development of a Classification System for Natural Impervious Cover in the Lake Tahoe Basin

Basic Information

Title:	Development of a Classification System for Natural Impervious Cover in the Lake Tahoe Basin
Project Number:	2004NV67B
Start Date:	3/1/2004
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	Nevada 02
Research Category:	Water Quality
Focus Category:	Models, Water Quality, Geomorphological Processes
Descriptors:	
Principal Investigators:	Mary Cablk

Publication

Final Report

A Classification System for Impervious Cover in the Lake Tahoe Basin

Investigators: Mary Cablk, Ph.D.

<u>Problem and research objectives</u>:

This research is unique in that natural impervious cover has not been addressed or investigated to date for the Lake Tahoe Basin or for areas in similar systems. Similar systems refer to areas undergoing or having undergone significant urban/suburban development that may directly or indirectly contribute to lake water quality or clarity issues. It is anthropogenic impervious cover, development such as roads, parking lots, and houses for example, that has been the focus of attention by basin managers and researchers. Natural impervious cover, such as granite for example, contributes sediments and/or nutrients to the lake. Furthermore, the physical attributes of this natural cover that determine its actual level of permeability or attenuation vary with environmental conditions and geographic location. Natural impervious cover is less likely if at all, to carry or concentrate pollutants from vehicles or human related activities directly into the lake or into streams, which then flow into the lake. This is in contrast to anthropogenic impervious cover, which serves as a direct conduit for pollutants, nutrients, and sediment. The nature of this research is thus to investigate and offer a solution to a potentially important piece of information, in the form of a classification scheme directly translatable into a data set, that may advance and refine existing means for assessing water quality issues at Lake Tahoe.

Natural impervious surfaces are visible both on the ground and from space. However, we do not have an accurate estimate or calculation of how much natural impervious surface exists in the basin, where exactly it occurs, its impact on water quality or clarity, or how it relates, physically and geographically, to anthropogenic impervious cover with respect to runoff (nutrient, sediment, pollutants). Before we can effectively discuss the impact of anthropogenic impervious surface on lake water quality and clarity, we must have an understanding of the “background” or contribution from natural impervious cover. In other words, there is no baseline against which to compare the degradation in water quality/clarity from development. I assert that this baseline can be developed and it can be mapped basin wide from existing data. The scope of this research includes the entire Lake Tahoe Basin as covered by 2002 Ikonos satellite imagery, which DRI already possesses. The proposed classification system would be applicable to the entire basin.

The objectives of this research were to develop a classification system for natural impervious cover and determine the feasibility of generating a subsequent classified data set. This classification was developed to be useful with existing models such as TMDL or other runoff process models in use or under development. The current classification system for impervious cover employed by TRPA is straightforward and includes only anthropogenic impermeable surfaces, not natural impervious surfaces such as granite or other rock surfaces. It is a binary classification. The idea of “soft impervious cover” has been broached by TRPA and the USFS. “Soft” cover would include compacted areas that may not be entirely impermeable, but does not retain its natural permeability. Examples of soft cover include gravel roads, gravel parking lots, compacted road base, and dirt roads. These cover types are comprised of a variety of materials, have different erosion potential, experience varying degrees of compaction, and also may or may not be or become completely impervious. These cover types are also different from hard natural rocks, loose DG over hard surfaces, or other surfaces that exist in the basin but are not used in the same manner as the above mentioned soft cover types. Nonetheless, both natural and soft impervious cover types clearly do not fall into the current classification employed in the basin. It is for this reason that a classification system, rather than a simple binary impervious/non-impervious schema, is very useful.

Overview:

Lake Tahoe is the second deepest lake in the United States and was formed between two and three million years ago in the Sierra Nevada Mountains. The lake and surrounding hydrologic basin lie in what is now politically delineated as California and Nevada. Best known for its deep, clear water, Lake Tahoe's land use history includes natural resource extraction, grazing, recreation and tourism. The latter two industries support the dominant present-day economic base and depend on the integrity of the environment of the lake and its surrounding landscape. At the same time the seasonal influxes of people for year-round recreation opportunities demand infrastructure and urban development to support both the local and tourist-based populations. Human demands on the basin's natural resources including the terrestrial landscape as well as the lake itself have altered the natural environment. As a result of the changes to the basin in recent human history, the lake has become a focal point of research. The primarily research focus is and has been related to the lake's water clarity and quality, which has been shown to be declining over time (Schuster and Grismer 2004; Hatch *et al.,* 2001). A great deal of research has focused on determining the cause(s) of the decline in clarity and associated decrease in water quality and on understanding the relationship between clarity and water quality within the basin.

Sedimentation and contaminant transport are two processes that decrease the lake's water quality and clarity. Both of these processes may occur over undisturbed ground but are accelerated and magnified when the land surface is altered and the effect of development on the landscape is pronounced (Claasen and Hogan 2002). Urban development facilitates sedimentation and contaminant transport directly. In fact, it has been shown that impervious surfaces are a major contributor to watershed degradation and can be used as indicators of watershed integrity (Arnold and Gibbons 1996). Paved surfaces are impervious and do not allow percolation into the underlying soil or substrate. As a result, water accumulates and can move with greater velocities over these impenetrable surfaces until it moves onto an unpaved surface. Because impervious surfaces concentrate and accelerate water, the water's force where it leaves the paved surface is capable of eroding or moving surface soil that would otherwise not erode. Contaminant transport into water bodies occurs through the same physical process but involves contaminants from vehicles that accumulate on paved surfaces. One could argue that if the surfaces were intact and unpaved, vehicles would not likely drive on them and thus contaminants would not enter water bodies or the terrestrial system. This brings to question the impact that non-paved but compacted areas might similarly have on water quality and clarity. To begin this discussion, some definitions are needed.

Methodology:

Impervious cover – definitions

Hard impervious cover is defined as paved surfaces such as roads, sidewalks and parking lots that are made of asphalt or concrete and are anthropogenic in origin. Houses or other structures are also considered impervious. Impervious surfaces are impenetrable by water and do not allow percolation into the underlying natural surface.

Natural impervious cover includes surfaces that are impervious to water but are natural in origin. The Lake Tahoe basin was formed millions of years ago by andesitic volcanism and deformation and was glaciated in the late pleistocene ice age (Gardner *et al.*, 2000). Evidence of the basin's natural history is evident where granite outcrops protrude from the landscape surface. The basin's Desolation Wilderness for example is renowned for its magnificent granite domes, outcrops, cliffs, and peaks. These granite structures are technically impervious because water does not percolate through them, however they do not meet the 'hard impervious' definition because the origin is natural and not anthropogenic.

Soft impervious cover exhibits some impervious characteristics but do allow for percolation and the parent material is not anthropogenic in origin. Soil compaction serves to reduce the ability of water to infiltrate the surface (Raper 2005) and soil compaction does differentiate 'soft impervious' from pervious surfaces. In some instances compaction of a surface coupled with the addition of gravel or rock material may create a surface that is dramatically altered in terms of its porosity. Dirt roads or highway pullouts for example may be created from the underlying parent material but with continual use compact dramatically. Some water may pool on these surfaces, run down gradient, or channelize similar to what occurs on paved surfaces, but only a fraction of the total water volume will infiltrate. These surfaces are impervious to some degree but are not entirely impenetrable. Furthermore, the degree to which the surfaces are impervious will vary in time and with use.

Together hard, natural, and soft impervious cover includes all landscape surfaces that are impacted by human activity. The objective of defining these three types of impervious cover at the gross level is to be able to classify the landscape features in space and attribute them characteristically along a temporal axis. Identifying the spatial and temporal nature of soft impervious cover is necessary to most accurately capture the effects from meteorological events in modeling or other analytical applications. While the focus of this project is the Lake Tahoe Basin, the resulting classification is transferable to any similar geographic region. Two processes of concern within the basin that are the focus of much research are sedimentation and nutrient loading. Impervious surfaces are hypothesized to play a role in sediment transport and nutrient loading and for this reason the ability to discretely characterize impervious surfaces is critical to understand how these features and associated processes relate to water quality and clarity.

Sedimentation and Nutrient Loading

Sedimentation and nutrient loading has been cited as a primary contributor to decreasing water quality and water clarity of Lake Tahoe and its tributaries (Byron and Goldman 1989). In particular, phosphorous has been identified as a nutrient of primary concern because it promotes the growth of algae, which directly decreases water clarity. With anthropogenic development comes new pathways for phosphorous transport into streams and into the lake directly. Sixty-three percent of the phosphorus that enters the lake is from direct runoff and stream loading (Murphy and Knopp 2000). Most of the research involving nutrient loading has focused within the water bodies measuring the effects of changes that originate in the basin and that are the result of disturbance. What remain unknown are the physical, chemical, and other processes that occur between the nutrient or sediment source and the water body. The specific sources that contribute to an increase in phosphorous, which in turn affects water bodies, have not been extensively identified, mapped or quantified. Understanding component processes of the larger watershed system is critical to understanding the relationship between development and water quality.

Sedimentation likewise negatively impacts the basin’s water bodies. Several studies in other regions have examined landscape characteristics that influence sedimentation rates from soft impervious surfaces, specifically unpaved forest roads. Studies in mountainous watersheds suggest that unpaved roads significantly alter storm flow response where there exist compaction, cutbanks, ditches, and erosion gullies (Ziegler and Giambelluca 1997). Forest roads, cutslopes, and footpaths were found to contribute a disproportionate level of sediment to watersheds relative to their physical area (Reid and Dunne 1984). Some natural impervious surfaces such as exposed bedrock may only contribute to background sedimentation and nutrient loading but other natural impervious surfaces, such as road cut escarpments, contribute significantly (Megahan *et al.*, 2001). A study in rural Kenya revealed that roads and pathways accounted for two percent of the watershed area, but contributed 25%-50% of the sediment load (Harden 1992). Factors such as total precipitation, road segment slope and length, substrate type, maintenance and use have been shown to contribute to increased sediment production in forest watersheds (Ramos-Scharron and MacDonald 2005, Reid and Dunne 1984). If soft and natural impervious cover are identified and mapped then the effects of these features can be factored into analyses of sedimentation and nutrient loading, which will increase the effective predictive strength of impact assessment models in the Lake Tahoe basin.

Although soft impervious cover has been shown to significantly contribute to sediment and nutrient loading, it has not been recognized as an important variable for inclusion into transport models. For example, four sources were identified as primary contributors to sediment and nutrient loading in Lake Tahoe basin watersheds by Hatch *et al.*, (2001), hard impervious surfaces, streambank erosion, stormwater runoff and storm drain systems.

Quantifying load sources is not straightforward in complex terrain. Meaghan *et al.*, (2001) applied the Universal Soil Loss Equation (USLE; Wishcmeier and Smith 1978) to cutslopes in a mountainous region in Idaho and found that almost half of the variability in sedimentation and erosion was unaccounted for by the model. Because universal soil equations were developed for agricultural scenarios in flat landscapes, the variables do not capture the full suite of elements that contribute to erosion in landscapes with complex terrain. This makes understanding physical processes in the Lake Tahoe basin challenging. The difficulty in quantifying erosion, runoff, load and transport in the basin with its complex terrain was recognized by Murphy and Knopp (2000). They identified the Lake Tahoe basin management agencies’ need for information and data that will specifically identify sources of nutrients and sediment. Finally, there are management implications for overlooking the role of soft and natural impervious cover such as underestimating loads, ineffectively focusing mitigation, and inaccurately assessing event mean concentrations (EMC).

Currently, the primary basin measure for water quality and clarity are Total Maximum Daily Load (TMDL) analyses of sediments and nutrients. The United States Environmental Protection Agency (USEPA) guidelines for monitoring water quality are TMDLs, which require quantitative data. Some TMDL models for the Lake Tahoe basin include roads specifically which may be parameterized to “impervious” or “pervious”, however these variables are not weighted or factored as sediment sources and thus do not contribute to the overall model output. Quantifying soft and natural impervious cover in the Tahoe Basin would provide data on sediment and nutrient sources that are absent from current analyses but are known to be important factors.

Mapping impervious cover

Standardizing data, such a classifying, increases analytical power. Standardized data can be compared across different scales of analysis and allows for comparison between studies. A classification system is one type of standardized data and is often applied to spatial data such as maps and satellite imagery. However, there is no ideal classification system with universal application, as it would be impossible to satisfy the needs of inquiry from all user perspectives. Often a classification system will be developed for an individual project that fits the specific project need. Sometimes this is driven by unique vegetation, mineral, or physical characteristics of interest and sometimes the classification is driven by the existing available data. When satellite imagery is to be the foundation data source, resulting classifications are often dependent on sensor resolution. Occasionally a classification system within a select geography will be able to span across a broad spectrum of inquiry and become the basis for many different analyses. The challenge in designing a new classification system is finding the balance between specificity and universality when defining the features to be classified and designing a framework for future analysis.

Typically, classifications are designed to suit the needs of the analyses and are based either on the landscape features of interest, species of interest, or some other measurable spectral attribute. For example, a study examining quality of running waters in central and northern Hellas, Greece, categorizes benthic macroinvertebrates as an index for modeling the ecological quality of streams (Artemiadou and Lazaridou 2005). The analysis fits into the European Union (EU) guidelines under the water framework directive, however the classification system may not be applicable to other areas of Europe and certainly not to all other continents. Because many classification systems are developed to suit specific project needs, these systems may or may not telescope into an existing national level scheme. This is due to the fact that the specific characteristics one encounters as the grain and extent of a study area becomes refined tends to increase in complexity and uniqueness with the finer scale. Classification systems are often location-specific and tailored to examine a particular aspect of the research discipline. Such classifications are difficult to adapt, if at all possible, beyond the original study and are attractive to few users because of the narrow focus. There are exceptions however, such as Dolan and Parker (2005), whose classification of the Bluffton Till Plain subsection of Indiana was one of the first studies to utilize the US Forest Service (USFS) hierarchical framework of ecosystem units in such a landscape. This classification system was also complementary to other studies in southern Indiana.

Few examples of universal classifications exist. The Anderson system of land use classification was developed in the 1970’s to provide a uniform basis for quantifying and monitoring land cover change (Anderson 1971). Anderson’s classification intentionally kept its focus broad, applicable to many users, and customizable to many diverse applications on local, state, and federal scales, becoming a standard system from which many other classification systems and analyses are based. In fact, in the early 1990’s Loveland *et al.* (1991) completed a classification at a 1km spatial resolution that was a conterminous land cover dataset, a natural evolution of the Anderson system with twenty years of technological advances of remote sensing. Similarly, soil and wetland classification systems have been developed over broad geographic regions and are being used for regulatory distinctions and incorporated into many research inquiries. Such systems have been developed to cross over broad spectrums of inquiry and therefore have been incorporated into many applications. For example, the National Wetlands Inventory (NWI) data (Cowardin *et al.*,1979) could be used to identify extent of wetlands or could be used in a wildlife-habitat modeling analysis. When a classification is developed in a broad and open-ended manner it can be used beyond its original intent. Being the focus of many scientific and regulatory inquiries, standardization of impervious cover classification in the Tahoe Basin is essential to understand the dynamic nature of the sources and processes that influence water clarity and water quality. Successful classification systems must strive to satisfy the needs of the majority of users and be based in scientific knowledge.

Historically the classification approach to impervious cover has been to categorize all roads, buildings, lawns, parking lots, etc. into an "urban" land use/land cover class. This is primarily because for decades the finest spatial resolution of U.S. sensors was no less than Landsat 30m imagery. The French SPOT satellite had a slightly finer spatial resolution but imagery was expensive and categorically land use/land cover was used to clump all urban and suburban features into one class. Differentiating grassy areas such as lawns and medians, unpaved lots with dirt or gravel surfaces, and other finer-spatial resolution urban or suburban features with 20m to 30m imagery was and remains difficult. For applications where different values would be applied to features based on function or materials, obtaining an acceptable level of accuracy in the analysis is likewise difficult when functionally different features are not spectrally distinguishable.

The advent of high-spatial resolution imagery brought about the opportunity to greatly advance the state of the art in feature mapping in the urban setting (Goetz *et al.*, 2003). At present the Space Imaging Ikonos sensor and the DigitalGlobe Quick Bird sensor provide commercially available high spatial resolution imagery (1m – 4m spatial resolution) but with limited spectral resolution. Still, despite having only three visible bands and one near infrared band, the spatial resolution of these images allow for identifying tremendous detail on the landscape. Individual roofs, paved walkways, and patios can be identified along with the larger physical features such as roads and commercial buildings of developed areas. The non-paved elements of suburbia such as parks, grass medians, and other landscaping are readily identifiable at a 1 m spatial resolution. Different functional values may be applied to these features in analyses with confidence in thematic accuracy.

The ability to identify and map impervious cover in any form is important for conducting analyses related to environmental integrity and impacts from development on ecological systems. Several studies have focused specifically on the definition, classification, and detection of impervious cover. For example, Arnold and Gibbons (1996) note the use of impervious surfaces in urban areas as indicator of watershed integrity. Hard impervious cover was mapped for the entire Lake Tahoe Basin in 2002 (Cablk and Minor, 2003) for use in urban planning by the Tahoe Regional Planning Agency (TRPA) and for water quality studies by Lahontan Regional Water Quality Control Board. The most studied form of soft impervious cover is dirt and gravel roads, which are considered important contributing factors in sediment and nutrient loading to watersheds (Reid and Dunne 1984, Ziegler and Giambelluca 1997, Ramos-Scharron and MacDonald 2005). Several factors influencing the effect of dirt roads on sediment and nutrient loading have been studied, including slope gradient, slope length, cover, rainfall energy, slope aspect, road length, and road age (Megahan *et al.* 2001). Harden (1992) identifies rural roads and footpaths as generating considerable although variable runoff and that these features are the most active runoff generating components of inhabited mountain watersheds. Hard impervious cover was mapped for the entire Lake Tahoe Basin in 2003 (Minor and Cablk 2004) for use in urban planning by the Tahoe Regional Planning Agency (TRPA) and for water quality studies by Lahontan Regional Water Quality Control Board.

Principal findings and significance:

Current Agency Perspectives

There are four agencies that have a significant role in the management of the resources in the Lake Tahoe Basin. The Tahoe Regional Planning Agency (TRPA) is a bi-state agency and the Lahontan Regional Water Quality Control Board ("Lahontan") is state of California. The two federal agencies are the US Forest Service Lake Tahoe Basin Management Unit (LTBMU) and the US Geological Survey (USGS). All of these agencies are responsible in some capacity for monitoring water quality and clarity and the activities that influence this. Each agency has specific and unique responsibilities that are governed by their specific mandate.

TRPA was the first bi-state regional planning agency in the US. The TRPA mission is to take a leadership role in preserving, restoring and enhancing the Lake Tahoe basin. TRPA is the planning agency for the basin and as such issues permits and develops and enforces regulations as well as serving as the primary interface between the public and regulations. This is the agency that governs development and regulates all activities that impact the landscape and the water bodies in the Lake Tahoe basin regardless of ownership. As such, TRPA works closely with the public and other stakeholders to maintain compliance with environmental thresholds. At present TRPA, the USFS and Lahontan are in the process of updating TRPA's Regional Plan, which guides all land use decisions in the basin and is the basis for all ordinances and environmental code.

The primary responsibility for protecting California's water resources is with the State Water Resources Control Board and the nine regional control boards. Lahontan is the regional control board that governs the waters of the Lake Tahoe basin. Lahontan's jurisdiction covers all of California east of the Sierra Nevada crest north of the Mojave Desert. Like TRPA, Lahontan adopts and implements a basin-wide plan, however Lahontan's mandate is specifically water quality. Although TRPA is the lead agency for implementing coverage transfer, or development, in the basin it is Lahontan that has the ability to review and evaluate the potential water quality impacts from proposed TRPA coverage increases. In this manner the two regulatory agencies work together towards maintaining the integrity of Lake Tahoe.

The US Forest Service is part of the US Department of Agriculture and is one of the largest federal land management agencies in the country. Although the USFS is best known perhaps for timber production, the Lake Tahoe Basin Management Unit is unique in that it adheres to a multi-use mandate. The USFS is largest landowner in the basin, managing over 150,000 acres. Because of the basin geography, the LTBMU managed landscape is openly visible to the public throughout the basin. Management activities are easily observed and scrutinized. One of the primary activities that the LTBMU is responsible for is fuel reduction to minimize risk of wildfire and related hazards. The USFS also has an active watershed restoration program to reduce or eliminate soil erosion from disturbed forested lands. Both of these activities relate directly to water quality and clarity of the lake because of the relationship between the terrestrial uplands and the water bodies within the basin.

The US Geologic Survey maintains the Lake Tahoe Data Clearinghouse, which is an information gateway partnered among federal, state, tribal and local agencies. This is in keeping with their national mission, to provide reliable scientific information about the earth. The USGS's role in the Lake Tahoe basin is to coordinate research, monitoring and other management related activities. They do not play a regulatory, planning, or enforcement role and neither does the USGS own or manage land. However, the importance of data serving and maintenance should not be overlooked. The clearinghouse itself serves digital data and geographic information system (GIS) data. The

USGS recognizes impervious cover and is currently mapping percent impervious cover estimates at a national level for urban areas as a database derivative of its 2001 National Land Cover Database (NLCD) (Homer *et al*, 2004). The USGS is developing the Tahoe decision support system (DSS). This purpose of the DSS is to develop a retrospective baseline against which current and projected development can compared, quantified and analyzed. The USGS role in this effort is to create reliable, historical data that can be used to assess water quality issues. The potential benefits of this type of retrospective research will be to evaluate early watershed decline and thus allow for comparison with current development trends. The recreated historic record will show watershed characteristics over time and will provide a baseline of impervious cover (defined as development) in the basin.

Together these four agencies play a role in the water quality of the basin either in regulation, management, data, or a combination thereof. Each agency recognizes impervious cover as a landscape feature, but their definitions vary slightly. In fact, only TRPA has a formal, written definition of impervious cover. The TRPA Code of Ordnances (chapter 2, page 2-14) defines hard coverage as man-made structures and soft coverage as compacted areas without structures, both of which are further described in the definition of 'land coverage'. The working definition that is employed by TRPA is impervious cover does not allow native plants to grow on its surface and/or less than 25% of water is able to infiltrate that surface. Lahontan makes reference to hard cover and soft cover within their Basin Plan but defers to the TRPA definition of land coverage. Likewise the USFS has no formal definition of impervious cover but defers to the TRPA definition. The USGS defines impervious surfaces in Homer et al. (2004) as impenetrable surfaces such as rooftops, roads or parking lots. Although each agency is using similar definitions of impervious cover that often point to the TRPA code, none of the definitions sufficiently characterize or differentiate the function of different surface cover types. Interagency definitions of imperviousness appear unclear other than the fact that they all are grounded in the TRPA code. This regulatory definition is not sufficient to investigate the myriad of physical processes present and of concern in the basin. Because impervious cover does play a large role there is a need for further clarification and standardization to be useful and effective.

While not an agency with a significant role in the Lake Tahoe basin, the US Environmental Protection Agency (EPA) has a definition of impervious cover (http://www.epa.gov/ATHENS/research/impervious). The EPA defines impervious cover as "the amount of land cover in roads, building and parking lots, and turf grass cover in a watershed and can seriously impact biotic integrity in associated streams". Both TRPA's and the EPA definitions are planning-oriented, regulatory, and descriptive but the EPA's definition differs from the TRPA definition by including effects. Including effects in the definition is problematic for several reasons. First the term 'serious' is not explicitly defined and what is 'serious' will vary from site to site. Second, there may be instances where there is no associated stream to impact. Finally, some streams may already have a compromised biotic integrity and thus the negative effects of development may not further degrade the stream. Including effects within a definition limits the utility of that definition and of the resulting features identified under it.

While there is a common definition written in TRPA code, the language does not cover the full suite of impervious surfaces that exist within the Lake Tahoe basin nor does it define all of the types of impervious surfaces that are of interest to the other agencies. For this reason we put forth a comprehensive classification system of impervious cover that can be used throughout the basin.

Proposed impervious cover classification

Based on the state of science of impervious cover for Lake Tahoe and for other regions as well as based on the need expressed by agency officials for improved identification of impervious surfaces in the basin, we developed a comprehensive classification for impervious cover in the Tahoe Basin. The classification is hierarchical to three levels and is relevant to the Lake Tahoe basin but is also designed to be applicable to other regions. The hierarchy of the three levels combined characterizes all landscape surfaces that are impacted by human activity. Beyond the functional class level (level III) the characteristics that further describe the behavior of the feature can be determined by a myriad of factors. These are termed *descriptors* and are grouped by attribute type into general descriptive categories. The descriptors would be considered a perpendicular axis that characterizes the behavior of impervious surfaces. The descriptors are not formally defined as part of the classification because they are user and inquiry driven.

The main premise underlying the three-tiered classification is that *surface behavior = f(materials, time, function).* The way in which an impervious surface behaves, in terms of percolation, erosion, nutrient loading, or any other process of interest, is a function of what the surface is made of, how long it was designed to exist, and its design purpose which we term 'function'. It is the interaction of materials over time that governs how a surface will perform in different contexts. The prescribed function of the surface adds further definition to differentiate the performance of that surface and

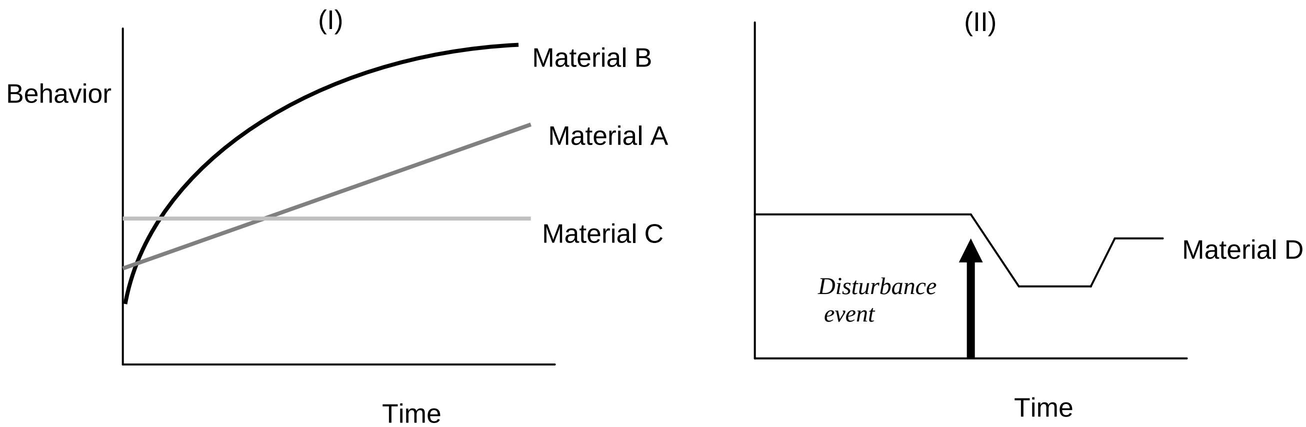

Figure 1. The behavior of an impervious surface is a function of its materials over time and its designed function. In example (I) there are three surfaces whose behavior, such as rate of erosion for example, differs over time with material composition. Material A might be a dirt road that compacts over time with regular vehicular traffic. Material B could be a gravel road shoulder that receives intermittant traffic. Material C represents a paved surface or a roof that behaves consistently over time. In example (II) material D behavior changes upon a disturbance event, indicated with an arrow, and does not recover entirely to its original level of behavior.

provides an easily recognizable terminology for discussion. Some surfaces, such as those categorized as 'soft' have greater variability in behavior than others. This variability exists within the 'soft' materials designation and across the temporal axis. A gravel driveway will behave differently from the Tahoe Rim trail during rain events due to the material out of which each is constructed. Many other attributes govern the difference in behavior of these two surfaces, but it is the surface's elemental composition that is the basis for first level differentiation. The descriptive attributes further serve to differentiate between them. Over time 'soft' surfaces are likely to change and the vectors of change are dependent upon the amount of time over which the surface exists or was intended to exist. For example firebreaks, in some instances, are constructed quickly to control wildfire spread but are then abandoned and allowed to revegetate without maintenance. The firebreaks' performance as impervious over time will vary with length of time from creation. 'Hard' surfaces, such as granite or pavement, will behave in predictable ways over very long time periods – namely they will shed water. Conversely, 'Soft' surfaces may change from 60% permeable to water to 40% permeable over short time periods such as weeks or months. Similarly they may perform at a relatively constant level of imperviousness until reaching a threshold brought about by disturbance or particularly large magnitude disturbance. Figure 1 demonstrates how surface behavior varies with material over time and how disturbance events can change surface properties. Behavior can be any process such as erosion, infiltration, or sediment production for example. Figure 2 shows the classification system in its hierarchical form.

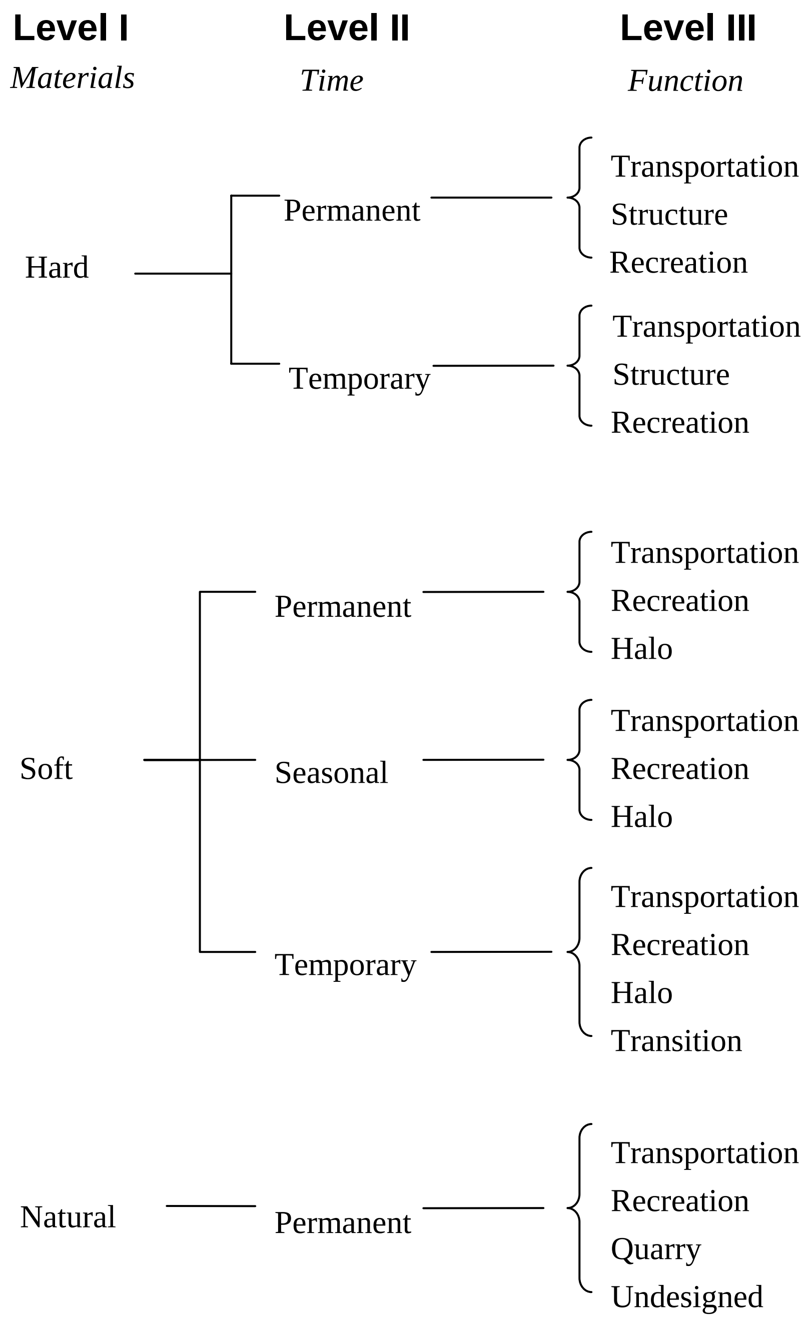

Figure 2. The three-tiered impervious cover classification. Level I is materials definition, level II is the temporal axis and level III is the functional definition. At level III all landscape surfaces that are affected by humans can be identified and differentiated. While any level of the classification can be parameterized in a modeling or other analysis, level III provides the most detail for evaluating effects.

Level I - Materials

This level defines the parent material of the surface and is the broadest definition of the classification. This is the top level of the classification because the parent material is the physical foundation of the surface. It is what defines the existence of the feature itself and it is the ultimate descriptor of the extent to which water infiltration can occur. In two of the

materials classes there is no infiltration, but in the soft cover class there may be a range of infiltration that will vary with parent material and compaction. Level I is an expansion of the existing TRPA definition and includes three types:

1. *Hard impervious cover* is defined as paved surfaces such as roads, sidewalks and parking lots that are made of asphalt or concrete and are anthropogenic in origin. Houses or other structures are also considered impervious. Impervious surfaces are impenetrable by water and do not allow percolation through to the underlying natural surface.

2. *Soft impervious cover* is defined as surfaces that exhibit impervious characteristics but allow some infiltration and are not anthropogenic in origin. Compaction is a primary factor that changes the physical characteristics of the parent material.

3. *Natural impervious cover* is defined as surfaces that are impervious to water but are natural in origin. In the Lake Tahoe basin granite outcrops are a common natural impervious feature.

Level II - Time

We define the second level as the persistence of the feature and/or feature properties. A feature can change its temporal existence between most of the level II categories with the exception of morphing into natural hard cover. Time allows for variability in effects of the three surface material types.

1. *Permanent* cover exists *ad infenitum*. It endures throughout the year and remains unchanged over time.

2. *Seasonal* cover type exists only during part of the year. This category defines snow-covered surfaces and compacted snow.

3. *Temporary* cover is non-permanent. These cover types come into existence with the intention of becoming transformed into a different cover class.

Level III - Function

This third level further refines the impervious surfaces in space and time based on its utility or design. The purpose of a feature, or the purpose of its design, will impact its behavior. Level III designations also achieve a level of specificity in language that enables immediate understanding of the feature itself. It is at level III of the classification that the greatest differentiation in behavior can be identified and quantified. There are seven types of level III function:

1. A *Transportation* feature was built for or to be directly related to vehicular traffic. This would include parking lots, road shoulders, pullouts or overlooks and driveways in addition to the ubiquitous road.

2. A *Structure* is anything constructed with a roof. This includes but is not limited to homes and businesses, gazebos, sheds and anything else that prevents water from reaching the ground underneath it.

3. A *Recreation* feature was built for the purpose of non-motorized vehicle use. This includes but is not limited to swimming pools, playgrounds, skateboard parks, footpaths, golf courses, ski runs and trails.

4. A *Halo* feature is defined as the footprint of use around a structure. Some examples of halo features are the compacted areas around buildings, ski towers, road ends, water tanks, and fire lookouts.

5. An area in *transition* comes into existence, dramatically changes the behavior of the cover, and is transformed into a different cover class. It is always temporary between two level III functional types and includes construction sites and access. An example is new construction of a shopping center or renovations or redesign of a golf course. In both of these situations large amounts of soft cover are exposed for short time periods.

6. A *Quarry* is the vertical or near-vertical surface of an open excavation or pit from which material is obtained by digging, cutting, or blasting. The base of the quarry where vehicles and heavy machinery operate would be considered either transportation or halo features.

7. An *Undesigned* feature lacks specific function; the feature simply occurs. Hard natural impervious cover such as granite outcrops, road cut escarpments are examples of undesigned features.

The functional categories, level III, define the surface parent material, how long the surface is intended to persist, and why it was built, if at all. Together the functional categories include all landscape surfaces that are impacted at human activity. Figure 3 shows examples of the functional level III categories in the Lake Tahoe basin near South Shore, CA. Beyond the functional categories we propose descriptor categories that further describe the behavior or physical properties of the functional class (Figure 4). The different descriptors are useful based on the specific inquiry. Not all projects have the same objectives nor ask the same questions. This is where some flexibility is required to meet the needs of the majority of users while maintaining consistent definitions in classification. This approach facilitates cross-agency and cross-research communication and data sharing. The descriptor categories allow analytical power through specificity – specifically in space (the first three miles of the road only or road slopes greater than 20 degrees) and over time (within one week of construction or within 12 hours of a major storm event). With this hierarchical classification questions can be asked regarding the impacts of the different impervious cover types on water quality or clarity because first, the different types have been clearly defined and second, an answer could be quantified by implementing the classification.

We propose some examples of descriptors that may be common to a number of user groups. However, the list of descriptors is not exhaustive as the types of inquiry are infinite. There will be some descriptors that are not relevant to a particular project where there may be others that are commonly used in most applications. The descriptors as we present them are characteristics that influence the behavior of different impervious cover types that have been defined to any of the three levels, although greatest analytical power will come from descriptors applied at level III. Additional segmentation beyond the third level allows the user to analyze potential impacts to the landscape or its water bodies from specific events or actions. Proposing the classification to level III and then allowing users to attribute it further is both consistent and specific to a level where the agencies, managers and scientists can commonly identify and communicate surface cover types. In this manner the classification provides a set of common definitions to manage a common landscape.

Use

Use may be segmented into *maintenance, frequency, and intensity*. Together these three categories describe specific characteristics relating to how humans affect the physical properties of an impervious surface, which in turn may relate to its performance. *Maintenance* has been cited in the literature (Ramos-Scharron and MacDonald 2005; Reid and Dunne 1984) as affecting sedimentation and could be attributed to a feature either as a categorical variable such as monthly, biannually, annually, or greater than annually or numerically, such as 7 week intervals. *Frequency* describes how often the feature is used and again this could be numerical, as in the number of days used per year or the number of vehicles per day, or categorical such as abandoned, low, medium, or high. The *intensity* of use describes the type of activity, specifically the weight class of the impacting force. For example, a user may define heavy machinery or commercial trucks, light work vehicles, cars, snowmobiles, bicycles, and foot traffic.

Topography

Topographic attributes of a feature may include aspect, slope, slope length, slope direction, elevation. Slope length is the distance that a feature carries a specific angle. Slope direction is the direction that the slope faces and differs from aspect, which is the cardinal direction of the underlying landform. Slope direction may vary from aspect when a road, for example, runs across a slope. Elevation may be of importance when evaluating events relating to snow.

Soil properties

Soil properties may include type, drainage characteristics, infiltration rate, parent material, grain size and depth to bedrock. For some applications more specific descriptions of the soil horizon may be merited. All of these descriptors are somewhat related but may help further define particular areas of importance within the landscape or different physical response patterns of the different cover.

Basin characteristics

Basin characteristics connect impervious surfaces to hydrological features. The location of impervious cover in relation to hydrological features such as streams or lakes is important because impervious surfaces are unlikely to impact water bodies that are physically above them. Distance to stream, depth to water table and basin shape, size and location as well as surface flow direction affect transport of nutrients and sediments from the impervious surface to water bodies downslope.

Disturbance

Compaction is an obvious type of disturbance that is an inherent characteristic of soft impervious surfaces. It is a function of use intensity and frequency but can be attributed specifically as a numerical parameter. A second type of disturbance is events, both natural and anthropogenic, such as wildfire frequency, burn intensity of most recent event, rainfall rate, storm event frequency, or mean snowfall.

Examples of functional categories

We provide examples of features that would be defined by each of the level III functional categories. This is not an exhaustive list but provides a fairly detailed accounting of the features of interest within the Lake Tahoe Basin. If applied to other landscapes additional features may be identified while others that pertain to the basin specifically may not appear.

Hard Permanent Transportation features include paved parking lots, paved road shoulders, paved pullouts or overlooks, paved driveways, paved roads, paved bike paths, paved airport runways and curbs.

Hard Permanent Structures include homes and businesses, gazebos, sheds, carports, and covered picnic areas, fire lookouts, greenhouses and information kiosks.

Hard Permanent Recreation features include swimming pools, paved playgrounds, skateboard parks, paved footpaths, tennis and basketball courts, paved RV or campsite pads, stadiums, and outdoor amphitheatres.

Hard Temporary Transportation includes highway interchanges or roads that are built to carry traffic during construction and maintenance of existing lanes. Temporary roads are created when the existing roads are damaged from disasters such as storm or flood events. Temporary roads are sometimes created while the original roads are being repaired.

Hard Temporary Structures are typically associated with construction or temporary storage. Examples include mobile trailers in use at a construction site, carports associated with construction, or interim storage facilities that people construct on their property.

Hard Temporary Recreation features may not actually exist in the basin at this time, but potentially could exist in the future.

Soft Permanent Transportation features are unpaved parking lots, road shoulders, pullouts or overlooks, driveways, roads, and bike paths, respectively. These include mountain bike trails, off-highway vehicle and jeep trails, power lines, and dirt or grass landing strips.

Soft Permanent Recreation features include unpaved playgrounds, schoolyards, soccer and football fields, running paths and trails, picnic areas, riding stables, and ski runs.

Soft Permanent Halo features include the compacted non-paved areas around buildings, ski towers, road ends, trailheads, water tanks, fire lookouts, medians between the sidewalk and the road, the base of climbing areas and may include backyards where animals are tied out or where human use compacts the ground.

Soft Seasonal Transportation features are snowmachine routes that do not follow an existing paved or dirt road. These are routes that exist only with snowpack or in extreme cases may include mud between snow patches. During wet conditions when the main route sports mud, drivers will often drive around the mud hole and create a new path that skirts the existing route. When the road dries and becomes directly passable again, these side routes may no longer be used.

Soft Seasonal Recreation features are snowshoe and ski trails that do not overlie existing trails or roads. Two examples are backcountry snow travel routes or tree island ski trails. Skate ski trails may be created over a meadow, wetland, or frozen lake. The underlying surface is natural but during the snow season it is compacted by the grooming process and by use.

Soft Seasonal Halo features may or may not overlie soft permanent halo features because the movement patterns on a snow surface may be different than on the earthen surface. Most of the soft seasonal halo effects will occur around ski lodges, ski parking areas, trailheads, and ski lifts.

Soft temporary transportation includes logging skid paths, can include logging roads that are constructed for one timber harvest and then closed and remediated, and firebreaks constructed during a wildfire event that are not intended to be maintained.

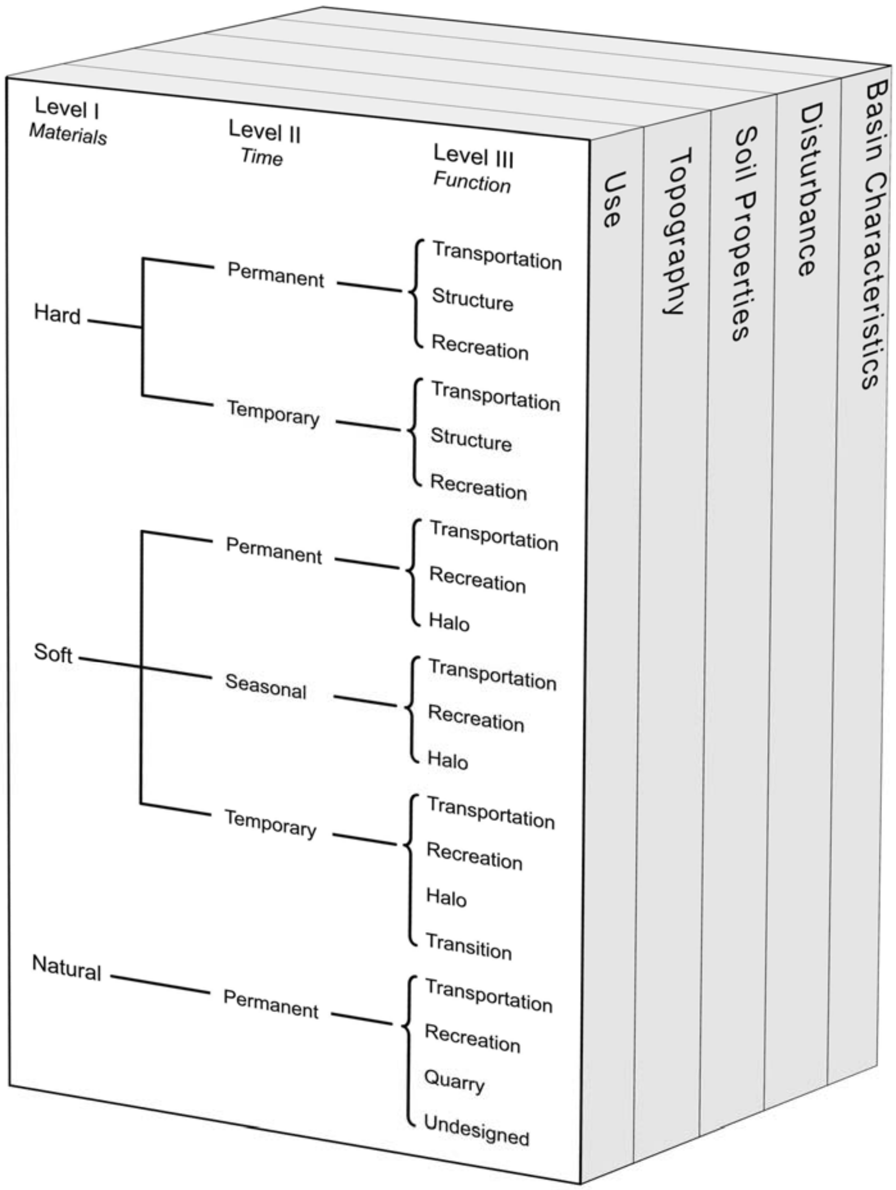

Figure 3. Three-dimensional schematic of the classification to level III with the descriptor axis. The descriptors are attribute categories that further determine the behavior of the impervious surface.

Soft temporary recreation features would include single tracks where hikers or horseback riders cut switchbacks. They are temporary because often once discovered by the management authority they are closed and remediated. Trail sections can be created temporarily while maintenance is performed on the main route.

Soft Temporary Halo may occur with the soft temporary transportation. When the temporary transportation feature is closed or decommissioned, the halo effect disappears concomitantly.

Soft Temporary Transition areas are construction sites including construction access. These features come into existence with groundbreaking and disappear when the final structure is completed. Golf course renovation is included between the time when the existing turf is removed and new turf is replaced.

Natural Permanent Transportation features are formal roads or bike trails that traverse natural stone or rock formations. It is unlikely that any features in the Lake Tahoe basin fall into this class, but in lands of the desert southwest such as Moab, UT, roads and trails would be included in this category.

Natural Permanent Recreation includes trails that occur on bedrock. Trails in the Desolation Wilderness and other places along the Sierra crest within the basin fall into this category. Typically the formal routes are marked by cairns or lined with small rocks to indicate the trail.

Natural Permanent Quarry is limited to the actual surface of a quarry that is being excavated, dug, cut or blasted.

Natural Permanent Undesigned features are granite outcrops, road cut escarpments that include granite or bedrock. Creek beds that have eroded the surface to bedrock are included in this class although the extent of these features may be variable within a stream.

Figure 4. Examples of features at functional level III impervious cover. The illustration uses 2002 Space Imaging Ikonos imagery. A = hard/permanent/transportation; B = soft/permanent/transportation; C = hard/permanent/structure; D = soft/permanent/halo; E = soft/permanent/recreation.

Discussion

The resulting impervious cover classification distinguishes 20 distinct functional categories. The expansion of existing definitions from the two-category soft/hard impervious designations to 20 well-defined and specific classes greatly increases analytical power. With this comprehensive classification there is now an opportunity to identify numerous features of interest that under the existing impervious cover two-class definition are lost. Furthermore, the resulting 20 classes are simple enough to be applicable throughout the entire Lake Tahoe basin landscape and capture all affected surface area. Being able to identify and delineate any and all impervious features is the initial step towards understanding the associated physical processes that are hypothesized to affect water quality and clarity.

With the new classification the landscape can be divided into different and distinct classes that capture a broad range of function. With this ability, it is possible to examine the landscape in terms of each different category, categorical function and in terms of different analytical contexts. The challenge at this point is to identify the associated values or weights for each of the newly refined impervious types within each category. Many of the features that are classified in the 20 functional categories are unstudied in terms of behavior such as erosion or infiltration. It is expected that additional research is necessary to determine what the values or rates will be as impervious cover has been redefined in more detail. It is also expected that the assigned values and weights may change based upon the inquiry. The effort to understand how to weight or parameterize the processes governed by impervious cover is worthwhile for several reasons. First, adopting the classification enables all of the stakeholders to view what the range of impervious cover types. Second, it will be possible to identify which functional feature types contribute to sedimentation, erosion, nutrient loading or other processes that impact water clarity and quality. The implementation of the classification will provide hard estimates about the current spatial extent of each type within the basin. Finally, the relevant features can begin to be quantified in terms of contribution to environmental issues through research.

We provide an example of how the proposed classification might be used to enhance and focus research efforts relating to a specific disturbance within the basin. The first step is to demonstrate the difference in the landscape from the original treatment of impervious cover compared with our classification imposed.

Implementation – Mapping impervious cover

High spatial resolution imagery is an obvious source from which to begin to classify the entire Lake Tahoe basin impervious cover. There exists basin-wide coverage at 1 m spatial resolution (Space Imaging Ikonos) that was purchased through a multi-agency agreement in 2002. This imagery, because it is wall-to-wall coverage, can provide baseline data and serve as a means to verify the classification. There also exists a hard impervious cover data layer (Cablk and Minor 2003) that can be refined to the level III with additional interpretation. The existing impervious cover data set was based on the TRPA definition and therefore only includes anthropogenic paved or roofed surfaces. Therefore it is the natural and soft impervious cover functional classes that remain unidentified. Some of these features could be readily mapped using the imagery or the imagery with ancillary data. Other features are not likely to be readily captured with imagery or with ancillary data and would require other means for mapping, such as ground delineation with global position systems (GPS). Some features might be partially identified such as trails, roads, or road shoulders but due to high canopy cover in forested tracts some modeling might be useful for completing the extent. The challenge with existing ancillary data layers such as soil, streams, or digital elevation data (DEM) is the relatively coarse spatial resolution and the timeliness, since existing data layers are often outdated or not updated in regular intervals.

Vector data, while limited in its utility, could be used in different ways to contribute to the impervious classification. First existing roads or trails can be buffered to their finite edges and then rasterized. These roads can be additionally buffered to capture shoulders and medians for example. Point features such as ski lift towers can also be buffered to give them full spatial extent.

The spatial resolution of the data layer that results from implementing the proposed classification should be one-half the size of the physically smallest feature that is of interest. If the smallest feature is a 10-meter wide road, then the spatial resolution should be 5-meters or less. If the smallest feature of interest is a footpath that is approximately 0.5 m then the spatial resolution of the data set should be approximately 0.25 m. This could present challenges because of the effort that would be required to map all trails or other small features within the basin. However this effort could be guided by imagery or by existing road and trail data sets. The level of spatial detail will also be governed by the inquiry. For example, if someone were to investigate the impacts of an area where many unofficial footpaths had been cut over time by hikers and horse riders, they may opt to focus on that area and explicitly map with GPS all of these features. The mapped trails, while more spatially detailed in that particular area, would still be categorized according to the classification and thus could be integrated into the larger impervious layer as a result.

As with the existing impervious cover data layer we recommend the classification be primarily raster based. This is because modeling and analytical power comes from raster data format. This is not to say that vector features might not be more appropriate for specific functional categories when the spatial resolution required is extremely fine, for example single footpaths, halo extents, features that are more vertical than horizontal such as road cuts or granite cliffs. What is most important about the impervious classification is to maintain the structure of the classes themselves for integration across studies and agencies. Maintaining the classification structure also serves to facilitate long-term data development when data from various studies are recompiled to update the comprehensive layer.

Conclusions

The development of impervious cover definitions has arisen from urban studies where urban and suburban development affects biotic integrity. The need was to refine previous maps that categorized “urban” into more specific classes, so that different processes could be attributed or parameterized based on land cover. As a result, most definitions of impervious focus on hard cover types in the urban matrix and soft cover is an afterthought and is lumped in because the spatial distribution is secondary. Soft cover easily describes yards, grass medians, and vacant lots, which are functionally semi-pervious but are not paved. Expanding this paradigm to include non-urban landscapes requires further definition to discriminate between the physical and functional elements of development. In this paper, we advance the definition and classification of impervious cover to capture the full suite of impacted surfaces that may affect water clarity and water quality across an entire basin.

We have explored how to asses and categorize the impacts that non-paved but compacted areas have on water quality and clarity. To begin the discussion we focused on definitions of various impervious cover types to distinguish between features found in the landscape expanding from the existing impervious/pervious binary definition to a more comprehensive definition that includes hard, natural, and soft impervious cover, capturing all affected features within the landscape. We then reviewed two physical processes of concern to the watershed, sedimentation and nutrient loading, setting impervious surfaces into the context of concern within the basin. Examining these physical processes, the way they are currently measured, and the relationship between impervious cover and these processes we recognize impervious cover as a critical element in understanding the function of these processes in the landscape.

After reviewing current agency perspectives we put forth a comprehensive classification system that defines and classifies all type soft impervious cover, this sets forth common definitions which can then be used to distinguish a common landscape. The classification system is elemental in form based upon the interaction of materials, time, and function. From this inclusive classification we proposed how all impervious surfaces could be identified and mapped with the intention that if these features are able to be quantified then the effects of these features can be factored into analyses of sedimentation and nutrient loading. This refining of the definition of impervious cover and refining of how impervious cover is classified will greatly increase the effective predictive strength of impact assessment models and provide a set of common definition from which to understand and study the landscape and processes active in the Tahoe Basin. Finally, we detail the resulting 20 classes to provide a context for future users of the system and note the challenge of weighting the classification system. Furthermore, we outline the necessary research steps to create the spatial layer representing the classification system.

This classification scheme needs implementation in its initial form to provide baseline data to the researchers and regulators of the basin. It will provide the necessary definitions and framework for interagency cooperation and understanding of what the range of impervious cover types are and what each functional feature types contributes to environmental issues. Once implemented the classification will provide hard estimates about the current spatial extent of each functional type and the relevant features can begin to be quantified in terms of contribution to environmental issues through research. Being able to understand and quantify the role of impervious cover in the basin will advance the understanding of the physical processes active in the basin and the relationship between different forms of development and the resulting environmental issues.

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Information Transfer Activities

This work was conducted in collaboration with Basin agency managers and scientists. They will review this report, comment on it and their comments will be incorporated into the document for submission to a peer-review journal.

a) **Conference Presentations:** none

b) **Publications:** none

Training Accomplishments: Funded new graduate pre-masters student.

Information Transfer Program

Development of National Institutes for Water Resources Website for the State of Nevada for Information Transfer

Basic Information

Title:	Development of National Institutes for Water Resources Website for the State of Nevada for Information Transfer
Project Number:	2005NV79B
Start Date:	3/1/2005
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	Nevada 02
Research Category:	Not Applicable
Focus Category:	Hydrology, None, None
Descriptors:	
Principal Investigators:	David McGraw, John J. Warwick

Publication

Statement of Critical Regional or State Water Problems

One of the primary challenges of any scientific endeavor is gathering and summarizing the vast amounts of existing data and information; water-related science in Nevada is no exception. The creation and maintenance of a website can help scientists and the public by summarizing existing information and providing a pathway to that information.

Benefits and Results

An internet presence has become essential for groups such as Nevada Water Resources Research Institute and often gives the public its first impression of an organization. The benefits of developing this website will be a more comprehensive forum for sharing the issues surrounding water in Nevada. For these reasons it is important to develop a website as part of the Institute's overall mission regarding the water resources of Nevada.

Nature, Scope, and Objectives of Research

This information transfer project will involve the development and maintenance of a web site dedicated to the NIWR. This website will be modeled after the websites of other states so as to provide some uniformity of content. The site will contain static information, updated as necessary. This information includes contact information, conference links and schedules, links to other websites containing information regarding Nevada's water resources (e.g., USGS, Nevada Water Resources Association, Desert Research Institute), mission statement, maps, downloadable reports and journal articles, and news and upcoming events.

The primary objective of this website will be to increase the Institute's presence on the internet and, as a result, increase its presence to the community.

The success of this website will be measured in increased web traffic and exposure to scientists and the public.

Methods, Procedures, and Facilities

The website will be written in plain HTML in such a way as to be accessible to all, regardless of browser or operating system. The site will conform to the World Wide Web Consortium guidelines for public websites to the extent possible.

Related Research

Though the creation of this website will not, by itself, spawn additional research, it will provide access to other programs and research of interest to Nevada's scientists and the public. For example, calls for proposals and scholarships could be listed on the site, with links to the appropriate organization providing the funding.

Training Potential

The website will foster communication between scientists and the public regarding water resources in Nevada. According to the Water Resources Research Act that created the Nation Institutes for Water Resources, each state's institute is to arrange for research that fosters the training and education of future water scientists, engineers, and technicians. A thorough and up-to-date website can provide the gateway for future scientists to learn more about water resources in general, and specifically Nevada's programs and organizations. It is expected that a website not only provide basic information, but the pathways to all other related websites such that the necessary training can occur.

Results

The website has been developed. It includes information about the Nevada Water Research Institute as well as links to the National website. There is a publications database associated with the website which will be the repository for all publications and conference proceedings associated with the National Institutes of Water Resources programs. The website will go "live" when some logistical issues are resolved. The website address will be: http://www.nwrri.dri.edu/.

Student Support

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	2	0	0	0	2
Masters	2	0	0	0	2
Ph.D.	2	0	1	0	3
Post-Doc.	3	0	0	0	3
Total	9	0	1	0	10

Notable Awards and Achievements

Publications from Prior Projects