A Simulation Model of Land-Use Change in the Lake Tahoe Basin of California and Nevada, as Used in a Decision-Support System

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Abstract: The Tahoe Land-Use Change model is a stochastic, spatially explicit simulation of future land-use change—in particular, development and retirement of individual parcels—in the Lake Tahoe Basin of California and Nevada. The Federal, State, and regional management agencies responsible for the basin are revising and integrating their 20-year plans to meet various goals, including maintaining or improving several environmental (e.g., lake clarity, forest health) and socioeconomic (e.g., affordable housing) characteristics. To assist this effort, the model projects the long-term outcomes of land-use-management decisions, including those relating to existing and potential government regulations, development activities, and conservation practices. The model results are probabilistic maps of parcel-specific changes in land use and the resulting changes in the amount and locations of developed parcels and land-use change. To capture the uncertainties and variation in the exact parcels of land selected for development or retirement by individuals acting in the basin, a single model run includes multiple iterations, from which cumulative statistics are taken to describe the results. The purpose of the model is to generate changes in the amounts and types of land use and land cover that form inputs to a basinwide model of pollutant loading to Lake Tahoe, which, in turn, generates inputs to a lake-clarity model. Together, these three models form a chain of tools that link land-use decisions to changes in a critical environmental quality—the clarity of Lake Tahoe—within a decision-support context. Eventually, these three models will become part of a larger, more complete decision-support system.

***Keywords*:** Stochastic-simulation land-use model; Lake Tahoe land-use regulation; agent-based modeling

1. INTRODUCTION

1.1 Overview

This paper describes a stochastic model of land use in the Lake Tahoe Basin that simulates rules about parcel development or retirement for conservation, projects spatially explicit land use/land cover changes, aggregates the results, and produces outputs suitable for integration into a larger decision-support system. We explain the regulatory setting of Lake Tahoe management; the goals of the decision-support system and the model's place within it; the structure, methods, and results produced; and the implications of these results.

1.2 Background

In the Lake Tahoe Basin on the California-Nevada State boundary, management agencies at the Federal, State, and regional levels are engaged in a collaborative process called Pathway 2007 (P7) to align and integrate their individual 20-year plans, so that they complement each other and can efficiently and effectively address a set of environmental and socioeconomic issues. The agencies are the Tahoe Regional Planning Agency (TRPA), the U.S. Forest Service (USFS), California's Lahontan Regional Water Quality Control Board (Lahontan), and the Nevada Department of Environmental Protection (NDEP). TRPA is a bi-state regional authority that regulates the development of private land parcels into residential, commercial, or recreational use through a system of allocations and permits. TRPA also monitors 36 indicators (Tahoe Regional Planning Agency, 2002) of environmental and socioeconomic conditions, many of which have specified regulatory standards. The USFS manages more than 80% of the land in the basin. Lahontan, which is responsible for managing California's regional water quality, is the lead agency in developing a Total Maximum Daily Load standard (TMDL), pollutant allocation, and pollutant-reduction plan under section 303b of the U.S. Clean Water Act. NDEP plays a similar role in Nevada. Together with five counties (El Dorado and Placer Counties in California, Washoe, Carson City, and Douglas Counties in Nevada), one incorporated city (South Lake Tahoe, Calif.), and a host of public- and private-interest groups, the P7 agencies have been reviewing TRPA's existing indicators, revising them and/or proposing new ones. The last step in the P7 process includes formulating strategies to achieve regulatory standards through combinations of policies, structural improvements, and other projects—collectively referred to as management controls to address environmental and socioeconomic conditions in the basin.

1.3 Tahoe Decision Support System Purpose

The Tahoe Decision Support System (TDSS) was envisioned as a tool to help P7 participants project the outcomes and assess the long-term impacts of alternative management scenarios. The TDSS' goal is to link existing process and/or statistical models of indicators (e.g., lake clarity, forest health, atmospheric ozone, recreational quality, traffic congestion, housing prices, scenic quality, etc.) and run them to generate outcomes of management control implementation (Halsing et al., 2005). Management-scenario outcomes manifested, for example, as newly developed parcels of land or changes in land cover, would be generated and become inputs into models designed to project changes in the indicators themselves. The end result would be a linked chain of models extending from management controls to the final impact on the indicators that the controls sought to address. Each step in this process would be a model whose output became input into the next model in the chain. Viewing the simulated outcomes of scenarios would allow them to be adapted and resimulated, as illustrated in Figure 1. Even with large uncertainties in each individual model, the insights arising from their use in assessing management controls should be valuable.

The land-use model discussed here, which is our first tool to generate management scenarios, creates inputs for two models built to establish the TMDL standards for load reductions of various pollutants (nitrogen, phosphorus, and fine sediment) that reach Lake Tahoe and impair its clarity and scenic values. Other indicators will be addressed with tools created in future project stages. The land-use model simulates parcel development and retirement as a result of land-use regulations and the spatially explicit changes in land use/land cover that result from them, producing critical inputs to the TMDL Watershed model, constructed for Lahontan by Tetra Tech, Inc. (Tetra Tech, Inc., 2005). This model simulates pollutant loading on the basis of the amount and location of land cover within each subwatershed in the basin and on such meteorologic factors as rainfall and snowmelt. A second model, the Lake Clarity model constructed at the University of California, Davis (Schladow et al. 2000), uses pollutant loadings and meteorology to simulate lake clarity over time.

Lake clarity is a major environmental concern that drives much of the research and management in the Lake Tahoe Basin. The lake has drawn attention because of its scenic beauty and its value as a tourist destination, yet land development and the resulting increase in impervious land cover have increased nitrogen, phosphorus, and sediment loading to the lake. Increased scattering of sunlight by particulates and increased algal growth enabled by the higher nutrient concentrations has caused a gradual decline in lake clarity. Although land conversion has greatly slowed, the decline in lake clarity has continued at an average rate of 1 ft of lost visibility per year (Murphy and Knopp, 2000). Any effort to restore lake clarity is contentious because of fears of harming the local economy, infringing on private-property rights, or reducing the amount or quality of recreational and tourist experiences. This situation demonstrates the critical need for a systematic way to analyze the tradeoffs and synergies among socioeconomic and environmental goals or between one environmental goal and another. The TDSS will eventually support those analyses and thereby help P7 participants make and implement management decisions.

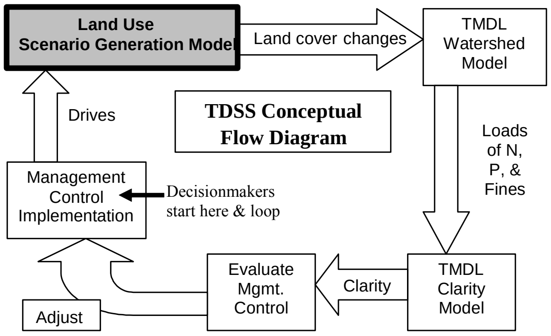

Figure 1. Process-flow diagram for the Tahoe Decision Support System. Land-use model in gray.

2. METHODS

2.1 Overview of Land-Use-Simulation Model

The Tahoe Land-Use Change model is a stochastic, spatially explicit simulation of future land-use change in the Lake Tahoe basin. Its purpose is to project the number of parcels developed or retired by the year 2027, when the P7 agencies' next set of 20-year plans expire. The model is being used to create and examine potential development scenarios in relation to the location and number of parcels converted to residential, tourist-accommodation, recreational, or commercial use, thereby providing the basis for an analysis of the associated changes in impervious cover, road construction, and population. The simulation, conducted at the parcel level, contains rules that embody existing and potential government regulations, development activities, and land-conservation practices. A single model run includes multiple iterations, each of which uses a separate sequence of pseudorandom numbers as the stochastic component while holding all other parameters constant. Cumulative statistics are gathered to describe the results of the iterations, and the model run is terminated by a stopping rule when the statistics fall within a user-defined confidence interval. Simulation results include probabilistic maps of land-use change, a statistical analysis of the probability distribution to describe average and extreme cases, and calculations of the amounts of land cover in such land uses as single-family dwellings (SFD), multiple-family dwellings (MFD), tourist-accommodation units (TAU), commercial use, protected open space, roads, and vegetated areas. Areas of pervious and impervious land are then aggregated by subwatershed within the basin for direct input into the TMDL Watershed model. Additional output includes an analysis of the stopping rule's functionality.

2.2 Parcel Development and Retirement Rules

The simulation begins with a geographic information system (GIS) parcel layer attributed with land-use and zoning data for 2004. This parcel layer was compiled and is maintained by TRPA for the purpose of issuing development allocations. TRPA limits the number of building permits for residential development through the issuance of these allocations. Each allocation gives the recipient the ability to seek a permit to build one housing unit: for an SFD, one allocation is required to apply for a building permit; a number of allocations equal to the number of housing units to be built are required for an MFD (e.g., building a duplex requires two allocations). In recent years, TRPA has issued approximately 271 allocations per year, of which 225 have resulted in development. Allocations that do not result in development are placed in an "allocation rollover pool" and can be used in future years for moderate-income housing or for a TRPA program exchanging the retirement of a sensitive lot for an allocation on a nonsensitive lot. TRPA also maintains a separate pool of residential bonus units, which may be used for affordable or moderate-income housing.

Development rights are removed from potential residential parcels through governmental or non-governmental agencies and through private owners purchasing parcels and either holding them to prevent development or trading the development rights for other benefits. Removal of development rights is hereafter referred to as retirement. Major retirement programs are the USFS' acquisition of urban lots to decrease runoff into Lake Tahoe, a TRPA program to retire sensitive lots in Placer and El Dorado Counties in exchange for an allocation on a nonsensitive lot, the California Tahoe Conservancy's acquisition of parcels on the California side of the basin, and a similar program run by the Nevada Division of State Lands in that State. Parcels that are retired instead of being developed are assumed to become and remain vegetated open space.

To run a simulation, a baseline and a list of development and acquisition rules is compiled in cooperation with TRPA (Hitchcock, written communications, 2004). For a single-family-residential simulation, the initial conditions and examples of development and retirement rules are presented in Box 1. Multiple-family-residential and commercial simulations were similarly configured and are discussed below.

2.3 Programming the Stochastic Model

If the simulation applied the development and retirement rules in the order listed in Box 1, there would be a bias toward retirement, because any fixed order will introduce bias. To avoid bias, the rules are separated into approximately 300 actions that are then applied in random order. To do this, agent-based modeling, which simulates the global consequences of local actions by "agents" or individuals in a population. The agents operate in a certain environment and behave according to procedural rules. This application had two types of agent: those seeking to develop parcels, and those

Initial condition: 1,150 units in the residential unit pool and 350 allocations in the allocation rollover pool
Each year: Issue 225 TRPA allocations, 24 (10%) reserved for multiple-family developments, and the rest for single-family developments. Add 46 allocations to the allocation rollover pool.
Rules: For each model year, develop and retire potential single-family dwelling parcels as follows:

- Retire 5-10 parcels in Placer and El Dorado Counties
- Retire 5 parcels in Washoe and Douglas Counties
- Retire 5 sensitive parcels in Placer County and develop 5 nonsensitive parcels elsewhere
- Develop 40 parcels in Placer County
- Develop 12 parcels in Douglas County
- Develop 113 parcels in El Dorado County
- Develop 60 affordable-housing units throughout the Basin

Box 1. Initial conditions and partial list of parcel development and retirement rules

seeking to retire them. The number of agents in the first group was set as the number of allocations released by TRPA each year (225), and the number in the second group was set as the number of parcels available for retirement in each county each year (e.g., five in Douglas County), because retirement-program targets are set at the county scale. The agents in these two groups are pooled together and then randomly selected (with the pseudorandom number generator described below) in each model year to determine the order in which they will perform their action. Their actions assume that adequate numbers of parcels are left in the pools of parcels suitable for these goals. If this is not the case, such as at the end of a model run when parcels suitable for retirement are rare, this agent is bypassed by the model, and the next agent is drawn. Thus, over model years, parcels are shifted into many land uses, including conservation retirement, and the pool of available parcels shrinks.

To generate the randomness required by the above-described stochastic process, this simulation uses the Mersenne Twister pseudorandom-number generator described by Matsumoto and Nishimura (1998), as implemented for the Python 2.4 Standard Library (Van Rossum, 1995). The Mersenne Twister has a period of $2^{19937} - 1$, far more than the 11,000 numbers generated in each iteration. The pseudorandom-number generator is seeded from an entropy pool fed by measuring disk read timings and network interrupts (implemented as the /dev/urandom/ device in MacOS X 10.3.7). The random numbers are used in two algorithms: choosing *k* items from a list of *n* items, and shuffling a list of *n* items. Both algorithms are from Knuth (1997), as implemented in the Python 2.4 Standard Library.

2.4 Stopping Rule

Because any single iteration of a stochastic model would be falsely deterministic, a successful stochastic-simulation model must address the number of times a simulation must be conducted to obtain sensible results. Here, a single model run includes multiple iterations. However, because the number of iterations needed to accurately project development and retirement patterns is unknown, a stopping rule was used in the simulations. Numerous iterations are performed, the statistics of outcomes are kept, and results are weighed against the specifics of the stopping rule until the mean and range of possible values are known with confidence.

More formally, let *P* be a population with an unknown mean μ and finite, nonzero variance. We wish to estimate μ to within $\pm\delta \in R^+$ with a confidence level of $1-\alpha, \alpha \in (0,1)$ by drawing the shortest sequence of samples $X = (x_1, x_2, \ldots x_n)$ necessary from *P*. If we knew the variance of *P*, we could calculate the number of samples needed, but without it we must determine when to stop collecting samples on the basis of measures from *X*. We define the following expressions for $n \in N$:

$$\bar{x}_n = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (1)$$

$$s_n^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x}_n)^2 + \frac{1}{n} \qquad (2)$$

Chow and Robbins (1965) provide a rule for when to stop the simulation. Choose $\alpha \in R$ to satisfy the integral:

$$\sqrt{2\pi}\int_{-a}^{a} e^{-u^2/2}\,du = 1-\alpha \qquad (3)$$

Let $(a_1, a_2, a_3 \ldots)$ be any sequence of positive real numbers converging to *a*. Collection of samples from *P* stops for the smallest $n \in N$, $n >= 3$, such that:

$$S_n^{\ 2} < \frac{n\delta^2}{a^2} \qquad (4)$$

Starr (1966) tested these results and observed that the use of estimators for the mean and variance produced a slightly optimistic confidence interval: an estimated confidence level of 99% corresponded to an actual confidence level of 98.752%. Law and Kelton (2000) provided a rule of thumb that if the distribution is "roughly symmetric" then the estimated confidence intervals behave similarly to the normal distribution. These simulations were run multiple times, and the run with the largest number of iterations needed to satisfy the stopping rule was chosen to protect against random early triggering of the stopping rule.

2.5 Simulating Other Land-Use Types

In addition to SFD land use, the model projects new commercial parcels and floor space, TAU, and areas designated for public services. Current regulations allow for an additional 200,000 ft^2 of commercial floor area, taken to be 25% of a parcel's area. Each potential commercial parcel is developed to reflect the existing commercial development within the parcel's planning area. The model assumes a policy-based addition of 300 TAU. According to TRPA, an additional 100,000 ft^2 of floor space will be designated for public services (40,000 ft^2 in the city of South Lake Tahoe, 20,000 ft^2 each in the other three jurisdictions). Again, floor space is assumed to be 25% of a parcel's area. No vacant parcels were used for public service in this model; instead, the new area goes toward expansion within existing public service lots. The model does not call for any new land transitioning to recreational use, although this land use may be added to the model's functionality later. Finally, we note that new open space is created only through the retirement of potential single-family dwelling parcels and/or associated conservation easements.

2.6 Spatial Distribution and Areal Analysis

Recall that the location of developed parcels is of primary importance for the TMDL Watershed model, because it needs the amounts of land cover in each parcel to be aggregated to the subwatershed scale. Therefore, one output of the simulations is parcel maps, with each parcel attributed with a set of probabilities denoting the chance that the parcel will be developed in each land-use category of interest. These probabilities are calculated from the results of the simulation, on the basis of the number of iterations in which a parcel was developed. Eventually, for inclusion into the TMDL Watershed model, these probabilities are converted, using basic GIS commands, into expected land areas of development. In each subwatershed are a set of parcels wherein each parcel has a probability of development and an area. If, for example, there are two potential SFD parcels – one of 2 acres with a 20% chance of development, and the other of 1 acre with a 60% chance of development – then taking the expected return yields the amount of additional SFD land. Here, 0.20 * 2 acres + 0.60 * 1 acre = 1 acre of SFD. By implication, a complementary amount of open space results: 0.8 * 2 acres + 0.4 * 1 acre = 2 acres of open space.

3. RESULTS

3.1. Primary Model Results

The results of these rules and processes are listed in the tables below. Table 2 lists the mean number of parcels and total number of housing units developed. The number of housing units does not equal the number of parcels because of multiple-family dwellings. These results include 734 units of affordable housing and 147 units of moderate-income housing as a product of TRPA programs designed to encourage such developments. Table 3 lists the total areas in each land use at the start and end of the simulation, as well as the absolute and percentage change in areas. The largest changes include an almost 53% reduction in open space – not surprising, because open space is the source for newly-developed land – and a 17% increase in residential land area. New commercial and SFD development is mostly located at the south end of the basin, clustered around Highway 50. Dispersed SFD development also occurs along the entire Lake Tahoe shoreline. Little MFD development occurs, but what does will be tightly clustered in an area west of the Tahoe airport in the southwestern part of the city of South Lake Tahoe.

3.2. Stopping-Rule Results

Simulation routinely stopped after approximately 5,000 iterations, fewer than expected. However, the simulation rule was focused solely on the number of SFD parcels developed and not on their location, and so multiple outcomes map into a single value going into the stopping rule leading to an early triggering of the rule. This model quickly converged on similar results despite the large number of possible outcomes. This limitation is now being addressed so as to generate useful inputs for the TMDL Watershed model.

	existing parcels	new parcels	existing housing units	new housing units
Residential	40,206	3,959	44,351	4,099
MFD	1,951	53	6,843	176
SFD	36,778	3,906	36,949	3,923
Other	1,477	0	559	0
Commercial	1,274	33		
Retail	420	12		
Entertainment	17	0		
Services	393	10		
Light industrial	92	3		
Wholesale	352	8		
Open space	9,570	783		

Table 2. Mean number of parcels and housing units developed by the end of simulation run (2027).

	Existing	New	Projected	% Change
Vacant (Eligible for dev't)	5,303	-2,806	2,497	-52.91%
Roads	4,426	0	4,426	0.00%
Residential	13,632	2,346	15,978	17.21%
TAU	376	0	385	2.53%
Commercial	977	18	995	1.89%
Public service	1,775	0	1,775	0.00%
Recreation	21,103	0	21,103	0.00%
Conserved open space	143,391	432	143,823	0.30%

Table 3. Land-use change in the Lake Tahoe Basin, in acres and in percentage change.

4. DISCUSSION

The implications of this research fall into two categories. The first implication concerns the model's utility in the Pathway 2007 process. This model is a tool to generate the most upstream part of a series of linked models, thereby allowing P7 participants to assess the likely outcomes of management decisions on a key natural resource, Lake Tahoe's clarity. The model is also useful for Clean Water Act and TMDL implementation. It has enabled further scenario-generation-tool creation for the TDSS project, because land use drives human population, transportation, and other dynamics. It has also yielded several useful results. For example, it showed that TRPA's goal of providing affordable housing and multiple-family dwellings is unlikely to be fulfilled under this set of development rules and retirement policies. It also showed that, although development does occur, the current rules seem adequate to protect stream environment zones and the most sensitive lots.

The second implication concerns details of the model itself. Although this land-use model would benefit from a more sophisticated stopping rule, it still remains quite useful; it accounts for randomness and variation and is currently in the process of being adapted to more accurately represent reality.

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