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Informing watershed planning and policy in the Truckee River basin through stakeholder engagement, scenario development, and impact evaluation

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ABSTRACT

In this study, we evaluated the water quality and quantity impacts of five restoration and land protection scenarios in the Truckee River watershed, in the context of regulatory goals. We used spatially explicit biophysical models to create scenarios with targeted places where the greatest water quality and supply benefits could be realized. We quantified how these scenarios would impact the sediment load, nitrogen load, phosphorous load, and annual water yield with hydrologic models. The scenarios included a “Business as usual” based on existing conservation plans (2015–2020) and four additional model-generated scenarios: a “Targeted” scenario using the “Business as usual” budget, two targeted “Increased budget” scenarios, and a “Targeted-climate smart” scenario adjusted based on climate change. We expected the model-generated scenarios to have a greater impact on biophysical factors than “Business as Usual,” and that the “Increased budget” scenarios would reach water quality regulatory goals. The “Targeted” scenario produced a small improvement in water quality over “Business as usual,” but did not meet regulatory goals. The “Increased budget” scenarios could meet water quality goals in one additional subwatershed if the budget is allocated to the most cost-effective activities to reduce sediment. Incorporating climate change caused the targeted locations of activities to shift in space, but the overall impact on biophysical factors was similar. This study demonstrates how science-based planning with stakeholder input can inform conservation investments across existing boundaries and lead to greater water quality improvements. By identifying where to implement different types of conservation activities and how much to invest, as well as revealing shortcomings in current assumptions about which activities to implement, this study can enable smarter and more effective land management investments.

1. Introduction

Payments for watershed services, sometimes called ‘water funds,’ are investment mechanisms that maintain or improve the services provided by natural ecosystems. These provisioning and regulating services range from water purification to surface and groundwater flow regulation. A water fund can diversify the types of stakeholders who fund conservation and lead to greater collaboration across different land ownerships in a watershed (Goldman-Benner et al., 2012). Developing a water fund can involve the use of a model to target locations for conservation investments to provide the greatest improvement in water quality or supply (Vogl et al., 2016, 2013). Models are also commonly used to quantify the impact of conservation activities on biophysical factors, or to link changes in biophysical factors to ecosystem services (MEA, 2005; Nelson et al., 2009; Smith et al., 2011; Guerry et al., 2015; Ouyang et al., 2016; Schroder et al., 2016). Developing models in an iterative process with stakeholder input can create the enabling conditions to inform decision making, policies, and implementation (Ruckelshaus et al., 2015).

Stakeholders in the Truckee River watershed in California and Nevada currently invest in land protection and restoration activities, and there has been considerable investment in the Lake Tahoe subwatershed to maintain lake clarity. The Tahoe Regional Planning agency coordinates funding for investments in the Lake Tahoe subwatershed through the ‘Environmental Improvement Program.’ This payment for watershed services program only covers a portion of the entire watershed. Additionally, investments

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are typically opportunistic, not spatially targeted for impact, and success is measured in acres or miles protected rather than in water quality improvements that investors are seeking to achieve. As a consequence, there is little sense of the scale of financial investment needed, or which activities should be implemented, to achieve the water quality goals.

To fill this gap, this study demonstrates how modeling and stakeholder input can be combined to determine where to spatially target conservation activities, and the amount of investment needed, in which activities, to reach water quality regulatory goals. Past modeling studies at subwatershed scales in the Truckee River watershed identified dirt road removal and maintenance, decreased road sand application, revegetation, and ski-area restoration as investments that can be implemented to attain regulatory sediment reduction goals (Grismer 2014; McGraw et al., 2001). We developed four future land use scenarios, with activities targeted to the best locations for water quality and supply improvement, using the Natural Capital Project's Resource Investment Optimization System (RIOS) model (Vogl et al., 2013). These scenarios were based on common stakeholder priorities, different budget levels, and climate change projections. We estimated how the scenarios, along with a business as usual scenario based on existing plans, affected water quality and yield with the Integrated Valuation of Environmental Services and Tradeoffs (InVEST) models (Sharp et al., 2014). We collaborated with stakeholders who were interested in, benefit from, or that have specific regulatory requirements that could be met by improving water quality and supply in the watershed.

We addressed how different conservation investment levels and climate change inputs affect water quality and quantity outcomes at a watershed-scale, compared to existing plans for conservation. We expected that the model-generated scenarios would provide more improvement in water quality and supply than the business as usual plan. Additionally, we expected that with increased investment there would be greater improvements in water quality that could meet regulatory goals in the subwatersheds. The purpose of the study was to inform stakeholders about the potential of a water fund. We included climate change because of the threat it poses for water supply under hotter and drier projections and to test how targeted activities might shift in space (U.S. Department of the Interior, 2015). We asked three questions that have relevance more broadly to planning for multiple objectives with a diverse group of stakeholders.

1. Does a model-generated scenario of restoration and land protection provide more water quality and supply improvement than the business as usual plan?
2. What level of conservation investment is needed to meet the regulatory water quality goals?
3. If climate change projections are incorporated into the model, does that change the targeted location for conservation investments or their total impact on water quality or quantity?

2. Methods

2.1. Study area

The Truckee River watershed (4512 square kilometer area) is a place where land management to improve water quality, reduce wildfire risk, and protect biodiversity are high priorities, providing a useful case study for implementing multi-benefit planning to improve outcomes. The Truckee River flows ~193 km from its headwaters at Lake Tahoe in the Sierra Nevada, California to Pyramid Lake, terminal lake in the Great Basin of Nevada. On the California side, water utilities rely primarily on groundwater for water supply, while in Nevada the river supplies drinking water for more than 400,000 people. In Nevada, downstream of the city of Reno, members of the Pyramid Lake Piute Tribe (residing within the Pyramid Lake Indian Reservation) use the river for water supply, agriculture, and the fishery for food and recreational income.

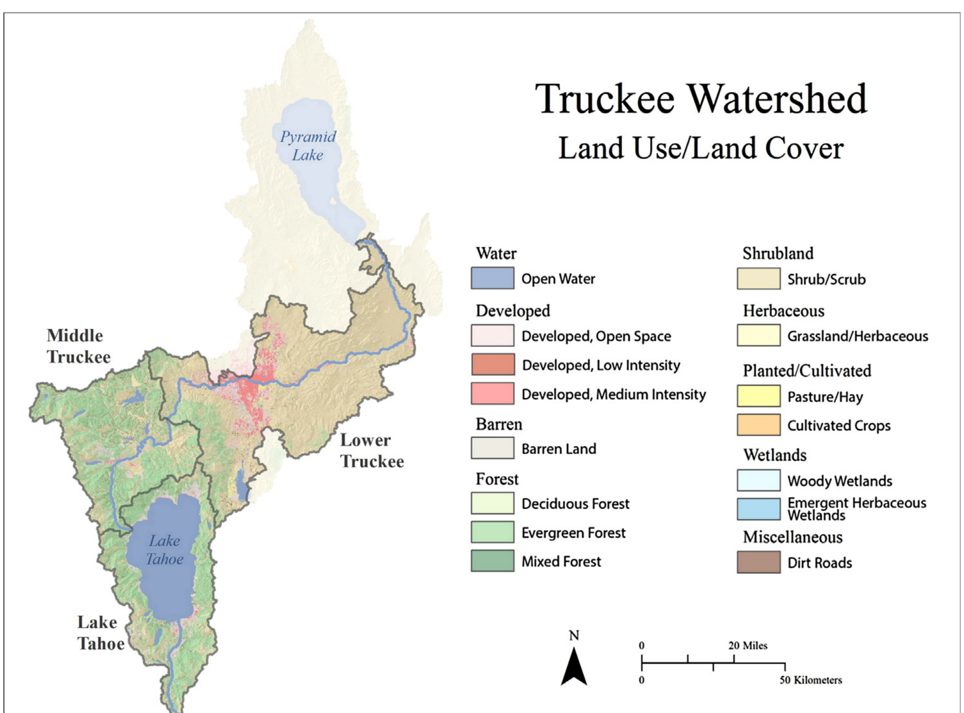

Fig. 1. Land cover map of the Truckee River watershed and the three subwatersheds.

A major focus of restoration and land protection funding in the Truckee River watershed has been to maintain Lake Tahoe's transparency (Tahoe Regional Planning Agency, 2016). Another primary focus is reducing the risk of large wildfires. Although wildfires are important natural disturbances in these forests and the forests have evolved to be fire-adapted, years of fire suppression and logging have altered forest conditions. Today there are areas of overly dense forest with high fuel loads (Safford and Van de Water, 2014). Given limited funding and continuing water quality problems, there is a need to maximize the cost-effectiveness of watershed investments to improve water quality, reduce fire risk, and account for the impacts of climate change.

2.2. Stakeholder engagement and priority setting

We divided the watershed into three subwatersheds based on stakeholder guidance: Lake Tahoe, Middle Truckee (from the outlet of Lake Tahoe to the U.S. Geological Survey stream gauge at Farad), and the Lower Truckee (from the Farad gauge to the inlet of Pyramid Lake; Fig. 1). We engaged water utilities who benefit from improvements in water quality and supply, forest managers who benefit from decreasing wildfire risk, and conservation groups who benefit from protecting biodiversity-rich habitats and improvements in water quality for aquatic species (Table 1). We adopted an iterative, collaborative process working with stakeholders to model the water quality and quantity impact of different scenarios to inform future land management (Fig. 2). Through stakeholder meetings, working sessions, a survey, and individual interviews, we solicited feedback on objectives, planned activities, costs, budgets, climate change projections, and the feasibility of different plans. We met with stakeholders three times as a large group over two years, met with smaller subwatershed groups in working sessions, and gathered additional information and comments via email and phone calls.

We identified common objectives by asking stakeholders to identify and rank the "priority objectives for your organization that drive your conservation and restoration spending" in a written survey emailed to stakeholders. The seven objectives included in the survey are objectives that could be modeled in RIOS along with wildfire risk reduction, an objective known to be important in the watershed. We instructed stakeholders that they did not have to rank all choices and they could add any additional objectives. The survey (n = 12) revealed that the most important objectives across the entire stakeholder group were, in order: erosion control, groundwater recharge enhancement, nitrogen reduction, flood risk mitigation, dry season baseflow, reducing wildfire risk, and phosphorous retention. Stakeholders did not add any additional objectives. We used the average score for each objective to weight the RIOS model and included biodiversity as an objective equal to erosion control, the most important objective based on the survey. We did this to reflect the missions of four stakeholders not included in the survey. Three stakeholders were not surveyed because they were added after the initial survey or did not respond to the survey.

Table 1
Stakeholders involved in the Truckee River Water Fund, categorized by subwatershed. Some group's missions span more than one subwatershed.

Lake Tahoe
California Tahoe Conservancy
South Tahoe PUD
Tahoe City PUD
Tahoe Regional Planning Agency
USFS—Lake Tahoe Basin Management Unit
Middle Truckee
Northstar Community Services District
Tahoe Truckee Sanitation Agency
The Nature Conservancy, CA
Trout Unlimited
Truckee Donner Land Trust
Truckee Donner PUD
Truckee River Watershed Council
USFS—Tahoe National Forest
Lower Truckee
NV Land Trust
Pyramid Lake Paiute Tribe
The Nature Conservancy, NV
Truckee Meadows Water Authority
Truckee River Flood Management Authority
Truckee Meadows Water Reclamation Facility
US Bureau of Reclamation

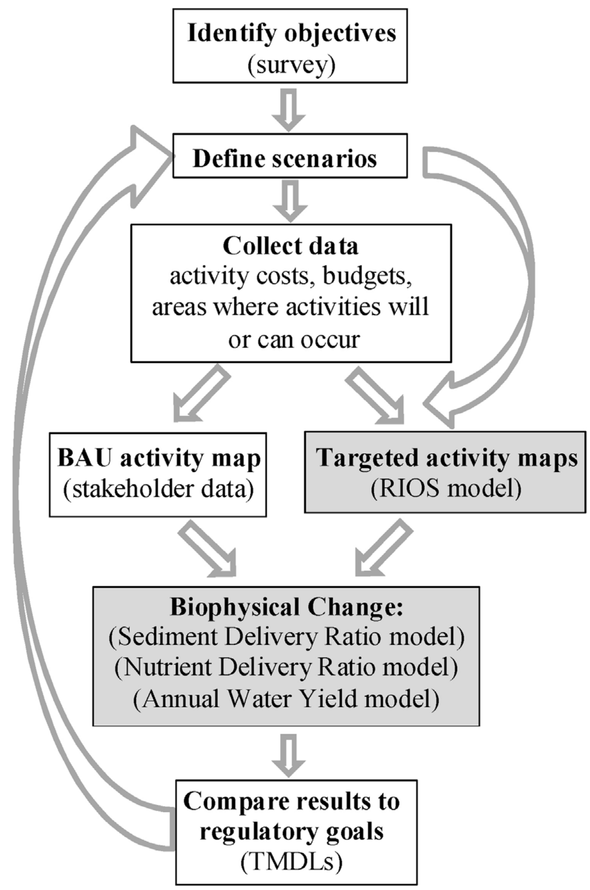

Fig. 2. Outline of stakeholder and modeling (grey boxes) progression for prioritizing land protection and restoration for multiple objectives in the Truckee River watershed.

2.3. Scenarios

We modeled the water quality and quantity impact from five scenarios based on implementing the activities described in Table 2:

(1) "Business as usual" (BAU) scenario for activities planned between 2015 and 2020.

RIOS modeled:

(2) "Targeted" scenario based on the same budget level as the "BAU" scenario.

Table 2
Five land use/land cover scenarios.

LULC scenario	Description	Budget ($ millions)		Activities	Time-period
1. “Business as usual“[a]	Stakeholders planned activity locations and cost.	$70		forest fuels reduction, land protection, meadow restoration, riparian restoration, dirt road maintenance	2015–2020
2. “Targeted”	RIOS modeled activities with budgets for each activity and subwatershed matching the “BAU” scenario.	$70		Same as BAU	2020–2025
3. “Increased budget-proportional”	RIOS modeled activities with budgets for each activity and subwatershed based on treating 10% and 30% of the available area for each activity.	Low budget, 10% area $175	High budget, 30% area $527	Same as BAU	unspecified future date
4. “Increased budget-sediment”	RIOS modeled activities with total budget matching the 10% and 30% scenario, but activities budgeted based on their cost-effectiveness for sediment reduction.	Low budget, sediment $175	High budget, sediment $527	riparian restoration, road maintenance, land protection	unspecified future date
5. “Targeted-climate smart”	RIOS modeled activities with budgets for each activity and subwatershed matching the “BAU” scenario, plus climate change inputs for precipitation and evapotranspiration.	$70		Same as BAU	2020–2025

[a] BAU—Business as usual.

(3) “Increased budget-proportional” scenario with 10% and 30% of the available area for each activity in each subwatershed treated, resulting in a budget 2.5 and 7.5 times the “BAU” budget.
(4) “Increased budget-sediment” scenario using the same increased budgets of 2.5 and 7.5 times the “BAU” budget, with the budget allocated across the entire watershed based on the cost effectiveness of activities to reduce sediment.
(5) “Targeted-climate smart” scenario based on the same budget level as the “BAU” scenario plus projected changes in precipitation and evapotranspiration with climate change. Using the model to target activities based on climate change was not unanimously supported among stakeholders, therefore we did not incorporate climate change impacts into any of the increased budget scenarios.

In the “BAU” scenario, activities that stakeholders currently invest in and that are modeled in this study include: forest fuels reduction, land protection, meadow restoration, riparian restoration, and dirt road maintenance and decommissioning. Across the entire Truckee River watershed, $70 million is planned for these activities from 2015 to 2020, allocated as follows: $45 million in Lake Tahoe, $21 million in Middle Truckee, and $4 million in Lower Truckee (Table 3). Stakeholders invest heavily in forest fuels reduction ($28 million) and meadow restoration ($22 million), with less investments in land protection ($11 million), riparian restoration ($9 million), and dirt road maintenance ($143,500). These planned investments represented our “BAU” budget.

To answer our first question, we used the “BAU” budget for the “Targeted” scenario to allow us to determine if there was any increased benefit from using the model to locate activities. We did this in the RIOS model by allocating the same amount of money to the specific activities and subwatersheds. We assumed a straight application of unit cost in RIOS; however, actual costs could be lower due to economies of scale, or higher for dispersed activities. The ranking of objectives in this and all subsequent RIOS model runs was derived from the stakeholder survey.

To answer the second question, we increased the budget and used the RIOS model to target activity locations under two different budget allocations. In the first scenario, we increased the percent of area treated for each activity in each subwatershed to 10% and 30% of the available area where individual activities could occur, leading to a total budget of $175 and $527 million, or 2.5 and 7.5 times the “BAU” budget. We called this scenario the “Increased budget-proportional” scenario as all activities were implemented proportionally. We selected the proportional increase values, 10% and 30%, based on the goals for forest fuel reduction to reduce the risk of wildfires. Treating 10–30% of a watershed through strategically placed mechanical forest thinning and prescribed wildfire will likely decrease the risk of large high-severity wildfires that could impact infrastructure, habitat, sediment and nutrient loading, and flooding (Ager et al., 2007, 2010; Finney et al., 2007; Syphard et al., 2011).

Table 3
Business as usual activities (2015–2020) and costs by subwatershed.

Sub-watershed	Data	Land protection	Riparian restoration	Meadow restoration	Forest fuels reduction	Dirt road maintenance	TOTAL
Lake Tahoe	Area treated (hectares)	8.4	0.2	4.3	231	–	
	Cost ($/m^2)	9.83	197.68	42.01	0.62	1.04	$45,305,431
	Budget	$8,235,431	$4,800,000	$18,020,000	$14,250,000	$-	
Middle Truckee	Area treated (hectares)	54	0	1	474	–	
	Cost ($/m^2)	0.47	148.26	41.18	0.30	1.04	$20,866,117
	Budget	$2,505,682	$0	$4,298,342	$14,062,093	$143,500	
Lower Truckee	Area treated (hectares)	0	2	–	–	–	
	Cost ($/m^2)	0.37	24.71	41.18	0.17	1.04	$4,100,000
	Budget	$0	$4,100,000	$0	$0	$-	
Total		$10,741,112	$8,900,000	$22,318,342	$28,312,093	0	$70,271,548

In a second increased budget scenario, we first calculated the cost effectiveness of each activity relative to sediment reduction, the most important objective across the entire stakeholder group. We calculated a cost effectiveness indicator by dividing the reduction in sediment at the pixel level (measured as the soil loss cover management factor as a proxy—see Supplemental material for more information) by the cost of the activity in each subwatershed. After ranking the activities based on the cost effectiveness for sediment reduction, we budgeted for the activities with the greatest cost effectiveness first until the budget was spent using the total budgets of $175 million and $527 million from the 10% and 30% "Increased budget-proportional" scenario to allow for a direct comparison of the two scenarios. We called this second increased budget scenario the "Increased budget-sediment" scenario.

To answer the third question, we relied on the Department of the Interior's *Truckee Basin Study* to determine the change in precipitation and evapotranspiration with climate change in what we called the "Targeted-climate change" scenario (U.S. Department of the Interior, 2015). The *Basin* study modeled climate change using the World Climate Research Program's Coupled Model Intercomparison Project phase 3 data by downscaling and grouping climate projections into five climate ensembles: warmer-drier, hotter-drier, hotter-wetter, warmer-wetter, and a central tendency. Our scenario incorporated the hotter-drier climate ensemble with the assumption that this would represent a worst case for water supply. Reductions in streamflow would require increased release from upstream reservoirs. Decreased snowpack and a faster snowmelt season would limit reservoir storage. Groundwater recharge would be decreased, and all of these changes would stress the water supply and possibly not meet demand. We used precipitation and evapotranspiration data from 2020 to 2051 to match the historical 30-year time interval from the PRISM average annual climate data (1981–2010) used in the other scenarios, and representing the period when the activities could likely be implemented (see detailed description in the Supplemental material). We incorporated only the change in precipitation and evapotranspiration, as land cover change due to climate change was not available. We did not model climate change in the Lower Truckee because the climate change inputs were not available for Nevada.

2.4. Modeling and analysis

The RIOS model targets locations for activities to increase benefits for water quality and quantity objectives along with the option for adding 'other' objectives. The model combines biophysical data and landscape context with cost data to produce land cover maps with targeted locations where activities are most likely to improve the specific objectives of interest to the user. The InVEST model incorporates the resulting RIOS land cover maps to estimate the benefits of activity implementation. Model data and sources are listed in the supplemental material. Although we did not calculate the economic value of the activities, we assumed that reduction in sediment, nitrogen, and phosphorous loads would benefit several of the stakeholders through decreased water treatment, decreased reservoir sedimentation, improved instream habitat, and greater water clarity in Lake Tahoe.

We mapped three additional areas to guide the RIOS model toward priority places for different activities: biodiversity hotspots, groundwater recharge areas, and wildfire hazard areas. We identified biodiversity hotspots in Lake Tahoe using the Tahoe Conservancy's priority 'sensitive lands.' In the Middle Truckee we relied on The Nature Conservancy's (1999) and Northern Sierra Partnership's (2016) priority lands for biodiversity protection. In the Lower Truckee, we delineated the riparian corridor along the mainstem of the Truckee River as a place for priority land protection based on its importance for endangered Cui-ui and threatened Lahontan cutthroat trout populations. We identified the Martis Valley aquifer and the Truckee Meadows aquifer as places where land protection could benefit recharge. We focused forest fuel reduction activities in zones identified as highest risk for wildfires that would be difficult for suppression resources to contain (Dillon et al., 2015). Reducing fuel loads only in high risk areas does not incorporate the multiple values that may dictate locations for forest fuels reduction: protecting homes or other infrastructure, strategically placing treatments to reduce wildfire spread, protecting wildlife habitat, or restrictions on treatment locations. We wanted to let the RIOS model target locations to improve water quality and supply based on biophysical processes first.

We used three InVEST models to estimate the water impacts from the five land use scenarios: Sediment Delivery Ratio (SDR), Nutrient Delivery Ratio (NDR), and Annual Water Yield (AWY). These models quantify the change in sediment load (kg/yr), nitrogen and phosphorous load (kg/yr), and annual water yield (m^3/yr) compared to the existing land cover. In a comparative study of different ecosystem service models, Bagstad et al. (2013, p. 30) described the InVest model as, "well-documented; can be independently applied and tested; amenable to widespread use . . . time consuming to parameterize . . . (and) extensively vetted in the peer-reviewed literature." In general, InVEST models take a simplified approach to quantifying and mapping ecosystem services, to allow for estimating biophysical processes in data- or time-constrained analyses. SDR uses the Universal Soil Loss Equation (USLE) and Sediment Delivery Ratio methods to estimate annual soil loss to streams. Its main limitations center around the USLE, as it only represents sheet erosion, and is highly sensitive to most input parameters. NDR takes a mass balance approach, determining initial nutrient load across the landscape, then estimating annual delivery to streams similarly to SDR. It is also highly sensitive to most input parameters, particularly the nutrient load and retention values, which are derived from empirical studies. We calibrated the SDR and NDR models based on studies in the Truckee River watershed to reduce uncertainty. AWY is a rainfall-runoff model based on the Budyko curve and annual average precipitation. It does not provide sub-annual information on water delivery, or differentiate between surface and sub-surface flows.

For each scenario, we created three land cover maps in RIOS: 1. existing, 2. all restoration and land protection activities are implemented, and 3. all restoration activities are implemented but the land protection areas are degraded and converted to low intensity development. We calculated the total benefit of each map using InVEST following the approach used by Vogl et al. (2016) and reported the sediment load, nutrient load, and water yield as relative values and calibrated absolute values (divided by the baseline, see supplemental material for the calibration):

$$T = (P - O) + (P - A) \times C$$

where,

T = Impact with the restoration activities implemented, plus the avoided degradation of protected land.

P = Impact with the restoration activities implemented and protected areas unchanged.

O = Impact with the existing land cover, no activities implemented.

A = Impact with restoration activities implemented and protected areas degraded.

C = Calibration value to adjust model results to empirical studies (see Supplemental material)

This approach values not only the tangible benefits of doing restoration activities (P–O), but also the marginal benefit of not allowing current healthy ecosystems to degrade in the future (P–A).

To simulate the impact of land protection and restoration, we assigned model parameters based on empirical studies in the watershed and meta-analysis of how these activities would change the parameters (Table 4). The only activity that did not impact water quality or quantity was forest fuels reduction, assuming it is done according to best management practices (Stephens et al., 2004; Murphy et al., 2006; Harrison 2012; Grismer, 2014). We estimated how the sediment and nutrient annual load results compared to local studies in the watershed and calibrated the Water Yield model results to the streamflow gauges for the three subwatersheds, the nutrient results for Lake Tahoe based on the TMDL documentation, and the sediment results for all three subwatersheds based on measured values (see the Supplemental material). Accounting for the relative proportion of sediment from different sources in the SDR model compared to the total sediment budget is a key step in estimating the impact of the scenarios. Based on sediment studies in the watershed, it is clear that hillslopes contribute a small amount of the total hillslope erosion that reaches the outlet (0.9–4%; Nolan and Hill, 1991; Maholland, 2002). Groundwater recharge, flood risk mitigation, and dry season baseflow were stakeholder second, fourth and fifth ranked objectives, but these could not be modeled with the AWY model because they are seasonal changes or involve surface and groundwater interactions not captured in the model.

2.5. Existing water quality standards

We compared the sediment and nutrient load reduction estimates from the five scenarios to current regulatory water quality goals in the watershed. The deep-water portion of Lake Tahoe is listed under Section 303(d) of the U.S. Clean Water Act for nitrogen, phosphorous, and sediment to address the decline in lake clarity. Forested uplands contribute 9% of fine sediment, 16% of nitrogen, and 26% of phosphorous loads to Lake Tahoe (Kuchnicki and Larsen, 2014). The milestone load reduction goal by 2025 for forested uplands is 12% fine sediment particles, 0% nitrogen (0 kg/yr), and 1% phosphorous (120 kg/yr, CRWQCB, 2010). We were unable to compare the sediment load reduction goal for Lake Tahoe to the modeled results because the total maximum daily load (TMDL) is set for a fine particle count, not a total suspended sediment load. Reaching the load reduction goals would likely improve clarity and maintain or improve the recreational value of the lake and tourism, the main industry in Lake Tahoe. The Middle Truckee River is listed for sediment to protect in-stream aquatic life from habitat loss due to siltation. The majority of sediment (90%) comes from non-urban areas and the goal is a 22% reduction in sediment from non-urban areas (9 million kg/yr, CRWQCB, 2008). Reducing the sediment load will have benefits for both in-stream habitat and reduced water treatment costs for the water utility in the city of Reno. Downstream of Reno, there are pollution load reduction goals for total phosphorous, turbidity, and temperature to improve instream habitat. Non-point sources contribute an average annual 69% of the phosphorous load in the Lower Truckee

Table 4
Sources for and assumptions regarding parameter values for different activities modeled in InVEST. The parameters are: Kc (crop coefficient for the Water Yield Model), USLE_C (cover management factor for the Sediment Retention Model), N_exp, P_exp, Eff_N, and Eff_P (nitrogen "N" and phosphorous "P" export and retention coefficients for the Nutrient Retention Model).

Activity	Original land cover	Focus areas	Assumptions	Sources
Land degradation	Deciduous forest, Emergent herbaceous, Evergreen forest, Herbaceous, Mixed forest Shrub/scrub, Woody wetlands	Areas of high biodiversity value, private lands	Land that is not protected is degraded and the land cover changes to 'developed low intensity' parameter values, except for USLE_C which increases by 80% and Kc which does not change. The increase in sediment with development will likely decrease over 40+ years due to natural adjustment post-development and erosion control measures. Kc does not change as we assumed stormwater designs mitigate development impacts on water yield.	Sediment: (Glancy 1988; Simon et al., 2003) Nutrients: (Coats et al., 2008)
Riparian restoration	Barren, Crop, Developed open space,* Emergent herbaceous,* Herbaceous, Pasture, Shrub/scrub, Unpaved road	Riparian buffer: 120 m in California and 270 m in Nevada, no Wilderness areas	Riparian restoration changes land cover to 'woody wetland' parameter values, except for land cover with asterisks where USLE_C is decreased by 52%, average value from local studies, and 'unpaved road' where Eff_N and Eff_P = 0.9 per the decrease in nutrients with riparian buffers (Zhang et al., 2010).	Sediment: (Susfalk and Fitzgerald 2009; Zhang et al., 2010) Nutrients: (Zhang et al., 2010) Water yield: (Loheide and Gorelick, 2005)
Meadow restoration	Emergent herbaceous,* Herbaceous, Shrub/scrub	Meadows as defined by (UC Davis 2016) plus adjacent wetlands (NHD 201 ×), no Wilderness areas	Meadow restoration changes land cover to 'emergent herbaceous' parameter values except for 'emergent herbaceous' where USLE_C is decreased by 34% and Eff_N and Eff_P = 0.9 per decrease in nutrients with riparian buffers (Zhang et al., 2010), as in riparian restoration.	
Dirt road maintenance	Unpaved road	Dirt road data layer (U.S. Forest Service)	Road restoration changes 'unpaved roads' to 'evergreen forest' parameters for Eff_N, Eff_P and Kc. USLE_C changes to 0.25, a decrease of 75% due to outsloping, rolling dips/water bars, low water crossings, paving at drainage crossings, adding aggregate in sensitive areas, and some decommissioning.	(DRI 2001-values of USLE_C used range from 0.1 to 0.5)
Forest fuels reduction	Evergreen forest	Areas of high and very high wildland fire potential (Dillon et al., 2015), no Wilderness areas	Forest fuel reduction (mechanical thinning and prescribed fire) has no impact on sediment or nutrient loads. This does not account for avoided sediment or nutrients post-wildfire.	Sediment: (Grismer 2014; Harrison 2012) Nutrients: (Murphy et al., 2006; Stephens et al., 2004)

and the average annual load reduction goal is 10% (29,894 kg/yr; NDEP, 1993, see supplemental material). Decreasing the phosphorous load will improve instream and Pyramid Lake habitat for one endangered and one threatened fish species.

3. Results

3.1. Scenario maps

The “BAU” scenario compared to the “Targeted” scenario revealed several differences in the location of activities (Fig. 3). In the “BAU” scenario, forest fuels reduction activities were concentrated around homes and upland areas that are accessible by dirt roads. Because the RIOS model works on a pixel scale, the “Targeted” scenario showed dispersed forest fuel reduction and other activities along streamlines and in specific drainages with volcanic geology. The “BAU” scenario consisted of large areas of concentrated activities. In the “Targeted” scenario, activities were located in the most upstream ends of each subwatershed, along areas of erodible volcanic andesite soils and steep-slopes, and over groundwater recharge areas where the impact of treatments will be optimized.

The “Increased budget-sediment” scenario at the $175 million total budget resulted in a budget allocated to, in order of cost effectiveness (Fig. 4 and supplemental material):

1. Dirt road maintenance in Middle Truckee
2. Dirt road maintenance in Lake Tahoe
3. Dirt road maintenance in Lower Truckee
4. Land protection in Lower Truckee
5. Land protection in Middle Truckee
6. Riparian restoration in Lower Truckee

No money was spent on any other activities in this scenario. In the “Increased budget-sediment” scenario at the $527 million budget level additional money was spent on: 6. Riparian restoration in Lower Truckee and 7. Land protection in Lake Tahoe, as these were the next most cost-effective activities to reduce sediment. The budget was spent based on treating 100% of the available area for each activity/subwatershed before spending any money on the next highest ranking sediment reducing activity.

In the “Targeted” scenario and “Targeted-climate smart” scenario, the overlap in activity locations was high (89%). The overlap varied by activity: riparian restoration activities overlapped the most (98%), followed by meadow restoration (93%), forest fuels reduction (79%), dirt road maintenance (68%) and land protection (10%). The large overlap in area for both riparian and meadow restoration may be due to the small area available for the activity. Dirt road restoration represents a small total area in the watershed, but there was less overlap perhaps because there was so little money budgeted for this activity in the two scenarios. In the “Targeted-climate change” scenario, the average annual precipitation decreased by 170 mm (19.9%) in Lake Tahoe and 238 mm (23.8%) in the Middle Truckee, while the average annual evapotranspiration increased by 88 mm (17.9%) in Lake Tahoe and decreased by 112 mm (20.1%) in the Middle Truckee. In Lake Tahoe,

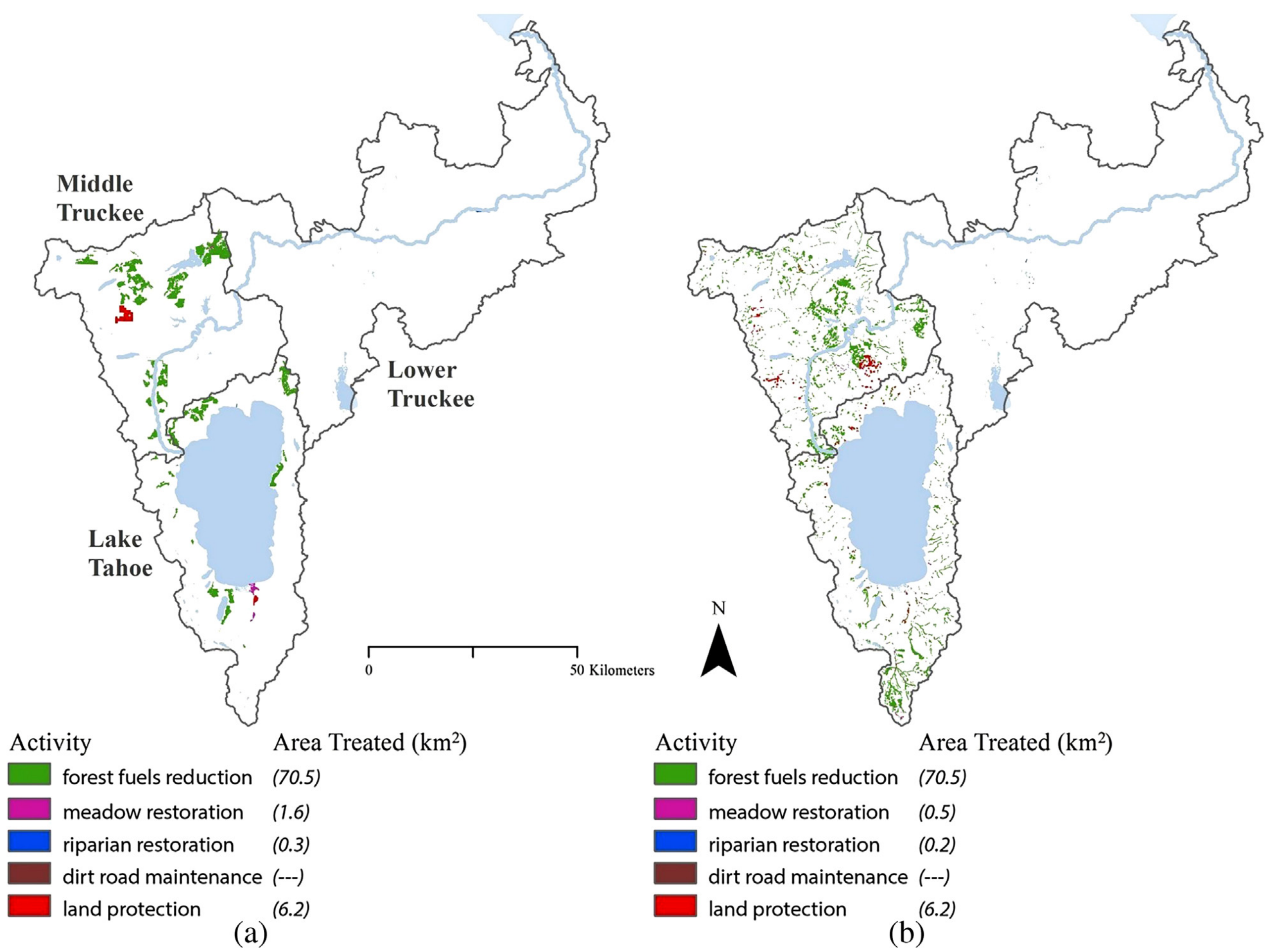

Fig. 3. The “Business as Usual” scenario (a) compared to a “Targeted” scenario for water quality improvement and water supply based on stakeholder objectives and the same budget as “Business as Usual” (b).

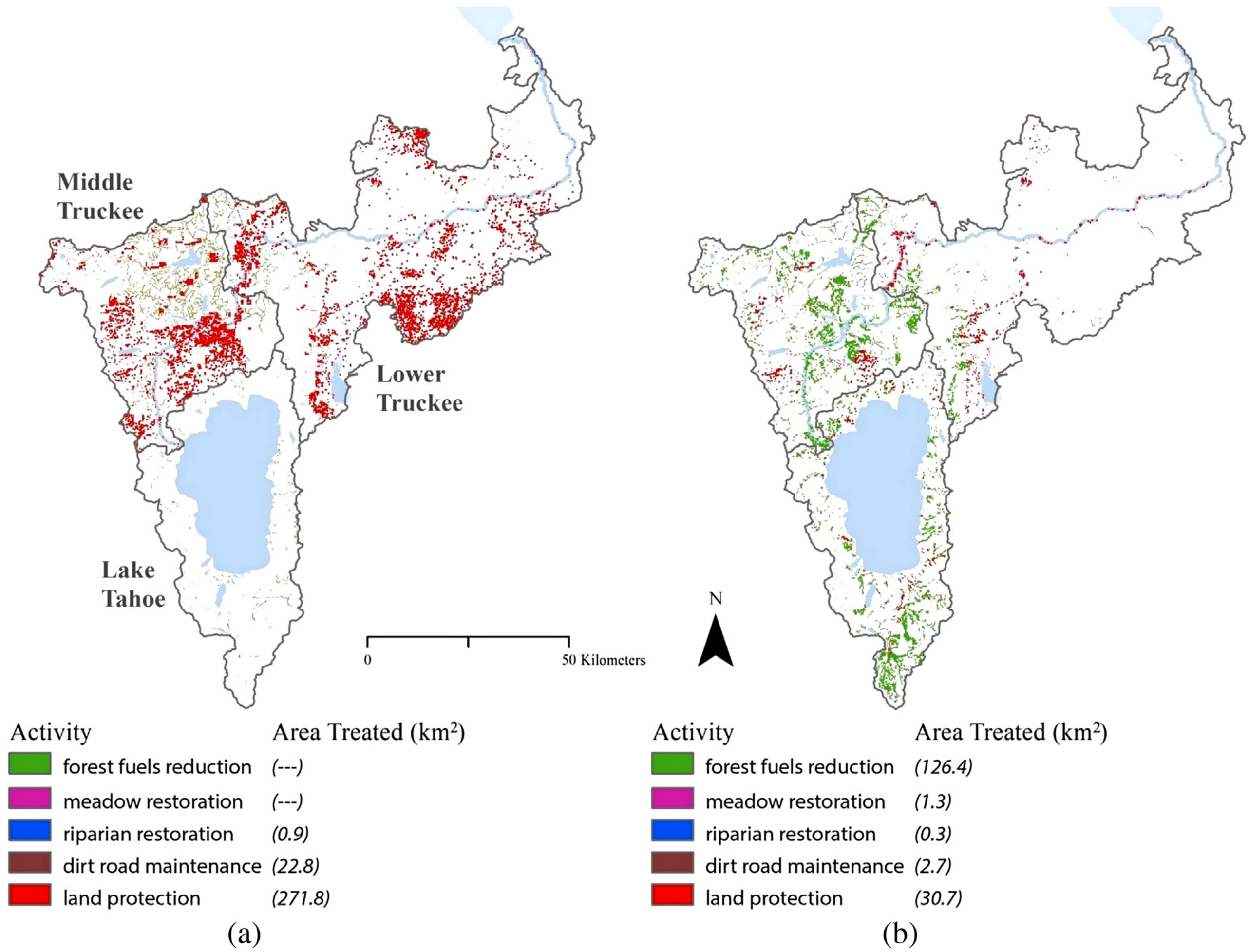

Fig. 4. "Increased budget scenarios" with the budget distributed based on the most cost-effective activities to reduce sediment (a), compared to proportionally treating 10% of the available area for each activity (b) at the same total budget level $175 million.

activities shifted from the northeast and south end of the subwatershed to the east side of the lake due to changes in precipitation and evapotranspiration. In the Middle Truckee, there was no apparent pattern to the shift in activities with climate change.

3.2. Water quality and quantity impacts

The InVEST SDR model includes hillslope erosion but not gully erosion, streambank erosion, or landslides. The model predicted 65 billion (65×10^9) kg/year of suspended sediment is mobilized in the Middle Truckee, which is within the magnitude of measured values over ten months at the Farad gauge (56×10^9 kg, Dana et al., 2004). Other measurements of annual suspended sediment at the Farad gauge are lower: 46 million kg/year (CRWQCB, 2010) and 46–87 million kg/year (Kuchnicki, 2001). If we assume that 0.9% of the modeled hillslope sediment reaches the outlet based on past studies, then the modeled sediment load in the Middle Truckee would be 584 million kg/year, which is still 7–13 times higher than the other direct measurements, but there is a large range in the measured values. Instream sediment transport along with sediment trapping in the dams are important consideration in the total sediment load; however, neither of these are accounted for in the SDR model.

The InVEST NDR results for the baseline condition were similar to measurements of existing loads in the Lower Truckee (NDEP, 1993). The model result for nitrogen load was 94,895 kg/yr, and direct annual measurements ranged from 91,323 to 771,482 kg/yr. The modeled result for phosphorous load was 18,460 kg/yr and direct annual measurements ranged from 10,676 to 169,013 kg/yr. The NDR results for the baseline condition were not as close to the basin wide load established for the Lake Tahoe TMDL (CRWQCB, 2010). The model results for nitrogen load was 19,308 kg/yr compared to the basin-wide load for forested uplands, 62,000 kg/yr. The modeled results for phosphorous was 1531 kg/yr and the TMDL basin-wide load for forested uplands was 12,000 kg/yr. We calibrated the nutrient values for Lake Tahoe to match the forested upland basin-wide loads.

The InVEST AWY model compared to empirical streamflow data for the same time period (1981–2010) was within −22% for Lake Tahoe, 7% for the Middle Truckee, and 21% for the Lower Truckee River, once estimates of consumptive water demand from the *Truckee Basin Study* (U.S. Department of the Interior, 2015) are taken into account (see Supplemental material).

In the "BAU" scenario, the sediment and nutrient load reduction was <2% across all three subwatersheds (Fig. 5). The "Targeted" scenario provided greater water quality improvements than the "BAU" scenario for all three subwatersheds. However, the difference in water quality improvement between the two scenarios was small due to the relatively small area treated (<10% of the subwatershed area for all activities). The maximum improvement in the "Targeted" scenario was 3.5% reduction in phosphorous in Lake Tahoe compared to 1.9% in the "BAU"

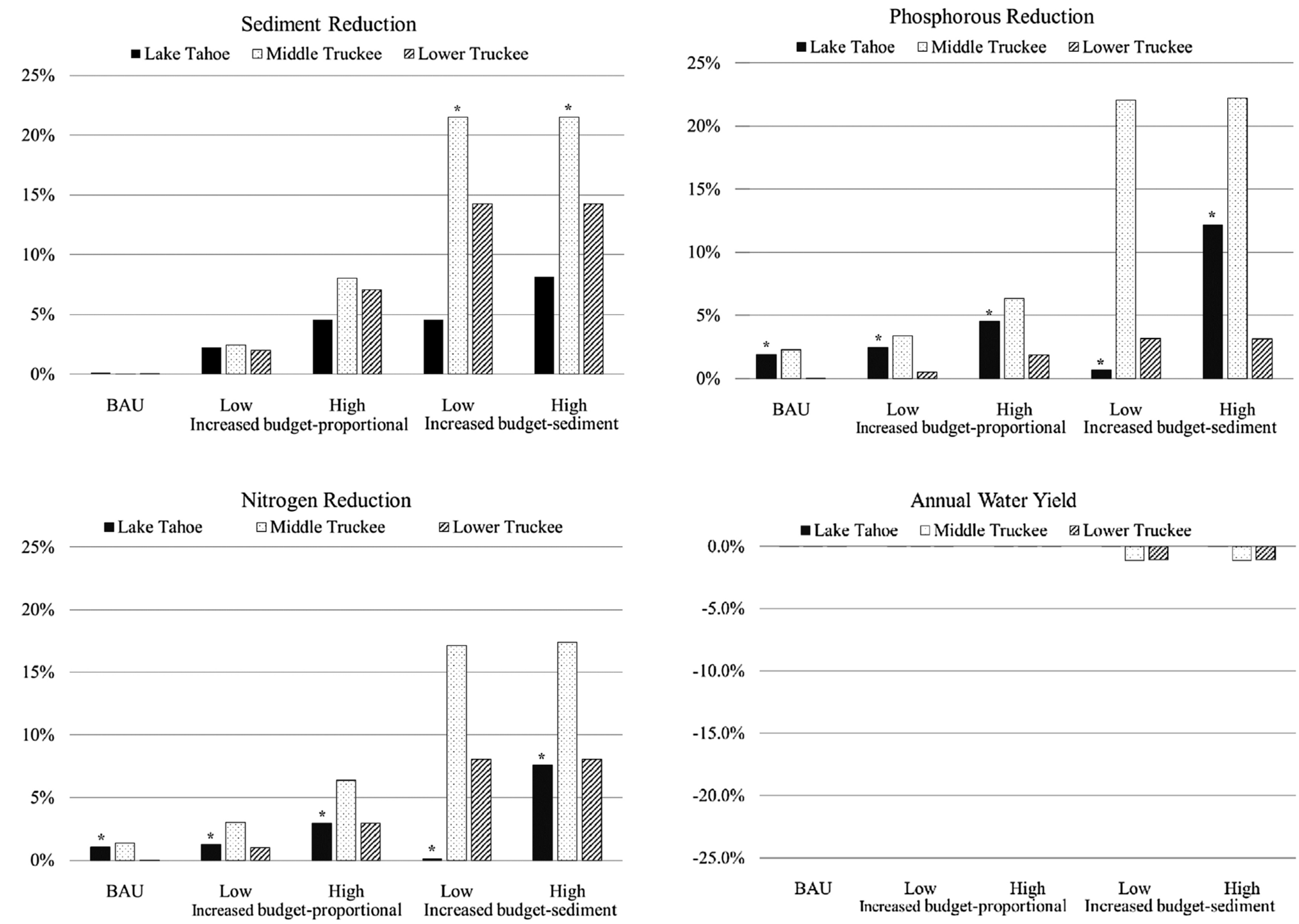

Fig. 5. Percent change relative to the baseline for each subwatershed from the "Business as Usual" and "Increased Budget" scenarios. Asterisks indicate where the Total Maximum Daily Load target was met or exceeded.

scenario. Nitrogen and phosphorous load regulatory goals for Lake Tahoe were met in all scenarios.

In the "Increased budget-proportional" scenario, with 10% and 30% of the area for each activity treated, the sediment load was reduced by 2–5% in Lake Tahoe, 2–8% in the Middle Truckee, and 2–7% in the Lower Truckee (Fig. 5). Nitrogen and phosphorous load reduction was greatest in the Middle Truckee compared to the other subwatersheds. Increased investment with 30% of the area treated and 7.5 times the budget of the "BAU" scenario only provided an additional 3% nitrogen reduction and 4% phosphorous reduction in Lake Tahoe. The sediment load reduction goal for the Middle Truckee and phosphorous load reduction goal for the Lower Truckee were not met in any of the proportional scenarios.

In the "Increased budget-sediment" scenario, the TMDL goal of 22% sediment reduction in the Middle Truckee was met at the $175 million budget level (Fig. 5, Table 5). If we consider subwatersheds individually, the sediment goal could be met by spending $68 million in the Middle Truckee: with $51 mill on dirt road restoration and $17 million on land protection. Additional sediment reduction did not occur in the Middle Truckee at the $527 million budget level because no additional work was modeled in this subwatershed. There were also large reductions in nitrogen and phosphorous loads due to land protection. As locations for restoration activities were targeted, they improved the water quality, but there was a small tradeoff with increased landscape water demand through evapotranspiration that results in a slight decrease in annual water yield ($<-1\%$, Middle Truckee and Lower Truckee). The phosphorous load reduction goal for the Lower Truckee was not met in this scenario.

There was little difference in water quality improvement with climate change. In the "Targeted-climate change" scenario, the sediment load reduction increased in Lake Tahoe by 1% and decreased in the Middle Truckee by 0.2% compared to the "Targeted" scenario. The difference in nutrient load reduction and water yield between these two scenarios was less than 1%.

4. Discussion

Our results provide evidence for the value of strategically targeted investments in conservation activities using models guided by the priorities of stakeholders/investors. Our "BAU" scenario shows that currently planned investments across the watershed are unlikely to meet the objectives of stakeholders, in particular for sediment reduction. Also, we found that targeting existing planned investments ($70 million) in the Truckee River watershed provides limited additional improvement in water quality, likely due to the small percent of the watershed impacted. In contrast, we predict that stakeholders can meet the Middle Truckee regulatory sediment reduction goal if they increase investment, in addition to being more strategic about where and what activities are implemented. To meet the regulatory requirement for sediment load reduction in the Middle Truckee would require an additional investment of $68 million in dirt road restoration and land protection. However, increasing investment proportionally across all five activities will not reach the regulatory sediment goal in the Middle Truckee.

These results match similar findings in previous studies. Grismer (2014) and Nelson et al. (2009) both concluded that a

Table 5
Water quality improvement and water supply as calibrated absolute values and percent change relative to the baseline for the increased budget scenarios compared to the Total Maximum Daily Load (TMDL) targets. Grey shading indicates where TMDL target was met or exceeded.

Subwatershed, ecosystem service	Units	TMDL	Low budget, 10% area $175 mill	High budget, 30% area $527 mill	Low budget, sediment $175 mill	High budget, sediment $527 mill
Lake Tahoe						
Sediment reduction	kg (10,000)/yr	*	67 *2%*	136 *5%*	136 *5%*	242 *8%*
Nitrogen reduction	kg/yr	0** *0%*	244 *1%*	568 *3%*	26 *0%*	1,469 *8%*
Phosphorous reduction	kg/yr	120** *1%*	293 *2%*	542 *5%*	83 *1%*	*1,459* *12%*
Water yield	m^3(10,000)/yr		2 *0%*	7 *0%*	0 *0%*	0 *0%*
Middle Truckee						
Sediment reduction	kg (10,000)/yr	900 *22%*	112 *2%*	366 *8%*	984 *22%*	984 *22%*
Nitrogen reduction	kg/yr		812 *3%*	1,714 *6%*	4,603 *17%*	4,687 *17%*
Phosphorous reduction	kg/yr		92 *3%*	174 *6%*	606 *22%*	*610* *22%*
Water yield	m^3(10,000)/yr		0 *0%*	2 *0%*	-32 *-1%*	-32 *-1%*
Lower Truckee						
Sediment reduction	kg (10,000)/yr		51 *2%*	181 *7%*	408 *14%*	366 *14%*
Nitrogen reduction	kg/yr		967 *1%*	2,799 *3%*	7,664 *8%*	7,654 *8%*
Phosphorous reduction	kg/yr	29,894 10%	96 *1%*	347 *2%*	583 *3%*	*578* *3%*
Water yield	m^3(10,000)/yr		19 *0%*	0 *0%*	-25 *-1%*	-25 *-1%*

*The TMDL for sediment is set for fine particles only and the model results include all hillslope particles.

**We used the TMDL for forested uplands to calibrate nitrogen and phosphorous results, see supplemental material.

small change in land use/land cover (<5% of the watershed) would not produce large impacts on biophysical factors because large amounts of area were un-impacted, pointing to the need for larger investments. Ruckelshaus et al. (2015) compared the impact of randomly located conservation activities to RIOS modeled activities at different budget levels. They showed that as the budget increased, the difference in sediment load reduction between random and modeled scenarios became greater, with about two times the reduction in the modeled scenario at higher levels of investment.

Our results were not consistent across watersheds, however, pointing to the need for considering different activities and objectives across watersheds. For Lake Tahoe, nitrogen and phosphorous load regulatory goals were met in all scenarios, showing little need for increased investment or targeting of activities. On the other hand, we could not directly compare the sediment load reduction to the regulatory TMDL goal, but our results show that increased investment would provide additional reduction. In the Lower Truckee, the results of additional investment would achieve one-third of the phosphorous TMDL goal, suggesting that stakeholders would probably need to implement other types of investments not currently being considered to fully meet this goal, such as changes in agricultural fertilizer use or constructed wetlands.

Incorporating predicted temperature and precipitation impacts of climate change affected where investments were spatially targeted, but did not significantly affect the overall impact on water quality or quantity. Specifically, activities in Lake Tahoe would need to shift from the northeast and south end of the lake to the east side of the lake in order to ensure that at least the same level of water quality benefits can be realized in the future as the region becomes hotter with less snow and more rain. This change moves activities across state boundaries from California to Nevada, emphasizing the importance of greater coordination and collaboration across jurisdictions. Our results are limited because we only incorporated one climate ensemble, representing the hotter-drier condition. Future studies could include all five ensembles to test how activities shift in space based on multiple ensembles and provide a more complete picture of possible future conditions and strategies to meet objectives.

The model results corroborated local knowledge and expert studies about where to implement conservation activities which built stakeholder confidence in the results. The RIOS model targeted activities in places of high erosion, which matched local knowledge and expert opinion about where activities would have the greatest potential to improve water quality. In Lake Tahoe, the largest drainages and areas with volcanic geology are the main sources of erosion as identified in the model, Kuchnicki and Larsen (2014), and CRWQCB (2010). Additionally, two drainages in the Middle Truckee, Bronco Creek and Grey Creek, are known to erode large amounts of sediment due to steep slopes and volcanic geology and these areas were targeted by the model for activities to reduce sediment loads (CRWQCB, 2008). In the Middle Truckee, stakeholders recognize that the aquifer is important for groundwater recharge and the "Increased budget" scenarios showed targeted land protection in the recharge areas. The model targeted activities close to streams because of the short flow path the stream, as shown other modeling studies (McGraw et al., 2001).

Strategic investment of a larger budget would require considerable coordination among stakeholders. One lesson from our study has been that this level of coordination may be rare. There is very little coordinated planning across jurisdictional boundaries and subwatersheds in this study area. This highlights the importance of engaging stakeholders in these kinds of planning studies, so the information generated can help increase collaboration and identification of common objectives that may only be achieved through coordinated action. The study provided a starting point for future collaboration by engaging stakeholders to define common objectives and set priorities. Using the TMDLs as thresholds allowed stakeholders to realize what they could achieve in individual subwatersheds, that respected the current boundary of Lake Tahoe as a sink for sediment and nutrients. Iteratively running the models with stakeholder input has led to greater credibility, saliency, and legitimacy of the results, ultimately increasing the likelihood that results will be used in planning and management decisions (Ruckelshaus et al., 2015; White et al., 2010). Three stakeholders have indicated they will use the "Targeted" scenario results to help prioritize where to invest in activities that are already budgeted. One stakeholder in the Middle Truckee intends to shift some of their attention towards dirt road maintenance and search for additional investors in this effort.

There were also limitations of this study that should be addressed in future work or similar studies. We were not able to quantifying multiple benefits prioritized by stakeholders beyond the water quality factors included. This limits our ability to address more of the synergies and trade-offs among different objectives. We also did not include a seasonal water model or groundwater model that would have allowed us to quantify the improvement in groundwater recharge, flood risk, and dry season baseflow, for some of the stakeholders' top objectives. Finally, our climate change prioritization was limited by including only one ensemble; future work should include multiple climate change ensembles given the degree of uncertainty among models, particularly for predicted changes in precipitation. We also encountered challenges with model parameterization. Additional empirical studies in the Truckee River watershed on the impacts of conservation activities on water quality and quantity, along with more synthesis of parameter values for this type of modeling across the Sierra Nevada would improve modeling efforts, as recommended by Nelson et al. (2009) and Bagstad et al. (2013).

5. Conclusion

By comparing the water quality impacts of currently planned activities to increased and spatially targeted investments in the same activities, this study demonstrates the potential for significantly increasing the return on investment using models. Also, our study provides evidence for the benefits of allocating investments to the most cost-effective activities in targeted locations, as this can help minimize the additional investment needed to reach prioritized objectives, in this case sediment reduction in the Middle Truckee. Our results also illustrate the value of spatially explicit modeling for clarifying where objectives are unlikely to be met by implementing selected activities. For example, we revealed that reaching phosphorous reduction goals in the Lower Truckee are unlikely under any circumstances if only those activities already planned are implemented. Rather, meeting this particular objective will require other activities not currently considered that could have a greater impact on phosphorous. This study also demonstrates how, through thoughtful planning, specific water quality goals can be achieved while also enhancing other values, including biodiversity protection and wildfire risk reduction, which were included in our models to target where work should be prioritized.

We would not have been able to develop realistic scenarios without the input from stakeholders who provided the data for the "BAU" scenario, defined where activities could and could not occur, and identified their common objectives, which were used to rank the RIOS model. This level of stakeholder input is critical and often a missing element of studies intended to inform planning and implementation. By engaging stakeholders so thoroughly, we were not only able to complete a much more realistic set of models, but to also create information that has a much higher likelihood of getting used. The spatially explicit scenario maps are currently informing stakeholders about where to prioritize locations for land protection, forest/riparian/meadow restoration, and dirt road maintenance based on their potential to improve water quality and supply. Also, stakeholders are using the results to make management and planning decisions based on current budgets. Moving beyond metrics of acres protected or miles restored to the impacts of conservation investments on biophysical factors provides a more direct link to the final ecosystem services. One next step would be to develop an economic and financial analysis to value the change in biophysical factors and link them to the beneficiaries. Creation of a water fund or other payment for watershed services in the Truckee River watershed would require greater coordination among stakeholders throughout the watershed. This study provides the information needed to compare how different levels of investment, in different conservation activities across subwatershed scales, impacts water quality and annual water yield.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2016.12.015.

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