Tahoe Environmental Observatory Network

Design and Implementation Recommendations

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Executive Summary

Introduction

Lake Tahoe, a world-class natural resource merits a world-class environmental monitoring system. This report presents initial recommendations for the establishment of the Tahoe Environmental Observatory Network (TEON) to serve the basin for decades to come. An interdisciplinary team of scientists developed a basin-wide monitoring system to generate robust data source on the status and change of environmental quality and ecosystem resilience for the Lake Tahoe basin ecosystem. TEON builds on historical and extant research and monitoring efforts to provide a comprehensive source of information to managers, researchers, and the public on past and current conditions in the basin, and future changes.

Landscape scale changes to the forests surrounding Lake Tahoe will have a large impact on many drivers of forest health, watershed integrity, biodiversity, and ultimately lake condition. The location and magnitude of future changes to this system are uncertain, driving the need for an improved understanding of ecosystem health and vulnerabilities over time, and for a mechanism for early warning that can lead to timely response and help guide strategic investments in management treatments to improve conditions. The combination of these tasks, along with input from managers responsible for monitoring environmental quality in the basin (notably TRPA and LTBMU), will provide the framework for developing a robust monitoring system for the basin.

Managers have struggled to develop an effective and informative comprehensive monitoring system for upland ecosystem conditions. The most robust and consistent monitoring programs in the basin have pertained to Lake Tahoe clarity, stream sediment delivery, some threatened and endangered species, air quality, and forest inventory (as per the US Forest Service national FIA program). Basin-wide ecosystem conditions that are mandated for attention by managers, but a lack of consistent, coordinated investment generally falls into one of the following categories: forest health, fire risk and threat, biodiversity, carbon, climate vulnerability/adaptation, habitat connectivity, aquatic invasive species, and drought vulnerability.

Goals and Objectives

The primary goal of TEON is to provide a comprehensive and informative source of information on the status and change in ecosystems across the basin. A secondary goal is to provide an early warning system for ecosystem conditions in the basin and a safety net for forest ecosystems, upland aquatic ecosystems, biodiversity, as well as for Lake Tahoe. TEON is envisioned to be spatially and topically broad and inclusive, to address various information needs to address multiple agency missions and mandates. Another objective of TEON is to support the monitoring objectives and information needs of local agencies to the degree possible.

Finally, TEON design recommendations are intended to leverage the many research and monitoring investments that have occurred in the basin over the past several decades and provide a rich source of data that new and ongoing monitoring efforts can build upon. Historical data provide a baseline of comparison for understanding the direction, magnitude and location of current and future change, as well as clues as to why conditions are changing. Historical data can help scientists and managers anticipate future locations and magnitudes of change that may occur over the next several decades.

TEON is designed to accomplish these outcomes through a combination of broad-scale and focused sampling design and data collection. Basin-wide monitoring is intended to provide a foundational understanding of the status and change of key metrics of ecosystem conditions at the landscape-level. Sentinel watersheds are intended to provide a more in-depth understanding of the magnitude, drivers, and consequences of change and the process-based linkages among connected and interdependent resources within and across watersheds.

Basin-wide Monitoring

Near-term objectives for basin-wide monitoring are to establish a current-day snapshot of conditions across a wide array of ecological features that also can be used as a point of comparison to evaluate change from past to present and present to future. Longer-term objectives for basin-wide monitoring are to identify spatially explicit and resource-specific patterns of change that can be used to improve understanding of the drivers, consequences, and mitigation strategies of change.

In general terms, basin-wide monitoring would be based on a combination of remotely sensed data and field-based data. Remotely sensed data are most commonly available across all lands, so 100% coverage across the basin and typically at 30-m resolution reflecting the resolution of most (freely available) satellite imagery. Sampling designs are required when monitoring is based on a sample of sites (as opposed to all sites), and the design parameters then determine which sites are selected for sampling. Most broadscale monitoring efforts use a combination of remotely sensed and field-based data sources, and so the grid cells may also become a scale at which these two different sources of data are both represented or summarized.

A broad-scale, omnibus, and efficient monitoring design needs to have a core set of sample sites that can be subset for analysis and augmented to address specific resource conditions, enabling scientists and managers to characterize different resources at different scales and levels of precision, and adjust to changing needs over time. A robust survey design has the following properties: probability-based, spatially representative, balanced and simple, and flexible to accommodate potential changes in the future (Theobald et al. 2007). Square and hexagonal grids are most commonly used to generate the systematic sample grid. Ideally, whatever grid type is used, it is scalable to meet the sampling intensity needs of different resources.

Basin-wide Core Metrics

Forest/Shrubland Resilience - Pertains to terrestrial ecotypes. Forests and shrubland ecosystems are parsed into three elements: structure, composition, and disturbance. Ideally, monitoring measurements and reporting pertain to one or more metrics in each subdomain and across the three elements. Approximately 30 core metrics are recommended, consisting of a mix of field-based and remotely sensed data sources. Remotely sensed metrics are not dependent upon LiDAR, given its expense and infrequent availability. Rather, remotely sensed metrics are based on publicly available data that are refreshed annually. If LiDAR or other complementary remotely sensed data become available, they can be used to augment or validate primary data sources.

Fire Dynamics - The Fire Dynamics Pillar has two elements: severity and functional fire. Ideally, monitoring measurements and reporting pertain to one or more metrics in each subdomain and across both Elements. The metrics recommended reflect a combination of basic fire ecology and metrics identified as important to managers in the basin (see Lake Tahoe West draft monitoring plan, 2022). They include descriptions of fires that have occurred, fire histories, and estimated probabilities of fire intensity based on current forest conditions (i.e., fuel characteristics). Metric values can be derived using a combination of field-based data collection, remote-sensing, and modeling.

Carbon Sequestration - Carbon storage in natural and working landscapes is recognized as a vital contribution to meeting carbon sequestration and carbon neutrality goals at a range of scales from regional to national. Forests and meadows play an outsized role in sequestering and storing carbon in a manner that provides multiple additional ecosystem services. Eight core metrics were identified for carbon monitoring, focused on total carbon, live tree carbon, and meadow carbon (Table 3-8). Most of them can be readily estimated from satellite imagery when combined with modeling, and plot-based imputations are also able to estimate carbon, but provide some of the least accurate measures of carbon. LiDAR-based measures, when available. are particularly valuable for providing measures of biomass that can be converted to carbon.

Biodiversity Conservation - Understanding how plant and animal populations and communities have changed over time is a critical part of managing this system for resilience to climate change and other stressors. The Biodiversity Conservation Pillar includes both terrestrial and aquatic ecosystems. Current and future characteristics of populations and communities within the basin are not predictable based on broad vegetation associations and wetland ecosystem types, so "coarse filter" conservation and monitoring approaches alone based on major ecotypes will not provide a credible representation and conservation approach for biodiversity, particularly with changing climate. Field data on species occurrence will be needed to effectively monitor and conserve biodiversity in the basin. Twelve focal species were identified as core, with an additional eight metrics to describe species diversity and community integrity.

Wetland Integrity - Wetlands consist of meadows, marshes, streams, lakes, ponds, and riparian ecosystems distributed across the basin. Wetlands of the Tahoe basin are one of the most threatened habitats, and these habitats provide ecosystem services that are directly tied to Environmental Improvement Program goals. The fate of aquatic ecosystems in the basin have direct effects on Lake Tahoe. Approximately 15-20 metrics of wetland integrity metrics were identified as recommended, covering a combination of fundamental wetland ecology and metrics of specific interest to managers in the basin. Remotely sensed data will provide a wide range of valuable data for describing and tracking wetland conditions, but field data will also be needed for at least a subset of metrics.

Water Security - Water security encompasses all aspects of water as an available resource for ecosystems, including plants, animals, and people. Water security includes quality, quantity, form, and availability. We identified eight recommended core metrics of water security that can be derived from a combination of remotely sensed and field-based data, with a strong additional emphasis on snow, soil moisture, and water discharge rates and timing.

Air Quality - Air quality encompasses particulates, gases, and impacts on visual quality. Although health impacts are a substantial focus of air quality standards and monitoring, they are not included here as metrics. The five recommended core metrics are intended as a starting point for discussions about how best to represent these air quality conditions in a manner that is most aligned with regulatory requirements and target conditions.

Fire-adapted Communities - The fire-adapted community pillar includes the degree to which communities are at risk of wildfire and their preparedness (physically and organizationally). The five recommended core metrics address the threat of wildfire to communities as a function of risk of fire, and focus on both the WUI and non-WUI areas.

Sentinel Watershed Monitoring

Lake Tahoe's water quality in both the nearshore and the center of the lake is partly controlled by the contributing watersheds that compose the Lake Tahoe Basin, yet the linkages between the uplands and the lake through the streams are poorly understood. TEON identifies and establishes watersheds for monitoring terrestrial and upland aquatic processes to better understand controls over inputs to Lake Tahoe. Near-term objectives for sentinel watershed monitoring are to establish prototype systems for the collection of terrestrial and aquatic data and identify optimal mechanisms to make that data publicly available real-time or near real-time. Longer-term objectives are to establish a suite of sentinel watersheds (provisionally 6 to 8) around the basin to provide a more robust source of information about watershed dynamics and their consequences for Lake Tahoe.

Sentinel watershed monitoring is intended to accomplish the following monitoring objectives: 1) trace the influences of water from snow and rain in the Lake Tahoe headwaters through soil, trees and rivers; 2) understand how rain and snow interact with soils to generate solutes, which are then transported to streams, undergo biogeochemical cycling and are eventually transported to Lake Tahoe; and 3) assess climatic conditions under the forest canopy, from headwaters to lakeshore.

The most valuable watersheds for sentinel watersheds are the seven that have USGS gauges and existing flow records (starting in the north and going clockwise around the basin): Third, Incline, Glenbrook, Trout, Upper Truckee, General, Blackwood, and Ward. Blackwood Creek and Glenbrook Creek were selected as the initial sentinel watersheds for TEON. The addition of the Upper Truckee watershed as a third sentinel watershed would have been a strong addition (the most differentiation from the other watersheds and greatest projected changes in future climates). However, due to logistical and financial constraints, Incline was selected as the third sentinel watershed, given that it is easy to access and in close proximity to the UNR campus so it serves an important secondary role as a demonstration site. Increasing the number of sentinel watersheds would strengthen the watershed monitoring dataset and confidence in observed relationships and trends.

Ten core metrics were identified as baseline data for sentinel watershed monitoring as initial investments in meeting the objectives of sentinel watershed monitoring. They address hydrodynamics directly (climate, precipitation, snow dynamics, water flow, nutrient loading, and oxygen) at various locations across the watershed (headwaters to mouth), and their relationship with biological response metrics (forest structure, plants and animals, carbon, fire).

Implementation Guideposts

The nuts and bolts of implementation cover an array of parameters and considerations that are touched on here: 1) spatial and temporal pattern of field data collection; 2) what entities are responsible for collecting which data sets and how are multiple entities being coordinated; and 3) data curation (quality control, integrity management, access).

Sustainability and Consistency

Sustainability and consistency are achieved through a balance of 1) identifying a set of core metrics (Tier 1) that provide a robust representation of pillar conditions; and 2) establishing a level of investment (institutions and funding) that is sustainable for at least the first 10 years. Monitoring does not need to be limited to the core set, rather additional data collection efforts can be modularized (Tier 2) so they build on the core set of data, but be funded and implemented individually, perhaps by a single agency, possibly funded by a non-government institution that has a particular interest in monitoring (e.g., Bear Aware for bear monitoring), and potentially less frequently or for shorter periods of time.

Sentinel watershed monitoring has a unique set of implementation considerations. The greatest value of sentinel watersheds is to have time series data for detailed measurements of multiple processes operating across the watershed. Generally, the investment in establishing a sentinel watershed has the greatest return on investment if data are collected for 10 or more consecutive years. The life of the equipment varies, but it is likely that technological advancement and the wear-and-tear of use would lead to replacing most equipment after 10-years.

Temporal Considerations

In terms of data considerations, generally the more frequent and comprehensive the resampling, the more sensitive the monitoring network will be to detecting change. The challenge is how best to allocate sample effort for field based metrics between more sites (better condition representation) and more frequent resampling (better change representation). Given the desirable balance of rigor and cost, panel designs tend to provide the best outcome of reducing error rates per unit of sampling effort. In short, a panel approach is a blend of the two approaches described above: an annual sample effort is established for a subset of sites, and the remaining sample effort alternates across different sites in different years – usually over a 5- to 10-year rotation period.

Sample Size Considerations

A tiered approach is recommended for building broad-scale monitoring sample size. The first step in this evaluation process would be to identify the ecotypes or components against which representation will be judged. Then strength of the representation of those components can be evaluated with each increment of additional samples.

Citizen Science for TEON

In addition to field-based and remotely sensed data collection to characterize species occurrence and habitat conditions, citizen science contributions can make a valuable contribution to systematically collected data. Ad hoc positive sighting data, such as those produced by iNaturalist or from other crowd-sourced photo collections can serve to provide data points for species or locations that are surprising and possibly early detections of change. Periodic events, such as Tahoe's Snapshot Day a bioblitz, Christmas bird counts or City Challenge, can serve to provide a more spatially comprehensive set of positive sightings to represent a point in time more comprehensively than the monitoring network. These types of citizen science contributions are particularly well-suited to the Lake Tahoe Basin because of the exceptionally high visitation it receives from nearby population centers, exponentially increasing the pool of potential contributors to any citizen science data stream.

Adaptive Management

Incorporating adaptive management into monitoring and project planning is especially important in the context of climate change. Adaptive management allows managers to account for the uncertainty that is inherent in climate change projections.

Planning for uncertainty and adaptively managing allows managers to modify interventions based on updated scientific findings and climate projections, new management techniques, or technological advances. Explicitly scheduling evaluation and feedback timing and mechanisms will be important to the success of the network. Reporting and responding on a 5-year cycle strikes a good balance between the potential for change and the additional investment needed for data analysis and synthesis.

Data Processing, Storage and Access

Data management is critically important to the success of monitoring systems. Each set of core metrics and associated methods of data collection have a unique set of considerations in terms of data management. TRPA and UNR have substantial capacity and mission alignment to collaborate and support initial TEON implementation. Growth of the network can be managed, in part, by ensuring that adequate funding is requested and secured for data management, analysis, and reporting.

Lake Tahoe Basin Environmental Atlas

Many large landscapes find that portraying information in the form of an atlas based on intermediate sized units is a very effective and relatable way to portray conditions and report status and change. Using a size that conforms with much of the source data (30-m satellite imagery), argues for 900x900-m units as a good scale to use as the base (can always scale up or down), equating to ~1600 units across the basin. In order to populate the LTBE Atlas, data on each metric needs to be converted to a value that can be attributed to each unit, based on the conditions across the unit. The use of a fixed reporting unit as the foundation of the Atlas will result in all metrics being converted to compatible scales, which in turn generates a powerful data tool enabling the comparison of values across metrics within a unit and over time within and among units at a scale that is relatable. The spatial covariance of metric conditions relative to one another can be evaluated at a point in time and over time within and across units, which has substantial value:

- Enables agencies to speak to any combination of metrics that are relevant to their programs and projects,
- Enables scientists to study how and why metrics are changing over time and relative to one another, providing valuable clues about drivers of change and potential tipping points,
- Enables the public to adopt and/or track their favorite Atlas unit, and could even be the focus of contests for documenting biodiversity (e.g., biodiversity challenges) and/or restoration.

Summary of Recommendations

Basin-wide Monitoring

TEON Steering Group - Science and management oversight and support will be needed for TEON to be successfully implemented and sustained for a decade. A TEON steering group could serve this purpose, where the group would identify priority investments, funding opportunities, reporting review, and adaptive management processes.

Basin-wide monitoring - Identify desired minimum sample sizes, determine the degree to which existing or historical sample sites provide a representative sample for the basin, and adjust the sample as needed (drop and/or add sites to achieve a balanced sample).

Wetland Integrity – Form a technical working group to solidify core sample sites and metrics.

Lake Tahoe Environmental Atlas - Explore the potential value, utility, and structure of an environmental atlas for the Lake Tahoe basin

Biodiversity Conservation - Form a technical group to finalize core metrics for biodiversity and associated monitoring to sufficiently represent the suite of metrics, including consideration for historical and current monitoring activities.

Air Quality – Form a technical working group to solidify core sample sites and metrics.

Water security -Form a technical group to evaluate the current snow monitoring system and derive a recommended base monitoring system for snow monitoring as part of the TEON system.

Remotely sensed data - Leverage existing open-source remotely sensed data sources (LANDFIRE, CECS) and their derivatives (TreeMap) to provide the foundation of landscape-wide vegetation change metrics to the degree possible. Consider investing in LiDAR-imputed product from Planet Lab (Salo product line) directly or in partnership with institutions operating at larger scales (TCSI, Sierra Nevada). Consider investing in LiDAR and hyperspectral data on a periodic and regular basis (5 years, ideally) to serve as calibration for modeled products and to provide a periodic map product that can represent change in some metrics with high accuracy and precision.

Sample allocation across space and time - Establish a panel design for field data collection. Metrics, methods, and metric-specific sample sizes need to be drafted before an assessment of annual sample effort could be determined, sites selected, and then panel allocations made. An annual resample panel of at least 30 sites is suggested to bolster confidence in estimates of annual change.

Environmental stratification - To the degree possible, do not pre-stratify, but rather set systematic sampling criteria (number of sample sites per hexagon) to build sample sizes to represent major ecotypes of interest, and then augment that sample with additional targeted sample locations.

Sentinel Watershed Monitoring

Gauging stations - We recommend building upon the existing UGS gauging of streamflow to also include chemistry data that allow for understanding aquatic ecosystem health and nutrient loading to the lake.

Climate sensors - We recommend upland sampling of climatological data – particularly high-quality precipitation measurements – that builds upon and infills gaps in existing networks. A network of in-situ soil moisture and tree-stress measurements provides data streams that otherwise do not exist, and thus is particularly valuable for direct insights, and for locally ground-truthing remote-sensing data.

Intensified sampling - We recommend increasing the intensity of sampling for a subset of features to enhance our understanding of upland-aquatic linkages (wetlands and meadows) and to evaluate climate impacts by intensively sampling along elevational gradients (forest and biodiversity metrics).

Chapter 1: Why Here, Why Now

1.1 Introduction

The Lake Tahoe basin is a world-class natural phenomenon which supports an important regional economy. The watershed and remarkably clear lake are vulnerable to many threats, the most pressing of which is climate change. Understanding how the basin has changed, and continues to change, is critical for setting thresholds for action that link to desired conditions. Our ability to rapidly detect the effects of climate change is limited by the complexity of the ecosystems within the watershed (e.g., meadows, riparian, upland forests, streams, lakes, and wetlands), and the local variability in climate by aspect and elevation.

These ecosystems lack a systematic monitoring program to identify and mitigate the effects of climate change. Aquatic and terrestrial habitats are linked by the exchange of subsidies that may affect primary productivity, food webs and water quality, however, the impacts of climate change on these linkages remain largely unknown. The interconnected nature of upland terrestrial and aquatic systems requires an environmental tracking system to simultaneously assess and provide vital information on related and potential causal factors operating across environmental gradients (e.g., temperature, precipitation, snowpack) and disturbance gradients (e.g., fire, urbanization, bark beetles). Further, aquatic and terrestrial habitats are linked by the exchange of subsidies that may affect primary productivity, food webs and water quality, however, the impacts of climate change on these linkages in the basin remain largely unknown.

We believe that a world-class resource merits a world-class environmental monitoring system. We investigated options for a robust basin-wide monitoring system to provide a scientifically reliable source of information on the status and change of environmental quality and ecosystem resilience, building on historical and extant research and monitoring efforts. This report presents our initial recommendations for the design to establish TEON on behalf of the basin and the resilience of the socio-ecological system that it supports.

1.2 The Lake Tahoe Basin

The Lake Tahoe basin is located in California and Nevada (Figure 1-1). The 880 km^2 (88,000 ha; 220,000 ac) Lake Tahoe basin, once considered for designation as a National

Park, contains the largest alpine lake in North America and is bounded by the crest of the Carson Range on the east and the Sierra crest on the west. The majority of the basin, approximately 80% of the land area, is National Forest System lands under the Lake Tahoe Basin Management Unit (LTBMU). The basin encompasses an elevational range from 6229ft to 10881ft, and it supports a diversity of forest, meadow and wetland ecosystems. The Lake Tahoe basin is located on the east-west boundary of 2 major biogeographic provinces (the Sierra and the Great Basin; Udvardy 1975), and in the vicinity of the north-south juncture of 4 smaller-scale bioregions (Mono-Inyo to the southeast, South Sierra to the southwest, North Sierra to the northwest, and Modoc Plateau to the north; Welsh 1994). The location of Lake Tahoe basin at this confluence of zoogeographic zones results in a diversity of environmental conditions and a unique array of flora and fauna around the basin, as well as some distinct distributions of biota around the basin.

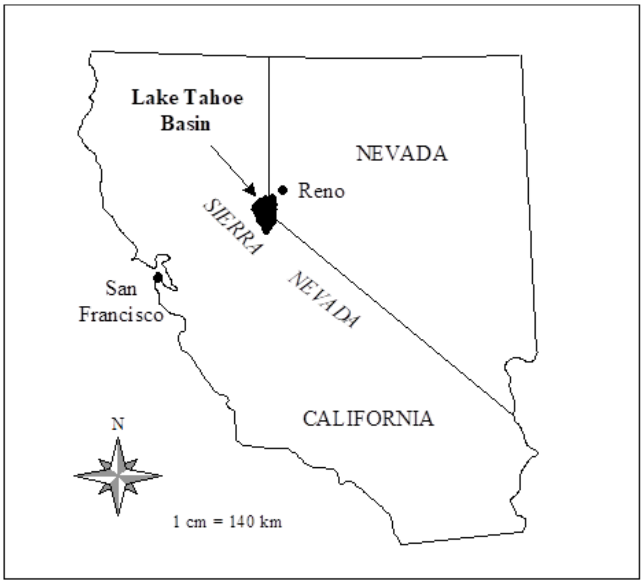


Figure 1-1. Location of the Lake Tahoe basin monitoring area.

1.3 Why a Monitoring Network for the Lake Tahoe Basin

Landscape scale changes to the forests surrounding Lake Tahoe will have a large impact on many drivers of forest health, watershed hydrology, biodiversity, and ultimately lake condition. Examples include forest structure and composition, fire frequency and intensity, hydrologic alterations (e.g., roads, diversions), meadow condition, biodiversity, stream channel conditions, and of course temperature and precipitation. Individually or combined, these upland conditions and drivers affect watershed hydrologic function, and as such the amount, timing, amount and quality of water delivered to Lake Tahoe.

Although the effects of upland disturbances on water quality and impacts to Lake Tahoe have been a focus of research for many years in the Lake Tahoe basin, forests are in crisis as a result of changing climates, prolonged and severe drought, and the threat of high severity fire. These important changes are pushing ecological systems into new configurations, and management responses are also taking on new dimensions (pace, scale, and intensity) for which existing models are ill-equipped to estimate forest ecosystem responses and effectively inform management.

Typically, environmental models are informed and improved incrementally, by studying some small portion of a larger process in isolation and then using those quantified relationships to inform one part of a larger model. However, we do not have the luxury of addressing all aspects of ecosystem processes in a piecemeal fashion. This project is intended to design a monitoring system that will improve our understanding of ecosystem change while also developing our understanding of the processes drive observed patterns using new and increasingly resolved information.

The location and magnitude of future system changes are uncertain, and early warning and response are critical management tools that will guide strategic investments in management treatments to improve future conditions. The combination of these tasks, along with input from managers responsible for monitoring environmental quality in the basin (notably TRPA and LTBMU), will provide the framework for developing a robust monitoring system for the basin.

1.4 Goal and Objectives of a Monitoring Network

The goal of TEON is to provide a comprehensive and informative sources of information on the status and change in ecosystems across the basin, and to serve as an early warning system for ecosystem conditions in the basin as both a safety net for forest ecosystems, upland aquatic ecosystems, and biodiversity, as well as for Lake Tahoe. The focus of the development work to date has been on ecological pillars of the basin's ecosystems, but the breadth of the 10 pillars of the TPOR Framework (Manley et al. 2023) makes it more readily expanded to encompass social, cultural, and economic aspects of the basin's ecosystems over time.

The Lake Tahoe West landscape restoration strategy was recently completed in 2021, and at the time of its development, it was considered a template for how restoration strategies could be expanded to the entire basin. The goals of the strategy are provided in the Box 1-1 below, and they provide a broad but fairly comprehensive set of desired outcomes that helped inform the metrics that would be most informative to agencies in the basin and how metrics would be evaluated to address questions of progress and management effectiveness.

Box 1-1 Lake Tahoe West landscape restoration strategy goals.

Landscape Restoration Strategy Goals

1. Forests recover from fire, drought, and insect outbreaks.
2. Fires burn at primarily low to moderate severities and provide ecological benefits.
3. Terrestrial and aquatic ecosystems support native species.
4. Healthy creeks and floodplains provide clean water, complex habitat, and buffering from floods and droughts.
5. People live safely with fire and enjoy and steward the landscape.
6. Restoration is efficient, collaborative, and supports a strong economy.

Objectives for TEON are four-parted: basin-wide and sentinel watersheds, near-term and long-term. Basin-wide monitoring is intended to provide a foundational understanding of the status and change of key metrics of ecosystem conditions at the landscape-level. Near-term objectives for basin-wide monitoring are to establish a current-day snapshot of conditions across a wide array of ecological features that also can be used as a point of comparison to evaluate change – past to present and present to future. Longer-term objectives for basin-wide monitoring are to identify spatially explicit and resource-specific patterns of change that can be used to improve understanding of the drivers, consequences, and mitigation strategies of change. This may inform how policy and management can make a positive contribution to conservation and sustainability for individual resources, ecosystems, and the basin's socio-ecological system as a whole.

Sentinel watersheds are intended to provide a more in-depth understanding of the magnitude, drivers, and consequences of change and the process-based linkages among connected and interdependent resources within and across watersheds. Near-term objectives are to establish prototype systems for the collection of terrestrial and aquatic data and identify optimal mechanisms to make that data publicly available in real-time or near real-time (some data types necessarily require initial quality control and assurance routines). Longer-term objectives are to establish a suite of sentinel watersheds (provisionally 6 to 8) around the basin to provide a more robust source of information about watershed dynamics and their consequences for Lake Tahoe.

1.5 Existing Monitoring Plans and Systems

Monitoring has been a strong emphasis for agencies in the basin for many decades, particularly over the past 40 years since the adoption of threshold standards by the Tahoe Regional Planning Agency (TRPA) and implementation of the National Forest Management Act, both of which identify environmental monitoring as a key management tool toward achieving stated environmental objectives. TRPA and the LTBMU rely on the network of agencies across the basin and their diversity of missions to collectively accomplish desired monitoring activities.

Lake Tahoe Info was built and supported by TRPA, and it tracks monitoring programs throughout the Tahoe Region. Featured programs have detailed monitoring data, maps, and photos available in the system. It directly reports on vegetation conditions, water quality, air quality, noise, and transportation. Other monitoring programs are tracked with useful information such as partnering agencies, related indicators, and documents.

Based on the summary compiled by TRPA, there are approximately 70 monitoring programs that are or were active within the past 10 years (Appendix A). In addition to the primary topics featured in Lake Tahoe Info, plant, fish and wildlife monitoring programs and efforts have had variable consistency over the past 20-30 years. In many cases, sample locations or entire programs have been suspended due to lack of funding. These efforts are carried out across multiple agencies as part of their individual monitoring programs. As a result, it is difficult to make inferences across resources, given differences in sampling design, methods, timing, and effort. Historically and to the present day, monitoring is heralded as critically important to effective and adaptive management, but other than a few high priority resources (such as some aspects of Lake Tahoe), comprehensive monitoring plans are rarely funded.

1.6 Important Gaps in Monitoring

As is the case both inside and outside the basin, monitoring investments tend to fall into one of two categories: 1) narrowly focused, resource specific monitoring to address short-term concerns or comply with requirements (e.g., TMDL, California spotted owl), or 2) broadly focused across large areas and/or based primarily on remotely sensed data as a means of reducing the cost of monitoring (e.g. US Forest Service Region 5 broader-scale monitoring program). Multiple, narrowly focused monitoring efforts make it challenging, if not impossible, to evaluate change across multiple resources and gain insights about ecosystem-level responses. In addition, lack of funding often results in periodic, sporadic, or short-duration efforts. Alternatively, remotely sensed data are relatively inexpensive to generate consistently over time from publicly available data, but often they are inadequate in detail, accuracy and precision and/or resolution for many important metrics, making it challenging to make inferences about spatially explicit change at small scales.

For all the reasons mentioned above, managers have struggled to develop an effective and informative comprehensive monitoring system for upland ecosystem conditions. The most robust and consistent monitoring programs in the basin have pertained to Lake Tahoe clarity, stream sediment delivery, some threatened and endangered species, air quality, and forest inventory (as per the US Forest Service national FIA program). New monitoring plans (e.g., Lake Tahoe West) are generally limited to existing data collection efforts, with the potential to be augmented by periodic investments in data updates (e.g., new lidar flights).

Basin-wide ecosystem conditions that are of high value to managers and for which existing monitoring efforts fall short of meeting agency needs generally fall into one of the following categories: forest health, fire risk and threat, biodiversity, carbon, climate vulnerability/adaptation, habitat connectivity, aquatic invasive species, and drought vulnerability. All of these features change over time as a function of management, natural disturbances, and changes in climate, and no single existing system of data collection can provide a spatially comprehensive and temporally cohesive source of data sufficient enough to inform management with confidence. Information needs and demands are also growing as new threshold standards are developed, as forest and meadow restoration and fire risk reduction investments look for accountability and effectiveness, and as climate impacts are being observed and even greater are projected in the next few decades.

1.7 A Monitoring Network that Serves the Basin

Close coordination with LTBMU and TRPA is a priority for this project toward the ability of TEON to inform and recast threshold standards, as well as basin-wide restoration efforts in support of the 10-year fire strategy and toward Caldor fire restoration efforts. As such, TEON is envisioned to be spatially and topically broad and inclusive, so as to maximize the ability to partition the resulting monitoring data as needed by managers to address various combinations of metrics to address agency mandates (Figure 1-2). TEON is not expected or designed to meet specific agency monitoring information needs, rather its design makes the data readily applicable to a variety of resource niches, interpretations, spatial scales, and temporal windows.

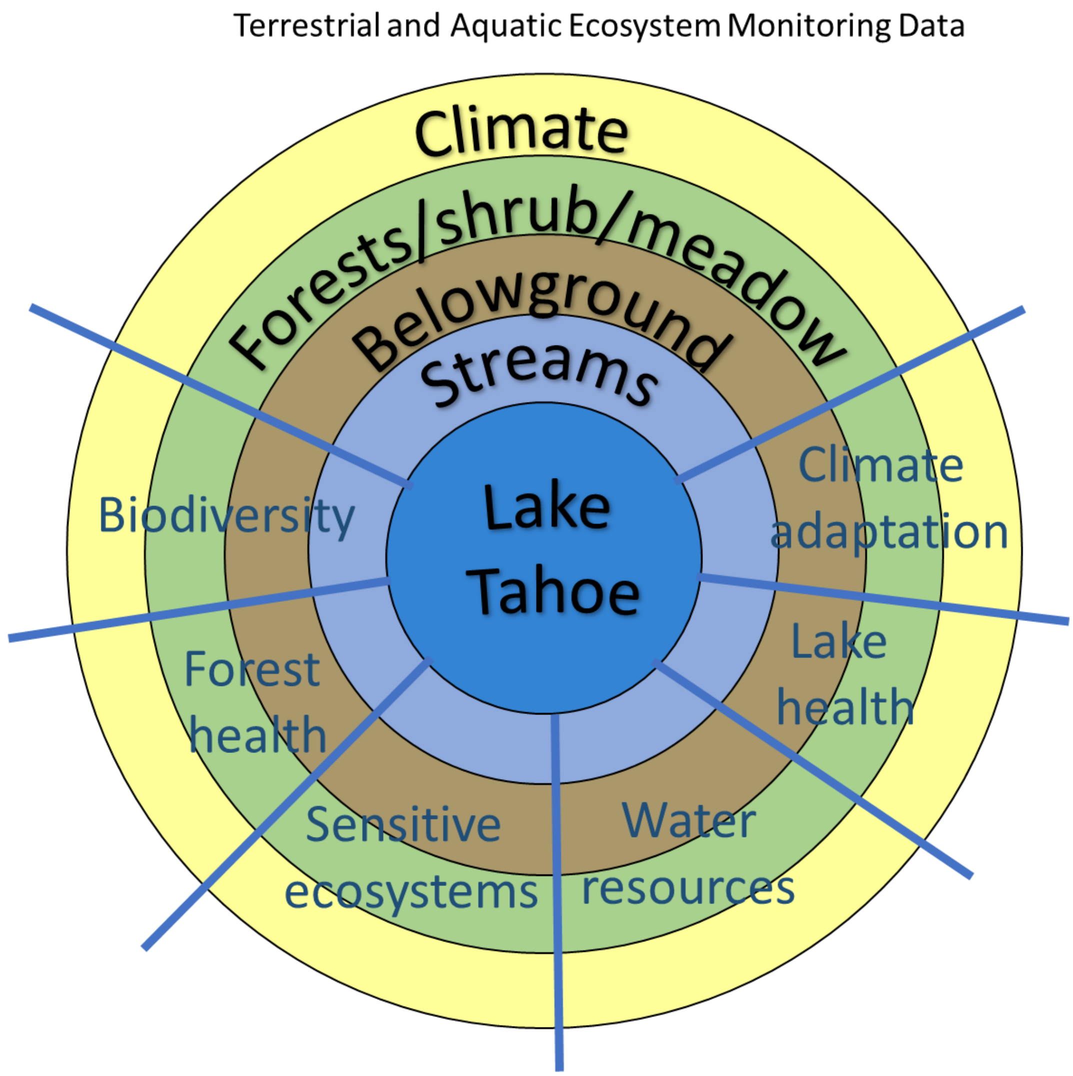


Figure 1-2. Ecosystem components (domains) are represented as the nested circles of the socioecological system of the Lake Tahoe basin, which can be cross-referenced to meet agency mandates, such as the categories of the Environmental Improvement Plan shown as pieces of the ecosystem pie.

Chapter 2: TEON Foundations

2.1 Framework for Socio-ecological Resilience

Translating the concept of resilience into concrete outcomes is necessary to guide and support tangible landscape management strategies. We used the Ten Pillars of Resilience (TPOR) Framework (Manley et al. 2023) to set goals and monitoring metrics to reach greater socio-ecological resilience (Figure 2-1). Socio-ecological resilience recognizes that humans and nature are inextricably connected, and humans play an increasingly central and active role in determining the future of ecosystem stability, function, and services. The TPSER Framework is hierarchical and consists of three levels: 1) Ten Pillars, which represent the primary constituents of resilient socio-ecological systems across forested landscapes (Figure 2-1); 2) Elements, which reflect the core features of each Pillar; and 3) Metrics, which represent the characteristics of each Element that directly or indirectly have bearing on resilient outcomes. We use the pillars as an organizational framework for TEON, in that the metrics to monitor are grouped by each of eight pillars (Figure 2-2). The metrics can be evaluated individually, by pillar, or in any other combination that addresses scientific or management questions.

2.2 Paired Basin-wide and Sentinel Watershed Monitoring

Patterned after other large-scale monitoring systems (e.g., NEON), TEON combines broad-scale data collection to reflect landscape patterns and processes with more in-depth data collection in strategic locations to reflect fine-scale processes and relationships. These two scales of data are highly complementary in providing information about status and trend across a breadth of resource conditions. Multiscale data also generate rigorous information on the likely drivers of change, and enhance our understanding of effective management activities in the near and long term.

Basin-wide Monitoring

Basin-wide monitoring is intended to provide a foundational understanding of the status and change of key metrics of ecosystem conditions. The location of sample sites is designed to provide an unbiased representation of conditions across the basin over time. This type of retrospective monitoring (i.e., looking backward in time, also known as surveillance monitoring) may not provide definitive information on the causal factors for observed changes, but can provide valuable evidence for the potential drivers of change.

Basin-wide monitoring will also facilitate comparisons of current to past conditions to enhance our understanding of how climate and other factors are likely to affect various environmental metrics. Comparisons of past to present conditions can identify or verify vulnerabilities, early changes of concern, and potential climate refugia. Over the longer term, broadscale monitoring will improve our understanding of the drivers and consequences of change before a critical tipping point is reached. This will inform how policy and management can make a positive contribution to conservation and sustainability for individual resources and the basin's socio-ecological system as a whole.

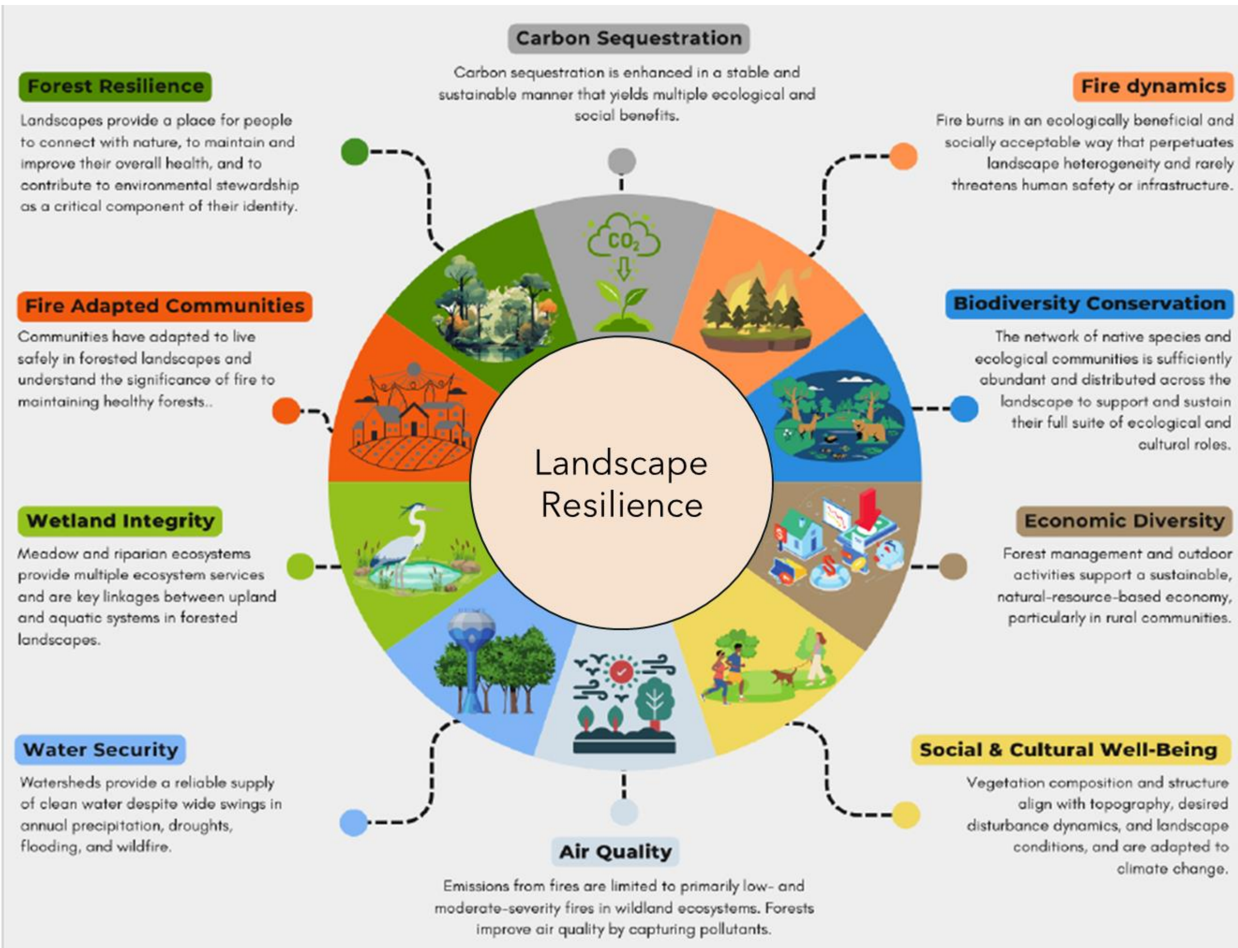


Figure 2-1. TPOR Framework for socio-ecological resilience, consisting of ten pillars (domains) and a description of their resilient outcomes (Manley et al. 2023).

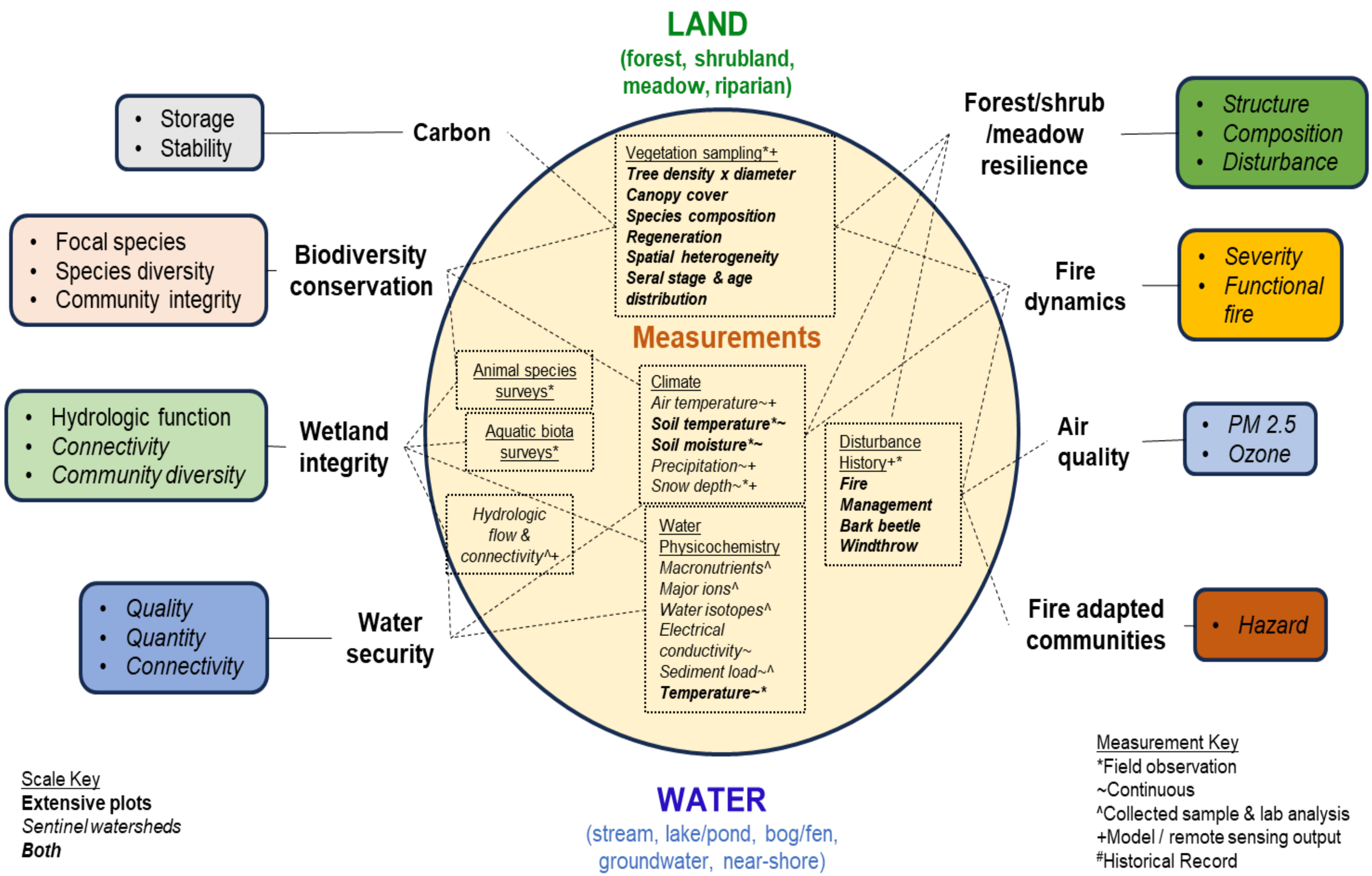


Figure 2-2. Conceptual model of the integrated nature of the TEON design, informing eight of the ten Pillars of socio-ecological resilience.

Sentinel Watershed Monitoring

The basin-wide monitoring network can help form hypotheses about causal factors driving observed changes. Monitoring that is focused on key cause-and-effect relationships in areas of expected change complements broad-scale surveillance monitoring by providing this finer-scale context. Sentinel watersheds are designed to provide a more in-depth understanding of directions, drivers, and consequences of change and the process-based linkages among resources within and across watersheds. Lake Tahoe's water quality in both the nearshore and the center of the lake is partly controlled by the contributions of watersheds that compose the Lake Tahoe Basin, yet the linkages between them are poorly understood. Sentinel watersheds serve to monitor terrestrial and upland aquatic processes in greater detail to elucidate these land-water-climate linkages and their implications for basin-wide dynamics and resilience.

The purpose of sentinel watersheds is to create a system where data collected within sentinel watersheds complements the basin-wide monitoring network, and to make additional, targeted investments in equipment and infrastructure to make the data available to the public in near real-time to expedite science, planning, and outreach.

2.3 Value of Building on Historical Investments and Data

The many research and monitoring investments that have occurred in the basin over the past several decades provide a rich source of data that new and ongoing monitoring efforts can build upon. Historical data provide a baseline of comparison for understanding the direction, magnitude and location of current and future change, as well as clues as to why conditions are changing. Historical data can help scientists and managers anticipate future locations and magnitudes of change that may occur over the next several decades.

Table 2-1 is a summary of historical data sets with the most spatially comprehensive and temporally relevant data available for informing monitoring design parameters and likely sources of consistent monitoring data in the future. (see Appendix A for a more comprehensive list)

Table 2-1. Sources of basin-wide recent historical condition data (past 20-30 years).

Pillar/metric	Data source	Data keeper
Forest resilience	Forest Inventory and Analysis	US Forest Service Pacific Northwest Research Station
	FIA densification	US Forest Service Region 5
	Multiple Species Inventory and Monitoring	US Forest Service Lake Tahoe Basin Management Unit (LTBMU)
	Common stand exams	US Forest Service LTBMU, CA State Parks, NV Division of State Lands
Fire dynamics	RAVG	
	MTBS	
Carbon	See forest data	
Biodiversity	California spotted owl	LTBMU
	Bald eagle and osprey	Tahoe Regional Planning Agency
	Multiple Species Inventory and Monitoring	LTBMU
	Fish species in streams	LTBMU
	Fish stocking	CA Department of Fish and Wildlife
	GLORIA high elevation plant community	CA Natural Resources Agency
	Invasive species	LTBMU
Air quality	Air quality sensors	CA Air Resources Board
Water security	Stream gauges	US Geological Survey
	TMDL monitoring	UC Davis
Wetland integrity	Stream condition surveys	LTBMU
	Meadow surveys	LTMBU and Region 5
	Lake and pond surveys	LTBMU
	Multiple Species Inventory and Monitoring	LTBMU
	SEZ viewer	Tahoe Regional Planning Agency

2.4 The Role of Field Testing

A substantial investment in testing equipment and methods in the field was made by the investigators developing the TEON network. The results of these investments are provided in detail in Appendices B, C, D, E, F and H. Field testing objectives differed between the basin-wide design and the sentinel watershed design. The basin-wide monitoring team used field testing to resample historical sites across the basin to derive some measures of what, where, and how much conditions changed. This work focused on forests and lakes, and resampled vegetation, birds, and amphibians and aquatic reptiles (aquatic only) at 30 terrestrial and 30 aquatic sites.

The sentinel watershed monitoring team used field testing to establish and evaluate the efficacy of a suite of measuring instruments to gather and transmit novel and standard data on fine-scale hydrologic dynamics and forest condition. The primary objective of sentinel watershed work accomplished to date was to establish prototype systems for the collection of terrestrial and aquatic data and identify optimal mechanisms to make that data publicly available in real-time or near real-time (some data types necessarily require initial quality control and assurance routines). Different sensor and data collection systems are being tested and evaluated. Simultaneously, various routes to efficiently transfer data from collection sites to publicly accessible cloud storage are underway. The results of this work are provided in detail in Appendix G.

Chapter 3: Basin-wide Monitoring

3.1 Basin-wide Monitoring: Design Parameters

A broad-scale, omnibus, and efficient monitoring design needs to have a core set of sample sites that can be subset for analysis and augmented to address specific resource conditions, enabling scientists and managers to characterize different resources at different scales and levels of precision, and adjust to changing needs over time. The facets of a monitoring design include: where data will be collected (sampling frame); the resource to be monitored, what will be measured, how it will be measured (response design); how many locations and how frequently it will be measured (sampling intensity); and how metrics will be summarized and interpreted (adaptive management). In this section we discuss the sampling frame and some rules of thumb regarding sampling intensity. The remaining resource-specific parameters are described in the sections that provide recommendations for monitoring each Pillar.

Spatially Balanced Survey Design

A robust survey design has the following properties: probability-based, spatially representative, balanced and simple, and flexible to accommodate potential changes in the future (Theobald et al. 2007). Probability sampling is a statistical technique used to garner a representative sample from a population, enabling users to make inferences about the entire population based on the sample. There must be some form of random sampling in order for any given member of the population to have some probability of selection, ideally an equal (or quantifiable) probability. Probability-based monitoring design is a key component of every large-scale federal monitoring program in the United States (US): the US National Park Service's Inventory and Monitoring Program; the US Forest Service's Forest Inventory Analysis Program, the US Natural Resource Conservation Service's National Resource Inventory, the Bureau of Land Management's Assessment, Inventory, and Monitoring program, the US Geological Survey's Land Cover Trends program and the US Environmental Protection Agency's Environmental Monitoring and Assessment Program (EMAP).

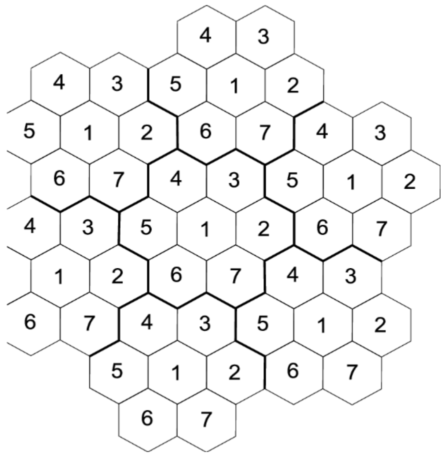
Monitoring applications of probability-based sampling led to the developing and application of spatial-balanced sampling (SBS) approaches, and specifically the Generalized Random-Tessellation Stratified Design (GRTSD) based on hexagonal sample units (Theobald et al. 2007, Theobald 2016). SBS approaches, such as GRTSD, are a combination of random and systematic sampling, where samples are randomly located within equal-sized units based on some form of a systematic grid.

Square and hexagonal grids are most commonly used to generate the systematic sample grid. Ideally, whatever grid type is used, it is scalable to meet the sampling intensity needs of different resources. Both of these grid configurations can be hierarchical so that units representing different scales can be nested and the appropriate scales of inference can be selected for each population. For example, smaller or less mobile species such as the Western toad may respond to environmental conditions on a small scale relative to mountain lions, requiring a nested design to estimate the occupancy of both species. Further, a general random selection may miss or under sample resources of specific interest (e.g., riparian), in which case the core set of sample sites would need to be augmented with additional sites located in riparian habitat. The scale of units for linear or small features commonly needs to be smaller than for area-based features.

Hexagonal grids are increasingly used because they are readily scalable and they have other desirable features (e.g., center points are equidistant from one another); however, square grids are also scalable and can meet most sampling objectives. Both FIA, the nation's forest monitoring system, and EMAP, the nation's freshwater monitoring system, are based on hexagonal grids (2360-ha and 4000-ha hexagons, respectively). More locally, the California spotted owl monitoring grid is also hexagonal (400-ha hexagons), but not spatially nested within FIA hexagons.

Recommendation: We recommend using the 30x30-m raster cells as the foundation of any systematic sampling design. Multiples of these can be used to represent larger square grid cells or the FIA hexagonal grid as the basis for the systematic grid for the Lake Tahoe basin-wide monitoring sampling frame. Ideally, the grid foundation is nested, so it can be scaled to smaller and larger sizes, as needed (Figure 3-1). For example, each 2360-ha hexagon can be partitioned into 7, 337 ha hexagons, and FIA hexagons can be clustered into groups of 7 to form 16,535 ha (42,000 ac) hexagons. However, for most resources, additional sampling within a hexagon can be accomplished by randomly locating additional sample locations within each FIA hexagon, unless spatial balance within a FIA hexagon is important. Similarly, a subset of FIA hexagons can be randomly selected from the clusters of 7 if sampling every FIA hexagon is not necessary or feasible. A square grid can also be used for as the foundation for a nested sampling unit design (e.g., Theobald 2016), it would require post-stratification to make inferences about conditions within FIA hexagons and to link the data to trends based on FIA plot data. The strength of the square grid is the ability to scale up and back down directly from 30x30-m pixels (scale of most remotely sensed data), and they are relatable. A 900 x 900-m sample unit contains 900, 30x30-m cells (81 ha; 2002 ac).

A



B

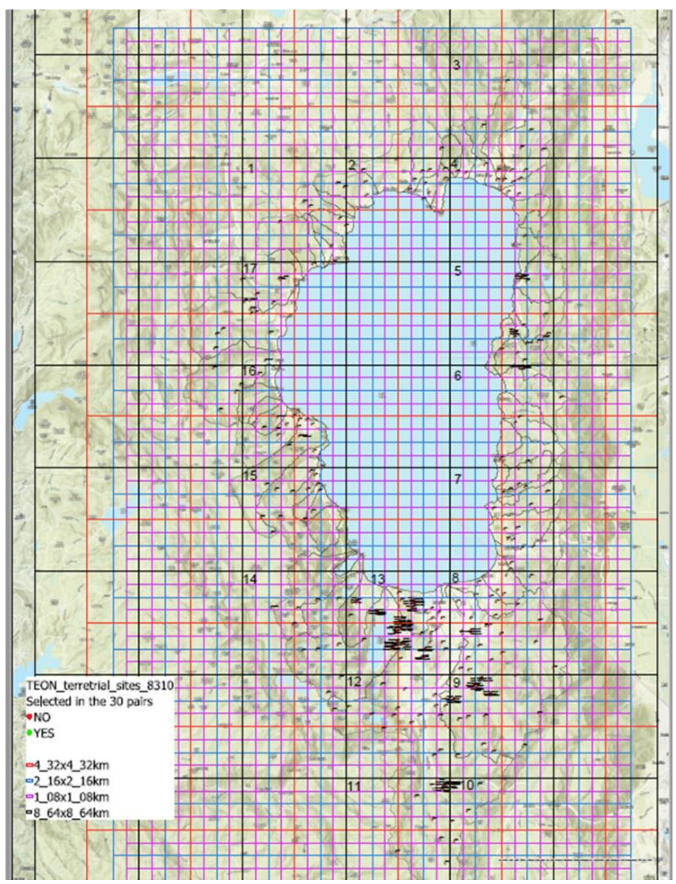


Figure 3-1. Hierarchical grid design. A) Clusters of 7 hexagons form higher level hexagons. B) Nested square grid cells.

Sampling Intensity and Field Site Selection

There is no substitute for field-based sampling, and it is the only reliable source of data for some metrics, particularly those that are not vegetation-centric or close derivatives thereof. Sampling intensity here refers to the number of sample sites. The other aspects of sampling that could be considered related to sampling intensity – area sampled at a site and the degree to which the site itself is sampled – are addressed in the response design section where sampling methods are described. Here, some general rules of thumb and options for starting points for sampling intensity and field site selection are discussed.

Generally, the larger the number of sample sites, the more sensitive a measure of change one will be able to detect. The frequency of sampling and the sample size combined will affect the period of time over which a change of a given magnitude can be detected. For any given metric, it is important to define the population being monitored, usually based on a definition of the resource of interest. For example, if we want to make inferences about forest conditions, we need to have a clear definition of what constitutes a forest. Based on a definitive definition, we can then determine the sample size that would result from different sampling densities and configurations.

Appendices A to D provide detailed descriptions of field methods that have been used over the past 20-25 years, and the results of a comparison of these historical conditions to current conditions for a sample of sites across the basin. These comparisons were conducted to inform TEON design parameters, specifically what is changing, how much change has occurred over the past 20 years, are there any indications that change is more substantial in some parts of the basin compared to others, and what can this all tell us about priorities for sampling location, intensity, and response design.

Basin-wide monitoring is intended to capture information across the full suite of conditions that exist in the basin. The basin-wide monitoring network is a core set of sites where all data on all of the foundational metrics are collected. A sample size of core 100 sample units is probably a good place to start. A sample of 100 sites is likely to provide a reasonably robust sample (~ > 50) of common resources, may provide an adequate sample for less common resources, and will under sample or miss rare and/or spatially clumped resources. Incremental additions of 50 or 100 sites to the initial sample of 100 sites provides a means of evaluating sample sizes needed to address various resources with a systematic random sample. It will not be possible for a systematic random sample to efficiently sample rare resources, thus the allocation of additional targeted sampling is typically needed for broad-scale monitoring systems to represent more rare or highly clumped resources.

Recommendation: The Multispecies Inventory and Monitoring effort in the early 2000s established 100 terrestrial sites on NFS lands and an additional 100 aquatic sample sites based on a systematic random sampling design with the FIA hexagons serving as the sample unit. Terrestrial sample sites were allocated to FIA hexagons based on the amount of NFS lands occupying the hexagon. These 200 sites could form the backbone of the core sample sites for TEON's basin-wide network. The terrestrial sites need to be augmented to be representative of all lands in the basin (not limited to NFS lands). As long as all lands have an equivalent probability of being selected for sampling, it does not matter if the sampling grid is square or hexagonal. Therefore, if the basin agencies wanted to switch to a square grid for sampling, it could be done prior to selecting additional sample sites to fill out the sample. A balanced design across all lands is likely to require an additional 50 sites or more to represent all publicly accessible lands, plus additional points to capture rare or clustered conditions.

Recommendation: Once the population of locations is defined for each of the metrics below, one may determine how best to ensure each metric is adequately represented in the sample. For example, some conditions are ubiquitous, such as land cover type, others are widespread, such as forest, and others are discrete or uncommon (aspen). For land cover type, an equitable sampling effort across the sampling grid accomplishes the objective of representation. For forests, representation would require the additional consideration of the cover of forest in each sampling grid. Similarly for aspen, consideration of where aspen occurred across the sampling grids would affect sample site location.

Recommendation: The first set of 100 sites would be derived from a combination of historical (priority) and new sites (as needed) to provide a spatially balanced and representative set of sites. The resulting sample size for each of the metrics would be determined. Then, increments of 50 additional sites could be selected from historical and new locations and the sample sizes for each metric recalculated. At each increment of sample size for the core sites, additional targeted sampling needs could be determined to meet minimum and desired sample sizes for each metric. Note, targeted placement of sample sites to capture conditions of a rare or uncommon condition cannot be used to address changes in anything but that targeted condition. For example, a site established to improve representation of aspen cannot be used to make inferences about overall vegetation cover type changes because they are biased by being placed in aspen stands.

Recommendation: Since environmental systems are dynamic, long-term monitoring designs must be robust to potential changes in the sampling frame, specifically target populations for each metric. Many natural resources will be changing in extent and distribution as a consequence of climate change, and changing distributions of resources of interest. One approach to mitigate this challenge is to select additional samples (10-20% more than anticipated are needed) that are randomly selected, but not sampled initially. They can be added to the network at some point in the future if sites in the original sample no longer belong to the target population (e.g., a pond is drained) or is no longer accessible (e.g., public lands converted to private lands). Similarly, all units can be selected and put in rank order for maximum future flexibility.

3.2 Basin-wide Monitoring: Metrics of Resilience

Each of the eight Pillars addressed in this report (Figure 2-2, all but Economic Diversity and Social and Cultural Well-being) will be represented by three primary Elements, that together will provide an indication of the resilience of each Pillar: 1) focal and/or special components, 2) diversity and/or abundance, and 3) integrity as a reflection of relationships that support processes and functions. For each Pillar, we identify a set of recommended metrics for each of the elements to form the foundation of the TEON monitoring system. This foundational set of metrics are selected based on a combination of the building blocks of pillar resilience and the feasibility of data acquisition. We did not limit data collection to existing or no-cost options, rather we aspired to recommend a foundational investment that achieved a balance between a robust and effective foundation of information across the pillars and one that is sustainable and efficient. In many cases, but not all, we identify options for additional metrics in the form of additional "modules" that would strengthen the representation and interpretation of each Pillar and could be an investment by one or more entities and/or for some period of time based on institutional mandates, interest, and capacity.

As indicated in the conceptual model of data collection to interpretation (Figure 2), data collection efforts and metric derivation have a many-to-many relationship, meaning that some data collection efforts will generate data that will feed many different metrics across different Pillars (e.g., vegetation data), and similarly some metrics will be derived from data collected through multiple different field methods. A matrix of relationships builds cohesion in the interpretation of conditions across metrics and Pillars, however it does complicate sample size considerations for field-sourced metrics. Sample size requirements for the most demanding metrics will drive the target sample size for the associated method(s). R-based programs such as GRTS can be used to optimize the spatial allocation of sample points to meet a range of metric sample size objectives.

Metrics, data inputs, representation, and interpretation summaries are provided below for each Pillar and their elements. The information provided below represents a brief summary of initial observations and recommendations derived from historical data, comparing historical and current conditions, and basic operating principles.

Forest/shrubland Resilience Pillar

Forest and shrubland resilience pertains to terrestrial ecotypes. Meadows (wet and dry) are considered a member of the Wetland Integrity Pillar, therefore metrics relevant to meadows are described in the Wetland Integrity Pillar. The Forest/shrubland Resilience Pillar is parsed into three Elements: structure, composition, and disturbance. Ideally, monitoring measurements and reporting pertain to one or more metrics in each subdomain and across the three Elements. Metrics recommended in Table 2-2 reflect fundamental forest and shrubland ecology and resilience dynamics, as well as basin-specific dynamics revealed by recent studies.

A 2024 resample of 30 terrestrial sites, originally sampled between 2003-2005, provide the basis for the recommended metrics in Table 3-1 (see Appendix B for details). Forest structure was found to be relatively stable between these time periods as measured by dominant tree species as well as percent cover of herbaceous plants and grasses. Shrub cover increased, as did the number of large trees. Snags did not significantly increase overall, although red fir snags (*Abies magnifica*) showed a substantial increase. Interestingly, while field plots showed stable or increasing density of large trees, remotely sensed data indicates a decline in late seral conditions over the past 20 and 40 years.

Table 3-1. Core metrics (~30) recommended for forest/shrubland resilience monitoring.

Subdomains	Metric	Source
Focal features	Ancient (extra-large >90 cm) tree density	Remote-sensing (lidar, height-based)
	Late seral forest by vegetation type - quantity and quality	Remote-sensing
	Invasive plant species	Field data
Diversity - Structure	Large (> 60 cm) tree and snag density	Remote-sensing and field data
	Ground cover	Field data
	Tree density x diameter class	Remote-sensing and field data
	Shrub species cover and distribution	Field data
	Horizontal and vertical heterogeneity	Remote-sensing and field data
Diversity - Composition	Vegetation cover type amount and distribution	Remote-sensing
Integrity	Seral stage x canopy cover x vegetation type - amount and distribution	Remote-sensing
	Disturbance type, intensity and frequency	Remote-sensing
	Tree mortality rates and sources	Remote-sensing and field data
	Tree species composition and dominance	Field data
	Shrub diversity and decadence	Field data

Fire Dynamics Pillar

The historic fire regime for the Tahoe basin varies by elevation, with lower altitudes experiencing frequent, low to moderate severity fire and higher altitudes characterized by infrequent, stand-replacing fire (Beaty and Taylor, 2007). Topography, including slope and aspect, also influences how fires spread and burn (Beaty and Taylor, 2008). Climate strongly impacts fuel availability, moisture, and fire weather conditions, particularly El Niño-Southern Oscillation and the Pacific Decadal Oscillation (Beaty and Taylor, 2008). The Waší·šiw (Washoe people) tended the land with low severity fire for thousands of years to promote resources with cultural values (Lake et al., 2017; Miller and Safford, 2017). The resulting fire regime at the lower montane zone was characterized by frequent (5 to 20 year fire-return interval) low to moderate severity fire, with limited high severity patches. Stand structure was heterogenous, with a variety of age classes represented, and was dominated by pines species (Safford and Stevens 2017). At higher elevations, the historic frequency of fire decreases, with mean fire returns in red fir forests in the upper montane zone of 40-50 years, with a severity that is primarily low to moderate with up to 20% high severity effects (Meyers et al. 2018). This pattern of decreasing frequency with increasing severity continues as elevation increases, with moderate fire occurring every 63 years on average in lodgepole pine stands and high-severity fire occurring every 394 years on average in subalpine forests (Mallek et al. 2013, Turner et al. 2019).

The arrival of Euro-Americans with the Comstock silver rush in the 1850s decimated the Waší·šiw and the historic fire regime they maintained (Taylor et al., 2016), ushering in an era of fire suppression and clearcut logging (Straka, 2007). Lack of regular fire in the lower montane zone has allowed fuels and tree densities to increase, shifting the dominant species from shade-intolerant pine to shade-tolerant white fir. Climate change is associated with longer, hotter, and drier fire seasons, with more extreme fire weather (Westerling et al., 2006; Parks and Abatzoglou, 2020, Parks et al., 2023). These socioecological changes, coupled with climate change, have increased the extent and frequency of high-severity fire in the mixed conifer forests of the Sierra Nevada (Parks et al., 2023; Taylor et al., 2016). While fire regimes in the upper elevations have not yet been significantly impacted, lower elevation forests are facing multiple interacting threats of drought, beetle invasion, and high-severity fire. Contemporary fires in the Lake Tahoe basin include the Gondola (2002), Showers (2002), Royal (2003), Angora (2007), Emerald (2016) and Caldor (2021) fires. These fires burned in large, contiguous patches of high-severity fire, affecting air and water quality, with some of them destroying homes, and all of them costing millions of dollars in fire suppression and recovery (e.g., damages and lost revenue) (Gedye, 2021; Saim and Aly, 2024; East et al., 2025). For over 10,000 years, the Waší·šiw maintained their presence in the Tahoe region, and their perspectives and knowledge are increasingly called upon in efforts to restore the historic fire regime. Co-management with the US Forest Service has increased access and restoration of traditional uses for ancestral lands in the Lake Tahoe Basin.

The Fire Dynamics Pillar has two elements: severity and functional fire. Ideally, monitoring measurements and reporting pertain to one or more metrics in each subdomain and across both Elements. The metrics recommended in Table 3-2 reflect a combination of basic fire ecology and metrics identified as important to managers in the basin (see Lake Tahoe West draft monitoring plan, 2022). They include descriptions of fires that have occurred, fire histories, and estimated probabilities of fire intensity based on current forest conditions (i.e., fuel characteristics). Metric values can be derived using a combination of field-based data collection, remote-sensing, and modeling.

Table 3-2. Core metrics recommended for fire dynamics monitoring.

Subdomains	Metric	Source
Focal features	High severity fire patch size	Remote-sensing (MTBS and RAVG)
	High intensity fire frequency and extent	Remote-sensing (MTBS and RAVG)
	Soil burn severity	Remote-sensing (MTBS)
Diversity	Fire frequency, extent and intensity	Remote-sensing (MTBS and RAVG)
	Fuel profile	Field data
	Conditional burn probability (estimated flame length)	Modeled fuel and fire behavior
Integrity	Fire as functional process	Remote-sensing (MTBS and RAVG) interpretation
	Resource benefit fire extent and distribution	FACTS or CA treatment tracker

Wetland Integrity Pillar

Wetlands consist of meadows, marshes, streams, lakes, ponds, and riparian ecosystems (Table 3-3) distributed across the basin. Aspen could be considered a wetland ecotype, but given that it is a forest type, it is addressed in the Forest/shrubland Resilience Pillar. Wetlands of the Tahoe basin are one of the most threatened habitats, with nearly 75% of marsh and 50% of meadow habitat lost since the early 1900s. This habitat provides ecosystem services that are directly tied to Environmental Improvement Program goals of improving lake clarity and overall water quality, supporting wildlife habitat and biodiversity, and increasing resilience to fire and climate change.

Table 3-3. Aquatic ecosystem ratings for the Lake Tahoe Basin, based on the system of Moyle (1996). "Rating" is based on the sum of the ratings on the three criteria: rarity, disturbance, and protection, with scores that range from 1 (poor condition) to 5 (good condition). "Confidence" reflects the reliability of the rating: H = high, M = moderate, L = low. Reproduced from Reiner and Oehrli (2000).

Lake Tahoe Basin-Entire					
Ecosystem	Rarity	Disturbance	Protection	Status/ Score	Rating
Lentic ecosystems					
Mountain pond	3.3	2.8	3.3	9.3	sp. concern
Alpine lake w/o native fish	3.3	2.3	2.8	8.4	sp. concern
Fen	1.3	2.0	2.5	5.8	threatened
Sphagnum bog	1.3	2.3	3.3	6.9	threatened
Alpine lake w/ native fish	0.3	2.0	4.0	6.3	threatened
Lake Tahoe	1.0	3.0	3.0	7.0	threatened
Marsh	0.5	1.5	3.0	5.0	threatened
Wet meadow	3.8	3.0	3.3	10.1	sp. concern
Lotic ecosystems					
Alpine snowmelt stream	3.3	3.7	4.3	11.3	secure
Cnfr forest snowmelt stream	4.3	3.5	4.3	12.1	secure
Alpine stream	2.5	3.7	4.3	10.5	sp. concern
Spring	3.5	2.8	3.0	9.3	sp. concern
Forest stream	3.0	2.8	2.8	8.6	sp. concern
Meadow stream	1.8	2.5	3.3	7.6	threatened
Trout headwater stream	5.0	3.0	3.5	11.5	secure
Stream with trout	4.0	2.5	3.5	10.0	sp. concern
Mainstem river	0.3	1.0	1.0	2.3	imperiled

Lakes and Ponds

There are numerous lakes and ponds within the basin which vary seasonally in size and extent, sometimes transitioning between ponds and wetlands in drier years. We used the US Fish and Wildlife National Wetlands Inventory and the Sierra Meadow Partnership data to delineate the aquatic habitats in the basin. We included surface waters (lakes and ponds) and wetlands (emergent and shrub/forested wetlands) for the entire Tahoe HUC 8 watershed. Because we were interested in understanding how ponds and lake systems specifically had changed over time, our sample included proportionally more of these habitats than is representative for the basin (Figure 3-2). We also tended to sample larger aquatic sites. The historical set of lakes and ponds initially sampled in 1997-1998 would provide a highly valuable population of sites as a core set for monitoring (Figure 3-3).

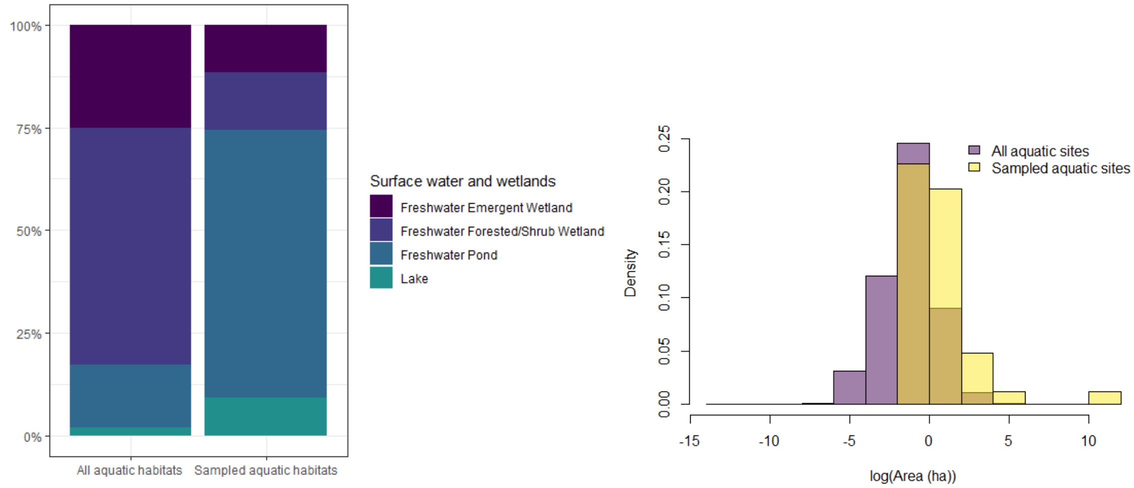


Figure 3-2. Proportion of surface waters (lakes and ponds) and wetlands in the Lake Tahoe basin and the re-sampled aquatic sites by type and area (hectares).

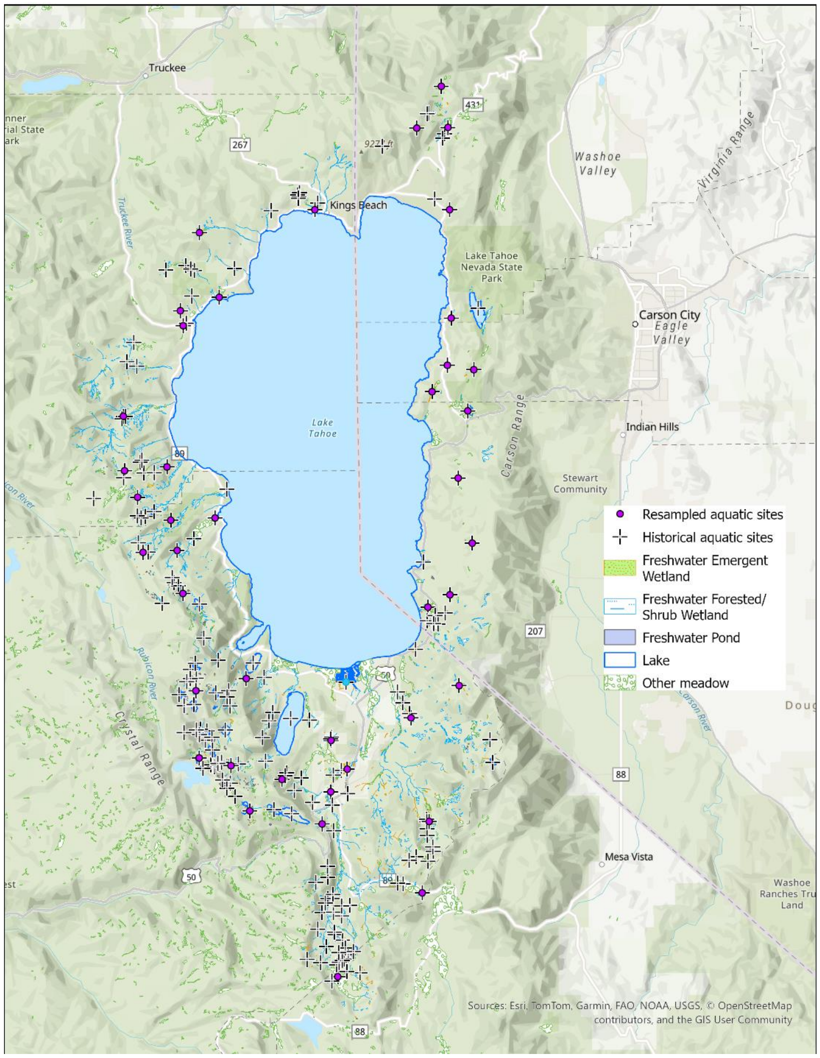


Figure 3-3. Lakes, ponds and wetlands (lentic ecosystems) in the Lake Tahoe basin and the subset that are part of the historical sample.

We used a global surface water dataset to evaluate how waters have transitioned between seasonal and permanent status from 1981 to 2021 (Peckel et al. 2016; https://global-surface-water.appspot.com/). This dataset classifies each pixel in Landsat images (30m resolution) as water or land, seasonal and permanent over this time period, allowing for comparisons. We mapped the lakes and streams in the basin and found that 99% of water bodies did not change from the permanent status assigned in 1981 (Table 3-4).

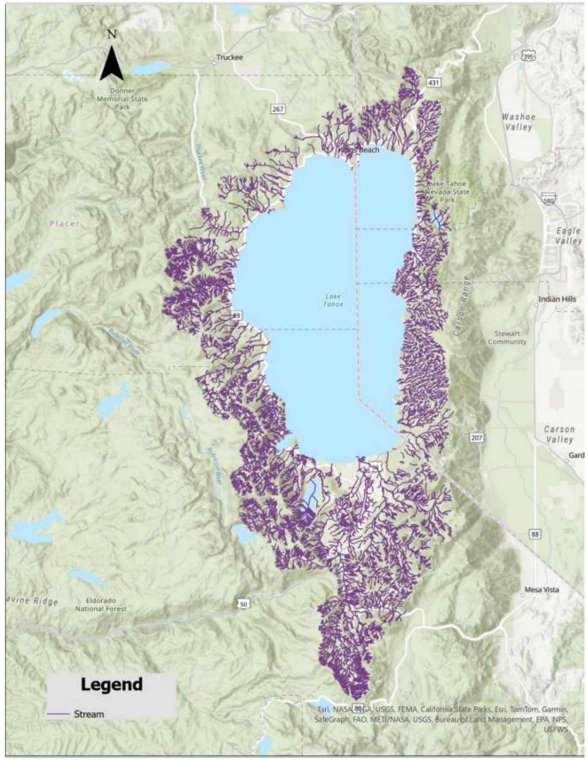
Table 3-4. Transitions between permanent water, seasonal water, and land at two points in time: 1981 and 2021.

Status	Area (ha)	
Unchanging permanent	50624.1	99.25%
New permanent	30.5	0.06%
Lost permanent	16.6	0.03%
Unchanging seasonal	93.9	0.18%
New seasonal	126.4	0.25%
Lost seasonal	12.4	0.02%
Seasonal to permanent	25.1	0.05%
Permanent to seasonal	79.8	0.16%

Streams and Riparian

The Lake Tahoe basin has hundreds of miles of streams and associated riparian zones (Figure 3-4A). Stream monitoring is an integral part of environmental monitoring to maintain Lake Tahoe's clarity. Monitoring programs have been in place for over 40 years, and they have fluctuated in their size and rigor over time. The Lake Thoe Interagency Monitoring Program (LTIMP) stream monitoring program was first initiated in 1979 to assess sediment and nutrient inputs from streams to Lake Tahoe, and to support research that aims to understand the drivers affecting the tributaries to Lake Tahoe (based on LTInfo website and other unpublished sources, Figure 3-4 B). The stream monitoring focuses on event-based conditions (large runoff events) and baseline conditions (low inflow during summer). Up to 10 streams have been monitored since the 1990s: five in California (Upper Truckee, Trout, General, Blackwood, and Ward) and five in Nevada (Third, Incline, Glenbrook, Logan House, and Edgewood). Six of these streams have been monitored since the early 1980s. All of these streams have or had primary monitoring stations near the point of discharge to Lake Tahoe.

A



B

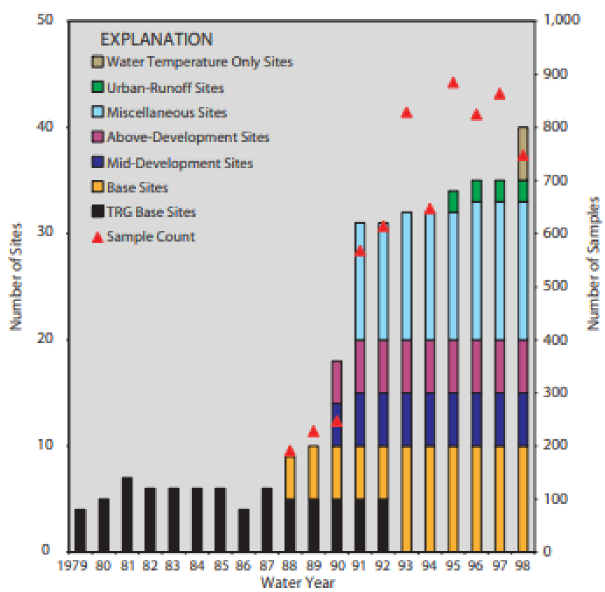


Figure 3-4. Streams (lotic ecosystems) in the Lake Tahoe basin (A) and monitoring effort for the first two decades from ~1980 to 2000 (B, from USGS Fact Sheet 138-00, LTIMP Tributary Sampling Design, Sites, and Periods of Record report 2000).

TMDL stream monitoring for sediment and nutrients receives a great deal of attention and resources due to its importance to the clarity of Lake Tahoe. As a result, it is supported by a strong science and management partnership. The role of TEON in this arena is to support the monitoring system that the lake clarity working group and TMDL staff have designed and implemented, and to complement that work to the degree necessary and possible to build a more comprehensive representation of stream conditions across the basin.

A number of additional substantial historical and current sampling and monitoring efforts form important building blocks for a comprehensive review and design for stream ecosystem monitoring across the basin. In the early 1990s, 80 stream reaches selected in a stratified random design across 20 of the 63 watersheds in the basin were established and sampled for a comprehensive suite of plant and animal species (Manley 2000). These reaches could serve as a valuable source of change data for stream and riparian conditions and biodiversity if resampled soon, and then incorporated into a more frequent and regular monitoring program. TRPA and the LTBMU invest individually and collaboratively to stream condition monitoring, including stream morphology, invertebrate sampling, and vertebrate surveys (fish and amphibians). The number of sites and frequency of sampling has varied over time. In 2023, TRPA assessed 72 streamside environment zones and sampled 25 streams for macroinvertebrate indicators of stream health (TRPA 2023 Annual Report). The LTBMU also has a robust Riverine Restoration Program that has been active (under this moniker) since 2003. A 10-year summary was generated in 2015 (LTBMU Riverine Restoration Program 2003-2014 report), and the LTBMU is in the process of repeating sampling in many of these (and other) restored streams to monitor their longer term trajectories.

Recommendation: A stream ecology or upland aquatic ecology group could be formed to evaluate historical sites and data, along with current investments in monitoring, to derive a recommended baseline monitoring system to track the ecology and integrity of upland aquatic ecosystems across the Lake Tahoe basin.

<u>Wetland habitats</u>

Wetland habitats are often considered as a continuum, varying by the source, extent, and timing of soil saturation, which is controlled by geomorphology. Wetland habitats for the purposes of TEON include marshes, meadows, and fens. Marshes are frequently or continually inundated with water and dominated by herbaceous vegetation that tolerates saturated soil. They tend to be a product of topography, forming along streams and lakes in poorly drained depressions; and hydrology, fed predominantly by surface water with some groundwater contributions. The soils of marshes tend to be highly organic and rich in minerals. Meadows have soils that are saturated for part or all of the growing season, with the water table occurring within a meter of the surface. They tend to be dominated by herbaceous species with water supplied from snowmelt that maintains groundwater levels throughout the dry season (Viers et al. 2013). Fens are a special class of wetlands that are peat-forming due to near constant groundwater inflow. Oxygen is limited by soil saturation, and low temperatures inhibit microbial activity, resulting in the slow and partial decay of organic matter into peat. In the Sierra Nevada, fens are defined by the depth of their peat layer, with a 40cm minimum which may take 2000 years to form. Plants root in the peat and derive nutrients and water from peat rather than the mineral soil. These highly specialized conditions make fens relatively rare in the Sierra, and also very sensitive to alterations in hydrology. There is an estimated 192 ac (77.7 ha) of fen habitat in the Tahoe basin that support nine rare plant species (Sikes et al. 2013).

There are several data products that may be used to evaluate wetland condition on a yearly basis, such as topographic wetness indices, water storage deficit, and the Normalized Difference Vegetation Index (NDVI) from remotely sensed data (Landsat imagery and publicly available products derived from Landsat) and metrics derived from the combination of NDVI and other features (such as provided by CECS). For example, we utilized the “lost meadows model”, a machine-learning tool that identifies areas that share geomorphic and climatic characteristics with existing meadows (Figure 3-5; Pope and Cummings 2023). These areas are potential meadows, that may have lost meadow hydrology and vegetation due to climate change, human infrastructure, and overgrazing. The potential or lost meadows identified by this model may be used when planning for both wetland integrity and fire-adapted communities. Functional meadows act as fire breaks, extending the effects of adjacent fuel treatments.

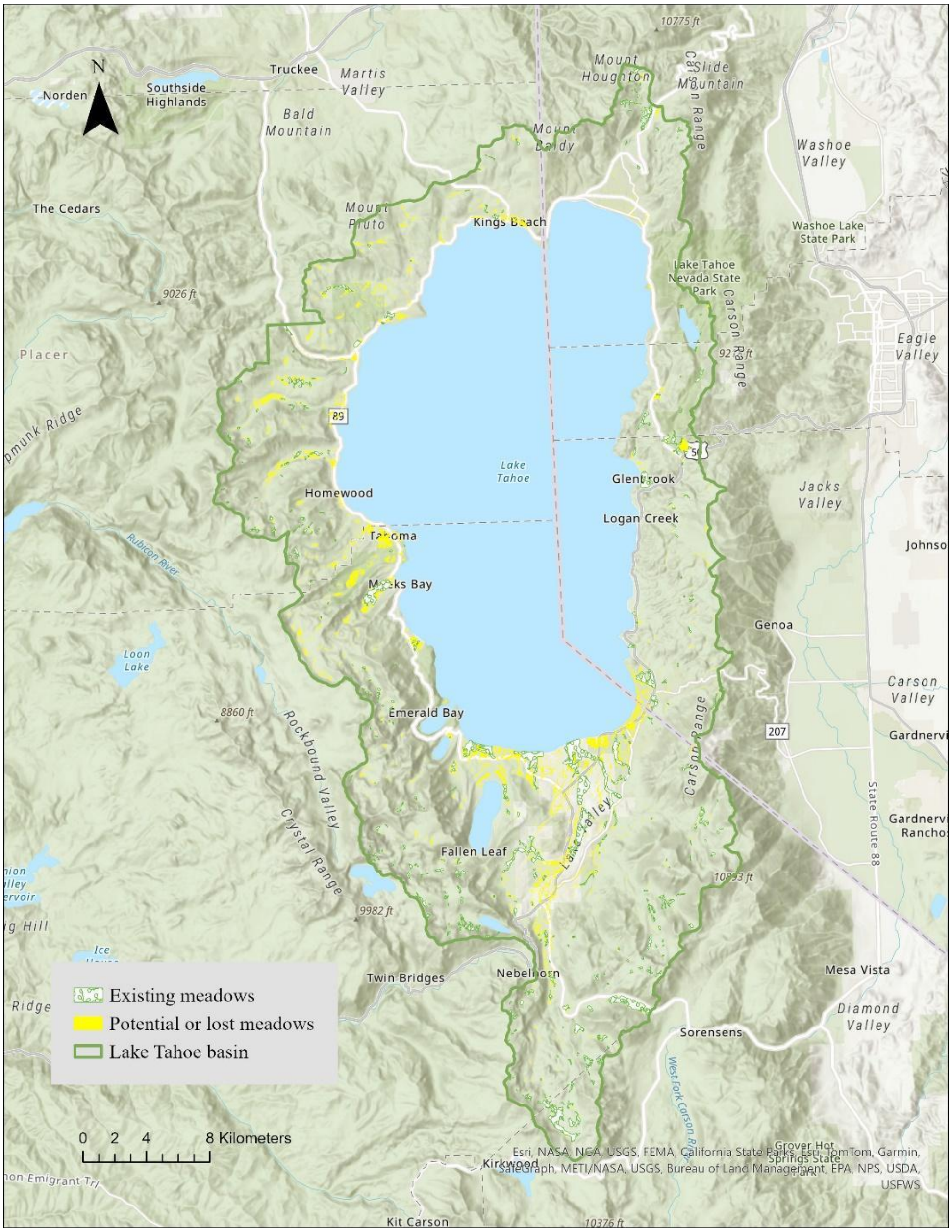


Figure 3-5. Map of the Lake Tahoe basin showing existing meadows from the Sierra Nevada MultiSource Meadow Polygons Compilation Version 2 (SNMMP, http:/meadows.ucdavis.edu) in green and potential meadow habitat from the "lost meadow model" (Cummings et al. 2023) in yellow.

In addition to remotely sensed data sources, the LTBMU and Region 5 regularly (every five years) collect field data on a set of 45 wetland plots located around the basin to monitor vegetation, hydrology, and soil conditions (Figure 3-6). This project was established in 2004 to evaluate existing conditions, identify restoration opportunities, determine restoration effectiveness, and provide a permanent monitoring system for wetlands in the basin. This dataset includes marshes, meadows, and fens.

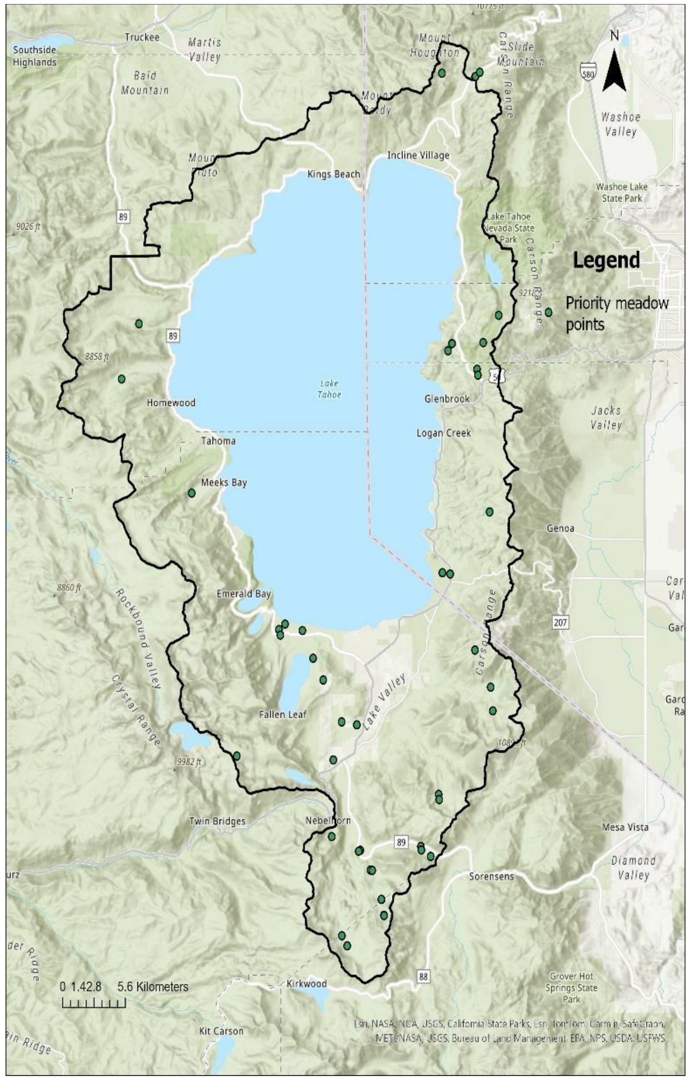


Figure 3-6. Wetland sampling locations visited every five years by the US Forest Service Region 5 and Lake Tahoe Basin Management Unit biologists.

Wetlands were selected to represent a range of environmental conditions, and were stratified by elevation and orientation (Table 3-5; Figure 3-6 and 3-7). Most wetlands in the basin are below 2400 meters in elevation, less than 50ac in area, with discharge slope or riparian hydrogeomorphology (Figure 3-8). The majority of secondary vegetation is conifer and riparian, with few wetlands dominated by bare ground or shrub or hardwood species. The sample roughly followed similar proportions of elevation, size, and hydrogeomorphology although the rarer types tend to be under sampled. The sites sampled include a mix of wet meadow (n=26), dry meadow (n=4), fen (n=11), aspen (n=2), and marsh (n=2) habitat.

Table 3-5. Lake Tahoe Basin Management Unit and Region 5 priority wetland sites by elevation and basin orientation.

Priority wetlands	East	West	Total
High elevation (>7500')	11	13	24
Low elevation	7	14	21
Grand Total	**18**	**27**	**45**

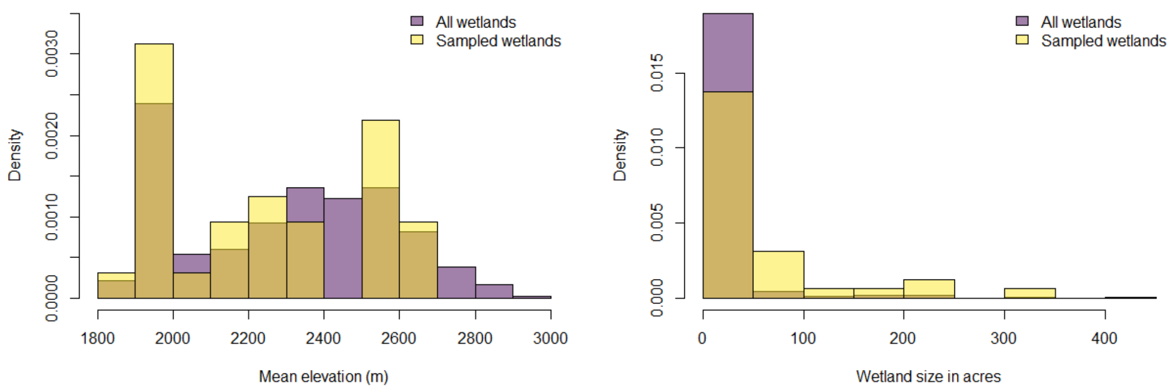


Figure 3-7. Elevation (m) and wetland area (ac) in the Lake Tahoe basin, and the sample of priority sites surveyed every five years by Region 5 and the Lake Tahoe Basin Management Unit.

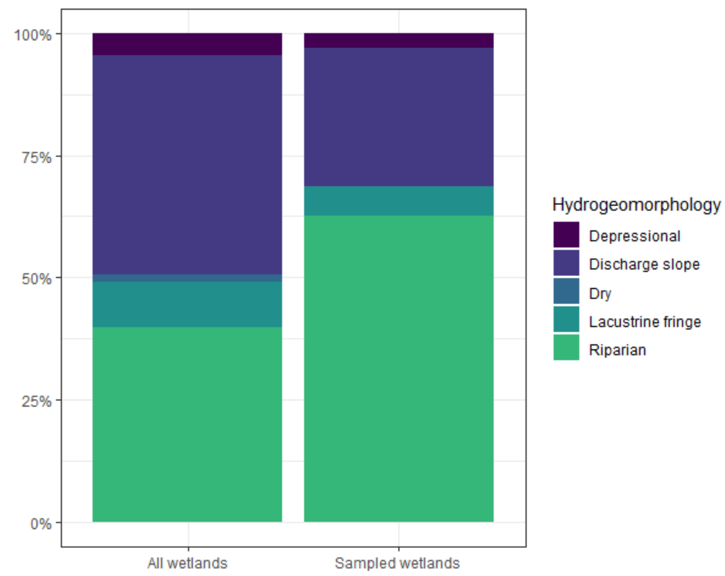


Figure 3-8. Hydrogeomorphology represented in the Lake Tahoe basin and the sample of priority site surveyed every five years by Region 5 and the Lake Tahoe Basin Management Unit.

Consistent and intensive data collection to describe each site follows the USFS Region 5 range monitoring protocol (Weixelman et al. 2020, 2011). Within each wetland, plots are located in homogenous plant communities, with 60 nested frequency subplots per plot. Nested frequency plots provide a repeatable and unbiased estimation of community structure and composition, and tend to be nondestructive, consistent across the growing season, and sensitive to change (Elzinga et al., 1998). This field sampling provides an opportunity to calibrate remotely sensed data and identify how well it captures the changes that are observed less frequently on the ground. This also provides finer-scale information that is not possible to collect with LiDAR.

The combination of remotely sensed data and field data provides an opportunity to calibrate remotely sensed data and identify how well it captures the changes that are observed less frequently on the ground. The wetland monitoring protocol is a robust survey that incorporates vegetation structure and composition, soil moisture and texture, channel incision, and geomorphology. This also provides finer scale information that is not possible to collect with LiDAR. We recommend continuing these surveys in addition to the remotely sensed data processing for TEON.

<u>Core metrics</u>

We recommend a core set of metrics that address the full scope of wetland ecosystem types in the basin (Table 3-4). The wetland integrity metrics listed in Table 3-6 represent a combination of fundamental wetland ecology, results from TEON investments in resampling historical wetland sites, and metrics of specific interest to managers in the basin. Remotely sensed data will provide a wide range of valuable data for describing and tracking wetland conditions, but field data will also be needed for at least a subset of metrics.

Table 3-6. Core metrics recommended for wetland integrity monitoring.

Element	**Metric**	**Source**
Focal features	Aquatic and terrestrial non-native species distribution and abundance	Field data
	Sensitivity of meadows to drought	Remote-sensing
	Beaver occurrence	
Diversity	Type and abundance of wetland ecosystems	Remote-sensing
	Stream connectivity	Remote-sensing
	Stream incision and channel stability	Field data (LTBMU)
	Extent and condition of riparian vegetation	Remote-sensing
Integrity	Native plant and animal species diversity by wetland type	Field data
	Conifer encroachment in meadows	Remote-sensing and LTBMU meadow monitoring
	Meadow vegetation vigor	Remote-sensing and LTBMU meadow monitoring
	Water ponding capacity of meadows	Remote-sensing and LTBMU meadow monitoring

We recommend continuing the Region5- LTBMU meadow monitoring surveys, and augmenting the sample as indicated by the results of current analyses of monitoring data, with emphasis on sampling some or all meadows in sentinel watersheds to provide a more comprehensive understanding of watershed hydrology in these focal watersheds. In addition, we recommend evaluating the condition of all meadows in the basin (number, extent, connectivity) using a combination of modeling and remotely sensed data. We also recommend continuing and expanding the existing Tahoe SEZ monitoring, including an evaluation of the sampling design and site selection to ensure the data can be used to make inferences about conditions across the basin.

Biodiversity Conservation Pillar

Improving wildlife habitat and biodiversity and restoring ecosystem health and resilience are key goals of the Environmental Improvement Program. Understanding how plant and animal populations and communities have changed over time is a critical part of managing this system for resilience to climate change and other stressors. The Biodiversity Conservation Pillar includes both terrestrial and aquatic ecosystems. Population and community ecology are the underpinning of biodiversity, and they do not necessarily conform to broad vegetation associations and wetland ecosystem types. Therefore, we address biotic diversity here as an overarching aspect of resilience that spans all ecosystem types. The metrics of biodiversity listed in Table 3-7 represent fundamental aspects of biotic diversity, results from TEON resampling of historical sites (2023-2024).

TEON resample results

By comparing historical data with contemporary data, we were able to observe some changes to biodiversity that have already occurred in the basin.

Plants - For the 30 resampled terrestrial points, we detected an increase in large trees, consistent across all the most dominant species across the Basin (White fir, Red fir, Lodgepole pine, Jeffery Pine), though presence of Whitebark pine was noticeably reduced, consistent with the scientific consensus of climate change effects on that species (Appendix B). Across all tree species and sites, prevalence of decadence features increased unilaterally, indicative of an increase in a variety of types of environmental stressors. Several additional metrics related to habitat suitability and fuels loading also showed significant change over the past 20 years, including increases in shrub cover, coarse woody debris ground cover, and mean litter depth and ground cover.

Birds - For the 30 resampled terrestrial points, we detected a substantial decrease in richness of avian species, with a decrease in mean species observed per visit from over 21 in 2003-05 to 18 in 2023-24 (Appendix D). This decrease declined with elevation, with the largest decreases observed in the previously most diverse locations at lower elevations (where the majority of species reside in the basin). A cluster analysis also revealed impacts of urbanization and severe wildfire on beta diversity.

Mammals - Cameras were deployed across 91 sites around the Lake Tahoe Basin in 2023, including the 60 resample points plus additional historical points that filled out a test of hierarchical camera sampling (Appendix F). A total of 56 different species were detected. The most common species detected, in decreasing frequency of detection, were Golden Mantled Ground Squirrel (*Callospermophilus lateralis*, 21% of the observations), Douglas's Squirrel (*Tamiasciurus douglasii*, 13.4%), American Black Bear (*Ursus americanus*, 12%), Coyote (*Canis latrans*, 9.6%), California Ground Squirrel (*Otospermophilus beecheyi*, 6.4%), and Steller's Jay (*Cyanocitta stelleri*, 3%). The most common species were also the most widely distributed across the sampled sites. Douglas Squirrel was observed at 80% of terrestrial sites and all (100%) of the aquatic sites. Golden Mantled Ground Squirrel was present at 58% of both terrestrial and aquatic sites, while American Black Bear was observed at 56% of terrestrial sites and 50% of aquatic sites. The major Orders observed are Rodentia (69.1%), Carnivora (24%), Passeriformes (4.3%) and Cathartiformes (1.2%).

Herpetofauna - For the resampled 30 aquatic sites, there was no perceivable change in diversity for amphibians and reptiles over the 20-year period. The visual encounter surveys used for herpetofauna are time consuming, with low detection probability that is often confounded by the timing of sampling and the life stage of each particular species. Additionally, species are highly variable in what type of aquatic habitat they use at particular life stages. For example, we did not detect the Sierra garter snake (*T. Couchii, formerly western aquatic garter snake*), one of the three garter snake species known to occur in the basin, which could be due to the rarity of this species or the difficulty in differentiating among the three species.

Fish, invertebrates and eDNA - We also attempted to test a novel method for evaluating aquatic communities: environmental DNA (eDNA). This method involves collecting and filtering water to capture the DNA that organisms shed throughout their lives, leaving a biochemical footprint of their presence. eDNA is becoming a standard approach for describing fish and invertebrate biota in streams, and it was our intention to evaluate fish and invertebrate composition from water samples. However, eDNA is less commonly used for other vertebrate taxa. It was our intention to target amphibians and reptiles, but we were also interested in the potential to detect mammal species of particular interest (e.g., beaver (*Castor canadensis)*, mink, mountain beaver (*Aplodontia rufa)*, and muskrat (*Ondatra zibethicus*)). One important limitation of eDNA is that it is best used for occupancy and not abundance, and does not provide information about breeding, age or sex that may be obtained in visual encounter surveys (Ruppert et al., 2019). Species that are semi-aquatic, such as the garter snakes in the Tahoe basin, there may be less DNA in the water, making them more difficult to detect. For rare and semi-aquatic species, visual encounter surveys are most effective when repeated multiple times per season and eDNA can help verify absence indicated by visual encounter surveys (Bailey et al., 2019).

Recommendation: Form a technical group to finalize core metrics for biodiversity and associated monitoring to sufficiently represent the suite of metrics, including consideration for historical and current monitoring activities.

Table 3-7. Core metrics recommended for biodiversity conservation monitoring.

Element	**Metric**	**Source**
Focal features - Plants	White bark pine	Field data
	Sugar pine	Field data
	Tahoe yellowcress	Field data
	Red fir	Field data
Focal features – Animals	California spotted owl	Field data
	American marten	Field data
	Northern goshawk	Field data
	Bald eagle	Field data
	Black bear	Field data
	Lahontan cutthroat trout	Field data
	Beaver	
	Bullfrog	
Diversity	Species richness	Remote-sensing and field data
	Species diversity	Remote-sensing and field data
	Beta diversity	Remote-sensing and field data
Integrity	Functional group diversity	Remote-sensing and field data
	Trophic diversity	Remote-sensing and field data
	Community diversity	Remote-sensing and field data
	Connectivity	Remote-sensing
	Protected activity center occupancy and vulnerability	Remote-sensing
	Invasive species (plant or animal)	Remote-sensing and field data

Carbon Sequestration Pillar

Carbon storage in natural and working landscapes is recognized as a vital contribution to meeting carbon sequestration and carbon neutrality goals at a range of scales from regional to national. Forests and meadows play an outsized role in sequestering and storing carbon in a manner that provides multiple additional ecosystem services, such as high value wildlife habitat, water storage and holding capacity, positive contributions to air quality, and outdoor recreation opportunities, among others. The Lake

Tahoe basin's land cover types are predominantly forests and meadows, and therefore is positioned to make substantial contributions to carbon sequestration. Further, meadow restoration in upper montane and subalpine ecosystems such as those that dominate the Lake Tahoe basin plays an outsized role in not only carbon storage, but also water retention and storage because precipitation falls primarily as snow in these zones. These critical hydrologic functions have a substantial effect on the processes that deliver sediment and nutrients to Lake Tahoe (see water security pillar for associated metrics).

Carbon storage in forests and shrublands is readily measured, modeled, and mapped from remotely sensed data sources. We recommend eight metrics for carbon monitoring, focused on total carbon, live tree carbon, and meadow carbon (Table 3-8). Lidar-based measures are particularly valuable for providing measures of biomass that can be converted to carbon. Less sensitive but more readily available measures of carbon can be garnered from satellite imagery when combined with modeling, and plot-based imputations are also able to estimate carbon, but provide some of the least accurate measures of carbon.

Table 3-8. Core metrics recommended for carbon sequestration monitoring.

Element	Metric	Source
Focal features	Large (> 60cm) tree carbon	Remote-sensing and field data
Diversity	Above ground live (AGL) carbon	Remote-sensing and field data
	Above ground live (AGL) tree carbon	Remote-sensing and field data
	Above ground live (AGL) large tree carbon	Remote-sensing and field data
	Total carbon (live and dead)	Remote-sensing and field data
	Meadow soil carbon	Field data
Integrity	Stable forest carbon	Remote-sensing and field data
	Stable meadow carbon	Remote-sensing and field data

Water Security Pillar

Water security encompasses all aspects of water as an available resource for ecosystems, including plants, animals, and people. Water security includes quality, quantity, form, and availability. We identified eight recommended metrics of water security (Table 3-9). TEON broad-scale monitoring did not focus strongly on water security, but broad-scale remote-sensing based airborne snow observatory (ASO) monitoring systems implemented elsewhere in the western US (e.g., Colorado Airborne

Snowpack Measurement Program) have tremendous value and would be a strong addition to hydrologic monitoring currently being conducted in the basin.

Recommendation: Form a technical group to evaluate the current snow monitoring system and derive a recommended base monitoring system for snow monitoring as part of the TEON system.

Table 3-9. Core metrics recommended for water security monitoring.

Element	Metric	Source
Focal features	Above ground water quality (stream gauges)	Field data
	Snow pack and water content	Field data
	Soil moisture	Field data
Diversity	Above ground water quantity (stream gauges)	Field data
	Stream incision and channel stability	Remote-sensing and field data
	Water availability	Remote-sensing and field data
Integrity	Meadow water ponding capacity	Field data
	Snow accumulation and melt dynamics	Remote-sensing
	Drought vulnerability	Remote-sensing

Air Quality Pillar

Air quality encompasses particulates, gases, and impacts on visual quality. Although health impacts are a substantial focus of air quality standards and monitoring, they are not included here as metrics. The recommended metrics in Table 3-10 are a starting point for discussions about how best to represent these air quality conditions in a manner that is most aligned with regulatory requirements and target conditions.

Table 3-10. Core metrics recommended for air quality monitoring.

Element	Metric	Source
Focal features	Days above PM2.5 regulatory threshold	Field data
Diversity	Particulate levels x source	Field data
	Ozone	Field data
	Visual quality	Field data
Integrity	Potential emissions	Remote-sensing and modeling

Fire-adapted Communities Pillar

The fire-adapted community pillar includes the degree to which communities are at risk of wildfire and their preparedness (physically and organizationally). The recommended metrics in Table 3-11 focus on the threat of wildfire to communities as a function of risk of fire.

Table 3-11. Core metrics recommended for fire-adapted communities pillar.

Element	Metric	Source
Focal features	Fire risk within WUI zones	Remote-sensing
	Fire ignition rates and distribution	Remote-sensing
Diversity	Intentional fire extent and distribution	Remote-sensing and field data
	Forest thinning extent and location	Remote-sensing and field data
Integrity	Fire frequency and intensity in WUI zones	Remote-sensing

3.3 Basin-wide Monitoring: Remotely Sensed Data

Remotely sensed data are increasingly a high value contribution to, and a complementary to field-based measurements of, condition data for broad-scale monitoring systems. Remotely sensed (satellite) data are freely and reliably available from a wide range of sources, and provide valuable information across 100% of a landscape (the basin, in this case). Satellite sources can vary over time, but there are now institutionalized mechanisms within the US Forest Service and other federal agencies dedicated to acquiring, interpreting, and generating spatial data layers from available satellite imagery. Further, new products are being innovated and made available on a regular basis.

Information on land cover types (e.g., rock, water, vegetation), vegetation cover, some aspects of vegetation condition (e.g., wetness and greenness), and burns (extent and severity) can be derived directly from satellite data, but more commonly satellite imagery is being used in combination with other data sources (e.g., FIA plot data, Lidar data, topographic features, substrate and soil features) to model suites of more detailed metrics across 100% of the landscape using imputation and related spatial modeling techniques. In most cases, the scale of the modeling units are 30-m pixels, but in some cases they can be as small as 3-m pixels (Planet data) or even sub-meter resolution (Lidar data). As such, remotely sensed data, and satellite imagery in particular, form an important building block for many modeled and mapped landscape vegetation and fire monitoring metrics.

LANDFIRE, CECS, and TreeMap

The primary remotely sensed products that can serve as a valuable source of status and change data for the Lake Tahoe basin include LANDIFRE, CECS, and possibly TreeMap. These three sources of interpreted, landscape vegetation and fire metrics are described briefly below. The metrics of greatest interest and potential value from each data source for TEON as part of the basin-wide monitoring are listed in Table 3-12. Some CECS map products and change detection results are available in Appendix A.

LANDFIRE (LF) is a program produces national scale, spatial products that represents the best available contiguous data for the United States (landfire.gov). LF data characterize the current states of vegetation, fuels, fire regimes, and disturbances. LF data characterize the current and historical states of vegetation, fuels, fire regimes, and disturbances. Additional products include reference data, land management activities databases, and ecological models. LF produces a comprehensive, consistent, scientifically credible suite of more than 25 geospatial layers, a reference database, and a set of quantitative vegetation models at a national extent. LF data are currently refreshed every other year.

The Center for Ecosystem Climate Solutions (CECS) is a team of nearly 50 scientists at 8 research institutions, with support from partners at state and federal agencies, nonprofits, and the private sector, all working together with the goal of developing thoroughly evaluated, accessible data products to inform and optimize land management decisions. CECS has developed remote sensing and geospatial tools to consistently quantify current conditions and the effects of past and ongoing management on an integrated, statewide scale. This data covers numerous categories of land surface characteristics, including:

- Biomass stocks and carbon dynamics
- Water balance and the delivery of runoff to rivers and groundwater
- Vegetation cover, and management or disturbance history
- Surface fuels and wildfire spread and severity.

Table 3-12. Primary sources of remotely sensed data available to the Lake Tahoe basin, with Lidar added for comparison.

	LANDFIRE	**CECS**	**TreeMap**	**Lidar-based products**
Refresh frequency	Every other year	Every year	Syncing with LANDFIRE	Variable for Lidar, annual for imputed products
Vegetation type – potential	Potential natural vegetation as per the Biophysical unit (BPU)	NA	NA	NA
Vegetation type - current	Vegetation association	Cover types	Forest type	NA
Vegetation structure and composition	Seral class	Late seral class	Tree list – stem density by species by diameter class	Tree density (TAO), height, and derived structure metrics
Fire history	Burn severity by year (MTBS)	Disturbance by year	NA	NA
Fire frequency	Fire return interval departure (MTBS)	Disturbance by year	NA	NA
Water balance and fluxes	NA	AET x P metrics	NA	NA
Carbon	NA	AGL carbon	AGL carbon	Derived from tree height and TAO density
Forest fuel	Total tons	Surface fuels	Total and by class	Can be derived
Air quality	NA	NA	PM2.5 emissions x burn intensity (derived)	NA

To achieve this, CECS researchers collected and homogenized existing data on these ecosystem metrics, and then improved upon this existing data by creating new datasets to fill critical gaps. This includes data on surface fuels, detrital carbon stocks, vegetation disturbance, and water and carbon exchanges. This data spans from 1986 to present, allowing users to examine the effects of past management or disturbance.

TreeMap is an imputed map product generated to fill the need for tree-level mapping for planning and assessment. FIA plot data are used to generate a set of relationships between environmental predictors - topography (slope, elevation, and aspect), location (latitude and longitude), biophysical variables (photosynthetically active radiation, precipitation, maximum temperature, minimum temperature, relative humidity, and vapor pressure deficit), and disturbance history (time since disturbance and disturbance type) - and forest characteristics – they then use a modelling approach that employed a random forests machine-learning technique to attribute forest characteristics to every 30-m pixel across the conterminous US.

FIA contains tree-level information from thousands of plots across the United States, but the plots don't provide wall-to-wall coverage. LANDFIRE provides a 30x30 meter grid of geospatial information like vegetation type and disturbance history for the entire United States, but lacks information at the tree level. Through an artificial intelligence technique, the scientists essentially matched each pixel of the LANDFIRE database with a forest inventory plot that best represented that area. For any 30x30-meter pixel, a TreeMap user can download tree-level information and produce maps of those attributes, like tree density, heights, and species.

Lidar and Imputed Lidar

LiDAR, an acronym for "light detection and ranging," is a remote-sensing technology that uses laser beams to measure precise distances and movement in an environment, in real time. LiDAR data can be used to generate everything from detailed topographic maps to the precise, dynamic 3D models that are required to safely guide an autonomous vehicle through a rapidly and constantly changing environment. LiDAR technology is also used to assess hazards and natural disasters such as lava flows, landslides, tsunamis and floods.

The Lake Tahoe basin has two sets of airborne Lidar – one from around 2015 and another around 2020. The imagery was generated and processed by JPL, and it was to provide sub-meter resolution data for vegetation and topographic characteristics. It is particularly accurate and useful in mapping canopy height, vegetation cover, carbon, and spatial heterogeneity. Three challenges with Lidar data are 1) it is expensive to obtain (~$150k to cover the entire basin), 2) it can take 1-2 years after the flight to receive processed products, and 3) there can be flight and processing problems that can extend the timeline and/or limit the utility of the data. As a result, Lidar data are less frequently obtained – commonly on a 5-10 year cycle, which when it comes to monitoring change translates to a slow response time - a minimum of a 10-year timespan to obtain three data points for any given unit of analysis. However, good quality Lidar that is relatively current is considered the most accurate source for the metrics it does well, and the one of the few reliable sources for fine-scale forest structural heterogeneity.

In the process of obtaining airborne Lidar, additional sensors can be simultaneously employed to gather additional useful vegetation and cover type data. Specifically, hyperspectral sensors can be used to collect images that complement Lidar data and broaden the array of metrics that can be derived. Hyperspectral data in forest management allows for detailed analysis of forest conditions by capturing a wide range of wavelengths across the electromagnetic spectrum, enabling identification of tree species, forest health, vegetation stress, carbon accounting, regeneration, and forest fuels, thereby providing valuable insights for informed decision-making in forest management practices. Hyperspectral data have the same limitations as noted for Lidar data.

Imputed Lidar products are now consistently available through various vendors, and they have proven to be reliable and useful sources for metrics that Lidar excels at measuring – namely vegetation height and cover, and the many derivative metrics that can be generated from these data. Planet Labs is currently producing an annualized imputed Lidar product at 3-m resolution for North America that is likely to provide the most accurate estimates of forest structure and carbon on an annual basis of all available data sources.

JEDI

The Joint Effort for Data Assimilation Integration (JEDI) is an open, community resource to enhance, develop, and test tools, components, and methodologies for data assimilation across multiple DA and modeling systems. The goal of the Joint Emissivity Database Initiative (JEDI) project is to create a unified land surface emissivity Earth System Data Record (ESDR). An ESDR is defined as a long-term consistent and calibrated dataset valid across multiple missions and satellite sensors for a given parameter of the Earth system, which are optimized to meet specific requirements in addressing science questions. Emissivity products are produced from NASA sensors in low earth orbit such as MODIS on the Terra and Aqua platform, AIRS on Aqua, ASTER on Terra, and the more recent VIIRS on Suomi NPP, all at different spatial, spectral and temporal resolutions. JEDI data are not broadly available yet, but there is excitement about the potential for these data to provide the same resolution and accuracy as airborne Lidar for a variety of coveted vegetation metrics.

Recommendation: Leverage existing open-source remotely sensed data sources (LANDFIRE, CECS) and their derivatives (TreeMap) to provide the foundation of landscape-wide vegetation change metrics to the degree possible. Consider investing in Lidar-imputed product from Planet Lab (Salo product line) directly or in partnership with institutions operating at larger scales (TCSI, Sierra Nevada). Consider investing in Lidar and hyperspectral data on a periodic and regular basis (5 years, ideally) to serve as calibration for modeled products and to provide a periodic map product that can represent change in some metrics with high accuracy and precision.

Chapter 4: Sentinel Watershed Monitoring

4.1 Sentinel Watersheds: Objectives and Selection

Lake Tahoe's water quality in both the nearshore and the center of the lake is partly controlled by the contributing watersheds that compose the Lake Tahoe Basin, yet the linkages between the uplands and the lake through the streams are poorly understood. In addition, a major effort is underway to manage the watershed for biodiversity and to minimize the impacts from wildfire, climate, and other environmental disturbances.

Sentinel Watershed Objectives

The Tahoe Environmental Observatory Network (TEON) identifies and establishes watersheds for monitoring terrestrial and upland aquatic processes to better understand controls over inputs to Lake Tahoe. The University of Nevada, Reno TEON team in partnership with their collaborators from the US Forest Service's Pacific Southwest Research Station and the Lake Tahoe Basin Management Unit have been investigating and testing sentinel watershed selection and sampling methods toward providing a set of recommendations for TEON sentinel watershed monitoring. The sentinel watersheds serve to provide fine-grained data that spans land and water processes through a combination of field staff and automatically collected research-grade data on climatic, soil, vegetation, wildlife, and water-quality data.

Near-term objectives of sentinel watershed monitoring were to establish prototype systems for the collection of terrestrial and aquatic data, and design publicly available databases that update in real-time or near real-time (some data types necessarily require initial quality control and assurance routines). These objectives were accomplished through the establishment of two sentinel watersheds. Longer-term objectives are to establish additional sentinel watersheds (provisionally 6 to 8) around the basin to provide a more spatially representative suite of response data, expand the breadth of data collection and research opportunity within each watershed, and to continue to enhance the accessibility of data and results to the public to strengthen the connection between people and their environment. They can also serve to focus research on topics of concern and interest to scientists and managers, expediting our understanding of complex systems and how management can effectively achieve and sustain desired outcomes.

Sentinel Watershed Selection Criteria

The watershed selection process requires careful balance involving the simultaneous consideration of numerous important factors, including (but not limited to):

- representativeness of the basin,
- accessibility of locations throughout the year (including high-elevation terrestrial sites)
- security and degree of removal from public view,
- fraction of urban development,
- size of watershed,
- elevation range of watershed,
- ability to connect with cellular versus satellite versus radio communications,
- land ownership (including sites of stream outlets to the lake),
- ongoing or previous research and monitoring activities
- capturing east-side versus west-side climates/geologies
- collocation of terrestrial and aquatic systems

For further discussion and collected data informing site selection, please see the attached Appendix H.

Sentinel Watershed Selection

For candidate sentinel watersheds, we only considered the seven watersheds that have USGS gauges and existing flow records (starting in the north and going clockwise around the basin): Third, Incline, Glenbrook, Trout, Upper Truckee, General, Blackwood, and Ward.

Blackwood Creek and Glenbrook Creek were selected as the initial sentinel watersheds for the demonstration project to determine the efficacy and possibilities for creating a Tahoe Environmental Observatory Network. In addition to consideration of the factors listed above, there were several key attributes that established them as ideal candidates.

- Blackwood Creek and Glenbrook are not dominated by lakes, to minimize water residence times and more directly observe climate-stream and upland-stream linkages.
- The differences in climate between Blackwood and Glenbrook imply strongly contrasting outlooks for how streamflow will change in projected future climates (Appendix H).
- Elevations and relative levels of development are similar between Glenbrook and Blackwood (Table 3), which is untrue of other East-shore watersheds: Third creek is almost 22% developed and has a max elevation of 3150m and mean elevation of 2508

m, and Incline is 15% developed with a max elevation of 2804 m and mean elevation of 2358 m.
- A history of research at Blackwood and Glenbrook watersheds facilitates understanding challenges and expectations, to optimize sensing and measurement approaches (see section 3.1)
- All three of the watersheds in Nevada have sufficient proximal roads to facilitate access, and none of the California watersheds provide ideal circumstances unless they are accessible via ski resort infrastructure.
- Incline Creek was also identified as a potential candidate because of expected administrative ease using University of Nevada, Reno Lake Tahoe campus. The campus also allows for availability of line power which is of major benefit for reliable sensor installations. A limitation of this site is that soil moisture and tree water status are influenced by irrigation; these factors are likely to indirectly influence air temperature and humidity as well. While climate and upland measurements are currently underway at the University's Lake Tahoe campus. We are continuing to evaluate the value of a single climate station at UNR-Tahoe, putting effort towards developing an Incline transect, or re-allocating the instrumentation to other sites.

While the pairing of Blackwood and Glenbrook provides a solid foundation for sentinel watershed monitoring, increasing the number of sentinel watersheds would strengthen the watershed monitoring dataset and confidence in observed relationships and trends. The addition of the Upper Truckee watershed as a third sentinel watershed would likely add the most differentiation from the other watersheds (e.g., location, precipitation, size, condition, topography) and introduce the watershed with the greatest projected changes in future climates (Appendix H); differentiation is desirable from a sentinel-watershed perspective. However, Upper Truckee introduces access challenges (see Appendix H), with Incline or Third Creek being the easiest to add to the current set, from a logistics perspective.

4.2 Sentinel Watersheds: Methods Testing

The sentinel watershed monitoring evaluation and testing was designed to address how best to accomplish the following monitoring objectives:

1. Trace the influences of water from snow and rain in the Lake Tahoe headwaters through soil, trees and rivers.
2. Understand how rain and snow interact with soils to generate solutes, which are then transported to streams, undergo biogeochemical cycling and are eventually transported to Lake Tahoe.

3. Assess climatic conditions under the forest canopy, from headwaters to lakeshore.

Three sentinel watersheds were tested over the course of the past two years (Figure 4-1). Within each watershed, instrumentation was established at multiple locations (Table 4-1) as part of testing and evaluating the best approach to capturing within-watershed dynamics and interactions (Figure 4-2).

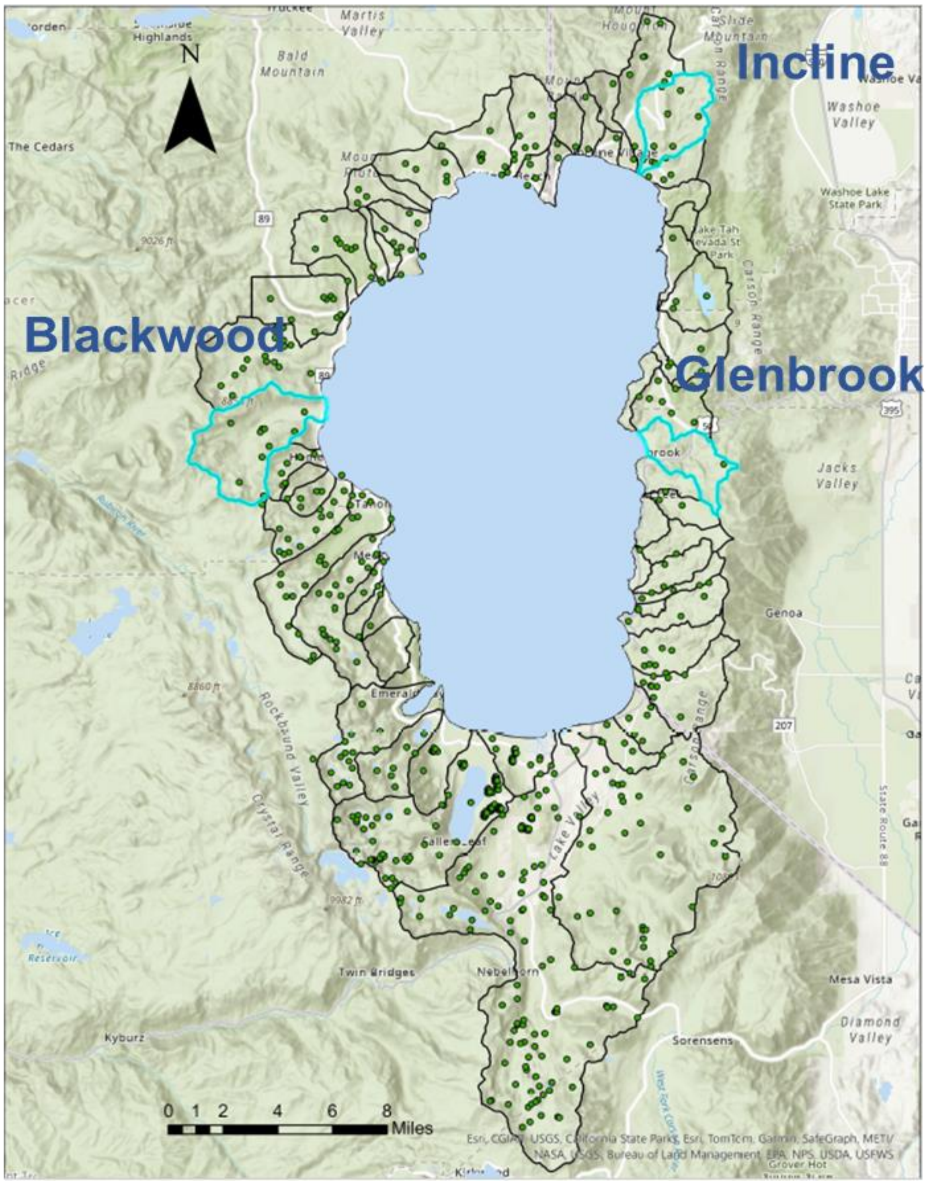


Figure 4-1. Provisional sentinel watersheds used to test and evaluate sampling equipment and methods.

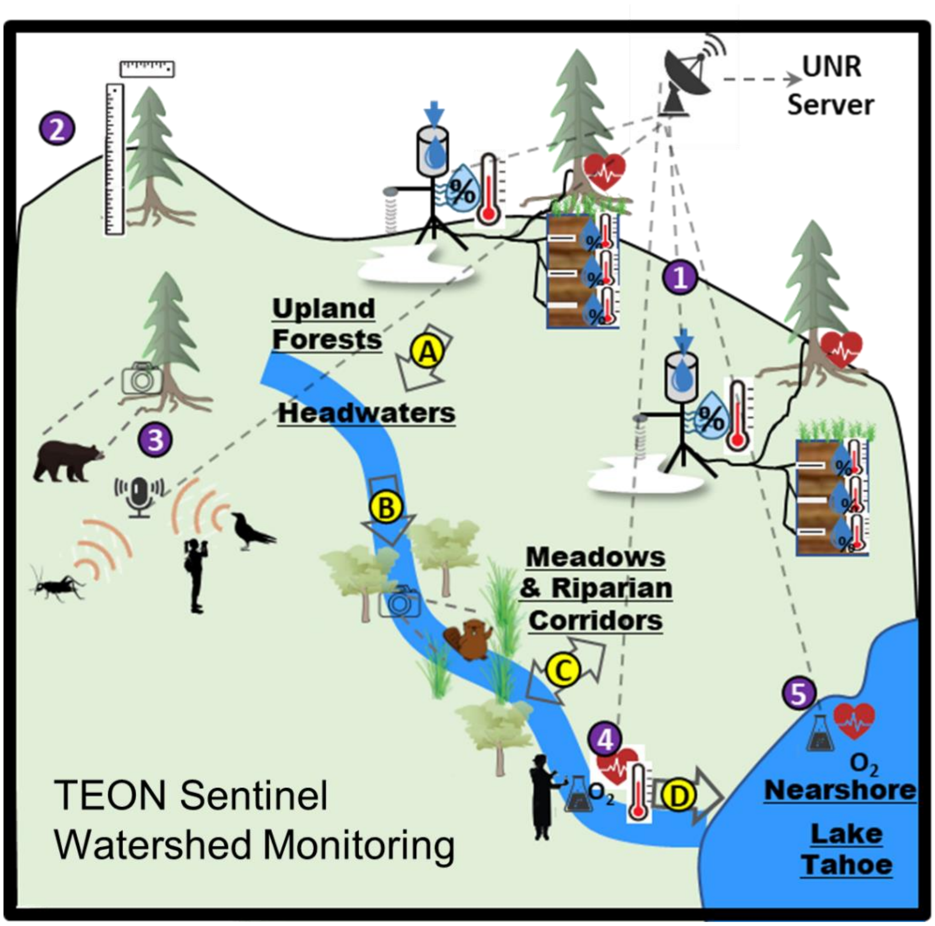


Figure 4-2. Graphical representation of instrumentation and data collection in a sentinel watershed. Letters in yellow indicate interfaces on the upland-stream-lake continuum, and numbers reflect measurements. A) Climate-terrestrial interactions determine water partitioning (up v. down) and solute exports. B) Headwater streams connect to uplands via surface- and ground- waters. C) Riparian areas and meadows are biogeochemistry and wildlife hotspots, modifying chemistry. D) Stream exports (e.g., C, N, & sediments) to lake reflect terrestrial inputs and subsequent modifications via biological, chemical physical processes. 1) Upland forest sensor stations with real-time monitoring of climate, soil moisture, tree water status, and time-lapse photos. 2) Manual measurements will include vegetation measurements (leaf area, height, cover), soil seepage fluxes. 3) Distributed acoustic recorders and camera traps will document wildlife. 4) Stream in-situ sensors monitor temperature, conductivity, dissolved oxygen, pH, and grab samples to analyze H2O stable isotopes, macronutrients. 5) Near-shore in-situ sensors and grab samples match the stream in-situ sensors to know stream in-flows effects on lake water quality.

Table 4-1. Watershed characteristics of basins defined by locations of sensor stations.

Metric	Glenbrook 1	Glenbrook 2	Blackwood 1	Blackwood 2
Location	East	East	West	West
Total stream length (km)	6.1	4.7	21.0	18.6
Annual precip (cm)	60.8	60.8	143.4	143.4
Mean Elevation (m)	2249	2287	2214	2244
Min Elevation (m)	1902	1973	1899	1932
Max Elevation (m)	2687	2687	2686	2686
Mean Slope (%)	28.8	28.0	31.8	32.8
Area (km2)	10.4	8.7	29.7	25.6
Percent forest	85	88	74	73
Percent wetland	< 1	0	1	1
Percent shrubland	11	9	23	25
Percent developed	4	3	2	<1

Across all years, we found net ecosystem productivity, and epilithic biomass were positively associated with ammonium concentrations at both streams. While streams have the potential to importantly remove nutrients sourced from headwaters before reaching the nearshore lake environment, our results suggest that long-term monitoring is needed to understand how long these effects persist from wet to dry periods, across distinct watershed. The dendrometers and soil moisture sensors revealed distinct variations in water content throughout the growing season and demonstrated the ability to detect plant water stress in real-time. Stable isotope analyses revealed distinct seasonal responses showing the elevation and precipitation source contributing to streams throughout the year. For more details on all testing of methods, please see the Appendix H.

Table 4-2. Summary of sentinel watershed monitoring sites used for testing methods.

Site Name	Site Coordinates (approx.)	Elev. (m)	Terrestrial sensors	Stream sensors	Data Telemetry
Blackwood 1	39° 06'26.67"N, 120° 09'43.69"W	1906	USGS gauging site, no additional sensors added		N/A
Blackwood 2	39°06'40.2" N, 120°11'12.8" W	1938	2 soil moisture sensors; 1 air temp/RH sensor; 8 tree dendrometers; 1 heated rainfall/snowfall gauge	Stream level logger; Aqua Troll 400 multiparameter geochemical sonde	No cell signal - need to explore other data telemetry options
Glenbrook 1	39° 05'17.00"N, 119°56'20.73" W	1909	2 soil moisture sensors; 1 air temp/RH sensor	N/A	Cellular data telemetry
Glenbrook 2	39°05'09.2"N, 119°55'19.3"W	1985	Installation not yet begun	Installation not yet begun	Installation not yet begun
Glenbrook 3	39°05'14.1"N, 119°54'36.8"W	2081	Proposed site determined to be inaccessible; monitoring will not be carried out here		
Glenbrook 4	39°05'36.4"N, 119°54'05.4"W	2309	2 soil moisture sensors; 1 air temp/RH sensor	N/A	Cellular data telemetry
Glenbrook 5	39°04'28.7"N, 119°53'28.5"W	2422	2 soil moisture sensors; 1 air temp/RH sensor	N/A	Cellular data telemetry
UNR Tahoe Campus	39°14'35.03"N, 119°56'25.21" W	1924	1 soil moisture sensor; 1 air temp/RH sensor	N/A	Cellular data telemetry

4.3 Sentinel Watersheds: Metrics of Integrity

The watershed methods tested helped to identify metrics that are both important ecosystem conditions, management relevant, and feasible to measure effectively (Table 4-3). The list of metrics for sentinel watersheds reflects the water security metrics that are uniquely addressed in sentinel watersheds and more intensive measurements of metrics being measured through broad-scale monitoring to enhance the ability to understand causal factors driving change, with particular emphasis on climate impacts.

We can generate metrics to better understand and evaluate system integrity. Using time series of data representing climate, water quality, and soil/plant water-status, we would be staged to identify anomalies. These could include increases in nutrient loading, or especially hot and dry periods, to trigger responses. Longer durations of monitoring are needed to establish what those critical anomalies are, as the range of variation in all of these metrics is large due to the intense seasonality of climate and water fluxes in the Sierra Nevada. Stream ecosystem respiration can be inferred through continuous monitoring of dissolved oxygen and temperatures, and this could be used to reflect other sources of disturbance beyond climatic variations (e.g., punctuated erosion or pollutant runoff events). The combination of dendrometers and soil moisture sensors will provide insights into short-term acute water stress events, the likes of which are likely to lead to mortality, pathogen invasions, of enhanced wildfire risk. At longer timescales of interpretation are precipitation totals and quickflow analyses using stable isotopes. Precipitation monitoring takes place in other locations within the Tahoe basin, but we have fairly limited insights into how snow inputs vary by storm across the basin, and how those heterogeneities accumulate. Stable isotope ratios can also indicate events that result in much more rapid precipitation-to-stream movement of water, which is crucial for interpreting water quality data; by itself, tracking these data could indicate changes in streamflow generation associated with, for example, changing snowmelt regimes, increasing urban development, or responses to wildfire.

Table 4-3 Sentinel watershed core metrics recommended for watershed monitoring.

Domains	Metric	Source
Water security		
Focal features	Climate: high temperature / low humidity anomalies	Climate sensors
	Precipitation totals	Climate sensors
	Terrestrial Water Stress	Dendrometers and soil moisture sensors
	Quickflow Ratios	Stable Isotopes
Integrity	Water Quality: TSS, Nitrate-N, Ammonium-N, Phosphorus Loading	Water grab samples
	Aquatic respiration	Dissolved Oxygen Sensors
Broad-scale metrics intensified		
	Forest structure and composition metrics	Remote-sensing and field data
	Plant, bird and mammal community metrics	Field data
	Meadow metrics (all meadows including lost meadows)	Field data
	Wetland habitat metrics (all wetland habitats)	Remote-sensing and field data

Recommendation: We recommend building upon the existing UGS gauging of streamflow to also include chemistry data that allow for understanding aquatic ecosystem health and nutrient loading to the lake. We recommend upland sampling of climatological data – particularly high-quality precipitation measurements – that builds upon and infills gaps in existing networks. A network of in-situ soil moisture and tree-stress measurements provides data streams that otherwise do not exist, and thus is particularly valuable for direct insights, and for locally ground-truthing remote-sensing data. We recommend increasing the intensity of sampling for a subset of features to enhance our understanding of upland-aquatic linkages (wetlands and meadows) and to evaluate climate impacts by intensively sampling along elevational gradients (forest and biodiversity metrics).

Chapter 5: Implementation

5.1 Broad-scale Monitoring Implementation Guideposts

A few initial considerations in implementation and adaptive management are intentions:

- Sustainability and consistency over time is critical
- Collaborative approach to data collection across agencies and between research and management
- Coordination across data collection efforts in terms of data curation, and data analysis and interpretation essential to maintain the integrity of the data and results

Sustainability and Consistency

Sustainability and consistency are achieved through a balance of 1) identifying a set of core metrics (Tier 1) that provide a robust representation of pillar conditions; and 2) establishing a level of investment (institutions and funding) that is sustainable for at least the first 10 years. Monitoring does not need to be limited to the core set, rather additional data collection efforts can be modularized (Tier 2) so they build on the core set of data, but be funded and implemented individually, perhaps by a single agency, possibly funded by a non-government institution that has a particular interest in monitoring (e.g., Bear Aware for bear monitoring), and potentially less frequently or for shorter periods of time. Tier 2 investments may also take the form of increasing sample sizes for features of interest where Tier 1 sampling does not provide sufficient sampling intensity to meet the objectives of an interested institution.

The nuts and bolts of implementation cover an array of parameters and considerations that are touched on here: 1) spatial and temporal pattern of field data collection; 2) what entities are responsible for collecting which data sets and how are multiple entities being coordinated; and 3) data curation (quality control, integrity management, access).

Sentinel watershed monitoring has a unique set of implementation considerations. Increasing the number of sentinel watersheds comes with costs and commitments. Instrumentation to obtain precise hydrologic measurements has a high upfront cost, both to purchase the equipment and to install it. Once it is installed, it requires regular visitation during the non-winter months, and additional investments to prepare for winter and bring equipment back on-line in the spring. We have found that one crew of two individuals (one skilled lead plus one technician) can maintain ~6 instrumented sites (~two watersheds), including managing instrumentation upkeep, data produced, and the collection and analysis of grab samples during the non-winter months (approximately April to November). The intensive terrestrial measurements of vegetation and wildlife (complements to the broad-scale monitoring) do not have this high initial cost, and but consistency in annual measurements over the same time period as the hydrologic measurements is an important part of gaining a better understanding of terrestrial-aquatic linkages and their individual and interdependent responses to climate and environmental change.

The greatest value of sentinel watersheds is to have time series data for detailed measurements of multiple processes operating across the watershed. Generally, the investment in establishing a sentinel watershed has the greatest return on investment if data are collected for 10 or more consecutive years. The life of the equipment varies, but it is likely that technological advancement and the wear-and-tear of use would lead to replacing most equipment after 10-years.

Temporal Considerations

In terms of data considerations, generally the more frequent and comprehensive the resampling, the more sensitive the monitoring network will be to detecting change. One might assume that the most robust approach would be to sample every site every year – for example, if 100 sites are selected as the core, all 100 sites would be sampled every year. Indeed, this approach offers the best representation of each site. Alternatively, if that effort was spread over more sites, and each site was sampled every 2 or 3 or 4 or 5 years, then the resulting sample size could grow to 200 (every 2 years) up to 500 (every 5 years). The strength of this approach is much stronger representation of conditions, and the limitation of this approach is that the change data per sample site is less frequent, and annual change is confounded with change in the sites being sampled which introduces error in the form of site differences.

Given the desirable balance of rigor and cost, panel designs tend to provide the best outcome of reducing error rates (type I and type II errors) per unit of sampling effort (e.g., FIA panel design). In short, a panel approach is a blend of the two approaches described above: an annual sample effort is established (100 sites in this example), a resample frequency is determined (max of 5 years suggested for the LTB). Below, an example based on a 4-year resample cycle is described. The annual capacity is reduced by 20% to create 5 panels - the number of years plus one. One panel is sampled every year to provide an annual measure of change that is not biased by site variability (in this case 20 sites per year), and the remaining 80 sites are a new set of sites each year for 4 years. The resulting sample size of sites in this example is (80 x 4) + 20 = 340 sites. Twenty sites is a small number of sites – it is probably advisable to have at least 30 sites in the annual resample, and adjust either the new sites per year or increase capacity for sites sampled per year. The annual panel and the remaining sites sampled each year need to be spatially balanced so that the annual panel and the annual samples are spatially representative.

Recommendation: Establish a panel design for field data collection. Metrics, methods, and metric-specific sample sizes need to be drafted before an assessment of annual sample effort could be determined, sites selected, and then panel allocations made. An annual resample panel of at least 30 sites is suggested to bolster confidence in estimates of annual change.

Spatial Considerations

Any monitoring effort must take care to ensure that the sample of sites which are monitored are representative of the ecological population about which inferences are being made. Chapter 3 describes how the FIA grid can act as the backbone of a spatially balanced sampling design by evenly distributing plots across the basin. But the ecosystems we wish to monitor are not necessarily spatially uniform – conditions vary across gradients of elevation, aspect, hydrological function, and human influence to name a few. Pre-stratifying sample sites by target ecosystem types can create statistical issues if sample sites can change strata over time. It is best to limit targeted sampling to a few discrete strata that are expected to be stable (not move into a different strata) over at least a few decades, if not longer. Stratifying sites by multiple ecotypes also can have the effect of either A) requiring such a large sample size to be prohibitively costly to monitor, or B) reducing the sample size within each strata so as to prevent meaningful conclusions for that group.

Recommendation: To the degree possible, do not pre-stratify, but rather set systematic sampling criteria (number of sample sites per hexagon) to build sample sizes to represent major ecotypes of interest, and then augment that sample with additional targeted sample locations.

Sample Size Considerations

A tiered approach is recommended for building broad-scale monitoring sample size. Target sample sizes and the associated representation that would result can be evaluated based on existing data to help inform priority levels of investment in broad-scale versus targeted sampling versus sentinel watershed sampling. The first step in this evaluation process would be to identify the ecotypes or components against which representation will be judged. Then strength of the representation of those components can be evaluated with each increment of additional samples.

Parsing the basin into components for the purposes of evaluating sample size adequacy can be based on a number of ecological criteria. In terrestrial systems, major vegetation types are probably the most informative, and in aquatic systems, major wetland ecotypes would be the most informative. Here, we explore what the terrestrial vegetation components might be.

The California Wildlife Habitat Relationship (CWHR) system vegetation-based habitat types provide a useful option, particularly because they include all forms of terrestrial and aquatic habitat types, plus barren and urban. Fifteen of the 59 CWHR habitat types (Mayer & Laudenslayer, 1988) occur in the LTB. Widespread habitats, such as Red Fir (RFR), Lodgepole Pine (LPN), Sierran Mixed Conifer (SMC), Jeffery Pine (JFP), Subalpine Conifer (SCN), White Fir (WFR), Barren (BRN), and Urban (UBN) are likely to accrue quickly in a stratified random sample of sites. Less extensive habitat types, such as Montane Chaparral (MCP), Alpine Dwarf Shrub (ADS), Juniper (JUN), Sagebrush (SGB), Aspen (ASP), Montane Riparian (MRI), and Wet Meadow (WTM) may require a larger sample size or targeted sampling to achieve meaningful statistical power. Yet a further simplification of this representation exercise would be to use broader habitat classes in the CWHR system, resulting in 13 CWHR categories total (versus 59), 8 of which are present in the Basin: Conifer Forest, Conifer Woodland, Hardwood Forest, Herbaceous, Shrub, Wetland, Barren, and Urban.

Recommendation: We recommend that a sample size evaluation be conducted to elucidate gains in representation and sample sizes with each increment of additional sampling effort. For example, an initial sample size could be in increments of 50 or 100, with the addition of samples first selecting a single sample point in a single subhexagon per FIA hexagon (~30 FIA hexagons), followed by selecting a single point in a second subhexagon, and so on until there is a single sample point in each of the 7subhexagons in every FIA hexagon (~210 sample points), followed by a second pass that locates a second point in each subhexagon (total of ~ 420 sample points), etc. Also, the location of points in each subhexagon could entail the location of one terrestrial and one aquatic, or perhaps in some other ratio (e.g., 2:1 terrestrial to aquatic). As additional samples are added, one would track gains in the representation and sample size for each component (in this example the 13 CWHR types and a commensurate set of aquatic ecotypes). Since these sample site locations with each subhexagon are randomly located (at least within terrestrial and aquatic ecotypes), each time this is done it would result in a slightly different result. As such, we recommend bootstrapping this exercise, so that the result would represent the average of 1000 or more outcomes.

Adaptive Management

One additional topic is analysis, interpretation, reporting, and adaptive management. In the category of managing workflow for both data collection, analysis, and adaptive management, other large landscape monitoring systems have adopted a strategy of collecting data for 4 years, and then taking year 5 to summarize and report out on results. For an annualized panel design, it would continue to be collected every year to provide that continuity. The downside of this 4-on:1-off strategy is the cost (staffing, vehicles, etc) of ramping down for year 5 and ramping back up in year 6. It may be more manageable to have an even flow of staffing and data collection. Both spatial and temporal patterns of field data collection can be informed and shaped by data and funding considerations.

Incorporating adaptive management into monitoring and project planning is especially important in the context of climate change. Adaptive management allows managers to account for the uncertainty that is inherent in climate change projections. Planning for uncertainty and adaptively managing allows managers to modify interventions based on updated scientific findings and climate projections, new management techniques, or technological advances.

The Monitoring Plan will provide critical data on the conditions of Lake Tahoe's west shore by incorporating the best available information and monitoring. Lake Tahoe West partners use data on environmental and socioeconomic conditions to adaptively manage interventions based on observed conditions. Lake Tahoe West's adaptive management approach will ensure accountability among partners, build shared understanding of various management approaches while also strengthening trust, and increase the effectiveness of restoration and management activities.

Figure 5-1 is adopted from Lake Tahoe West's adaptive management plan, which focuses on how monitoring and assessment activities and the data collected as part of that monitoring plan would feed into adaptive management. Based on the general premise for adaptive management outlined for the Lake Tahoe West project, we suggest a pathway for TEON monitoring data to be provided to and considered in adaptive management:

- Identify favorable, unfavorable, and trigger point conditions for each metric and place-based combinations of conditions that would inform determinations of resilience, opportunity for improvement, or concern that may precipitate further assessment and the need or priority for management investment or intervention;
- Monitor and assess status and change
- Track and monitor progress toward achieving and maintaining environmental quality and resilient conditions across the basin through regularly scheduled summary, analysis, and reporting.

Recommendation: Science and management oversight and support will be needed for TEON to be successfully implemented and sustained for a decade. A TEON steering group could serve this purpose, where the group would identify priority investments, funding opportunities, reporting review, and adaptive management processes.

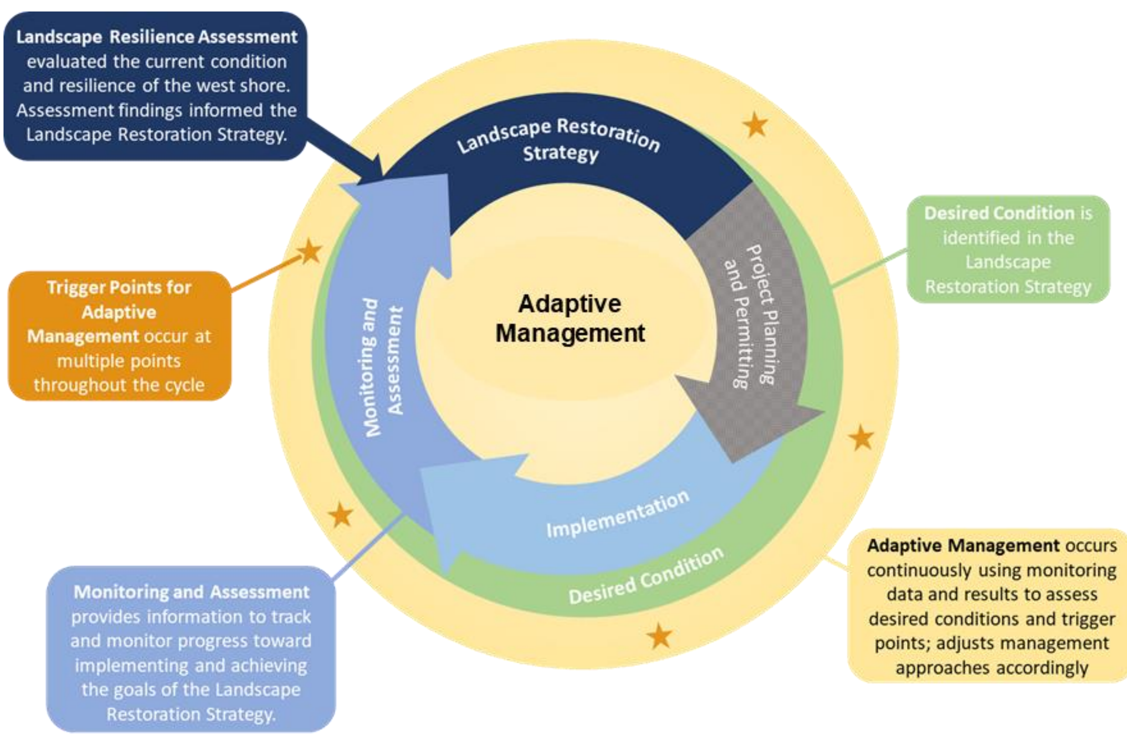


Figure 5-1. Adaptive management cycle from the Lake Tahoe West project draft monitoring plan.

5.2 Lake Tahoe Basin Environmental Atlas

Many large landscapes find that portraying information in the form of an atlas based on intermediate sized units is a very effective and relatable way to portray conditions and report status and change. For the purposes of measuring metrics, the 30-m resolution of most data are sufficient resolution to capture measures in sufficient detail to address status and change. However, 30-m pixels are not terribly useful when it comes to communicating with the public or tracking change over time. Larger subunits are most useful for tracking change over time - sufficiently large to represent the condition at a meaningful scale - sufficiently small to portray change in distribution and dispersion across the basin over time.

A common scale used for environmental atlas products is 1-km squares (Figure 3-1 B), and there are approximately 1300 1-km^2 squares in the Lake Tahoe basin. Units based on land features, such as watersheds, are also useful, but having consistent sized units across the basin has strong advantages in analysis and interpretation. For Lake Tahoe, this is a minimum number - ~10 to 30 per watershed - and more could be useful - perhaps at the 0.5 km^2 scale, which would result in 5200 units, four-times as many as the 1-km2 unit size. At this scale, the size and number of the units verges on unrelatable. Also, using a size that conforms with much of the source data (30-m satellite imagery), argues for 900x900-m units as a good scale to use as the base (can always scale up or down), equating to ~1600 units across the basin. Linear features, such as streams, could benefit from a smaller unit - and in their case, 0.5 km^2 unit sizes could serve this function well.

In order to populate the LTBE Atlas, data on each metric needs to be converted to a value that can be attributed to each unit, based on the conditions across the unit. For remotely sensed data available at the 30-m scale, and that equates to 900 pixels (30 x 30 pixels) in each unit. Across those 900 pixels, values could be averaged or summed or their variance described, etc. For field-based data, there may or may not be a sample unit in each cell. It is expected that metric values derived from point data would be derived through modeling and attributed to units based on environmental covariates (e.g., habitat suitability models for wildlife species).

The use of a fixed reporting unit as the foundation of the Atlas will result in all metrics being converted to compatible scales, which in turn enables comparing metric values across metrics within a unit and over time within and among units at a scale that is relatable. For example, the habitat occupancy status for each focal species, metrics of species diversity, and metrics of community integrity and connectivity would all be attributed to a unit as averages, minimums, maximums, dominance or other representations. Positive species sightings could also be attributed to units. Similarly, metrics of large tree density, seral stage, fire regime, fire risk, and SDI will also be attributed to each unit. Finally, aquatic site conditions where they occur would also be attributed to each unit, to indicate that an aquatic site occurs within the unit and its condition. The spatial covariance of metric conditions relative to one another can be evaluated at a point in time and over time within and across units, which has substantial value:

- Enables agencies to speak to any combination of metrics that are relevant to their programs and projects,
- Enables scientists to study how and why metrics are changing over time and relative to one another, providing valuable clues about drivers of change and potential tipping points,
- Enables the public to adopt and/or track their favorite Atlas unit, and could even be the focus of contests for documenting biodiversity (e.g., biodiversity challenges) and/or restoration.

Place-based units are also more stable, making it easier to track substantive change over time, and track spatial shifts in condition. They also lend themselves to measures of spatial resilience, which could be developed for the basin. Finally, for all of the reasons stated, they may be a superior future option as the foundation and focus of some or all threshold standards for TRPA.

Recommendation: Explore the potential value, utility, and structure of an environmental atlas for the Lake Tahoe basin

5.3 Citizen Science in TEON

In addition to field-based and remotely sensed data collection to characterize species occurrence and habitat conditions, citizen science contributions can make a valuable contribution to systematically collected data. Ad hoc positive sighting data, such as those produced by iNaturalist or from other crowd-sourced photo collections (e.g., John et al. 2024) can serve to provide data points for species or locations that are surprising and possibly early detections of change. Periodic pulse events, such as a Tahoe's Snapshot Day (water quality), bioblitz (biodiversity), or annual events such Christmas bird counts or

City Challenge, can serve to provide a more spatially comprehensive set of positive sightings to represent a point in time more comprehensively than the monitoring network. Additional options for Lake Tahoe include the “adopt a watershed” program (EPA), and tapping into existing organized efforts, such as the Truckee River Watershed Council.

While these data do not fulfill the probability-based requirement, they can help identify gaps in distributions or species detections that are not being covered or detected through the systematic sampling. Such efforts are particularly well-suited to the Lake Tahoe Basin because of the exceptionally high visitation it receives from nearby population centers, exponentially increasing the pool of potential contributors to any citizen science data stream.

In addition to data collection, Citizen Science can be a valuable contributor to data management and amplifying public engagement. For example, the Adopt a Watershed program includes the public educating the public about their watershed, taking a personal interest in the fate of the plants, animals, and water in one or more watersheds, and supporting conservation efforts in a variety of ways. This program is

Recommendation: Leverage and enhance citizen science contributions toward meeting the objectives of TEON as an early warning system.

5.4 Data Management and Accessibility

Data Collection and Storage

An important consideration in implementing an environmental monitoring network is the sheer amount of data management and processing that must be done. For field data, such as that collected on forest structure and composition, we recommend the use of tablets and digital datasheets to reduce the amount of time spent entering and proofing data. We used ESRI’s Survey123 software because of its relatively simple yet robust interface, as well as the fact that it is a well-established product that is widely used and trusted within the environmental monitoring community. Digital datasheets should include quality assurance checks to prevent erroneous species codes, unlikely sizes, and missing data while in the field. If tablets are not available, we recommend entering data as soon as possible after collection, preferably by the team that collected the data, so that any errors or missing data are corrected immediately. However, manual data entry into a database offers another step at which errors (typographical or relational) can be introduced to the data management process; for this reason too we suggest Survey123, as it seamlessly uploads data to ESRI's ArcGIS Online portal, complete with relational connections and easily shared at the organizational level or broader in graphical and tabular format.

Data generated by automated recording units can be particularly unwieldy due to size and processing requirements. ARU data from a single season can measure in the terabytes, and requires either a substantial number of man-hours to listen to recordings and identify species, or the use of still-improving AI-based software to process audio files and extract species information. We used Cornell University's BirdNET model, in large part because it is open source and thus presents minimal barriers to use; additionally, it has an easy-to-use interface and is under active development, increasing the chances it remains a relevant and useful tool in the rapidly expanding world of AI. As of yet such software is less accurate than a good human ear (see Appendix D), but the time savings are such that we highly recommend the combined use of such an AI model and human identification. Given the current limitations of AI in bird identification, it is essential that the raw audio files be retained in addition to derived data formats for direct analysis; the rapid pace of development in AI technology suggests that within the next 5-10 years a model surpassing human-level ID accuracy is likely, so the maintenance of raw files allows future models to be run on the same data – this will allow more accurate analysis of wildlife trends in the Basin. Audio files should be stored on a local hard drive both as a backup and because we have found processing speeds to be higher when using local storage as compared to cloud storage. A cloud-based repository or server can be used to facilitate integration with external institutions or datasets (e.g. the Sierra Nevada Bioacoustic Monitoring Data Hub, University of California, Berkeley and California Department of Fish and Wildlife), which is important given the collaborative nature of land management in the Tahoe Basin.

Camera trap data should be managed using reputable software that includes AI trained to filter out blank photos and provide preliminary identification for other captures. All data should be uploaded to an external hard drive as a back-up, and then uploaded to the software system of choice. We used Wildlife Insights, an online data repository with AI that provides some initial data cleaning. Because camera traps often capture many blank images (ie, images without an animal) due to wind, shadows, and precipitation, we recommend that all photos that are assigned "blank" status by AI be accepted to save time. We acknowledge that this may lead to the loss of some animal observations, but these will likely be very small individuals like chipmunks and squirrels, or very difficult to identify to species due to being very far from the camera or barely in the frame. The California Department of Fish and Wildlife terrestrial data processing protocol includes helpful instructions for how to upload, identify and process photos in Wildlife Insights (https://storymaps.arcgis.com/collections/a074c5321dd64ca2902ba72c7012ae64?item=

1). Once photos are classified, spreadsheets with metadata on deployments, locations, and times may be downloaded along with the detection data for summary and analysis.

Data Sharing and Public Products

There are two levels of data sharing to be considered, with different audience and data resolution targets. Data targeted for managers and researchers should be accessible as raw spreadsheets to allow for data manipulation and analyses. As requested by managers, the raw data should include code that quickly summarizes key resources to generate reports or figures. Ideally some user interface would allow for managers to select resources and locations of interest and rapidly generate the desired statistics or figures. For data aimed at the general public, we suggest utilizing existing data resource Lake Tahoe Info (https://www.laketahoeinfo.org/), hosted by the Tahoe Regional Planning Agency.

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