SIMULATION MODELING AND ANALYSIS OF OVERNIGHT VISITOR USE OF THE YOSEMITE WILDERNESS

Final Report to National Park Service, Yosemite National Park, El Portal, California

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EXECUTIVE SUMMARY

INTRODUCTION AND OBJECTIVES

In response to overuse in the Yosemite wilderness, a mandatory permit system was implemented in 1972. Subsequently, the wilderness was divided into 53 management zones, and an overnight camping capacity was established for each. In order to minimize the probability that use exceeds zone capacities, without imposing excessive regulation on users once they enter the wilderness, a trailhead quota system was implemented in 1977. Trailhead quotas were derived from permit data and a simulation model that related zone use to trailhead use. However, changes in the characteristics of wilderness visitors could change the effectiveness of the quota system in preventing overuse, but no systematic study of Yosemite wilderness use has been conducted since the 1970s.

The goal of this study was to assess current use of the Yosemite wilderness. Because of the complexity of interaction among factors that determine use in an individual zone on an individual night ("zone-night"), a computer simulation model, populated with current data on visitor characteristics, is the best way to accomplish this goal. Objectives were:

1. Quantify wilderness visitor characteristics;
2. Compare characteristics of current wilderness users with those of the 1970s;
3. Construct, populate and validate a wilderness use simulation model that
    a. incorporates observed itinerary deviation characteristics,
    b. predicts means and percentiles of use at the zone-night resolution, and
    c. includes the effect of wilderness use originating outside of Yosemite;
4. Employ the simulation model to
    a. quantify current use at the zone-night and annual scales by source,
    b. estimate probabilities of capacity exceedance at the zone-night scale,
    c. quantify the dependence of zone use on trailhead use, and
    d. find a trailhead assignment scenario that achieves "no exceedance"; and
5. Identify both the most heavily used zones and trailheads and the zones and trailheads that have the greatest potential to absorb increased use.

METHODS

We constructed a stochastic simulation model of wilderness use with ExtendSim OR software. Distributions of party size, trailhead selection, and trip date were created directly from the 2010 wilderness permit database, using information from all 14,497 parties that started trips during the 1 May to 30 September season and intended to spend at least one night in the Yosemite wilderness. Trip date was assigned deterministically in the model; all other characteristics were assigned or simulated stochastically. Party size, trip date, and trailhead were the only attributes assigned at the initiation of a simulated trip. Trailheads were assigned randomly by an algorithm that filled trailheads in order of popularity according to observed probabilities of trailhead selection. On average, parties that were assigned a trailhead at quota were reassigned the next most popular trailhead that was available. Instead of creating a fixed set of travel itineraries, travel route and trip duration for each party were created dynamically according to a zone transition probability matrix that was created from the permit database. Additional transition matrices and user attribute distributions were created for Yosemite wilderness use that originated at surrounding U.S. Forest Service (USFS) trailheads.

We surveyed a random sample of 1,123 wilderness visitors to quantify their deviation from intended itineraries and then applied the observed rates of spatial deviation stochastically in the model. Temporal deviation was modeled by changing the odds of exiting the wilderness in the transition matrix, without changing the relative transition probabilities among the zones. The factor by which exit odds were adjusted was determined by requiring mean trip duration produced by the model to match our estimate of mean trip duration of actual users. This estimate was produced by adjusting intended trip duration of all trips in the permit database by the deviation characteristics observed in the sample. The odds adjustment factor was the only model parameter determined by calibration; all other parameters were determined directly from the database or sample.

We used statistical model verification and validation methods to ensure that model algorithms were implemented correctly and that intended use at the zone-night resolution matched observed values. Based on behavior of variance in model outputs, we determined that 1,000 season-long replicates were adequate to provide accurate estimates of output, and we based all of our results on 1,000 replicates. We used the model to simulate current conditions, find a trailhead redistribution scheme that lowered use in the most heavily used zones, and determine the effects of filling all trailhead quotas on every day. The end user of the model can easily adjust the trailhead quotas and the number of parties that start on each day of the season to investigate other situations.

RESULTS

Mean intended trip duration in 2010 was 2.48 nights, which was significantly lower than the value of 2.94 observed in the 1970s. Mean party size was 2.92, which was significantly lower than the value of 3.26 observed in the 1970s. However, the permit itinerary adherence rate of 34.2% was not significantly different than the rate of 37.7% observed in the 1970s. In 2010, 36.2% of parties deviated temporally from their intended itineraries, and 54.4% deviated spatially. Spatial and temporal deviations were not independent; 25.2% of all parties deviated both spatially and temporally. The mean temporal deviation was a decrease of one night in trip duration. Trips were shortened at a rate of 0.42 nights per night the party intended to spend in the wilderness, and this rate was not significantly different than the value of 0.33 estimated in the 1970s. When applied to all permitted parties, temporal deviation lowered mean trip duration to an estimated actual value of 2.12 nights. Taken together, spatial and temporal deviation reduced the season-total estimate of Yosemite-derived use 14.7%, from 105,571 visitor nights based on intended itineraries to 89,997 based on simulations that incorporated deviation. Use from outside of Yosemite contributed an additional 10,010 visitor nights (Table E1), thereby comprising 10% of total use, compared with an estimated 4% in the 1970s. About 0.5% of total season-long use occurred in frontcountry backpacker camps.

Table E1. Mean annual use and bounds on the middle 95 percentiles of use, by source.

Source	Mean Annual Use (visitor nights)	% of Use	2.5th percentile	97.5th percentile
Yosemite trailheads	89,997	90.0%	88,255	91,740
Bridgeport USFS	3,010	3.0%	2,517	3,504
Other USFS	6,235	6.2%	5,707	6,764
Pacific Crest Trail	765	0.8%	727	802
TOTAL	100,007	100%	98,121	101,895

The eight most heavily used zones accounted for 43.6% of total use (Table E2), compared with 51.1% in 1973 and 36.9% in 1979. This group includes five of the eight most heavily used zones in the 1970s. Snow Creek, May Lake, and Yosemite Creek were in the top eight in 2010 but not in the 1970s; all of these are adjacent to trailheads. Mean use in each of Sunrise Creek, Snow Creek, Glen Aulin, and May Lake exceeded capacity on at least one night. Together, they accounted for 50 zone-nights on which mean use exceeded capacity and 203 zone-nights on which capacity exceedance probabilities were greater than 20%. In addition, capacity exceedance probabilities in Vogelsang were greater than 20% on 34 nights. Use originating outside of Yosemite had relatively little effect on any single zone except Lyell Canyon, where 22.5% of use originated outside of the park.

Table E2. Use (visitor nights) in the eight most heavily used zones. The Relative Use Index is percent of total use due to that zone divided by its percent of capacity. Values greater than 3 indicate at least a 20% chance that use exceeds capacity on more than one night.

Code	Zone	Capacity	YOSE use	%YOSE use	Total use	% Total use	Relative Use index
59	Little Yosemite Valley	150	7679	8.53%	7922	7.92%	2.22
68	Yosemite Creek	100	6964	7.74%	6973	6.97%	2.93
72	Lyell Canyon	125	4892	5.44%	6313	6.31%	2.12
66	Sunrise Creek	50	5547	6.16%	5807	5.81%	4.88
67	Snow Creek	50	4595	5.11%	4605	4.61%	3.87
81	Glen Aulin	50	4003	4.45%	4122	4.12%	3.46
63	Vogelsang	50	3779	4.20%	3950	3.95%	3.32
75	May Lake	50	3864	4.29%	3872	3.87%	3.25

By lowering trailhead quotas at nine of the most popular trailheads and redistributing an average of 3,575 parties from these trailheads to the least popular trailheads in the park, we simulated a condition in which mean use exceeded capacity on only one zone-night. The probability that use exceeded capacity was greater than 30% in only eight out of 8,109 possible zone-nights, compared with 134 zone-nights under current conditions. When every trailhead is filled to quota every day, a maximum of 1,196 parties per day are allowed into the wilderness, equating to a mean of 2,260 visitor nights per day. This rate of use is only 54% of the total zone capacity of 4,200, yet travel patterns are such that even in absence of temporal or spatial preference for trailheads, use in many zones greatly exceeds capacity. Under maximum allowable use, zones with the greatest mean use, relative to capacity, are Bridalveil Creek, Snow Creek, and Yosemite Creek. Use exceeds 150% of capacity in Snow Creek and Yosemite Creek on nearly every night. These two zones are among the most heavily used under current conditions as well. On the other hand, there are many zones in which use never exceeds capacity, even with every trailhead full on every night.

Under current conditions, most zones receive the majority of their use from only a few trailheads. Every zone except Washburn Lake and Twin Lakes receives at least 20% of its use from a single trailhead, and 18 zones receive over 50% of their use from a single trailhead. Part of this observed zone use-trailhead relationship is determined by visitor preference in time and space. The zone use-trailhead relationship produced by filling each trailhead to quota on each day removes spatiotemporal visitor preference for trailheads and results in the inherent relationship between zone use and trailhead of origin that is determined by the geography of the park, the physical capabilities and short-term behavior of wilderness users in selecting routes and camping locations, and the trailhead quotas themselves. Under this "true" relationship, the distribution of use across trailheads is more uniform than that currently observed, and comparison between the true zone-trailhead relationship and the current relationship allows identification of the trailheads that contribute the most to visitor use relative to their quota (e.g., Mirror Lake to Snow Creek) and those that contribute the least relative to their quota (e.g., Westfall).

MANAGEMENT IMPLICATIONS

Our results have three primary implications for management.

1. **Adjustment of permit data.** Deviation from intended itinerary reduces use levels about 14% from those estimated from raw permit data. Thus, management actions made to lower zone use that are informed strictly by use figures derived from permit data are likely to be overly conservative. On the other hand, about 10% of total zone use originates from outside of the park. Based on current conditions, a procedure for estimating actual use from the permit database, without having to go through the entire simulation procedure, is to first reduce permit-derived use estimates by 14%. Then, increase the resulting use in Lyell Canyon by 30% and use

in all of the other zones by about 1.5%. This method can be applied at the resolution of zones or zone-nights and will result in a better estimate of actual use conditions than simply using the raw permit data.

2. **Effects of shorter trip durations.** Although shorter trip durations do not necessarily lead to zone capacity exceedances, they do lead to a greater fraction of total use in zones that are readily accessible from trailheads. Snow Creek, May Lake, and Yosemite Creek are among the eight most heavily used zones today, but none were in the top eight in the 1970s, providing some evidence that a preference for shorter trips may be leading to increased use in some zones. Redistributing some of these shorter trips to parts of the park that receive less use could lower capacity exceedance probabilities under current use levels and trip characteristics.
3. **Effectiveness of trailhead quotas.** As detailed in lengthy analysis in the full report, we conclude that the inherent relationship between zone use and trailhead use has probably changed very little since the inception of the quota system, given that this relationship is based primarily on geography, physical capabilities of wilderness users, and the quotas themselves. The zone-use trailhead relationship based on actual use patterns may have changed somewhat due to changes in user preferences, but even with preference removed, geography dictates that most use in most zones will come from a relatively small number of trailheads. Thus, the original quota system remains a viable basis from which to determine future management. More importantly, our "no-exceedance" solution illustrates one of a theoretically infinite number of ways in which current use can be redistributed to lower-use areas in the park to achieve substantially lower probabilities of capacity exceedance without changing overall use, temporal distribution of use, or any other party or trip attribute. Therefore, we have shown that not only is the trailhead quota scheme a viable approach to managing use in wilderness zones but more importantly that a specific trailhead quota scheme exists that reduces capacity exceedance in Yosemite. This scheme can serve as a starting point for developing others that can achieve management objectives under socially acceptable conditions.

INTRODUCTION

ADMINISTRATIVE MANDATE

Social science research in support of park planning and management is mandated in the *National Park Service Management Policies 2006* (Section 8.11.1, "Social Science Studies") (NPS 2006). Such research is needed to provide a scientific basis for park planning, development, operations, management, education, and interpretive activities. The last time information on wilderness use patterns in Yosemite was collected systematically was in the 1970s, when the original wilderness travel use simulator was created and trailhead quotas determined. This study, a cooperative effort between Yosemite National Park and Humboldt State University, will provide the data needed for Park personnel to make informed decisions regarding wilderness management in Yosemite.

With the Wilderness Act of 1964 (U.S.P.L. 88-577), Congress established the National Wilderness Preservation System, protecting vast roadless areas with significant recreational, ecological, geological, scientific, educational, scenic or historical value. Although the Wilderness Act served to establish the system, it did not establish a methodology for protecting the resources and values from overuse by the visitors for whom it was, in part, created. It guided agencies, such as the National Park Service (NPS), to "be responsible for preserving the wilderness character of the area" and "administer such area for such other purposes for which it may have been established as also to preserve its wilderness character." The most recent NPS guidelines on wilderness stewardship direct units to establish wilderness character baseline levels and to continue monitoring opportunities for solitude (NPS 2011a).

YOSEMITE WILDERNESS VISITOR USE

The Yosemite wilderness experienced heavy use in the late 1960s and early 1970s; used peaked in 1975 at 218,890 visitor nights and averaged 172,310 visitor nights from 1972 to 1979 (van Wagtendonk 1981; Figure 1). In the early 1970s it had become apparent that the Yosemite wilderness was experiencing overuse, and in 1972 a mandatory permit system was implemented for all overnight visitors. Subsequently, the wilderness was divided into management zones, which align roughly with watersheds (Figure 2, Appendix A), and an overnight camping capacity was established for each zone (van Wagtendonk 1981, 1985; Appendix A). In order to minimize the probability of use exceeding zone capacities without imposing excessive regulation on the experience of wilderness users, a trailhead quota system was implemented in the park in 1977 (van Wagtendonk 1981). Trailhead quotas were derived from permit data and a simulation model that related zone use to trailhead use (van Wagtendonk and Coho 1986). Thus, although the management *objective* is to minimize zone capacity exceedances in the backcountry, the management *action* is implemented at trailheads to allow the maximum amount of freedom to visitors once they are in the wilderness (van Wagtendonk 1981). Wilderness overnight use dropped in 1983 to less than half the 1975 peak, but this decrease was attributed to a general decrease in the popularity of backpacking rather than to implementation of trailhead quotas (van Wagtendonk 1981). From the late 1970s through the early 2000s, visitor use of the Yosemite wilderness decreased, but in more recent years it has grown, increasing from 63,108 visitor nights in 2005 to 147,742 in 2009 (NPS 2011c; Figure 1).

However, knowledge of these overall use figures alone is not sufficient to determine if, when and where use is exceeding established zone capacities and what sort of management actions can be taken to lower use if capacities are being exceeded. First, use numbers are usually calculated from wilderness permit data, which reflect the intended wilderness travel itineraries of visitors. Van Wagtendonk and Benedict (1980) found that 62% of parties visiting the Yosemite wilderness deviated from intended itineraries, so use figures derived from permit data may not reflect actual use. Second, a substantial number of visitors to the Yosemite wilderness enter through trailheads on U.S. Forest Service (USFS) land, and this use is not necessarily tracked through Yosemite's permit system. Van Wagtendonk (1981) estimated this use at 4% of the total Yosemite wilderness use in the 1970s. Conversely, many wilderness trips permitted in Yosemite include nights spent outside of the park; van Wagtendonk (1981) estimated that about 8% of all permitted visitor nights fell into this category. Third, because use is not distributed uniformly in time and space, analysis at the spatiotemporal resolution of each zone on each night (hereafter referred to as a "zone-night") is required to quantify when and where capacities are likely to be exceeded. Finally, the trailhead quotas determined in the 1980s were selected to minimize the probability of zone capacity exceedance under the visitor characteristics that existed at that time. If these characteristics have changed substantially, management strategies sufficient to minimize capacity exceedance in the 1980s may not be sufficient to minimize it today. Current wilderness visitors tend to take shorter trips than did their counterparts several decades ago (Hall and Cole 2007), skewing the spatial distribution of use more towards zones in close proximity to trailheads. However, increased relative use of zones near trailheads could be offset by an overall decrease in use, resulting in little change in use in a particular zone. Thus, the current status of use at the zone-night level cannot be readily assessed with simple queries of the wilderness permit database. Because of the complexity of interaction among the factors that determine use at the zone-night level, a computer simulation model, populated with current data on visitor characteristics, provides the best way to assess the current status of wilderness use in Yosemite.

COMPUTER SIMULATION MODELING

When systems are too complex for analytic solutions and real world experimentation is not feasible, computer simulation models can provide insight and answers. A computer simulation model is a simplified version of a real system, implemented on a computer, that allows for analysis and experimentation. Computer simulation models have proven to be effective in informing the management of wilderness areas (Poiter III and Manning 1984; Underhill et al. 1986; Manning and Wang 1999; Bishop and Gimblett 2000; Lawson et al. 2003, 2004; van Wagtendonk 2004; Cole 2005; Lawson et al. 2006). The majority of simulations for recreational use are currently implemented in the general-purpose simulation environment called ExtendSim (Imagine That 2010). ExtendSim is an object-oriented, discrete-event dynamic simulation package. Although mainly used in the business world, ExtendSim is well suited to model and simulate many complex systems, from value stream mapping for lean production systems (Shararah et al. 2009) and modeling of a multiproduct inventory (Kopytov et al. 2008) to computer network design (Stone 2000). Just like wilderness use simulation modeling, these problems reduce to tracking attributes of entities as they move throughout a system.

Simulation modeling using ExtendSim has been used in many national parks and forests, including Acadia National Park (Manning and Wang 1999), Arches National Park (Lawson et al. 2003), Isle Royale National Park (Lawson et al. 2004), and the Desolation Lakes area of the John Muir Wilderness (Lawson et al. 2006). In general these simulation models can be used to describe and analyze use conditions that are currently in practice. Managers can use these baseline simulations to gather information that is difficult and costly to observe. By providing managers with detailed information about how visitors are currently using the area, these baseline data can assist managers in proactive monitoring by helping identify potential problems (Lawson et al. 2003; Manning and Wang 1999). Simulation modeling can also be used in a predictive or experimental sense. Various management strategies can be tested in a comprehensive, low-cost way that is free of public and political consequences. Managers can also test various use possibilities in combination with management policies, allowing them to see what effects their decisions will have in a variety of future use conditions (Lawson et al. 2003; Hendee and Dawson 2002). These capabilities make computer simulation a valuable tool for identifying potential problems and evaluating the long-term costs and benefits that the solutions to these problems bring (Lawson et al. 2006). In general, computer simulation modeling of recreation can contribute significantly to recreation planning and management (Cole 2005).

GOALS AND OBJECTIVES

The goal of this study was to assess current use of the Yosemite wilderness, with particular emphasis on identifying zones in which nightly use is likely to exceed capacity during periods of heavy use and trailheads that are the primary contributors to capacity exceedance. Furthermore, because current management is based on the results of this type of analysis conducted in the 1970s, meaningful assessment of current conditions requires comparison of current use characteristics with those observed in the 1970s. Thus, the study objectives were:

1. Quantify wilderness visitor characteristics, including party size, trip duration, and itinerary deviation;
2. Compare characteristics of current wilderness visitors with those of visitors in the 1970s;
3. Construct, populate and validate a wilderness use simulation model that
    a. incorporates observed itinerary deviation characteristics,
    b. predicts means and percentiles of use at the zone-night resolution, and
    c. includes the effect of wilderness use originating outside of Yosemite;
4. Employ the simulation model to
    a. quantify current use at the zone-night and annual scales by source,
    b. estimate probabilities of capacity exceedance at the zone-night scale,
    c. quantify the dependence of zone use on trailhead use, and
    d. find a trailhead management scenario that redistributes current use spatially to achieve a "no-exceedance" condition; and
5. Identify both the most heavily used zones and trailheads and the zones and trailheads that have the greatest potential to absorb increased use.

Objectives 4a, 4b and 4d were specifically requested by Yosemite personnel: *"…it would be beneficial to see the following results in tabular format across zones: 1) existing conditions (including percentage of time/number of nights that exceedances and 'capacity surplus' are occurring per zone) 2) solve for no exceedances in existing zone capacities…*" (email communication dated 22 December, 2010, from Bret Meldrum, Branch Chief, Visitor Use and Social Sciences, Yosemite National Park).

STUDY AREA

The Yosemite Wilderness includes 281,855 ha, nearly 95% of the park, which is situated on the western slope of the Sierra Nevada (NPS 2008). Elevations vary from just under 866 m on the western boundary to just over 3,962 m along the Sierra crest. Yosemite National Park experiences a Mediterranean climate with typically long, hot summers and mild winters. Annual precipitation ranges from 915 mm at 1,200 m elevation to 1,200 mm at 2,600 m. Between October and April, most of the precipitation falls as snow. From May through September, precipitation is infrequent. Mean daily temperatures range from -4 to 12 degrees Centigrade at Tuolumne Meadows at 2,600 m. At the Park's south entrance near Wawona (elevation 1,887 m) mean daily temperature ranges from 2 to 19 degrees Centigrade. At elevations below 1,500 m, temperatures are hotter; the mean daily high temperature at Yosemite Valley (elevation 1,209 m) ranges from 8 to 32 degrees Centigrade. At elevations above 2,500 m, the hot, dry summer temperatures are moderated by frequent summer thunderstorms, along with snow that can persist into July. The combination of dry vegetation, low relative humidity, and thunderstorms results in frequent lightning-caused fires (NPS 2004).

The Yosemite wilderness permit database lists 68 trailheads (Appendix B), which access 1,112 km (691 mi) of trail (van Wagtendonk 2003, Appendix C). Although van Wagtendonk (2003) identified 375 traditionally used wilderness campsites, specific camping locations in most wilderness zones are not formally designated. However, wilderness visitors must occupy designated campsites when camping at Little Yosemite Valley or near the Glen Aulin, May Lake, Sunrise, Merced Lake, and Vogelsang High Sierra Camps. Dozens of additional trailheads and hundreds of kilometers of trail exist on USFS land adjacent to Yosemite. The Emigrant Wilderness borders the Yosemite Wilderness to the north, the Hoover Wilderness to the east, and the Ansel Adams Wilderness to the south. Two popular long distance hiking trails traverse Yosemite's wilderness: the John Muir Trail stretches from Yosemite Valley south to Mount Whitney, and 80 km of the Pacific Crest National Scenic Trail are within the park (van Wagtendonk 2004).

Trailhead quotas are enforced through the wilderness permit system. Permit reservations may be made up to 24 weeks in advance of the date of entry into the wilderness. Up to 60% of each trailhead quota may be filled by reservations, and the remainder is available to visitors arriving at the Park the day before or day of their trip on a first-come, first-served basis. Unclaimed reservations are made available if not acquired by 10 a.m. on the first day of the trip (Hendee and Dawson 2002). The permit system also acts as a mechanism for education by giving park staff the opportunity to convey information about minimum impact regulations and practices to visitors (Boyers et al. 2000).

DATA COLLECTION AND ANALYSIS

SAMPLING PROCEDURES

In order to quantify permit itinerary adherence, we distributed a survey instrument to a random sample of permitted parties during the 2010 season. According to the Yosemite wilderness permit database, 12,276 wilderness permits were issued in 2009. With a potential 5% increase in use, it was estimated that 13,000 permits would be issued in 2010. Assuming a 60% response rate, a 10% sample size (n=1,300) would require 2,167 survey instruments to be distributed. The 2009 permit data and previous studies (van Wagtendonk 1981) showed that wilderness use in Yosemite is not distributed uniformly throughout the season of highest use, 1 May – 30 September, which we define as the study period. Use on weekends and holidays is much higher than on weekdays, and use increases gradually from the season's beginning, peaks around late July and early August, and rapidly declines to essentially zero by the end of September (Figure 3). In order to sample according to the temporal distribution of use, the sample frame was defined as all weekends (Friday and Saturday nights for regular weekends; Friday through Sunday nights for the three-day holiday weekends of Memorial, Independence, and Labor days) and all weekdays in the study period. The sample frame was stratified into two strata: 1) all weekends, as defined above, and 2) the remaining weekdays. Within each stratum, a given unit's probability of being selected for sampling was equal to the proportion of total visitor-nights in that stratum accounted for by trips that began in that unit, according to the 2009 permit data. Based on these probabilities, a random number generator was used to select 3 weekends and 13 weekdays during the study period. This stratified sampling technique is more statistically efficient than a census approach and allowed investigators to minimize the burden of survey distribution on Park Service personnel (Watson et al. 2000). Due to unforeseen circumstances, survey instruments were not distributed on one of the randomly selected dates but were distributed on a day belonging to the same stratum during the following week.

Surveys were administered under OMB Expedited Approval for NPS-sponsored public surveys permit # 1024-0224 NPS # 09-014 (expiration 31 December 2010) and NPS scientific research and collecting permit # YOSE 2010 SCI 0048 Study ID 0041 (expiration 31 December 2010).

Survey instruments were distributed to all visitors who obtained a wilderness permit on each selected sampling date. Most visitors begin their trip on the day they receive their permit, but a few begin their trip on the following day. Because trips are identified by start date in the permit database rather than by the date the permit is obtained, there is a slight discrepancy between the number of surveys that were distributed on sample dates and the number of trips that started on those dates. However, we assume that the number of parties that obtained a survey on a sample date and began their trip the following day is the same as the number of parties that started their trip on a sample day but obtained their permit the previous day and therefore did not receive a survey. Under this assumption, the number of parties that started their trips on a given sample date is an unbiased estimator of the number of parties that received a survey instrument on that sample date.

Survey instruments were distributed at all Yosemite stations that issue wilderness permits (Yosemite Valley Wilderness Center, Tuolumne Meadows Wilderness Center, Hetch Hetchy Entrance Station, Big Oak Flat Information Station, and Wawona Visitor Center at Hill's Studio) to all visitors who obtained a permit on each sampling date. Permit identification numbers were recorded on the instrument to later compare actual party routes with intended itineraries. Surveys were also distributed throughout the study period to all visitors planning to spend at least one night in the Yosemite wilderness at the Bridgeport Ranger District Office in Bridgeport, California; White Mountain Ranger Station in Bishop, California; Mono Basin Scenic Area Visitor Center in Lee Vining, California; Mammoth Lakes Visitor Center in Mammoth Lakes, California; Eastern Sierra InterAgency Visitor Center in Lone Pine, California; Groveland District Ranger Office in Groveland, California; Mi-Wok District Ranger Office in Mi-Wuk Village, California; Summit District Ranger Office in Pinecrest, California; Bass Lake Ranger District Office in North Fork, California; High Sierra Ranger District Office in Prather, California; and Mineral King, Lodgepole, and Cedar Grove Ranger stations in Sequoia & Kings Canyon National Park

(Figure 4). The objective of distributing surveys at these locations was to quantify the influence on zone use of parties entering from outside the park. Party size was recorded on surveys distributed outside the park because not all stations permitting Yosemite access maintain detailed permit databases. The completed surveys were returned either in person directly to Yosemite or U.S. Forest Service (USFS) permit stations, by way of returned rental food canisters, by direct placement in food canister return boxes, in drop boxes at park road exits, on trail at park boundaries at Dorothy Lake, Bond, and Donohue Passes, by mail, or electronically following e-mail reminders to late respondents. Due to unforeseen circumstances, no surveys were distribution to visitors intending to enter Yosemite who obtained permits at the Bridgeport Ranger District office. However, Park personnel later obtained copies of all wilderness permits issued at the Bridgeport station and entered itineraries and party characteristics from those permits into a database of the same structure as the Yosemite wilderness permit database. We were then able to use this Bridgeport database to characterize Yosemite wilderness use originating from Bridgeport.

In order to conduct a non-response bias check, we attempted to contact parties that obtained but did not return a survey. We were able to obtain information from 75 of these parties. Each of them provided the total number of nights they spent in the Yosemite wilderness. The temporal deviation for these trips was computed by subtracting the number of nights the party intended to spend from the number of nights actually spent in the wilderness. This calculation was repeated for the sample of survey respondents. Statistical methods were used to compare temporal deviation between respondents and non-respondents.

SURVEY INSTRUMENT

Surveys consisted of map diaries on which respondents marked their trip routes from entry trailhead to campsite to campsite to exit trailhead, indicating each campsite's location with a circled number corresponding to the night of their trip. The park was divided into five sectors, and visitors received survey instruments corresponding geographically to their trailhead of entry and intended route (Figure 5, Appendix D).

SAMPLE PROPERTIES

After removing permits for trips that were cancelled by the permitted party, the permit database contained 15,764 permits, of which 2,755 were issued on the selected sample dates. Of these, 1,134 surveys with at least some viable information were returned, for a response rate of 41.2%. Of the 15,764 permits in the database, 14,497 were issued to parties that initiated their trip within the 1 May to 30 September study period and intended to spend at least one night in the Yosemite wilderness. All of these permits contained intended itineraries, from which the number of nights these parties intended to spend in the Yosemite wilderness could be computed. The returned surveys included 1,123 for which a complete usable intended trip itinerary was available in the permit database, thus lowering the effective response rate to 40.8% for the purposes of quantifying spatial and/or temporal deviations from intended trip itineraries. These usable surveys comprised a random sample of 7.75% of all parties that began their trip in the 1 May to 30 September window, but because sampling probabilities were calculated in proportion to visitor nights and not on parties, these surveys accounted for 9,511 intended visitor nights or 9.00% of the 105,715 intended visitor nights in the Yosemite wilderness during the study period.

Based on information received from participating Forest Service permit stations, it was estimated that 870 surveys were distributed to parties entering the Yosemite wilderness whose trips began outside the park. A total of 147 survey instruments were received from visitors whose trips originated outside Yosemite, equating to a response rate of 16.9%. Of those received surveys, 83 contained viable data, thus lowering the effective response rate from this visitor base to 9.79%. Data obtained from the Bridgeport Forest Service station included permits issued to 325 parties that intended to spend at least one night in the Yosemite wilderness.

Of the 75 non-respondents we were able to contact, 35 (46.7%) reported an actual trip duration that differed from the intended duration, compared to 417/1123 = 37.1% of survey respondents. A two-sample proportion test indicated that this difference was not significant (z = 1.36, P = 0.111). A Kolmogorov-Smirnov test showed that the distribution of temporal deviations was not significantly different between respondents and non-respondents (D = 0.083, P = 0.743). A Mann-Whitney test showed that there was no significant difference in median deviation between respondents and non-respondents (W = 41042, P = 0.670). Therefore, there is no evidence that non-respondents behaved differently with respect to temporal deviations than survey respondents. It is possible that non-respondents could have displayed different patterns in spatial deviation than respondents, but this is unknowable without completed surveys. The lack of difference in temporal deviations and the high correlation between temporal and spatial deviation (see below) suggests that the sample has little if any non-response bias with respect to deviations from intended itinerary.

SPATIAL AND TEMPORAL DEVIATIONS

Temporal deviations were defined as the difference between actual and intended number of nights spent in the Yosemite wilderness. Deviations between actual and intended number of nights spent outside of the Park or of total trip duration, including nights on the same trip spent both within and outside of the Park, were not analyzed, other than for the purpose of evaluating non-response bias (reported above). Henceforth, the term “trip duration” refers to the number of nights the party spent or intended to spend in the Yosemite wilderness (including frontcountry backpacker camps), regardless of whether the trip included nights spent elsewhere. We defined spatial deviation as any difference in the sequence of zones visited. For example, if the intended itinerary was two nights in zone A followed by one night in zone B and one night in zone C (i.e., AABC) and the actual itinerary was ABC, we would not count this as a spatial deviation, only a temporal deviation, because the sequence of zones was the same. This definition is the same one used by van Wagtendonk and Benedict (1980), allowing direct comparison of our results to theirs. Temporal and spatial deviations were determined and evaluated by comparison of map diary surveys to permit records of sampled respondents.

Of the 1,123 survey respondents, 40 (3.6%) did not even enter the wilderness (Table 1). Another 385 (34.3%) reported taking a wilderness trip different in duration than intended (Table 1). Mean intended trip duration among all survey respondents was 2.71 days (standard deviation = 1.69), whereas actual trip duration was 2.35 days (standard deviation 1.45). Trips were shortened by as much as 11 days and lengthened by as much as 9 days. Among the parties that deviated temporally, the mean temporal deviation was -1.02 days (standard deviation = 1.45, Figure 6). Linear regression showed that temporal deviation duration did not depend on the start date of the trip ($P = 0.833$) or on party size ($P = 0.492$) but that it did depend significantly on intended duration ($P < 0.001$). Regression of temporal deviation against intended trip duration alone yielded

$$y = 0.513 - 0.423x, \tag{1}$$

where y = deviation in days (negative = shorter trip) and x = intended trip duration in days ($R^2 = 0.303$, residual standard error = 1.218). This equation implies that as intended trip duration increases, the number of days by which the trip is shortened also increases.

Spatial and temporal deviations were not independent of one another ($\chi^2 = 70.9$, df = 1, $P < 0.001$). Parties had a very strong tendency to either deviate both spatially and temporally or to not deviate at all (Table 1). The odds of deviating spatially were 3.1 times greater if the party deviated temporally than if it did not deviate temporally. Logistic regression was used to analyze the probability that a party would make any type of deviation, again using only the 1,083 sampled parties that actually entered the park. The probability of deviating depended significantly on party size ($P = 0.002$) and intended

Table 1. Summary of deviations reported by survey respondents.

Deviation type	Frequency	Percent
Spatial only	328	29.2%
Temporal only	102	9.0%
Spatial and temporal	283	25.2%
No wilderness entry	40	3.6%
No deviation	370	32.9%
Total	1,123	99.9%

trip duration ($P < 0.001$). The odds that a party would deviate from its intended itinerary decreased by a factor of 0.89 for every additional party member and increased by a factor of 2.42 per additional day of intended trip duration. The logistic regression model was:

$$\text{Probability of deviation} = 1 / [1 + \exp(1.080 + 0.171p - 0.884x)], \qquad (2)$$

where p = party size and x = intended trip duration (days). Model residual deviance was 1162.0 (df = 1,080), compared to a null deviance of 1390.8 (df = 1,082).

The primary reason to assess deviation from intended itineraries was to apply an adjustment to the intended itineraries in the Yosemite wilderness permit database in order to estimate visitor use based not on intended trip duration but on actual duration. Because the linear regression model presented above applies only to trips that deviated temporally, it explains only 30% of the variability in trip duration and does not include parties that obtained a permit but did not even enter the park. Thus, linear regression of actual trip duration as a function of trip start date, party size, and intended trip duration was performed using all 1,123 surveys. Actual trip duration did not depend significantly on trip start date ($P = 0.786$), so this predictor was eliminated from the model. Actual trip duration depended significantly on party size ($P = 0.000276$) and intended trip duration ($P < 0.001$). The regression equation was

$$\text{actual duration} = 0.270 + 0.0433p + 0.695x, \qquad (3)$$

where p = party size and x = intended trip duration ($R^2 = 0.622$, residual standard error = 0.927, df = 1120). This equation is used later in calibrating the simulation model.

COMPARISON OF PAST AND PRESENT VISITOR CHARACTERISTICS

We compared party size, intended trip duration, and itinerary adherence rates observed in 2010 with those observed by van Wagtendonk and Benedict (1980), who surveyed 1,088 Yosemite wilderness users in 1976, 1977, and 1978. Mean party size was smaller by 0.34 (11.6%) in 2010, and mean intended trip duration was 0.46 days shorter in 2010 (Table 2). Both of these differences were statistically significant ($t = 3.48$, df = 999, $P < 0.001$ for party size; $t = 7.15$, df = 999, $P < 0.001$ for intended trip duration).

Because van Wagtendonk and Benedict (1980) did not contact parties that obtained permits but did not enter the backcountry, this category was removed from the 2010 data (Table 1) to compare permit itinerary adherence between the two time periods (Table 3). A Chi-square test for independence showed that the distribution of deviation types differed between the 1970s and 2010 ($\chi^2 = 28.7$, df = 3, $P < 0.001$). Post-hoc proportion tests with Bonferroni's correction for multiple comparisons ($\alpha = 0.05/3$, two-sided alternative) showed that there was a significantly smaller proportion of trips reporting some sort of temporal deviation in 2010 (z = 2.48, P = 0.013) and a significantly larger proportion of trips reporting some sort of spatial deviation in 2010 (z = 3.85, P < 0.001). However, there was no significant difference in overall deviation rate (z = 1.71, P = 0.087); 62% of the parties sampled in the 1970s deviated in some way, compared with 66% in this study.

Table 2. Trip attributes (mean and standard deviation) observed in the 1970s (van Wagtendonk and Benedict 1980) and in 2010. The 1970s figures were computed from a sample of visitors, whereas the 2010 data were computed from the population.

Attribute	1970s	2010
Party size	3.26 (s.d. = 3.09)	2.92 (s.d. = 2.30)
Intended trip duration	2.94 (s.d. = 1.99)	2.48 (s.d. = 1.98)

Table 3. Comparison of sample trip deviations between 1970s (van Wagtendonk and Benedict 1980) and 2010.

Deviation type	1970s	2010
Spatial only	226 (20.8%)	328 (30.3%)
Temporal only	154 (14.1%)	102 (9.4%)
Spatial and temporal	298 (27.4%)	283 (26.1%)
No deviation	410 (37.7%)	370 (34.2%)
Total	1,088	1,083

Temporal deviations in the 1970s ranged from shortening a trip by 8 days to lengthening it by 3 days (van Wagtendonk and Benedict 1980), compared with a range of shortening by 11 days to lengthening by 9 days in 2010. The mean deviation was -0.58 days in the 1970s, compared with -1.02 in 2010. The regression equation relating deviation to intended trip duration in the 1970s was $y = -0.39 - 0.33x$, where y = deviation in days (negative = shorter trip) and x = intended trip duration in days (R^2 = 0.303, residual standard error = 0.96). This equation is very similar in slope and predictive power to ours (equation 1). The slope in these equations represents the mean number of days a trip is shortened per day of increase in the intended trip duration and in both equations indicates that trips with longer intended durations were shortened more, on average, than trips with shorter intended durations. The 95% confidence interval on the slope estimate in our regression equation (1) was [-0.49,-0.36]. Although van Wagtendonk and Benedict 1980 did not report a standard error or confidence interval for the slope estimate in their regression equation, the similarity in reported sample and regression properties between their analysis and ours indicates a 95% confidence interval of about [-0.39,-0.27] for their slope estimate, indicating that the two slope estimates are probably not significantly different from one another.

YOSEMITE WILDERNESS USE SIMULATION MODEL

The model stochastically simulates trips taken by parties through the wilderness zones throughout the season and records the number of campers in each zone on each night. This output is consistent with the definition of zone capacities, which specify the maximum desired number of visitors in the zone per night. The model was implemented with ExtendSim OR simulation software and is discrete in time (days) and space (wilderness zones) to match the finest resolution information available.

ESTIMATION OF MODEL PARAMETERS

The base data for the model were taken from 2010 Yosemite wilderness permits. Because Yosemite has an established permit system and because a high fraction of parties using the wilderness obtain permits (van Wagtendonk and Benedict 1980), this is considered an accurate source for wilderness use data (Hollenhorst et al. 1992; Hendee and Dawson 2002). The permits were entered into a database, which was then sorted to retain only permits relevant to the study. In particular, we removed permits for parties that cancelled their permitted trip, started their trip outside the 1 May to 30 September study period, or started their trip in Yosemite but did not intend to spend any nights in the park. The remaining 14,497 permit itineraries were analyzed to create empirical distributions for party size, number of parties, start date, and entry trailhead distribution.

Although start date theoretically has a temporal probability distribution, start date is not used stochastically in the model. Instead, the number parties released on a given day is fixed from simulation to simulation in the observed temporal distribution of these 14,497 parties. This is done for two reasons. The first is to retain the correct temporal relationships among wilderness use and weekdays, weekends, and holidays, given that use is much higher on weekends and holidays (Figure 3). The second is to align spatial distribution of use with temporal accessibility of high-elevation trailheads. In Yosemite, several trailheads are inaccessible until the snow melts. To capture the effect this has on the Park's visitor use, separate trailhead distributions were created for the respective periods before and after the opening of the Tioga road (Figure 2). The date of road opening serves as a proxy for trail accessibility because it is the primary access to many popular trailheads affected by snow closures. In 2010 this date was June 5, which is ten 10 days later than the mean over the 1977-2010 period. Despite our use of a fixed number of parties starting on each day, the model user is free to alter the number of parties that start on any given day to simulate desired scenarios.

Unlike most simulation models of backcountry travel, the routes parties can take in our model are not chosen from a finite set. Instead, permit itineraries were used to create a transition matrix that governs where a party spends its next night, based on its current location. Each nightly transition in the permit database was recorded in a matrix whose rows represent the current location and columns represent subsequent location. These values were normalized along the rows so that each row represents the transition probabilities to all other zones (columns) from the given zone (row). For example, the value stored in entry [A,B] of this matrix is the probability of transitioning from zone A to zone B. Similarly, the value stored in [A,A] represents the probability of spending another night in zone A. So that we did not have to preselect trip durations, we also included another state in the transition matrix that represents ending the trip, either by returning to a trailhead or by transitioning from a Yosemite wilderness zone into adjacent USFS wilderness and not returning to the park. Including the exit transition also prevents trips from ending in a zone that is too far away from a trailhead or adjacent USFS wilderness to allow a party to spend its last night in the park there. In creating the transition matrix, we included the possibility that a party exits the Yosemite wilderness, spends nights in adjacent USFS wilderness, and then returns to the Yosemite wilderness to end its trip. However, these types of itineraries were extremely rare; almost all parties that started their wilderness trip in Yosemite and subsequently traveled into adjacent USFS wilderness did not return to Yosemite later in their trip. By using this transition approach, we were not forced to use just a sample or limited set of possible routes, and therefore the model is based on very few a priori assumptions regarding travel itineraries. In addition to the 53 wilderness zones, the three frontcountry backpacker camps were included as possible camping locations in the model, corresponding to inclusion of those as possible camping locations in permit itineraries.

SIMULATING TRIPS

To simulate an individual trip, the model first determines the party's size from the empirical distribution. After comparing trip start date to the date of snow melt, a random entry trailhead is assigned from the appropriate empirical distribution. The number of trips already originating at that trailhead is then checked to make sure the daily quota has not been reached. If the quota has been reached, then that trailhead is removed from the list of possible starting trailheads, and a new trailhead is randomly selected from the remaining choices. Because the probability distribution governing this selection was generated from the permit data, it reflects the relative popularity of the trailheads among wilderness users. Thus, on average, this method of modeling the trailhead quota scheme has the effect of filling the most popular trailheads first and then reassigning visitors who desire those trailheads to the next most popular trailheads that are still available. We were unable to include five of the possible trailheads in the model because the permit database contained no itineraries that started at any of these trailheads (Appendix B).

Once a party has been assigned a starting trailhead, an initial wilderness zone is chosen from a distribution of zones reachable from that trailhead, and the party spends its first night in that zone. Subsequently, the party's trip is determined stochastically from the transition matrix, which allows the party to stay another night in the zone it is in, transition to a new a zone, or transition out of the wilderness (Figure 7). The model multiplies the number of nights stayed in the zone by the size of the party to track how many visitor nights are spent in each zone. To simulate the entire season, trips are started according to the actual temporal distribution of trips observed in 2010 over the annual season.

SIMULATING ROUTE CHOICE DEVIATION

Survey results showed that parties that deviated spatially were more likely to deviate early in their trip than later. Some 54.4% of parties in the sample deviated spatially (Table 1); 30.6% spent their first night in a different zone than intended, 17.2% first deviated from intended spatial distribution on the second zone visited, and 6.5% first deviated from intended spatial distribution after their second zone transition. Characterizing these deviation rates based on intended transition from one zone to another rather than on intended camping location on a given night is consistent with the way we defined spatial deviation. To simulate spatial deviation, the model tracks how many zones a party has already visited and whether or not the party has already deviated. Each time a party transitions (including into its first zone), there is a chance that, if the party has not previously deviated, that it deviates from its "intended" trip by visiting a different zone. Specifically, each party has a probability of 0.306 of deviating from its intended itinerary on the first night of its trip. If the party does not deviate on its first night, then it has a probability of 0.172 of deviating spatially on the next night it intends to spend in a different zone. If it does not deviate from either the first or second intended camping location, then it has a probability of 0.065 of deviating on its third zone. If the party has not deviated by its third zone transition, then it does not deviate spatially, and all zone transitions are computed from the transition matrix, which, because it was created from the permit database, corresponds to intended itinerary.

If a party is determined to be a spatial deviant, a new transition is selected from the row of the transition matrix corresponding to the current zone, without replacement of the transition originally drawn. In the case of first-zone deviation, the re-drawn transition is taken from the zones reachable from a party's particular trailhead. For example, suppose that a party is selected to deviate after spending its first night in the intended zone (call it A), and the possible transitions from this zone were to remain in A with probability 0.1, spend the next night in zone B with probability 0.5, spend the next night in zone C with probability 0.3, and exit the back country with probability 0.1. Suppose that the random transition selection is to spend the next night in zone B. Then we interpret this as the party's intended transition, given that this probability was selected from the transition matrix that was created from the permit database. However, because this party was selected to spatially deviate, we force it to spend the second night in a zone other than B. This is accomplished by re-drawing a new random transition from the same distribution except that the possibility of transitioning to B is now removed. The new distribution is thus to remain in zone A with probability 0.2, spend the next night in zone C with probability 0.6, and exit with probability 0.2. After randomly selecting one of these choices for the party's second night, the remaining transitions are selected from the original transition matrix, under the convention that a spatial deviant is defined by the first deviation from intended spatial itinerary; regardless of subsequent transitions, the trip has already deviated spatially, and there is no meaningful way to define subsequent deviations. This algorithm forces the party to do something other than what it originally intended, but it does so in a way that preserves relative transition probabilities, so that the resulting "actual" itineraries are realistic.

SIMULATING TRIP DURATION

Since the model does not preselect trip duration but rather determines trip duration implicitly via the transition matrix, we could not apply regression equation (3) directly to each simulated party, because equation (3) requires knowledge of intended duration, which is not pre-assigned in the model. Instead, we considered the overall effect of temporal deviation on trip duration across all parties and all nights. Applying the regression equation (3) to the full permit database reduced the mean trip length from 2.48 nights to 2.12 nights. Thus, to simulate the effect of temporal deviation, we calibrated the model to produce a mean trip length of 2.12 nights.

Because trip length is a decreasing function of exit probability, to lower mean trip length, we needed to increase the exit probability in the transition matrix, while keeping all other probabilities in relative proportion (that is, the ratio of non-exit probabilities p and q within a given row remains the same after the transformation). To accomplish this, we uniformly increased the odds of exiting across all zones and then rescaled the remaining probabilities in each row to obtain a new transition matrix (row entries sum to one). By altering the odds, we retain the relative exit odds across all rows (that is, the ratio of exit odds from any two zones remains the same after the transformation). This procedure allows for an increase in exit probabilities without altering the zone transition dynamics. Specifically, if column k of the transition matrix T corresponds to exiting the wilderness, then the odds of exiting from the current zone i is $T_{ik} / (1 - T_{ik})$. To decrease mean trip length, we let the new odds of exiting be $T'_{ik} / (1 - T'_{ik}) = C \cdot T_{ik} / (1 - T_{ik})$, for all rows i, where $C > 1$ is the same for all rows. This uniformly increases the odds of exiting across all rows i. This is equivalent to defining the new probability as

$$\hat{T}_{i,k} = \frac{C T_{i,k}}{1 + (C-1) T_{i,k}}. \qquad (4)$$

To then redefine the transition matrix to have these new probabilities but retain row sums equal to 1, we rescale the remaining probabilities in that row by letting

$$\hat{T}_{i,j} = \frac{1 - \hat{T}_{i,k}}{\sum_{j \neq k} T_{i,j}} T_{i,j}. \tag{5}$$

This procedure defines a new transition matrix $\hat{T}'$ with lower mean trip duration than that allowed by T.

To find how much we needed to raise the odds of exiting, we computed a new transition matrix according the procedure above, performed 1,000 simulations with that new transition matrix, and calculated the mean trip length over all parties and simulations. We started by doubling the odds of exiting (C = 2 in equation 4) and then used the bisection method (Dennis and Schnabel 1983) to iteratively converge on the value of C that generated the desired mean trip length of 2.12. Because spatial and temporal deviations were not independent of one another, the bisection algorithm to find C was performed concurrent with implementation of the spatial deviation algorithm so that the correct mean trip duration could be determined. To reduce the mean trip duration from 2.48 to its desired value of 2.12, the odds of exiting were increased by a factor of C = 1.795.

PREDETERMINED VERSUS DYNAMIC TRIP CHARACTERISTICS

We emphasize here the dynamic nature of trip simulations in our model. The only trip characteristics that are assigned to a simulated party at the beginning of its trip are start date, party size, and trailhead. End users of the model can easily adjust trailhead quotas and the number of parties that start on each day, if desired. Even trailhead assignment is somewhat dynamic in the sense that if a party's selected trailhead is at quota on that day, a new trailhead is selected from the remaining trailheads available on that day. Itinerary and trip duration are determined dynamically as the party travels, based on probabilities of state transition. These dynamic algorithms include the effects of spatial and temporal deviation. Thus, camping locations and trip duration of each simulated party are not known until the party completes its simulated trip.

We also emphasize that the model is not a "black box" simulation containing numerous parameters whose values have been chosen through a calibration procedure to minimize differences between model-predicted and observed use. The parameter C governing increase in exit odds is the only model parameter whose value was determined through a calibration procedure. This procedure was based on analytical theory and involved matching only mean trip duration between model output and the observed value. No parameterization was performed by attempting to match model-predicted and observed wilderness use, which is the ultimate output desired from the model. Instead, model validation was used to show that our modeling approach yields use values consistent with those observed.

EXTERNAL TRAILHEAD INFLUENCE

By analyzing surveys and permit data we received and extrapolating total visitor use based on survey return rates, we were able to determine separate party size distributions, transition matrices, and overall numbers of parties for trips originating outside of Yosemite. We received adequate survey returns from parties who obtained permits at the USFS stations in Groveland, Prather, Mammoth, North Fork, Lee Vining and Lone Pine. For trips on the Pacific Crest Trail or trips that were permitted at the USFS station in Pine Crest, characteristics were estimated by Yosemite personnel familiar with such trips. As mentioned above, we received a full database of permits issued at Bridgeport and used the same methods to convert those permit data into model parameters as we used with the Yosemite permit data. The model for externally originating trips is essentially the same as the general model except that entry trailhead is now a station of origin (Mammoth, Lee Vining, and Lone Pine were combined into a single “east” group), and each station has its own corresponding transition matrix. Party size distribution was calculated from the pooled USFS data, and the temporal distribution of use was assumed to follow the distribution of use originating within the park, except that the temporal distribution for Bridgeport trips was taken directly from the Bridgeport database. Because we did not survey the parties from Bridgeport for deviation, we used the intended (permitted) itineraries in calculating the transition matrix. Since party and trip attributes for all parties except those originating at Bridgeport were calculated from actual use patterns, no deviation adjustment was needed. Simulated visitor use for trips originating outside of the park was added to the model-predicted visitor use for trips originating within the park.

SIMULATION PROCEDURES

To determine the number of simulation replicates needed to obtain accurate estimates, we performed n independent replicates of the validation model (described below), where n (sample size) assumed twenty different values ranging uniformly from 10 to 1,000 on a logarithmic scale. We then plotted variance of visitor use over the n replicates as a function of n for two different zone-nights, one a high-use zone-night and the other a low-use zone-night. Results showed convergence of variance above about 400 replicates (Figures 8 and 9). We also plotted estimates of the probability of zone capacity exceedance for a zone with high exceedance probability to assess how many replicates were needed to obtain accurate predictions of exceedance probability. Results showed convergence of exceedance probability at sample sizes exceeding about 500 (Figure 10). Thus, any number of replications exceeding 500 is expected to produce reliable estimates of use and capacity exceedance. We ultimately chose to use 1,000 replicates of each model scenario, given that we used 1,000 replications to calibrate the temporal deviation algorithm and given that the implementation was efficient enough to perform 1,000 replicates in less than two hours on a personal computer. One replicate constitutes an entire 1 May through 30 September season of use.

All scenarios were run for 153 daily time steps representing 1 May through 30 September. The main output for each scenario is a table containing the mean and variance over all stochastic simulations of visitor nights spent in each zone on each night across the entire season and a second table containing how many person-nights each trailhead contributed to each of the wilderness zones. Because the mean over a large number of simulations does not reflect the possible extreme values that can occur, we also produced output detailing the frequency with which each zone is over capacity on each night. We measure the frequency as the number of simulations in which each zone is at a given exceedance of capacity on each night. When divided by the total number of simulations, this gives the probability of the exceedance level in that zone on that night. For example, suppose that the capacity of zone 67 is 50, and that the number of persons spending the night on zone 67 on 30 June exceeded 50 in 400 of the 1,000 stochastic simulations and exceeded 55 in 300 of the 1,000 simulations. Then we would report that there was a 40% probability of exceeding capacity in zone 67 on 30 June and a 30% probability of exceeding 110% of capacity in zone 67 on 30 June. Additional data are stored depending on the specific scenario. All binning and visualizations are consistent across scenarios to allow for comparison.

MODEL VERIFICATION AND VALIDATION

Model verification confirms that algorithms are implemented correctly (i.e., does the model do what we intend it to do?), and model validation confirms that output matches reality (i.e., does what we tell the model to do produce realistic results?; Lawson et al. 2006). The validation model uses data only from the permit itinerary database with no spatial or temporal adjustment and so models intended use. As a result, this model contains no calibrated parameters at all; recall that the only calibrated parameter in the model is the exit odds adjustment factor that accounts for deviation. Output for this model is compared to summary statistics calculated from the itinerary database, which represents intended use. Because there were a small number of permit itineraries with intended camping locations indicated only as "unspecified," we included "unspecified" as a 57th possible camping location in the validation model, in addition to the 53 wilderness zones and three backpacker camps. The only model algorithm that was stochastically implemented directly from an empirical distribution was party size. This algorithm was verified by comparing party size distribution between model output and permit data. Other model algorithms (e.g., the transition matrix adjustment for trip duration) were verified on their own prior to their incorporation into the model. All other party, trip and use attributes were simulated from partially or fully dynamic algorithms, so comparison of these attributes between model output and permit database constitutes model validation rather than verification.

Individual parties were used as the observational unit for comparison of party size and trip duration distributions. One season-long model simulation was used to generate these parties. Sample size was 14,497 for both model and permit database, except that trip durations were not obtained for 82 model-simulated parties that had not yet completed their trips by 30 September, when model runs end. A Kolmogorov-Smirnov test was used to test for equality of distributions, and a t test was used to compare means. For party size, there was no significant difference in either the distribution (D = 0.005, P = 0.999) or the mean (t = -0.482, df = 28986, P = 0.630) between the model and permit database (Table 4, Figure 11). Although the trip durations did not have the same distribution between the model and the permit database (D = 0.133, P = 0), there was no significant difference in the mean (t = -0.523, df = 28785, P = 0.601; Table 5, Figure 12).

Table 4. Party size verification summary.

Source	Min.	Q1	Median	Mean	Q3	Max.	st. dev.	*n*
Permit database	0	2	2	2.92	3	15	2.30	14,497
Model	1	2	2	2.93	3	15	2.33	14,497

Table 5. Intended trip duration validation summary.

Source	Min.	Q1	Median	Mean	Q3	Max.	st. dev.	*n*
Permit database	1	1	2	2.49	3	77	1.98	14,497
Model	1	1	2	2.47	3	25	2.10	14,415

The distributions of starting trailheads from the permit database and from one season-long model simulation were generated by counting number of trips starting from each of the 64 possible trailheads. The resulting contingency table of counts was too large to allow a sufficient number of permutations to be generated to use Fisher's exact test, and there were too many expected frequencies less than five to use a Chi-square test. Furthermore, with this large of a number of category levels, any test will almost certainly result in rejection of the null hypothesis that the distributions are the same, even if the relative differences are not that large. However, relative frequency histograms showed very similar distributions (Figure 13). Small differences between the two histograms result from differences between how the model reassigns starting trailheads to parties whose first choice was at quota and how this reassignment is done in practice. Recall that the model uses a reassignment algorithm that, on average, assigns trailheads in descending order of popularity. In reality, some visitors who are denied access to a trailhead select a new trailhead based on a decision other than simply selecting the next most popular trailhead that is available. This decision may result from a combination of the visitor's desire and the suggestions of the issuing permit agent. In absence of any data on how these decisions are made, we assumed that the "next most popular trailhead" rule for reassignment would be the simplest rule that could be implemented in the simulations and still model reality in the majority of cases. Figure 13 suggests that this reassignment rule generally reflects the actual choice of trailheads.

Graphic output of use resulting from a single simulation of the validation model compares well to intended 2010 use, as reported in the permit database (Figure 14). The output averaged over 1,000 simulations shows a similar pattern, but smooths year-to-year variability that results from the stochastic elements in the model (Figure 15). To statistically compare model-generated intended use figures with observed intended use figures, we first note that we have only one observation of actual use, namely the 2010 season. Because the observational unit for zone use is one season, we take the viewpoint that the model defines a population of all possible realizations of visitor use that could be observed over a large number of years. We estimate this population by simulating 1,000 seasons. Then, we test the null hypothesis that the observed use belongs to the model-predicted population by testing whether the observed use falls within a 95% prediction interval of use predicted by the model. This 95% prediction interval includes variance in estimating the population mean from the 1,000 simulations and variance around this estimated mean.

Calculation of prediction intervals for model-predicted use requires means and variances across 1,000 stochastic simulations. For season-total use summed across all zones and all nights, we stored all 1,000 total use values and computed means and standard deviations directly. Because season-total use is a sum of use across all zones and all nights, we expect it to be normally distributed across the 1,000 replications. Although a Shapiro-Wilk test for normality provided some evidence of departure from normality (W = 0.997, P = 0.055), a histogram and normal probability plot showed that any deviation from normality was slight (Figure 16). Thus, we used a normal prediction interval for season-total use. The 95% prediction interval for season-total use across all zones was 103,941 ± 1742 = [102199, 105683], and the observed intended use from the database was 105,715. The observed intended use falls slightly outside of the prediction interval. However, the use calculation from the database includes about 200 visitor nights after 30 September that are attributable to parties who had not yet completed their trips by the end of September, and the model-produced estimate does not include this use. Accounting for this use results in overlap between the model-generated prediction interval and the permit database value, indicating that at a 5% level of significance, we do not reject the null hypothesis that observed use belongs to the model-predicted population.

Across all zone-nights, direct calculation of means and standard deviations would require storing 8,721 use values (57 zones × 153 nights) over 1,000 simulations. To avoid using this much storage, note that

$$\bar{x} = \frac{\sum_{i=1}^{1000} x_i}{1000}, \tag{6}$$

so to compute the mean $\bar{x}$ of use in a particular zone-night over 1,000 simulations, we need only store the running sum $\sum_{i=1}^{k} x_i$, where k takes on all values from 1 to 1,000. Similarly,

$$Variance = \frac{\sum_{i=1}^{1000}(x_i - \bar{x})^2}{999} = \frac{\sum_{i=1}^{1000} x_i^{\,2} - 1000\bar{x}^2}{999} \tag{7}$$

so we need only store the running sum of $x_i^{\,2}$ in addition to the sum of x_i. This requires two 57 × 153 matrices (one for the sum of x_i and the other for the sum of $x_i^{\,2}$) rather than 1,000. To use these means and variances to calculate prediction intervals, the distribution of use across simulations must be known. At the zone-night scale, the assumption of normality is not appropriate, especially for zones that receive little use. To assess the distribution of use at the zone-night scale, we plotted variance in use over the 1,000 simulations versus mean use for all 8,721 zone-nights in the validation model. The variances were generally a little larger than the square of the mean, but the overall relationship was quadratic (Figure 17). This implies that zone-night use is exponentially distributed. Thus, we constructed 95% prediction intervals for each zone-night based on exponential distributions with $mean = \sqrt{variance}$. At 95% confidence for each zone-night, we expect observed zone-night use to fall outside the 95% prediction interval in fewer than 5% of the 8,721 zone-nights. Observed intended use fell outside of the modeled 95% prediction interval in less than 1% of all zone-night combinations. Thus, we do not reject the null hypothesis that observed use at the zone-night level belongs to the model-predicted population of use.

VISITOR USE SCENARIO MODELING AND ANALYSIS

CURRENT USE SCENARIO INTENT & OUTPUT

This scenario simulates actual Yosemite Wilderness visitor use, including the effects of spatial and temporal deviation. The frontcountry backpacker camps were retained in this model, but the possibility of transitioning to the "unspecified" zone was removed. This scenario is modeled in two components, one representing visitor use from trips originating in Yosemite and the other incorporating additional visitor use from trips originating outside the park. The model's temporal deviation algorithm was validated by comparing model-predicted use with that of the permit database after adjustment for temporal deviation. The distribution of spatial deviations is compared to that observed in the sample of survey respondents to verify the spatial deviation algorithm.

Trips originating in Yosemite

Mean use from trips originating in Yosemite was 89,997 visitor nights per year, with a 95% prediction interval of 89,997 ± 1,743 (Table 6). As expected, use is greatest between the end of June and Labor Day (Figure 18); the nights with highest use were 3, 24, and 31 July; 6 and 7 August; and 4 September. The zones in which mean use exceeds capacity on one or more nights are Sunrise Creek (zone 66), Snow Creek (zone 67), May Lake (zone 75), and Glen Aulin (zone 81). These zones are clearly depicted in Figure 18; numerical values are given in the accompanying spreadsheets (Appendix D). The four zones mentioned above have the highest probabilities of capacity exceedance (Figures 19-21). However, other zones that are under capacity *on average* may still exceed capacity on some nights in some years (Figure 19, Appendix D). Of these zones, Vogelsang (zone 63) has the highest probabilities of capacity exceedance. Use in some zone-nights exceeded 110% or even 150% of capacity in a substantial fraction of simulations (Figures 20-21).

Except for Washburn Lake (zone 61) and Twin Lakes (zone 92), every zone receives at least 20% of its use from a single trailhead, and 18 zones receive over 50% of their use from a single trailhead (Figure 22). Two of the four highly used zones identified above receive a majority of their use from a single trailhead. The May Lake trailhead (ID 36, Appendix B) contributes 54% of the use observed in the May Lake zone (zone 75), and the Glen Aulin trailhead (ID 81) contributes 62% of the use received by the Glen Aulin zone (zone 81). See accompanying spreadsheets for numerical values (Appendix D).

Effect of deviation

Deviation reduced model-predicted mean annual use by 13.4%, from 103,941 visitor nights to 89,997 visitor nights, and this reduction was statistically significant (t = -163.66; df = 1947; P = 0). The reduction in overall use was reflected at the zone-night level, greatly reducing occurrences of mean use exceeding capacity (Figures 15 and 18). For example, without accounting for deviation, mean use in Glen Aulin (zone 81) is predicted to exceed capacity on 57 nights during the season (Figure 15), whereas when deviation is included, mean use in that zone does not exceed capacity on any nights (Figure 18).

Table 6. Mean annual use and bounds on the middle 95 percentiles of use, by source, under current conditions. Use figures include the backpacker camps, which account for an average of 498 annual visitor-nights (0.5% of total). Discrepancy in total use with the table in Appendix A is due to rounding.

Source	Mean Annual Use (visitor nights)	% of Use	2.5th percentile	97.5th percentile
YOSE trailheads (Appendix B)	89,997	90.0%	88,255	91,740
Bridgeport USFS	3,010	3.0%	2,517	3,504
Other USFS	6,235	6.2%	5,707	6,764
Pacific Crest Trail	765	0.8%	727	802
TOTAL	100,007	100%	98,121	101,895

To compare model results with data, regression equation (3) relating actual trip duration to party size and intended trip duration was applied to the 14,497 parties that started trips in the study period to compute the expected number of nights each party spent in the wilderness as a function of party size and intended trip duration. The calculated expected trip duration was then multiplied by the party size to estimate total visitor use and summed over these 14,497 parties to obtain an estimate of total visitor use. This estimate was 93,795 visitor nights, 10.8% lower than the intended use of 105,715. The 95% confidence interval for this estimate was 93,975 ± 818 = 93,975 ± 0.87%. This confidence interval does not intersect the model-produced prediction interval, even after accounting for the extra use after 30 September that is included in the database-derived figure. In particular, the simulation model predictions are lower than those produced by adjusting the permit database for temporal deviation. The primary reason for this is that equation (3) includes the effect of party size on temporal deviation and applies the deviation adjustment one party at a time, whereas the model simulates temporal deviation through the transition matrix, which is applied in a dynamic manner independent of party size. Because larger parties tended to have slightly longer trips, the simulation model slightly underestimated total use. A secondary reason for this is that the regression method of predicting actual use from intended trip characteristics assumes continuous, normally distributed trip duration adjustments when in reality, trip durations are positive integers, most often 1 or 2 days, and therefore duration adjustments are neither continuous nor normally distributed.

However, it is worth observing that although party size was a statistically significant predictor of trip duration, its effect was extremely small, an increase in mean trip duration of only 0.0433 nights per additional party member. Given that mean party size was 2.92, the average effect of party size on trip duration was an increase of only 0.126 nights. When party size is removed from the regression of actual trip duration, the predictive ability of the model is only slightly reduced. The resulting regression equation is

$$\text{actual duration} = 0.389 + 0.699x, \tag{8}$$

where x = intended trip duration ($R^2 = 0.618$, residual standard error = 0.932, df = 1121). Recall that $R^2 = 0.622$ for the model that included trip duration as a predictor, so the two models both explain about 62% of the variability in trip duration. Applying regression equation (8) to the permit database instead of equation (3) leaves mean trip duration unchanged at 2.12 nights, but it produces a total use estimate and 95% confidence interval of 90,648 ± 819, which now overlaps with the prediction interval produced by the model. After accounting for the extra post-September use, the deviation-adjusted use figure derived from the permit database and that generated by the model differ by less than 0.5%, thereby validating our dynamic approach to incorporating temporal deviation. A Chi-square test for independence indicated no evidence of difference in distribution of spatial deviation classes between the survey sample and one season-long simulation of the model (χ^2 = 0.111, df = 3, P =0.990, Table 7).

Table 7. Spatial deviation rate verification summary.

Deviation	Model	Survey Sample
None	6,547 (45.4%)	472 (45.6%)
1st zone transition	4,415 (30.6%)	344 (30.6%)
2nd zone transition	2,548 (17.7%)	194 (17.2%)
3rd+ zone trnasition	925 (6.4%)	73 (6.5%)

Additional influence from outside Yosemite

Trips originating outside of Yosemite accounted for a mean of 10,010 additional visitor-nights during the study period, increasing the total use estimate during the study period to 100,007 visitor nights per year, with a 95% prediction interval of 100,007 ± 1,888 (Table 6). Sources outside of Yosemite therefore accounted for 10% of total visitor use. Of that use, an estimated 498 visitor nights per year (0.5% of total use) occurred in the backpacker camps. Adding the use from external sources had relatively minor effects on the overall patterns of zone use and capacity exceedance (Figures 23-25, compared with Figures 18, 19 and 21), although use in specific zones on specific nights is obviously higher with the additional use (see Appendices A and D for numerical values). The five zones mentioned above (Sunrise Creek, Snow Creek, May Lake, Glen Aulin and Vogelsang) had the highest rates of capacity exceedance regardless of whether use originating from outside sources is included. However, even when use from all sources is included, these are the only five zones in which the probability of capacity exceedance is greater than 20% on more than one night of the season (Figure 23). Sunrise Creek, Snow Creek, May Lake, and Glen Aulin are the only four zones in which the probability of capacity exceedance is greater than 30% on any given night of the season (Figure 23). It is worth noting that even after adding use from outside of Yosemite, the overall effect of incorporating deviation is still to reduce the occurrence of zone capacity exceedance that would be predicted from permit itineraries alone (comparison of Figures 15 and 23).

Including all sources of use, the eight most heavily used zones accounted for a mean of 43,564 visitor nights, 43.6% of total use (Table 8, Appendix A). Of use in these zones, only that in Lyell Canyon was disproportionately increased by addition of use from trips originating outside of the park. Use from outside of the park accounted for 22.5% of all use in Lyell Canyon, compared with 10% of use across all zones and less than 5% of use in each of the other seven most highly used zones. However, the eight zones with the highest total use are also the eight zones with the highest use that originates from Yosemite trailheads

(Appendix A). We chose to present the top eight zones here to compare with the results of van Wagtendonk (1981), who presented use figures from the 1970s for the top eight zones.

Although total use figures are relevant to management, the objective of the trailhead quota system is based on use relative to capacity. Some of the most heavily used zones have very high capacities (e.g., Little Yosemite Valley, zone 59, capacity = 150), so that high use does not necessarily equate to capacity exceedance. Conversely, zones with low capacities could conceivably contribute a relatively small percentage to overall use but still experience relatively high rates of capacity exceedance. Distinguishing total use from capacity exceedance requires detailed analysis of use data at the zone-night level, i.e., sorting through individual entries in the data tables (Appendix D). To provide a quicker and easier way to identify the zones in which use is most likely to exceed capacity, we developed an index that measures potential for capacity exceedance but can be easily computed from annual summary data and readily interpreted. This index is calculated by computing the percentage of total season-long use contributed by a given zone and dividing by the percentage of the total zone capacity of 4,200 accounted for by that zone's capacity. Values of this index that are near one indicate that the zone is used roughly in proportion to its capacity. Values larger than one indicate that the zone is heavily used relative to capacity and therefore has a higher potential for use to exceed capacity. Values less than one inidcate that the zone is lightly used relative to capacity. Given that temporal distribution of trips is roughly the same across all zones (other than lighter use of the high-elevation zones early in the season when use is light anyway), this index, even though defined by season-long use, will roughly correspond to the relative frequency of zone capacity exceedance. Values for the eight most heavily used zones appear in Table 8; values for all zones appear in Appendix A.

Table 8. Use (mean season-total visitor nights) in the eight most heavily used zones. YOSE use refers to that originating only at Yosemite trailheads. The Relative Use Index is the percent of total use contributed by that zone divided by its percent of capacity.

Code	Zone	Capacity	YOSE use	%YOSE use	Total use	% Total use	Relative Use index
59	Little Yosemite Valley	150	7679	8.53%	7922	7.92%	2.22
68	Yosemite Creek	100	6964	7.74%	6973	6.97%	2.93
72	Lyell Canyon	125	4892	5.44%	6313	6.31%	2.12
66	Sunrise Creek	50	5547	6.16%	5807	5.81%	4.88
67	Snow Creek	50	4595	5.11%	4605	4.61%	3.87
81	Glen Aulin	50	4003	4.45%	4122	4.12%	3.46
63	Vogelsang	50	3779	4.20%	3950	3.95%	3.32
75	May Lake	50	3864	4.29%	3872	3.87%	3.25

Table 8 illustrates the difference between use and capacity exceedance. None of the three most heavily used zones have the largest probabilities of capacity exceedance. However the five zones with the highest probabilities of capacity exceedance are among the eight most heavily used zones. The use index clearly distinguished these five zones from the others. In fact, the five zones with the highest use indices in Table 8 were also the five zones with the highest use indices among all zones (Appendix A), indicating that this simple and easily calculated index provides an accurate way to identify the zones with the higest probabilities of capacity exceedance. Use indices for all zones not listed in Table 8 were less than 3, implying that under current total use levels, a use index value of 3 or higher indicates that capacity exceedance probabilities can exceed 20% on more than one night during the season.

USE REDISTRIBUTION SCENARIO INTENT & OUTPUT

The intent of this scenario is to find a “no-exceedance” solution, as directed by Yosemite personnel. In a system as complex as Yosemite, there are an infinite number of such solutions, most of which would be irrelevant to actual management. For example, one possible solution is simply to deny parties entry into the park, thereby reducing both total use and the probability of capacity exceedance at the zone-night level. Clearly, this is not a realistic management option. Another possible solution is to redistribute use temporally, forcing a larger fraction of parties to use the wilderness prior to Memorial Day and after Labor Day. Although initial implementation of the quota system in the 1970s resulted in some temporal redistribution of use in Yosemite (van Wagtendonk 1981), it is unlikely that temporal redistribution alone can substantially reduce zone capacity exceedance probabilities in the middle of the summer. Thus, in absence of specific constraints or rules to use in finding such a condition, we chose to use a well defined procedure that redistributes use in space rather than time so that the resulting “no-exceedance” scenario accommodates the same number of parties on each day of the season as occurs under current conditions and can be implemented in the model with objective rules rather than via ad hoc redistribution of individual parties. We implemented this scenario using only Yosemite-derived trips to avoid confounding the zone-use trailhead relationship with use originating outside of the park.

Our procedure involved three steps: 1) identify the trailheads that contribute most to capacity exceedance, 2) use the model to determine how many parties would need to be moved from these trailheads to other trailheads in order to lower exceedance probabilities to an acceptable level, and 3) redistribute the required number of parties from the high-use trailheads to the low-use trailheads. Based on the zones that currently exceed capacity with the highest probabilities (Figures 19-21) and on the current zone use-trailhead contribution relationship (Figure 22 and Appendix D), we identified eight trailheads that are primary contributors to capacity exceedance (Table 9). We then defined “acceptable use” as no zone exceeding capacity on any given night in more than 30% of all simulations.

To achieve this level of use, we had to reduce the quota of these eight trailheads by the respective amounts listed in Table 9. Once these new quotas were met in the simulation, subsequent parties selecting that trailhead on a particular day were temporarily withheld from entering the wilderness.

Table 9. Trailhead quota adjustments required to reduce use to acceptable levels. This is defined as no zone exceeding capacity on any night in more than 30% of simulations.

Trailhead ID	Trailhead	Quota	Adjusted Quota
20	Happy Isles to Little Yosemite Valley	30	10
21	Happy Isles to Sunrise/Merced Lake	10	5
22	Mirror Lake to Snow Creek	25	18
23	Yosemite Falls	25	18
35	Porcupine Creek	25	18
39	Sunrise Lakes	20	8
41	Cathedral Lakes	25	10
45	Lyell Canyon	40	30
46	Glen Aulin	35	22

Thus, after steps 1 and 2 in this process, we created a condition in which the mean use does not exceed capacity in any zone (Figure 26). More importantly no zone exceeds capacity on any given day in more than 30% of all simulations (Figure 27), as desired. When zones do exceed capacity, they rarely exceed their capacities by a large amount (Figures 28-29). To achieve this acceptable use level, a mean of 3,040 parties were withheld each year, which represents 11,457 individuals and, multiplying by the average trip length of 2.12, about 24,889 visitor nights. Although the overall pattern of trailhead contribution to zone use was changed very little, careful examination shows that the contributions of these eight trailheads to the highest-use zones was decreased (Figure 30, compared to Figure 22).

To accommodate the parties that were withheld in steps 1 and 2, they needed to be reassigned to trailheads in such a way that use would remain near the acceptable levels achieved by removing these parties altogether. Because the model already includes an algorithm that reassigns the next most popular trailhead to parties that draw a trailhead that is at quota, this reassignment mechanism obviously does not lead to reduction in use. In fact, this reassignment mechanism leads to the capacity exceedances generated by the Current Use Scenario (Figures 19-21). Thus, we modified the trailhead assignment algorithm to send parties to the *least* popular trailheads once the popular trailheads were filled to quota. Although this is not necessarily a realistic reassignment solution, it is more realistic than denying the parties entry into the park or reassigning their trip temporally from the high-use periods to early May or late September. It also illustrates that spatial redistribution in some form can be effective at reducing capacity exceedance. To accomplish this reassignment, we redefine the entry trailhead probabilities so that the least popular choice has the highest probability of selection and the most common choice has the lowest probability. That is, we define the new probability q_i of selecting trailhead i as

$$q_i = \frac{1}{p_i \sum \frac{1}{p_i}} \tag{9}$$

where p_i = the original probability of selecting trailhead i. With this transformation, the arithmetic mean of the trailhead probability distribution is transformed to the harmonic mean, and the harmonic mean is transformed to the arithmetic mean. The maximum probability of 0.10 was transformed to 0.000102, and the lowest probability of 0.00006 was transformed from 0.00006 to 0.15.

Trailhead quotas set at the minimum of either their actual values or those in Table 9, and total visitor use was maintained at current levels. Then, when a party draws a trailhead with full quota in this scenario, it choose a new trailhead from the transformed distribution (equation 9), which forces parties to begin trips in the parts of the park that receive lower use. The resulting zone capacity use levels in this scenario are similar to those achieved after steps 1 and 2 of this process, as desired. There was only one night in one zone on which mean use exceeded capacity, but it exceeded capacity by less than 10% (Figure 31). Use in only eight out of 8,109 possible zone-nights across all zones and all nights had more than a 30% probability of exceeding capacity (Figure 32), compared with 134 zone-nights under current conditions, even when external use is included (Figure 24). Only two zone-nights had more than 30% probability of exceeding 110 % capacity (Figure 33). This scenario has no nights in any zone when use exceeds 150% of capacity in more than 10% of the 1,000 simulations (Figure 34). To achieve these results, an average of 3,575 parties was redistributed to less used parts of the park according to the trailhead selection probabilities defined by equation (9). The trailhead contribution to zone use for this scenario is shown in Figure 35, which shows clear differences in the zone-use trailhead relationship (compare with Figure 22). In particular, there is much more uniform contribution to use across trailheads under the Redistribution Scenario than under the Current Use Scenario.

MAXIMUM ALLOWED USE SCENARIO INTENT AND OUTPUT

The Maximum Allowed Use Scenario evaluates maximum visitor use by allocating maximum daily visitor entries at every trailhead as allowed by the current quotas on every day of the simulation period. There are several trailheads that do not have quotas (Appendix B), so we set quotas at 10 for these trailheads in this scenario. Because the same number of visitors enters every day, there is no longer a dynamic component; therefore this scenario represents a stable equilibrium of wilderness visitation. This scenario has multiple objectives. The first is to identify the total amount of wilderness use that would be allowed under the current quota system, which can then be compared to the total zone capacities. The second objective is to identify the spatial distribution of this use. The third objective is to generate the "true" dependence of zone use on trailhead of origin. The zone use-trailhead relationship generated by the Current Use Scenario primarily reflects trailhead popularity and only secondarily reflects trailhead quota. The relative contribution of trailheads to zone use in this scenario is confounded by the spatiotemporal distribution of trailhead selection and thus does not completely reflect either the trailhead quotas or the accessibility of zones from trailheads. The Maximum Use Scenario eliminates both temporal and spatial preference for trailhead selection and thus generates a relationship between zone use and trailhead that is based only the accessibility of zones from trailheads, given itineraries selected by current wilderness users. Again, to avoid confounding this relationship with use originating outside the park, that use was not included in this scenario.

The quota scheme used in this scenario, which is essentially the same used in actual practice, allows no more than 1,196 parties per day to enter the wilderness. Multiplying this by the mean trip duration of 2.12 nights yields a maximum use rate of 2,535 visitor nights per day. The Maximum Allowable Use Scenario resulted in a mean rate of 2,260 visitor nights per day, with the slight difference being due to stochasticity in the model. The sum total of all zone capacities is 4,200; thus the maximum allowed use about 54% of total capacity.

However, spatial use is clearly not uniformly distributed, even when trailhead use is proportional only to quota and not to visitor preference, resulting in exceedance of zone capacity in many zones (Figures 36-39). Under this scenario, zones with the greatest mean use, relative to capacity, are Bridalveil Creek (zone 55), Snow Creek (zone 67), and Yosemite Creek (zone 68). Under this scenario, there is a 100% probability that visitor use exceeds 110% and 150% of capacity in Snow Creek (zone 55) and Yosemite Creek (zone 68) on nearly every night (Figures 38-39). The latter two of these are among the most heavily used zones under current conditions as well (Table 8). On the other hand, predominant travel patterns are such that, despite maximum use conditions, visitor use in many zones does not on average, reach 50% of capacity (Figure 36), and many of those same lesser-used zones have no nights on which the model predicts any chance of capacities being exceeded (Figure 37).

The zone use-trailhead relationship generated by this scenario (Figure 40) is substantially different than that under current conditions (Figure 19) and in fact is more similar to that generated by the Redistribution Scenario (Figure 35). Both the Redistribution Scenario and the Maximum Allowable Use Scenario force larger fractions of use to originate from trailheads that are currently lightly used, resulting in a more uniform distribution of zone use across trailheads. However, it is also clear that regardless of how heavily or lightly used a trailhead is, the spatial relationships among trailheads and zones and the physical limitations and behavior of wilderness users determine the frequencies with which a given zone is visited by parties originating at a given trailhead; that is, there will always be certain trailheads that are the primary contributors to use in certain zones.

Similar to the way in which a measure of relative zone use was defined, we defined a measure of relative trailhead popularity by dividing the percent of use originating from a particular trailhead under the Current Use Scenario by that generated by the Maximum Use Scenario by the percent of use originating from that trailhead (Appendix B). Values of this "popularity index" near one indicate that the trailhead is contributing to use roughly in proportion to its contribution to the total visitor quota. Values larger than one indicate that the trailhead is contributing more to overall use than its contribution to the quota, and values less than one indicate that the trailhead is contributing less use than its contribution to the quota. The trailhead popularity index is not as robust or useful a measure as the relative zone use index because some trailheads have very small quotas relative to others and some have no quotas at all. Furthermore, there are many trailheads that are managed separately in the permit system but are essentially in the same geographic location (e.g., the five Happy Isles trailheads), so analyzing these trailheads by group rather than individually would probably give more accurate measures of relative trailhead use and popularity. Nonetheless, this index provides a quick and easily understood way to identify trailheads currently being used in excess of their overall contribution to quota (e.g., Mirror Lake to Snow Creek, ID 154, popularity index 4.92) and those that could absorb more use relative to their contribution to overall quota (e.g., Westfall Meadow, ID 141, popularity index 0.06; Appendix B).

DISCUSSION

MODEL CAPABILITY

We were created and validated a model of wilderness use that reproduced observed use characteristics at the zone-night resolution with a minimal set of assumptions and calibrated parameters. The validation trials show that averaged over many simulations, the model produces the same wilderness trip statistics as those reported in the permit database. Since modeled party sizes were selected randomly from the observed empirical distribution of party sizes in the database, we expect no significant difference between the two. However, the comparison of trip durations between the model and the database is more interesting. Although the two samples come from different distributions, they showed no statistical difference in means, medians, or quartiles. This validates our approach to modeling trip duration dynamically with transition probabilities rather than by predetermining trip duration to each party at the beginning of its trip. The transition matrix approach also avoided having to limit itineraries to a finite set. Observed use from the 2010 permit database falls within the model's prediction intervals, indicating that any small differences in starting trailhead distribution or trip duration that may exist between the simulation model and the permit database did not affect spatiotemporal distribution of wilderness use. We also found that 1,000 replicates were sufficient for accurate estimation.

The Current Use Scenario demonstrates the model's use as a tool to monitor current conditions. This scenario accounts for both itinerary deviation and USFS trailhead contribution to produce our best estimate of actual wilderness visitor use in 2010. The Redistribution Scenario shows how the model can be used as a predictive tool to test various management scenarios. The Maximum Allowed Use Scenario shows the model can be used in a much more experimental sense, testing conditions that are not truly feasible but that still may provide insight into the system. It also allowed us to calculate the system's inherent zone use-trailhead relationship, unconfounded by visitor preference for particular trailheads. Had we selected the trip itineraries from a fixed set, no matter how large, the model would not have retained the full complexity of this relationship.

We were able to take advantage of built-in ExtendSim commands to build most model components. For the quota system and transition matrix algorithm, we created custom equation "blocks" in ModL, the programming language used by ExtendSim. Although this model could have been implemented on a number of other platforms, the ferocious efficiency of ExtendSim allowed for incredibly fast simulations, even with large models. This model was able to run 1,000 simulations, each controlling 15,000 parties over 153 days in just over an hour on a home computer (2.71GHZ processor, 4.00GB RAM). This efficiency was crucial while applying the bisection algorithm to account for deviations and makes the model a viable tool to test various scenarios.

By defining the model output to be consistent with the definition of capacity we were able to create results that were additive across various models. This allowed us to combine the results from the general Yosemite model with the results from the USFS stations and Pacific Crest Trail hikers. This allows for a much more complete representation of use in Yosemite's wilderness. This is critical, as it represents the actual conditions of use in the Park, not just the manageable portion that consists of parties that start their trips in Yosemite. Incorporating outside use in this dynamic fashion is much more meaningful than a simple raw count of how many parties entered the Park, as it relates the use to the management unit of nightly capacities.

The stochastic nature of the model worked as predicted, and over many simulations values such as party size converge to the empirical distributions on which they are based. More than that however, the stochastic nature of the model allows for deeper insight and more flexibility than a standard statistical analysis. By using a stochastic framework we neither limited the possible routes taken by parties nor predefined trip durations. This means that any feasible trip that can occur in Yosemite has a possibility of occurring in the model. Since Yosemite is such a large and interconnected area, creating "typical" itineraries would be difficult and would not accurately reflect the full picture of use in the park.

Lastly, the model accounts for spatial deviation dynamically. Unlike temporal deviation, spatial deviation is defined categorically so there is no way to measure its effects by an average of some quantity. Since Yosemite has such a high rate of deviation, accounting for it in the model allows simulation of crucial information that is not available otherwise. Standard statistical analysis may tell us how many parties deviate, but not what effect it has on overall wilderness visitor use. The only way to see the effects of spatial deviation in the Park is to simulate it. By not using preselected routes or durations, we were able to dynamically alter routes to represent deviation. Comparing Figure 15 with Figure 18 shows what a drastic effect the deviation has.

COMPUTER SIMULATION MODELING AS A PLANNING TOOL

The findings of this study and the simulation model allow the park a more accurate, and more quantitative, understanding of existing conditions. The vastness of the wilderness, and its many access points, limits the ability of managers to precisely monitor visitor use conditions, particularly the number of visitors camped overnight in any given wilderness zone. The model provides managers with reliable estimates of these hard-to-measure variables. The spatiotemporal model outputs allow managers to identify the place and time that use occurs, especially when and where there is concern that concentrated use could lead to conflicts among different user types or impacts to fragile ecological resources or wildlife habitat (Lawson 2006).

With this model, resource managers will be able to evaluate the effectiveness of alternative management strategies more efficiently and with less risk than trial-and-error methods. They may evaluate potential visitor use demands and develop informed plans to prepare for those potential conditions (Lawson 2006). The results from the Current Use Scenario provide park managers information about current use conditions to inform establishment of a baseline of wilderness character as mandated by the recently revised Director's Order 41 on Wilderness Stewardship (NPS 2011a). The other scenario results provide "sideboards" that may help facilitate the prescriptive process of selecting management alternatives.

The Redistribution Scenario gives managers a glimpse of visitor use distribution under a management strategy of redistributing visitors who cannot access their first-choice trailheads to the least popular trailheads in the park. Although this strategy may not be fully feasible, the results of this scenario show that it is possible to greatly reduce zone capacity exceedance through spatial redistribution alone. This scenario is only one of a theoretically infinite number of such solutions, providing evidence that the long-standing approach to managing wilderness zone use through trailhead assignment is valid and providing an example of how the model can be used to find such "no-exceedance" solutions. Therein lies the beauty of the interactive model – it provides managers the ability to try out any number of possible solutions in a simulation environment, allowing them to choose and implement the solution most likely to succeed in protecting wilderness resources and experiential values such as solitude.

The Maximum Allowed Use Scenario provides two key pieces of information; the first is simply the zone usage that could theoretically result from the current trailhead quota scheme under maximum use, and the second is the true dependence of zone use on trailhead-of-origin, determined by geography, human behavior and physical capacity, and the current trailhead quotas. In this case it was shown that the maximum overall use allowed by the trailhead quotas is only about 54% of overall zone capacities. However, many zones are well over capacity in this scenario, while others remain relatively lightly used. This non-uniform distribution of use is a result of the spatial relationships among trailheads and zones and the physical capabilities and behavior of wilderness users, all of which are retained in the zone transition probability matrix. The true relationship between zone use and trailhead-of-origin was used to create a trailhead popularity index, which gives a quick and easily understood method for identifying the most highly used trailheads and those for potential to absorb more use.

CURRENT USE CHARACTERISTICS AND COMPARISON WITH THOSE OF THE 1970S

There are two primary purposes of comparing current use characteristics with those observed in the 1970s. The first is to draw general conclusions about overall magnitude and spatiotemporal patterns of use. The second is to assess how changes in visitor attributes might affect use patterns and the trailhead quota scheme, which was developed from conditions that existed in the 1970s.

Spatiotemporal patterns of use

Although wilderness use has increased in recent years, it remains substantially lower than at its peak during the 1970s. There is some evidence that use of the Yosemite wilderness originating outside of the park has increased; we estimated this component of use at 10% of the total, compared to 4% in the 1970s (van Wagtendonk 1981). Current temporal distribution of use (Figure 3) is very similar to that of the 1970s (Figures 1 and 2 in van Wagtendonk 1981); the vast majority of use occurs between Memorial Day and Labor Day and is much higher on weekends and holidays than on temporally adjacent weekdays. In 1973, the first year of the quota system, the eight most heavily used zones accounted for 51.1% of total use. In 1979, those zones accounted for only 36.9% of total use (Table 3 in van Wagtendonk 1981). In 2010, the eight most heavily used zones accounted for 43.6% of total use. Without analyzing this kind of information over a large sequence of years, it is not possible to determine whether there has been a systematic temporal trend in these figures or whether their variability is due to random effects. Five of the eight most heavily used zones in the 1970s remain among the eight most heavily used zones today (Little Yosemite Valley, Vogelsang, Glen Aulin, Lyell Canyon, and Sunrise Creek). Merced Lake, Illilouette Creek, and Young Lakes were in the top eight in the 1970s;

the first two of these were ranked 10th and 14th in use in 2010. There is currently no camping allowed at Young Lakes (zone code 82).

Little Yosemite Valley (zone 59) has remained the most highly used zone in Yosemite since the 1970s, currently accounting for 7.9% of total use. However, because the capacity of Little Yosemite Valley is 150 persons per night, there are no nights on which the probability of capacity exceedance is greater than 10% (Figure 24). It has such a high capacity, especially considering its comparatively smaller size, because it has a regulated, designated, backpacker campground with toilets and bear-proof metal food lockers. It is also the most likely overnight camp for the many visitors who intend to climb Half Dome, because it is the nearest site with restroom facilities and ranger station.

Sunrise Creek (zone 66, Figures 2 and 41), just north of Little Yosemite Valley, was among the eight most popular zones in the 1970s and currently experiences the 4th highest use, accounting for 5.8% of all use. However, unlike Little Yosemite Valley, Sunrise Creek is has the highest rate of capacity exceedance; mean visitor use in Sunrise Creek exceeds capacity on 46 nights (Figure 23). Of the visitor nights that accumulate in Sunrise Creek, 25% are attributable to visitors who began their trip with a permit for Happy Isles to Little Yosemite Valley. Those wilderness permits are meant for visitors intending to spend their first night in the Little Yosemite Valley backpacker campground. Fourteen percent of visitor nights in Sunrise Creek are attributable to trips originating at Happy Isles to Sunrise/Merced Lake. Those permits are for visitors using the Happy Isles trailhead intending to spend their first night either to the north or east of Little Yosemite Valley. Thus, 39% of all nights spent in Sunrise Creek are attributable to visitors originating at the Happy Isles trailheads.

There are two prominent peaks within a one-day hiking distance from their nearest trailheads that are attracting the substantial amount of visitor use to the Sunrise Creek zone. Half Dome is likely the most iconic feature in Yosemite National Park, and Clouds Rest is quickly becoming one of the most highly sought destinations. Half Dome attracts so many visitors that the park has recently implemented a day use permit system during the high-use period implementing a daily quota of 400 persons allowed to summit in order to manage for safety and experiential factors (NPS 2011b). It is no wonder then, that such highly sought peaks would draw visitor use to the feature vicinities as they do. Sunrise Creek is fed by streams draining off the southeastern flank of Clouds Rest and the zone offers a prime location for a backpacking campsite from which the visitor could make day hikes to the summits of both Half Dome and Clouds Rest (Figure 41).

The other two trailheads contributing most to Sunrise Creek are along the Tioga Road. The Sunrise Lakes trailhead is approximately 6.8 trail miles (11 km) from the Clouds Rest summit. It would seem that Clouds Rest is also attracting use from the north from visitors who climb it, then spend nights in Sunrise Creek. The increasing popularity of the John Muir Trail may also be contributing to use in Sunrise Creek. The 210-mile (338 km) route, which begins in Yosemite Valley and ends at the summit of Mount Whitney, has been called “the best hike ever” and America’s most beautiful hike (Bastone 2010). The same two trailhead permits that most contribute to Sunrise Creek use are also the highly coveted permits for visitors beginning the John Muir Trail. Backpackers seeking a first-come, first-served permit have been known to arrive at the Wilderness Center in Yosemite Valley as early as 3:00 a.m. to be first in line when the permits become available at 7:30 am. The John Muir Trail bisects Sunrise Creek, so it follows that much of its overnight use is attributable to hikers on the John Muir Trail.

Glen Aulin (zone 81) received the third highest use in the 1970s and currently experiences the sixth highest use, accounting for 4.1% of all use. It has the second highest rate of capacity exceedance under current conditions; mean use exceeds capacity on 2 nights during the season (Figure 23), and the probability of capacity exceedance is greater than 30% on 34 nights (Figure 24). Glen Aulin is a popular “high country” destination in the park. The relatively short distance (5.3 trail miles, 8.5 km) and its mostly downhill slope make the hike from the trailhead parking lot along the Tuolumne River to the backpacker camp at Glen Aulin very attractive to wilderness visitors. Also, the designated backpacker camp at Glen Aulin has a toilet and food storage lockers, which add comfort to the experience of most visitors. The lockers’ presence allows visitors to avoid the necessity of carrying the extra weight of a bear-proof food storage canister. A previous Yosemite study found 43% of wilderness visitors who did not carry a canister purposely limited their trips to destinations with the lockers to avoid being regulated to use a canister (Martin and McCurdy 2009). May Lake (zone 75), which currently accounts for 3.9% of all use, also has a designated backpacker campground with facilities. It has the fourth highest rate of capacity exceedance; the probability of capacity exceedance is greater than 30% on 14 nights (Figure 24).

Effects of changes in party attributes

When compared with those of the 1970s, current Yosemite wilderness visitors are more likely to deviate spatially and are less likely to deviate temporally. When current parties do deviate temporally, their range of temporal deviations is larger than that observed in the 1970s, and the mean length by which trips are shortened is greater. However, overall deviation rates have remained fairly constant in time at around 64%, and the amount by which temporally deviating parties shorten their trip as a function of intended trip duration has changed relatively little, averaging a shortening of about 0.38 nights per additional day of intended duration. We did not attempt to quantify the fraction of wilderness users that did not even obtain a permit; van Wagtendonk and Benedict (1980) estimated this fraction at 8% of all users. We assumed it to be 0 and did not attempt to adjust our use figures to account for non-permitted use.

Compared to visitors of the 1970s, current wilderness visitors travel in smaller parties and take shorter trips. One consequence of shorter trips is a relative increase in use in zones relatively close to trailheads and a relative decrease in use in zones further away, although as mentioned in the introduction, a relative increase in use due to shorter trip durations does not necessarily lead to an increase in capacity exceedance probabilities. However, three of the eight most heavily used zones in 2010 that were not in the top eight in 1979 (Snow Creek, Yosemite Creek and May Lake) are adjacent to trailheads. Given that total wilderness use has declined since the 1970s and that temporal distribution of use remains unchanged, it is likely that the tendency toward shorter trips has contributed to increased relative use in these three zones. It is also possible that increasing popularity of iconic destinations, along with an increased visitor preference for campsite amenities, has resulted in more concentrated use in zones containing established backpacker camps and zones with popular routes such as the trails that connect the Yosemite Valley with the Tioga Road.

The key to the Yosemite wilderness management system, which attempts to achieve wilderness use objectives based on trailhead management, is the relationship between zone use and trailhead use. To determine whether this relationship has changed since the 1970s, we would need to have data relating use at the zone-night resolution to trailhead of origin from that time period. In absence of such data, we cannot make any definitive statements about how this relationship may have changed. However, we argue that the "true" relationship between zone use and trailhead of origin has not changed, even though the relative popularity of trailheads among users may have changed. This true relationship, which was computed from our Maximum Allowable Use scenario, is unconfounded by temporal pattern of use and popularity of trailheads among visitors, but it is dependent on trailhead quota and the deviation-adjusted transition matrix. Furthermore, because it represents *relative* contributions to use (e.g., fractions of total use that originate from given trailheads), it is not dependent on the actual magnitude of use, which is determined by number of parties, party size and trip duration. Thus, even though total use, party size and trip duration have changed between the 1970s and 2010, because trailhead quotas remained unchanged, the only variables that could change the relationship between trailhead of origin and zone use are the deviation-adjusted transition probabilities, which depend on intended itinerary and itinerary adherence. Given that the latter has not changed since the 1970s, the only way the relationship between zone use and trailhead could change is if the spatial component of intended itineraries has changed. These spatial components are unlikely to have changed because they reflect the trail network and geography of the Park backcountry, which have not changed. Furthermore, it is unlikely that the physical capabilities of wilderness users or their short-term behavior related to route selection and camping locations have changed either, even though overall trip duration has decreased. Through analysis of the transition matrix and model output, we have shown that shorter trips can be accommodated by increasing the odds of exiting from any given zone, without changing the relative transition probabilities among the zones. This implies, for example, that if the most likely place to spend a night after leaving zone A is zone B, then it remains so regardless of how a party got to A, how many nights it spent there, where it goes after B, and whether the night spent in A was the 2nd night of a 4-night trip or the 5th night of an 8-night trip. In other words, even if overall trip durations were longer in the 1970s, the transition probabilities among zones, given that the party chooses not to exit, have probably remained unchanged. Thus the current "true" relationship between zone use and trailhead of origin is most likely the same as that of the 1970s.

Therefore, we conclude that any changes to the relationship between zone use and trailhead that have occurred since the 1970s are related to shifts in visitor preference for certain trailheads rather than to inherent changes in the zone-trailhead relationship, which is determined by trailhead quotas, physical geography, physical capabilities of wilderness users, and their short-term behavior in moving among wilderness zones and selecting campsites. Thus, the inherent zone use-trailhead relationship upon which the current management scheme is based still forms a valid basis for management. However, managers may wish to consider more careful refinement of the quota scheme, including the ways in which visitors might be guided towards lower-use areas of the park, based on the tools we have provided.

IMPLICATIONS OF SPATIAL REDISTRIBUTION OF USE

The Current Scenario clearly shows that under current visitor preferences for trailheads and timing of their wilderness trips, there are five zones with high probabilities of capacity exceedance. This scenario uses a trailhead reassignment mechanism that has an average effect of sending visitors to the next-most popular trailheads once the most popular trailheads reach quota. Although we do not know if this is exactly what happens in practice, the validation results (Figure 13) suggest that this reassignment mechanism is probably close to what occurs in practice. Therefore, the current quota scheme, together with a mechanism that essentially fills trailhead quotas in decreasing order of preference, is allowing relatively high probabilities of capacity exceedance in five of the zones.

However, this observation does not mean that the quota-based scheme is an invalid way to manage wilderness use. To the contrary, the Redistribution Scenario shows that the frequency and probability of capacity exceedance in these five zones can be substantially reduced through spatial redistribution of use alone, without altering either overall use or temporal distribution of trips. This implies that not only is the *concept* of meeting backcountry use objectives through frontcountry trailhead management valid but also that in fact these objectives *can* be met. Our redistribution scenario provides an explicit example of this, through the quotas offered in Table 9 and a reassignment scheme that sends parties to areas of the park that are currently lightly used (equation 9). This is only one of an infinite number of such theoretical scenarios and provides a template for managers to use to determine other such scenarios.

In general there is a well-defined procedure for finding such "no-exceedance" scenarios. First, use either graphical or tabular output from the Current Use Scenario (e.g., Figures 23-25, Appendix D) or the relative use index (Table 7, Appendix A) to identify the zones with the highest probability of capacity exceedance. Then use the current zone use-trailhead relationship (Figure 22, Appendix D) to determine which trailheads currently contribute the largest fraction of visitors to those zones. The true zone-use relationship (Figure 40, Appendix D) or the trailhead popularity index (Appendix B) can be used to identify trailheads that are currently underused relative to their quotas. Then iteratively lower quotas at the highly used trailheads, while increasing use in the underused trailheads until desired use levels are attained. In our example, we used Figure 22 to determine that the zone most frequently over capacity (Sunrise Creek, zone 66) is fed primarily by the Happy Isles, Sunrise Lakes, and Cathedral Lakes trailheads. The necessary adjustments to those trailheads to produce acceptable use resulted in a 40.9% reduction in daily quota, from 235 to 139 visitors per day entering those trailheads. The quantitative portion of this exercise, of course, is the easy part. It is difficult to predict how visitors seeking permits would react to conditions of such reduced access. Quotas can be increased at certain other trailheads to allow for the same total amount of wilderness access, but those other trailheads are clearly not as popular with visitors. Would visitors accept a less preferred trailhead, one that likely would not lead to their desired destination? Would they decline to take a wilderness trip at all if they could not gain access via their preferred trailhead?

Visitors are drawn to certain highly desired or iconic destinations in the Yosemite wilderness, so it is also possible that even with reduced quotas at certain trailheads, visitor use patterns could adjust such that the probabilities of zone-to-zone transitions change from the current condition to reflect the draw those iconic destinations such as Half Dome have on visitors. Demand to reach that summit is so great now that visitors seeking first come first serve permits to Little Yosemite Valley are willing to accept permits for the Illilouette Creek drainage where they spend a "layover" night before being assured of camping at Little Yosemite Valley the next night in preparation for their Half Dome ascent. Another possible outcome of greatly reducing use at certain popular trailheads is that visitor use could increase in other portions of the wilderness that are currently more lightly used. This could have the effect of increasing visitor use impacts to resources in those more pristine portions of the wilderness, as well as decreasing opportunities for solitude. In the long term, this could have the effect of narrowing the range of conditions and opportunities available in the Yosemite wilderness.

Nonetheless, our results clearly show that zone use objectives can be met through trailhead management and therefore that the basic management scheme implemented in the 1970s remains valid today.

FREEDOM TO ROAM AND REGULATORY RATIONALES

The Yosemite trailhead quota system is designed, in part, to allow visitors the freedom to roam, and gives visitors the right to alter their plans serendipitously. It provides maximum freedom to visitors consistent with wilderness experience and resource constraints (van Wagtendonk and Coho 1986). This characteristic may increase the potential of Yosemite wilderness experiences to provide visitors with a sense of inspiration, escape, and/or autonomy. This study found strong evidence that visitors are altering their trips in both time and space, thereby demonstrating both the necessity for managers to allow for, and proof of visitors exercising, those rights to freedom.

This study also found that that on some nights, a portion of the wilderness management zones likely receive use exceeding their set numerical user capacities. This study produced a tool for Yosemite National Park that allows managers to find combinations of trailhead quotas that bring visitor use levels in those overused zones back down to capacity while still accommodating the same overall amount of wilderness visitor use. It is ultimately up to park managers to decide how best to use the modeling tool provided, but it may be worth noting that a previous study using stated-choice modeling found that Yosemite wilderness visitors would be willing to accept a lower chance of receiving a permit in order to receive improvements in other conditions such as having fewer encounters during their trips (Newman et al. 2005). It is also worth noting that a study in Oregon and Washington found that wilderness visitors are more supportive of use limits if the rationale given is protection of the environment rather than protection of experiences (e.g. solitude, Cole and Hall 2008a). Therefore, if managers implement an alternative trailhead quota configuration that reduces use, actual visitors are more likely to accept it in regard to what they may gain experientially, while the public at large (including non-visitors) may be more likely to support it in consideration of resource preservation. Also, past comparisons of wilderness visitors at high-use trailheads to visitors at trailheads receiving moderate use found that at very high-use trailheads fewer people feel that solitude is critical to an authentic wilderness experience, those visitors were more likely to report that trail encounters did not matter to them, and that more encounters would be tolerable since those visitors had more lenient standards. This suggests that visitors to high-use destinations make "psychological adjustments to heavy use" (Cole and Hall 2008b).

LIMITATIONS OF THIS STUDY

It was not within the scope of this study to evaluate certain aspects of wilderness management and use in Yosemite National Park. The overnight zone capacities determined in the 1970s by park scientist Jan van Wagtendonk were not examined or questioned. Some wilderness researchers maintain that the accuracy of capacity estimates could be increased if more varied information is considered to enable the refinement of estimates based on new and potentially better information. The accuracy of capacity estimates should also consider all management actions being taken. Making trails more durable, improving wilderness facilities, and teaching Leave-No-Trace techniques may increase capacity if such actions reduce the effects of per capita use (Cole and Carlson 2010).

The High Sierra Camps exist as enclaves surrounded by, but not actually a part of, the Yosemite Wilderness. The camps are a popular destination in the park and offer visitors a chance to enjoy the resource while retaining access to such amenities as canvas walled tents, raised beds, and prepared meals. The capacities of the zones in which the camps are located do not account for the occupancy of the High Sierra Camps, and overnight visitors to the camps do not obtain wilderness permits. Therefore, while those visitors, along with the mule-trains that resupply the camps, surely affect the resource and experience of other visitors, those effects are beyond the scope of this study.

FURTHER RESEARCH

To best assess the validity of the model developed for this study one would ideally compare model output data to actual data from the system this model is designed to replicate. Researchers could use similar methods to gather itinerary and spatiotemporal deviation information in the future and compare results to those predicted by the model (Lawson et al. 2006).

To further enhance the accuracy of the model researchers could gather more detailed information about wilderness use not documented in the permit database (i.e. data on non-permitted trips and trips originating from outside the park). In particular, we estimate that about 10% of wilderness use in Yosemite is due to trips originating outside of the park, yet survey return rates from USFS-permitted trips was low, leading to uncertainty in the characteristics of these trips. To enhance the ability of the model to predict visitor behavior it is advisable that park managers seek more information about how visitors select trailheads, and the visitor response to full quotas, in order to better understand visitors' decision-making processes. With such information, managers could make more informed choices when evaluating different visitor use scenarios to simulate with the model. For example, rather than a trailhead reassignment scenario in which denied visitors are automatically reassigned to the next most popular trailhead that is still below quota or to a low-use trailhead, managers could create a trailhead reassignment algorithm in the model by which visitors are reassigned to trailheads in a more realistic fashion. This could also help managers improve their own decision-making processes when choosing between education or regulation strategies for wilderness management (Lucas 1990). While our model simulates *how* visitors interact with the resource, it would be improved if we learned more about *why* visitors choose places to visit in the Yosemite Wilderness.

Although we incorporated some degree of seasonal variability in use by using different trailhead assignment probabilities, respectively, before and after the opening of the Tioga Road, the model could potentially be refined to include more detailed dependence on snow and weather conditions early in the season. With enough detailed data, different trailhead selection probability distributions and zone transition matrices could be created for different conditions, allowing managers to more carefully refine predictions of visitor use under a range of conditions. Finally, although it was not within the scope of this study, simulation modeling could be used to explore interactions among day-use visitation and overnight wilderness users in zones adjacent to trailheads.

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Watson, A.E., D. Cole, D.L. Turner, P.S. Reynolds. 2000. Wilderness recreation use estimation: A handbook of methods and systems. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, GTR-RMRS-56, Ogden, Utah.

FIGURES

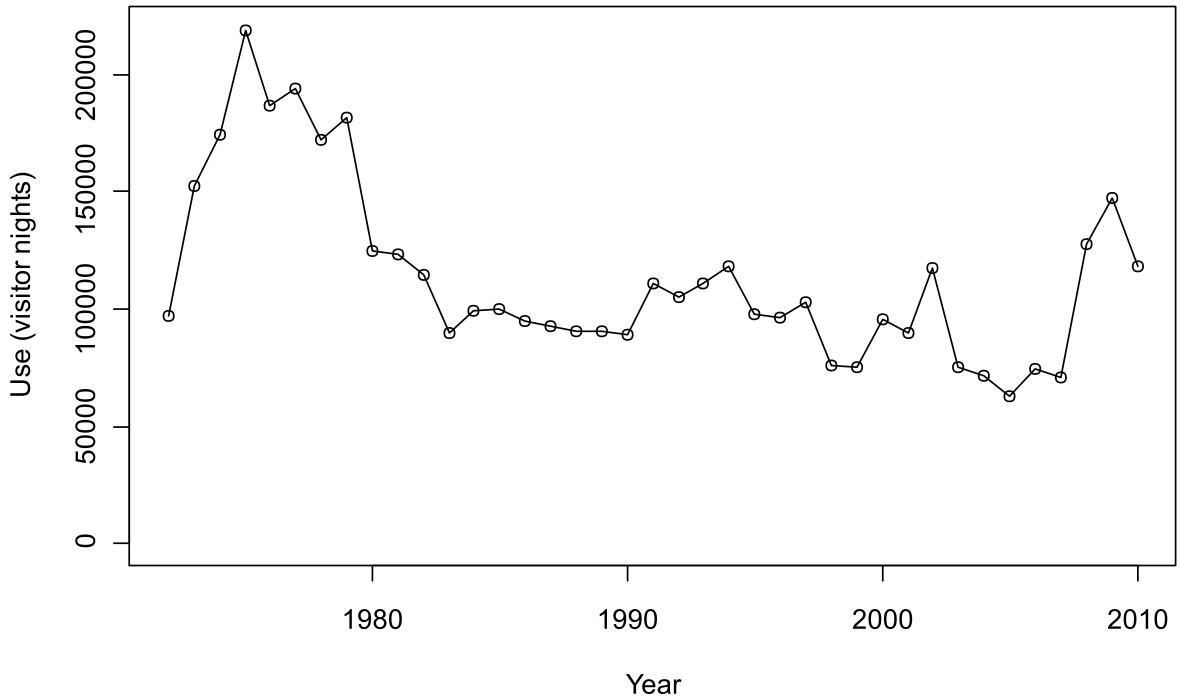


Figure 1. Temporal trend in wilderness use. Data for 1972-1979 are from van Wagtendonk (1981); data for 1980-2010 are from (NPS 2011c).

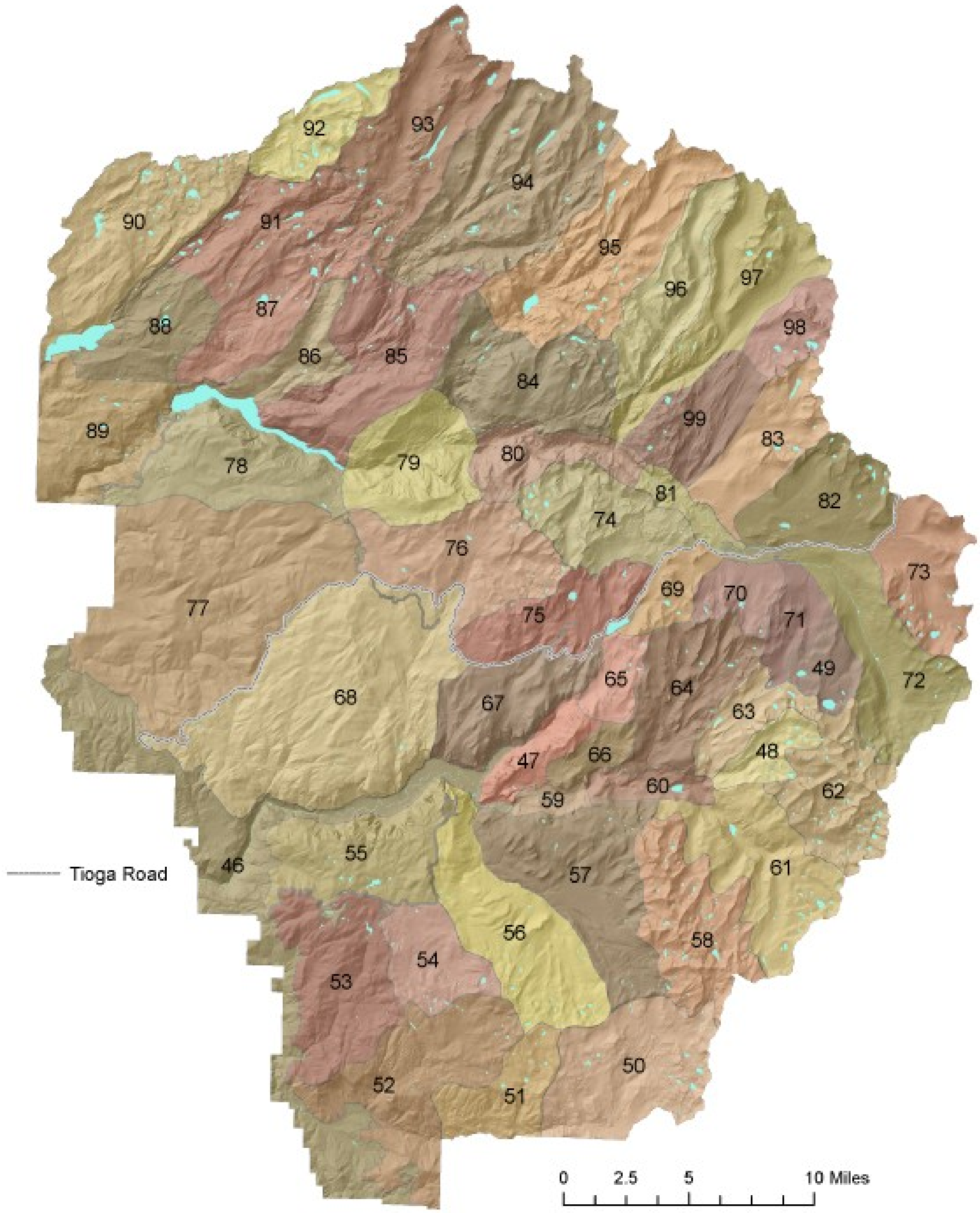


Figure 2. Wilderness management zones. The Tioga Road is shown because its date of opening in the spring is a proxy for accessibility of high-elevation trailheads. The simulation model uses different distributions of trailhead-of-origin before and after this date.

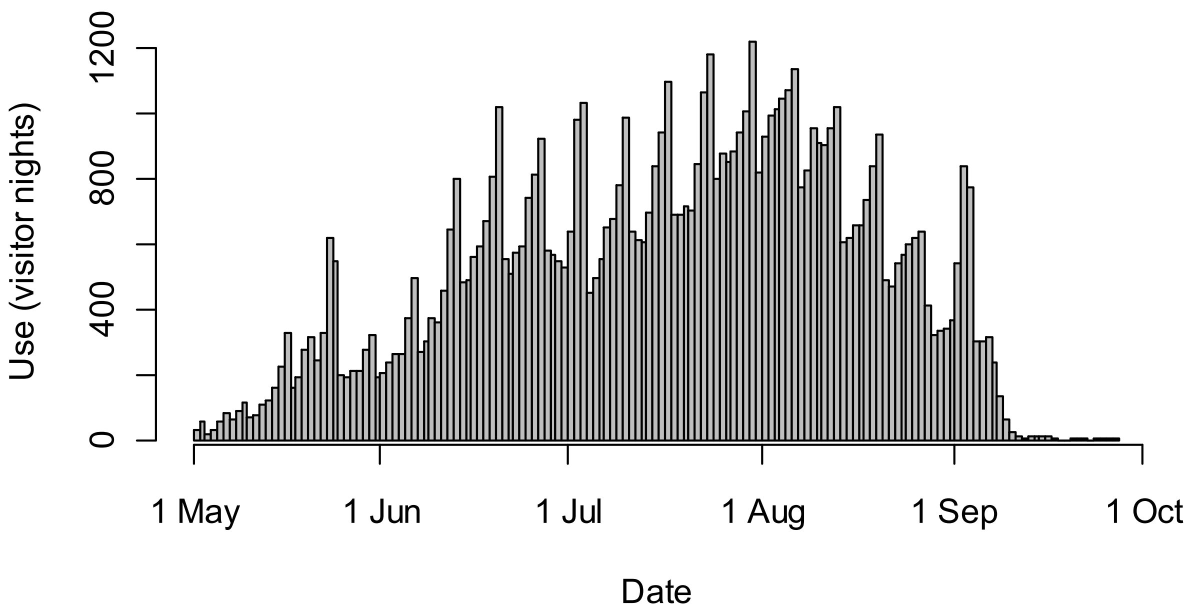


Figure 3. Temporal distribution of use from 2009 data.

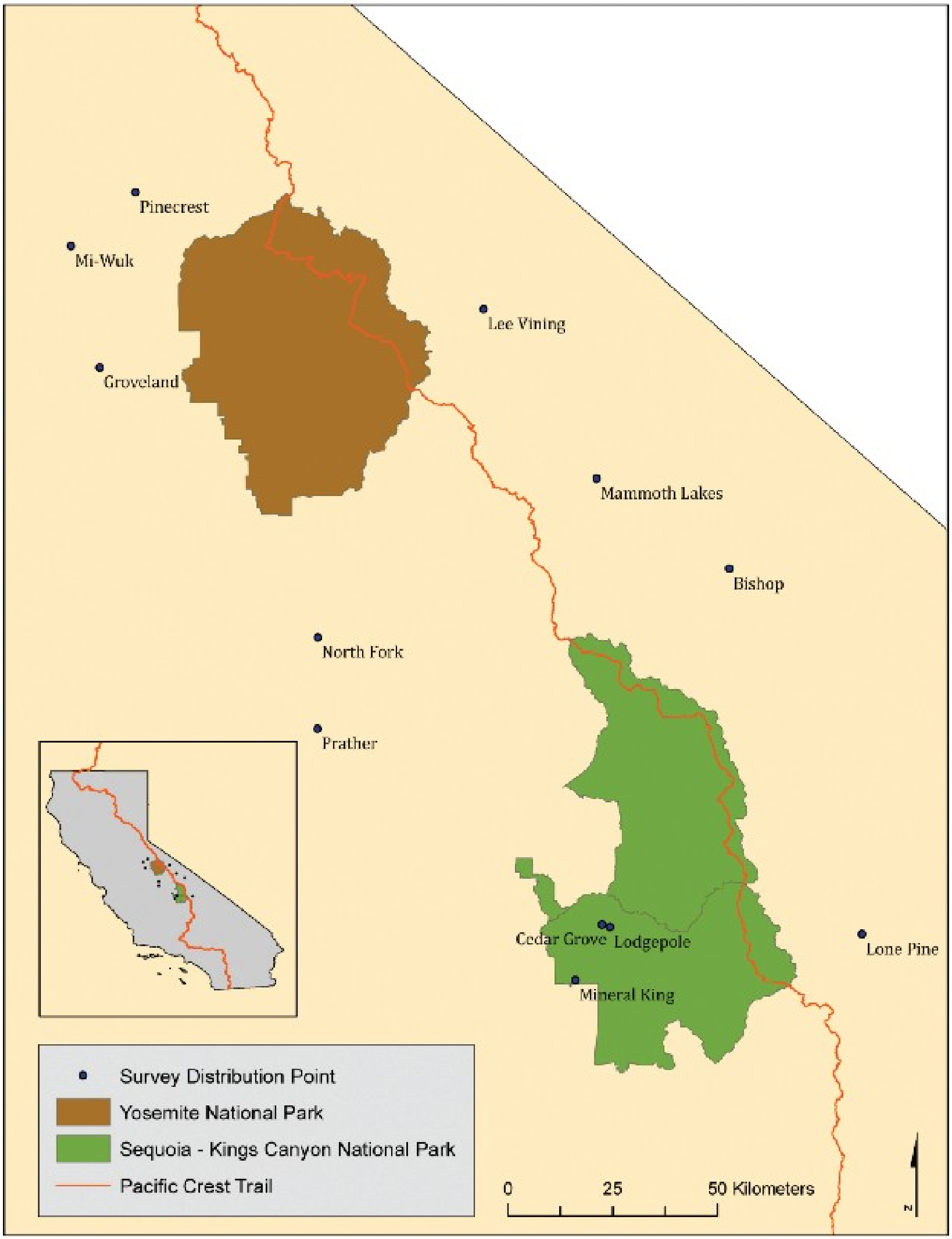


Figure 4. Map showing location of stations outside of Yosemite at which surveys were distributed.

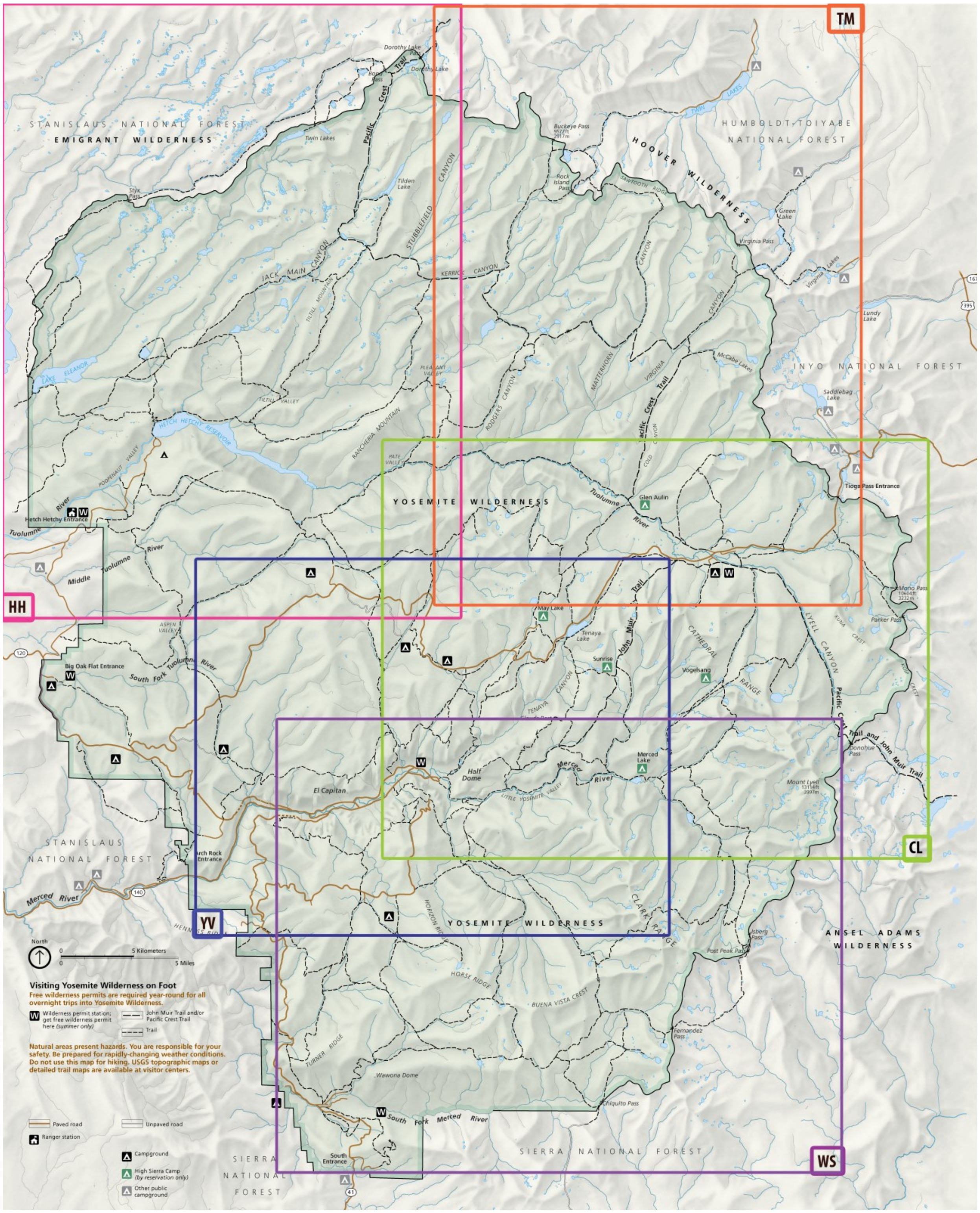


Figure 5. Survey instrument map sectors. The individual sector maps appear in Appendix C.

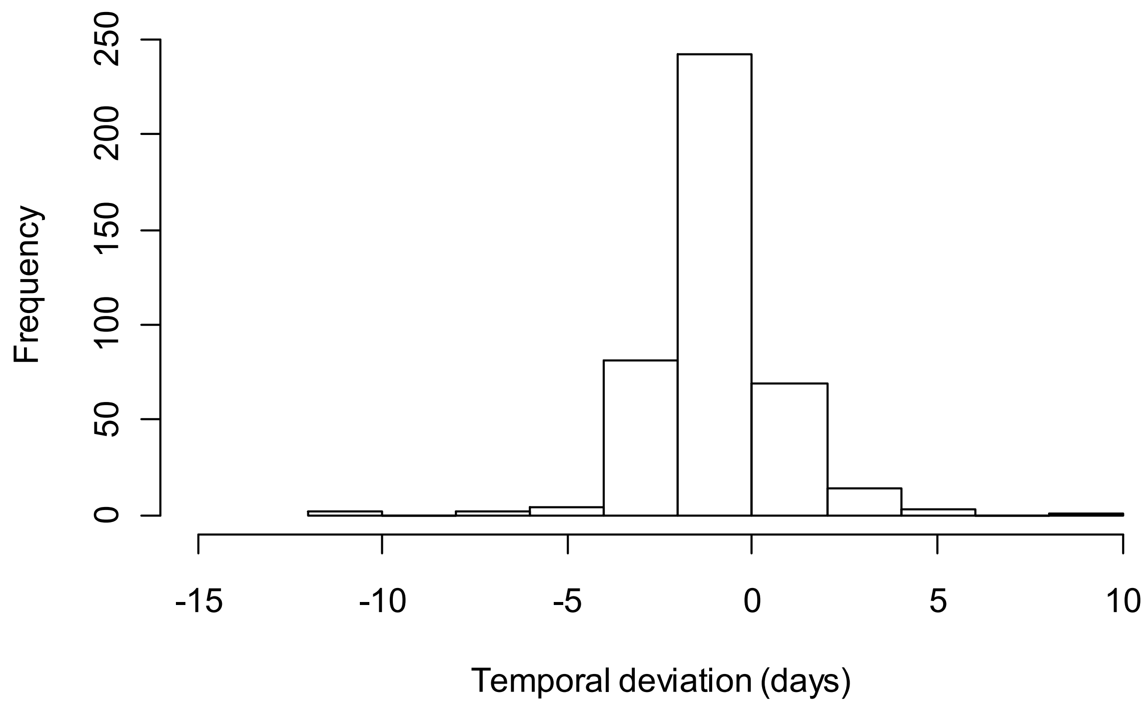


Figure 6. Distribution of temporal deviations reported by survey respondents.

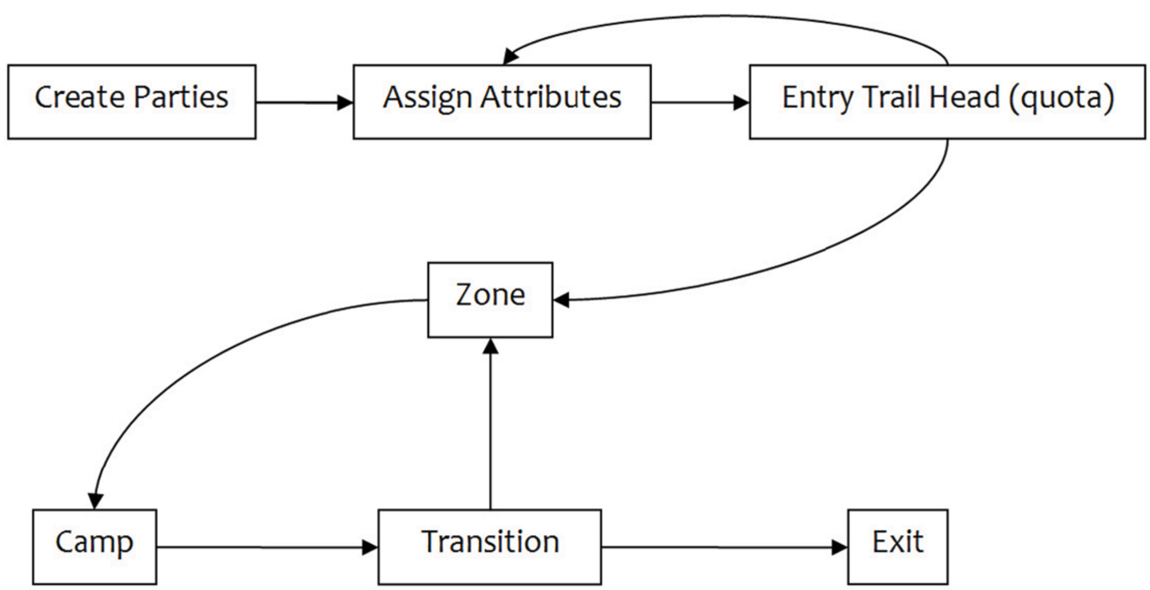


Figure 7. Model flow diagram. The only attributes assigned at the beginning of a simulated trip are date (deterministic), party size (stochastic), and trailhead of origin (stochastic). Itinerary (including deviations) and trip duration are generated dynamically and stochastically within the model and are not known and recorded until the party exits from the wilderness.

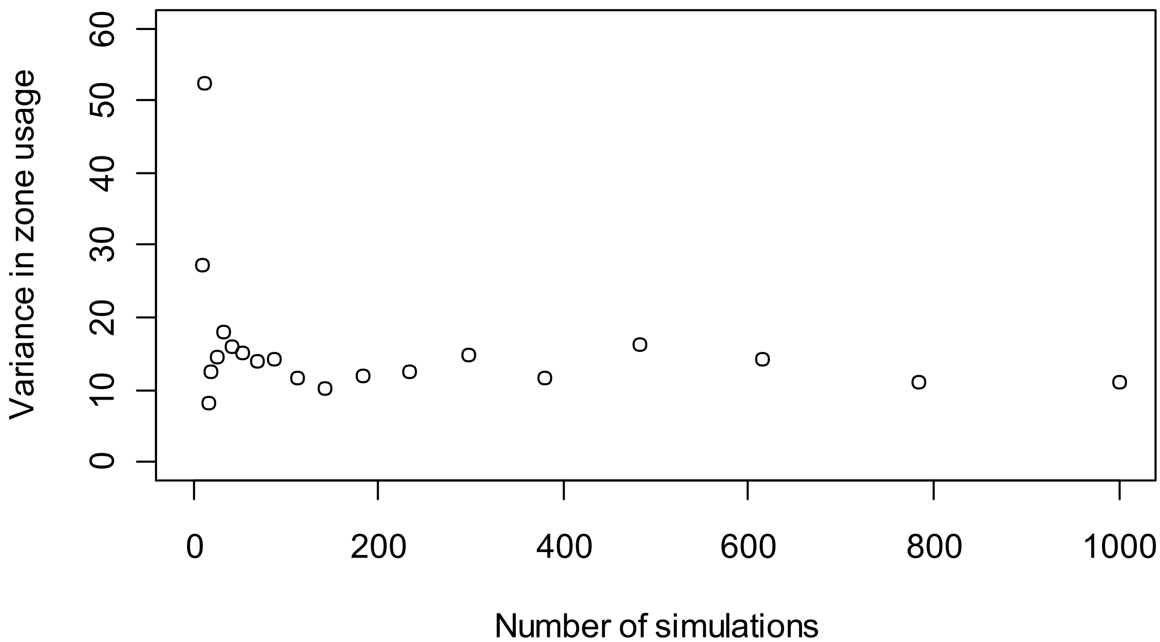


Figure 8. Sample variance in model-simulated use in a low-use zone-night as a function of number of simulations.

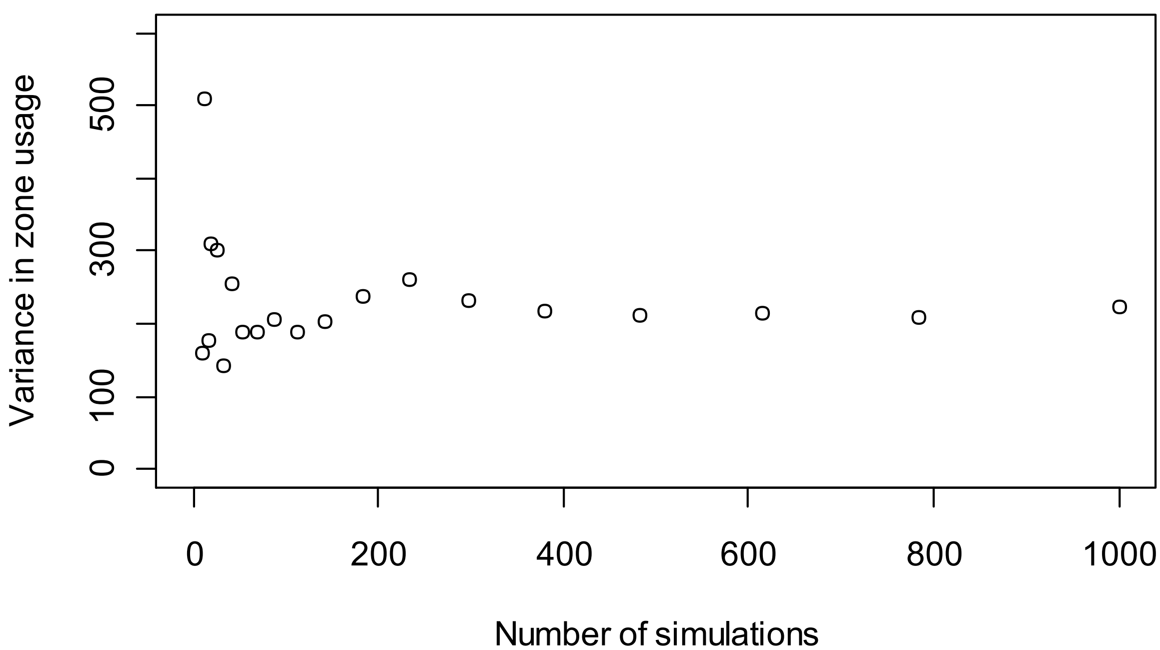


Figure 9. Sample variance in model-simulated use in a high-use zone-night as a function of number of simulations.

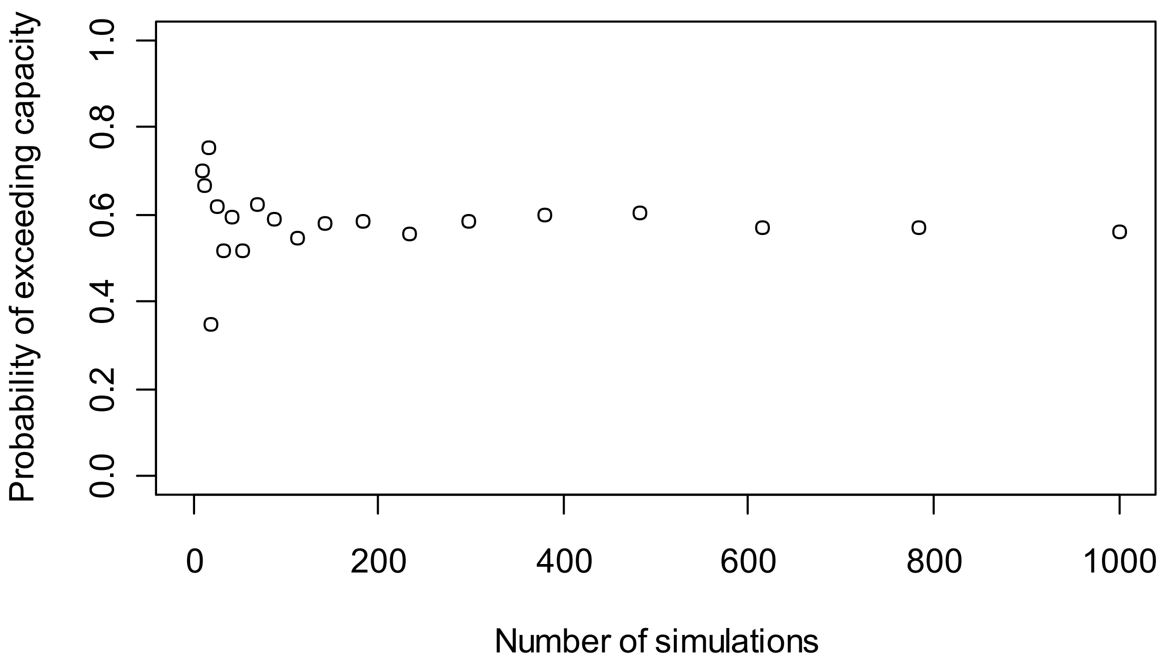


Figure 10. Estimated zone capacity exceedance probability for a high-use zone-night as a function of number of simulations.

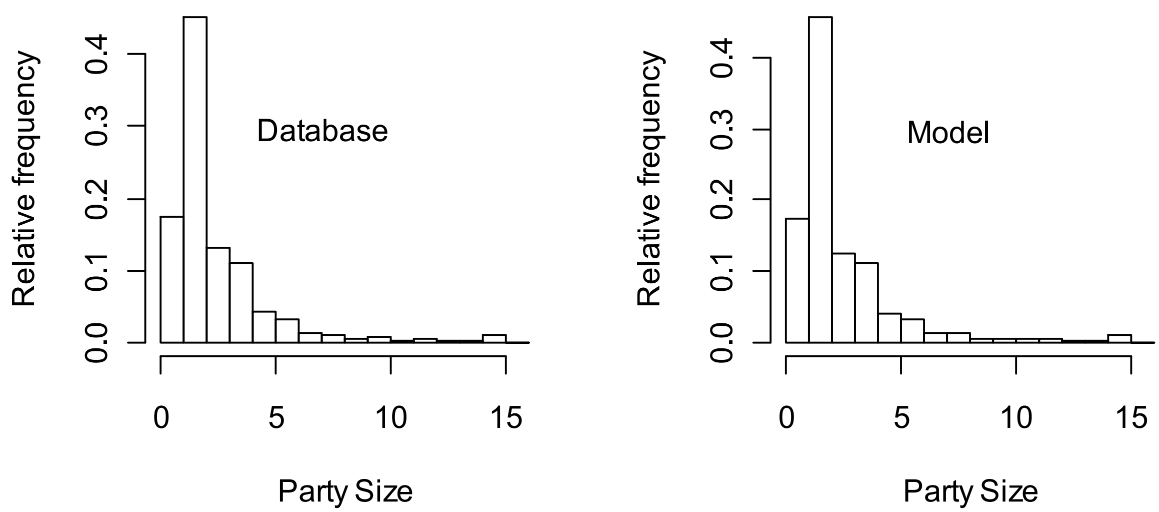


Figure 11. Distribution of party size from the permit database and a single simulation of the validation model.

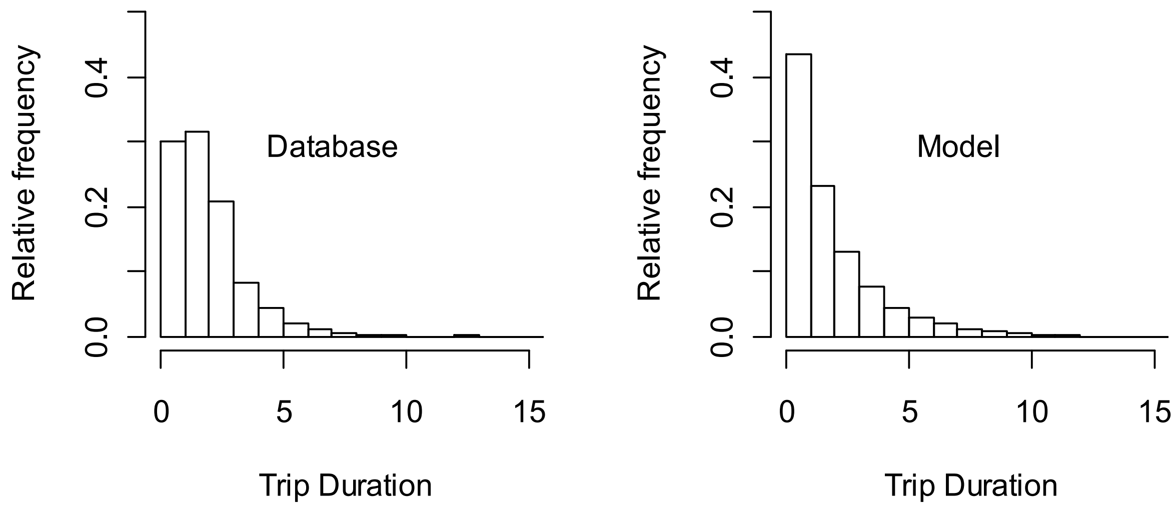


Figure 12. Distribution of intended trip duration from the permit database and a single simulation of the validation model.

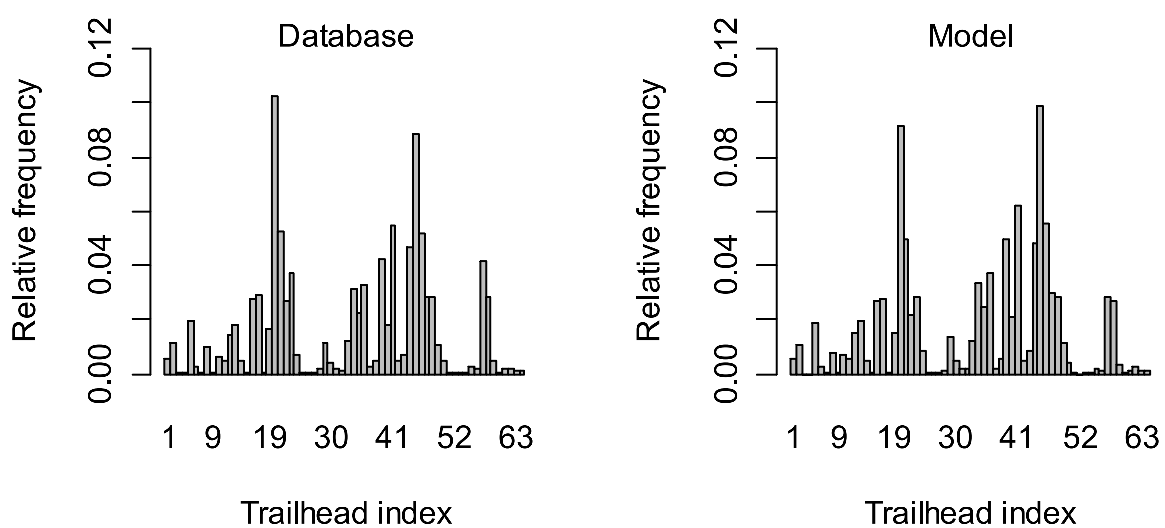
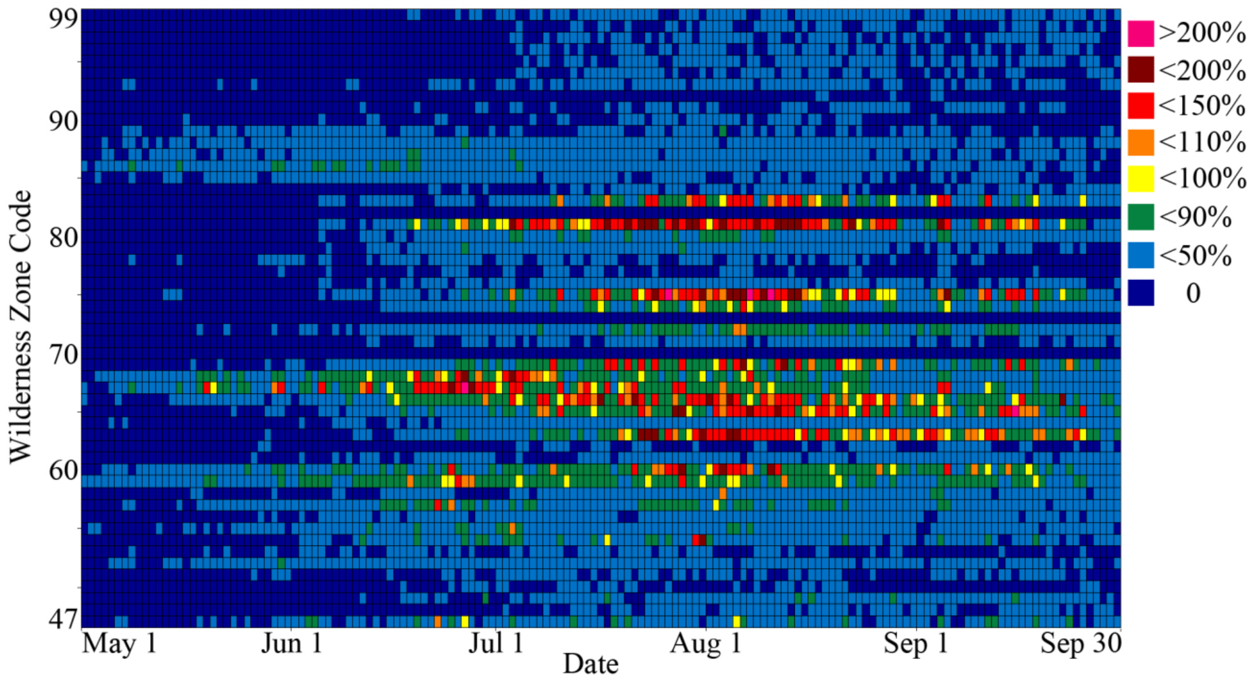


Figure 13. Distribution of entry trailheads from the permit database and a single simulation of the validation model. See Appendix A for a key to these trailhead indices.



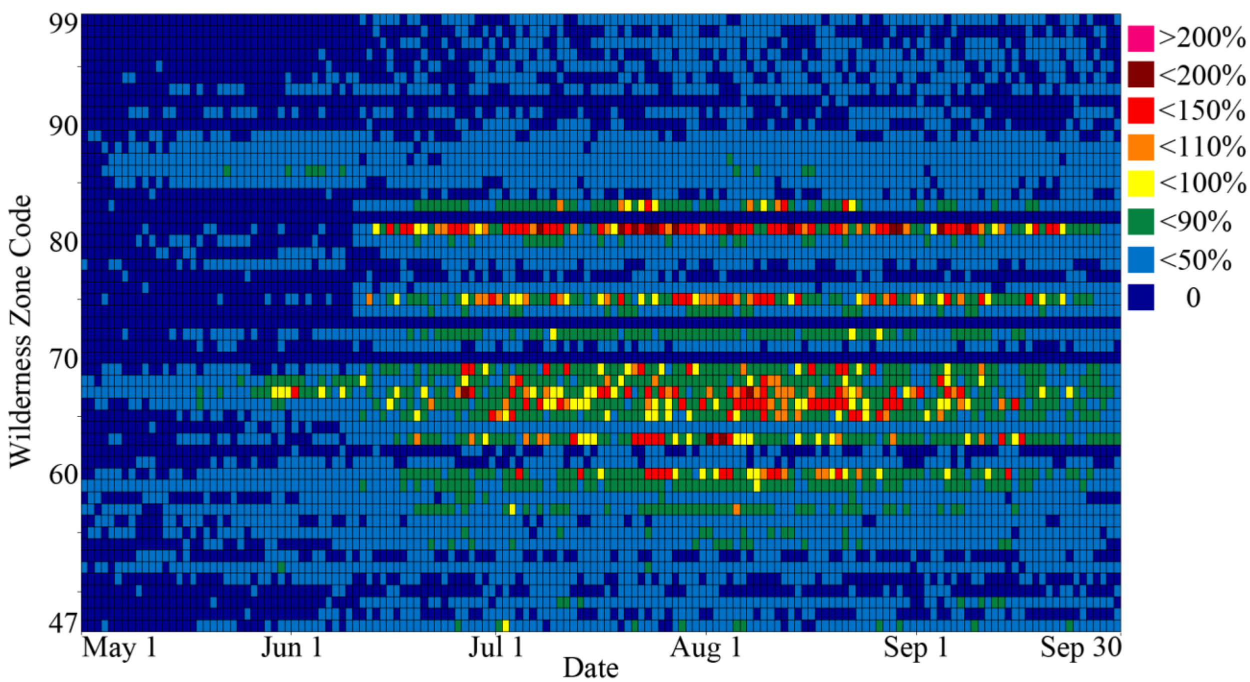


Figure 14. Comparison of intended wilderness use by zone-night as calculated from the permit database (top) with use predicted by one simulation of the validation model (bottom). Figures show use as a fraction of zone capacity.

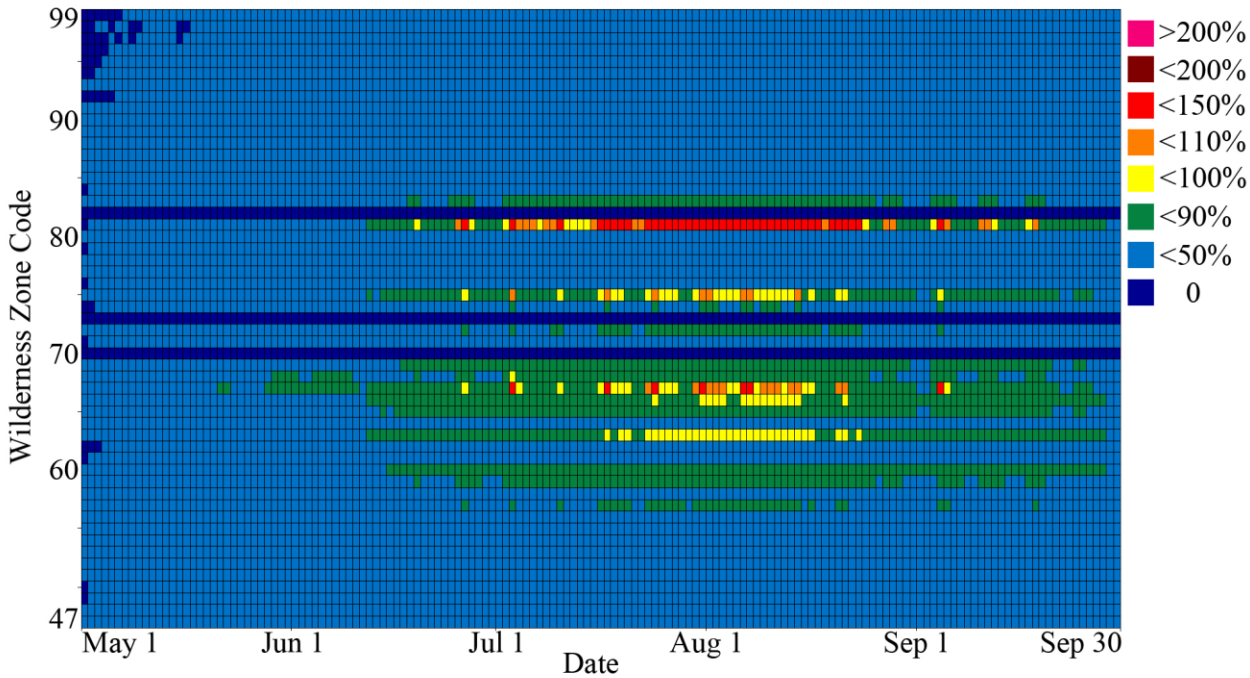


Figure 15. Mean wilderness use over 1,000 simulations of the validation model, expressed as a fraction of capacity.

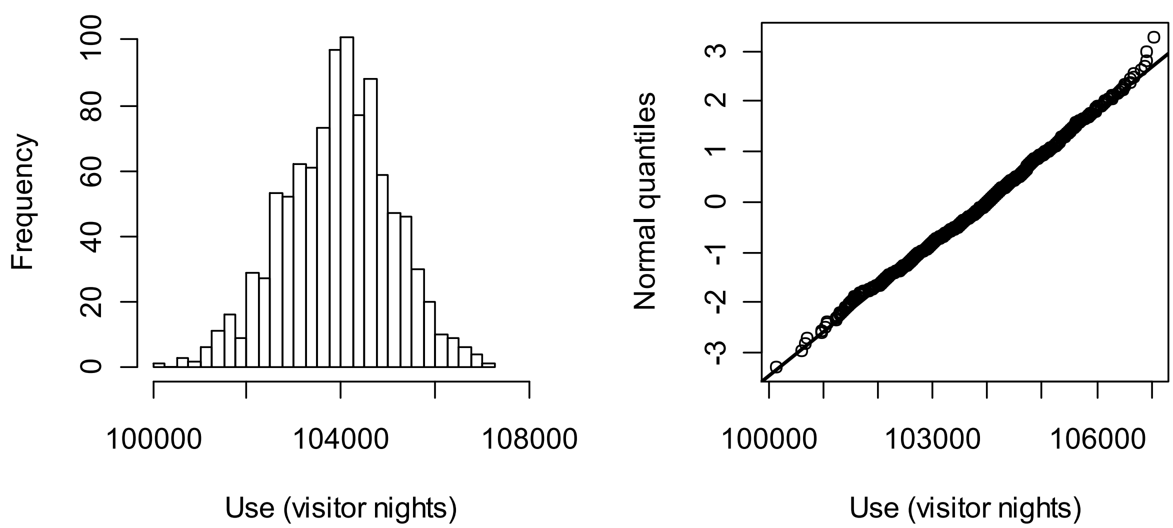


Figure 16. Histogram and normal probability plot showing distribution of season-total use across 1,000 simulations of the validation
model.

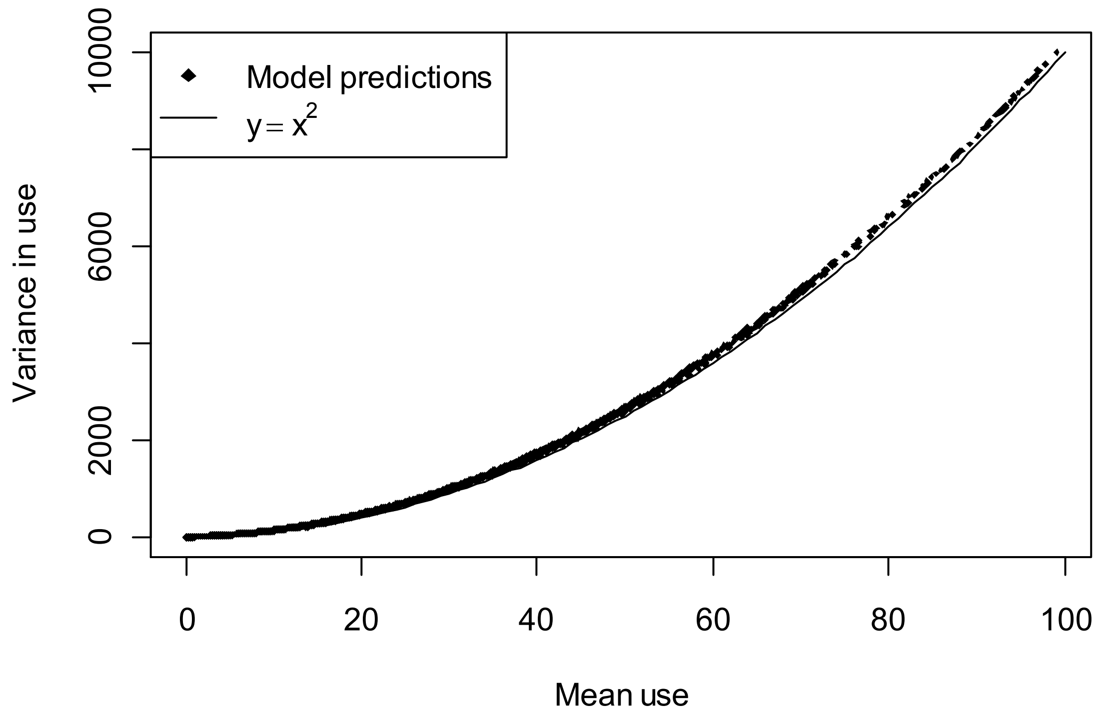


Figure 17. Relationship between variance and mean of individual zone-night use across 1,000 simulations of the validation model.

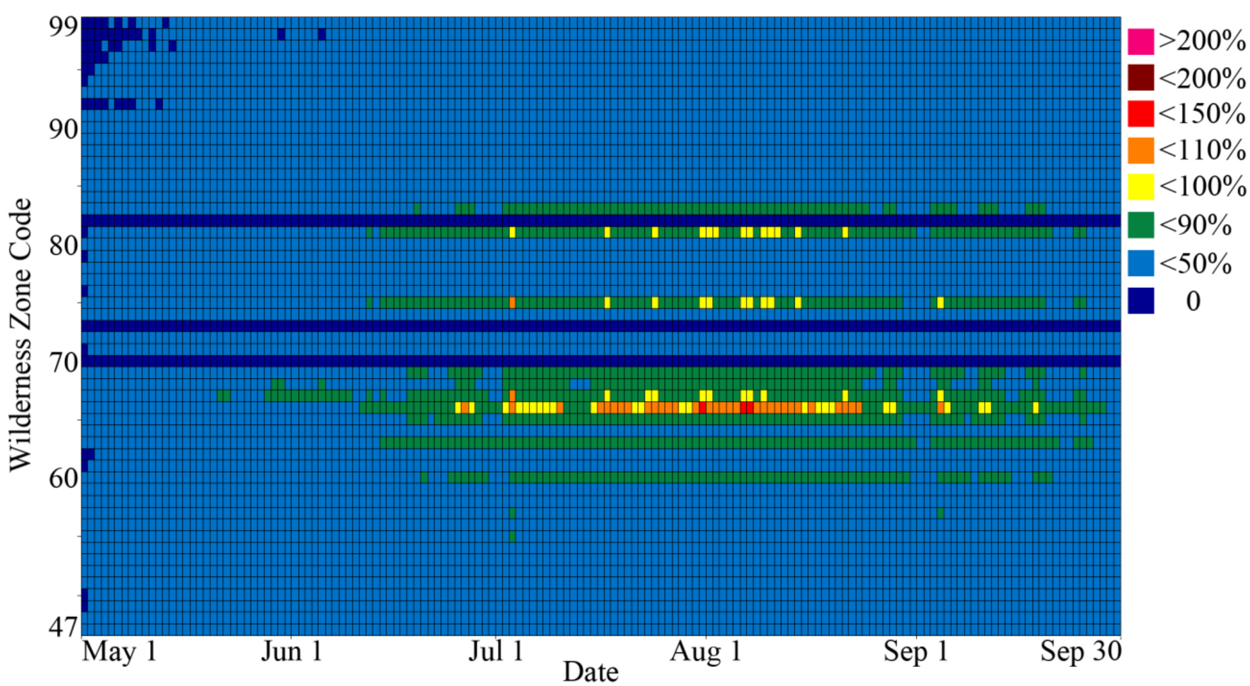


Figure 18. Mean wilderness use over 1,000 simulations of the Current Use Scenario, expressed as a fraction of zone capacity.

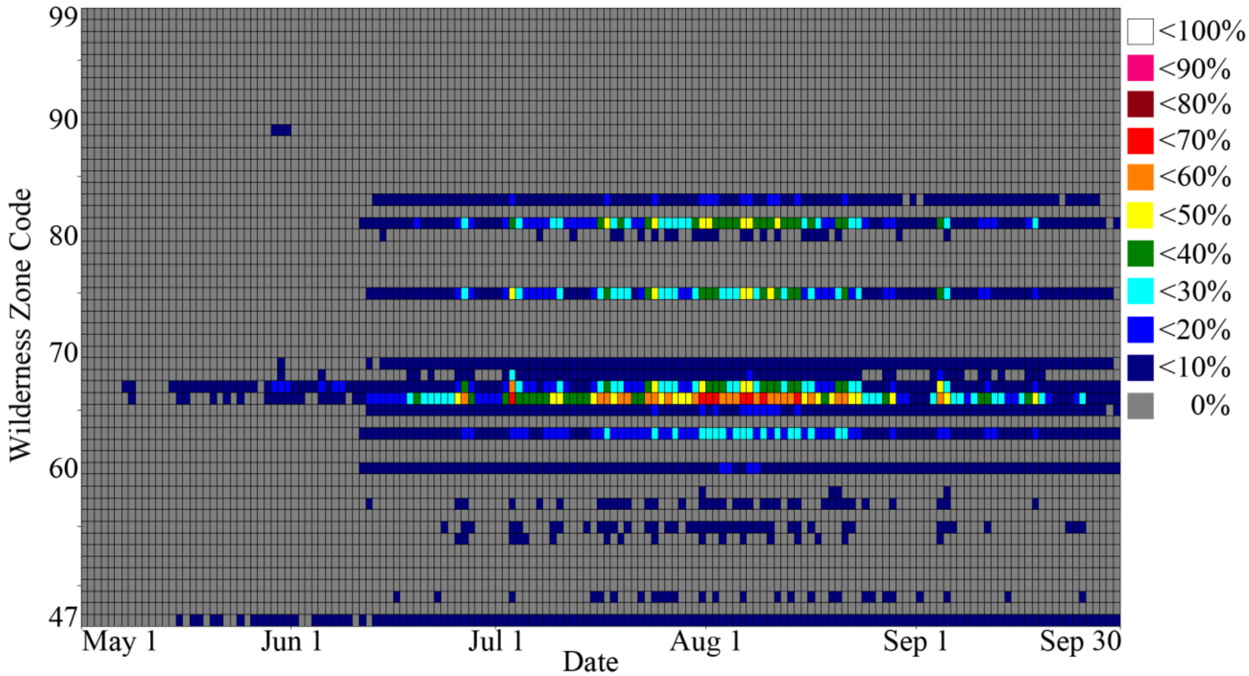


Figure 19. Probability of use exceeding capacity over 1,000 simulations of the Current Use Scenario.

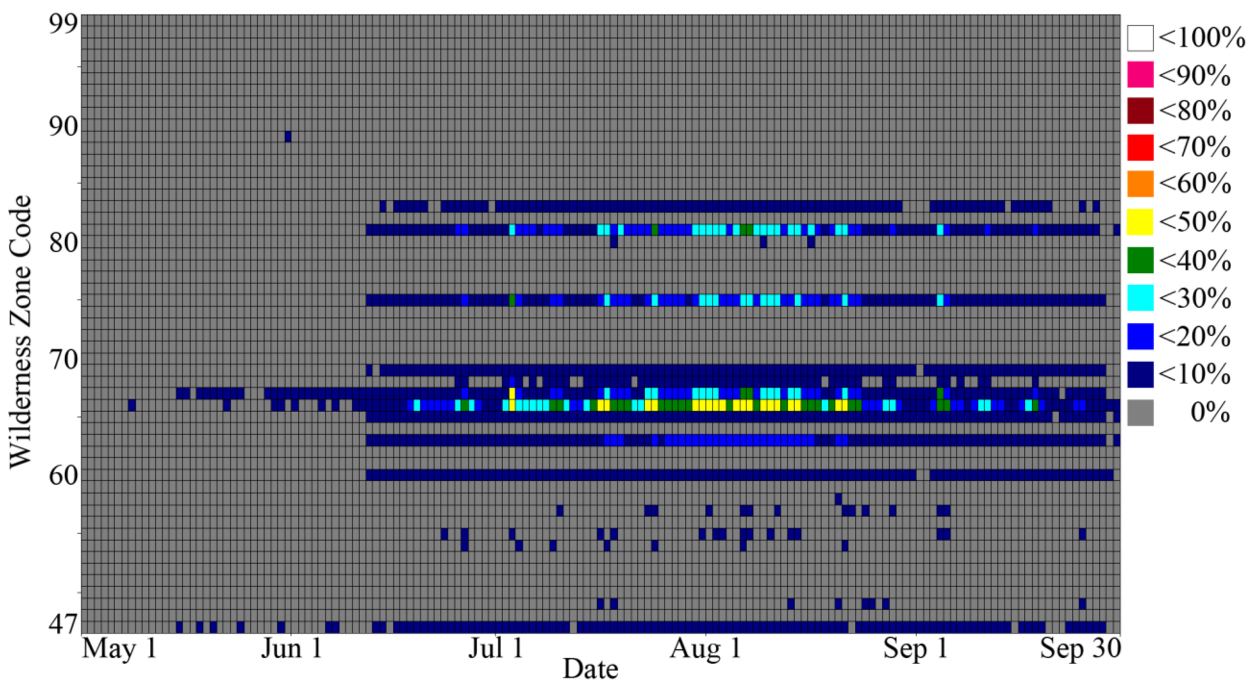


Figure 20. Probability of use exceeding 110% of capacity over 1,000 simulations of the Current Use Scenario.

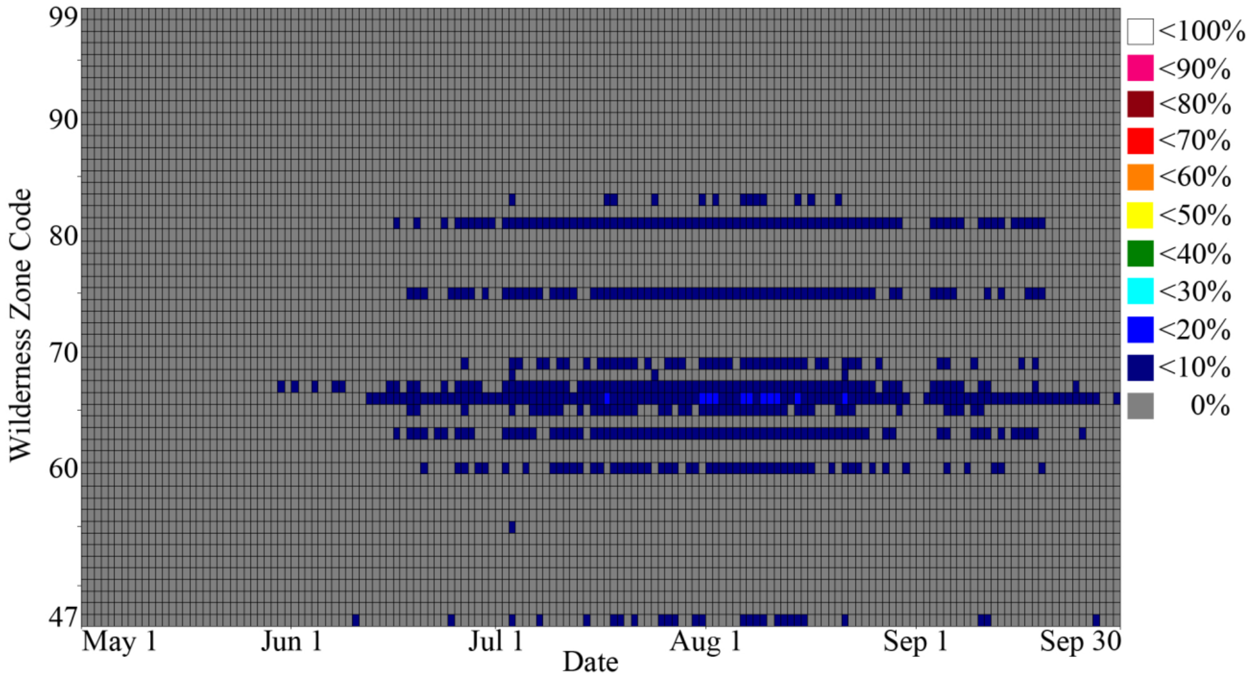


Figure 21. Probability of use exceeding 150% of capacity over 1,000 simulations of the Current Use Scenario.

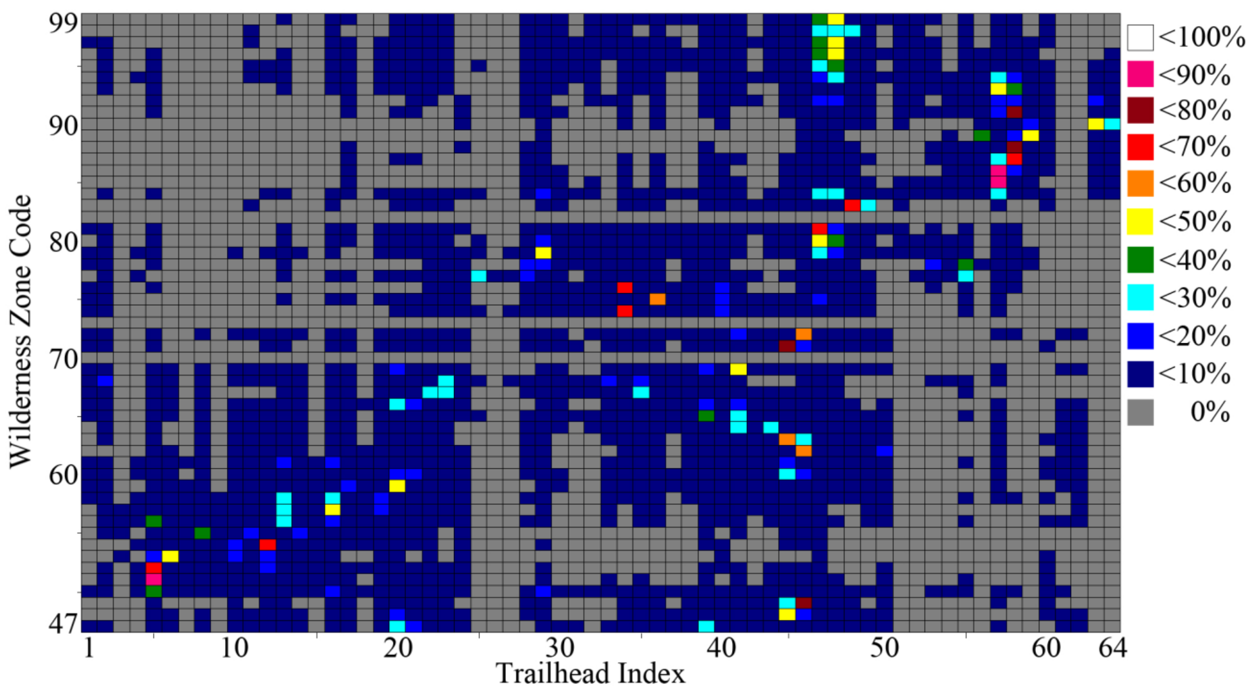


Figure 22. Trailhead contribution to zone use for the Current Use Scenario. See Appendix A for a key to these trailhead indices.

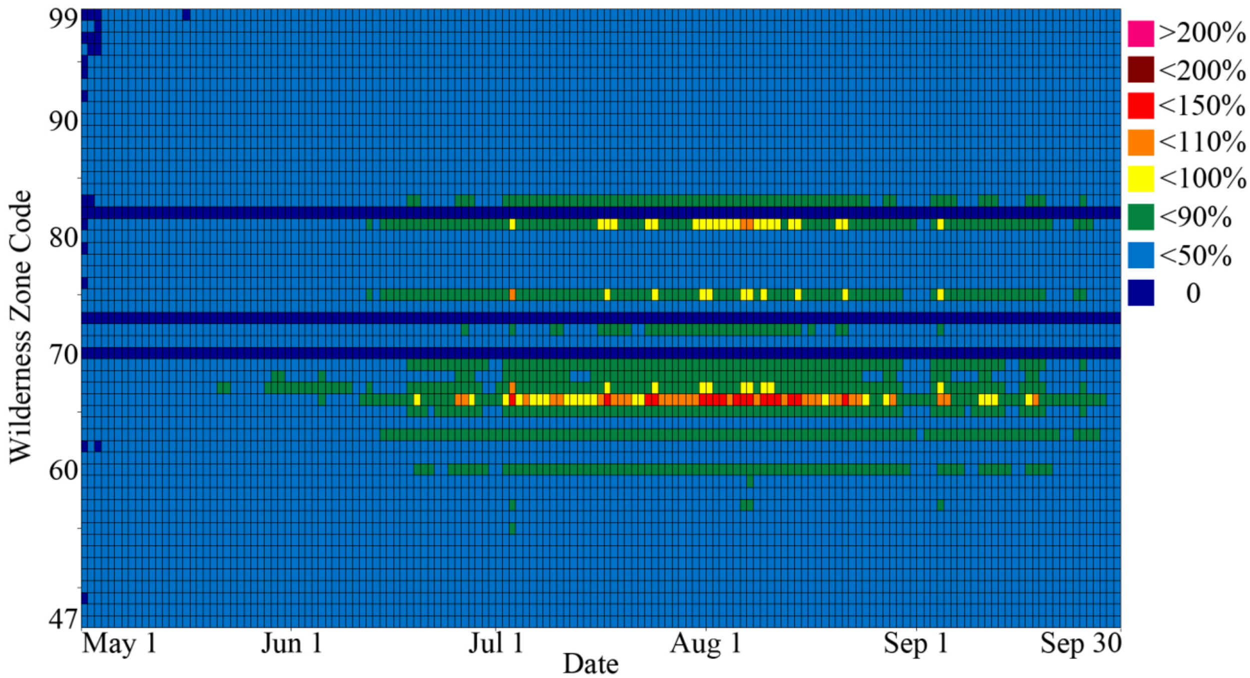


Figure 23. Mean wilderness use over 1,000 simulations of the Current Use Scenario, including additional influence from outside Yosemite, expressed as a fraction of zone capacity.

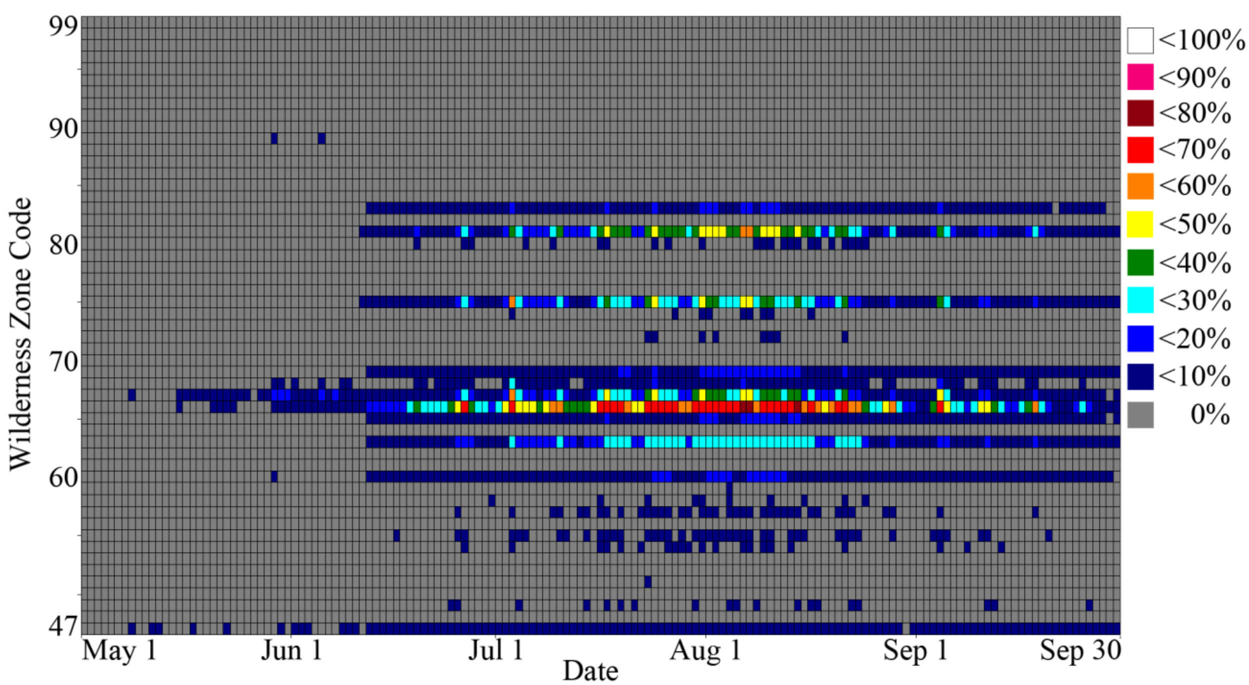


Figure 24. Probability of use exceeding capacity over 1,000 simulations of the Current Use Scenario, including additional influence from outside Yosemite.

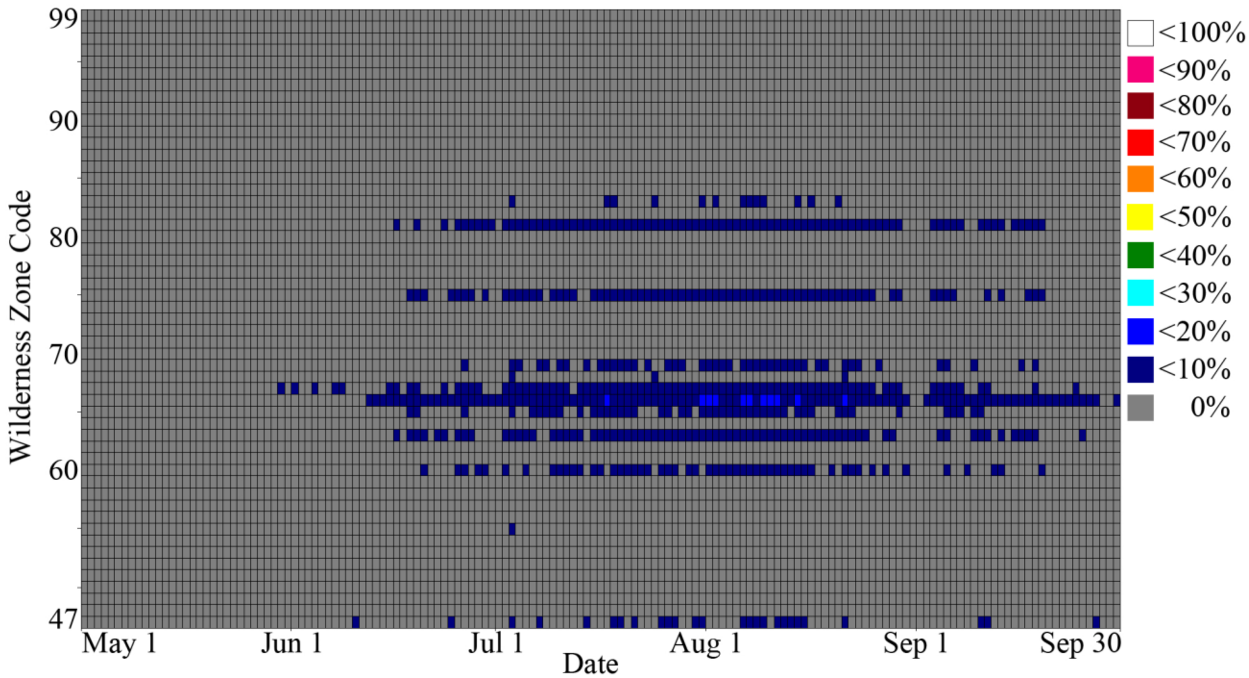


Figure 25. Probability of use exceeding 150% of capacity over 1,000 simulations of the Current Use Scenario, including additional influence from outside Yosemite.

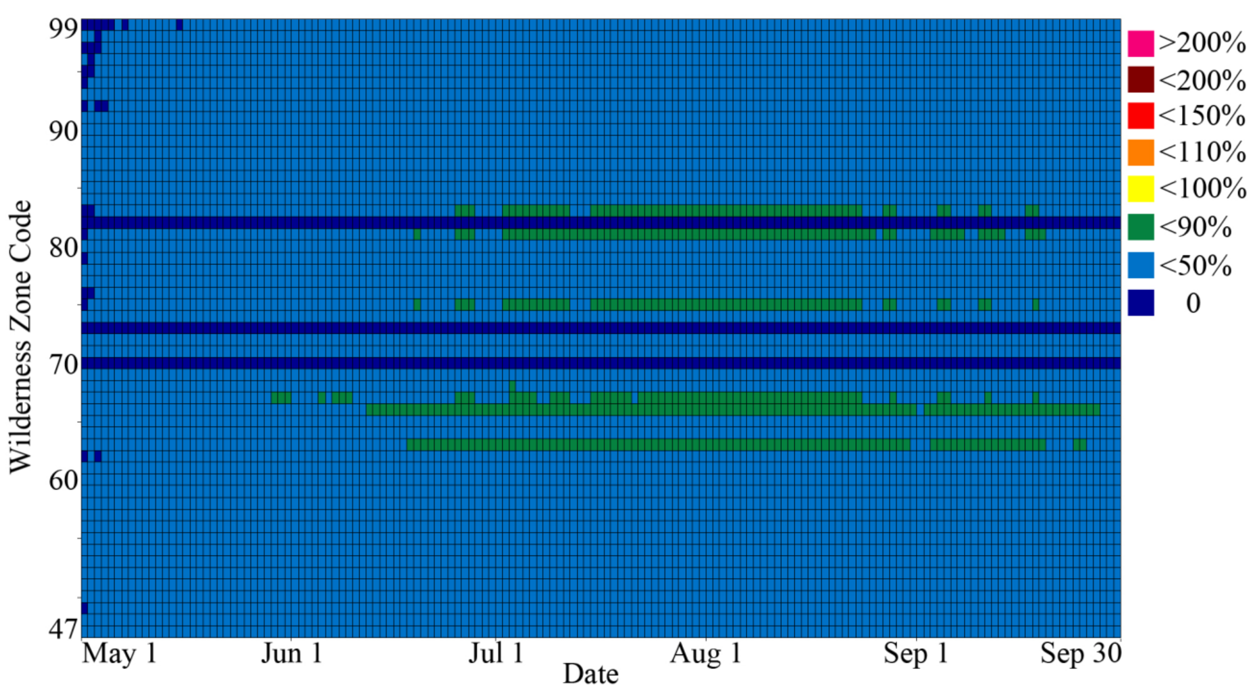


Figure 26. Mean wilderness use over 1,000 simulations after steps 1 and 2 of the Redistribution Scenario, expressed as a fraction of zone capacity.

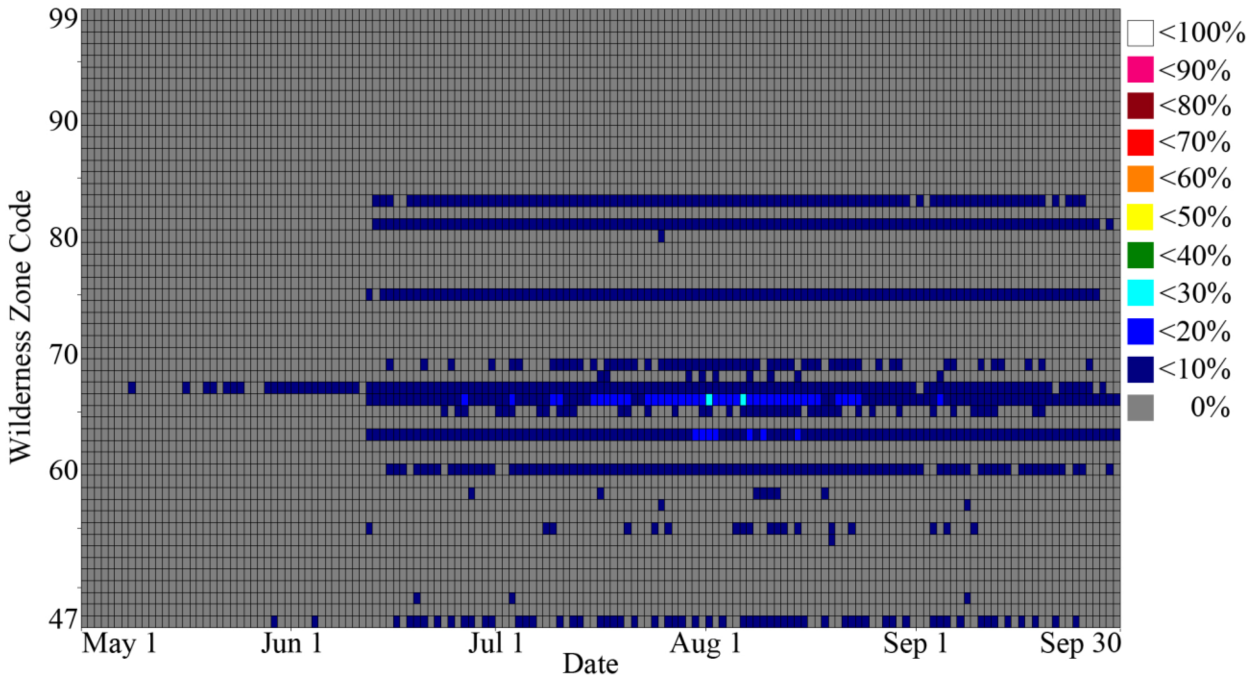


Figure 27. Probability of use exceeding capacity over 1,000 simulations after steps 1 and 2 of the Redistribution Scenario.

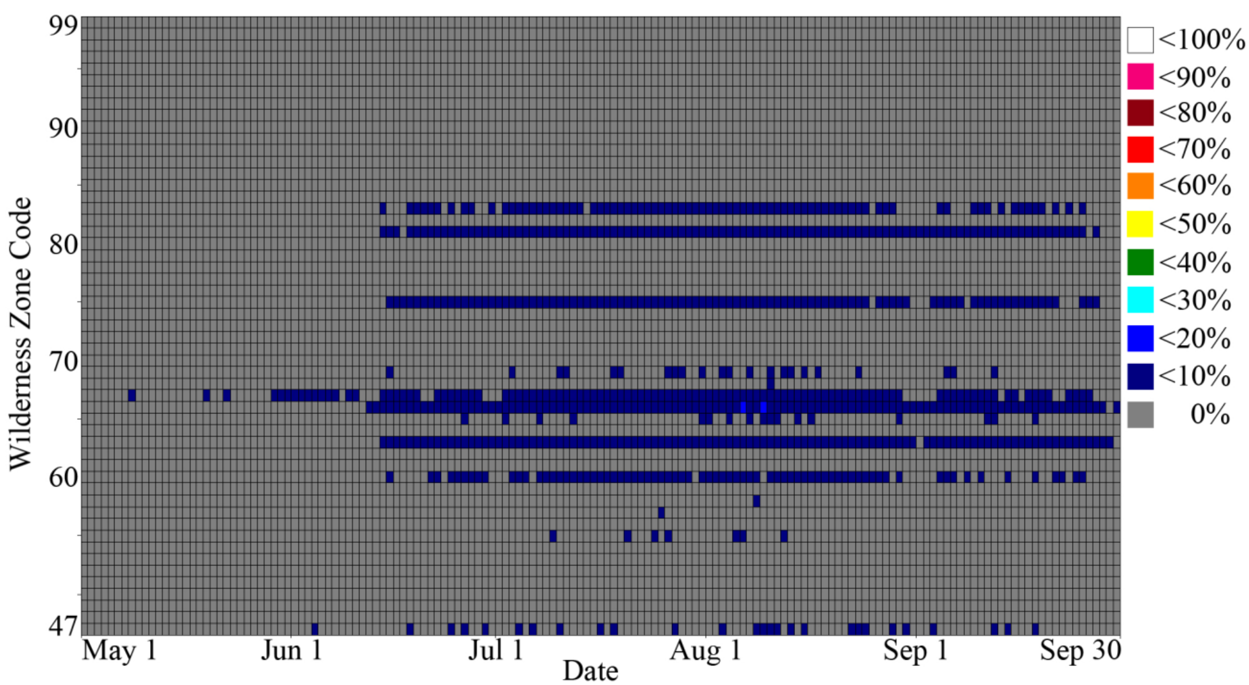


Figure 28. Probability of use exceeding 110% of capacity over 1,000 simulations after steps 1 and 2 of the Redistribution Scenario.

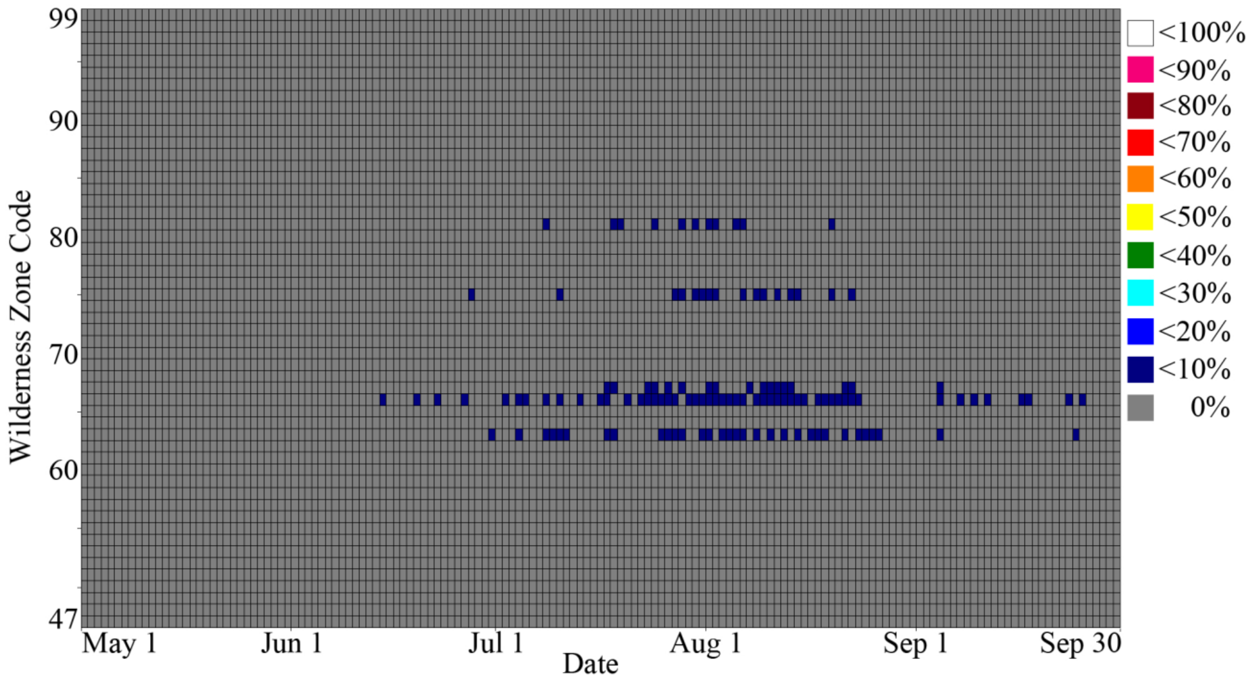


Figure 29. Probability of use exceeding 150% of capacity over 1,000 simulations after steps 1 and 2 of the Redistribution Scenario.

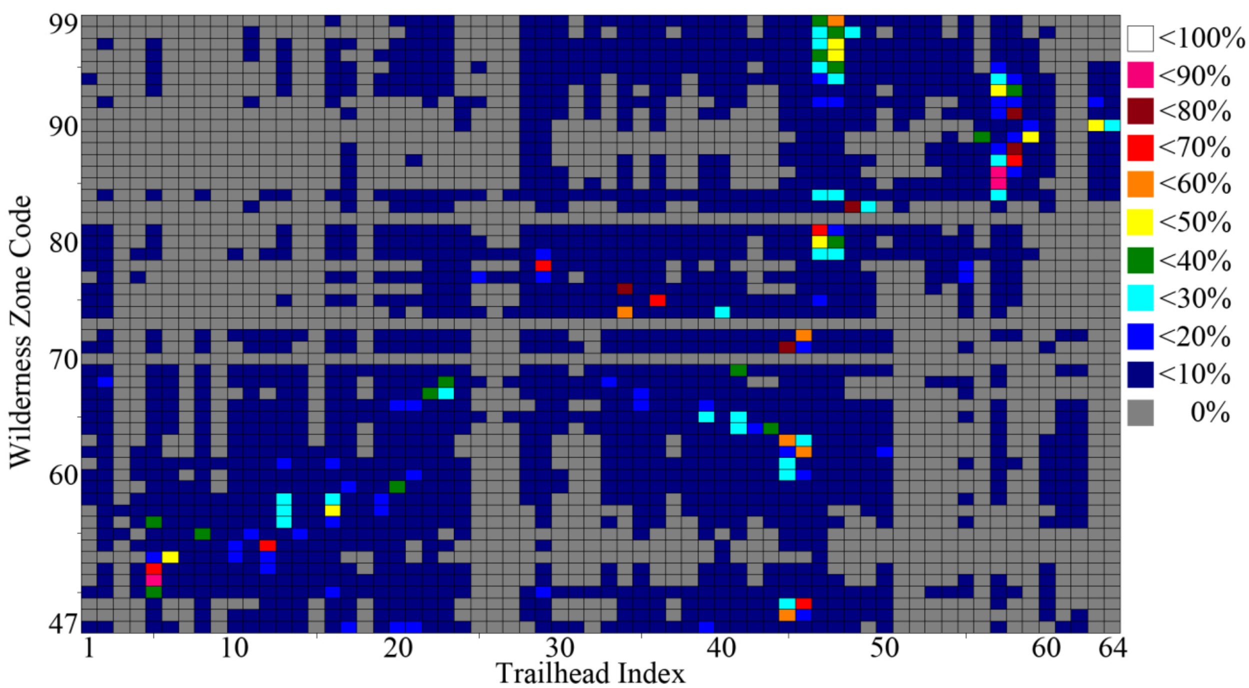


Figure 30. Trailhead contribution to zone use after steps 1 and 2 of the Redistribution Scenario. See Appendix A for a key to these trailhead indices.

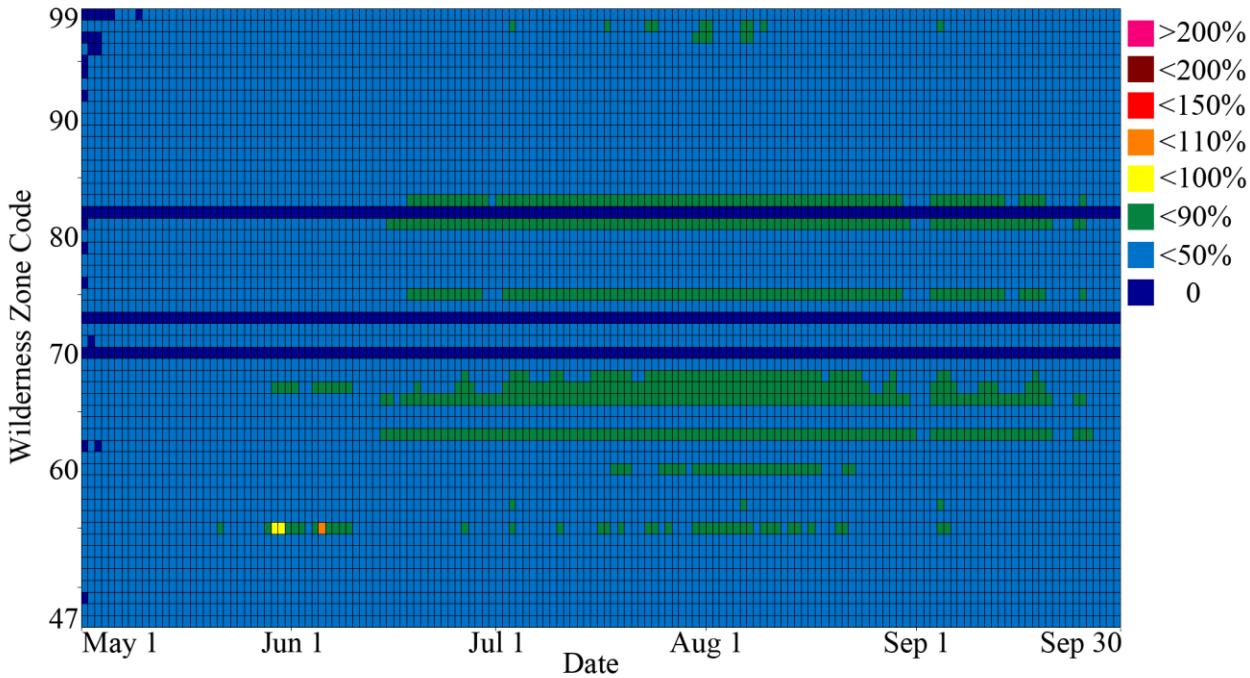


Figure 31. Mean wilderness use over 1,000 simulations of the Redistribution Scenario, expressed as a fraction of zone capacity.

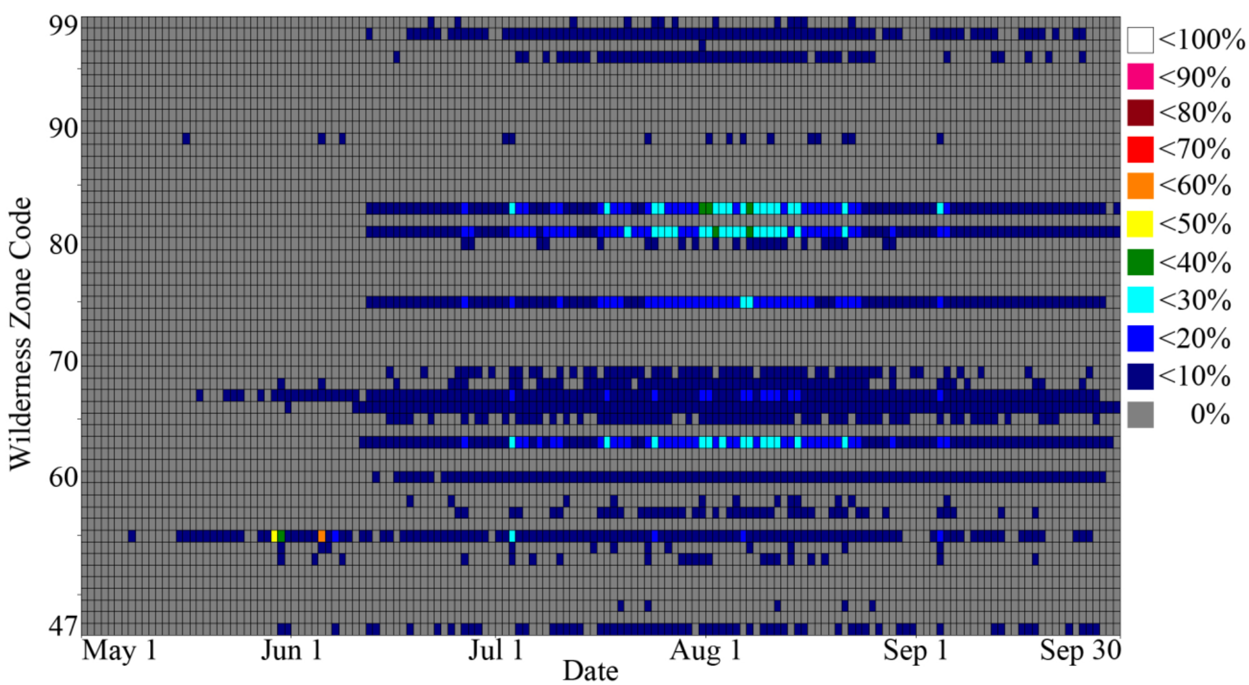


Figure 32. Probability of use exceeding capacity over 1,000 simulations of the Redistribution Scenario.

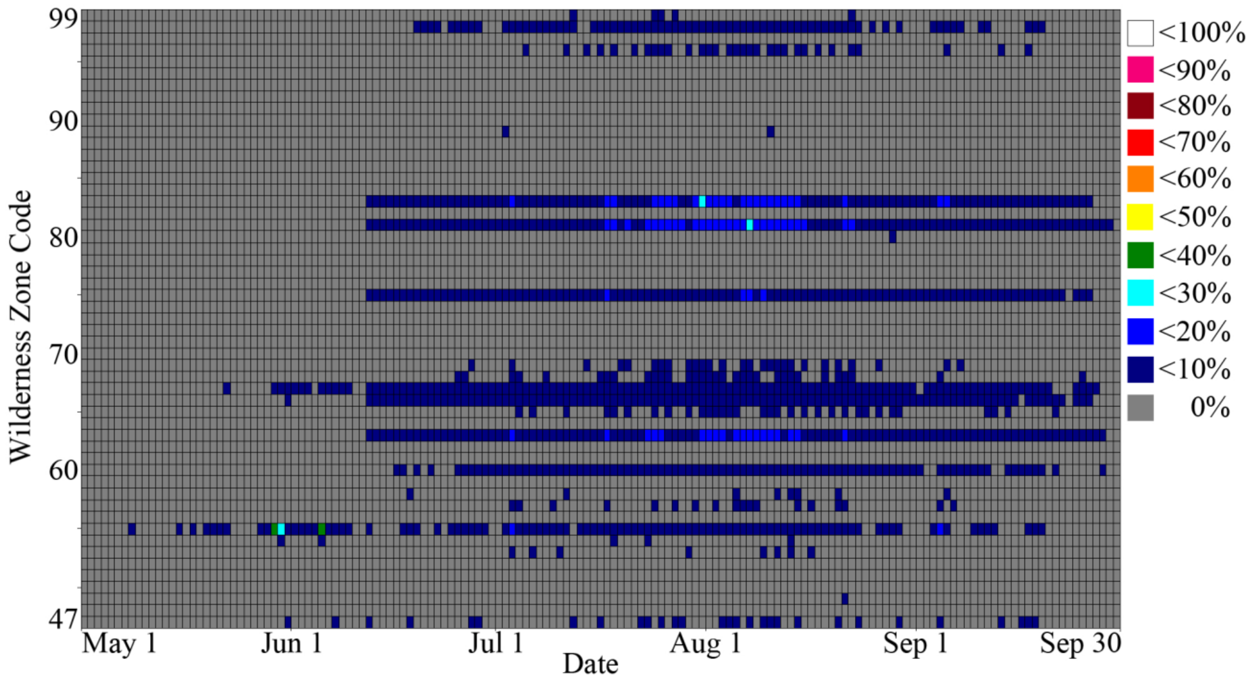


Figure 33. Probability of use exceeding 110% of capacity over 1,000 simulations of the Redistribution Scenario.

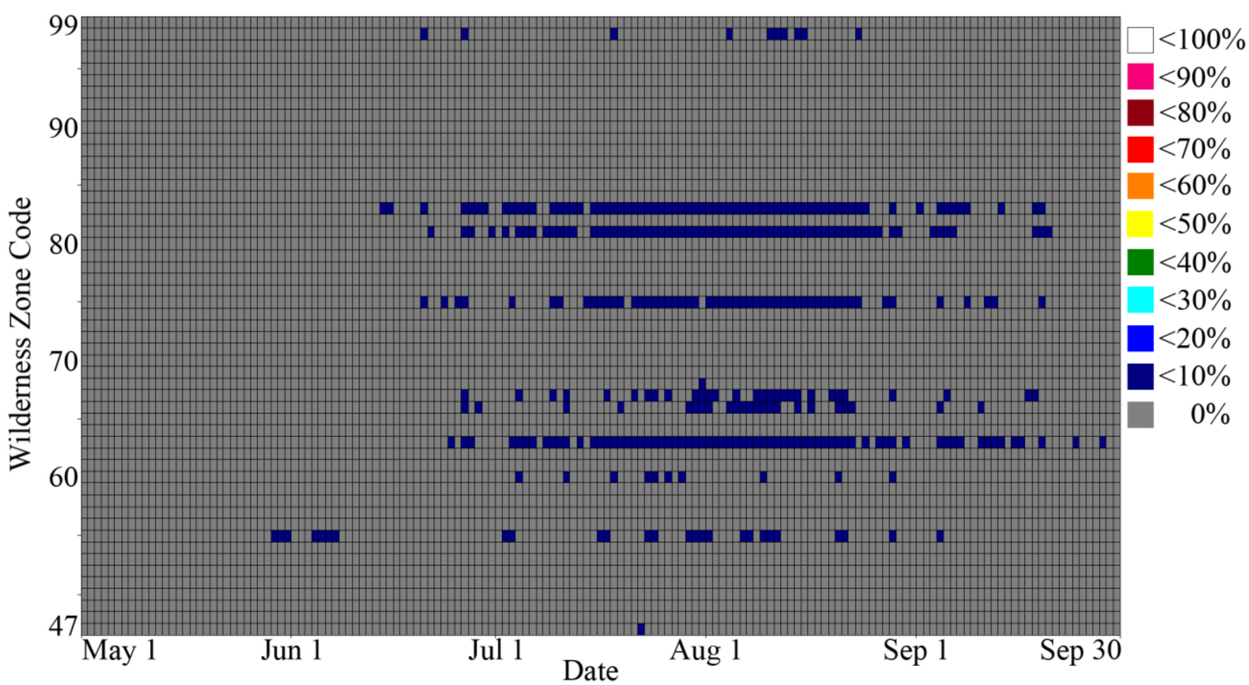


Figure 34. Probability of use exceeding 150% of capacity over 1,000 simulations of the Redistribution Scenario.

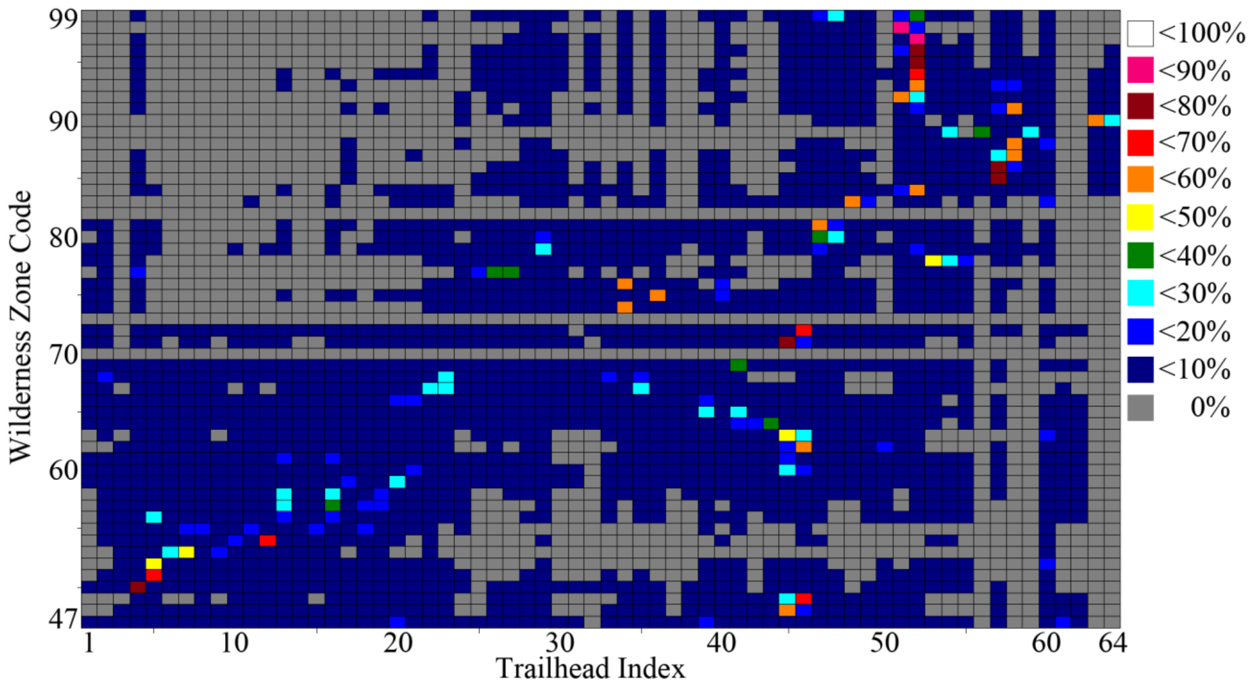


Figure 35. Trailhead contribution to zone use for the Redistribution Scenario. See Appendix A for a key to these trailhead indices.

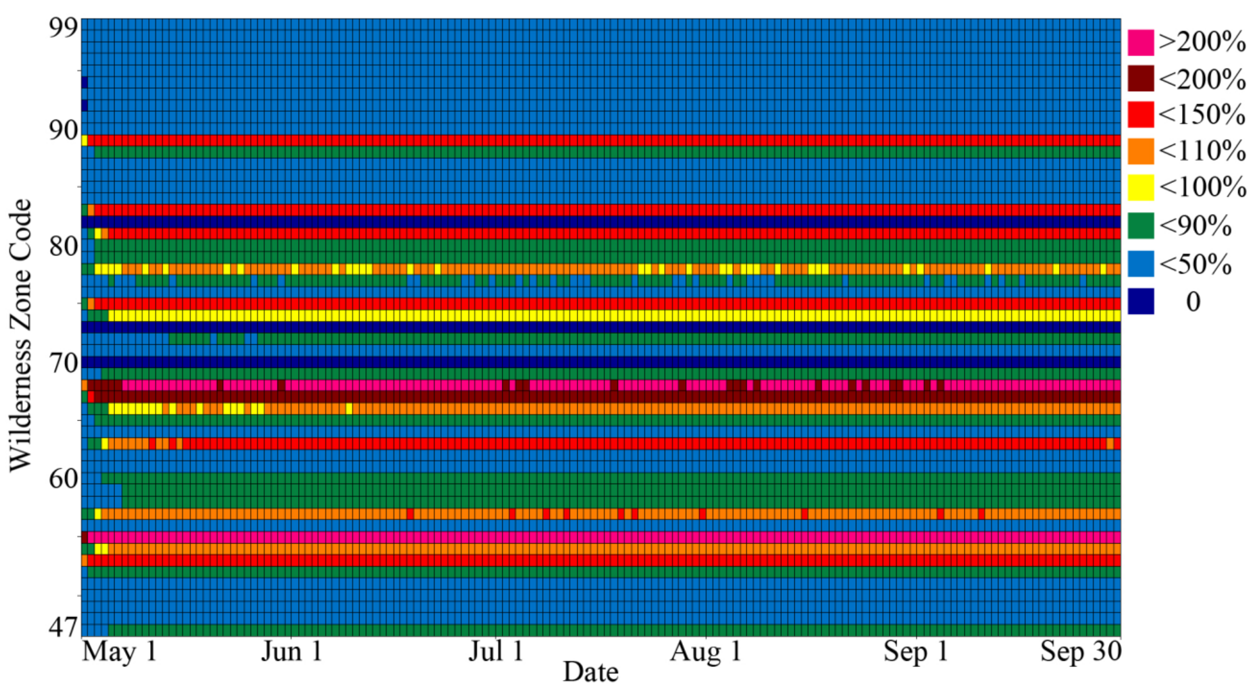


Figure 36. Mean wilderness use over 1,000 simulations of the Maximum Use Scenario, expressed as a fraction of zone capacity.

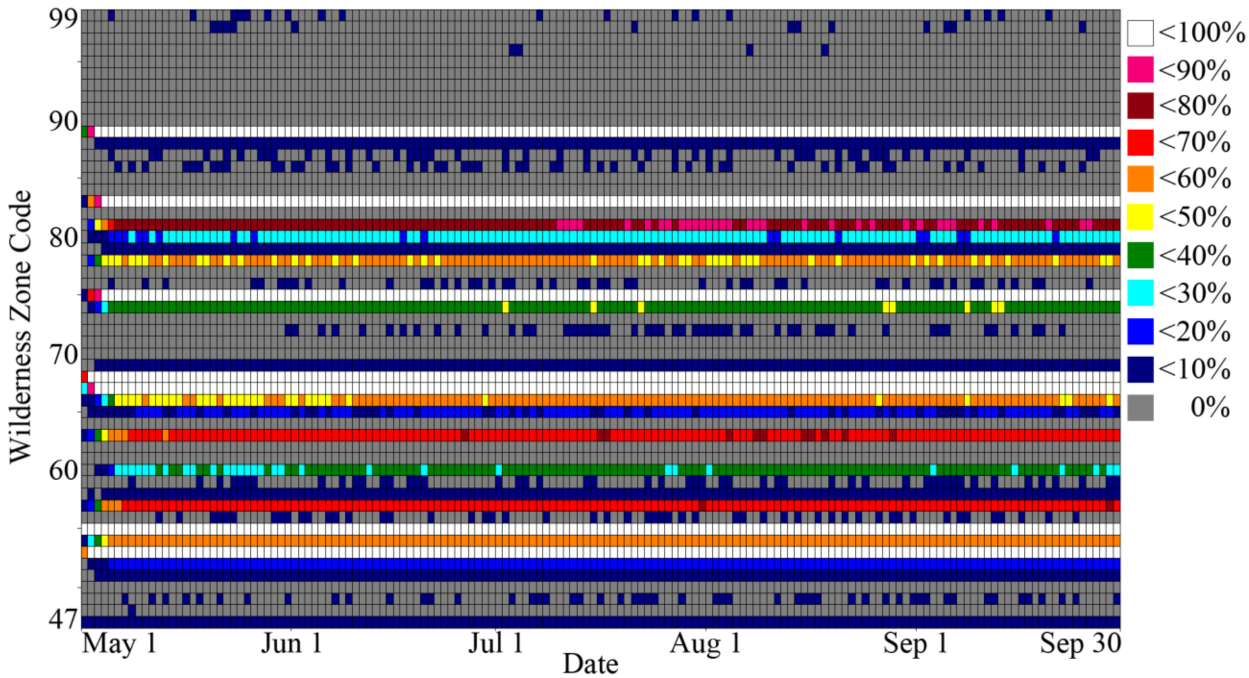


Figure 37. Probability of use exceeding capacity over 1,000 simulations of the Maximum Use Scenario.

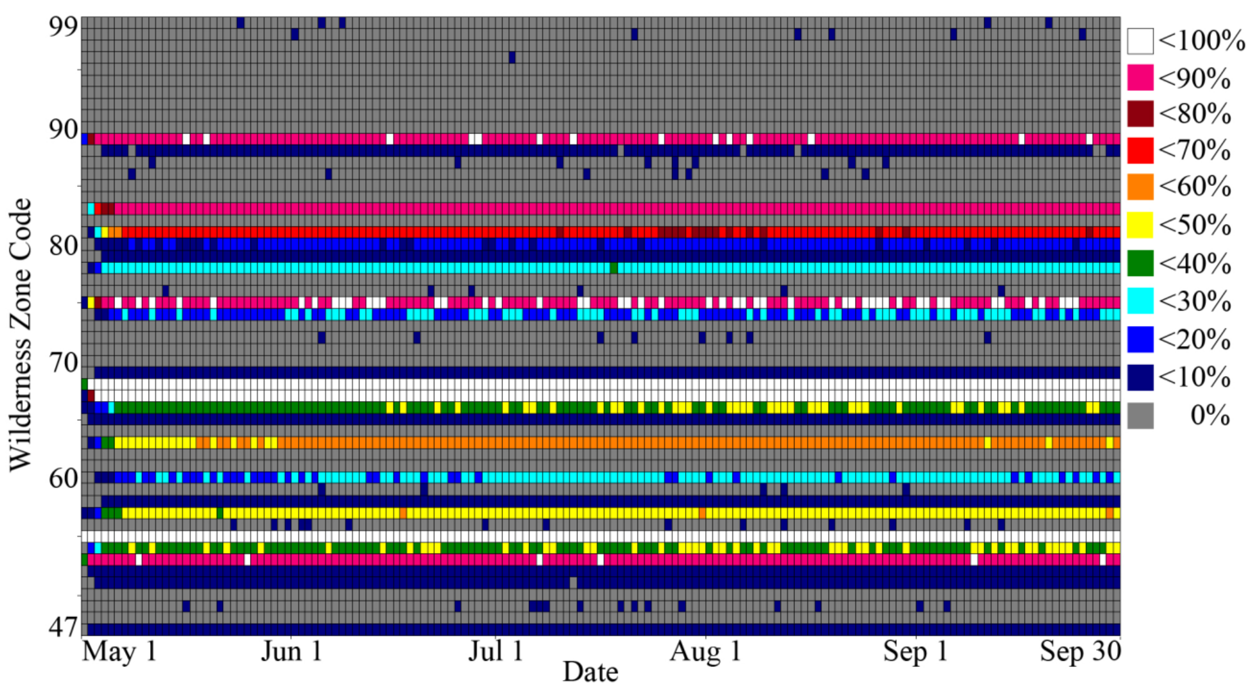


Figure 38. Probability of use exceeding 110% of capacity over 1,000 simulations of the Maximum Use Scenario.

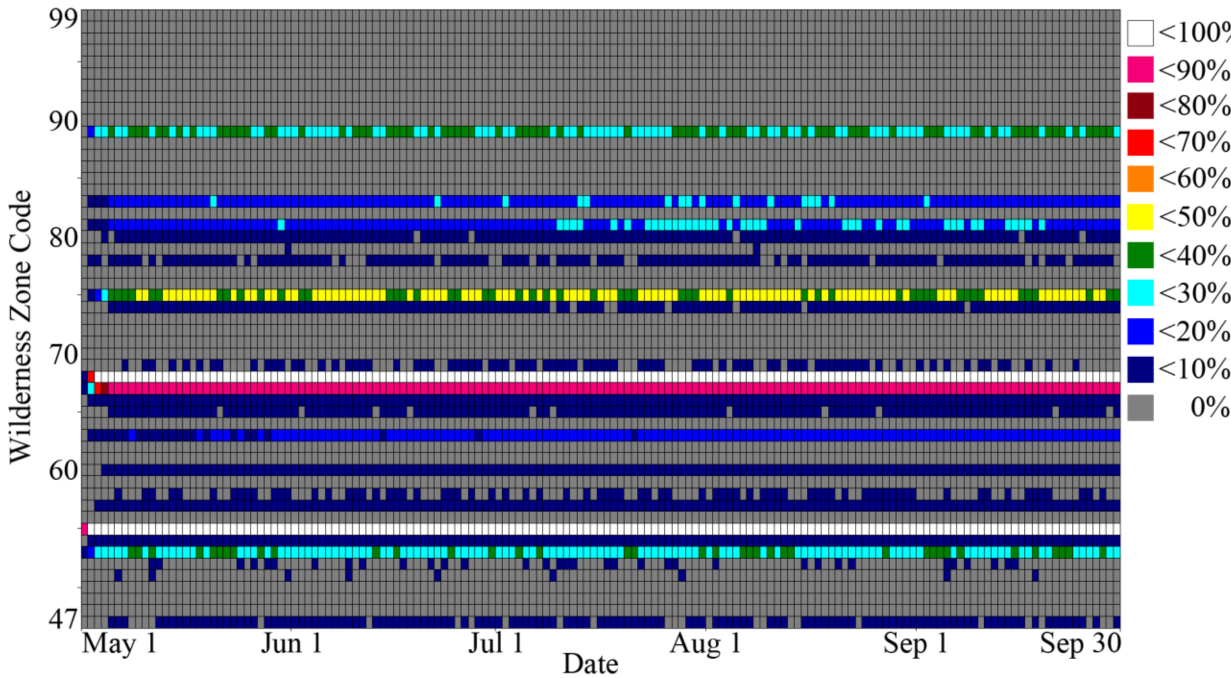


Figure 39. Probability of use exceeding 150% of capacity over 1,000 simulations of the Maximum Use Scenario.

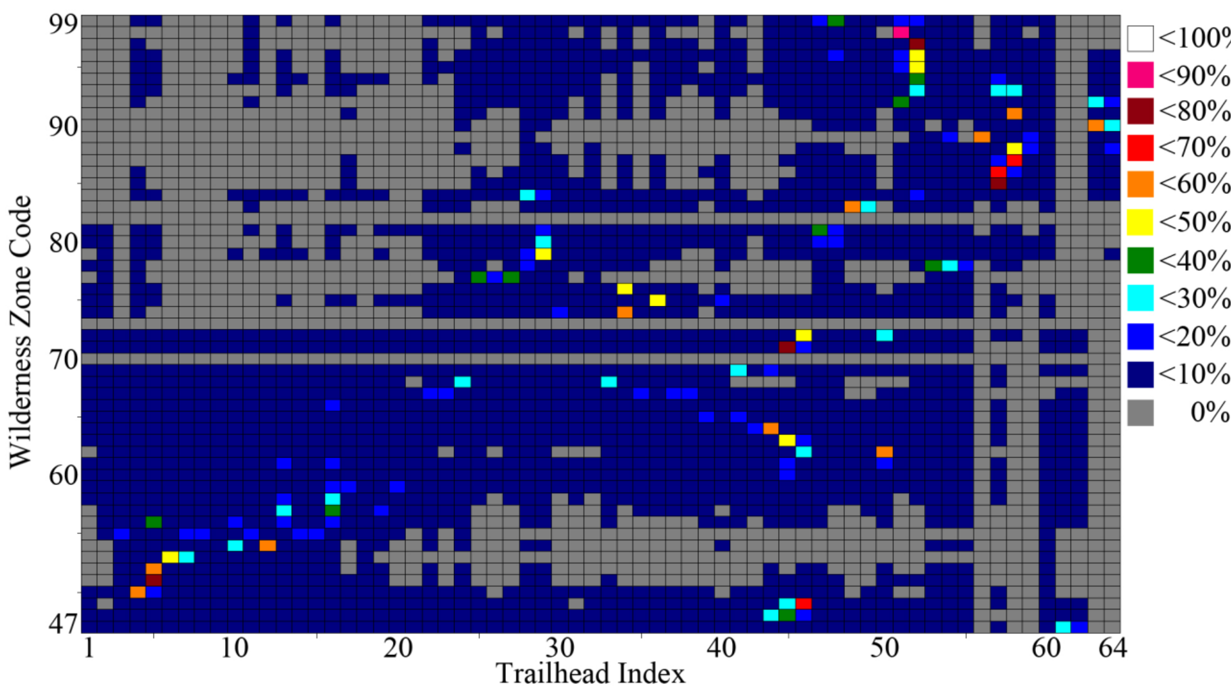


Figure 40. Trailhead contribution to zone use for the Maximum Use Scenario. See Appendix A for a key to these trailhead indices.

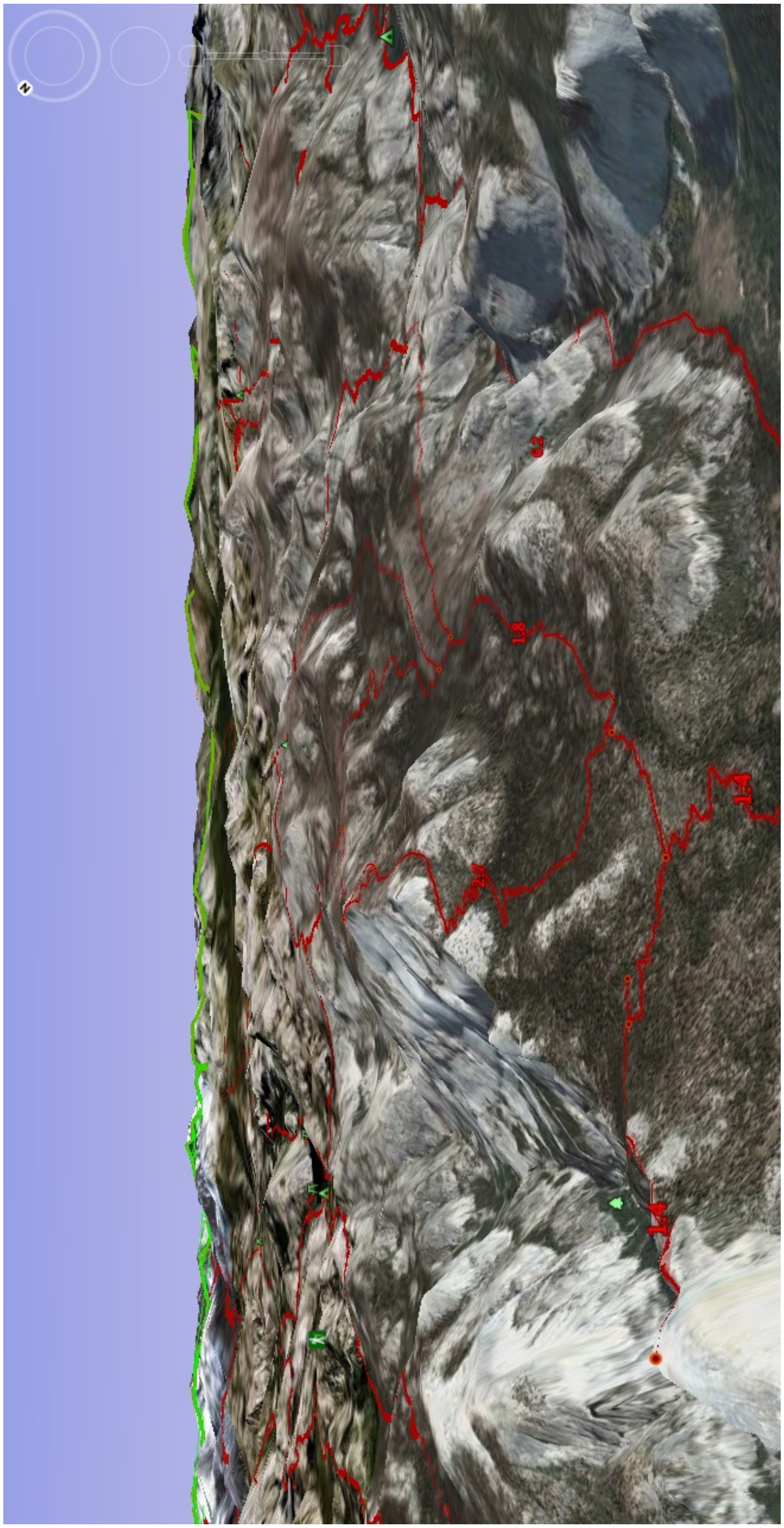


Figure 41. Features drawing use to Sunrise Creek (zone 66).

APPENDIX A. WILDERNESS ZONE SUMMARY

The following table summarizes wilderness zone parameters and use. Zone codes are those used in the wilderness permit database and those used on vertical axis labels of figures in this report. Use reported in the table is the mean of annual use over 1000 model simulations. "YOSE use" is that originating from Yosemite trailheads, which are listed in Appendix B. "Total use" includes additional use from USFS trailheads and the Pacific Crest Trail. Rank is based on total use, excludes backpacker camps, and uses the convention that 1 = zone with highest use and 50 = zone with lowest use.

The last column of the table contains the ratio of percentage of total use the particular zone receives to the percentage of total capacity accounted for by that zone, which is the relative use index of Table 7. Values near 1 indicate that use in that zone is roughly proportional to the zone's capacity. Value larger than one indicate that the zone receives high use relative to its capacity, and values less than one indicate that the zone receives very little use relative to its capacity.

This table is also provided in the spreadsheet "zone table.xlsx" as described in Appendix D.

ID	Code	Wilderness Zone	Capacity	% Capacity	YOSE use (visitor nights)	% YOSE use	Total Use (visitor nights)	% Total use	Total Use Rank	% Total Use/ % Capacity
1	1	Unspecified	NA	NA	0	0.00%	0	0.00%	NA	NA
2	47	Half Dome	25	0.60%	883	0.98%	924	0.92%	33	1.55
3	48	Lewis Creek	50	1.19%	279	0.31%	335	0.34%	44	0.28
4	49	Evelyn Lake	50	1.19%	1274	1.42%	1351	1.35%	24	1.13
5	50	South Fork Merced R.	150	3.57%	135	0.15%	1119	1.12%	29	0.31
6	51	Johnson Creek	50	1.19%	547	0.61%	576	0.58%	38	0.48
7	52	Chilnualna Creek	100	2.38%	1751	1.95%	1753	1.75%	20	0.74
8	53	Alder Creek	50	1.19%	415	0.46%	413	0.41%	42	0.35
9	54	Ostrander Lake	50	1.19%	1105	1.23%	1108	1.11%	30	0.93
10	55	Bridalveil Creek	50	1.19%	1765	1.96%	1759	1.76%	19	1.48
11	56	Buena Vista Creek	100	2.38%	1201	1.33%	1199	1.20%	27	0.50
12	57	Illilouette Creek	75	1.79%	3065	3.41%	3190	3.19%	14	1.79
13	58	Clark Range	50	1.19%	925	1.03%	1433	1.43%	22	1.20
14	59	Little Yosemite Valley	150	3.57%	7679	8.53%	7922	7.92%	1	2.22
15	60	Merced Lake	50	1.19%	3330	3.70%	3393	3.39%	10	2.85
16	61	Washburn Lake	150	3.57%	550	0.61%	913	0.91%	34	0.26
17	62	Mount Lyell	50	1.19%	158	0.18%	186	0.19%	48	0.16
18	63	Vogelsang	50	1.19%	3779	4.20%	3950	3.95%	7	3.32
19	64	Echo Creek	100	2.38%	1293	1.44%	1458	1.46%	21	0.61
20	65	Sunrise Lakes	50	1.19%	3329	3.70%	3371	3.37%	11	2.83
21	66	Sunrise Creek	50	1.19%	5547	6.16%	5807	5.81%	4	4.88
22	67	Snow Creek	50	1.19%	4595	5.11%	4605	4.61%	5	3.87
23	68	Yosemite Creek	100	2.38%	6964	7.74%	6973	6.97%	2	2.93
24	69	Cathedral Lakes	50	1.19%	3286	3.65%	3538	3.54%	9	2.97
NA	70	NO CAMPING	0	0.00%	0	0.00%	0	0.00%	NA	NA
25	71	Rafferty Creek	50	1.19%	520	0.58%	575	0.57%	39	0.48
26	72	Lyell Canyon	125	2.98%	4892	5.44%	6313	6.31%	3	2.12
NA	73	NO CAMPING	0	0.00%	0	0.00%	0	0.00%	NA	NA
27	74	Ten Lakes	100	2.38%	3282	3.65%	3284	3.28%	12	1.38
28	75	May Lake	50	1.19%	3864	4.29%	3872	3.87%	8	3.25
29	76	Grant Lakes	100	2.38%	1331	1.48%	1337	1.34%	26	0.56
30	77	South Fork Tuolumne R.	200	4.76%	131	0.15%	129	0.13%	49	0.03
31	78	Cottonwood Creek	100	2.38%	380	0.42%	379	0.38%	43	0.16
32	79	Pate Valley	100	2.38%	1381	1.53%	1388	1.39%	23	0.58
33	80	Waterwheel Falls	75	1.79%	2648	2.94%	2680	2.68%	15	1.50
34	81	Glen Aulin	50	1.19%	4003	4.45%	4122	4.12%	6	3.46
NA	82	NO CAMPING	0	0.00%	0	0.00%	0	0.00%	NA	NA
35	83	Conness Creek	50	1.19%	3173	3.53%	3196	3.20%	13	2.68
36	84	Pleasant Valley	100	2.38%	216	0.24%	234	0.23%	47	0.10
37	85	Rancheria Mountain	100	2.38%	1345	1.49%	1344	1.34%	25	0.56
38	86	Tiltill Valley	100	2.38%	2553	2.84%	2563	2.56%	16	1.08
39	87	Lake Vernon	100	2.38%	1821	2.02%	1883	1.88%	17	0.79
40	88	Laurel Lake	100	2.38%	1695	1.88%	1815	1.81%	18	0.76
41	89	Miguel Meadow	50	1.19%	569	0.63%	574	0.57%	40	0.48
42	90	Kibbie Creek	100	2.38%	158	0.18%	772	0.77%	36	0.32
43	91	Frog Creek	100	2.38%	184	0.20%	235	0.24%	46	0.10
44	92	Twin Lakes	50	1.19%	11	0.01%	49	0.05%	50	0.04
45	93	Tilden Lake	150	3.57%	322	0.36%	977	0.98%	31	0.27
46	94	Kerrick Canyon	200	4.76%	139	0.15%	944	0.94%	32	0.20
47	95	Benson Lake	150	3.57%	277	0.31%	1178	1.18%	28	0.33
48	96	Matterhorn Canyon	50	1.19%	174	0.19%	702	0.70%	37	0.59
49	97	Virginia Canyon	100	2.38%	207	0.23%	851	0.85%	35	0.36
50	98	McCabe Lakes	50	1.19%	169	0.19%	282	0.28%	45	0.24
51	99	Cold Canyon	50	1.19%	496	0.55%	556	0.56%	41	0.47
52	100	Tuolumne BP Camp	NA	NA	128	0.14%	425	0.43%	NA	NA
53	101	Yosemite Valley BP Camp	NA	NA	57	0.06%	57	0.06%	NA	NA
54	102	White Wolf BP Camp	NA	NA	15	0.02%	15	0.02%	NA	NA
		TOTALS	4,200	100.00%	89,997	100.00%	100,008	100.00%		1.00

APPENDIX B. TRAILHEAD SUMMARY

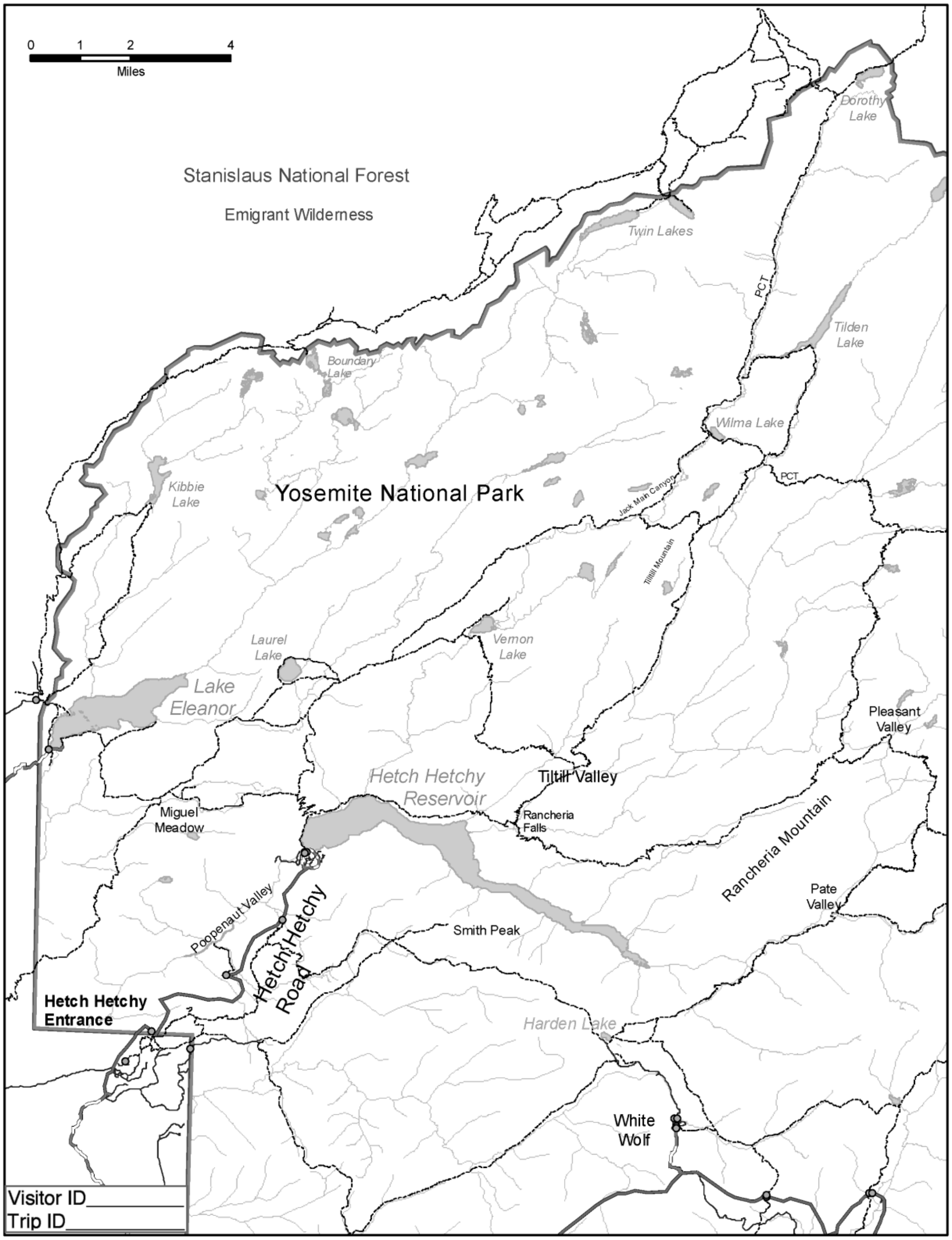
The following table summarizes trailhead parameters and use contributions. Trailhead ID and code are those used in the wilderness permit database. The trailhead index is what is used on horizontal axis labels of figures in this report. This index is used instead of either ID or code because neither IDs nor codes comprise a sequence of consecutive integers, making concise labeling of graph axes impossible. An "NA" index indicates that the trailhead was not used in the simulation model because the permit database did not contain any trip itineraries that started at that particular trailhead. Use figures are percent of total Yosemite-derived wilderness use originating from that trailhead under the Current Use and Maximum Allowable Use scenarios, respectively. The distribution of use across trailheads under the Current Use scenario primarily reflects popularity of the trailhead and only secondarily reflects trailhead quotas. The distribution of use across trailheads under the Maximum Allowable Use scenario reflects trailhead quotas only. That is, the percentage of total use contributed by a given trailhead is essentially the same as the percentage of total quota accounted for by that trailhead. Slight differences between percentage of use and percentage of quota are due to stochasticity in the model and to the particular itineraries that are likely to result from trips originating at a given trailhead. Model trailhead quotas were set at 10 for all trailheads used in the model that do not have a real quota. The contribution ranking convention is 1 = highest contributor to use, 64 = lowest contributor to use. The combined contributions of the USFS trailheads and Pacific Crest Trail are not included in any of these figures; these sources account for 9.75% of total use.

The last column of the table contains the ratio of the percentage of Yosemite-derived use contributed by the trailhead under current conditions to the percentage of use contributed by that trailhead under the Maximum Use scenario. Values of this "trailhead popularity index" near one indicate that the contribution of that particular trailhead under current use conditions is roughly proportional to that trailhead's contribution to the total quota. Values great than one indicate that the trailhead's contribution to total use is large relative to its quota; trailheads with these values are the most popular. Values less than one indicate that the trailhead contributes a small fraction of total use relative to its quota; trailheads with these values are the least popular.

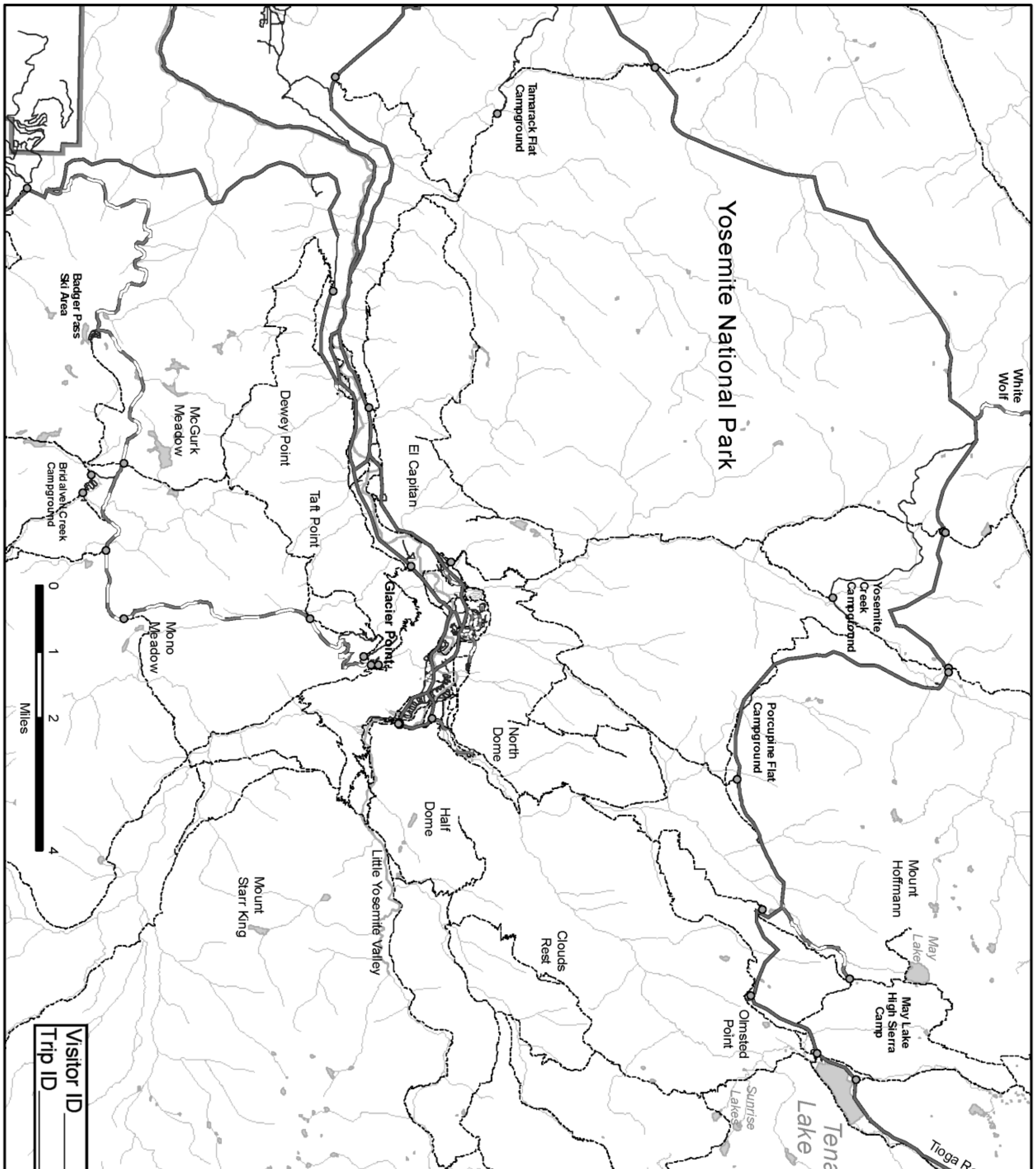
This table is also provided in the spreadsheet "trailhead table.xlsx" as described in Appendix D.

Index	ID	Code	Trailhead Name	Quota	% current use	Current use rank	Max use quota	% max use	%current/%max
1	131	41	Rockslides	10	0.51%	33	10	0.91%	0.56
2	132	421	Old Big Oak Flat Road	10	0.99%	26	10	0.90%	1.09
NA	133	431	Mariposa Grove	None	NA	NA	NA	NA	NA
3	134	581	Badger Pass	None	0.00%	60	10	0.80%	0.00
4	135	591	Crane Flat	10	0.01%	58	10	1.11%	0.01
NA	136	592	Merced Grove	None	NA	NA	NA	NA	NA
5	137	611	Chilnualna Falls	40	0.02%	55	40	3.99%	0.00
6	138	621	Alder Creek	25	0.00%	61	25	2.05%	0.00
7	139	631	Deer Camp	25	2.54%	16	25	1.89%	1.35
8	140	641	Pohono Trail (Wawona Tunnel/Bridalveil)	10	0.25%	41	10	0.80%	0.31
9	141	651	Westfall Meadow	10	0.05%	50	10	0.79%	0.06
10	142	652	Bridalveil Campground	25	0.77%	29	25	2.07%	0.37
11	143	653	McGurk Meadow	15	0.03%	52	15	1.21%	0.03
12	144	661	Ostrander (Lost Bear Meadow)	25	0.61%	31	25	2.06%	0.29
13	145	671	Mono Meadow	20	0.42%	36	20	2.19%	0.19
14	146	681	Pohono Trail (Glacier Point)	15	1.38%	24	15	1.24%	1.12
15	147	691	Pohono Trail (Taft Point)	10	2.17%	18	10	0.80%	2.72
16	148	692	Glacier Point->Illilouette	30	0.47%	34	30	3.20%	0.15
17	149	693	Glacier Point->Little Yosemite Valley	10	0.06%	48	10	0.87%	0.07
18	150	694	Four Mile Trail	None	3.42%	10	10	0.92%	3.74
19	151	701	Happy Isles->Illilouette	10	1.68%	20	10	1.09%	1.55
20	152	702	Happy Isles->Little Yosemite Valley	30	0.03%	53	30	0.86%	0.04
21	153	703	Happy Isles->Sunrise/Merced Lake	10	1.52%	22	10	0.51%	2.97
22	154	711	Mirror Lake->Snow Creek	25	7.14%	1	25	1.45%	4.91
23	155	721	Yosemite Falls	25	2.68%	14	25	1.48%	1.82
24	156	731	Tamarack Creek	25	2.59%	15	25	2.26%	1.15
25	157	741	South Fork of Tuolumne River	25	3.43%	9	25	1.95%	1.76
26	158	751	Aspen Valley	10	0.73%	30	10	0.78%	0.94
27	159	761	White Wolf->Aspen Valley	25	0.04%	51	25	1.95%	0.02
28	160	762	White Wolf->Smith Meadow	25	0.01%	59	25	2.43%	0.00
29	161	763	White Wolf->Pate Valley	30	0.01%	57	30	3.32%	0.00
30	162	771	White Wolf Campground	10	0.19%	43	10	0.99%	0.19
31	163	781	Lukens Lake->Yosemite Creek	10	1.49%	23	10	0.90%	1.66
32	164	782	Luken->Lukens Lake	10	0.42%	35	10	1.01%	0.42
33	165	791	Yosemite Creek Campground	25	0.16%	45	25	2.27%	0.07
34	166	801	Ten Lakes	40	0.15%	46	40	3.91%	0.04
35	167	811	Porcupine Creek	25	1.33%	25	25	1.45%	0.92
36	168	821	May Lake	25	3.66%	7	25	2.26%	1.62
37	169	831	May Lake->Snow Creek	10	2.05%	19	10	0.79%	2.58
38	170	841	Olmsted Point	10	3.14%	12	10	0.83%	3.79
39	171	851	Sunrise Lakes	20	0.18%	44	20	0.80%	0.22
40	172	861	Murphy Creek	15	0.39%	38	15	1.38%	0.28
41	173	871	Cathedral Lakes	25	3.64%	8	25	1.01%	3.59
42	174	872	Budd Creek (cross-country only)	5	1.60%	21	5	0.50%	3.17
43	175	881	Nelson Lake	15	4.86%	4	15	1.61%	3.03
44	176	882	Rafferty Creek->Vogelsang	20	0.34%	39	20	2.27%	0.15
45	177	883	Lyell Canyon	40	0.85%	27	40	2.60%	0.33
46	179	885	Glen Aulin	35	4.35%	6	35	2.25%	1.94
47	180	886	Glen Aulin->Cold Canyon/Waterwheel	15	6.45%	2	15	1.69%	3.81
48	181	887	Young Lakes via Dog Lake	20	5.57%	3	20	1.78%	3.13
49	182	888	Young Lakes via Glen Aulin Trail	10	2.70%	13	10	0.89%	3.02
NA	183	891	Gaylor Creek	None	NA	NA	NA	NA	NA
50	184	901	Mono/Parker Pass	15	2.53%	17	15	1.43%	1.77
51	185	911	Gaylor Lakes (no camping)	None	0.84%	28	10	1.28%	0.66
NA	186	912	Mount Dana (no camping)	None	NA	NA	NA	NA	NA
52	187	913	Tioga Pass	None	0.00%	62	10	1.73%	0.00
NA	188	921	Base Line Camp Road	25	NA	NA	NA	NA	NA
53	189	933	Cottonwood Creek	25	0.42%	37	25	2.28%	0.18
54	190	931	Mather Ranger Station	25	0.02%	54	25	2.07%	0.01
55	191	941	Smith Peak	15	0.00%	63	15	1.31%	0.00
56	192	942	Poopenaut Valley	25	0.01%	56	25	2.09%	0.01
57	193	951	Rancheria Falls	35	0.00%	64	35	3.02%	0.00
58	194	952	Beehive Meadows	35	0.09%	47	35	3.35%	0.03
59	195	953	Miguel Meadow	15	0.06%	49	15	1.24%	0.05
60	196	305	Unspecified	None	0.26%	40	10	0.95%	0.28
61	255	704	Happy Isles->Snake Dike Bivy	3	0.25%	42	3	0.26%	0.96
62	256	705	Happy Isles->Northwest Regular Route	3	4.35%	5	3	0.24%	18.29
63	257	328	Kibbie/USFS	None	3.39%	11	10	0.86%	3.96
64	260	329	Lake Eleanor/USFS	None	0.52%	32	10	0.85%	0.61

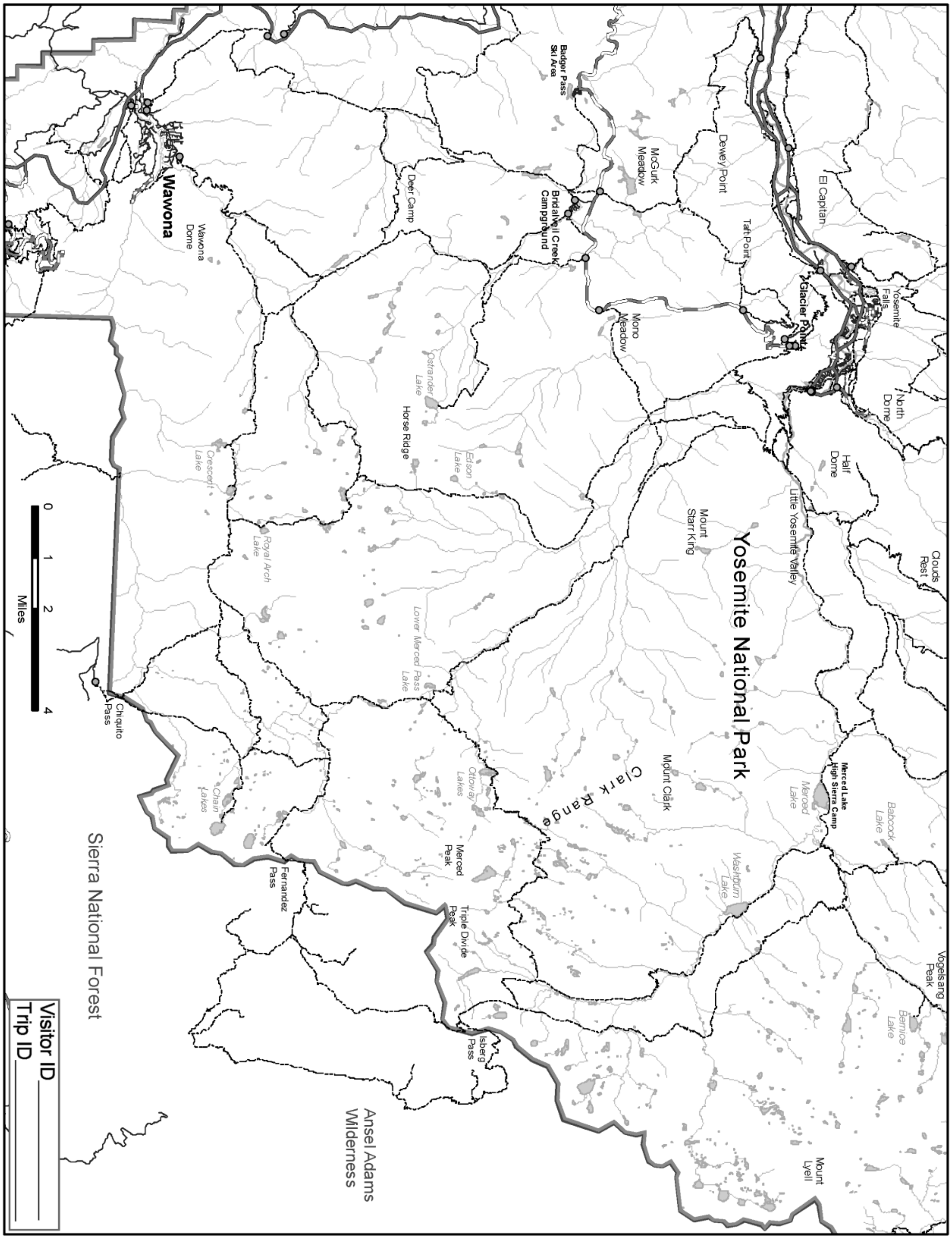
APPENDIX C. SECTOR MAPS DISTRIBUTED WITH SURVEY INSTRUMENT



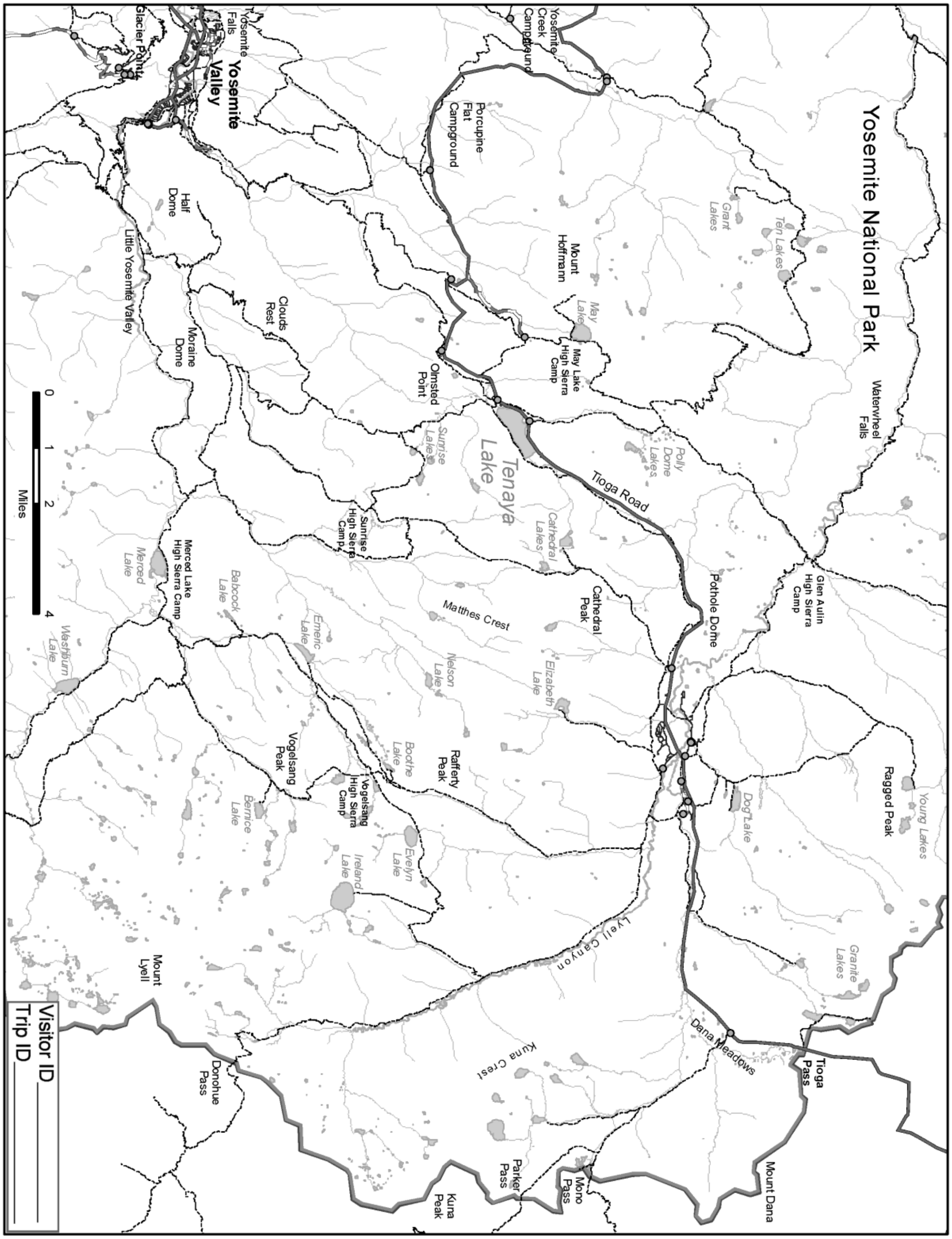
Hetch Hetchy sector map.



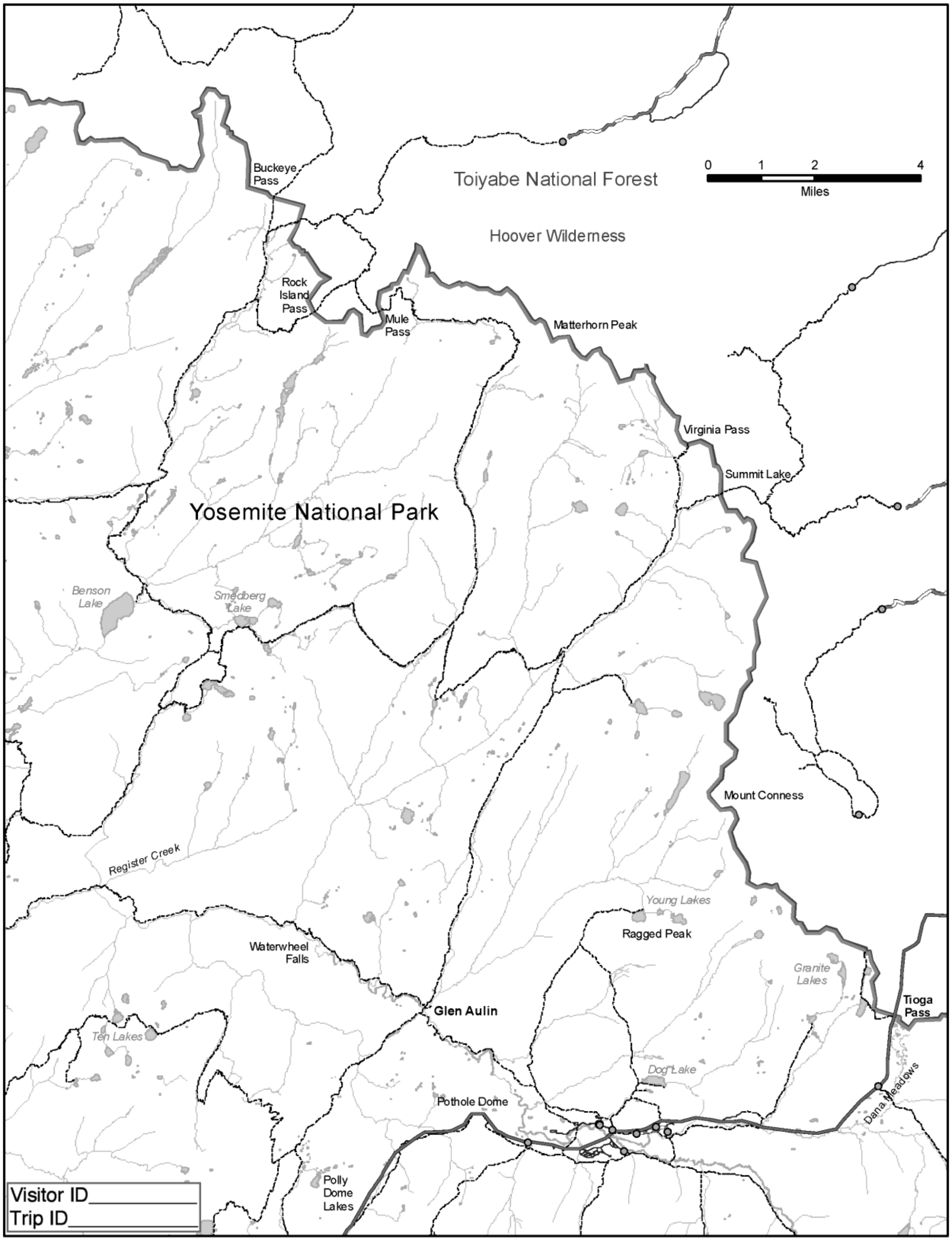
Yosemite Valley sector map.



Wawona/South sector map.



Cathedral sector map.



Tuolumne sector map.

APPENDIX D. INDEX TO ACCOMPANYING SPREADSHEETS

This report is accompanied by tabular data submitted in the form of Excel spreadsheets (.xlsx). Some of these files contain data depicted in figures or tables in the report. "Mean" refers to the mean over 1000 model simulations. "YOSE-origin" refers to use from trips that originate from the trailheads listed in Appendix B. Unless specified otherwise, the data are reported for current conditions.

File name	Contents	Also in
exceedance	Probability of zone capacity exceedance, all use	Fig. 24
NonYOSE mean use	Use (visitor nights) by zone-night originating from outside YOSE	
percent use by th	Percent of total zone use by source (YOSE trailheads, USFS+PCT)	
percent use by YOSEth	Percent of YOSE-origin zone use by trailhead	Fig. 22
Total mean use	Mean use (visitor nights) by zone-night from all sources	Fig. 23
trailhead table	Trailhead summary table	App. B
true zone_th	Percent of YOSE-origin zone use by trailhead, Max. Use scenario	Fig. 40
use by th	Total use (visitor nights) by source (YOSE trailheads, USFS+PCT)	
use by YOSEth	YOSE-originating zone use by trailhead	
YOSE max use	99^{th} percentile of YOSE-origin use (visitor nights) by zone-night	
YOSE mean use	Mean YOSE-origin use (visitor nights) by zone-night	Fig. 18
zone table	Wilderness zone summary table	App. A