

A GIS/Simulation Framework for Assessing Change in Water Yield over Large Spatial Scales

(Short title: Assessing Change in Water Yield)

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ABSTRACT / Recent legislation to initiate vegetation management in the Central Sierra hydrologic region of California includes a focus on corresponding changes in water yield. This served as the impetus for developing a combined geographic information system (GIS) and simulation assessment framework. Using the existing vegetation density condition, together with proposed rules for thinning to reduce fire risk, a set of simulation model inputs were generated for examining the impact of the thinning scenario on water yield. The approach allows results to be expressed as the mean and standard deviation of change in water yield for each 1 km² map cell that is treated. Values for groups of cells are aggregated for typical watershed units using

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area-weighted averaging. Wet, dry and average precipitation years were simulated over a large region. Where snow plays an important role in hydrologic processes, the simulated change in water yield was less than 0.5% of expected annual runoff for a typical watershed. Such small changes would be undetectable in the field using conventional stream flow analysis. These results suggest that use of water yield increases to help justify forest-thinning activities or offset their cost will be difficult.

Millions of hectares of dry coniferous forest in the western United States are at risk for catastrophic crown fires because of structural changes (shifts in species and crown density) that have developed as a result of effective fire suppression since the early 1900s (Sampson 1999). Mechanical thinning is one management tool that can be used to control catastrophic fire risk and move the forest back towards its historic fire-resilient state. However, mechanical thinning produces large quantities of wood and bark that must generally be removed from the forest. The fate of this material is problematic, for in many cases the material is not suitable for conventional wood products (lumber or chips) and/or there is no local wood products industry. Many parties are exploring novel uses of this material. One proposed use is as feedstock to produce bioenergy. Producing bioenergy either in the form of ethanol or power is an attractive option since these markets are large enough absorb the quantities of material that would be generated if thinning was used to reduce the regional risk of fire. Furthermore, the production of bioenergy from this material has air quality and greenhouse gas benefits especially in comparison to prescribed burning or crown fires.

Because of its interest in bioenergy, the U.S. Department of Energy (DOE) is supporting research and assessments of the technical, economic and environmental feasibility of relying on

forest thinning to reduce fire risk as a feedstock source for bioenergy. This paper describes the DOE-sponsored development and application of a framework for assessing the potential effect of thinning western coniferous forest on water yield at a regional (1000+ square kilometer) scale. Water yield effects were of particular interest to DOE because of their important energy, environment and economic implications. Water is often the most valuable commodity coming out these regions. Altering forest canopy through thinning could change evapotranspiration and thus water yield. And although mechanical removal of biomass for reduction of fire risk and production of bioenergy may not be economically attractive on its own, benefits, such as increased water yield, could improve economic viability of the region.

The framework described here, while developed to be applicable across the west, was targeted towards understanding the water yield implications of widely applying a forest fire reduction strategy considered in the Herger-Feinstein Quincy Library Group Forest Recovery Act (Department of the Interior and Related Agencies Appropriations Act, Section 401 1998). This Act, passed and signed into law in October, 1998 as part of the omnibus budget bill, is "... a community stability plan to promote ecologic and economic health for certain Federal Lands and communities..." in the Sierra Nevada mountains in California. The Act sets forth activities for fuelbreak construction, thinning of selected forest areas and riparian management and restoration. Our goal was an assessment-level examination of the change in water yield that might result if the fire reduction management treatments proposed in the Act were applied across the entire 42,000 square kilometer study area. Specifically, group selection to reduce crown density to fire resilient-level and the creation of defensible fuel profile zones along ridges were both addressed. We wish to note that the management scenario we model differs significantly

from the actions described in the Act. The Act considers only public lands and targets treating up to 283 square kilometers (70,00 acres) of forest each year for five years. While we use two management treatments proposed in the Act, we apply these treatments to all private forestlands in addition to all the public lands considered suitable for treatment in the Act. Thus we treat a much larger area and examine the implications of full-scale implementation of forest thinning to reduce the risk of catastrophic fire on regional water yield. We do not, however, include any public lands (such as wilderness or National Parks) that are excluded in the Act. Figure 1, developed in part from data provided by the Quincy Library Group (QLG) and Vestra Resources of Redding, California, shows the total area we evaluated, excluded areas and California watersheds.

To address the water yield changes associated with the regionally applied thinning treatments, we adapted an assessment model developed for silvicultural management (Troendle 1979) for use with a geographic information system (GIS) and applied this model to the study area shown in Figure 1. As part of the assessment, we developed a new leaf-area index map to characterize the forest vegetation. Because of the large area to be evaluated (approximately 42,000 square kilometers), some innovation was required to reduce computations. An important objective was to estimate the expected statistical range of response, rather than produce a single result.

Consequently we used an efficient, systematic sampling method, Latin Hypercube sampling (Iman and Helton, 1985). More specifically, the PRISM program (Gardner and others 1983) was used to generate multiple model-input files for a modified Monte Carlo simulation analysis. The results could then be used to evaluate mean response and variance of change in water yield. The method also includes area averaging to represent results for watershed accounting units, where

not all of the forested area is treated. This approach allows an assessment at several scales and produces representative results for each of those scales. A qualitative examination of dominant seasonal patterns in evapotranspiration changes was also included.

The assessment framework

Because of the scale of the QLG study area, the framework that was selected draws upon use of a geographic information system (GIS) and data derived in part from remote sensing. Mauser and Shadlich (1998) suggest that although there are current limitations to such an approach, it holds considerable promise for the future as new sensors and instruments for data collection evolve. These developments, together with the summarizing and visualization power inherent in GIS, argue that this combination of remote sensing and GIS will continue to grow in power as more refined data become available and computing speed and memory capacity improve. Current emphasis on development of general circulation models that include feedback between the atmosphere and landscape, via soil-vegetation-atmosphere transfers, (e.g. Avissar 1998) also supports the likelihood of improved capability to use a GIS/remote sensing system to explore water resources issues. Avissar points out that such systems will probably be most effective if they focus at the scale of the problem from the outset, rather than attempting to scale up from individual plot-sized field experiments. Regardless, it is apparent that the GIS/remote sensing framework also must include a modeling interface to allow quantitative assessments. The framework suggested here and illustrated by example, can be visualized as a three-part system:

- Study definition and model selection, followed by assembly and manipulation of spatially-distributed data (GIS data layers) to generate input files for the hydrologic simulation model,
- Modified Monte Carlo simulations of expected change in water yield resulting from forest management practices to produce location-specific results for statistical summary, and
- Analysis and spatial (GIS) display of results for evaluation and interpretation. Results may suggest repeating the steps with different data or models.

Application of the framework

Study definition and model selection

Simply stated, if it were possible to go from current forest conditions to a more open, fire-resistant situation, how much would water yield change? To address this question, we assumed that vegetation removal for fire suppression would be a combination of group selection and fuel breaks. We ignored access road issues. The goal was to explore the overall potential for water yield for a large enough area to be representative if a fire-suppression management plan like the one proposed by the QLG were fully deployed at a regional scale.

To estimate change in water yield from vegetation management, actual evapotranspiration must be related to the change in vegetative characteristics. The simplest way is through regression models (e.g. Douglass and Swank 1975), where factors like fractional reduction in basal area and the insolation index are used to estimate annual change in runoff. This approach requires observations from paired watershed studies for a range of representative conditions. Evaluations using this approach for the Sierra Nevada have been completed recently (e.g. Marvin 1996 and Kattleman 1996). Alternatively, simulation of actual evapotranspiration and runoff, using

physical, climatic and vegetative properties can be used to derive change in water yield (defined as the difference between precipitation and actual evapotranspiration). Huff and Swank (1985) describe an example of this latter approach, applied to a long-term clear cutting and regrowth experiment at the Coweeta Hydrologic Laboratory in western North Carolina. However, as the complexity of the method increases, data requirements become more difficult to satisfy.

An intermediate strategy uses calibrated simulation models with field observations to extend the experimental evidence. This approach allows development of simplified relationships to forecast expected change in runoff from forest manipulation (Troendle 1979). Because of simpler data requirements for this methodology, we chose this approach and, specifically, the Forest Service assessment model (USDA 1980). We also chose to emphasize *change* in water yield caused by forest thinning, rather than the absolute annual total. Huff and Swank (1985) concluded this measure was more reliably achieved.

The Water Resources Evaluation of Non-Point Silvicultural Sources (WRENSS) methodology

The Forest Service (WRENSS) methodology was originally published in the form of an assessment handbook (USDA 1980). The portion dealing with changes in water yield was converted to a computer program to facilitate its use, and has continued to evolve (e.g. Bernier 1986, Swanson 1991). A modified version of the Fortran program was developed for our analysis (Huff and others 1999) for use on a workstation where it could interface directly with GIS data.

WRENSS data requirements

The WRENSS model differentiates between two types of watershed units. The first distinction is whether a snow pack affects hydrologic processes. Where this occurs, the areas are called "snow-dominated process" (SDP) units. SDP units are further differentiated by an "energy-aspect," i.e. a combination of slope facing direction and elevation. In units where snow pack plays a significant role, the model has the capability for snow redistribution. However, in the Central Sierra, where wet snow conditions prevail, the redistribution feature is not used. The other type of watershed includes "rain-dominated process" (RDP) units. Where hydrologic behavior is rain dominated, there is a requirement for a soil depth parameter, which is related to soil moisture retention and availability. WRENSS divides the annual cycle into seasons, which vary in number depending on the location of the study area. For the Central Sierra, four seasons are used. Seasonal precipitation, together with time of year, is used to estimate a corresponding baseline evapotranspiration value. The other essential data element is vegetation density. WRENSS uses plant/tree species and either leaf-area index or basal area to characterize the vegetative cover. Leaf-area index (LAI) is the ratio of (one sided) leaf surface area per unit underlying ground surface area. Basal area is the total cross-section of tree stems, generally at breast height and inclusive of bark, per unit surface area. It is necessary to describe both pre- and post-treatment vegetative characteristics to estimate change in water yield.

Sensitivity of change in water yield to model parameters

The PRISM program (Gardner and others 1983) was used for a sensitivity analysis of randomly selected RDP and SDP clusters. The analysis included 13 input parameters for the RDP clusters and 7 input parameters for the SDP clusters. For the RDP clusters, variables included in the analysis were seasonal precipitation values (4 values), seasonal values for LAI both before and after thinning (8 values), and rooting depth (1 value). For the SDP clusters the variables included seasonal precipitation (4 values), pre- and post-thinning basal area (2 values) and a parameter (1 value) that describes the limiting basal area above which evapotranspiration will be at the potential limit. Input data sets for the sensitivity analysis were generated from a normal distribution for the selected input parameters using 500 equal-probability class intervals, and each parameter was varied $\pm 1\%$ about its mean value. Sensitivity indices ranked the input parameters having the most influence on change in water yield. Results are presented in Table 1.

For SDP energy aspects, there are two basic patterns: Most of the low energy aspect clusters show slightly higher sensitivity to pre-thinning basal area than to post-thinning basal area. The exception, cluster 15, has a lower initial value for basal area than the other clusters in this group and shows much higher sensitivity to post-thinning basal area. For the higher energy aspect clusters, two of the three examples show the highest sensitivity to post-thinning basal area and a secondary sensitivity to the parameter describing the basal area threshold where water use reaches its maximum value. Changes in evapotranspiration are primarily linked to vegetation cover density before and after treatment. In the rain dominated process clusters, the primary sensitivities involve spring and winter season LAI. It may seem surprising that precipitation does not influence change in water yield. This result simply emphasizes the difference between change in water yield and total water yield. The latter is primarily affected by precipitation, while the former depends on changes in vegetation cover.

Table 1. Summary of water-yield changes versus WRENSS parameters

(Values indicate % of change in water yield attributed to the parameter indicated).

Results for snow dominated process clusters with low energy aspects					
WRENSS Parameters	Cluster 14 cells North aspect	Cluster 15 cells North aspect	Cluster 191 cells South aspect	Cluster 254 cells South aspect	Cluster 358 cells E/W aspect
Pre-thinning basal area	57.6	0.8	57.2	55.3	57.8
Basal area at maximum water use	2.2	20.0	0.8	3.6	1.3
Post-thinning basal area	40.3	79.3	42.3	40.9	41.0
Total explained change	100.1	100.1	100.3	99.8	100.1
Results for snow dominated process clusters with higher energy aspects					
WRENSS parameters	Cluster 98 cells North aspect	Cluster 286 cells South aspect	Cluster 494 cells E/W aspect		
Pre-thinning basal area	56.8	0.0	0.0		
Basal area at maximum water use	0.7	17.1	17.8		
Post-thinning basal area	42.9	83.0	82.3		
Total explained change	100.4	100.1	100.1		
Results for rain dominated process clusters					
WRENSS parameters	Cluster 627 cells	Cluster 638 cells	Cluster 629 cells		
Fall pre-thinning LAI	7.0	0.3	7.4		
Winter pre-thinning LAI	12.6	10.1	11.5		
Spring pre-thinning LAI	18.1	27.7	23.3		
Summer pre-thinning LAI	3.7	0.1	1.9		
Fall post-thinning LAI	9.4	10.1	8.9		
Winter post-thinning LAI	10.1	9.5	9.6		
Spring post-thinning LAI	37.0	39.0	35.3		
Summer post-thinning LAI	3.1	4.2	3.0		
Total explained change	101.0	101.0	100.9		

GIS Data Assembly

Spatial Resolution

The minimum spatial resolution is important for any GIS analysis. We chose a 1-km map cell resolution on the basis of data availability, size of the study area and computing considerations.

Energy-Aspect

We used a digital elevation model (GTOPO30, available through the web at <http://edcwww.cr.usgs.gov/landdaac/gtopo30/README.html>) to define the energy-aspect for each map cell. There are three aspect categories: North, South or a combination of East/West. The aspect or facing direction is determined using the following azimuth definitions:

North	:	< 45 degrees or > 315 degrees
South	:	≥ 135 degrees and ≤ 225 degrees
East/West	:	Everything not N or S

The energy level depends, in part, on the importance of snow pack accumulation and melt to the hydrology of the unit. Although ideally based on hydrograph response, we used elevation class as a surrogate for energy level in our large-scale assessment. Based on discussion with local foresters, sites below an elevation of 610 m were assumed to be rain dominated (RDP), while sites above 610 m were assumed to be snow dominated (SDP). The intermediate and low-energy

aspects were defined as being above elevation 1220 m above sea level. The classification was high-energy aspect for elevations between 610 m and 1220 m above mean sea level.

Seasonal Precipitation

Seasonal precipitation totals were constructed from the monthly values contained in a statistical-topographic model for mountainous terrain (Daly and others 1994). These totals represent synoptic conditions. To explore wetter and drier years, precipitation was increased to 150% of average to represent a wet year, and decreased to 65% of average for the dry year case. These adjustments were selected from water year precipitation summaries (1983-1998) available through the California Department of Water Resources web site (<http://cdec.water.ca.gov/cgi-progs/previous/PRECIPOUT>). The Sacramento River Basin data were used, and the values were selected to stay within observed ranges in precipitation (173% of average for a wet year and 56% of average for a dry year) over the past two decades, although there were a few wetter and a few drier years. Because of our focus on annual change in water yield, rather than actual runoff, we believe this is acceptable.

Vegetative Characteristics

The model requires that both the existing and the thinned forest vegetation be characterized in terms of leaf surface area or basal area. We developed a new 1-km resolution, spatial data set of maximum projected (one-sided) leaf area index (LAI) for the entire study area. The LAI data were developed in a three-step procedure using 1-km resolution Advanced Very High Resolution

Radiometer (AVHRR) data provided by the NOAA/NASA Pathfinder program, together with a digital elevation model. In the first step, a Greenness Index was computed as the ratio of the near infrared to the red reflectance value for each AVHRR map cell. The Greenness Index was computed for 11 different composite periods during the growing season. Next, the Greenness Index was used to estimate LAI by inverting a mechanistic radiative transfer model of the canopy. This model accounts for effects of sensor view angle, solar elevation, leaf optical properties, background reflectance, canopy leaf angle distribution and foliage clumping on the bi-directional reflectance above the canopy (Nikolov 1998). Finally, the maximum LAI from the 11 estimates was used to represent the optimal seasonal LAI for each map cell (Figure 2).

WRENSS characterizes vegetation by dominant tree species and vegetation cover density. Unfortunately, the coefficients that define WRENSS options for tree species are limited by data availability in Region 7 (Central Sierra). In the snow-dominated regions of the study area we used the "lodgepole pine" option because the Ponderosa pine option is not available in WRENSS for Region 7. In the rain-dominated areas we used the "conifer" option.

The leaf area index of the forest (m^2/m^2) is used to indicate cover density for RDP sites and the basal area (m^2/ha) is used for SDP sites. The original WRENSS model uses the total as opposed to the projected leaf surface area in its relationships. We adapted the model coefficients to allow direct use of projected leaf area index for RDP units. We transformed total leaf surface area to projected LAI by dividing by a factor of 2.5, a compromise between flat leaves, which have a conversion factor of 2.0 (surface to projected area) and rounded conifer needles, which may have a conversion factor of 2.8 to 3.2 (Johnson 1984).

For SDP map cells (above 610m elevation), the optimal seasonal LAI was transformed to basal area using the following equation:

$$\text{Basal area} = (a + b \cdot \text{LAI}) \cdot \text{LAI}$$

Where $a = 20.33$ and $b = -1.31$ and basal area is given in units of square meters per hectare.

This relationship was developed using literature values relating surface leaf area or projected leaf area to basal area in ponderosa pine dominated stands (Gholz 1982, Runyon and others 1994, Whittaker and Neiring 1975 and Gholz 1976); published allometric equations relating Ponderosa Pine, true fir, and Douglas fir foliage mass to tree dbh (Gholz and others 1979, Waring and others 1978, Cable 1958, Kittridge 1944); literature values on projected or total leaf surface area per unit foliage mass (Pierce and others 1994, Cable 1958); and forest inventory data from the Plumas and Lassen National Forests. Literature values present an inconsistent or incomplete picture of the relationship between basal area and leaf surface area. Allometric equations differed by almost a factor of two in their projections of leaf mass for the same size ponderosa pine tree. Thus considerable professional judgement was exercised in developing this relationship.

In the rain-dominated areas, WRENSS also requires an estimate of relative rooting depth. This parameter is a measure of water-holding capacity of the rooting zone. To estimate this depth parameter, we used a GIS coverage that provides a measure of plant-available water capacity (STATSGO, National Cartography and GIS Center, 1991). The integrated capacity to a depth of

1.5 meters, expressed as a depth of water per unit area of soil, is related to soil depth through a measure of the fractional volume of water between field capacity and wilting point. We assumed a conversion factor of 10 to scale the plant-available water to an equivalent rooting depth of soil.

Characterizing vegetation management scenarios

The area that was shown previously in Figure 1 (42,067 km²) was the starting point for the analysis. Areas of non-forest vegetation were removed, reducing the available area to 22,122 km². Existing wilderness, off base (e.g. proposed wilderness additions), deferred (i.e. areas of special concern such as botanical areas), lakes, areas north of Highway 299, or in Blacks Mountain or Swain Mountain were excluded, which further reduced eligible area to 16,662 km². Vegetation cover density, as indicated by the leaf area index data, was the final factor in determining eligible areas that were thinned as described below.

Group or Individual Tree Selection thinning

To simulate the effect of thinning on vegetation density, we assumed that map cells selected for group (or individual tree) selection would have a post-treatment leaf area index of 2.0 or a basal area of 34.4 m²/ha (150 ft²/acre), composed primarily of large diameter trees. Sensitivity analyses showed results that were more sensitive to the thinning threshold than to the LAI to basal area conversion equation. The actual number of map cells meeting the criteria for group or individual tree selection was 3248.

Most of the 1-km map cells were likely to contain a mixture of various forest cover densities and non-forest conditions (roads, towns, clear-cuts etc). Thus map cells that are not thinned in our analysis (because their initial LAI is less than 2.0) could well include some forest stands that have a leaf area index greater than 2.0. These stands would be thinned if the spatial resolution of the data were finer. Thus our estimate of reduction in vegetation density is conservative and may underestimate the land area that would be thinned.

Defensible Fuel Profile Zones

To represent fire breaks, which are termed Defensible Fuel Profile Zones (DFPZ), we assumed forests along watershed boundaries (ridge lines) would be thinned to an LAI of 1.5 or a basal area of 27.5 m²/ha (120 ft²/acre) in a 100m-wide swath. Estimating the change in water yield for vegetation removal to create defensible fuel profile zones was a challenge, since the spatial scale associated with the DFPZ areas is smaller than the 1-km resolution used for the rest of the analysis. Instead of using finer spatial resolution, an empirical target basal area that generated approximately the same change in water yield was derived. The targets for thinning in DFPZ map cells were established as 31.3 m²/ha (equivalent LAI of 1.71) for low-energy SDP map cells, 31.5 m²/ha (equivalent LAI of 1.72) for higher-energy SDP map cells, and a LAI of 1.88 for RDP map cells. 3203 map cells were thinned using the DFPZ criteria.

Pre- and Post-thinning LAI distributions for treated map cells

Pre- and post-thinning leaf-area index distributions for thinned map cells are shown in Figure 3. The effect of the vegetation management scenario was to reduce vegetation density for all map cells with a leaf-area index value greater than 2.0 for group selection or 1.8 for DFPZ thinning. Thus, the post-thinning distribution shows increased frequencies in the LAI=2.0 and LAI=1.8 categories to reflect the reductions in higher LAI categories. The same assessment framework could be used to evaluate other treatment scenarios.

Managing the data (to condense the problem)

Focus on the map cells to be treated

Application of minimum LAI requirements reduced the total number of eligible map cells that were thinned to a total of 6451. Most (6304) were in snow-dominated process areas. There were 3991 low-energy SDP cells and 2313 higher-energy SDP cells that were eligible to be thinned. There were relatively few RDP map cells (147). All remaining map cells were excluded from consideration by the management plan, or had vegetative cover that fell below the thinning threshold. For all the excluded map cells, the change in water yield is zero, since no changes in vegetation (and corresponding evapotranspiration) occur between pre- and post-treatment conditions.

Cluster Analysis

To reduce the number of individual simulation runs and obtain a measure of likely variability of results, geographic multivariate cluster analysis (SAS Institute 1985) was used. The objective

was to group all eligible map cells with similar model input parameters. Rather than dividing the mountainous Quincy area geographically into contiguous sub-regions for simulation, we employed a purely statistical clustering of map cells based on the multivariate hydrologic characteristics of each cell (i.e., the input variables for the WRENSS model). The clusters that resulted were spatially disjoint, but were similar with regard to physical, hydrologic, forest, and thinning characteristics.

RDP cells underwent separate Principal Component Analysis (PCA), since RDP input variables included pre- and post-thinned LAI, and were thus different from SDP units. In addition, RDP units also have a relative root depth parameter that was considered. After orthogonal equamax axis rotation, scree plots of eigenvalues for both RDP and SDP clusters indicated that retention of three Principal Components was most appropriate.

Factor scores for each map cell were submitted to a clustering procedure (FASTCLUS, SAS Institute 1985) using the k-means algorithm (MacQueen 1967). Each of the six possible elevation/aspect combinations for SDP cells, and the RDP map cells were clustered separately, resulting in clusters that contained cells of only a single elevation/aspect class. To ensure uniform and comparable within-cluster hydrologic heterogeneity, the maximum radius for clusters in data space was specified rather than the explicit number of desired clusters. Thus, more hydrologically heterogeneous elevation/aspect combinations were divided into more clusters in a way that was driven by the data. Finally, all map cells were merged, and clusters were re-numbered by ascending elevation/aspect class. The end result was 586 SDP clusters and 56 RDP clusters.

Characterize the statistical properties of each cluster

The statistical characteristics (mean, standard deviation, maximum and minimum values for each input variable) for each cluster were determined from an analysis of the GIS data for all map cells within that cluster. These spatial statistics within each cluster provided the basis for generating input data files in the subsequent analysis.

Generate model input

Latin Hypercube Sampling

To preserve the spatial variability in hydrologic characteristics, we simulated water yield change for each cluster by using 100 independent WRENS simulation runs. We employed Latin Hypercube (LH) sampling (Iman and Helton 1985), to construct WRENS input data sets based on the statistical characteristics previously defined for each cluster. LH sampling divides the range of each input parameter into equal probability class intervals and ensures that the entire range of each parameter will be well represented with fewer samples than random Monte Carlo simulations would require.

In addition, the type of frequency distribution for each variable was also specified. The PRISM program (Gardner and others 1983) created 100 different model input data sets (realizations) for

each cluster. This statistically representative distribution of input data sets allows calculation of a distribution of simulated hydrologic outputs. Rather than a single result, a mean and variance of simulated hydrologic response was produced for each cluster. Thus, all cells in each cluster have the same mean and variance for the simulated change in water yield. Parameters that were allowed to vary among input data sets included seasonal precipitation, pre- and post-thinning vegetation cover (LAI or basal area), the parameter describing cover density when evapotranspiration reaches the potential value (SDP units only), and the rooting depth parameter (RDP units only).

A potential problem was identified during the course of doing the simulation studies. Each cluster has a pre-treatment and post-treatment distribution for leaf area index or basal area. However, if there is overlap between the distributions, it is possible for pre- and post- treatment values selected by the LH method to "cross over." This results in the highest leaf area index or basal area being assigned to the post-treatment input data set. Physically, the overlap represents a fraction of the map cell that would not be thinned because vegetative cover density is below the treatment threshold. We simply set the post-treatment value equal to the pre-treatment value for these situations.

Simulate the results

Multiple model runs

For each of the 495 SDP clusters, three different scenarios (average, wet and dry annual precipitation conditions) involving 100 simulations each were completed. For RDP clusters,

model results are not affected by varying precipitation amounts, so only the average annual precipitation case was simulated. Statistical properties (mean and variance) of the change in water yield were determined and saved for later export to the GIS data set. Simulations (163,200 individual model runs) took about five days of machine time on a 300 Mhz DEC Alpha workstation.

Summary of results: Change in water yield

We explored the potential changes in water yield (upper limits) that could result from complete implementation of the philosophy included in the Quincy Library Group Forest Recovery Act. This assumption narrows the focus to the effects of the vegetation manipulation, and eliminates the influence of annual variations in precipitation. We examined average, dry and wet years, and report the corresponding changes in water yield for those scenarios. The results are strongly dependent on the scale of the reporting unit. We have chosen to summarize results at three different scales:

- individual map cells,
- watersheds (California watersheds on the QLG Community Stability Proposal /Vestra map),
- USGS hydrologic units, (see the USGS web site at <http://water.usgs.gov/public/GIS/huc.html>).

Surprisingly, the original WRENSS model predicted a net loss in water yield for thinning on many SDP clusters. The model was originally developed from field results for clear-cutting experiments when experimental data for thinning only were not available. Subsequent studies

(e.g. Troendle 1987) indicate that thinning significantly reduces winter interception loss and may also reduce summer soil water depletion, at least in wet years. This result would argue that a net loss in water yield associated with thinning is unlikely. We assumed that in any season where the original model shows a net loss in water yield following thinning, the seasonal change in water yield is zero. This adjustment may underestimate actual gains, but is supported by current understanding (C.A. Troendle, personal communication 1999). Table 2 is a summary of simulated change in water yield for the various scales that were considered. The original model simulation results are shown, along with values that were modified to correct for the new information on thinning. The recompiled results are shown in the "Adjusted" column and are referred to hereafter as adjusted values. The net effect was to increase the mean water yield for the average treated cell by about 3.2 mm. Since negative values were removed, the range decreased and there was also a slight drop in the associated standard deviation. Although we believe the adjusted values best represent the change in water yield for the scenario presented, we also show the original model results to allow comparisons.

Individual cell (cluster) results

RDP map cell results show the largest changes in water yield as a result of thinning. For all cells that were treated, the overall uncorrected change in water yield was $+ 2.0 \pm 14.5$ mm for a year with average precipitation. The range across all treated cells was -15.4 to $+ 165.6$ mm. After adjusting the negative seasonal values to zero, the mean response was $+5.2 \pm 13.7$ mm and the values ranged from 0.0 to 165.6 mm. Similar changes occurred when the cells were subdivided into the three dominant types of WRENSS units (SDP low energy, SDP intermediate to high

**Table 2. Summary of Annual Change in Water Yield for Average Conditions
(for cells, watersheds and hydrologic units).**

Where a single range is given, all ranges are the same.

Description	Number of units	Original model			Adjusted Model (non-negative change in seasonal water yield)	
		Type Year	Mean change (± standard deviation) (mm)	Range (mm)	Mean change (± standard deviation) (mm)	Range (mm)
All thinned cells	6451	Dry	1.60 ± 14.35	-14.4 to 165.6	4.6 ± 13.6	0.0 to 165.6
		Average	1.99 ± 14.48	-15.4 to 165.6	5.2 ± 13.7	
		Wet	2.08 ± 14.62	-16.4 to 165.6	5.5 ± 13.7	
SDP low energy cells	3991	Dry	-1.37 ± 0.14	-13.7 to 6.9	2.89 ± 0.11	0.0 to 7.63
		Average	-1.19 ± 0.16	-15.4 to 6.9	3.40 ± 0.14	0.0 to 7.67
		Wet	-1.34 ± 0.17	-16.4 to 7.0	3.62 ± 0.15	0.0 to 7.67
SDP higher Energy cells	2313	Dry	1.54 ± 0.15	-4.9 to 6.9	2.54 ± 0.14	0.0 to 6.91
		Average	2.31 ± 0.19	-4.9 to 7.8	3.30 ± 0.18	0.0 to 7.85
		Wet	2.84 ± 0.21	-4.9 to 8.2	3.84 ± 0.20	0.0 to 8.57
RDP cells	147	All	83.0 ± 1.01	11.1 to 165.6	83.0 ± 1.01	11.1 to 165.6
Thinned California Watersheds (cells)	16973	Dry	0.61 ± 0.04	-14.4 to 165.6	1.74 ± 0.03	0.0 to 165.6
		Average	0.75 ± 0.05	-15.4 to 165.6	1.97 ± 0.04	
		Wet	0.79 ± 0.05	-16.4 to 165.6	2.09 ± 0.05	
Thinned Hydrologic Units (cells)	46969	Dry	0.22 ± 0.015	-14.4 to 165.6	0.63 ± 0.012	0.0 to 165.6
		Average	0.27 ± 0.017	-15.4 to 165.6	0.71 ± 0.015	
		Wet	0.28 ± 0.018	-16.4 to 165.6	0.76 ± 0.012	
Larger Water Accounting Units						
Thinned California Watersheds	429	Dry	0.82 ± 3.60	-5.2 to 33.9	2.10 ± 3.30	0.0 to 34.4
		Average	1.01 ± 3.66	-5.3 to 34.2	2.37 ± 3.36	0.0 to 34.6
		Wet	1.07 ± 3.77	-5.8 to 34.4	2.53 ± 3.41	0.0 to 34.9
Thinned Hydrologic Units	15	Dry	0.46 ± 0.68	-0.11 to 1.95	0.98 ± 1.03	0.001 to 3.35
		Average	0.54 ± 0.72	-0.09 to 2.07	1.09 ± 1.11	0.002 to 3.56
		Wet	0.56 ± 0.72	-0.10 to 2.06	1.15 ± 1.15	0.002 to 3.65

energy and RDP). There is a clear progression of increasing yield as one moves to situations where more energy is available for evapotranspiration (Table 2). Frequency distributions, showing the number of cells associated with different annual change in water yield values (Figure 4), provides insight on the cell results presented in Table 2. The adjusted SDP map cell values generally range from 0 to 7 mm, with a mean of about 3.4 mm. Note that about half of all treated SDP map cells show no change in annual water yield. The other half show an increase mostly between 6 and 8 mm. The RDP cells show a range for change in water yield between 11 and 166 mm, with a mean value of about 83 mm. Even though RDP map cells represent only about 2% of all thinned areas, they contribute nearly one third of the average change in water yield across all treated map cells (Table 2).

Statistical summary of basic results (adjusted values)

Spatial aggregation of results

Figure 5 shows a map of adjusted water-yield changes by individual map cell for the entire study area. The patterns suggest that DFPZ cells along watershed boundaries were responsible for most of the change in water yield. The cells from the middle of the watershed units (group and individual tree selection cells) mostly showed no change in water yield for the example scenario. Based on a combination of Figures 4 and 5, it appears that the group selection map cells generally contribute zero change in water yield and the DFPZ map cells contribute the positive changes. This result clearly suggests that the threshold for positive change in water yield for SDP units is between LAI (and associated basal area) values of about 1.8 and 2.

Aggregation to California watershed scale

As the area increases, the mean change in water yield diminishes. All California watersheds where at least one cell within the basin was thinned (429 watersheds out of 936 in the study area) were considered. There are two ways to calculate statistics for these units: area-weighted values for all cells, and “even-weighted” values by aggregated watershed. In the top portion of Table 2, the mean area-weighted adjusted change in water yield in a typical map cell (for all California watersheds) was calculated by summing values for all cells in the area and dividing by the total number of cells. To determine the standard deviation for the area-weighted change in water yield, we used a weighting factor (N_c/N_w), where N_c is the number of treated cells in a cluster and N_w is the total number of cells in all watersheds; the variance for each cell in the cluster; and a covariance term, which reduces to zero if the variances are uncorrelated (e.g. Snedecor and Cochran 1982). We have assumed that the clustering process renders the cells in each cluster essentially independent from cells in other clusters. Thus, we obtain the area-weighted variance as the sum of the product of the square of the weighting factor and variance over all clusters in the watershed. The standard deviation is shown in Table 2. The area-weighted values correspond to the average cell within the entire extent of all treated watershed areas (16,973 cells). For this analysis, the adjusted change in annual water yield was 1.97 ± 0.04 mm, with a range from 0 to 34.6 mm between the lowest and highest watershed. In the lower portion of Table 2, the even-weighted values by watershed are given. They represent the mean and standard deviation of the 429 individual watershed area-weighted values. The mean value for an average precipitation year was 2.37 ± 3.30 mm. This latter value represents the typical variability among individual watersheds. The spatial distribution of water-yield changes in the

study area is shown in Figure 6. The associated frequency distribution of change in water yield for the 429 watersheds that contained at least one thinned map cell is shown in Figure 7.

Hydrologic Units

Fifteen U.S. Geological Survey hydrologic units (HUCs) contained at least one treated cell. The average (area-weighted) change in water yield for a typical cell within the full area of all 15 units (46,969 cells) was 0.71 ± 0.015 mm, with a range between 0 and +3.56 mm. The even-weighted mean and standard deviation for the 15 hydrologic units (average size was 3130 cells) for an average year was 1.09 ± 1.11 mm. Note that we use the same assumptions as described for California watershed calculations to determine the error terms for typical cells in hydrologic units, except N_w becomes the number of cells in all 15 hydrologic units. The spatial distribution of water yield changes by USGS HUC is shown in Figure 8. Figure 9 displays the frequency distribution of water-yield changes for the 15 HUC areas that contained at least one map cell where forest thinning was simulated.

Evaluation

Magnitude of change in water yield

The results suggest that it will be extremely difficult to use conventional methods (e.g. streamflow measurement analyses) to quantify changes in water yield resulting from forest thinning. Average expected annual runoff is approximately 600 mm for the study area (Kattelman 1996). Even at the scale of a typical California watershed (~ 40 km²), the change in

annual water yield under the modeled scenario is only about 0.3% of the typical total runoff (Table 2). The range in values, however, indicates that individual areas could have significantly higher water yield compared to the average. Normal year to year variability that results from differing climatic conditions eclipses the increases in water yield simulated for the example scenario. Thus, the aggregation process, using area-weighted values, is an important aspect of the methodology because it allows estimation of changes in water yield that are smaller than could be detected by conventional flow measuring techniques.

Seasonal distribution of changes

To examine the seasonal timing of expected changes in water yield, two representative sets of cluster results (one SDP and one RDP) were compared. Both SDP categories were similar, so only one SDP example is shown. Figure 10 illustrates the seasonal distribution of adjusted net change in evapotranspiration for representative clusters from snow and rain dominated hydrologic regimes. Normalized values were obtained by taking the quotient of seasonal evapotranspiration and the annual total change. Similar normalized values of seasonal precipitation are shown.

In the SDP cluster (higher energy aspect; Figure 10), the most notable feature is that most (~70%) of the change in annual water yield (average value is $+8.0 \pm 3.2$ mm with a range between 0.1 to +12.9 mm) occurs during the summer season. Change in simulated seasonal water yield represents the difference between pre- and post-treatment evapotranspiration. During summer it is more indicative of soil moisture content, although the relationship between soil moisture and stream flow is complex and non-linear. A reduced summer soil-moisture deficit

probably indicates earlier onset of runoff in the following water year, rather than increased summer flows. This result suggests a useful target (soil moisture changes and/or summertime low flow) for field studies to evaluate thinning operations for SDP units.

There is a fairly uniform seasonal distribution of change in water yield for the RDP cluster (Figure 10). The selected cluster showed a net annual gain of 74.2 ± 3.7 mm in water yield between pre- and post-treatment conditions. The range was from 65.2 to 85.0 mm, with the largest seasonal contributor in spring, even though the most precipitation occurs in the winter season. RDP clusters represent a small fraction of all treated areas, but as indicated earlier their impact on change in water yield at the watershed scale is significant. If RDP areas are included in vegetation management plans, conventional measurements to estimate change in water yield may be feasible.

Implications for monitoring effect of vegetation management

Hydrologic issues

Perhaps the most striking facet of this analysis is the effect of increasing scale, where the importance of excluded areas on achievable water yield becomes obvious. Most studies of forest thinning are done at a small plot or watershed scale. This approach is necessary to accurately quantify the changes. However, as the size of the area increases, and smaller fractions of the landscape are actually treated, the overall effect becomes more difficult to measure directly. At some point, the natural variability in annual precipitation patterns, coupled with the reduced average effect of thinning, will eliminate the opportunity to directly measure the response using

stream flow. At that point, quantification must rely on aggregation of results from smaller, representative study areas.

The analysis also shows that the most dramatic simulated gains in water yield occur in the RDP areas. Even though there are relatively few of them, the RDP areas may represent areas where effects of thinning would be most easily measured.

Generality of the assessment framework

The methodology that was established for this evaluation is useful for structuring a systematic approach to a variety of issues. The example presented here illustrates that even a simplified scenario can yield useful insights for issues that involve a large area. The important contribution is in the framework and associated methods, rather than the specific example. The framework offers a powerful tool for future progress. It provides the opportunity to identify and assemble new spatial data sets and models for systematic evaluation of alternative management strategies.

The effects of large-scale vegetation management are difficult to evaluate, particularly when it is desirable to have multiple benefit targets (i.e. fuel reduction, bioenergy development, fire risk, water quality and quantity changes). The general approach embodied in the framework presented here can be useful for addressing a variety of questions systematically. It need not be confined to water-related issues. By substituting other models and other spatial data, a broad variety of issues can be addressed.

Finally, the spatially-explicit organization of information that is inherent in GIS data sets can provide a guide for gathering and organizing data. For example, reliability of change in water yield estimates could be improved with refined basal area information, as well as more explicit description of vegetation species. Thus the example analysis provides a guide for future data synthesis. An important part of this synthesis depends on the spatial resolution and models used in the analysis. Evaluation of effects of vegetation management on timing and water quality of stream flow will require more refined data and models. Development of massively parallel computer models that link the terrestrial and aquatic systems in a three-dimensional representation and also allow greater temporal resolution are a worthy goal for the future. In such a context, the application framework presented here has utility for designing and testing alternative forest management scenarios on the entire ecosystem before they are implemented.

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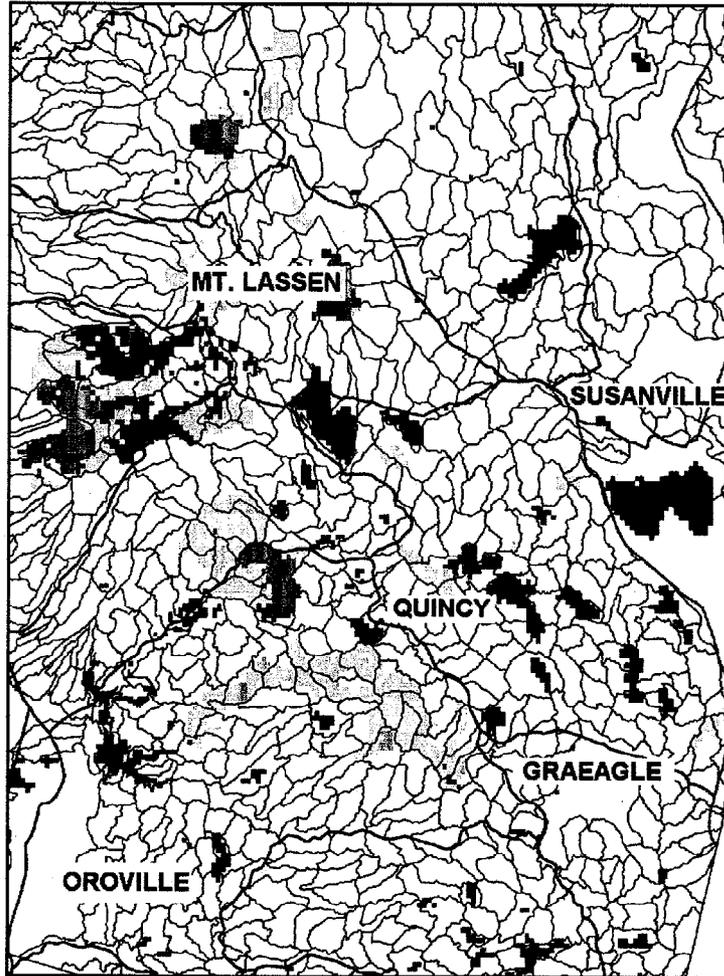
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FIGURE TITLES

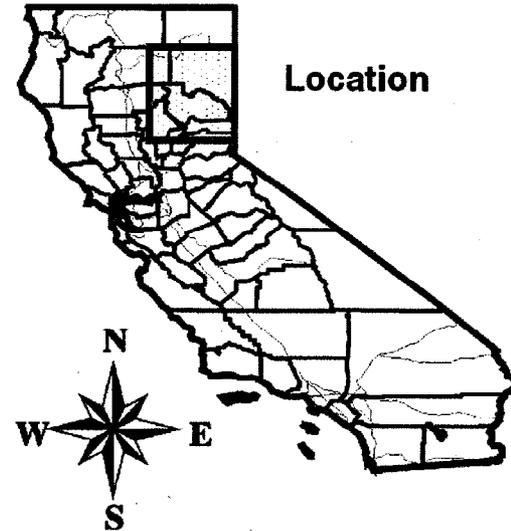
1. The study area evaluated for change in water yield as a result of forest thinning. Highlighted areas were excluded from consideration. California watersheds were used to aggregate area-weighted results.
2. Estimated maximum leaf-area index values within the study area. Map cell resolution is 1-km on a side.
3. The pre- and post-thinning leaf-area index distributions among all map cells that had simulated thinning.
4. The frequency distribution of change in water yield at the individual cell level for each hydrologic regime that was modeled. Nearly half of all cells that were thinned showed no change for average annual conditions.
5. The spatial distribution of change in water yields by individual map cell within the study area. The simulated defensible fuel profile zones (DFPZ), which were assumed to follow watershed boundaries, are clearly evident.
6. The spatial distribution of change in water yields by California watershed for average annual conditions. Only watersheds with at least one treated cell are shown.
7. The frequency distribution of water-yield changes by watershed for an average annual precipitation pattern.
8. The spatial distribution of water-yield changes by USGS HUC. All shaded areas had at least one treated cell within their boundary.
9. The frequency distribution of water-yield changes by USGS HUC for average annual conditions.

10. The seasonal precipitation and change in water yield distributions, expressed as the fraction of total annual change, for representative groups of cells for snow- and rain-dominated areas.

Water-Yield Evaluation Area



- Lakes
- Off Base
- Existing Wilderness
- Deferred
- California Watersheds
- Y Roads and Highways

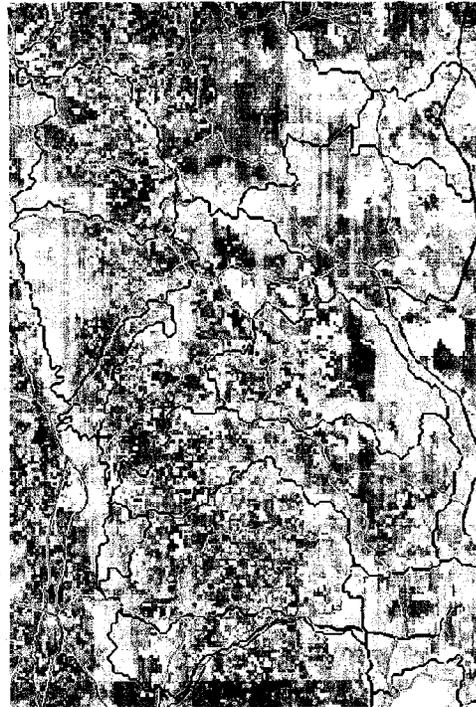
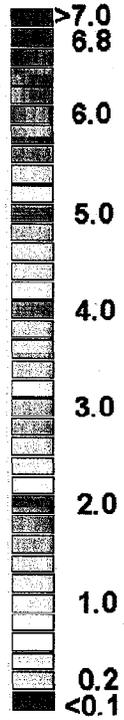


Huff and others

Assessing Change in Water Yield

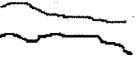
Figure 1

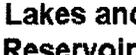
Leaf Area Index

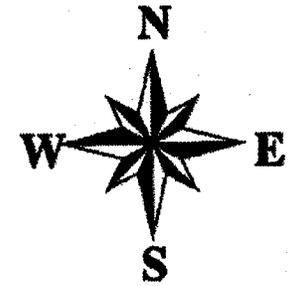


Legend

 USGS HUC Boundary

 Roads and Highways

 Lakes and Reservoirs

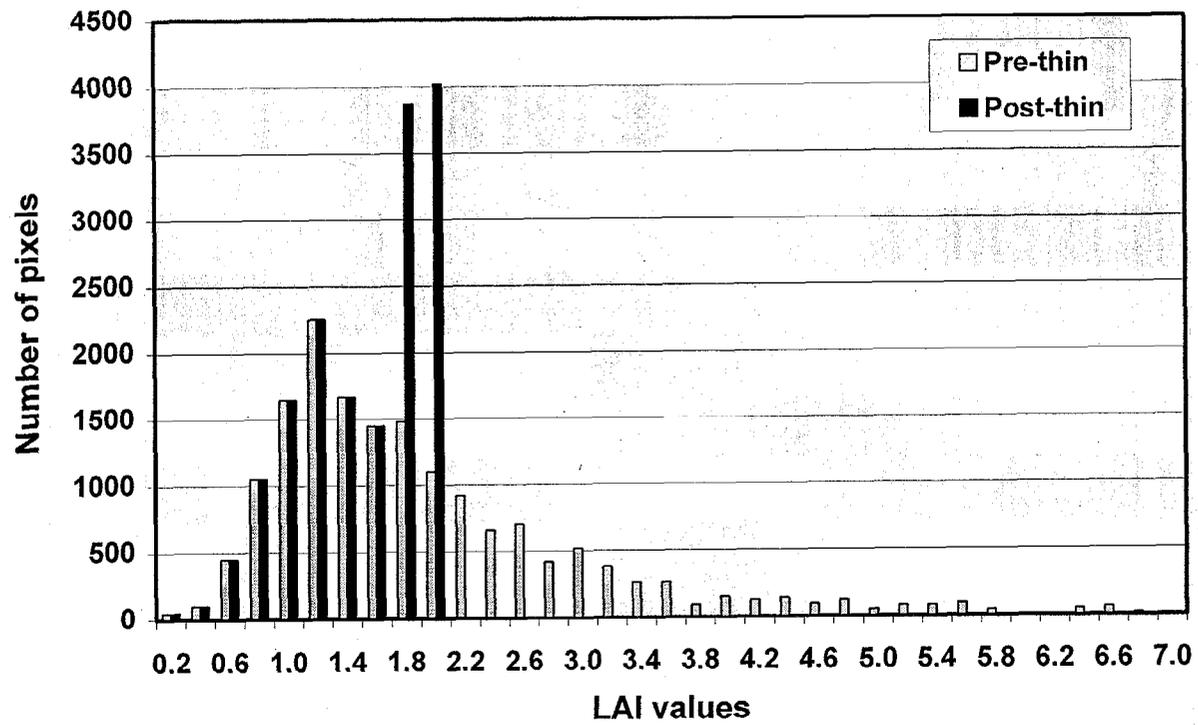


Huff and others

Assessing Change in Water Yield

Figure 2

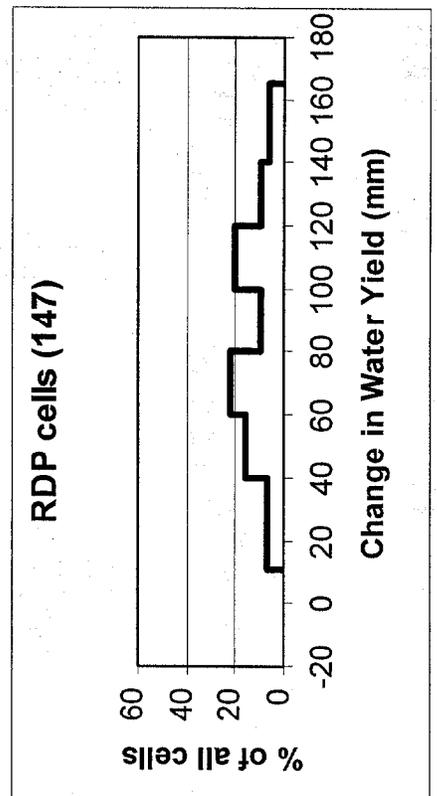
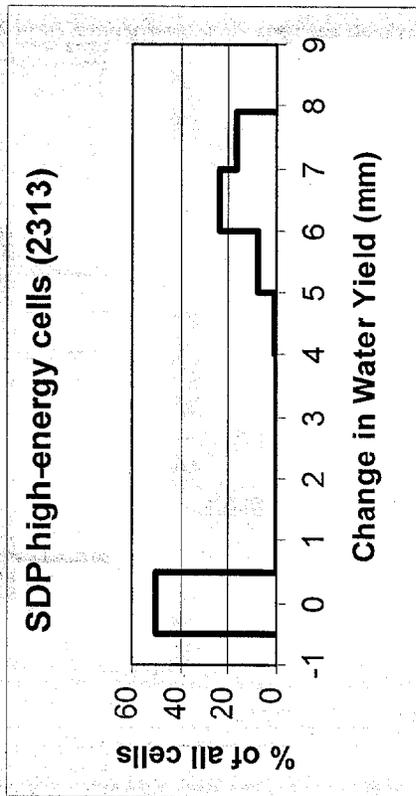
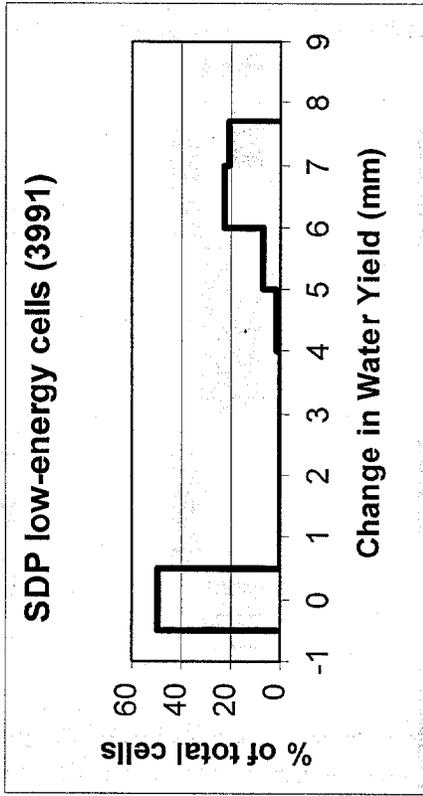
Pre- and Post-thinning LAI



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Assessing Change in Water Yield

Figure 3



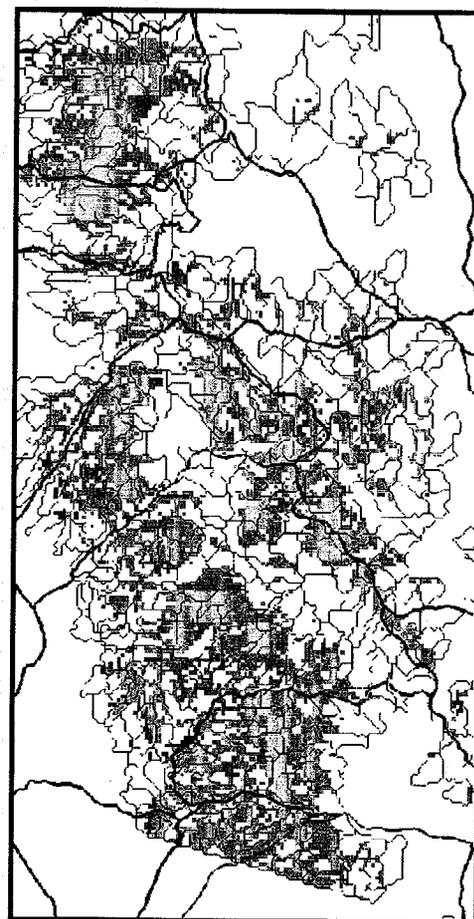
Huff and others

Assessing Change in Water Yield

Figure 4

**Change in Water Yield
by
1-km Cell
(Average Year)**

- Not thinned
- No change
- < 1 mm
- 1 to 4 mm
- 4 to 7 mm
- 7 to 10 mm
- 10 to 60 mm
- 60 to 150 mm
- > 150 mm



Kilometers
0 25 50



Location

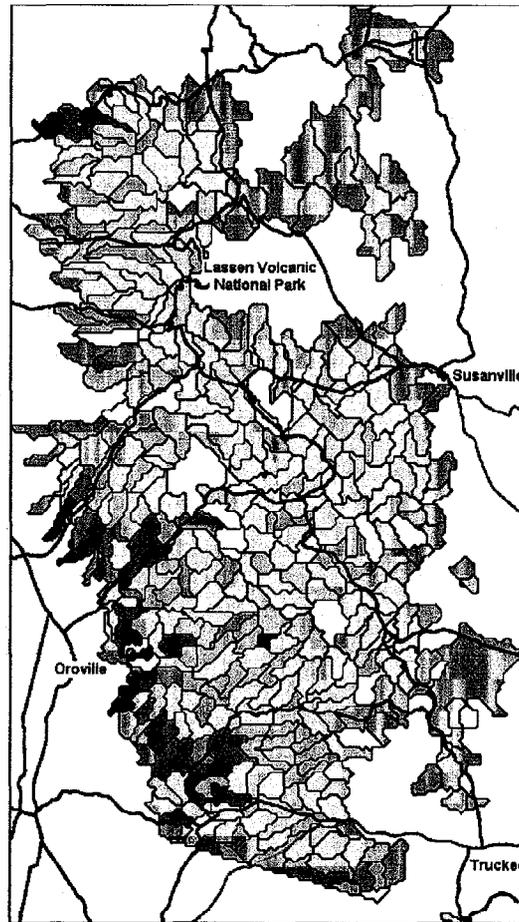
Huff and others

Assessing Change in Water Yield

Figure 5

**Change in Water Yield
by
California Watershed
(Average Year)**

- No change
- 0.01 to 0.50 mm
- 0.51 to 1.00 mm
- 1.01 to 1.50 mm
- 1.51 to 2.00 mm
- 2.01 to 2.50 mm
- 2.51 to 3.00 mm
- 3.01 to 3.50 mm
- 3.51 to 4.00 mm
- 4.01 to 4.50 mm
- 4.51 to 5.00 mm
- 5.01 to 10.00 mm
- 10.01 to 15.00 mm
- 15.01 to 20.00 mm
- > 20 mm



Kilometers

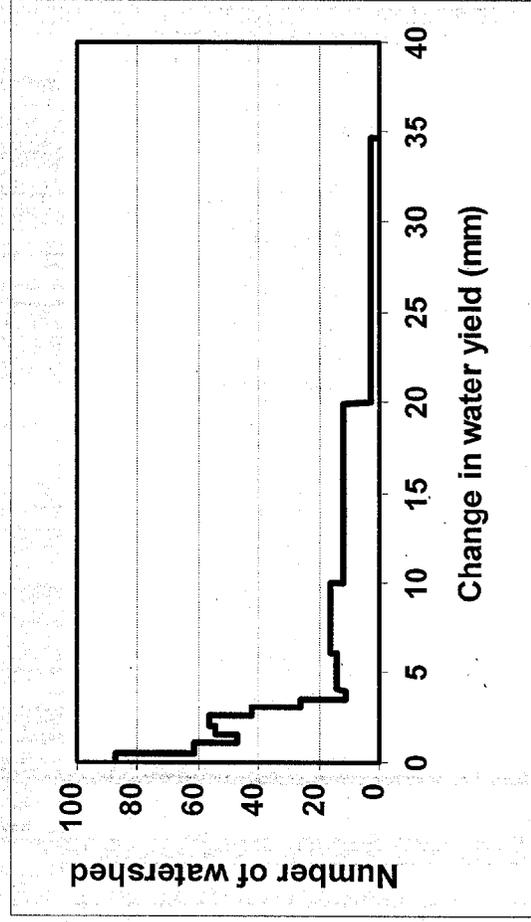
0 25 50



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Assessing Change in Water Yield

Figure 6



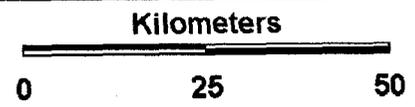
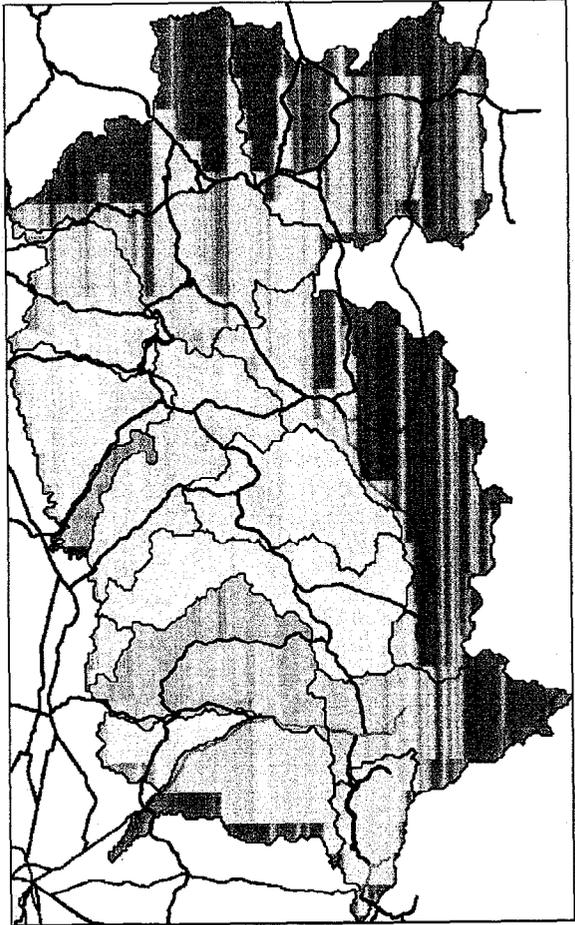
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Assessing Change in Water Yield

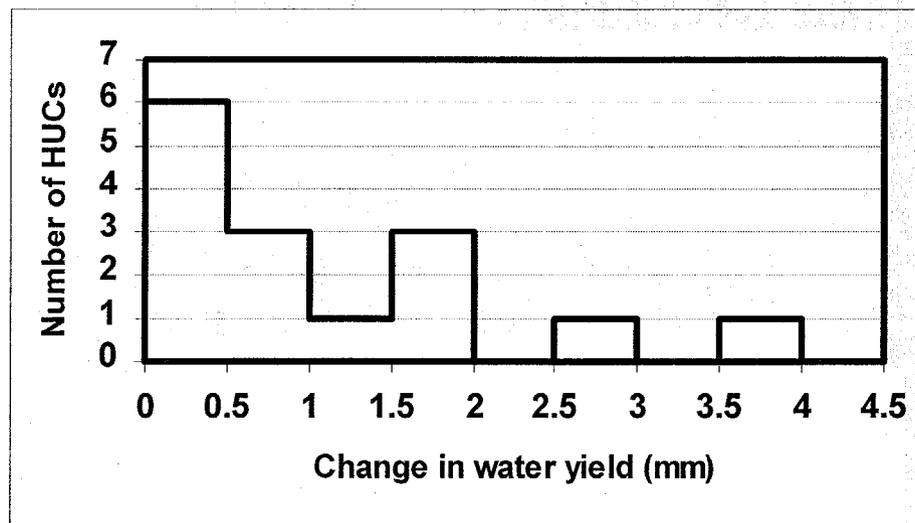
Figure 7

Change in Water Yield by USGS HUC

- No change
- 0.01 to 0.50 mm
- 0.51 to 1.00 mm
- 1.01 to 1.50 mm
- 1.51 to 2.00 mm
- 2.01 to 2.50 mm
- 2.51 to 3.00 mm
- 3.01 to 3.50 mm
- 3.51 to 4.00 mm



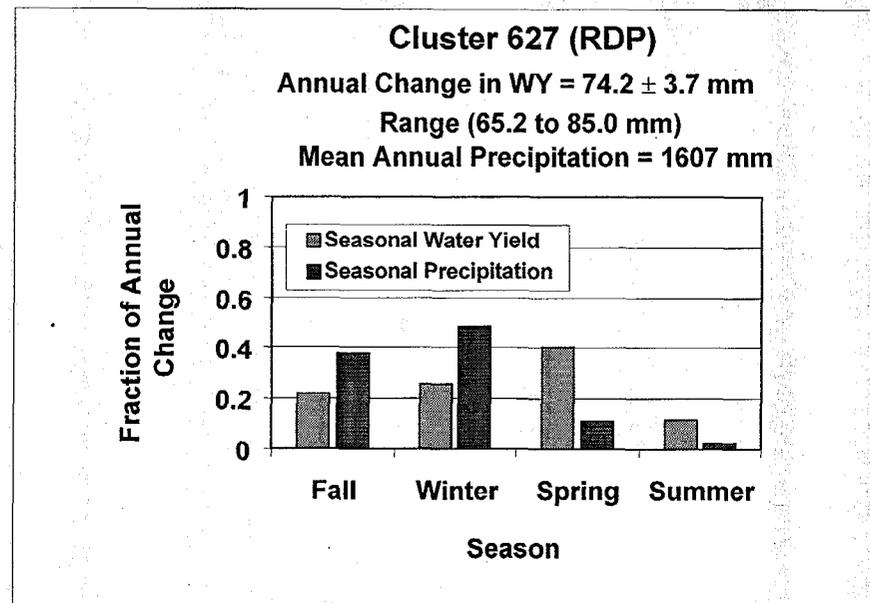
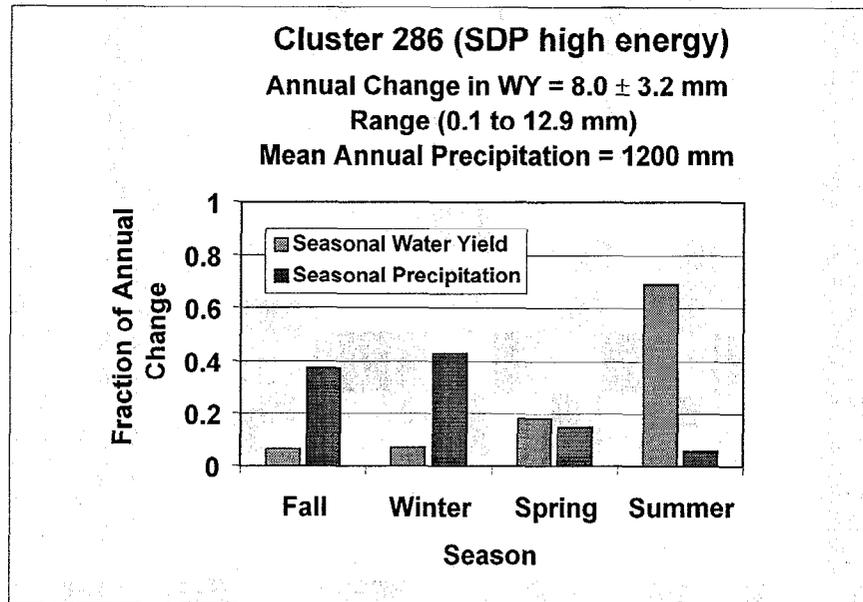
Huff and others
Assessing Change in Water Yield
Figure 8



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Assessing Change in Water Yield

Figure 9



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Assessing Change in Water Yield

Figure 10