Managing Forests for Water Yield: The Importance of Scale

Examination of expected change in water yield for a large area where vegetation thinning has been proposed in the Sierra Mountains of California, indicates that the size of the area has an important bearing on annual runoff. Results indicate that average changes in annual runoff per unit area for large areas would typically be less than 0.4%. Such changes can only be quantified by extrapolation of paired watershed studies because direct measurement is not feasible.

(KEY TERMS: Forest Hydrology; GIS; WRENSS; water yield; modeling, simulation.)

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Management of forest vegetation and it's relationship to water yield has become a lively issue. The U.S. Forest Service has come under attack in northern Colorado for failing to have a forest management strategy that includes consideration of water yield for downstream users, including fish and wildlife (Swanson, 1998). Some claim it is possible to get substantial increases in runoff with modest vegetation management, while others say that even aggressive vegetation removal is likely to have only localized effects. We've examined one aspect of the issue, quantity of the change in annual runoff in response to forest thinning, for a large portion of the Sierra Nevada Mountains in central California. The area that was studied is shown in Figure 1.

Water-yield estimates.

We've used the WRENSS (Water Resources Evaluation of Non-Point Silvicultural Sources) methodology (U.S. EPA, 1980) for assessing the water-yield impact of changes

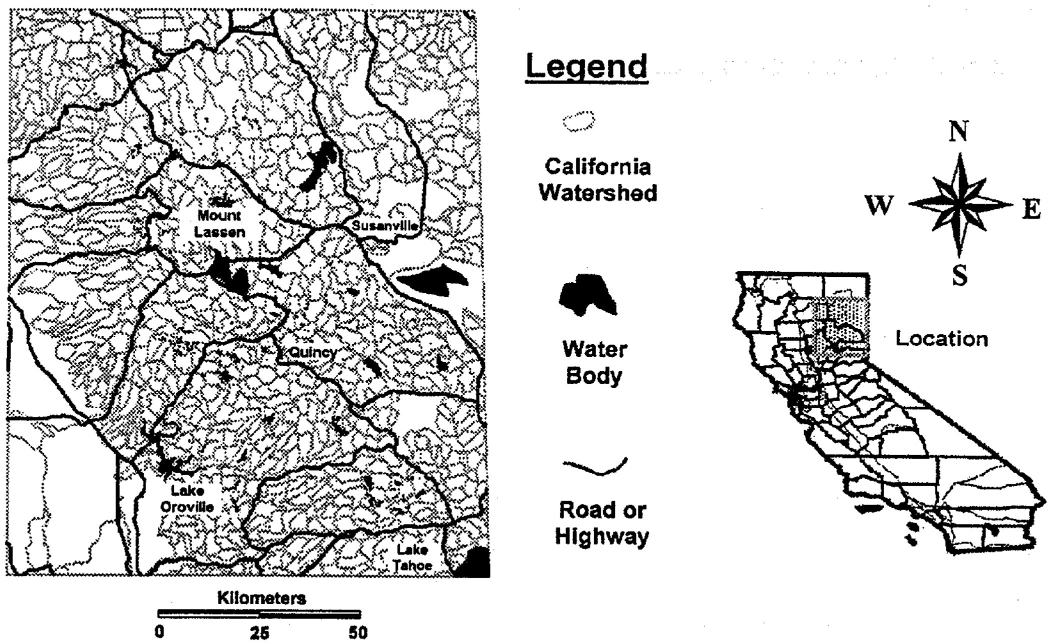

Figure 1. The study area in California used to explore effects of vegetation thinning for fire control on water yield.

in vegetation cover from thinning or clearing (e.g. Swanson, 1998, Troendle 1979). Briefly, WRENSS is a methodology for estimating annual evaporative losses. It includes field-derived relationships between seasonal precipitation, physical characteristics of a watershed (such as slope, aspect and elevation), vegetation cover density and vegetation rooting depth. The hydrologic component of WRENSS is designed to compare pre- and post-treatment vegetation conditions and estimate the change in water yield for both snow-dominated and rain-dominated areas. WRENSS is available as an executable computer program (e.g. Swanson, 1998) and also in the form of FORTRAN source code

(Huff and others, 1999). We adjusted original model results to incorporate information on the effects of thinning on water yield (Troendle, 1987). The sequence of WRENSS hydrology model calculations is shown in Figure 2. The water-use modifier factors (Figure 2) relate vegetation cover density and the ratio of actual and maximum or baseline (fully forested) evapotranspiration. The modifier coefficients were derived from calibrated models when the WRENSS methodology was developed (U.S. EPA, 1980). Elements above the horizontal dashed line in Figure 2 represent inputs, while model outputs occur below the line.

Effects of vegetation management on water yield.

To examine the effect of large-scale vegetation management policies on runoff, we identified thinning levels for fire-break construction and general fuel removal from overstocked coniferous forests and modeled the change in water yield between current conditions and a hypothetical end point that represents a sustainable forest condition.

The objective was to examine the maximum likely change in water yield that could be achieved from a large-scale thinning operation aimed at fire resilience, biofuel production and sustainable generation of other forest products. We were particularly interested in examining the relationship between size of area treated and water-yield production.

For our analysis, we assumed a scenario that included a large study area (> 40,000 km^2) containing both public and private forests. The area also included areas with inherent restrictions on forest thinning (e.g. National Park land, wilderness areas, special habitat areas and areas set aside as wild and scenic river buffer zones) in addition to several large

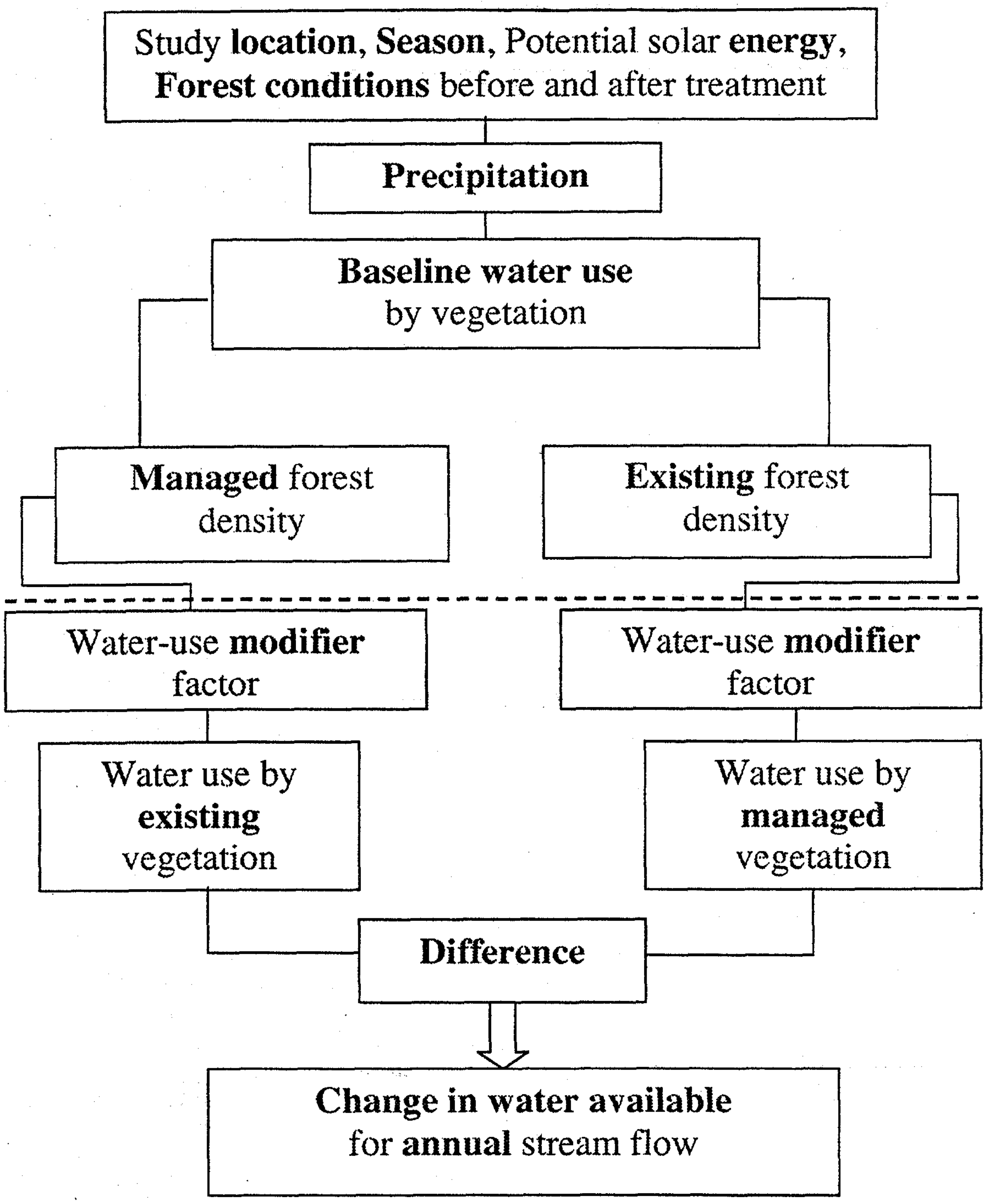

Figure 2. The sequence of WRENSS hydrology model calculations.

lakes and reservoirs. Such areas are typical of most extensive forests, and represent practical constraints to the amount of clearing or thinning that is possible. In addition, areas where the vegetation density is low (e.g. developed areas, range and farm land or tundra) will not support further vegetation clearing, so the areas considered eligible for clearing were required to be forested and have vegetation density greater than a set threshold (see next paragraph). As our primary measure of vegetation density, we used the leaf-area index (LAI), which is the total (one-sided) leaf area (m^2) within a 1-m^2 column area, projected from the ground surface to the top of the tree canopy. We developed a map of LAI values for each 1-km^2 cell within the study area and stored the information in a geographic information system (GIS) data table. This allowed us to use the vegetation information, together with rules for when and how much to thin, to develop the necessary data to simulate pre- and post-treatment conditions for determining the corresponding change in water yield. We also grouped similar cells into classes, to reduce the number of computations needed.

For the study area (shown previously in Figure 1), imposing the constraints to exclude areas set aside and protected, together with non-forested land, reduced the total eligible area for thinning to 16,662 km^2 (i.e. over 60% of the area was ineligible for consideration). Application of minimum LAI requirements (LAI $\geq$1.8) further reduced simulated thinning operations to only 6451 km^2 (only a little over 15% of the original study area). The area-weighted LAI for treated cells dropped from 3.2 to 1.9 as a result of simulated thinning. For each treated 1-km^2 cell, the simulated change in annual water yield for average climatic conditions and our thinning scenario ranged between 0.0 and

165.6 mm. We determined the mean and standard deviation for each group or class of cells by analyzing results of repeated runs of the WRENSS program, where we allowed the model parameters to vary according to their distributions among all cells in the class. For all thinned cells, the mean and standard deviations were 5.2 mm and 13.7 mm respectively. For comparison, typical total annual runoff in the study area is about 600 mm.

Aggregation of cell results to the watershed scale

Because only about 15% of the region's area is likely to be treated, it is important to aggregate the effects of thinning a patchwork of individual map cells to the watershed scale. For example, Figure 3 shows an idealized watershed where there are 40 individual 1-km^2 map cells. There are four different classes of cells, where each class represents a set of cells with statistically similar, but not identical, properties. The statistical

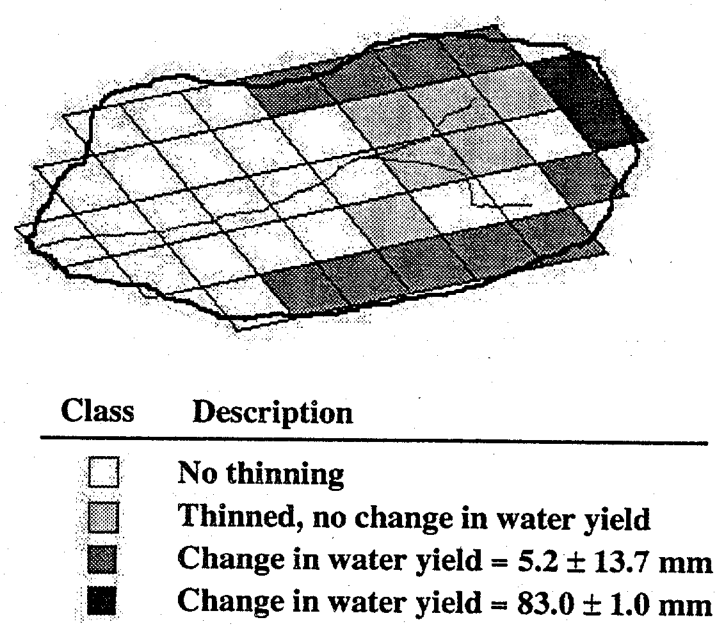

Figure 3. Idealized representation of a watershed with 40 individual cells and 4 different classes of treatment effects. The shading indicates each of the classes of cells.

grouping process (cluster analysis) renders the classes essentially independent of one another. Furthermore, each class of cells has a distribution of properties that can be used with a simulation model to produce a range of values of estimated change in water yield. This range in values represents the spatial variability among cells, and can be used to determine a mean and variance for water yield within each class of cells. Even though the example illustrated in Figure 3 suggests spatial continuity for cells within a class, it is not required by the analysis procedure. In general, cells in a given class are not necessarily adjacent; they simply have similar properties (e.g. precipitation, slope, aspect, LAI and rooting depth). For the class of cells with no thinning (excluded from treatment because of administrative policy or because vegetation density was too sparse), there is no change in water yield. These 22 cells are unshaded in Figure 3. The second class of cells includes those that were thinned, but had a small enough change in vegetation density that there was no simulated change in water yield. The lightest shading represents these six cells in Figure 3. The third class of cells includes areas where, for this example, we assume a mean change in annual water yield of 5.2 mm and a standard deviation of 13.7 mm. The standard deviation is a measure of the spatial variability in annual water yield within a class of cells. The fourth class (two cells in our example) was assumed to have a mean change in annual water yield of 83.0 mm and a standard deviation of 1.0 mm.

For the idealized watershed in Figure 3, the area-weighted mean value for change in water yield (Snedecor and Cochran, 1980) is:

$$\overline{x}_w = \sum_{i=1}^{N_w} \lambda_i x_i$$

where

$\overline{x_w}$ is the weighted mean change in water yield for the watershed

λi is the weighting factor for class i

x_i is the mean change in water yield for class i

N_w is the total number of cells in the watershed

and

$$\lambda_i = \left(\frac{N_i}{N_w} \right)$$

where N_i is the number of cells in class i.

For the variance in change in water yield for the watershed

$$\sigma_w^2 = \sum_{i=1}^{N_w} \lambda_i^2 \sigma_i^2 + 2\sum_{i=1}^{N_w} \sum_{j>i}^{N_w} \lambda_i \lambda_j Cov(x_i, x_j)$$

where

σ_w is the standard deviation of change in water yield for the watershed , σ_i is the standard deviation of change in water yield for the cells in class i, j is all integers from i+1 to N_w for any value of i, $Cov(x_i, x_j)$ is the covariance between x_i and x_j and the other terms are as previously defined.

This becomes

$$\sigma_w^2 = \sum_{i=1}^{N_w} \lambda_i^2 \sigma_i^2$$

when we assume the covariance terms are zero because the analysis renders the classes independent of one another, as previously noted. The result of applying this aggregation process for our idealized example case is summarized in Table 1.

Table 1. Summary of example calculations for determining area-weighted mean and variance of change in water yield (mm) for a watershed from individual cell values.

Cluster Number i	Mean Change (x_i)	Standard Deviation (σ_i)	Number of Cells (N_i)	λ_i	Contribution to σ_w^2
1	0.0	0.0	22	0.55	0.0
2	0.0	0.0	6	0.15	0.0
3	5.2	13.7	10	0.25	11.73
4	83.0	1.0	2	0.05	0.0025
Watershed Summary	5.45	3.42	40	1.00	11.73

The area-weighted watershed change in water yield from our idealized scenario is thus 5.45 ± 3.42 mm. This example illustrates some of the things we saw in the more comprehensive analysis of the study area. Most cells (85% of the area) had no change in water yield because they were not thinned. Some cells that were thinned still exhibited no simulated change in water yield. Many cells showed a modest change in annual water yield from thinning, and a few cells with large changes made a significant contribution to the overall change in water yield for the aggregated watershed area. The example shown here is representative of typical small watersheds, as defined by the State of California, in the study area (see Fig. 1). The average size of a small watershed in our study area is about 40-km^2 over all watersheds that were treated (429 total).

To represent all treated watersheds in the study area, there were two ways of aggregating results. One method is to calculate simple statistics for the population of mean change in annual water yield for all 429 affected watersheds. This approach applies uniform weighting to all watersheds, regardless of size. This number is useful as a means for characterizing the typical small basin, but does not accurately estimate the mean and standard deviation for the larger area. The alternate approach is to expand the size of the area considered and use the same cell-based approach illustrated in Table 1. We think this is a more appropriate way of aggregating cumulative changes in water yield for larger areas. Using the cell-based area-weighted approach for the study area, our scenario produced 5.2 ± 13.7 mm change in water yield for each treated 1-km^2 map cell, 1.97 ± 0.04 mm over the 16,973-km^2 area represented by small watersheds that had at least one treated cell, and 0.71 ± 0.015 mm for major hydrologic unit code (HUC) watersheds (e.g. HUC 18020121 is the North Fork Feather River in California). Although the change in water yield per unit area decreases as the size of the area increases, the actual volume of water produced (product of area and runoff per unit area) will increase. For example, the annual volume of water produced from the aggregated area of all watersheds that had at least one thinned cell in our scenario would be in excess of 33 million cubic meters. This results from vegetation removal if the stable end point (assumed for the thinning) could be maintained and is less than 0.4% of expected total annual runoff volume. In reality, regrowth of thinned areas and the impracticality of fully implementing the scenario would reduce this upper limit estimate.

Conclusions

The bottom line of our study suggests that increases in runoff can be anticipated in association with the thinning included in planned vegetation management (e.g. the Herger-Feinstein Quincy Library Group Forest Recovery Act [Department of the Interior and Related Agencies Appropriations Act, Section 401, 1998]). As the treated area increases, total runoff volume will also increase. However, the change in yield relative to expected annual runoff is quite small. Even at the scale of a single treated 1-km^2 area, we would anticipate average increases in water yield of the order of 1%. Since the U.S. Geological Survey considers streamflow measurements within 5% of the actual value for 95% of the observations to be “excellent” and there is considerable annual variability in runoff, it should be obvious that the expected changes we project are unlikely to be measureable. This is not to say that in some local circumstances there will never be observable changes, simply that at the large scale, it will only be possible to estimate the effects of forest thinning on yield, but not to quantify them by direct measurement. This places added importance on the need for new, small-paired-watershed studies to quantify effects of thinning to allow improved extrapolation of water-yield estimates.

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