Forest Hydrology GIS

Managing Forests for WATER Yield

The Importance of Scale

Examination of expected changes 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. At the smallest scales, some treated areas may have easily measured changes in water yield, with the potential for impacts on aquatic biota and water quality. The average changes in annual runoff per unit area for large tracts, however, are too small to be measured directly and thus must be quantified by using models to extrapolate existing knowledge.

By Dale D. Huff,
Bill Hargrove, M. Lynn Tharp,
and Robin Graham

Management of forest vegetation and its relationship to water yield has long been a lively issue. The USDA Forest Service has been criticized 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 say it is possible to get substantial increases in runoff with modest vegetation management; others contend that even aggressive vegetation removal is likely to have only localized effects. An excellent historical review of this subject is available (Ziemer 1986) and is recommended reading.

The Santiago Agreement, which addresses criteria and indicators for sustainable management of forests ("Sustaining the World's Forests," 1995), lists "enhancement of ability to predict impacts of human intervention on forests" as one indicator of progress. The work presented here attempts to build toward such an improved capability. We have 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 *(fig. 1)*. For the remainder of this article, the term *water yield* is understood to represent the annual cycle, unless otherwise stated.

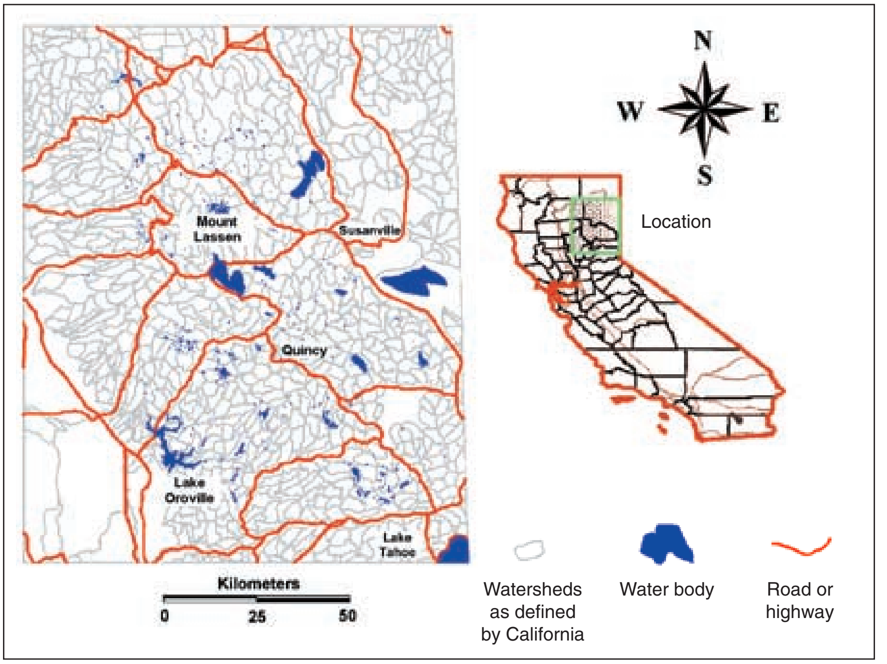

***Figure 1.* The study area in California used to explore effects of vegetation thinning for fire control on water yield.**

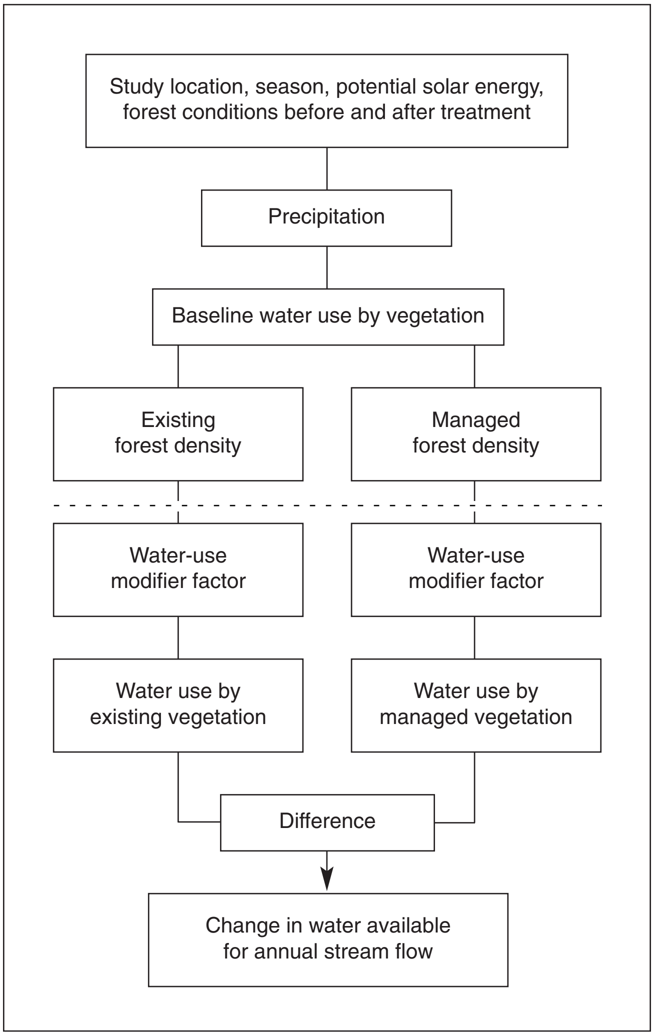

Figure 2. **Sequence of WRENSS hydrology model calculations.**

Water-Yield Estimates

Bosch and Hewlett (1982) analyzed data from 94 catchment experiments and reinforced Hibbert's earlier conclusion (1967) that water yield increases with reduction of forest cover. They suggest a generalization that conifer cover types can be expected to produce about a 40-millimeter change in annual water yield per 10 percent change in forest cover. However, they note that reductions in forest cover of less than 20 percent resulted in changes in water yield that were not detectable by measuring stream flow. Logic, they argue, dictates that somewhere between zero treatment and 20 percent cover reduction, the effect will be negligible, but the data are too sparse to allow more precise estimates.

We have used the Water Resources Evaluation of Nonpoint Silvicultural Sources (WRENSS) methodology (US EPA 1980) to assess the water-yield impact of changes in vegetation cover from thinning or clearing (e.g., Troendle 1979; Swanson 1998). 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 vegetation conditions before and after treatment 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 et al. 1999). We adjusted original model results by setting any negative changes in seasonal water yield to zero, based on the assumption that thinning will never reduce water yield (Troendle 1987). The sequence of WRENSS hydrology model calculations is shown in *figure 2.* The water-use modifier factors 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 (US EPA 1980). Elements above the horizontal dashed line in *figure 2* represent inputs; model outputs are below.

Effects of Vegetation Management

To examine the effect of large-scale vegetation management on runoff, we identified thinning levels for firebreak construction and general fuel removal from overstocked coniferous forests, then 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 increase.

For our analysis, we chose as a scenario a large study area (> 40,000 square kilometers). It was typical of most extensive forests in that it contained both public and private lands, several large lakes and reservoirs, and tracts subject to 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)—all practical constraints to the amount of clearing or thinning that is possible. In addition, because areas with low vegetation density (e.g., developed areas, range, farmland, or tundra) will not support further clearing, the areas considered eligible for thinning were required to be forested and have vegetation density greater than a set threshold. As our primary measure of vegetation density, we used the leaf-area index (LAI), which is the total (one-sided) leaf area per square meter within a 1-square-meter column area, projected from the ground surface to the top of the tree canopy.

We used NASA remote sensing data and a radiative transfer model of the canopy to derive a map of LAI values for each 1-square-kilometer 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 pretreatment and posttreatment conditions for determining the corresponding change in water yield. The thinning rules we applied were based on the Herger-Feinstein Quincy Library Group Forest Recovery Act (Quincy Library Group 1998) and assumed fire-resilient stands with an LAI of < 1.8 and firebreaks with an LAI of < 1.5. We also used multivariate cluster analysis to group similar cells into classes. This allowed us to reduce the number of necessary computations by a factor of 10.

For the study area, imposing the constraints to exclude setaside, protected, and nonforested land reduced the total eligible area for thinning to 16,662 square kilometers (more than 60 percent of the area was ineligible for consideration). Application of minimum LAI requirements for thinning (LAI ≥ 1.8, which is roughly a basal area of 135 square feet per acre) further reduced simulated thinning operations to only 6,451 square kilometers (a little over 15 percent of the entire 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-square-kilometer cell, the simulated change in annual water yield for average climatic conditions and our thinning scenario ranged between 0 and 165.6 millimeters. We determined the mean and standard deviation for each group or class of cells by analyzing results of 100 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 deviation was 5.2 and 13.7 millimeters, respectively. By comparison, typical total annual runoff in the study area is about 600 millimeters.

Aggregating the Cell Results

Because only about 15 percent of our area was likely to be treated, it was important to aggregate the effects of thinning a patchwork of individual map cells to the watershed scale. *Figure 3* illustrates the calculation method with a hypothetical example. It shows an idealized watershed containing 40 1-square-kilometer map cells. The example uses four classes

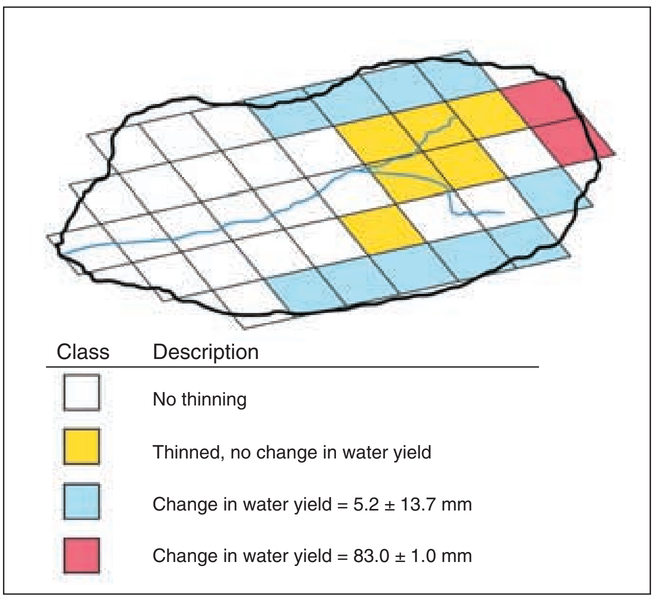

Figure 3. **Idealized representation of a watershed with 40 individual cells and four different classes of treatment effects. The shading indicates each of the classes of cells.**

of cells, where each class represents a set of cells with statistically similar but not identical properties. The statistical grouping process (cluster analysis) renders the classes essentially independent of one another. In general, cells in a given class (cluster) are not necessarily adjacent; they simply have similar properties (e.g., precipitation, slope, aspect, LAI, and rooting depth). 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.

For the class of cells with no thinning (excluded from treatment because of administrative policy or because vegetation density was too sparse), the example assumes there is no change in water yield. The second class of cells in the example is representative of minor thinning, where vegetation density was reduced less than 10 percent (general fuel removal). WRENSS calculated no change in water yield for these cells. The third class of cells in the example is typical of firebreak construction, where vegetation density was reduced about 35 percent on average. We used the mean and standard deviation for all thinned cells (5.2 ± 13.7 millimeters) to represent this category of cells. The fourth class of cells in the example is representative of thinning in rain-dominated areas, where vegetation density changes were about 35 percent, and WRENSS predicted an annual water yield of 83 millimeters and a standard deviation of 1 millimeter.

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

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

where $\bar{x}_w$ is the weighted mean change in water yield for the watershed, λ_i is the weighting factor for class i, x_i is the mean change in water yield for cell class i, N_w is the total number of cells in the watershed and

$$\lambda_i = \frac{N_i}{N_w}$$

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 statistical grouping process renders the classes independent

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.

Cell 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

of one another, as previously noted. The result of applying this aggregation process for our idealized example case is summarized in *table 1.*

The area-weighted watershed change in water yield from our idealized scenario is thus 5.45 ± 3.42 millimeters. This example illustrates some of the patterns we saw in the more comprehensive analysis of the study area. Most cells (85 percent 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. The example shown here is representative of typical small watersheds, as defined by California, in the study area. The average size of a small watershed in our study area is about 40 square kilometers over all watersheds that were treated (429 total).

To represent all treated watersheds in the study area, we can aggregate the results in two ways. 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 alternative 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 a 5.2 ± 13.7 millimeter change in water yield for each treated 1-square-kilometer map cell, 1.97 ± 0.04 millimeters over the 16,973-square-kilometer area represented by small watersheds that had at least one treated cell, and 0.71 ± 0.015 millimeters for major hydrologic unit code (HUC) watersheds (e.g., HUC 18020121 is the North Fork Feather River in California).

From those results, it is clear that as the size of the watershed increases, the fraction of the area treated tends to decrease. The change in water yield at the individual cell scale ranged from 0 to 166 millimeters. At the typical watershed scale (~40 square kilometers), change in water yield ranged between 0 and 34 millimeters. Finally, at the HUC scale, the change in water yield ranged between 0 and 4 millimeters.

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 increase in water volume results from vegetation removal if the stable end point (assumed for the thinning) can be maintained and is less than 0.4 percent 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

We have illustrated an approach and presented typical results from a single application over a large area. Grouping individual cells with similar characteristics and then executing the model repeatedly for each group is an effective way to obtain simulation results over a wide area. The approach allows for the preservation of a statistical distribution of individual cell input values within each grouping through the simulation, producing a statistical distribution of model results for each group. These statistical results can be recalculated for any scale of interest, from individual cells to watersheds to HUCs. This approach is general and can be used with other simulation models besides WRENSS.

There is considerable room for extension and refinement of the analyses. For example, use of a 1-square-kilometer cell size provides only a coarse definition of vegetation density and other basin characteristics that are important for detailed analyses. The WRENNS methodology is also limited by its reliance on empirical water-use factors that must be derived from water-yield experiment observations, which in turn are relatively sparse. Therefore, the absolute magnitude of the values obtained through this study are based on estimates that have considerable uncertainty. Even so, the general magnitude of the results and the patterns they exhibit are consistent with independent analyses by other investigators and should be useful as a guide to future research directions.

Our study suggests that increases in runoff can be anticipated in association with the thinning included in planned vegetation management. 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-square-kilometer area, we would anticipate average increases in water yield of the order of 1 percent. As the US Geological Survey considers stream-flow measurements within 5 percent of the actual value for 95 percent 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 measurable.

That is not to say that in some circumstances there will never be observable changes, but simply that at the large scale, the effects of forest thinning on yield can only be estimated, not quantified by direct measurement. At the smallest scales, some treated areas are likely to show easily measured changes in water yield, with the potential for impacts on aquatic biota and water quality. This emphasizes the need for new, small paired-watershed studies to quantify effects of thinning to allow improved extrapolation of water-yield estimates. Such new work in our study area could provide a basis for refining water-use coefficients in WRENSS, or perhaps allow calibration of other, more process-oriented models.

Literature Cited

BOSCH, J.M., and J.D. HEWLETT. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55:2–23.

HIBBERT, A.R. 1967. Forest treatment effects on water yield. In *International symposium on forest hydrology,* eds. W.E. Sopper and H.W. Lull. Oxford: Pergammon.

HUFF, D.D., W.W. HARGROVE, and R.L. GRAHAM. 1999. *Adaptation of WRENSS-Fortran-77 for a GIS Application for Water-Yield Changes, ORNL/TM-13747.* ESD Publication Number 4860. Oak Ridge, TN: Oak Ridge National Laboratory.

QUINCY LIBRARY GROUP. 1998. Department of the Interior and Related Agencies Appropriations Act, Section 401, 1998.

SNEDECOR, G.W., and W.G. COCHRAN. 1980. *Statistical methods.* 7th ed. Ames: Iowa State University Press.

SUSTAINING THE WORLD'S FORESTS: THE SANTIAGO AGREEMENT. 1995. *Journal of Forestry* 93(4):18–21.

SWANSON, R.H. 1998. Forest hydrology issues for the 21st century: A consultant's viewpoint. *Journal of the American Water Resources Association* 34(4):755–63.

TROENDLE, C.A. 1979. Hydrologic impacts of silvicultural activities. *Journal of the Irrigation and Drainage Division,* ASCE, 105(IR1):57–70.

———. 1987. *The potential effect of partial cutting and thinning on streamflow from the subalpine forest.* Research Paper RM-274. Fort Collins, CO: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station.

US ENVIRONMENTAL PROTECTION AGENCY (US EPA). 1980. *An approach to water resources evaluation of non-point silvicultural sources* (procedural handbook EPA-600/3-84-066). Environmental Protection Agency, Athens, GA: EPA Environmental Research Laboratory.

ZIEMER, R.R. 1986. Water yields from forests: An agnostic view. In *Proceedings of the California Watershed Management Conference,* eds. R.Z. Callahan and J.J. DeVries. Wildland Resources Center report 11. Berkeley: University of California.

Dale D. Huff (e-mail: ddhuff@esper.com) is consulting hydrologist, Bill Hargrove and M. Lynn Tharp are staff researchers, Computational Physics and Engineering Division, and Robin Graham is forest ecologist and head, Ecosystem and Plant Sciences Section, Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831. *Funding: Office of Fuels Development, Department of Energy Office of Energy Efficiency and Renewable Energy.*