EXTRAPOLATION OF WATER-YIELD IMPROVEMENT STUDIES ON UPLAND WATERSHEDS TO LARGER RIVER BASINS

Peter F. Ffolliott[1]

Extrapolation of the results from water-yield improvement studies to increase streamflow from on upland watersheds to larger river basins and then to downstream points of water use involves a series of sequential steps. Conditions on the upland watersheds from which results of the studies are extrapolated must be characterized in terms of the climatic, physiographic, vegetative, institutional, social, and economic conditions on the watersheds. Areas within the larger river basins that are not constrained by these conditions are then delineated relative to the possibility of implementing the results of the water-yield improvement studies. Increases in streamflow estimated from these treatable areas in the larger river basins are routed to downstream points of use in the temporal context of delivering the estimated increases in water supply to these points in the final step of the extrapolation process. While this extrapolation process has been followed in earlier analyses (Thorud 1974, Ffolliott and Thorud 1975), knowledge of the potentials for water-yield improvement is more comprehensive at this time (Baker 1999, Baker and Ffolliott 2000), and methodologies to implement the extrapolation process are more sophisticated.

CONDITIONS ON WATERSHEDS

Conditions of the upland watersheds studied must be summarized in terms of the climatic, physiographic, vegetative, and other relevant biophysical features and institutional and socioeconomic conditions to provide a basis for extrapolation of the results from these watersheds to the larger river basins. The watersheds are characterized by:

- Ownership status - responsible administrating agency on public lands.
- Climate (weather patterns) - season and annual precipitation amounts and distribution and temperature regimes.
- Vegetation - dominant plant communities including main tree overstory species and herbaceous plant species.
- Physiography - geologic formations, topographic features, and soil origin and properties.
- Other key features and conditions of importance to the extrapolation process.

This information can be obtained from relevant literature (Brown et al. 1974, Clary et al. 1974, Rich and Thompson 1974, Ffolliott and Thorud 1975, Hibbert 1979, Baker 1999, Baker and Ffolliott 2000), resource classifications, and inventory summaries. It can also be spatially displayed by GIS procedures to determine the proportions of the watersheds delineated by the identified conditions.

Studies to be extrapolated from the upland watersheds must also be comprehensively described in relation to the vegetative management practices implemented (clearing, thinning, conversion of tree overstories, etc.) and comparative benefits and costs that are associated with these management practices.

The results of these studies are "case studies" that represent points on a continuum of possible vegetative management practices. Intervening (missing) points on this continuum can be generated through appropriate simulation techniques.

TREATABLE AREAS ON RIVER BASINS

Vegetative communities on the upland watersheds studied and their respective distributions have been mapped on 15 river basins into which Arizona had been arbitrarily delineated (Figure 1) to illustrate the extrapolation procedure. Precipitation isohyets and land ownership patterns

---

[1] University of Arizona, Tucson

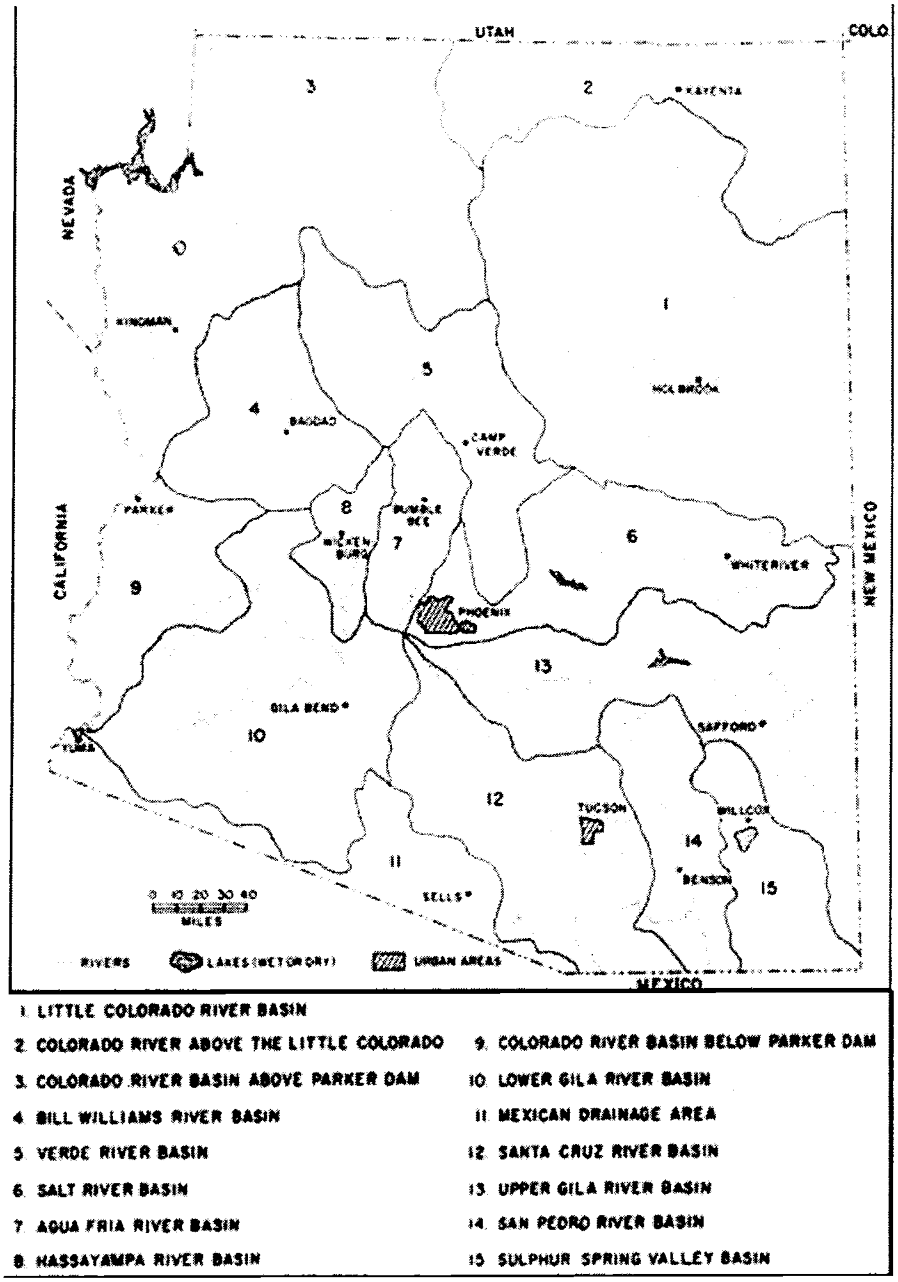

Figure 1. Major river basins in Arizona delineated to illustrate the extrapolation methodology (adapted from Ffolliott and Thorud 1975).

were superimposed on each vegetative community and the total acreage within each precipitation strata determined by ownership for each of the river basins. Following downward adjustments necessitated by constraints to the implementation of a vegetative management practice, the "potentially treatable areas" are combined with the estimates of increases in streamflow obtained from the upland watersheds. Other than ownership, these constraints include climate (weather), vegetation, physiography, vegetation, institutional, social, and economic limitations (Figure 2). Still other constraints are included in the extrapolation were necessary.

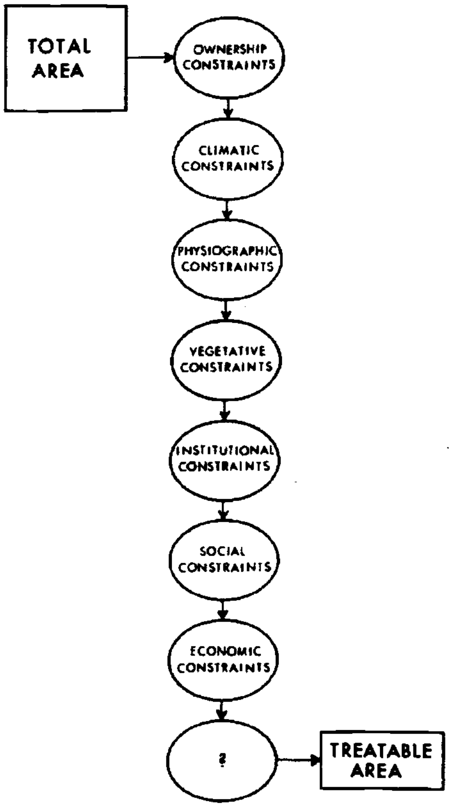

Figure 2. Land ownership, climatic, physiographic, vegetative, and other constraints to implementation of operational water-yield improvement treatments (adapted from Ffolliott and Thorud 1975). Additional constraints might be necessary in some river basins.

A few "caveats" are offered to show how some of these constraints can be evaluated in making the downward adjustments in total areas to obtain treatable areas in the river basins. An analysis by Hibbert (1979) indicated that vegetative management practices could increase streamflow only on areas receiving at least 18 inches of annual precipitation. Hibbert reasoned that annual precipitation amounts below 18 inches would be effectively used by residual tree overstories and increases in subsequent growth of herbaceous plants on the treated area. This finding alone suggested that in Arizona, high-elevation montane forests and portions of low-elevation chaparral communities have the "best theoretical potentials" for achieving water-yield improvement (Baker 1999, Baker and Ffolliott 2000).

A minimum density of trees is often specified by a watershed manager in deciding whether a prescribed vegetative management practice should be implemented on a treatable area. It is assumed in the extrapolation process that the proportion of the area that is stocked to a minimum density level corresponding to the density of the prescribed practice represents the proportion of the area that can be treated by this prescription (Ffolliott and Worley 1973). If this proportion is deemed too small for the prescribed vegetative management practice to effectively increase streamflow, the original prescription might be discarded in favor of one that places a larger proportion of the area under management.

Vegetative management practices can be implemented in the montane forests of Arizona to structure the tree overstories in a manner that "optimizes" snowpack accumulation-melt processes to (in turn) enhance the significant role that snowmelt-runoff plays in streamflow-generation in many of the river basins (Ffolliott and Baker 2000).

Studies of these management practices indicate that aspects representing cooler sites vis-a-vis warmer sites are crucial in planning of these management practices (Ffolliott et al. 1989, Baker 1999). More snow is retained throughout the winter season on the cooler sites than on warmer sites, and, as a consequence, more snow is available to increase the volume of snowmelt-runoff water in the spring. Knowledge of the proportions of cooler and warmer sites on a treatable area, therefore, helps in determining how to either synchronize or de-synchronize snowmelt-runoff regimes depending on the watershed management purpose.

ROUTING WATER DOWNSTREAM

It is not a purpose here to specify algorithms for routing water downstream among those that are available for this purpose. However, to illustrate this step in the extrapolation process, the method of routing streamflow from upland watersheds to downstream reservoirs that was used by Brown and Fogel (1987) in the Salt and Verde River Basins (see Figure 1) is outlined. Computer simulations "with" and "without" streamflow increments representing estimates of increases in streamflow from treatable areas in the river basins were superimposed onto the streamflow regimes in the Salt-River Basins such that the "with" minus the "without" case was assumed to represent the effect of vegetation management on water storage and routing in the river basins. A 10-year time horizon and one-month time step was selected by Brown and Fogel in these simulations that were made for a series of scenarios reflecting the timing of annual streamflow increases and the operating rules of downstream reservoirs. This procedure was repeated 100 times for each scenario with a set of unique random inputs for each of the scenario to obtain a probability distribution of the allocation for each account of streamflow.

Normal (pre-treatment) streamflow volumes into the reservoirs on the river basins were simulated with a lag-3 Markov model with 94 years of monthly data (1889-1982). This Markov model predicted streamflow for a selected time-period as a function of the predicted streamflow for the previous time period with historical streamflow and a random variable that required that streamflow within the time period be normally distributed about its mean. Logarithmic transformations of the streamflow data approximated a necessary normal distribution. Use of the lag-3 Markov model was an improvement over the more commonly used single-lag model that resulted in over-predictions in the wetter months and the lag 2-model. A 1,000-year test of the lag-3 Markov model indicated that the means of the logarithmic transformations of monthly predicted streamflow differed from the means of the logarithmic transformed historical streamflow by 2 percent or less.

Monthly estimates of increases in streamflow were added to the estimates of normal streamflow to simulate the augmented streamflow regimes. A problem encountered by Brown and Fogel in the routing procedure was that the simulation models available (at the time) to estimate streamflow increases relied on annual precipitation regimes as the primary input, and, unfortunately, precipitation records for the treatable areas on the river basins were spatially and temporally inadequate for this purpose. As a consequence, a link between normal stream flow in the mainstems of the Salt and Verde Rivers and precipitation on the treatable areas could not be specified within their acceptable levels of precision. Lacking this preferred procedure, three separate approaches were applied by Brown and Fogel in estimating increases in streamflow. These approaches consisted of the following steps:

- Estimating the annual increases in streamflow (per acre) associated with each annual estimate of normal streamflow.
- Apportioning the estimated annual increases in streamflow by month.
- Extending the (per-acre) estimates of the estimated annual increases in streamflow to a river basin from the estimates of treatable acreage within the river basin.

Procedural details of implementing these approaches to obtain the estimates of increases in streamflow are outlined by Brown and Fogel (1987) and, therefore, will not be repeated in this paper.

Simulations of streamflow from treatable areas to the downstream reservoirs on the Salt and Verde Rivers "with" and "without" the estimated increases in streamflow indicated that less than one-half of the annual increases in streamflow observed on these watersheds following implementation of the water-yield improvement treatments would reach the reservoirs about 100 miles downstream. It was hypothesized by Brown and Fogel that much of the remaining water would accumulate in storage within the river basins.

Parenthetically, a series of alternative scenarios suggested that about 40 to 60 percent of the annual streamflow increase would be delivered to downstream users if these scenarios were followed.

CONCLUDING COMMENTS

Estimates of increases in streamflow following implementation of vegetative management practices refer to on-site responses at the outlet of the watersheds. Allowances have not been made to this point in the extrapolation processes for transmission depletions or consumptive water-use by riparian vegetation that might occur between the outlet of the upland watersheds and downstream reservoirs or other points of use. Furthermore, these estimates of streamflow increase are commonly reported in terms of average weather and hydrologic conditions for the specific study-period that are unlikely to occur every year. These increases are large in some years and small or non-existent in other years depending mostly on the variations in annual precipitation and soil-moisture storage on the watersheds. Durations of the increases in streamflow on the upland watersheds are generally limited to only a few years with these increases often approaching pre-treatment streamflow levels after 10 years or less (Baker 1999, Baker and Ffolliott 2000). It must be expected, therefore, that durations of the estimates of increases in streamflow from the treatable areas within the larger river basins will be similar.

It is improbable that all of the treatable areas identified within a river basin can be treated simultaneously since relatively large acreages are involved. A temporal scheduling (sequencing) of treatments is more likely to occur. As a consequence, the estimated total increase in streamflow from all of the treatable areas within a river basin will be less than the increase observed on the upland watersheds. It cannot be assumed that all of the treatable areas identified for treatment are homogeneous in every respect. The impacts of a treatment on a treatable area, therefore, will not be uniformly the same.

Current managerial experience and policy indicate that to be economically feasible, vegetation management practices implemented for water-yield improvement must also benefit other collateral natural resources and values such as forage production, wildlife habitats, and recreational activities in addition to increasing streamflow (Baker 1999, Ffolliott et al. 2000). Without these other benefits, implementation of vegetation management practices that enhance streamflow might not be acceptable to the public.

REFERENCES

Baker, M. B., Jr., compiler. 1999. History of watershed research in the Central Arizona Highlands. USDA Forest Service, General Technical Report RMRS-GTR-29.

Baker, M. B., Jr., and P. F. Ffolliott. 2000. Contributions of watershed management research to ecosystem-based management in the Colorado River Basin. In: Ffolliott, P. F., M. B. Baker, Jr., C. B. Edminster, M. C. Dillon, and K, L. Mora, technical coordinators. Land stewardship in the 21st century: The contributions of watershed management. USDA Forest Service, Proceedings RMRS-P-13, 117-126.

Brown, H. E., M. B. Baker, Jr., J. J. Rogers, W. P. Clary, J. L. Kovner, F. R. Larson, C. C. Avery, and R. E. Campbell. 1974. Opportunities for increasing water yields and other multiple use values on ponderosa pine forest lands. USDA Forest Service, Research Paper RM-129.

Brown, T. C., and M. M. Fogel. 1987. Use of streamflow increases from vegetation management in the Verde River Basin. Water Resources Bulletin 23:1149-1160.

Clary, W. P., M. B. Baker, Jr., P. F. O"Connell, T. N. Johnsen, Jr., and R. E. Campbell. 1974. Effects of pinyon-juniper removal on natural resource products and uses in Arizona. USDA Forest Service, Research Paper RM-128.

Ffolliott, P. F., and M. B. Baker, Jr. 2000. Snowpack hydrology in the southwestern United States: Contributions to watershed management. In: Ffolliott, P. F., M. B. Baker, Jr., C. B. Edminster, M. C. Dillon, and K. L. Mora, technical coordinators. Land stewardship in the 21st century: The contributions of watershed management. USDA Forest Service, Proceedings RMRS-P-13, pp. 274-276.

Ffolliott, P. F., and D. B. Thorud. 1975. Water yield improvement by vegetation management: Focus in Arizona. National Technical Information Service, PB 246 055.

Ffolliott, P. F., and D. P. Worley. 1973. Forest stocking equations: Their development and application. USDA Forest Service, Research Paper RM-102.

Ffolliott, P. F., M. B. Baker, Jr., and V. L. Lopes. 2000. Watershed management perspectives in the Southwest: Past, present, and future. In: Ffolliott, P. F., M. B. Baker, Jr., C. B. Edminster, M. C. Dillon, and K. L. Mora, technical coordinators. Land stewardship in the 21st century: The contributions of watershed management. USDA Forest Service, Proceedings RMRS-P-13, pp. 30-36.

Ffolliott, P. F., G. J. Gottfried, and M. B. Baker, Jr. 1989. Water yield from snowpack management: Research findings in Arizona and New Mexico. Water Resources Research 25:1999-2007.

Hibbert, A. R. 1979. Managing vegetation to increase flow in the Colorado River Basin. USDA Forest Service, General Technical Report RM-66.

Rich, L. R., and J. R. Thompson. 1974. Watershed management in Arizona's mixed conifer forests: The status of our knowledge. USDA Forest Service, Research Paper RM-130.

Thorud, D. B. 1974. The Arizona Watershed Program in review - conclusions and recommendations. Arizona Watershed Symposium 18:58-60.