WATER YIELD OPPORTUNITIES ON NATIONAL FOREST LANDS IN ARIZONA

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Abstract

Water Yield improvement opportunities were estimated for National Forest lands in Arizona. The land base available for treatment was reduced in a stepwise manner to account for administrative, climatic, and ownership contstraints. Research relationships were built upon, and then applied to the remaining land base to project water yield estimates. A continuum of management prescriptions was then displayed to show the range of opportunities. Only the chaparral, ponderosa pine, and mixed conifer types show opportunities of significance. Water yield increases can be realized principally from conversion of chaparral to grass and could add an additional 25 to 70 thousand acre-feet. The ponderosa pine zone could add an additional 15 to 30 thousand acre-feet with intensive management by reducing stocking levels on the commercial National Forest lands. Little opportunity exists within the mixed conifer zone and increases would amount to less than 10 thousand acre-feet. Annual contributions of National Forest lands are likely to range from 40 thousand to 100 thousand acre feet; this will be highly variable depending upon precipitation quantities.

Introduction

Modifying vegetation for multiple use benefits, especially water yield improvement, has been discussed in Arizona and nationally for many years. The first question asked was--can we increase water yield through vegetation management? In addressing this question, water yield relationships were developed on small test watersheds to establish baseline response information (Brown, 1970).

As this information was gathered and analyzed, research efforts began to answer the first specific question and enable speculation on large scale water yield opportunities within Arizona (Ffolliott and Thorud, 1975). It soon became apparent that other resources besides water had equal, if not more, importance (Brown, H. et al., 1974). This paper will follow the same line of development (i.e., from site-specific water yield projections, to long-term large scale projections, and will include multiple resource projections and trade-offs) and applies the knowledge of past research to determine realistic water yield opportunities on National Forest lands within Arizona.

Methodology For On-Site Water Yield Estimates

Water yield opportunities are controlled principally by climate and vegetation. These two dynamic components must be accounted for as continuous variables constantly changing in time and space. When dealing with water yield improvement opportunities, we must understand and predict, as best we can, not only climatic influences but their associated probabilities.

Precipitation and Runoff Distributions

In the many pilot programs for quantifying water yield, three critical assumptions have been made: (1) water yield increases depend on annual or seasonal precipitation; (2) annual or seasonal precipitation follows a normal (bell-shaped) distribution and therefore "means" are expressive; and (3) since precipitation is distributed normally, runoff is likewise distributed normally. Subsequently, water yield increase opportunities were reported as "averages" that might be realized.

The question obviously surfaces--does precipitation, or more importantly runoff, follow a normal distribution? To best answer this question, we would need long-term pre and post-treatment runoff data that are not available. The next best alternative is to evaluate some long-term USGS streamflow records representing various vegetation and precipitation regimes. Preliminary work has been done in this area (Solomon and Schmidt, 1978; Solomon and Schmidt, 1981). Not surprisingly, much of the streamflow data was not distributed normally but was skewed to the right (Figure 1).

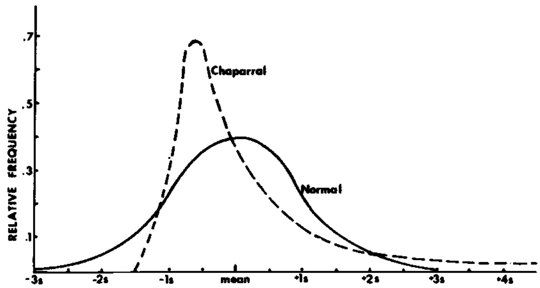

Figure 1. Annual water yield distribution for the chaparral ecosystem.

The chaparral ecosystem has a markedly skewed distribution; over 65 percent of the observed yearly (water year) runoff totals are below the arithmetic "mean". At progressively higher elevations, the skew is less apparent; preliminary results show that the spruce-fir ecosystems do not differ statistically from the normal distribution. Although, some small research watersheds within the spruce-fir do show skewed distributions for runoff. Thus the widely used arithmetic mean is not representative of recoverable water yield increases, particularly for the chaparral ecosystem (Hibbert, 1979). This points out an area for concern when trying to make long-term inferences from relatively short-term research information. As a result, past projections appear to have over estimated potentials.

In summary, inferences based on short-term experimental studies should be scrutinized to assure that the statistical assumptions are valid and that the use of the "mean" is meaningful. Some tools may require adjustment to accurately predict long-term water yield opportunities and probabilities (Hibbert, 1979). In Arizona, adjustments are probably necessary for hot/dry ecosystems up to the ponderosa pine ecosystems. Runoff and precipitation distributions are believed to be nearly normal for ecosystems found at elevations above the ponderosa pine and adjustments are probably not necessary.

Extrapolation of Research Results

Vegetation communities have been broadly stratified in the investigation of water yield (Clary et al., 1974; Hibbert et al., 1974; Brown, H. et al., 1974; Rich and Thompson, 1974). Water yield research in Arizona, since the 1950's, has focused on four broad vegetation types: chaparral, pinyon-juniper woodlands, ponderosa pine forests, and mixed conifer forests (including the spruce-fir). Other vegetation types either possess minor water yield opportunities (grasslands, desert shrub), occupy small acreage within Arizona (alpine, aspen, high elevation grasslands), or are managed primarily for other multiple use benefits (riparian).

Numerous relationships exist for predicting water yield opportunities within each of the four vegetation types (Clary et al., 1974; Clary, 1975; Hibbert et al., 1974; Brown, H. et al., 1974; Rich and Thompson, 1974). Only chaparral, ponderosa pine forests, and mixed conifer forests show opportunities for significant water yield improvement in Arizona (Ffolliott and Thorud, 1975; Clary et al., 1974; Clary 1975). This paper focuses on these three vegetation types for appraising water yield opportunities on National Forest lands in Arizona. Existing predictive relationships are elaborated to better address management needs. A step-by-step methodology is used to formalize a model and nomographs for use in projecting water yields on National Forest land (Solomon and Schmidt, 1980).

Chaparral. In chaparral vegetation, streamflow is increased by converting deep-rooted shrubs to shallow-rooted grasses and forbs that use less water. A relationship for predicting water yield in chaparral was developed by Solomon and Schmidt (1980). Elevation zones were used to infer temperature regimes, and water yield increases were calculated for complete conversion to grass rather than partial conversion (e.g., from 80 percent to 30 percent shrub cover). Resulting water yield increase opportunities for chaparral appear in Table A.

The yield predictions in Table A are lower than those projected by Ffolliott and Thorud (1975) and Hibbert et al. (1974). These lower estimates are primarily a result of adjusting for additional data since 1975 (Solomon and Schmidt, 1978) and using the 50% exceedence level (i.e., the level at which you can expect 50% of the values to be higher and 50% of the values to be lower) as being more meaningful to management than the arithmetic mean (Hibbert, 1979).

Ponderosa Pine. As with chaparral, much research has been done on water yield improvement opportunities in ponderosa pine forests (Brown, H. et al., 1974; Rich, 1972; Ffolliott and Thorud, 1975; Baker 1975). The integrated relationship used by Baker (1975) was used to generate Figure 2. Seasonal mean winter precipitation was changed to a more general, and readily understood, annual precipitation. Runoff values are expressed as 50% occurrence levels. Figure 2 represents water yield increases as dependent on level of vegetation removal as well as precipitation.

Table A. Long-term water yield increase opportunities for chaparral assuming complete conversion of overstory shrubs to grass.

Long-Term Mean Annual Precipitation (Inches)	Long-Term "Mean" Yield Increase (Inches)	50% Exceedence Level Yield Increases (Inches)
16	.2	.1
20	1.1	.8
25	3.3	2.7
30	4.5	3.7

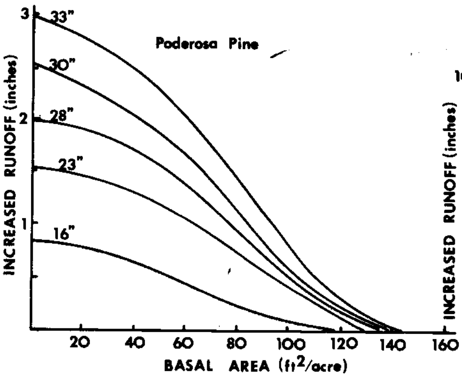

Figure 2. Water yield increase opportunities for the ponderosa pine forest.

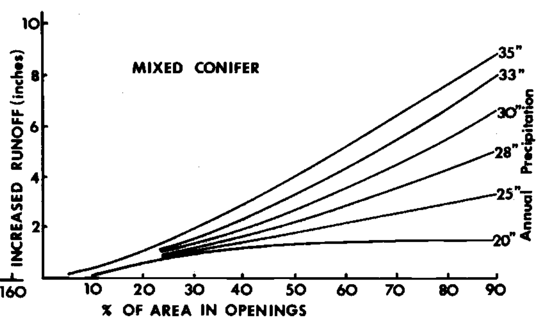

Figure 3. Water yield increase opportunities for the mixed conifer zone.

Mixed Conifer. In mixed conifer forests, water yield is best increased through intensive patch-cutting schemes (Rich and Thompson, 1974). These patches redistribute snow and decrease evapotranspiration to increase runoff. The relationships of Rich and Thompson (1974) were used to estimate water yield improvement increases. Figure 3 will be used in subsequent sections to develop water yield increases for the mixed conifer forest. Increased water yields are expressed as expected arithmetic means since runoff from this zone is assumed to be normally distributed.

Summary

The previous discussion dealt with the predictive "tools" (based on state-of-the-art research) that can be used to generate a regional appraisal of water yield increase opportunities for National Forest lands in Arizona. Table B summarizes these approaches and shows supplemental information needed to use these tools.

Table B. Summary of estimating techniques for water yield improvement.

Vegetation Zone	Estimating Technique	Supplemental Information Needed
Chaparral	Table 1	Acres treated, precipitation zone
Ponderosa Pine	Figure 2	Acres treated, precipitation zone, management prescription
Mixed Conifer	Figure 3	Acres treated, precipitation zone, management prescription

Water Yield Opportunities

To make accurate and defensible estimates of water yield increases, a considerable amount of information is required. This information is scant or even absent in many cases. Therefore, we have made assumptions recognizing the level of uncertainty involved.

Three components must be assessed to determine realistic water yield improvement opportunities: (1) water yield increases per treated unit; (2) net acres available and suitable for management; and (3) management prescriptions applied. The first component was discussed in the previous section. In this section, the second and third components will be quantified. The net acres available and suitable for water yield management in each vegetation type is estimated by adjusting the gross acreages downward for various fixed and variable constraints. Fixed constraints are those that are generally unchangeable, including land ownership, administrative designation (e.g., wilderness), and ecological suitability. Variable constraints are those affecting management decisions, including land (operable topography), multiple use mix, sociopolitical considerations, and economic trade-offs.

When all the fixed and variable constraints are accounted for, a net treatable acreage is left. These net acres can then be treated at various levels of intensity to increase water yield. However, these on-site increases may not necessarily be realized by downstream users because of possible transmission losses.

In our analysis of National Forest lands, all the fixed constraints were assessed. The only variable constraints assessed were land and multiple use. Social, political, and economic constraints were not assessed because they must remain a management decision based upon a high degree of uncertainty and vary with time and space.

The methodology followed is shown in Figure 4.

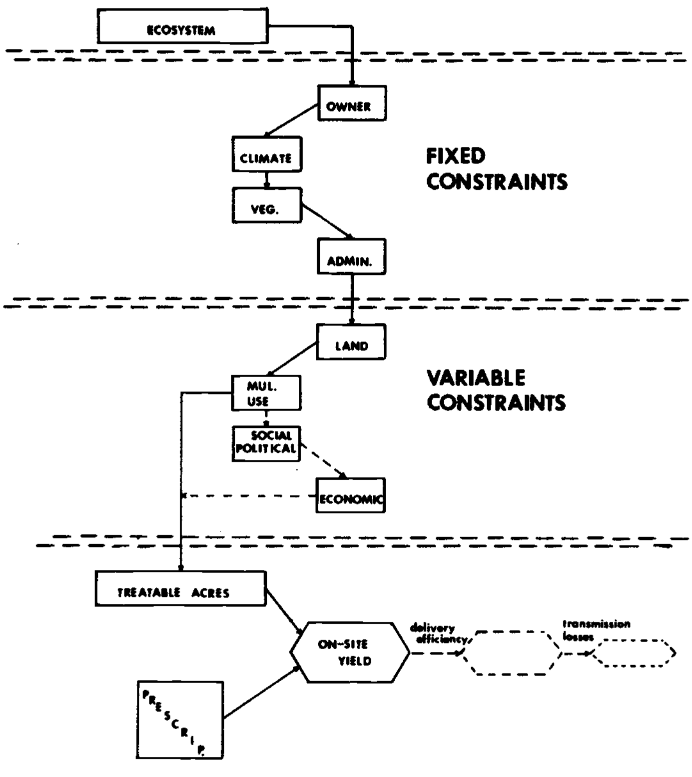

Figure 4. Methodology used in estimating water yield opportunities.

Fixed Constraints

Estimates of potential water yield increases depend on how many "net" acres are available for treatment. These acres are determined by overlaying vegetation maps (Brown and Lowe, 1980), administrative maps, and U.S. Weather Bureau isohyetal maps for mean annual precipitation. Acreages available for water yield improvement prescriptions as a resultant of these stepwise reductions for fixed constraints are shown in Table C.

Table C. Stepwise reduction of available treatable lands (million acres) due to fixed constraints.

Vegetative Community	Total Land Base in the State 1/	National Forest Ownership	Administratively Treatable 2/	Ecologically Suitable 3/
Chaparral	2.8	1.6	1.3	.7
Ponderosa Pine	4.3	3.3	2.4	2.0
Mixed Conifer	.31	.18	.15	.09

1/ Based on Brown and Lowe (1980).

2/ Removes wilderness or special use designations which limit management prescriptions, and removes noncommercial forest land.

3/ Removes acres ecologically unsuited for treatment: chaparral (isolated patches, overstory density less than 30 percent, annual precipitation less than 16 inches); ponderosa pine and mixed conifer (isolated patches, unstable soils).

These available lands are displayed by precipitation zones in Table D to better show opportunities and to better utilize Table A, Figure 2 and Figure 3 in further calculations.

Table D. Acres of National Forest lands available for water yield improvement.

	Mean Annual Precipitation (Inches)								
Vegetation	16-18	18-21	21-24	24-26	26-29	29-31	31-35	35+	Total
				Thousand Acres					
Chaparral	10	100	495	70	40	10			721
Ponderosa Pine		180	812	450	492	46	20		2000
Mixed Conifer				22	26	17	21	4	90
Total	10	280	1307	542	548	73	41	4	2811

Variable Constraints

After accounting for the fixed constraints, the next step in the analysis is to evaluate variable constraints. These "management decision" constraints are summarized in Table E.

In the endeavor to evaluate water yield opportunities on National Forest lands in Arizona, assumptions regarding prescriptions and associated constraints, shown in Table E, must be made (i.e., what growing stock levels will be used, what slope criteria will be used, etc.). Rather than make these assumptions, as has been done in previous efforts (Brown, T. et al., 1974), a display of the continuum of opportunities over the range of the "variable constraints" was chosen (Solomon and Schmidt, 1980).

Chaparral. Figure 5 was constructed by combining water yield projections from Table A with acreages shown in Table D. Additionally, a slope exceedence curve (Solomon and Schmidt, 1978) was applied across all precipitation zones.

Table E. Variable constraints used in assessing water yield increase opportunities.

Vegetation	Land Constraints	Multiple Use Constraints
Chaparral	Operable slope criteria (this is important because an estimated 50% to 60% of the chaparral is between 30% slope and 60% slope) (Brown et al., 1975)	Percent of project area actually converted (i.e., the creation of mosaic patterns for wildlife and asthetics) will be a consideration.
Ponderosa Pine	Acres subject to management (limited by slope, economics).	Growing stock levels that stands will be managed for (limited by desired volumes, wood quality, wildlife).
Mixed Conifer	Acres subject to management (limited by slope, economics, esthetics).	Percent of project area functioning as openings for redistribution of of snow and reduced ET (limited by land stability, erosion, asthetics, wildlife)

Regardless of the actual alternative, by using such a display technique, one can quickly assess the relative trade-offs in water yield increases as slope criteria and percent conversion prescriptions change. Additionally, the display shows the entire realm of alternatives and allows a comparison against potential water yield. As an example, Point A would yield an additional 42,000 acre-feet of water (50% exceedence level) by operating up to 40% slope on all available land and a mosaic pattern with 60% of an area in openings.

Ponderosa Pine. Unlike, chaparral, the accepted multiple use management of ponderosa pine does not imply clear-cutting or type converting from pine to grass (Schubert, 1974; Baker, 1975). Rather, it involves silvicultural treatments where timber stands are reduced in their stocking from high levels and allowed to regrow. Therefore, when discussing water yield improvement opportunities within this vegetation type, we must look at increases in water yield for various levels of thinning or harvesting.

Figure 6 depicts the existing stocking distribution for the commercial Forest lands in Arizona extrapolated from the Salt and Verde drainages (Ffolliott and Solomon 1976). Also shown are distributions that could be possible by the year 2020. Case I is based on a timber management emphasis (Schubert, 1974). Case II is based on a water yield emphasis (Baker, 1975). Note, in Case I that the distribution curve shows a greater percentage of land stocked between 40 and 80 Ft^2/acre because of restocking needs, while positive increases in water yield are realized by reducing the acres within basal area class 100-140 Ft^2/acre to some lower levels.

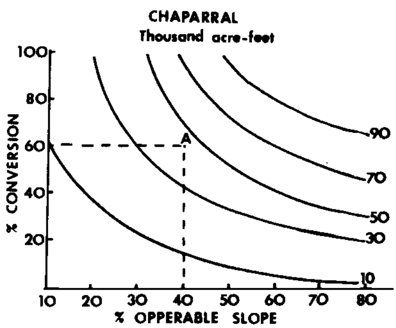

Figure 5. Water yield increase opportunities in the chaparral on National Forest land.

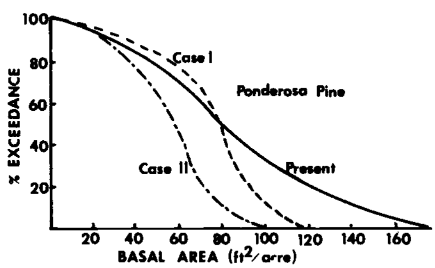

Figure 6. Stocking distributions for ponderosa pine forest.

By adjusting water yield increases from curve to curve in Figure 6 coupled with Table D, water yield improvement opportunities can be estimated as shown in Figure 7.

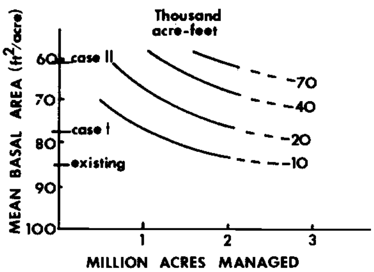

Figure 7. Water yield increases opportunities in ponderosa pine on National Forest lands.

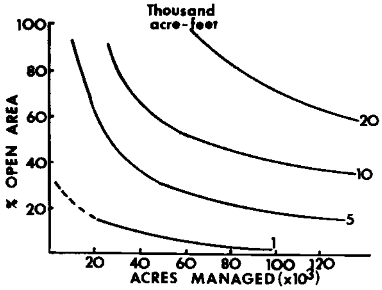

Figure 8. Water yield increases opportunities in the mixed conifer on National Forest lands.

It is believed that opportunities for water yield increases within the pine zone have already been partially realized from past management (Solomon and Schmidt, 1978). Future opportunities of 10,000 to 40,000 acre-feet exist, depending on the management prescription and acres managed to that prescription as shown in Figure 7.

Mixed Conifer. Intensive management of mixed conifer could significantly increase annual water yield per unit area treated. Intensive management is defined as a patch-cutting scheme with openings three to eight tree heights in width. The area of "effective" clearings could approach 30 to 40 percent of the total intensively managed area (Rich and Thompson, 1974; Ffolliott and Thorud, 1975). Figure 8 depicts the water yield increases that could be expected for various management options.

The mixed conifer zone, due to limited extent, offers little in the way of total water yield improvement opportunities. Even with intensive management for water yield purposes, only 7,000 acre-feet of increase is realistically attainable. Additionally, the mixed conifer zone is far removed from where the increased water would be put to beneficial use, so transmission losses should be considered.

Knowledge Shortfalls and Uncertainties

Throughout the development and analysis of data, many concerns surfaced that contribute to the uncertainty of the projected estimates. Listed below are the major concerns:

1. Discrepancies exist among estimates of acreage for the various vegetation zones. These discrepancies may result from lack of standard criteria for defining each vegetation type.

2. Rainfall isohyetal maps may not be accurate. Checks need to be made of the accuracy of these maps. The resolution for high rainfall areas needs to be improved.

3. Long-term rainfall and runoff "frequency distributions" were uncertain. These distributions need to be more accurately quantified.

4. Vegetation density distributions (chaparral) and stocking levels (ponderosa pine) for each vegetation zone were approximated. These densities and stocking levels need to be quantified with greater accuracy.

5. More recent research data indicates that estimates of water yield increases per unit area may not be to a desirable "state-of-the-art". Greater precision and accuracy should be forthcoming as more years of information are added to the research data base.

6. On-site and channel transmission losses need to be estimated. This will have to be accomplished on a watershed by watershed basis, but research will have to be done to better quantify these losses.

7. Water yield increases that occur during high runoff years may be lost because of reservoir regulation and spill over of increased volumes. Therefore, the years with the highest water yield increases may not give the greatest recoverable increases in water yield.

8. Cost effectiveness of management prescriptions is uncertain. Greater knowledge of these costs could help better define the upper limits of water yield improvement opportunities.

Conclusions

Water yield opportunities exist on National Forest lands in Arizona, although not of the magnitude projected from previous estimates (Ffolliott and Thorud, 1975; Hibbert, 1979). These water yield projections are shown in Table F.

Table F. Water yield projections from National Forest lands in thousands of acre-feet.

	Vegetation Zone				
	Chaparral	Ponderosa Pine	Mixed Conifer	Other	Total
Base level current yield (50% exceedence)	173	740	76	520	1,509
Increases from management	25-70	15-30	3-7	0	43-107

1. Future intensive management can increase water yield from National Forest lands an additional 3 to 7 percent over current yields.

2. Future opportunities can best be realized through intensive management of chaparral. Almost 60 to 70 percent of future water yield increases can be generated from type converting chaparral vegetation.

3. The ponderosa pine forest shows opportunity for moderate water yield increases. These increases would result from a more intensive timber management program and could account for 30 to 35 percent of future increases in water yield.

4. Management of the mixed conifer zone offers opportunities for substantial water yield increases per unit area. The drawback is the limited amount of acreage that can be managed effectively.

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