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EVALUATING THE EFFECTS OF WATER YIELD MANAGEMENT

by

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A watershed is a flexible, complex land area. It is flexible because it can be manipulated to serve various purposes, either singly or in any combination. Multiple-use watersheds, a basic concept for the beneficial management of our natural resources are used for the production of timber, forage and water, for wildlife habitat, and for outdoor recreational purposes. Watersheds are complex in that they differ in climate, soil types, kind and density of vegetation, topography and orientation. Because of these differences, and perhaps other undetermined ones, results from experimental watersheds cannot be extrapolated very readily to predict similar results from another watershed.

The management of water source areas for the purpose of producing beneficial changes in the hydrologic regimen is a subject of increasing concern, expecially in the water-short southwestern United States. Since water source areas are generally associated with forested sites, vegetation manipulation of forests to alter the quantity and timing of streamflow has drawn the attention of both the forest manager and the water supply engineer. While the production of water may be the prime concern in the management of a specific watershed, consideration must be given to possible trade-offs involving the other products obtained from a watershed. The term watershed management is generally defined to mean the administration and regulation of all the available resources of a watershed for the production of water, control of erosion, regulation of streamflow and the control of floods. A broader definition of watershed management would, therefore, include all of the watershed's products, i.e., water, timber, forage, wildlife and recreation.

The objectives of this paper are, first, to review the research that deals with the management of watersheds for water production as its primary purpose, particularly those projects whose results may be applicable to conditions in the southwestern United States. Secondly, a methodology is suggested for evaluating water yield improvement practices in light of the entire water supply, storage and delivery system. The procedure, a modification of one proposed by Hawkins (1) consists of first utilizing a time series of precipitation to account for the variable nature of the input to the hydrologic system. Then, a watershed model is required that relates the inputs to the hydrologic products of a watershed, water and sediment, for a given set of site conditions. Finally, the procedure should include some type of analysis that will consider the entire system in a manner that the benefits to the ultimate consumer can be realistically determined.

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DEVELOPMENT OF WATERSHED MANAGEMENT

Watershed Management is a relatively new science as evidenced by a lack of a large body of solidly established facts and well-proven relationships that characterize older sciences. Certainly there is a backlog of facts and relationships that are available from the older sciences, but in the aggregate, there is still much to learn.

Interest in watershed management probably had its inception around the beginning of the twentieth century amidst a conflict between foresters and geologists on one side and engineers and meteorologists, including the Chief of the U.S. Weather Bureau on the other side (2). The latter group claimed that forests have virtually no effect on precipitation and little or no effect on streamflow. A direct outcome of this difference of opinion was the cooperative effort of the Forest Service and the Weather Bureau in planning a field study under controlled conditions to determine the effect of forests on runoff. On June 1, 1910, the two bureaus jointly initiated at Wagon Wheel Gap, Colorado on a tributary of the Rio Grande River the first investigation of its kind in the world. The study resulted in a report by Bates and Henry (3) that has become a classic in watershed literature. The conclusion drawn was that forests do have an effect on runoff but that this effect depends on so many factors which vary greatly from watershed to watershed that generalizations on the subject are impossible.

Soon after the Wagon Wheel Gap report, Hoyt and Troxell (4) reanalyzed these data and added information obtained from two watersheds in southern California, one of which was denuded by fire in 1924. Again it was concluded that forests do exert an influence on streamflow. The Sierra Ancha Experimental Watersheds located within the Tonto National Forest in central Arizona were formally established in 1932 although certain phases pertaining to range management were started as early as 1921. One of the first reports dealing with modern watershed management concepts was presented by Wilm (5).

The relation of forests and other vegetation to watershed conditions has excited foresters, engineers and others ever since floods and water shortages have caused substantial losses to human developments. An example of the spread of this interest to other areas is evidenced by the First West Pakistan Watershed Management Conference (6). With the added push of a population explosion in the Southwest, research programs in watershed management have been greatly accelerated. The now famous Barr report (7) recommended an operational program for managing one of Arizona's more important watersheds, the combined basin of the Salt and Verde Rivers, to produce additional water primarily for meeting irrigation needs. Results of current research that may be applicable to the above basins will be discussed in the next section.

WATER YIELD MANAGEMENT PRACTICES

The logical management of watersheds for the enhancement of water yields requires that the hydrologic response to any given treatment be predictable. This response may be in the form of any or all of the following:

1. Total annual water yield and its timing, both seasonally and

annually.

2. Peak flows, their amount and frequency.
3. Water quality, primarily suspended sediment.

Forecasting the above hydrologic factors requires quantifiable knowledge of the relationships between these factors and such site variables as climate, soils, vegetation, geology, elevation, orientation, etc. Some scientists are attempting to classify runoff potential according to forest types (8) while others feel that local climate holds the key (9). In any case, estimates of actual and potential runoff for the western United States have been made (7, 10, 11). Unfortunately many of the measurements are either short term or have been made on watersheds containing a mixture of forest types.

With the exception of flood control investigations, little has been done to quantify significant hydrologic parameters, develop watershed prescriptions, predict the effects of vegetation management and inaugurate watershed management action programs. Research has indicated some of the possibilities for improving water yields.

Most of the water used in the western United States originates as snow intercepted by mountains. Generally, precipitation and water yield increase with elevation. A very good opportunity for increasing water yield occurs within the snowpack zone. Snow is more readily controlled than rain as it can be stored and released by the management of vegetation or by some mechanical means such as snow fences. Summarizing the remarks of Dortignac (12), a leading watershed management specialist, the following are treatments that may be used to produce long-term water yield increases (with re-treatment) from forested areas primarily through a reduction of evapotranspiration:

1. Change the arrangement of tree canopy.
   a) Convert uneven-age stands to even-age.
   b) Favor species that require, consume and lose the least water.
   c) Change structure of canopy.
2. Convert stands to other species in large blocks.
   a) To trees with less crown foliage, less extensive and shallower root system, shorter growing periods, and efficient uses of water.
   b) Replace brush with shallow-rooted herbaceous vegetation.
3. Convert to low-growning, low-water consuming species in small openings or narrow strips (grass, prostrate shrubs, and carpet vegetation).
   a) On riparian and moist sites.
   b) On relatively stable land slopes.
4. Remove or kill understory woody vegetation--particularly deep and extensively rooted plants.

It has been demonstrated by research experiments that water yield can be increased without damaging the quality of water being produced on these treated watersheds. Three experiments cited probably more than any others, are the Wagon Wheel Gap (3), Fool Creek (13) and Workmen Creek (14) studies. Hibbert (15) summarizes the results of 39 studies, including the above three, concerned with forest treatments designed to alter streamflow characteristics. Since then several other studies have been published (16, 17, 18, 19). Table 1 presents the results of

selected studies which may be applicable to Arizona watersheds.

Table 1. Effect of vegetative manipulation on streamflow

Watershed	Elev.	Mean annual Precip	Mean annual Runoff	Treatment	Avg. incr.
	(Ft.)	(In.)	(In.)		(In.)
Forest					
Fool Creek	9700	30.0	11.1	39% cut in strips	2.9
Wagon Wheel Gap	9600	21.1	6.1	84% clear cut	1.0
Workmen Cr. (N.)	6800	32.0	3.4	32% cut, moist sites	1.5
Beaver Cr. (12)	7000	24.0	6.0	100% clear cut	2.7
Beaver Cr. (9)	7300	27.0	6.8	33% cut in strips	2.9
Castle Cr. (W.)	8200	27.0	2.4	17% cut in blocks	4.0
Chaparral					
Three Bar (D)	5300	27.7	0.9	Fire, regrowth of shrubs	2.0
Three Bar (C)	4800	24.7	0.8	Fire, brush suppression and conversion to grass	5.9
Three Bar (B)	3300	21.3	0.3	Fire, conversion to grass, shrubs controlled on 40% of area	2.1
Placer Co.	600	25.0	5.7	Conversion to grass	2.4

The impetus for the Arizona efforts was in large part due to the previously mentioned Barr report (7). This report, spurred on by declining ground water levels due to excessive irrigation pumping, investigated the economic feasibility of increasing the water yield from the Salt-Verde drainage basin. The investigation was confined to these watersheds since they produce most of Arizona's irrigation water and storage is normally available to impound additional water. With the technical assistance of leading watershed management specialists, the report proposed a program that would manage the watersheds primarily for water. This included a drastic thinning of ponderosa pine stands, thinning of spruce to favor snow deposition, expanded eradication of juniper and pinyon-pine and the modification of stream-side vegetation to reduce water loss. It was estimated that application of this program would result in an additional supply of 285,000 acre-feet of water per year, an increase of about 25 percent over the long term mean. Table 2 presents the potential increase in water yields resulting from treating the various vegetative types as given in the Barr report (7). Recent studies have indicated certain refinements in the estimates shown in this table. The yield increases for the subalpine and the ponderosa pine areas appear to be within reach as seen by the studies on Castle Creek (16) and on Beaver Creek (19). On the other hand, treating the pinyon-juniper vegetative areas may prove to be a marginal operation due to the uncertainity of the increased streamflow volumes. The yield increase for the pinyon-juniper type is on the order of magnitude of one-half inch per year, an amount that may be difficult to ascertain in streamflow measurements.

Overlooked in the Barr report was the potential that existed in the chaparral zone. One of the first clues to its possibilities resulted

Table 2. Potential increase in water yield of Salt and Verde River Basins as a result of treatment[a]

Cover type and class	Treatable area	Estimated present yield	Probable increase
	(acres)	(inches)	(inches)
Ponderosa pine			
Stream banks	30,000	4.0	4.0
Moist slopes	100,000	4.0	2.0
Poor timber area	250,000	3.0	1.5
Good & intermediate	600,000	4.0	1.0
Non-commercial	200,000	3.0	1.2
Subalpine area			
Pure spruce	30,000	12.0	4.0
Aspen-spruce-fir	75,000	12.0	3.0
Pinyon-juniper			
Dense stands	200,000	1.2	0.8
Valleys	500,000	1.2	0.6
Slopes	1,000,000	1.0	0.4
Lower riparian area	40,000	---	18.0

a From Barr, G. W. et al, Recovering rainfall, Part I, 33 pp., Arizona Watershed Program, 1956.

from a 1959 wilfire on the Three Bar Watersheds in Central Arizona. The fire killed all above ground vegetation. Taking advantage of this opportunity, a treatment of chemically suppressing the shrub sprouts and conversion to grass was initiated. Water yields were then compared with those from the areas in which the chaparral was allowed to recover. High sediment rates followed the fire and continued on the control watershed until an adequate herbaceous cover was established about 3 years later. Between 1960 and 1969, water yields increased from 7 percent of average annual precipitation to over 23 percent (18).

Encouraged by results such as these, the Salt River Valley Water Users' Association inaugerated a cooperative program in 1964 with the U.S. Forest Service to actively manage the Associations' watersheds for increased water yields. The initial treatments included the control of chaparral, juniper and riparian vegetation.

A STRATEGY FOR ANALYSIS

In studying the results of the various vegetative manipulation experiments, one point becomes readily apparent. The relationship between water yield increases and precipitation is decidedly non-linear. Thus, in making an analysis to determine the effectiveness of a given treatment, mean annual values of yield increase may not reflect the true picture.

Distribution of Yield Increases

In discussing the conversion of chaparral to grass, Hibbert (18) reported that both the annual pretreatment yield and the yield increase is related to annual precipitation by a power function. With such a relationship, a frequency distribution of yield increases can be readily obtained by transformation from a distribution of annual precipitation. This procedure will result in a more exact evaluation of the treatment that produces the yield increase. For example, a pre-ponderance of low precipitation years resulting in low flows may result in insignificant increases. On the other hand, the large increases coming in wet years may cause the available storage facilities to spill, and hence, waste some of the yield increases.

Use of Watershed Models

Where mean values for streamflow increases and a record of pretreatment streamflow are available, the procedure of Hawkins (1) can be employed. Using the data obtained from the pretreatment streamflow record, years of monthly streamflows can be simulated by one of the generating techniques discussed by Askew et al (20). The yield increases are then added to these amounts in a uniform fashion to obtain a simulated record for the treated watershed.

In certain instances, however, the management of watersheds may involve predicting yield increases from ungaged watersheds or where streamflow records are not long enough to establish stable frequency distributions. In these instances, watershed models together with research data such as shown in Table 1 and precipitation models offers a means for obtaining a simulated record of streamflow for both treated and untreated watersheds.

The use of mathematical models for simulating the hydrologic response of a watershed has been firmly established (21). Examples of such models are the Stanford Model (22), the models proposed by Anderson (23), the model developed at Purdue University (24) and the USDA Hydrograph Laboratory Model (25). Inputs to models of these types, precipitation, can be a stochastic model of daily or storm precipitation such as proposed by Gabriel and Neuman (26), Grace and Eagleson (27), Todorovic and Yevjevich (28) and Fogel et al (29).

Storage - Yield Function

The next step concerns consideration of the available or required storage facilities in relation to the downstream water requirements. Water flows into a storage reservoir in accordance with the precipitation on the watershed and the resulting runoff. Both of these time series can be described in statistical terms. Water flows out of the reservoir according to predetermined operating rules or demand schedule. Flow increases produced by land management when the reservoir was full and spilling would be wasted if there were no additional downstream storage. Thus, not all flow increases would necessarily be of value to the downstream user. It would depend on the amount of storage available, the demands at the time of the increased flow and on the nature of the reservoir inflow both prior to and after treatment. Streamflow varies from year-to-year in a manner that produces wet and dry sequences.

Increases in streamflow during dry sequences would be of definite value to the downstream user whereas the same may not be true during the wetter periods.

Using a simulated streamflow record as inflow into a reservior, a storage-draft analysis can be made for any kind of demand schedule, such as water for irrigation, power, municipal use, etc. The storage-draft relationship, sometimes called a storage-yield function, can be obtained by the well-known work of Rippl (30), the sequent peak method as described by Fiering (31) or by other procedures. The sequent peak method being amenable to computer analysis as well as being less ambiguous than other common methods currently being used, will be discussed in more detail.

For an N-period record of streamflow (Q) into a proposed reservior, the question concerns finding the minimum storage capacity (S) of the reservior such that there will be no draft (D) deficiency. The inflow and draft data is first recycled to produce a 2N-period record. Essentially, the sequent peak method, shown in Fig. 1, is described as follows:

1. Calculate cumulative net inflow, $\sum_{i=1}^{n}(Q_i - D_i)$ for n = 1, 2, ... 2N.
2. Locate the first peak (local maximum), P_1, of the cumulative net inflows.
3. Locate the "sequent" peak, P_2, which is defined as the next peak of greater magnitude than the first.
4. Find the lowest trough (local minimum), T_1, between the pair of peaks, and calculate $P_1 - T_1$.
5. The above steps are then repeated for all sequent peaks in the time series.
6. The minimum storage capacity of the reservoir such that no draft deficiency will occur is $S_m = \max (P_j - T_j)$.

Changing the drafts without altering the inflows will change the shape and extent of the peaks and troughs with the result that a new storage requirement is obtained. Repeating this for various drafts will result in a storage-draft relationship similar to that shown in Fig. 2. Note that as storage approaches infinity, the draft approaches a limit of the average annual inflow.

Plotting the storage-draft curves for both the treated and the untreated watershed now allows an estimate to be made of the value of the treatment to the downstream water users. Consider the alternatives to planners. For storage facilities that are already in existence, the amount of increased streamflow that would be available is simply the difference between the two curves at the given storage (see Fig. 3). As mentioned earlier the increased flow resulting from treatment would be greater than the available increase due to reservoir spills. On the other hand, the land treatment could result in a smaller storage facility for the same demand. It is at this stage where the relative benefits and costs of the treatment adopted to increase streamflow should be evaluated. An analysis of this aspect is beyond the scope of this paper and can be the subject for several dissertations.

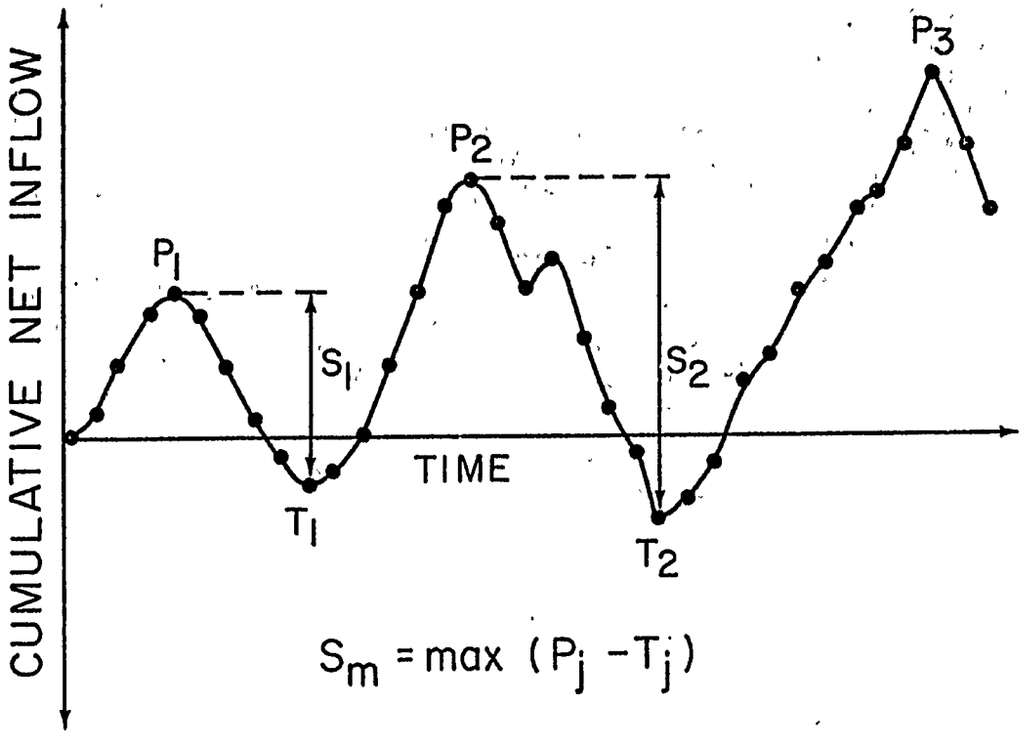

Fig. 1. Sequent Peak Procedure for Determining Reservoir Storage Capacity

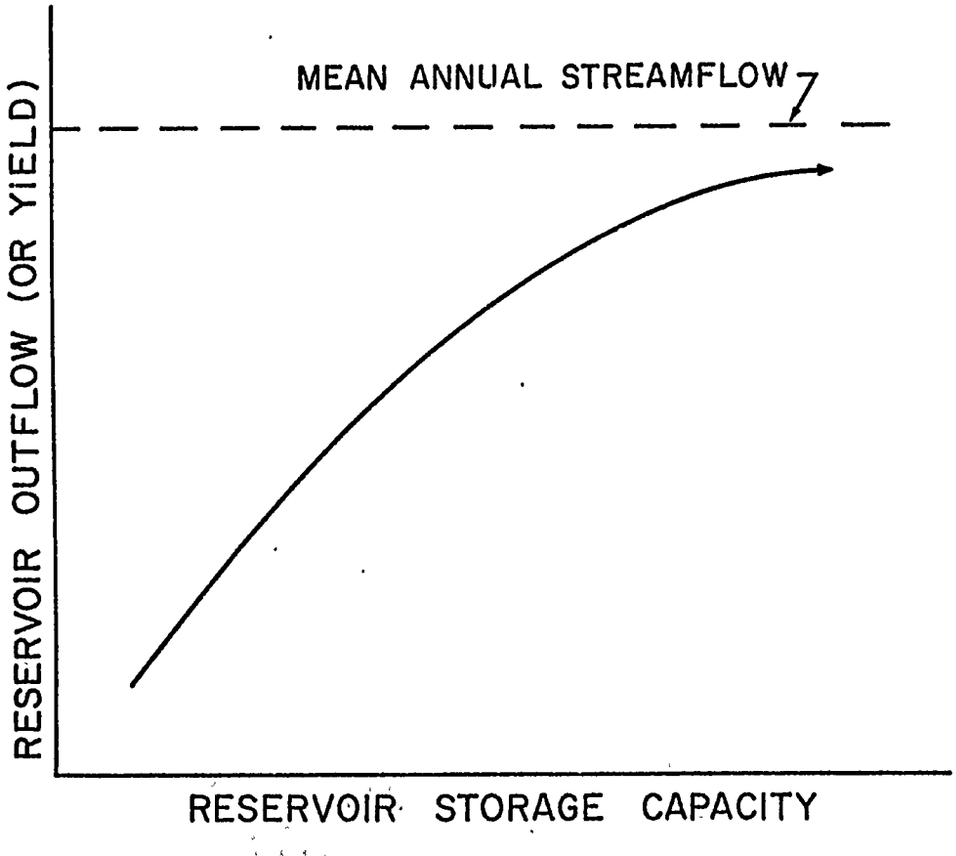

Fig. 2. Typical Storage-Yield Function for a Reservoir

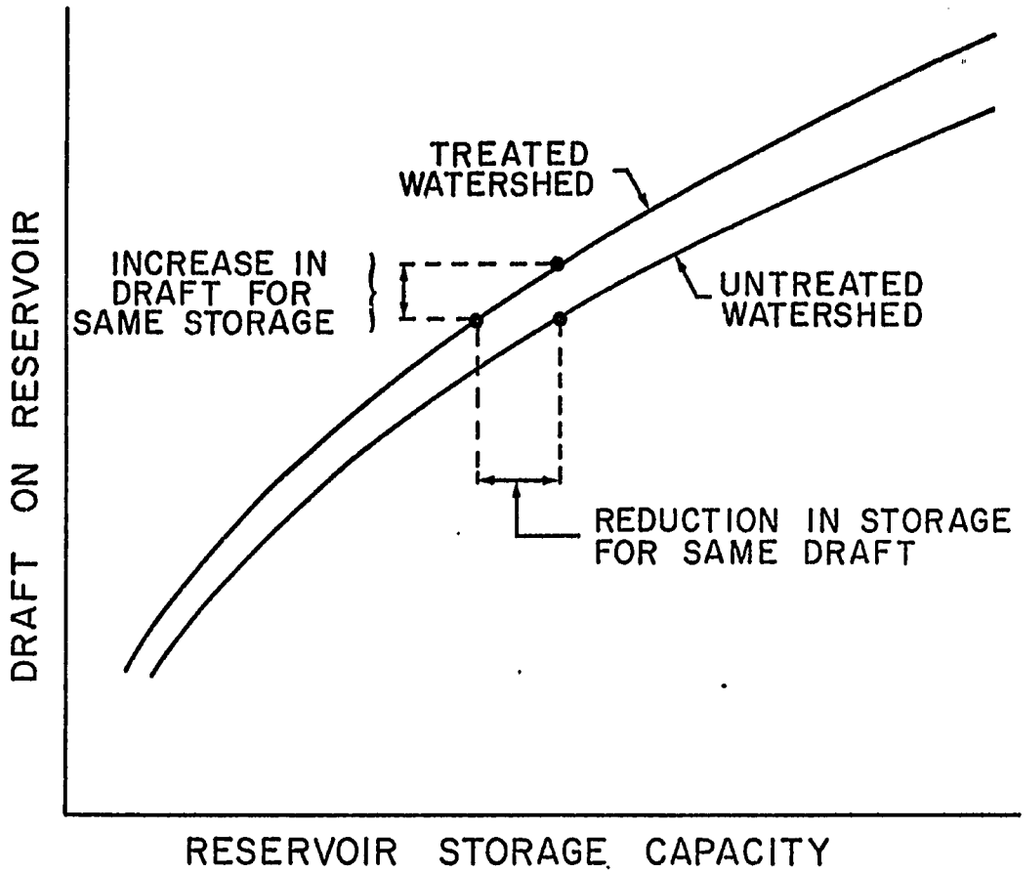

Fig. 3. Illustrating Effect of Watershed Treatment on Storage-Draft Relationship

SUMMARY AND CONCLUSIONS

Watershed Management, an imaginative approach to partially solving water problems of the West is in its infancy insofar as its adoption as an operational practice is concerned. In only a few areas is this being considered as a means for alleviating water shortages. One of these areas is the Salt River-Verde River drainage basin in Central Arizona. Some fifteen years ago, watershed specialists were advocating wholesale alterations to the vegetation in order to gain additional water for irrigation. Encouraged by the results of research, one of the first large-scale operational watershed management programs has been underway for several years.

In studying the results of the many experiments designed to determine the extent of water yield increases, one point stands out above all others. While increases are being measured, predicting the response to a given treatment is accomplished with a great deal of uncertainity. This is not a condemnation of watershed management as it reflects on the shortcomings of surface hydrology in general.

Not only will the uncertainity problem probably remain with watershed management for some time to come, but land managers will also have to come to grips with problems that are legal and aesthetic in nature. Nevertheless, research in watershed management must be allowed to

continue as the potential in vegetative manipulation has definitely been demonstrated and interest is continually spreading.

One area in which research is needed concerns the evaluation of land treatments in the face of uncertainity--uncertain inputs and uncertain relationships between input and output. Reliable models are needed for predicting all the effects on a watershed upon which some treatment has been imposed. In addition, the entire system must be considered, from source of the product to its eventual use. A procedure is presented in this paper which considers the relation between watershed outflow, the watershed's response to precipitation, and the downstream demand for water. The methodology consists of a time series of precipitation transformed by the watershed into another time series, streamflow. In turn, another transformation takes place as this outflow is treated as inflow into a storage facility which releases a predetermined flow to meet specific water requirements.

In practice, a study to determine the value of streamflow increases is not a simple task. The possible trade-offs between the products of a watershed must be considered. Land managers are confronted by many constraints, physical, budgetary, legal, social and political, in attempting to meet the increasing demand for timber, water, forage and recreation. Here is another area which requires additional research. Decision-making models in the face of uncertainties are needed to assist the administrators of wildland areas. Such models must have continuous feedback to increase the possibilities for success as additional information becomes available.

In summary, land managers will no doubt have increasingly more sophisticated tools at their disposal to control the quantity and timing of streamflow in their quest to meet the future demands for watershed products. Only those practices dealing with the manipulation of vegetation were discussed in this paper. There is every reason to assume that other methods may prove to be even more efficient. The use of some chemicals to reduce infiltration and others to reduce transpiration are known possibilities that are currently being investigated. If the need, the interest, and the lack of readily transferrable information are any criteria, watershed management research should be on the increase.

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