REGIONAL TRAINING COURSE

MAB

WATERSHED RESOURCES MANAGEMENT AND ENVIRONMENTAL MONITORING

HUMID-TROPICAL ECOSYSTEMS

A

REGIONAL TRAINING COURSE

IN

NATURAL RESOURCES MANAGEMENT

AND

ENVIRONMENTAL MONITORING

IN

HUMID-TROPICAL ECOSYSTEMS

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PREFACE

Watershed resources play a significant role in the development of any country. Dependent upon the location of a watershed, they furnish a diversity of primary wood products, contribute forage for livestock and wildlife, yield water for municipal, agricultural and industrial developments, and provide many forms of aesthetic and recreational uses.

In respect to water yield, runoff from the upper reaches of a watershed flows downstream, supplying water to valleys and joining lakes, rivers and oceans. Along this path, man's activities may continually alter the natural hydrologic flow. Land use manipulations for agriculture, urban development, forest harvesting, engineering and mining purposes are important developmental activities. Unfortunately, these activities can often have destructive consequences, such as increasing the rate of sedimentation. Whether or not land use manipulations bring about desired optimum benefits for a country depends, in part, upon the magnitude of the destruction of the environment. Therefore, along with the various natural resource products and uses derived from a watershed, the associated disadvantages of developmental activities should also be fully evaluated. It is here where the role of effective watershed management becomes important.

Effective watershed resources management in many countries is currently in the formulative stages. While there may be a trend to effectively manage a country's water-related resources, the accumulated effects of previous abusive use of watersheds will continue to be felt for some time. It is urgent for all concerned with watershed management to know and apply relevant strategies and techniques that will promote effective management and use of a country's natural resources.

At present, current misuse of watershed resources can be attributed to two important factors: misuse of vegetative cover on a watershed for short-term economic gains; and lack of an efficient management system to implement goals and policies for the watershed resources in a country. Essentially, these factors are management-oriented problems which may be solved for better overall results.

While there is a growing realization of the destructive consequences of past and, at times, current misuse of watershed resources, the necessary elements of what constitutes effective use of these resources often elude watershed resource managers and land use planners. Consequently, a well-meaning policy based on an improper understanding of a watershed ecosystem may be as detrimental as mismanagement. A case in point may be a policy to indefinitely ban the harvesting of timber on otherwise potentially harvestable watershed areas. Similarly, it may be unwise to prescribe timber harvesting on areas potentially sensitive to erosion without a thorough understanding of the ultimate consequences.

To acquire understanding of the impacts of alternative watershed resource management practices and to provide input to the formulation of more effective watershed management policies, a need for long-term environmental monitoring exists. As part of a program for long-term environmental monitoring, the following subjects must be addressed: biological, geophysical, chemical and anthropological. Specific topics to be considered under biological monitoring include flora and fauna checklists; descriptions of biotic populations and communities; and quantifications of ecosystems processes and dynamics. Geophysical topics include measurement of precipitation, air temperature, and streamflow; description of soil type and associated physical and chemical properties; and estimates of area or volume of landslides, intensity and extent of windstorms, *etc*. Chemical monitoring includes the detection of pollutants and monitoring of natural substances through examination of critical components in the atmosphere, precipitation, surface water, soil and litter, and vegetation. Anthropological monitoring includes assessment of demographic characteristics, land ownership patterns and legal structures.

The primary reason for offering a regional training course in WATERSHED RESOURCES MANAGEMENT AND ENVIRONMENTAL MONITORING is to provide background in which natural resource managers and land use planners concerned with watershed resources can identify relevant goals, synthesize appropriate policies, and implement proper management practices. Only by acquiring the training necessary to obtain required baseline information (through environmental monitoring) to formulate watershed resources goals, policies, and management practices can this overall purpose be achieved.

This syllabus has been prepared to furnish a framework to a Regional Training Course in WATERSHED RESOURCES MANAGEMENT AND ENVIRONMENTAL MONITORING IN HUMID-TROPICAL ECOSYSTEMS. A primary sponsor of the course was the United Nations Educational, Scientific, and Cultural Organization's Man and Biosphere (MAB) Program. Funding was made available, in part, through the United States' Agency for International Development (AID) as a contribution to the AID/MAB Education and Training Program.

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Much of the subject matter presented in the syllabus is basic to acquiring an understanding of watershed resources management and environmental monitoring, with special emphasis on humid and tropical ecosystems. This syllabus is a second version (the prototype being dated *September 1979*), to be revised as necessary to accommodate the purposes and objectives of subsequent courses.

Peter F. Ffolliott
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CHAPTER I

CONCEPTS OF WATERSHED RESOURCES MANAGEMENT

INTRODUCTION

In addition to well-defined agricultural lands and urban areas is a major portion of the earth's habitable land surface which is forest or rangeland, wild lands, marginal lands or undeveloped lands. For lack of a more specific term, these residual lands will be called watershed lands. They include more than 80 percent of the land on earth. It is to these watershed lands that we must look for increased productivity of food, fiber, energy, and living space for our growing population, and it is these lands that currently stand in great danger all over the world.

This course is directed toward the understanding, planning, development and management of the land and water resources of watershed lands. It is aimed particularly at some of the major problems that concern the use of these lands in the developing countries.

PROBLEMS OF WATERSHED LANDS

The problems of watershed lands in the developing countries are often connected to social and economic patterns which endanger the environment. At present, three billion human beings inhabit the earth. Each day, 200,000 more individuals are added to our planet's population. By the year 2000, the population could increase to 6 billion. As the population increases pressure upon natural resources, our planet will need careful management if mankind is to survive. However, human survival alone is not enough. The developing nations are aspiring to equal economic and social standards that will require a more fair share of these resources.

Worldwide, the ratio of land to population is dwindling: in a number of countries, the amount of cultivated land per person is less than half a hectare. Only a few decades ago, food production was increased in most countries by cultivating additional hectares or by extending grazing areas. Now that option is disappearing in many regions.

At present, between 50 and 80 percent of the population of the developing nations live on watershed lands. For these millions of people, it is a fact of life that the harder they work, the poorer they get. Their land is either too steep or too dry or the soil is too poor to support more than an average level of existence for a few people. Because of increasing population and current land uses, fragile environments are being subjected to mistreatment.

As populations increase, peoples migrate into fragile areas. In the more humid regions, forested slopes are cleared for fuel, fodder and primitive cultivation. Fires are allowed to escape from fields and burn indiscriminately; forests are grazed to an extent that prevents their reproduction; networks of trails are established with no concern for the erosion hazard they create. The consequences are accelerated soil loss and land deterioration, environmental degradation, and further impoverishment of the rural inhabitants themselves. In more arid areas where cultivation or wood harvesting is not possible, overgrazing is practiced to the extent that more than 4 million square kilometers of the earth have been converted to unproductive deserts during the past fifty years.

Another problem in both humid and arid areas is the loss of the protective cover of the soil and the reduction of the soil reservoir--the principal means by which water and erosion are controlled on watershed lands. The results have been increased flooding of valleys and shifting of stream beds resulting in water and silt invading prime agricultural land, irrigation structures, reservoirs, settlements, and communications. Stream flow during dry periods becomes unreliable and insufficient for the prevention of disease, the maintenance of irrigation works, and for urban and industrial needs. Ground water levels decline, resulting in the failure of springs and wells.

EXAMPLES OF WATERSHED LANDS AND THEIR PROBLEMS

Steep and Mountainous Watershed Lands

Steep and mountainous watershed lands make up almost one quarter of the earth's land surface and are inhabited by 10 percent of the total world's population. A great proportion of these lands have mesic or humid climates, vegetative cover (often forest) with little arable soil, and low population densities. Some of the most severe problems of steep land watersheds are seen in Nepal where erosion, increased by man's activities, is contributing 250 million cubic meters of silt to the Ganetic Plain each year. According to Napli observers, the beds of the rivers in the Terai Plain of southern Nepal are rising by 15 to 30 centimeters annually which leads to flooding and changing river courses. The Kosi River, for example, has shifted its course 115 kilometers westward within the past 150 years, leaving 15,000 square kilometers of once fertile land buried under a mass of sand and rubble. This process has left 6.5 million persons homeless.

The ever increasing populations of Nepal and other countries in the region are moving further into the mountains and higher up the slopes to seek a means of livelihood. Even with the aid of terracing, which the farmers of Nepal have been practicing for centuries, these slopes are too steep and the soils too thin for intense cultivation. Nevertheless, a single acre of cultivated land must now support four people. The demands of increasing population result in the cultivation of less suitable soils and steeper lands which leads to a reduction of overall productivity in the country. In the densely populated eastern hills of Nepal, as much as 40 percent of what once was farm land has been abandoned and allowed to revert to bush because it is no longer fertile enough to support crops. These lands are the sites and sources of severe eroding, massive land slides, and severe gully erosion. However, cultivation is responsible only in part for the rapid deterioration of the watersheds. Nepal's forest lands stand in much greater jeopardy. The demands made by increasing numbers of livestock (over 15 million at present) are taking their toll on the forests of the steep hillslopes by fodder harvesting and overgrazing. Forest and range fires also present a serious problem.

In many of the steep and mountainous watershed lands of the world, the effects of timber and firewood extraction, forest clearance for cultivation, grazing, looping for fodder, and burning of the undergrowth, combined with inefficient timber utilization are causing a general degradation of the forests. The destruction of the forests of these steep and mountainous watersheds increases every year. In Nepal, for example, these lands (over 80 percent of the country) are likely to be almost totally denuded by the end of the century.

Dry Watershed Lands

Arid and semiarid regions are not often thought of as watershed lands. However, the water relationships of these regions are perhaps more critical to a greater number of people on earth than those of more humid regions. Water is always in critical balance with arid ecosystems and this balance is presently being upset by man and his animals at alarming rates over vast areas.

Dry regions cover more than one third of the earth's land surface. Slightly over half of the dry area is inhabited by 630 million people. The remainder is so dry and unproductive that it cannot support human life. The degradation of land and water resources by human activities is turning potentially productive dry lands into unproductive deserts in Asia, Africa and Latin America. This process is called desertification. It has been estimated that a collective area larger than Brazil, with rainfall above the level classified as semiarid, been degraded to desert-like conditions.

About 60 million people in the developing countries live on the semiarid region between deserts and more humid areas. Desert encroachment in West Africa has received the greatest international attention recently. Reliable reports from the Sahara estimate that 650,000 square kilometers of land suitable for agriculture or intensive grazing have been lost to that desert over the past 50 years.

One of the most outstanding examples of the problems of dry watershed lands is the Thor Desert of Western Rajasthan in India. An average of 61 people now occupy each square kilometer of these lands. A consequence of this population pressure has been the extension of cropping to submarginal lands which are fit only for forest or range. Meanwhile, as the land available for forage shrinks, the number of grazing animals swells. The area available exclusively for grazing in Western Rajasthan dropped from 13 to 11 million hectares between 1951 and 1961, while the population of goats, sheep and cattle jumped from 9.4 to 14.4 million. The livestock population is still growing. During the decade of the 1960's the cropped area expanded from 26 percent to 38 percent of the total area, squeezing the grazing area even more.

As long as current land use patterns continue, the livelihood of tens of millions living in the arid lands of India will, at best, remain at its current dismal level. At worst, a prolonged drought in the future will mercilessly rebalance the number of people with the available resources. As it is, relief programs for the arid zones are seriously draining the governments' funds and food stores.

Present land use patterns in desert environments must change so that delicate water relations are not pushed beyond their limits. As the number of people and animals living in the arid zones climbs and the quality of the land on which they must live at the same time declines, the impact will be global unless solutions are found.

Humid Tropical Watershed Lands

There is a common fallacy that the world can fall back on its tropical watershed basin lands. One quarter of the Asian, African and Latin American tropics are occupied by these lands. The Amazon Basin, for example, includes nearly 40 percent of the South American continent, yet it is inhabited by less than 3 percent of its population.

Another common fallacy is that these lands, because they support a rich and diverse plant cover, must also be suited to intensive agriculture. Unfortunately, tropical rain forests are closed systems with most of the available nutrients tied up in the vegetative canopy. The nutrients are easily released to the soil if the canopy is burned. Thus, these lands are well suited to slash and burn agriculture which has been practiced in tropical regions for thousands of years. It only becomes a serious threat when production pressures become too great to allow a long enough recovery period between slash and burn cycles. There is good evidence that these pressures were largely responsible for the collapse of several jungle civilizations, notably the Mayan civilization of Central America and the ancient Khmer Empire of Cambodia. Their agricultural practices led to cementation and loss of fertility of the lateritic soils they farmed.

Increasing demands for food and fiber are now placing pressure upon tropical watershed lands on a global scale. In eastern Nigeria, for instance, the most densely populated part of Africa south of the Sahara, shifting agriculture has been forced into shorter and shorter rotation cycles to the point that it has become continuous cropping. The result is a loss of nutrients and breakdown of the soil structure. This decline has been severe in Africa where per capita food production has actually declined over the past twenty years.

One of the best examples of the problems of tropical watershed lands are those in the Amazon basin. Most of the soils of the Amazon basin are poor and could perhaps best be exploited through forestry or nonagricultural practices. Only about 4 percent of the Brazilian portion of the Amazon have soils with medium to high fertility. Most of the better soils are in narrow plains along the banks of rivers, and their development for large scale agriculture will require large expenditures for drainage and flood control. Nevertheless, the Amazonian governments have programs to help new farmers from other regions settle in the basin. Since 1971, fifty thousand families have settled along a proposed highway between Peru and the Atlantic. With few financial and administrative resources, and less knowledge of tropical farming techniques, even the most successful produce at subsistence levels. It is probable that many more colonists will find it impossible to make a living and will abandon their plots after the soil has been severely degraded by over-intense, inappropriate cultivation.

THE WATERSHED OR A UNIT FOR DEVELOPMENT

The fundamental unit of water resource management is the watershed basin. It may be a catchment area for the precipitation provided to stream channels or a larger basin which contributes water to a particular river channel or set of river channels. Biologists, ecologists, and biogeographers have turned to the watershed as an ideal unit in which to develop the ecosystem approach. Systems engineers and economists view the watershed as the basis for study and development in terms of river basin planning for economic development. Hydrologists and engineers consider the watershed to be a system within which a balance can be struck between inflow and outflow of water and energy.

The term watershed implies a domain or system within boundaries. The boundaries may be physical ones, such as watershed divides, or they may be defined by processes such as runoff. The watershed domain may be further divided into subcomponents of smaller watersheds or into subprocesses such as overland flow. Watersheds may be controlled with physical structures such as the series of dams operated by the Tennessee Valley Authority in the United States or uncontrolled as are most watersheds in developing countries.

In a social science context, the watershed has recently emerged as a logical unit of understanding and policy making. This emergence is closely connected, in the course of general economic development, with technological change and shifting demands for the main products of a watershed: hydroelectric power, water, timber, livestock, agricultural crops and the amenities.

THE ROLE OF THE WATER RESOURCE MANAGER

The water resource manager may be asked to control a watershed to meet some objective through the application of upstream treatments. His objectives may be to: increase water yields, provide a dependable supply of water for downstream use, improve forest, range and small farm production on the watershed, maintain a specified standard of water quality, reduce erosion and flood hazard, or enhance recreation and wildlife on the watershed. These tasks might involve the selection of appropriate cover types, harvesting methods, and plant cover or crop management systems. The water resource manager may have to consider the feasibility of reservoirs in combination with upstream watershed structures and land treatments. The development of surface or ground water for human and/or animal use or small scale irrigation may also be one of his responsibilities. The water resource manager must be knowledgeable in hydrology and he must be always aware of the needs, customs and traditions of the people who live within and depend directly upon the watershed areas for their livelihoods. The lives of those people living downstream from a watershed are also affected by its multiple and integrated products. Perhaps the most important task of the water resource manager is to apply his skills toward solving, in ways which will be of greatest benefit to mankind, the numerous problems associated with land use which currently threaten large areas of the earth.

It is the task of the water resource manager to reduce this impact, but simply creating new sources of water will not solve the problem. In fact, the development of water in dry environments is often a major cause of desertification. With water, livestock numbers inevitably increase, and each new watering spot becomes a nucleus for further expanding the desert. The water resource manager in dry environments must not only know the techniques of water development, but must confront the dilemma of: what is essential to the survival of society over the long term is usually contrary to what is essential to the survival of the individual over the short term.

The watershed manager in humid, tropical watershed lands must know small farming practices and alternatives to these practices, transport systems and economic marketing, and the hydrology and soils of humid tropical regions. In steep or mountainous regions, he must be familiar with the techniques of erosion control, reforestation, and forest management. He must deal with the problems of shifting cultivation, fuel wood harvesting, and forest grazing. Groundwater development and stream control may be an important part of his job.

THE DEVELOPMENT OF WATER RESOURCES

There is clear evidence that the physical potential exists on earth to feed a much larger population than now lives here. Despite this encouragement, it must be remembered that the resources of individual countries vary widely. Even India is capable of producing much more food than is now being grown because of its abundant sunlight and deep soils.

Water resource development takes a long time before it yields benefits. Political leaders in both the rich and poor countries have short term goals. They focus on immediate and popular concerns. Yet the conservation and production of the resources of watershed lands depend on long term and expensive commitments. Both the developed and developing countries must be ready to make this commitment to the development of the world's watershed lands if future worldwide disaster is to be avoided.

It is important to recognize that the problems of watershed lands do not necessarily arise from physical limitations nor from lack of technical knowledge. The limitations on production and abundance are found in the political and social structures of nations and the economic relations among them. The resources are there, and their successful development depends upon the will of men. The water resource manager can help strengthen this will by presenting and implementing good, practical solutions for developing the productivity of watershed lands which will provide the greatest benefit to man in the long run.

It must be pointed out that solutions do exist. Much is known and much more remains to be learned. The problems are complex and touch sensitive areas of the political, economic and technological structures of nations. Solutions will not be easy to find. They will require knowledge, imagination and courage: but they can be obtained when the best minds endeavor to develop wise policies that will also be acceptable to the public.

This course has been developed for medium level technicians and professionals engaged in the management and development of watershed lands in developing nations. A major aim of this syllabus is to provide the water resource technician or manager with information which will help him improve present land use practices and inform him of other concepts and techniques in land and water use.

It should be understood that because of the large scope of this syllabus, exact solutions to each specific problem of watershed lands as they may exist under the physical, social and economic conditions in each of the developing nations cannot be given.

Watershed lands are defined broadly as habitable areas of the earth, but do not include well defined agricultural lands, urban areas, or special reserve areas. Because the production from these lands is linked with water, a basic portion of the course will deal with fundamentals of hydrology; and, because most of the problems in develop-ing the multiple products of watershed lands are of social and economic origin, the course will emphasize this aspect of development.

CHAPTER II

STATISTICAL METHODS

INTRODUCTION

To many, statistical methods and procedures appear to limit progress. At the very least, people may be frustrated when attempting to apply statistical methods and procedures to interpret statistical analyses.

Much of the above-mentioned difficulty may be due to not understanding the basic objectives of statistics. Essentially, two primary objectives exist: to estimate population parameters and to test hypotheses about these parameters.

An example of the first objective is the application of statistical techniques to estimate the mean (average) of a population. The statistician's job is to derive proper methods of collecting the required source data and, then, calculating the desired statistic (*e.g.*, the estimated population mean).

An example of the second objective is to test the hypothesis (theory) that the estimated population mean equals or exceeds a predetermined value. It is the statistician's job to develop appropriate tests of hypotheses to satisfy this objective. Here, emphasis will be placed on the first objective, specifically, to develop estimates of population parameters from a series of random values obtained from a sample of a population.

DEFINITIONS

To apply statistical methods and procedures to natural resource management problems, it is necessary to develop a working knowledge of the terms commonly employed in statistics.

The term *statistics*, for instance, has two accepted meanings. Statistics (plural) refers to the collection or organization of source data (*i.e.*, annual lumber production in Arizona). Statistics (singular) is the science of analyzing the collected measurements and, guided by the results of the analysis, inferring general truths.

A complete aggregate of individuals or items in one category is a *population*. An *infinite* population is composed of practically an unlimited number of individuals or items; while, a *finite* population is made-up of a limited number of individuals or items

A *population parameter* (*i.e.*, the mean) is a quantitative characteristic which describes a population. A *statistic* is a quantitative characteristic which describes a sample obtained from a population. Statistics based on samples are used to estimate population parameters.

Measurements or observations of small portions of a population is a *sample*. It is not information about the sample which is being sought, rather, about the population from which the sample was taken. The assumption is made that information obtained from a sample also holds for the population.

A measurable characteristic which varies in amount or magnitude (tree volume *etc.*) is a *variable*, or variate. Variables that are capable of exhibiting every possible value within any specified range are *continuous* variables; variables that are manifested in limited graduations or isolated values are *discrete* variables, or discontinuous variables. A variable of an associated pair whose value is considered to depend upon that of the other variable in the pair is a *dependent* variable; a variable of an associated pair whose value is considered to determine (or predict) that of the other variable in the pair is an *independent* variable. (In some cases, two or more independent variables can be used in association with one dependent variable.) The definitions of other terms relevant to statistical methods and procedures may be found in standard references dealing with statistical techniques.

DISTRIBUTION FUNCTIONS

A definite pattern of frequency of occurrence of units of each of a series of equal classes is a *frequency distribution function*. A frequency distribution function shows, for a population, the relative frequency with which different values of a variable (X) occur. By knowing the frequency distribution function, it is possible to determine what proportion of the individuals are within certain size limits.

Each population has its own distinct frequency distribution function. However, there are certain general types of functions that occur quite often. The most common are the normal, the binomial, and the Poisson. The *normal frequency distribution*, which is the familiar bell-shaped distribution, is widely used in statistical analyses of watershed resources measurement (Figure 1). Theoretically, the normal frequency distribution exhibits the following properties: the mean, median, and mode are identical in value; small variations from the mean occur more frequently than large variations; and positive and negative variations about the mean occur with equal frequency.

The *binomial frequency distribution* is associated with data where a fixed number of individuals are observed on each unit and the unit is characterized by the number of individuals having some particular attribute. The *Poisson frequency distribution* may arise where individual units are characterized by a count having no fixed upper limit, particularly if zero or very low counts tend to predominate.

In addition to knowing the relative frequency that different values of a variable (X) occur in a population, one may also wish to know what proportion of a population lies between specified limits of X. For example, a watershed resources manager might wish to know what proportion of all precipitation events occurring on a river basin lie within a particular interval of X values, where the interval of X values defines a range in precipitation amounts. To obtain this sort of information, it is necessary to construct a *cumulative frequency distribution* function. Normally, to develop a cumulative frequency distribution function, values of X are cumulated starting with the smallest value of X and proceeding to the largest value (Figure 2). Cumulative frequency distribution functions that are developed by starting with the largest value of X and proceeding to the smallest value are commonly referred to as *exceedence curves*.

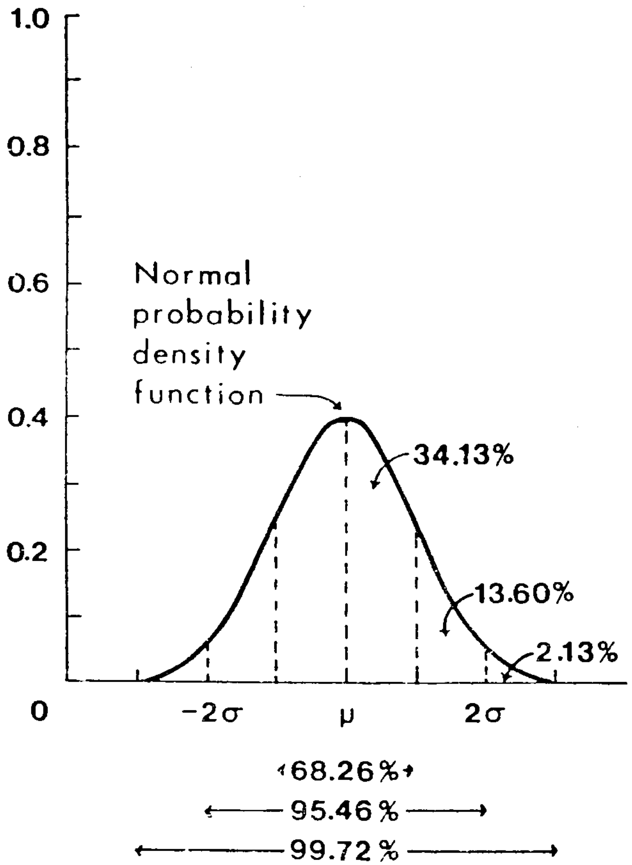
BASIC TERMS AND CALCULATIONS

To develop an understanding of statistical methods and procedures, it is important to obtain a working knowledge of basic terms and calculations.

Measures of Central Tendency

Many problems in natural resource measurements require the determination of a central value of a series of random values obtained from a sample of a population. Often, some kind of "average" is desired, but this is not the only measure of central tendency.

Perhaps the *mean* (or average) is the most familiar and commonly used measure of central tendency. Given source data obtained from a simple random sample (note: all statistical formulae described in this chapter have their roots in simple random sampling), the mean is calculated as follows:



'igure 1. The normal frequency distribution function.

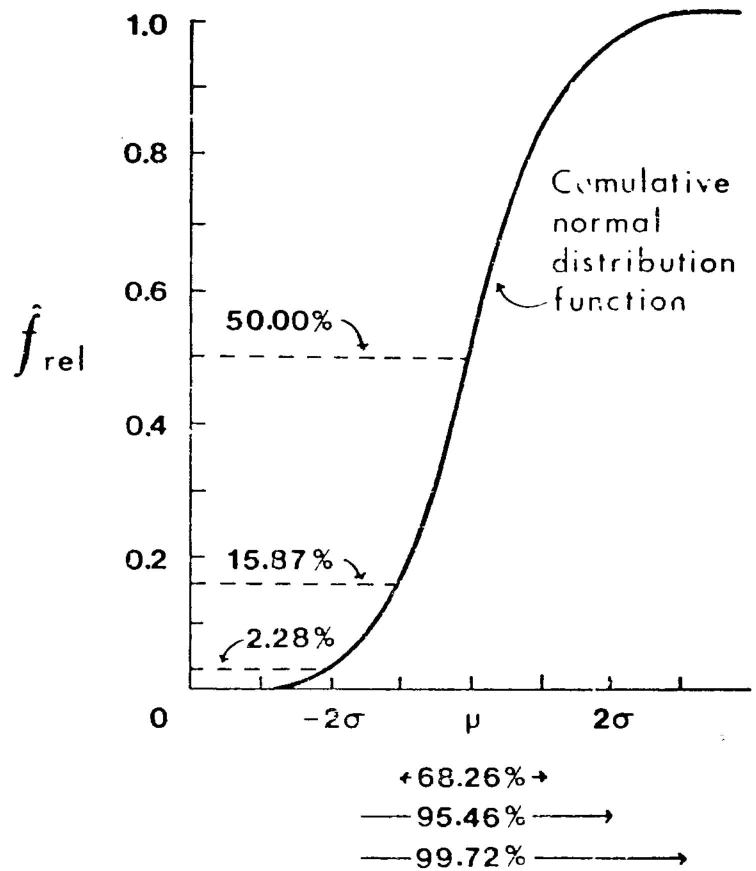


Figure 2. The cumulative frequency distribution function.

$$\bar{x} = \frac{\Sigma x}{n}$$

where:

$\bar{x}$ = estimated population mean
x = individual random value in the sample series
n = number of random values in the sample series (*i.e.*, sample size).

Another measure of central tendency is the *median*. The median of a series of random values obtained from a sample of a population, arranged (ranked) in order of size, is the value halfway through the series. If the number of random values is odd (3, 5, 7, *etc.*), little problem exists in selecting the median. However, if the number of random values is even (4, 6, 8, *etc.*), the "true" median is the value halfway between the two central values.

Still another measure of central tendency is the *mode*. When a series of random values is arranged by classes and frequencies (*i.e.*, a frequency distribution), in many cases one class (or a few classes) show the highest frequency of occurrence. The class (or classes) with the highest frequency of occurrence indicates the mode (or modes).

In applying statistical methods and procedures to natural resource measurement problems, it is often assumed that the basic measurements exhibit a normal frequency distribution. With a normal frequency distribution, the mean, median, and mode are identical. However, if the basic measurements are not normally distributed, these measures of central tendency are not identical. In these latter instances, care must be exercised to select the measure of central tendency most appropriate to the specific problem.

Measures of Dispersion

Measures of central tendency are fundamental descriptions of a series of random values obtained from a sample of a population. However, other measures may also be necessary for a "finer" definition of a series of random values. Measures of dispersion (or variability) serve this purpose since they define the extent to which individuals in a series vary from the central tendency.

The *range* represents the total interval between the smallest and largest values in a series of random values obtained from a sample of a population. It gives preliminary information on dispersion of random values in a series.

Perhaps the most important measure of dispersion is the *variance*, which characterizes the variability of individual random values about the mean. This measure gives an idea of whether most individuals in a series are close to the mean, or spread out. Given basic source data obtained from a simple random sample, the variance is calculated as follows:

$$s^2 = \frac{\Sigma(x - \bar{x})^2}{n - 1}$$

where:

s^2 = estimated variance

and the other terms are defined as above.

Another mathematical expression of the variance, and a formula more easily solved, is:

$$s^2 = \frac{\Sigma x^2 - \frac{(\Sigma x)^2}{n}}{n - 1}$$

where all terms are defined as above. The square root of the variance (s) is the *standard deviation*, which is used in calculating the coefficient of variation, among other statistics.

Generally, a series of random values obtained from a sample of a population which exhibits a large mean shows more variability than a series of values from a population with a small mean. The *coefficient of variation* facilitates comparisons of variability about different sized means. It is a measure of relative variability. Given basic data obtained from a simple random sample, the coefficient of variation is calculated as follows:

$$CV = \frac{s}{\bar{x}}$$

where:

CV = estimated coefficient of variation
s = standard deviation (square root of the variance)
$\bar{x}$ = estimated population mean

Usually, there is variation among the individuals in a series of random values obtained from a sample of a population, which can be measured by calculating the variance. It is conceivable, therefore, that variation may also exist among a series of estimated means calculated from a set of different random samples obtained from a population. The *standard error of the mean* is a measure of dispersion among different sample means, just as the variance is a measure of dispersion among individuals in a series of random values.

Fortunately, it is not necessary to take many different random samples to calculate the standard error of the mean. A satisfactory estimate can be calculated directly from a single sample.

The calculation of the standard error of the mean depends on how the random sample was selected. If the sample was drawn from an infinite population (*i.e.*, a population that is large relative to the sample size), and given basic data obtained from a simple random sample, the standard error of the mean is calculated as follows:

$$s_{\bar{x}} = \sqrt{\frac{s^2}{n}} = \frac{s}{\sqrt{n}}$$

where:

$s_{\bar{x}}$ = estimated standard error of the mean

and the other terms are defined as above.

Confidence Limits

The statistical way of indicating the reliability of an estimate of a population parameter (a statistic) is to establish *confidence limits*. For an estimate of a population parameter made from a normally distributed population, and given basic source data obtained from a simple random sample, confidence limits about an estimated mean are calculated as follows:

$$CI = \bar{x} \pm (s_{\bar{x}})(t)$$

where:

CI = estimated confidence limits
$s_{\bar{x}}$ = estimated standard error of the mean
t = tabular value (Table 1) used to define a statement of the level of probability for statistical inferences.

Table 1. The Distribution of the t Statistic

	Probability		
df	0.1	0.05	0.01
1	6.314	12.706	63.657
2	2.920	4.303	9.925
3	2.353	3.182	5.841
4	2.132	2.776	4.604
5	2.015	2.571	4.032
6	1.943	2.447	3.707
7	1.895	2.365	3.499
8	1.860	2.306	3.355
9	1.833	2.262	3.250
10	1.812	2.228	3.169
11	1.796	2.201	3.106
12	1.782	2.179	3.055
13	1.771	2.160	3.012
14	1.761	2.145	2.977
15	1.753	2.131	2.947
16	1.746	2.120	2.921
17	1.740	2.110	2.898
18	1.734	2.101	2.878
19	1.729	2.093	2.861
20	1.725	2.086	2.845
25	1.708	2.060	2.787
30	1.697	2.042	2.750
∞	1.645	1.960	2.576

The Distribution of t

A portion of the distribution of the t statistic is given in Table 1. To use with a simple random sample, the column labeled *df* (degrees of freedom) will equal one less than the sample size (n - 1). The columns labeled *probability* refer to the odds specified. In the development of confidence limits at the 90 percent probability level, for instance, the t values in the 0.10 column are used. If confidence limits at the 95 percent probability are specified, the 0.05 column is used *etc.*

SAMPLING TECHNIQUES

Obviously, it may be desirable to have a complete census of a population. A complete enumeration is rarely possible, however, and a sample is usually taken.

Sample Size

Samples cost money, but so do errors. The primary objective of sampling is to take enough observations to obtain a desired level of precision--no more, no less. The number of observations to be taken in a sample depends upon two factors: the inherent variability of the population being sampled and the desired level of precision (*i.e.*, sampling error).

The equation used to calculate a sample size is derived by transforming the relationship expressing the confidence limits for the mean. Here, it is desired to have the product $(s_{\bar{x}})(t)$ equal to or less than some arbitrarily specified level of precision. Thus:

$$E = (s_{\bar{x}})(t)$$

where:

E = specified level of precision

and the other terms are defined as above. This relationship may also be expressed as follows:

$$E = \sqrt{\frac{s^2}{n}}\,(t)$$

The equation used to calculate a sample size is derived by squaring all of the terms in the above relationship, and then solving for n (the sample size). Therefore, assuming that a simple random sample will be implemented, the sample size is calculated as follows:

$$n = \frac{(s^2)(t^2)}{E^2}$$

where:

n = sample size

and the other terms are defined as above. To calculate sample size, it is necessary to have an estimate of the variance, which can be obtained from a preliminary sample of the population. Also, a t value at the appropriate level of probability is needed and the level of precision must be specified.

Size and Shape of Individual Sample Units

The size and shape of the individual sample units affect the cost and precision of sampling. Often, small plots exhibit more variability than large plots and, in many instances, circular plots may be easier to establish than rectangular plots. It is necessary, therefore, to select the size and shape of individual sample units that are compatible with the sampling objectives and the inherent variability of the population being sampled.

Sampling Designs

After computing the sample size and selecting the appropriate size and shape of the individual sample units, it becomes necessary to allocate the sample units to obtain source data necessary to estimate the required population parameters. The problem is to decide on the most efficient sampling design in terms of the sampling objectives and the characteristics of the population.

Many sampling designs and variations of sampling designs exist. Three basic sampling designs often employed in natural resource measurements are: simple random sampling, stratified random sampling, and systematic sampling.

The fundamental idea behind *simple random sampling*, when allocating a sample of n units is that every possible combination of n units has an equal chance of being selected. And, the selection of any given sample unit is completely independent of the selection of all other units. (All of the statistical methods and procedures previously discussed in this chapter have their roots in simple random sampling.)

Often, previous knowledge of a population can be used to increase the precision, or usefulness, of a sample. *Stratified random sampling* takes advantage of certain types of information about a population by grouping homogeneous units of a population together on the basis of some characteristic (vegetation, cover type, age class, utilization class, *etc.*). Then, each unit, or stratum, is sampled (using a simple random sampling design) and the group estimates are combined to estimate population parameters.

As the name implies, sample units in a *systematic sample* are allocated, not randomly, but mechanically, according to a predetermined pattern. Systematic sampling has been widely used in natural resource measurements for two reasons: the location of individual sample units in the field is often easier and cheaper, and there is a feeling that a sample deliberately spread out over a population may be more "representative" than a simple random sample. Statisticians may not argue against the first reason, but they are less willing to accept the second. Estimation of sampling errors of a sample requires more knowledge about a population than is usually available.

REGRESSION ANALYSES

An important statistical tool often used in analyzing natural resource measurements is *regression analysis*. The basic objective of regression analysis is to quantify relationships between two or more variables.

A *simple regression* defines the relationship between a dependent variable (Y) and one independent variable (X). A simple *linear* regression is used with a straight-line relationship between two variables. Other simple regression analyses may involve nonlinear relationships (parabolic, exponential, logarithmic, *etc.*).

The general model for a simple regression is:

$$Y = a \pm b\ (X)$$

where:

Y = dependent variable
X = independent variable
a,b = regression coefficients estimated by statistical formulae, as given below:

$$b = \frac{\Sigma(XY) - \frac{(\Sigma X)\ (\Sigma Y)}{n}}{\Sigma X^2 - \frac{(\Sigma X)^2}{n}}$$

$$a = \overline{Y} - b(\overline{X})$$

There are several methods of determining "how well" a regression line fits the sample data. Often, the coefficient of determination (r^2) is calculated, as follows:

$$r^2 = \frac{(\Sigma(XY) - \frac{(\Sigma X)\ (\Sigma Y)}{n})^2}{(\Sigma X^2 - \frac{(\Sigma X)^2}{n})\ (\Sigma Y^2 - \frac{(\Sigma Y)^2}{n})}$$

One common means of interpreting the coefficient of determination is: if the r^2 value is 0.65, "65 percent of the variation in Y is associated with X." For example, 65 percent of the variation in annual precipitation amount is "explained" by elevation.

Frequently, the dependent variable is related to more than one independent variable. If this relationship can be estimated, using *multiple regression* analysis, it may allow more precise predictions of the dependent variable than is possible by a simple regression.

The general model for a multiple regression is

$$Y = a \pm b(X_1) \pm c(X_2) \pm \ldots$$

where:

a,b,c = estimated regression coefficients.

KEY TO BASIC STATISTICAL TESTS

Many of the foregoing definitions are basic. The concepts presented are quite general and underlie most of statistical theory. Little has been offered in terms of specific direction for the user. Obviously, further and more specialized training is one remedy. However, until this is obtained, there are several points that a user should consider to improve his general statistical performance:

(1) First, and probably most importantly, *understand the method you intend to use*. It should be evident that statistics is an extensive and complex subject. In fact, statisticians are often unsure of their own conclusions and commonly discuss

them with their colleagues for verification. So, *be sure that you know the method thoroughly;* then, you will be much less likely to misuse it.

(2) *Keep it simple.* Where there is a choice, use the simpler method. There is no need to apply the latest analysis tool if an older, simpler one tells us what we want to know. Furthermore, there is less chance of going wrong when the simpler method is used.

(3) *Plan ahead.* To obtain an adequate performance, planning must be done at the outset. Be sure to allow enough time for all aspects of an investigation. Unfortunately, a common practice is to leave analysis and interpretation to a time when there is no possible way to do an adequate job.

(4) *Adopt a critical attitude* when examining the results of an analysis. Try to let the data (rather than your preconceptions) lead your thoughts.

(5) *Statistical analysis cannot be completely reduced to a routine process.* In particular, do not be led astray by "computer analysis" packages. While many computer programs are good tools, it should be kept in mind that computers do not analyze --and they never will. Become familiar with programs which are useful, but do not surrender your analyses to them.

(6) *Respect your professional judgment.* Your training and experience give you an ability to see the elements and relationships in your science and profession better than a layman.

To assist watershed resources managers in selecting the appropriate statistical test to apply in given situations, the following key to basic statistical tests is presented. While this key includes many of the commonly employed statistical methods and procedures available for consideration, the user is advised to consult statistical references before making a final decision as to approach in analyses.

Step Number	Go to Step Number
1. Enumeration (or attribute or discrete) data only	2
1. Continuous (or measurement) data; or both continuous and enumeration data	4
2. Only two criteria of classification for each attribute . . . . CHI-SQUARE 2x2	
2. More than two criteria of classification for one or more of the attributes	3

Step Number		Go to Step Number
3.	Two criteria for one attribute, more than two for the other . . . . . . CHI-SQUARE Rx2	
3.	More than two criteria for each attribute . . . . CHI-SQUARE RxC	
4.	One group of sampling units	5
4.	Two or more groups of sampling units	8
5.	Two variables measured in each sampling unit	6
5.	More than two variables measured in each sampling unit . . . MULTIPLE REGRESSION	
6.	Neither variable dependent on the other . . . . CORRELATION	
6.	One variable dependent on the other	7
7.	Straight line relation between variables . . LINEAR REGRESSION	
7.	Curved line relation between variables. CURVILINEAR REGRESSION	
8.	One variable measured for each sampling unit	9
8.	Two or more variables measured for each sampling unit	12
9.	Only two groups of sampling units	10
9.	More than two groups of sampling units . . . . . ANALYSIS OF VARIANCE	
10.	Individuals from one group paired with those in the other. t-TEST, PAIRED INDIV	
10.	Individuals not paired	11
11.	Groups of equal size . . . . . t-TEST, EQUAL GROUPS	
11.	Groups of unequal size . . . . t-TEST, UNEQUAL GROUPS	
12.	Two variables measured in two or more groups . . . . COVARIANCE	
13.	Three or more variables measured in two or more groups . MULTIPLE COVARIANCE	

CHAPTER III

THE HYDROLOGIC CYCLE

INTRODUCTION

The hydrologic balance or water budget is both a fundamental concept of hydrology and a useful method for the study of the hydrologic cycle. The hydrologic cycle represents the processes and pathways involved in the circulation of water from land and water bodies, to the atmosphere and back again (Figure 1). The cycle is complex and dynamic but can be simplified if we categorize components into input, output or storages. Input such as rainfall, snowmelt and condensation must balance with changes in storage and with outputs which include streamflow, groundwater, and evapotranspiration. The water budget is essentially an accounting procedure which quantifies and balances these components.

The quantities of water in the atmosphere, soils, groundwater, surface water and other components are constantly changing because of the dynamic nature of the hydrologic cycle. At any one point in time, however, quantities of water in each component can be approximated. If we consider the total water resource on the earth, only about 3 percent is fresh water. About 77 percent of this fresh water is tied up in the polar ice caps and glaciers, and 11 percent is stored in deep groundwater aquifers, leaving 11.6 percent for active circulation. Of this 11.6 percent, only 0.55 percent exists in the atmosphere and biosphere (from the top of trees to the lowest roots). The atmosphere redistributes evaporated water by precipitation and condensation. Components of the biosphere partition this water into runoff, soil water storage, groundwater or back to the atmosphere.

The hydrologic processes of the biosphere and the effects of vegetation and soils on these processes are of particular interest to watershed managers. Processes such as precipitation, infiltration, percolation, evaporation, transpiration, surface-runoff, subsurface flow and groundwater flow can all be affected by land management activities. Likewise, man can alter the magnitude of various storage

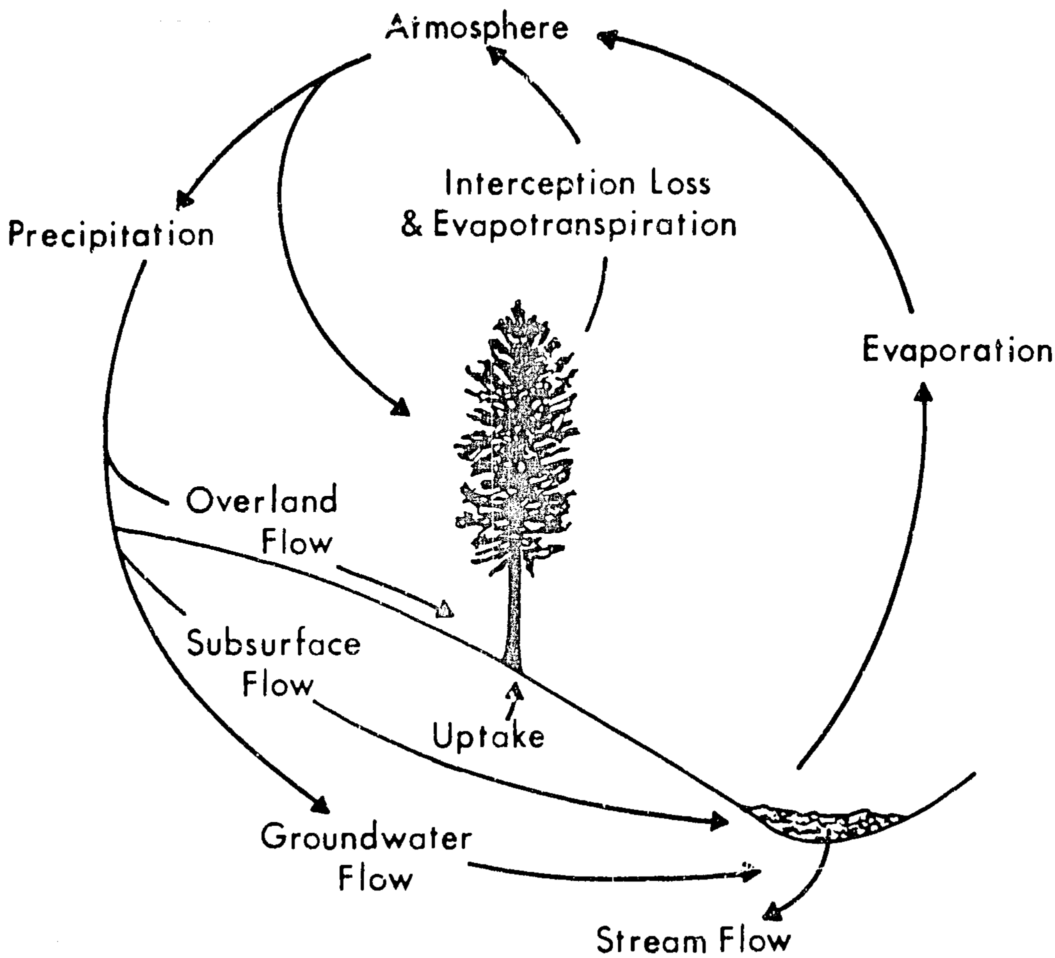


Figure 1. The hydrologic cycle.

components including soil water, snowpacks, lakes, reservoirs and rivers. With a water budget we can examine existing watershed systems, quantify the effects of management impacts on the hydrologic cycle and in some cases predict or estimate the hydrologic consequences of proposed or future activities.

HYDROLOGIC PROCESSES

Precipitation

Precipitation occurs when three conditions in the atmosphere are met: (1) the atmosphere becomes saturated, (2) small particles or nuclei are present in the atmosphere upon which condensation or sublimation can take place, and (3) water or ice particles must unite and grow large enough to fall under the influence of gravity. Saturation results when either the air mass is cooled until the saturated vapor pressure is reached or when moisture is added to the air mass. Rarely does the direct introduction of moist air cause precipitation. More commonly precipitation occurs when an air mass is lifted, becomes cooled, and reaches its saturated vapor pressure. Air masses are lifted as a result of (1) frontal systems, (2) orographic effects, or (3) convection. Different storm and precipitation characteristics result from each of these lifting processes.

Frontal precipitation occurs when two air masses of different temperature and moisture content are brought together by general circulation and air becomes lifted at the frontal surface. A *cold front* results from a cold air mass replacing and lifting a warm air mass. Conversely, a *warm front* results when warm air rides up and over a cold air mass. Cold fronts are characterized by high intensity rainfall or relatively short duration and usually have less areal extent than warm fronts. Widespread, gentle rainfall is more characteristic of warm fronts.

Orographic precipitation occurs when an air mass is forced up and over mountain ranges as a result of general circulation. As the air mass becomes lifted, a greater volume of the air mass reaches saturation vapor pressure resulting in a general increase in precipitation with increasing elevation. Once the air mass passes over mountains, a lowering and warming of the air occurs. This results in a rain shadow effect on the leeward side of mountain ranges.

Convective precipitation, as characterized by summer thunderstorms, is the result of excessive heating of the earth's surface. When the air adjacent to the surface becomes warmer than the air mass above, lifting occurs. As the air rises and condensation takes place, the latent heat of vaporization is released, more energy is added to the air mass and consequently more lifting occurs. Rapidly uplifted air can reach high altitudes where water droplets become frozen and hail forms or becomes intermixed with rainfall. Such rain or hail storms are of the most severe precipitation events anywhere. High intensity, short duration rainfall over rather limited areas characterize convective storms. Numerous thunderstorms can occur over a widespread area, however, and can cause flash flooding.

Interception--Net Precipitation

Once rainfall or snowfall has occurred, the type, extent, and condition of vegetation can strongly influence where and how much precipitation reaches the soil surface. Dense coniferous forests in northern latitudes and the multi-storied canopies of the tropics can catch and store large quantities of precipitation which ultimately evaporate and are lost from the watershed. In the tropics, over 70 percent of the annual precipitation may be lost via interception. As we proceed to more arid or semi-arid environments, and more sparse vegetation, the interception losses become less important. Although we generally consider forests to have the highest interception losses, at times, grasses may intercept 10 to 20 percent of gross precipitation.

Not all the precipitation which is caught by a forest canopy is lost to the atmosphere. Much may drip off the foliage or run down the stems and thereby reach the soil surface. Conversely, not all the precipitation that penetrates the forest canopy becomes available for either soil water or runoff. The litter which accumulates on the forest floor can store large quantities of precipitation which ultimately evaporate.

In most water budget studies, interception loss is considered to be an important storage term which should be subtracted from gross precipitation. The result is *net precipitation*, or that amount of precipitation that is available to either replenish soil water deficits or become surface, subsurface or groundwater flow out of the system.

Movement of Water Into and Through the Soil

The rate of new precipitation, once it reaches the forest floor or soil surface, depends upon the soil surface conditions and the physical characteristics of the soil itself. Of primary interest are those factors which affect the rate at which water can enter the soil and the subsequent rate of movement through the soil.

Plant material or litter on the soil surface influences the amount and rate of movement of water into the soil surface. Litter can be viewed as two hydrologically distinct layers: (1) an upper horizon composed of leaves, stems and other undecomposed plant material, and (2) a lower horizon of decomposed plant material which behaves much like mineral soil. The upper horizon protects the soil surface from the energy of raindrop impact which could displace smaller soil particles into voids and effectively seal the soil surface. Plant debris also hinders any surface runoff which might occur and, in effect, minimizes overland flow. The lower horizon has a substantial storage capacity, over 200 percent by weight in some instances. Thus plant litter is important as both a storage component and as a protective cover which maintains an "open" soil surface condition favorable for high rates of water entry into the surface.

The process by which water enters the soil surface is called *infiltration*. Infiltration results from the combined forces of capillarity and gravity. If we applied water to a dry, medium textured soil, a very rapid initial infiltration rate would be observed. This high initial rate is due to the strong physical attraction of soil particles to water (capillarity). As time proceeds and the soil water content increases. the rate of infiltration eventually becomes a constant. At this time, infiltration is only as rapid as the rate which the soil can drain under the influence of gravity. The process of saturated flow through the soil mantle under gravitational forces is called *percolation*.

Evapotranspiration

Evaporation from soils, plant surfaces and water bodies, and transporation through plant stomata are often considered collectively as evapotranspiration (ET). Evapotranspiration is of particular interest to watershed managers because it strongly affects the water yield characteristics of an area and is often influenced by forest and range management practices.

The evaporation process is simply the net loss of water from a surface by means of a change in state of water from liquid to vapor. The requirements for evaporation or transpiration are:

(1) a flow of energy to the evaporating or transpiring surface;
(2) a flow of vapor away from these surfaces; and
(3) a flow of liquid water to these surfaces.

If one or more of these flows are changed, there is a corresponding change in the total ET loss from a surface. Conditions that control the net flow of energy by radiation, convection, and conduction to evaporating surfaces determine the amount of energy available for the latent heat of vaporization. The albedo or reflectivity of the evaporating surface determines the proportion of incident solar radiation that is absorbed by the surface. This absorbed solar radiation plus the net longwave radiation constitutes the net all-wave radiation which is available to evaporate water, heat the air, or heat the soil system. When water is readily available, most of this net radiation is utilized in the ET process. Some studies have shown that over 80 percent of net radiation is utilized in ET for well-watered soils with a dense vegetative cover. As water becomes limiting, a greater proportion of the net radiation goes into heating the air and soil surfaces.

Runoff

Runoff refers to the various processes and pathways by which excess water becomes streamflow. Excess water represents that part of total precipitation which runs off the land surface and that which drains from the soil and is thus not consumed by ET. Some water flows rather quickly to produce streamflow yet other pathways have a detention storage time which may take weeks or months for excess precipitation to show up as streamflow. If we were to identify the major pathways of flow and compare these with a streamflow hydrograph (the graphical relationship of streamflow discharge (m^3/sec) plotted against time) from a watershed, the runoff process can be somewhat simplified (Figure 2).

A perennial stream, *i.e.*, one which flows throughout the year, is most likely being fed by groundwater, pathway "D" (Figure 2). This component sustains streamflow between periods of precipitation or snowmelt. Because of the long and tortuous pathways involved, groundwater flow, hence baseflow, does not respond quickly to moisture input.

Once rainfall or snowmelt occurs, several additional pathways of flow feed streamflow. The most direct pathway from precipitation to streamflow is that part which falls directly into the stream channel, called *channel interception* (A in Figure 2). This component causes the initial rise in the streamflow hydrograph and ceases soon after precipitation stops. *Surface runoff* or *overland flow* occurs from impervious areas or areas in which the rainfall rate exceeds the infiltration capacity of the soil (B). Some surface runoff is detained by the roughness of the soil surface, but nevertheless represents a quick flow response to moisture input, second only to channel interception. During a rainstorm, this component of the hydrograph would be relatively large for urban areas but typically insignificant for forested areas with deep soils.

Subsurface flow or *interflow* is that part of precipitation which infiltrates, yet arrives at the stream channel over a short enough time period to be considered a part of the storm hydrograph, illustrated as pathway "C" (Figure 2). This is considered to be the major contributing pathway of storm hydrographs from forested watersheds.

The sum of channel interception, surface and subsurface flow is called *direct runoff* or *stormflow*. Direct runoff is the part of the hydrograph of interest when we look at the flood-producing characteristics of most watersheds.

Although we can conceptually visualize the four major pathways of flow, subsurface flow is particularly difficult to measure or separate from the others. Also, the actual pathway from rainfall to

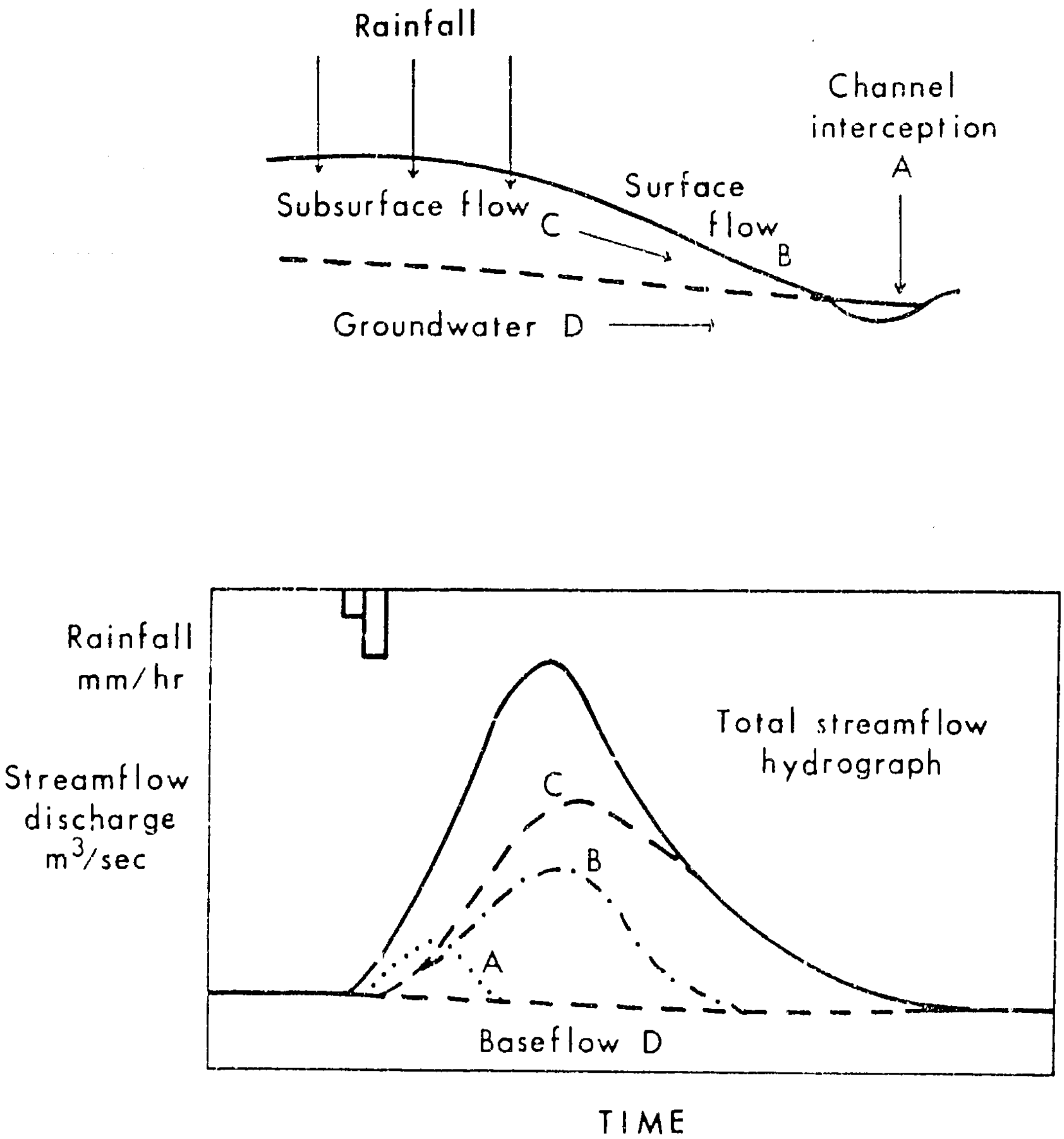


Figure 2. The relationship between pathways of flow from a watershed and the resultant streamflow hydrograph.

streamflow may in reality involve surface and subsurface flow. Water may infiltrate in one area and exfiltrate downslope and run over the land surface for some distance. Conversely, some surface runoff may collect in depressions in the land surface to be evaporated or infiltrated at some later time. By viewing the total streamflow hydrograph, therefore, we are seeing the total integrated response of a watershed to some quantity of moisture input.

WATER BUDGET CONCEPT

The water budget is simply an application of the conservation of mass principle to the hydrologic cycle. That is, for a given watershed and a certain time interval:

$$I - O = \Delta S$$

where:

I = inflow of water to the system
O = outflow of water from the system
ΔS = change in storage of the volume of water in the system.

Substituting with the hydrologic components of a watershed or river basin, the above relationship for a given time interval becomes:

$$P - (Q + ET) \pm L = \Delta S$$

where:

P = total precipitation
Q = total runoff or streamflow, including measured groundwater flow
ET = total evaporation and transpiration losses
L = leakage out of the system by deep seepage (-) or leakage into the system (+) from an adjacent watershed
ΔS = change in storage in the system

Water budgets can be determined for small plots, headwater drainages, large river basins or even continents. If a water budget was to be determined over one year for all land and water areas, the total change in storage would usually be very small.

By looking at the ratio ET/P we can make relative comparisons of the abundance of water. A high ratio indicates a more arid climate (Australia), a lower ratio a more wet climate (Europe). Water budgets for such large areas do not tell us anything about the distribution of precipitation and streamflow within the continents. The unequal distribution of water supplies over continental areas and with respect to season results in many of our water resource problems. Thus, water budget studies are typically performed on river basins or individual watersheds, and often for time periods shorter than one year.

THE WATER BUDGET AS A HYDROLOGIC METHOD

The application of a water budget as a hydrologic tool is relatively simple; if all but one component of a system can either be measured or estimated, then we can solve directly for the unknown part.

The annual water budget for a watershed or drainage basin is often used because of the simplifying assumption that changes in storage over a year period are very small in many instances. Computations for the water budget could be made, beginning and ending with wet months (A - A') or dry months (B - B') as illustrated in Figure 3. In either case, the difference in soil water content (storage) between the beginning and ending of the period is small. By measuring the total precipitation and streamflow for the year, the annual evapotranspiration (ET) can be estimated from the following:

$$ET = P - Q$$

Provided that a reasonable estimate of precipitation on the watershed is obtained, the next major assumption is that the total outflow of liquid water from the watershed has been measured. This implies that there is no loss of water by deep seepage to underground strata and that all groundwater flow from the watershed is measured at the gaging site. If certain kinds of geologic strata such as limestone underlie a watershed, the surface watershed boundaries may not coincide with the boundaries governing the flow of groundwater. In such cases there are two unknowns in the water budget, ET and groundwater seepage (L), which result in:

$$ET + L = P - Q$$

If losses to groundwater are suspected, they can sometimes be estimated by specialists in hydrogeology who have knowledge of geologic strata and respective hydraulic conductivities.

The change in storage can sometimes be difficult to quantify when we cannot assume that change in storage is small over the time interval. Estimates of change in storage become more difficult as computational interval diminishes and as the size of the area under investigation increases. The change of storage for a small vegetated plot may involve only periodic measurements of soil water content. Such measurements can be made gravimetrically (weighing a known volume of soil, drying the soil in an oven and reweighing), with neutron attenuation probes or other methods. As the size of the area increases, the storage changes of surface reservoirs, lakes and groundwater must also be considered. Stage-elevation-outflow data are needed to evaluate

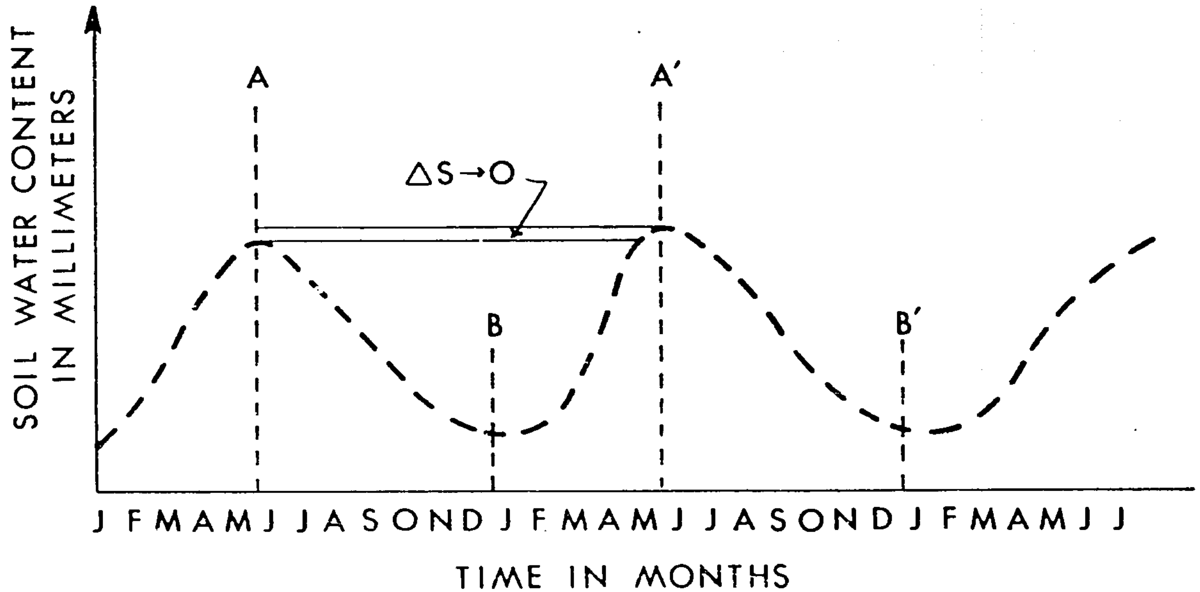


Figure 3. Hypothetical fluctuation of soil moisture on an annual basis.

changes in lake or reservoir storage, and are not particularly difficult to analyze when compared with storage changes in surface soils and geologic strata.

The soil-water-storage component is usually distinguished from geologic strata in water budget computations, as that part which can be depleted by evapotranspiration. Diurnal as well as seasonal changes in storage of the soil mantle can be significant. The underlying geologic strata, on the other hand, represents a zone in which changes in storage are slow. Recharge and drainage account for changes in storage within strata below the soil mantle. These strata along with unconsolidated sand and gravel deposits are the sources of sustained streamflow yield (baseflow) from many watersheds.

Energy Budget

Solar energy is the driving force of the hydrologic cycle. As with the water budget, the components of the energy cycle can be identified and partitioned. Some of these components can then be related to parts of the water budget. The linkage between the water and energy budgets is direct; net energy available at the earth's surface is apportioned largely as a result of quantities of water in the various storage components. The primary purposes for studying the energy budget, like the water budget, are to develop a better understanding of the hydrologic cycle and to be able to quantify or estimate certain parts of the cycle. The energy budget has been widely used to estimate evaporation from bodies of water, the potential evapotranspiration for terrestrial systems, and has also been used to estimate snowmelt.

The earth's surface neither gains nor loses significant quantities of energy over long periods of time, but there may be a net gain or a net loss for any given time interval due to different types of solar radiation. The net radiation is the residual of incoming and outgoing short-wave and long-wave radiation. The albedo or reflectivity of the terrestrial system determines the proportion of total incoming short-wave radiation which is reflected from natural surfaces back into the atmosphere. The apportionment of solar radiation is also affected by weather conditions. On the average, about 85 percent of the total downward stream of solar radiation is direct solar, but during cloudy days the diffuse or scattered short-wave radiation is the only short-wave input. Likewise, the long-wave radiation components are affected by atmospheric conditions. A cloudy or hazy atmosphere essentially traps long-wave radiation which would otherwise be lost from the earth, resulting in a larger incoming component than an outgoing component. The emitting constituents of long-wave radiation in the atmosphere are primarily CO_2, O_3 and the liquid and vapor forms of water. Terrestrial objects absorb and radiate long-wave radiation very efficiently, approaching 100 percent. Therefore, reflectivity of long-wave radiation by terrestrial objects is considered negligible.

The energy budget (or energy balance) can be described by:

$$R_n = (S + s)(1 - \alpha) + I\downarrow - I\uparrow$$

where:

R_n = net radiation in langleys/time
S = direct solar radiation in langleys/time
s = indirect, scattered solar radiation in langleys/time
α = albedo, or reflectivity of surface to solar radiation
$I\downarrow$ = incoming longwave radiation in langleys/time
$I\uparrow$ = outgoing longwave radiation in langleys/time

Net radiation may either be positive or negative for any arbitrary time interval. When positive, R_n represents excess radiation energy for some time interval, which can be allocated in the following manner:

$$R_n = (L)(E) + H + G + P_s$$

where:

L = lantent heat of vaporation in calories/gram
E = evaporation in grams or centimeters^3
H = sensible heat in langleys
G = heat of conduction to ground in langleys
P_s = energy of photosynthesis in langleys

The net radiation (R_n) available at a surface is important from a hydrologic standpoint because it is usually the primary source of energy for evaporation, transpiration and snowmelt. Typically when snow is present, the majority of net radiation is apportioned to snowmelt (80 cal g^{-1}). In snow-free systems, the allocation of net radiation is highly dependent upon the presence or absence of water. If water is abundant and is readily available for evaporation and transpiration, then large amounts of energy are consumed in the evaporation process (about 585 cal g^{-1} at common terrestrial temperature). Little energy is left to heat the air or ground. On the other hand, if water is limiting, a greater amount of energy is available to heat the air, the ground surface and other terrestrial objects. Losses (or gains) of energy to the interior earth do not change rapidly with time and are usually negligible. Similarly, energy consumed in photosynthesis, although of unmeasurable importance to life on earth, is a very small quantity in hydrologic terms and is usually not considered.

WATER BUDGET EXAMPLE

Each watershed is a unique system which responds to precipitation and energy inputs according to its biological and physical characteristics. The following example should provide the reader with some insight into the usefulness of the water budget method.

Streamflow yield and other components of the hydrologic cycle can be obtained for tropical ecosystems by using a water budget to couple climatological records with knowledge of the watershed system. Average soil texture and depth, and the rooting depth or extent to which the existing forest community can deplete soil water should be known. Generalized relationships of soil texture and "plant available water" (Figure 4) can then be used with estimates of soil depth to obtain values of the total soil water holding capacity and the total water available for evapotranspiration. For most tropical forest ecosystems, roots are assumed to fully occupy the soil system and evapotranspiration is considered to occur at or near the potential rate. Estimates of potential ET and rainfall are then coupled with the above soil-plant characteristics to provide an accounting of water surplus or deficit for given time increments.

An example of mean monthly water budgets based on climatological data from two different areas in Thailand is presented in Table 1. The mean monthly rainfall (item 1) is the input item of the accounting method. Potential ET for each month is listed as item 4. Actual ET (item 5) is either the total available moisture (item 3) or the potential ET (item 4), whichever is smallest. The available soil water is determined as the difference between field capacity and permanent wilting point. The quantity of soil water available to plants when soils are fully recharged for Chanthaburi and Chiang Mai are 279 mm and 124 mm, respectively. The first month's calculation, without actual soil-water content data, would appear to be somewhat of a guess. Errors associated with unknown antecedent soil water status can be minimized, however, if the accounting begins with a month in which the soil is typically recharged with water. The month which ends the rainy season, in these examples October, is a good starting month. The total available moisture (item 3) is determined from the sum of the rainfall and the initial soil moisture content (item 2). The remaining available moisture (item 6) is determined as the difference between total available moisture and actual ET. Any amount in item 6 which is in excess of the soil-water capacity is calculated as runoff in item 8.

Historical data rather than mean monthly values can be analyzed in a similar manner as Table 1, if we were interested in evaluating the water yield associated with some observed sequence of rainfall, perhaps a drought period. Water budget analyses of drought sequences are useful for determining storage requirements for water supply or hydroelectric reservoirs. Likewise, sequential monthly values for several years could be analyzed "before and after" some management activity which

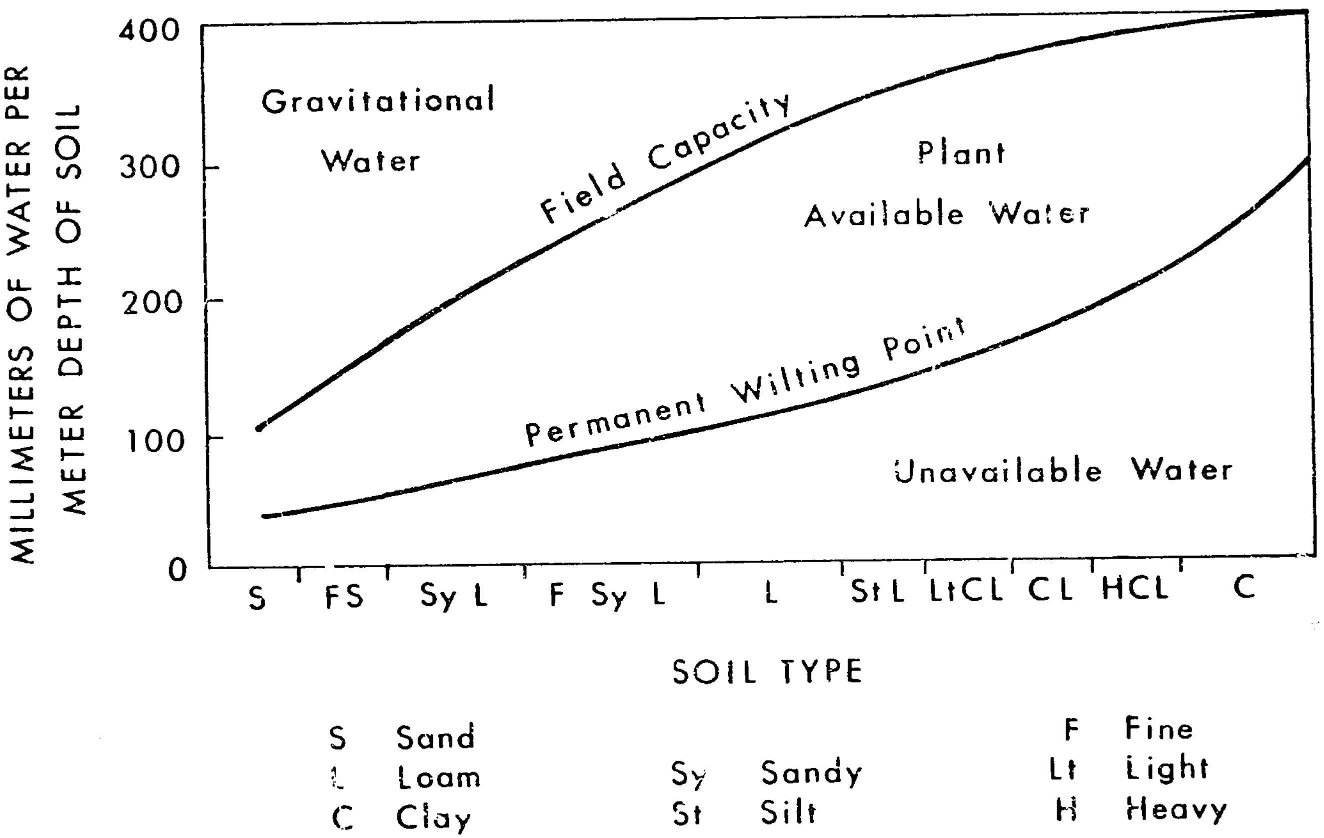


Figure 4. Typical water characteristics of different textural soils.

Table 1. Average monthly water budgets for two stations in Thailand.

Station: Chanthaburi, Thailand	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	YR
						mm							
1. Average rainfall	231	74	15	48	46	76	117	325	498	444	439	478	2791
2. Initial soil moisture	279	279	238	135	75	18	0	9	215	279	279	279	--
3. Total available moisture	510	353	253	184	121	94	117	334	713	723	718	757	--
4. Potential ET	123	115	117	109	103	110	108	119	123	128	129	124	1408
5. Actual ET	123	115	117	109	103	94	108	119	123	128	129	124	1392
6. Remaining available moisture	387	238	136	75	18	0	9	215	590	595	589	633	--
7. Final soil moisture	279	233	136	75	18	0	9	215	279	279	279	279	--
8. Runoff	108	0	0	0	0	0	0	0	311	316	310	354	1399

Station: Chaing Mai, Thailand													
1. Average rainfall	130	46	10	5	10	13	51	127	132	198	232	290	1244
2. Initial soil moisture	124	124	63	0	0	0	0	0	24	46	124	124	--
3. Total available moisture	254	170	73	5	10	13	51	127	156	244	356	414	--
4. Potential ET	114	107	102	99	85	87	87	103	110	117	120	112	1243
5. Actual ET	114	107	73	5	10	13	51	103	110	117	120	112	935
6. Remaining available moisture	140	63	0	0	0	0	0	24	46	127	236	302	--
7. Final soil moisture	124	63	0	0	0	0	0	24	46	124	124	124	--
8. Runoff	16	0	0	0	0	0	0	0	0	3	112	178	309

affects the actual ET. For example, the effect of clearcutting on water yield can be estimated by changing the effective rooting zone in the soil system after clearcutting and recomputing the water budget. Approximate effects on water yield may then be obtained as the results of a modified "effective soil water storage capacity."

A water budget analysis is only as good as the *input data* and the *assumptions* which have been made. Such assumptions include: (1) there are no deep seepage losses or "leakage" from or to the system, (2) transpiration responses are linearly related to available soil water content (unless better knowledge of physiological responses is available), and (3) rainfall intensitites do not affect the volume of runoff, *i.e.*, runoff only occurs when field capacity is exceeded. The assumption on leakage is always difficult to evaluate. Likewise, the manner in which the community of forest species respond to diminishing soil water content is unknown. The third assumption for tropical forest ecosystems is likely valid because of the extremely high infiltration capacities of soils.

CHAPTER IV

INVENTORY TECHNIQUES

INTRODUCTION

Fundamental to watershed resources management is an accurate evaluation of the components of the ecosystem. Techniques to measure or inventory precipitation, streamflow, water quality, timber, range and wildlife are presented.

PRECIPITATION MEASUREMENTS

The measurement of precipitation is an integral part of most hydrologic projects. Information on precipitation--amount, intensity, type, frequency, duration--is essential to much of the research and to the development of operational programs in the management of watershed lands.

Types of Gauges (Point Measurements)

Three types of precipitation gauges are now in general use: the standard gauge--size varies with standards established in individual countries--(usually read after each storm event or at relatively short predetermined time intervals); the storage gauge (manufactured in several sizes and read only periodically); and the recording gauge which records rate of precipitation as well as depth.

Selection of Raingauge Sites

Three general types of natural factors which affect the variation in amounts of precipitation over an area are: weather itself, in terms of area distribution of condensation processes and types of circulation of and within storms; topography of a scale large enough to affect the weather; smaller scale terrain effects which influence the performance of the gauge. The selection of a gauge site, which is representative of the surrounding area, will be influenced primarily by the latter factor.

Local anomalies in the rainfall pattern may be produced by small-scale topographic influences or by obstructions which distort the wind pattern in the immediate vicinity of the gauge. This distortion may make the particular gauge site nonrepresentative of the general region, introducing an error in the determination for the area. In regions of flat topography, this factor is usually of minor importance. In mountainous terrain, it may account for much of the variation in precipitation measurements. Variation in precipitation may be attributed in some cases to variations in the local exposure of gauge sites rather than in actual differences in the distribution of precipitation.

An ideal exposure would eliminate all turbulence and eddy currents near the gauge. Individual obstructions, whether a building or a tree, may set up serious eddy currents and, as a general rule, should not be closer to the gauge than twice (preferably four times) the height of the object above the gauge. When objects are numerous and uniform, such as in a forest opening, their height above the gauge should not exceed about twice their distance from the gauge.

At exposed sites, compensate for the lack of natural protection by shielding or by using pit gauges. The Nipher shield is recommended if the precipitation is primarily rain, the Alter shield if a substantial portion of the precipitation is snow.

Number of Gauges Required

The number of rain gauges required to measure precipitation will increase with the size of the watershed. The use of random sampling as a means of excluding bias in the selection of gauge sites and for estimating the number of gauges needed is suggested. However, in areas of dense brush or forest, this type of rainfall sampling may not be practical owing to the difficulty of obtaining adequate sampling sites.

Rainfall variability on a watershed for monthly, seasonal, or annual periods can be estimated at much lower operating cost by using a regular network which is read after each storm event. By reading storage gauges monthly or seasonally, the effects of storm types on variability may be lost, but systematic differences in precipitation between parts of the watersheds for these longer periods can be estimated.

Methods of Calculating Mean Watershed Precipitation

The mean depth of precipitation over a watershed is required in most hydrologic investigations. Several procedures are used in deriving this value. The three most common are the arithmetic, the Thiessen, and the isohyetal methods.

Arithmetic Method

A straight arithmetic average is the simplest of all methods for estimating the mean rainfall on a watershed (Figure 1). This method yields good estimates in level terrain if the gauges are numerous and uniformly distributed. Even in mountainous country with a dense rain gauge network, arithmetic averages will yield fairly accurate results if the orographic influences on precipitation are considered in the selection of gauge sites. However, if gauges are relatively few and irregularly spaced and precipitation over the area varies considerably, the arithmetic mean is likely to differ greatly from the results derived by other methods.

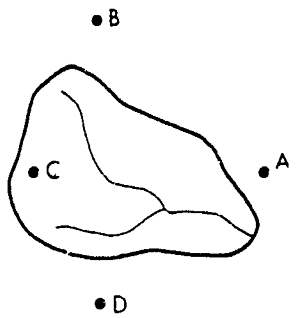
Thiessen Method

This method involves determination of an area of influence for each station. Polygons are formed from the perpendicular bisectors of lines joining nearby stations (Figure 1). The area of each polygon is determined and is used to weigh the rainfall amount of the station in the center of the polygon. The entire area within any polygon is nearer to the rainfall stations contained therein than to any other, and it is, therefore, assumed that the rainfall recorded at that station should apply to that area. The results are usually more accurate than the arithmetic average unless a large number of gauges are used. The Thiessen method allows for nonuniform distribution of gauges by providing the weighting factor for each gauge. The method assumes linear variation of precipitation between stations and makes no attempt to allow for orographic influences.

Isohyetal Method

In the isohyetal method, station location and amounts are plotted on a suitable map, and contours of equal precipitation (isohyets) are drawn (Figure 1). The average depth is then determined by computing and dividing by the total area. Many investigators indicate this as theoretically the most accurate method of determining mean watershed precipitation. But it is also by far the most laborious.

The accuracy of the isohyetal method depends upon the skill of the analyst. An improper analysis may lead to serious error. If linear interpolation between stations is used, the results will be essentially the same as those obtained with the Thiessen method.



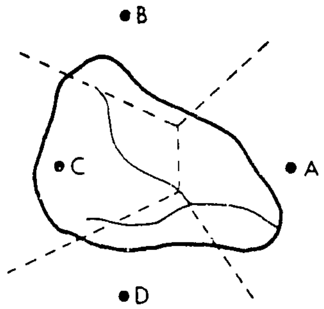
SOURCE DATA:

Daily rainfall measured at each gage in centimeters

A	B	C	D
4	8	10	6

$$\text{Arithmetic Mean} = \frac{4 + 8 + 10 + 6}{4}$$

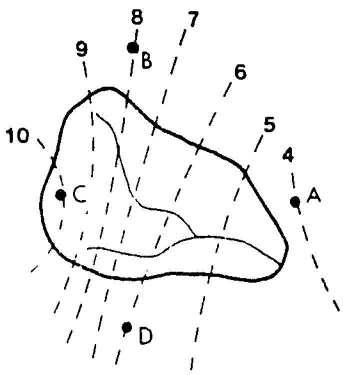
$$= 7 \text{ centimeters}$$



THIESSEN POLYGON:

Station	Depth (cm)		Area in Polygon*		Volume (cm)
A	4	x	.28	=	1.12
B	8	x	.09	=	0.72
C	10	x	.49	=	4.90
D	6	x	.14	=	0.84
			sum	=	7.6 cm

*As a fraction of total area



ISOHYETAL:

Mean Depth (cm)		Area Between Isohyets*		Volume (cm)
4.5	x	0.12	=	0.54
5.5	x	0.25	=	1.38
6.5	x	0.14	=	0.91
7.5	x	0.13	=	0.98
8.5	x	0.18	=	1.53
9.5	x	0.14	=	1.33
10.5	x	0.04	=	0.42
		sum	=	7.1 cm

Figure 1. Methods for estimating average rainfall for a watershed.

STREAMFLOW MEASUREMENTS

Measuring Streamflow

Streamflow data is perhaps the most important information needed by both the engineer and the water resource manager. Peak flow data are needed in planning for flood control or engineering structures (*e.g.*, bridges, culverts, *etc.*). Minimum flow data are required for estimating the dependability of water supplies. Total runoff and its variation must be known for design purposes (*e.g.*, investigative works, storage reservoir, *etc.*).

A stream hydrograph (see Figure 2, page 29) is a record of the discharge of a watershed as it changes with time. It provides a record that shows the effects of the hydrologic processes which occur in a watershed and, therefore, the hydrologic condition of the watershed.

Analyses of single storm hydrographs (the reaction of a stream to a rainstorm event or period of snowmelt) can indicate the condition of a watershed and provide information on the effects of land use and management practices. Storm hydrographs can be separated into components of quick return flow (primarily surface runoff) and subsurface runoff (base flow and interflow).

The stage of water in a stream is readily measured at some point on a stream reach with a staff gauge or a clock-driven water level recorder. The problem is to convert a record of the stage of a stream to discharge or quantity of flow per unit of time. This is done either by stream gauging or with precalibrated structures such as flumes or weirs constructed in the stream.

Measuring Discharge

One of the simplest ways of measuring discharge is to observe how far some floating object tossed into the stream travels in a given length of time. A measurement of the cross sectional area of the stream should be made simultaneously; the two should then be multiplied together:

$$Q = VA$$

where:

Q = discharge in cubic meters per second
V = velocity in meters per second
A = cross section in square meters

However, a simple measurement such as this would not be very accurate, particularly for a large stream because velocity varies from point to point with depth and width over the cross section of a stream.

The velocity at the surface is greater than the mean velocity of the stream; thus, a reduction factor is needed if the velocity is measured at the surface. Generally, it is assumed to be about 85 percent.

If the cross section of a stream is divided into finite vertical sections, the velocity profile can be estimated by measuring individually the mean velocity of each section. The area of each section can be determined and the average discharge of the entire stream is then computed as the sum of the product of area and velocity of each section as follows:

$$\sum_{1}^{n} A_i V_i$$

where: n = the number of sections

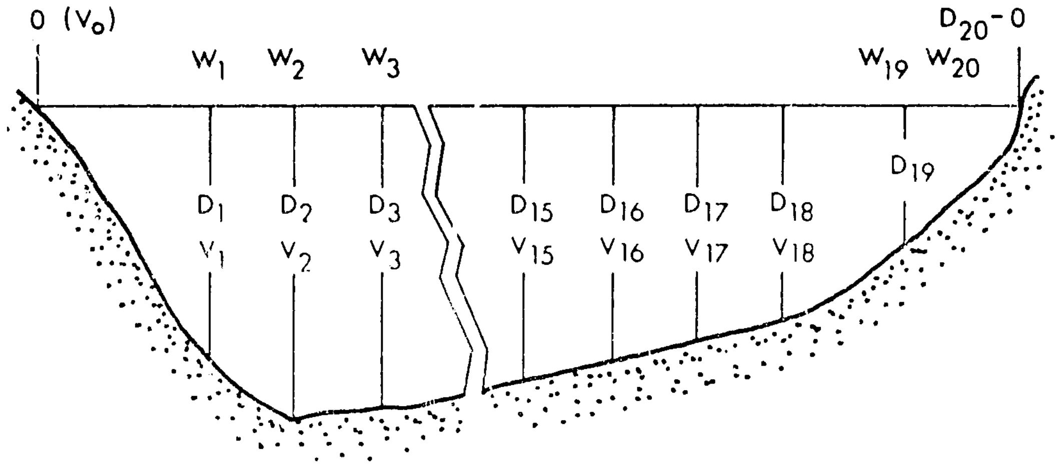
The greater the number of sections, the closer the approximation. However, for practical purposes, 10 sections are usually enough under ideal conditions, but 20 are commonly used. The actual number then depends upon the stream's channel and the rate of change in the stage. The following rules should be observed: depth and velocity should not vary greatly between verticals, and the measurements should be completed before the stage changes too much (a 15 centimeter change is too much for most cases).

There are two ways to estimate areas. They are: the midsection method where each vertical is considered the midpoint of a rectangular subsection extending halfway to the midsection of the other vertical, and the mean section method where each section is considered a trapezoid. The midsection method is most commonly used (Figure 2).

Velocity and depth of verticals can be taken by wading into the stream, from cable car, boat or bridge. Velocity is usually measured with a current meter. There are several ways of performing a velocity measurement. For depths greater than 0.5 meter, two measurements are made for each section at 20 and 80 percent of the total depth. For depths less than 0.5 meter the current meter is set at 0.6 of the depth. For shallow streams less than 15 centimeters, a pygmy meter is used which is simply a smaller version of a current meter.

The most critical aspect of stream gauging is the selection of a control, that is, the point on the stream for which a rating curve is to be developed.

In a longitudinal profile of a stream bed and the water surface for a given reach, ABCDEF represents the profile of the water surface during a low stage of the stream (Figure 3). At this stage the section at C serves as a control for the reach extending up to B and the section at C is the control for the reach leading up to D. The reaches AB, CD,



$$Q = \frac{W_1 + W_2}{2} V_1 D_1 + \frac{W_2 + W_3}{2} V_2 D_2 \text{ etc.}$$

W width cm
D depth cm
V velocity cm/sec
Q discharge cm^3/sec

Figure 2. Measurements needed to record channel cross section and velocity.

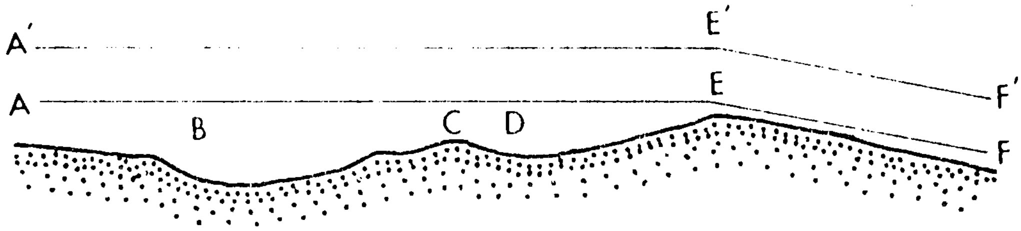


Figure 3. Longitudinal profile of a stream.

and EF act as their own controls throughout their respective lengths at this low stage. When the water surface rises approximately to the stage represented by the profile A'E'F', the section at E becomes the control for the entire length of channel from A to E.

Except in places where a rock outcrop creates either a waterfall or a rapids with considerable drop, longitudinal river profile is a practical necessity in determining the location of the various controls in any given length of stream channel. The best control is the one that is the most nearly permanent and that functions as a control throughout all stages of the river.

There must be of course a nearby gauging station equipped with a water stage recorder that has hydraulic connections with the water in the stream.

Precalibrated Structures for Streamflow Measurement

Weirs and Flumes

On small watersheds, (less than 800 hectares in size), particularly experimental watersheds, precalibrated structures are often used because of their convenience and accuracy. The most common types of precalibrated structures are weirs and flumes. Weirs are often preferred for gauging small watersheds particularly those with perennial flows. Where heavy sediment-laden flows are common, flumes are often more convenient. A flume is a stabilized channel (without an impoundment) with access to a stilling well. Flumes also must be used where the gradient of the stream is particularly low.

Weirs or flumes can be constructed of concrete, (because of its strength and permanence, probably is used the most), treated wood, concrete blocks, metal and many other materials. The notch of a weir is often a steel blade set into concrete, and flumes are often lined with steel for permanence.

Weirs. As used here, a weir includes all components of a stream-gauging station that incorporates a notch control (Figures 4 and 5). An impoundment of water (the weir basin) is formed upstream from the wall or dam containing the notch. A stilling well with water-level recorder is connected to the weir basin. A gaugehouse or some other type of shelter is provided to protect the recorder.

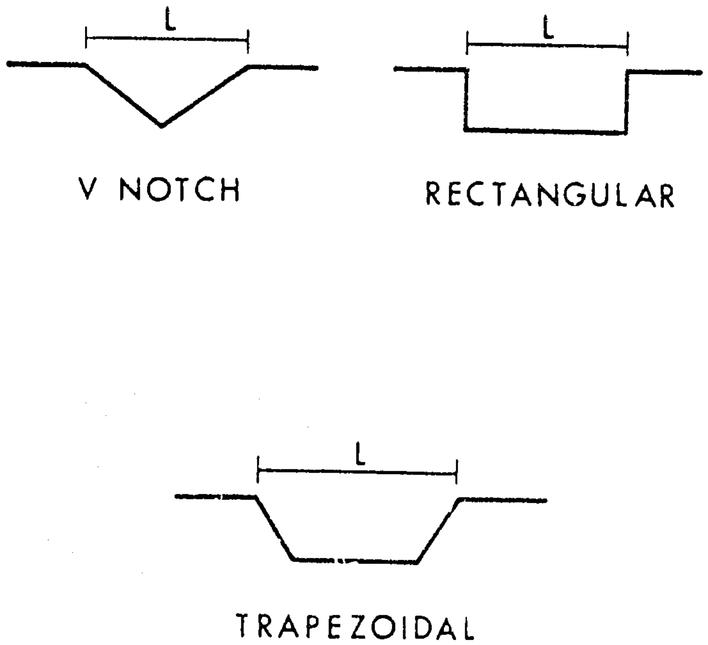


Figure 4. Types of notches.

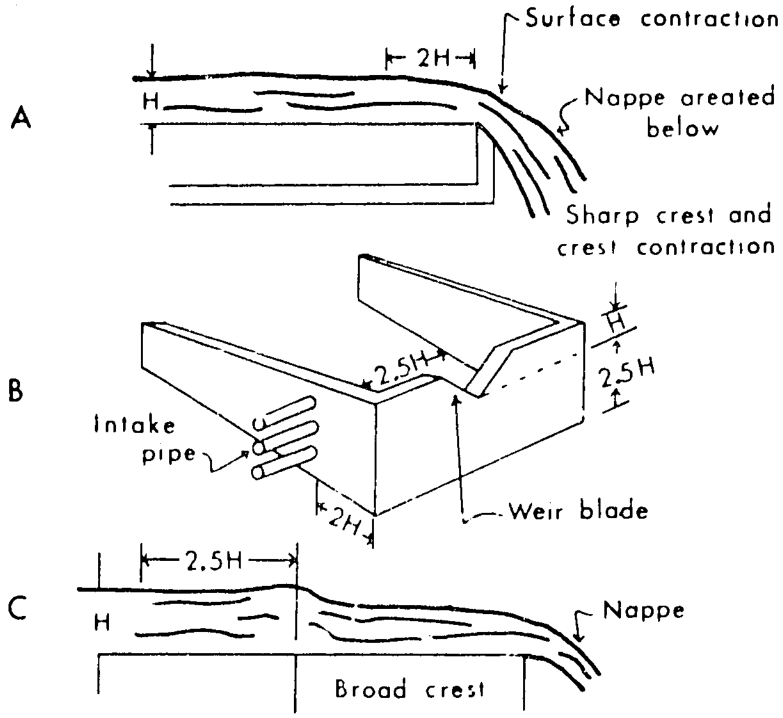


Figure 5. Schematic diagrams of general hydraulic relationships for weirs. A = flow characteristics over a sharp-crested weir. H = the depth of water producing the discharge. B = minimum requirements for proper discharge when H equals greatest expected depth for a sharp-crested V-notch weir with end and crest contractions. C = flow characteristics over a broad-crested weir of rectangular cross section.

The cutoff wall or dam is used to divert through the notch all water (above or below the streambed) moving down the channel. Where possible, the cutoff wall is tied into bedrock or other impermeable material so that no water can flow under or around it. But where leakage is apt to occur, the weir basin is sometimes constructed as a watertight box.

The edge or surface over which the water flows is called the crest. Weirs can be either sharp crested or broad crested. A sharp-crested weir has a blade with a sharp upstream edge so that the passing water touches only a thin edge and springs clear of the rest of the crest.

A broad-crested weir has a flat or broad surface over which the discharge flows. Broad-crested weirs are generally used where sensitivity to low flows is not critical and where sharp crests would be dulled or damaged by sediment or debris.

The rectangular weir has vertical sides and horizontal crest. Its major advantage is its capacity to handle high flows. However, the rectangular weir does not provide for precise measurement of the low flows of small experimental watersheds--a small increase in head will give only a slightly increased discharge.

The trapezoidal weir is similar to the rectangular weir. Its sides, of course, are sloped from the vertical. It has a smaller capacity than a rectangular weir of the same crest length; the discharge is approximately the sum of discharges from the rectangular and triangular sections.

Sharp-crested V-notch or triangular weirs are often used where accurate measurements of low flows are important. The V-notch weir may have a rectangular section above to accommodate infrequent high flows.

<u>Flumes</u>. A flume is an artificial open channel built to contain flow within a designed cross section and length. The types of flumes that have been used on small watersheds are described here.

HS, H and HL flumes developed and rated by the Soil Conservation Service have converging vertical sidewalls cut back on a slope at the outlet to give them a trapezoidal projection. These have been used largely to measure intermittent runoff.

The Venturi flume has a gradually contracting section leading to a constricted throat and an expanding section immediately downstream. The floor of the Venturi flame is the same grade as the stream channel, whereas that of the Parshall flume (described below) is depressed in the throat section. Stilling wells for measuring the head are at the entrance and at the throat; the difference in head at the two wells is related to discharge. Venturi flumes are rectangular, trapezoidal, triangular, or any other regular shape. They are widely used in measurement of irrigation water.

The Parshall flume, a modification of the Venturi flume, measures water in open conduits and is widely used, especially for measuring irrigation water. It consists essentially of a contracting inlet, a parallel-sided throat, and an expanding outlet, all of which have vertical sidewalls. It can measure flows under submerged conditions. Two water-level recorders are used when measuring submerged flow, one in the sidewall of the contracting inlet and the other slightly upstream from the lowest point of the flow in the throat. When measuring free flow, only the upper measuring point is used.

The San Dimas flume measures debris-laden flows in mountain streams. It is rectangular and has a sloping floor (3 percent gradient) that functions as a broad-crested weir except that the contraction is from the sides rather than the bottom; therefore, there is no barrier to cause sediment deposition. Depth measurements are made in the parallel-walled section at about the midpoint. Rapid flow keeps the flume scoured clean.

Summary. The type of flume or weir to be used depends upon several factors: maximum and minimum flows; accuracy needed in determining total discharge, high flows, and low flows; amount of sediment or debris that is expected, and whether it is suspended or bedload; channel gradient; channel cross section; underlying material; accessibility of site; financial limitations; and length of study.

Maximum and minimum flows likely to be encountered must be estimated before construction. Such estimates can be made from observation of high and low flows and high watermarks and from information given by local residents, or they might be based on the area of the watershed and records from other gauging stations in the region. Maximum expected flood peaks can also be estimated from rainfall, soil, and cover data, using a method developed by the U.S. Soil Conservation Service. The maximum and minimum flow to be measured at any degree of precision depend upon the objectives of the study and the extremes that might occur.

WATER QUALITY MEASUREMENTS

To evaluate the kinds and amounts of substances present in water, representative water quality measurements are obtained. Usually, a sampling program is necessary, as continuous monitoring of water quality is difficult. A good water quality sampling program requires knowledge of the system being sampled and an understanding of the time and space distribution patterns of the variables being sampled. A major source of error in obtaining water quality information is a nonrepresentative sampling effort.

Quite often, a *grab sample* obtained in a clean glass or plastic container is satisfactory for preliminary analysis. A single grab sample is representative of the stream discharge only at the time of sampling. Samples collected weekly or monthly can provide an indication of water quality over time for many streams.

Once obtained, grab samples may have to be treated to protect against degradation of the contents. For example, if water samples are to be used later for organic analysis, the sample may have to be frozen or otherwise preserved. If a water sample is to be retained for later analysis, the sample container should be marked so that its identity is not lost.

Chemical Quality

The chemical constitutents of water are derived from many sources, including gases from the atmosphere, weathering products of rocks and soils, and decomposition of plants and other organic materials. Many land management activities on a watershed can affect the kinds and amounts of chemical constituents present.

Methods of determining chemical quality of water include analysis of a standard volume of water obtained in a grab sample and direct measurements of a particular constituent in the aquatic environment.

Photometric or *colormetric* methods involve the addition of a measured amount of a reagent to a standard volume of water, and then relating the intensity of color to the concentration of the substance present. Required instrumentation consists of a light source, a photocell, and a meter (Figure 6). The amount of light absorbed is proportional to the amount of substance in the water.

Titrametric or *volumetric* methods require the addition of reagents of known concentration to a standard volume of water. These methods are designed to give an abrupt color change after a certain amount of reagent is added (Figure 7). The concentration of the chemical constituent in the water is proportional to the amount of reagent added.

Instrumentation is available to permit direct measurement of some chemical substances in the aquatic environment. Standardized oxygen and pH probes have been developed to measure dissolved oxygen and pH *in situ*. Similarly, electrode probes can be used to determine the concentration of many chemical ions.

Sediment Measurements

Sediment refers to the rock and mineral particles transported by water; while, *sedimentations* is the process of deposition of transported particles from water. Sediment is often divided into two components: *suspended sediment* and *bedload*. Usually, measurements of

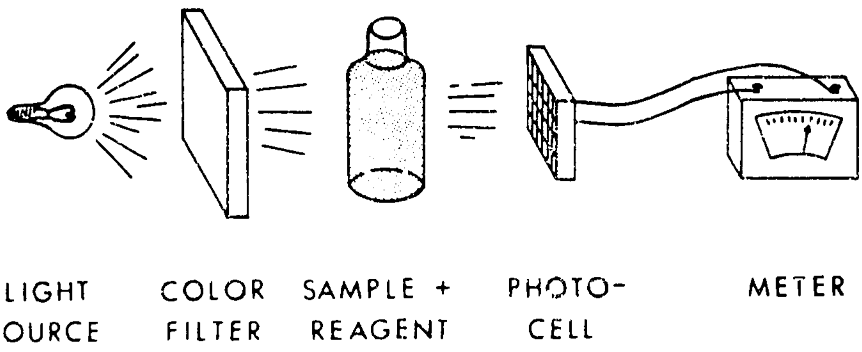


Figure 6. Photometric method for determining the chemical quality of water.

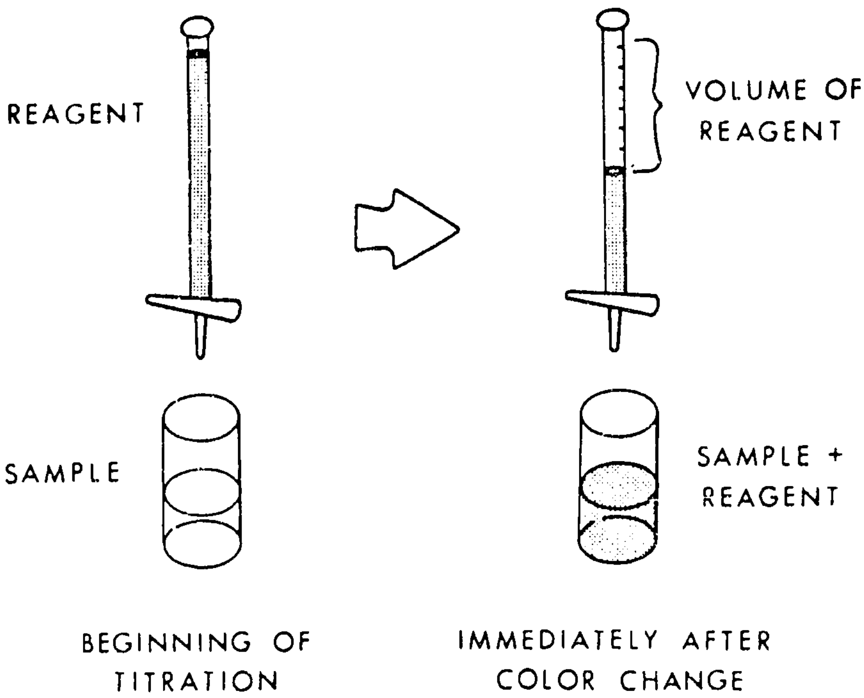


Figure 7. Titrametric method for determining the chemical quality of water.

suspended sediment and bedload are made separately because of differences in sizes of particles and in distribution of the particles in a stream.

Suspended Sediment

Suspended sediment usually consists of small particles (clays, silts, and fine sands) kept aloft from the stream channel by the turbulence of flowing water. As suspended sediment concentrations vary with depth and distance across a stream, a major difficulty in determining suspended sediment amounts for a stream is obtaining a representative sample.

Various techniques are available to estimate suspended sediment. The collection of grab samples is a common procedure, especially for small streams. However, this method may not be reliable because of the problems mentioned above.

Single-stage samplers, consisting of a container with an inflow and an outflow tube at the top, are commonly used on small, fast-rising streams. A single-stage sampler begins its intake when the water level exceeds the height of the lower inflow tube, and continues until the container is full. Therefore, only the rising stage of the hydrograph is sampled, which may limit the use of the data.

Depth-integrating samplers minimize the sampling bias involved with fixed, single-stage samplers. A depth-integrating sampler has a container that allows water to enter as the sampler is lowered and raised at a constant rate. Consequently, a relatively uniform sample for a given vertical section of a stream is obtained. Depending upon the size of the stream, a number of these samples can be taken at selected intervals across the channel.

After a suspended sediment sample is obtained, the liquid portion is removed by evaporating, filtering, or by using a centrifuge, and the amount of sediment is weighed. Often, the dry weight of suspended sediment is expressed as a concentration in milligrams per liter (or in ppm).

Bedload

Bedload is the larger, heavier sediments (sands, gravels, and cobbles) that slide, roll, or bounce along the bottom or bed of a stream channel.

No single device for measuring bedload is reliable, economical, and easy to use. While a number of bedload samplers exist, none are widely used. Estimates of bedload can be obtained by measuring the amount of material deposited in basins or traps behind sediment dams.

Bacteriological Quality

To index the presence of specific pollutants and to detect changes in water quality, indicator organisms are commonly sampled. For example, analysis of fecal coliform, a bacteria that characteristically inhabits the intestines of warm-blooded animals, can be used as an indicator of pollution by humans or other animals.

A parameter relating to the amount of biodegradable materials present in water is the biochemical oxygen demand (BOD). BOD measurements require a laboratory examination over a 5-day period, and often provide a satisfactory index to the amount of organic material present.

Temperature Measurements

The temperature of water acts as a regulator of biological activity and, therefore, is important in evaluating the types of organisms present in a given body of water. Surface temperatures can be measured with standard liquid-in-glass thermometers. Thermocouples are frequently used to obtain temperatures at lower depths.

TIMBER INVENTORY TECHNIQUES

Timber inventories are concerned with the measurement of individual trees, forest stands, growth rates, and site quality. As timber overstories often relate to the production and uses of associated watershed resources, knowledge of the general concepts of timber inventory can be useful.

Individual tree measurements form the basis for estimating the volume of primary wood products which may be derived from trees. Also, individual tree measurements coupled with a measure of tree density can describe the value of a forst. Individual tree measurements normally considered include measurement of diameter, height, volume and age.

The most frequent individual tree measurement made is diameter breast high (dbh), which is the average stem diameter at 1.3 meters above the ground. Other measurements of diameter may be taken at any arbitrary reference point. Tree diameters are measured with instruments collectively known as *dendrometers*, such as a diameter tape or caliper. In addition to diameter, height measurements are necessary to estimate the volume of a tree. Two height measurements commonly taken are total height and merchantable height, with total height being the distance from the ground to the tip of the tree and merchantable height being a measure of the usable portion of a tree. Heights are measured with instruments collectively known as *hypsometers*, including the Abney level and clinometer.

Given knowledge of diameter and height, the volume of a tree can be estimated from an appropriate volume table. A volume table specifies the average volume of a tree in terms of diameter and height. Volume units are frequently cubic meters, and volume tables may include the volume of the stump, bark, limbs, *etc.*

The average growth rate of a tree is its volume divided by its age. While the volume of a tree is relatively easy to determine, quantification of age is more difficult. There are three common methods used to ascertain the age of a tree--by general appearance (size, shape of crown, texture of bark, *etc.*), by branch whorls, or by annual rings. Unfortunately, tree growth is generally not characterized by annual rings in many forest regions of the world, such as tropical forests.

A primary objective of any timber inventory is to obtain estimates of the density of forest stands. Expressions of density are many, with number of trees, basal area (cross-sectional area at dbh of all trees on a hectare), and volume. Obviously, it would be desirable to have a complete census of all of the individual trees in a forest stand. This is rarely possible, however, and sampling is commonplace.

There are many considerations such as sample size, plot size, sampling design, *etc.* involved in developing an efficient sampling scheme to describe the density of a forest stand. Most of these considerations are discussed in standard forest mensurational references and, therefore, will not be detailed here.

The estimation of growth rates of individual trees and forest stands is an important part of timber inventory. Generally, past growth rates are analyzed to establish a pattern for projecting growth into the future. Many techniques designed to evaluate past growth rates of individual trees have been developed, with remeasurement of permanently marked trees and use of growth percent formulas (simple interest formula, Pressler's formula, *etc.*) commonly employed. Two commonly used methods of estimating the growth of forest stands are through applications of yield tables and stand structure analysis. Expression of growth may be gross or net, depending upon whether or not mortality is considered.

The determination of site quality is important in identifying the productivity, both present and future, of forest stands. Site is considered to be the aggregate of all environmental conditions affecting the growth and survival of a forest or other plant community. Theoretically, it is possible to determine site quality by measuring all of the many factors affecting the productivity of forest stands and integrating them into a single index. However, such an approach may not be of much value to a practicing forester.

Of all the measures of site quality, tree height in relation to age has been found the most practical, consistent and useful (Figure 8). Height growth is sensitive to differences in site quality, little affected

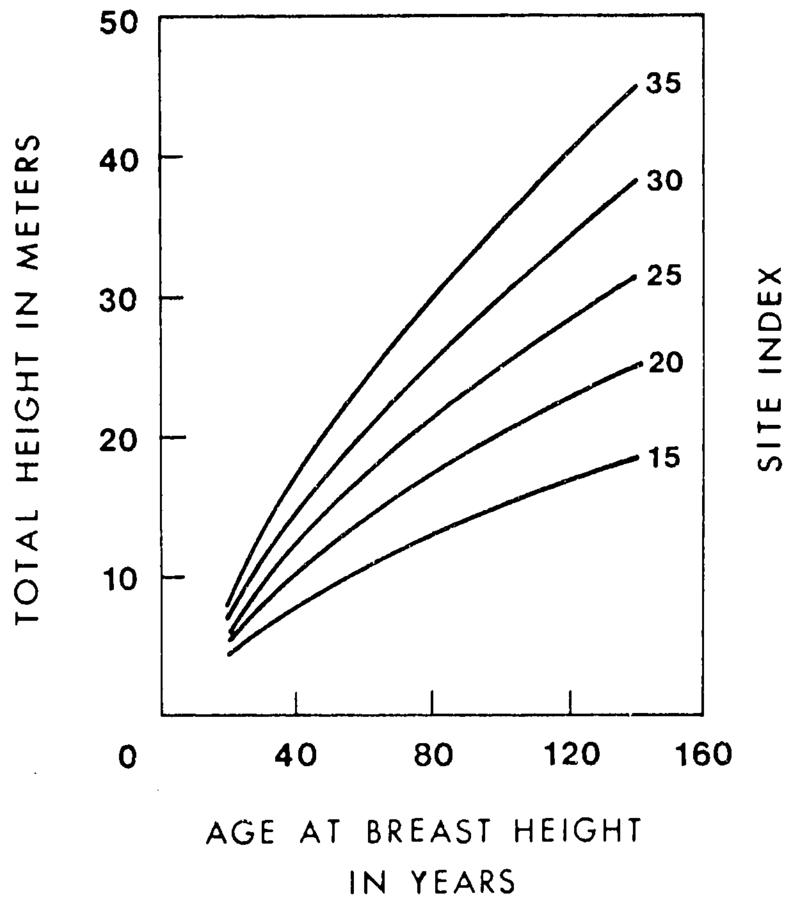


Figure 8. Site-index relationships for young-growth ponderosa pine in the southwestern United States. The index age is 100 years at breast height.

by density of the forest stand, and strongly correlated with volume. This measure of site quality is termed site index, with the usual practice being to define site index in terms of total height of dominant or co-dominant trees in well-stocked, even-aged stands at specified ages.

RANGE INVENTORY TECHNIQUES

Quite often, forage is produced for domestic livestock and wildlife on a watershed. Therefore, range inventories may be necessary to characterize watershed resources for multiple benefits. Range inventories are commonly designed to measure forage production and utilization for purposes of determining carrying capacities.

Clipped plots may be used to determine the weight of forage produced over a growing season. The general procedure is to locate plots of known area and clip forage plants as near to the ground as practical. Individual plant species may be clipped separately and weighed in the field if their growth characteristics allow for easy separation. If too much time is required in the field to separate the plants, total forage clipped on plots may be saved for subsequent sorting and weighing in the laboratory.

While plots of any size can be used, a 1-square-meter plot (one meter on a side) is often recommended. With this plot size, the forage in grams, multiplied by 10, will be converted to forage yield in kilograms per hectare. Sampling design selected is dependent on desired level of precision, costs, *etc.* Forage production near the end of the major growing season is often of primary importance, although biases may exist from sampling at this time because important forage species may have reached peak development earlier.

Utilization of forage plants is expressed as the percentage of the current forage weight that has been removed by grazing animals. There are many different techniques for determining utilization, but the simplest method is to select a key species (a palatable and abundant plant) and estimate the percentage use of this species. These estimates can be made in conjunction with clipping of forage plants to determine production. In fact, if utilization is heavy, clipped weights will have to be adjusted to account for the portions of plants removed by grazing.

A primary use of forage production is to calculate carrying capacity. Perhaps the best way to illustrate the calculation of carrying capacity is through an example.

Usually, domestic livestock carrying capacity is expressed in terms of animal unit months (AUM). An animal unit is the equivalent of 450 kilograms of animal live weight, or a cow and a calf. The forage required to provide for one animal unit month is variable, depending upon the ecosystem. For purposes of illustration, approximately 450 kilograms of forage (dry weight) will be assumed to be the forage requirement.

A proper use factor is used to control the amount of forage produced that is subsequently utilized by domestic livestock. Through the proper use factor, use of the forage resource can be adjusted to reflect the condition of the range. In the hypothetical example, a proper use factor of 0.65 (65 percent) has been selected. Given this information, and assuming that the forage produced (dry weight) is 375 kilgrams per hectare, the carrying capacity would be estimated as

$$\text{Carrying capacity} = \frac{(\text{forage produced})(\text{proper use factor})}{(\text{forage requirement})}$$

$$= \frac{(375)(0.65)}{(450)} = 0.5 \text{ AUM per hectare}$$

Therefore, one animal unit could graze on 1 hectare for 0.5 months, with two hectares required to provide forage for 1 AUM. Twenty-four hectares would be needed to carry one animal unit for a year.

WILDLIFE INVENTORY TECHNIQUES

Management of wildlife resources is an effort to attain a balance between the food and cover available and the animal populations that are favored. Wildlife inventory problems are generally threefold: estimation of numbers of animals, determination of animal productivities, and evaluation of wildlife habitats.

There is voluminous literature on methods of estimating numbers of animals. If the more commonly used methods are grouped, three primary approaches become evident: a direct method of census, an indirect method of indexing, and a ratio method of assessing population change. Direct census methods include aerial countings, which are used when animals congregate and where vegetative overstories are minimal. One of the oldest procedures is through driving, where a line of observers moves through an area like beaters with other observers stationed at the end of the census area to count the animals pushed ahead. Variable strips are often employed to count animal numbers, particularly in situations where extensive areas are to be inventoried.

Indirect methods of indexing population numbers are based on counts of something other than the animals themselves. Such methods are commonly used to census smaller, quickly producing animals and on big game ranges less accessible to direct counting. Call counts are widely used to assess game bird populations. To calculate population numbers, direct censusing is required from a sample to obtain a ratio of call counts to actual numbers. Pellet group counts are often used in an indirect census of big game. Through knowledge of defecation rates, counts of pellet groups accumulated over time can be converted to estimates of population numbers.

The more commonly used ratio methods fall into two categories--those based on the banding or marking of animals and those based primarily on kill data from legal hunting. The first category is illustrated by a calculation procedure known as the Lincoln index. Here, a number of animals are captured, banded or marked, and then released back into the population. When animals from the population are later recaptured, the ratio of total banded animals to the banded animals recovered can be used to calculate the size of a population. An example of the second category is Kelker's ratio, which requires data on population structure and changes in sex and age ratios resulting from legal hunting.

The second classic division of wildlife inventory, productivity, has its base in the census, but usually involves further computation ana comparison with past records. Generally, the smaller the animal, the faster their production, normal population loss, and regeneration each year. The average tree squirrel lives less than one year, but even larger animals have a turnover or replacement by new individuals. Therefore, a variety of animals are being managed and the changes in composition within a group must be measured, accordingly. Both hunted and non-hunted populations should be censused with production measurement. Hunted populations vary because the hunting can definitely modify the population: non-hunted populations vary because of natural losses.

Evaluation of habitats is a third classic wildlife inventory. Measurement of habitat quality can be broken down into the elements of habitat required by most wildlife species and then treated separately to judge a habitat's ability to support a population of animals. Habitat elements to consider in an inventory include water, food, cover (both protective and thermal), and spatial arrangement of water, food and cover. Most wildlife need all of these elements within their normal daily range of movement. If these basic elements of habitat periodically reoccur in several locales over a watershed, highly productive wildlife populations are more likely to develop.

CHAPTER V

HYDROLOGIC METHODS

INTRODUCTION

Hydrologic information is required for most watershed resources planning activities, studies, or projects. Often there are few hydrologic, meteorologic, and biophysical data available at locations of interest. Even with adequate data, it is sometimes difficult to decide upon the most appropriate hydrologic method to use. Numerous methods exist for determining hydrologic characteristics such as peak streamflow, stormflow volumes, mean annual water yield, and critical low-flow sequences. Hydrologic methods range in complexity from simple mathematical equations for predicting peak flow up to complex computer models capable of simulating continuous streamflow records. This chapter presents an overview of hydrologic methods and discusses guidelines for application.

CRITERIA FOR SELECTING METHODS

Selecting the appropriate hydrologic method should involve careful consideration of:

(1) the type of information required,

(2) available data and information,

(3) physical and biological characteristics of the watershed,

(4) technical capabilities of the individual performing the study, and

(5) time and manpower constraints.

Study objectives usually dictate the type of information required (Table 1) and, in some cases, indicate which method should be used. Sizing culverts for rural roads, for example, require peak flow estimates associated with some predetermined risk. Runoff is usually from small, simple drainages and errors in the estimate of peak flow do not result in great economic loss. Therefore, simple, quick methods are applicable. Conversely, peak flow estimates for flood plain mapping may require a more complex but reliable method. More time and effort may be justified in flood plain mapping if errors could result in large economic loss or loss of life.

Table 1. Project Objectives and the Corresponding Hydrologic Information Needed.

Objective	Hydrologic Information Needed
Storm drainage - culvert design	Peak flow rates for small contributing area
Flood plain delineation	Peak flow rates and associated stages
Conservation storage requirements for a reservoir	Streamflow rates or volumes during critical drought periods
Water quality assessment	Volumes, discharge rates for selected events
Feasibility for min-hydro project	Low streamflow sequences during critical drought periods
Land use impacts on water yield	Runoff volumes over time

After determining which hydrologic characteristics are of interest, an assessment must be made of available information and data. Streamflow, precipitation, and other data are often insufficient for all but the simplest of hydrologic methods. Sometimes climatic and hydrologic information from previous work in proximity to the study area is useful.

Watershed characteristics including size, shape, vegetative cover, topography, soils, and geology must also be evaluated in selecting an appropriate method. Some hydrologic methods can only be used for small, homogeneous drainages, while others can be applied to large complex watersheds. Before some techniques can be used, watersheds must be subdivided according to soil, vegetation, and topography.

The capacity or capability of the individual or organization performing the study is another important consideration. One should be knowledgeable about the methods used and their limitations. A common constraint with current technology is the availability and type of computer facilities and software. Computer programs are invaluable for most large-scale water resource investigations.

SIMPLIFIED METHODS

Simplified methods are those which have been developed for small, relatively homogeneous watersheds or for situations where a quick estimate is desired. Too many such methods exist for thorough coverage here. Our purpose is to illustrate some commonly used methods.

Direct Transfer of Hydrologic Information

Hydrologic information can be directly transferred from a gauged to an ungauged watershed if the two watersheds are hydrologically similar. The hydrologic similarity between two watersheds depends on the following:

(1) watersheds should be within the same meteorological regime;

(2) physical and biological characteristics such as soils, geology, topographic relief, type and extent of vegetative cover, land use, watershed shape, and drainage density should be similar; and

(3) the differences in drainage area between watersheds should be within an order of magnitude.

The method of direct transfer can be applied in two ways. First, the entire historical record from the gauged watershed may be transferred, with minor adjustments for differences in the size of drainage areas. The observed streamflow record could be multiplied by the ratio of ungauged to gauged watershed area. The second approach would be to transfer hydrologic characteristics (such as the 100-year flood peak), again, adjusting for drainage area differences. The entire flood frequency curve for an ungauged location may be estimated by adjusting curves developed from a similar but gauged watershed.

The direct transfer approach is applicable only if the assumption of hydrologic similarity is met. The method is quick and easy to use. If a significant amount of adjustment is needed to transfer hydrologic information from the gauged to the ungauged watershed, however, poor estimates will result.

Simplified Formulae

Numerous mathematical formulae have been developed to estimate hydrograph characteristics such as peak flow. A thorough discussion of such methods is presented in most hydrology textbooks. Simplified formulae relate some hydrographic characteristic to certain measurable watershed characteristics. These methods are restricted to small, simple watersheds, and have been used most frequently to design urban drainage systems and road culverts.

The rational method is perhaps the most commonly used simplified formula. This approach can be used to estimate peak flow from rainfall of uniform intensity and distribution over the watershed. The basis of the rational method is that the maximum rate of runoff occurs when the entire watershed area contributes at the outlet. Therefore, peak flow estimates are valid only for storms in which the rainfall period is at least as long as the watershed time of concentration. Time of concentration is the time required for the entire watershed to contribute runoff at the outlet. The rate of runoff for peak flow (Q_p) in cubic meters per second, is related to some percentage of rainfall intensity:

$$Q_p = CIA$$

where:

C = runoff coefficient relating proportion of rainfall contributing to peak runoff.

I = rainfall intensity in mm/hr

A = drainage area in hectares

The assumption that rainfall intensity is uniform over the entire watershed for a period equal to the time of concentration is seldom met under natural conditions. To apply this method, rainfall intensity-duration values associated with an acceptable risk are used.

Peak flow estimates by the rational method are highly dependent upon the runoff coefficient (C) selected. Runoff coefficients are presented in most hydrology and engineering textbooks. A relatively flat area with 30 percent impervious area would have a runoff coefficient of about 0.40. Moderately steep watersheds with 70 percent impervious area may have runoff coefficients up to 0.80.

Similar simplified formulae have been developed for regions around the world. The values of peak flow obtained from such formulae should be used with caution and must be viewed as quick and rough estimates. Such methods are useful, however, and will continue to be widely used because they are simple and require very little information or data.

GENERALIZED RAINFALL-RUNOFF METHODS

Some hydrologic investigations require more detailed information than can be provided by the simplified methods previously discussed. Generalized rainfall-runoff methods include techniques of hydrograph analysis, dynamic hydraulic routing, and continuous streamflow synthesis. Each method is an abstraction of the physical system and uses generalized mathematical functions for estimating rainfall-runoff characteristics. Such methods are usually referred to as hydrologic models.

Unit Hydrograph Concept

The unit hydrograph concept provides the basis for several hydrologic models of greater complexity and wider application than the simplified formulae. Unit hydrograph (UHG) models do not simulate or even attempt to quantify the various hydrologic processes involved from rainfall to streamflow. Rather, this method relies on parametric or "blackbox" relationships between rainfall input and streamflow output (Figure 1).

The unit hydrograph is defined as that hydrograph which represents *1 unit (1 millimeter) of direct runoff* and *is unique for each watershed*. The concept can best be understood by examining the isolated storm method of developing a UHG (Figure 2). Streamflow records for the watershed are first examined for single-peaked, isolated hydrographs which result from short duration rainfall of relatively uniform intensity. Once a hydrograph is selected, the *direct runoff volume* is determined by separating the more uniform baseflow from the rapidly changing stormflow component. The direct runoff volume is converted into millimeters of depth for the watershed area. Next, the mean watershed rainfall, which caused the direct runoff hydrograph, is determined. This rainfall is distributed with respect to time. The total rainfall amount is then compared to the direct runoff volume. Losses are determined as the difference between mean watershed rainfall and direct runoff (effective rainfall). The magnitude of losses is a function of antecedent moisture conditions. In Figure 2, a uniform loss rate was assumed. The duration of effective rainfall is then determined (in this case 2 hours). The ordinates of direct runoff for the storm are then divided by the millimeters of direct runoff to yield ordinates corresponding to 1 millimeter of direct runoff.

The duration of effective rainfall defines the unit hydrograph, *i.e.*, a UHG developed from an effective rainfall of 6-hour duration is a 6-hour UHG. (A 2-hour UHG was determined in Figure 2.)

The unit hydrograph is actually an index of runoff for a particular watershed and represents the integrated response of that area to a given rainfall input. The shape of the UHG is characteristic of the watershed for a given intensity of effective rainfall. The UGH method assumes that the effective rainfall and loss rate are relatively uniform over the entire watershed area. Also, the watershed characteristics which affect runoff response must remain constant from the time that the UHG is developed until the time that it is applied.

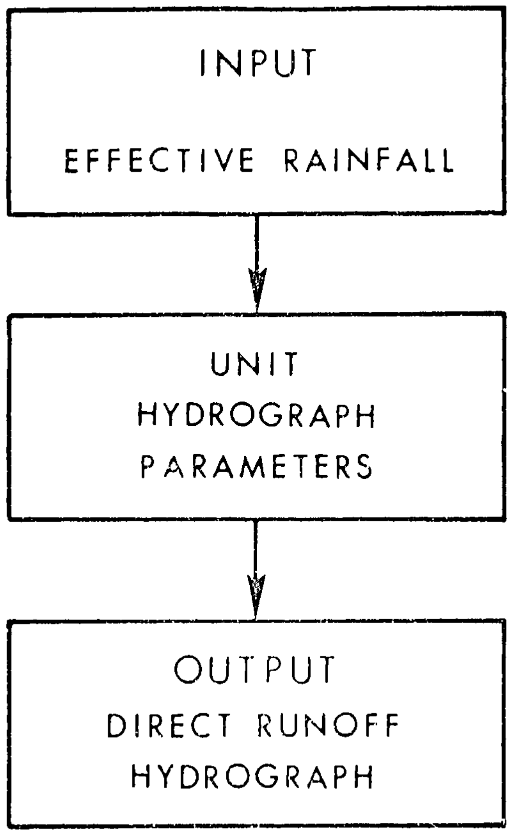


Figure 1. Unit hydrograph approach.

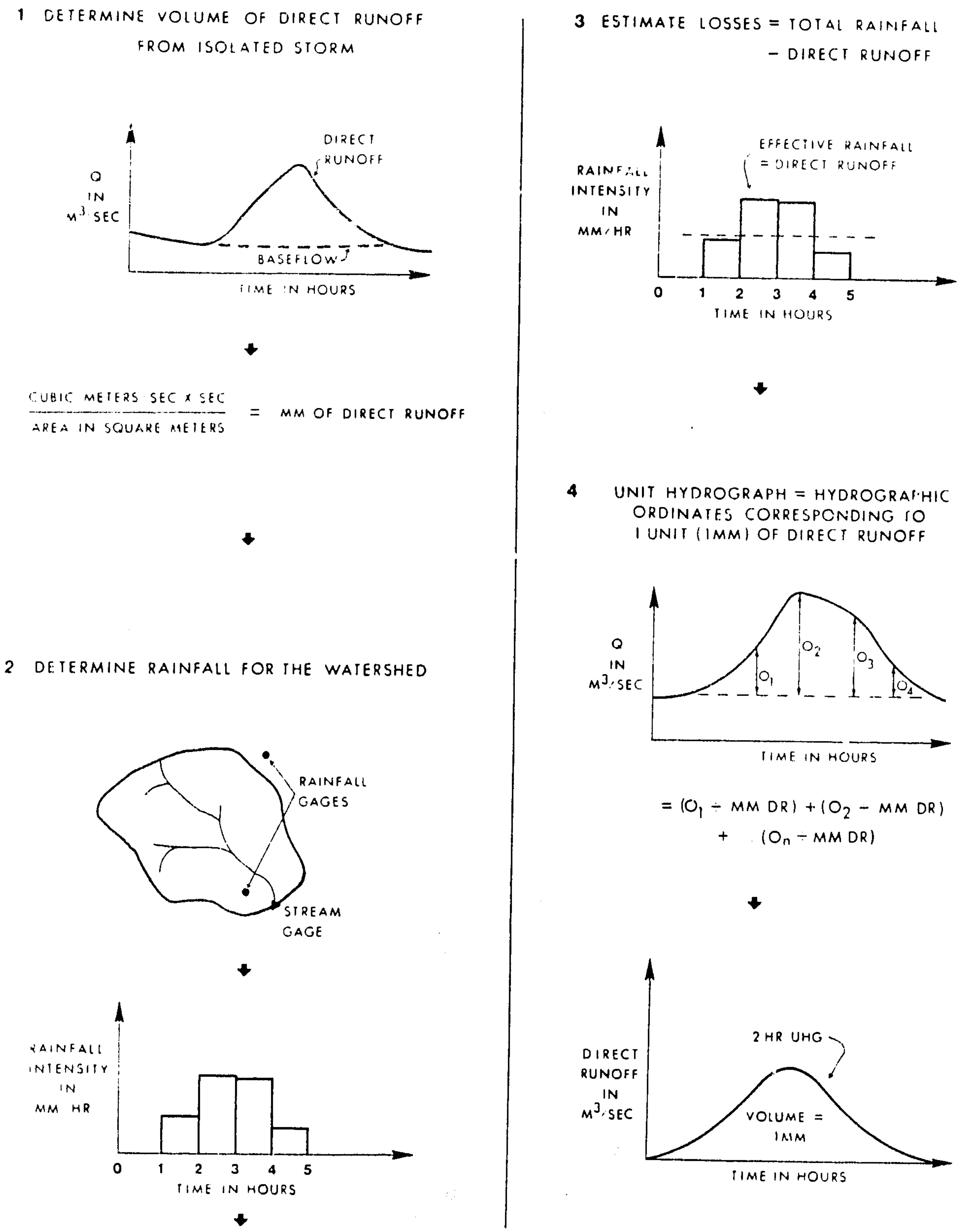


Figure 2. Development of a unit hydrograph by the isolated storm approach.

In order to apply a unit hydrograph, the average watershed rainfall must first be estimated. Next, loss rates are subtracted from total rainfall to obtain effective rainfall. The quantity of effective rainfall is then multiplied by the UHG ordinates corresponding to the same duration of effective rainfall (Table 2). A 1-hour UHG, in this case, is directly applied to 1-hour increments of effective rainfall. Unit hydrograph models are linear; 20 millimeters of effective rainfall yields a direct runoff hydrograph with ordinates 20 times that of the UHG. The resulting direct runoff hydrograph is then added to the base flow, if any, to obtain the total runoff hydrograph. It must be emphasized that the UHG developed from a specified duration of effective rainfall can be applied to effective rainfall which fell over the same duration. Thus, a 6-hour UHG cannot be applied directly to an effective rainfall which occurred over 2 hours. Several methods are available to convert a unit hydrograph from one duration to another and are discussed in most hydrology texts.

Table 2. Application of a Unit Hydrograph.

Time hr	1-hr UHG Ordinates m^3/sec	Effective Rainfall mm	Direct Runoff a m^3/sec	Direct Runoff b m^3/sec	Direct Runoff subtotal m^3/sec	Base Flow m^3/sec	Total Discharge m^3/sec
0	0.0	0	0.0	0.0	0.0	12	12
1	0.5	20	10.0	0.0	10.0	12	22
2	5.0	30	100.0	15.0	115.0	12	127
3	10.0	0	200.0	150.0	350.0	12	362
4	7.5	0	150.0	300.0	450.0	12	462
5	5.0	0	100.0	225.0	325.0	12	337
6	2.5	0	50.0	150.0	200.0	12	212
7	0.0	0	0.0	75.0	75.0	12	87
8	0.0	0	0.0	0.0	0.0	12	12

The above unit hydrograph method is of limited value for most watershed studies because both rainfall and streamflow data must be available. Since streamflow data are seldom available at locations of interest, synthetic unit hydrograph models have been developed. These models consist of mathematical expressions that relate measurable watershed characteristics to unit hydrograph characteristics. Runoff hydrographs for ungauged watersheds can be estimated with synthetic UHG models if loss rates can be approximated.

Unit hydrograph models have been used extensively for flood analyses and the design of spillways and flood control storage. These include the Snyder, the Clark, and the Soil Conservation Service (SCS) methods. The SCS method will be discussed in greater detail because runoff can be estimated directly from soil-vegetation characteristics of a watershed.

The SCS method, used in the TR-20 computer model, incorporates generalized loss-rate and runoff relationships developed from watershed studies in the United States. Soil-vegetation-land use characteristics are related to curve numbers (CN) which indicate the runoff potential for a given rainfall (Table 3). Soils are classified hydrologically into four groups:

A = high infiltration rates usually deep, well-drained sands and gravels;

B = moderate infiltration rates, fine to moderate texture;

C = slow infiltration rates, moderate to fine textured;

D = very slow rates usually clay soils or shallow soils with a hardpan near the surface.

Three antecedent moisture conditions (AMC) are also considered:

AMC I = dry;

AMC II = near field capacity;

AMC III = near saturation

After the CN is determined, rainfall is converted to direct runoff graphically (Figure 3).

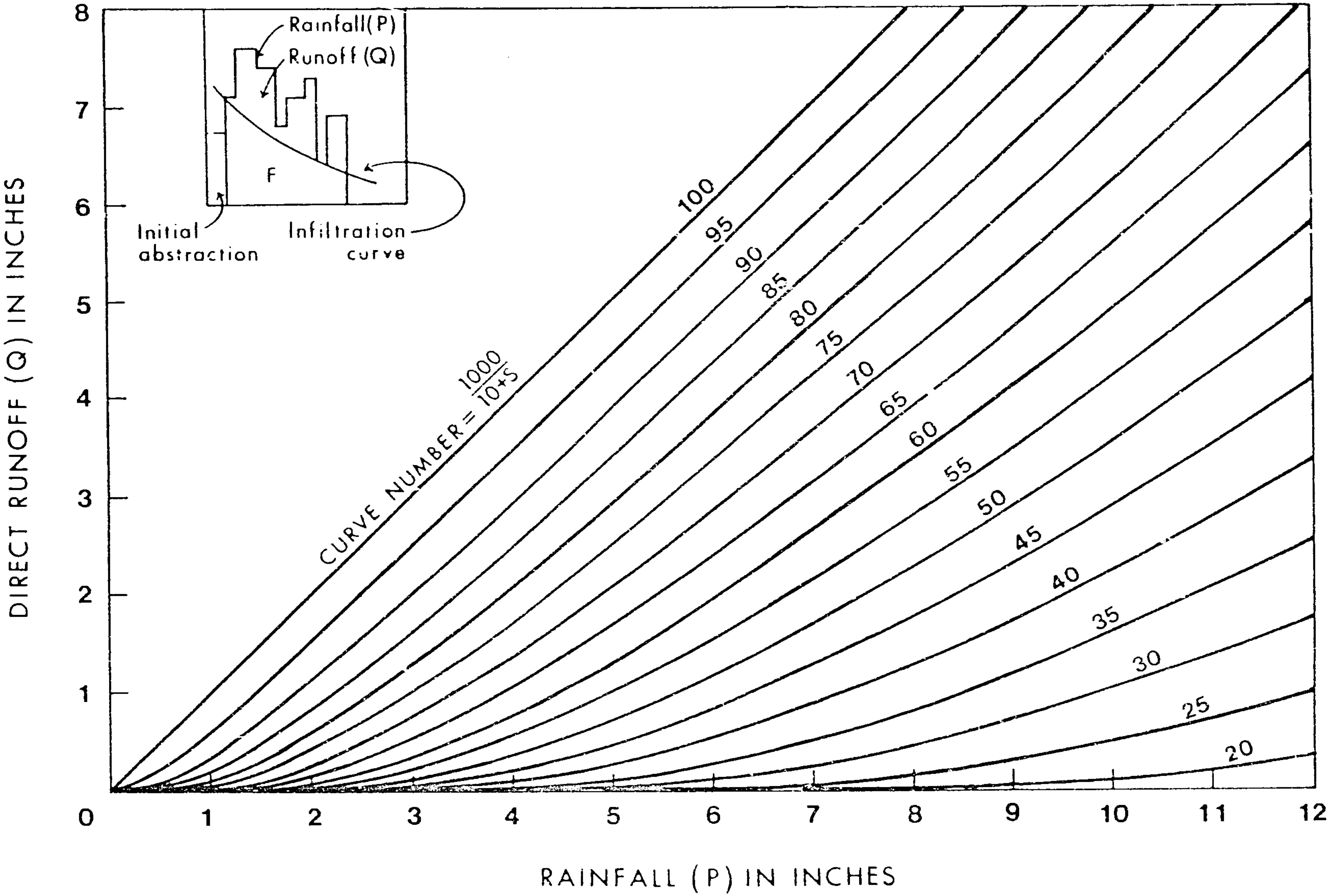


Figure 3. United States Soil Conservation Service rainfall-runoff relationships for curve numbers.

$Q = \frac{(P-0.2S)^2}{P+0.8S}$ P=0-12 inches; Q=0-8 inches.

Table 3. United States Soil Conservation Service Relationships Between Soil-Cover Complexes and Curve Numbers (CN) for Antecedent Moisture Condition (AMC) II in Puerto Rico.

Cover and condition	Hydrologic soil group A	B	C	D
Fallow	77	86	91	93
Grass (Bunch grass, or poor stand of sod)	51	70	80	84
Coffee (no ground cover, no terraces)	48	68	79	83
Coffee (with ground cover and terraces)	22	52	68	75
Minor crops (garden or truck crops)	45	66	77	83
Tropical kudzu	19	50	67	74
Sugarcane (trash burned; straight-row)	43	65	77	82
Sugarcane (trash mulch; straight-row)	45	66	77	83
Sugarcane (in holes; on contour)	24	53	69	76
Sugarcane (in furrow; on contour)	32	58	72	79

For the SCS model to be valid, curve number relationships should be determined for each hydrographically different region. The relationships developed in the United States are generally applicable to small watersheds less than 13 square kilometers with average slopes less than 30 percent.

Once effective rainfall is determined, a hydrograph can be produced. Peak flow (q_p) is determined by the triangular hydrograph method:

$$q_p = \frac{KAQ}{T_p}$$

Where:

K = constant

A = area in square kilometers

Q = flow volume in millimeters

T_p = time to peak in hours, where $T_p = \frac{\Delta D}{2} + .6T_c$

ΔD = duration of unit excess rainfall in hours = 0.133 T_c

T_c = estimated time of concentration in hours

Example

A 102 millimeter rain fell over an 11.9 square kilometer watershed with a grass cover, soils in group C, and an AMC II. The duration of rainfall was 6 hours. Estimate the direct runoff volume and the corresponding peak flow.

(1) from Table 1, CN = 80.

(2) Enter Figure 5 with 102 millimeters of rain and CN = 80. The direct runoff is approximately 52 millimeters.

(3) Peak flow discharge for the watershed with a time of concentration (T_c) of 2.3 hours, is determined as follows:

$$T_p = \frac{\Delta D}{2} + .6\ T_c$$

$$= \frac{0.31}{2} + (.6 \times 2.3) = 1.53 \text{ hours}$$

$$q_p = \frac{484 \times 4.6 \times 2.06}{1.53} = 2998 \text{ cfs } (83.9\ m^3/\text{sec})$$

Changes in direct runoff associated with changes in the soil-vegetation complex are determined largely by the CN relationships. For example, converting from tropical kudzu, hydrologic soil group C, AMC = II, to a grass cover, changes the CN from 67 to 80. This in turn, would result in an increase in direct runoff from 14 millimeters to 32 millimeters for a 76 millimeter rain. In some instances, the time of concentration could also be altered which would affect the peak and general shape of the stormflow hydrograph.

Generalized Watershed Models

The previous section dealt with single-event methods or models which allow estimates of peaks or stormflow volumes with limited data. Sometimes an estimate of continuous streamflow response is needed. Such information is useful for determining reservoir-conservation storage requirements, for water quality investigations, and for estimating differences in annual streamflow or low-flow before and after watershed modifications. Models with greater complexity and more extensive data requirements are then needed.

Most generalized watershed models are continuous simulation programs which use a water budget approach. Hydrologic processes such as interception, evaporation, transpiration, and infiltration are simulated to varying degrees. Some processes may be simulated conceptually, based on a relationship with some measurable watershed characteristic. More rarely, components are calculated directly from physical measurements (physically based). For either case, processes must be linked together mathematically so that the conservation of mass principle is not violated. To be manageable, most such models are "lumped" (i.e., spatial variability of processes and characteristics over the watershed unit is ignored). Modeling units should, therefore, be relatively homogenous in terms of hydrologic characteristics.

The generalized watershed models developed in recent years differ in terms of concepts, level of complexity, and input requirements. For general application, models should be conceptually sound, flexible in design, and physically relevant. Input data requirements should not be unreasonable and output should be of a type which can be conveniently used. The utility of such models depends on input-output capabilities and on the transferability of parameters to ungauged or altered watersheds. (Typical components of a continuous simulation model are illustrated in Figure 4.)

REGIONAL ANALYSIS

A regional analysis is a statistical approach in which generalized equation, graphical relationships, or maps are developed for the purpose of estimating hydrologic information at ungauged sites. Runoff factors, unit hydrograph coefficients, and streamflow frequency characteristics can be estimated for ungauged watersheds that are within the same climatic region as gauged watersheds. Any pertinent information within the region should be used to relate watershed characteristics with hydrologic characteristics. In one extreme, a regional analysis may be used to estimate runoff coefficients or peak flow in cubic meters per second per square kilometer associated with a specified recurrence interval. At the other extreme, a regional analysis may be used to estimate parameter values needed to execute a complex hydrologic model.

Regional streamflow frequency analysis is the most commonly applied regional analysis. Equations and maps are developed which allow the derivation of exceedence frequency curves for ungauged areas in the following manner:

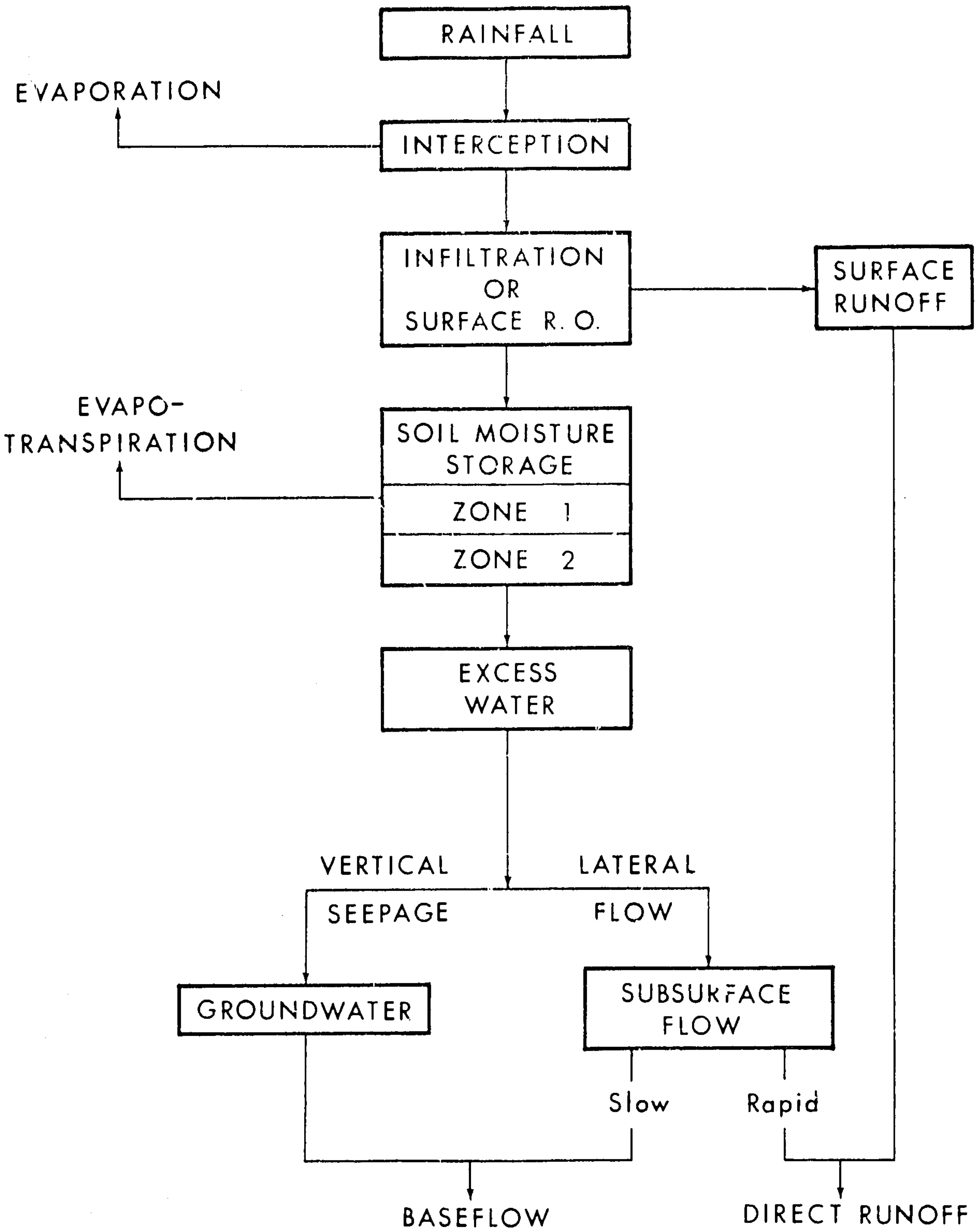


Figure 4. Hydrologic processes and runoff relationships.

(1) Select components of interest such as the mean annual peak flow, 100-year recurrence interval peak flow *etc.*

(2) Select explanatory variables (characteristics) of gauged watersheds such as drainage area, watershed slope, percentage of area covered by lakes, *etc.* Prediction variables are determined by regression analysis, as previously discussed.

(3) Derive prediction equations with single or multiple linear regression analysis.

(4) Map and explain the residual errors, which are the differences between calculated and observed values at gauged sites. The residuals constitute unexplained variance in the statistical analysis. Since it is impossible to include all variables which influence a particular hydrologic response, the mapping of unexplained variances can sometimes indicate other factors which are important. Sometimes mapped residuals will indicate a relationship between the magnitude of the residual error and watershed characteri tics such as vegetative type or soils.

(5) Determine frequency characteristics for ungauged locations by applying the regression equation with adjustments as indicated by the mapped residual errors.

Regional analysis has been widely applied in the United States where streamflow or other hydrologic information is available, within different climatic regions. The method must be used with care, however, since only one or, perhaps, a few components of the hydrologic system are included in the analysis. The results should always be considered a rough estimate of the true hydrologic characteristics.

CHAPTER VI

VEGETATIVE MANAGEMENT AND WATER YIELD

INTRODUCTION

To meet world demands for surface and ground water, several approaches to water augmentation and methods for better water management have been explored. Water harvesting, reuse, salvage (by removal of riparian plant communities), and vegetation management on upstream catchments are some of these approaches.

The management of vegetation on upstream catchments to increase the yield of usable water is of special interest. Water yield can be increased by vegetative treatments that benefit, or are at least compatible with, other natural resource objectives. Concepts of vegetation management for water yield improvement will be presented, along with a brief summary of several worldwide studies on the effects of altering vegetative cover on water yield.

VEGETATION MANAGEMENT FOR WATER YIELD--CONCEPTS

Many studies conducted throughout the world have demonstrated that annual water yields can be increased following the implementation of vegetation management practices. In general, the increased runoff is attributed to decreased evapotranspiration on the watersheds. That is, following treatment, less precipitation input is converted to vapor as a result of rainfall and snowfall interception and transpiration, and more is made available for streamflow runoff. Presumably, the reduced evapotranspiration is due to changes in the structure and composition of vegetation on the watershed.

Evaporation processes generally account for a significant proportion of the annual precipitation input on most watersheds. Consequently, the potential to increase water yield by decreasing evapotranspiration is attractive. For example, 85 to 95 percent of the annual precipitation is evaporated or used by plants on many watersheds in arid and semiarid regions, leaving only 5 to 15 percent available for streamflow runoff. On high elevation mountain watersheds in the snow zones of the world, the annual water yield may be as high as 50 percent of the precipitation input, but the evapotranspiration component is still significant and potentially subject to reduction through vegetation management.

Perhaps the above concepts may best be illustrated with a hypothetical, but realistic, water budget for a forested watershed (Table 1). Prior to treatment, average annual precipitation and evapotranspiration were 635 and 560 millimeters (mm), respectively, leaving 75 mm for streamflow runoff. After the implementation of a vegetation management practice, perhaps a partial harvesting of the forest overstory in a timber management operation, the annual streamflow runoff was increased by 25 mm (from 75 to 100 mm) due to a reduction in evapotranspiration of 25 mm (from 560 to 535 mm). The annual precipitation input of 635 mm remained the same, as basic precipitation patterns are usually not affected by modifications in the structure and composition of vegetation cover.

In the case illustrated, annual water yield increased by 33 per cent, while annual evapotranspiration decreased by 5 percent. It should be noted that, no matter what vegetation management practice is imposed on watersheds, the annual evapotranspiration may only slightly change. However, as demonstrated above, even a small reduction in evapotranspiration may cause significantly increased streamflow runoff.

Indications are that, for appropriate conditions and situations, water yields can be augmented by vegetation management practices without denuding watersheds of plant cover and without unacceptable changes in erosion and sedimentation. Evidence also suggests that vegetation management designed for water yield improvement can be developed to be compatible with other natural resource uses and values.

If the structure and composition of vegetation at the interface of earth and atmosphere can be modified by management practices,

Table 1. Average annual precipitation, evapotranspiration, and runoff for a hypothetical watershed in a treated and untreated condition.

Water Budget Component	Untreated (mm)	Treated (mm)
Precipitation	635	635
Evapotranspiration	560	535
Runoff	75	100

evapotranspiration may be reduced with the result that more of the annual precipitation input will be released from watersheds as usable water. This concept is the primary basis for the belief that vegetation can be managed for water yield improvement as well as for other natural resource products and amenities.

SUMMARY OF WATER YIELD IMPROVEMENT EXPERIMENTS

Experimental catchments, often supplemented by plot studies and computer modeling, have been used on numerous occasions to demonstrate that the hydrologic relationships of a river basin may be significantly affected by the implementation of a vegetation management practice on upstream catchments. These management practices, often imposed as a water yield improvement practice, include various types of forest cutting or removal, changes of forest cover from one tree type to another, or more drastic changes in which a forest cover is replaced by another type of vegetation.

As an overview of the potentials for water yield improvement through vegetation management, a brief summary of several worldwide studies on the effects of altering vegetative cover on water yield and the significance of the resulting conclusions are presented.

Emmenthal Mountains

In 1900, an early study of the effects of forest treatments on water yield was carried out in the Emmenthal Mountains of Switzerland. Here, measurements of climate, precipitation, and streamflow were made on two small catchments, one forested and the other pastureland, to determine the influence of forests on water production. Despite attention to detail, there was no way to ascertain that the observed differences in streamflow between the two catchments were caused only by differences in vegetation cover.

Wagon Wheel Gap

A second attempt to quantitatively analyze the influence of forests on water yield was made in the Wagon Wheel Gap investigation of 1911. The control watershed approach (in which streamflow from two similar catchments are compared during a period of "calibration," and then treating one catchment while leaving the other untreated as a control) was first used in this study of two forested catchments in the Colorado Rockies of the western United States. After eight years of calibration, one of the catchments was denuded by removing the scrub aspen and coniferous vegetation. Then, for seven additional years, streamflow from the denuded areas was compared with flow from the control catchment. This investigation conclusively demonstrated that clearing forest cover did increase streamflow. This study also demonstrated that changes in water yield could be quantitatively assessed.

Coweeta Hydrologic Laboratory

In 1934, the Coweeta Hydrologic Laboratory was established by the USDA Forest Service to analyze the effects of various forest cutting and vegetative conversion treatments on water yield in the humid mountains of the eastern United States. Mixed hardwoods with basal area densities of 20 to 25 square meters per hectare characterized the original forest conditions on the twelve experimental catchments at Coweeta. Treatments implemented and then evaluated included clearcutting with and without control of regrowth, poisoning of forest overstories on portions of catchments with regrowth restricted, and thinning above and below by selective logging.

With the exception of limited thinning (25 percent of the basal area removed), the treatments evaluated increased water yield by varying amounts. In general, these increases were greatest immediately after treatment and the duration of effect was dependent, in part, upon the severity of treatment. One of the catchment studies is the site of the only cutting experiment replicated in time.

Kamabuti

Coniferous and deciduous forest overstories on a small mountainous catchment in Kamabuti, Japan were cleared in 1948, with subsequent annual recutting of sprouts. Significant water yield increases were observed following treatment, although these increases were restricted to the growing season.

Fernow Experimental Forest

In 1951, the USDA Forest Service began gauging on several small catchments at the Fernow Experimental Forest in the Allegheny Mountains of West Virginia in the eastern United States. Original forest conditions on these catchments were mixed hardwoods at 20 to 25 square meters of basal area per hectare. After calibration, water yield improvement studies were designed and implemented to determine effects of logging on streamflow. Treatments evaluated consisted, for the most part, of thinning by alternative silvicultural practices.

As was found at Coweeta, with the exception of limited thinning (in this case, approximately 15 percent of the basal area removed), the treatments evaluated increased water yield by varying amounts. Also, these increases were greatest immediately after treatment.

Fraser Experimental Forest

To assess effects of forest cutting on snow pack dynamics and subsequent streamflow, the USDA Forest Service logged mature lodgepole pine and spruce-fir in strips and blocks on an experimental catchment in the

Colorado Rockies of the western United States. As a result of this treatment in which about 40 percent of the catchment was clearcut from 1954 to 1956, streamflow increased during the snowmelt period (essentially May and June). This increase in water yield was attributed, primarily, to redistributions in snowpacks brought about by a restructuring of the forest overstories.

Kimakia

In 1956, the high montane and bamboo forests on an experimental catchment at Kimakia in Kenya, East Africa, was cleared and planted to patula pine. Vegetables were grown among the pines until the third post-treatment year (when the pines were 3 to 5 meters high). A large increase in water yield was observed following cutting, with the greatest increases immediately after treatment. No change in seasonal patterns of streamflow occurred.

San Dimas Experimental Forest

At San Dimas, located in the semiarid region of California in the western United States, the USDA Forest Service selectively treated chaparral vegetation thought to use proportionally large quantities of water. In 1958 and 1959 riparian vegetation was cut and regrowth controlled on one experimental catchment (less than 2 percent of the area treated), while chaparral on moist sites with deep soils was sprayed with herbicides on another catchment (about 40 percent of the area treated). Both treatments increased water yield, with dry-season streamflow affected more significantly.

A disastrous wildfire swept San Dimas in 1960, destroying all existing vegetation. Dry-season streamflow increased appreciably following the wildfire on the two catchments treated, while streamflow from untreated (control) but burned catchments did not.

H. J. Andrews Experimental Forest

To determine how logging activities affect streamflow on the western slope of the Cascade Range in Oregon, United States, two experimental catchments were subjected to staged treatments (road construction, cutting of the coniferous overstories, and burning) during the period of 1959 to 1963. Significant increases in water yield occurred in the low flow season after each treatment, but they were small in actual volume (less than 0.1 mm per day).

Jonkershoek Forest Reserve

Analysis of streamflow from an experimental catchment on the Jonkershoek Forest Reserve, South Africa, has shown a 50 percent increase in water yield after one third of the radiata pine forest cover was removed 16 years following planting. Presumably, most of the increase in flow was due to less transpiration losses. This effect of increased streamflow was maintained for three years after the thinning treatment.

Junquillar Basin

To evaluate effects of established land use patterns on the western slope of Chile's coastal mountains, three experimental catchments (two burned and an unburned control) were gauged in the Junquillar Basin during 1970. Native vegetation on the area included small trees (roble maulino, white boldo, and litre), shrubs, and a few grasses. Radiata pine had been planted on the burned catchments, a common practice in the region.

While still exploratory, preliminary results have indicated that streamflow from the catchments did not differ noticeably. However, peak flows, which are more sensitive to treatment and may be more important in a region of high rainfall, were higher on the burned areas.

North Maroondah

Measurements of effects of thinning radiata pine plantations and regrowth mountain ash on streamflow volumes were the subject of major experimental catchment studies conducted by the Melbourne and Metropolitan Board of Works in the North Maroondah area of Australia. Preliminary results suggest that forest manipulations involving thinning of these forest cover types may be a feasible approach to increasing Melbourne's water supplies.

Arizona Watershed Program

Watershed managers in the southwestern United States, a semiarid region with short water supplies, have been particularly interested in evaluating possibilities of water yield improvement by vegetation management. As a result, the Arizona Watershed Program (involving federal, state, and private interests) was formulated to study the influence of vegetation management practices on the hydrologic processes affecting water yield improvement. While many vegetation types have been investigated, results of experimental catchment studies to date indicate that the greatest opportunities for water yield improvement by vegetation management are found in chaparral shrub communities, pinyon-juniper woodlands, ponderosa pine forests, and mixed conifer (including aspen) forests.

It appears that water yield from chaparral shrub communities can be increased by removing shrub overstories and establishing a cover of grasses and forbs. Although experimental catchments have been established by the USDA Forest Service at several locations in chaparral, only the Three Bar Watersheds, located in east-central Arizona, will be considered here.

In 1956, four small catchments (B, C, D, and F) were established on Three Bar. All were burned over by wildfire three years later. With the exception of Catchment C, all of the catchments were seeded with grass shortly after the fire; Catchment B was reseeded; and Catchment C seeded for the first time in 1960. After calibration, control of chaparral shrub regrowth with herbicides was attempted on Catchments C and B and changes in water yield were observed. On Catchment C, the shrubs were controlled through aerial applications and hand treatments with herbicides. Annual water yield following treatment increased over 325 percent. Hand application of herbicides to the shrubs on the north-facing slopes, comprising 40 percent of Catchment B, increased annual water yield by 320 percent. Complete conversion on Catchment F resulted in an annual water yield increase of approximately 700 percent.

Originally thought to have potential, improving water yield by manipulating pinyon-juniper woodlands does not appear promising at this time. On Beaver Creek and Corduroy Creek, experimental catchments located in north-central and east-central Arizona, respectively, removal of pinyon-juniper overstories by mechanical techniques (chaining, cabling, and hand clearing) has not increased water yield. However, water yield was improved on one experimental catchment by killing pinyon and juniper trees with herbicides and leaving them stand. The increase on Beaver Creek Catchment 3 after aerial spraying of herbicides was 65 percent annually. However, this study was too limited to make general statements about chemical conversion treatments for increasing water yield.

Opportunities for and estimates of water yield improvement through vegetation management in ponderosa pine forests are synthesized from the results of experiments on Castle Creek, located in east-central Arizona, and Beaver Creek. For purposes of discussion, vegetation management options in ponderosa pine forests may be placed into two categories: clearing of forest overstories and thinning of forest overstories. Various alternatives are possible within these categories, however. For instance, clearings can be arranged and oriented in various patterns, and intensity of thinning can be varied.

Clearing of ponderosa pine from one sixth of the West Fork of Castle Creek and thinning the remaining five sixths increased annual water yield by over 25 percent. On Beaver Creek Catchment 12, an increase of approximately 30 percent has occurred annually since the complete clearing of the forest overstory. Clearing forest overstories from 20 meter side strips and leaving alternating uncut strips 60 meters wide increased annual water yield by nearly 15 percent on Beaver Creek Catchment 9. Thinning the forest overstory by group selection on Beaver Creek Catchment 17 increased annual water yield by about 20 percent.

Estimates of water yield improvement through the manipulation of mixed conifer forest overstories are based, in part, upon partial conversion experiments on the Workman Creek Watershed in east-central Arizona. On the North Fork of Workman Creek, deciduous riparian vegetation was removed, and two thirds of the moist-site and dry-site forests were converted to grass. The resulting increase in water yield was approximately 85 percent. On the South Fork of Workman Creek, annual water yield increased nearly 115 percent after an individual tree selection cut was followed by a conversion cut.

DISCUSSION OF WATER YIELD IMPROVEMENT EXPERIMENTS

A review of worldwide studies of the effects of altering vegetative cover on water yield suggests that several generalizations can be made:

(1) reduction in densities of forest overstories increases water yield;

(2) establishment of forest overstories on sparsely vegetated land decreases water yield; and

(3) response of water yield to treatment is highly variable and, for the most part, unpredictable.

The above generalizations must be qualified when specific experiments are considered but, in most instances, they are accurate. With few exceptions, the worldwide studies have shown a definite response to vegetative cover alteration. However, the magnitude of treatment response has varied considerably. For example, removal of scrub aspen and coniferous vegetation in the Colorado Rockies of the western United States caused streamflow to increase only 35 millimeters during the first year after treatment, while complete cutting and removal of high montane and bamboo forests in the mountains of East Africa increased water yield in excess of 450 millimeters during the first year. These extremes reflect the diverse nature of the results and suggest the complexity of the causative factors.

To summarize, the results of experimental catchment studies suggest that vegetation management may have potential for increasing water yield on many drainages throughout the world. Furthermore, if desired, many of these management practices can be designed to maintain or enhance the production and use of associated natural resources, including timber, domestic livestock, wildlife, aesthetics, and soils. Such possibilities are not surprising, as many of the vegetation management practices tested in various parts of the world are employed to benefit other natural resources. Therefore, it seems possible that vegetation management can satisfy increasing demands for other natural resources while it is increasing water yield.

The results presented in this overview are based, for the most part, on research tests and not operational programs. Hopefully, these research findings can be coupled with economic and social considerations to develop operational practices that will provide multiple benefits.

It must be emphasized, however, that total areas potentially suited to vegetation management practices aimed at increasing water yield must be reduced to account for all of the possible constraints in implementing an operational water yield improvement practice on a particular watershed. Generally, the total areas must be adjusted downward by considering the constraints to implementation (Figure 1). Only after these constraints have been taken into account can treatable area be estimated.

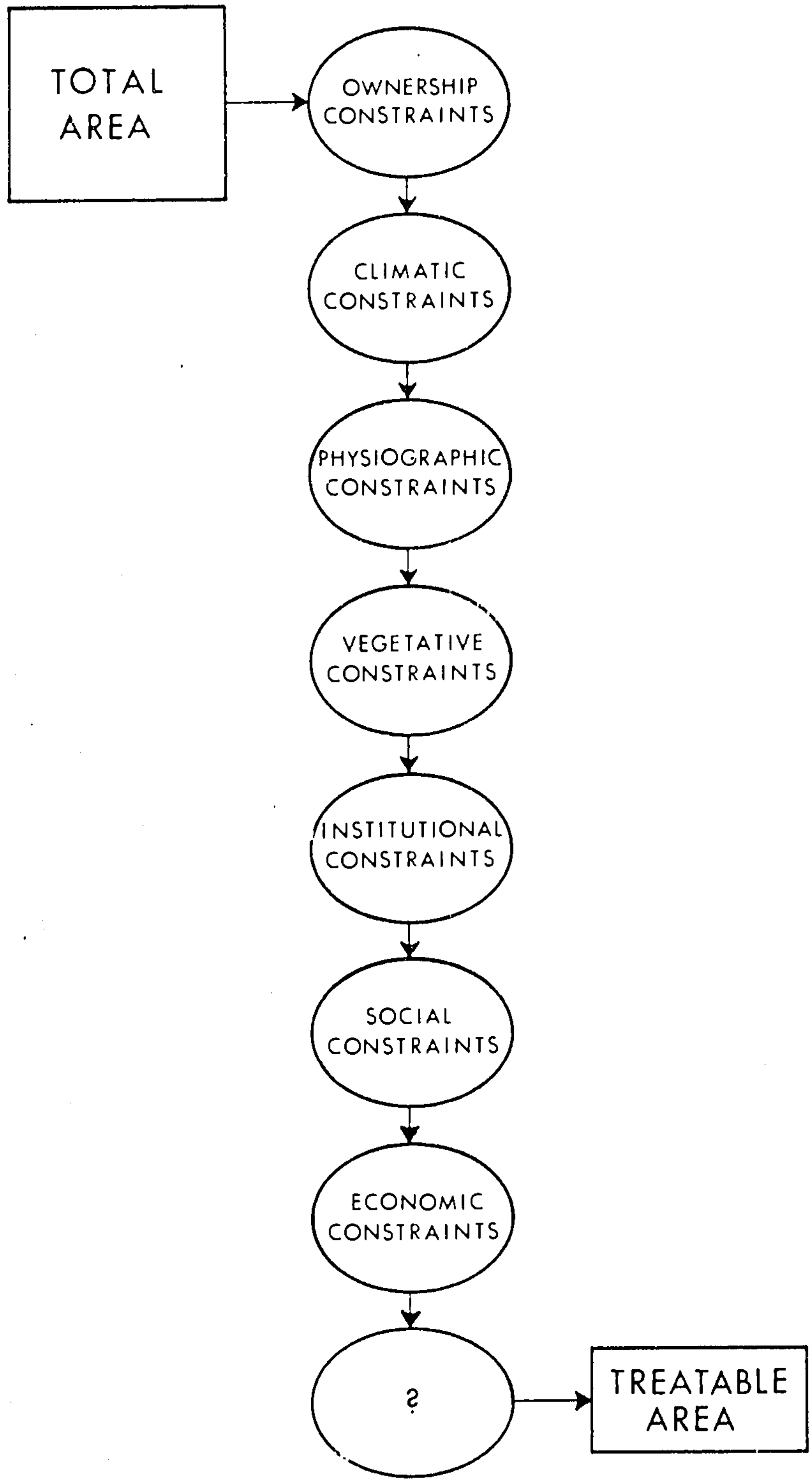


Figure 1. Constraints encountered by watershed managers when estimating treatable area for water yield improvement practices.

CHAPTER VII

EROSION PROCESSES AND CONTROL

INTRODUCTION

This chapter attempts to summarize the available body of knowledge and hypotheses on erosion processes, gully formation, and control. Included are: fundamental erosion processes, classification of gullies, objectives in gully control, types of control structures, cost relations, and recommendations.

EROSION PROCESSES

In general, there are three basic erosion processes on upland watersheds: surface erosion, mass wasting, and channel or gully erosion.

Surface erosion involves the detachment and subsequent removal of soil particles and small aggregates from land surfaces. This type of erosion is caused by the action of raindrops, thin film flows, and concentrated overland flows. It results in sheet erosion, rills, small gullies, *etc.* While seldom serious in forested areas, surface erosion can be an important source of sediment from rangelands and cultivated lands.

Mass wasting (or mass movement) is an important type of erosion in steep, mountainous country. Mass wasting includes erosion in which cohesive masses of soil are displaced. Movement can be rapid, as with landslides, or it may be quite slow, as with slumps and soil creeps. Man's activities can greatly accelerate the process of mass wasting.

Channel or *gully erosion* is the detachment and movement of material, either individual soil particles or large aggregates, from a stream channel. This kind of erosion is a major form of geologic erosion which, under poor land management, can be greatly accelerated.

All of the above erosion processes can occur singly or in combination. At times, it is difficult to distinguish or separate between the basic types of erosion because, in reality, there is a continuum of forms.

The control of channel or gully erosion is a particularly important responsibility of watershed resources managers. To develop effective control measures, an understanding of gully formation and control structures is necessary.

CLASSIFICATION OF GULLIES

Discontinuous Gullies

Gullies may be classified as *discontinuous* or *continuous*. Discontinuous gullies may be found at any location on a hillslope. Their start is signified by an abrupt headcut. Normally, gully depth decreases rapidly downstream. A fan forms where the gully intersects the valley. Discontinuous gullies may occur singly or in a system of chains in which one gully follows the next downslope. These gullies may be incorporated into a continuous system either by fusion with a tributary, or may become a tributary to the continuous stream net themselves by a process similar to stream "capture." In the latter case, shifts on the alluvial fan cause the flow from a discontinuous gully to be diverted into a gully, falling over the gully bank. At this point, a headcut will develop that proceeds upstream into the discontinuous channel where it will form a nickpoint. Headward advance of the nickpoint will lead to gully deepening.

Continuous Gullies

The continuous gully begins with many fingerlike extensions into the headwater area. It gains depth rapidly in the downstream direction and maintains approximately this depth to the gully mouth. Continuous gullies nearly always form systems (stream nets). They are found in different vegetation types, but are prominent in the semiarid and arid regions. It appears that localized or regional depletion of any vegetative cover can lead to gully formation and gully stream nets, if other factors such as topography and soils are conducive to gully initiation.

During the youthful stage, gully processes proceed toward the attainment of dynamic equilibrium; while, in the old age stage, a gully loses the characteristics for which it is named and resembles a river or "normal" stream. Gully development may not end with old age, however. Environmental changes, such as induced by new land use and climatic fluctuation or uplift, may lead to rejuvenation, throwing the gully back into the youthful stage. We must also recognize that gully development is not necessarily an "orderly" process, proceeding from one condition to the next "advanced" one.

OBJECTIVES IN GULLY CONTROL

Main Processes of Gully Erosion as Related to Control

The mechanics of gully erosion can be reduced to two main processes: *downcutting* and *headcutting*. Downcutting of the gully bottom leads to gully deepening and widening. Headcutting extends the channel into ungullied headwater areas and increases the stream net and its density by developing tributaries. Thus, effective gully control must stabilize both the channel gradient and channel headcuts.

Long-Term Objective of Controls--Vegetation

In gully control, it is of benefit to recognize long- and short-term objectives because often it is very difficult or impossible to reach the long-term goal (vegetation) directly; gully conditions must be first altered. Required alterations are the immediate objectives.

Where an effective vegetation cover will grow, gradients may be controlled by the establishment of plants without supplemental mechanical measures. Only rarely can vegetation alone stabilize headcuts, however, because of the concentrated forces of flow at these locations. The most effective cover in gullies is characterized by great plant density, deep and dense root systems, and low plant height. Long, flexible plants (such as certain tall grasses), on the other hand, lie down on the gully bottom under impact of flow. They provide a smooth interface between flow and original bed, and may substantially increase flow velocities. These higher velocities may endanger meandering gully banks and, in spite of bottom protection, widen the gully. Trees, especially if grown beyond sapling stage, may restrict the flow and cause diversion against the bank. Where such restrictions are concentrated, the flows may leave the gully. This is very undesirable because, in many cases, new gullies develop and new headcuts form where the flow reenters the original channel.

Engineers' Measures--An Aid to Vegetation Recovery

If growing conditions do not permit the direct establishment of vegetation (due to climatic or site restrictions, or to severity of gully erosion), engineering measures will be required. These measures are nearly always required at the critical locations where channel changes invariably take place. Examples are nickpoints on the gully bed, headcuts, and gully reaches close to the gully mouth where deepening, widening, and deposition alternate frequently with different flows. Nickpoints signify longitudinal gradient changes; a gentler gradient is being extended toward headwaters by headcutting on the bed. Normally, critical locations are easily definable.

An effective engineering design must help establish and rehabilitate vegetation. Revegetation of a site can be aided in different ways. If the gully gradient is stabilized, vegetation can become established on the bed. Stabilized gully bottoms will make possible the stabilization of banks, since the toe of the gully side slopes is at rest. This process can be speeded up mechanically by sloughing gully banks where steep banks would prevent vegetation establishment. Banks should be sloughed only after the bottom is stable, however,

Vegetation rehabilitation is also speeded if large and deep deposits of sediment accumulate in the gully above engineering works. Such alluvial deposits make excellent aquifers, increase channel storage capacity, decrease channel gradients, and thus, decrease peak flows. Channel deposits may also raise the water table on the land outside the gully. They may reactivate dried-up springs or may convert ephemeral springs to perennial flow. All these results create conditions much more favorable to plant growth than those existing before control.

Watershed Restoration Aids Gully Control Measures

Measures taken outside the channel can also aid revegetation processes in the gully. Improvements on the watershed that: increase infiltration and decrease overland flow, and spread, instead of concentrate, this flow, will benefit gully healing processes. A study on sediment control measures showed that sediment yields were reduced 25 to 60 percent by land treatment and land use adjustments, as surveyed at 15 to 20 year old flood water retarding structures in the southern Great Plains. But when combined land treatment and structural measures were applied, sediment yields were reduced 60 to 75 percent. Normally, however, gully improvements can be attained quicker within the gully than outside, because of concentration of treatment and availability of higher soil moisture in the defined channel.

Since watershed restoration measures are only supplemental to gully control, some examples will suffice here: seeding and planting with and without land preparation and fertilization; vegetative cover conversions; and engineering works such as reservoirs, water diversions, benches, terraces, trenches, and furrows.

Immediate Objectives of Control

Different types of measures benefit plants in different ways. It is therefore important to clarify the type of help vegetation establishment requires most. Questions should be answered such as: Is the present moisture regime of the gully bottom sufficient to support plants, or should the bottom be raised to increase moisture availability? One must recognize that a continuous, even raising of the bottom is not possible.

The immediate objectives of a gully treatment must consider other aspects in addition to plant cover. Usually, these considerations involve hydraulics, sedimentations, soils, and sometimes the logistics required for the management of the watershed. For instance, management may call for deposits of maximum possible depth at strategic locations to provide shallow gully crossings. Thus, if sediment catch is a desirable objective, large dams should be built. But if aesthetic considerations make check dams undesirable (and watershed logistics and revegetation offer no problems), the gully bottom may be stabilized with dams submerged into the bed, and thus invisible to the casual observer.

These examples illustrate how important it is to clarify the immediate and overall objectives of a planned treatment before deciding on approaches and measures. The objectives determine the measures; the measures determine the type of result.

GULLY CONTROL STRUCTURES AND SYSTEMS

Types of Porous Check Dams

The most commonly applied engineering measure is the check dam. Forces acting on a check dam depend on design and type of construction material. Nonporous dams with no weep holes, such as those built from concrete, sheet steel, wet masonry, and fiberglass, receive a strong impact from the dynamic and hydrostatic forces of the flow. These forces require strong anchoring of the dam into the gully banks, to which most of the pressure is transmitted. In contrast, porous dams release part of the flow through the structure, and thereby decrease the head of flow over the spillway and the dynamic and hydrostatic forces against the dam. Much less pressure is received at the banks than with nonporous dams. Since gullies generally are eroded from relatively soft soils, it is easier to design effective porous check dams than nonporous ones. Once the catch basin of either porous or nonporous dams is filled by sediment deposits, however, structural stability is less critical because the dam crest has become a new level of the upstream gully floor.

Loose rock can be used in different types of check dams. Dams may be built of loose rock only, or the rock may be reinforced by wire mesh, steel posts, or other materials. The reinforcements may influence rock size requirements. If wire mesh with small openings is used, rocks may be smaller than otherwise required by the design flow.

Some different types of check dams will be described, but the field of check dam design is wide open. Many variations are possible. The torrent control engineers of Europe have been especially successful with filter or open dams. Most of their designs are for large torrents where stresses on the structures are much greater than those in gullies, generally. Other types of filter dams have vertical grids, or grids installed at an angle to the vertical.

All the torrent control dams are quite sophisticated and costly. Such high costs are often justified in Europe, however, since population densities require the most effective and lasting control measures. These qualities are especially important if the basic geologic instability of the alpine torrents is considered. In contrast, most gullies in the western United States are caused by soil failure. Life and high-cost property are not usually endangered. Simpler, less expensive structures will therefore be preferable. Some of the most effective and inexpensive dams are built mainly from loose rock. They will, therefore, be emphasized in the descriptions that follow.

Loose Rock

Since loose-rock dams (Figure 1) are not reinforced, the angle of rest of the rock should determine the slope of the dam sides. This angle depends on the type of rock, the weight, size, and shape of the individual rocks, and their size distribution. If the dam sides are constructed at an angle steeper than that of rest, the structure will be unstable and may lose its shape during the first heavy runoff. For the design of check dams, the following rule of thumb can be used: the angle of rest for angular rock corresponds to a slope ratio of 1.25 to 1.00; for round rock, 1.50 to 1.00.

Wire-Bound Loose Rock

A wire-bound check dam is identical in shape to that of a loose-rock dam, but the loose rock is enclosed in wire mesh to reinforce the structure. The flexibility within the wire mesh is sufficient to permit adjustments in the structural shape, if the dam sides are not initially sloped to the angle of rest. Therefore, the same rock design criteria are required for a wire-bound dam as for a loose-rock structure.

The wire mesh should: be resistant to corrosion, be of sufficient strength to withstand the pressure exerted by flow and rocks, and have openings not larger than the average rock size in the dam. Wire mesh may not be effective in boulder-strewn gullies supporting flows with heavy, coarse loads.

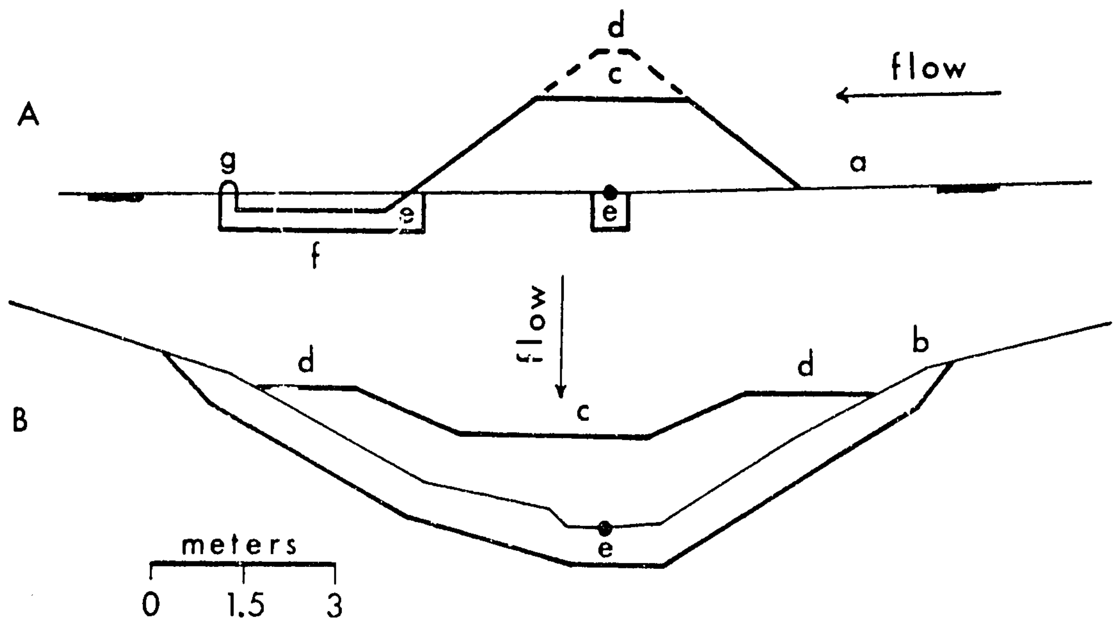


Figure 1. Construction plans for a loose-rock check dam.
A = section of the dam parallel to the centerline of the gully.
B = section of the dam at the cross section of the gully.
a = original gully bottom. b = original gully cross section.
c = spillway. d = crest of freeboard. e = excavation for key.
f = excavation for apron. g = end sill.

Single Fence

Single-fence rock check dams (Figure 2) differ greatly in shape and requirements of construction materials from the loose-rock and wire-bound dams. These structures consist of: a wire-mesh fence, fastened to steel fenceposts and strung at right angles across the gully, and a loose-rock fill, piled from upstream against the fence. The rock fill can be constructed at an angle steeper than that of rest for two reasons: (1) The impact of flows will tend to push the individual rock into the fill and against the dam, and (2) Sediment deposits will add stability to the fill and will eventually cover it.

The design of this type of check dam should emphasize specifications for the wire mesh, and the setting, spacing, and securing of the steel fenceposts. The wire mesh specifications will be the same as those for the wire-bound dams.

The steel fenceposts should be sufficiently strong to resist the pressure of the rock fill and the flows, and must be driven into the gully bottom and side slopes to a depth that insures their stability in saturated soil. If it is impractical to drive posts to sufficient depths, the stability of the posts should be enhanced by guys. These guys should be anchored to other posts that will be covered and thus held in place by the rock fill.

In general, spacing between the fenceposts should not be more than 1.2 meters to prevent excessive pouching (stretching) of the wire mesh. Where conditions do not allow this spacing, a maximum of 1.5 meters can be used, but the fence must be reinforced by steel posts fastened horizontally between the vertical posts. Excessive pouching of the wire mesh reduces the structural height and impairs the stability of the dam.

Double Fence

The double-fence rock check dam has two wire mesh fences, strung at a distance from each other across the channel (Figure 3). In this type of dam, a well-graded supply of rocks is essential, otherwise the relative thinness of the structure would permit rapid throughflow, resulting in water jets. Double-fence dams should only be built if an effective rock gradation can be obtained.

When flows of large magnitude (2 meters^3/second, for example) or gullies on steep hillsides are encountered, the base of the double-fence dam should be wider than the crest. This will add structural stability and increase the length of the flow through the lower part of the dam.

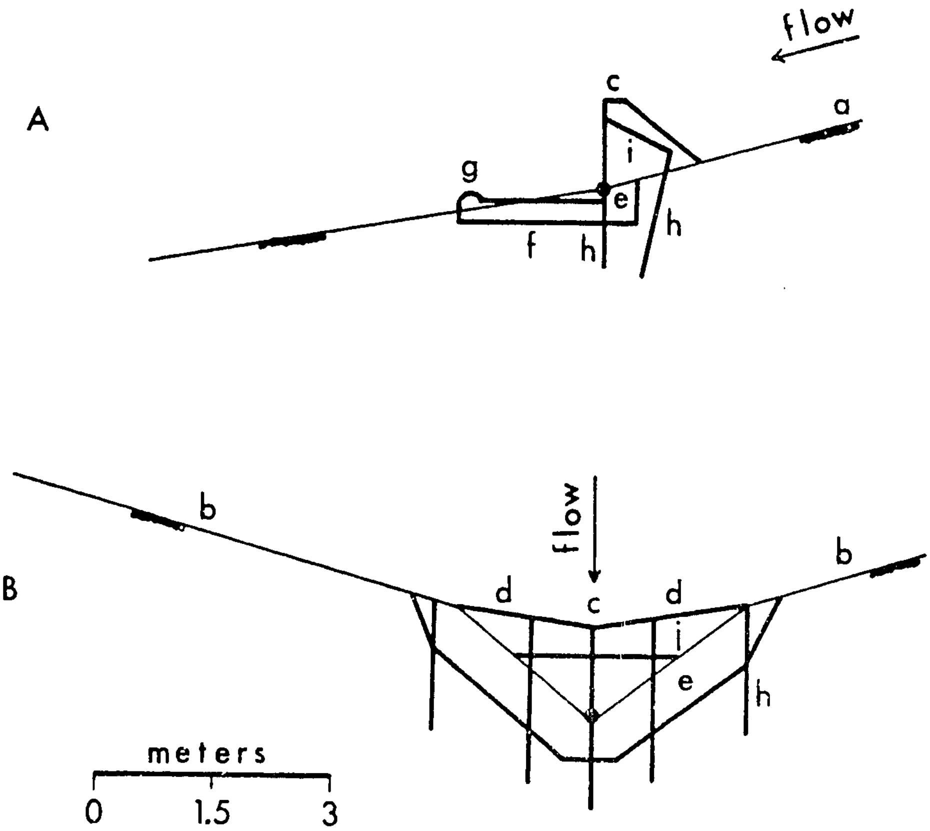


Figure 2. Construction plans for a single-fence rock check dam.
A = section of the dam parallel to the centerline of the gully.
B = section of the dam at the cross section of the gully.
a = original gully bottom. b = original gully cross section.
c = spillway. d = crest of freeboard. e = excavation for key.
f = excavation for apron. g = end sill. h = steel fencepost.
i = guys. j = rebar, 13 millimeters in diameter.

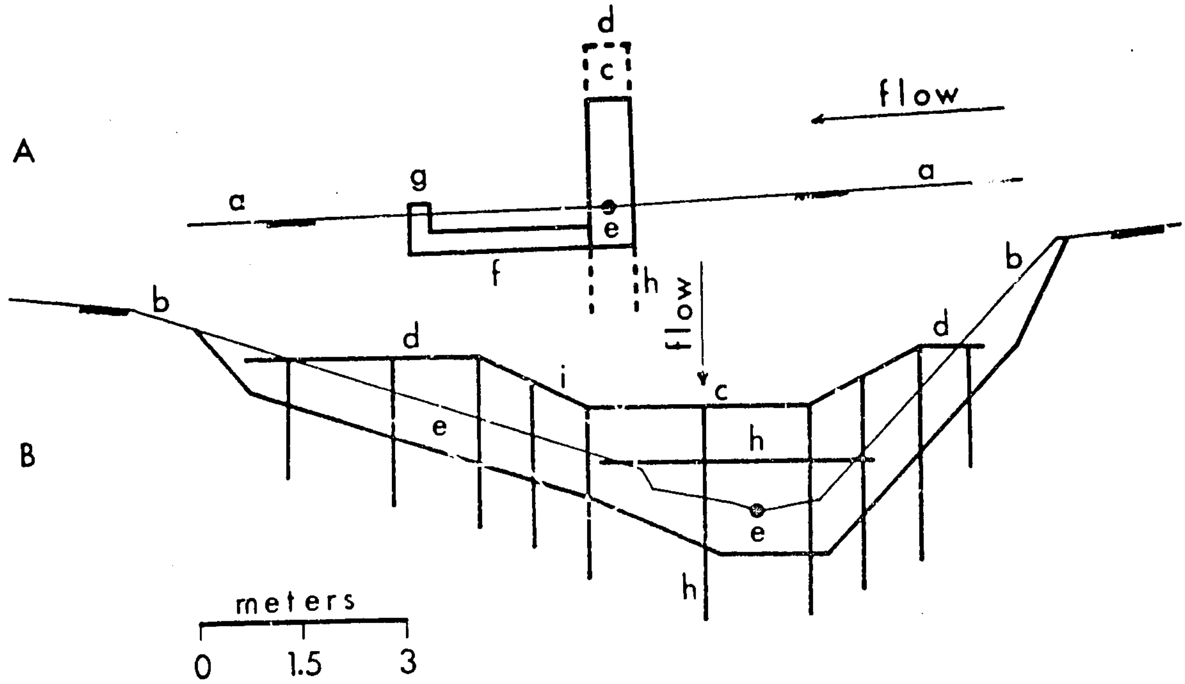


Figure 3. Construction plans for a double-fence rock check dam.
A = section of the dam parallel to the centerline of the gully.
B = section of the dam at the cross section of the gully.
a = original gully bottom. b = original gully cross section.
c = spillway. d = crest of freeboard. e = excavation for key.
f = excavation for apron. g = end sill. h = s[illegible]l fencepost.
i = rebar, 13 millimeters in diameter.

Gabion

A gabion check dam consists of prefabricated wire cages that are filled with loose rock. Individual cages are placed beside and onto each other to obtain the dam shape. Normally, this dam is more aesthetically pleasing, but it is more costly than loose-rock or wire-bound rock check dams.

Headcut Control

Headcuts can be stabilized by different types of structures, but all have two important requirements: porosity in order to avoid excessive pressures and thus eliminate the need for large, heavy structural foundations; and some type of inverted filter that leads the seepage gradually from smaller to larger openings in the structure. (Otherwise, the soils will be carried through the control, resulting in erosion.) An inverted filter can be obtained if the headcut wall is sloughed to such an angle that material can be placed in layers of increasing particle size, from fine to coarse sand and on to fine and coarse gravel. Good results may also be obtained by use of erosion cloth, a plastic sheet available in two degrees of porosity.

If rock walls reinforced by wire mesh and steel posts are used, site preparation can be minimized. Loose rock can be an effective headcut control if the flow through the structure is controlled also. As in loose-rock check dams, the size, shape, and size distribution of the rock are of special importance to the success of the structure. The wall of the headcut must be sloped back so the rock can be placed against it.

If the toe of the rock fill should be eroded away, the fill would be lost. Therefore, stabilization of this toe must be emphasized in the design. A loose-rock dam can be designed to dissipate energy from the chuting flows, and to catch sediment (Figure 4). Sediment depositions will further stabilize the toe of the rock fill by encouraging vegetation during periods with no or low channel flow.

General Design Criteria

Loose Rock

Loose rock has proved to be a very suitable construction material if used correctly. Often it is found on the land and thus eliminates expenditures for long hauls. Machine and/or hand labor may be used. The quality, shape, size, and size distribution of the rock used in construction of a check dam affect the success and lifespan of the structure.

Obviously, rock that disintegrates rapidly when exposed to water and atmosphere will have a short structural life. Further, if only

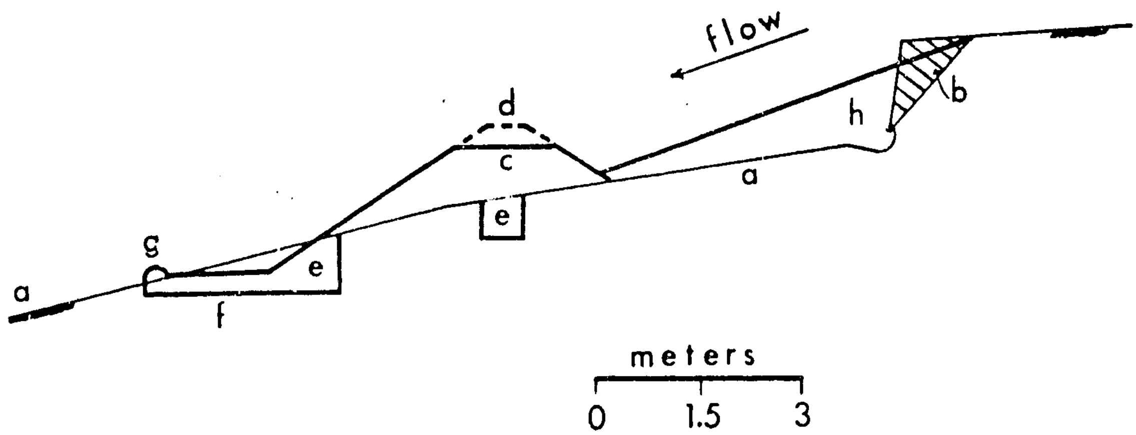


Figure 4. Construction plan for a gully headcut control with a loose-rock check dam. The section of the structure is parallel to the centerline of the gully. a = original gully bottom. b = excavated area of headcut wall. c = spillway. d = crest of freeboard. e = excavation for key. f = excavation for apron. g = end sill. h = rock fill.

small rocks are used in a dam, they may be moved by the impact of the first large water flow, and the dam quickly destroyed. In contrast, a check dam constructed of only large rocks that leave large voids in the structure will offer resistance to the flow, but may create water jets through the voids. These jets can be highly destructive if directed toward openings in the bank protection work or other unprotected parts of the channel. Large voids in check dams also prevent the accumulation of sediment above the structures. In general, this accumulation is desirable because it increases the stability of structures and enhances stabilization of the gully.

Large voids will be avoided if the rock is well graded. Well-graded rock will permit some flow through the structure. The majority of the rock should be large enough to resist the flow.

Since required size and gradation of rock depend on size of dam and magnitude of flow, strict rules for effective rock gradation cannot be given. The recommendations given below are empirical values derived from gully treatments in the Colorado Rocky Mountains, and should be evaluated accordingly. The designer should use these values only as a guide for his decision.

As a general rule, rock diameters should not be less than 10 centimeters, and 25 percent of all rocks should fall into the 10 to 14 centimeter size class. The upper size limit will be determined by the size of the dam; large dams can include larger rock than smaller ones. Flat and round rock, such as river material, should be avoided. Both types slip out of a structure more easily than broken rocks, which anchor well with each other.

In general, large design peak flows will require larger rock sizes than small flows. As an example, assume that the designed total dam height ranges between 1 and 2 meters, where total height is measured from the bottom of the dam to the crest of the freeboard. Type of dam is loose rock without reinforcement. Design peak flow is estimated not to exceed 1 meter^3/second. An effective rock gradation would call for a distribution of size classes as follows:

Size	Percent
10-14 cm	25
15-19 cm	20
20-30 cm	25
31-45 cm	30

If, on the other hand, dam height would be increased to 3 meters, rock up to 1 meter diameter, constituting 15 percent of the volume, could be placed into the base of the dam and the second size class decreased by this portion. If peak flow was estimated not to exceed 0.75 meter^3/second, the 31 to 45 cm size class could be eliminated and 55 percent of the volume could be in the 20 to 30 centimeter class.

Spacing

The location of a check dam will be determined primarily by the required spacing of the structures. Requirements for spacing depend on the gradients of the sediment deposits expected to accumulate above the dams, the effective heights of the dams, the available funds, and the objective of the gully treatment. If, for instance, the objective is to achieve the greatest possible deposition of sediment, high, widely spaced dams would be constructed. On the other hand, if the objective is mainly to stabilize the gully gradient, the spacing would be relatively close and the dams low.

In general, the most efficient and most economical spacing is obtained if a check dam is placed at the upstream toe of the final sediment deposits of the next dam downstream. This ideal spacing can only be estimated, of course, to obtain guidelines for construction plans.

Normally, objectives of gully control require spacings of check dams great enough to allow the full utilization of the sediment-holding capacity of the structures. Determination of this spacing requires definite knowledge of the relationship between the original gradient of the gully channel and that of sediment deposits above check dams placed in the gully.

Keys

Keying a check dam into the side slopes and bottom of the gully greatly enhances the stability of the structure. Such keying is important in gullies where expected peak flow is large and where soils are highly erosive (such as soils with high sand content). Loose-rock check dams without keys were successfully installed in soils derived from Pikes Peak granite, but estimated peak flows did not exceed 0.2 meters^3/second.

The objective of extending the key into the gully side slopes is to prevent destructive flows of water around the dam and consequent scouring of the banks. Scouring could lead to gaps between dam and bank that would render the structure ineffective. The keys minimize the danger of scouring and tunneling around check dams because the route of seepage is considerably lengthened as voids in the keys become plugged, the length of the seepage route increases. This increase causes a decrease in the flow velocity of the seepage water and, in turn, a decrease in the erosion energy.

The part of the key placed into the gully bottom is designed to safeguard the check dam against undercutting at the downstream side. Therefore, the base of the key, which constitutes the footing of the dam, must be designed to be below the surface of the apron. This is of particular importance for fence-type and impervious structures because of the greater danger of scouring at the foot of these dams. The water flowing over the spillway forms a chute that creates a main critical area of impact where the hydraulic jump strikes the gully bottom. This location is away from the structure. The sides of loose-rock and wire-bound check dams slope onto the apron, on the other hand, and no freefall of water occurs.

The design of the keys calls for a trench, usually 0.6 meters deep and wide, dug across the channel. Where excessive instability is demonstrated by large amounts of loose materials on the lower part of the channel side slopes or by large cracks and fissures in the bank walls, the depth of the trench should be increased to 1.2 or 1.8 meters.

Dam construction starts with the filling of the key with loose rock. Then the dam is erected on the rock fill. Rock size distribution in the key should be watched carefully. If voids in the key are large, velocities of flow within the key may lead to washouts of the bank materials. Since the rock of the keys is embedded in the trench and therefore cannot be easily moved, it is advantageous to use smaller materials, such as a mixture with 80 percent smaller than 14 centimeters.

Height

The effective height of a check dam is the elevation of the crest of the spillway above the original gully bottom. The height not only influences structural spacing but also volume of sediment deposits. In most cases, dam height will be restricted by one or all of the following criteria: costs, stability, and channel geometry in relation to spillway requirements. Cost relations between different types of rock check dams will be discussed later. Stability of impervious check dams should be calculated where life and/or property would be endangered by failure.

Severely tested check dams in Colorado had maximum heights as follows: loose-rock and wire-bound dams, 2.2 meters; and fence-type dams (thickness of 0.6 meter), 1.8 meters.

In gullies with small widths and depths but large magnitudes of flow, the effective height of dams may be greatly restricted by the spillway requirements. This restriction may result from the spillway depth necessary to accommodate expected debris-laden flows.

Spillway

Most gullies have either trapezoidal, rectangular, or V-shaped cross sections. For structural gully control, design storms should be of 25 years magnitude and, as a minimum, spillways should accommodate the expected peak flow from such a storm. In mountainous watersheds, however, where forests and brushlands often contribute large amounts of debris to the flow, the size and the shape of spillways should be determined by this expected organic material. As a result, required spillway sizes will be much larger than if the flow could be considered alone. Spillways designed with great lengths relative to their depths are very important here. Yet, spillway length can be extended only within limits because a sufficient contraction of the flow over the spillway is needed to form larger depths of flows to float larger loads over the crest. The obstruction of a spillway by debris is undesirable since it may cause the flow to overtop the freeboard of the check dam and lead to its destruction.

The characteristics of the sides of a spillway are also important for the release of debris over the structure. Spillways with perpendicular sides will retain debris much easier than those with sloping sides; in other words, trapezoidal cross sections are preferable to rectangular ones. A trapezoidal shape introduces another benefit by increasing the effective length of the spillway with increasing magnitudes of flow.

The length of the spillway relative to the width of the gully bottom is important for the protection of the channel and the structure. Normally, it is desirable to design spillways with a length not greater than the available gully bottom width so that the waterfall from the dam will strike the gully bottom. There, due to the stilling-basin effects of the dam apron, the turbulence of the flow is better controlled than if the water first strikes against the banks. Splashing of water against the channel side slopes should be kept at a minimum to prevent new erosion. Generally, spillway length will exceed gully bottom width in gullies with V-shaped cross sections, or where large flows of water and debris are expected relative to the available bottom width. In such cases, intensive protection of the gully side slopes below the structure is required.

Apron

Aprons must be installed on the gully bottom and protective works on the gully side slopes below the check dams, otherwise flows may easily undercut the structures from downstream and destroy them.

Apron length below a loose-rock check dam cannot be calculated without field and laboratory investigations on prototypes. Different structures may have have different roughness coefficients of the dam side slope that forms a chute to the flow if tailwater depth is low. Differences in rock gradation may be mainly responsible for the different roughness values.

The design procedures for the loose-rock aprons were therefore simplified and a rule of thumb adopted: the length of the apron was taken as 1.5 times the height of the structure in channels where the gradient did not exceed 15 percent, and 1.75 times where the gradient was steeper than 15 percent. The resulting apron lengths included a sufficient margin of safety to prevent the waterfall from hitting the unprotected gully bottom. The design provided for embedding the apron into the channel floor so that its surface would be roughly level and about 0.3 meters below the original bottom elevation.

At the downstream end of the apron, a loose-rock sill should be built 0.15 meter high, measured from channel bottom elevation to the crest of the sill. This end sill creates a pool in which the water will cushion the impact of the waterfall.

The installation of an end sill provides another benefit for the structure. Generally, aprons are endangered by the so-called ground roller that develops where the hydraulic jump of the water hits the gully bottom. These vertical ground rollers of the flow rotate upstream and, where they strike the gully floor, scouring takes place. Thus, if the hydraulic jump is close to the apron, the ground roller may undermine the apron and destroy it. The end sill will shift the hydraulic jump farther downstream, and with it the dangerous ground roller. The higher the end sill, the farther downstream the jump will occur. Since data on sediment and flow are not usually available, a uniform height of sill may be used for all structures.

Ephemeral gullies carry frequent flows of small magnitudes. Therefore, it is advisable not to raise the crest of the end sills more than 0.15 to 0.25 meter above the gully bottom. End sills, if not submerged by the water, are dams and create waterfalls that may scour the ground below the sill. At higher flows, some tailwater usually exists below a sill and cushions, to some extent, the impact from the waterfall over the sill.

Where the downstream nature of the gully is such that appreciable depth of tailwater is expected, the installation of end sills is not critically important. The hydraulic jump will strike the water surface and ground rollers will be weak.

Bank Protection

Investigations have shown that check dams may be destroyed if flows scour the gully side slopes below the structures and produce a gap between the dam and the bank. Since water below a check dam is turbulent, eddies develop that flow upstream along each gully side slope. These eddies are the cutting forces.

Several types of material are suitable for bank protection. Loose rock is effective, but should be reinforced with wire-mesh fence, secured to steel posts, on all slopes steeper than 1.25 to 1.00. The design should provide for excavation of the side slopes to a depth of about 0.3 meter so that the rock can be placed flush with the surrounding side slope surface to increase stability of the protection. Excavation of surface materials also assures that the rock would not be set on vegetation. Banks should be protected for the full length of the apron.

The height of the bank protection depends on the characteristics of channel, flow, and structure. Where gullies have wide bottoms and spillways are designed to shed the water only on the channel floor, the height should equal total dam height at the structure, but can rapidly decrease with distance from the structure. In contrast, where the waterfall from a check dam will strike against the gully banks, the height of the bank protection should not decrease with distance from dam to prevent the water from splashing against unprotected banks.

In gullies with V-shaped cross sections, the height of the bank protection should be equal to the elevation of the upper edges of the freeboards of the dam. In general, the height of the bank protection can decrease with increasing distance from the dam.

CONSTRUCTION PROCEDURES

Before construction starts, the following design features should be staked and flagged conspicuously:

(1) Mark the centerline of the dam and the key trenches, respectively, on each bank. Set the stakes away from the gully edge to protect them during construction.

(2) Designate the crest of the spillway by a temporary bench mark in the gully side slope sufficiently close to be of value for the installation of the dam.

(3) Mark the downstream end of the apron.

(4) For loose-rock and wire-bound dams, flag the upstream and downstream toes of the dam proper.

Caution is required during excavation to avoid destroying the stakes before the main work of installation begins.

The construction of all dams should start with the excavation for the structural key, the apron, and the bank protection. This very important work can be performed by a backhoe or hand labor. Vegetation and loose material should be cleaned from the site at the same time.

The trenches for the structural keys will usually have a width of 0.6 meter, therefore a 0.5 meter wide bucket can be used on the backhoe. If the construction plan calls for motorized equipment, two types of backhoes can be used. One, mounted on a rubber-wheeled vehicle and operating from a turntable, permits the backhoe to rotate 360 degrees. This machine travels rapidly between locations where the ground surfaces are not rough and works very efficiently in gullies whose side slopes and bottoms can be excavated from one or both channel banks. The other type can be attached to a crawler tractor. This type proves to be advantageous at gullies that are difficult to reach, and at ones with widths and depths so large that the backhoe has to descend into the channel to excavate. In deep gullies with V-shaped cross sections, temporary benches on the side slopes may be necessary. Often, the bench can be constructed by a tractor with blade before the backhoe arrives.

The excavated material should be placed upstream from the dam site in the gully. The excavated trench and apron should then be filled with rock. Since a special graded rock is required for the keys, rock piles for keys must be separate from those used in the apron and dam proper. Excavations can be filled by dumping from a dump truck or by hand labor. During dumping operations, the fill must be checked for voids, which should be eliminated.

If dump trucks are loaded by a bucket loader, some soil may be scooped up along with the rock. Soil is undesirable in a rock structure because of the danger of washouts. To avoid soil additions, use a bucket with a grilled bottom that can be shaken before the truck is loaded. Other devices such as a grilled loading chute would also be appropriate.

Dumping rock into the dam proper has two advantages: The structure will attain greater density, and rocks will be closer to their angle of repose than if placed by hand. Hand labor can never be completely avoided, however, since plugging larger voids and the final dam shape require hand placement. Where gullies are deep and dumping is impractical, rock chutes may be used.

Often, gully control projects are planned to provide employment for numbers of people. This objective can easily be accomplished if sufficient supervision is available for the individual steps in the construction. Special attention is needed at the spillway and freeboard. In loose-rock and wire-bound structures, where the shape of the dam is not outlined by a fence as in the other types, experience shows there is a tendency to construct the spillways smaller than designed.

In wire-bound dams, a commercial, galvanized stock fence, usually about 1.2 meters wide, can be used. The stay and line wires should not be less than 12-1/2 gage low-carbon steel, the top and bottom wires 10 gage low-carbon steel, and the openings in the mesh 0.15 meter. To connect ends of the fence or to attach the fence to steel posts, a galvanized 12-1/2 gage coil wire is sufficiently strong.

The wire mesh of required length and width should be placed over the gully bottom and side slopes after the trench and apron have been filled with rock. Generally, several widths of mesh will be needed to cover the surface from bank to bank. If several widths are required, they should be wired together with coil wire where they will be covered with rocks. The part not to be covered should be left unattached to facilitate the fence stringing operations around the structure.

Before the rock is placed on the wire mesh for the installation of the dam proper, the mesh should be temporarily attached to the gully banks. Otherwise, the wire mesh lying on the gully side slopes will be pushed into the gully bottom by the falling rock and buried. Usually, stakes are used to hold the wire mesh on the banks.

After the dam proper is placed and shaped, the fence can be bound around the structure. Fence stretchers should be applied to pull the upstream ends of the fence material down tightly over the downstream ends, where they will be fastened together with coil wire. Then the bank protection below the dam should be installed.

The installation of single- and double-fence dams begins with the construction of the fences after excavation is completed. Construction drawings should be followed closely here because the final shape of the dams will be determined by the fences. Conventional steel fenceposts can be used. In some locations, the great height of posts may offer difficulties for the operator of the driving equipment, and scaffolds should be improvised. A pneumatically driven pavement breaker with an attachment can be used to ease the job of driving. Since relatively great lengths of hose may be attached this tool may be used in deep gullies and on sites with difficult access.

At single-fence dams, dumping of rock is practical if the gully is not excessively deep or wide. At double-fence structures, hand labor, a backhoe, or a clamshell will be required. The rock should be placed in layers and each layer inspected for large voids, which should be closed manually by rearranging rocks.

Much time and effort can be saved during construction if a realistic equipment plan is established beforehand. Such a plan requires an intimate knowledge of the cross sectional dimensions of the gullies and their accessibility to motorized equipment. Pioneer roads that might be needed because of lack of access are not only important for equipment considerations, but will also enter into the cost of the construction.

If equipment is to be used, as a general rule, it appears to be advantageous to use heavier and larger machines if their mobility is adequate. Although hourly costs for heavier machines are usually greater, the total cost for a job is reduced.

With few exceptions, conventional construction equipment is not sufficiently mobile to operate in rough topography without pioneer roads. In watershed rehabilitation projects such as gully control, road construction is undesirable because it disturbs the ground surface and may lead to new erosion. It is therefore desirable to consider crawler-type equipment only.

COST RELATIONS

Relationships between the installation costs of the four different types of rock check dams described here are based on research in Colorado. The relationships are expressed by ratios (Figure 5) to avoid specific dollar comparisons. When considering the cost ratio, one must keep in mind that differential inflation may have offset some finer differences in cost. It is advisable, therefore, to test the cost of individual structures by using material and volume requirements as given by the equations. The cost ratios (Figure 5) can then be adjusted, if necessary.

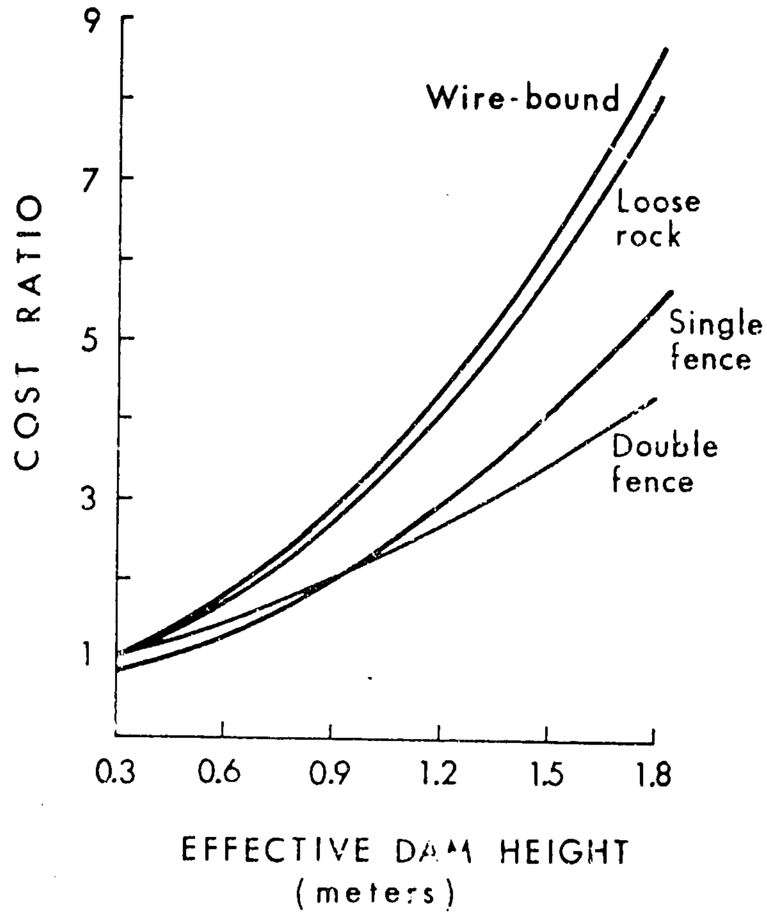


Figure 5. Installation cost of four different types of check dams as a function of effective dam height. The cost ratio is the cost of a dam related to the cost of a loose-rock dam, 0.3 meter high, built with angular rock.

It is obvious that the cost of installing a complete gully treatment increases with gully gradient because the required number of dams increases. However, there is one effective dam height at which the cost is lowest (Figure 6). In the sample gully, this optimum height for loose-rock dams is about 0.6 meter, for single-fence dams 0.7 meter, and for double-fence dams 1.1 meters. A constant gully cross section was assumed. In reality, of course, gully cross sections usually change between dam sites. The optimum height for lowest treatment costs is not a constant, but changes between gullies, depending on shape and magnitude of the gully cross sections at the dam sites.

Since the cost of the dam is directly proportional to the rock volume, rock requirement will be dependent upon dam height (Figure 6). This means that, in a given gully, there is one dam height at which rock requirements for a treatment are smallest.

A treatment cannot be evaluated on the basis of cost of installation alone, because recognition of benefits is part of the decision making process. Sediment deposits retained by check dams can be incorporated into a cost ratio that brings one tangible benefit into perspective. Sediment has been cited as the nation's most serious pollutant. The sediment-cost ratio increases (treatment is increasingly beneficial) with dam height and decreases with increasing gradient.

Since single-fence and double-fence dams cost less than loose-rock and wire-bound loose-rock dams for an effective height greater than 0.3 meter, the sediment-cost ratio is more favorable for the fence-type structure. The ratios remain smaller than 1.0 in all gradients larger than 5 percent for treatments with loose-rock and wire-bound loose-rock dams, and on gradients larger than 7 and 9 percent for treatments with single-fence and double-fence dams, respectively.

The importance of sediment-cost ratios in relation to gully gradient and effective dam height becomes apparent in situations where not all gullies of a watershed can be treated. Gullies with the smallest gradient and largest depth, and highest possible fence-type dams should be chosen if other aspects, such as access or aesthetic value, are not dominant.

OTHER GULLY CONTROL STRUCTURES AND SYSTEMS

Nonporous Check Dams

Rock can be used for the construction of wet masonry dams. Limitations in available masonry skills, however, may not permit this approach. A prefabricated concrete dam was designed and a prototype installed in Colorado. It required very little time and no special skills for installation. The capital investment for this dam is larger than for a rock structure, however. A prestressed concrete manufacturer

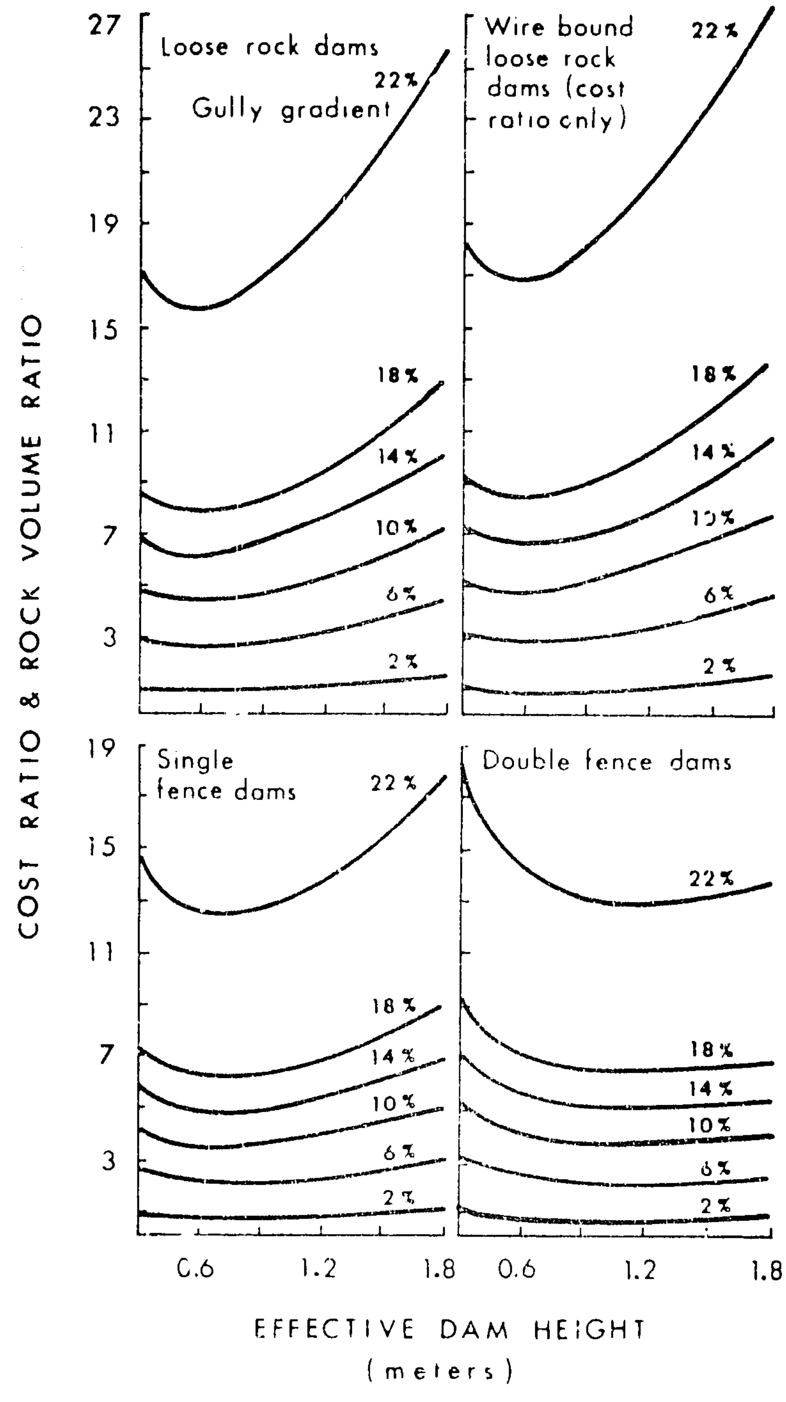


Figure 6. Relative cost of installation of check-dam treatments and relative angular rock volume requirements in gullies with different gradients as a function of effective dam height. The cost and rock volume ratios relate the cost and rock volume of a treatment to those of a treatment with loose-rock dams 0.3 meter high installed on a 2 percent gradient.

must be available reasonably close to the project area and the construction sites must be accessible to motorized equipment. Where aesthetic considerations and land values are high (recreational sites and parks, for example), a prestressed, prefabricated concrete check dam may be the answer.

Check dams may also be built from corrugated sheet steel. For successful application, a pile driver is required to assure proper fit of the sheets. Excavating trenches for the sheets jeopardizes dam stability if the refill is not compacted sufficiently. Quite often, insufficient depth of soil above the bedrock does not permit this dam type.

Earth Check Dams

Earth check dams should be used for gully control only in exceptional cases. Basically, it was the failure of the construction material, soil (in combination with concentrated surface runoff), that caused the gully. Gullies with very little flow may be an exception if the emergency spillway safely releases the flow onto the land outside the gully. The released flow should not concentrate, but should spread out on an area stabilized by an effective vegetation cover or by some other type of protection such as a gravel field. Most gullied watersheds do not support areas for safe water discharge.

Standpipes or culverts in earth check dams generally create problems, because of the danger of clogging the pipe or culvert inlet, and the difficulty in estimating peak flows. Therefore, additional spillways are required.

If soil is the only dam material available, additional watershed restoration measures (such as vegetation cover improvement work and contour trenches) should be installed to improve soil infiltration rates, to enhance water retention and storage, and thus to decrease magnitude and peak of gully flows.

Vegetation-Lined Waterways

With the exception of earth check dams, gully control measures described previously treat the flow where it is--in the gully. In contrast, treatments by waterways take the water out of the gully by changing the topography. Check dams and waterways both modify the regime of the flow by decreasing the erosive forces of the flow to a level that permits vegetation to grow. In waterways, however, flow is modified compared with the original gully, in two ways: lengthening the watercourse, resulting in a gentler bed gradient; and widening the cross section of flow, providing very gentle channel side slopes. This latter measure leads to shallow flows with a large wetted perimeter (increase in roughness parameter). Both measures substantially decrease flow velocities, which in turn decrease the erosive forces.

Contrasted with check dam control, waterway projects strive to establish a vegetative cover when land reshaping is finished. Indeed, a quick establishment of an effective vegetation lining is the key to successful waterways. It follows that the prime requisites for a successful application are precipitation, temperature, and fertility of soils, all favorable to plant growth. Other requisites are:

(1) Size of gully should not be larger than the available fill volumes;

(2) Width of valley bottom must be sufficient for the placement of a waterway with greater length than that of the gully;

(3) Depth of soil mantle must be adequate to permit shaping of the topography; and

(4) Depth of topsoil must be sufficient to permit later spreading on all disturbed areas.

Design criteria or prerequisites in terms of hydraulic geometry are not yet available.

Vegetation-lined waterways require exact construction (therefore, close construction supervision) and frequent inspections during the first treatment years. The risk, inherent to nearly all types of erosion control work, is greater for waterways at the beginning of treatment than for check dam systems. To offset this risk, in Colorado, 19 percent of the original cost of installation was expended for maintenance, while for the same period of time, only 4 percent was required at check dams.

Eight percent less funds were expended per linear meter of gully for construction and maintenance of grassed waterways than for check dams. This cost difference is not significant, especially if the greater involvement in waterway maintenance is recognized. In deciding on the type of gully control, one should consider not only construction costs but also risk of the prerequisites for vegetation-lined waterways.

SUMMARY OF DESIGN CRITERIA AND RECOMMENDATIONS

Spacing decreases with increasing gully gradient and increases with effective dam height. Number of check dams increases with gully gradient and decreases with increasing effective dam height. Expected volumes of sediment deposits increase with effective height.

For practical purposes, gully gradients ranging from 1 to 30 percent do not influence volumes of sediment deposits in a treatment. On gradients larger than 30 percent, sediment catch decreases more distinctly with increasing gradient.

Rock volume requirements are much larger for loose-rock and wire-bound loose-rock dams than for fence-type dams. At effective dam heights larger than 0.6 meter, treatments with double-fence dams require the smallest amounts of rock.

At effective dam heights larger than about 0.5 meter, loose-rock and wire-bound loose-rock dams are more expensive than fence-type dams. The difference in cost increases with height. Single-fence dams are less expensive than double-fence dams at effective heights up to 1.0 meter.

Regardless of gradient, in a given gully, there is one effective dam height for each type of structure at which the cost of treatment is lowest (Figure 6). For each type of treatment, rock requirements are smallest at the optimum effective dam heights for least costs (Figure 6). The sediment-cost ratio (the value of expected sediment deposits divided by the cost of treatment) increases with effective dam height and decreases with increasing gully gradient. At effective dam heights of about 0.6 meter and larger, single-fence dams have a more pronounced beneficial sediment-cost ratio than loose-rock or wire-bound loose-rock dams. At effective dam heights of 1.1 meters and larger, treatments with double-fence dams have the largest sediment-cost ratios.

CHAPTER VIII

WATER QUALITY

INTRODUCTION

The hydrologic cycle depicts the movement of water through a forest ecosystem. Water flow is a major component of the environment, linking together the atmospheric, soil, biotic and stream compartments of the system. Since water is the carrier of materials and energy between the atmospheric and terrestrial portion of the system and the stream, an understanding of the processes which affect water quality in forest streams has as its basis an understanding of the hydrologic process.

DISSOLVED CHEMICAL CONSTITUENTS

To understand various impacts, one must realize that forest streams are not separate and distinct from the area they drain, but are an integral part of the ecosystem. As water comes into contact with each part of the system, the chemical characteristics adjust accordingly. Chemical reactions and physical processes occur as the water contacts the atmosphere, soil and biota. It is these processes and the condition of each compartment that determine the amount and kind of chemical species in solution.

The major sources of dissolved constituents in water draining upland watersheds are: geologic weathering of parent rock, meteorological inputs, and biological inputs. Chemical and physical weathering converts rock minerals into soluble or transportable form. Dissolved matter, including organic compounds and mineral ions, are added to the forest ecosystem in precipitation, dust, and other aerosols. The biological inputs are mainly materials gathered elsewhere and deposited in the forest by animals (including man) and the photosynthetic production of organic material from inorganic substances, followed by the subsequent breakdown of the organic back to the inorganic compounds.

In undisturbed ecosystems, the rock substrate and soil generally control the relative concentrations of metallic ions (cations such as Ca^+, Mg^{++}, K^+ and Na^+), while the relationship of biological and biochemical processes in the soil to precipitation rarely governs the anionic (HCO_3^-, NO_3^-, and $PO_4^=$) yield. Anions, such as chloride (Cl^-), nitrate (NO_3^-), and sulfate ($SO_4^=$), at least in the absence of abundant sulfide minerals, originate from the atmosphere; the output of these ions is regulated by soil processes.

Although appreciable quantities of nitrogen, sulfur, and other elements are often found in precipitation and in dust and dry fallout between rains, the soil under natural forest conditions is considered the greatest contributor of dissolved elements to runoff. Other components of the ecosystem (biologic, atmospheric, rock substrate), through their influence on soil processes and properties, play an important role in determining the chemistry of outflow.

Such dissolved compounds can leave a system by water transport over and through the soil or forest floor to either groundwater or surface flow.

The above processes are often lumped under the term nutrient cycling, which consists of inputs, outputs and the movement of dissolved solids within the system. This is chiefly concerned with outputs, that is, the streamflow from upland basins and the various factors influencing the chemical components in this runoff.

The movement of water through the soil, along with biological activity, controls the ionic composition of water leaving upland watersheds as streamflow. The most chemically active components of a forest soil are the clay and organic colloids. Soil colloids have a large capacity to exchange ions in solution for those adsorbed on their surfaces. Clays have high exchange capacities compared with most other minerals because of their large surface area per unit volume and their negative electrical charge.

A simplified picture of the exchange process would be that cations absorbed on soil colloids are selectively exchanged for hydrogen ions from the soil water. The hydrogen ions come principally from the solution of carbon dioxide in water and dissociation of the resulting H_2CO_3 molecule into a hydrogen ion and bicarbonate ion. The dissolved carbon dioxide originates chiefly in the metabolism of microorganisms and plant roots in the soil. Based on the above assumptions, only the water remaining for some time in interstices between soil particles is likely to pick up an appreciable load of dissolved carbon dioxide and consequently be effective in leaching mineral ions.

Studies have shown that the ionic concentrations and their relationships to discharge are quite variable. For example, a direct relationship exists between H^+, NO_3^- concentrations and discharge, but no relationship between discharge and the concentrations of Mg^{++}, Ca^{++},

$SO_4^=$, and K^+ has been found in streams on an experimental forest in New Hampshire. Elsewhere, individual cation concentrations, when considered throughout the year, appeared to be independent of discharge rate on four experimental watersheds in the Appalacian mountains of the eastern United States. An inverse relationship to cation concentrations and discharge of selected streams has been reported in the Rocky Mountains. Also, an inverse relationship between ion concentrations and discharge was observed from a stream in California. In large streams, general ionic concentrations are commonly lower at times of high flow than at low flow due to the long residence time of water in the soil during the dry weather, which gives more opportunity for chemical reactions.

Land management practices can significantly influence ionic balances. For example, if the cation-anion balance of the soil solution is changed temporarily by the addition or subtraction of an ionic species due to logging or fire, the equilibrium is restored by an equivalent change in the concentrations of oppositely charged ions.

Once water has reached an effluent stream, it is often considered to consist of a base flow fraction made up of ground water that infiltrates into the channel and a direct runoff fraction, which in turn enters the drainage system during and soon after precipitation periods. The direct runoff presumably has no residence time in the ground water reservoir and only a short contact with soil or vegetation. As mentioned earlier, reactions in the soil zone are commonly extensive enough that the direct runoff has a considerably higher dissolved-solids content than the original rain or snow. Sometimes, the base flow has a still greater dissolved load. Based on the assumptions outlined above, the solute concentration of river water would be inversely related to flow rate. This would not necessarily be the case if the stream were influent with base flow nonexistent.

Other natural factors in the stream itself that influence ionic composition include: reactions of water with mineral solids in the streambed and in suspension, reactions among solutes, losses by evaporation and by transpiration from plants growing in and near the stream, and effects of organic matter and aquatic organisms. This latter set of natural factors results in fluctuations of composition that bear little relation to discharge rates.

Chemical equilibria probably control a few properties of water in flowing streams. For example, the ion-exchange reactions of solutes with suspended sediment probably are rapid enough that they usually are at equilibrium. Certain oxidations, such as ferrous to ferric ion, also normally reach equilibrium. For biological processes such as the utilization and production of carbon dioxide and oxygen, the equilibrium approach is not necessarily appropriate. If the stream is to be considered a dynamic system, which it is, kinetics would better describe its chemistry rather than using a steady-state equilibrium approach. For example, the processes whereby biological organisms consume organic loads of the stream can often be better studied and understood by applying rates of reactions and processes.

When a forest is harvested (especially clearcut), trees no longer take up nutrients and the nonmerchantable parts of trees increase forest litter. The removal of the forest canopy changes the microclimate, making it warmer and reducing evapotranspiration, resulting in an increased soil water content. This increased temperature and water content of the soil accelerates the activity of microorganisms that break down organic matter. The greatly increased respiration of these organisms raises the carbon dioxide partial pressure of the soil atmosphere, which in turn increases the bicarbonate anion level and leaching loss of cations from the system. Nitrogen losses as nitrate may also occur, when it is produced by the oxidation of organic matter (nitrification) and not utilized by the forest vegetation which has been removed.

Recent studies throughout the United States do show that following clearcutting, there is an increased loss of nutrients (cations and nitrate) from the logged area along with an increased runoff volume. This increased ionic loss along with increased runoff would possibly tend to give concentrations of ions a less noticeable increase, but total losses should be quite outstanding.

Studies have also shown that slash burning following logging produces an even greater increase in the release of ions from the forest floor litter and mineral soil. This increase in the release of ions is due to the breakdown of the organic debris to a soluble form, making it easily removed from the soil by leaching water. Generally, this process can lead to an increase in the total loss of nutrients in streamflow. However, the above may not always happen. For example, a moderately severe fire in a conifer stand had no specific effect on the concentrations of Ca^{++}, Mg^{++}, Na^{+}, K^{+}, or HO_3^{-} in the stream. It was postulated in this study that ash constituents were dissolved by light rainfall and leached into the permeable forest soil before the first snow. Because of the acidic nature of the soil, the dissolved cations were absorbed on the exchange complex instead of being washed directly into the stream. Of course, rains of high intensity following a severe fire could move large quantities of soluble ash compound into flowing streams. As the forest regenerates following a perturbation, the dissolved load of the stream also returns to levels experienced before the disturbance.

In summary, the dissolved load of streams after various forest activities, such as clearcutting or burning, is a function of the several soil, vegetative and climatic characteristics that describe a forest ecosystem. Soil characteristics, such as porosity and texture, determine the pathway and rate of water movement in or over soil, soil erodibility, and how strongly nutrients will be held within the soil matrix. Vegetative characteristics, such as species composition, influence the rate of nutrient uptake. The rate of revegetation controls the rapidity with which recycling begins after system disruption. The leaching rate is influenced by form, chemistry, amount and intensity of precipitation. Generalization of effects of forest management in widely differing upland ecosystems is precluded by the intricate interaction among these many variables.

SUSPENDED SEDIMENT

In some instances, undisturbed upland watersheds generally have low suspended sediment concentrations (10 to 20 ppm average concentration). Higher concentrations are often the result of a perturbation to the drainage area such as roads, logging, or natural catastrophes which can cause accelerated erosion.

Erosion of soils produces sediment in waters draining forest lands. Three major erosion processes are of concern: surface erosion, mass soil movement, and channel erosion. Surface erosion is the direct result of rain striking unprotected soil surfaces. Soil particles are detached and transported by overland flow across the soil surface. This process is relatively nonexistent in the nondisturbed, well protected forest floor which has a high infiltration rate. Accelerated erosion can be expected in cases where the protective forest floor litter has been removed exposing mineral soil along with soil compaction.

Mass soil movement is the process by which large volumes of soil and rock materials move downslope under the influence of gravity. This movement is usually prevalent in areas where the geologic substrate is naturally unstable.

Channel erosion is the result of abrasion by water or debris on the stream bank and bed. This erosion process can contribute heavily to suspended sediment. It was found, for instance, that 25 percent of the sediment yields in the western United States could be attributed to logging activity, 25 percent to agriculture and 50 percent to bank cutting in the main river.

In general, increased velocity of streamflow will give an increased concentration of suspended sediment. Also, any practice that reduces the stability of the streambank or other watershed surfaces will cause suspended sediment to increase.

Roads and road building are considered to be the principle sources of suspended sediment. Studies and observations have shown that as much as 90 percent of the sediment produced from timber sale areas in the northern regions of the United States comes from roads.

There have been numerous studies relating forestry activities to accelerated erosion and sedimentation. Generally, it has been found that watershed damage from felling, limbing and bucking of trees during timber harvesting is probably negligible.

Skidding and yarding activities can cause accelerated erosion; however, the great variety of techniques and machines used in this operation provide alternatives for minimizing damage on many sites. A major rule here is: the less compacting and disturbing the contact with the forest floor, the less watershed damage will result from skidding and yarding.

Balloon logging probably results in the least compaction and disturbance because the logs are transported free in the air over most of the cut area. Grapple and yarding systems are intermediate between skyline and high lead, as they combine features of each. The most destructive technique of all is tractor logging.

Harvest areas on upland watersheds are subject to erosion until new vegetative cover is established, since it is the exposed mineral soil that is a major source of suspended sediment. Furthermore, varying degrees of damage to the forest floor result from the several combinations of harvesting and log transport systems.

In a study, clearcutting and removal of trees by the balloon system resulted in the lowest soil sediment deposited in streams and had the smallest exposure of bare soil. Clearcutting by tractor, as expected, exposed the most mineral soil (over 30 percent).

Once an area is logged, slash is frequently eliminated by controlled burning. Intense fires often lead to accelerated erosion. Extremely hot fires consume vegetation, litter and duff materials and leave the soil unprotected. Such fires may also reduce the organic content of the soil and alter the stability of surface soil aggregates. Infiltration rates are often reduced and surface runoff can be increased by the production of a nonwettable surface layer. Controlled burns are usually not intense enough to cause erosion problems.

Fire can also be a contributor to accelerated mass wasting, due largely to the destruction of the natural mechanical supports of soils. In the western United States, logging and burning produced increases in mass soil movements due to the loss of mechanical support of the root systems of trees and plants. Many other studies support the relationship of fire, logging and road building to accelerated mass movements and resulting stream sedimentation.

BACTERIOLOGICAL QUALITY

Quite often, bacteriological indicators are employed to gain knowledge of the biological quality of streamflow. An estimate of these organisms is a relatively simple, fast and inexpensive index of pollution, especially when the membrane filter technique is used. Knowledge of cycles and variability of bacteria in natural waters and the relationships of bacteria to physical environmental factors is sparse.

There have been some studies of relatively undisturbed watersheds describing bacteria-environment relationships.

Seasonal coliform trends have been studied and evidence of relationships between coliform counts and certain physical environmental factors (streamflow and air temperature) have been found. Great increases in logging and stream turbidity over a period of years did not affect coliform densities, but it should be noted that the logging was on municipal watersheds and disturbance was probably minimal.

An assessment of the causes of variation in bacterial numbers of a small, unpolluted stream in the Rocky Mountains of the United States indicated that the most important cause of bacteria population fluctuations was summer rainstorms of short duration, producing overland flow. When streamflow is stable during periods of no precipitation, bacterial numbers can be related to the size of the water-streambed contact surface. As streamflow increases after precipitation, bacteria are deposited in the ground water associated with the stream and are later released into the stream as it recedes. Bacterial numbers fluctuate during the winter even when temperatures are as low as 0° to 5.5°C. It has also been found that when cattle graze in marshy areas adjacent to the stream, the bacterial density of the stream rises. The bacteria counted were coliform and total bacteria.

In a measurement of bacterial groups in streamflow from mountain watersheds in the Rocky Mountains of the western United States, total coliform, fecal streptococcus, and fecal coliform bacterial groups were closely related to the physical parameters of the stream, and they were especially dependent on the "flushing effect" of runoff from snowmelt and rain, summer storms, or irrigation. The seasonal trend for all bacterial groups was similar: low counts prevailed while the water was at 0°C; high counts appeared during rising and peak flows caused by June snowmelt and rain; a short "post-flush" decrease in bacterial counts took place as the runoff receded in early July; high bacterial counts were again found in the July-August period of warmer temperatures and low flows; and counts declined in September.

Concerning evidence that the forest floor can act as a bacterial filter, it has been found that snowmelt water that had percolated through a strip of forest on the bank of a reservoir contained fewer bacteria than water that had not passed through the forested strip.

The major sources of fluctuations in bacterial content (especially fecal coliform) that can lead to pollution levels in stream water are concentrations of any warm blooded animals on the watershed including man, livestock, or big game animals. If bacterial content of stream water is to be kept below pollutional levels, strict attention must be given to all sources of potential contamination by living organisms.

THERMAL QUALITY

Water temperature may or may not be critical to the survival of the flora and fauna residing in a given stream. However, the composition of these communities will change when there is a change in stream temperature. An elevation of the water temperature will cause increased biological activity which will place a greater demand on the dissolved oxygen in the stream. In addition, increased biological activity may be detrimental to the health of the fauna and even replace existing fish with warm water species. The population dynamics and the type, quantity, and quality of the food of the fauna living within the stream will also change with variations in water temperature.

Clearing the timber overstory adjacent to a stream is one way the water temperature will be increased. Removal of the trees increases the area of the stream exposed to radiation from the sun. That increased exposure is associated with a rise in temperature is logically predicted if one considers an energy budget of the water in a stream. If the trees are removed from the banks of a stream having a certain average temperature, the only change in the energy budget is an increase in solar energy entering the system from the additional area of illuminated stream surface. The temperature will rise as there are no new outlets of energy from the system. Increases in stream temperature may range from fractions of a degree centigrade for a slight opening to over ten degrees centigrade for a clearing of the watershed.

A mathematical model developed in the western United States has been used to predict stream temperatures following modifications of the vegetation shading the stream. This model states that the change in stream temperature is a function of the surface area of the stream exposed to direct solar radiation, the net solar radiation load of the exposed water surface, and the discharge of the stream. The model is operated using variables which describe the physical situation of a stream with vegetation bordering it. For application to a specific case, the existing exposed surface area of the stream, the stream discharge, and the amount of incoming solar radiation is determined. The density and thickness of the vegetative strip bordering the stream and the height of the trees are used to compute the effective unshaded area of the stream surface. The orientation of the stream, time of year, and physiography of the site are required to determine the effective radiation loading.

The model may be operated several times to determine the effects of various methods of forest cutting on the stream temperature. Such predictions of changes in stream temperature may also be used as input to other models whose outputs are the amount of dissolved oxygen in the stream or the impacts on plant and animal communities associated with the water. Due to interrelationships of plants and animals, there may be an effect in several populations due to a change in the stream temperature. Changes in stream temperatures may have severe consequences in certain ecosystems. Thus, one should examine possible effects and choose appropriately before implementing a vegetative treatment.

CHAPTER IX

WATER HARVESTING

INTRODUCTION

Water harvesting systems may be defined as artificial methods whereby precipitation can be collected and stored until it is beneficially used. The system consists of a catchment, which is made more impervious by artificial means than it was in its natural state, and a storage facility for the harvested water.

The elements of the water harvesting system and the development of modern techniques will be presented. In addition, various methods of treating catchments and storing harvested water and the economics of water harvesting systems will be discussed.

ELEMENTS OF WATER HARVESTING SYSTEM

Water Collection

There is no single method of treating catchments to increase runoff that is universally applicable. Each site must be individually evaluated in order to determine the optimum treatment that will produce water from a given site for a particular use.

In the design of a water harvesting system, numerous factors must be considered. They include: the amount of runoff to be expected from storms of various magnitudes, the ratio of runoff to precipitation or runoff efficiency, and the effect of the selected treatment on the quality of the water. The runoff efficiency is highly variable, depending upon storm intensity, the permeability of the surface of the watershed, the degree of saturation of soil of the watershed, *etc.* Precipitation is a random variable; the selection of a particular treatment to induce runoff and the size of the catchment should reflect the uncertainty of precipitation and runoff.

For almost all treatments, there is a minimum threshold amount of precipitation required to saturate the catchment surface; below this amount, virtually no runoff occurs. However, once this threshold has been exceeded, the relationship between storm precipitation and runoff will be essentially linear.

A catchment can be made more impervious using the following methods: land surface alteration, chemical treatments, soil cementation treatments, and ground cover modification. In land alteration, runoff can be increased by: clearing and smoothing, shaping and compacting. The two basic types of chemical treatment are the use of water repellents (such as silicones) and clay dispersants (such as sodium salts). Soil cementation treatments include the mixing of asphalt, cement, resins and polymers into the soil. Ground covers that have been used for catchment construction can be classified as: exposed membranes (including butyl, plastic and asphalt), covered membranes, generally utilizing gravel to cover plastic sheeting, reinforced cement-mortar coated plastic, sheet metal, concrete, reinforced asphalt and asphalt planking.

Water Storage

Various methods of storage have been used with the above methods of catchment construction. These methods include: above-ground tanks and lined reservoirs.

The above-ground tanks have been constructed from: steel, reinforced concrete, metal grain bins with flexible liners, butyl bags, wire reinforced stucco and railroad tank cars and other types of surplus tanks.

The earth reservoirs have been sealed with various types of membrane liners and by mechanical and chemical treatment. The membranes that have been used include: plastic and butyl rubber sheeting, unreinforced and reinforced asphalt membranes, and reinforced cement-mortar coated plastic. Mechanical and chemical treatments include: mechanical compaction with and without the use of a compacting agent such as enzymes, clay dispersants which are also sometimes compacted, water repellants, polymers such as SS-13, and betonite.

Evaporation and Seepage Control

Evaporation and seepage control are needed in order to successfully store harvested water. The methods used in achieving this control are generally dependent on the size and function of the storage facility. Frequently, the same materials are used for both the catchment and the reservoir because seepage control and runoff inducement must both function so as to reduce the entry of water into the soil. Like the catchment, the size of the reservoir must anticipate the precipitation and runoff variability of the particular site. In some instances, evaporation has been controlled by use of chemicals such as long chain alcohols, by use of floating and suspended covers of butyl rubber and plastic sheeting on small tanks, and by completely filling the tank with rock.

DEVELOPMENT OF MODERN WATER HARVESTING TECHNIQUES

Since the 1950s, the technology of water harvesting has developed variety and sophistication. In Australia, "roaded" catchments, based upon the concept of compacted earth, were constructed over thousands of hectares in order to collect water for agricultural purposes. In a roaded catchment, the soil is graded into a series of parallel ridges, having gentle slopes that permit water flow into the ditches that separate them. The ditches then channel the water to storage areas, or the water may be used directly at the site.

In the United States, catchments were built in the 1950's out of sheet metal for watering livestock. Also during this period, experimentation was undertaken with plastic and artificial rubber membranes, for the construction of both catchments and of reservoirs. Since then, butyl rubber catchments have been installed in many areas. More than 300 catchments in the state of Hawaii have been constructed of this material.

A number of experiments have been attempted on Indian reservations in the western United States. Not all the techniques have been successful, but some have worked well. One catchment at Shongopovi, on the Hopi reservation, has provided supplemental domestic water since the early 1930's; this catchment was constructed with very little disruption of the natural topography. On the Navajo reservation, butyl rubber catchments and storage bags are successfully used by stockmen. A concrete catchment is being constructed on coal mine spoils on the Black Mesa to test the feasibility of water harvesting for agricultural purposes on the spoils.

In 1961, waterproofing the soil itself to serve as a catchment structure was attempted. Materials that imparted hydrophobic properties to the soil, thus decreasing its permeability to water were tested. These materials included sprayable asphaltic compounds, plastic and metal films bonded to the soil, soil compaction and dispersion, and field fabricated asphalt and fiberglass membranes.

Water harvesting techniques for the growing of shrubs on coal strip mine soils in New Mexico have been explored. It was found that treatment of the ground with paraffin increased water runoff and the growth of two month old saltbush and Siberian peashrub transplants; the soil moisture content of treated plots was increased by about twenty percent.

There is considerable variation in the cost longevity and efficiency of the above methods of catchment and storage construction.

These systems would need to be evaluated for each site in order to select the best system. Some of the systems to be discussed in the following section have been developed and/or tested at the University of Arizona in the United States over the past fifteen years. In general, these systems are among the most economical of those mentioned above. These water harvesting systems were designed to: provide a dependable supply of stock water, provide a high quality water for domestic and industrial supplies, and extend agriculture into lands presently uncultivated due to lack of water.

WATER HARVESTING CATCHMENTS TESTED AT THE UNIVERSITY OF ARIZONA

Some of the more economical materials mentioned in earlier sections of this chapter have been tested in the Water Harvesting Program at the University of Arizona; the most expensive materials, such as sheet metal, concrete, asphalt panels and asphaltic pavements, were not tested. The results from small plots using exposed unreinforced asphalt membranes have shown that, although relatively inexpensive, this method is undesirable due to cracking caused by oxidation, plant germination and swelling and shrinking of the soil subgrade. Based on the results of small plot tests, economics and experience of other researchers, large scale testing at the University of Arizona has been limited to the following treatments: compacted earth, sodium, gravel covered plastic and reinforced chip-coated asphalt catchments. A discussion of these catchments follows. *(Note: All cost estimations presented in the following section are in 1978 U.S. dollars, and unless otherwise noted, are based upon construction methods used in Arizona.)*

Compacted Earth Catchments (CE)

The Public Works Department of Western Australia initiated in 1948 a program of construction of Roaded Catchments. These catchments consisted of clearing, shaping and contouring to control length and degree of slope and compacting with the aid of pneumatic rollers. An estimated 2500 roaded catchments have been installed principally to supply water for livestock use. These averaged approximately 1 hectare in size. There are also 21 roaded catchments totalling 706 hectares and ranging in size from 12 1 to 70.8 hectares presently being used to furnish domestic water for small towns in Western Australia.

This relatively large scale use in Australia of the compacted earth catchment attests to their utility. A 0.4 hectare compacted earth catchment was constructed in the spring of 1970 at Atterbury Experimental Watershed located near Tucson, Arizona, USA. A design similar to those in Australia was used. Two 121.9 meter long drains spaced 15.2 meters apart collected water from 7.6 meter long slopes. The drainage channels were covered with plastic and gravel to prevent erosion and water loss. The catchment was shaped by a grader following a 1.27 centimeter rainfall. The plot was then smoothed using a tractor-drawn rotary rock rake. This proved to be an excellent method of smoothing. Following an additional 1.27 centimeters of precipitation, the plot was compacted using a 23.6 metric ton vibratory drum roller. The drainage channels were also lined at this time. The total cost of the catchment was approximately $250 including wages at $3.50 per hour. The cost would be more if the catchment site were more remote, unless several catchments were installed at one time. For large catchments, the cost should be less than $370.60 per hectare, the cost being primarily dependent on the cost of clearing and shaping. The smoothing and compaction costs on a large plot would be relatively low. There has been little maintenance since the plot was installed. Maintenance would consist primarily of weed control. If care were taken not to disturb the surface while controlling weeds, the road surface should improve with age.

During the 18-month project period, a total rainfall of 50.11 centimeters occurred. The compacted plot yielded 17.68 centimeters or 35.3 percent of the total rainfall. This represented an increase of 15.34 centimeters over the water yield from a control plot. The amount of precipitation required to initiate runoff was about 0.51 centimeter

Assuming a life of 20 years, an interest rate of six percent, and an efficiency of 35 percent in a 30.48 centimeter rainfall area, the cost of water harvested from the compacted plot would be approximately $0.48 per cubic meter. This price does not include weed control costs. Economy of scale would reduce this cost even further on larger catchments.

Sodium Treated Catchments

Results from previous research indicate that small amounts of sodium, when applied to the surface of desert soils where there is little or no vegetation, will cause a dramatic reduction in infiltration rate. The effect, however, has been found to be temporary. Sodium does cause a clay migration from the surface. Clay lenses have been created in the laboratory and the field through the use of a relatively heavy treatment of sodium chloride. These clay lenses have been found to be migratory in the sandy loam soil (clay content = 11 percent) at Atterbury Experimental Watershed. When the lenses are close to the surface, they have a large effect on runoff. As the lenses move down in the soil profile, the effect becomes negligible.

The application of a relatively light treatment of sodium to a grass-covered soil does not result in a significant change in infiltration rate. The maintenance of a grass cover seems to be incompatible with the use of a light treatment of sodium chloride to increase runoff.

Results have indicated that sodium chloride can be used in increasing runoff where the soil is bare. Periodic disking and smoothing of the soil surface may be needed along with retreatment of sodium chloride in order to maintain a low infiltration rate. The disking may also be required to return the clays to the surface. This method of treatment would require shaped catchment areas to minimize the length and degree of slopes so that erosion would not be excessive.

Perhaps the most effective use of sodium chloride is in conjunction with the compacted earth catchment. The sodium not only renders the catchment more impervious but is an effective way to control weeds. Weeds are the major maintenance problem in compacted earth catchments. The Compacted-Earth Sodium-Treated (CEST) Catchment has been field tested on a 0.4 hectare site at Page Experimental Ranch in Arizona. The catchment was prepared in the spring of 1971 in the same way as the CE Catchment at Atterbury Experimental Watershed. After shaping, the plot was rototilled to destroy soil structure. Four and one half metric tons of granulated salt were then added using a fertilizer spreader. The granulated salt was mixed into the upper 5 centimeters of soil and the soil surface smoothed using the rotating tractor-drawn rock rake. Following a 1.01 centimeter rainfall, the catchment was compacted with a drum roller. The total cost of the CEST Catchment was approximately $450. This catchment was constructed to serve a dual purpose. Grapes and deciduous fruit trees have been planted in the drainageways. Water is stored both in the soil and in a 56,850,000 liter storage tank where it is available for use during dry periods. Thus, the catchment can produce both food and water. This type of dual system should be more acceptable to the general public than bare catchment areas. The efficiency of this system neglecting soil-stored water has been greater than 50 percent of the total rainfall.

Gravel Covered Plastic (GCP)

The use of exposed plastic for water harvesting has been unsuccessful due to ultra-violet induced oxidation, wind, and mechanical damage. The use of gravel protects the plastic from sunlight and wind. Gravel covered plastic catchments were first installed at the University of Arizona in December of 1965. The 0.015 millimeter polyethylene plastic in early installations is still in excellent shape.

In order to reduce costs of the gravel covered plastic catchment, two different types of automated installation were developed. One type was a plastic laying gravel chute that fits on the back of a dump truck. By means of the chute, plastic could be laid down and covered in one installation.

A more controlled method of installation of GCP catchments can be attained through the use of a modified self-propelled chip spreader. Where specialized gravel spreading equipment is not available, the catchment has been installed at a rate of 185.8 square meters per hour using a front-end loader and a crew of five.

Large areas of the world have sufficient gravel in the upper soil profile to cover the plastic. Because of this, a machine was developed that would extract the gravel from the soil, lay plastic and cover the plastic with the extracted rock. Considerable research effort was expended in the successful testing of this type of machine which was called the Gravel Extracting Soil Sifter (GESS).

A catchment is properly constructed if the plastic is covered with the minimum size and depth of gravel needed to provide a complete cover and resist erosion (Figure 1). On a 10 percent slope 30.48 meters long, a 1.27 centimeter cover of 0.48 to 0.95 centimeter gravel will withstand a 45.7 centimeter per hour intensity rainfall. In contrast with the CE and CEST catchments, the GCP Catchment produces sediment free water, a primary consideration in domestic supplies. The cost depends on the method of installation. In general, it would be approximately $2475 per hectare for large catchments installed with an improved version of the GESS using 0.0254 millimeter polyethylene plastic. The use of imported gravel would increase the cost to over $3713 per hectare. The projected life of a properly constructed and maintained GCP catchment is twenty-five years. With a 70 percent efficiency and a 6 percent amortization rate, the cost of water would be 0.089 per cubic meter in a 30.48 centimeter rainfall zone.

Chip-coated Reinforced-asphalt Catchments

Another type of catchment is the fiberglass reinforced asphalt catchment. Several of these catchments have been field tested in Arizona. Work at the University of Arizona in the area of reinforced asphalt catchments have centered around the use of plastic, both polyethylene and polypropylene, as the reinforcement material. The treatment consists of a prime coat of emulsified asphalt followed by a layer of 0.0102 millimeter polyethylene sheeting or polypropylene matting, which is then immediately covered with a top coat of emulsified asphalt and 0.32 to 0.48 centimeter chips. This Asphalt-Plastic Asphalt-Chip coated (APAC) catchment has many good features. It requires approximately one third the amount of gravel as a GCP Catchment. The treatment should work on any soil type since the plastic reinforcement prevents cracking. Treatment can be completed at one time. No curing time is needed during construction. The plastic should last at least 25 to 30 years if the catchment is properly maintained. Retreatment would be made by sweeping loose chips from the surface and laying down a new asphalt and chip protective coating. Based on the use of similar treatments in the roofing industry, retreatment would probably be needed every 10 to 15 years. Results from small plots indicate the catchment will cost at least twice as much as the GCP Catchment but will have an efficiency of 90 to 95 percent. This treatment has sufficient merit; large scale testing is planned.

WATER STORAGE METHODS COMPATIBLE WITH WATER HARVESTING

In general, the water storage techniques tested at the University of Arizona have been related to stock water supplies and consequently are

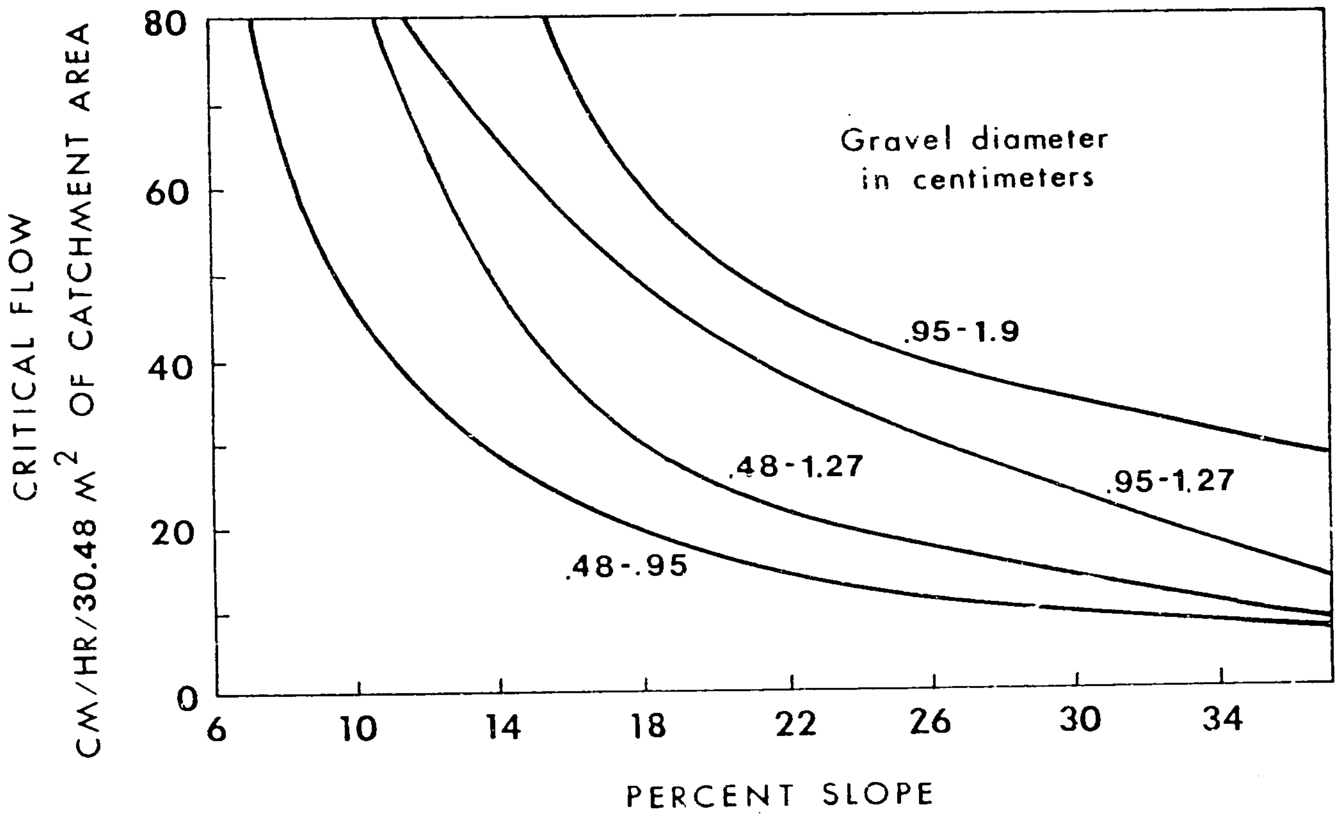


Figure 1. Critical flow versus slope for selected size of gravel cover.

limited in size. The basic treatment would also be suitable for larger reservoirs, with the possible exception of the rock-filled tank or those tanks utilizing the suspended cover for evaporation control. The seepage and evaporation control methods outlined here can also be used on existing or new reservoirs that are filled from other sources of water.

Plastic-lined Rock-filled Reservoir

The construction of this tank was prompted by the availability of commercial rock pickers which make the collection of rock for small tanks economical. Although decreasing storage by over 50 percent, the rock greatly reduces evaporation loss and practically eliminates any chance of mechanical damage including vandalism.

The tank is first excavated, then the surface is raked smooth. Two or three layers of 0.0254 millimeter polyethylene plastic is then laid down and covered with used rubber tires. The tires are filled with silty clay cover material to reduce the significance of any holes that may inadvertently occur in the plastic. The tires protect the plastic liner as rocks are added to the tank. In the United States, used rubber tires can be easily obtained at no cost. In areas where used tires are difficult to obtain, a 30.48 to 45.72 centimeter layer of soil on slopes less than 1:3 or a reinforced coat of cement-mortar could be used on the tank to protect the plastic. Three rock-filled tanks have been constructed in Arizona using a rotary drum commercial rock picker in areas containing sufficient rock to make the system economical. The cost is dependent upon the site and method of collection of the rock. The tanks were constructed for a cost of approximately $2300 for 94.6 cubic meters net storage with $1600 expended for the filling of the tank with rock. A reel-type rock picker was tested in connection with the construction of the above tanks. These tests indicated that the use of this type of picker should reduce costs by 50 percent.

Plastic-lined Concrete-coated or Earth-covered

The various methods of seepage control were outlined in the introduction. Plastic lining, if properly covered, offers a positive method of seepage control that is very competitive with other methods. Tests have indicated that a layer of silty soil, or a 1.90 centimeter layer of wire mesh reinforced cement-mortar will greatly reduce the seepage loss through holes that may inadvertently be placed in the plastic liner. The reinforced mortar coating is placed directly on the plastic and has proven to be an effective cover to use on steep slopes. This coating may either be placed using gunnite equipment or can be hand plastered. The cost of this cover is less than $2.15 per square meter.

In order to reduce the cost of installation on larger reservoirs, the same equipment developed for laying graveled plastic catchments can be used for laying and covering of plastic liners with soil. On smaller tanks, of the size used for stock purposes, the soil covering is generally installed using hand labor. The economy and strength of a reinforced mortar covered plastic tank makes it practical to construct a walk-through cattle trough that is directly connected to the tank. This design avoids the need for a float valve which is subject to malfunction and vandalism. The use of the mortar covering also makes it possible to run water directly from the catchment into the tank, thus avoiding any chance of stoppage.

A Coupled-Expanded Polystyrene Asphalt-Chipcoated (CEPAC) Raft can be used for evaporation control. This system, first tested in the spring of 1972, is essentially 100 percent effective in preventing evaporation loss for the area covered. Any size of polystyrene sheets can be coupled together. Those tested at the University of Arizona have been primarily 2.54 centimeters thick, 1.62 x 1.62 meter sheets. These sheets are coated with emulsified asphalt and immediately covered with 0.16 to 0.32 centimeter chips. The sheets are coupled together using a coupler made out of two short lengths of slotted 3.81 centimeter PVC pipe. An outer frame of 3.17 centimeter PVC pipe filled with water provides a protective bumper for the rafts which have been constructed up to 148.6 square meters. These rafts can be coupled together to cover as large a body of water as desired. The cost of this system is less than $1.07 per square meter.

A suspended cover of butyl or reinforced plastic would be recommended for smaller tanks used for domestic control in which it is desirable to keep out foreign material or eliminate algae growth.

Sodium Treated Reservoirs

When there is sufficient clay in the soil and the incoming water is higher in sodium than calcium, the use of sodium salt is the most economical treatment for seepage control. A 567.8 cubic meter tank at Page Ranch, constructed in connection with the salt treated catchment, was sealed in 1971 with sodium chloride at the rate of 11.20 metric tons per hectare. The seepage loss at the tank appears to be insignificant, and due to the fact that the incoming water has more sodium than calcium, the life of the seal is indefinite. Evaporation is controlled through the use of CEPAC Rafts.

DISCUSSION OF THE ECONOMICS OF WATER HARVESTING SYSTEMS

To determine the most feasible method of water harvesting, costs and estimated life of the catchments must be considered. In addition, each site and potential water use should be examined in order to determine which catchment and method of storage to use.

The use of the CE and CEST Catchments are limited to areas where soil conditions are favorable. Both the CE and CEST Catchments should not be built where soils are difficult to compact. Tests to date have indicated that clay content should not be less than five nor greater than 35 percent. For soils with the higher clay content, it would also be important to have more sand than silt, otherwise erosion problems would be unsolvable.

Water produced from a CE or CEST Catchment contains considerable sediment. In the case of the CEST Catchment, this sediment is finely dispersed and will remain in suspension. Although salt treated, the water from a CEST Catchment has less than 500 parts per million total salinity and can be used for most purposes including agriculture. Although more expensive, the CEST Catchment is generally preferred over the CE Catchment since the sodium not only increases the efficiency of the catchment but also serves as an herbicide which reduces maintenance costs.

A sodium treated tank would probably be the best to use in conjunction with a CE or CEST Catchment. Periodic retreatment of the tank may be necessary with a CE Catchment.

A graveled plastic catchment should be considered where gravel is economically available, the soil condition is not suitable for a CE or CEST Catchment, and/or a sediment-free water is desired. Generally, a plastic-lined reservoir would be used in conjunction with the GCP Catchment. A rock filled tank should be considered with the GCP Catchment if there is sufficient rock in the area and vandalism is a problem. Otherwise, a CEPAC raft covering would be recommended for evaporation control, unless the water were to be used directly for domestic use. In the latter case, a suspended cover would be recommended.

The APAC system would be used in areas where: soil or gravel conditions are such as to make the CE, CEST or GCP Catchments impractical, and/or rainfall and/or storage considerations were such that a high efficiency would be needed to maintain a firm water supply. In general, the same type of storage system used for the GCP Catchment could be used for the APAC system. The size of the storage reservoir could be reduced due to the higher efficiency of the APAC system.

Although more research is needed, costs of installation of water harvesting systems have been greatly reduced through application of modern techniques and methods described in this paper. Water harvesting should be considered whenever new water supplies for domestic and livestock use in developing arid and semiarid lands are needed. If the cost is low enough or the value of the crop is high enough, the water harvesting systems described in this paper can also be used to develop new agricultural lands where water is presently unavailable.

CHAPTER X

RESERVOIR MANAGEMENT

INTRODUCTION

Reservoirs are often an integral part of most watershed resources management programs. Reservoirs can be used to store and release water to enhance the general well being of people; they can help provide sustained water supplies for irrigation, municipal and industrial use, hydroelectric power generation, dillution of pollutants, and navigation, or they may be used to reduce floods. In nearly all regions, streamflow may be excessive during some seasons and insufficient in others. Not only do water supplies vary with time, location, quantity, and quality; the demand for water is highly variable. In particular, regions with well defined wet and dry seasons usually experience the greatest demands for water at a time when supplies are the lowest. Reservoirs can often provide the principle means of controlling and managing water supplies for human needs downstream.

Although the focus of this syllabus has been watershed resources management, it should be evident that such management must often be coupled with reservoir management to achieve water resource goals. The linkages among water resource goals, watershed management, and reservoir operation are important (Table 1). In some instances, a reservoir must be constructed in a basin to achieve water resource goals. For example, some type of storage reservoir is needed to provide water supplies during dry periods, regardless of watershed management activities. Water yield can be increased in many areas by converting from deep rooted (trees) to shallow rooted (grass) vegetation. However, without a reservoir, much of the increased water yield would likely flow from the area during high runoff periods and would be unavailable when irrigation was needed. Conversely, sound erosion control practices should accompany any reservoir project to prevent the storage capacity from filling up with sediment before the design life of the project. Economics usually dictate that sedimentation be controlled.

Table 1. Watershed and reservoir management as they relate to several water resource management goals.

Water Resource Management Goals	Watershed Management Objectives/Activities	Reservoir Management Objectives/Activities
Increase available water supplies for irrigation, municiple, *etc.*	Manipulate vegetative cover to increase water yield, (convert from deep rooted to shallow rooted species on watershed) Minimize/control erosion and sedimentation to maintain storage space in reservoir for the duration of design life. Rehabilitate watersheds in poorly managed areas.	Provide storage to accommodate increased water yield and also to provide firm yield for demands.
Reduce flood hazard.	Maintain vegetation and soils in good condition through proper land management; maximize infiltration and minimize surface runoff. Rehabilitate where necessary. Minimize sedimentation of channels to maintain channel capacity.	Provide storage space which can be used to store runoff during flooding. Store during periods of high runoff and release during dry periods
Maintain surface water supplies with a high quality for human consumption or fisheries resources.	Restrict or carefully manage land use activities conducive to production of sediments, disease carrying organisms. Maintain vegetation and soils in good condition. Rehabilitate watersheds where needed.	Regulate outflow to enhance desirable downstream water quality characteristics (dissolved oxygen and temperature).
Provide hydroelectric power.	Manage watersheds to sustain life of reservoir project as above.	Maintain a dependable storage with sufficient head to generate enough electricity to meet demands

When flood control is a goal, watershed management practices designed to maintain high infiltration rates and low surface runoff are needed. Such practices can affect the magnitude of the average annual flood. When extremely large storms occur of a less frequent nature, studies have shown that the condition of soils and vegetation have a minimal effect. In such cases, a reservoir can provide considerably more flood control. Certain "people" management options are available, however, to reduce flood hazard. Flood plain management (*i.e.*, keeping people and buildings out of flood hazard areas), offers a viable alternative to reservoirs. Social and economic factors should be carefully considered when evaluating such alternatives.

Social and economic problems are often associated with the construction of reservoirs. Relocation of people, loss of productive bottomlands, and adverse environmental impacts must be weighed against the benefits of a reservoir. Planning for the sustained and wise use of the benefits of reservoirs is essential if the benefits are not to become liabilities. For example, a flood control reservoir may lend a false sense of security and create overdevelopment of the flood plain downstream. Since no flood control reservoir is 100 percent effective, the potential for flood losses may be increased.

RESERVOIR OPERATION AND STORAGE

Once the need for a reservoir has been established, the following questions must be answered: can more than one goal be achieved, that is, should a multipurpose rather than a single-purpose reservoir be considered? Are the demands for storage with a multipurpose project competitive with respect to time? And what storage volume is required to meet demands?

Reservoir Operation

Political and economic decisions usually dictate whether a single-purpose or multipurpose reservoir is to be constructed. The needs of a region (including water supply, irrigation, electrical power, navigation, and flood protection) should be considered. It is usually more economicalto construct a reservoir capable of meeting several requirements rather than one. Also, it is possible in many instances to meet more than one demand with a fixed storage. For example, a given volume of storage may provide flood control during the rainy season, but that same volume may provide water supply needs during the dry season. If hydroelectric power is being generated, there may be constraints placed on the operation of the reservoir pool to maintain the required head of water.

Sometimes the demands for water are competitive for the same time period. Storage volumes in the reservoir must then be allocated to meet these competitive demands. Typically, this is accomplished by comparing demands with storage volumes and partitioning total storage (Figure 1).

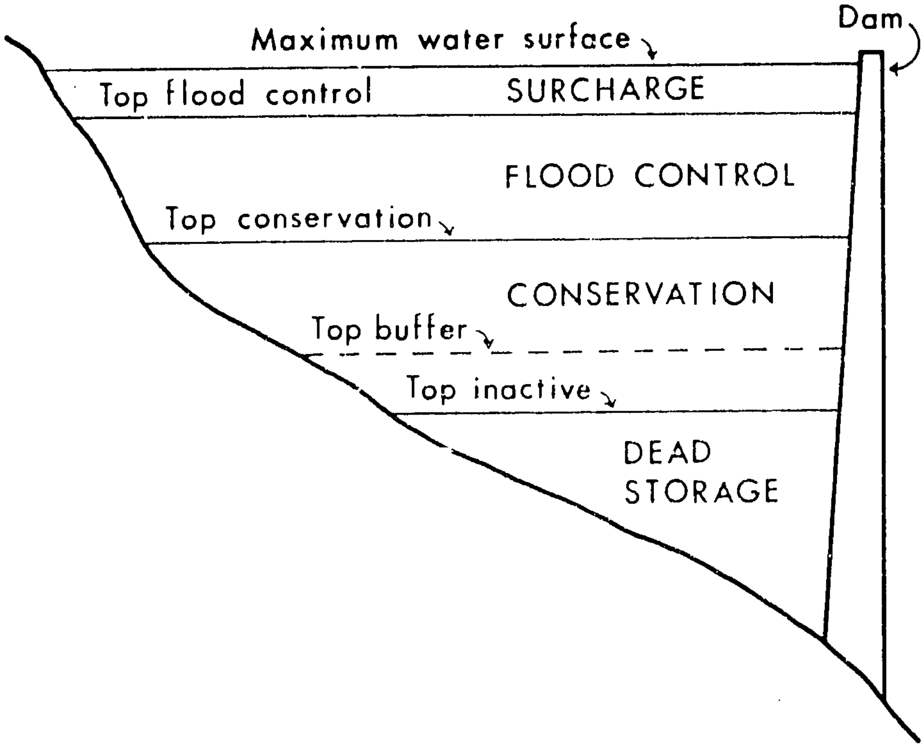


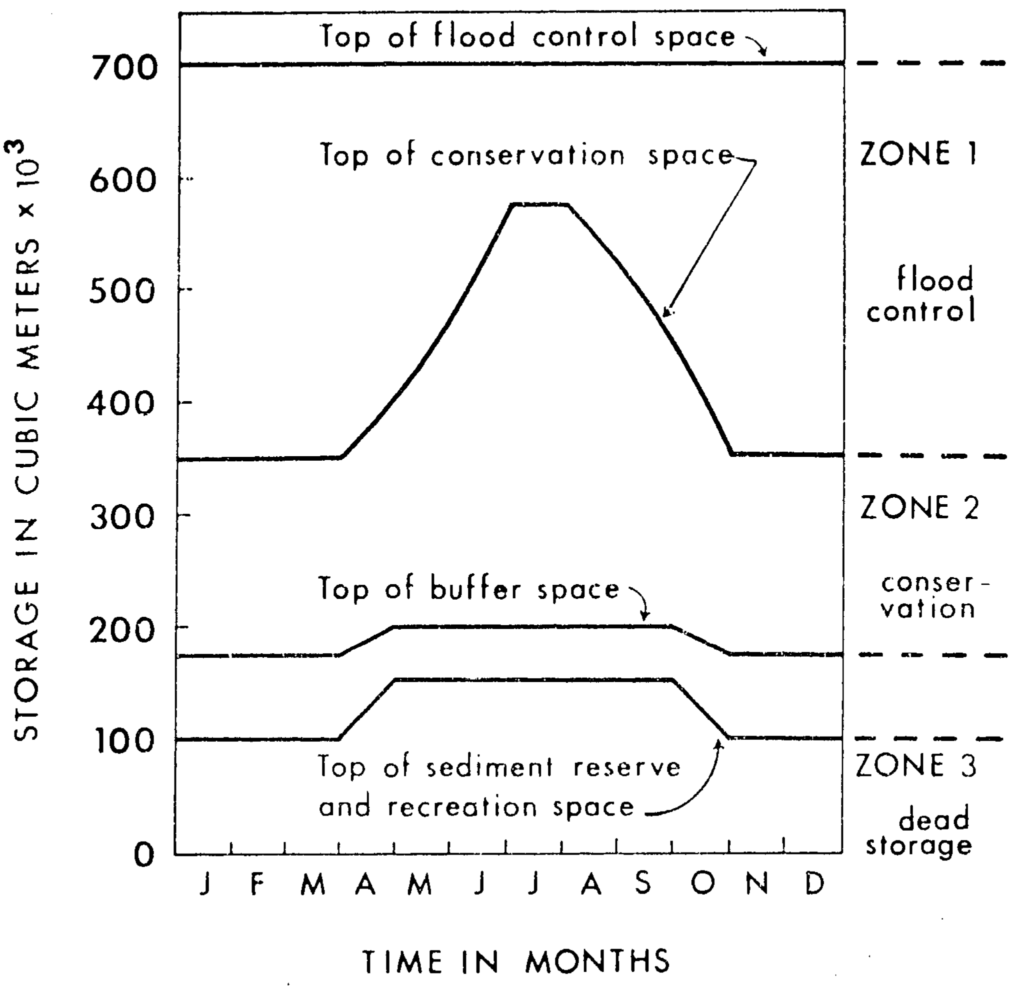
Figure 1. Allocation of storage for a multipurpose reservoir.

This partitioning process involves both the determination of required volumes, to be discussed later, and establishing operating rules to specify how the reservoir is to be managed.

The elevations of the various zones are used as guides for operation and can vary seasonally (Figure 2). The flood control zone would be evacuated of water at a time corresponding to the flood season (in this example, by the end of October). The reservoir would then be kept at the top of conservation space (bottom of flood control space) to provide sufficient storage to control flooding. The top of the flood control pool is used to maintain the integrity of the reservoir. Once the pool elevation rises above this level, as much flood water as possible is released to prevent the dam from collapsing. Once into Zone 1, the reservoir is operated to release the maximum amount of water without causing flooding. Ideally, this would coincide with bank-full conditions downstream. This operating rule would be in effect until the end of the flood season, April in this example. During the dry season, part of the flood control space is used for conservation storage (Zone 2). A system of priorities may be established within Zone 2 to insure that vital water needs will be met. In this example, a buffer space is provided for high priority use. An illustration would be a reservoir which provides for both irrigation and municipal water supplies. Zone 2 would be operated to satisfy irrigation demands until the pool dropped to the top of the buffer space. At this time, irrigation demands would not be met to meet higher priority municipal needs. Zone 3 represents the dead storage component of the reservoir which contains enough space to trap and retain sediment over the life of the project. Operating gates on the reservoir are above the top of Zone 3; therefore, the only time the pool elevation can drop below this zone is when the reservoir is evacuated as far as possible with control gates, and evaporation and seepage exceed reservoir inflow.

The development of *rule curves* (guidelines for reservoir operation, usually specifying target storages on a monthly basis) involves considerable knowledge of the variability of inflow to the reservoir and a clear understanding of seasonal water demands, priorities, and the downstream channel capacity. Historically high and low streamflow sequences are usually used to develop and test rule curves to insure that water requirements and all constraints are met. When historic records are limited, a regional analysis may be performed to extend data. Other options may be to synthesize streamflow records with either deterministic or stochastic models.

Rule curves serve as guides in the operation of a reservoir. Of course, the opportunity to adhere to these guides is improved by providing the reservoir manager with accurate, real-time forecasts of inflow. Many operating constraints must usually be considered along with the rule curves. For example, most reservoirs have restricted rates of change of outflow to prevent rapid surges of water downstream. In some cases, this may cause the reservoir pool elevation to deviate from the rule curve. Similarly, rule curves may occasionally be violated to accommodate



Fiaure ?. Onerational rule curves illustratinn seasonallv varyina storaqe requirements of a multinurnose reservoir.

temporary anomalies in this system. Examples would include changes in operation to accommodate the passage of migrating fish or to assist downstream efforts to remove a barge which has gone aground. However, such deviations in rule curve operating should not be allowed to adversely affect some other part of the system.

Reservoir Storage

Determining the storage volumes for a proposed reservoir, called *reservoir yield analysis* requires streamflow information at the reservoir site and all water demands (volumes) for the reservoir. Several methods can be used to determine these storage volumes. The method used depends upon: the type of study being performed (is the study preliminary or the final detailed storage determination?), whether a single-purpose or multi-purpose reservoir is desired, the availability of streamflow data and other hydro-meteorological information, and the variability of demands to be placed on the reservoir. The type of reservoir yield analysis can be categorized as either simplified or detailed sequential analysis.

Simplified Analysis

Simplified methods of evaluating storage requirements are useful when it is desired to save time and resources, when approximate results are adequate, or when we wish to obtain a good initial estimate to a more detailed, sequential study. *Sequential mass curve* and *nonsequential mass curve* (depth duration analyses) are examples of simplified methods.

The *sequential mass curve*, or Ripple method, is probably the most common simplified procedure; it consists of graphically estimating the storage required to produce a given yield. To use the Ripple method, the demand must remain fairly constant, that is, seasonal variations in the demand for water from the reservoir cannot be analyzed. Also, the watershed characteristics which control streamflow must remain fairly uniform over the period of streamflow used in the analysis.

To apply the Ripple method, streamflow at the reservoir site must first be accumulated in a mass curve, construction in units of volume (Figure 3). The demand or desired yield can be represented by a straight line with a slope equal to the desired yield rate.

The *nonsequential mass curve analysis* is another simplified method of estimating reservoir storage. With this approach, the risk or the frequency of shortage assoicated with a given yield can be determined. The steps necessary to use the nonsequential method are demonstrated in the following:

(1) rank low flow events, designating the lowest as Number 1, the second lowest as Number 2, *etc.*

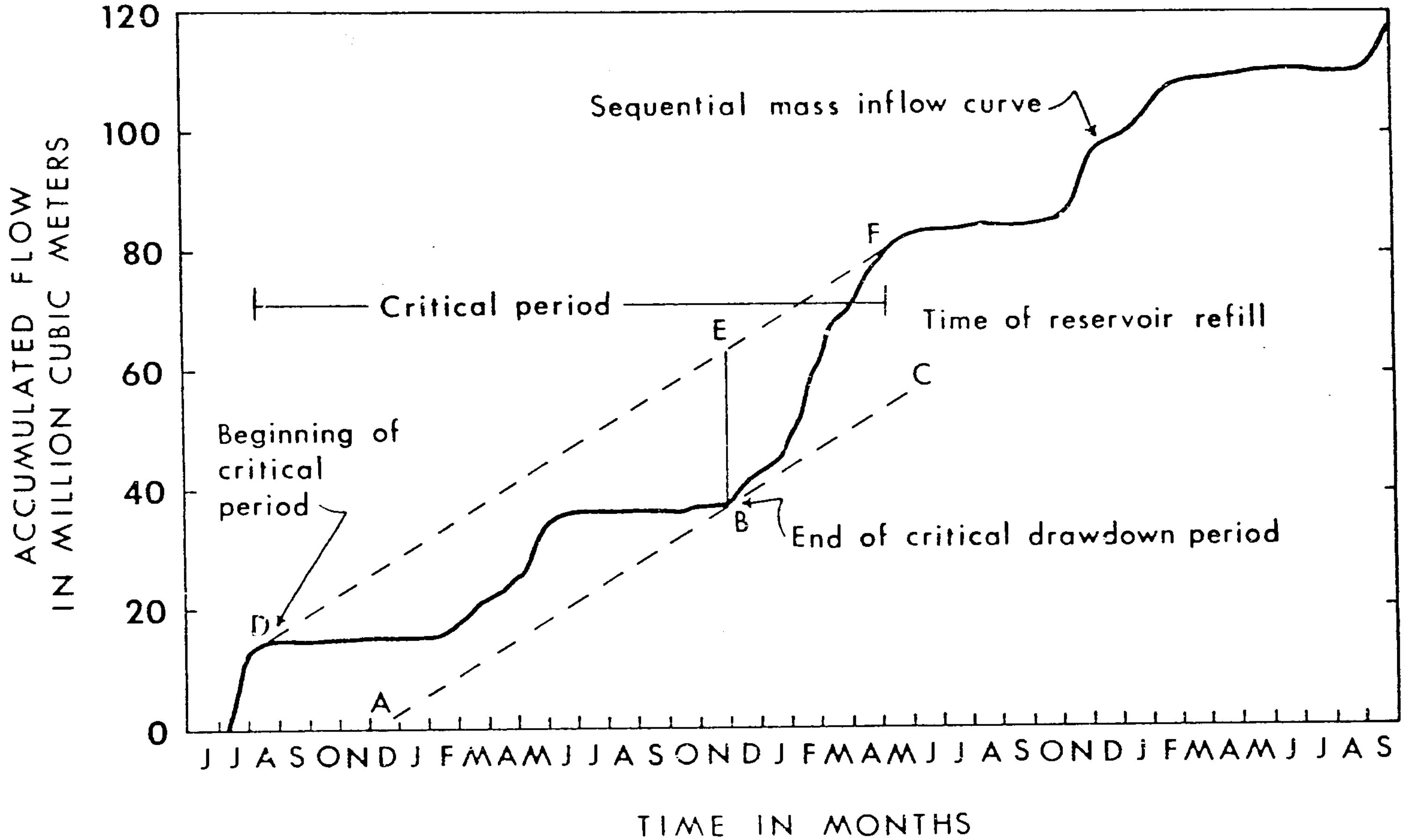


Figure 3. The sequential mass curve or Ripple method of determining reservoir storage. Given: desired yield = 38 million m^3/year. Construct line ABC with slope = 38 million m^3/year tangent to mass curve at B (lowest possible point of tangency). Construct line DEF parallel to ABC and tangent to mass curve at D (highest point of tangency prior to B). Line BE represents the maximum storage requirement to produce the desired yield (about 26 million m^3 is required).

(2) compute the median-plotting positions of nonexceedence frequency for ranked low flow events. For the 8 year period, the first 5 months could not be used to estimate 6 month low flow volumes. The effective record was, therefore, 8 years less than 5 months, or 7.58 years. The plotting position (PP) for the lowest 6 month volume was:

$$PP = 1 - (0.5)\ 1/N$$

$$= 1 - (0.5)^{1/7.58} = 1 - 0.9128 = 0.0872$$

Which means that the probability of a 6 month flow volume being less than 67.1 $m^3 \times 10^6$ would be 0.0872 or 8.7 percent. The formula for the plotting position of other volumes is

$$PP = 0.0872 + (\Delta R) \left(\frac{\Delta P}{\Delta I} \right)$$

where:

$\Delta P = 0.9128 - 0.0872 = 0.8256$
$\Delta I = 7.58 - 1 = 6.58$
$\Delta R = \text{Rank} - 1$

The number of events ranked is the smaller of N/n or R where:

N = number of months in the record
n = number of months in duration
R = rank of the last event with PP < 0.50
(In this example R = 4)

The ranked volumes were:

Rank	6 month Volume ($m^3 \times 10^6$)	Plotting Position (percent)
1	67.1	8.72
2	69.7	21.27
3	69.9	33.82
4	72.1	46.37

(3) plot the low flow events (Figure 4). These nonsequential mass curves are smoothed graphically to insure mutual consistency, that is, so curves do not cross.

(4) minimum runoff duration curves are then obtained by plotting points from the low flow frequency curves on logrithmic paper (Figure 5). The flow rates which are in cubic meters per second (Figure 2) are converted to volume (Figure 5).

(5) select the risks that are considered reasonable for the type of project being studied and, along with the required demand, evaluate the storage requirements (Figure 6). The nonsequential mass

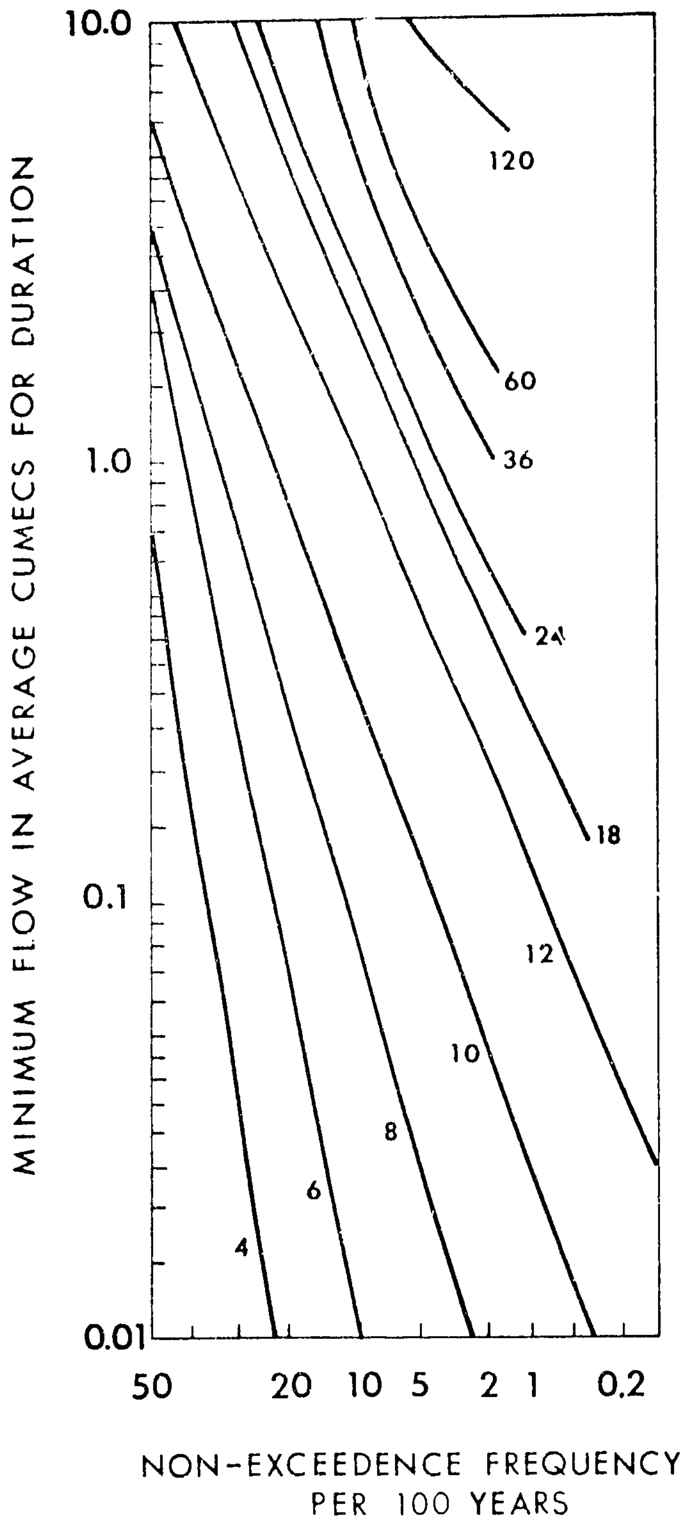


Figure 4. Low-flow frequency curves based on 35 years of historical flows. Parameter is duration in months. Values obtained from partial-duration analysis of independent (non-overlapping) events.

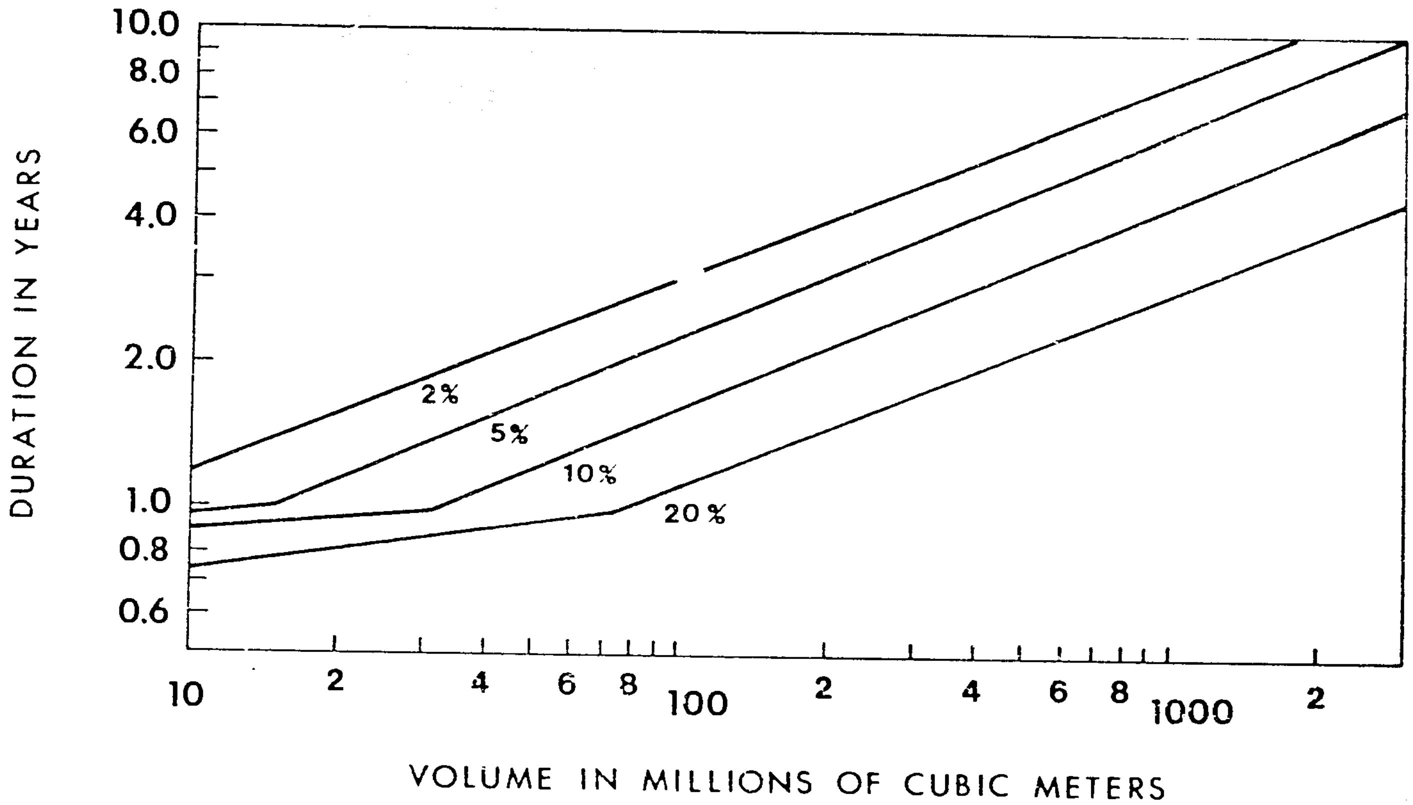


Figure 5. Minimum runoff-duration curves (based on Figure 4). Parameter is non-exceedence frequency in percent of years.

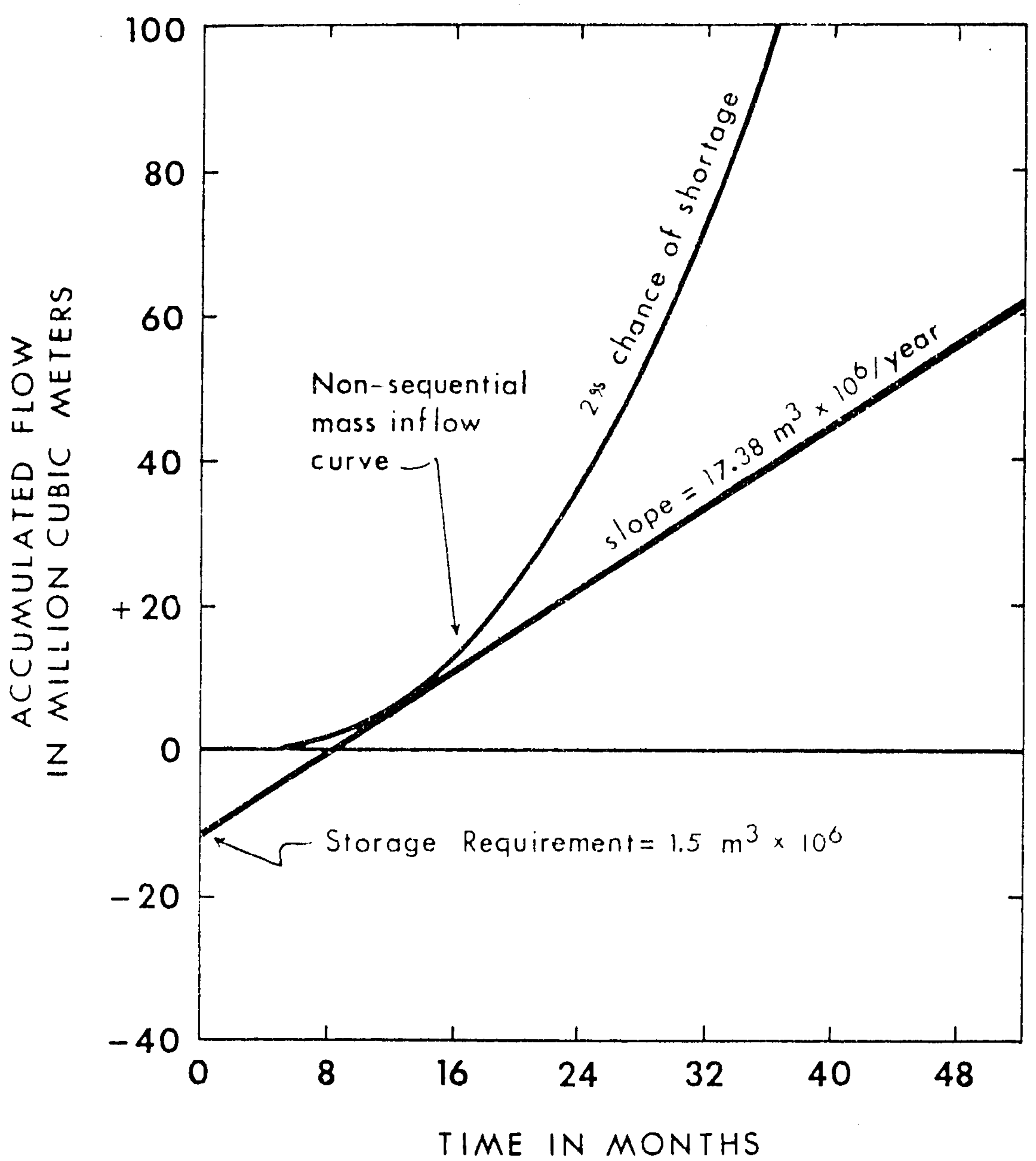


Figure 6. Non-sequential mass curve method of determining reservoir storage (from Figure 5).

curve is the selected volume duration curve plotted on arithmetic grid. This is used as the estimate of yiled. To determine the storage requirement, a straight line with a slope equivalent to the demand is plotted tangent to the mass curve. The absolute value of the negative vertical intercept represents the storage requirement (in this example, 11.5 $m^3 \times 10^6$).

The results from this example yield the storage required to meet the specified demand, in this case, 17.38 $m^3 \times 10^6$/year. Thus there would be a 2 percent change of having a shortage with the storage of 11.5 $m^3 \times 10^6$. Again, there are some constraints with the use of this method. The nonsequential mass curve does not reflect the seasonal variation of flows. Also, if demand varies seasonally, the procedure cannot be used. This method is only as good as the nonexceedence frequency curves from which it is based. Therefore, several years of record are needed. Typically, adequate streamflow data are not available to utilize either one of the two simplified approaches. In such cases, continuous simulation models may be used to generate streamflow for a particular area based upon precipitation records which are often more abundant.

Detailed Sequential Analysis

The most accurate method of determining reservoir storage requirements is by the detailed sequential analysis. This approach is usually considered more acceptable than the previously described techniques because all inflow and outflow to the reservoir site are examined during sequence of critical low flow events. Reservoir storage requirements then are evaluated with a procedure based on the principal of conservation of mass. The conservation of mass is expressed by the following continuity equation:

$$I - O = \Delta S$$

where:

- I = total inflow volume to the reservoir during a specified time period
- O = total outflow volume during the same time period
- ΔS = change in storage volume in time period.

The change in storage can be expressed as follows:

$$S = S_t - S_{t-1}$$

where:

- S_t = storage volume at end of time t
- S_{t-1} = storage at end of time t-1

By substitution and rearrangement: $S_t = S_{t-1} + I_t - O_t$

A repetitive solution of the above equation together with an examination of constraints, storage boundaries and service priorities is called a *sequential routing study*.

Because of the detailed nature of a sequential analysis, computer programs are often used. Sequential routing can be performed by hand calculations, particularly when determining the storage capacity of a simple single reservoir, but the work is tedious.

Design Floods

Design floods or design storms are selected for reservoir studies as standards against which performance of the facility may be evaluated. The design flood is simply the runoff from a large storm and is defined by some selected criteria.

Design floods are typically referred to as spillway, reservoir, or project design floods. The spillway design flood is that flood which is selected to determine the size of the spillway of the reservoir. The reservoir design flood refers to the event selected for sizing the flood control storage of a reservoir. The project design flood is that which is used to determine the size of the project.

There are several approaches to determine design floods for one of the above purposes. The *probable maximum flood* (PMF) is that flood which may be expected from the most severe combination of hydro-meteorological conditions that are reasonably possible for an area. Typically, such a large event is used in the design of a spillway, particularly where failure would be disastrous in terms of loss of life. The *standard project flood* (SPF) is usually smaller than the probable maximum flood. Often a figure of 40 to 60 percent of the PMF rainfall is used to generate the standard project flood. It is usually used as an upper limit design flood for major reservoirs or local protection projects. In either case, the estimated flood events are based on sound knowledge of the meteorological conditions in the region. A certain amount of judgment is used in determining both of these floods. An alternative approach would be to determine floods with specific exceedence intervals such as the 20 year, 50 year, or 100 year event. A risk is thus associated with these design floods. Reservoirs should probably not be designed on the basis of recurrence intervals except where loss of life is not a factor or where the economic impacts of failure are insignificant. It must be realized that a reservoir designed on the basis of, for example, a 100 year recurrence interval flood has associated with it a risk of failure of 67 percent over a 100 year period. In the case of multiple projects, the design on the basis of the 100 year event could be very misleading. If we have 100 reservoirs designed in this manner, there is a 67 percent chance that one of those reservoirs will fail in any given year.

As with low flow analyses used in conservation-storage studies, stochastic streamflow data may be generated for flood analyses. The concept of the design storm or design flood is simply that we can pre-select the performance criteria which we wish to use for a particular water resource facility. Again, this performance criteria may be based on many factors other than hydrologic considerations. The economical, institutional, political, environmental, and social aspects may be determining factors in the selection of performance criteria.

Selection criteria for design floods are usually established by an agency which is responsible for designing and operating the reservoir. If a project has a very high dam with a large volume, and it is determined that the structure cannot be overtopped without disastrous consequences, a probable maximum flood would be likely chosen for spillway design. On the other hand, run of river hydroelectric power plants or diversion dams may be designed by means of a standard project flood in which case the structure could be overtopped without suffering serious damage. Small dams which impound one to two million cubic meters or less, or small recreational type lakes and farm ponds may be designed on the basis of floods with a specified recurrence interval. In such cases where a dam is low enough and the storage small enough so that no serious hazard exists to downstream inhabitants, an event such as the 50 year recurrence interval flood may be selected.

Methods of generating design floods have previously been discussed. In the case of standard project flood or the probable maximum flood generation, one would likely select a model such as the unit hydrograph and take meteorological (rainfall) data and generate streamflow. In the case of recurrence interval design floods, the study would involve a statistical analysis of existing streamflow records. Very often this requires a regional analysis to determine streamflow responses for ungauged sites.

CHAPTER XI

ECONOMIC ASPECTS

INTRODUCTION

For the hydrologist or watershed manager concerned with action programs and getting technically sound project proposals implemented, economics is of central concern--as are politics, social pressures, *etc.* This is the basic rationale for including an economic perspective in this course. While the academic hydrologist at times can quite justifiably ignore economics and politics in his search for the "best" technical approach to a watershed problem, the practitioner--who is of central concern to this course--cannot ignore the broader picture, *i.e.*, the conditions which determine the commitment and capacity to *implement* hydrology projects.

WATERSHED OBJECTIVES AND PROJECT PLANNING

Most land-use related projects involve implications in terms of changes in water quality and/or quantity. Thus, most such projects should include explicit consideration of water related impacts and of potential activities to achieve acceptable watershed protection standards. In some cases the major objectives of a project may be water related and constitute the reason why the project is being considered and proposed. In other cases, water related concerns may merely enter the project analysis in the form of constraints on other project activities.

Basically, project planning involves: definition of objectives, identification of alternatives to meet objectives, design of alternatives in terms of specific required inputs and outputs, analysis or appraisal of alternatives, and choice among alternatives. It is a dynamic and reiterative process which uses feedback from past and ongoing operations to improve future project planning activities.

The focus of this paper is on one of the elements in the overall planning process, namely analysis or appraisal. We limit ourselves to the *economic* analysis and appraisal process, recognizing full well that most projects involve other appraisals, including: *technical appraisal* (a main subject covered in the present course), *commercial appraisal,* or the consideration of the availability of inputs when needed and the actual uses or requirements for outputs, *institutional and organizational appraisal,* which deals with the consistency of a given project alternative in terms of the institutional structure existing and the organizational capacity to undertake a project; *managerial appraisal,* or the consideration of whether or not in fact there is the managerial capacity available to implement and execute a given project; and *financial appraisal,* or the consideration of budget implications and financial profitability.

THE BASIC FRAMEWORK FOR AN ECONOMIC ANALYSIS

An economic analysis is carried out to provide information for decision making on the costs and benefits or economic impacts associated with a project and the relationship between costs and benefits, *e.g.,* whether the benefits exceed the costs for a given project alternative.

The emphasis here is on *economic* analysis from a national, public point of view, as distinct from the closely related *financial* analysis, which is of central concern to private entities. The public sector is also interested in financial considerations, since a project cannot be undertaken unless it is financially viable, *i.e.,* within the budget limits of the public sector or agency considering the project. A financial or budget analysis for a watershed project is fairly straightforward and involves consideration of financial (money) outflows and inflows for a given entity or group of entities.

There are two main applications of economics in project planning. First, we are interested in the economics of *alternative designs* (or project opportunities) to achieve the *same* objective(s). This involves analysis of "mutually exclusive" project alternatives. Second, once the "best" design for meeting a given objective has been chosen, *i.e.,* the economically "optimum" design, economics is relevant in terms of deciding whether or not in fact the project will be undertaken, when other known uses for scarce resources are considered.

Economic analyses of watershed projects are no different in principle or concept than economic analyses for any other type of project. Basically, in an economic analysis we are concerned with economic efficiency associated with alternative allocations of resources, *i.e.,* how to achieve the greatest benefits with given resources, or how to minimize the expenditure of resources in achieving given benefits. Some analytical issue and empirical problems are particularly important for watershed related projects. Some of these issues and problems relate to economic factors, and they are the main subject of this paper. Others relate primarily to technical factors and their treatment is properly the task of hydrologists; many of these have been discussed in earlier sessions of the course. Thus, we do not discuss them further here, other than in terms of how the economist can interact with the hydrologist in determining what physical input-output information is needed in order to carry out an economic analysis. A basic point is that the physical relationships must be quantified *before* an economic analysis can be carried out. Thus, the present discussion proceeds under the assumption that such information can be generated. Given the fact that the lack of such information is in practice the major bottleneck encountered in most watershed project appraisals, it may seem that this assumption is made here to avoid a major problem. In fact, it is made to emphasize the point that the *economist cannot solve the information and data problems associated with watershed projects*. What he can do is to suggest a systematic approach to *identifying* direct and indirect negative and positive impacts associated with a project, and point out what information and data are needed for him to be able to *value* these various impacts.

STEPS IN AN ECONOMIC ANALYSIS

The nature and the amount of detail included in an economic analysis of a watershed project will vary from project to project and from institution to institution. However, some general guidelines can be mentioned. First, a meaningful economic analysis can be carried out only when objectives have been clearly specified and alternatives for meeting the objectives have been identified in terms of the physical input and output relationships involved.

Second, any economic analysis should include at least the following five steps:

(1) *Developing physical input-output relationships for alternatives and indirect effects in a form appropriate for the economic appraisal.* This means organizing input and output information in terms of basic physical units and in terms of the times when inputs are required and outputs will be forthcoming. The appropriate units are those with which values can be associated. The time element is critical, since the economist will eventually have to adjust costs and benefits that occur at different times to a common time basis.

(2) *Estimating appropriate unit values for inputs and outputs.* In a financial analysis, market prices are used; in an economic analysis, some market prices are adjusted to take into account differences between social value and market value and an attempt is made to derive monetary value (social values) for nonmarket inputs and outputs or impacts associated with a project. Again, economic unit values (usually called "shadow prices") are organized by time periods, recognizing the fact that they will likely change over time.

(3) *Combining the physical input and output information with the unit values to arrive at a total value flow for the project* (such as illustrated in Table 4). This is a basic table for the economic analysis,

since from it will be derived the various measures of economic project worth which will be used by decision makers in making their choices among project opportunities.

(4) *Calculating measures of project worth appropriate to the project and the institution undertaking the analysis.* The most common measures involve "adjusting" costs and benefits which occur at different times to a common point in time, generally the present. The process of adjustment is called discounting (and compounding) and the basis for the adjustment factor used is the relevant discount rate, generally determined at the national level and applied to all projects in all sectors, to insure consistency in results for diverse types of projects.

(5) *Testing the sensitivity of the calculated measures of project worth to changes in assumptions concerning input-output relationships, unit values, etc., for which some uncertainty exists.* Treatment of uncertainty is a critical step in the analysis process, since in most cases we will be quite uncertain about many of the values assumed in the analysis.

PARTICULAR ISSUES OF CONCERN IN HYDROLOGY PROJECTS

Based on review of a number of hydrology/watershed management projects in developing countries, it appears that there are some specific analytical and empirical issues which are particularly common for watershed projects. These are discussed in the remainder of the paper.

The specific points selected for further treatment are the following:

(1) Consideration of alternative means for achieving goals.

(2) Determination of project scope and context.

(3) Identifying costs for watershed projects.

(4) Identifying benefits for watershed projects.

(5) Treatment of benefits and costs in multiple purpose projects.

(6) Presenting cost and benefit information in an appropriate form.

The fact that there are only six points does not mean that they are the only ones of concern to the analyst of a watershed related project.

EXAMPLES

The first of the examples is an economic analysis of alternative logging systems. The objective of the analysis is to find that system that maximizes net revenue subject to a constraint on maximum allowable sediment discharge. It is an example of an economic analysis to provide information for an operational decision where water related concerns are entered as a constraint.

The second example illustrates in summary form an economic analysis of a major watershed project designed to reduce the rate of sedimentation in a reservoir, thereby extending the useful life of the reservoir and producing additional downstream benefits. The project also involves several other elements, including wood production in combination with watershed protection, pasture improvement, and general improvement of upstream agriculture.

Example No. 1: Watershed Considerations as a Constraint in a Project

The growing worldwide concern for environmental protection makes this type of example relevant.

A 20 hectare woodlot is to be harvested. The lot occupies land along a river with an average slope of 20 to 30%. In order to prevent erosion and decrease resulting sediment flows, a clearcut will not be allowed by regulatory agencies. For this reason a selective cut will be made. However, it is anticipated that with standard logging techniques about 3.6 metric tons of sediment per hectare will enter the river the first year after the harvest. This amount of sediment is considered unacceptable by authorities and they will not issue the harvesting permit unless measures are taken to reduce sediment to no more than 1.8 metric tons per hectare. Thus, the forest manager must find an alternative that will reduce sedimentation of the river by at least 1.8 metric tons per hectare per year at the lowest cost possible, *i.e.*, he is searching for the least cost alternative for logging the area that will meet the constraint.

Harvestable volume on the woodlot is 300 cubic meters per hectare which can be sold for $10 per cubic meter.

If all 20 hectares had been harvested using standard methods, it is estimated that the following costs and returns would have then obtained:

Returns

300 cubic meters/ha x $10/cubic meter x 20 ha equals $50,000

Costs

labor: 1000 man hours x $2.00/hr equals 2,000
tractor: 250 hours x $25/hr equals 6,250
loading/transport: 120 hours x $20/hr equals $2,400
total cost: $10,650

Net revenue

$60,000 minus $10,650 equals $49,350

However, as mentioned the standard method is not acceptable because of the high sediment discharge associated with it. Two alternatives are proposed that would meet the maximum discharge restriction.

The *first* feasible alternative consists of leaving a 25 meter wide buffer strip (no cutting) along the river. The woodlot has a shoreline of 1600 meters, therefore, cutting would be reduced to a total of 16 hectares instead of 20 hectares. This means a loss of 4 hectares of timber or 300 cubic meters x 4 hectares x $10 per cubic meter which equals $12,000 of revenue foregone. This is considered a cost for this alternative. It is assumed that other costs would be reduced by 20 percent since only 16 hectares could be harvested. Thus, costs other than revenue foregone would decrease to $8,520 (20 percent less than $10,650). Total cost of this alternative would be $20,520 ($8,520 plus $12,000).

The *second* alternative which meets the sediment discharge requirements consists of establishment of 40 meter filter strip in which no machines are allowed. All commercial timber (*i.e.*, 300 cubic meters per hectare) on this 6.4 hectare filter strip can be cut but must be winched out at a higher cost. On the 6.4 hectares of the filter strip are estimated to be $8,094. For the remaining 13.6 hectares, costs will drop to an estimated $7,242 to reflect reduction in area logged. Thus, total cost of this alternative will be $15,336.

Assuming that these are the only two alternatives considered that meet the sediment discharge restriction, we would choose the lowest cost alternative or the filter strip approach. Revenue would be $60,000 as before and cost would be $15,336, for a net return of $44,664, which compares with a net return of $29,480 in the buffer strip alternative. The information generated in this analysis further indicates that the cost of the sediment discharge restriction would be $49,350 minus $44,664 or $4,686.

Example No. 2: Economic Analysis of a Watershed Protection and Management Project

Some years ago a reservoir was built along the Sierra River to provide storage of water for downstream use during periods of low flow. Downstream uses include irrigation on some 9,500 hectares and domestic water use by the local population. It has been found after five years of operation that the reservoir is silting in at a much faster rate than initially anticipated, thus reducing effective capacity and ability to meet water requirements downstream. Siltation is occurring at a rate of 4 million cubic meters per year. Present reservoir capacity is down to 100 million cubic meters. At the present rate of siltation, it will only be four years before capacity is reduced to a point where it can no longer meet estimated water requirements of downstream users. (Domestic water use is increasing at a rate of about 6.19 percent per year, while irrigation use is fairly constant.)

Project Goal

To prevent the reduction (or loss) of water related downstream benefits (those that would be lost without the project include crop values and health and satisfaction associated with domestic water use), the project would extend the effective capacity and life of the reservoir by reducing the rate of siltation from 4 million cubic meters per year to 1 million cubic meters per year. Since there was apparently no problem of flood damage with or without the project, flood prevention was not included as a goal. It could be added in as a goal and treated in exactly the same way, if it was a problem.

Project Points of View

(1) Downstream users of water have a direct interest in maintaining the capacity of the reservoir so that they can continue to receive water during the dry periods when river flow is inadequate to meet requirements;

(2) Upstream users of the land which would be affected by the various conservation measures proposed for the project are interested in how such measures would affect them. If effects are negative, some form of compensation may be included in the project plan;

(3) The nation at large is concerned with increased crop consumption, improved welfare of domestic water users, and losses or gains incurred by upstream land users.

The point of view adopted in the analysis is primarily that of the nation, although the other two viewpoints are also considered.

Identification and Valuation of Project Costs

To accomplish the project goal, the following project components have been proposed in the technical design and analysis:

(1) Establish protection forest on the most critical areas where no other activity should take place because of slope or critical nature of soil protection.

(2) Establish protection/production forests on areas that need permanent protection but which are less critical so that some forest utilization can take place on a controlled basis.

(3) Build terraces on some of the most critical areas with very unstable soils.

(4) Manage and maintain pasture lands on a rotation, based on their carrying capacity and ability to regenerate. This will primarily involve control and policing activities together with technical assistance.

(5) Establish forest management on existing natural forest areas. This would include control of harvest and other activities, watershed protection inputs into access road establishment, inventory and other information gathering activities.

(6) Establish an overall watershed management and administration unit within the regional government to supervise and control implementation of an integrated watershed management program for the whole watershed, including the above elements. Include extension services for local farmers.

In the project documentation, appropriate technology, input requirements and timing for each of the project components were analyzed. Based on an initial survey of the total watershed of 17,500 hectares, the scale of each of the project components was determined, as shown in Table 1. Average input requirements per hectare were estimated and applied to the total areas to arrive at total labor, equipment and other input requirements. These input requirements together with unit value estimates were then used by the economist in valuing the project costs, which are summarized on lines 4 through 8 of Table 2.

In developing economic values for inputs, only unskilled labor was shadow priced. Other inputs were valued in the economic analysis at their financial or market price values.

A project period of 26 years was considered appropriate, considering the relevant social discount rate of 12 percent.

Identification of Benefits

Reservoir demand (*i.e.*, the demand on water from the reservoir which would not be available without it) is estimated at 86 million cubic meters in the first year (year 0) of the project as shown on the first line of columns 5 or 6 of Table 2. The capacity of the reservoir

Table 1. Areas associated with each project component

Component	Hectares
Protection plantings	760
Protection/production plantings	870
Terraces	320
Pasture use control	3,850
Natural forest management	3,160
Watershed planning & administration	(17,500) 1/

1/ Including the parts of the watershed not requiring direct action.

Table 2. Watershed project: identification of water benefits.

(millions of m3/yr)

(1) Year	(2) Reservoir Capacity without project	(3) Reservoir Capacity with project	(4) Difference with & without project	(5) Reservoir Use without project 1/	(6) Reservoir Use with project 2/	(7) Difference in use with & without
0	100	100	0	86.0	86.0	0
1	96	99	3	86.4	86.4	0
2	92	98	6	86.8	86.8	0
3	88	97	9	87.2	87.2	0
4	84	96	12	84	87.7	3.7
5	80	95	15	80	88.2	8.2
6	76	94	18	76	88.7	12.7
7	72	93	21	72	89.2	17.2
8	68	92	24	68	89.8	22.8
9	64	91	27	64	90.4	26.4
10	60	90	30	60	90	30.0
11	56	89	33	56	89	33
12	52	88	36	52	88	36
13	48	87	39	48	87	39
14	44	86	42	44	86	42
15	40	85	45	40	85	45
16	36	84	48	36	84	48
17	32	83	51	32	83	51
18	28	82	54	28	82	54
19	24	81	57	24	81	57
20	20	80	60	20	80	60
21	16	79	63	16	79	63
22	12	78	66	12	78	66
23	8	77	69	8	77	69
24	4	76	72	4	76	72
25	0	75	75	0	75	75

1/ Constrained by demand for water during first 4 years then constrained by capacity as demand outstrips supply

2/ Constrained by demand for first 10 years then constrained by capacity as demand outstrips capacity even with the project

3/ This is the measure due to the project, *i.e.*, the difference in use with and without the project is 100 million cubic meters at present (start of project) and is decreasing by about 4 million cubic meters per year due to siltation. (See Col. 2 of Table 2) Thus, in about four years from the present the estimated capacity of the reservoir *without* the project would just be equal to demand. From then on, the reservoir would not meet the requirements for water from it.

With the project, it is estimated that the rate of siltation can be reduced to about 1 million cubic meters per year. Thus, the reservoir will be able to meet requirements for a longer period of time, although eventually, even with the project, demand for water will outstrip the capacity of the reservoir. This will occur in year 10 (compare Cols. 3 and 6).

A first reaction might be to use the difference between the without and with project capacities as shown in Col. 4 as a measure of benefits. However, this would overstate benefits, since even without the project, the reservoir could satisfy demand for four more years. With or without the project, the benefits would be the same during those first four years and, thus, the benefits due to the project would be zero during that period (years 0 through 3). For the next six years (years 4 through 9) capacity *with* the project would still be above demand. Thus, with the project, the benefits due to the project for this period would be the difference between estimated demand and supply *without* the project, or the demand deficit which would start to be felt in year 4 if the project were not undertaken. (This is the difference between raw items in Cols. 5 and 5) In year 10 demand would start to outstrip supply even *with* the project. Thus, from year 10 and on to the end of the project, the appropriate benefit figures would be the differences in capacity with and without the project (*i.e.*, the difference between Cols. 2 and 3). Using the above approach, the increased water use due to the project is identified and shown for each year (Col. 7 of Table 2).

The figures shown in Cols. 5 and 6 are gross figures which include evaporation from the reservoir, estimated to average about 54 million cubic meters per year. Since the evaporation would be approximately the same with and without the project, there is no need to adjust the figures shown in Col. 7. They represent net increases in *effective* water use.

In addition to the direct benefits associated with increased reservoir capacity, there will be some timber related benefits from the combined production/protection plantings (Table 3). In years 6 through 10 there will be some minor thinning volumes available and in years 17 through 21 there will be final harvest volumes available.

In addition to the water and timber related benefits, the following indirect benefits were identified but not quantified in the study:

(1) Eventual increases in livestock production due to regulation of grazing on watershed lands. (At present, many of the

Table 3. Inputs and outputs--production forest components.

	0	1	2	3	4	5	6	7	8	9	10	11-16	17	18	19	20	21
Hectares planted	174	174	174	174	174								174	174	174	174	174
Thinning harvest																	
ha							174	174	174	174	174						
m^3/ha							20	20	20	20	20						
Total m^3							3480	3480	3480	3480	3480						
Final Harvest																	
ha													174	174	174	174	174
m^3/ha													525	525	525	525	525
Total m^3(1000)													91.3	91.3	91.3	91.3	91.3

pastures are marginal due to overgrazing.) The project would restore these lands.

(2) Aesthetic values will increase as the land is rehabilitated.

(3) Access roads required for protection and other watershed management activities will permit faster and cheaper access by farmers to markets and increased mobility for extension personnel so they can reach more farmers.

(4) The project is expected to result in an increase in water quality in addition to quantity. A reduction in suspended loads carried over the reservoir dam will decrease the need for maintenance on individiual irrigation installations.

Valuation of Benefits

Based on studies of crop increases made possible by irrigation, it was estimated that irrigation water flowing out of the reservoir would return a *net* of P2 per cubic meter of water. Since the major portion of the water is used for irrigation, there was no feasible way of placing a value on the water used for domestic purposes, and there is no feasible way of allocating the *increased* water made possible by the project to irrigation and domestic use, it was decided to value the domestic water at the rate used for irrigation, namely P2 per cubic meter. This was recognized to be a conservative estimate. Using this value per cubic meter and the water increase figures in Col. 7 of Table 2, the corresponding annual water related benefits from the project were determined (Row 1 of Table 4).

The wood production benefits were valued at P290 per cubic meter on the stump. This value was a parity price based on the value of imported wood. The parity price was adjusted down by 10 percent to reflect the lower quality of project wood. Total wood production benefits are shown on Line 2 of Table 4.

Other benefits were not valued due to inadequate data or to the inappropriateness of attempting to quantify values, *e.g.*, for the aesthetic benefits.

Comparing Costs and Benefits

As indicated (Line 9 of Table 4), there is a net cost involved in the project for the first four years, after which the value flow turns positive and increases steadily over the life of the project. Using a rate of discount of 12 percent, we arrive at a Net Present Worth (NPW) for the project of some P292 million. The rate of return (ERR) of the project would be well in excess of 50 percent.

Table 4. Value flow table.

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
	millions of pesos																									
BENEFITS																										
1 Irrigation & domestic use	0	0	0	0	7.4	16.4	25.4	34.4	45.6	52.8	60	66	72	78	84	90	96	102	108	114	120	126	132	138	144	150
2 Wood production							1.0	1.0	1.0	1.0	1.0							26	26	26	26	26				
3 Total	0	0	0	0	7.4	16.4	26.4	35.4	46.6	53.8	61	66	72	78	84	90	96	128	134	140	146	152	132	138	144	150
COSTS																										
4 Planting protection forest	3.4	4.5	1.1																							
5 Planting production forest	1.3	1.6	1.6	1.6	1.6	0.3												1.3	1.6	1.6	1.6	1.6	0.3			
6 Terrace construction	0.8																									
7 Management costs 1/	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
8 Total	6.5	7.1	3.7	2.6	2.6	1.3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.3	2.6	2,6	2.6	2.6	1.3	1.0	1.0	1.0
9 NET BENEFIT (COST)	(6.5	7.1	3.7	2.6)	4.8	15.1	25.4	34.4	45.6	52.8	60	65	71	77	93	89	95	125.4	131.4	137.4	143.4	149.4	130.7	137	143	149
10 Present Value at 12%	(6.5	6.3	2.9	1.8)	3.0	12.9	12.9	15.6	18.4	19.0	19.3	18.7	18.2	17.6	17	16.3	15.5	18.3	17.1	15.9	14.9	13.0	10.8	10.1	9.4	8.8
11 EPW at 12%	NPW at 12% P292 million																									

1/ Including protection and extension services, maintenance and administration.

The high returns to this project can be explained quite easily. Since the reservoir was already in place and its cost represented "sunk costs," they were not included in the analysis of the project. Thus, the small amount of additional expenditure required for the watershed protection activities (the project) were compared with the returns which actually include the total incremental benefits from the reservoir. Obviously, if one were analyzing a new reservoir project, the situation would be quite different, since the substantial expenditure for the reservoir would have to be added into the cost stream for the project, while the benefits would remain approximately the same.

DISCUSSION OF ISSUES

The two examples presented are representative of the types of economic analyses one encounters for watershed related projects. The following discussion outlines some of the major issues which arise concerning these examples.

Considering Alternative Means for Achieving Project Goals

Project planners should explore alternative means for achieving given project goals. If only one alternative is presented to the decision maker, his only decision is whether to accept or reject it. On the other hand, if information is presented which permits him to look at a range of alternative means for achieving a goal, then he can more thoroughly consider and weigh the implications of different courses of action.

In Example 1, two alternatives to the standard logging approach were considered explicitly in the analysis. If other known alternatives had been available then they should also have been considered. In this case, the objective was to find the lowest cost alternative that met the maximum allowable sediment discharge restriction or constraint. Thus, one should note that costs and benefits for the standard logging approach were used only as a basis for comparison since it was, by definition, an unacceptable alternative due to the fact that it did not meet the constraint. Thus, actually only two alternatives were compared, the buffer strip one and the filter strip one. If others had been available (technically defined) they could very easily be included in the analysis.

The appraisal did not consider alternatives in the case of Example 2. However, there appear to be two which might have been considered. The first is the use of dredging at some future date to maintain reservoir capacity equal to demand. The second is the expansion of the reservoir to increase capacity so it can meet demand even when siltation occurs. In addition, the report on which this example is based did not discuss alternative technologies and scales for project components, nor did it go into the relative advantages of alternative timings of project activities to more efficiently achieve the goal of the project. Finally, although some of the project components were separable in terms of costs, the analysts did not have information on which to base a separation in terms of benefits. Thus components were not analyzed separately and it was not possible to evaluate alternative *combinations* of project activities to find a more efficient overall solution for meeting the goals.

Determining Project Scope and Context

A major question facing project planners is what to include and what not to include within the scope of a given project.

From a practical point of view, it boils down to a question of where to cut off the endless chain of effects or impacts associated with a given project. The theoretical answer is: "Include all the impacts." The practical answer is: "Include all those impacts which you can identify and which appear to be large enough relative to the direct and immediate impacts to make a difference in the cost and benefit flows." The object of a project evaluation is to generate the information needed to make a sound decision as to whether or not the project has benefits exceeding costs and, if so, whether the benefits exceed the costs by a large enough margin to make it worthwhile to commit scarce resources to the project rather than to some alternative use. If the direct benefits associated with a project are large enough relative to costs to make the project worth undertaking from an economic point of view, then spending a large amount of effort and funds on further analysis of all the various indirect impacts will not be worthwhile. However, if the project is marginally unacceptable, then there is a much stronger case for detailed analysis of indirect impacts. No general guidelines can be put forth here on how to determine the appropriate cutoff for considering indirect impacts. That will depend on each project situation, the knowledge of the project planners and staff specialists, the cost and time involved in generating information on indirect impacts, and the objectives of the institution sponsoring the analysis.

In the case of Example 1, the scope was very narrow, mainly due to the fact that the project involved a very small area and probably had insignificant indirect impacts. The example illustrates well the type of brief, uncomplicated analysis associated with operational decisions. Once this particular situation had been analyzed and the best logging method chosen (the lowest cost method that met the constraint) it is likely that that method was accepted and used for other similar logging situations without further analysis, *i.e.*, this simple analysis served as the basis for developing an operational guideline for logging that says: "In situations of riverside logging, a filter strip system is the cheapest alternative logging system which meets the specified maximum allowable sediment discharge constraint."

In the case of Example 2, the project scope included the major impact elements, with the exception that there was no consideration given to how the project would affect the farmers upstream on the watershed lands who would have to change their operations due to conversion of land to forest or due to curtailment of grazing on critical watershed lands. Similarly, there was no quantitative analysis of the positive impacts on farm economies associated with the improved road network and the increased mobility and availability of extension services. Ideally, these should have been included in the analysis, and one would expect--even without having information on the project background and area--that it would have been possible to provide some more explicit treatment of these impacts.

The question of project scope is closely related to other aspects of project definition. These are: project points of view, cost and benefit identification.

Concerning project points of view, Example 1 can be identified with two: the logging operator (or company involved with logging the area), and the public point of view concerning sediment discharge. In this case, the public point of view has been expressed in terms of the maximum allowable discharge regulation and thus does not need to receive further consideration in the analysis. The logging operator or company point of view (assuming that this is a private entity involved) is really the point of view from which the analysis is carried out, *i.e.*, the question is: "What is the minimum cost we have to incur to achieve the constraint?" If the public sector is doing the logging, the question remains the same from an economic efficiency point of view.

Example 2 is somewhat more complex in terms of points of view. As stated in the text, there are three points of view identified, namely the downstream water users, the upstream land users and the national point of view which incorporates the other two points of view within an overall objective function. The downstream users' point of view defines the scope of the project at that end: the project should be defined broadly enough to include the necessary downstream costs to achieve the benefits accruing to the downstream users. On the other hand, the upstream land users' point of view defines the scope of the project at that end: the project should be defined broadly enough to include those costs and benefits for that group that occur because of the project. As mentioned earlier, there did not appear to be adequate consideration given to this point of view and the associated costs and benefits.

Consideration of points of view helps the analyst in identifying the appropriate scope and in identifying relevant costs and benefits for use in the economic, financial and social analysis for the project. The following two sections discuss cost and benefit identification in terms of economic efficiency analysis.

Identifying Costs

One can specify three main categories of costs involved in watershed projects. These are.

Structures and Work Costs

These include costs of dams, gully plugs, construction of contour furrows or terraces, channel construction or improvement, road relocation, retainer walls, *etc.*, and maintenance of these structures and facilities.

Vegetation Manipulation Costs

These mainly include costs of removal of vegetation and planting and management costs associated with the establishment of new vegetation.

Value of Outputs Foregone

Even eroded or deteriorated lands may be producing values through grazing, subsistence farming, *etc.* These activities may have to be curtailed for a period of time in order to restore land to some higher level of productivity. The value of such production foregone should be included as a project cost. In the case of a protection project, timber harvested per unit area may be reduced due to the introduction of buffer strips along rivers, streams, roads, *etc.* Selective harvest may have to be imposed on steep hillsides which may in turn reduce the present value of harvests. This reduction is a cost.

The first two categories of costs are quite obvious, and both examples treated these in an adequate fashion. The third category--value of outputs foregone--is also relevant to both cases. In Example 1, it can be noted that the analyst treated the value of timber foregone through creation of a buffer strip as a cost. He could also have merely reduced the total benefit figure by this amount, thus treating this value foregone in terms of benefits. Either way would have produced the same result, since the objective was to arrive at the alternative with the highest net return.

In the second example, there were values of outputs foregone from changes in land use that should have been considered but were not, as explained in the previous section. This supports the point made earlier that project scope points of view and cost and benefit identification are closely interrelated. Since the upstream land users' point of view was not adequately defined, the analyst also missed identifying explicitly changes in value of output associated with upstream land use due to restriction of grazing on some lands and shift in land use from agriculture to forestry on other lands.

Identifying Benefits Using the "With and Without" Test

The basic approach suggested for identifying costs and benefits involves use of the "with and without" test. Basically, this means that the analyst asks and answers the question: "What would the situation likely be without the project over the period of years contemplated for the project and what would the situation likely be with the project?"

The particular point to emphasize here is that the "without" project situation is not the same as the present situation for most types of watershed projects. Thus, over time, without the proposed watershed project, soil conditions might deteriorate, erosion might increase, *etc.* The analyst has to make sure that these changes are taken into account (Figure 1). Without the project, conditions would deteriorate until in year *n* production would have decreased to Y. With the project, it is estimated that production will increase to Z. The point to note here is that *both* Z minus X *and* X minus Y are legitimate benefits to be attributed to the project. Thus, the analyst will not only need to estimate the increase in production which will be possible (*i.e.*, Z-X) but he will also have to make an estimate of the losses which will be avoided (*i.e.*, X-Y). Example 2 illustrates this point.

Application of the "with and without" test also brings out another point related to benefit identification and valuation (which is also illustrated by Example 2). The point is that merely because a project changes some physical dimension in a positive way, this does not necessarily mean that there is a benefit involved. In Example 2, the project starts immediately to reduce the level of siltation in the Sierra reservoir and thereby increases the effective capacity of the reservoir. However, even without the project the level of capacity of the reservoir is in excess of demand and will continue to be so for the next 4 years. Applying the "with and without" test, the analyst can see that consumption of water (the relevant benefit parameter) will remain the same with or without the project for this period. Thus, the benefit (losses avoided) due to the project will be zero during the first four years, or until the capacity of the reservoir *without* the project would have fallen below requirements for water. This point applies more broadly to many different types of watershed projects.

The above point relates to the fact that in an economic efficiency analysis, benefits should be measured in terms of human consumption. Thus, for example, the hydrologist may provide an estimate of metric tons or cubic meters of soil loss that can be avoided by undertaking a given project. But this information is not enough for an economic analysis. In order to value the benefits from the project, such losses avoided have to be translated into a schedule of crop or other consumption losses avoided. Thus, agricultural experts have to come up with a relationship between soil loss and crop production or soil loss and production of some other consumption item. This consumption loss can then be valued and used as the benefit in the economic efficiency analysis.

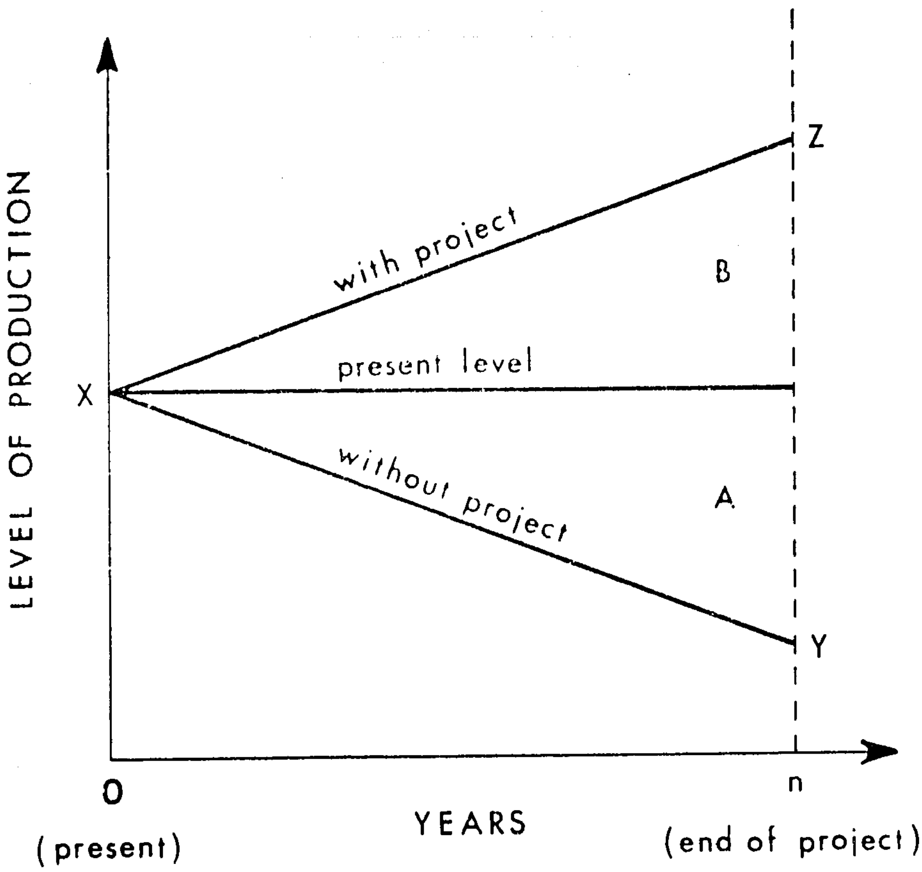


Figure 1. Identifying benefits using the with and without test. A = losses avoided. B = production increases over present level.

Treatment of Benefits and Costs in Multiple Purpose Projects

A point worth mentioning here is the need to use care and caution in identifying costs and benefits associated with multiple purpose projects which include a watershed management element. For exmaple, in some cases, trees planted on denuded lands as part of a watershed protection or restoration project will also be managed for controlled harvest for fuel or other products. In such cases, both types of benefits will have to be included in the analysis. Of course, any associated costs involved in harvest will have to be subtracted, if roadside value for the harvest is used instead of stumpage value. Proper allocation of tree planting costs to the watershed benefits and the wood output benefits is difficult. If timber production is the main objective of the project with watershed protection or restoration as a secondary purpose, then one practical approach would be to allocate the basic costs to the timber objective. Any *additional* costs of vegetation management to achieve the constraint or watershed objective would be allocated to the watershed component of the project. Similarly, in the case of logging road redesign to meet certain watershed constraints or objectives, the equivalent of the minimum road cost to get the timber out would be attributed to the timber element, while the additional costs associated with higher standards to meet the watershed objectives would be allocated to the watershed element.

In the case of a primary purpose watershed project, the cost of tree planting or other activities would be associated with the primary purpose and benefits, while timber benefits would be treated as secondary benefits. As mentioned earlier, it is important in such cases to remember to subtract any secondary *costs* associated with the timber production up to the point of valuation of the timber (*e.g.*, stumpage level, delivered log level, *etc.*).

Timing of Costs and Benefits--Presenting Cost and Benefit Information

Most watershed projects tend to be longer term projects in the sense that the inputs occur over a considerable period of time and the benefits accrue over an even longer period of time. Further, benefits and costs are constantly changing over time.

A main problem is to develop a sound estimate of the timing of the benefits. Restoration projects generally take time to implement. Full productivity is restored slowly in most cases. For example, if trees are planted on a deteriorated watershed, the full protective effect on erosion control will take some time to achieve.

In order to keep track of the project assumptions regarding the build-up to project benefits and costs over time, it is essential to use appropriate physical flow tables and, ultimately, properly designed value flow tables. (Such tables are shown as Tables 3 and 4 in Example 2 in this paper.)

Treatment of Uncertainty

Watershed related projects are particularly subject to great uncertainty in terms of the values of costs and benefits used. Thus, it is important that project appraisals include explicit treatment of uncertainty. Neither of the two examples presented earlier did so, and that is perhaps a typical situation found in most economic appraisals.

There are some simple techniques, such as sensitivity analysis and break-even analysis, which can be applied rather easily and cheaply in most cases. Basically, sensitivity analysis involves varying assumptions concerning the values of key parameters and then testing the sensitivity of the chosen measures of project worth to such changes. A break-even analysis is aimed at identifying values of key parameters which would switch the profitability of a project from acceptable to unacceptable levels.

SUMMARY AND CONCLUSIONS

The present paper presents an overview of some special problems associated with economic analyses of watershed projects. The paper presents some examples and case studies of economic analyses of watershed projects and provides insights into how the analyst can consider watershed elements when they are imposed as constraints on projects that have other goals (*e.g.*, wood production).

A question remains: What lessons and conclusions can be drawn in terms of how the economist can work more effectively with hydrologists, foresters, agronomists and other technical specialists in attempting to provide improved analyses of watershed projects? Based on the discussion in this paper and a review of a number of watershed project appraisals, the following points are relevant in answering this question:

(1) In general, it would appear that the weakest link--or the major problem--in carrying out an appraisal of a watershed project relates to the identification and quantification of the *physical* input-output relationships and the costs and benefits involved. Once costs and benefits have been appropriately *identified* and *quantified* in physical terms, there do not appear to be any *special* problems involved in *valuing* them and comparing them in terms of the measures of project worth commonly used. With regard to this point, it would appear that there are a lot more data available on input-output relationships than is generally thought and used in projects. The problem is that very little has been done to bring this information together in a *practical* form that can be used by the general project planner. Thus *there is a need to spend a lot more time and effort in developing comparative studies and translating highly technical information into practical guidelines that can be used by project planners.*

We fully recognize that the technical specialist and researcher may argue that each case is a different one and that it is impossible to transfer the experience from one situation to another situation. While we agree that there is seldom a situation where experience from one project fits perfectly the conditions for another project, we also suggest that most analysts are dealing with averages and orders of magnitude in their attempts to analyze new projects, particularly in developing countries. They have no choice.

(2) *Economists and the other technical specialists have to interact at all stages in the project planning process*, for the economist cannot carry out an economic analysis unless he has the basic physical input-output information on which to base his analysis. *The economist has to make known at an early stage his information needs.* If he does not, then he can rightly be criticized. However, the primary responsibility for generating the needed information lies squarely on the shoulders of the hydrologist and other technical specialists. This is not within the economist's area of competence. His main responsibility starts when the *appropriate* information has been generated. We stress the word "appropriate" since in a number of cases it has been observed that a great deal of information has been accumulated for a project, but it is not the *right* information for the purposes of quantifying and valuing costs and benefits. Thus, for example, it is not enough to have information on average per hectare soil losses under various conditions. The agronomist and soil experts must make a specific link between soil loss and crop loss, for benefits in this case have to be specified in terms of *consumption* losses avoided. We do not "consume" soil, we consume the products grown on it. In order to value such product losses *avoided* through implementation of a watershed project, we will need to link soil loss to crop production changes. The same argument holds for other types of relationships.

With the above in mind, *we strongly recommend that if an economic analysis is to be carried out for a watershed project, then the economist should be included in the planning process at an early stage so he can make his information needs known.* It may well be that the information he needs cannot readily be generated with available time and funds. In such cases, it will not be possible to carry out an economic analysis that considers both costs and benefits. Rather, the economist will have to stock to a cost-effectiveness analysis or some other types of partial analysis. Or, at the extreme, he will have to state that an economic analysis is not possible, given the present state of knowledge and data availability. However, at this point we should stress again that, in many cases, more information is available than is generally thought and used. It would be well worthwhile to spend some time and effort on bringing together such information in a form that is readily understood by general project planners and decision makers.

CHAPTER XII
INSTITUTIONAL CONSIDERATIONS

INTRODUCTION

In essence, two sets of limitations dictate the degree of success in watershed resources management. First, there are natural limits involving biological, physical and hydrological relatioships, which determine the responses of watershed resources to a given management practice. (To a large extent, the materials presented in this syllabus are directed toward considerations of these natural limits.) Second, institutional limits to watershed resources management, which include legal, social and economic concerns, are every bit as important as natural limits in the development of an effective management strategy. Institutional limits, unlike natural limits, are established by man to meet specific conditions and, therefore, can be modified by man in response to changes in legal, socioeconomic and political situations.

LEGAL CONSIDERATIONS

Perhaps the most important of the institutional limits to watershed resources management involves legal considerations, or limits sanctioned by law. In specific, two primary areas of law must be regarded in the development of watershed resources management strategies: laws which address the ownership and use of water, and laws which regulate the use of land.

Laws of Water Ownership and Use

Individual countries have formulated legal frameworks in which laws of water ownership and use can be made. In general, these legal frameworks have evolved in accordance with the development and subsequent utilization of the water resources in a country. While it is not possible to generalize laws which treat the ownership and use of water, brief mention of the two types of water law applicable to the United States may be of interest.

In the eastern part of the United States, the doctrine of riparian rights, based upon common law, prevails. Under riparian law, all of the owners of land touching the lake or stream course of natural water have the right to use the water. It is important to note that with this right, the use of water by an owner cannot harm the equal right of any other riparian owner; thus, upstream owners must insure that downstream users receive water that is unchanged in quantity, quality and regimen. With the exception of withdrawal for domestic use, any use which reduces the right of other riparian owners is prohibited or requires compensation.

In the arid regions of the western United States, the doctrine of prior appropriation has been developed to regulate water use. This doctrine of water use is different than riparian rights, in that it was developed to guarantee water supplies where land and natural resources are essentially worthless without water. Under prior appropriation, the first to claim a limited water supply had the first right to its use. However, the claimant was restricted to the amount of water he could use beneficially. Any other person was entitled to claim water in excess of a first claimant's use. Claims could be made for successive units of unclaimed water until the supply was exhausted. In times of short water supply, the first claimant had priority to use the limited supply, the second had the next priority, and so on, until the supply was fully appropriated.

A combination of riparian law and prior appropriation is used in some states. Even in some states with the same basic type of water law, details of application and interpretation often vary.

Laws Regulating Land Use

Laws regulating the use of land are also varied, with individual countries formulating those laws appropriate to their needs. Many of these laws are regulatory in nature; others have been designed to establish public policy to insure adequate consideration of natural resource values on watersheds. Again, a brief discussion of some of the more important laws that regulate the use of land in the United States may illustrate the purposes of such laws.

The Forest Preserve Law of New York State is an example of a regulatory law that considers the importance of maintaining water yields from upland areas for use by man. By this law, the Adirondack Park was established in 1892, with the provision that the state-owned lands within the Park be preserved, maintained and cared for as land open (for the health and pleasure of all people) and as forest lands (necessary to the preservation of the important rivers in New York). An amendment in 1894 provided that these state-owned lands should be protected from sale and that the timber on these lands should not be sold, removed or destroyed. Unfortunately, the restrictive nature of this law has prevented subsequent applications of water yield improvement practices involving timber harvesting, a means of land management designed to relieve water shortages. Therefore, a well-intentioned law has somewhat prevented attainment of the objective for which it was established.

As mentioned above, not all of the laws regulating the use of land are restrictive. Some of these laws have been formulated to set public policy with respect to recognition of natural resource values on watersheds. Two of the most important of these are the "multiple use laws" that set policy for the management of public lands in the United States under the jurisdiction of the Forest Service and the Bureau of Land Management. Though separate laws exist for each agency, these laws establish policy for the management of public lands so that all of the various natural resources involved (water, timber, forage, wildlife, recreation, *etc.*) be considered in the planning effort. However, these laws do not prescribe the means to meet planning goals; these decisions are left to the respective management agencies.

It should be clear that a watershed resources manager must be aware of all laws, both regulatory and permissive, applicable to his particular situation to do a proper job.

SOCIAL CONSIDERATIONS

In essence, legal considerations are "formalized rules" that guide the conduct of watershed resources managers. Less explicit, but equally important, guidelines derived from other cultural features (tradition, religion, folklore, *etc.*) also dictate the activities permitted by, or demanded of, these managers. As with laws, these other social considerations must be reflected in the decision making processes. Failure to do so may lead to adverse reactions that can severely restrict operational freedom.

It is beyond the purpose of this syllabus to describe in depth examples where social considerations determine the options available to watershed resources managers. However, from the flood plains of the Mekong River Basin in Southeast Asia to the fragile desert environments of Northern Africa, situations can be found in which social patterns restrict the implementation of particular management practices, What is important to remember is that to answer questions such as whether or not an erosion abatement practice should be initiated, whether or not a flood control reservoir should be constructed, *etc.*, the cultural features that characterize a society must be considered.

In essence, it becomes the responsibility of a watershed resources manager to function within existing social limitations or, if possible, determine how these limitations can be modified to achieve a desired end. As social constraints are often difficult to assess precisely and because they are not usually susceptible to easy solutions, inclusion of these concerns in a management strategy can easily be ignored; however, to do so would be folly. If sound watershed resources management is not achieved, it may likely be the result of a lack of human understanding rather than a lack of technological ability.

ECONOMIC CONSIDERATIONS

Quite often, watershed resources managers must select the best course of action in implementing a management practice, given a set of alternative plans. The decision of which alternative to select and implement often requires economic considerations. Although a part of the institutional framework, economics involve certain patterns of rational analysis, the techniques of which are well-established in many situations.

No attempt will be made here to provide a review of economic theory and practice. Furthermore, structures in which economic analyses are made are often unique in a given country. Generalizations are difficult. Many of the more general aspects of economic considerations in watershed resources management have been presented elsewhere in this syllabus.

To make an economic assessment of alternative courses of action, three general criteria are usually analyzed to form a basis of choice. These criteria are:

(1) to maximize benefits;

(2) to maximize the returns on an investment; and

(3) to achieve a specified "production goal" at least cost.

It is conceivable that no single course of action will satisfy all criteria at the same time. However, analyses of these criteria should give the decision maker a better understanding of the economic implications of selecting a particular course of action.

To analyze the first two criteria, maximizing the benefits and the returns of an investment, estimates of physical responses to alternative management actions and associated costs of implementation must be known. This information can be obtained from previous experience or, if the course of action is newly prescribed, through simulation techniques. In either case, the source data must be objective and representative of the situation being studied.

To satisfy the third criterion, achieving a specified "production goal" at least cost, goals must be established for various levels of production. These goals are often set through value judgements made by watershed resources managers, coupled with long-range goals derived through the political process.

CHAPTER XIII

MODELING AND SIMULATION TECHNIQUES

INTRODUCTION

Models, regardless of their purpose, are simply representations of how some part of the real-world operates. Models are often essential for the solution of complex problems, but models do not have to be complex to be useful. In fact, models can vary in structure from simple, logical statements, to network diagrams or to sets of detailed mathematical equations. With the advent of present-day electronic computer systems, the development and subsequent application of models has progressed quite rapidly.

In general, models may be *deterministic* or *statistical*. A deterministic model shows a relationship between variables without any random elements: a statistical model presents relationships between variables in terms of probability distributions. Both types of models are useful in watershed resources management.

Simulation techniques are used to reproduce the behavior of a system in the form of a model that closely represents real life. Through simulation, appropriate models are operated to obtain alternative solutions to management problems. Simulation techniques do not necessarily generate optimal solutions, rather they show alternative results that allow an investigator to make a decision on the levels of inputs that are best for a given purpose. Simulation exercises are normally carried out on digital computers, since these exercises usually require much calculation. However, the concept of simulation is not dependent on electronic computers; simpler exercises can be executed without them.

It is not the purpose of this syllabus to introduce the details of modeling and simulation techniques. Rather it is hoped that the reader will gain a general understanding of how these methodologies can be applied to evaluate the potential impacts of alternative watershed resources management.

DEVELOPMENT OF MODELS

Models can be developed from source data in a number of ways. One common approach is through linear regression analysis. With this approach, the *best straight line* through a scatter diagram of source data is calculated, with the independent variable regressed against the dependent variable. The best line will facilitate prediction of the dependent variable from knowledge of the independent variable. Statistically, the line is positioned such that the deviations of actual dependent values at observed independent value points from those predicted by the linear regression equation (when squared and summed) are minimal.

Often, when source data are plotted in a scatter diagram, a straight line is not the appropriate regression model to use. In these instances, curvilinear (nonlinear) functions should be selected to represent the data. Again, regression constants are calculated to minimize the sum of squares of the deviations of observed and predicted dependent values.

In a curve fitting process, it is quite useful to use a regression model that expresses some natural relation between the variables. Sometimes, knowledge of the behavior of the variables used in a relationship allows one to select one regression model over another.

From the multitude of regression models from which to choose, selection of the one to represent a given data set is somewhat of an art. The person making the choice should be aware of the statistical characteristics of various regression models, as this may reduce time and costs required to arrive at an appropriate fit of the data. Knowledge of the following regression models will often suffice for many data sets encountered in watershed resources management: linear, polynomial, logarithmic, semilogarithmic, and periodic. One, or some combination, of these forms will usually fit the source data. However, other regression models may be more appropriate in a specific case.

The assemblage of one or more appropriate *predictive functions*, such as those defined by regression analysis, may allow for simulation of a given system. Simulation of a system may be used to achieve the following: examination of the response of a system to different inputs and levels of inputs; determination of parameter sensitivity; optimization of system design; observation of the effects of system modification; evaluation of overall performance and suitability; and assessments of subsequent development in a system and collection of any required support data.

With the advent of computer equipment has come the synthesis of computer simulation techniques. Mathematical models that were previously interpreted manually can now be analyzed on a computer, allowing the models to be operated rapidly. Consequently, models can now be increased in complexity and sophistication. This increased speed of computation facilitates the use of modeling techniques seldom used before due to their excessive time requirements.

In computer simulation modeling, mathematical models of a system are constructed. These models are then translated into a set of instructions in a higher order computer language, such as FORTRAN (FORmula TRANslation). Models expressed in a computer language are entered into a computer and the appropriate descriptive or input data are introduced. Then, through "solutions" of the models, output that predicts system response is obtained.

For ease of operation, many models require input data introduced to them through answers to questions posed to the user by the program. These are termed *interactive models*, in contrast to numbers on cards or assemblages of data records which are input to *batch* or *noninteractive* models.

Computer simulation modeling is widely used in many fields of science, largely due to the savings of time and cost associated with it, and the flexibility it exhibits as an analytic tool.

WATERSHED RESOURCES SIMULATION MODELS

A group of interactive computer simulation models has been developed to aid natural resource managers estimate the impacts of land management practices on ecosystems. The group includes three general modules: WATER for assessing streamflow yield, sedimentation and chemical quality; FLORA for estimating responses of vegetation (*e.g.*, forest overstory, herbaceous understory, *etc.*); and FAUNA for evaluating wildlife habitats, carrying capacities (wild and domestic), and population dynamics (Figure 1). A command system enables users to operate all modules through a common language written in straightforward user terminology. This design provides flexibility in representing management activities by operating selected modules interactively.

The computer simulation models have been designed to be used by resource management professionals at remote locations to obtain reliable predictions using readily available data and modest computer equipment. To date, models have been developed to evaluate the effects of silvicultural practices on forest ecosystems. The methodology is readily adaptable to the severe problems of shifting agriculture, fuelwood harvesting, and forest grazing practices which prevail on the upland watersheds in most of the developing nations. This project will modify and adapt the procedure to these problems.

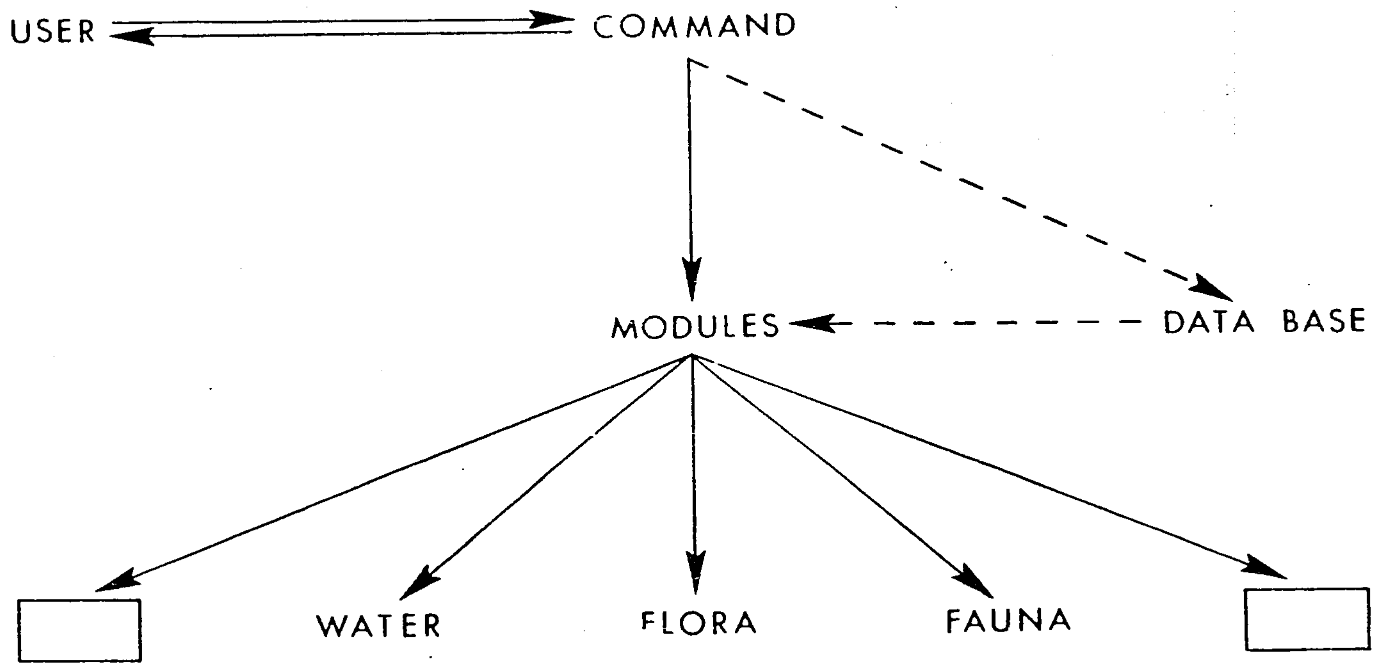


Figure 1. Components of watershed resources simulation models.

WATER MODULE

The WATER module is comprised of generalized components to predict streamflow yield, as well as suspended sediment and chemical quality of streamflow.

Streamflow Yield

The requirement for a small model with simple data needs to represent streamflow yield has led to the development of a model called YIELD (Figure 2). Within YIELD are several water yield prediction components which may be included in other simulation models to predict water yield.

One modular component simulates a water balance on a daily basis. Data inputs that are required from the user are few and commonly available. Another component is a water balance model developed to handle various depths and textures of soil, and either coniferous or deciduous forests.

Coupled with these water yield components may be other models, such as those which predict the accumulation and melt of snow. There are currently two models in YIELD which may be utilized to predict water yield from snow. One is a model based on degree day concept of snowmelt. Another is a routine which models intermittent snowpacks and is dependent on four daily input variables: maximum and minimum temperatures, precipitation and shortwave radiation. A general model, which predicts water yield from an area for all times of the year, includes models for both snow and nonsnow conditions. Initializing requires only limited knowledge of watershed and snowpack parameters.

The primary "driving variable" within YIELD is daily precipitation. The primary initialization variable is a measure of forest density conditions, expressed here in terms of basal area. Outputs from the model are values representing daily runoff, change in soil moisture, evapotranspiration, melt and deep seepage. Linkages to other components in the group are used to obtain basal area, while the outputs of daily runoff are, in turn, inputs to the components used to predict sediment and chemical quality.

Sedimentation

Another modular component in WATER, called SED, predicts the amount of suspended sediment in streamflow (Figure 3). This model is structured to offer a choice between two alternative sets of input data requirements. Depending upon the data which are available, the user will select one set to be used. Input data, which either represent forest density conditions or spatial distributions of organic materials

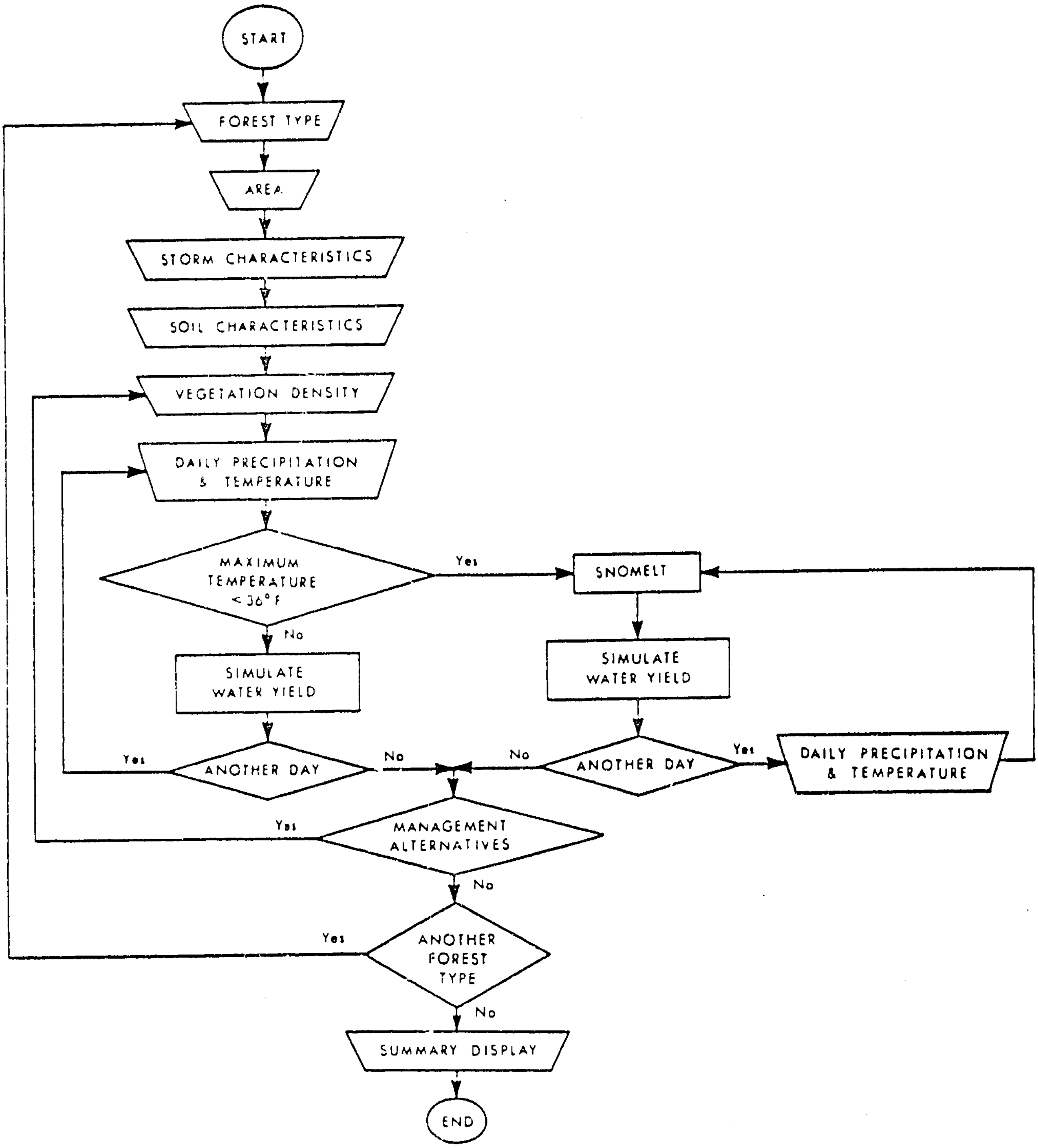


Figure 2. Flowchart of YIELD.

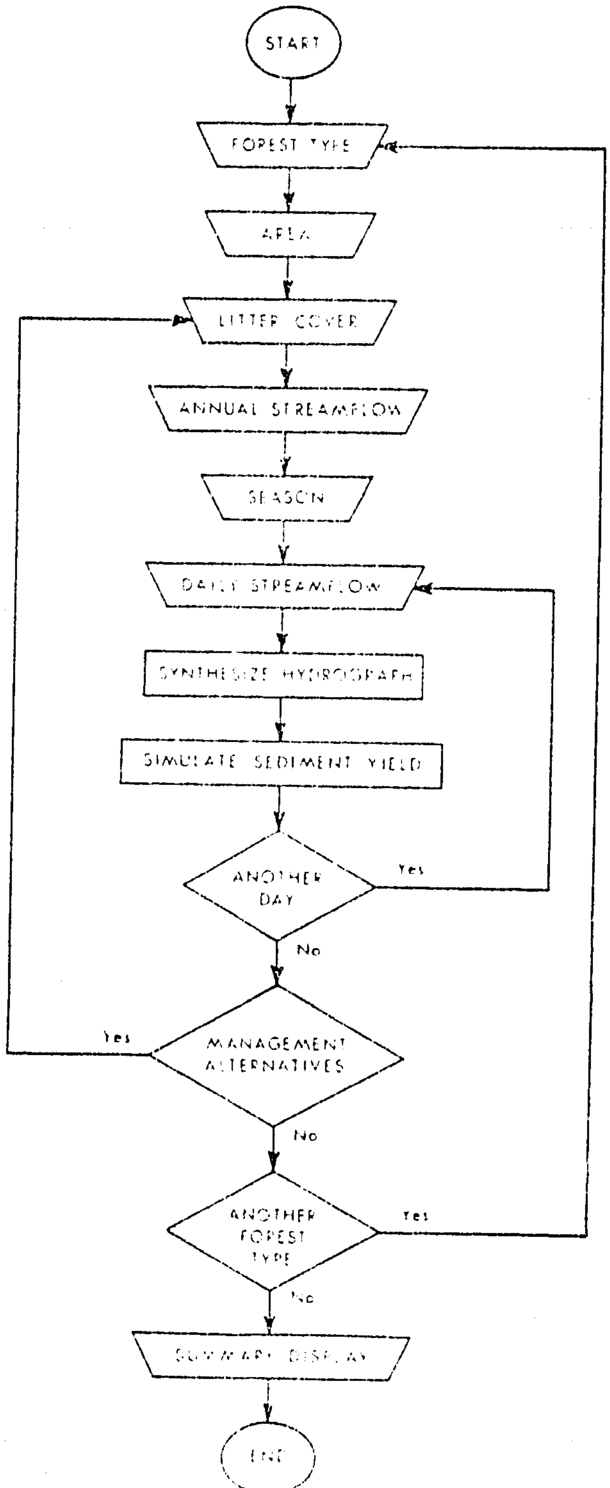


Figure 3. Flowchart of SED.

on a forest floor, are entered directly by the user or generated by other models. The other data input needed, streamflow yield, may be obtained from YIELD. The program outputs the maximum concentration of suspended sediment each day, the maximum streamflow discharge, and the total weight of suspended sediment produced under alternative silvicultural management practices simulated.

Chemical Quality

As an initial attempt at developing a modular component to predict the chemical quality of streamflow, a simulator has been devised to estimate maximum concentrations and daily volumes of selected dissolved chemical constituents. This component of WATER, called CHEM, is specifically aimed at describing the chemical quality of discharges from watersheds in forest ecosystems (Figure 4). The primary "driving variable" is streamflow quantity, the magnitude of which will often vary with alternative silvicultural management practices. This input variable can be entered directly by the user or obtained from outputs from YIELD.

Presently, thirteen constituents are estimated with the CHEM framework: calcium (Ca^{++}), magnesium (Mg^{++}), sodium (Na^{+}), chloride (Cl^{-}), sulfate (SO_4), carbonate (CO_3), bicarbonate (HCO_3), fluoride (F^{-}), nitrate (NO_3^{-}), phosphate (PO_4), total soluble salts, hydrogen ion (*p*H), and conductivity. Efforts are underway to include other water quality parameters, such as heavy metals (Zn, Fe, Cu, Pd, Cd, *etc.*) and dissolved oxygen.

FLORA MODULE

The FLORA module consists of computer simulators that predict the growth, yield, and diversity of forest overstories, the production and (to some extent) composition of herbaceous understories, and the development and accumulation of organic material on the forest floor.

Forest Overstories

The component simulators designed to estimate the growth and yield of forest overstories generally fall into two categories: first, models that are broadly structured to represent a wide variety of tree species (or tree species groups); and second, models that are specifically structured to represent a particular tree species (or tree species group).

Within the first category, three simulators have been developed, or are presently under development. These simulators, called TREE, STAND and FOREST will estimate the growth and yield of an individual

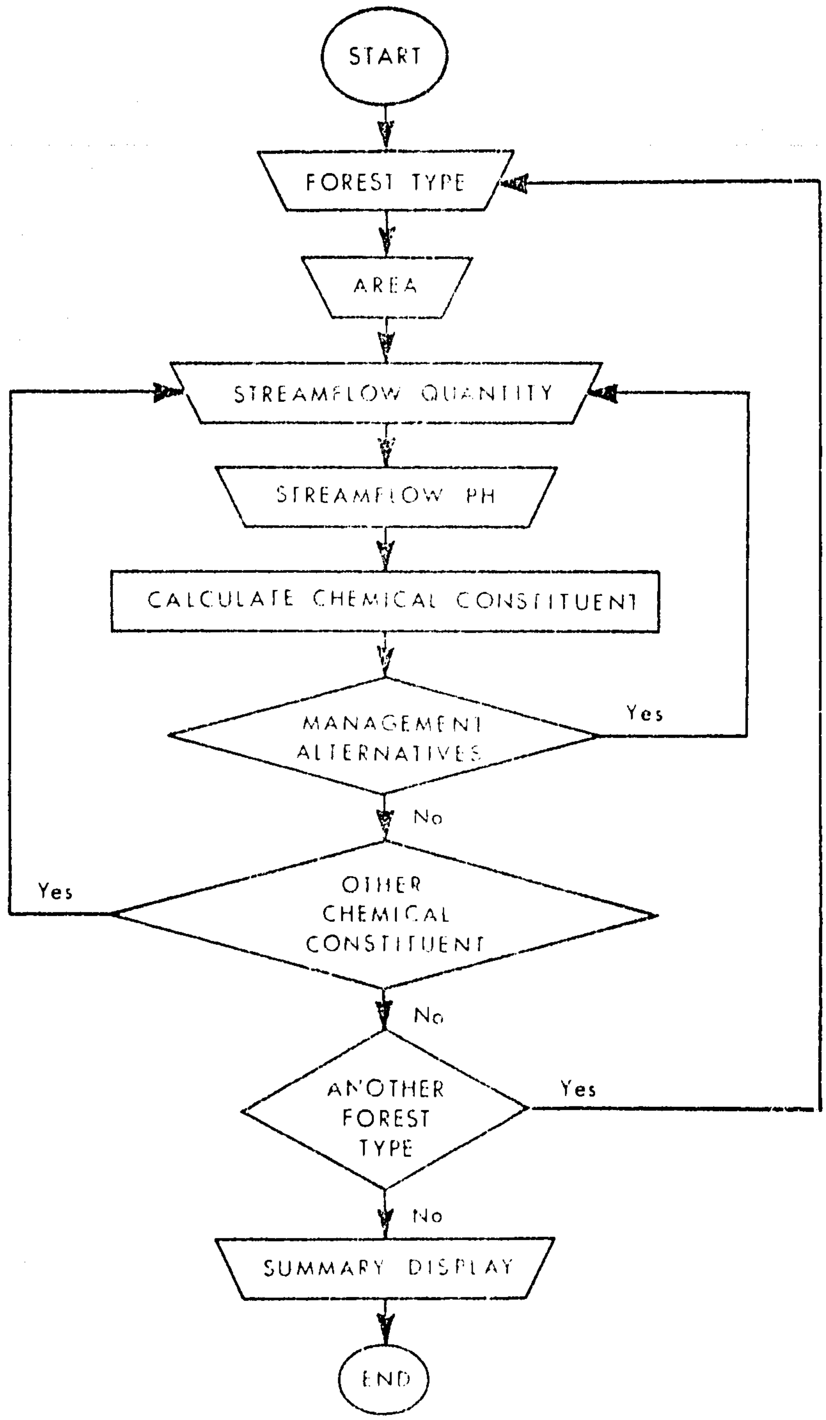


Figure 4. Flowchart of CHEM.

tree, a forest stand (by definition, a community of trees possessing sufficient uniformity in composition, age, spatial arrangement, or condition to be distinguishable from adjacent communities), and an entire forest property, respectively.

TREE is an interactive modification of a computer model that simulates the growth of an individual tree from knowledge of diameter, height and volume. In addition, one can easily see how individual tree growth is influenced by tree size and age. While this is not a new concept in forestry, the approach exemplified by TREE differs from that of others who have employed mathematical formulas to simulate tree growth phenomena.

The primary reason for including TREE in the group of models is to analyze changes in tree growth influenced by alternative silvicultural management practices. Such assessments furnish direct insight to the understanding of the dynamics of even-aged and uneven-aged forest stand developments.

STAND, is structured to estimate the growth and yield of forest stands comprised of single tree species or a mixture of tree species (Figure 5). In essence, the mensurational input to STAND involves the simplification of stand projection methods applicable to uneven-aged forest stands.

The simulation objective of STAND is to predict the growth (both gross and net) and yield of forest stands prior to and, if appropriate, following the implementation of various silvicultural management practices. Inputs to this modular component include a listing of trees per hectare by size class, and associated diameter growth rates and volume expressions. As management is prescribed to change these inputs, posttreatment growth and yield are interactively generated. Silvicultural management practices that can be simulated within STAND represent an array of viable options for the different forest stand compositions being considered.

Outputs derived from STAND, including summaries of basal area levels through time prior to and following a management redirection, are readily used by other modular components in FLORA and others. As the manipulation of forest overstories is a primary management activity affecting many aspects of an ecosystem, such interfaces among modular components are critical to realistic simulation of an ecosystem's overall behavior.

FOREST is being assembled as an interactive version of other general computer models that have been structured to simulate the growth and yield of single or mixed tree species, and even-aged or uneven-aged forest properties. This modular component addresses topics of forest growth and yield such as seed production, dispersal and germination, as well as competition, mortality and stocking manipulation by man.

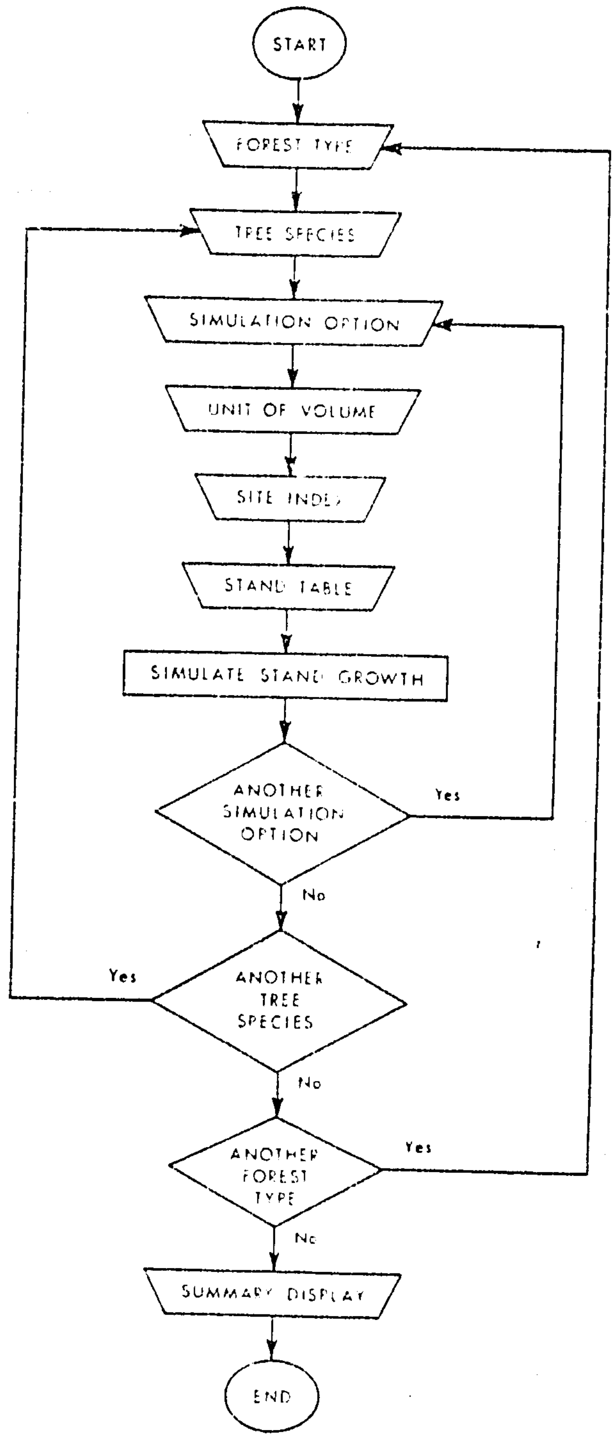


Figure 5. Flowchart of STAND.

In concept, inputs to FOREST include a set of real or generated tree locations and associated tree characteristics. Each tree is then grown for a specified number of projection periods, based on potential growth functions modified by competition measures synthesized from relative tree size, crowding and shade tolerance. Mortality is generated conjecturally and depends, in part, upon the competitive status of the individual trees. Reproduction is represented by simulating seed production and germination and, if appropriate, sprout production from the forest overstory. Numerous site alterations and harvesting options can be specified as the forest develops over time. Outputs from FOREST will be in the form of periodic tables displaying data on stocking, mortality and yield for an array of primary wood products and total biomass.

There are many examples of simulators designed to estimate the growth and yield of a particular tree species (or tree species group). In using these models, users generally initialize the model by selecting prestored stand tables, by entering tallies from point sample inventories, or by entering the number of trees per hectare by size class. Then, harvests can be specified at intervals through a sequence of questions and answers to meet a particular management objective.

In addition to computer simulators that predict growth and yield, a modular component is under development in FLORA to estimate the diversity of (and within) forest overstories. This component, called DIVER, has two primary options with respect to manipulations of forest overstories: clearing and thinning. The clearing option derives a diversity index that represents the edge irregularity of a clearing (or other type of forest opening). The thinning option calculates a diversity index that represents the proportion of an area that is stocked to different forest density levels.

The diversity index derived by the clearing option is based on a previously reported analytical model that quantifies wildlife habitat. The geometric shape with the greatest area and the least perimeter or edge is a circle. If the ratio of circumference to area of a circle is arbitrarily given in index of 1, a formula can be used to compute an index for comparison of any area with a circle. The higher the index value is above 1, the greater the irregularity, and, by definition within DIVER, the greater the diversity.

In the thinning option, the calculated diversity index is obtained through solutions of forest stocking equations that are developed for the particular forest type and size class distribution being evaluated. Stocking equations define curves which describe the proportion of a forest area (the dependent variable, expressed in percent) that is stocked to minimum basal area levels (the independent variable). Values that represent minimum basal area levels for alternative silvicultural management practices are the required inputs to the simulator.

Herbaceous Understories

A computer simulator has been structured within the FLORA module to estimate herbage (all understory species) production from knowledge of forest overstory parameters, precipitation amount, and if appropriate, time since the implementation of a silvicultural management practice. Depending upon the particular simulation objective, a user may operate this component, called UNDER, individually or as part of another model (Figure 6). In the latter instance, outputs from other modular components in FLORA and other modules in the group are utilized as inputs. An interactive language is used in either case.

Many of the previous attempts at developing computer simulation techniques to estimate herbage production have been dependent, primarily, on input variables depicting forest density conditions. While this approach remains viable and has been utilized in several UNDER subroutines, the herbage production simulator will eventually also utilize knowledge of forest overstory growth. Estimates of herbage production that are based on knowledge of this variable appear consistently of higher precision than those based on knowledge of forest density alone.

Subsequent additions to UNDER will facilitate partitioning of simulated herbage production into (at least) three categories: grasses and grasslike plants, forbs and half-shrubs, and shrubs.

Organic Material

Two modular components describe the development, accumulation and distribution of organic material on a forest floor. One component, referred to as FLOOR, estimates the accumulation of tree leaves and needles (by layer of decomposition) on a forest floor at a point-in-time, the rate of accumulation with respect to time, and the spatial distribution in space. Other components called CROWN and BOLE predict the magnitude of tree crown and branchwood accumulation, respectively, associated with alternative silvicultural management practices being simulated. These models may be executed individually or as part of other models.

FLOOR is an interactive component which outputs parameters that describe the development, accumulation and distribution of tree needles and leaves as a function of forest density levels (usually expressed as basal area) for different management practices (Figure 7). In terms of accumulation at a point-in-time, the following individual layers are considered: litter, fermentation, humus and total. To date, the rate of litter accumulation is the only FLOOR simulation output that provides a time dimension. Regarding spatial distribution, only the total forest floor (all layers) is represented.

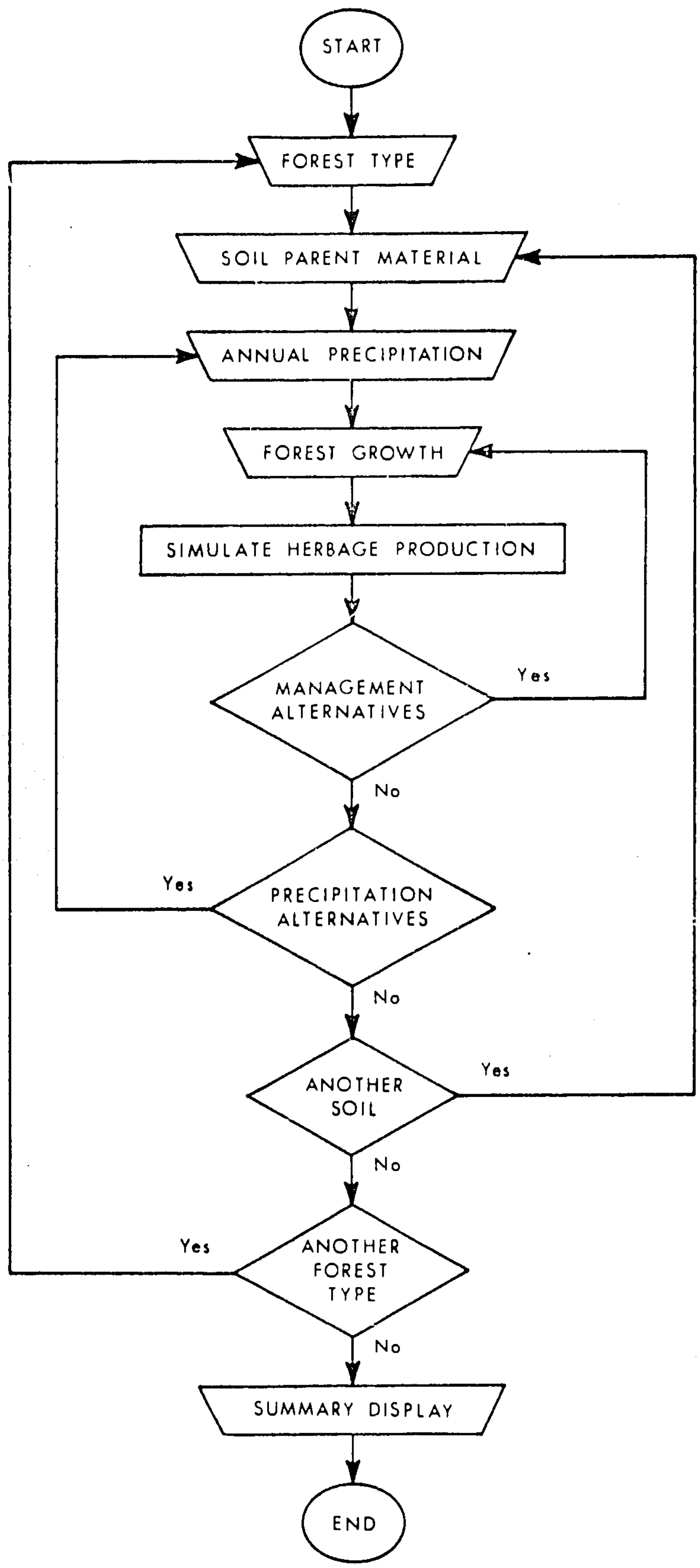


Figure 6. Flowchart of UNDER.

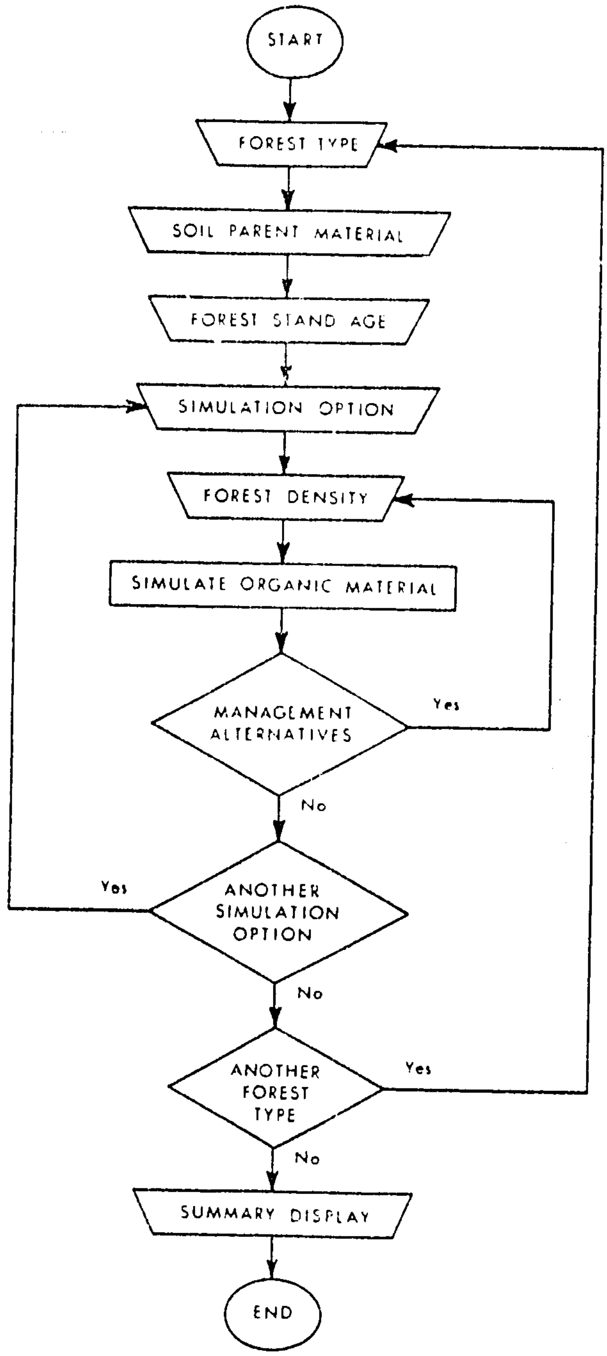


Figure 7. Flowchart of FLOOR.

CROWN and BOLE are intended to present knowledge of tree crown and branchwood volumes by area for a given forest stand prior to the implementation of a silvicultural management practice. These volumes provide a reference point to assess the quantity of tree crowns and branchwood that will occur as logging residues on the forest floor after a management treatment.

FAUNA MODULE

The FAUNA module includes interactive computer simulators that describe the habitat quality for a variety of animal species, the potential animal carrying capacity of an area, and the dynamics of selected animal populations within specific ecosystem situations.

Habitat Assessment

Simulators that assess habitat quality fall into two categories: models broadly structured to represent a variety of animal species (including game, nongame and domestic) and models specifically structured to represent a particular animal species.

An example of a modular component in the first category is HABRAN (HABitat RANking) (Figure 8). In essence, this component synthesizes ranked response predictions which, in turn, can be summarized and arrayed as pattern recognition models. Within HABRAN, animal habitats are assigned numerical values ranging from 0 to 10, with habitat quality in an ecosystem increasing with numerical value. The specific assignment of these values is achieved through analyses of functions that relate habitat preference to readily available inventory-prediction parameters, the magnitude of which are altered by alternative silvicultural management practices. By comparing numerical habitat quality values for existing conditions with those predicted for habitats modified by management redirection, either an increase (+), a decrease (-), or no change (0) is determined. Then, a matrix of pluses, minuses and zeroes arrayed for all animal habitats and management alternatives of interest (by definition, a pattern recognition model) can be displayed to provide insight into comparative management impacts.

The HABRAN component of the FAUNA module is, in a sense, a first-level-of-interest assessment of the impacts of alternative silvicultural management practices. In many instances, this sort of analysis may be all that is required. However, if estimates of carrying capacities and animal distributions are needed, other modular components may be called into play.

Many simulators exist to represent habitat quality of a particular animal species. In most instances, changes in food, cover, and diversity resulting from the implementation of a silvicultural management practice are used to simulate changes in the rating of habitat quality.

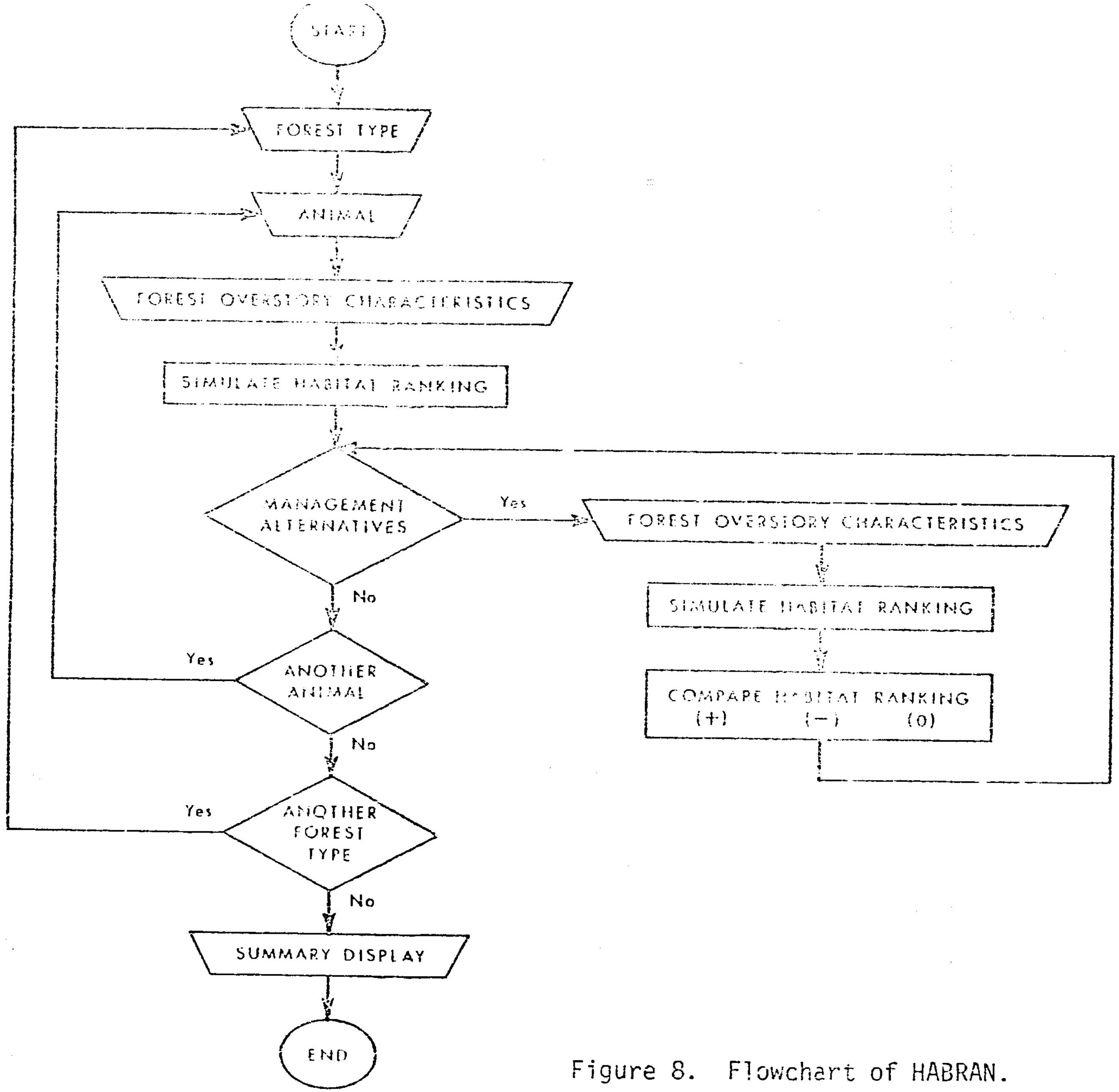


Figure 8. Flowchart of HABRAN.

Animal Carrying Capacity

In the modular component that has been structured to predict animal carrying capacity, referred to as CARRY, herbage production (entered as a direct input by the user or obtained from the herbage production simulator) is partitioned into usable forage for domestic livestock and wildlife species (Figure 9). Appropriate plant species to include in each forage component were ascertained from existing literature relevant to the preferred foods for these animals, along with information about appropriate or proper utilization percentages.

It has been assumed that the proper use factors to be applied in CARRY will be introduced by the user in an attempt to meet specific management objectives. It may be necessary, for example, to reduce a proper use factor on a particular range that has been subjected to prolonged overgrazing pressures. As baseline information relating to proper use factors increases, the ability to predict carrying capacities will improve accordingly.

The amount of usable forage required per animal unit month (AUM) for the animal species being considered is input directly by the user.

With respect to the number of months that domestic livestock and wildlife species will actually be consuming forage on any tract of rangeland, this value is quite variable depending, in part, upon weather factors that characterize the particular ecosystem and year of simulation (time of snowfall in the autumn, time of snowpack disappearance in the spring, *etc.*). At best, only estimates based on local knowledge of average situations in the long run can be made. However, to provide a point-of-departure in utilizing CARRY, specific forage consumption time durations have been selected. It should be emphasized that the user can readily override these default duration values to more accurately reflect local conditions if better information is available.

At this time, relatively little can be said about possible constraints that may affect the distribution of animals that are considered by CARRY. While it is known that various factors may restrict (or at least modify) animal movement, explicit identification and subsequent quantification are currently difficult. Conceivably, portions of a tract may be eliminated from use because of movement constraints (physiography, fences, *etc.*), which may necessitate appropriate reductions in animal stocking rates.

The effects of alternative silvicultural mangement practices on animal carrying capacities of a given area are primarily evaluated through predictions of changes in the level of herbage production. As forest overstories are reduced in density, a corresponding increase in herbage production commonly occurs. The increased production of herbage is then partitioned into forage which, in turn, is converted into AUM values that are distributed over the range.

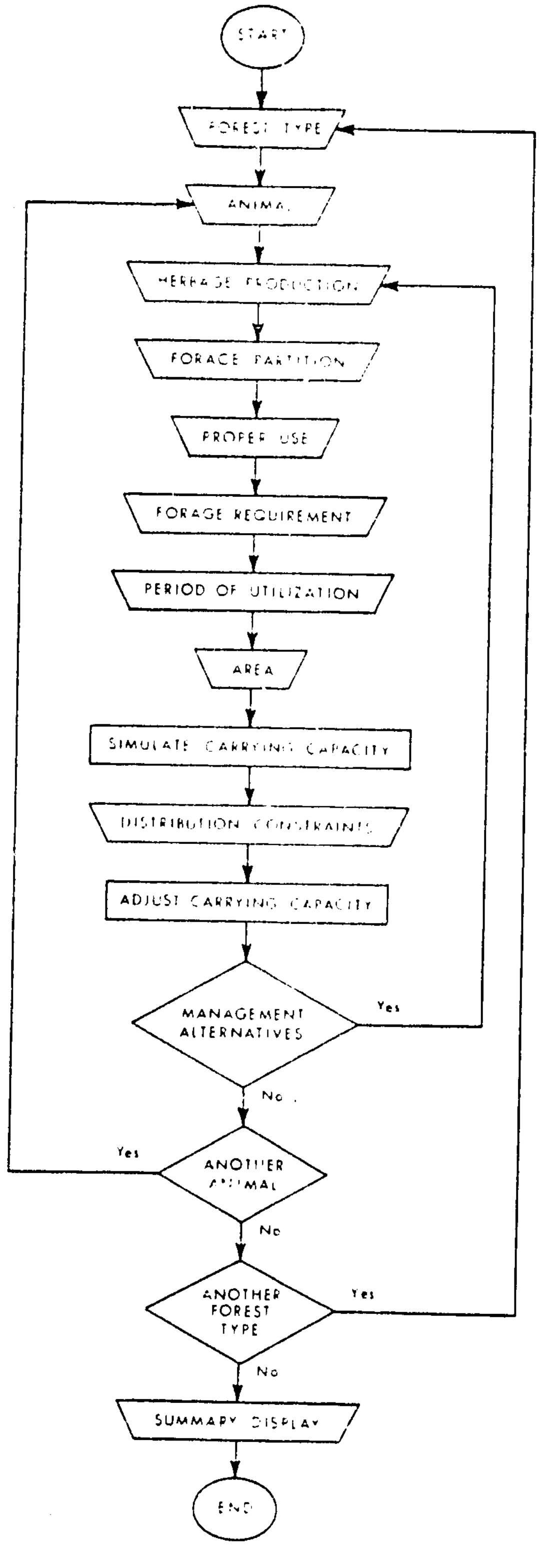


Figure 9. Flowchart of CARRY.

Population Dynamics

Although still in the formulative stage, an interactive population dynamics model, called DYNAM, is intended to predict the impacts of silvicultural management practices on the reproduction, growth, mortality, and structure of selected animal populations. More specifically, this modular component is to predict the manner by which a given population, specified by the user as reflecting existing conditions within an ecosystem, will respond to changes in food, cover and diversity that are attributed to management redirection.

THE COMMAND SYSTEM

The command system of the group of watershed resources simulators is largely dispersed into the respective modules. In fact, there is little evidence of a main command system in the overall operation of the group of models. Initial selection of the modules and components to be used and subsequent assignment of default values needed in the operation are handled by the command system. Also, timing and sequencing of operation of individual modular components are carried out by the system. Additionally, summary displays (tables, graphs, maps, *etc.*) of the simulation results are achieved through the command system.

All of the modules in the group have been structured to have three modes of operation: initialization, cycling in time and summarization. In the initialization mode, all needed data are either introduced directly by the user or entered from stored files. The second mode of operation is a cycling in time of the processes being simulated (daily streamflow, yearly forest growth, *etc.*). Finally, the third mode of operation is summary and, if appropriate, other activities at the end of a simulation problem.

When a user informs the command system which modular components are to be operated, he also states when they are to be used in the simulation problem. For example, the component CHEM may be required to operate only in the fifth year of simulation, while all other components may be operated every year. The command system stores this directive and acts accordingly.

The entire system is designed to operate with minimal input data. Default values are offered with nearly all of the interactive questions posed so that, whether or not the user has the required data or reason for overriding the default values, simulation can still proceed. Similarly, if a module or component is not directly included in a simulation problem, default values are loaded into the system to provide estimates of needed parameters normally obtained as output from the unused modular components.

After the system cycles through the specified number of simulation years, individual models are entered into the summary mode of operation. Any needed computations to allow display summaries of the operation to be output are done at this point. Output summaries may be obtained either on a local computer terminal or at a central computer location. These summaries may be brief or detailed, depending upon the user's need. In general, the parameters shown are representative of the various modules and components used in the problem. If a component is not used and default data are utilized, the parameters for the unused component will not alter the display.

FUTURE DIRECTIONS

Future work in the development of computer simulation models designed to assess the inputs of land management practices will follow two directions: synthesis of other modules and components, and extrapolation of the interactive system into other forest and range ecosystems.

While in various stages of development, several other modules and components are recognized as part of the group of computer models. For example, to facilitate overall planning with respect to a particular simulation problem, a module called PLAN is being structured to generate a PERT network of activities necessary to reach an objective. Another module, referred to as AREA, calculates the adjusted surface area of management units within an ecosystem, correcting for sloping or broken terrain. As knowledge of site quality is required as input to some modular components in the group, a module called SITE is under development to generate site quality directly (through estimation of site indices) or indirectly (through analyses of plant indicators, physiography, soil surveys, *etc.*). Outputs from this module will describe productivity potentials for both forest overstories and herbaceous understories.

To evaluate depth and quality of view within an ecosystem in terms of current and, if appropriate, anticipated conditions, a module named SEEN is being evaluated as part of the group. Another module, called FIRE, predicts the probability occurrence of wildfires of given intensities from knowledge of fuel properties and sequencing of meteorological events; this module also estimates the impacts of fire on an ecosystem. SNOW is a module that interactively simulates the dynamics of snow pack accumulation and melt within forests comprised of trees in varying spatial arrangements. ROAD allows for predictions of sediment loads resulting from the construction of roads with alternative design criteria.

To further aid managers and planners in analyzing land use alternatives, a module that facilitates the development and subsequent display of basic production economics models (production functions, product-product relationships, *etc.*) has been synthesized. This module, referred to as ECON, also includes components that represent various LP and Goal programming techniques. Other modules and components will be considered within the group to more completely provide socio-economic simulation capabilities.

The primary emphasis in the initial developmental work on the group of models has been placed on simulation within forest ecosystems in the United States. Current plans are to extend this work into other forests and, as the need arises, into range and arid ecosystems.

Many of the modular components in the group that have been synthesized only require "localization" of coefficients for use in other ecosystems. Other models, particularly those structured to represent an explicit plant or animal species, are only appropriate for use in simulating those ecosystems in which they occur and must be replaced by other species-specific models that characterize other ecosystems under consideration. However, even here, replacement is relatively easy within the overall structure of the command system.

CHAPTER XIV
ENVIRONMENTAL MONITORING

INTRODUCTION

Understanding the impacts of watershed resources management policies and providing significant input in formulating more effective watershed resources policies requires long-term environmental monitoring. A program of long-term environmental monitoring must address basic scientific questions and ecosystem functions as well as policy, human health, and safety issues. For the purposes of this syllabus, reference to environmental monitoring shall mean the process by which selected environmental variables are systematically observed, measured, and interpreted for defined purposes. Such purposes will be directed toward describing the state of an environment and identifying trends.

NEED FOR LONG-TERM MONITORING

In 1971, the Scientific Committee on Protection of the Environment (SCOPE) reported that the imperfectly understood cause and effect relations and environmental budgets of many substances had given rise to important questions relating to the complex interactions between man and his bio-environment. Furthermore, it was recommended that a program be initiated to obtain a picture of how all of these processes occur, the rates at which they take place, the timing and nature of equilibrium situations, and their effects on man and the life-support systems of air, water, soils, climate, and biota. Also, a need to develop mathematical simulation models of environmental interactions that can predict the results expected from varying types and degrees of remedial actions was recognized. The capability of advance-warning before an adverse situation becomes irreversible is absolutely essential.

The United Nations Environment Program (UNEP) stated in 1977 that an ecosystem is best considered as a total concept with the natural resources its components. Soils, air, water, animals, plants, and other genetic resources combine to form ecosystems in which the fate of individual resources is bound with that of others and of the ecosystem as a whole. Problems in an ecosystem can be examined within the context of the ecosystem itself or by considering natural resources occurring widely in different ecosystems. At the same time, the intricacies of ecosystem functions demand a specific and quantitative approach to the solution of problems brought about by imbalances in the systems.

In general, timely and accurate data from long-term monitoring projects are invaluable to agencies managing their lands within certain guidelines. Yet, seldom is there sufficient knowledge about an ecosystem to totally assess the impacts that a given land management practice may exert. For example, fire was long considered contrary to the concept of conserving an ecosystem. However, after long years of scientific study, it is now understood that fire can play a critical role in ecological succession and, in some cases, should be allowed to run its natural course.

There is an increasing need to know the effects that actions such as timber harvesting, livestock grazing, or controlled burning will have on future uses of land. Long-term environmental monitoring clearly provides one solution to better land management and is in the interest of any country's future.

Recently, a framework for international long-term environmental monitoring programs was identified by UNESCO's Man and Biosphere (MAB) Program. Under the monitoring framework established by MAB, countries are able to emphasize nationally important subject areas and implement monitoring programs at a level necessary for sound decision making.

In Scandinavia, scientists have long monitored atmospheric deposition in their countries to determine the effects of decreasing *p*H levels and to better understand long-range atmospheric transport. The World Meteorological Organization (WMO) has a global network of weather stations that monitor atmospheric conditions, including *p*H levels. Recently, the United States has begun to monitor atmospheric depositions due to a concern over the apparent trend toward a lower *p*H in northeastern and northcentral regions of the country. Within the framework of the MAB environmental monitoring program, a "chemical" monitoring effort has been initiated to provide data on which to base air pollution control laws and to better understand the issues of atmospheric transport.

Recognition is made of the fact that some countries may have minimal interest in atmospheric deposition, while being quite concerned about other facets of their environment. Under such conditions, individual countries may choose to emphasize subject areas that help them better understand and quantify the interactions between man and his environment.

DATA MANAGEMENT

Information and data exchange are obvious requirements if the results of an environmental monitoring program are to have wide benefit. Numerous information and data exchange systems exist. For example, UNESCO uses a computer-based system to provide continuously updated information relating to MAB studies in many countries. UNEP uses national focal points in its International Referral System (IRS) to link the source of information with requests from throughout the world.

Before a long-term environmental monitoring program is begun, basic questions regarding data management must be resolved. Determination of user groups, hierarchical options, analytical methods, bibliographic files, *etc.* must be addressed. Proper management of large masses of source data in itself can contribute to scientific advances, as happened in several instances with the International Biological Program (IBP). There is a rapidly growing trend in the scientific community toward reanalyzing data using newer concepts. Therefore, the availability of monitoring data, both historical and current, plays a critical role in filling important data gaps and allows other scientists to broaden their monitoring efforts.

Information and data exchange systems have reached a point such that they can be designed 80 to 100 percent complete in terms of storage, access, quality control, analytical capabilities, and editing prior to entry of the first data item. With proper design, data coming from 100 monitoring stations to a central facility with terminals or mini-computers at the monitoring site would require no more personnel at the facility than that coming from 10 stations.

IMPLEMENTING A LONG-TERM ENVIRONMENTAL MONITORING PROGRAM

Using the long-term environmental monitoring framework established by MAP as a guideline, a philosophy upon which a monitoring program should be developed consists of three fundamental precepts. First, land managers and policy makers would be in an improved decision making position if better basic information were available to them on a timely basis. Second, a great deal stands to be accomplished through increased cooperation between the many organizations which conduct ecological monitoring and research activities. Finally, there are processes occurring in the natural environment which can only be understood through an examination of long-term data sets.

The underlying theme behind development of a long-term monitoring program is to determine a process which provides increasingly sophisticated amounts of information relating to the interaction and sensitivity of an ecosystem. Therefore, a "state-of-knowledge" is necessary to acquire gross levels of data on features such as surface water, topographic maps, land use maps, soil and geologic conditions, *etc.* With the establishment of a "state-of-knowledge," various parameters may be identified as significant to the ecology or to the human management of an area. In some cases, the parameters may be specific to the area or the surrounding area (such as a declining species) while they are of global significance in other areas (such as the CO_2 cycle).

Recognizing the importance of environmental monitoring and using the MAB framework as the basis, four broad subject areas relevant to a long-term monitoring program can be identified: biological, geophysical, chemical, and anthropological.

Among the biological topics to be considered in an environmental monitoring program are flora and fauna species checklists, descriptions of biotic populations and communities, and quantifications of ecosystem processes and dynamics (Table 1). Geophysical topics include measurements of precipitation, air temperature, and streamflows; descriptions of soil types and associated physical and chemical properties; and estimates of areas or volumes of landslides, intensity and extent of windstorms, *etc.* (Table 2). Chemical monitoring topics involve the detection of pollutants and measurements of natural substances through the examination of critical components in the atmosphere, precipitation, streamflow, soil and litter, and vegetation (Tables 3). Anthropological monitoring includes the assessment of demographic characteristics of an area, land ownership patterns, legal and institutional structures, *etc.* (Table 4).

GUIDELINES AND STANDARDS IN ENVIRONMENTAL MONITORING

As may be expected, long-term environmental monitoring programs can assume different levels of sophistication. Depending upon the specific objectives in a country, guidelines and standards to monitor an ecosystem should provide a flexible progression from a minimum level of monitoring effort to an extensive and intensive monitoring program. Monitoring of a particular area should be trailored to meet the specific needs of the area.

To provide a basis for the design of a long-term environmental monitoring program, the framework established by MAB can be considered as broad guidelines and standards. Here, three levels of monitoring have been specified, ranging from the least sophisticated and technologically intensive (level one) to the most sophisticated and technologically intensive (level three).

While level three is the most sophisticated and technologically intensive, it does not necessarily represent the "best" approach to a particular monitoring effort. If adequate and reliable source data can be obtained by simpler monitoring techniques, they whould be used. Indeed, it should be noted that many of the elements at level three may be projects of limited duration, possibly repeated at intervals as long as five years apart.

Table 1. Biological topics in an environmental monitoring program.

Types of Data	Level One	Level Two	Level Three
Species	List of vascular plants & vertebrate animals Significant species (rare, endangered, extinct, economic, exotics)	Habitat preference Geographic distribution Residence status (migratory, permanent, ephemeral) Reference collection Trophic level-major species	Inventory endemic plants and animal species Identify & monitor indicator species for pollutants, growth rates, habitat requirements Archive select plant & animal tissues
Populations/ communities	Relative abundance (rare, common, abundant) of major vertebrate and vascular plant species Major communities Low level aerial photos ERTS imagery	Annual census major species 1-3 permanent plots Low level aerial photos (100m) (5 yr cycle) on seasonal basis Estimate net productivity (major producers) Composition (major vegetative communities)	Population dynamics major vertebrate species Quantify distribution and abundance major plants and animals Describe ecosystems within Reserve Monitor for changes in composition, trophic organization, and diversity Permanent plot system Groundtruthing
Ecosystem processes			Successional patterns Energy flows Nutrient and System respiration Nutrient retension
Ecosystem dynamics			System shifts Gene pool diversity Genetic drift

Table 2. Geophysical topics in an enviornmental monitoring program.

Types of Data	Level One	Level Two	Level Three
Event/occurrence	Recording and where possible, quantifying unusual geological, geophysical or meteorological events, such as mass wasting, earthquake, windthrow, *etc.*		
Meteorology			
precipitation	Monthly storage	Daily or weekly storage	Recording gages along precip. gradient:
air temperature	Daily max/min	Standard weather station to include shortwave solar, & recording hygrothermograph	Recording weather station compatible with WMO network
Geology/Geomorphology	Geological map - - - - - - - - - Morphology - - - - - - - - - - -		Geological map at 1:24,000 Minerology of parent materials
coastal			
permafrost			Channel characteristics
Hydrology			
streams	Inventory perennial & intermittent streams	Stage neight at rated cross section	Automatic gaging
lakes/streams	Perennial or intermittent ice free dates	S*age height, inlet/outlet discharge	Automatic gaging
wetlands			Automatic gaging
groundwater		Seasonal depth measurement	Map groundwater resources
Soils	Soil type map Rooting depth	Organic content Mechanical analysis Physical analysis Infiltration rate	Water holding characteristics Soil/water erodibility indices Soil productivity (composite index)
Geochemistry			
precipitation	pH		
soils	pH	Cation exchange capacity	
water	pH		
surface		NO_3, N, PO_4, P	
ground			
physical water quality	Temperature	Turbidity, color	Total dissolved solids, suspended and bedload

Table 3. Chemical topics in an environmental monitoring program.

Level Two								
Level One								
			Atmospheric deposition				Atmospheric	
Measurement	Rainfall	Surface waters	Wet (rain)	Dry (dust)	Surface waters	Accumulation-animals, soil, litter, vegetation	Gasses	Particulates
pH	X	X	X	X	X			
Cond.	X	X	X		X			
$SO_4^=$			X	X	X			
PO_4			X	X	X			
Cl^-			X	X	X			
NO_3^-			X	X	X			
NH_4^+			X	X	X			
K^+			X	X	X			
Na^+			X	X	X			
Ca^{++}			X	X	X			
Mg^{++}			X	X	X			
Hg				X	X	X	X	X
Pb				X	X	X		X
Cd				X	X	X		X
As				X	X	X		X
SO_2							X	
O_3							X	
Level Three								
Trace metals			X	X	X	X		X
TSP								X
Benzopyrene			X	X				
Cl hydrocarbons			X		X	X	X	

Table 4. Anthropological topics in an environmental monitoring program.

Types of Data	Level One	Level Two	Level Three
Map	Land use map (every 5 years)		
Activities	Human activities (farming, trapping, hunting, mining, recreation, forestry, industry, *etc.*)	Quantify (yield/acre, visits, economic species yield, board feet, tons, miles, *etc.*)	Inputs (fertilizer, pesticide) Outputs (yield/area)
Ownership	Land ownership public (area) private (area)	Public-area by agency Private-area by size class, # of owners	Private names of owners by area
Demography	Human population (#) residents neighbors visitors	Age/sex distribution Diet Educational levels Health (incidence of disease) Housing (type, location)	Per capita income Physiological parameters Origin of visitors (nationality, #)
Animals	Livestock, Pets, Other domestic } by species	Quantify (#)	
Legal	Acts, Regulations, Policies } as affecting reserve	Management plan Management activities (type, extent, frequency)	
Education	Research & training activities by type	Quantify Support (facilities, budget, staff)	
Development	Public facilities, infrastructure, services (sewer, water, electricity, roads, hospitals, campgrounds	Quantify Locate on map(s)	
Benefits	Benefits derived by man	Quantify	

CHAPTER XV

WATERSHED RESOURCES MANAGEMENT IN THE MULTIPLE USE CONCEPT

INTRODUCTION

Watershed management is simply a component of the overall management plan and system to the wildland administrator actively pursuing a multiple use land management. Similarly, timber management, range management, and wildlife management are components of the management scheme. In many instances and situations, one or two of the wildland resource products may prevail due to local demands. However, even when one tree or a stand of timber is cut for sawtimber to attempt to increase water production, herbage production and aesthetic and recreational values will almost certainly be affected. Therefore, to effectively and efficiently practice one component of multiple use management, such as watershed management, the wildland administrator must be aware of the associated wildland resource management implications.

THE MULTIPLE USE CONCEPT

In almost any discussion of wildland management problems, multiple use management is cited as a guiding principle. At times, one gets the impression that multiple use is a cure-all for all the problems of wildland administration. However, while there has been little difficulty in gaining general acceptance of the multiple use concept, it has had far less success as a working tool of management. Most people concede that timber or water production is not necessarily the sole production function of wildlands, and that forage, wildlife and recreation should be considered in management decisions. But how much managerial effort should be allocated to each potential land use is a problem that wildland administrators have not always been able to resolve. Reconciliation of conflicting interests continues to be an important responsibility of wildland management agencies.

MEANING AND OBJECTIVE OF MULTIPLE USE

The term *multiple use* may be applied either to areas of land or to particular wildland resource products. When applied to land areas, multiple use refers to the production and management of various resource products or resource product combinations on a particular land management unit. The relation of several resource products on a management unit to one another may be competitive, complementary, or supplementary. A *competitive relation* exists between resource products when one must be sacrificed to gain more of another, as may occur between timber and water or between timber and forage. In *complementary relations*, both resource products increase together, as may occur between forage and water once the timber has been removed. A *supplementary relation* is one such that changes in one resource product have no influence on another, as may take place with livestock and wildlife within limited ranges or changes in forage production.

Conceivably, the relation of several resource products to one another on a particular land management unit may be competitive, complementary *and* supplementary, depending on the area of management concern. In this situation, it is important for the wildland administrator to know what area of management concern confronts him. For example, if working with a supplementary relationship between timber and water, the administrator may not be able to influence water production by altering timber production (Figure 1).

When applied to a particular wildland resource, multiple use refers to the utilization of the resource products for various purposes. Water may be utilized for irrigation, industry or recreation. Timber may be used for lumber, pulpwood, or Christmas trees. Forage may have value as feed for livestock and wildlife, or for watershed stabilization. Here again, the utilization of resource products may be competitive, complementary or supplementary.

In practice, multiple use management involves both the multiple use of land areas and of particular wildland resource products. Demands on particular resource products (water) for specific uses (irrigation), in turn, place demands on the land where the resources are produced (watersheds).

The basic objective of multiple use management is *to manage the wildland resource product complex for the most beneficial combination of present and future uses*. The idea of maximizing the benefits from a given resource product base is not new, but it has become more important as competition for limited and interrelated resource products increases.

The multiple use concept as described by law does not necessarily demand that every land unit in question should be utilized for all possible uses and resource products simultaneously. Instead, most public wildlands are utilized, to varying degrees, for a wide array of uses, as dictated by productivity and demand.

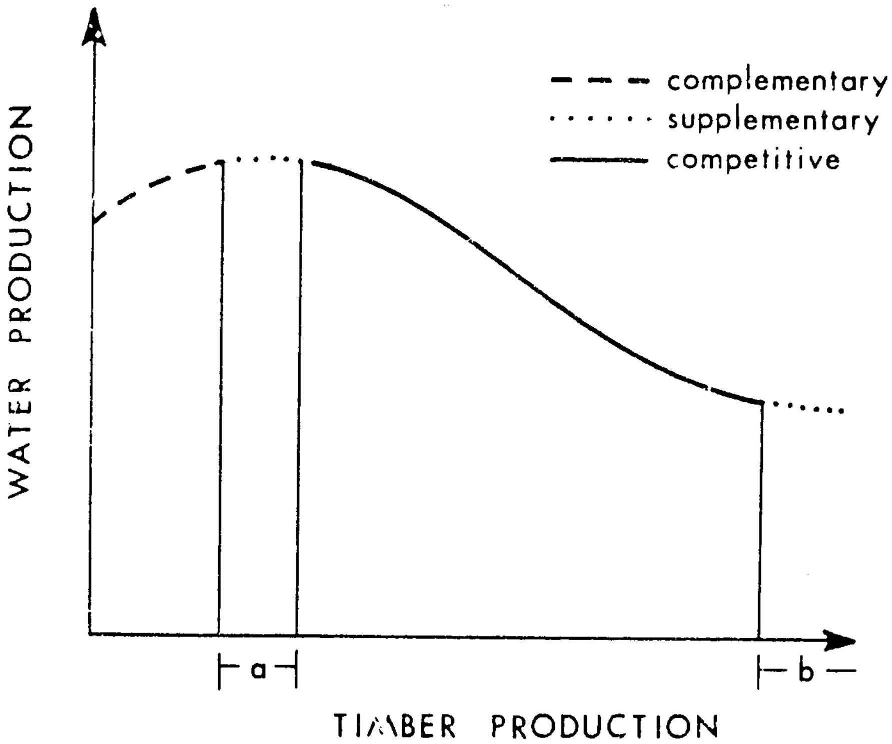


Figure 1. A hypothetical relationship between water and timber production on a land management unit, illustrating competitive, complementary, and supplementary relations. It is imperative that the wildland administrator ascertain which relation confronts him before implementing a land management redirection. Here, for example, the administrator will not be able to influence water production by altering timber production if operating in area "a" or "b."

Multiple use land management of wildlands may be accomplished by any one of the following options, or by combinations of the three:

(1) Concurrent and continuous use of the several wildland resource products obtainable on a particular land management unit, requiring the production of several goods and services from the same area.

(2) Alternating or rotating the uses of the various resource products or resource product combinations on a unit.

(3) Geographical separation of uses or use combinations so that multiple use is accomplished across a mosaic of units, any specific unit area being put to the single use to which it is most suited.

All of these options are legitimate multiple use management practices and should be applied in the most suitable combinations.

From society's point of view, regardless of the land management unit in question, multiple use involves a broader set of parameters that concern the private investor. Generally, society is more interested in preserving wildland benefits for future generations, requiring investments beyond the dictates of limited business economics. On the other hand, the private investor makes decisions based upon relatively short-term profit motives commonly related to limited resource product uses. Effective multiple use management should accommodate the full spectrum of today's needs and provide for tomorrow's requirements.

TYPES OF MULTIPLE USE MANAGEMENT

There are two fundamental types of multiple use land management, that which is resource-oriented and that which is area-oriented. *Resource-oriented* multiple use management is dependent upon knowledge of interrelationships describing how the management of one resource affects the production of others, or how one use of a particular resource affects other uses of the same resource. Essentially, substitutions between resource products or resource uses, and the associated benefit-cost comparisons of alternative production combinations are taken into account. Resource-oriented management may deal with a single resource product with alternate uses, or with two or more resource products with alternate uses for each.

Resource-oriented multiple use management requires the understanding of wildland resource production capacities. However, to accomplish effective and efficient multiple use management, resources must not only be related to each other but also to the needs and wants of people. *Area-oriented* multiple use management meets this general objective through consideration of the physical, biological, economic and social factors relating to wildland resource product development in a particular place. This type of management provides a framework in which information concerning the administration of land management units can be arranged, analyzed and evaluated for the purpose of making sound management decisions. Area-oriented management draws that information needed to describe wildland resource product potentials from resource-oriented management and then relates this to the dynamics of local and regional demands. Area-oriented management is not necessarily intended to replace other forms of management, but rather to complement it. Hopefully, this will help to close the gap between resource management and problems on the ground.

INTEGRATING WATERSHED MANAGEMENT WITH MULTIPLE USE

The problems of integrating watershed management within the multiple use concept, a necessity in effective and efficient wildland management, are not always fully realized by the wildland administrators. While these problems may often be structured in resource-oriented management objectives during the initial phases of management implementation, wildland administrators must continually be aware of area-oriented management implications, especially when management plans and systems are developed for application over large land areas. Numerous land management considerations, policy formulations and institutional conflicts confront the wildland administrator attempting to integrate the component parts of multiple use land management. Although many of these issues are common to all components, several problems unique to watershed management implementation must be considered.

Land Management Considerations

Often, watershed management involves the development, evaluation, and application of land management systems designed to alter water production. The impact of management systems on a river basin may extend beyond simple attempts to alter the flow of water into downstream reservoirs. Many wildland resource products in addition to water are in demand from upstream lands, and these resource products must be allocated to maximize total benefits to society.

Land management systems designed to alter water production are commonly recommended by various interests groups. These systems often require sweeping modifications of vegetation on lands where the potential to alter water production is the highest. Some of these systems could jeopardize other land values; and some are irrevocable, at least in the short run, in that they can easily be made but cannot be undone if they turn out to be mistakes. Furthermore, technological and economic guidelines have not been sufficiently developed to carry out the implementation of the system effectively and efficiently, in many cases.

The implications of land management systems designed to alter water production are of particular interest to upstream land management agencies since these agencies are charged with administering a large portion of the potentially better water yielding areas. But, because these management agencies are committed to the concept of multiple use management, the implications of these land management systems extend beyond considerations of water production alone.

The problem is to determine advantages and disadvantages of land management systems designed to alter water production before the systems become operational.

Estimates of Wildland Resource Products

Measurements of the yields of all wildland resource products are necessary to determine their responses to land management systems. These products include water, timber, range for livestock and wildlife, and recreation. Consequently, estimates of water yield and quality before and after a management system has been imposed are desirable. Timber growth and quality measurements should also be obtained on a before and after basis. Likewise, records of forage production and utilization can subsequently be translated into beef gains and wildlife habitat potential. Records of game and hunter use can be used to assess recreational values.

The measurements of wildland resource products on a management unit can be summarized in tabular form as a *product mix*. This table describes multiple use by quantitatively presenting all resource products derived from a particular area or class of land. Product mixes developed before a land management system is implemented will form a reference for comparison with product mixes developed after implementation. These comparisons will show what is gained and sacrificed in multiple use terms, assuming that a resource product response to a system can be determined with before and after measurements. Such comparisons form a basis for deciding among land management systems in terms of an appraisal of the advantages and disadvantages in resource product responses (Table 1).

On one hectare, if things remain as they are, T_0, the annual output will be 4.2 cubic meters of timber growth, enough forage for 0.068 kilograms of livestock gain, 0.021 deer, and 15 centimeters of water. No timber will be cut.

With conversion of moist sites to grass, T_1, the annual output will be 2.5 cubic meters of timber growth, enough forage for 0.48 kilograms of livestock gain, 0.034 deer, and 22 centimeters of water. Approximately 9.0 cubic meters of timber will be cut on each hectare.

Columns T_2 and T_3 contain the elements of uneven-aged and even-aged forest management systems, respectively.

Table 1. Product Mix Vectors for Southwestern Ponderosa Pine Forests 1/

Item	T_0 As is	T_1 Convert	T_2 Uneven-aged	T_3 Even-aged
Timber cut (cubic meters)	0.0	9.0	4.9	3.8
Timber growth (cubic meters)	4.2	2.5	5.5	5.2
Livestock (kilograms gain)	0.068	0.48	0.0045	0.27
Wildlife (number of deer)	0.021	0.034	0.032	0.033
Water (centimeters)	15.0	22.0	16.0	18.0

1/ Adapted from efficient development and use of forest lands: An outline of a prototype computer-oriented system for operational planning by R.J. McConnon, 1965.

It is important to note that, if T_0 is the best as judged by an assessment of the advantages and disadvantages in natural resource product and use response, the existing management system should be continued.

Direct Costs and Benefits

Determining the costs of implementing and maintaining a land management system, as well as the direct returns associated with the management system, is prerequisite to efficient multiple use land management.

A large body of information on costs is available in the literature. Unfortunately, these data normally reflect a particular economic situation and time, and cannot easily be adjusted to local conditions. Consequently, gross job time costs data in terms of physical input-output variables characterizing the management system and land area may be required. Inputs collected include labor time, equipment time, direct supervision time, and materials. Outputs specify total production as units thinned, cleared, *etc.* Costs are then determined by multiplying inputs by current wage rates, machine rates, and material costs. The sum of costs divided by the number of production units accomplished gives an estimate of the average unit costs for a management system.

Direct returns to the land management unit may largely be dependent on the sale of timber removed in the initial establishment of the management system. Remember, calculations based on a "saw-timber-only" market, as currently exists within many market areas, could become obsolete if a pulpwood or veneer mill is installed. The presence of these additional outlets could alter the expected dollar returns by making previously unmerchantable material saleable. Therefore, since market conditions can change quickly, and since they affect returns so significantly, the timber resource should be described in terms of multi-product potentials, providing timber quality and yield information for management and utilization decisions on a continuing basis.

Direct returns derived from other resource products, *i.e.*, forage for livestock and wildlife, recreation, *etc.*, could conceivably be determined by comparable objective analyses, although these markets may be more poorly defined than timber.

The flexibility derived from the collection of objective cost-benefit data will allow land management systems to be reevaluated as economic conditions change through time. Consequently, a system initially considered economically impractical could become operational with a change in wage or machine rates, or with increased market outlets.

Economic Evaluations

To make an economic evaluation of a recommended land management system designed to alter water production, the following criteria could be selected to form a basis of choice:

(1) Maximize benefits.

(2) Maximize the returns on an investment.

(3) Achieve a specified production goal at least cost.

Data required to satisfy the first two criteria include estimates of resource product values and physical responses resulting from land management redirection, and costs of implementing the management system. To satisfy the third criterion, goals often derived through the political process must be established for various levels of production.

Economic evaluations essentially consist of an array of pertinent economic analyses designed to help wildland administrators make a better decision. Individiaul analysis may yield a one-answer solution to the problem of selecting a land management system that maximizes the returns to the land. A group of such analyses, based on different criteria, will result in an array of items for decision makers. Such an array may include:

(1) Estimates of multiple use production associated with different land management systems.

(2) Estimates of costs of management alternatives.

(3) Least cost solutions for different goals of multiple use production.

(4) Gross and net benefits associated with a range of management alternatives.

(5) Investment returns and cost-benefit ratios associated with different management systems.

Policy Formulations and Institutional Conflicts

Given the above array of economic relationships, the watershed manager (acting as a wildland administrator) should be able to choose the best course of action in terms of implementing a land management system. However, it is anticipated that there may be policy issues and institutional conflicts that must be resolved before a land management system becomes operational within the multiple use concept.

The question of who will pay for the establishment of a new land management system *specifically* designed to alter water production must be answered. The group of people that executes the system may not derive direct benefits from all of the multiple uses affected. For instance, it is questionable whether the U.S. Forest Service, who will carry out many of the operational programs necessary to implement a management system, will receive benefits commensurate with their costs. The role of downstream groups benefiting from increased water production from upstream lands will have to be established regarding costs.

The costs and benefits of a land management system designed to alter water production to society's needs must be ascertained. Various viewpoints will need to be adopted so people can determine how a management system is going to affect them individually and collectively.

Local groups on or near the land area directly affected by a land management system will want to know how a program may affect them personally. Their viewpoint can be developed by the valuation of raw multiple use products onsite or by the value added through manufacturing stages in the economic stream from resource to consumer within the local area. A single economic solution may not be suitable, but analyses reflecting the various viewpoints may yield the required answer.

Regional interests will probably bear a large portion of the investment in a land management system. A determination of the effects of a management system on a state's economy seems appropriate to this viewpoint. Finally, the national viewpoint must be the basis for some evolution, primarily because most of the land that may be subjected to a management system will be federally managed and the federal government will make at least a portion of the investment.

Perhaps the greatest problem facing the watershed manager pursuing multiple use land management is that of developing an efficient institutional framework through which land areas subjected to the multiple use concept can be managed. A realistic multiple use management plan (such as that outlining a land management system designed to alter water production) must either work within the existing institutional structure, or modify it in order to be effective. An evaluation of the political and social organizations through which wildland resources are currently administered may suggest a necessity for institutional reform.

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