Defn. Hydrology

Hydrology

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CHAPTER I

INTRODUCTION

The Hydrologic Cycle

Water constitutes one of our most valuable natural resources. Without it no form of life is possible. It not only supplies both the animal and vegetable kingdoms with daily sustenance but also provides highways of transportation, is a source of power, and serves many other useful purposes. At times, however, this normally helpful servant becomes temporarily transformed into a most destructive agent, through the medium of storms and floods, laying waste valuable property, taking a heavy toll of life, and eroding and carrying to the sea millions of tons of rich and fertile soil annually.

In one form or another, water occurs practically everywhere, varying in quantity from an almost unlimited supply in the oceans to nearly none in desert regions. It occurs in the atmosphere as water vapor, clouds, and precipitation. On the earth's surface it is found principally in streams, in lakes, and in the oceans, and beneath the ground surface it occurs under various classifications, as will be explained later.

Although at any instant by far the largest portion of the total water supply is stored in the oceans, a constant circulation is taking place. Evaporation from the ocean's surface is continuous. Although most of the moisture so evaporated condenses and returns at once as rain, a considerable portion is carried by the winds over the land areas where it is precipitated as rain, hail, sleet, or snow or condenses as dew or frost on the surface of vegetation and other objects. Nearly all the moisture in the form of dew and frost either is evaporated directly or is consumed by vegetation and then transpired through the vegetal pores. That which falls as precipitation, however, has a much more varied experience. Some is re-evaporated before it reaches the earth. Another part is intercepted by vegetation, buildings, and other objects, and part of this is re-evaporated directly. Another portion runs off from the ground surface into the streams and is returned to the sea. Still another portion percolates into the ground. For this, there are numerous outlets: part of it is held by capillary action at or near the surface and is evaporated therefrom; another part is used by vegetation and returned to the air through the process of transpiration; still another portion joins the ground water and slowly finds its way to the streams, appearing after days, months, and sometimes much longer periods as groundwater flow; and finally, an amount that is usually insignificant but in a few drainage basins is of considerable importance, percolates to great depths and appears after long intervals, often at far distant points, as springs, artesian wells, and geysers.

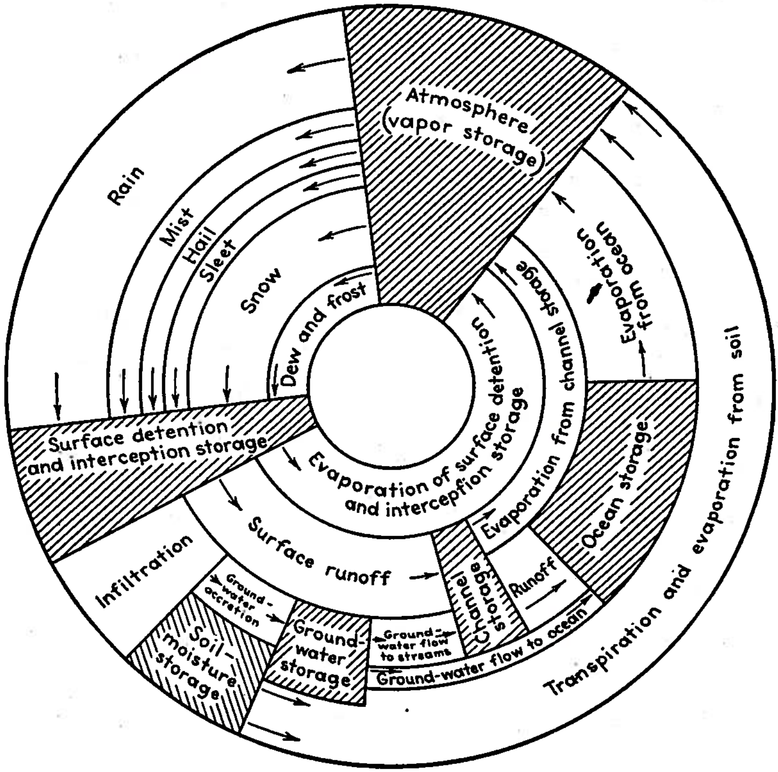

Fig. 1. The hydrologic cycle. Shaded areas represent storage; arrows indicate flow. Read diagram counterclockwise.

Of the water that reaches the streams comprising the headwaters of the large drainage systems perhaps only a small portion flows directly to the sea. The remainder is evaporated from the surface of streams and lakes through which the streams flow, is used and transpired by vegetation growing along their margins, or seeps into the ground along the water courses where the groundwater table is lower than the surface of the streams. This last portion may later return to the same channel at points downstream; it may through underground channels find an outlet in distant springs, other river channels, lakes, or the sea; it may be reached and utilized by deep-rooted vegetation; or, finally, it may join the more or less permanent ground waters, appearing perhaps years later as springs and geysers.

This sequence of events, which is represented graphically in Fig. 1, is called the *hydrologic cycle.* It provides the groundwork upon which the science of hydrology is constructed.

Hydrology Defined

Hydrology is the science that deals with the processes governing the depletion and replenishment of the water resources of the land areas of the earth. It is concerned with the transportation of water through the air, over the ground surface, and through the strata of the earth. In other words, it is the science that treats of the various phases of the hydrologic cycle. A knowledge of hydrology is of basic importance in practically all problems that involve the use and supply of water for any purpose whatsoever. It is, therefore, of value not only in the field of engineering but also in forestry, agriculture, and other branches of natural science.

The questions that the hydrologist is called upon to answer are extremely varied. Sometimes he is most concerned with a determination of the maximum flood flow that may be expected every few years, as in certain drainage problems; at other times, as in the design of the spillway for an important dam, his problem is to determine the maximum flow that will occur once in a thousand years or more. The best procedures in solving these two problems may be entirely different as will be explained later. Again, the problem, often encountered by the municipal or sanitary engineer, may involve a determination of the minimum average low water flow for a day, a month, or a longer period. Or it may be a determination of the long-term average yield. In some instances the manner in which that yield varies throughout the year or from year to year is of little or no importance; in others, its variation is of major importance. And so the hydrologist is presented with a great variety of problems, no two of which require the same data or involve the same methods of procedure for solution. For instance, in determining the maximum flood that may be expected he will be but little concerned with evaporation and transpiration losses, but if he wishes to determine the low water flow or the long-term average yield he will be very much interested in those losses. As a result, a broad general knowledge of the basic principles of hydrology is essential for the proper solution of these various problems.

History of Hydrology

Hydrology is a relatively new branch of the natural sciences. Although in ancient ruins unmistakable evidence has been unearthed that advanced knowledge in many of the sciences was held by man thousands of years ago, it appears that no such evidence of an early knowledge of the principles of hydrology has ever been found. In fact, one need not go back many years to find a time when there was practically no literature on the subject. It is believed that greater advancement has been made in the development of this science during the present century than was made during all previous history.

As an illustration of the tremendous changes that have occurred in this science recently, one need but recall that it was only a few years ago when runoff was generally considered and expressed as a percentage of rainfall. We now know that runoff is that which is left from the total rainfall after evaporation, transpiration, and various other factors have taken their toll; in other words, stream flow equals rainfall minus losses, not rainfall times a percentage factor. In a similar manner, it was not long ago that engineering literature was replete with discussions of the use of statistical and probability methods for determining maximum flood flows that could be anticipated with any given frequency. It can now be shown conclusively that such methods often produce results that are grossly misleading when applied to short-term discharge records for determining the maximum flood that may be expected to occur with a frequency of, say, once in a thousand years. And so these and many other of the earlier concepts have only recently been replaced by better and sounder theories.

Two milestones mark this progress. The first, the concept of the unit hydrograph, stands as a monument to LeRoy K. Sherman. The second, the theory of infiltration capacity, is one of the many contributions of Robert E. Horton. These, along with the work of W. W. Horner, Merrill Bernard, and a great many others, have so changed our knowledge of this subject that we may refer to the present century and, in fact, even to the period since 1930 as representing the dawn of the science of hydrology. Other advances are unquestionably in the making, but sufficient progress has already been made so that the student may rest assured that this science now provides him with a most useful tool for determining the answer to almost any problem that he may encounter in this field.

Practical Value of Hydrology

To the beginning student of hydrology, the natural question that first arises is: Why are we concerned with knowing all the complicated relationships between precipitation and runoff? Inasmuch as it is easier to measure the runoff from a drainage basin than to determine the average precipitation on that basin, since the latter requires measurement at a number of places, why not measure the runoff in the first place and be done with it? Why bother about the precipitation?

The difficulty of course lies in the fact that a river is not like a tract of land which, once surveyed, forever retains these same dimensional characteristics. Instead, the volume of water flowing in any given stream varies from day to day and from year to year. It is never absolutely constant even for a day. Frequently the magnitude of these changes is slight, but occasionally it is very large. For some streams the maximum flow is many thousand times the minimum, but for others this ratio is relatively small. Likewise for any stream the maximum flow for any one year will bear a certain ratio to the minimum flow, but for any other year that ratio will be entirely different. Furthermore, for any given stream the maximum, minimum, and average flows for any short period, for example five years, may be and often are radically different from those for any other, similar period.

Therefore, in order to determine the regimen of a stream over a long period of time, as must be done in the solution of a wide variety of engineering problems, it is necessary either to have discharge records covering such a long period or to have other data and a knowledge of the relationship between the known data and the stream flow so that the flow may be determined with a satisfactory degree of accuracy. Rainfall and general climatic conditions affect our daily lives more directly than does stream flow. This statement is true at least for the average layman, even though it may be questioned by the engineer. As a result, records of rainfall, temperature, humidity, barometric pressure, and the like were initiated long before stream-flow records were even considered. Furthermore, rainfall and general climatic records require but little skill and training on the part of the observer, whereas reliable stream-flow records demand the services of an engineer or at least of a skilled technician.

Consequently, rainfall and climatic records are available for almost any drainage basin in the entire United States, oftentimes covering periods of fifty years and sometimes a hundred years or more. On the other hand, stream-flow records are comparatively few and far between. On only a few streams are there good, reliable records that are continuous for a period of fifty years or more. Many records are brief or intermittent and usually missing for the period for which they are most urgently needed. Sometimes good records are available on the main stream, whereas the problem at hand calls for a knowledge of the yield of a tributary far removed from the site of the available records, or vice versa. Often a close examination will reveal the fact that some of the existing records were obtained by methods or under circumstances that subject their accuracy and reliability to serious question.

Practically never does the engineer have the experience of finding available all the necessary stream-flow records at the proper site on the stream in question. Nearly always it is necessary either to use the records obtained at a more or less distant point or to extend the records to cover a longer period. In any case, the selection of the proper procedure is dependent upon a thorough understanding of the principles of hydrology.

Increasing Importance of Hydrology

In the early stages of development of our country, the water resources did not possess the same importance that they now have, nor do they now play the prominent role that they seem destined to assume in the future. In the early days those resources were entirely adequate to meet all the needs that then existed. They could be had merely for the asking. Seldom were the resources developed to the limit of their possibilities but only to the extent of meeting the then existing requirement. As a result, but little concern was felt regarding the need for data and knowledge of the ultimate capacities of our rivers and underground sources to meet the many demands to which they now are and in the future will be subjected.

With the advance of civilization and a steadily increasing population, rivalry and competition for the use and control of our water resources have developed and are becoming more and more intense. In the pioneer days that use was practically restricted to logging, fishing, navigation, and small commercial power plants where the power was used in saw mills, flour mills, and small factories. Seldom was any attempt made to utilize all the power that was available at any site. How different is the picture today! On streams of any size practically all power plants are now hydroelectric and are installed right up to the limit of economic feasibility — in fact, many contain installations that are well beyond that limit. Storage reservoirs are in demand whereby the flood waters may be conserved and utilized during periods of low flow. For the benefit and protection of wildlife, however, the recreational interests insist that those reservoirs be maintained as nearly as possible at a constant level, a point which is at variance with the wishes of the power interests.

An increasing number of municipalities and industries are obtaining their water supplies from rivers. Their need for a supply that is as free as possible from contamination is in direct conflict with the interests of other cities and industries, located upstream, that wish to discharge their sewage and industrial wastes into that same river. Where the rainfall during the growing season is insufficient to meet the needs of vegetation, the withdrawal of water from the streams for irrigation purposes is in conflict with practically all other needs.

A careful examination of the manner in which each different utilization of our water resources affects the availability of those same waters for other purposes reveals the fact that each different use may be in conflict with most of the others. Although it is true that occasionally two uses may be found that on the surface appear to operate in harmony, more often than not that harmony will be found to be more apparent than real. As an illustration, the storage of flood waters in reservoirs to supplement the low flows for power development, irrigation, water supply, or other purpose appears to be in perfect accord with flood prevention. Upon second thought, however, it is seen that storage for any of the former purposes demands that the reservoir be kept filled as much of the time as possible so that the water will be available when needed, whereas for flood prevention the reservoir should be emptied as quickly as practicable so that its capacity for storage will be available when the next flood arrives.

Furthermore, the competition for our water resources is certain to become more and more keen in the years to come. This increase will occur not only among the various types of uses that exist today but among the new uses that will develop. For instance, the fact is now well established that farm irrigation is profitable not only in the western part of the United States, to which area this practice was long confined, but also in the Midwest and even in certain sections of the East. When this truth becomes fully realized, a new impetus will be given to the demands for water in those areas.

Likewise the field of air conditioning is only in its infancy at the present time. This practice is almost certain to enjoy a tremendous growth. Inasmuch as some of the methods of air conditioning require large amounts of water, usually obtained from underground supplies, serious problems are almost certain to be created. With the advent of other at present unforeseen developments of similar nature and with a steadily increasing congestion of population, the competition for our water resources is certain to increase as time progresses.

In the adjustment of these conflicts and in the proper solution of the many problems arising in connection with them, complete data on our water resources and a full understanding of the principles of hydrology become a vital necessity.

Need for New Laws

To meet the new conditions and the ever-expanding demands, new laws will have to be enacted. Although literally deluged with a superfluity of legislation governing most of our daily activities, by way of strange contrast we are left almost entirely in the dark on the important question of our rights in connection with our natural water resources. At least that is the situation in most of the states. For example, in Michigan there are a few legislative enactments relating to matters such as fish ladders in dams and the right of the public to fish in waters in which fish have been planted at public expense, a law restricting the pollution of streams, and a few others. All other matters are governed by judicial decree, and these decisions are frequently conflicting. In general, they find root in the old common law of England and are based upon priority of use, a doctrine which under present-day conditions is woefully inadequate. On such an important point as the extent and limitations of the right of the public and the riparian owner on any stream, one will search in vain for a clean-cut definition either by legislative act or by court decree. Those acts and decrees frequently contain references to "navigable" and "non-navigable" waters, to "the water's edge," to "the low-water mark" and "the high-water mark," etc., but specific definitions of these terms are glaringly absent.

A few states, principally in the West, have good up-to-date laws regulating the use of our water resources, but in most states a complete new water code is urgently needed. In the preparation of that code, the hydrologist should take an important part, for only he fully understands the proper solution of the many intricate problems that are arising and will continue to arise with increasing frequency in connection with the use and control of our natural water resources.

Need for More Basic Data

The most serious obstacle that always confronts the engineer in his study of problems dealing with stream flow is invariably the lack of data. These data include the following:

1. Stream-flow records.
2. Precipitation records.
3. Topographic maps.
4. Ground-water data.
5. Evaporation and transpiration data.
6. Data on the quality of the available supply.

It may be observed that these data can be divided into two general classifications. The first class includes records of variable factors showing the variations in either quantity or quality of the supply from time to time. Stream-flow and precipitation records are of this type. The other class includes data of a more or less permanent character, such for instance as topographic maps of the drainage basin. To obtain the first kind requires a long period of time, and, other things being equal, the value of the records increases directly with the length of period covered. On the other hand, the value of the other class of data has no relation whatever to the length of time required for collection. It would be possible, for instance, to obtain the topography of an entire drainage basin in a month or even less with a sufficiently large staff, but not even an army of the most highly trained engineers could determine the regimen of a stream in so short a time.

Throughout the entire United States, the federal government maintains about 2900 stream-gaging stations. A number of other stations are maintained by private agencies, but the records obtained are not always available to the public. Large areas oftentimes covering important drainage basins can be found that are practically without any discharge records. On many others the records are so short and intermittent as to be of little value. It is a conservative statement to say that few, if any, government expenditures are more urgently needed or yield greater dividends than money for stream-flow records.

The U. S. Weather Bureau is at present maintaining about 8000 precipitation stations throughout the country. Except for the records that are being obtained by the Forest Service, the Soil Conservation Service, and a few other agencies from their experimental investigations, these are practically the only precipitation records available. Throughout the entire United States the average distance between adjacent precipitation stations is between 20 and 30 miles. Taking into consideration the large differences in rainfall that are often shown by the records of any individual storm at two stations less than 20 miles apart, it at once becomes apparent that, with the present number of precipitation stations in operation, it is impossible to determine to a satisfactory degree of accuracy the amount of precipitation that falls on any drainage basin during one of the more intense storms. For the more general storms of less intensity but covering large areas, the present records may provide a satisfactory basis for such determination, but unquestionably there are many intense storms covering relatively small areas that fall between stations and are unrecorded. This fact constitutes one of the serious obstacles in the path of those who attempt to determine the relationship between precipitation and runoff. Consequently a great many additional precipitation stations, judiciously located, are needed.

Furthermore, of the above total number of precipitation stations now being maintained by the Weather Bureau, only about 2100 have recording rain gages. For many hydrologic studies, continuous records showing the varying intensities of rainfall are essential. The number of recording stations should therefore be increased as rapidly as possible.

Topographic maps and also soil and geologic maps provide a most valuable aid in the study of problems relating to stream flow and ground-water supply. From them may be obtained data on the character of the terrain, rock outcrops, area of basin, length of stream channel, stream density, and a vast amount of other valuable information. The U. S. Geological Survey is engaged in making a topographic map of the entire United States. At present that work is less than half completed. The map is published in sections, each section being about 16½ inches by 20 inches and usually covering either 15 minutes or 30 minutes of latitude and the same amount of longitude, although either larger or smaller scales are sometimes used depending upon the importance and character of the terrain covered. This work is carried on by the Survey in cooperation with the individual states. The progress in any state, therefore, depends upon the extent of the cooperation accorded. In about ten states, most of them in the eastern part of the country, the work is completed; in the remainder, varying degrees of progress have been made, and in many states the areas covered are so scattered that the available maps are of but little value in hydrologic studies.

Most of the data that have been collected on evaporation, transpiration, and ground water have resulted from investigations conducted by the U. S. Weather Bureau, the U. S. Geological Survey, the Bureau of Plant Industry, the Bureau of Soils, the Forest Service, the U. S. Corps of Engineers, and other government agencies. Valuable contributions have been made by various universities, scientific organizations, and private individuals. An enormous amount of further investigation and study is needed along these lines, however, before these data can be properly correlated and used in the solution of hydrologic problems.

The duty of collecting these basic data is primarily a governmental function. No private individual or organization can be expected to finance and carry on the long, laborious, and expensive observations and experiments that are required for their collection. Especially is this true inasmuch as these data are used for the benefit of the general public. In view of the vast current government expenditures, it is unfortunate that the federal departments in charge of the important function of collecting these basic data continually find themselves seriously handicapped through lack of funds so that their work is either curtailed or completely stopped, thus greatly reducing the final value of the results.

Opportunities for Research

Here is a field in which the opportunities for research are almost unlimited. There are so many factors that affect stream flow, precipitation, and their interrelationship that to prepare a complete list of all the subjects that are in need of investigation would be a long and difficult task. However, the vast extent of the work that remains to be done in this field should deter no one from engaging in it. Although the main problem taken in its entirety is much too large for any one person to solve single handed, it naturally divides itself into a large number of smaller fields, any one of which provides abundant opportunity for research. Just as tiny raindrops slowly wear away the rock, so also will small contributions toward our general store of knowledge on these subsidiary questions eventually build up a chain of evidence that will solve the many current mysteries in the field of hydrology.

Hydrologic Failures

It is an unfortunate trait of human nature that all professions alike hesitate to advertise their failures. Notable successes are broadcast for all the world to hear, but failures are spoken of only in muffled tones. Professional pride and ethics are the principal reasons for this situation. It is nevertheless true that a full knowledge of the failures and their causes provides some of the most valuable information that can possibly serve to guide the engineer or other professional practitioner.

No attempt will be made here to present a list of the almost countless failures that have resulted from a faulty understanding of the principles of hydrology. The history of hydraulic structures is literally filled with examples of such failures. Beyond question a very large majority, perhaps over 90 per cent, of all failures of

hydraulic structures are directly due to hydrologic reasons rather than to structural weaknesses. This may be due in part to the fact that the principles of structural design have been more completely formulated and have been better understood, but it is also due in part to the fact that a greater safety factor is used in structural work than will ever be permissible in hydrologic computations. In the former, a factor of 3 or 4 is not uncommon, whereas in the latter case the requirements of economic design do not permit such high factors of safety.

Examples of hydrologic failures include the failure of dams resulting from inadequate spillway capacity, causing overtopping and erosion of embankments; the economic failure of water-power developments, storage reservoirs, and water-supply systems resulting from an overestimate of the available supply; the failure of a sewerage or drainage system to function as planned due to the occurrence of more intense storms than were anticipated; the failure of highway and railway bridges and culverts resulting from inadequate waterway openings; and so on for every type of hydraulic structure. At this point, it should, however, be explained that practically never should a structure be so designed that it could accommodate any possible flood to which it might be subjected. The only possible exception to this general rule is where a failure would result in great human suffering, loss of life, and tremendous property damage. In other cases, the problem is purely economic. The question is simply one of determining to what extent expenditures are justifiable from an economic viewpoint. In other words, it may oftentimes be true (paradoxical as it may seem) that the best-designed structure would have insufficient capacity for the very largest floods, whereas a poorly designed structure might have adequate capacity.

It is not uncommon to hear a learned judge, in rendering a decision in a case involving damages resulting from an unprecedented flood or other unusual natural phenomenon, refer to such occurrence as "an act of God." Such expressions are often misleading. It would be equally appropriate to refer in the same way to every rainfall or to every wind that blows. Every natural phenomenon springs from natural causes and occurs in exact obedience to definite natural laws. When those laws are once fully understood it will in all probability become possible to predict the occurrence of storms, floods, and all other natural phenomena far in advance and with nearly the same degree of certainty as that with which it is now possible to predict the exact hour of sunrise on any day of the year.

Hydrologic Data

Many types of hydrologic data are collected and published by agencies of the federal government. Other data are collected by such organizations as the Tennessee Valley Authority, the Miami Conservancy District, and agencies of state governments. It is frequently possible to obtain valuable information from the engineering staffs of municipalities or power companies, from consulting engineering firms, and sometimes from amateur observers. More detailed information than that which is published may often be obtained from the organization that made the observations.

A complete description of information available from federal agencies is given in "Principal Federal Sources of Hydrologic Data," *Tech. Paper* 10, Water Resources Committee of the National Resources Planning Board. Another useful general reference is "Inventory of Unpublished Hydrologic Data," *U. S. Geological Survey Water-Supply Paper* 837.

In the following list are given some of the more important sources of hydrologic data.

Precipitation

Climatological Data, U. S. Weather Bureau (hourly).

Hydrologic Bulletin, Daily and Hourly Precipitation, U. S. Weather Bureau and U. S. Corps of Engineers. (These bulletins may be found at regional offices located in Albany, N. Y.; Macon, Ga.; Chicago, Ill.; Cincinnati, Ohio; Kansas City, Mo.; Fort Worth, Tex.; Albuquerque, N. Mex.; Portland, Oreg.; and San Francisco, Calif.)

"Storm Rainfall of Eastern United States," *Tech. Reports*, Part V, Miami Conservancy District. (Intense storms.)

Storm Rainfall in the United States, U. S. Corps of Engineers. (Intense storms.)

"Rainfall Frequency-Intensity Data," *U. S. Department of Agriculture Misc. Pub.* 204.

Other sources of information on precipitation are the Tennessee Valley Authority, the U. S. Soil Conservation Service, and the U. S. Forest Service.

Stream Flow

U. S. Geological Survey Water-Supply Papers.

Stream-flow data are also obtained by the U. S. Corps of Engineers, the

Tennessee Valley Authority, the U. S. Forest Service, and the U. S. Soil Conservation Service.

Evaporation from Water Surfaces; Temperature; Wind Velocity; Humidity

Climatological Data, U. S. Weather Bureau.

Information may also be obtained from the U. S. Bureau of Reclamation, the U. S. Soil Conservation Service, the U. S. Forest Service, and the Tennessee Valley Authority.

Ground Water

U. S. Geological Survey Water-Supply Papers.

Ground-water records are also obtained by many state agencies, the U. S. Corps of Engineers, the Tennessee Valley Authority, the U. S. Soil Conservation Service, and the U. S. Forest Service.