

DEFICIENCIES IN HYDROLOGIC RESEARCH

UNITED STATES.

NATIONAL RESOURCES PLANNING BOARD

1940.

---

**DEFICIENCIES IN HYDROLOGIC  
RESEARCH**

**1940**



**NATIONAL RESOURCES PLANNING BOARD**

---

# DEFICIENCIES IN HYDROLOGIC RESEARCH

---

Report of the  
Special Advisory Committee on Hydrologic Data



*A National Resources Committee Publication*

*Issued by the*

NATIONAL RESOURCES PLANNING BOARD

UNITED STATES GOVERNMENT PRINTING OFFICE

WASHINGTON : 1940

---

For sale by the Superintendent of Documents, Washington, D. C. - - - - - Price 25¢ cents

EXECUTIVE OFFICE OF THE PRESIDENT  
NATIONAL RESOURCES PLANNING BOARD  
WASHINGTON, D. C.

March 2, 1940.

THE PRESIDENT,  
*The White House.*

MY DEAR MR. PRESIDENT:

A report on Deficiencies in Hydrologic Research, prepared under the direction of our Water Resources Committee, is submitted herewith for your consideration.

Although construction of works for water use and control is progressing on a wide front, understanding of the basic processes by which water circulates on the earth and in the atmosphere is far from complete. There are many very serious gaps in knowledge of that hydrologic cycle. The experience of the past ten years with unusually destructive droughts and floods has dramatized our lack of data; for example, on the frequency and intensity of low and excessive stream flow and on the effects of vegetal cover upon run-off. These gaps should be closed as speedily as practicable if adequate plans for drainage-basin development are to be prepared.

The attached document calls attention to the major deficiencies in current research work and suggests desirable lines of study by all interested groups—Federal and non-Federal. Prepared as a stimulus of improved research, it helps to lay a firm basis for practical and effective water planning in the future.

Respectfully submitted.

FREDERIC A. DELANO, *Chairman,*  
CHARLES E. MERRIAM,  
GEORGE F. YANTIS.

## NATIONAL RESOURCES PLANNING BOARD

FREDERIC A. DELANO

CHARLES E. MERRIAM

GEORGE F. YANTIS

*SUCCESSOR TO THE:*

---

---

### NATIONAL RESOURCES COMMITTEE

HAROLD L. ICKES, *Chairman*  
*Secretary of the Interior*

FREDERIC A. DELANO  
*Vice Chairman*

HARRY H. WOODRING  
*Secretary of War*

HENRY A. WALLACE  
*Secretary of Agriculture*

HARRY L. HOPKINS <sup>1</sup>  
*Secretary of Commerce*

Col. F. C. HARRINGTON <sup>2</sup>  
*Works Progress Administrator*

FRANCES PERKINS  
*Secretary of Labor*

CHARLES E. MERRIAM

---

<sup>1</sup>Succeeded Daniel C. Roper, who resigned Dec. 23, 1933.

<sup>2</sup>Succeeded Mr. Hopkins upon his appointment as Secretary of Commerce.

---

### ADVISORY COMMITTEE

FREDERIC A. DELANO, *Chairman*

HENRY S. DENNISON

CHARLES E. MERRIAM

BEARDSLEY RUMEL

---

### STAFF

CHARLES W. ELIOT <sup>2d</sup>  
*Director*

HAROLD MERRILL  
*Executive Officer*

---

### WATER RESOURCES COMMITTEE

ABEL WOLMAN, *Chairman*

HARLAN H. BARROWS  
MILTON S. EISENHOWER  
THORNDIKE SAVILLE  
ROGER B. McWHORTER  
C. G. PAULSEN <sup>1</sup>

EDWARD HYATT  
JOHN C. PAGE  
T. B. PARKER  
R. E. TARBETT

JULIAN L. SCHLEY  
Represented by:  
WILLIAM A. SNOW  
JULIUS T. WENZEL

GILBERT F. WHITE, *Secretary*

---

### ADVISORY COMMITTEE ON HYDROLOGIC DATA

THORNDIKE SAVILLE, *Chairman*

DONALD M. BAKER  
H. K. BARROWS  
MERRILL BERNARD

A. B. JONES <sup>2</sup>  
N. C. GROVER <sup>1</sup>  
W. W. HORNER  
ROYCE J. TIPTON

L. A. JONES  
JOSEPH JACOBS  
C. E. RAMSER

---

<sup>1</sup> Mr. C. G. Paulsen succeeded Mr. N. C. Grover who retired from Government service on February 1, 1939.

<sup>2</sup> Maj. A. B. Jones succeeded Maj. W. D. Luplow, who participated in much of the preparation of this report.

NATIONAL RESOURCES COMMITTEE  
NORTH INTERIOR BUILDING  
WASHINGTON

*June 29, 1939.*

MR. FREDERIC A. DELANO,  
*Chairman, Advisory Committee,  
National Resources Committee,  
Washington, D. C.*

DEAR MR. DELANO: A report on Deficiencies in Hydrologic Research, prepared by the Special Advisory Committee on Hydrologic Data, is transmitted herewith.

The preparation of this report entailed a careful study of the research programs currently under way by various agencies. It involved also a study of the existing situation as to needs for information in considerable part growing out of the experience of the various committee members and others interested in water problems. It is intended that the report will serve as a guide for the use of research workers engaged in hydrologic or related investigations and in that way encourage further exploration in this field.

A previous report on Deficiencies in Basic Hydrologic Data presented a comprehensive outline, from a national viewpoint, for the adequate collection and publication of fundamental data relating to precipitation, stream flow, evaporation, ground water and other elements of the hydrologic cycle.

These basic data are the foundations upon which must be based the design and operation of all work for the conservation and utilization of water resources. But these data are valueless without adequate techniques with which to interpret and apply them to specific problems. Research alone provides the techniques which are essential to the solution of flood control, irrigation, drought, soil erosion, and other problems encountered in the development of a water policy which is both hydrologically and economically sound. Because the need for scientific approach to the interpretation of hydrologic phenomena and related factors is so important to the economic life of the country, the Water Resources Committee feels that the suggestions contained in this report are of paramount importance.

Present information on the significance and interrelation of different phases of the hydrologic cycle contains much that is in need of further verification and there is a serious lack of understanding of the significance of many phenomena. Improvement of this situation can best be effectuated by a competently organized and thoroughly coordinated long-range research program given continuity by adequate appropriations. Such an appropriation policy, with provisions for a reasonable and necessary expansion of the facilities, would very largely eliminate such duplication of effort as now occurs as a result of a fluctuating financial support and lack of continuity.

Such a program would involve expenditures insignificant in amount compared with the savings which would be effected in the cost of hydraulic structures which now have to be designed to provide for an adequate factor of safety based in part upon lack of knowledge of the effect of hydrologic and related phenomena.

Further advantages would accrue from the dissemination of information on current research activities, therefore the proposal for a central "clearing house" and coordinating agency should be immediately consummated.

The Water Resources Committee concurs in the recommendations of the Special Advisory Committee on Hydrologic Data.

Respectfully submitted,

The WATER RESOURCES COMMITTEE

ABEL WOLMAN, *Chairman*

*Chief Engineer, Maryland State Department of Health*

HARLAN H. BARROWS,  
*University of Chicago.*

MILTON S. EISENHOWER,  
*Land Use Coordinator,  
United States Department of Agriculture.*

EDWARD HYATT,  
*State Engineer of California.*

ROGER B. MCWHORTER,  
*Chief Engineer,  
Federal Power Commission.*

JOHN C. PAGE,  
*Commissioner,  
Bureau of Reclamation.*

T. B. PARKER,  
*Chief Engineer,  
Tennessee Valley Authority.*

C. G. PAULSEN,<sup>1</sup>  
*Acting Chief Hydraulic Engineer,  
United States Geological Survey.*

THORNDIKE SAVILLE,  
*Dean, College of Engineering,  
New York University.*

Maj. Gen. JULIAN L. SCHLEY,  
*Chief of Engineers,  
United States Corps of Engineers.*

(Represented by Col. W. A. SNOW.)

R. E. TARBETT,  
*Senior Sanitary Engineer,  
United States Public Health Service.*

JULIUS T. WENZEL

*In Charge Interdepartmental Coordination,  
Office of Land Use Coordination  
United States Department of Agriculture*

---

<sup>1</sup> Mr. C. G. Paulsen succeeded Mr. N. C. Grover, who retired from Government service on February 1, 1939.

NATIONAL RESOURCES COMMITTEE

NORTH INTERIOR BUILDING

WASHINGTON

*June 29, 1939.*

MR. ABEL WOLMAN,  
*Chairman, Water Resources Committee.*

DEAR MR. WOLMAN: The Special Advisory Committee on Hydrologic Data submits herewith a report on Deficiencies in Hydrologic Research.

The Committee, after a survey of the field of current hydrologic research, has prepared a brief description of investigations deemed essential to the clarification of existing information or in making available new information on many hydrologic phenomena. These proposals have been grouped by broad classification of phenomena and are designed to serve as guides in the attack on major problems in hydrology and hydrologic investigations.

Research in hydrology has advanced rapidly on a wide front during the past few years. On this account significant changes have occurred in certain lines of activity mentioned in this report during the time of its preparation and publication. No report of this character can be thoroughly up-to-date when it is issued, but the Committee feels that the items presented in Chapter III as individual research proposals are generally representative of the best contemporary thought on the several subjects. Intensive research on certain phenomena is responsible for a very rapid change of status of our knowledge of these phenomena and emphasizes the importance of a familiarity with current research on the part of anyone inaugurating hydrologic-research undertakings.

Chapter IV of the report is indicative of the manner in which the independent research items of the previous chapter may be integrated into a broad research program involving the many interrelated hydrologic phenomena. The areal unit upon which such a broad program is based is a small drainage basin.

The Committee realizes full well that research in this or any field of scientific investigation should not be hampered by numerous regulations and predetermined conclusions; rather the investigator should be encouraged to exercise initiative in his study. Certain advantages, however, are to be gained through the coordination of research activities, and the Committee has set forth recommendations to effectuate this as well as to encourage cooperative research by the many educational institutions throughout the Nation which have qualified personnel and adequate facilities. The research items of chapter III, however, constitute the essence of the Committee recommendations and are submitted without priorities as between items or sections.



In the work the Committee has had available as consultants the services of Robert E. Horton, consulting hydrologist, Voorheesville, N. Y., and Adolph F. Meyer, consulting engineer of St. Paul, Minn. The cooperation and assistance of W. D. Collins, Chief, Division of Quality of Water, Geological Survey; and A. G. Fiedler, Senior Engineer, Geological Survey, United States Department of the Interior; W. W. McLaughlin, Consulting Engineer, Soil Conservation Service; and D. B. Krimgold, Soil Conservationist, Soil Conservation Service, United States Department of Agriculture, were of great value in preparing many of the research items. The Committee is greatly indebted to the many persons who have reviewed the various research items and improved the report by their comments.

Respectfully submitted,

THORNDIKE SAVILLE, *Chairman, Special Advisory Committee on Hydrologic Data; Dean, College of Engineering, New York University*

DONALD M. BAKER,  
*Consulting Engineer,  
Los Angeles, Calif.*

H. K. BARROWS,  
*Consulting Engineer,  
Boston, Mass.*

MERRILL BERNARD,  
*Chief, River and Flood Division,  
United States Weather Bureau.*

N. C. GROVER,  
*Chief Hydraulic Engineer,  
Geological Survey.*

W. W. HORNER,  
*Consulting Engineer,  
Professor of Civil Engineering,  
Washington University.*

JOSEPH JACOBS,  
*Consulting Engineer,  
Seattle, Wash.*

A. B. JONES,  
*Corps of Engineers,  
United States Army.*

L. A. JONES,  
*Chief, Division of Drainage Investigations,  
Bureau of Agricultural Engineering.*

C. E. RAMSER,  
*Principal Soil Conservationist,  
Soil Conservation Service.*

ROYCE J. TIPTON,  
*Consulting Engineer,  
Denver, Colo.*

---

# DEFICIENCIES IN HYDROLOGIC RESEARCH

---

## CONTENTS

	Page
Introduction	1
I. Summary and Recommendations	3
II. General Research Principles and Procedures	5
General procedures	5
Review of literature	5
Statement of objectives	5
Sources of data	5
Observational and experimental work	7
Analysis of data	7
Presentation of results	7
III. Proposals for Projects in Hydrologic Research	9
Section I. Precipitation and Interception	9
Item 1. Rain gage location and exposure	9
Item 2. The improvement and refinement of snow measurement methods	11
Item 3. The dependability of individual station records as determined by the analysis of existing precipitation records	12
Item 4. The determination of the precipitation provinces of the United States	13
Item 5. The station year, or composite record method, of determining rainfall rate duration frequencies	13
Item 6. Variations in precipitation occasioned by altitude and changes in altitude	14
Item 7. The interrelation of rainfall intensity, duration, and areal distribution	15
Item 8. The sequence of occurrence of rainfall intensity rates	16
Item 9. Limiting storms and regions of like storm potentialities	16
Item 10. The effect of large bodies of water upon precipitation to leeward	17
Item 11. The interception of precipitation	19
Section II. Infiltration	19
Item 1. The nature and mechanics of infiltration	19
Item 2. Methods of measuring infiltration and infiltration capacity	20
Item 3. Effect of surface conditions and vegetal cover on infiltration	21
Item 4. Areal and basin infiltration	23
Section III. Evaporation, Transpiration, Consumptive Use	24
Item 1. Factors that influence evaporation	24
Item 2. The improvement of instruments and standardization of equipment and procedures for measuring evaporation	25
Item 3. The relationship of evaporation from pans to that from open water surfaces	27
Item 4. The relationship of meteorological conditions at various open water evaporation at the ground surface	27

	Page
III. Proposals for Projects in Hydrologic Research—Continued	
Section IV. Evaporation, Transpiration, Consumptive Use—Continued	
Item 5. Insolation as a measure of open water evaporation	27
Item 6. Evaporation from snow and ice	28
Item 7. Evapo-transpiration losses	29
Item 8. Consumptive use	30
Section IV. Ground Water and Percolation	31
Item 1. Water level recorders and artesian pressure recorders	31
Item 2. Differences in water levels between the inside and outside of cased wells	31
Item 3. The relation of ground water fluctuations to the texture of the water-bearing material	32
Item 4. Improvement of method for determining porosity, permeability, moisture equivalent, and specific yield of aquifers	33
Item 5. The effects of the physical characteristics of a material upon its porosity, permeability, and specific yield	34
Item 6. The compressibility and elasticity of water bearing materials	34
Item 7. The relationship of ground water to stream flow	35
Item 8. The use of geophysical methods in prospecting for ground water	36
Item 9. The motion of ground water toward localities of discharge	36
Section V. Run-off and Stream Flow	39
Item 1. Run-off from snow cover	39
Item 2. Stream flow under ice conditions	40
Item 3. Flow duration curves	40
Item 4. Interpolation of missing run-off data	41
Item 5. Extension of short time stream-flow records	41
Item 6. Estimation of run-off in the absence of stream-flow records	41
Item 7. Run-off estimates based on partial drainage areas	42
Item 8. Run-off records from small drainage areas	42
Item 9. The scour, deposition, and transportation of silt	43
Item 10. The development of methods for synthesizing stream-flow data	44
Item 11. Special methods of estimating stream flow	45
Item 12. The effect of the manner of precipitation occurrence upon run-off	46
Item 13. The response to precipitation of streams fed by ground water	47
Item 14. Frequency of rates of run-off	47
Item 15. Probable run-off during critical periods	47
Item 16. Mean or average run-off periods	48
Section VI. Quality of Waters	49
Item 1. The factors determining ground-water composition	49
Item 2. The sources of soluble salts in surface waters	49
Item 3. The relation of land use to the composition of surface waters	50
Item 4. The intrusion of salt water in tidal streams	50
Item 5. The contamination of ground water	51
IV. Drainage Basin Studies	53
Appendix A. The Coordination of Hydrologic Research	59
Appendix B. Statistical Methods in Hydrology	61
Appendix C. Comprehensive Research on Run-off and Stream Flow	63
Appendix D. Standard Forms for Reporting Basic Hydrologic Data	75
Appendix E. Bibliography	89
Index	93

---

## INTRODUCTION

---

During the course of preparation of the report *Deficiencies in Basic Hydrologic Data*<sup>1</sup> and following its publication, the existence of major deficiencies in hydrologic research became increasingly evident to the Special Advisory Committee on Hydrologic Data. The importance of an improved and coordinated program of research in hydrology as one of the basic needs in water planning was brought to the attention of the Water Resources Committee. The Special Advisory Committee on Hydrologic Data was subsequently authorized to prepare a report having as its objective the formulation of procedures for correcting some of the deficiencies in hydrologic research.

The Committee proceeded to canvass briefly hydrologic research activities throughout the Nation. From these data and from personal knowledge of the Committee and special consultants, specific research projects were drafted and submitted individually by members

of the Committee for consideration by the Committee as a whole.

The resulting revisions were sent to more than fifty selected reviewers in all parts of the Nation, for comments, suggestions, and criticisms of content, and to two outstanding hydrologists for critical analyses as to content and completeness of program.

The proposals presented in chapter III thus represent the coordinated thought of competent authorities located in all sections of the country with respect to deficiencies in present-day hydrologic research.

Mr. Robert E. Horton, of Voorheesville, N. Y., and Mr. Adolph F. Meyer, of Minneapolis, Minn., served as special advisors; Ivan Bloch served as secretary to the Committee during the preparation of much of the report; and O. J. Baldwin acted as secretary to the Committee in the completion of its work. The complete revision of the original research proposals in the interest of uniformity of style and smoothness of presentation has been a major contribution by Mr. Baldwin to the work of the Committee.

<sup>1</sup> National Resources Committee, September 1936, United States Government Printing Office, Washington, D. C., 30 cents.

---

## I. SUMMARY AND RECOMMENDATIONS

---

The deficiencies in hydrologic research are closely related to the corresponding deficiencies in hydrologic data as set forth in a previous report.<sup>1</sup> The improvement of the collection of basic data and the promotion of systematic research have common objectives: A better foundation of scientific knowledge for the many projects throughout the Nation which are to be erected for the utilization and control of water, as well as for the efficient and economical operation of those projects already constructed. The major defects of present-day research in hydrology as developed by this study may be grouped into—

- (1) the lack of a comprehensive understanding of the problem under consideration;
- (2) lack of adequate hydrologic and related data to permit a comprehensive investigation or the derivation of accurate conclusions;
- (3) lack of scientific knowledge of many characteristics of water behavior and the interrelationship of land and water phenomena;
- (4) lack of coordination of the efforts of investigators, with the resultant duplication of effort and lack of correlation of results.

Such defects are by no means confined to hydrologic research but are inherent in most research, which, by its very nature, must be more or less spontaneous. The nature of research work makes it a matter of individual attainment; restricted funds may make the examination of certain phases of the problem financially impossible; inadequate training may restrict the outlook of the investigator, limiting to a narrow field the application of the principles developed; and research publication policies may be such that the publication of basic data is restricted and the utility of the work thus greatly impaired.

It is obvious that research should be subjected to a minimum of regimentation. Nevertheless, a statement of some of the major problems in hydrology requiring further study is desirable as a guide for investigators in directing their attack to problems of major rather than minor importance. Evidence of the need of further research on major problems is found in the proposals presented in chapter III of this report. This list is not exhaustive but represents many subjects that are in urgent need of further study either to fill a

gap in present-day knowledge or to clarify existing information. In all projects, practical utility should be the major test with respect to the inauguration and prosecution of research.

Much of the current research in hydrology is conducted by agencies whose primary functions are not of a research character, and whose funds might be more advantageously spent through cooperation with agencies having a primary interest in hydrologic research. Cooperative research with the many educational institutions, particularly engineering schools, having adequate staff and facilities should be developed and encouraged.

In considering the reviews of research projects, the Committee was impressed with the number of comments from engineers and other scientists which adverted to the need for an agency to act in a coordinating and "clearing house" capacity for hydrologic research. The importance of having a central agency of this character, not itself engaged in research work, is stressed by the Committee.

### Recommendations

The Special Advisory Committee on Hydrologic Data is of the opinion that the initiation of a coordinated hydrologic research program is of importance and should receive the consideration of those agencies engaged in or concerned with hydrologic research. The value of an expansion of present programs, or the re-orienting of those under consideration, would be much enhanced by project developments paralleling those proposed in chapter III and in harmony with the suggestions which follow:

(a) The definite research proposals presented in chapter III are without priority in arrangement. The very nature of research and the conditions under which it is pursued make the question of relative importance very largely a matter of personal choice or of specific local needs. It will be recognized, however, that a natural sequence of items occurs within types of problems, and recognition should be given this natural order in setting up a research program.

(b) Full advantage should be taken of the exceptional opportunities, in personnel and facilities, offered by many of the educational institutions of the Nation, particularly engineering colleges, for prosecuting hydrologic research on a cooperative basis. Such cooperation

<sup>1</sup> *Deficiencies in Basic Hydrologic Data.*—National Resources Committee, September 1936, United States Government Printing Office, Washington, D. C., 30 cents

frequently will necessitate only the furnishing of equipment by the cooperating Federal, State, or other agency.

(c) A coordinating and clearing house service should be established with the functions (1) of issuing, at stated intervals, bulletins on hydrologic research either contemplated or under way; and (2) of maintaining an

*National Resources Planning Board*

active contact with and a source of information for all organizations contemplating or engaged in hydrologic research.

(d) The Committee urges that any agency undertaking any of the hydrologic research projects outlined in chapter III avail itself of the "clearing house" and coordinating sources described in appendix A.

---

## II. GENERAL RESEARCH PRINCIPLES AND PROCEDURES

---

### General Procedure

The general method of attack on research problems, whether in the field of hydrology or otherwise, should follow a logical and orderly pattern. Experience has indicated such a sequence of the steps to be:

- (1) a careful review of pertinent literature on the specific subject and on important associated subjects;
- (2) the preparation of a concise statement of the objectives of the proposed work, together with an outline of its organization and the investigative procedure to be followed;
- (3) the organization and execution of the necessary experimental and observational work on the phenomena being studied;
- (4) the analysis of collected data, both separately and in conjunction with the work of other investigations in the same or associated fields;
- (5) a presentation and interpretation of the results of the analysis, as studied individually and as it may support or refute the conclusions of previous research.

### Review of Literature

The importance of a careful review of selected literature in the field of the proposed investigation and in closely related fields can hardly be overstated. Its objectives should be those of determining the scope of the work already performed, the adequacy and reliability of the experimental and observational methods used, the range of experimental values covered, and the significance of other factors which may influence the essential character of the work.

Experience indicates that the observance of a reverse chronological order is a most satisfactory method of approach in the review of literature, as it results in a certain natural selection of material; but the value of an occasional almost unknown article, often in an obscure publication, should not be overlooked. The review should be extended to include all available material, particularly that in foreign publications. A systematic analysis of all articles, in keeping with the objectives previously stated, together with details of procedure, methodology, etc., should be made and studied prior to the initiation of experimental or observational work. As a part of this analysis, all formulae should be converted to a uniform

basis of notation for purposes of comparing coefficients, variables, etc.

### Statement of Objectives

Upon completion of the review of literature, a concise statement of the objectives of the proposed research should be prepared. As a part of this statement, there should be included an outline of the organization of the experimental and observational work and a documentation of the procedure to be followed insofar as such documentation is possible.

At this stage in the development of the research project, discussion with representatives of Federal and other agencies working in this and related fields will be found most helpful in devising the required forms, determining procedure, and reviewing the proposal for completeness. Many agencies engaged in or connected with research in the various phases of hydrological problems are listed in the following section.

### Sources of Data

A considerable proportion of the hydrologic data collected in this country has been secured through the instrumentalities of Federal agencies. Foremost in the early work of this nature were the Weather Bureau of the United States Department of Agriculture and the Geological Survey of the United States Department of the Interior. More recently, the Soil Conservation Service has conducted much large-scale hydrologic research as have also the Forest Service and the Bureau of Agricultural Engineering. The resources and records of each should be explored. The "308"<sup>1</sup> and review reports of the Corps of Engineers include, in many instances, elaborate hydrologic studies on rainfall and streamflow which do not appear in the published reports. This material may be consulted in the offices of the District Engineers of the War Department.

Other Federal agencies whose work is in fields closely

<sup>1</sup> "Reports authorized under provisions of House Document 308 (68th Cong., 1st sess.), which was enacted into law, with modifications, in section 1 of the River and Harbor Act of January 21, 1927, and under the provisions of section 10 of the Flood Control Act of May 15, 1928. Supplemental reports of similar nature were authorized by section 6, River and Harbor Act, of August 30, 1935 (P. L. 407, 74th Cong.) and by section 7, Flood Control Act of June 22, 1936 (P. L. 738, 74th Cong.). These reports deal with the formulation of plans for navigation, flood control, power, and irrigation on the major streams of the country. The status of all "308" reports is given in the Annual Report of the Chief of Engineers under title "Survey for Navigation, Flood Control, Power, and Irrigation."

associated with hydrology have, on many occasions, engaged in studies not only of certain phases of hydrologic phenomena but also of the factors influencing those phenomena. Likewise, valuable contributions have been made by other than Federal agencies, as for example, Technical Report No. 5—*Storm Rainfall of Eastern United States*—of the Miami Conservancy District, and the numerous public and private agencies and individuals whose reports and publications are included in the bibliographical references referred to in appendix E.

The agencies grouped in the following lists are those that have been active in hydrologic investigations. Not all agencies shown, particularly those agencies of non-Federal character, have been engaged in hydrologic work in all parts of the country. The chief value of the list is to indicate the principal sources which should be explored before engaging upon a hydrological research project.

*Department of Agriculture*

Bureau of Agricultural Engineering.  
Bureau of Biological Survey.  
Bureau of Plant Industry.  
Forest Service.  
Soil Conservation Service.  
Weather Bureau.

*Department of Commerce*

Bureau of the Census.  
Bureau of Fisheries.  
Bureau of Standards—National Hydraulic Laboratory.  
United States Coast and Geodetic Survey.

*Department of the Interior*

Bureau of Mines.  
Bureau of Reclamation.  
Division of Grazing.  
General Land Office.  
National Park Service.  
Office of Indian Affairs.  
Geological Survey—Water Resources Branch including District Offices.  
Geological Survey—Conservation Branch.

*State Department*

International Boundary Commission—United States and Mexico.  
International Joint Commission.

*Treasury Department*

Public Health Service

*War Department*

Corps of Engineers, United States Army.  
District Engineer offices.  
Mississippi River Commission.  
Great Lakes Survey.  
Board of Engineers for Rivers and Harbors.  
Beach Erosion Board.

*Independent Agencies*

Civilian Conservation Corps.  
Farm Credit Administration.  
Federal Power Commission.  
Panama Canal.  
Federal Emergency Administration of Public Works.  
Tennessee Valley Authority.  
Works Progress Administration.

*State*

State Engineers  
Boards of Public Works.  
Conservation Departments.  
Health Departments.  
Utility Commissions.  
Drainage Districts.  
Irrigation Districts.  
Forestry Departments.  
Water Resources Boards and Commissions.  
Planning Boards, Commissions, etc.

*Municipal*

Water Boards.  
Sewerage Boards.  
Power and Light Commissions.  
Park Commissions.  
Public Works Commissions.

*Miscellaneous*

Educational Institutions (particularly those interested in engineering and the sciences).  
Agricultural Experiment Stations.  
Flood Control and River Regulating Agencies.  
Conservancy Districts (such as the Miami and the Muskingum).  
Conservation organizations.  
Public Utilities—including Water Companies.  
Engineering Societies.

A number of these agencies are conducting intensive hydrologic investigations in various sections of the country, both on specific subjects and on general problems. The rate of data collection, in many instances, has exceeded that of analysis and publication; many records are not available in printed form but may be consulted upon request. A few of the areas of intensive study and the agency responsible for local investigations are listed herewith. The location of other areas may be obtained from the responsible agency.

A. Forest Service, United States Department of Agriculture.

- (a) San Dimas Experimental Forest, Glendora, Calif.
- (b) Wasatch Experimental Forest, Farmington, Utah.
- (c) Coweetah Experimental Forest, Franklin, N. C.

B. Soil Conservation Service, United States Department of Agriculture.

- (a) North Appalachian Experimental Watershed, Coshocton, Ohio.



- (b) Black Lands Experimental Watershed, Waco, Tex.
- (c) Oklahoma Climatic Research Center, Guthrie, Okla. (Not in operation at this date, records in Washington office.)
- (d) Muskingum Climatic Research Center, New Philadelphia, Ohio.

C. Tennessee Valley Authority.

D. Weather Bureau—Geological Survey—Commonwealth of Pennsylvania. (Joint investigation of large watershed.)

E. Municipalities of St. Louis, Mo., and New Orleans, La. (Intensive urban studies.)

F. Miami Conservancy District, Dayton, Ohio.

G. Muskingum Conservancy District, New Philadelphia, Ohio.

Published data will often provide the major source of information on hydrologic phenomena. There is a great wealth of this material, and it appears in a multiplicity of languages. An exhaustive list of articles, pamphlets, bulletins, and other publications on the subject is beyond the scope of this study. Nevertheless, a starting point from which to initiate a review of technical literature is desirable, and the Committee has accordingly included in appendix E a number of references to recognized standard texts on hydrology and associated subjects, together with an extensive list of technical and scientific societies whose publications form the medium through which much hydrological data become available. References to particular articles and publications have been omitted, and in lieu thereof, the Committee has included numerous references to recently published bibliographies of selected papers on specific subjects related to hydrology.

#### Observational and Experimental Work

The recording of experimental data or the assembling of data from published sources should be carried out on carefully devised forms of a standard nature and of such clarity that the significance of the recorded data is readily apparent.<sup>2</sup> A point frequently overlooked in preparing recording forms for data to be subjected to analysis is that of the subsequent analytical procedure to be applied. The recording form should be carefully designed and tested for conformity to the analytical methods to be used. Extreme care should be exercised in recording the data; errors in recording should be clearly and carefully corrected by lining out the erroneous item and inserting the corrected figure. The

date and the initials of the person making the correction should be a part of all corrections on original data sheets and in computations.

The need for careful and accurate observation of experimental work is patent. Not only must all data having a direct application to the problem be recorded, but all associated phenomena, regardless of apparent insignificance, should be listed to permit a broader use of the observations. Not infrequently, additional instrumentation, available at small expense, will make possible the use of the data in associated work not contemplated in the original project.

#### Analysis of Data

The analysis of the collected data is largely an individual process and dependent upon the nature of the problem under investigation. Statistical methods are valuable adjuncts to many hydrological research problems. They may be used to evaluate the reliability of results, or as intrinsic procedures to establish conclusions. It is important that these methods should be used only by one thoroughly familiar with their scope and their applicability to the particular type of problem under investigation. (See appendix B.)

#### Presentation of Results

The presentation of the results, like the analysis of the experimental data, is a highly individualized problem. As a general guide to the contents of the presentation, there should be included a recapitulation of the methods used, a detailed description of the instrumentation, and an explanation of any special techniques used in the observations and in the analysis of the data.

Where feasible, graphical methods of presentation should be used showing results both from the current studies and in comparison with other work.

The help and cooperation of agencies such as the Weather Bureau, Soil Conservation Service, and the Geological Survey should be solicited in the foregoing steps. Their counsel and assistance will aid materially in the preparation and presentation of research projects. In many instances, also, extensive unpublished data may be revealed and serve to decrease both the necessary instrumentation and work. The function of a central "clearing house" would be most helpful in establishing contacts between those proposing research, those engaged in similar research activities, and those who may be of assistance in the prosecution of new research.

<sup>2</sup> The Special Advisory Committee on Hydrologic Data has prepared forms for recording certain basic hydrologic data. These are included in appendix D and are accompanied by detailed instructions covering their use.

---

### III. PROPOSALS FOR PROJECTS IN HYDROLOGIC RESEARCH

---

Hydrologic phenomena are influenced by many inter-related factors that make difficult the sharp definition of boundaries between the different fields of investigation. Broad general classifications are possible if the stages through which water must pass in traversing the hydrologic cycle are used as a basis for the grouping.

These stages are not sharply definable as to order of occurrence, with some, in fact, overlapping all others. They may be broadly grouped in accordance with those portions of the hydrologic cycle relating to (a) precipitation and associated phenomena; (b) infiltration, as the phenomena of the entrance of a portion of the precipitation into the soil profile; (c) surface and sub-surface runoff as sources of stream flow; (d) the movement of water within the lithosphere; and (e) the return of water to the atmosphere from each of the preceding stages through evaporation and transpiration. A sixth classification includes research relating to the soluble and suspended mineral load acquired by water in its passage over and through the earth's crust.

The research proposals which have been prepared have been grouped accordingly. However, each has been made as nearly as possible an independent item

through defining the scope of the research by a statement of the specific objectives. This seems desirable as a means of securing a greater interest in hydrologic research even though independent investigation of the separate items obviously leads to duplication in the observation of certain supplemental data. In chapter IV a comprehensive investigation of hydrologic phenomena, using a small drainage basin as the areal unit, has been described to show the manner in which the various items may be integrated into a board research program.

The objectives of the independent research items have been discussed in the light of the most recent thought and developments. Those investigators familiar with the field of hydrologic research are aware of the rapidity with which developments are occurring in certain phases as a result of intensive investigation. For this reason some of the research items proposed may be quickly invalidated by new data and concepts. In these fields an intimate knowledge of current research activities is of great importance if duplication of research is to be avoided.

#### I. Precipitation and Interception

##### Item No. 1. Rain Gage Accuracy, Location and Exposure

*Objectives.*—1. The determination of the accuracy of the rainfall catch as influenced by factors such as size of gage, location, exposure, frequency of reading, etc.

2. The determination of the reliability of a single rainfall catch as a measure of the rainfall received upon an adjacent area or region.

*Discussion.*—The occurrence of rather wide variations in the amount of rainfall as recorded by similar gages in the same locality is well known and has been studied at various times. There is need, however, for further work in determining and evaluating the factors causing such variations. The first stage of such an investigation is that of comparing the catch of the standard Weather Bureau 8-inch gage with that obtained by gages of other diameters and with that of the various types of recording gages, including a range of diameters for each type. Consistent differences between established type and diameters should be presented as

conversion factors or rating curves in order that all catches may be adjusted to a standard base. Obviously the investigations should be conducted under conditions as free from the influence of other factors as are possible to obtain.

A second study should be devised to establish the relationship between the catch of the standard gage and that of storage gages read daily, weekly, monthly, or less frequently. A phase of this study might include investigating the effectiveness of a film of oil or other device for reducing evaporation from storage gages read at infrequent intervals.

The evaluation of the efficacy of the 8-inch circle as a collecting medium, according to accepted theories of sampling, is worthy of further investigation. The significance of the variation in depths recorded by closely grouped gages under different intensities of rainfall as well as the relationship of the local variation to that of more widely separated gages should be determined. Each of the preceding investigations relate to some phase

of rain gage accuracy and if possible should be carried on simultaneously using the same gages.

The selection of a site for the experiment is the most important initial step, as conditions of exposure and location offer complexities not found in other problems. The catch of a rain gage has been assumed to represent with comparative accuracy, in flat open country, the rainfall received over an adjacent area or region. Even this remains to be completely demonstrated. In addition the segregation and the evaluation of the effects of ground obstacles, elevation, slope, aspect, topographic position and other location factors must be analyzed and weighted if a representative sample of rainfall over an area is to be obtained by a single gage catch or group of catches.

The problems of exposure of the rain gage are of two classes dealing (a) with the effect of both horizontal and vertical clearance with reference to nearby objects, (b) with the effect of the vertical distance of the gage from the ground surface.

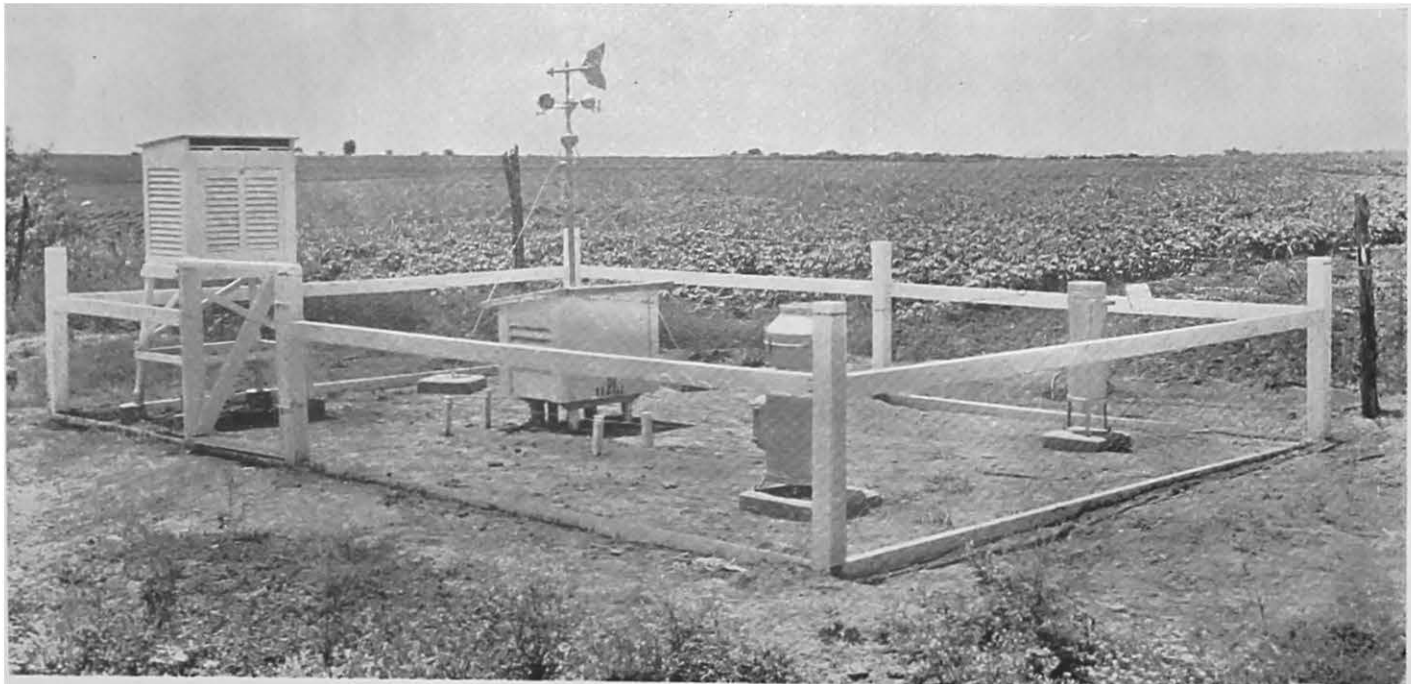
Within group (a) are found those problems involving minimum clearances, both horizontal and vertical, between the gage and fences, trees, buildings and other nearby objects. Certain phases of the problem, involving rainfall velocity, direction, density, and wind direction through short distances, might readily be given analytical study in the laboratory prior to field observations.

Group (b) embraces those problems of exposure en-

countered in most large cities where opportunities to establish observational points are largely limited to the tops of buildings. Under such conditions it is necessary to move gages frequently with the consequent impairment of the value of the record. Research on the subject is very meagre and further work should be of material value in adjusting and correcting records obtained under these conditions.

The proposed research on location should be designed to accumulate data from sufficient storms, over selected areas, to embrace a full range of areal factors, including regional studies of the prevailing direction and velocity of storm movements. Study areas should be equipped with a full complement of meteorological instruments.

The last investigation, dealing with the reliability of the rain gage as a sampling medium, concerns the adequacy of existing types of gages to record, in depth per unit horizontal area, the true rainfall depth received on a sloping ground surface. The rainfall catch is normally expressed as a depth over a horizontal (map) area and the reduction of rainfall to volume or stream flow is invariably on the basis of a map area. The error introduced by this method when applied to broken or mountainous country has not been accurately evaluated. Studies should be devised to determine the position of the plane of the gage circle, with respect to the ground, that will most accurately record the true depth of rainfall received.



U. S. SOIL CONSERVATION SERVICE

FIGURE 1.—A second order meteorological station in operation at the North Appalachian Experiment Station, Coshocton, Ohio. The instruments, left to right, are instrument shelter, soil thermograph anemometer and wind-direction instrument, weighing recording rain gage, and a standard 8-inch rain gage.

**Item No. 2. The Improvement and Refinement of Snow Measurement Methods**

*Objectives.*—1. The development of improved methods of snowfall measurement.

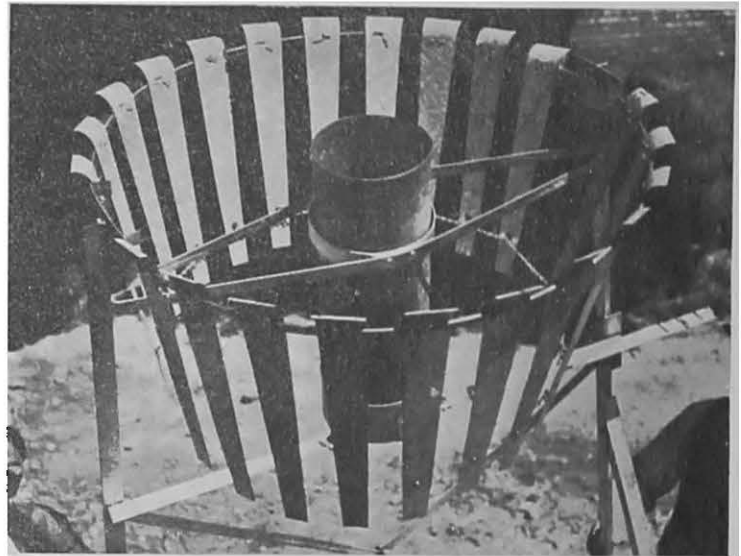
2. The development of improved methods of snow depth measurement.

*Discussion.*—Snow is a form of precipitation differing from rainfall in that it may remain on the ground and accumulate for a considerable period or for an entire season. Under favorable climatic conditions small losses may occur from runoff, infiltration, or evaporation during these periods. Under such conditions the snow undergoes changes which completely dissociate it from the meteorological factors which produced it. In other localities, snowfall is subject to intermittent melting throughout the winter and rarely accumulates in appreciable amounts.

Accurate measurement of the snowfall at the time of fall is necessary to maintain the continuity of daily precipitation records of the Weather Bureau. In the regions of extensive accumulation it is important also to determine accurately the water content of the accumulated snowfall on account of its effect upon runoff. It is the run-off from the accumulated snow in many regions of the West that largely determines the yield of the next seasons crops. Moreover, the run-off from the melting snow will, in varying degree, affect flood discharges as well as river regulation from the standpoint of power production, navigation, and low water flow.

The necessity to perpetuate the records of daily precipitation makes imperative the improvement of existing snow gages or the development of new ones. An acceptable snow gage must incorporate into its design the proper shielding of the gage to overcome the effects of wind gusts, vertical air currents, eddy currents, and the negative pressures set up by the flow of air past the lip of the gage. Studies made by the Weather Bureau have indicated the efficacy of brine as a melting agent and the effectiveness of an oil film to prevent evaporation and absorption in the storage type gage. These procedures should be further explored. Other features to be investigated further are the proper height of the gage above the ground, and the comparative effectiveness of various flexible shields. The consistency and accuracy with which the average of a battery of snow gages will reflect average water depth as compared with measurements on snow survey courses should be determined.

Another phase of snow measurement requiring further study is that of the comparative catch of snow gages of various types and diameters and a comparison of these results with those obtained in the use of snow boards, snow boxes, and other depth-measuring devices.



U. S. WEATHER BUREAU

FIGURE 2.—A flexible shield for the protection of the snow gage against air currents. Hinged at the top, the metal leaves swing inward under wind pressure, shielding the gage.

The determination of the snow mantle depth, in contrast to the snowfall depth, has been, of necessity, developed along different lines. Experience gained through the North and West in recent years has demonstrated the reliability of the snow course as a sampling medium. Properly located and weighted to represent all characteristics of the watershed, the use of the snow course is presumably in conformity with sound theories of sampling. There is, however, need for a concise statement of the basic assumptions involved in snow surveying as a sampling process and the theory upon which it is based.

Research on the refinement of snow depth determinations is roughly divisible into three phases: the selection of a representative course; the improvement of methods of sampling both physically and statistically; and the development of techniques utilizing aerial and panoramic photography as adjuncts to the actual sampling.

The factors of location influencing the accuracy of the snow course as a sampling medium have not been adequately evaluated. Observations on the effect of reorienting snow course tangents, together with a study of the optimum number of observations required to reflect accurately the range of conditions encountered in snow producing regions appear to be the major improvement needed in snow course selection. Included in this phase of research is the continuation of studies on the quantitative effects of vegetal cover, elevation, slope aspect, etc., upon the snow course record.

Improvements in the physical sampling of the snow mantle are primarily those of standardization of methods for arriving at the average snow depth, water content, and snow density, and the coordinating of snow survey measurements to a common date. The refinement of statistical methods in correlating snow course

observations, over wide areas, to determine accurately the average depth of the snow mantle within a watershed represents a major need. The natural limitations on such refinements can be approached in studies on the consistency with which snow courses in the same or adjacent area, and observed under as nearly identical conditions as possible, will produce comparable results for the average water content of the snow mantle.

The third phase of research in snow depth measurements concerns the development of technique in photographic observations. The use of panoramic photography as a means of comparing seasonal melting with established normals<sup>1</sup> should be thoroughly investigated, as should also the use of aerial photography as an aid to snow surveying. If satisfactory methods of analysis can be developed, the use of photography for supplementing ground observations would provide a means of greatly increasing the extensiveness of snow surveys, particularly in defining the lower limits of the snow mantle.

**Item No. 3. The Dependability of Individual Station Records as Determined by the Analysis of Existing Precipitation Records**

*Objectives.*—1. The evaluation of the dependability of station records or portions of records as evidenced by their departure from a common trend.

2. The reasons for lack of dependability as they may be disclosed by an examination of the station history.

<sup>1</sup> The term "mean" or "average" rather than "normal" is preferred by the committee. The latter term is used at times in this report to conform to practice long established by certain federal agencies.

3. The evaluation of the relative accuracy of different methods of interpolating missing precipitation records.

4. The determination of satisfactory gage settings or exposures as revealed by field examinations.

*Discussion.*—It is generally recognized that the exposures of many standard cooperative precipitation stations have varied considerably during the existence of the station. The records of some of the cooperative observers vary materially in accuracy, and in many instances have required the interpolation of missing or obviously erroneous data. First-order stations have also been subjected to changes in gage exposure during the period of record, and there is reasonable doubt as to whether the recorded catch is representative of the precipitation experienced at the station.

Research involving the examination and evaluation of records of, and the examination of instruments and exposure at, Weather Bureau stations was suggested in a previous report on Deficiencies in Basic Hydrologic Data, published in September 1936 (p. 65, sec. E, 1 (b) and 1 (c)). Inasmuch as the republication of precipitation records has been recommended by the Special Advisory Committee on Hydrologic Data, the evaluation and adjustment of existing records should be consummated prior to any new general publication.

The initiation of this project would first require the segregation of the complete precipitation records for a group of stations to be analyzed. This might be organized geographically in accordance with the areas covered by each section office of the United States Weather Bureau. Thus there would be available a complete set of station records including a history showing the



U. S. WEATHER BUREAU

FIGURE 3.—Experimental shielded snow gages being investigated at Terminal, Utah. These consist of the standard 8-inch rain gage protected against air currents by movable and fixed shields of various designs. The studies include comparisons of the effect of varying the flexible shield shown in figure 2 both as to size and spacing.

changes in gage location and exposure, the changes in observers, and the inspections made of the particular station with comments on the exposure and other conditions existing at the time of inspection.

The original records should be consulted in order to develop a complete history of the values interpolated and the methods used. At the same time, records of gages in the area obtained by other agencies should be secured wherever possible.

Studies of accuracy and consistency of rainfall records should invariably be made separately for winter and summer conditions in northern regions where a large amount of winter precipitation occurs as snow.

There are various lines of approach to this subject. One consists in plotting rainfall relation curves between adjacent stations. When cumulative rainfall depths at one station are plotted against those of another, the slope and abrupt changes in direction of the plot, together with the station history, may be helpful in identifying a cause of error in the records at one or both of the stations. It is to be borne in mind that the difference in rainfall amount at two adjacent stations, either in individual storms or as regards the average rainfall, may result either from differences in rainfall duration alone, difference in rainfall intensity alone, or from a combination of the two.

The coefficient of variation of rainfall as well as progressive means may be determined season by season, and a trend line plotted therefrom. An abrupt increase or decrease in the coefficient of variation, which, being a ratio, is independent of the value of the mean may afford some evidence of a systematic error in the record. Another check closely related to the coefficient of variation is the range ratio. This is the ratio of the difference between the maximum annual and the minimum annual rainfall to the mean annual rainfall. Analysis of many long rainfall records shows that, in a region having a given rainfall regime, the range ratio is remarkably constant. If a given record shows an abnormally high or abnormally low range ratio, it should be examined critically for possible discrepancies or systematic errors.

#### **Item No. 4. The Determination of the Precipitation Provinces of the United States**

*Objective.*—1. The delineation of regional boundaries within which precipitation is approximately equal or similar in amount, seasonal distribution, rate and duration, probability of occurrence, and normals and departures; and the preparation of maps showing the boundaries of provinces embracing those precipitation characteristics which fall within the same regional limits.

*Discussion.*—The phenomenon of precipitation in the United States is known to be transitional. Lines of equal rainfall generally take decreasing values progressively inland from the principal moisture sources of the Gulf of Mexico, and the South Atlantic, but increase inward on the westward slopes of the maritime regions of the Pacific. Evidence of a stability in the regimen of country-wide precipitation can be cited in the form of maps of annual rainfall, the isopluvial charts of the Miami Conservancy District, the rainfall depth charts by Yarnell and others, and the maps of climatic regions by Thornthwaite.

The size or extent of a precipitation province has so far not been determined, although it is realized that wide variations are to be expected. In the Miami Conservancy District studies the assumption was made that the area embraced by the odd-numbered degrees of latitude and longitude were small enough to insure equal rainfall characteristics and thereby justify the combination of the rainfall records within the quadrangle. The sections and divisions into which the Weather Bureau stations are grouped in some cases constitute another system of subdivision which takes into account similarities obvious in the rainfall record as now published.

It is not to be expected that boundaries of precipitation provinces can be fixed with such exactness as to embrace all phases of the precipitation phenomenon outlined herein as objectives for research. Annual rainfall varies markedly within comparatively short distances. Regions having different annual rainfall may experience the same intensity-duration relationships. Orographic influences can be expected to vary both the size and shape of precipitation zones throughout the country. It is probable, however, that provinces may be defined within reasonable limits wherein the several precipitation characteristics are substantially the same. On the maps proposed under the last objective, the delineation of the regions is expected to be such that the variations of dissimilarities within each separate region would be approximately equal or proportional.

There are several criteria which may be used for comparing the precipitation characteristics of two or more stations. Among them are moving monthly means; cumulative deviations from monthly means; the adherence to a uniform slope when cumulative depth at one station is plotted against that of another; and the correlation between comparable data in terms of the coefficient of variation or the range ratio.

#### **Item No. 5. The Station-Year, or Composite Record Method, of Determining Rainfall Rate-Duration Frequencies**

*Objectives.*—1. The determination of the statistical soundness of the station-year method as related to

records of concurrent and nonconcurrent periods and to different intensities of the same duration.

2. The development of methods of validating the composite record by comparison of frequencies thus obtained with those established from single long term records when available, and by the determination of correction factors to reduce the composite record to a valid length.

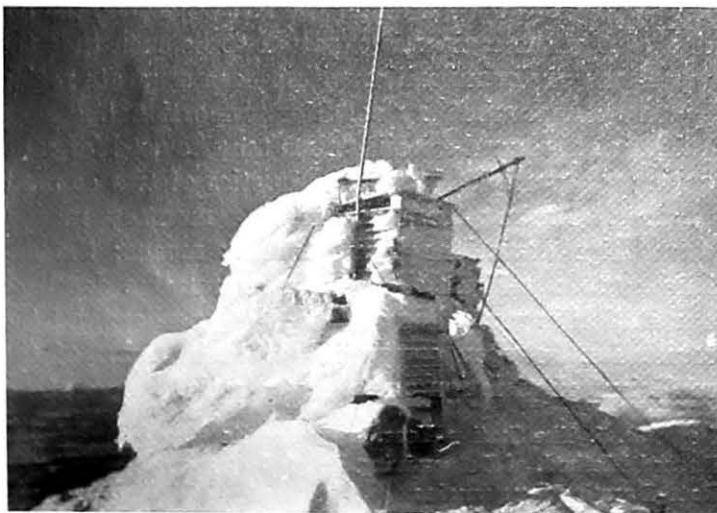
3. The development of criteria for checking the independence of a particular station by (a) identifying those stations which do not add to the significance of the composite record and (b) by determining, within a region, those stations which give the most significant composite record.

*Discussion.*—The development of adequate methods of determining the average frequency of high intensity rainfall has been a problem troubling engineers and hydrologists for many years. Various approaches have been developed with more or less success.

The station-year method has perhaps been the most widely used and had an outstanding application in the studies by the Engineering Staff of the Miami Conservancy District in their work on storm rainfall of the eastern United States.<sup>1</sup> Meyer utilized the method in developing rainfall rate equations for durations up to two hours. Other investigators have applied the method to frequency studies in various sections of the country, although Yarnell developed frequency charts based on statistical treatment of the records at the first order stations of the Weather Bureau.

The station-year method provides for the development of a synthetic long time record by combining the short records of stations in the particular region. The sta-

<sup>1</sup> "Storm Rainfall of the Eastern United States, Technical Bulletin V, The Miami Conservancy District.



MOUNT ROSE OBSERVATORY

FIGURE 4.—An example of one of the difficulties encountered in securing hydrological observations in mountainous country. Frost feathers forming on the shelter and exposed instruments damaged the station located at the summit of Mount Rose.

tistical soundness of the method is questioned by some, as well as the impossibility of obtaining, in any real sense, additional years of rainstorm experience by combining contemporary records from several stations. It has been advanced as a practical approach to the more accurate approximation of the true frequency-intensity relationship than is possible from the record of normal length from any single station because of the inclusion in the composite record of extreme storm experiences which are believed to be of less frequent occurrence than their position in a single station record would indicate, or which might be entirely lacking in such a record.

The method has limitations. Where the synthetic record is composed of short-term records from stations relatively near each other, the frequency relationship will be disproportionately influenced by the storms experienced during the short record; likewise storms of a frequency exceeding the actual length of station record will not be correctly represented. Where component records are from widely separated stations isolated storms of high intensity may be missed, and the accuracy of the frequency relationship impaired.

Newly established sources of rainfall intensity data and the studies of storm morphology available through the work of the Soil Conservation Service in Oklahoma and Ohio, together with data previously developed, offer splendid opportunity for correlative investigation; for the refinement of various statistical techniques; and for the verification of newly established hydrometeorological principles. Refinement of the methods of analysis may overcome to a considerable extent the paucity of data now existing throughout much of the West where a more complete knowledge of rainfall rate-duration-frequency relationship is greatly needed.

Certain phases of the objectives are concerned almost entirely with statistical analysis and may be expected to engage the attention of those persons interested primarily in statistical approaches.

#### Item No. 6. Variations in Precipitation Occasioned by Altitude and Changes in Altitude

*Objective.*—1. The determination and evaluation of the effect of altitude and changes of altitude as factors influencing the rate, duration, and amount of precipitation received throughout the country.

*Discussion.*—The assumption that precipitation increases with an increase in altitude is one frequently made in discussions of precipitation problems. There are strong indications, however, that this assumption is not universally applicable and that there are limitations beyond which it does not apply. No thorough-going study has been made of the phenomena, and at the present time the inability to weight properly the effect of altitude and altitude changes of the collecting stations

is one of the principal detractors in the analyses and graphic presentation of precipitation data.

The problem to be investigated is primarily that of separating altitude influences from those of gage location, exposure, etc., and research devised for study of it should be carried on concurrently with or follow that proposed on rain gage location and exposure (sec. 1, item 1). Likewise the marked climatic and physiographic differences between the eastern and western United States will necessitate separate consideration so that the research should be closely coordinated with that proposed on the delineation of rainfall provinces (sec. 1, item 4).

Preparatory to basic research, a preliminary investigation should be carried out to determine possible correction factors that would permit a more extensive use of the rainfall data already available from mountainous regions. In such study, data from excised valleys should be excluded. In planning this preliminary investigation and the basic research, the studies of the Forest Service on the influence of altitude on rainfall rates and duration as conducted on the San Dimas Experimental Forest should be of value.

The proposed research would necessitate the establishment of rain gages on selected slopes, both windward and leeward, throughout the entire range of altitude, together with such additional equipment as may be necessary to measure influencing meteorological factors. Continuous records of precipitation over a period of

years at these stations should be studied and correlated with records of nearby standard stations. The proposed research should be carried on in each of the major rainfall provinces in order that a more effective coordination and correlation of results may be possible.

**Item No. 7. The Interrelation of Rainfall Intensity, Duration, and Areal Distribution**

*Objectives.*—1. The determination of the interrelation of rainfall intensity and duration as expressed by intensity-duration curves.

2. The determination of the interrelation of rainfall intensity and areal distribution as expressed by area-depth curves.

*Discussion.*—Extensive research on intensity-duration relationships as related to particular areas has been conducted by Meyer, the Miami Conservancy District, Bernard, Yarnell, and others, and a rather satisfactory accumulation of information on the subject has been assembled. From data now available the probable frequency of a particular rainfall intensity-duration combination can be determined within reasonable limits for numerous localities. Major storms have also been studied by various agencies in efforts to determine the relationship of the total rainfall at the point of maximum to the average rainfall over the storm area; the results have been expressed, generally, in terms of total rainfall dur-

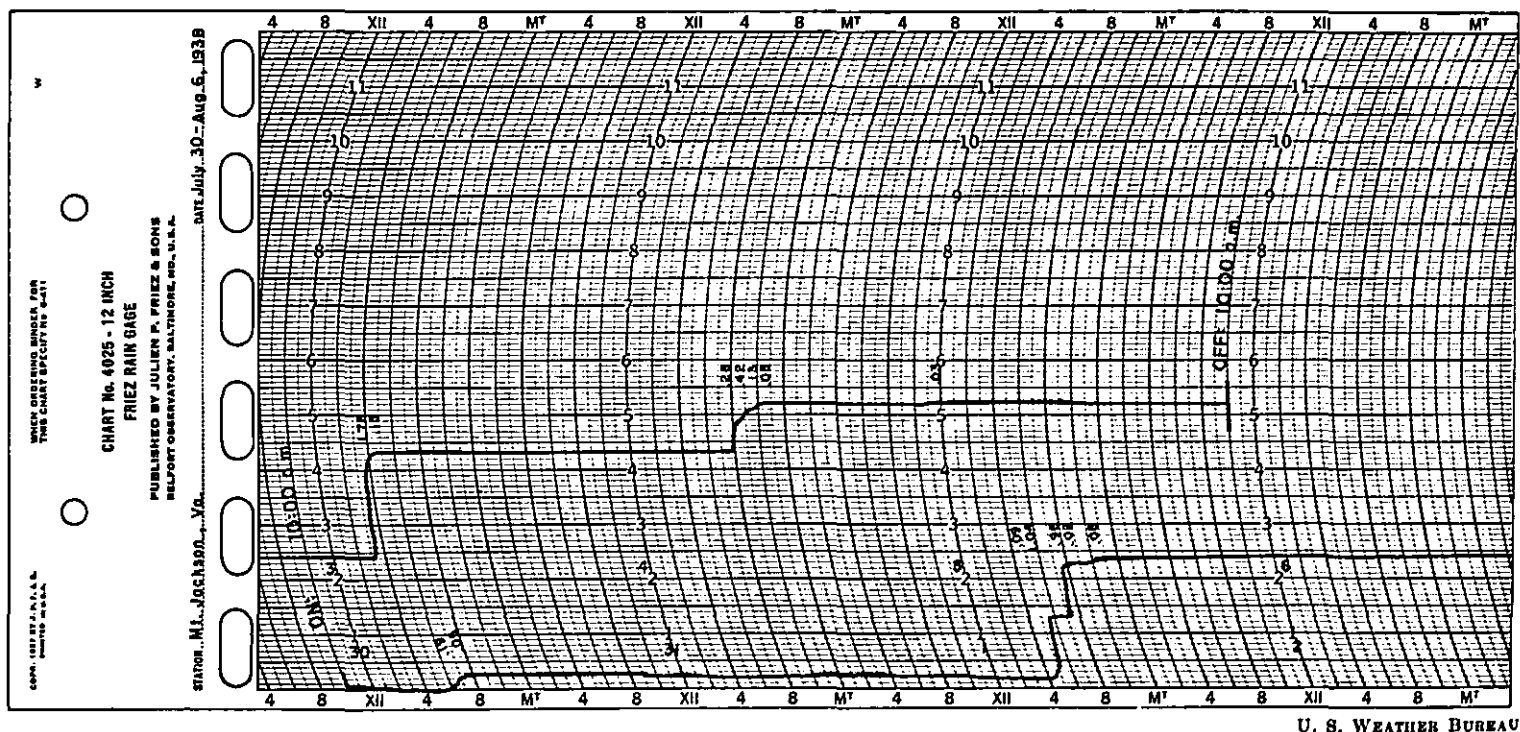


FIGURE 5.—A chart from a recording weighing rain gage, showing the recorder trace of rainfall received in the period July 20 to August 6, 1938, at Mount Jackson, Va., and the manner in which the trace is used to investigate rainfall intensity relationship.



ing the storm instead of in terms of rainfall intensity.

In the design of urban storm drainage systems and of flood protection structures, in areas of high property value, the customary procedure has been to use rainfall intensities of known frequency of occurrence and assume them to be uniform over the area. This practice has been common for projects involving drainage areas of less than 100 square miles, and is critically responsive to storms of not more than three or four hours duration.

In the absence of better information, engineers have used the same procedure for areas of considerable size and have compensated the error involved by using reduced run-off factors. This technique can scarcely be considered rational even though the results are reasonably accurate. Accordingly it is highly desirable that information be acquired which will permit the conversion of rainfall intensities at a given point, to average intensities on an areal basis.

The suggested research would involve, primarily a study of the intensities occurring in periods of exceptional rainfall, and particularly the variation in intensity over the area covered by such rain. The most important function of the study would be the development of correction factors which, when applied to intensity-frequency data, would make it applicable as an average intensity for a specific duration over a specified area. Any new values of intensity-frequency relationships which might be developed for particular stations would be incidental to the study.

The study should be undertaken in areas where there are sufficient recording rain gages to permit the collection of the requisite data, as for example in the Tennessee Valley area, in the Muskingum Valley of Ohio, and under the joint Weather Bureau—Geological Survey—Pennsylvania State project. It is believed that the gage concentrations in these areas are or will be adequate for undertaking studies for eastern conditions, covering areas up to several thousand square miles. For small areas, representative of eastern and mid-western conditions, the gage installations in some of the metropolitan areas, such as St. Louis, New Orleans, Boston, and New York, will probably be adequate, although a few additional gages would be desirable. Studies in these metropolitan areas should deal with intense storms having durations of 15 minutes to 3 hours and covering areas of 5 to 100 square miles.

Rainfall data should be secured for intense storms at all gages in each of the areas by successive simultaneous short intervals of approximately 15 minutes. From the simultaneous observations, the intensity at each gage and the average intensity over the area could be secured and the relationship between them developed for each time interval. For the larger areas a similar study should be made using longer periods of time;

possibly two, four, and eight times the interval used for the short duration studies. Careful consideration should be given to the desirability of conducting the first studies in a section where intense rainfalls are frequent and the majority of the annual precipitation occurs as rainfall.

#### Item No. 8. The Sequence of Occurrence of Rainfall Intensity Rates

*Objectives.*—1. The determination of the sequence of occurrence of rainfall intensity rates throughout a storm.

2. The determination of the tendency for rainfall to follow an identifiable intensity pattern or sequence for a particular precipitation province and type of storm.

*Discussion.*—The fact of a variation in rainfall intensity rates for intense rainfall of both long and short duration is well established by observation. Likewise previous studies have indicated that appreciable differences in runoff exist for storms of given total rainfall and duration, depending upon whether the high intensity rainfall occurs during the early, intermediate, or later parts of the storm period. The effect of such variation in rainfall intensity sequence on the runoff from a given drainage basin has been clearly demonstrated in the construction of a unit hydrograph for the stream.

It is expected that the proposed research will disclose the existence of possible intensity sequences for each type of storm in the various precipitation provinces of the country. The existence of such storm patterns in given areas could be utilized in more accurate predictions of runoff through the application of infiltration capacity values and the unit graph than would otherwise be possible.

The quantitative effect of differences in rainfall intensity rates is obviously much greater for short intense storms than for general storms covering large areas. The investigation suggested in this proposal may be advantageously correlated with those of items 4 and 7 of this section. The intensity data secured in item 4 could serve as a basis for design of additional observational work as needed.

#### Item No. 9. Limiting Storms and Regions of Like Storm Potentialities

*Objective.*—1. The determination of the possible physical limitations on amount, duration, and areal distribution of storm precipitation within various regions, and the delineation of specific regions within which such limiting storms would be equally likely to center in critical positions over any drainage basin of the region.

*Discussion.*—The modern meteorological approach of “air-mass analysis,” which gives consideration to the physical properties and interactions of the major air currents, as related to storms, is the basis of study upon which the investigation is proposed. To a considerable extent the work would consist of detailed study and analyses of the large scale storms and “fronts” as they have occurred throughout the country. The air mass analyses and other weather maps, including available upper air data, would form the basis for the study of the relation of past storms to the maximum possible storms.

Under the proposed study the country would be divided into regions within which it is expected that limiting storms would be equally likely to center in a critical position over any drainage basin in the region. Such regions would embrace extensive areas in the Great Plains where physiographic influences are a minimum and where storm magnitude and durations are fixed by distance from and relative position with respect to moist air mass sources. The areas embraced by the regions of like storm magnitude will reduce rapidly as the mountainous sections of the West and of the East are approached and will be confined, in some instances, to a single basin or to one slope of a mountain range.

The first step in a study of this character is that of selecting storms of such areal extent that they will be directly applicable to a wide range of sizes of drainage basins.

Other phases of the proposed study include (a) the grouping of storms with respect to their probable seasonal occurrence; (b) the determination of the effects of mountain ranges on rainfall distribution; (c) the relationship of the stability and moisture content of air masses to the frequency and intensity of rainfall within them; (d) the possible rate of upward movement of air on isentropic or frontal surfaces and its relation to precipitation; (e) the cause of prolonged abnormalities in large-scale atmospheric circulation and their effect in producing intense storms; (f) the persistency and frequency of various atmospheric flow patterns over selected regions; (g) the causes of convergence and divergence in the air masses and their effects on the processes of condensation and precipitation; (h) the probable maximum length of time for which a given intense storm structure can be maintained over a given area; (i) the development of criteria for estimating the magnitude of depth-area relationship at their limiting values; (j) the construction of synthetic storms of various critical patterns conforming to limiting depth-duration and depth-area relationships.

#### Item No. 10. The Effect of Large Bodies of Water Upon Precipitation to Leeward

*Objective.*—1. The determination of the effect exercised by large bodies of water or swamps upon precipitation to leeward.

*Discussion.*—Little published information is available upon this subject. It is one with respect to which there has been much speculation, especially as to whether large new water bodies, such as the lakes above Boulder Dam and Fort Peck Dam may increase precipitation in some areas to leeward of the prevailing wind direction.

This investigation has two aspects, one dealing with the effect of large water bodies which have long been in existence the other with new water bodies. In either case there would be required the following information: (a) Humidity gradients over large and small lakes, (b) variations in humidity with distance from the shore of the lakes, and (c) concurrent wind



U. S. FOREST SERVICE

FIGURE 6.—A device for collecting crown intercepted precipitation, showing the collecting collar and container for determining the precipitation which would reach the ground by travel along the trunk.

directions and velocities. All of this should be studied with respect to the occurrence of precipitation at points indicated from records of wind direction and velocity during periods of high evaporation and resultant increase in moisture content of the air.

The study should involve an examination of precipitation records as to seasonal amounts and over considerable areas in indicated directions from water bodies. The station records for the area under examination should be averaged in small selected groups to determine whether the records of any one group of stations appeared to include an excessive amount of precipitation not explainable by differences in elevation or topographic features.

Studies undertaken through this method should best be located in semiarid regions where the effect of water surface evaporation would not be confused with humidity resulting from transpiration.

The second aspect of the problem would deal with the effect of (a) recently created water bodies, or (b) where large water bodies or swamp areas have been removed through drainage. In such localities, the study would consist of the examination of precipitation values to leeward of the locality before and after the

change in water surface condition, and an attempt made to determine whether the precipitation records in the area under investigation exhibited a sharp break in trend concurrent with the change in water surface condition.

#### Item No. 11. The Interception of Precipitation

*Objective.*—1. The determination of the amount of precipitation intercepted by different plant covers and its seasonal variation.

*Discussion.*—Interception consists of that part of precipitation caught and retained on the foliage and aerial parts of plants, and later returned to the atmosphere through evaporation without having reached the ground. For the purpose of this discussion the term "interception storage" is used to denote the amount of precipitation which under various atmospheric conditions, is intercepted by the aerial parts of a plant and prevented from reaching the ground. "Interception capacity" is the maximum amount of interception which a plant or plant species may retain under the most favorable conditions of rain intensity and wind velocity.

Interception storage and interception capacity vary with plant species and the stage of plant development. Many plants and plant associations, however, have similar interception characteristics and could be considered as a single class. Furthermore, it has different values for summer precipitation in the form of rain and winter precipitation in the form of snow and sleet. Thus any investigation of interception should cover the complete cycle of annual growth or change in plant condition.

Lack of information on interception has probably resulted in a tendency to overemphasize its importance. Although some investigations have been made on interception by trees and in forests, both in this country and abroad, there is little published data concerning interception by crops, grasses, and other low growing vegetation. There is need for a thoroughgoing investigation of the many phases of interception, particularly from the standpoint of determining the net interception over given large areas.

The investigations might logically be concerned with single plants of a given kind; however, a greater value will accrue from studies given areal significance either by correlation with plant density or through simultaneous studies over a large area. Two classes of observations would be needed, those relating to the vegetal cover—its age or stage of growth, height, shape, aerial structure, areal coverage, density and condition; and those dealing with meteorological phenomena such as rainfall intensity in the open, wind velocity and direction at the height of the plants, etc.



U. S. FOREST SERVICE

FIGURE 7.—An installation used by the Forest Service in measuring the trunk drainage of intercepted precipitation in a young stand of Shortleaf Pine. Special rain gauges are used to measure the precipitation which penetrates the crowns of trees.

The technique of determining interception storage for low dense vegetation will tax the ingenuity of the investigator but should not be found generally difficult for trees and high growing plants. It is important that the work be designed to adequately cover the area affected if results are to be obtained by which the prob-

able interception for any storm occurring at any time of the year may be reliably estimated. It should be borne in mind, however, that interception may be a small factor, quantitatively, and if such is the case extreme precision in the observation may not be warranted.

## II. Infiltration

### Item No. 1. The Nature and Mechanics of Infiltration

*Objectives.*—1. The determination of the relationship between the penetration of water into the soil and the texture, structure, and other physical properties of the soil.

2. The determination of the difference in the rate and amount, if any, of infiltration resulting from the application of water by flooding, sprinkling, artificial rainfall, and natural precipitation, respectively.

3. The determination of the effect of depth and velocity of the surface film of water upon the infiltration rate.

4. The determination of the effect upon the infiltration rate of initial soil moisture content, interstitial air, soil and water temperature, and other physical phenomena.

5. The determination and evaluation of the factors affecting the change in rate of infiltration or infiltration capacity with duration of infiltration.

*Discussion.*—Infiltration is the entrance of water into the soil. It is a surface phenomenon and is distinct from the disposition of water after it has entered the soil.

Infiltration capacity is the greatest rate at which a given soil when in a given condition can absorb falling rain or melting snow when such phenomena occur at a rate which equals or exceeds the rate of infiltration. If the rain intensity is less than the infiltration capacity, the rate of infiltration is the rain intensity. If the rain intensity is greater than the infiltration capacity, the rate of infiltration is limited by the infiltration capacity.

The true significance of infiltration observations cannot be set forth accurately unless the physical processes governing its action are clearly understood. Without this understanding, neither the proper method of making measurements nor the correct interpretation of the results themselves can be determined. The initial condition of the soil, including its moisture content, the



U. S. WEATHER BUREAU

FIGURE 8.—A glaze storm. Precipitation under these conditions is intercepted extensively by vegetation and in part is returned to the atmosphere through evaporation.

temperature of the soil and of the water, and other factors all have pronounced effects. These are recognized by most investigators, but little attention has been given them in past observations. Almost nothing is known about the phenomena taking place as the water enters the soil, the effect of surface water depth on the rate of infiltration, and the significance of capillary forces. Texture, structure, temperature, cultivation, and insect perforations dominate the infiltration rate, but their quantitative and relative influences are not known, nor have the factors that control the decrease in rate with time, generally observed in the early stages of infiltration, been investigated and correlated.

Some students of the subject have advanced the idea that minimum infiltration capacity is closely correlated to some one or other of the physical factors of the soil, such as noncapillary porosity and moisture equivalent. These possibilities merit further investigation. It is the purpose of this investigation to study all relevant factors and to determine the underlying mechanics of infiltration.

The factors to be investigated, i. e., the effect of soil structure, temperature, initial soil moisture content, void space, etc., should be determined. In planning the investigation, the natural approach to the basic processes and factors may logically be through laboratory work on synthetic soils in the first instance. The investigation of structure must be done on natural soil profiles either in the field or laboratory. All questions that can be disposed of by laboratory work on soils of uniform texture and structure should be studied first, before going into the study of natural soil profiles.

In presenting the results, the aim should be to show clearly, and as far as possible quantitatively, the effect of each of the factors investigated on the rate of infiltration, including among other items: (1) The effect

of variations in the value of the factor on its influence on infiltration; (2) its relative effect as other factors change in value; and (3) the change in its effect with the duration of infiltration.

#### Item No. 2. Methods of Measuring Infiltration and Infiltration Capacity

*Objectives.*—1. The determination of the limitations of present methodologies, instruments, and techniques for measuring infiltration; and the relationships of the measurements as made to the amounts and rates of infiltration under natural conditions.

2. The development and testing of new instruments and methods for measuring infiltration.

3. The development of a standard methodology for the measurement of infiltration and infiltration capacity and the establishment of its relationship to other methods which have been or may be used.

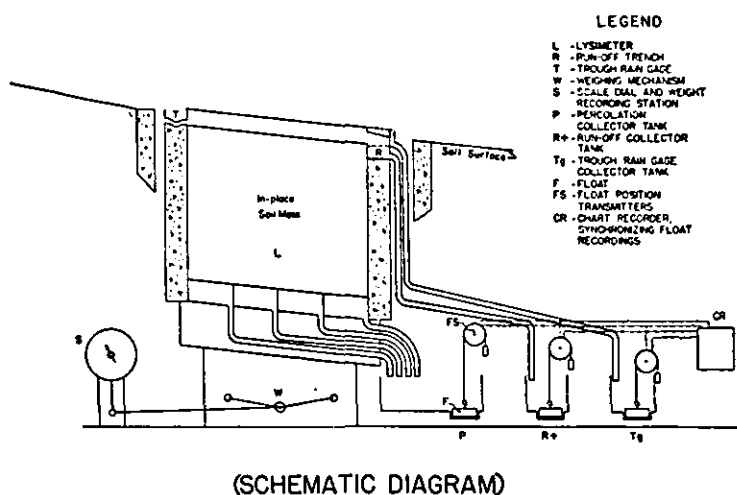
*Discussion.*—No recognized standard device or methodology now exists for the measurement of infiltration. Moreover, the limitations of those now in use have not been investigated adequately nor have results from them been sufficiently discussed in technical literature.

Numerous devices, methods, and techniques have been employed to measure infiltration or to obtain infiltration indices, the soil being tested either in place or after its removal to a container, a process which largely destroys its structure. Water is applied by flooding, sprinkling, or by natural rain. Infiltration lysimeters have been used in Germany and Switzerland, and a modified form is now in use at several of the Soil and Water Conservation Experiment Stations of the Soil Conservation Service. Infiltration rings of various diameters and depths have been tried, but little published data concerning them are available. Infiltration is most frequently measured by the difference between water applied to the soil surface and the amount running off and is, therefore, often obtained from observation on small run-off plots. The diversity in technique and devices employed, together with a lack of comparison between the different methods, renders the reduction of much of the data to a common base of reference an impossible task.

Before effective progress in the measurement of infiltration and infiltration capacity can be made, a standard technique is required—one that recognizes and measures all of the pertinent influences, reduces them to a standard basis of comparison, and determines the relation of the observations to the actual infiltration into the soil.

It need hardly be said that an understanding of the mechanics of infiltration is essential to the development of a proper methodology, and the investigations of

### WATERCYCLE LYSIMETER



U. S. SOIL CONSERVATION SERVICE  
 FIGURE 9.—A schematic diagram of the water cycle lysimeter developed by the Soil Conservation Service for use in their hydrologic investigations.

methodology of measurement and of the mechanics of infiltration are closely interrelated.

As a part of the proposed investigations, there should be comparative studies made of the use of lysimeters, infiltration rings, small plots, and any new devices that may be developed. The effect upon infiltration capacity of applying water by different means—flooding, sprinkling, artificial rainfall, and natural rainfall—should be determined. The effect of impact from high-intensity rainfall should be investigated, and also the effect of departure of the applied precipitation from uniform distribution patterns and intensities, together with the permissible amount of variation in such departure.

In infiltration measurements, careful attention should be given to the effect of (a) the size of area treated, (b) the depth of soil column isolated, and (c) the possibility of a lateral movement of the infiltrated water on increasing the apparent infiltration; the determination of the necessary auxiliary observations such as soil and water temperature, initial moisture content, etc.; and the development of standard bases of temperature moisture conditions, etc.; for use in comparing various observations.

The presentation of the results of any investigation should include a clear and concise statement of the methods used, including their defects, if any, for guidance in future work; the manner of reducing observations to standard conditions of temperature, initial soil moisture content, etc.; and a comparison of the observations secured by the investigation with those of other investigators as a general index of the reliability of the methods and procedure used.

### Item No. 3. Effect of Surface Condition and Vegetal Cover on Infiltration

*Objectives.*—1. The determination and evaluation of the effect of surface irregularities, tillage and soil amendments on the amount of infiltration, and upon the infiltration rate and capacity.

2. The determination of the relationship of the degree of land slope to the effect on infiltration exerted by surface irregularities.

3. The determination of the effect of surface conditions, including vegetal cover, on infiltration capacity and on total infiltration during precipitation periods.

4. The determination of the seasonal change in infiltration capacity, especially as related to various factors influencing it, and also in those factors affecting infiltration opportunity for given soils and plant covers.

*Discussion.*—Investigations in recent years indicate that for any given soil, slope, and character of surface cover there is a specific limiting rate of infiltration which is called the infiltration capacity; that for any

specific precipitation period there will be an initial infiltration capacity which will depend to a material degree on the soil moisture present or, as has been recently suggested, upon the unoccupied noncapillary porosity; that the infiltration capacity will decrease during the period over which infiltration occurs; and that there is a seasonal variation in infiltration capacity which may be due to changes in surface cover, changes in soil moisture, changes in the plant root system, or to other biological activity. If these assumptions are substantially correct, there is definite need for further research to show the manner in which infiltration capacity is affected by the controlling variables and for the development of quantitative values.

In the light of our present-day knowledge of the subject, it appears reasonable to assume that mass infiltration during a precipitation period will be equal to the mass precipitation which occurs at less than infiltration capacity, plus mass infiltration which occurs at a capacity rate during periods when precipitation exceeds this rate, plus infiltration following precipitation which is derived from surface detention and which may be controlled in part by infiltration capacity rates and in part by the length of infiltration opportunity, plus the infiltration of water after the period of



U. S. SOIL CONSERVATION SERVICE  
 FIGURE 10.—The installation of a lysimeter at North Appalachian Experiment Watershed, Coshocton, Ohio. The lysimeter in the form of a bottomless box is heavily loaded with sand (10 tons in this instance) and the walls forced down around an undisturbed column of natural earth. The earth under the cutting edge is removed and the soil column carefully shaped to fit the interior of the lysimeter.

precipitation (i. e., water which has been retained in depressions). Any research, therefore, which is concerned with total infiltration during precipitation periods, as representing increase in soil moisture, must take account not only of infiltration capacity, but also of the opportunity for infiltration at subcapacity rates.

The basis of comparison of infiltration capacity for different soils and different plants should be on a surface free from all surface retention except that created by inherent characteristics of the soil or of the plants. An entirely separate investigation should be made of the effect of surface cover in providing an increased opportunity for infiltration by extending the infiltration period beyond the duration of rainfall.

The amount of water retained in surface depressions decreases as the surface slope increases. It is quite likely that the character of natural surface retention also changes with change in slope. Because of the relatively large effect of surface retention, particularly in storms of short duration, the amount of its decrease with increasing slope is important.

With regard to plant cover, it is not sufficient merely to designate the type, density, and condition of the root system. The plant not only undergoes a seasonal development, but its root system is affected by the density of the stand, which varies widely.

Inasmuch as infiltration capacity is known to vary continually, the seasonal change in infiltration capacity is essential to an understanding of this phenomenon and to the application of infiltration capacity values. The rate of infiltration is influenced by temperature,

soil moisture, condition of the soil structure, the activity of insects and soil bacteria, the stage of growth and density of plant cover, and other factors having a seasonal cycle of change. These create changes in the rate of infiltration throughout the year. This has a material effect on run-off, and as a result, a given storm will produce different rates and amounts of run-off, depending on the time of year at which it occurs. Investigation of these seasonal changes is, therefore, required for the purpose of determining the range and variation in infiltration rates and amounts. Obviously, such an investigation should include observations over at least one complete year.

The soils, vegetative cover, and the insect life and soil organisms they support, are modified by the region where they are found, and it is not to be expected that the same plant on a similarly textured soil will give the same results in two different regions. There is, therefore, a geographical element that should be recognized in extending researches conducted in one place to other places.

Investigational work on the effect of vegetal cover on infiltration should be correlated with that proposed under items 1 and 2 of this section. The planning of the detailed procedure to be followed and a careful check of the completeness of the observations to be made are of prime importance in this investigation.

The investigation may cover either various crops and plant covers on a given soil or a given plant cover on different soils or different phases of the same soil type, using in either case the soil devoid of cover as a basis



U. S. FOREST SERVICE

FIGURE 11.—A watershed in Polk County, Tenn., showing slopes where all vegetation has been killed by fumes from copper smelters. Precipitation falling on these slopes has little opportunity to penetrate the ground; run-off rates are high and are accompanied by severe soil erosion. (See also fig. 21.)

of comparison. The work should be planned to embrace the complete cycle of plant growth, including the various possible conditions preceding the beginning of the growth as well as those following the end of plant growth.

The methodology should receive careful attention and should conform to the standards set up by the investigations under item 2 of this program. The rate and amount of water applied, the manner of its application, and the interval between applications require thoughtful planning. Thorough consideration should be given to the supplemental measurements needed for complete interpretation of the observations.

Observations should include the amount of significant surface retention and detention and a discussion of their effects in extending infiltration opportunity, and consequently total infiltration.

In connection with seasonal investigations, the soil and its cover should be in its natural state and subject to all normal, natural conditions such as, for instance, insect activity, temperature, etc.

A parallel series of measurements on plots protected from natural rainfall but on which the predetermined normal precipitation for the locality is artificially applied would, if feasible, prove valuable and give a base for comparison. This would entail a study of the normal amounts, intensities, and dates of occurrence of rainfall, as a guide for the application of a so-called normal precipitation.

Results should be presented to show the variation in infiltration capacity with time and the time-amount of infiltration during periods of excess rainfall under various conditions and at different stages of plant growth. They should include, among other things, the physical characteristics of the soil profile, the growth history of the plant cover, physiographic characteristics of the plot or area such as degree of slope, surface roughness and retention, dates of storms, the time-intensity record of all storms producing run-off, the maximum intensity as well as total rainfall in storms not producing run-off. The individual observations should be presented, as well as any summation, analysis, and interpretation of the data.

#### Item No. 4. Areal and Basin Infiltration

*Objectives.*—1. The development of methods for the determination of infiltration characteristics of drainage basins from measured infiltration capacity of small areas within the basin.

2. The development of means by which the infiltration capacity of a watershed may be expressed in terms of the infiltration capacities of its component parts and tributaries.

3. The determination of methods by which the areal infiltration of a drainage basin may be obtained from precipitation and stream-flow data, and the determination of the limitations of such methods.

*Discussion.*—Variations in the structure of the soil, surface retention, density of plant cover, and other factors will cause differences in infiltration capacity within an area. Since practical considerations will confine direct measurement to small isolated areas for which the infiltration capacity may be determined by sprinkling plot, ring, or tube methods, there is created the problem of investigating and determining the proper method of relating the direct measurements on the small areas to the performance of the area as a whole.

It is assumed that field studies of soils, slopes, and vegetal cover may permit a division of the area within a drainage basin into areal classes, all of the area in each class having substantially the same infiltration capacity under any one seasonal condition; also, within each such areal class for all parts of the area, the infiltration capacity may be expected to vary in approximately the same way with changes in seasonal condition and with duration of infiltration during precipitation periods. Investigation is needed to—

1. Determine the practicability of such procedure.
2. Develop the proper methodology for determining the infiltration capacities adaptable to each such areal classification.
3. Determine for selected drainage basins the methodology for combining the infiltration capacity of the component parts to give the net filtration capacity applicable to the basin as a whole.

It appears reasonable to assume that the maximum rate of infiltration for a drainage basin can be determined by the proper integration of the infiltration capacities of its component areas and expressed as the mean infiltration capacity for the entire basin. Investigation could then be pursued by deducting this factor from precipitation intensities during a particular storm to determine the approximate value of excess rainfall and flood flow. It appears that this may be possible for storms having precipitation intensity throughout in excess of the greatest value of infiltration capacity of any of the areal classes.

The determination of the infiltration capacity of a drainage basin, by use of the areal rainfall on the watershed in conjunction with the run-off from the basin, has been attempted by several investigators, with sufficient success to demonstrate the feasibility of this approach where adequate data are available. It appears that this method may be limited to relatively small drainage basins adequately covered by recording precipitation gages, so that the rainfall intensity pat-



tern for the whole basin may be rather definitely known. Under these conditions it appears possible that for specific storms of relatively high intensity, a mean infiltration capacity for the basin as a whole may be determined. More work along this line is needed to improve and further develop these methods, particularly to determine the limits with respect to a drainage basin and with respect to the type of storm within which the resulting mean infiltration capacity may be determined with reasonable accuracy. Further investigation is also needed to determine the extent to which values of mean infiltration capacity so derived for specific storms may be translated into values usable in connection with storm precipitation of different types and intensities. This procedure may provide a means of comparing the estimated infiltration derived from direct measurements with the actual infiltration of the watershed.

The advisability of undertaking research of this magnitude prior to the development of a generally accepted methodology is open to question. The value of proposed methodologies might, however, be determined by testing them in a small uniform area.

For the proposed studies, a relatively uniform drainage basin having the same plant cover, soil type, and soil profile should be selected and studied. From this

point the investigation should proceed to more complex areas as suitable methods are developed and evaluated. The number of direct measurements to be taken will depend upon the variability of conditions over the basin. The best procedure in the first instance may be to take a large number of sample areas on which to make direct measurements and from these determine the probably error as the number is reduced.

The result sought is the infiltration capacity characteristics of the composite area as determined from the infiltration capacities of the sample areas. The natural surface retention should be presented as a separate and independent factor. The infiltration capacity of the more complex areas, those having different slopes, soil types or profiles, and plant covers, would seem to require the separate determination of the infiltration capacity of each of the component areas, and a study of the manner in which they should be combined to give net values applicable to the entire area.

The proof of the accuracy of the direct methods is the results determined from the areal precipitation on and the run-off from the area after making the proper corrections for surface and channel detention. The investigation should, therefore, include arrangements for measuring the natural precipitation on the area and the run-off from the area.

### III. Evaporation, Transpiration, Consumptive Use

#### Item No. 1. Factors That Influence Evaporation

*Objective.*—1. The determination and evaluation of the factors governing evaporation from large water surfaces.

*Discussion.*—The evaporation occurring over the surface of a large body of water is a complex phenomenon influenced both directly and indirectly by a great many factors. Studies have indicated a direct relationship between evaporation and (a) the intensity and direction of the radiant heat from the sun, (b) the character (laminar or turbulent) and velocity of the air movement, (c) the temperature of the water and of the air at the water surface, (d) the humidity and possibly the humidity gradient near the water surface, (e) the barometric pressure, (f) the size and surface form of the body of water. There are other factors such as altitude, mineral content, time of day or night, character of terrain and vegetal cover near the body of water, etc., that are believed to affect evaporation, but their relationship has not been defined.

There is great need to determine accurately the effects of various meteorological factors upon evaporation rates from large water surfaces in order that this water loss may be more properly considered in the design of

water utilization projects. Work of this nature has been carried on by the Bureau of Agricultural Engineering, the Weather Bureau, and by hydrologists, but their efforts have frequently been hampered by the absence of essential data pertaining to some of the factors. There is available in the files of these agencies much data needing further analysis.

This study is designed to investigate under controlled laboratory conditions, the effects of solar radiation, wind, humidity, temperature, and barometric pressure on evaporation from open water surfaces. The investigation would require the use of a laboratory installation such that the various meteorological factors could be artificially controlled and changes in conditions limited to the particular factor under investigation.

The laboratory data thus obtained should be checked with standard field installations where complete meteorological data are being collected and where actual evaporation losses from open water surfaces are being measured. It is desirable that the mean temperatures at the site of the field observations should be comparatively high in order to give relatively large numerical values to the evaporation losses. There should also be sufficient annual variation in temperature, wind movement, and humidity to permit a determination of

the effect of these factors. Large lakes in basins where there is little seepage loss and concrete lined municipal water supply reservoirs might be utilized for this purpose, provided inflow and outflow can be accurately measured.

Other factors whose effect on evaporation rate and quantities should be studied in the field include (a) the altitude and depth of water under given meteorological conditions; (b) the increase of surface area through the formation of turbulent water, white caps, and the atomizing of spray; (c) the variation in wind velocity and direction over large and small lakes; (d) the relative humidity and vapor pressure gradients over large and small lakes; (e) the variations in humidity with distance from the lake shore; (f) temperature gradients in the body of water from the surface to the bottom; (g) variations in geological formations, topography, vegetal cover, etc., of the adjacent land areas; (h) seasonal temperature variations in open water bodies and the lag with respect to air temperature variations.

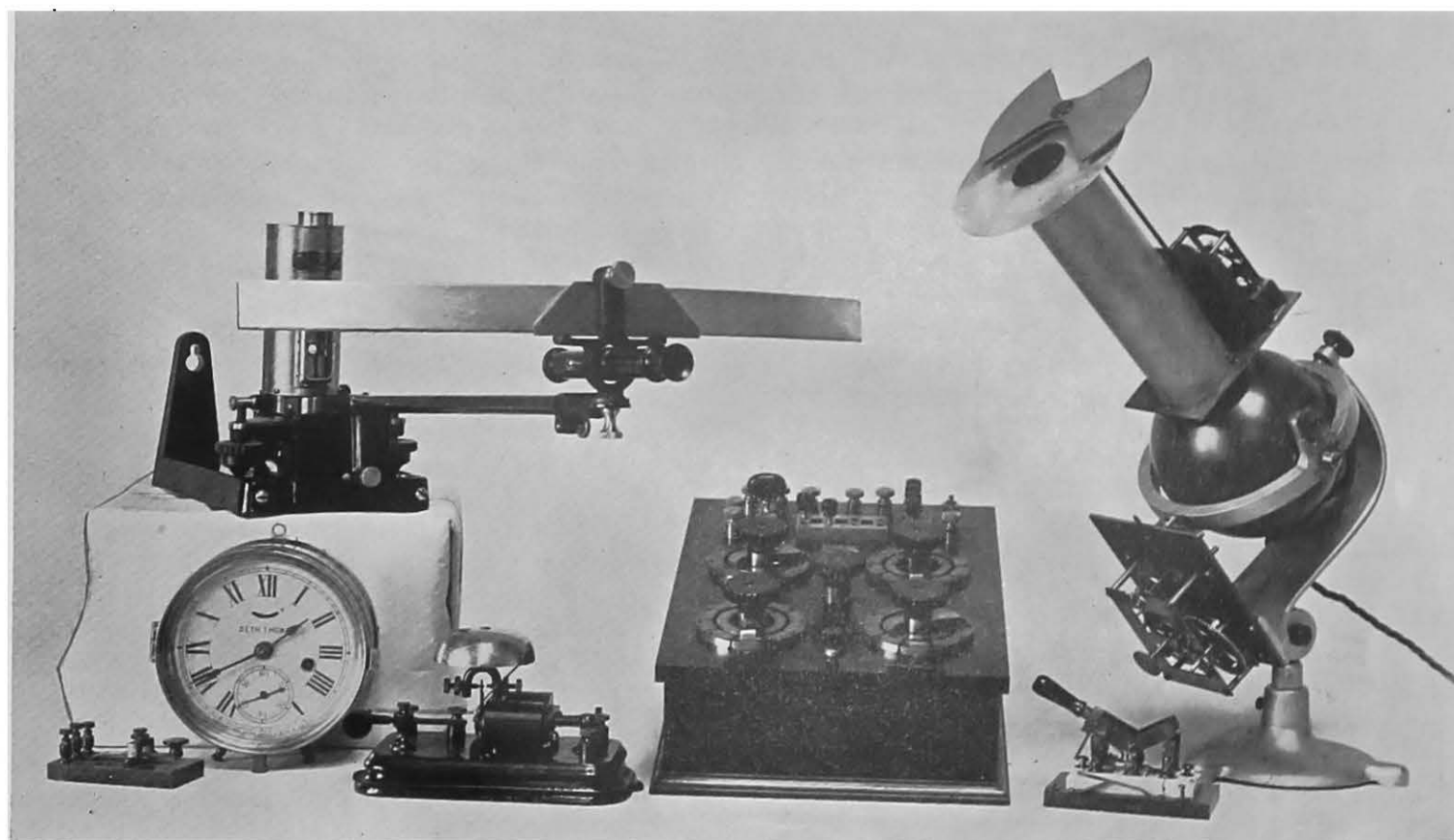
The data collected should be analyzed with the ultimate objective of developing a formula for rates of evaporation, in which the very small or negligible factors would be eliminated, and in which the constants and variable may be supplied from meteorological data normally available.

**Item No. 2. The Improvement of Instruments and Standardization of Equipment and Procedures for Measuring Evaporation**

*Objectives.*—1. The development of improved instruments to supplant and supplement those now used for measuring evaporation.

2. The determination of the most desirable instrument or instruments for observing each of the several meteorological factors influencing evaporation.

3. The determination of the essential observations which must be made and recorded to permit the acceptance of evaporation data calculated therefrom.



U. S. WEATHER BUREAU

FIGURE 12.—The Marvin pyrheliometer used by the Weather Bureau in measuring intensity of solar radiation. On the right is shown the pyrheliometer on its equatorial clock-driven mounting, by means of which it can be kept pointed toward the sun. By means of the diaphragmed tube a beam of solar rays of known area is admitted to the blackened surface of the silver disk inclosing a nickel wire. This wire acts as a resistance thermometer to measure the rate at which the silver disk alternately warms and cools, when it is exposed to and shaded from the sun by a shutter which is automatically opened one minute and closed the next by circuit closers on the clock (at the left). The temperature measurements are made by means of a wheatstone bridge (center) and a sensitive galvanometer (upper left). Signals made by a telegraph relay and bell (center) enable the observer to make reading at the exact time intervals required.

4. The standardization of conditions for the use of the various items of equipment and the detailed procedure to be followed in making all observations.

*Discussion.*—Present day instruments and equipment used in determining evaporation are considered to be reasonably adequate for the purpose; never the less better instruments from the viewpoint of lesser cost, greater ease in installation, increased accuracy, and simpler observations, are an outstanding need. This is particularly true in the field of continuous recording devices for determining evaporation losses from pans. Effort should be directed toward improving existing types of instruments and developing new types more suitable for the several observations required.

In the past, there has been a wide variation in the types of equipment used, in the methods of installation, and in making the observations, with the result that evaporation data obtained at different places and by different observers are not always comparable. To obtain an accurate determination of loss by evaporation, a number of meteorological conditions must be observed. One or more types of instruments should ultimately be adopted as standard for each of the several purposes and only those records should be accepted which are obtained with standard instruments.

Not all investigators observe all factors which affect evaporation. With one or more of the variables unknown, the calculated evaporation loss is subject to question and cannot be properly compared with evaporation data where all factors are known. Therefore, there should be established the minimum essential conditions and natural phenomena which must invariably be observed to secure acceptance of the calculated evaporation loss.



U. S. WEATHER BUREAU  
 FIGURE 13.—A typical Weather Bureau first class station for the measurement of evaporation from water surfaces. From left to right the equipment includes an instrument shelter, an 8-inch standard rain gage, anemometer, and evaporation pan with hook gage well.

The most serious defect in present investigations of evaporation is the lack of uniformity in the conditions under which even the best existing equipment is used, and in the procedure of taking observations. For example, in some investigations the land pans have been buried; in other experiments they have been exposed; wind movement in some cases has been measured very near the water surface; in others it has been measured at a height of several feet above the pan and in others not at all. The character of the wind movement over the pan is often not observed. It is very important that the detailed installation of standard equipment and the technique of making observations of all kinds be standardized.

In carrying out the investigations, existing instruments and equipment should be studied and their deficiencies determined through analyses of the results produced by each, as well as by consultation with numerous investigators who have used the various types of instruments. The needed improvements, as revealed by the study, should be incorporated into new or improved designs of instruments and developed in collaboration with instrument makers. The new instruments should then be tested extensively in the field, both trained and untrained observers being used. Upon completion of the testing program, one or more instruments should be selected as standard for observing each of the factors essential to the accurate calculation of evaporation.

In order that evaporation results may be consistently acceptable, minimum requirements for observations should be established to include (1) uniform methods of using the various instruments; (2) uniformity in the technique of making observations; (3) limits of accuracy in the measurement of the essential meteorological observations or other phenomena.

Concurrent observations using the present Weather Bureau class A pan should be made in conjunction with the development of new standard equipment. The relationship between the results obtained with both class A pans and the improved apparatus should be established so that past records made with class A pans may be utilized with satisfaction.

The use of the psychrometric difference between wet and dry bulbs as a standard measure of the rate of evaporation should be investigated for the winds of the velocity produced when the psychrometer is whirled, as well as for the whirling velocity plus that of the wind existing at the times of observation. Correlation of such measurements with those of pan evaporation should be undertaken, inasmuch as psychrometer data have been collected for many years by the Weather Bureau.

**Item No. 3. The Relationship of the Evaporation from Pans to that from Open Water Surfaces**

*Objectives.*—1. The determination of the relationship between the evaporation from a pan of a given form and setting and that from nearby large water areas under varying climatic conditions, length of observation period, etc.

2. The determination of the meteorological observations essential in defining and expressing the relationship of evaporation from a pan to that from a large water surface.

3. The determination of the type and size of pan whose evaporation characteristics bear the most simple and direct relationship to those of a large body of water.

4. The determination of relationship between various sizes, types, and settings of evaporation pans through concurrent observations on groups of such pans in various sections of the country.

*Discussion.*—The accurate evaluation of the evaporation from open water surfaces is essential in determining the economic soundness of many water resources development projects, and, as the observation of evaporation from pans is a relatively simple and inexpensive process, it is highly important that the relationship of the former to the latter be established for the various types, sizes and settings of pans and for other varying conditions which may affect the relationship.

Data on evaporation losses from pans of three and four feet in diameter when compared with similar data for pans of 12 feet in diameter and a tank of 85 feet in diameter indicate a smaller evaporation from the larger bodies. Theoretical research based on the underlying physical processes confirm the general relationship, and empirical curves have been derived for expressing the relation between pans and large bodies of water for a very few cases.

The evaporation pans now in use vary widely in size, type, insulation, and setting, and their relationship to one another and to open water is not at all well established. Unquestionably, some types of pan should and will be abandoned when and as proven inadequate by research. There is, however, need for an expanded program of research on this phase of evaporation which should be carried on under widely different climatic conditions. Continuous records of evaporation from different types and settings of pans are now being secured at several points in California. Records are also being obtained of the evaporation from large bodies of water immediately adjacent to these pans for determining the relationship between the evaporation from the two types of water surfaces.

The observations upon which the relationships must be based should be continued over a period of several years and should include observations on all meteorological and other factors influencing evaporation as set forth in item 1, section III.

**Item No. 4. The Relationship of Meteorological Conditions at Various Elevations to Open Water Evaporation at the Ground Surface**

*Objective.*—1. The determination of the relationship between the meteorological conditions as observed at various distances above the ground and the evaporation from nearby open water surfaces at ground surface level.

*Discussion.*—Meteorological data secured from observations on top of buildings are generally recognized as frequently differing from those obtained at ground level. The correlation of meteorological observations taken at ground level with evaporation losses is discussed in the preceding item. It is now desired to correlate meteorological data taken on top of buildings with evaporation losses from water surfaces at ground level. If this can be done, it will be possible to estimate evaporation losses in many localities where long Weather Bureau records exist, but where no observations have been made on evaporation from open water surfaces, either by pans or otherwise.

An expansion of this investigation would involve correlation between (a) meteorological observations on top of buildings (b) meteorological observations at ground level, and (c) evaporation observations at ground level.

The observations upon which the determination of relationships must be based should be continued over a period of several years and should include observations on all meteorological and other factors influencing evaporation as set forth in item 1, section III.

**Item No. 5. Insolation as a Measure of Open Water Evaporation**

*Objectives.*—1. The determination of the relation between insolation and evaporation from open water surfaces.

2. The determination of the suitability of the solar radiation method of measuring evaporation and its applicability under a wide range of climatic conditions.

*Discussion.*—The use of the "energy" or "heat balance" approach in determining evaporation losses has been advanced by some scientists<sup>2</sup> but for various reasons has not received wide acceptance. The concept involved is the application of the thermodynamic prin-

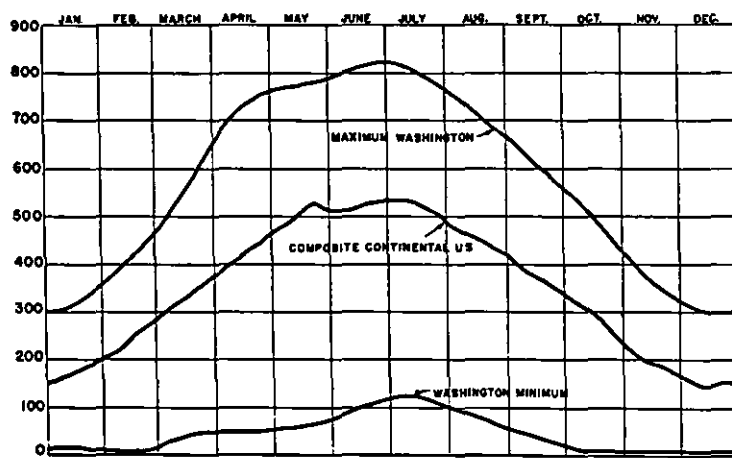
<sup>2</sup> One of the chief proponents of this method is Prof. N. W. Cummings, San Bernardino Valley Junior College, San Bernardino, Calif., whose most important publications have appeared in *Physical Review*, Vol. 30, 1927; *Bulletin 68*, National Research Council, 1929; and in *Transactions of the American Geophysical Union*.

principle that the quantity of water which can be changed from a liquid to a gaseous state at any given temperature is limited by the amount of heat applied to the water, or in other words, that the quantity of heat required per unit volume of water is constant for a stated water temperature.

In general terms, the "energy" approach to evaporation is based upon the assumption that a lake may be treated as a system in thermodynamic equilibrium and that the quantity of water evaporated from the system multiplied by the latent heat of vaporization must equal the heat applied to the body (which in this case is that received from solar and sky radiation) minus the heat lost by back radiation from the water surface, plus the heat transferred between the air and water, plus the heat received by conduction from the surrounding container walls (the earth), plus the difference between the heat content of the inflow and the outflow of the body of water (as applied to lakes), plus the heat stored in the body of water.

The method appears to be of major value in determining seasonal evaporation because all energy components are small except evaporation, solar and sky radiation, and the heat transfer with the atmosphere. The method is applicable to any length periods of time provided that the necessary observations can be obtained on the different heat sources. Investigators have demonstrated that the larger part of evaporation, perhaps as much as four-fifths of the total, is caused by heat received from direct solar and sky radiation and that the remainder is caused by heat transferred from the atmosphere and the surrounding container.

Solar radiation received at a point on the earth's surface varies with latitude and with atmospheric conditions; in northern latitudes it is greater in summer than in winter, and on clear days than on cloudy days. It can be computed on this basis, but it can also be readily measured, and observations are being currently made



U. S. WEATHER BUREAU  
 FIGURE 14.—Average daily maximum and minimum values in gram-calories per square centimeter of total solar and sky radiation on a horizontal surface, Washington, D. C.; and the average values for 16 stations in the continental United States.

by the Weather Bureau at several points in the United States.

The investigation of evaporation from large bodies of water by the "energy" method is based on solar and sky radiation measurements. In the study of this general method, including exploration of the specific methodology of individual investigators, observations on the temperature gradients in the lakes, observations on the temperature and quantity of inflow and outflow, the velocity, temperature, and character of the air movement over the lake where the greatest possible accuracy of determination is desired, humidity gradients, barometric pressures, and evaporation losses from completely insulated land pans<sup>3</sup> are needed for purposes of comparison.

The investigation could be conducted at existing evaporation stations by the installation of equipment for measuring solar radiation. Such investigation should lead to the development of relationships between evaporation and solar radiation which would permit the computation of evaporation losses from solar radiation observations and other meteorological data already being taken. The determination of the quantitative importance of each of the heat sources and the development of a mathematical expression for evaporation in terms of these factors would make possible the calculation of evaporation losses for remote regions within predetermined limits of accuracy.

#### Item No. 6. Evaporation from Snow and Ice

*Objectives.*—1. The determination of the best equipment and technique for the measurement of evaporation from snow and ice under varying conditions.

2. The determination of the rate of evaporation from ice for varying conditions of air temperature, humidity, exposure, wind movement, ice thickness, temperature of water under the ice, etc.

3. The determination of the rate of evaporation from snow for varying conditions of air temperature, humidity, exposure, wind movement, thickness and density of the snow, etc.

4. The determination of the rate of evaporation from snow in forested areas as compared with that from snow in open areas.

5. The determination of the rate of evaporation from loose, detached snow masses, freely exposed, as compared with that from unbroken dense bodies of snow.

*Discussion.*—Evaporation from snow and ice is a matter of special concern in those areas of the United States where a large part of the water storage occurs in that form. Knowledge as to what portion of this storage is lost by evaporation will aid materially in

<sup>3</sup> These data are required to permit the determination of the back radiation heat losses and could be dispensed with in the case of the development of a satisfactory instrument for measuring back radiation.

forecasting runoff, which is of vital importance to irrigation and power interests, and for domestic water supplies as well as for flood control.

Only meager information is available relative to the evaporation from snow and ice. Not only is little known as to the technique of measuring this evaporation, but no satisfactory means for its measurement have yet been devised with relation to either equipment or methodology.

Laboratory and field methods should be devised for the measurement of evaporation from snow and ice of various characteristics such as density, color (as might result from vegetal matter), thickness, etc. These methods should be correlated with variations in field conditions such as location of snow and ice, and characteristics of underlying surfaces of ground or water. Correlation of the evaporation from snow and ice with meteorological factors such as temperature, humidity, wind velocity, and insulation should be undertaken.

**Item No. 7. Evapo-transpiration Losses**

*Objective.*—1. The determination and evaluation of the factors which control the amounts and rates of evapo-transpiration losses.

*Discussion of objective.*—Consumptive use of water in connection with irrigation and the amount and rates of run-off to be expected from land surfaces are affected by evapo-transpiration losses. The rate of evaporation from soil surfaces depends upon the three general factors (a) size and shape of soil grains which determine the area exposed to evaporation, (b) the rate of movement, by capillarity, of the moisture upward from the water table to the soil surface, (c) transpiration from vegetal cover, which affects soil evaporation materially, depending upon the type and stage of development of vegetation.

Experimental work has indicated that it is impossible effectively to separate evaporation and transpiration losses from land surfaces, and it is therefore recommended that experiments be set up to include both evaporation and transpiration losses for various soils and vegetal cover.<sup>4</sup>

An endeavor should be made to determine the relationship between evaporation and consumptive use by crops and native vegetation, since with such data available, the evaporation from pans might be translated into consumptive use for the benefit of those attempting to estimate available water supplies and to determine rates of run-off from watersheds.

Evapo-transpiration studies have been made or are

under way in Arizona, California, Colorado, Florida, Nebraska, Oregon, and Utah and should be expanded to include all sections of the country. The investigation includes evapo-transpiration losses from (a) fruit trees, (b) field crops, including small grains, (c) native vegetation including water-loving plants, (d) various types of bare soils at different heights above the water table, (e) canals, ditches, and natural water courses, and (f) from natural ground water containing definite percentages of sodium chloride and other salts in solution, and from the waters used in irrigation.

One part of the investigation, dealing with evaporation, should determine the mechanics and physics of the evaporation of soil moisture, including a study of the upward movement of soil moisture by capillary action in relation to the rate of soil moisture loss by evaporation from the surface; the effect of air and soil temperature, wind velocity, relative humidity, and other meteorological factors on evaporation from soils; the effect of surface conditions of the soils, which would include the effect of cultivation and mulches, and the incorporation of organic materials into the upper horizon of the soil; the effect of diurnal and seasonal variations in evaporation from soils for which much of the data obtained in studying the effect of surface conditions of the soil could be used and could be correlated with continuous observations throughout the year.

Another part of the investigation concerns evapo-transpiration losses and includes the determination of the rate and amount of loss for different plants under standard conditions. It should include the development of standard conditions under which all plants could be compared and to which variations in conditions in various researches could be referred.

The investigation should determine also the relation of the evapo-transpiration losses to soil and air temperature, wind movement, insolation, and other meteorological factors; to soil moisture content and the evalua-

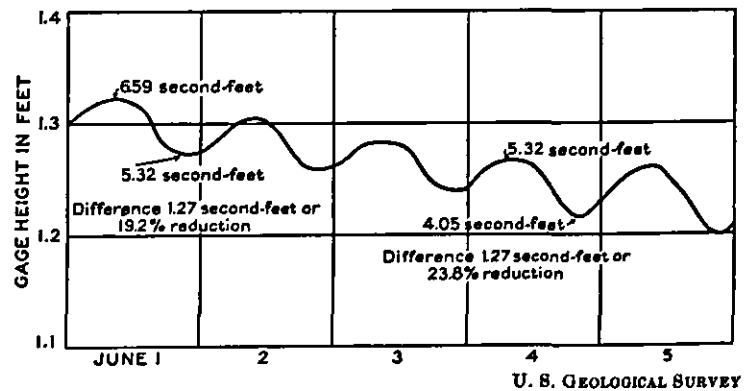


FIGURE 15.—Gage height graph of Owens Creek at Lantz, Md., June 1-5, 1932, showing the effect of transpiration on stream flow.

<sup>4</sup> A new approach to the determination of evaporation from soil and vegetal surfaces has been proposed by C. W. Thornthwaite and Benjamin Holzman, *Monthly Weather Review*, January 1939.

tion of the wilting coefficient; and to diurnal and seasonal variations under various vegetative and soil conditions. It should evaluate the effect of plant density upon evapo-transpiration losses, as there is some evidence that overcrowding may reduce foliage to such an extent as actually to decrease the total water losses. The effect of the depth of the water table and of heavy vegetation along ditch banks must be considered.

The correlation of the data obtained for evapo-transpiration with evaporation from pans, and the development of coefficients that will make possible the determination of the evapo-transpiration losses from evaporation pan observations should be made a part of the study of evapo-transpiration losses.

#### Item No. 8. Consumptive Use

*Objectives.*—1. The determination of farm and valley (basin) consumptive use in several areas with a wide climatic range.

2. The isolation and evaluation of nonbeneficial water consumption from total water consumption in areas having a wide climatic range.

3. The correlation of consumptive use with the major factors affecting it.

*Discussion.*—Consumptive use is defined as “the sum of the volumes of water used by the vegetative growth of a given area in transpiration or building of plant tissue and that evaporated from adjacent soil, snow, or intercepted precipitation on the area in any specific time.”<sup>5</sup>

A knowledge of consumptive use and the elements that comprise it is of particular importance in arid and semiarid regions where irrigation is practiced. It has also assumed importance in certain areas in the humid region, principally as a result of the effects of recent droughts. It is, therefore, essential to a determination of ultimate possible water developments in the river basins throughout the entire country.

In those areas where the need for supplemental water is vital, research is particularly important on the isolation of nonbeneficial water consumption from total water consumption, and on the separation of the nonbeneficial consumption into recoverable and nonrecoverable items. Some work of this nature has been

done in certain of the Western States, and an attack was made on the problem in connection with the Upper Rio Grande Joint Investigation.

Existing data should be collected and correlated with data on evaporation from free water surfaces and with various other meteorological data. A study should be made of total valley consumptive use or of information that will serve as an index to such use in those areas where adequate inflow and outflow data of proper quality exist, by studying the trend of change in valley consumptive use with changes in acreage of irrigated areas, type of vegetal cover, change in drainage development, etc.

A major field research project would involve a determination of valley consumptive use in typical areas in the arid region (where annual precipitation is less than 15 inches) chosen with regard to range in climate. This would involve largely the measurement of surface inflow and surface outflow, and the determination of accretion or depletion of ground water storage. Areas should be chosen where there is no appreciable movement of ground water out of the area. Other basic data needed in connection with such a study relate to (a) areas of crop and noncrop plants; (b) areas of free water surface; and (c) areas where the water table is sufficiently close to the surface to be a factor in evaporation or transpiration. Material changes in ground-water storage should be ascertained.

Other phases of such a field investigation should include (a) a determination of farm consumptive use from a well drained representative area in the valley where accurate measurement of the inflow, outflow, and ground water storage can be made; (b) tank and plot studies to determine the rate of evaporation from free water surfaces and from soil with the water table at various depths, and the evapo-transpiration factor for typical crop and noncrop plants growing within the valley; (c) the analysis of results isolating nonbeneficial consumption from total consumption within the valley, breaking down the nonbeneficial consumption into various classes such as evaporation from seeped areas and stream channels, and evapo-transpiration of noncrop plants; and (d) the correlation of results, particularly beneficial consumption, with factors which affect them, such as temperature, growing season, wind movement, etc. Such a study should be continued over a period of not less than 5 years.

<sup>5</sup> *Regional Planning Part VI.—Upper Rio Grande*, National Resources Committee, February 1938, Washington, D. C.

#### IV. Ground Water and Percolation

##### Item No. 1. Water Level Recorders and Artesian Pressure Recorders

*Objective.*—1. The improvement of instruments used for the measurement of water levels in observation wells.

*Discussion.*—The water stage recorders used in ground-water investigations are usually of either the float or the pressure element type. These types have been developed primarily for recording stream stages and are not sufficiently responsive to small or very slow fluctuations occurring in observation wells. Instruments of greater sensitivity are needed for use both in deep wells and in flowing wells.

Atmospheric pressure changes are reflected frequently in observation wells by fluctuations in water levels that have no bearing on ground-water discharge, recharge, or the quantity of stored underground water. A recorder which would effectively compensate for atmospheric pressure changes would be a valuable adjunct to ground-water investigation.

The first step in the improvement of existing instruments, or the development of new ones, is that of determining the needs of those organizations whose activities require the use of water level recorders in observation wells. A careful study of these needs by one thoroughly familiar with the operation and limitations of recorders now manufactured, and with existing patents, should make possible the stating of specifications for an improved recorder. Insofar as possible, the best features of existing instruments should be selected, and either by improvement thereon or by new design, an endeavor should be made to develop better instruments.

##### Item No. 2. Differences of Water Level Between the Inside and Outside of Cased Wells

*Objectives.*—1. The determination of the differences of water level between the inside and outside of cased wells under water table conditions and under artesian conditions.

2. The determination of the causes, magnitude, and the significance of the lag in fluctuations of water levels inside and outside of wells of various diameters.

*Discussion.*—The fluctuations of water levels in wells are not the effects of simple forces acting singly, but rather the resultants of complex interacting forces which greatly increase the difficulties of interpretation. A study of the effects produced by different rates of pumping, for instance, may be complicated through changes caused by variations in atmospheric pressure and by ocean tides, either singly or in combination.

All of these factors must be evaluated. If these fluctuations are observed under conditions free from other influences, much valuable information may be afforded on ground-water conditions in the area.

Included in these studies is consideration of a number of complex and obscure problems such as the rapid rise of water levels during rains and their subsequent rapid decline. It is believed that such rapid rise and decline do not represent equivalent recharge and depletion, but are due to unrecognized defects in well construction, effects of pressure produced by saturated soil, the air in soil interstices, or to other causes that have been suggested but not rigorously investigated. The barometric fluctuations that have been observed in water table wells seem to indicate that the water level in the well is not the true water table and therefore may be misleading as to recharge, unless the true conditions are understood.

A first step in these studies would be the delineation of those areas in which significant water level or artesian pressure fluctuations occur. The availability of observation wells in the more promising areas should be determined and the most suitable ones equipped with stage recorders. Supplementary observation wells should be installed as required, together with the instruments necessary to secure complete meteorological data.

The observations on water level fluctuations should be analyzed and correlated with data on meteorological phenomena and with data on the geology of the region in order to interpret and evaluate the factors that produce the fluctuations.



U. S. SOIL CONSERVATION SERVICE  
 FIGURE 10.—A ground-water observation well showing the stage recording instrument installation, reference point, and well cover. Located at the North Appalachian Experiment Station, Coshocton, Ohio.



**Item No. 3. The Relation of Ground-Water Fluctuations to the Texture of the Water-Bearing Material**

*Objectives.*—1. The determination of the relationship of the rise and fall of the ground-water table to the texture of the material in the capillary fringe.

2. The determination of the relationship of the texture of a water-bearing material to the specific yield of such material.

*Discussion.*—There has been but little extended research on the subject of the interrelationship existing between the free water surface in a well and the water in the capillary fringe and of the effect of texture upon the specific yield of an aquifer.

In a fine grained material, the earth is invariably moist for a distance of several feet above the water table, as a result of the phenomena of capillarity. Small communicating interstices form irregular capillary tubes through which water is drawn upward by molecular attraction and is held in this suspended position at a height above the water such that the molecular attraction of the particles is in equilibrium with the pull of gravity. This moist belt of variable thickness is designated as the "capillary fringe." It generally varies in thickness inversely as the size of the interstitial openings, being thin for material such as sand and gravel and quite thick in material with small interstices such as clay or silt deposits.

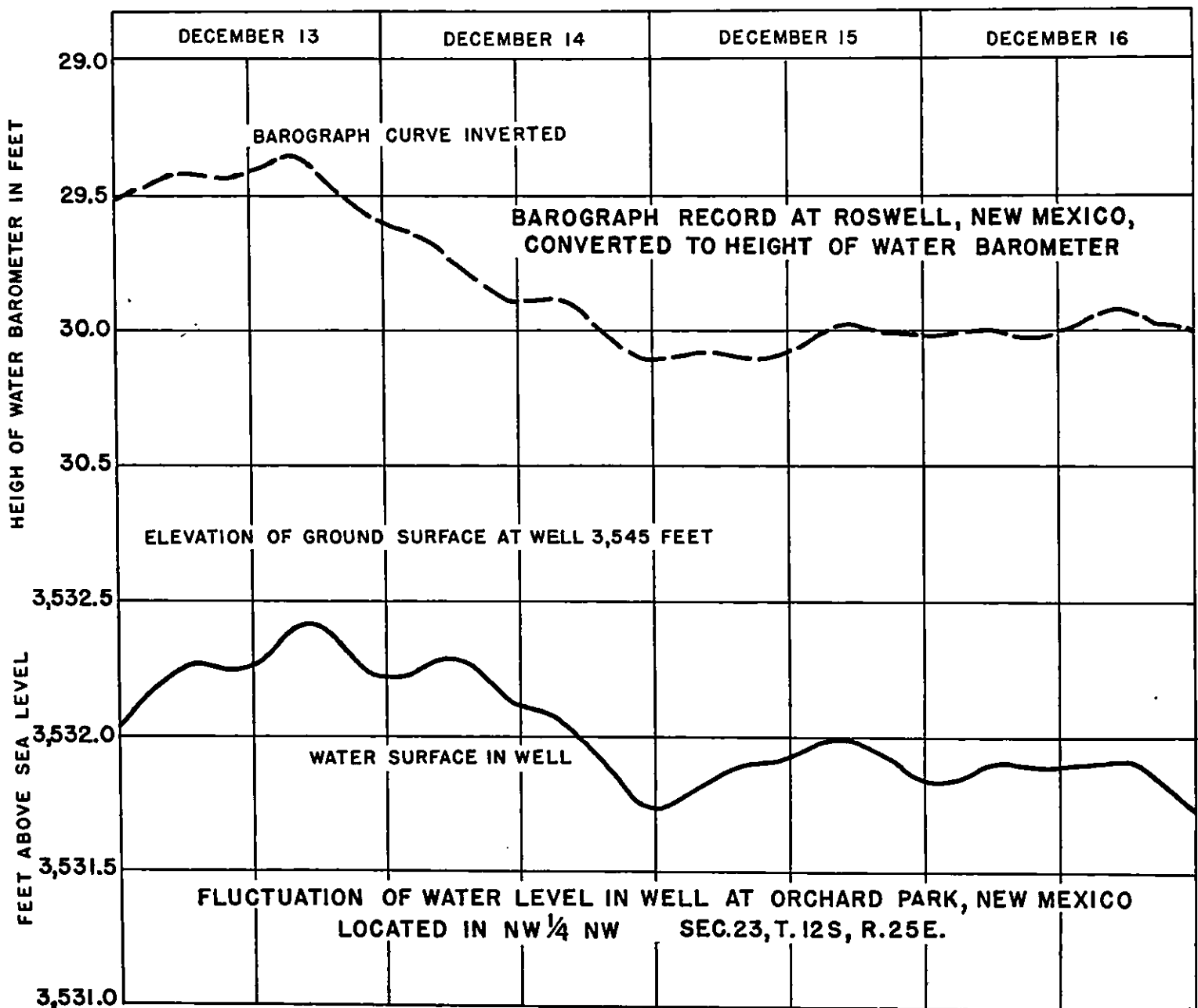


FIGURE 17.—Curves showing the fluctuation of ground-water levels with variations in atmospheric pressure. Fluctuations of this nature, when superimposed upon a recharge or discharge curve, may greatly complicate the accurate interpretation of such curves.

Because the capillary fringe is subject to considerable variation in thickness, as well as in the rate at which it can absorb or release water, the effect which it produces on the free water surface in a well is also a variable factor which must be considered in any intensive studies of infiltration and recharge.

A decline in the water table, for example, produces a temporary increase in the thickness of the fringe from which water will be slowly returned to the zone of saturation. A similar lag results from a sudden rise in the ground-water level. The movements of water to and from the capillary fringe present intricate problems, not well understood, that are fundamental to accurate determination of ground-water recharge and discharge.

The quantity of water that a saturated rock or fine grained material will furnish depends upon its specific yield or water-yielding capacity. Any change in the level of the water in the zone of saturation is reflected in a rise or fall of the water level in wells reaching the zone.

Existing methods of determining capillary effect and specific yield should be analyzed critically. The most promising modes of attack should be selected, or new methods for the study of these subjects in relation to water wells should be devised. In connection with the latter, consideration must be given to the fact that the characteristics of the material "in situ" may be quite different from those of the material usually tested in the laboratory.

Detailed field observations on water level fluctuations, effect of pumping, drawdown and recovery rates, temperature, etc., should be correlated and interpreted in the light of laboratory methods where possible.

**Item No. 4. Improvement of Methods for Determining Porosity, Permeability, Moisture Equivalent, and Specific Yield of Aquifers**

*Objectives.*—1. The evaluation of the methods of collecting and laboratory testing of samples used in ascertaining the porosity, permeability, moisture equivalent, and specific yield of water-bearing formations.

2. The evaluation of the field methods used in ascertaining the porosity, permeability, and specific yield of water-bearing formations, including consideration of the dye method, the Slichter electrolytic method, the Thiem method and the Theis recovery-of-head method.

3. The comparison of the relative accuracy and effectiveness of the field and laboratory methods used in determining the hydrologic properties of an aquifer.

4. The determination of the relation between the

physical characteristics and stratigraphy of the water-bearing material and the hydrologic properties listed above.

*Discussion.*—It must be realized that the conditions of laboratory tests do not accurately simulate the natural conditions under which water-bearing materials occur. For this reason, it is important to study the same problems by field tests to obtain comparison with laboratory tests. The approach to this problem lies in the observation of certain phenomena, such as fluctuations in head resulting from changes in rates of pumping. From an analysis of the draw down and recovery-of-head observations, the physical characteristics of the aquifer can be determined with reasonable accuracy. These are representative of average conditions because of the interrelation of the various physical properties of the aquifer.

Heretofore, studies have been rather largely restricted to those possible in connection with specific projects, and have not always been representative of natural conditions because of cost and other restraining influences. It is desirable to have funds available for the drilling of wells in critical areas and for making pumping tests under conditions that can be definitely controlled and that are free from the limitations imposed by the necessity of adapting the tests to the operation of public or industrial water works.

Studies should be conducted where possible in both artesian and non-artesian areas, free from disturbing influences, such as flowing wells, pumping wells, tidal fluctuations, etc., in order that the different field methods can be compared under identical conditions. The observation wells should include those of large diameter for pumping and others of smaller diameter to permit observations on the water level, and to permit the introduction of dyes, electrolytes, etc., used in certain of the field methods. The wells should be carefully constructed, and a detailed record of formations, including cores from the consolidated formations, should be compiled for each well.

Additional observations should also be made in different areas using the most satisfactory of the field methods, in order to determine the range in accuracy to be expected under different geological and hydrological conditions. In making such tests, attention must be given to other factors which may produce fluctuations in water level aside from those being studied at the particular instant.

The studies should include consideration of the effects of irregularities in capillary action in holding water above the water table and in reducing specific yield. Long, vertical soil columns, for draining over a period of one or more years, should be observed for change in yield during successive periods of time.

**Item No. 5. The Effect of the Physical Characteristics of a Material Upon its Porosity, Permeability, and Specific Yield**

*Objectives.*—1. The determination of the effect of the physical characteristics of size, shape, sorting, arrangement of grains, etc., on the porosity, permeability, and specific yield of a water-bearing material.

2. The development of improved methods for determining hydrologic properties of water-bearing materials.

*Discussion.*—The most common type of water-bearing material consists of deposits composed of rock fragments which have been more or less rounded by wear before they were deposited. In such deposits, the water is found in the irregular spaces between the rock particles.

Slichter, in his classical studies<sup>6</sup> on the motion of ground water, defined the relations of size, shape, and degree of assortment of grains to porosity. Other investigators have added to his basic studies and have contributed materially to the fund of knowledge on the movement of ground water.

The quantity of water available and the rate at which it can be supplied is dependent both upon the rate at which the aquifer is recharged and upon its porosity, permeability, and specific yield. Therefore, there is need for extensive studies to determine the effect of

<sup>6</sup> "Theoretical Investigation of the Motion of Ground Water"—United States Geological Survey, 19th Annual Report, 1899.

size, shape, and gradation of the component particles upon the permeability and specific yield of an aquifer. Such information would be of great practical value in connection with the development of ground-water supplies.

In evaluating the effect of the physical characteristics of the material composing an aquifer upon its hydrological properties, the tests should be designed to cover the gaps which exist in present research data. Starting with materials of simple shape and of uniform size, the investigation should be extended to include numerous tests on material of different shapes and sizes and in different degrees of assortment. Such tests should include microscopic examinations to determine the angularity of the smaller sizes of materials and the size of the interstitial spaces.

One function of the investigations outlined above should be the refinement of existing or the development of new methods of testing water-bearing materials.

**Item No. 6. The Compressibility and Elasticity of Water-Bearing Materials**

*Objectives.*—1. The determination of the processes involved in the compressibility and elasticity of water-bearing materials.

2. The determination of the magnitude of the compression and expansion of water-bearing materials under changes of pressure and of the magnitude of the lag accompanying the compression or expansion.



FIGURE 18.—Ground-water wells installed for the observation of ground-water levels and movements. Other groups of wells are located at intervals in and along the valley and the velocity of ground-water movement determined by electrical means. Coweeta Experimental Forest, N. C.

U. S. FOREST SERVICE

3. The determination of the temporary and permanent effects of changes of pressure upon the porosity, permeability, and specific yield of an aquifer.

4. The determination of the effects of changes of water level upon the sinking or rising of the land surface.

*Discussion.*—The study of these phenomena is important as bearing directly on the question of the source of artesian waters, whether by recharge or by removal from storage, and of the extent of permanent decrease in permeability of aquifers with reductions in pressure.

Some phases of this problem should be studied in the laboratory; others can be carried on in connection with studies of porosity, permeability, specific yield, and in connection with the construction of dams and oil-well drilling and technology. Certain phases will require observations during a considerable number of years in areas of heavy pumping, and for this purpose there is needed an assurance of the continuation of the necessary long-term program of water-level observations and pumpage records.

The subdivisions of the general program into specific phases for special investigation is not entirely apparent at this time, due to the inherent character of the project and the limited information available on the full significance of compressibility and elasticity.

The areas should be located in regions where the phenomena of compressibility and elasticity appear to exist in marked degree, as in the Dakota sandstone and in regions where the draft from wells and the resulting compression is reflected in subsidence of the land surface; also in areas such as the Bradford oil field in Pennsylvania, where water is being pumped into artesian strata under high pressure.

The Theim and Theis methods should be applied. It also will be necessary to inaugurate a long program of recording water levels, artesian pressures, and yield. In order that periodic measurements may be made of land surface subsidence, there must be careful instrumental leveling to tie in such areas with adjacent stable areas.

Laboratory tests should be conducted to determine the compressibility and elasticity of material from artesian aquifers. Laboratory methods should be devised for simulating compression and elasticity in order to carry out exhaustive tests leading to the determination of the effect of these phenomena on porosity, permeability, and specific yield.

The laws of wave propagation and related phenomena should be investigated and applied in a mathematical study of the rate of pressure movement effects in relation to the several physical properties of artesian aquifers. Precise tests should be made in the field and, if possible, in the laboratory, on rates at which pressure

effects are transmitted through water-bearing strata, the nature of the impulse that is transmitted, and its laws of propagation. The investigations proposed herein require the collaboration of the hydrologist and geophysicist.

**Item No. 7. The Relationship of  
Ground Water to Stream Flow.**  
(To be correlated with item 13, sec. V)

*Objectives.*—1. The improvement of present methods and the development of new methods for differentiating ground water run-off from surface run-off.

2. The determination of the effect of the geologic structure upon the movement of ground water to or from surface stream flow.

3. The correlation of ground-water levels with changes in ground-water run-off.

*Discussion.*—The correct evaluation of the role of ground water in producing stream flow is fundamental in evolving more effective ways of forecasting the latter, particularly during protracted periods of deficient precipitation. The "unit hydrograph" and the "channel storage" methods represent the most recent approaches to the problem of stream flow forecasting. Ground-water run-off, however, is dependent upon several major factors having no relation to meteorological conditions. The movement of ground-water may be either inflow or outflow or both, depending upon the stratigraphy and rock structure of the basin.

In order to distinguish between ground-water run-off and surface-water run-off the "channel storage" and



U. S. GEOLOGICAL SURVEY  
FIGURE 19.—Ground-water flow from Thousand Springs along the Snake River in south central Idaho. Surface stream flow is greatly stabilized by outflow derived from such sources.

"unit hydrograph" methods should be carefully studied and refined, and possible new methods developed in order more adequately to relate the minor fluctuations of effluent seepage with fluctuations in atmospheric pressure, transpiration, and other controls which have heretofore escaped attention. It is likewise essential that careful studies be made involving a variety of geological conditions, where an accurate determination can be made of the influence of the controlling geological structures.

The relation of the geologic structure to ground-water run-off and stream flow can be approached through the comparative study of drainage basins having relatively uniform geologic conditions throughout, and through detailed studies of specific basins with reference to the geologic control of the storage and movement of ground water. The entire subject of water perched on and in part discharged from the subsoil (B soil zone) and other surficial horizons of low permeability should be considered.

#### Item No. 8. The Use of Geophysical Methods in Prospecting for Ground Water

*Objective.*—1. The determination of the application and the relative value of electrical, seismic, gravimetric, magnetic, and other geophysical methods of prospecting for and investigating ground water.

*Discussion.*—Much of the information pertaining to ground water must be obtained from wells, but because of the lack of adequate well data, ground-water investigations have often been severely handicapped. Geophysical methods can be applied to determine approximately certain physical properties of the formations below the water table. Correctly interpreted, these data, correlated with those from other methods, should be of definite value in the study of ground-water phenomena.

Four principal methods of geophysical exploration are in use at the present time; the electric, the seismic, the gravimetric, and the magnetic. Each of these methods has been successfully used in studying earth structures which effect the occurrence of ground water. Studies should be made to determine the relationships between electrical resistivity and the texture of water-bearing materials.

The first tests in these investigations should be made in selected areas in which ground water occurs under simple conditions, i. e. fairly close to the surface and having a minimum of complicating factors. Geophysical tests (involving the methods being studied) should be made and test wells then drilled to the desired depths. Careful logs of the wells should be secured during drilling, together with samples of each of the unconsolidated formations, in as nearly their natural

conditions as possible. Cores from each of the consolidated formations should be secured for use in laboratory analysis. It is highly important, also, that samples of the water in each of the horizons be taken for chemical analysis. Tests of the cores secured should be made to determine the electrical resistivity of different textures, degrees of porosity, specific yield, and degrees of mineralization of the water.

The geophysical data should be correlated with the data obtained from the test wells and with the laboratory analyses. As the simpler problems are solved, the investigations should be extended to include areas where conditions are more complex and water-bearing material occurs at greater depths.

The use of resistivity methods in determining the rate and depth of rainfall penetrations should be carefully studied. It may be possible that by sinking an insulated shaft fitted with equally spaced electrodes or similar devices, the penetration of the moisture could be traced through measuring the changes in electrical resistivity at regular intervals.

#### Item No. 9. The Motion of Ground Water Toward Localities of Discharge

*Objective.*—1. The determination of the mathematical and physical laws relating to the motion of ground water toward localities of discharge.

*Discussion.*—The primary technical question involved in the utilization of ground water in any locality is the position of the water level or piezometric surface at some future time under the influence of an actual or assumed regimen of discharge by wells. This question is involved in the economics of development of a new district, as its answer indicates the safe yield, or maximum perennial yield that it is practicable to obtain. The answer also indicates the consequences of withdrawal in excess of the safe yield either in the lowering of water levels beyond the limit of economic pumping or in the inflow of nearby waters of unsuitable quality, especially on sea coasts.

Nearly all ground-water bodies may be assumed to have been, under natural conditions before the sinking of wells, in a state of approximate dynamic equilibrium with the average recharge adjusted to the average natural discharge. The introduction of wells into this natural hydraulic system represents a new discharge superimposed upon that existing previously. As a consequence, the movement of water through the entire ground-water body is changed to some extent by the diversion of water to the new discharge. This diversion must be accomplished by a change in the hydraulic gradients and by a lowering of the water table or piezometric surface at the well. The lowering of the water table or piezometric surface necessarily

involves the extraction of some water from storage and this must continue until a new equilibrium is established; the recharge being balanced by the aggregate discharge from the old natural outlets and the new artificial outlets. In other words, assuming no

important secular or long-term cyclical climatic change, abstractions from storage must take place, and water levels must fall, until the artificial discharge is balanced either by an increase in the recharge, or a decrease in the previously existing natural discharge. The length of time necessary to attain the new equilibrium varies with different water bodies. Other conditions being equal, it will be shorter in artesian than in nonartesian aquifers; in materials with a low specific yield than in those with a high yield; in aquifers with a high permeability than in those with a low permeability; and in small water bodies where points of recharge and natural discharge are relatively close to the developed area than in large water bodies.

Mathematically, the basic laws of flow of ground water, as pointed out by Slichter and others a generation ago, are closely analogous to those involved in heat conduction and in electricity. Therefore, much of the extensive mathematics of these two sciences can be transposed to ground-water hydraulics by competent mathematical physicists through a change of dimensions. It seems probable that approximate formulae and concepts, perhaps accurate within the range of error necessarily involved in the ground-water data, can be so transferred as to solve many practical problems in ground-water hydraulics.

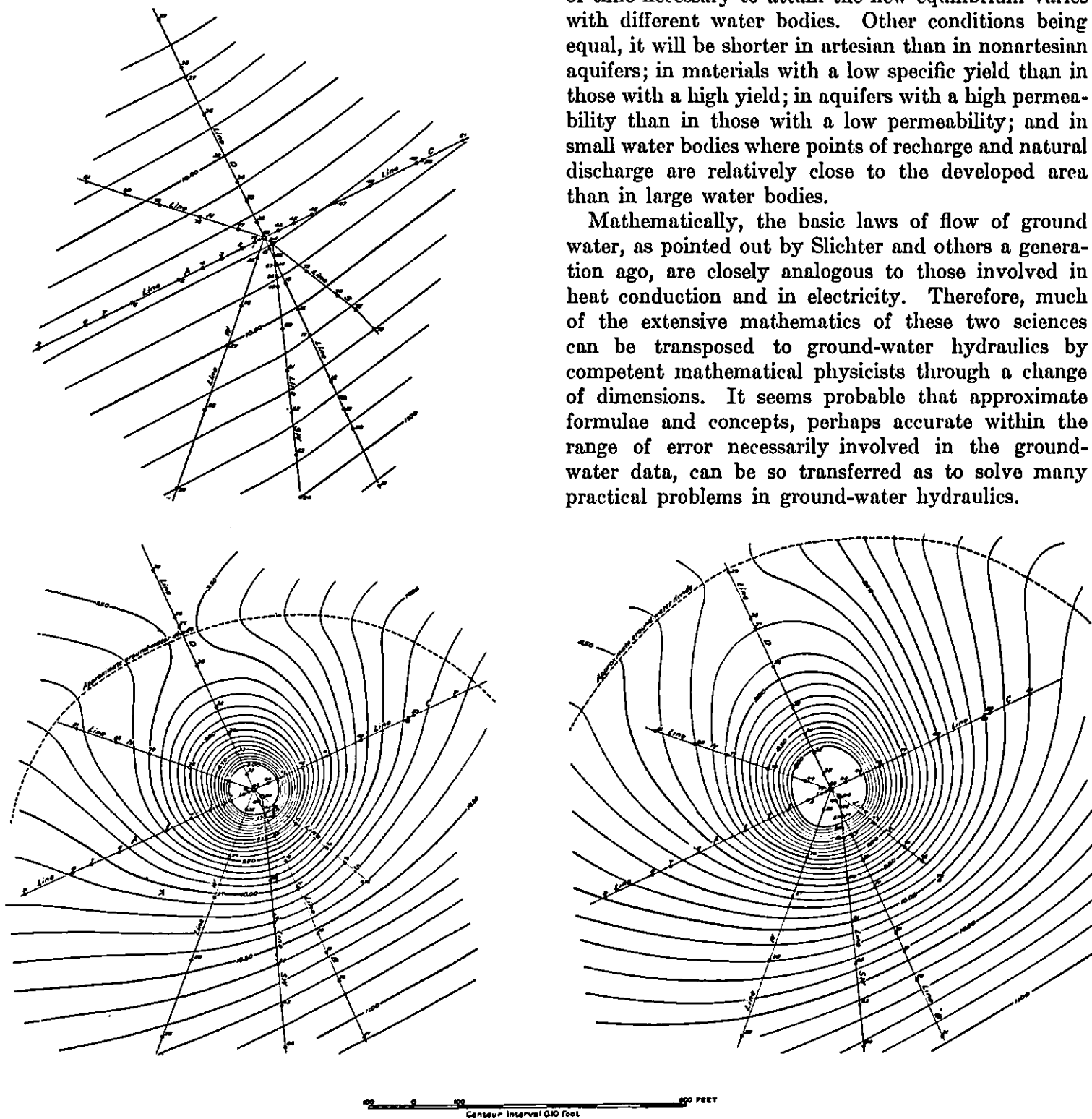


FIGURE 20.—The cone of depression formed around a pumping well. At the upper left is shown the slope of the water table; at the lower left the cone of depression after 12 hours pumping; and at the right, the cone of depression after 48 hours pumping. Continued pumping may result in diversion from adjacent subsurface watersheds. (See fig. 21.)

Such problems may concern, in homogeneous materials, the shape of the cone of depression at various times due to pumping for comparatively short periods, the rate of recovery of water levels in previously pumped wells, the determination of permeability and specific yield from the shape of the cone of depression during pumping, the determination of permeability merely from the rate of recovery of a pumped well, the characteristics of bank storage in certain reservoirs, and the motion of ground water in the vicinity of drains.

Certain factors in ground-water hydraulics however, apparently have no analogues in the theories of either electricity or the conduction of heat. Among such factors are the hydraulic interaction of the capillary fringe and the water below the water table, and the change in the ability of an aquifer to carry water as the water table is drawn down and consequently the cross-sectional area available for flow is decreased. Hence many problems connected with the movement of water in an aquifer are peculiar to the subject itself, and a solution for these problems cannot be borrowed from the mathematics of other sciences. Among such problems are the shape of the water table in earth dams, and, of great importance to ground water hydrology, the effects of long-continued pumping of nonartesian water in an area having initially a sloping water table.

Another aspect of such a mathematical study is its probable value as a means of geophysical exploration.

The discharge of a well generally entails an observable movement of the ground water for a considerable distance around it. This movement is affected by the physical characteristics of the aquifer in the area involved. The hydraulic phenomena at the well itself are therefore affected in some degree by the physical conditions in all of the part of the aquifer affected. It is therefore within the realm of possibility that close observation and interpretation of water levels and discharges of wells may give clues to the characteristics of the aquifer at some distance.

It appears possible that through the proper interpretation of pumping tests clues may be found to discontinuities in the aquifer caused by faulting, interfingering of sediments, or other causes.

The solution of problems dealing with an idealized aquifer, under assumptions of homogeneity and isotropy and a capacity to transmit water independently of the pressure, should be attempted. This phase of the study is analogous to the problems of the conduction of heat in solids. Primary problems include the interrelations at any time between the lowering of the piezometric surface, the duration and amount of discharge, and the permeability, specific yield, and thickness of the aquifer when: (1) a well is discharged at a uniform rate for a given time; (2) a trench is discharged at a uniform rate; (3) the water level in a trench or other linear feature is changed a fixed amount

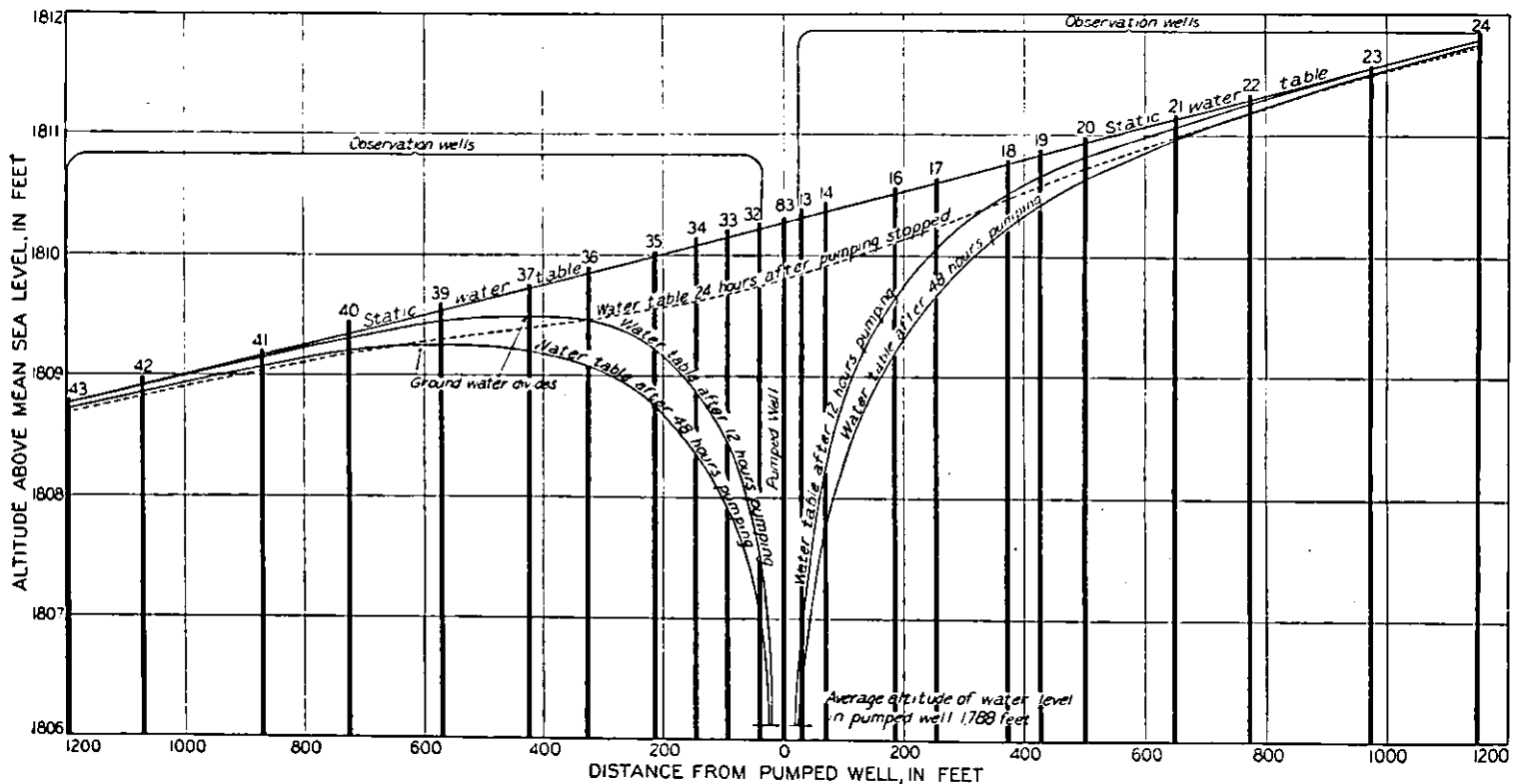


FIGURE 21.—A sectional view of the cone of depression of the pumped well shown in figure 20. The section is taken along the line B—D.

and thereafter held constant. These are the approximate theoretical ground-water problems involved respectively in: (1) pumping well or a localized group of wells; (2) pumping a series of wells closely spaced in a more or less linear pattern; (3) constructing a drain in areas of high water table or impounding water in a more or less linear reservoir. These results should be assembled in the form of diagrams and tables suitable for the convenient use of engineers and hydrologists.

The extension of the mathematical treatment of the more complex problems actually found in nature should be undertaken, taking into account so far as possible, actually known heterogeneous and anisotropic characteristics of the aquifer and changes in its ability to conduct water as the water table is lowered, or in the

case of artesian aquifers, as the aquifer is compacted by the release of internal pressure.

The basic theory of model analysis applied to ground water should be developed with the aim of constructing models using fluids, heat, or electricity, to solve problems in ground-water movement too complicated for mathematical analysis.

Mathematical research must deal with idealized media simpler than those actually found in nature. As a consequence, all mathematical deductions should be checked in the field, and, to some extent in the laboratory, to ascertain whether or not the simplifying assumptions are valid within allowable limits of error. This requires a close cooperation between investigators engaged in quantitative field problems and those engaged in theoretical research.

## V. Run-off and Stream Flow

### Item No. 1. Run-off from Snow Cover

*Objective.*—1. The determination of the water yield from snow cover as affected by watershed characteristics and climatic factors

*Discussion.*—Equal accumulations of winter snowfall often produce widely varying amounts of spring run-off and diverse flood peaks. Water is normally released from a melting snow mantle through rising temperatures, warm rains, or a combination of the two; the effect of solar radiation; and condensation from warm, damp winds. Elevation, particularly as it is related to temperature, is also a contributing factor. It is not only desirable to know the total amount of water available within the snow mantle, but also to be able to predetermine the circumstances under which it will be released and delivered to points of ultimate use on the lower reaches of the stream system.

This research project is designed to disclose the factors that determine run-off from snow and their interrelation. The first phase deals with a study of the factors involved in the melting of snow and their relation to total run-off from snow and the rates of such run-off. Studies should be conducted on the effective combinations of rising temperature and rainfall to produce excessive run-off from a snow mantle; the temperature at various snow depths; temperature divergences between valley and mountain stations; the effect of vegetal cover on the melting of snow, both in forest areas and in the open; the effect of chinook winds on snow cover; the effect of intermittent melting and freezing upon snow density and ultimate run-off; the value of late snows in protecting old snow against premature melting; the damping effect of an existing snow mantle on run-off from rainfall; and the relation be-



U. S. FOREST SERVICE  
 FIGURE 22.—Apparatus used for simulating the conditions under which run-off from melting snow is absorbed by a soil in flowing over the soil surface. Developed and used by the Forest Service in the Boise National Forest.



tween precipitation at mountain valley stations and adjacent snow courses.

Included also in this phase of the investigation should be (a) studies of mass curves of degree-days above freezing and their slope up to the time of maximum run-off from snow on different drainage basins; (b) the determination of the snow melting constant or quantity of snow reduced to water, per degree-hour of temperature excess above 32° F.; (c) a determination of the factors that control the depth and volume of slush or water held as capillary water at the base of a melting snow bed; and the relation of the thickness of this layer to snow density and its transmission capacity, or the rate of flow of this capillary water down the slope.

The second phase of the investigation concerns the surface conditions in the drainage area, which control losses to the run-off from melting snow. A quantitative determination of run-off from melting snow will depend largely upon the success with which those factors can be evaluated that control the amount of melted snow lost to run-off through infiltration, transpiration, and evaporation. It is therefore essential that more basic knowledge be secured through research regarding the relation of the rate of snow melting to infiltration; the relation of the rate of snow melting to ground-water levels; the depth of frost penetration under various conditions of temperature, exposure, and vegetal cover; the effect of ground-water conditions of the preceding season or seasons on the relation of run-off to snow cover; the effect of fall soil moisture upon the depth of freezing and upon the percolation of melting snow; the effect of early and later snowfall, with respect to deep freezing of soil, on the percolation of melting snow; the effect of high winds in moving appreciable quantities of snow from one basin to another; the evaporation from the interior of snow masses and from snow surfaces on the ground and on vegetation (see item 6, sec. III); the

disposal of melt-water in the snow mass above the base layer (this includes the effect of refreezing when temperatures fall below 32° F. at night, and the effect of recrystallization and change of snow structure and density by melt-water as it passes down through the snow layer); and the evaluation of the time lag and storage lag between surface melting and appearance of water in streams.

The last phase concerns the determination of the effect upon run-off of the precipitation occurring after the completion of a snow survey. During intervals between snow surveys and after they have ceased for the winter season, precipitation may occur in the form of either rain or snow, and may modify the conditions of snow cover as previously observed. Methods for taking into account this precipitation increment should be determined, both from the viewpoint of snow on the ground and its water content.

#### Item No. 2. Stream Flow Under Ice Conditions

*Objective.*—1. The development of improved methods of determining stream flow under ice conditions.

*Discussion.*—The publication of Water Supply Paper 337<sup>7</sup> in 1913 represented a critical review of the effect of ice on stream flow and on stream flow measurements as of that date. Since then, developments in equipment and procedure have been such as to make a revision of this report highly desirable. There is particular need for an exposition of the effect of ice on the flow of small streams, those draining a few square miles, such as are being studied extensively by various agencies.

Such an investigation would be accomplished largely by a compilation and critical review of the developments in instruments and procedures now in use.

The effects of ice on stream flow, through a reduction in channel size for a given gage height and an increased frictional resistance because of the ice covering, should be studied. Adjustments in gage heights for reduction in flow should be correlated with such factors as temperature, precipitation, total flow of the stream, etc., for drainage area of various sizes.

#### Item No. 3. Flow Duration Curves

*Objective.*—1. The determination of types of flow duration curves applicable to drainage basins in different localities.

*Discussion.*—By plotting flow duration curves on the basis of flow as a percent of mean flow, it is often possible to compare curves from different rivers in the same general region and to determine type curves for such regions which will be of value in extending the use of stream flow data to streams which have not been gaged.



U. S. CORPS OF ENGINEERS  
 FIGURE 23.—Ice on the Ohio River at Van Port, Pa., February 21, 1936, before the flood. Stage-flow relationships are greatly affected by ice, and flow determination becomes exceedingly difficult.

<sup>7</sup> Water Supply Paper 377, "The Effects of Ice on Stream Flow," W. G. Hoyt U. S. Geological Survey, 1913.

Flow duration curves should be prepared with a suitable time base to include all available records. These curves should then be compared and studied, both singly and in terms of composite curves for well-defined regions. Equations may then be derived which will express stream flow in terms of a flow duration curve applicable to a given region or basin.

#### Item No. 4. Interpolation of Missing Run-off Data

*Objective.*—1. The determination of the relative accuracy of various methods of interpolating missing records of daily, monthly, and annual stream flow.

*Discussion.*—The flow records of a stream are frequently found to be missing for periods varying from a few days to entire seasons for a particular station and in order to obtain a continuous record such missing records must be estimated.

It is the purpose of this study to determine the relative accuracy of various methods customarily in use for estimating such missing records, and to ascertain the most desirable method to be used under given hydrological and physical conditions.

The different methods in use or derived in estimating streamflow for various periods (daily, monthly, seasonal, and annual) should be checked against actual records of stream flow for similar periods. For each type of missing record (daily, monthly, or annual) studies should be made to determine the relative accuracy of the different methods used when missing records are assumed to occur during periods of high, medium, and low stream flow; the relative accuracy of different methods for different lengths of period of missing record; and the influence of hydrological and physical characteristics encountered in various drainage basins upon the accuracy of the methods used.

#### Item No. 5. The Extension of Short-Time Stream Flow Records

*Objective.*—1. The determination of the validity of existing methods of extending stream-flow records, and the development of new methods.

*Discussion.*—Many records of stream flow of relatively short length are available at given points in drainage basins. In making hydrologic studies, it is desirable frequently to expand these short-time records to embrace a period of sufficient length to include wide variations in occurrence, so that conclusions reached in the study may have the highest practicable reliability.

Numerous methods in use for accomplishing this purpose give results of varying quality and accuracy. The method used in a particular case may depend upon the judgment or experience of the person making the study, the time available for making it, the availability of data, the quality of results desired, etc.

It is the aim of this research to test the accuracy and quality of estimated records obtained by the use of various methods, to determine the effect of different hydrological and physical characteristics upon such accuracy and quality, to develop new methods if possible, and to test the results obtained by the use of these new methods.

Drainage basins should be selected where records of stream flow are available for periods of at least 30 to 40 years. Care should be exercised to see that the records are of good quality and that diversions, importations, or regulation above the station where the records are taken, have not affected the natural flow or that the records show exactly to what extent the factors named have affected the natural flow. In most cases the estimated records will be for seasonal or annual run-off, although in some instances monthly records may be developed.

Various methods, particularly those in general use in the locality, should be used for extending records, and the extended records obtained by each method should be checked against the actual records for the period. The accuracy and quality of estimated records should be appraised by the application of such statistical measures as the coefficient of correlation; the coefficient of variation; the probable error of the mean for a given period; the ratio of the maxima and minima to the mean and to each other; by flow duration curves, etc.

The research should include studies of the accuracy and quality of (a) complete records derived by various methods; (b) derived records for periods of extreme high and low stream flow; (c) estimated records based on short-time records secured during periods of high, moderate, and low flows; (d) the increase in accuracy and quality of estimated records with increase in length of the base records; and (e) the effect upon the accuracy and quality of estimated records resulting from varying the assumptions made in the use of a given method.

Similar studies should be conducted to determine the influence of hydrological and physical characteristics encountered in various basins upon the accuracy of the methods used; to determine the accuracy and quality of estimated records obtained through the development of new or improved methods; and to compare the results obtained by the application of each method to different types of streams and to streams affected by widely different hydrologic conditions.

#### Item No. 6. The Estimation of Run-off in the Absence of Stream Flow Records

*Objectives.*—1. The determination of the validity of existing methods and the development of new methods of estimating run-off from drainage basins for which no actual run-off records are available.

2. The determination of the effects of various hydrological and physical characteristics of basins upon the accuracy and quality of results obtained with such methods.

*Discussion.*—The occasion frequently arises where it becomes necessary to estimate run-off (mean, seasonal, or even daily) from a drainage basin for which no actual stream-flow records exist. This investigation is designed to test the accuracy and quality of estimated records, arrived at by the various methods, by comparing them with actual records of run-off for drainage basins of more or less similar hydrological and physical characteristics, and also to test the accuracy and reliability of new methods which might be developed during the course of the study.

This investigation is similar to the studies proposed on the interpolation of missing run-off data (sec. V, items 4 and 10) and differs only in the fact that, instead of having short-time records available for study, no records exist for the streams being studied. The basins selected for comparison should have records of considerable length and of good quality. The methods used for estimating run-off should include all of those in customary use in the localities.

The studies should include an investigation of the relative accuracy of (a) estimated mean run-off for periods of various length, and for periods of high, normal, and low run-off; (b) for extremes of run-off; (c) complete estimates of run-off as derived by various methods; (d) the influence of hydrological and physical characteristics of various drainage basins upon the accuracy of the different methods in use; and (e) the effect of the variations in the assumptions made in connection with a given method upon the accuracy of estimated records.



#### Item No. 7. Run-off Estimates Based on Partial Drainage Areas

*Objective.*—The development of improved methods for estimating run-off from drainage areas by the use of measured run-off from small tributary drainage areas.

*Discussion.*—It often becomes necessary to estimate run-off from a drainage basin for which no data exist, but where records are available on one or more of the minor subdrainages. Methods have been proposed for the routing and assembly of flows from subdrainages constituting in whole or in part the drainage basin of a larger stream. Reference may be made to a number of papers in the Transactions of the Geophysical Union, the publications of the American Society of Civil Engineers, and in the proceedings of the Upstream Engineering Conference in 1936.<sup>8</sup> If these methods are tested and found satisfactory, or if better methods are developed, a more rational procedure of estimating stream flow will result which will be of great practical importance.

Small drainage areas (preferably less than ten square miles) for which records of flow are available, lying within a larger basin for which stream-flow records are also available, should be selected for the study. Methods for estimating the flow of the larger basin based upon those of the small drainage basins should be checked against the actual flow records of the larger basin. The improvement of existing methods and the possible development of new procedure should result from the research.

#### Item No. 8. Run-off Records from Small Drainage Areas

*Objective.*—1. The development of improved methods for obtaining records of run-off from small drainage areas.

<sup>8</sup> *Headwaters, Control and Use*, United States Government Printing Office, Washington, D. C., April 1937.



U. S. FOREST SERVICE

FIGURE 24.—Two views of the gaging station operated by the Geological Survey on Duck Creek in the Copper Basin area of Tennessee. Smelter fumes have completely denuded the area of vegetation resulting in a rapid run-off and heavy erosion. The discharge shown occurred within one hour after a moderate rainfall over the 13.0 square mile watershed. A maximum run-off of 7,080 second-feet (545 c. f. s./s q. mi.) was recorded on April 6, 1936.

*Discussion.*—Data on run-off from small drainage areas of less than 2 or 3 square miles are important in the study of hydrologic phenomena, as these areas may be studied intensively. The physical and other characteristics of the drainage area and existing hydrologic conditions affecting run-off may be determined with greater detail upon these small areas than upon larger ones. Information on the run-off from such small drainage basins is also of value in the proper design of highway and railroad culverts, of check dams and other similar structures, in the design of sewers and drains for paved and unpaved city areas and in connection with soil conservation methods.

The comparatively small amount of basic run-off data, available from such areas, has been obtained through the use of current meter stations, usually with some form of weir or other artificial control. It is essential that improved methods be developed, and that the practicability be explored of using calibrated laboratory models of the control and stream channel in its vicinity as a means of obtaining better results at gaging stations.

All existing gaging stations with drainage areas ranging from a few acres to several square miles should be listed, showing methods used in obtaining discharge, the range in discharge, difficulties encountered in the studies, probable accuracy of the results, and any other pertinent information. (The cooperation of the Geological Survey, the Forest Service, and the Soil Conservation Service will be valuable in this compilation.) These data should be analyzed and conclusions drawn as to the adequacy and accuracy of methods now in use.

A number of the stations which can be considered as representative of the locality are located in different sections of the country and are equipped with either weirs or other controls. From these, appropriate stations should be selected and careful surveys of the streams made in the vicinity in order that models of the controls may be tested or calibrated. The model calibration measurements should be made at the nearest available stream-flow laboratory so that the test data can be used with gage heights at the actual stations in making estimates of discharge.

Results based upon the model calibrations should be compared over a period of time with those obtained from the actual station. The comparison and study of results obtained and of relative costs should indicate the practicability of this method of obtaining stream-flow records and serve as a basis for future procedure.

#### **Item No. 9. The Scour, Transportation, and Deposition of Silt**

*Objective.*—1. The determination of the laws governing scour, transportation, and deposition of silt by flowing water.



U. S. SOIL CONSERVATION SERVICE  
 FIGURE 25.—Gaging stations on small streams must have a control weir so designed as to magnify stage-discharge relationships for low flows. The control weir shown, known as the Columbus notch, is designed to permit the accurate measurement of small flows. The banks are shaped and sodded to provide stable stage-discharge relationships for high stages.

*Discussion.*—The scour, transportation, and deposition of silt are phenomena which must be dealt with in studies of aggradation and degradation of stream channels and water courses, and of infiltration and other related phenomena. Their influence enters also into many hydrologic problems of great economic importance, such as erosion control, silting of reservoirs, silting of streams and canal systems, the irrigation of lands with silt-laden waters, the replenishment of depleted ground-water supplies by water spreading, the control of scour below dams, and many others.

The scour of a material by flowing water is influenced by a number of factors such as the properties of the material through or over which the water flows, its texture, structure, and state of aggradation, the type of vegetal cover which may exist in the channels or on the surface through and over which the water is flowing, and the quantity and kind of material being transported by the stream, either as bed load or in suspension.

Other factors influencing these phenomena include the quantity, velocity, and turbulence of the flowing water, its depth of flow and the shape and specific gravity of the material subject to the action of the water. The depth and extent of the water into which a silt laden stream is discharged will influence the deposition of the material. The temperatures of the respective waters may possibly influence the deposition. Relative temperatures and specific gravity of intimate mixtures of fine silt determine whether or not a silt-laden stream will pass through a reservoir.

Empirical formulae have been developed in an attempt to solve the source of the problems of scour, transportation, and deposition of silt, but these are limited in their application to the specific locations and types of material upon which the formulae are based. A considerable amount of information has been col-

lected by various agencies in the United States and abroad, but in most cases it has not been subjected to exhaustive analyses nor has it been fully utilized. Many phases of the problem have not been investigated and many basic data are still lacking.

The investigation should include exhaustive analyses of the results of previous investigations to determine the quantitative relationship of the above mentioned factors to scour, transportation, and deposition by flowing water and to determine and evaluate any other factors not included above. The analyses should indicate what further observations and experimental data are necessary to define the natural laws governing the phenomena and should define the laboratory and field investigations necessary to verify the conclusions made and to reach new ones.

**Item No. 10. The Development of Methods for Synthesizing Stream Flow Data**

*Objectives.*—1. The determination of run-off resulting from the influence of causative factors taken in any desired combinations.

2. The determination of the effect of changes in one or more of the causative factors upon the accuracy of forecasting of run-off resulting from a known sequence of observable phenomena.

3. The development of methods for the synthesis of stream flow data from observed hydrologic and physiographic characteristics of the drainage basin.

*Discussion.*—The occasion sometimes arises wherein



U. S. FOREST SERVICE

FIGURE 26.—A gaging station in the San Dimas Experimental Forest showing the type of station used in measuring silt-laden flow from mountainous areas. The V-notch weir is used for measuring small flows.

the run-off characteristics of a drainage basin must be determined and stream flow data synthesized without recourse to even fragmentary records on either the stream itself or on adjacent streams of apparently similar characteristics. Under such conditions there are available only generalized data on climatic and topographic characteristics of the basin, and essential features of the synthesized stream flow, such as seasonal distribution, maximum and minimum rates and volumes, and the total flow, must be determined from an analysis of those factors which influence run-off.

There are many proposals which contemplate the modification of some factor or factors which actually or presumptively influence stream flow, such, for example, as different size flood control reservoirs, various kinds of land use and treatment, spreading of flood waters, etc. The determination of the fact and character of such influence involves, in considerable measure, the application of synthesizing procedures in the determining of the run-off resulting from an assumed combination of factors.

The synthesizing procedures are of major significance also in forecasting run-off with respect both to rates and volumes, an increasingly important service in the regulation of streams canalized for navigation and in the operation of flood control reservoir systems. If it is assumed that pertinent causal factors are known or can be determined, the problem then becomes one of predicting the result of their integration as reflected in stream flow.

The proposed project involves the complete and enlightened analysis of the influence upon stream flow of antecedent soil moisture, surface detention, lake and channel storage, ground-water contributions varying from surficial to deep ground sources, etc. The proposal embraces all scientific investigations of stream flow phenomena which elucidate procedures for estimating stream flow in the absence of direct measurements and in a form suitable for practical application.

The techniques to be employed in this type of investigation are in a state of rapid change and development, and it is essential that investigators should be familiar with current progress in order that their efforts may be wisely directed. The field is broad and may embrace widely diversified projects involving many phases of the hydrologic cycle. It includes the analysis of phenomena associated with the unit hydrograph, recession hydrograph, channel storage, infiltration, etc., in which there is a steadily growing fund of information and with which familiarity is essential to the wise direction of effort.

It is contemplated that the investigation will be related primarily to existing meteorologic, hydrologic, edaphic, geologic, biologic, and other relevant factors. In the application of the results of these investigations,

preliminary work would involve the checking of synthesized run-off data, prepared for a particular stream, against the actual flow records of varying lengths and the evaluation of the relative effect of the different factors by altering the combination used. These data and factors could then be used in synthesizing records on other streams even though the combination of factors might differ widely from those used in the preliminary work.

#### Item No. 11. Special Methods of Estimating Flood Flow

*Objectives.*—1. The development of discharge coefficients and characteristics of dam crests for use in estimating flood discharges.

2. The development of improved methods of estimating flood discharge by means of the changes in water surface gradients through restricted channel sections.

3. The refinement of the slope-area method of estimating excessive flood flows.

*Discussion.*—Gaging station controls are not always available or operative for the measurement of stream flow during periods of excessive discharge and it becomes necessary to supplement actual measurement with estimates of the flood flows after the flood. Special methods are warranted in these cases even though the accuracy of such results may not be comparable to that of the customary measurements. Among the more important types of special methods available for use in estimating excessive discharge are, in relative order of accuracy: (a) The calibration of overflow dams and chute spillways; (b) the measurement of flow by observing the change in water surface gradients through restricted channel section such as exist at bridge piers, abutments, etc., (c) the slope-area method which makes use of the cross-sectional area of the channel and the slope of the water surface profile in estimating quantity.

The use of overflow dams and chute spillways offer probably the most reliable means of obtaining supplemental data provided accurate discharge coefficients are available for the discharge section under various degrees of submergence. Compilations of discharge coefficients and other data pertinent to estimating discharges over dams and other types of overflow crests may be found in Water Supply Paper 200<sup>9</sup> and in reference D-9, of appendix E. Many supplemental investigations have been conducted in recent years and data have been assembled in the files of Federal and other agencies and in the technical literature. There is a distinct need for this information and it should be brought together and correlated.

The contracted channel section offers a medium whereby flood discharges may be estimated by observa-



U. S. GEOLOGICAL SURVEY  
FIGURE 27.—An example of a section of stream used in "slope-area" determinations of flood discharges where a current meter gaging station is impracticable. This is a better-than-average reach for this kind of measurement because of its stable channel and freedom from trees and other flow impediments.

tion on the changes in surface water gradients. Methods for the calculation of discharge through such sections have been developed by the Miami Conservancy District. Additional investigations have been conducted by the United States Waterways Laboratory and the Department of Agriculture in cooperation with the University of Iowa. The methods evolved have not received very wide acceptance and the real potentialities of the contracted section as a flow meter yet remain to be demonstrated. Much of the hesitancy in using the restricted section for this purpose perhaps has been due to the instability of the channel when located in an erodable bed.

The slope-area method of determining flood discharge affords a means of estimating flow where no better method is available. This method as applied is far outside the field of experiment and ordinary experience and has, of necessity, been used to determine flood flows under conditions of extreme turbulence and where debris, sediment, and entrained air were present in unknown quantities. Although heretofore considered a method of last resort, the slope-area concept is useful as a practical approach to estimating excessive discharge and as a means of testing and strengthening results obtained by other methods, especially when used by persons of wide experience in this field.

Each of the above special methods are in need of further investigation and refinement. Careful examination and analysis of field data should throw light upon the practical application of the principles involved. Investigation in the laboratory should prove valuable in establishing the characteristics of different types of dam crests and contracted sections by the use of scale-prototype relationships.

The study of the slope-area method in the laboratory may be possible and should be investigated although

<sup>9</sup> *Weir Experiments, Coefficients and Formulas*, (Revision of Water Supply Paper 150), R. E. Horton, U. S. Geological Survey, 1907.

the extreme conditions of turbulence, entrained air, debris, and silt load encountered in nature may be difficult to simulate in a laboratory investigation.

**Item No. 12. The Effect of the Manner of Precipitation Occurrence Upon Run-off**

*Objectives.*—1. The determination of the effect of variations in distribution and intensity of precipitation during a given period upon the run-off for that period.

2. The determination of the effect of the amount, distribution, and nature of precipitation occurring prior to a given period upon the run-off for that period.

*Discussion.*—It is well recognized that the run-off from a given drainage basin varies with the precipitation upon the basin. The rate as well as the total amount of run-off will vary, during a given period, with the variation in intensity and distribution of precipitation occurring in that period, and also with the antecedent amount, distribution, and nature of precipitation.

In making studies of stream-flow and run-off for drainage basins where records do not exist, or where they are of short duration, it becomes necessary to know the

effects of variations during and prior to a given period in order to arrive at estimates of reasonable accuracy. For example, a year during which 20 inches of rain fell upon a drainage basin might be expected to show a certain amount of run-off, if the rainfall was evenly distributed. If the rainfall occurred within a few months, the run-off would be much greater; if a considerable proportion of it occurred during a few heavy storms, the run-off would be still greater. Furthermore, if the precipitation during the previous season was 35 inches, the run-off might be much greater than if the previous season's precipitation was but 12 inches.

This study is designed to determine both qualitatively and quantitatively, the influence of variations in the manner of precipitation occurrence upon the run-off from representative drainage basins in the country, and to ascertain the effects of variations in hydrological and physical characteristics upon such influence.

The effect upon run-off of various manners of distribution of given amounts of precipitation occurring during a stated period, such as a season or a year, should be investigated. This phase of the investigation should include studies on the effect of an even distribution of rainfall throughout the period; the distribution at the normal rate for the locality; and the concentration of various portions of the precipitation within short periods, ranging from a few months to a few days or even a few hours.

The effect of various manners of distribution of given precipitation amounts occurring prior to a stated period upon the run-off for that period should likewise be investigated. The period during which run-off is to be considered might be a complete season or year or a single storm while the period during which precipita-



FIGURE 28.—Stream-gaging station on the Ohio River near dam 53. Special methods of stream-flow determination are necessary under flood conditions such as these.

tion is considered might consider antecedent periods from a few weeks to a season or more.

The effect of variations in the distribution of antecedent and concurrent precipitation, in stated amounts, upon the extremes of stream flow during a stated period should be investigated. At the same time, the influence of various hydrological and physical characteristics of the basin upon such effects should be delineated.

Consideration should also be given to undertaking these studies on the basis of the effects of mass precipitation upon mass run-off at rates in excess of certain amounts. For example, values might be developed either seasonally or for storm periods, for the effect of mass precipitation occurring at rates in excess of one-tenth of an inch per hour, or at rates in excess of two-tenths of an inch per hour. This type of approach might make possible the development of values of infiltration capacity.

**Item No. 13. The Response to Precipitation of Streams Fed by Ground Water**

*Objective.*—1. The determination of the manner in which streams fed by ground water respond to precipitation and the factors which influence such response.

*Discussion.*—A portion of the flow of any stream comes from precipitation which reaches the stream as surface water. A portion of the flow is also derived from precipitation which falls upon the drainage basin, passes into the ground, and at a later date reaches the stream as ground water outflow.

The relationship between precipitation and stream flow resulting from surface run-off is the subject of several other research items in this report. However, for many streams, a substantial part of the stream flow is received from ground-water sources. It is proposed in this study to determine for such streams the lag in time between the occurrence of precipitation and the increase of ground-water flow to the stream resulting from such precipitation.

The investigation should determine the effect upon the lag in time between occurrence of precipitation and response of stream flow occasioned by such factors as the distance between the location of the precipitation and the point where response is evident; the intensity and amount of precipitation; the slope of the ground surface and of the ground-water table; the soil type and the geologic structure within the basin; the vegetal cover; and the temperature and barometric pressure.

Other phases of the problem to be investigated deal with the influence of those factors mentioned upon the magnitude of the response; and with whether the increase in stream flow is derived directly from precipitation, or whether it comes from ground water which is displaced by precipitation reaching the ground-water table at a distant point.

**Item No. 14. Frequency of Rates of Run-off**

*Objective.*—1. The determination of frequencies of run-off rates of various magnitudes, particularly from drainage areas of less than 10 square miles.

*Discussion.*—The aspect of importance in this study is the relative frequency of extremes of low and high flows. This requires, however, a complete frequency curve covering all flows as a means of extending and studying the extremes of flow. A time base over an adequate period is essential.

Frequency curves should be plotted for such stream-flow records, as are available for sufficient time periods. By plotting discharge as a ratio of mean flow, different streams may be compared and probable values of extremes of low and high flows may be determined. This may also enable the use of short-time records, where comparison can be made with some long-time index station. (See appendix B "Statistical Methods in Hydrology," also item 5, sec. V.)

**Item No. 15. Probable Run-off During Critical Periods**

*Objective.*—1. The determination of the maximum and minimum yields which may be expected during critical periods from drainage basins of various characteristics in different parts of the country.

*Discussion.*—While stream flow and run-off from a given drainage basin may vary from season to season, these also vary in cyclic fashion due to periods of generally wet or dry years of varying length. These periods may vary in length, and in occurrence in different parts of the country, and the departure of the mean run-off from normal run-off for a period may vary with different factors.

It is the purpose of this study to determine the manner in which these cyclic variations of run-off occur in different parts of the country, their length, the magnitude of departure from average run-off which may be expected during consecutive periods of one or more years within a cycle, and the effect upon the magnitude of variation or departure of such things as variations in hydrological phenomena or physical conditions. The information developed will be useful in affording a better understanding of the hydrology of the country, and will serve as a guide in defining problems of water supply, utilization, and control.

Care should be exercised in the selection of stream-flow records to insure that they are of good quality and have not been affected by upstream diversions, impoundments, etc., or that data are available for the accurate evaluation of these factors. The accuracy of the methods used for extending records should be checked, as suggested under item 4, section V, and the records extended to cover the longest possible period of time.



Periods of subnormal and supernormal stream flow can be developed by the use of moving averages or of residual mass curves. The latter are recommended as giving sharper definition to periods of deficiency, or excess, and also as showing accumulated departures from normal in a clearer manner.

The expression of run-off for a given year as a percentage of a long-time average will simplify computations and allow for easier comparison of studies on different drainage basins. In order to facilitate comparisons between drainage basins throughout the country, the mean of an identical period should be taken as a base for all studies, and the 35-year period, 1900-34, inclusive, is suggested.

The investigation should include with reference to various parts of the country: Studies of the length of subnormal and supernormal periods of stream flow; the existence or absence of synchronism between such periods; the magnitude of accumulated departures from the mean of the base period, both plus and minus; the magnitude of departures, both plus and minus, from the mean of the base period of run-off for single years and for periods of 2 or more consecutive years, for

various drainage basins; and the influence upon the last two items of various hydrological and physical characteristics of drainage basins. (See appendix B, "Statistical Methods in Hydrology".)

**Item No. 16. Mean or Average  
Run-off Periods**

*Objective.*—1. The determination of the minimum length of record needed for the establishment of "average" (sometimes called normal) run-off for various parts of the country, and the probable departure from the "average" when shorter lengths of record are used.

*Discussion.*—The term "average" or "normal" is applied to the arithmetical mean of a series of such length that when new terms are added to the series, the mean of the resulting series does not vary appreciably from that of the original series. It is customary in the everyday use of the term "normal" to refer to a long time mean or average, with, however, no length of record being specified.

Where seasonal variations in run-off are relatively small in magnitude and wet and dry cycles are not pronounced, the mean of relatively short records may,

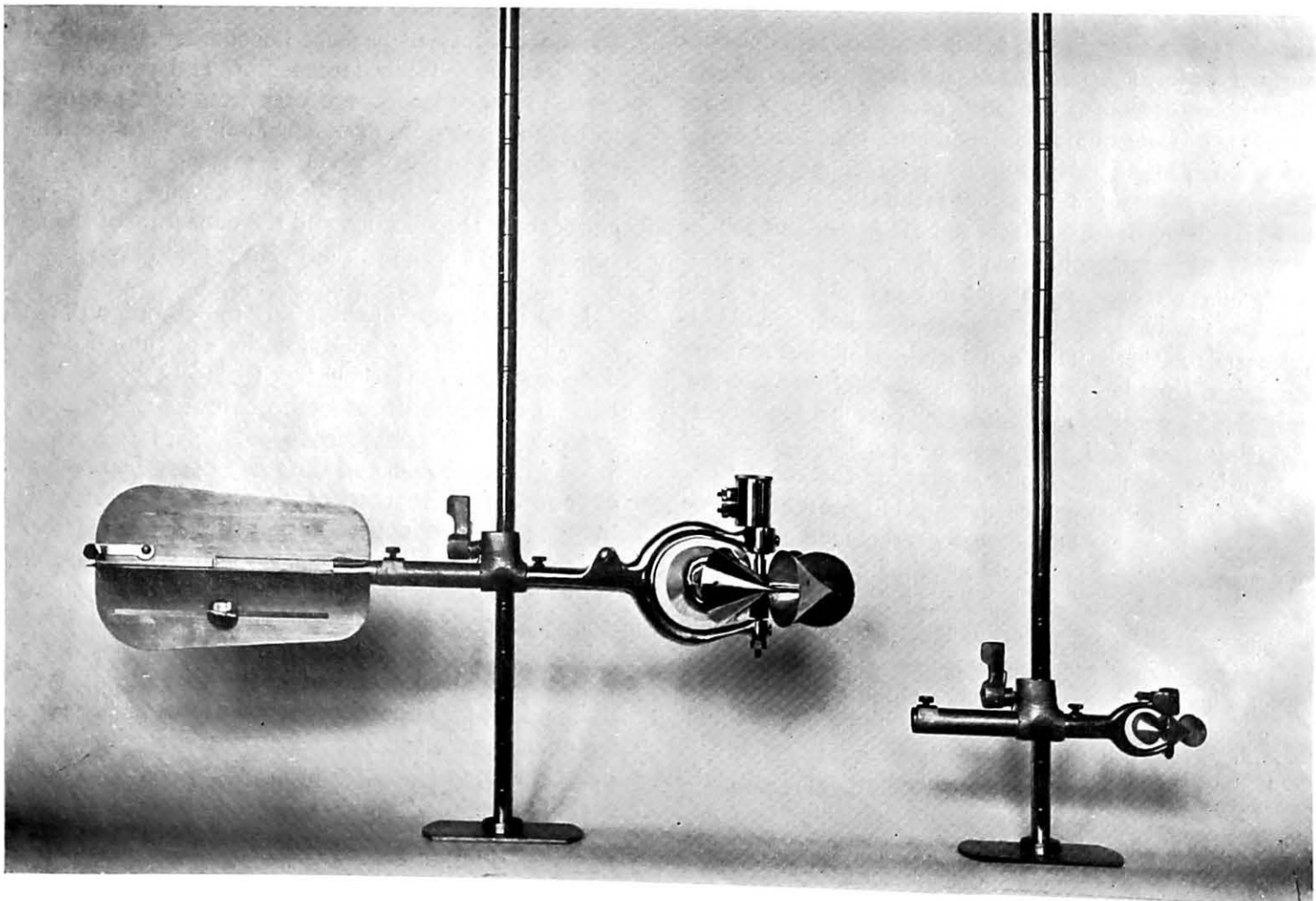


FIGURE 29.—Geological Survey standard and pygmy current meters. The standard meter is best adapted for use in depths greater than one foot; the pygmy meter for use in shallow water greater than 0.3 foot in depth. A satisfactory instrument for field use where depths are less than 0.3 foot remains undeveloped.

U. S. GEOLOGICAL SURVEY

in many instances, be considered as a normal, while with larger seasonal variations in seasonal run-off and distinct cycles, a much longer period becomes necessary. The shorter the length of record, the more variation can be expected of the "normal" from the "mean."

It is the purpose of this study to determine, for drainage basins in various parts of the country, the length of record necessary to give a mean run-off which may be considered as a "normal" run-off under the above definition, to determine the probable departures from such normal of the means of records of shorter length, and to ascertain if possible the relationship between the foregoing and various hydrological and physical characteristics.

It is recognized that stream flow records of adequate length are not to be had in all sections of the country, but existing records can be utilized to obtain a useful estimate of "normal" values.

The records to be used in the study should be carefully selected for quality and for freedom from the effects of upstream diversions, importations, regulations, etc., unless data are available for the accurate evaluation of these factors. The methods used in extending records should be checked for accuracy as suggested in item 5, section V.

The various phases of the investigation to be studied are (a) the probable maximum departure, plus or minus, of means of periods of shorter length from the mean of a long record, probably seventy years, or more; (b) the relationship between such probable maximum departures and the magnitude of the coefficient of variation or other measures of variation; (c) the effect of using the mean of a complete wet and dry cycle of stream flow



U. S. GEOLOGICAL SURVEY  
 FIGURE 30.—A sinkhole in the gypsiferous Pecos Formation found in the Roswell Artesian Basin of New Mexico. Ground water has leached out the soluble material to form underground channels. Surface waters entering these channels may become highly mineralized through contact with the soluble salts contained in the formations.

as an average instead of the mean of a longer period of record, where the cycles are pronounced, it may be found that a mean derived from such a cycle, even though it be of varying length throughout the period of record, more closely approaches the "normal" than means derived from longer periods of record; and, finally, the relationship between various hydrological and physical characteristics encountered in the drainage basins studied and the results developed in the above studies.

## VI. Quality of Water

### Item No. 1. The Factors Determining Ground-Water Composition

*Objective.*—1. The determination of the processes whereby rock minerals are taken into solution by water, and the factors which limit the final concentration of each of the minerals.

*Discussion.*—Much research has been conducted by soil scientists on the subject of soil solution, but little is known of the limiting conditions which control the solution of minerals by the deep ground waters. This study proposes an investigation of the facts which control or determine the mineral composition of ground waters without restricting the methodology to any specific soil depth. The investigation would involve a study of the processes whereby water takes into solution the various constituents that are found in natural ground and surface water and, also, a study to determine the conditions which limit the final concentration of each constituent in a natural water.

Laboratory experiments should be performed to determine the rates at which reactions take place between water and various natural soil and rock materials and the influence of the various factors of temperature, pressure, etc., upon the reactions. This preliminary exploration will assist in the development of laboratory and field studies which should lead to a knowledge of the conditions which limit the concentration of each constituent, especially silicon, iron, calcium, magnesium, sodium, bicarbonates, sulphates, and chlorides in ground water.

### Item No. 2. The Sources of Soluble Salts in Surface Waters

*Objective.*—1. The determination of the sources of the salt load of a stream at a given point.

*Discussion.*—This research proposal deals with the determination of the sources of the salt load of a stream, the flow of which is derived from natural tributaries, from drainage ditches, and from ground-water sources.

Work of this type is of great importance in determining the effects of head-water diversion on streams of low salinity emptying into streams of higher salinity, where the downstream waters are used for irrigation purposes and are of such salinity that the diversion of a part of the better quality water from the tributaries would result in a salinity downstream that would be injurious to plant growth. For example, the waters of a stream are derived from three tributaries of approximately equal discharge, two of which are high in salt content with the third relatively pure, and are used for irrigation. The diversion of water from the third tributary may increase the salt load of the water in the main stream to the point where it will be unsuited for irrigation.

Investigations such as proposed have been performed on the upper Rio Grande. A specific project is now underway on the Pecos River in New Mexico, and similar investigations would be desirable in all agricultural regions where irrigation or drainage works have been constructed or are contemplated.

The procedure being used in the Pecos River investigation is indicative of that to be followed in general. A point should be selected at which the salt load is to be determined and an adequate stream gaging station installed and operated. The distribution of the soluble salt contents of the stream throughout the section of the stream at the point selected and at nearby points should be determined, and a program of sampling and analyses adopted to insure an accurate determination of the annual and seasonal load of dissolved salts. Samples should be collected at regular intervals and at changes of stage and analyzed; the stations should be operated for a minimum of a year and preferably for at least a 10-year period.

Similar stations should be selected and operated on tributary streams, drainage canals, and such other points on the main stream as may be necessary to determine the proportion of the total salt load contributed by each of the tributary streams and in specific reaches of the main stream.

A program of ground-water studies should be adopted, including test wells for the measurement of levels and composition of ground water, to determine the direction of flow between the stream and the ground-water reservoir.

#### Item No. 3. The Relation of Land Use to the Composition of Surface Waters

*Objective.*—1. The determination of the effect of land use and changes in land use upon the quality of surface waters.

*Discussion.*—The mineral content of water depends in part upon the rapidity with which surface and ground waters travel from the farthest reaches of a

drainage basin to the main channels. Where the velocity is decreased, the water is given more time to dissolve acid compounds from decomposing vegetal litter and is given a longer contact with the soil and subsoil, thereby probably increasing the amount of dissolved mineral salt carried into the streams. Thus, changes in vegetal cover and land use should have some effect upon the quality of both surface and under-ground waters.

The proposed investigation is designed to establish the possible relationships between run-off and land use characteristics and the quality of the surface run-off and the ground water. The investigation would involve the collection and analysis of adequate samples from streams draining watersheds on which changes in vegetal cover and land use were being made, together with detailed data on the nature and magnitude of such changes. Supporting data in the form of accurate and adequate stream flow records would be necessary.

The results should show any change in the total load of dissolved and suspended matter as well as its seasonal distribution. Due to the variability of the mineral content of surface waters, the project should be conducted over the maximum possible period of time, probably on the order of 10 to 20 years, to permit the observation of the long time effects of the changes in land use on the quality of the water.

#### Item No. 4. The Intrusion of Salt Water in Tidal Streams

*Objective.*—1. The determination and the evaluation of those factors responsible for the intrusion of salt water into tidal streams.

*Discussion.*—The intrusion of salt water into tidal streams, due to decreased streamflow resulting from deficient run-off and diversion of waters for irrigation and other purposes, has become a serious problem in many sections. Investigations on the variations and the control of salinity in certain large rivers indicate that the development of the relationship between the salt water intrusion and the stream discharge, tide, wind movements, and temperature for the individual stream would be of great importance in determining the upstream limits of various salt concentrations.

In general, this investigation might follow the lines of the investigations described in *Bulletin 27* of the Division of Water Resources of the California Department of Public Works on the salinity of the Sacramento-San Joaquin Delta and Upper San Francisco Bay. Other investigations which would be of value in establishing a procedure for studying the intrusion of salt water are those conducted on the salinity of the Delaware River, reported in 1935, by the Bureau of Engineering, Department of Health of the Commonwealth of Pennsylvania, and on the Connecticut River, reported

in *Bulletin S-1*, by the Connecticut State Water Commission.

**Item No. 5. The Contamination of Ground Water**

*Objective.*—1. The determination of the sources, trends, and manner of mineral contamination of ground water.

*Discussion.*—Sea water contamination of underground waters, resulting from excessive draft, has been known for many years and the general principle recognized. There are many other sources of contamination by mineral salts about which very little is known. Oil well brine and refinery wastes, mine seepage, industrial plant wastes and others serve as contaminating agents in many sections but have not received the critical study needed.

The proposed investigation is designed to give insight into the manner in which ground-water contamination

occurs, its source and movement through the subsurface formations, and the long time trend of such contamination. The data needed in such a study include continuous records of salt water concentration and contamination in surface and subsurface waters used in agriculture, industry, and for other purposes.

The investigation should be undertaken in selected areas where comprehensive data on the geologic occurrence of water and the composition of water being used are available or could be collected. Test and observation wells should be selected or drilled as needed in order to observe the change occurring in the composition of the water with the passage of time. A systematic program of sampling and analysis should be continued for as long a period as necessary to secure the required data. The length of time will vary with each project. One may be completed in a year, whereas another may require several years of observations.

---

## IV. DRAINAGE BASIN STUDIES

---

### General

The research projects enumerated in chapter III have been described in a manner which it is hoped will encourage independent investigation of the particular projects. In discussing the objectives of these proposals, no attempt has been made to show the interrelation between the various problems or the influence of other factors upon them, although reference has been made in several instances to the desirability of correlating the work of two or more items.

The research projects described are obviously interrelated in many instances, and the greatest value from investigative work will result when these independent items are integrated into a comprehensive research program. The supplemental observations required in conducting independent investigations could be made to serve in more than one phase of a comprehensive investigation, with a consequent over-all saving in both technical and financial resources.

The following outline has been prepared as a Committee report on the manner in which the different research proposals may be integrated into an intensive research program wherein the interrelated hydrologic phenomena may be observed simultaneously for their individual characteristics and also for their relationship one to another.

The drainage basin has been used as the areal unit most suitable for this type of comprehensive research. The size of the basin is not of paramount significance but should be of such extent as properly to accommodate the contemplated investigations.

In appendix C, Mr. Robert E. Horton has utilized this outline as well as other contributions of the Committee to present a suggested program for correlative research on run-off phenomena.

### Objectives

The determination qualitatively and quantitatively of:

1. The nature, magnitude, and interrelationships of hydrologic phenomena entering into the occurrence and disposal of water on drainage basins.

2. The effect upon these phenomena of climatic, physiographic, and other physical factors, representative of various drainage basin conditions in the United States.

3. The applicability to larger drainage basins and reliability of results obtained from hydrologic studies on small areas.

### Discussion of Objectives

A comprehensive study of a drainage basin will afford an opportunity of carrying out a composite program of hydrologic research in an economical manner, as well as of determining the interrelationship, over a considerable area, of hydrologic phenomena and of factors which influence them.

Coordinated, comprehensive studies of representative drainage basins will demonstrate and evaluate the many complex interrelationships which exist. The results from such studies will enhance the value of existing hydrologic data obtained from single-purpose investigations. In addition, these basins will serve as logical centers of hydrologic research, where various methods of measurement and analysis can be developed and tested with effectiveness and economy.

### Procedure

Inasmuch as hydrologic phenomena are affected in nature, magnitude, and interrelationship by factors related to the physical characteristics of drainage basins, a number of drainage basins throughout the country should be selected so as to include reasonably wide variations in:

1. Geographic location, with respect to climatic zones and meteorologic phenomena.
2. Physiography, including elevation, ground surface, slopes, and drainage densities.
3. Geologic formations.
4. Cover:
  - (a) Vegetal, including crops and land-management practices.
  - (b) Urban conditions.
5. Soils—types and textures.
6. Different objectives in the utilization and control of waters.

The size of the areas selected will vary in accordance with circumstances, local conditions, and the opportunity afforded to observe various phenomena. Intensive studies should be undertaken on small areas of 10 to 25 square miles. These may be included within larger areas, up to several hundred square miles, of which general studies may be made. Such small areas should reflect representative conditions, and information obtained from them should afford an opportunity for areal interpretations, subject to rigorous testing of applicability and reliability.

The selection of basins will require very careful consideration, including the major problems of utilization

and control, broadly differentiated into problems of arid and of humid regions, and the availability of existing data (such as topographic, agricultural, hydrologic, etc.).

In general, the character and nature of basic data selected during any studies of drainage basins in different parts of the country will be similar, and although many of the subjects to be studied will also be similar, climatic and regional factors may cause a change in emphasis as between investigations conducted in different parts of the country.

Phases of the hydrologic cycle and their interrelationships which should be investigated in order to attain the objectives include—

1. Occurrence, distribution, and nature of precipitation, including interception.
2. Occurrence and nature of infiltration, infiltration capacities, and infiltration rates.
3. Occurrence and nature of evaporation from soil and water surfaces.
4. Occurrence and nature of transpiration.
5. Groundwater behavior.
6. Occurrence and nature of surface detention and channel storage.
7. Occurrence and nature of surface run-off, including overland flow.

In many small drainage basins, the investigation should include observations upon the origin, transportation, and deposition of silt carried by surface run-off.

The program of study must be flexible in order to include topics which will develop as the study proceeds, and for the expansion of activities of which the importance might not have been apparent at the outset.

Any study initiated should be planned to continue for a period of sufficient length so that reasonable variation in magnitude, occurrence, and behavior of hydrologic phenomena and influencing conditions can be encountered and observed. The necessary time for the collection of basic data will vary with the locality and also with the manner in which phenomena and conditions fluctuate. For example, wide variations in precipitation intensity may occur within a period of 2 or 3 years for a certain locality, whereas in another location such variations will be found only once in 5 or 6 years. Even for such periods, extremes of different phenomena to be observed are unlikely to occur, and when it is possible to continue observations for a longer period, proportionately more valuable results will be obtained. The effect of cultural activities upon water regimen will call for studies over longer periods in order to determine such effects. In general, it is believed that the time required for the initiation of a drainage-basin study and the collection of basic data will range from 3 to 8 years, with an additional time of from 1 to 2 years necessary to analyze, interpret, and present the results.

*Basic data.*—The basic data necessary for the study will be of two types:

1. Those pertaining to permanent physical conditions.
2. Those pertaining to conditions and phenomena which fluctuate during the course of the investigation.

The following outline covers in general the basic data which should be available for the study. Where such data do not exist, they must be secured. The detail in which such data are to be collected will depend upon local conditions and upon the specific objectives of the study.

#### Basic Data To Be Collected

The basic data, collection of which must be a part of the program of the particular investigation, include:

*A. Drainage basin characteristics.*—Data relative to permanent physical conditions of the drainage basin including:

1. *Topography.*—Adequate surveys of the basin should be made and should indicate contours, water courses, bodies of water (natural and artificial), swamp or overflow areas, water conduits, roads, buildings, and other similar features.

2. *Geology.*—The geologic structure for the basin should be determined and shown by appropriate maps and cross sections; the character of underlying rocks should be studied with respect to their ability to store or transmit water. Ground-water basins or aquifers should be investigated as to extent, capacity, and specific yield of materials within the zone of ground-water fluctuation.

3. *Soil type.*—Soils should be investigated and their type determined in the light of influence upon infiltration capacity and rates, as well as of actual physical structure, with particular emphasis upon erodibility.

4. *Vegetal cover.*—Maps should be made of the distribution of vegetal cover in the basin. These studies are needed in order to estimate the amount of interception of precipitation, the retarding effect of vegetation upon surface flow, the effect upon soil evaporation, transpiration, erosion, etc.

5. *Land use.*—Existing land use at the initiation of the study should be determined, as should previous changes during recent years and also changes during the course of the study. Maps should be prepared.

6. *Land and stream slopes and drainage densities.*—Profites of the streams should be taken, together with detailed data on land slopes. The "density" or frequency of definable water courses should also be determined.

*B. General meteorological conditions.*—Data relative to past and current meteorological phenomena. A sufficient number of stations should be established throughout the basin to determine the occurrence and behavior of meteorologic factors including:

1. *Temperature.*—Daily mean, maximum, and mini-

mum; means and range for different time and seasonal periods. Continuous records for correlation with evaporation and other phenomena will be needed. Data on soil temperatures should be obtained; during frozen season it will be necessary to determine the periods when the ground is frozen and the depth of frost penetration.

2. *Barometric pressure.*—Continuous records.

3. *Relative humidity.*—Data should be collected for various parts of the basin in order to detect areal variations.

4. *Wind velocities and direction.*—These should be observed at various points in the basin and at various elevations above the ground. The extent of these studies will depend upon the scope of the basin hydrology being investigated.

5. *Insolation.*—Measurements should be made particularly with reference to evapo-transpiration determinations.

The above data should be correlated with general meteorologic information for that section of the country in which the basin is located, with reference to storm

paths, storm morphology, and to air-mass movements.

C. *Precipitation.*—Numerous rain gages of the recording type should be installed for the accurate determination of the distribution, quantity, and intensity of rainfall in the basin. Standard rain gages may be used for distribution and quantity determinations and for checking recording gages. The location of the rain gages should be carefully selected so as to obtain maximum areal coverage, as well as to collect "spot" data in conjunction with specific investigations. Where snow is an important factor, snow gages and snow courses should be established. Means for measuring dew or fog should be considered, particularly in relation to the effect of such precipitation upon water consumption by vegetal cover and the moisture content of soils.

Records should include:

1. Hourly, daily, monthly, and yearly values for all parts of the basin. (Shorter periods may be necessary for some studies.)

2. Details of storm precipitation for use in unit-graph studies and others.

3. Areal variations and variations with respect to

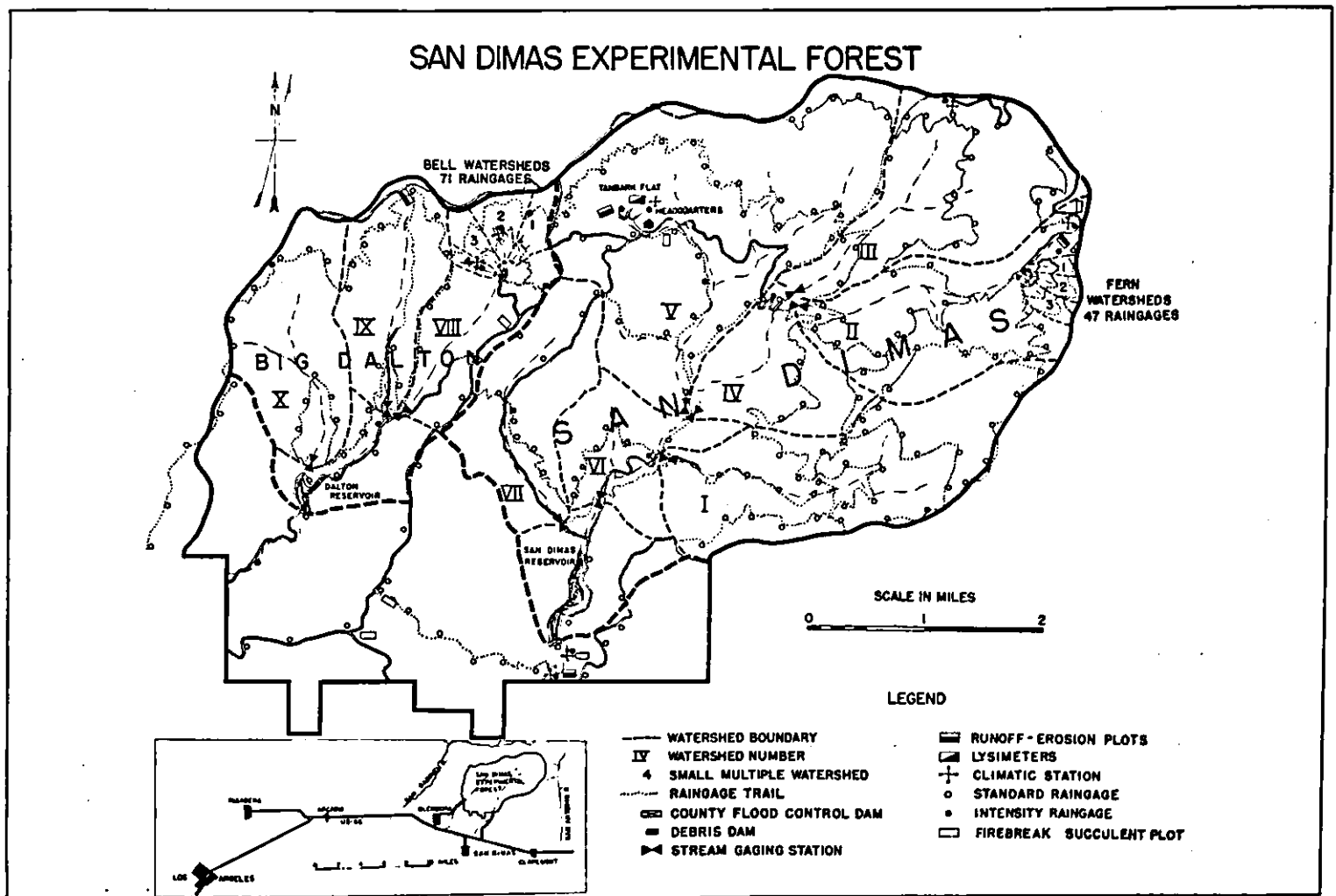


FIGURE 31.—San Dimas Experimental Forest near San Dimas, Calif. Approximately 13,000 acres are included in the two watersheds above controls. (10,210 acres in the San Dimas, and 2,720 in Big Dalton.)

altitude and other factors.

4. Snow depths and water content of snow.

5. Interception by various types of cover, including artificial conditions (for urban areas) should be observed wherever possible.

*D. Infiltration.*—This phase of the hydrologic cycle is generally observed through deductive analyses of data obtained for the other phases of the cycle. However, laboratory work such as the use of soil tubes may be useful in providing information on infiltration capacities and rates. Lysimeter installations are valuable for direct observations.

*E. Evaporation.*—Pan observations of evaporation from water surfaces should be carried on at several points in the basin. If lakes, ponds, or reservoirs exist, pan observations should be correlated with open water surface observations. Such evaporation observations should always be corrected with measurements of the following:

1. Temperature: soil, water, and air.
2. Insolation.
3. Wind velocities and direction at surface and above surface.
4. Barometric pressures.
5. Relative humidity and water vapor.
6. Turbidity and color of water.

*F. Evapo-transpiration.*—Where oils and cover are involved, additional determinations are necessary such as:

1. Soil moisture—at various levels in soil profile.
2. Types, penetration, distribution, and consumptive use of vegetation.
3. Relations of soil profiles with water table profile.

Transpiration measurements may be performed by laboratory and field methods. Efforts should be made to separate transpiration from evaporation losses.

Lysimeter as well as "small plot" methods may be used for the determination of evapo-transpiration rates. Correlation with pan measurements should be undertaken.

*G. Ground water, percolation.*—Ground-water wells should be located at carefully selected points in the basin. These wells should be equipped with automatic recorders to observe all types of fluctuations. Accretions to ground water from precipitation, channel percolation, irrigation, and other sources of moisture should be determined. Measurements should be made of the flow from springs, water extracted from wells and used within or without the basin, and variations in the level of surface and ground water in swamps should be noted.

Percolation observations may be made in the field or laboratory. These are valuable in determining rates of seepage and other phenomena related to ground water. Chemical quality of ground water should be determined.

*H. Run-off, stream flow.*—Plot experiments should be correlated with larger areal observations. Each stream

in the basin and diversion therefrom and each importation into the basin should be equipped with suitable gaging stations and control weirs. For small areas and plots, special measuring devices may be required.

Silt samplers should be made a part of the equipment where essential. Data collected should include:

1. Daily, monthly, and yearly records for all observations. Observations at shorter intervals are necessary for small areas.
2. Storm run-off.
3. Flood flows, stream velocities, flood wave velocities, times of concentration, etc.
4. Minimum flows; daily, monthly, and yearly.
5. Diurnal fluctuations.
6. Movement of silt.
7. Observations on stream density currents.
8. Changes in pond, lake, or reservoir levels, and corrections for storage where necessary.

*I. Quality.*—The utilization of water in the area selected for the drainage basin should control the extent of these observations. However, this phase should not be neglected in view of its effect on soils, evaporation, rate of flow, etc. Silt measurements should be obtained wherever necessary.

In all measurements involving rates, it is important to attain close synchronization. Therefore, a drainage basin study should attempt to provide for a system which will refer all observations to a standard time base.

#### Studies to be Made from Collected Data

The collection of data indicated above will enable innumerable studies to be made. These may be divided, in general, into the following two classes.

1. Specific relationships, as, for example:
  - (a) Run-off and precipitation—both for storm periods and seasonal time units.
  - (b) Evaporation and transpiration—as affected by temperature, wind velocity, humidity, vapor pressure, etc.
  - (c) Snow melting (where pertinent) as affected by temperature, precipitation, solar radiation, etc.
  - (d) Effect of drainage basin characteristics upon run-off.
  - (e) Other specific relationships, outlined in chapter III of this report as follows:

Section I.—Precipitation and Interception.

Items 1, 5, 6, 7, 8, 9 (in part), 10, 11.

Section II.—Infiltration.

Items 1, 2, 3, 4.

Section III.—Evaporation, Transpiration, Consumptive Use.

Items 1, 2, 3, 4, 5, 6, 7, 8.



Section IV.—Ground Water and Percolation.

Items 1, 2, 3, 4, 5, 7, 8, 9.

Section V.—Run-off and Stream Flow.

Items 1, 2, 5, 7, 8, 9, 10, 11, 12, 13, 15.

Section VI.—Quality of Water.

Items 1, 2, 3, 4, 5.

2. General relationships and analysis, as, for example:

(a) The applicability and reliability of applying results from small area studies to the determination of the hydrology of larger areas.

(b) An accounting of the water received and disposed of for the basin and its subdivisions, and a check of the elements of the hydrologic cycle over the time of observations; and others, including such proposals in chapter III as:

Section I.—Precipitation and Interception.

Items 2, 3, 4, 6, 7, 8, 9.

Section V.—Run-off and Stream Flow.

Items 3, 4, 5, 13, 14.

---

## APPENDIX A. THE COORDINATION OF HYDROLOGIC RESEARCH

---

Several types of agencies are engaged at present in hydrologic research. Within each of the individual agencies there are frequently special groups which are prosecuting such research. The major types of agencies are:

1. Federal agencies.
2. State (and other political subdivisions) agencies.
3. Quasi-public agencies.
4. Private agencies.
5. Educational and scientific institutions.
6. Technical and scientific societies.

Although there is a degree of cooperation between these agencies in the collection of basic data, the research efforts are on the whole distinctly uncoordinated. Even within the same agency special groups frequently are prosecuting research having the same objectives. Research is performed too often with limited regional and functional scope, and with inadequate funds. The approach to most problems in hydrology and the resultant procedure are restricted largely by the philosophy and experience of the group undertaking the investigation.

A major difficulty in hydrologic research is due to the universality of the subject, and the many fields of science which are affected by it. Agriculturists, agronomists, biologists, chemists, engineers, foresters, geologists, meteorologists, physicists and others concerned with natural phenomena are hydrologists at times and in varying degree, often without recognizing the hydrologic significance of certain of their researches. Thus much valuable hydrologic knowledge is frequently unveiled to a few technicians who are unaware that others are groping for the same information, although perhaps with different objectives.

For example, research investigations may be conducted within a single organization in the same locality: The botanist may be studying transpiration as related to evaporation from porous cup atometers and wind velocities at various heights above the ground; the hydrologist may be studying evaporation from open water surfaces and observing both open water evaporation and wind velocities at the water surface; the physicist may be studying solar radiation intensities at the earth's surface. Obviously, if each of the three investigators was aware of the undertaking of the others, there might well result a coordinated research of wider scope and utility which would not impair but might enhance the results of the specific investigations.

An important approach to the coordinating problem is the one of information. An active, central source of

reference would allow for the rapid and wide distribution of the proposals for and the results of hydrologic research, not only for the United States, but universally as well. Although a great amount of data has been collected by many agencies, such data are often not available nor their existence known to interested parties. Such unfortunate procedures lead not only to excessive duplication which means a waste of funds but also to initiation of new research projects under unnecessary handicaps.

The Water Resources Committee has authorized the Special Advisory Committee on Hydrologic Data to initiate a comprehensive coordination of research activities in hydrology as soon as funds become available. This coordination of research activity would be undertaken through two major activities:

1. Periodic bulletins would be published and widely distributed among interested agencies giving information on research projects, and indicating whether they were proposed or under way, the phase of hydrology being studied, the type of research (field laboratory, statistical, etc.) and other pertinent data.<sup>1</sup> Each project would be further described by title, by whom undertaken, persons in charge, etc., together with a brief description of the objectives, procedure, apparatus, etc.

2. The maintenance of an active contact with and a source of information to all organizations engaged in hydrologic investigation or proposing to enter into such work.

The performance of the first function would entail cooperation between the Water Resources Committee and various organizations, notably the American Geophysical Union and its affiliates here and abroad, with the editors of technical publications in all fields, but most particularly in those dealing with water problems, and with educational institutions and others indicating a willingness to participate in this endeavor

The material to be gathered would be abstracted whenever possible and would be classified according to some standard procedure. New sources of data and unpublished material (such as theses) would be indicated in a separate section.<sup>2</sup>

The activity in gathering the material described

---

<sup>1</sup> As an initial step in the functioning as a coordinating agency, the Special Advisory Committee on Hydrologic Data is proposing to make available shortly a summary of the hydrologic research being currently conducted by the different Federal agencies.

<sup>2</sup> This proposal would make available in hydrology a periodical compilation analogous to that in hydraulics furnished by the Bureau of Standards in "Current-Hydraulic Laboratory Research." During the time this report has been in preparation, the Bulletin of the Bureau of Standards has been expanded in scope to include hydrologic research conducted at the hydraulic laboratories. It does not attempt to cover all hydrologic research.

above should complement the second function indicated. By initiating and maintaining a close contact with research organizations, the office would be in a position to establish a subject file and in time should act as a clearing house between agencies. It would be, for the present, a coordinating influence functioning chiefly on the basis of its wide informational scope, and therefore of value to those contemplating or conducting research, as well as to those using its results

As a result of this work, the Water Resources Committee would be able to note duplications as well as deficiencies in various research programs, either due to

regional or functional limitations. Those members of the Water Resources Committee who were also members of the Special Advisory Committee on Hydrologic Data would be expected to keep closely in touch with the activities described, and from time to time submit proposals and programs dealing with hydrologic research for the advice of the Special Advisory Committee on Hydrologic Data. From such advice, or upon their own volition, these members of the Water Resources Committee would render reports to or request action by the Water Resources Committee with respect to hydrologic research.

---

## APPENDIX B. STATISTICAL METHODS IN HYDROLOGY

---

### General

The application of statistical principles and procedures to the analysis of hydrologic data has opened new approaches to the solution of many problems. A major difficulty in the use of statistical methods has been a lack of understanding of their limitations. Too frequently statistical methods have been used by investigators not familiar with the limitations of such procedures. Impressive arrays of figures and imposing formulae may produce misleading conclusions in the hands of one not adequately familiar with the underlying philosophical premises or mathematical derivations. The following outline has been prepared to show certain types of statistical studies that may be undertaken and to delineate a logical order of procedure in such investigations.

### Objectives

1. The analysis and comparison of statistical procedures heretofore applied or suggested as useful in the field of hydrology.
2. The development of improved statistical and analytical procedures applicable to hydrologic investigations.

### Discussion of objectives

Numerous statistical procedures have been applied to the solution of hydrologic problems, and new procedures or modifications of old procedures can be devised to improve statistical methods in hydrology. Some statistical procedures that have been applied in hydrologic investigations were derived for application to sciences quite different than those of hydrology. Other procedures have been developed for specific areas or regions, and by implication have been assumed to be generally applicable. Still others are defective either in the hypotheses underlying their development or application, or as to the reliability of the results.

There has been collected and made available in recent years a large amount of hydrologic data which should make possible more precise and scientific tests and comparisons of statistical procedures applicable to hydrology.

The analysis and comparison of statistical procedures useful in the field of hydrology should include the application of these methods to records of hydrological data of every kind. It may be carried on by individuals or groups of any kind who have sufficient knowledge of both mathematics and hydrology. It may be undertaken in any part of the country, and may be confined to a specific type of hydrologic data

or problem. It should be designed to test and enunciate clearly the validity of and restrictions upon numerous statistical and analytical procedures commonly used in hydrological investigations, as well as to devise improved statistical methods in hydrology.

A specific undertaking may relate, among others, to any one of the following typical applications of statistical attack upon hydrologic problems:

1. Magnitude-frequency characteristics of hydrologic phenomena.
2. Tests for periodicity and cyclic nature of hydrologic phenomena.
3. Tests of accuracy and adequacy of a series of observations of hydrologic phenomena, including tests to determine the existence of errors or of inconsistencies in the record.
4. Tests of empirical formulae.
5. Tests of the effect of accidental or observational errors upon a given statistical process.
6. Tests of composite records produced by combining a number of individual records.
7. Critical studies of the significance and utility of such procedures as mass curves, trend lines, departures from the mean, moving averages, etc.

### Procedure

(a) The kind of hydrologic phenomena for which the data are to be investigated: i. e., rainfall intensity, annual floods, flood peaks, storage, minimum or seasonal precipitation or run-off, evaporation, and inconsistencies in records, etc. should be determined.

(b) It is highly essential that the mathematical and philosophical bases for the various methods of applying statistical investigations should be clearly understood before a specific research is undertaken.

(c) The kind of statistical procedure to be studied should include:

1. Empirical formulae.
  2. Statistical arrays, as frequency curves, duration curves, correlation studies, etc.
  3. Semiempirical methods.
  4. Statistical-graphical methods.
  5. Mathematical analysis.
- (d) Each method should be analyzed, considering:
1. Philosophical premises.
  2. Mathematical bases.
  3. General or specific application.
  4. Data needed.
  5. Relative work involved.

(e) Those methods shown definitely impracticable or inapplicable to the specific study should be discarded.

(f) The remaining methods should be applied to a number of long-term records. The accuracy of the data used should be carefully determined, as well as the effect of land-use, vegetation, or physiographic changes during the period of record.

(g) The results of the investigation should be analyzed to determine:

1. Conformity to principles of item "d" above.
2. Closeness of fit of derived curves.
3. Effect of length of record. Long records may be broken down into segments for this study. Appropriate treatment should be given apparent cycles so that their inclusion may not vitiate the validity of the results.

4. Effect of very small or very large magnitudes of observed data upon the general procedure and its interpretation.

5. Proper consideration of the effect of physiographic, vegetal cover, land use, and other physical changes during the period of record.

(h) Modifications of procedures used, and the development of new procedures should be investigated.

(i) The best statistical procedure should be determined to use for investigating the kind of hydrologic data being studied, indicating necessary qualifications in drawing conclusions due to such factors as regional influences, limitations inherent in the statistical method, etc.

---

## APPENDIX C. COMPREHENSIVE RESEARCH ON RUN-OFF AND STREAM FLOW

---

The Special Advisory Committee on Hydrologic Data has described in chapter IV the manner in which many of the research proposals of chapter III may be integrated in a comprehensive hydrologic research program using a small drainage basin as the areal unit for the research.

In the following paper, Mr. R. E. Horton, consultant to the Committee, has prepared a stimulating discussion of this Committee report, and of the preliminary reports of the various Subcommittees which formed the basis for it, which the Special Advisory Committee on Hydrologic Data believes should appear as an appendix to its report.

The Committee report has been reviewed by Mr. Horton with the objective of bringing together those separate research projects having primary significance

in their influence upon run-off and stream flow. In elaborating upon the various phases of a drainage basin research program, emphasis has been placed upon the development of the fundamental relationships existing between the various phenomena, rather than the derivation of empirical expressions, in order that the results may be of wide applicability instead of being limited to the specific areas used in the research.

Mr. Horton's valuable contribution contained in this appendix, while constituting in part a discussion of chapters III and IV of this report, is in essence an original document. As such it represents the personal views of the author and is not to be considered as a Committee report nor necessarily to represent the views of the members of the Committee either individually or collectively.

### Suggestions for a Comprehensive Research on Run-off Phenomena

by Robert E. Horton

#### Objectives

This is a preliminary outline for a comprehensive study of run-off phenomena. It seems that this problem has usually been attacked from the top rather than from the bottom. Instead of working from the simple to the complex, the inverse order has usually been used. Instead of seeking to establish fundamental relationships generally applicable, an attempt has been made to derive empirical relations which, at best, are of limited range of application.

The research needed is one which will further establish the fundamental processes, the independent variables by which they are controlled, and the relations between these variables, and at the same time provide a better basis than now exists for practical applications.

It is to be understood that this outline is tentative, as it does not seem possible to prepare an adequate outline for further research until, using present data, the initial correlative research, as outlined below, has been carried out.

Before setting up a new outline, it should be pointed out that this is to be a study of run-off phenomena—not primarily a study either of evaporation, infiltration, ground water or water losses. Separate, well-outlined research into these topics has been proposed and should be carried out. Work done on these subjects in connection with the research on run-off should be limited to collecting necessary data for the interpretation of the run-off phenomena. The collection of these auxiliary data may well be guided by the separate research on these particular topics, and care should be taken to measure all the independent variables needed, so that the data obtained in the run-off research may contribute to the study of these other topics.

Types of hydraulic work involving the use of run-off estimates include among others:

1. Domestic, industrial, livestock, and irrigation water supplies.
2. Hydroelectric power plants.
3. Flood-control detention dams and levees.
4. Navigation channels and locks.
5. Drainage works on agricultural land, including those for mosquito control.
6. Sanitary and storm sewers for urban areas.
7. Highway and railway drainage ways, including bridges, culverts and roadside ditches.
8. Erosion-control structures and practices.
9. Regulation of flow for pollution control, navigation, and recreation.

There are many other practical needs to be met, and in addition there is the scientific value of a knowledge of run-off, as in morphology,<sup>1</sup> in physiography, in glaciology, and in land forms.

In preparing this report, the preliminary draft of chapters III and IV were consulted, as well as several special subcommittee reports<sup>2</sup> to the Special Advisory Committee on Hydrologic Data which dealt with comprehensive drainage basin investigations. Appropriate material from these sources has been incorporated in the following proposals. The phenomena of run-off from snow-covered areas have not been given special or separate treatment in this paper for the reason that a full outline for research on this subject has been separately prepared.

<sup>1</sup> The study of the development of land forms under the action of natural agencies.

<sup>2</sup> These subcommittee reports include (1) "The Unit Hydrograph," (2) "The Development of Synthetic Stream Flow Data," (3) "Drainage Basin Studies" by D. B. Krimgold, (4) "Drainage Basin Studies" by H. K. Barrows, (5) "Drainage Basin Studies" by Ivan Bloch.

**Correlative Research**

Before any comprehensive field or laboratory research on run-off is undertaken, a comprehensive correlative research should be carried out utilizing the large mass of accumulated research and experimental data, much of it recently collected but still unanalyzed. There is a strong, natural tendency to rush ahead with costly, elaborate programs for new research by persons who either do not know the background of the subject or, for one reason or another, have not taken stock of existing knowledge of the subject. In particular, the subject of run-off requires a thoroughgoing balancing of accounts to date before further field or laboratory research is undertaken. The objectives of this initial correlative research should be:

1. To find out what is already known or can be determined from existing data regarding the fundamental laws and physical processes governing run-off phenomena.
2. To find and point out the gaps in existing knowledge and outline the research needed to fill these gaps. It may easily happen that many questions included in the outlines referred to above can be fully and satisfactorily answered by suitable analysis and study of existing data and review of work already done.
3. To develop and compare the accuracy of methods of estimating run-off—annual, monthly, and daily—from data generally available, avoiding purely empirical methods, and analyzing the hydrologic basis of each method and pointing out its limitations.

**Run-off Plat Experiments**

Before outlining the correlative research, it should also be noted that certain run-off processes and phenomena may best be studied from run-off plat experiments. These include the laws of direct surface run-off or overland flow, the effect of depression storage on surface run-off, the effect of soil type, condition, and roughness, and the effect of vegetational cover, particularly the effect of grass and other close-growing vegetation on the depth of surface detention and the character and velocity of overland flow; also the effect of surface roughness, slope and length of overland flow. The run-off plat experiments used should include

both those with artificial and with natural rainfall. Every drainage basin containing a more or less complex drainage net is in effect the summation of individual plats, from each of which only surface run-off occurs. As a rule, the plats vary in length of overland flow, slope, and other characteristics. Fully controlled conditions for evaluation of the laws governing surface run-off phenomena can, therefore, be more easily obtained from experiments on plats than from natural drainage basins. The application of these laws to composite drainage basins, comprising plats of different lengths and characteristics, can best be undertaken when the laws governing surface run-off are fully determined.

Run-off plat experiments are being conducted by the Soil Conservation Service at the following stations<sup>2</sup>:

- |                                    |                                 |
|------------------------------------|---------------------------------|
| Amarillo, Tex. (new station).      | LaCrosse, Wis.                  |
| Athens, Ga. (new station).         | Marcellus, N. Y. (new station). |
| Beemerville, N. J.                 | McCredie, Mo. (new station).    |
| Bethany, Mo.                       | Pullman, Wash.                  |
| Clarinda, Iowa.                    | Safford, Ariz.                  |
| Dixon Springs, Ill. (new station). | Spartanburg, S. C.              |
| Gallup, N. Mex.                    | State College, Pa.              |
| Guthrie, Okla.                     | Statesville, N. C.              |
| Hays, Kans.                        | Temple, Tex.                    |
| Ithaca, N. Y.                      | Tyler, Tex.                     |
|                                    | Zanesville, Ohio.               |

There are available at these stations many unanalyzed data on run-off plats. Unfortunately, the original data collected at these stations are not at present transmitted to Washington. Practically no original data have been published. As a rule, determinations have been made only of total run-off, or run-off in particular storms, without adequate accompanying data. Collection of all the original data and a thoroughgoing analysis thereof, using appropriate and consistent methods, should be carried out. (1)<sup>4</sup>

<sup>2</sup> Since this appendix was prepared, this list has been considerably extended.  
<sup>4</sup> Numerals in parentheses refer to references at the end of this appendix.

TABLE 1.—Results of experiments on sprinkled plats, Soil Conservation Service, Colorado Springs, Colo.

No.	Item No.	326 a	326 b	326 c	326 a1	326 a2	326 a3	327 d	327 e	327 f	327 g
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
		(*)	(*)	(*)				(Z)	(Z)	(Z)	
1	Date.....	5-21-37	5-21-37	5-21-37	5-21-37	5-21-37	5-21-37	5-19-37	5-19-37	5-19-37	5-19-37
2	Plat size.....ft.	21 x 6	21 x 6	21 x 6	21 x 6	21 x 6	21 x 6	21 x 6	21 x 6	21 x 6	21 x 6
3	Plat area.....sq. ft.	126	126	126	126	126	126	126	126	126	126
4	Plat slope.....percent	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
5	Percent cover.....	25	25	25	25	25	25	45	45	45	45
6	Soil No.....	12	12	12	12	12	12	12	12	12	12
7	Initial condition.....	Dry	Moist	Moist	Dry	Dry	Dry	Dry	Moist	Moist	Dry
8	Rain intensity, <i>i</i> .....i. p. h.	5.60	4.20	3.00	4.00	3.03	2.00	5.60	4.11	2.97	4.06
9	Infiltration capacity, <i>f</i> .....i. p. h.	1.78	2.10	2.57	1.90	1.70	1.62	2.16	2.30	2.49	3.11
10	Supply rate, $\sigma$ .....i. p. h.	3.82	2.10	0.43	2.10	1.24	0.38	3.44	1.72	0.48	0.95
11	Total time, <i>t<sub>s</sub></i> .....hr.	0.417	0.300	0.400	0.417	0.697	0.483	0.456	0.367	0.307	0.433
12	Initial time, <i>t<sub>0</sub></i> .....hr.	0.05	0.0	0.0	0.033	0.133	0.150	0.066	0.033	0.100	0.133
13	Net excess, <i>t<sub>e</sub></i> .....hr.	0.367	0.300	0.400	0.334	0.534	0.333	0.400	0.334	0.267	0.300
14	Depression storage, <i>V<sub>d</sub></i> .....inch.	0.10	0	0	0.17	0.165	0.057	0.241	0.052	0.048	0.126
15	Maximum detention, $\delta_p$ .....inch.	0.42	0.14	0.05	0.30	0.24	0.10	0.33	0.080	0.040	0.140
16	Maximum run-off, $\gamma_s$ .....i. p. h.	3.82	2.10	0.43	2.10	1.24	0.38	3.43	1.81	0.57	1.05
17	$\gamma_p/\sigma$ .....	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.05	1.19	1.107
18	<i>M</i> .....	2.18	1.50	1.55	2.80						
19	<i>K<sub>s</sub></i> .....	28.2	44.2	41.0	52.5						
20	<i>I</i> .....	0.62	1.12	1.09	0.15						
21	Duration residual run-off, <i>t<sub>r</sub></i> .....	0.05+	0.05	0.017	0	Not determined	0.067	0.067	0.050	0.016	0.050
22	Total run-off, <i>Q<sub>s</sub></i> .....inch.	1.28	0.62	0.12	0.57	0.588+	0.099	1.365	0.578	0.134	0.311
23	Total net supply, $\Sigma-\sigma t_e$ .....inch.	1.40	0.70	0.17	0.70	0.661	0.127	1.38	0.574	0.128	0.285
24	<i>Q<sub>s</sub>/Z</i> .....	0.914	0.885	0.705	0.814		0.780	0.986	1.008	1.042	1.091
25	Mean soil, surface temperature ° F.....										
26	Initial moisture, percent dry weight.....										
27	Moisture equivalent of soil.....										
28	<i>n</i> .....	0.52	0.183	0.203	1.152						

\*Experiments carried out on same plot in sequence.  
 ZExperiments carried out on same plot in sequence.

While the matter of analysis will not be gone into in detail here, it should be pointed out that run-off plat experiments, using either natural or artificial rainfall, are capable of furnishing a large amount of fundamental or basic information regarding the laws and processes involved in surface run-off which are not being obtained from these data at the present time. For illustration, the accompanying table shows numerical data obtained from the analysis of a few of the sprinkled plat experiments of the Soil Conservation Service at Colorado Springs, Col. The derived data include the infiltration-capacity, the total rainfall excess, rainfall intensity and excess intensity, the volume of depression storage, the maximum run-off intensity, the law of overland flow, including the exponent  $M$  and the coefficient  $K_S$  in the equation  $\gamma_S = K_S \delta^M$  connecting rate of surface run-off with depth of surface detention (2). The total amount of surface run-off is also shown and its relation to the total net supply of rainfall excess. In addition, the maximum depth of surface detention can be determined, and when this is known, together with the run-off intensity, the velocity of overland flow can be ascertained, since velocity = volume divided by the cross-section area of the flowing stream. Velocity of overland flow and depth of surface detention are the two fundamental hydrologic quantities needed in the determination of the relation of surface run-off to soil erosion. Other factors governing soil erosion depend on the soil condition and cover. These may well be included in the same analysis.

In this connection it should be pointed out that there is a close relationship between total surface run-off in a given storm and total rainfall excess, and this fact affords a simple rational basis for estimating surface run-off. (2) The purpose of this discussion is not to stress this or any other method but to call attention to the possibilities, so long neglected, of determining surface run-off phenomena in a rational manner from the analysis of run-off plat experiments.

Among specific problems requiring research which can well be undertaken from existing run-off plat data are the following:

1. The determination of variation in type of surface run-off with roughness, soil cover, and varying percentage of subdivided or turbulent flow. This requires determination of the coefficient  $K_S$  and the exponent  $M$  in the surface run-off equation  $\gamma_S = K_S \delta^M$ . It should be noted that this equation for the simple case of turbulent flow is but a particular form of Manning's equation. (3)

2. Variation of coefficient of surface run-off  $K_S$  with length of overland flow, slope, roughness, and type of flow. The object of this is to provide a basis for selection of appropriate values of  $K_S$  for application to different types of areas, much in the same way as a roughness coefficient " $n$ " in the Manning formula is selected for a particular case from values determined by experience.

3. Conditions under which surface run-off or overland flow on steep slopes is of the bore or wave type.

4. Relation of the length of overland flow to surface run-off intensity and total surface run-off. Preliminary discussion of this subject appears in papers by Bartel, (7) Musgrave, (8) and Horton (9).

5. Determination of the volume of depression storage on different types of soil surfaces, with different slopes and different types of cover.

6. Effect of vegetation, particularly grass cover, on (a) type of overland flow, as indicated by the pertinent values of the coefficient  $K_S$  and exponent  $M$ ,<sup>4</sup> (b) maximum run-off intensity, (c) total surface run-off and total infiltration.

7. Effect of slope and surface roughness on surface run-off, particularly where overland flow is (a) subdivided by grass, etc., (b) partially laminar, (c) of the wave or bore type.

8. Effect and character of variation of infiltration-capacity during progress of rain, as regards its effect on run-off intensity, total surface run-off, and total infiltration.

9. Effect of varying rain intensity during rainfall excess on surface run-off intensity, comparing (a) uniform rain intensity, (b) maximum rain intensity at beginning of rainfall excess, (c) maximum rain intensity at middle of rainfall excess interval, (d) maximum rain intensity at end of storm.

10. Effect of residual rainfall on total run-off and total infiltration.

A preliminary discussion of some of these questions is given in *Surface Run-off Control*, by Robert E. Horton, chapter II of *Head Water Control and Use*, Upstream Engineering Conference 1936, pages 16-41. For later discussion see references (23) and (24).

### Small Drainage Basins

Another class of problems can best be studied from results obtained on small natural drainage basins. This includes the relation of ground water to run-off, the effect of varying physiographic types of drainage basins and drainage nets, and the effect of forest or other vegetative cover on run-off. Such basins also furnish a desirable basis for determining the effect of the combination of unit areas of different types and of subaquifers on both surface run-off and ground water flow. They also afford a check on the applicability of plat experiments to larger areas.

With reference to the second type of data, namely, those obtained from small drainage basins, records now being collected, but which remain unanalyzed, include those obtained at the San Dimas Forest Experiment Station, the Coweeta Experiment Station, North Carolina, the Wasatch Experiment Station at Salt Lake, the North Appalachian Experiment Station near Coshocton, Ohio, and the Black Lands Experimental area near Waco, Tex., and at various field experiment stations of the U. S. Soil Conservation Service, U. S. Corps of Engineers, and U. S. Geological Survey. Original data for small watersheds at U. S. Soil Conservation Service stations are now being published for official use. These present a desirable range of conditions from those in the San Dimas, Calif. area, where there is little ground water, to those in the Coweeta experimental area, where run-off is apparently mainly from ground water flow. A specific method of analysis of the results obtained at these stations cannot be outlined until more of the complete original records are available for study, and the procedure must depend on the character of the data collected. The main objective should be the determination of the same factors as for experimental plats, and, in addition, the determination of ground water and soil moisture conditions, where ground water flow exists. Several other objectives can be attained from records on such small drainage basins under certain conditions.

Given adequate data for a small drainage basin, including suitable daily ground water level records, a complete analysis of the hydrograph is possible. This should proceed in the following order for each stream:

1. Determination of infiltration capacity.
2. Determination of ground water depletion curves.

Separate curves are required for summer and winter conditions, and from these there can be determined—

1. The amount of ground water storage corresponding to different ground water outflow rates or to different ground water stages, as indicated by suitably located index wells;
2. The amount of water abstracted directly or indirectly from the water table by vegetation.

<sup>4</sup> It is to be noted that  $K$ , and  $M$  are readily determined for turbulent flow. Their determination for other types of flow requires experimental data.



Further analysis of the hydrograph requires, also, curves showing the normal relation of water losses to rainfall. Both these and the ground water depletion curves usually require at least a 10 years' record for their suitable determination. Given these working tools, the following can also be accomplished, for suitable periods:

1. Separation of ground water flow from surface run-off.
  2. Determination of total surface run-off.
  3. Determination of total ground water run-off.
  4. Determination of ground water flow index or average relation of total ground water run-off to total run-off. This index is closely correlated with the tendency for occurrence of surface erosion, with the regimen of the stream, and with its physiographic characteristics.
  5. Correction of the monthly run-off for changes in (a) ground water storage, (b) channel storage, (c) soil moisture storage.
  6. Determination of the net actual or coincident water losses from the drainage basin after correction for end effects or changes in storage during the month. Such water losses are distinguished from the apparent water losses as usually determined, which represent rainfall minus total run-off, and may be greatly affected by changes in storage.
  7. Tracing the progress of soil-moisture day by day throughout the growing season for entire drainage basins. This can be accomplished for suitable periods beginning and ending with ground water accretion, so that it is known that there is no change in soil moisture storage. For preliminary discussion of this method, see paper by Robert E. Horton on Stabilization of Stream Flow, *Journal of Forestry*, November 1937. (20)
  8. Transpiration. Given, in connection with other data, adequate records of measured evaporation from the soil, the actual transpiration rates from the whole drainage basin can then be determined from the gain or loss of soil moisture, since transpiration takes place entirely from within the soil. Adequate data on transpiration and its seasonal march are a fundamental need in hydrology, especially for forested and irrigated areas.
  9. Relation of rainfall to water losses, both apparent and actual.
  10. Relation of infiltration to water losses.
- The last two items provide data for estimation of monthly

run-off from rainfall and infiltration capacity. Monthly run-off may be considered as rainfall minus apparent water losses. The application of the water-loss method of estimating monthly run-off is hampered by the fact that apparent water losses include various storage effects. The analyses previously described make it possible to determine these storage effects and take them into account. The relation between run-off and infiltration is generally much closer than that between run-off and rainfall.

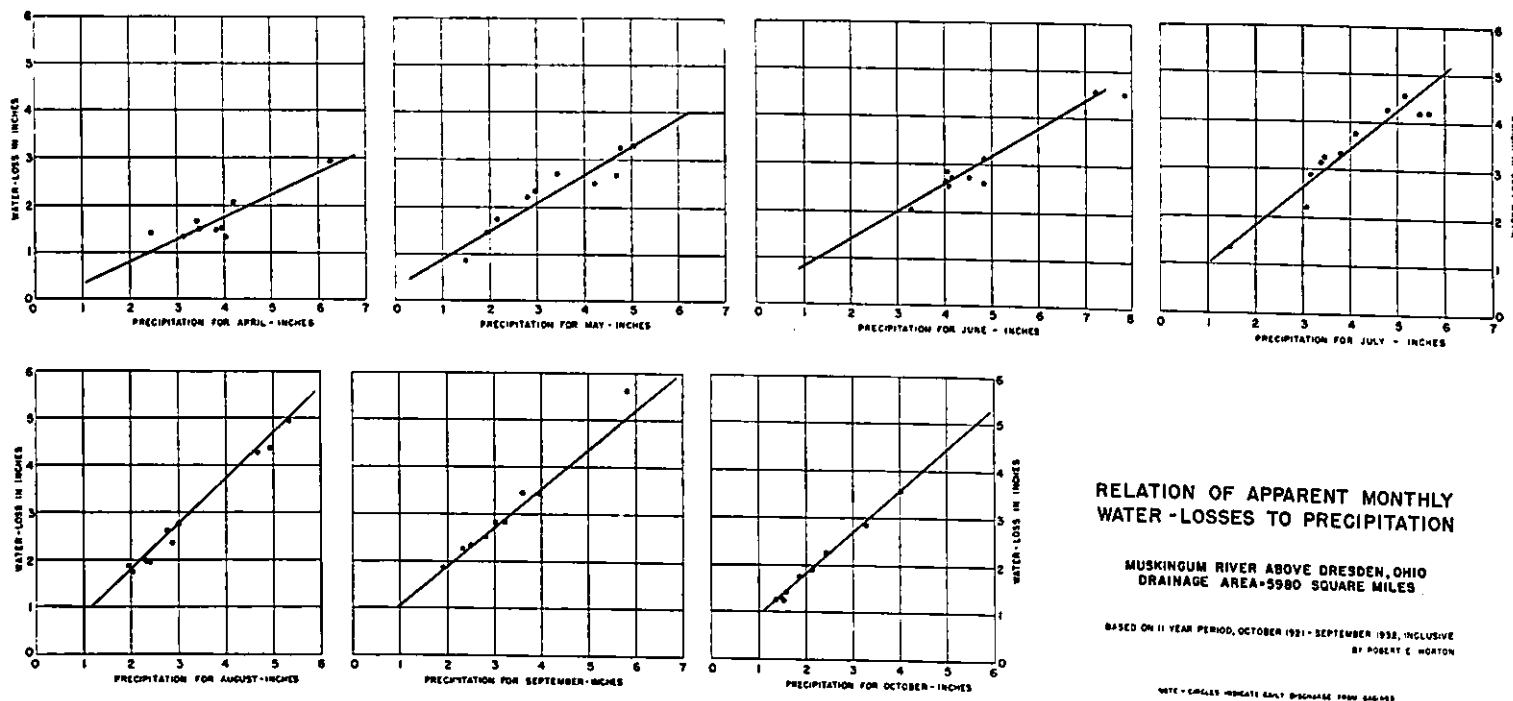
The analysis should therefore include determination of total monthly infiltration, (a) by determination of total surface run-off and subtraction from total rainfall, (b) by determination of total rainfall excess and subtraction from total rainfall. A comparison between the two methods should be made in each case to determine the coefficients to be applied to the latter to give the former, as the latter is much the more simple method and can be applied in cases where the former is inapplicable for lack of adequate data.

When such analyses have been carried out over a sufficient range of conditions, they will provide the numerical data and coefficients necessary for application to all types of areas, in the reverse process of synthesis of the hydrograph or determination of run-off from the independent variables by which it is controlled.

There is one other factor required, however, namely, channel storage. While determination of channel storage for both rising and receding stages should be carried out in the analysis of run-off from small drainage areas the volume of channel storage on small areas (under five square miles, for example) is often so small relative to that on large areas that it may be (a) either neglected altogether, or (b) impossible to determine with great accuracy. Discussion of channel storage is therefore taken up in connection with large drainage basins.

Larger Areas

There is a third class of problems best studied from data collected from drainage basins having areas of, say, 1,000 to 10,000 square miles. This includes the effect of variation of rain intensity in both space and time, the effect of direction and rate of storm travel across the drainage basin, and the effect of channel storage. These studies also include certain factors which



modify the relation of channel storage to outflow rate, including wave velocity and time and direction of transit of the storm over the drainage basin, and the effect of storms covering only a part of a drainage basin.

The analysis requires, as before, (a) normal ground water depletion curves for winter and summer conditions, (b) normal rainfall-water-loss relation curves. For purposes of illustrating what is meant by these, the accompanying charts containing examples are included herewith. To obtain these curves usually requires at least a 10 years' continuous record.<sup>6</sup>

The examples given show only summer ground water depletion curves. On drainage basins with surface aquifers at not too great depths, ground water depletion curves for winter conditions may differ appreciably from those for the summer or growing season because of the direct abstraction of water from the water table by vegetation. Hence separate ground water depletion curves must, in general, be used for summer and winter conditions. Because of the interruption of stream flow records by ice, data available for determination of satisfactory winter ground water depletion curves are mostly wanting in the northern states.

Some existing drainage basins yield excellent normal rainfall water loss relation curves, others give poor relation curves. The degree of correlation between rainfall and water losses depends partly on the accuracy of the rainfall and run-off measurements and partly also on the relation of ground water flow to total run-off, as explained in subsequent notes on the relation of run-off to antecedent rainfall.

It should be noted that this discussion relates to normal or average water loss curves. These serve a variety of useful purposes, both in the analysis of the hydrograph and in the estimation of run-off for engineering purposes, but it should be kept in mind:

1. That the consistency of relation of apparent water losses to rainfall shown by such normal curves does not usually hold true during individual storm periods. This results from the fact that the principal source of water losses is transpiration by vegetation. Veihmeyer and others have shown that transpiration takes place, other things being equal, at a rate which is

<sup>6</sup> Ground water depletion curves may be determined from shorter records provided suitable drought periods occur.

nearly independent of the soil moisture content of the soil, provided this content is between the limits of the wilting point as a minimum and field moisture capacity as a maximum.

2. A straight line relationship between rainfall and water losses on average or normal water loss curves, as shown by the example given, is purely empirical. While it happens that a straight line fairly represents the data within the limits of the range of variation of rainfall in many cases, it is known that the relation of normal water losses to rainfall is not linear.

Best results in the analysis of run-off from large areas can usually be obtained for drainage basins without any extensive natural lakes, swamps, natural or artificial regulation, or diversion. Suitable ground water level records are also needed within the drainage basin to serve as indicators of times when ground water accretion takes place. Also there must be adequate rainfall data, particularly records of rain intensity and duration. Because of the increased cost of collecting necessary data and analyzing it, as compared with small areas, studies of run-off phenomena for large areas should be limited to those lines of research which cannot be satisfactorily pursued from data for small areas.

At the present time, there are not very many drainage basins of 1,000 to 10,000 square miles area in the United States for which suitable continuous stream flow records are available.<sup>7</sup> There are few cases where there are more than one or two recording rain gages within such a drainage basin, and fewer still where adequate ground water level records are also available. The nearest approach to adequate data for study of such drainage basins exists in the Atlantic coast and Appalachian Mountain regions.

Before extensive studies of the factors requiring the use of records from larger areas can be carried out, additional data must be collected. For this purpose, streams on which long, continuous gaging records already exist are to be preferred, for the reason that the existing records serve for the determination of fundamental working tools, such as ground water depletion curves and normal water loss curves. Extension of the field research should therefore be limited to establishing adequate

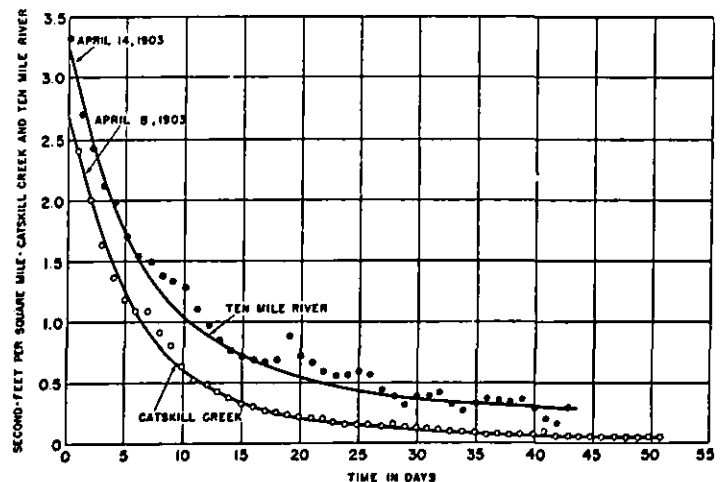
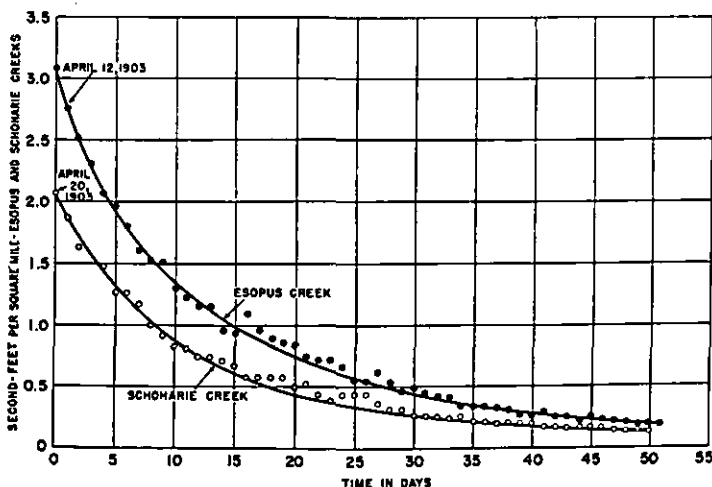
<sup>7</sup> Since this appendix was written, extension of the network of recording rain gages has been undertaken by the U. S. Weather Bureau, U. S. Soil Conservation Service, and the U. S. Corps of Engineers.

GROUND-WATER DEPLETION CURVES NEW YORK STREAMS

DROUGHT PERIOD, APRIL - JUNE, 1903

(FROM NY STATE ENGINEER'S REPORT 1903, SUPPLEMENT, P 17)

BY ROBERT E. HORTON



NOTE - PLOTTED POINTS DAILY DISCHARGE FROM GAGING

rainfall, ground water level, and evaporation records, together with additional stream flow records.

In connection with ground water level records, it should be noted that these are used mainly as indexes to determine precisely the times when ground water accretion takes place. Experience shows that many ground water level records are not sufficiently sensitive for this purpose. In general, ground water levels taken from wells in valley fill adjoining streams are worthless for this use, as may also be ground water level records taken too close to a divide between phreatic drainage basins or sub-basins. Fortunately, it is not necessary to have a large number of ground water level records. Two or three good, sensitive ground water level records within a moderately large drainage basin will generally suffice for index purposes.

Among the factors which can best be studied from larger areas are channel storage, and the effect on channel storage of storm direction, storm travel, and areal rain distribution.

### Channel Storage

Run-off in the ordinary sense is channel outflow. Channel outflow represents surface run-off and ground water flow as modified by channel storage. It is evident that the determination of the volume of channel storage at different stream stages or discharge rates, for both rising and falling stages and for different types of storms, is fundamental both to run-off analysis and run-off synthesis or stream flow estimation. Total channel storage in a drainage basin can readily be determined for the recession side of a stream rise (11) (12).

The total volume of channel storage in a stream system at a given stream stage at the outlet or corresponding to a given outflow rate is not generally the same during rising as during receding stages. Furthermore, determination of the relation of channel storage volume to outflow rate cannot be accomplished in the same simple manner for rising as for receding stages but can be accomplished where adequate data are available by complete analysis of the hydrograph. Unfortunately, as already noted, data for such complete analyses are not generally available for large drainage basins, and those for small drainage basins do not give results safely applicable to stream rises on larger drainage basins. For example, Horton found (12) for receding stages a volume of channel storage of only 1,650 cubic feet per square mile at a discharge rate of 1 c. s. m. on Ralston Creek, draining 3 square miles, as compared with channel storage volumes ranging generally from 100,000 to 200,000 cubic feet per square mile at the same discharge rates on drainage basins of 1,000 square miles or over. Meinzer *et al* (13) found channel storage ranging from a total of only 5,000 to 16,000 cubic feet on Difficult Run, with a drainage area of 1 square mile.

It is, of course, physically possible to determine the volume of channel storage from a stream rise or recession by cross-sectioning at frequent intervals all the streams in the drainage basin and taking gage readings at each cross-section during a storm. This method is, however, wholly impracticable for application excepting to very small streams. Where there are several good gaging stations separating the streams into suitable reaches, the channel storage capacity of each reach can readily be approximated for different stream stages from suitable hydrographs, especially where, as is usually the case, the average of the cross-sections of the stream in the reach approximates some form of parabola.

Objectives of the study of channel storage from larger areas should include:

1. Determination of the Horton channel storage equation or relation of volume of channel storage to gage height or channel outflow rate during receding stages.
2. The same for rising stages.

3. Variation in the volume of channel storage in the same area for both rising and receding stages in different types of storms or according as the rain splash<sup>8</sup> proceeds (a) upstream, (b) downstream, or (c) transversely across the drainage basin; for partial area stream rises or floods where the rainfall excess is concentrated (a) in the lower portion of the drainage basin, and (b) where it is concentrated in the headwaters of the drainage basin; for general storms where rainfall excess and subsequent surface run-off cover the entire drainage basin.

4. Relation of volume of channel storage corresponding to an outflow rate of 1 c. s. m., to (a) slope and physiographic type of drainage basin, (b) drainage density (12), (c) size of drainage basin.

The importance of a comprehensive research on channel storage is further emphasized in connection with the unit-graph method. Objectives of these studies of larger areas include:

1. Evaluation of channel storage in terms of storm type, as a guide in selecting proper coefficients or factors for use in conjunction with the unit-graph or other methods of estimating channel outflow.

2. Determination of the degree to which channel storage behaves as if concentrated in a single reservoir and the degree, if any, to which this relationship is modified during both rising and receding stages by differences in storm characteristics and rate and direction of storm travel.

3. Determination of the manner in and extent to which channel storage effects are modified by movement of flood wave crests, particularly with reference to applicability of the Seddon equation (22). Application of this equation requires knowledge of stream widths. In conjunction with collection of data, stream widths at various stages should be determined at a considerable number of cross-sections, sufficient to give a fairly reliable average. (A method of determining approximate stream widths by the application of the storage equations to hydrographs has recently been developed by Horton and will be described in a forthcoming paper.)

4. Determination of water losses and infiltration-capacity over large areas. Maps showing water losses, total infiltration, normal water losses, normal total infiltration and, in particular, minimum and average infiltration-capacity over large areas are among the fundamental needs of both scientific and applied hydrology. Such maps can be prepared in a large measure from existing data. A start toward the last named has been made by Horton (14). This study could probably readily be extended, using data for the 1936 floods in eastern United States, which will appear shortly in a series of Water Supply Papers.

### Special Research

The research so far suggested has been concerned mainly with fundamental relationships among the independent variables governing run-off phenomena. There is, however, an unlimited field for additional research in relation to the practical application of these basic principles—in particular into methods of estimating stream flow where complete records are not available. Some of this secondary research could be undertaken immediately, some must be deferred until the basic research has reached a suitable point.

The following examples have been outlined to illustrate desirable topics to be covered in a general study of run-off. While these are outlined here as individual research topics, the research should be carried out in conjunction with and be coordinated with the broader general research on run-off outlined in this paper.

<sup>8</sup> The area on which rain is falling at a given time during a storm.

Item A. Stream Flow Estimation<sup>9</sup>

*Objectives.*—The objective of this research is to improve methods of estimating and extending stream flow records under various conditions where such estimation or extension is necessary in the practical application of run-off data.

There are two general classes of problems involving estimation of stream flow:

1. Those involving run-off in individual storms, including floods. In these problems surface run-off is of prime importance, and in such problems ground water flow and water losses may often be neglected or approximated.

2. Problems involving total run-off, its variation and distribution over longer intervals, as a month or a period of years. For such problems surface run-off, ground water flow, and water losses are of about equal importance.

*Discussion.*—This whole subject of estimation of stream flow requires more logical and rational treatment than it has received. Total run-off may be considered either as:

1. Rainfall minus water losses.

2. Surface run-off plus ground water flow. Both of these viewpoints are useful in run-off estimation.

3. A more or less constant percentage of rainfall. This concept is less reliable. The relation of coincident rainfall to run-off ranges from almost perfect correlation for wholly impervious areas in regions of constant climate, to a very small correlation for drainage basins with deep, permeable soils where the stream flow is almost wholly ground water flow. In northern climates, the correlation may be high in winter for run-off from snow on frozen ground, and low in summer. In climates with marked rainy and dry seasons, the correlation may be good during the rainy season but is obviously zero during the rainless season, for streams supplied by ground water.

In research relative to methods of estimating run-off, it should always be kept in mind that the application of such methods is nearly always limited by the extent and character of the data available. Two problems may be fundamentally the same, but the methods of solution must, of necessity, often be quite different because of limitations or differences in the character of available data. A large part of the labor in the solution of hydrologic problems is finding a means of arriving at a solution with incomplete data.

*Procedure.*—Correlative research on run-off should cover a broad field, including, among other things:

1. Methods of estimation of mean annual run-off.

2. Methods of estimation of monthly run-off. (Engineers use monthly run-off extensively because it provides reasonably approximate results with much less labor than if daily run-off is used. Estimates of monthly run-off are at best approximations, but they should receive attention because of their practical utility and with a view to their betterment.)

3. Methods of estimation of continuous run-off or synthesis of the hydrograph.

There is a wide range of conditions to be considered, and each method should be studied with reference to its validity and applicability:

1. In cold climates and at high elevations where ice and precipitation from snow predominate.

2. In temperate climates.

3. In more arid climates, where run-off is intermittent or ephemeral.

The methods should also be studied with reference to their applicability in regions with:

1. Rainfall distributed throughout the year.

2. Regions with seasonal climate where there is little or no rainfall throughout a considerable period of the year, and stream flow, if any occurs, is derived from natural surface and ground water storage.

They should also be considered with reference to their applicability to different types of stream regimen:

1. Relatively or wholly impervious areas, such as rocky, mountain areas, where there is relatively little ground water flow.

2. Regions in which run-off comprises both surface run-off and ground water flow.

3. Highly permeable regions, from which there is little or no surface run-off, and ground water flow predominates.

It seems obvious that there is no one method best or most applicable under this range of conditions, and the final objective of the research should be the development of new, more flexible and better methods covering the full range of conditions described.

There are also several types of problems which commonly arise in connection with the estimation of run-off, including among others:

1. Extension of a short stream flow record at a given location so as to cover a longer interval, adequate to give a truly representative picture of the run-off regimen.

2. Having given an adequate run-off record at one location on a stream, to determine the run-off at another location on the same stream.

3. To determine the run-off at a given location in a drainage basin where there is a short run-off record, and long run-off records are available on adjacent drainage basins.

4. To determine the run-off in regions where actual gaging data are not available on the same or adjacent streams. This is by far the most difficult and important problem of estimation of run-off, for the reason that over the larger portion of the earth no stream flow records are kept. In this problem, in particular, differences in methods dependent on differences in climatic conditions, and types of stream regimen come strongly into play.

It is not necessary here to inventory the specific procedures in existence which should be studied, but it may be noted that there are various formulas and methods which have been proposed for estimating mean annual run-off, both in this country and abroad. Among methods which have been proposed for estimating monthly run-off are those of Vermeule and Meyer, and among methods for synthesis of the hydrograph are the unit-graph method of Sherman (19), the distribution-graph method of Bernard (10), Folse's method (21), and the infiltration theory of Horton (3).

With reference, for example, to extension of stream flow records, existing methods include the use of run-off relation curves, which show the relation between run-off at station "b," having a short record, to the run-off for the simultaneous period at station "a," having a long record. These curves are then used to extend the record at station "b." Similar results can be obtained by the use of duration curves derived at the two stations from the simultaneous records (Wisler's method). The method can be extended to take into account variation of the relative rainfall amounts from the normal in the two areas.

## Item B. Relation of Run-off to Antecedent Rainfall

*Objectives.*—In estimates where the use of rainfall data are involved, a study of the relation of run-off not only to coincident but to antecedent rainfall should be carried out. For example, the monthly run-off may show a correlation of 50 percent with coincident rainfall, 40 percent with the preceding month's

<sup>9</sup> See also Items No. 5, 6, and 10 of section V, chapter III.

rainfall, 30 percent with the second month preceding, and so on. Some work has been done on this subject by Collins and Snyder (14), Maynard (5), Horton and Grunsky (6), (27), and others.

*Discussion.*—The hydrologic basis of the relationship of run-off and water losses to antecedent rainfall has not been worked out. The subject is important both in relation to stream flow estimation, crop prediction, and stream flow prediction. Antecedent rainfall does not—except in special cases—contribute any direct surface run-off during a given month. It may, however—

1. Increase the surface storage at the beginning of the month and so increase the outflow from lakes, swamps and marshes.
2. Increase the ground water storage at the beginning of the month and so increase the coincident ground water run-off.
3. Increase the soil-moisture-storage at the beginning of the month and so decrease the amount of infiltration required to restore field-moisture-capacity and hence permit larger accretion to ground water, and more ground water run-off.

#### Item C. Water Loss Methods

*Objectives.*—This is a correlative research, the object of which is to compare and, if possible, improve and determine the accuracy of water loss methods of estimating total run-off, such as are commonly used in England and to some extent in continental Europe.

*Discussion.*—The writer uses the term “water losses” in the sense of water which is actually lost from the drainage basin through evaporative processes. These losses are of three kinds: (a) Interception by vegetation, (b) evaporation from the soil surface or evaporation of moisture from within the soil, (c) transpiration by vegetation. The latter obviously takes place entirely from previous infiltration, but it may take place either from the soil-moisture zone or directly from the water table. “The use of water losses” with meanings other than that given above is to be deprecated. The use of the expression “consumptive use” is undesirable. The water is evaporated—not “consumed” or chemically changed—and returns in due course to the surface phase of the hydrological cycle.

Because of the threefold effect of antecedent rainfall on run-off, an adequate research on the subject requires the use of data from drainage basins where suitable ground water level records are available and where the march of soil-moisture-storage is or can be determined, either by the run-off analysis method of Horton or by field measurements. These requirements are best met by the use of data for small drainage basins.

Water loss methods deserve and require special consideration as there are extensive regions (England and Sweden, for example) where mean annual run-off can quite closely be determined by subtracting a constant allowance for water losses from the rainfall. Monthly run-off is estimated by a similar method. The basis for this procedure is the relative constancy of water losses as compared with run-off. One adaptation of the method is to the estimation of long-term run-off at a location where there is only a short record, and only rainfall data are available for longer intervals.

Water losses are more closely related to total infiltration than to rainfall. Total infiltration can be quite closely determined from hourly rainfall data where the infiltration-capacity of the soil is known. The determination of the relation of water losses to total infiltration on numerous drainage basins would apparently provide valuable data for use in estimation of stream flow in the absence of run-off records. For example, if the total infiltration and surface run-off are determined from hourly rainfall, and it is known that the water losses are a nearly constant fraction “*m*” of the total infiltration “*F*,” then the ground-water

flow will be  $(1-m) F$  plus or minus the ground-water depletion.

Various correlative research in relation to water losses should include:

1. Preparation of maps of annual average water losses. A start toward this has been made by Horton. (16).
2. Study of the relation of annual water losses to evaporation from water surfaces. It appears that the ratio

$$\frac{\text{Water loss}}{\text{Evaporation}}$$

may be relatively constant in a given climatic region. If so, evaporation records can be used as a basis of estimating water losses and, in turn, for determining mean annual run-off from rainfall.

3. Transpiration, the most important of evaporative water losses, is derived wholly from within the soil, and hence from infiltration. The single study which has been made of the subject (15) indicates (a) a high degree of correlation between water losses and total infiltration, (b) a relatively constant ratio of apparent water losses to total infiltration. Since total infiltration can be quite closely approximated from hourly rainfall on an area where the infiltration capacity is known, the water loss ratio may prove to be a valuable index of average run-off.

4. Further study of the relation of water losses to latitude and elevation. (16) (17) This research is of great importance in connection with scientific hydrology, with reference to the hydrology of glaciers and polar ice-caps, as well as in relation to applied hydrology, particularly for mountain regions where water supply is derived mainly from melting snow.

Second in importance is evaporation from the soil, which takes place at the surface but mainly from water which has entered the soil as infiltration.

The third type of water loss—interception by vegetation—is directly related to rainfall duration and consequently closely correlated with infiltration.

In general, water losses can be segregated into their three components only if two are measured. This requires collection of data adequate to estimate interception and evaporation from the soil.

It can readily be seen that a comprehensive correlative research based on data at present available but unanalyzed is not a simple matter. The data have been collected by different bureaus and agencies. It may be hoped, however, that these agencies will view the matter in a truly scientific spirit and that a plan can be worked out which will lead to a coordinated analysis of all these data. For this purpose it would seem advisable to set up an advisory board to direct the correlative research. This board should obviously include some wholly disinterested persons not connected with any of the bureaus or agencies collecting the data, but having a comprehensive knowledge of both the background and physical processes of run-off phenomena. In addition, there should be on this board a representative of each bureau or agency engaged in collecting the data, so that the work done by each agency may be analyzed in the light of the knowledge and experience gained by the others engaged in similar work.

#### Item D. The Unit-graph Method

*Objectives.*—The objective of this correlative research is to determine the hydrologic basis of the unit-graph methods, to devise, if possible, methods of preparing synthetic unit-graphs, and to determine the limitations and accuracy of the methods, particularly as applied to the determination of flood outflow graphs.

*Discussion.*—While the unit-graph method as originally presented by L. K. Sherman (19) purported to be a method of estimating channel outflow day by day from rainfall, it involved the assumption that the surface run-off graph and the ground water flow were known or could be determined.

The essential feature of the method, as pointed out in *Water Supply Paper 772*, is the unit-graph itself. The unit-graph is a graph, derived from a hydrograph, showing the manner in which the surface run-off from a 1-day rain which produced 1 inch depth of surface run-off, is distributed as channel outflow on the same and subsequent days. The unit-graph has an area, expressed in inch-miles of run-off, numerically equal to the drainage area, expressed in square miles.

Another graph, of identically the same type, has been developed by Merrill Bernard. This is called the "distribution-graph," which differs from the unit-graph only in the respect that it has an area of unity, so that the ordinate for a given day represents the fraction or percentage of the total run-off from a given day's rain which will appear as outlet flow on the same or some subsequent day.

The following discussion applies equally to the unit-graph and the distribution-graph, the advantage of the latter being chiefly that since the areas of distribution-graphs from different drainage basins are always unity, their characteristics are readily compared.

The unit-graph is based on the assumption that all channel outflow graphs resulting from 1-day rains have the same length or time base, and their areas and ordinates are therefore directly proportional to channel outflow rates. Originally, the assumption was also made that all hydrographs appurtenant to a given outlet point in a given drainage basin, resulting from a 1-day rain, are identical regardless of rainfall distribution, differences in channel storage, or differences in ground-water flow.

Since both surface run-off and ground water flow can, given adequate data, be quite accurately determined, the effect of channel storage in modifying the surface run-off graph remains the least understood and most outstanding problem of potomology, or the science of rivers and streams. There are three possible methods of solving this problem:

1. The time contour method—long in use in conjunction with the rational method of estimating storm-water flows. Data for application of this method to large areas are almost always wanting and its validity is open to serious question.

2. The channel storage method. This involves the determination of channel storage during rising and receding stages. Such determination is easily made for receding stages but not so readily made for rising stages. While this method is still in a state of development, it involves nothing aside from observed data excepting the storage equation.

3. The unit-graph method. Both the channel storage and the unit-graph method take into account automatically channel storage volume and effects, as determined by the characteristics of the drainage net and outlet channels, and these two methods are closely related. It appears, however, as shown by studies contained in *Water Supply Paper 772*, that unit-graphs for the same location are not identical but are considerably modified by various factors, particularly:

- (a) The amount of initial channel storage.

- (b) The actual duration and time of occurrence of rainfall excess in a 1-day rain.

- (c) Rainfall distribution over the drainage basin.

- (d) Velocity and direction of travel of the storm over the drainage basin—whether from mouth to source or the reverse, or across the basin.

Exactly these same factors affect the application of the channel storage method, and the two should unquestionably be studied

together. This research can be carried out on relatively large drainage basins where channel widths are known, so that the volume of channel storage can be quite accurately estimated for rising as well as receding stages, and where there are sufficiently numerous gaging stations to show the progress in modification of the outflow graph in course of transit.

In this connection an important practical problem arises, namely, that of determining the unit-graph at some point on a stream from the unit-graph for the stream at the site of an existing gaging station.

The problem of determining the modification of unit-graphs by various factors is really identical with the problem of determining the modification of a flood wave in its course through a stream channel, and it would seem that this particular research should properly be included in the topic of research on flood waves. Since field data are required, and the necessary data can and should be obtained in conjunction with additional field research on large drainage basins, as outlined above, the research on unit-graphs and related problems should apparently be carried out cooperatively in conjunction with the research on flood waves.

Since the channel outflow graph reflects the changes in the surface run-off or channel inflow graph in course of transit, it appears that much could be accomplished through laboratory experiments toward answering the problems enumerated above regarding the modification of unit-graphs by various factors. The primary effect of differences in direction and velocity of storm travel is to modify the channel inflow or surface run-off graph. If, therefore, experiments were carried out with various types of channel inflow graphs, and the corresponding forms of channel outflow graphs were measured, the results would form a basis for answering these questions. The results of such a series of small-scale laboratory experiments carried out by the Horton Hydrologic Laboratory have recently been published. (26) Such laboratory research is properly a part of the program for flood wave investigation.

#### Item E. Additional Field Research

*Objectives.*—Nearly all the preceding discussion in this paper relates to correlative research, capable of being carried out by the use of existing data. The objectives of the additional field research proposed here are to provide the necessary data for completing the picture of run-off phenomena. This includes particularly the effect of different types of drainage net and channel storage, the phenomena of partial-area run-off, and a variety of other problems in reference to composite drainage basins, which cannot well be studied from data for smaller drainage basins.

*Discussion.*—It is obvious that the additional field research needed cannot be adequately outlined at the present time. It is probable that some additional independent variables should be determined, even at such elaborately equipped field experiment stations as those in the San Dimas forest and Coweeta area in the southern Appalachians. For example, it is desirable that measurements of rainfall interception and direct evaporation from the soil should be made for use in segregating water losses into their three principal elements, and providing a better basis for determination of the march of soil-moisture and its relation to ground water run-off. Also it is desirable that Dines pressure-tube anemometers or some other recording type of anemometer should be installed which will register gustiness and permit of the segregation of periods of laminar and turbulent air flow, as it appears certain that this has an important effect not only on evaporation from water surfaces but on evaporative water losses, and hence on total run-off.

It is clear that additional field data are urgently needed with reference to a large number of drainage basins for the determination of factors of channel storage, etc., incapable of satisfactory study from smaller areas. It is desirable to select for this purpose drainage basins comprising as far as possible a single topographic and physiographic type, rather than composite basins. Also it is desirable to use drainage basins where there is no large degree of artificial regulation so that the natural stream regimen, velocity of transit of flood waves, and other data can be adequately determined. It is also desirable to select drainage basins for which there is at least a 10-year record of run-off at one or more locations, as these records can be used to establish fundamental relationships, such as ground-water depletion curves and rainfall-water loss relation curves, which would otherwise require long-continued records before analysis of the data could begin.

*Procedure.*—The data to be collected should comprise:

*Maps.*—Adequate topographic, geologic, and soil maps. The latter should show by contour lines the surface minimum infiltration-capacity, field-moisture-capacity, and moisture-equivalent of the soil. There should also be maintained, annually, maps of culture, showing the areas devoted to each kind of vegetation—natural and cultivated.

*Stream gaging.*—It is of first importance that the stream-flow records should be complete and accurate throughout the entire year, including the winter season. Gaging stations should be established at suitably frequent intervals to determine the run-off both as to intensity, total amount, relative times of occurrence, and other characteristics for each principal subdivision of the drainage basin. In general, there should be a gaging station on the main stream and on each principal tributary just above its confluence with the stream. In case of important tributaries, gaging stations should be established on these at suitable distances and on their principal tributaries.

*Rainfall.*—Recording rain gages should be established, at least one in every 100 square miles of drainage area. In addition to the recording rain gages there should be a sufficient number of other gages to fix definitely the boundaries of the rain smear produced by every shower and the exact time of the beginning and ending of rainfall. This can be accomplished either through the use of a sufficient number of cooperative observers or, perhaps better, by the use of a simple recording device, less costly than a recording rain gage, which shows the exact time of beginning and ending of rain fall. While it is desirable to have sufficient recording rain gages to determine therefrom accurately the rainfall on the whole area or any major subdivision, this may be impracticable. The number of nonrecording rain gages required depends on the rainfall range and cannot be specified in general terms. It should be sufficient to give an accurate determination of rainfall amount in every storm, but an excessive number of gages is not desirable because it greatly increases the labor of reduction of data.

*Ground water.*—There should be an extensive and fairly complete system of ground-water-level records, care being taken to locate wells so that they are free from backwater from streams and sufficiently sensitive to indicate accurately times of ground-water accretion. It is desirable that the drainage basins used should be free from artesian aquifers deriving their supply from or yielding their supply to extraneous areas.

One part of the geological survey of the area should include determination of the boundaries of the surface aquifers and the relation of external watershed lines of the topographic and surficial ground water-basins.

*Stream width.*—There should be a survey of the streams in the drainage basin from which the width of streams and volume of channel storage at various stages could be determined. From

the topographic surveys, the average length of overland flow and average slope in each subdivision of the drainage basin should be determined.

*Meteorologic data.*—There should be a suitable number—say one to every 1,000 square miles—of central meteorological stations where evaporation from water surface and from the soil surface should be measured, and records of air temperature, soil surface temperature, wind velocity—both laminar and turbulent—and humidity, should be regularly maintained.

*Snow and frost.*—For drainage basins in northern climates, accurate records should be kept of soil temperature at different depths to determine the depth of frost penetration throughout the winter season, and continuous records should be kept, by a sufficiently large number of observers, of the depth of snow on the ground and its water equivalent, to provide an adequate basis for determination of the equivalent water volume of snow storage.

One use of the results of this investigation would be in connection with the study of flood wave phenomena. Though this should in the main be a separate topic of research, it should also be coordinated with the run-off research to provide all data required in both researches.

Because of the relatively great cost of carrying out such research as that outlined above, the number of drainage basins studied should be limited and the research carried out progressively, beginning with one or two drainage basins and extending the number when and as studies of additional areas are found to be necessary to establish fundamental relationships. It is, however, obvious that such studies should ultimately include drainage basins involving all of the following physiographic and climatic regions:

1. A drainage basin in a mountainous or semimountainous region in middle latitudes, with precipitation distributed more or less uniformly throughout the year. The Susquehanna and Delaware drainage basins come within this class.

2. A plains drainage basin, with relatively flat topography and rainfall heavier in the summer season. Various streams in the Mississippi drainage basin would meet this requirement, such as the Muskingum basin. In connection with drainage basins in flatter regions, two principal cases occur:

- (a) Those with fine-textured soil, such as loess and some prairie soils.

- (b) Those deeply overlain with highly permeable sands. It is probable that drainage basins could be found which would cover both of these subtypes in both middle and southern latitudes. Sandy drainage basins occur in Michigan and Florida, but their utility for this research is doubtful because of underlying artesian aquifers.

3. A semitropical drainage basin in a mountainous region, with rainfall distributed throughout the year. Some southern Appalachian streams meet this requirement.

4. A semitropical drainage basin, with relatively flat topography and rainfall throughout the year. Drainage basins in the lower Mississippi valley may be found which meet this requirement.

5. A drainage basin in a semiarid, mountainous region, middle latitudes, as in the Rocky Mountain regions.

6. A drainage basin in a semiarid, mountainous region, semitropical latitude, as in the Mexican mountain regions.

7. A drainage basin in a monsoon climate or with marked rainy and dry seasons; mountainous. Some drainage basins in California meet this requirement.

8. A drainage basin with seasonal rainfall, semitropical, semidesert conditions, plains or flat region.

In order to make this study complete, so as to include more northern climates and truly tropical conditions, it would be

necessary to go outside the limits of the United States, but it is possible that cooperation with other countries could be secured. Information is greatly needed, both for practical application and in relation to hydrology of glaciers and other scientific problems, regarding run-off phenomena in extreme northern latitudes.

With reference to tropical conditions, the study requires for its completion the investigation of run-off phenomena in drainage basins such as those of central Africa and India, where there is excessive rainfall during the winter season but nearly complete absence of rainfall during the summer. A start has been made in this direction by a study of the hydrology of the Congo River in Africa (18).

High mountain areas and glacier drainage basins have not been included for the reason that these basins are generally relatively small, and the character of the hydrologic phenomena of such drainage basins does not lend itself readily to the determination of the particular factors investigated in this research. Research covering the hydrology of such drainage basins is, however, greatly to be desired, for various reasons, including:

(a) The great agricultural value of water from melting snow and its value for power production and other uses.

(b) Because of the fact that the hydrology of high mountain areas, including water losses and other characteristics, is less completely determined than for almost any other type of drainage basin.

*Agencies designated for task.*—It is evident that a research so broad in scope cannot be carried out by any one person or single agency. The study of the main branches must of necessity be carried out under the direction of some coordinating agency to secure orderliness and completeness. At the same time, there are many minor elements which could be investigated with some such direction by any qualified person or agency interested in the subject. The situation is complicated, and the difficulty of covering the field adequately is greatly increased by two things:

1. The basic data are being collected by and are scattered through many different Government bureaus.

2. A large amount of work has already been done within and outside Government bureaus, and nearly all of this has been done by persons who were deeply imbued with certain commonly accepted ideas and viewpoints and who might, if engaged in further research, find it difficult to go back to fundamental principles.

Apparently such a research as here proposed, either correlative or experimental, however greatly it is needed, can only be carried out if:

1. Government bureaus and agencies in possession of basic data will take a sufficiently scientific attitude of mind to permit these data to be used freely and fully, regardless of the results which may come therefrom.

2. If a wholly disinterested coordinating agency can be set up to direct the research.

The fundamental functions of this directive or coordinating agency would be administrative. It should have authority to requisition for use in the research any and all pertinent data existing in governmental bureaus and agencies.

In addition, there should be an advisory board comprising representatives of all Government bureaus interested in run-off phenomena and all interested outside groups, including those concerned with hydroelectric power, navigation, water supply, sewerage, and land drainage, as well as of representatives of the sciences, including botany, ecology, agriculture, and meteorology, directly interested in run-off phenomena.

It is assumed that the members of this advisory board would serve without compensation, but provision should be made to pay their traveling expenses, so that meetings of the advisory

board as a whole could be obtained. In addition, the central coordinating agency should have authority to employ and pay for adequate consulting service, to be used in conjunction with the services of the advisory board. Consultants should include hydrologists most eminently fitted by their breadth of knowledge of the background of hydrology, also physicists and mathematicians competent to evaluate physical relationships between the different processes and to provide the best possible methods of mathematical treatment of the data.

#### Acknowledgments

The preliminary draft of this paper was submitted for consideration to many persons. In particular, useful suggestions and criticisms have been received from Robert E. Kennedy, LeRoy K. Sherman, Dr. J. E. Church, H. T. Critchlow, Capt. Hans Kramer, John B. Alexander, David W. Persons, M. E. Schmidt, B. H. Hendrickson, John W. Pritchett, O. E. Meinzer, K. L. Roberts, and C. S. Jarvis. In addition, the paper was made the topic of discussion at a meeting of the Run-off Committee, Association of Hydrology, Washington, April 30, 1938. Mr. W. G. Hoyt, chairman of the Committee, presided at this meeting. Among those taking part in the discussion were LeRoy K. Sherman, W. W. Horner, Franklin Snyder, Merrill Bernard, D. B. Krimgold, C. R. Hursh, L. K. Hill, Waldo E. Smith, W. B. Langbien, and W. G. Hoyt.

#### References

1. Horton, Robert E., *Analysis of Simulated Rainfall Experiments*, report prepared for United States Soil Conservation Service.
2. Horton, Robert E., "Hydrologic Interrelations of Water and Soils," *Proc. Soil Science Soc. of America*, v. 1, 1937, pp. 401-429.
3. Horton, Robert E., *Surface Run-off Phenomena*, Part I: "Analysis of the Hydrograph," Publ. 101, Horton Hydrologic Laboratory.
4. Collins and Snyder, "Run-off as a Function of Previous Precipitation;" contained in "Rainfall, Run-off, and Evaporation," by L. K. Sherman and Robert E. Horton; *Association Internationale D'Hydrologie Scientifique*, Paris, May 1933, pp. 59-69.
5. Maynard, M. E., "Mode of Flow of Underground Waters in Permeable and Semipermeable Terrains," *Le Genie Civil*, July 4, 1931; also, *Annales*, Ministere de l'Agriculture, "Direction des Eaux et du Genie Rural, Rapports et Notes Techniques (France et Etranger)," fasc. 61, Paris: Imp. Nat., 1931, pp. 168-170.
6. Horton and Grunsky, *Hydrology of the Great Lakes*, Sanitary District of Chicago, 1927.
7. Bartel, F. O., *First, Second, and Third Progress Reports*, "Soil Erosion and Run-off Experiments, Raleigh, North Carolina," North Carolina Experiment Station in cooperation with United States Department of Agriculture, 1925 and 1928.
8. Musgrave, G. W., "The Infiltration Capacity of Soils in Relation to the Control of Surface Run-off and Erosion," *Journal, American Society of Agronomy*, 1935, v. 27, pp. 336-345.
9. Horton, Robert E., "Surface Run-off Control," contained in "Head Waters Control and Use," *Proc. Upstream Engineering Conference*, Washington, 1937, Government Printing Office.
10. Bernard, Merrill M., "An Approach to Determinate Stream Flow," *Trans. Am. Soc. C. E.*, v. 61, 1935, pp. 347-395.
11. Horton, Robert E., "Natural Stream Channel Storage," *Trans. A. G. U.*, 1936, pp. 406-415.
12. Horton, Robert E., "Natural Stream Channel Storage" (second paper), *Trans. A. G. U.*, 1937, pp. 440-456.



13. Meinzer, Cady, Leggette and Fischel; "Channel Storage Method of Determining Effluent Seepage," *Trans. A. G. U.*, 1936, pp. 415-418.
14. Horton, Robert E., "Determination of Infiltration-Capacity for Large Drainage Basins," *Trans. A. G. U.*, 1937, pp. 371-385.
15. Horton, Robert E., "The Role of Infiltration in the Hydrologic Cycle," *Trans. A. G. U.*, 1933, pp. 446-460.
16. Horton, Robert E., "Water Losses in High Latitudes and at High Elevations," *Trans. A. G. U.*, 1934, pp. 351-379.
17. Church, J. E., "Evaporation at High Altitudes and Latitudes," *Trans. A. G. U.*, 1934, pp. 326-342.
18. Uhl, William F., "The Upper Congo River Drainage Basin," *Trans. A. G. U.*, 1933, pp. 425-431.
19. Sherman, L. K., "Stream Flow from Rainfall by the Unit-graph Method," *Eng. News-Record*, v. 108, 1932, pp. 501-505.
20. Horton, Robert E., "Hydrologic Aspects of the Problems of Stabilizing Stream Flow," *Journal of Forestry*, v. 35, No. 11, November 1937, pp. 1015-1027.
21. J. A. Folse, *A New Method of Estimating Stream Flow Based Upon a New Evaporation Formula*, Carnegie Institution, Washington, Publ. 400, 1929.
22. Seddon, James A., "River Hydraulics," *Trans. Am. Soc. C. E.*, v. 43, June 1900, pp. 179-243.
23. Horton, Robert E., "The Interpretation and Application of Run-off Plat Experiments with reference to Soil Erosion Problems," *Proc. Soil Science Soc. of America*, v. 3, 1938, pp. 340-349.
24. Horton, Robert E., "Analysis of Run-off Plat Experiments with Varying Infiltration-capacity," *Trans. A. G. U.*, 1939, pp. 693-711.
25. Horton, Robert E., "Relation of Soil-moisture and Antecedent Rainfall to Run-off and Run-off Prediction"; to be published in *Trans. International Commission on Snow and Ice. General Assembly, International Geophysical Union, Washington, 1939.*
26. Horton, Robert E., "Channel Waves Subject Chiefly to Momentum Control," *Extract of the Bulletin of the Permanent International Assoc. of Navigation Congresses*, No. 27, January 1939, Brussels, 1939.

---

## APPENDIX D. STANDARD FORMS FOR REPORTING BASIC HYDROLOGIC DATA<sup>1</sup>

---

The absence of uniformity in methods of reporting basic hydrologic data was one of the points emphasized at a conference of hydrologists held at Coshocton, Ohio, on May 2 and 3, 1938. The Soil Conservation Service sponsored the conference for members of the American Geophysical Union and the Research Advisory Committee of the Soil Conservation Service. Following the meeting a resolution was prepared by representatives of Federal agencies and others, requesting the Water Resources Committee of the National Resources Committee to explore the feasibility of standard forms which could be used in reporting basic hydrologic data relating to precipitation and run-off from small drainage areas.

The Water Resources Committee requested its Special Advisory Committee on Hydrologic Data to investigate the development of the requisite forms, keeping in mind the objectives to be fulfilled by the development, namely that (1) the forms should be of such character that they could be used in the exchange of hydrologic data between different Federal agencies and between Federal agencies and other groups; (2) the forms should be sufficiently complete and detailed as to permit and encourage their adoption by Federal agencies and other groups engaged in hydrologic research.

Investigations are being currently conducted by many Federal and other agencies into the relationship between precipitation and run-off from small watersheds. All too frequently the immediate worth of these investigations is materially lessened by the absence of uniformity in the manner of reporting the basic data and by the consequent difficulty encountered in their use. Investigation revealed that standardization of the methods of compiling these data was not only possible, but desirable for the efficient and thorough analysis of them, particularly if they were to be used by other than the collecting agency. The detail to which the compilation of data should be carried would, of course, be limited by the detail and precision of the basic data itself.

The interested agencies were concerned primarily with hydrologic data pertaining to small watersheds. For the purpose of the Committee, a small watershed has been arbitrarily defined as one of ten square miles or less. The forms relating to run-off have been prepared on this assumption but are not necessarily restricted to use on watersheds of this small size. The forms for re-

porting precipitation refer in general to a single precipitation station and do not involve an areal concept in their use.

The Special Advisory Committee has confined itself to the preparation of forms for the reporting of basic hydrologic data only. The uses to which the basic data are put and the interpretations derived therefrom are the responsibility of the using agency and should not be circumscribed by standardization. For this reason, the Committee advocates a rigorous differentiation between the compilation of basic hydrologic data and any compilation of derived data which the agencies may care to make.

Six forms were evolved covering the reporting of these basic data as follows:

Form P-1.—Hourly Precipitation Record.

Form P-2.—Excessive Precipitation.

Form P-3.—Record of Rainfall Intensity.

Form PR-4.—Summary of Precipitation and Run-off by Storms for the Year Ending ....., 19...

Form R-5.—Record of Run-off.

Form R-6.—Record of Mean Hourly Run-off Rate.

Forms P-1, P-2, P-3, and PR-4, deal primarily with some phase of precipitation and are applicable to any study involving those phases. In considering forms for reporting basic run-off data, it was found that small watersheds tend to resolve themselves into two groups, those having an intermittent stream flow and those yielding a continuous stream flow. This difference, not necessarily a function of the size of the drainage area, was considered of sufficient importance in adding to the complexity of the problem to warrant separate reporting for the two classes of flow. Two forms have been prepared, R-5, which is applicable to areas yielding an intermittent flow and R-6, which is designed for use on watersheds yielding a continuous flow.

Detailed instructions have been prepared for each of the six forms together with examples showing the manner in which the information in the headings and columns should be filled in. Certain types of hydrologic data will be too numerous to be confined to one sheet and in such cases it is suggested that the individual agencies secure continuation sheets carrying abridged headings as noted in the instructions.

A method of making these standard forms available for general use is dependent largely upon the demand for them. It is expected that this demand will warrant their being printed on a good quality translucent paper suitable for blue printing and bound in tablets of convenient size.

---

<sup>1</sup> In the preparation of this report the Committee has had the assistance and cooperation of Messrs. E. H. Munns and I. H. Sims of the Forest Service; Messrs. L. L. Harrold, D. B. Krimgold, and H. R. Leach of the Soil Conservation Service; Mr. W. B. Langbein, Geological Survey and Mr. R. E. Spencer, U. S. Weather Bureau.

Form F-1

Agency Weather Bureau

File No. 1254  
Sheet 1 of 1

HOURLY PRECIPITATION RECORD

Rain gage: Type Preis: Reconnaissance,  
weighing and recording, 9 inch  
1 inch on chart = 1.50 inches of precipitation.  
1 inch on chart = 64 minutes of time.

Time standard: Eastern  Central   
Mountain  Pacific

Springfield, West Virginia (near)  
(station designation)

Elevation (mean sea level) 700 feet.

Lat: 39° 28'; Long: 78° 41'  
Section \_\_\_\_\_ Township \_\_\_\_\_ Range \_\_\_\_\_

Month February Year 1959  
Station description is , is not , available upon request.

Date	Amount, end of hour to end of hour, in inches																								Daily total	Accumulated total
	A. m. hour ending												P. m. hour ending													
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12		
1																									0	
2										.01	.05	.01	.01	.01								.05	.03	.13	.13	
3	.06	.01	.01	.01	.01	.03	.17	.11	.13	.25	.50	.21	.15	.02				.02	.01	.01				1.51	1.64	
4																									0	1.64
5											.01	.01													.02	1.66
6											.01											*.05	*.02	*.08	1.74	
7		.04	.01	.01																					.06	1.80
8																	.01	.05	.05	.06	.05	.05	.01	.26	2.06	
9																	.02	.06	.06	.01	.07	.02		.18	2.24	
10	.02	.05	.01	.02																					.10	2.34
11																										
12																										
13																										
14																										
15																										
16																										
17																										
18																										
19																										
20																										
21																										
22																										
23																										
24																										
25																										
26																										
27																										
28																										
29																										
30																										
31																										

Amounts from precipitation other than rain will be identified by reference marks as follows:  
 \* Snow.  
 † Mixed rain and snow.  
 ‡ Hail, sleet, etc.  
 T Amounts of precipitation less than 0.01 inch (trace).

INSTRUCTIONS TO ACCOMPANY FORM P-1  
"HOURLY PRECIPITATION RECORD"

This form is intended for the tabulation of hourly precipitation by months.

**Heading**

(a) *Agency*.—Give the name of the agency reporting the data.

(b) *File number*.—Give the agency's file number which may be referred to in requesting copies of the record.

(c) *Rain gage type*.—Give the type, make, and capacity of the gage, i. e., "Weather Bureau Standard Tipping Bucket," "Friez, Reconnaissance, weighing and recording, 12 inch." Indicate the depth and time scales of the recorder, i. e., "1 inch on chart=1½ inches of precipitation, 1 inch on chart=64 minutes of time."

(d) *Elevation*.—Give the mean sea-level elevation of the rain gage in feet.

(e) *Time standard*.—Indicate by a check mark whether Eastern, Central, Mountain, or Pacific standard time.

(f) *Latitude and longitude*.—Record the geodetic position of the gage as nearly as can be determined. The section, township, and range of the public land survey system where available should be given in addition to or instead of the geodetic position.

(g) *Station designation*.—Give State and nearest town as well as station number or name, i. e., "Springfield, W. Va. (near)."

(h) *Date*.—Give the month and year covered by the record.

(i) *Station description*.—Indicate by a check mark whether or not a station description containing information on date of establishment, continuity of record, exposure of rain gage, etc., is available.

**Columns**

Record under each of the hour columns the total precipitation received in the 60-minute period immediately preceding the hour shown in the column heading.



**INSTRUCTIONS TO ACCOMPANY FORM P-2  
"EXCESSIVE PRECIPITATION"**

This form is intended for the tabulation of excessive rainfall by 5-minute intervals from charts of recording rain gages.

**Heading**

(a) *Agency*.—Give the name of the agency reporting the data.

(b) *File number*.—Give the agency's file number which may be referred to in requesting copies of the record.

(c) *Rain gage type*.—Give the type, make, and capacity of rain gage, i. e., "Weather Bureau Standard Tipping Bucket," "Friez, Reconnaissance, weighing and recording, 12 inch." Indicate the depth and time scale of the recorder, i. e., "1 inch on chart = 1½ inches of precipitation, 1 inch on chart = 24 minutes of time."

(d) *Time standard*.—Indicate by a check mark whether Eastern, Central, Mountain, or Pacific standard time.

(e) *Elevation*.—Give the mean sea level elevation of the rain gage in feet.

(f) *Station designation*.—Give State and nearest town as well as station number or name, i. e., "North Platte, Nebr.;" "Fairfield, Ga. (station R-102)," etc.

(g) *Date*.—Give the month and year in which the excessive precipitation occurred.

(h) *Latitude and longitude*.—Record the geodetic position of the gage as nearly as can be determined. The section, township, and range of the public land survey system where available should be given in addition to or instead of the geodetic position.

(i) *Station description*.—Indicate, by a check mark, whether or not a station description containing in-

formation on date of establishment, continuity of record, exposure of rain gage, etc., is available.

In case where more than one sheet is used in tabulating a single rainfall period only items (a), (b), (f), and (g) listed above need be filled out in the heading of each of the continuation sheets, or separate forms with abridged headings may be used for continuation sheets.

**Columns**

*Column 1*.—Give the *even clock hour preceding the beginning of the excessive rate* of rainfall and the date, i. e., if the excessive rate began at 8:07 p. m. on September 8, record as "8:00 P." and immediately below it the date. Indicate a. m. and p. m. by letters "A" and "P" respectively.

*Column 2*.—Tabulate the amount of precipitation prior to the beginning of the excessive rate of precipitation.

*Column 3*.—Tabulate the time at which the excessive rate of precipitation began.

*Columns 4-15*.—Tabulate under the proper 5-minute clock interval the amount of precipitation received during that interval. The amount received during the 5-minute interval should be entered in the upper space and cumulative total entered in the lower space.

NOTE.—The criteria for excessive rates of precipitation may vary with different parts of the country. For example, the Weather Bureau has long used the criteria shown in the table below for many parts of the United States.

Duration in minutes...	5	10	15	20	25	30	35	40	45	50	55	60	120
Amount—Inches.....	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	1.00

Where the criteria used in this report are different from the above, define excessive rainfall in the space provided at the bottom of the form.

Form P-3

Agency Soil Conservation Service

File No. 5706  
Sheet 1 of 1

RECORD OF RAINFALL INTENSITY

Rain gage: Type 9" Fergusson weighing Fairfield, Ga. (Station R-102)  
(Station designation)

1 inch on chart =  $\frac{1}{2}$  inches of precipitation.  
1 inch on chart = 25 minutes of time.

Dates Sept. 16 to 1936  
Lat.: 33° 9' 8"; Long.: W 83° 8' 7"  
Section \_\_\_\_\_ Township \_\_\_\_\_ Range \_\_\_\_\_  
Elevation (mean sea level) \_\_\_\_\_ feet.

Time standard: Eastern  Central   
Mountain  Pacific

Station description is , is not , available upon request.

Date	Time	Time interval	Accumulated depth*	Depth for—		Intensity for—		Remarks
				Each time interval	Regular time interval	Each time interval	Regular time interval	
	Hr.-min.	Min.	In.	In.	In.	In./hr.	In./hr.	
1	2	3	4	5	6	7	8	9
Sept. 16	3:47p		.00	---	---	---	---	Rain began
	50	3	.08	.08	.08	1.60	.96	
	52	2	.14	.06	---	1.80	---	
	55	3	.14	.00	.06	.00	.72	
								No rain
	4:36p	41	.14	.00	---	.00	---	
	40	4	.19	.05	.05	.75	.60	
	43	3	.22	.03	---	.60	.00	
	45	2	.22	.00	.03	.00	.36	
								No rain
	4:55p	10	.22	.00	.00	.00	.00	
	5:00p	5	.23	.01	.01	.12	.12	
	5:10p	10	.24	.01	.01	.06	.06	
	20	10	.25	.01	.01	.06	.06	
								No rain
	7:06p	106	.25	.00	---	.00	---	
	10	4	.27	.02	.02	.30	.24	Rain ended
								Standard gage at same location measured 0.31 inch for entire storm period

\* Figures adjusted to agree with measured rainfall.

MAXIMUM DEPTH AND INTENSITY FOR SELECTED TIME INTERVALS

Duration min.	2	5	10	15	20	30	1 hr.	2 hr.	4 hr.	6 hr.	12 hr.
Depth, inches..	.07	.14	.14	.14	.14	.14	.22	.25	.27	---	---
Intensity, in./hr.	2.10	1.68	.84	.56	.42	.28	.22	.13	.07	---	---

Tabulated J. Smith 2-6-39 Computed R. Brown 2-8-39 Checked W. E. Doe 2-9-39

## INSTRUCTIONS TO ACCOMPANY FORM P-3 "RECORD OF RAINFALL INTENSITY"

This form is intended for the tabulation of rainfall intensity from charts of recording rain gages.

**Heading**

(a) *Agency*.—Give the name of the agency reporting the data.

(b) *File number*.—Give the agency's file number which may be referred to in requesting copies of the record.

(c) *Rain gage type*.—Give the type, make, and recording capacity of the recording rain gages, i. e., "9 inches Ferguson weighing gage"; "100 inches Stevens Type W float gage," etc. Indicate the depth and time scales of the recorder, i. e., "1 inch on chart=1½ inches of precipitation"; "1 inch on chart=25 minutes of time."

(d) *Time standard*.—Indicate by a check mark, whether Eastern, Central, Mountain, or Pacific standard time.

(e) *Elevation*.—Give the mean sea level elevation of the rain gage in feet.

(f) *Station designation*.—Give the State and nearest town as well as the station number or name, i. e., "Fairfield, Ga. (station R-102)."

(g) *Dates*.—Give the period covered by the form, i. e., "September 16 to September 17" if the rain occurred on both dates, or "September 16 to -----" if the rain began and ended on the same day.

(h) *Latitude and longitude*.—Record the geodetic position of the gage as nearly as can be determined. The section, township, and range of the public land survey system where available should be given in addition to or instead of the geodetic position.

(i) *Station description*.—Indicate by a check mark whether or not a station description containing information on the date of establishment, continuity of record, exposure of rain gage, etc., is available.

(j) At the bottom of the sheet state by whom and the dates on which the data were tabulated, computed, and checked.

In cases where more than one sheet is used in tabulat-

ing a single rainfall period only items (a), (b), (f), and (g) listed above need be filled out in the heading of each of the continuation sheets, or separate forms with abridged headings may be used as continuation sheets.

**Columns**

*Columns 1 and 2*.—Tabulate the dates and clock time of:

- (1) Beginning of rainfall.
- (2) Significant changes in rainfall intensities as indicated by the rain gage chart.
- (3) End of rainfall.
- (4) Regular clock times such as 5 minutes, 10 minutes, 15, 30, one hour, etc. The smallest clock time to be used will be governed by the time scale of the recording rain gage. Indicate "a. m." and "p. m." by letters "A" and "P," respectively.

*Column 3*.—Enter the difference in minutes between consecutive entries of column 2.

*Column 4*.—Tabulate the adjusted depths of rainfall corresponding to each time shown in column 2. Where the measured depth in a standard can or recorder varies from the recorder graph values, the latter should be adjusted to conform to the measured depth.

*Column 5*.—Record the depth of rainfall for each of the time intervals tabulated in column 3.

*Column 6*.—Record the depth of rainfall for each regular time interval such as 5, 10, 15, 30, or 60 minutes.

*Column 7 and 8*.—Record the intensities for each time interval and for the regular time intervals.

**Maximum Depth and Intensity for Selected Time Intervals**

The rainfall depths to be recorded in this table for the various durations will be taken directly from the charts. The intensities for the various durations will be obtained by dividing the depths by the corresponding durations.



Agency Soil Conservation Service

File No. 4378  
 Sheet 1 of 1

**SUMMARY OF PRECIPITATION AND RUN-OFF BY STORMS  
 FOR THE YEAR ENDING Sept. 30, 1939**

Characteristics of drainage area:

Size 5230 acres.  
 Elevation (mean sea level) 1430 feet to 1820 feet.  
 Slope: Average 25 %, range 5 % to 50 %.  
 Soil types: Muskingum Silt Loam - 100%  
(Names and percentages of area)  
 Cover: 40% 20% 20% 20%  
(Percent of area: Cultivated-meadow-pasture-woods)

Instrumentation:

Run-off station: Current Meter; art. control; recorder.  
Type (current meter, gauge, etc.)  
 Precipitation stations: 50 nonrecording; 10 recording  
(Number and type)  
 Records available for years: 1937  
 Additional data available: Wind, Humidity, Soil Moisture

Deer Creek

(Name of drainage area)

Fairfield, Ohio (Station No. 4)

(Station designation)

Station description is  , is not  , available upon request.

Lat.: 40 ° 2 ' 9 " ; Long.: 82 ° 8 ' 6 "  
 Section \_\_\_\_\_ Township \_\_\_\_\_ Range \_\_\_\_\_

Date	Precipitation									Run-off					Temperature			Remarks
	Began	Duration	Amount	Maximum intensity					Time		Amount	Maximum rate	Time* of Max.	Max. deg. F.	Min. deg. F.	Mean deg. F.		
				5 min.	15 min.	30 min.	60 min.	1 hr.	Began	Duration								
	Hr.-min.	Hr.-min.	In.	In./hr.	In./hr.	In./hr.	In./hr.	In./hr.	Hr.-min.	Hr.-min.	In.	C. I. A.	Hr.-min.					
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
April																		
5	6:21a	3-20	0.23	.48	.48	.24	.16	.10	-	-	0	0	-	50	38		Time data - Station 4	
6	11:10p	1-16	2.08	8.40	8.40	3.00	2.00	1.04						48	36		Ground wat. Time data - Station 4	
7									12:05a	60-0	1.22	4210	1:15	55	40			

\*Elapsed time after run-off began—col. 10.

**INSTRUCTIONS TO ACCOMPANY FORM PR-4**  
**"SUMMARY OF PRECIPITATION AND RUN-OFF BY STORMS**  
**FOR THE YEAR ENDING..... 19.."**

This form is intended for the tabulation of summaries of all rainfall and run-off records for 1 year from individual small watersheds generally less than 10 square miles.

(1) The data tabulated in this form may be sufficient for certain purposes. This form will also serve as an index which can be used in selecting individual storms for detailed study.

(2) For watersheds with dry weather flow of long duration this form will be supplemented by Form R-6 "Record of Mean Hourly Run-off."

### Heading

(a) *Agency*.—Give the name of the agency reporting the data.

(b) *File number*.—Give the agency's file number which may be referred to in requesting copies of the record.

(c) *Characteristics of a drainage area*.—The "size" and "slope" are self-explanatory. Under "elevation" give the range of mean sea level elevation in feet from the lowest to highest points of the drainage area, thus 140 feet to 1,820 feet. Under "soil types" give the names of the predominating soil types and the percent of the area, thus "Huston clay 50 percent," "Wilson clay loam 30 percent," "others 20 percent." Under "Cover" show percent of area in cultivation, wood, grass, etc., thus, "pasture 50 percent," "cultivated 45 percent," "woods 5 percent."

(d) *Instrumentation*.—Under "Run-off station" indicate the type of measuring station thus "current meter, natural control, staff gage"; "current meter, Columbus deep notch, water level recorder." In case of calibrated devices give the maximum capacity, thus, "Calibrated triangular weir 450 c. f. s." Under "precipitation station" indicate the number and type of rain gage thus: "50 nonrecording, 10 recording." Under "records available" give the years for which records from this drainage area are available, thus: 1933-1935, 1937. Under "additional data available" indicate what other data in addition to those reported are available, thus "humidity, soil moisture," etc.

(e) *Name of drainage area*.—Give the name of the principal stream. If the stream is unnamed, give it as a "tributary of" and the name of the stream into which it drains.

(d) *Station designation*.—Give the State and nearest town as well as the station number or name, i. e., "Fairfield, Ohio (station No. 4)."

(g) *Station description*.—Indicate by a check mark whether or not a station description containing information on the date of establishment, continuity of record, changes of gage datum elevation, changes in instruments, and in the controls, etc., is available.

(h) *Latitude and longitude*.—Record the geodetic position of the gage as nearly as can be determined. Section, township, and range of the public land survey system where available should be given in addition to or instead of the geodetic position.

Only items (a), (b), (e), and (f) need be filled out in the headings of continuation sheets, or separate forms with abridged headings may be used as continuation sheets.

### Columns

*Column 1*.—Give months and dates of precipitation and run-off.

*Columns 2 to 9*.—The data entered in these columns may be obtained from the record of one of the recording rain gages on the drainage area or from a composite record of all rain gages. A note indicating which alternative was followed should be given in the "Remarks" column. A blank space is reserved in the heading of column 9 for the insertion of a time period, the maximum intensity for which may be of particular value.

*Column 10*.—On the proper date line give the time of beginning of surface run-off resulting from the corresponding precipitation tabulated in columns 2 to 9.

*Column 11*.—Give the time in hours and minutes from the beginning to the end of surface run-off resulting from the precipitation tabulated in columns 2 to 9.

*Column 12*.—Give the total surface run-off in inches for the period entered in column 11.

*Columns 13 and 14*.—Give the maximum rate of run-off in c. f. s. and the elapsed time in hours and minutes between the beginning of run-off and the instant at which the maximum rate of run-off was reached.<sup>1</sup>

*Columns 15 to 17*.—Give the maximum and minimum or the mean daily temperatures in °F.

*Column 18*.—"Remarks" The space in this column can be used for the notes mentioned above and for such other notes as may be helpful in interpreting the record, such as "Rate of run-off highest on record," "Duration of rainfall uncertain due to failure of clock," "Ground frozen," "Snow," etc.

<sup>1</sup> Similar information for secondary peaks in discharge may be given under "Remarks."

Form R-5

Agency Soil Conservation Service

File No. 3768

Sheet 1 of 1

RECORD OF RUN-OFF

Station type: Triangular weir, 150 cfs  
(Current meter, flume, etc.)

Tributary to Crooked Creek  
(Name of drainage area)

Elevation of gage datum (m. s. l.) 612 feet.

Fairfield, Ga. W-II  
(Station designation)

Gage datum elevation of point of zero flow 1.50 feet.

Gage type Water level recorder

Catchment area 28.7 acres.

1 inch on chart = 1/10 feet.

Dates March 30 to 1937

1 inch on chart = 25 min. ,        hr.

Lat.: 31° 42' 38"; Long.: 96° 52' 48"

Section        Township        Range       

Time standard: Eastern  Central   
Mountain  Pacific

Station description is , is not , available upon request.

Date and time	Time interval	Accumulated time	Gage height	Discharge rate from rating table, dated		Average discharge for time interval	Run-off from the area		Remarks
				C. f. s.	In./Hr.		For the time interval	Accumulated	
Hr.-min.	Min.	Hr.-min.	Ft.	C. f. s.	In./Hr.				
1	2	3	4	5	6	7	8	9	10
Mar. 30									
4:30p			1.67	.0612	.0022				See Form R-6 for antecedent dry weather flow
5:00	30		1.65	.0447	.0016	.0019	.0010		
5:30	30		1.64	.0347	.0013	.0014	.0007		
6:00	30		1.63	.0314	.0011	.0012	.0006		
6:30	30		1.62	.0257	.0009	.0010	.0005		Surface Run-off began
6:53	23	0	1.62	.0257	.0009	.0009	.0003	0.	
6:55	2	2	1.63	.0314	.0011	.0010	.0000	0.	
7:00	5	7	1.65	.0447	.0016	.0014	.0001	.0001	
7:05	5	12	1.69	.0807	.0029	.0022	.0002	.0003	
7:08	3	15	1.74	.145	.0051	.0040	.0002	.0005	
7:09	1	16	1.78	.213	.0076	.0064	.0001	.0006	
7:10	1	17	1.81	.275	.0097	.0086	.0001	.0007	
7:11	1	18	1.87	.428	.0152	.0124	.0002	.0009	
7:12	1	19	2.06	1.21	.0427	.0290	.0005	.0014	
7:13	1	20	2.34	3.32	.1177	.0802	.0013	.0027	
7:14	1	21	2.60	6.52	.2309	.1743	.0029	.0056	
7:15	1	22	2.78	9.53	.3373	.2841	.0047	.0103	
7:16	1	23	2.96	13.2	.4687	.4030	.0067	.0170	
7:17	1	24	3.10	16.6	.5891	.5289	.0076	.0246	
7:18	1	25	3.24	20.5	.7268	.6580	.0109	.0355	
7:19	1	26	3.25	20.8	.7370	.7319	.0122	.0477	Peak
7:20	1	27	3.24	20.5	.7263	.7319	.0122	.0599	
7:22	2	29	3.18	18.8	.6655	.6962	.0232	.0831	
7:23	1	30	3.12	17.2	.6078	.6364	.0106	.0937	Trough
7:24	1	31	3.12	17.2	.6078	.6078	.0101	.1038	
7:25	1	32	3.13	17.4	.6174	.6126	.0102	.1140	
7:26	1	33	3.20	19.4	.6857	.6520	.0109	.1249	
7:27	1	34	3.30	22.3	.7908	.7832	.0123	.1372	

Tabulated H. M. Dix Computed H. M. Dix Checked T. E. Elliott

\* Insert units used. Conversion factor for drainage area: 1 c. f. s. = .0345 in./hr.

**INSTRUCTIONS TO ACCOMPANY FORM R-5**  
**"RECORD OF RUN-OFF"**

This form is intended for the tabulation of run-off from small areas generally less than 10 square miles. (For small watersheds having a continuous yield this form should be supplemented by Form P-6.)

**Heading**

(a) *Agency*.—Give the name of the agency reporting the data.

(b) *File number*.—Give the agency's file number which may be referred to in requesting copies of the record.

(c) *Station type*.—Indicate method of measurement and the type of control, i. e., "current meter with natural control"; "current meter with Columbus deep notch," etc. In case of calibrated devices give maximum capacity, i. e., "calibrated Parshall flume 1,200 c. f. s.," "calibrated triangular weir 450 c. f. s."

(d) *Elevation of gage datum*.—Give the mean sea level elevation of the zero of the page. (This is not necessarily the mean sea level elevation of the point of zero flow.)

(e) *Gage datum elevation of the point of zero flow*.—Give the differences in elevation between the zero of the gage and the point of zero flow.

(f) *Gage type*.—Indicate the type of gage, i. e., "staff gage," "chain gage," "water level recorder." In the case of staff and chain gages give frequency of readings. For water level recorders give the stage and time scale, i. e., "1 inch on chart = 1 foot." "1 inch on chart = 1 hour." Indicate by a check mark whether time is in minutes or hours.

(g) *Time standard*.—Indicate by a check mark whether Eastern, Central, Mountain, or Pacific standard time.

(h) *Name of drainage area*.—Give the name of the principal stream. If the stream is unnamed, give the name of the stream into which it drains.

(i) *Station designation*.—Give the state and nearest town as well as the station number or name, i. e., "Fairfield, Ga. (station W-11)."

(j) *Catchment area*.—Give the size of the drainage area in acres.

(k) *Dates*.—Give the period covered by the form, i. e., "March 20 to March 23," if the run-off was continuous during the period, or "March 20 to -----" if the run-off began and ended on the same day.

(l) *Station description*.—Indicate by a check mark whether or not a station description containing information on the date of establishment, continuity of record, changes, of gage-datum elevation, changes in instruments, and in the controls, etc., is available.

(m) *Latitude and longitude*.—Record the geodetic position of the gage as nearly as can be determined. Section, township, and range of the public land survey system where available should be given in addition to or instead of the geodetic position.

(n) In cases where more than one sheet is used in tabulating a single run-off period, only items (a), (b), (h), (i), and (k) listed above need be filled out in the headings of the continuation sheets, or a separate form with abridged headings may be used as continuation sheets.

(o) At the bottom of the sheet state by whom and the dates on which the data was tabulated, computed, and checked.

(p) Insert the value of the conversion factor to be used for this drainage area in reducing run-off in cubic feet per second to run-off in inches per hour.

**Columns**

*Column 1*.—Give date and time of a sufficient number of gage heights to permit accurate plotting of the hydrograph. In case of watersheds with dry-weather flow it may be well to record several gage heights preceding the rise. The dates need only be entered at the beginning of record and at midnight.

*Column 2*.—Enter the difference in minutes between consecutive entries in column 1.

*Column 3*.—Give the accumulated time at the end of each time interval recorded in column 2 from the beginning of rise in stage.

*Column 4*.—Give gage height in feet corresponding to each time tabulated in column 1.

*Columns 5 and 6*.—Give rates of discharge in c. f. s. and in inches per hour corresponding to each gage height tabulated in column 4.

*Column 7*.—Record the arithmetic average of consecutive values tabulated in columns 5 and 6 which correspond to the beginning and end of each time interval tabulated in column 2. Insert the units used.

*Column 8*.—Multiply each of the values tabulated in column 7 by the corresponding time intervals (col. 2) and by an appropriate factor to convert the data into the units used in column 8. Insert the units used.

*Column 9*.—Give the progressive summation of the values tabulated in column 8 from the beginning of the rise in stage. Insert the units used.

*Column 10*.—On the proper date and time lines enter notes indicating: beginning of surface run-off, peaks and troughs, end of surface run-off, and such other remarks as will aid in interpreting the record.



**INSTRUCTIONS TO ACCOMPANY FORM R-6**  
**"RECORD OF MEAN HOURLY RUN-OFF RATE"**

This form is intended for the monthly tabulation of mean hourly run-off from small drainage areas (generally less than 10 square miles) with dry weather flow continuous over long periods. It will supplement Form R-5 which covers only periods of surface run-off.

**Heading**

(a) *Agency*.—Give the name of the agency reporting the data.

(b) *File number*.—Give the agency's file number which may be referred to in requesting copies of the record.

(c) *Station type*.—Indicate method of measurement and the type of control, i. e., "current meter with natural control"; "current meter with Columbus deep notch," etc. In case of calibrated devices give maximum capacity, i. e., "calibrated Parshall flume 1,200 c. f. s.," "calibrated triangular weir 450 c. f. s."

(d) *Elevation of gage datum*.—Give the mean sea level elevation of the zero of the gage. (This is not necessarily the mean sea level elevation of the point of zero flow.)

(e) *Gage datum elevation of the point of zero flow*.—Give the difference in elevation between the zero of the gage and the point of zero flow.

(f) *Gage type*.—Indicate the type of gage, i. e., "staff gage," "chain gage," "water level recorder." In the case of staff and chain gages give frequency of readings. For water level recorders give the stage and time scales, i. e., "1 inch on chart=1 foot," "1 inch

on chart=1 hour." Indicate by a check mark whether the time is in minutes or hours.

(g) *Time standard*.—Indicate by a check mark whether Eastern, Central, Mountain, or Pacific standard time.

(h) *Station description*.—Indicate by a check mark whether or not a station description containing information on the date of establishment, continuity of record, changes of gage datum elevation, changes in instruments, and in the controls, etc., is available.

(i) *Latitude and longitude*.—Record the geodetic position of the gage as nearly as can be determined. Section, township, and range of the public land survey system where available should be given in addition to or instead of the geodetic position.

(j) *Name of drainage area*.—Give the name of the principal stream. If the stream is unnamed, give the name of the stream into which it drains.

(k) *Station designation*.—Give the State and nearest town as well as the station number or name, i. e., "Fairfield, Ga. (station W11)."

(l) *Catchment area*.—Give the size of the drainage area in acres.

(m) *Date*.—Record the month and year covered by this form.

**Columns**

Record under each of the hour columns the mean hourly run-off rate for the 60-minute period immediately preceding the hour shown in the column heading.

---

## APPENDIX E. BIBLIOGRAPHY

---

Material published on hydrology and its many phases may be found in a wide variety of scientific literature. It would be a task well beyond the scope of this report to attempt to compile an exhaustive list of the articles, pamphlets, books, etc., which have been written on the subject. The compilation of bibliographies of the most important publications in each of the several fields of hydrologic research have been undertaken previously by different agencies, as, for example, those listed as references A-2-4-6-12-13. In addition, several scientific societies prepare annual bibliographies of current literature within the different fields.

To compile selective bibliographies on the research subjects covered in this report would, to a very considerable extent, duplicate bibliographical lists compiled within recent years and could scarcely be justified. For this reason, the Committee has limited the following bibliography to the listing of recently published works containing bibliographies; scientific societies whose publications contain articles on hydrology and hydrologic data; commercial technical periodicals; and general textbooks on hydrology and related subjects, all of which contain extensive bibliographic references. These references will provide the research worker with a point from which to initiate a review of the technical literature on hydrology but leave to the individual the evaluation of the material.

### A. Bibliographies on Hydrology and Some Related Subjects

1. *Bibliography of Hydrology*. Published annually for the United States, American Geophysical Union, Section of Hydrology.
2. Bibliography of Rainfall Intensities, Run-off and Flood Flows; *Water Supply Paper 771* and *772*, U. S. Geological Survey, 1936.
3. "Bibliography and Index of Publications of the Geological Survey, Relating to Ground Water," *Water Supply Paper 427*, U. S. Geological Survey, 1920.
4. *Bibliography on Soil Erosion, and Soil and Water Conservation* (compiled by S. H. Gaines), Miscellaneous Publication 312, U. S. Department of Agriculture, 1938.
5. *List of Publications and Abstracts*, R. E. Horton, Hydrologic Laboratory, Voorheesville, N. Y., Publication #112, September 1937.
6. *Bibliography on Soil and Water Conservation and Hydrology*, Sub-Committee on Bibliography and Reports, American Society of Agricultural Engineers, June 21-24, 1937.
7. Bibliography—*Public Health Engineering Abstracts* (include United States Sewage and Waste—current abstracts), Public Health Service, U. S. Treasury Department.
8. Bibliography—*Circular 24* (List of Publications), Current Hydraulic Laboratory Research, National Bureau of Standards, U. S. Department of Commerce.
9. Bibliographies of specific subjects are frequently published in Annual Reports of Committees, American Geophysical Union.
10. *Experiment Station Record* (Abstracts of Literature), published semiannually, U. S. Department of Agriculture, Washington, D. C.
11. *Selected Bibliography on Upstream Engineering*, Soil Conservation Service, September 22-24, 1936.
12. "Selected Bibliography on Erosion and Silt Movement," *Water Supply Paper 797*, U. S. Geological Survey, 1937.
13. *Bibliography on Land Drainage*, Bureau of Agricultural Engineering, 1936.
14. "Inventory of Unpublished Hydrologic Data," *Water Supply Paper 837*, U. S. Geological Survey, 1938.
15. Engineering Index Service, New York City.
16. *Annotated Bibliography of Economic Geology*, Economic Geology Co., Urbana, Illinois, Vol. I-X, 1928-1938 (published annually and contains section on ground water giving abstracts of current ground water literature).
17. *List of Publications of U. S. Geological Survey*, U. S. Geological Survey.

### B. Scientific Societies and Publications— With Reference to Hydrology

#### United States

1. American Academy of Arts and Sciences, *Proceedings*.
2. American Association of Petroleum Geologists, *Bulletin*.
3. American Association for the Advancement of Science, *Science*.
4. American Chemical Society, *Chemical Abstracts; Industrial and Engineering Chemistry*.

5. American Fisheries Society, *Transactions*.
6. American Forestry Association, *American Forest and Forest Life*.
7. American Geographical Society, *Proceedings; Geographical Review*.
8. American Geophysical Union, *Transactions*, especially Sections on Hydrology, Meteorology, and Oceanography.
9. American Institute of Electrical Engineers, *Transactions; Electrical Engineering*.
10. American Institute of Mining and Metallurgical Engineers, *Mining and Metallurgy; Transactions*.
11. American Mathematical Society, *Transactions*.
12. American Meteorological Society, *Bulletin* (monthly).
13. American Philosophical Society, *Proceedings*.
14. American Physical Society, *Bulletin; Physical Review; Review of Modern Physics*.
15. American Shore and Beach Preservation Association, *Shore and Beach* (quarterly).
16. American Society of Agricultural Engineers, *Transactions; Agricultural Engineering*.
17. American Society of Agronomy, *Journal; Proceedings*.
18. American Society of Civil Engineers, *Civil Engineering; Proceedings; Transactions*.
19. American Society of Mechanical Engineers, *Mechanical Engineering; Transactions*.
20. American Society of Plant Physiologists, *Plant Physiology*.
21. American Soil Survey Association, *Bulletin*.
22. American Standards Association, *Bulletin*.
23. American Statistical Association, *Journal*.
24. American Waterworks Association, *Journal*.
25. Association of American Geographers, *Annals*.
26. Association of American State Geologists, *Journal*.
27. Association of Scientific Apparatus Makers of the U. S. A. (also Optical Society of America), *Review of Scientific Instruments*.
28. Boston Society of Civil Engineers, *Journal*.
29. Carnegie Institution of Washington, *Bulletins, Reports, etc.*
30. Connecticut Society of Civil Engineers, *Papers, Transactions and Proceedings*.
31. Ecological Society of America, *Ecology; Bulletin*.
32. Franklin Institute of Philadelphia, *Journal*.
33. Geological Society of America, *Bulletin*.
34. National Academy of Science, *Proceedings*.
35. National Research Council, *Bulletins*.
36. New England Waterworks Association, *Journal*.
37. Smithsonian Institution, *Bulletins, Reports, etc.*
38. Society of American Foresters, *Journal of Forestry*.
39. Society of American Military Engineers, *Military Engineer*.
40. Society of Economic Geologists, *Proceedings*.

41. Washington Academy of Sciences, *Journal*.
42. Western Society of Engineers, *Bulletin; Journal*.

#### Canadian

43. Canadian Society of Technical Agriculturists, *Scientific Agriculture*.
44. Engineering Institute of Canada, *Transactions; Engineering journal*.
45. National Research Council, *Canadian Journal of Research*.
46. Royal Canadian Institute, *Transactions; Proceedings*.
47. Royal Society of Canada, *Proceedings and Transactions*.

#### Foreign

48. *Annales des Ponts et Chaussées* (monthly), Paris.
49. Association Internationale d'Hydrologie Scientifique, Paris, *Bulletins, etc.*
50. Institution of Civil Engineers, *Proceedings; Journal, Abstract of Papers*.
51. Institution of Water Engineers, *Transactions*.

#### C. Publications—With Reference to Hydrology

1. *Engineer* (weekly), London.
2. *Engineering News-Record*.
3. *Scientific Monthly*.
4. *Verein Deutscher Ingenieure*, Berlin.
5. *Waterworks and Sewerage*.
6. *Waterworks Engineering*.
7. Canada Department of Interior, *Water Resources Papers*.
8. Great Britain Department of Scientific and Industrial Research, *Water Pollution Research*.
9. U. S. Weather Bureau, Circulars A, B, C, D, E, F, G, I, L, M, N, O, P, Q, and R; *Monthly Weather Review* (includes current bibliography); and *Bulletins*.
10. U. S. Geological Survey, *Water Supply Papers; Professional Papers; Annual Reports; and Lists of Publications*.
11. U. S. Bureau of Standards, *Bulletins; Current Hydraulic Laboratory Research* and *Research Bulletin* or reprints.
12. U. S. Department of Agriculture, *Technical Bulletins; Miscellaneous Publications; Circulars; Lists of Publications* and other publications, including those from Bureau of Agricultural Engineering, Forest Service, Soil Conservation Service, Biological Survey, etc.
13. U. S. War Department, Office of Chief of Engineers, "308" Reports, reports dealing with hydrology, navigation, flood control and hydro power of most of the important drainage basins of the United States (many unpublished hydrological



data are on file in the office of the District Engineers); Congressional documents, reports to Congress on navigation improvements; Stream Gaging Records on the Mississippi; Reports of the Mississippi River Commission; Reports of Chief of Engineers; and Reports of Beach Erosion Board.

14. U. S. Coast and Geodetic Survey, Bulletins; Manuals; *Hydrography*, including charts; Maps of Coastal Waters; and *Inland Coast Pilot*.

#### D. General Textbooks on Hydrology and Related Subjects

1. Barrows, H. K., *Water Power Engineering*, 2nd Edition, New York, McGraw-Hill Book Company, 1934.
2. Baker, D. M. and Conkling, H., *Water Supply and Utilization*, New York, John Wiley and Sons, 1930.
3. Blair, Thomas A., *Weather Elements*, New York, Prentice Hall, Inc., 1937.
4. Brunt, D., *Physical and Dynamic Meteorology*, Cambridge University Press, 1934.
5. Brooks, C. E. P., *Climate Through the Ages—A Study of Climatic Factors*, London, E. Benn, Ltd., 1926.
6. Dixey, Frank, *A Practical Handbook of Water Supply*, London, Thomas Murby & Co., 1931.
7. Humphreys, W. J., *Physics of the Air*, 2nd Edition, New York, McGraw-Hill Book Company, 1929.
8. Huntington, E. and Visher, S. S., *Climatic Changes—Their Nature and Causes*, Yale University Press, New Haven, 1922.
9. King, H. W., *Handbook of Hydraulics*, New York, McGraw-Hill Book Company, 1933.
10. Lacey, J. M., *Hydrology and Ground Water*, London, Lockwood & Son, 1926.
11. Mead, D. W., *Hydrology*, New York, McGraw-Hill Book Company, 1919.
12. Meyer, A. F., *Elements of Hydrology*, 2nd Edition, New York, John Wiley and Son, 1928.
13. Muskat, Morris, *The Flow of Homogeneous Fluid Through Porous Media*, New York, McGraw-Hill, 1937.
14. Tolman, C. F., *Ground Water*, New York, McGraw-Hill, 1938.
15. Trewartha, G. T., *Introduction to Weather and Climate*, New York, McGraw-Hill Book Company, 1937.

#### E. General Textbooks on Statistical Analysis

1. Carse and Shearer, *Fourier Analysis and Periodogram Analysis*.
2. Elderton, *Frequency Curves and Correlation*, London, Layton, 1927.

3. Ezekiel, M., *Methods of Correlation Analysis*, John Wiley & Sons, 1930.
4. Fisher, R. A., *Statistical Methods for Research Workers*, London, Oliver and Boyd, 1930.
5. Fry, Thornton Carle, *Probability and its Engineering Uses*, New York, D. Van Nostrand Company, 1928.
6. Goulden, C. H., *Methods of Statistical Analysis*, New York, John Wiley & Sons, 1939.
7. Hazen, Allen, *Flood Flows*, New York, John Wiley & Sons, 1930.
8. Mavis, F. T., *The Construction of Nomographic Charts*, International Textbook Company, 1939.
9. Mills, Cecil Frederick, *Statistical Methods*, New York, H. Holt and Company, 1924.
10. Rietz, Henry Lewis, *Handbook of Mathematical Statistics*, New York and Boston, Houghton Mifflin Company, 1924.
11. Running, Theodore Rudolph, *Empirical Formulas*, 1st Edition, New York, John Wiley & Sons, Inc.
12. Carnegie Institution of Washington—Reports of the Conference on Cycles.

The general references indicated below are to documents which contain data and which may be obtained from Federal agencies, or from the Superintendent of Documents, United States Government Printing Office, Washington, D. C. The number in parentheses at the head of each reference is the number of the price list, available for free distribution by the Superintendent of Documents, in which this publication would be listed if still in stock.

It must also be remembered that many items indicated in the Bibliography of this appendix include sources of data applicable not only to the specific subject treated by the item but to other phases of hydrology as well.

#### Climatology, Precipitation, Stream Flow, etc.

- (48) Climatological Data of the United States: *Weather Statistics* (monthly) and Special Bulletins, Weather Bureau.
- (48) *Climatic Charts for the United States*, Weather Bureau.
- (48) *Daily River Stages on Principal Rivers of the United States*.
- (15) Floods: Miscellaneous Water Supply Papers on Various Important floods in various parts of the country.
- (48) *Meteorological Yearbook*, Weather Bureau (annually).
- (48) Miscellaneous Congressional Documents and Hearings on Flood Control for Various Sections and Rivers of the Country.
- (48) *Monthly Weather Review* and supplements, Weather Bureau.

- (48) *Snow and Ice Bulletin*. Included in subscription to *Weekly Weather and Crop Bulletin*.
- (15) Stream Measurement: Miscellaneous Reports on Progress of Stream Measurement, etc.
- (48) Surface Water Supply of the United States. These are available for every major drainage basin of the United States and should be ordered accordingly.
- (48) Weather Maps—Daily Weather Maps.
- (48) *Weekly Weather and Crop Bulletin*.
- (15) Annual Reports of Geological Survey, including papers on Hydrography.

**Instrumentation, Hydraulics, etc.**

- (36) Bureau of Standards, *Journal of Research* (monthly).
- (36) Bureau of Standards, *Technical News Bulletin* (monthly).

**General**

- (15) Classified Lists of Projects of the Agricultural Experiment Station, 1930.

- (36) *Experiment Station Record* (monthly).
- (36) *Journal of Agricultural Research* (semi-monthly).
- (15) List of Bulletins of Agricultural Experiment Station for various calendar years.
- (36) *Soil Conservation* (monthly).
- (36) *Monthly Catalogue of United States Public Documents*.
- (36) *Monthly Check List of State Publications*.

**Maps**

- (53) *Forest Regions of the United States*.
- (53) Geological Survey: Geologic, topographic and other maps and folios.
- (53) *Land Use Areas*, published by Agriculture Department.
- (53) Maps issued by Coast and Geodetic Survey.
- (53) *Mississippi River Commission Map*.
- (53) Soil Conservation Survey Maps, Agriculture Department.
- (53) *Soils of the United States*, issued by the Bureau of Chemistry and Soils, Department of Agriculture.

---

## INDEX

---

- Aquifer  
compressibility and elasticity of, 34  
porosity, permeability of, 33, 34  
Artesian pressure recorders, 31  
Baldwin, O. J., 1  
Bibliography, hydrologic research, 73, 89  
Consumptive use, determination of, 30  
Corps of Engineers, U. S., 5  
Data, sources of, 6  
Drainage basins  
infiltration characteristics, 23  
run-off records, 42  
studies, 53  
Evaporation  
factors influencing, 4  
insolation as a measure of, 27  
measurement equipment, standardization, 25  
open water surface to pan, relation of, 27  
projects, 24  
snow and ice, 28  
Evapo-transpiration, determination, 29  
Flood flow, estimation of, 44, 45  
Forest Service, U. S., 5  
Forms for reporting data, 75  
Geological Survey, U. S., 5, 7  
Ground water  
aquifer, effect of texture, 32  
composition, 49  
contamination of, 51  
depletion curves, 67  
fluctuations in, 32  
motion of, 36  
projects, 31, 47  
prospecting for, 31, 36  
relationship to stream flow, 35  
Horton, Robert E., 1, 53, 63, 73, 74  
Hydrologic research  
coordination of, 59  
major defects, 3  
projects, 9  
Hydrology, statistical methods, 61  
Infiltration  
areal and basin, determination, 23  
effect of surface condition and vegetal cover, 21  
measurement project, 20  
nature and mechanics of, 19  
projects, 19  
Insolation, as a measure of evaporation, 27  
Interception, projects, 9  
Meyer, Adolph F., 1  
Miami Conservancy District, 6  
Percolation, projects, 31  
Precipitation  
effect of bodies of water upon, 17  
excessive, form for reporting, 79  
hourly record, form, 77  
interception, 19  
projects, 9  
Precipitation—Continued.  
provinces, determination, 13  
rainfall intensity record, form, 81  
summary by years, form, 83  
variations due to altitude, 14  
Rainfall intensity, duration, and distribution, 15  
Rainfall intensity rates, sequence of, 16  
Rain gage accuracy, location, and exposure, 9  
Recommendations, 3  
Run-off  
channel storage, 68  
estimation of, 41, 42  
frequency of rate, 47  
mean hourly rate, form, 87  
periods, 48  
plat experiments, 64  
projects, 39  
records, form, 85  
relation to antecedent rainfall, 69  
research, 63  
snow cover, 39  
summary by years, form, 83  
unit graph, 71  
San Dimas Experimental Forest, 55  
Salts, soluble in surface waters, 49  
Salt water, intrusion of, 50  
Silt, scour, transpiration, deposition, 43  
Snow measurement, 11  
Soil Conservation Service, U. S., 5, 7  
Special Advisory Committee on Hydrologic Data, 1, 3, 59, 60, 63  
Station records  
analysis, 12  
dependability, 12  
Station-year method  
rainfall frequencies, measurement, 13  
statistical soundness, 13  
Stream flow  
derived from ground water, 47  
duration curves, 40  
estimation, 69  
ice conditions, 40  
projects, 39  
research, 63  
synthesis, 44  
Storms, limiting 16  
Surface water  
composition, effect on land use, 50  
salt content, source and intrusion, 49  
Tidal streams, salt water intrusion, 52  
Transpiration, projects, 24  
Vegetal cover, infiltration effect, 21  
Water, quality of, 49  
Water levels  
fluctuation in wells, 31  
recorders, 31  
Water Resources Committee, 59  
Weather Bureau, U. S., 5, 7