

Floodflow computation

Methods compiled from
world experience

A. A. SOKOLOV

S. E. RANTZ

M. ROCHE



The Unesco Press

Recent titles in this series

18. Hydrological effects of urbanization. Report of the Sub-group on the Effects of Urbanization on the Hydrological Environment.
19. Hydrology of marsh-ridden areas. Proceedings of the Minsk Symposium, June 1972.
20. Hydrological maps. *Co-edition Unesco-WMO*.
21. World catalogue of very large floods / Répertoire mondial des très fortes crues / Catalogo mundial de grandes crecidas / Всемирный каталог больших паводков.
22. Floodflow computation. Methods compiled from world experience.

For details of the complete series please see the list printed at the end of this work.

Floodflow computation

Methods compiled from
world experience

By A. A. SOKOLOV, S. E. RANTZ and M. ROCHE

A contribution to the International Hydrological Decade

The Unesco Press Paris 1976

Published by The Unesco Press
7 Place de Fontenoy, 75700 Paris
Printed by NICI, Ghent

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of the publishers concerning the legal status of any country or territory, or of its authorities, or concerning the frontiers of any country or territory.

ISBN 92-3-101350-5
© Unesco 1976
Printed in Belgium

Preface

This work is the twenty-second volume to appear in the 'Studies and Reports in Hydrology' series, a series which was begun by Unesco, along with the publication of the 'Technical Papers in Hydrology' series, when the International Hydrological Decade (IHD) was launched.

The International Hydrological Decade, which ended in 1974, was launched in 1965 by the General Conference of Unesco at its thirteenth session. Its purpose was to advance knowledge of scientific hydrology by promoting international co-operation and by training specialists and technicians. At a time when the demand for water is constantly increasing as a result of the rise in population and of developments in industry and agriculture, all countries are endeavouring to make a more accurate assessment of their water resources and to use them more rationally. IHD has been a valuable means to this end.

By the end of the decade in 1974, national committees for the decade had been formed in 107 of Unesco's 135 Member States to carry out national activities and contribute to regional and international activities within the programme of the decade. The implementation of this programme was supervised by a co-ordinating council, composed of thirty Member States selected by the General Conference of Unesco, which studied proposals concerning the programme, recommended the adoption of projects of interest to all or a large number of countries, assisted in the development of national and regional projects and co-ordinated international co-operation. The promotion of collaboration in developing hydrological research techniques, exchanging hydrological data and organizing hydrological networks was a major feature of the programme of IHD, which encompassed all aspects of hydrological studies and research. Hydrological investigations were encouraged at national, regional and international levels, to strengthen and improve the use of natural resources in view of both local and global needs. The programme enabled countries well advanced in hydrological research to exchange information and developing countries to benefit from such exchanges in order to elaborate their own research projects and plan their own hydrological networks, taking advantage of the most recent developments in scientific hydrology.

Conscious of the need to continue the efforts developed during the International

Hydrological Decade, and following the recommendations of Member States, the General Conference of Unesco decided at its seventeenth session to launch after the end of the decade a long-term intergovernmental programme, the International Hydrological Programme, and defined its basic objectives. These objectives are: (a) to provide a scientific framework for the general development of hydrological activities; (b) to improve the study of the hydrological cycle and the scientific methodology for the assessment of water resources throughout the world thus contributing to their rational use; (c) to evaluate the influence of man's activities on the water cycle, considered in relation to environmental conditions as a whole; (d) to promote the exchange of information on hydrological research and on new developments in hydrology; (e) to promote education and training in hydrology; (f) to assist Member States in the organization and development of their national hydrological activities.

As was done for the decade, the activities of the International Hydrological Programme are co-ordinated at international level by an intergovernmental council composed of thirty Member States. They are periodically elected by the General Conference and their representatives chosen by national committees.

The International Hydrological Programme became operational on 1 January 1975 and is to be executed through successive phases of six years' duration.

The purpose of the continuing series 'Studies and Reports in Hydrology' is to present the data collected and the main results of hydrological studies undertaken within the framework of the decade and the new International Hydrological Programme, as well as to provide information on the hydrological research techniques used. The proceedings of symposia will also be included. It is hoped that these volumes will furnish material of both practical and theoretical interest to hydrologists and governments and meet the needs of technicians and scientists concerned with water problems in all countries.

Contents

Foreword		13
1	Determination of optimum design probabilities of flood discharge	
1.1	Objectives of studies of design probability	15
1.2	Determination of optimum design probability by analytical methods	16
1.2.1	U.S.S.R. practice	16
1.2.2	United States practice	17
1.2.2.1	Pre-project conditions	18
1.2.2.2	Project conditions	18
1.2.2.3	Graphical analysis	19
1.2.3	French practice	20
1.3	Standard design probabilities for various hydraulic structures	21
1.3.1	U.S.S.R. practice	22
1.3.2	Polish practice	24
1.3.3	Indian practice	25
1.3.4	Netherlands practice	25
1.4	Adjustment of design discharge for statistical sampling error	25
1.4.1	U.S.S.R. practice	25
1.5	Selected references	26
2	Probability distributions used in hydrologic design	
2.1	General	28
2.2	Empirical frequency curves	28
2.2.1	Empirical formulas for computing the probability of individual events	29
2.2.2	Probability graph paper	32
2.2.2.1	Normal-probability graph paper	32
2.2.2.2	Extreme-value probability (Gumbel) graph paper	35
2.2.2.3	Goodrich probability graph paper	35
2.2.2.4	Other probability graph papers	37
2.3	Theoretical probability distributions	37
2.3.1	Continuous binomial distribution—Pearson type III	37
2.3.2	Logarithmic normal distribution	41
2.3.2.1	Japanese practice	44
2.3.2.2	United States practice	46
2.3.3	Three-parameter gamma distribution	49
2.3.3.1	U.S.S.R. practice: Kritsky-Menkel distribution	49
2.3.4	Extreme-value (Gumbel) distribution	51

2.3.4.1	Japanese practice	54
2.3.5	Choice of a theoretical probability distribution	54
2.3.5.1	French practice	55
2.3.6	Computation of distribution parameters from observed data (U.S.S.R. practice)	58
2.3.6.1	Method of maximum likelihood	62
2.3.6.2	Example of a flood-frequency curve computation (U.S.S.R. practice)	62
2.3.7	Error analysis of distribution parameters computed from observed data	69
2.4	Selected references	70
3	Use of streamflow data in computing flood-frequency curves	
3.1	Streamflow-data requirements	73
3.1.1	Quality control of peak-discharge data	73
3.1.2	Sample size of peak-discharge data	74
3.1.3	Homogeneity of time series	77
3.1.4	Tests for homogeneity of time series	78
3.1.4.1	Homogeneity criterion for the mean of time series	79
3.1.4.2	Homogeneity criterion for the standard deviation of time series	81
3.1.4.3	Example of a homogeneity test for snowmelt and rainstorm peak discharges	82
3.2	Frequency curves of peak discharge	84
3.2.1	Computation of flood-frequency curves for a station using annual peak discharges	84
3.2.1.1	U.S.S.R. practice	85
3.2.1.2	United States practice	87
3.2.2	Combination of the observed peak-discharge series at several stations (station-year method)	89
3.2.3	Computation of flood-frequency curves using more than one peak discharge per year (method of 'peaks above a base')	90
3.3	Frequency curves of flood volume	91
3.3.1	Determination of flood duration	91
3.3.2	Computation of the frequency curve of flood volume	93
3.4	Selected references	93
4	Methods of floodflow computation and analysis where streamflow data are inadequate	
4.1	Principles of floodflow computation by genetic and empirical equations	95
4.2	Empirical reduction equations	96
4.2.1	Reduction coefficient based on drainage-basin size	98
4.2.1.1	U.S.S.R. practice	98
4.2.1.2	Italian practice	98
4.2.2	Reduction coefficient based on lag time	99
4.2.2.1	U.S.S.R. practice	99
4.2.2.2	Algerian practice	100
4.2.3	Determination of parameters of empirical reduction equations from regional streamflow data	101
4.2.4	Determination of parameters of empirical reduction equations when streamflow data are inadequate	106
4.3	Peak-discharge equations based on flood volume	108
4.3.1	U.S.S.R. practice	109
4.3.2	Italian practice	110
4.3.3	Central and south-west Africa	111
4.4	Peak-discharge equations based on the genetic isochrone principle	114
4.4.1	Basic equation of the Rational method	114
4.4.2	Determination of time of concentration for use in Rational method	115
4.4.2.1	United States practice	116
4.4.2.2	Central American practice	116

4.4.2.3	Italian practice	116
4.4.2.4	Canadian practice	116
4.4.2.5	U.S.S.R. practice	117
4.4.3	Determination of precipitation intensity for use in Rational method	119
4.4.3.1	Method used for areas having adequate records from recording-precipitation gauges	119
4.4.3.2	Methods used for areas having inadequate records from recording-precipitation gauges	121
4.4.3.3	Regional precipitation depth-area relations	124
4.4.4	Determination of runoff coefficient for use in the Rational method	127
4.4.5	Computation of peak discharge by the Rational method	129
4.4.5.1	U.S.S.R. practice	129
4.4.5.2	Spanish practice	134
4.4.6	Computation of peak discharge for an ungauged site based on a nearby gauging-station record	135
4.4.6.1	U.S.S.R. practice	135
4.4.7	Computation of the peak-discharge frequency curve for a short-term gauging station from long-term precipitation data	136
4.4.7.1	French practice	136
4.5	Determination of volume of flood runoff	136
4.5.1	Indian practice	137
4.6	Computation of peak snowmelt discharge in regions of low relief (plains and valleys)	137
4.6.1	Determination of parameters in equations of peak snowmelt discharge	138
4.6.1.1	U.S.S.R. practice	138
4.6.2	Computation of peak snowmelt discharge for an ungauged site based on nearby gauging-station records	142
4.6.2.1	U.S.S.R. practice	142
4.7	Determination of snowmelt flood volume	142
4.8	Computation of snowmelt intensity	143
4.8.1	U.S.S.R. practice	144
4.8.2	United States practice	145
4.8.3	General equations for basin melt during periods of rainfall	145
4.8.4	General equations for basin melt during rain-free periods	146
4.9	Computation of peak snowmelt discharge in mountain regions	148
4.9.1	Empirical equations for computing peak snowmelt discharge in mountain regions	148
4.9.1.1	U.S.S.R. practice	148
4.9.2	Relation of snowmelt equation parameters to altitude and orientation of mountain slopes	150
4.10	Computation of design storms and rainfall excess	150
4.10.1	General considerations	151
4.10.2	Methods of computing design storms	152
4.10.2.1	Method 1. Design storm estimated from probable maximum depth-duration data; estimate of rainfall excess	153
4.10.2.2	Method 2. Design storm estimated by transposition of record storm; estimate of rainfall excess	156
4.10.2.3	Method 3. Design storm estimated by modified storm transposition; estimate of rainfall excess	157
4.11	Selected references	158
5	Methods of developing design-flood hydrographs	
5.1	Flood-hydrograph models	161
5.2	Flood-hydrograph models based on the shape of recorded hydrographs	162
5.2.1	Use of the maximum recorded hydrograph at the study gauging station	162
5.2.1.1	U.S.S.R. practice	162
5.2.2	Use of hydrographs recorded at base gauging stations	163
5.2.2.1	U.S.S.R. practice	163

5.2.2.2	Romanian practice	165
5.3	Design hydrographs for snowmelt floods in small basins	166
5.4	Development of a model hydrograph by stochastic methods	168
5.4.1	Polish practice	168
5.4.1.1	First variant	168
5.4.1.2	Second variant	168
5.5	Development of design hydrographs by the unit-hydrograph method	169
5.5.1	Basic principles of the unit-hydrograph method	169
5.5.2	Separation of surface-runoff hydrograph from hydrograph of total runoff	172
5.5.2.1	United States practice	173
5.5.2.2	United Kingdom practice	175
5.5.3	Computation of rainfall excess from total storm rainfall	175
5.5.3.1	United Kingdom practice	176
5.5.3.2	United States practice	177
5.5.3.3	Indian practice	182
5.5.4	Unit-hydrograph derivation	182
5.5.4.1	Unit hydrographs from isolated unit storms	182
5.5.4.2	Unit hydrographs from records of major floods	184
5.5.4.3	Synthetic unit hydrographs	187
5.5.4.4	S-curve hydrographs	193
5.5.4.5	Summary and example of synthetic unit-hydrograph computation	195
5.5.5	Transformation of design rainfall to the flood-runoff hydrograph	199
5.5.5.1	Comparison of unit hydrographs derived from recorded major and minor flood hydrographs	199
5.5.5.2	Modification of unit hydrographs for design-flood computation	200
5.5.5.3	Computation of the design-flood hydrograph by the unit-hydrograph method	200
5.6	Computation of the design-flood hydrograph by the isochrone method	203
5.6.1	Variation of the runoff coefficient with time in the isochrone method	206
5.6.1.1	French practice	206
5.7	Analytical expressions of hydrograph shape	209
5.7.1	U.S.S.R. practice	209
5.7.2	Polish practice	212
5.7.2.1	Reitz-Kreps equation	212
5.7.2.2	Pearson distribution equations—types III and IV	212
5.7.2.3	Three-parameter equation	213
5.7.3	Japanese practice	213
5.8	Relation of hydrograph shape to basin characteristics	215
5.8.1	Size and configuration of the basin	215
5.8.2	Drainage pattern and density	215
5.8.3	Channel slope	216
5.8.4	Overland slope	216
5.8.5	Natural storage	217
5.9	Selected references	218
6	Methods of computing design river and lake stages	
6.1	General	220
6.2	Determination of design stage from stage-discharge data	220
6.3	Determination of design stage from stage data alone	222
6.3.1	U.S.S.R. practice	226
6.4	Determination of design stage from short-term stage-discharge data	228
6.4.1	United States practice	230
6.5	Backwater corrections to the design stage for the effect of ice	231
6.5.1	U.S.S.R. practice	232
6.6	Transfer of design stage from one site to another on the same stream	234
6.6.1	Method 1	234
6.6.2	Method 2	234
6.6.3	Method 3	235

6.6.4	Method 4	236
6.7	Computation of design discharge in the absence of any stage-discharge information for the study stream	240
6.8	Selected references	240
7	Methods for evaluating floodflow characteristics by field investigation	
7.1	General	242
7.2	Determination of historic flood stages from high-water marks	243
7.3	Elements of the field investigation	245
7.3.1	Selection of the study reach	245
7.3.2	Selection of cross-sections to be surveyed	246
7.3.2.1	U.S.S.R. practice	246
7.3.3	Determination of the water-surface profile from high-water marks	247
7.3.3.1	U.S.S.R. practice	248
7.3.3.2	United States practice	249
7.3.3.3	Bulgarian practice	250
7.3.3.4	Romanian practice	250
7.3.4	Determination of mean water-surface slope from the surveyed flood profile	250
7.3.4.1	U.S.S.R. practice	250
7.3.5	Determination of roughness coefficient	251
7.3.5.1	U.S.S.R. practice	252
7.3.5.2	United States practice	257
7.3.5.3	Indian practice	258
7.4	Computation of mean velocity at peak stage	260
7.4.1	U.S.S.R. practice	260
7.5	Computation of discharge at peak stage	261
7.5.1	U.S.S.R. practice	261
7.6	Determination of exceedance probability of peak discharge evaluated by field investigation	264
7.7	Selected references	265
8	Application of analogue and digital computers for modelling floodflow	
8.1	General	266
8.1.1	Analogue computers	266
8.1.2	Digital computers	267
8.2	Application of analogue computers for computing design-flood hydrographs	267
8.2.1	Use of the Duhamel integral	267
8.2.1.1	U.S.S.R. practice	269
8.2.2	Use of other equations with the analogue computer	272
8.2.2.1	Use of direct and indirect analogue computers	272
8.2.2.2	Channel flood routing by analogue computer (Japanese practice)	273
8.2.2.3	Simulation of flood-control operations by analogue computer (Japanese practice)	273
8.2.2.4	Channel design by analogue computer (Japanese practice)	276
8.3	Mathematical simulation of floods by digital computer	277
8.3.1	General	277
8.3.2	Types of mathematical models	278
8.3.3	Simple linear models—influence-function method	279
8.3.3.1	Italian approach	281
8.3.4	Models that include physical elements	282
8.3.4.1	Multistratum models	284
8.3.4.2	Snowmelt-runoff models	287
8.3.5	Multiparametric models and optimization methods	288
8.3.5.1	U.S.S.R. approach	290
8.4	Selected references	292

Foreword

From time immemorial floods have been a recurring menace in every country of the world. Many courses of action may be taken to prevent or alleviate the misery and damage that floods bring, but all such actions require a knowledge of the magnitude and frequency of flood stages and discharges. The problem of floodflow computation is therefore one of the most pressing in hydrology and is studied by scientists of all nations. Consequently flood studies were a prominent part of the programme of international co-operation in hydrology known as the International Hydrological Decade (IHD), which operated under the auspices of Unesco during the years 1965–74. Flood studies will be continued within the framework of the International Hydrological Programme.

Among the stipulations of the IHD programme was the establishment of a working group charged with the collection of information on flood studies and the compilation of the methodologies used in the participating countries for computing floodflow, particularly in those situations where hydrometeorological data are sparse or non-existent. Several complementary activities were carried out under Unesco's sponsorship. In 1967, in co-operation with the World Meteorological Organization (WMO) and the International Association of Scientific Hydrology (IASH), the International Symposium on Floods and their Computation was held in Leningrad. At that meeting more than 100 reports from many nations were presented. In addition, a report, 'Flood Studies: An International Guide for Collection and Processing of Data', was prepared by the working group and published by Unesco in 1971; its purpose was to unify and systematize the collection and processing of floodflow data in the participating countries. Extensive information on floods has been collected and is being compiled in the preparation of a world catalogue of major floods.

The present publication, a casebook on methods of computing floodflow, has been prepared in accordance with the programme developed by the IHD working group on floods and low-flow computation. It follows in logical sequence 'WMO Technical Paper No. 98' (1968), *Estimation of Maximum Floods*, which deals with international experience in the meteorological aspects of floodflow computation. The present work is a compilation of methods, drawn from world experience, on

the computation of the magnitude and frequency of stages and discharges associated with both rainfall and snowmelt floods, with particular reference to the use of such information in the hydrologic design of engineering projects.

The following aspects of floodflow computation are treated here: determination of optimum design probabilities for flood discharge (Chapter 1), probability distributions used in hydrologic design (Chapter 2), methods of floodflow computation and analysis using streamflow data (Chapter 3) and in situations where streamflow data are inadequate (Chapter 4), methods of developing design-discharge hydrographs (Chapter 5) and computing design river and lake stages (Chapter 6), methods for evaluating flood characteristics by field investigation (Chapter 7), and the application of analogue and digital computers for modelling floodflow (Chapter 8).

This work was compiled from material received from the national IHD committees of the following countries: Bangladesh, Brazil, Bulgaria, Canada, Costa Rica, France, German Democratic Republic, Hungary, India, Italy, Japan, Netherlands, Poland, Romania, Spain, U.S.S.R., United Kingdom and the United States.

The work itself was prepared by a group of scientists at the State Hydrological Institute (U.S.S.R.) under the leadership of Professor A. A. Sokolov and Professor A. I. Chebotarev. The contributions of individual authors are as follows: Chapters 1 and 2, Dr B. M. Dobroumov; Chapter 3, Dr A. V. Rozhdestvenskij; Chapter 4, Professor A. I. Chebotarev and Dr B. I. Serpik (Sections 4.1 to 4.5); Dr A. I. Okhinchenko (Sections 4.6 to 4.9); Professor M. S. Grushevskij (Section 4.10); Chapter 5, Professor M. S. Grushevskij; Chapter 6, Dr O. L. Markova; Chapter 7, Dr O. B. Voskresenskij; and Chapter 8, Professor M. S. Grushevskij.

Acknowledgement is made of the contributions to individual chapters by S. E. Rantz (United States), M. Roche (France) and J. Cruette (France) at meetings of the editorial panel in Leningrad (October 1974) and Paris (April 1975). Special thanks are due to L. V. Lavrova (U.S.S.R.), whose devoted efforts as interpreter and translator in the preparation of the text and in meetings of the editorial panel, represent a major contribution to this report.

As indicated earlier, this work is intended for use in studies involving the hydrologic and economic design of flood-control facilities and other structures within the reach of floodwaters and as a basis for developing flood forecasting techniques.

1 Determination of optimum design probabilities of flood discharge

1.1 Objectives of studies of design probability

In the design of a hydraulic structure consideration must be given to the flood risk involved. The probability always exists that a flood of such magnitude will occur, that the design capacity of the structure will be exceeded, with resulting damage to the land and to the structure itself. The first step, therefore, in the design of a hydraulic structure is a flood-frequency study to determine the probability of exceedance of floods of various magnitudes. The next step is the determination of the optimum flood probability to be used in the design of the structure.

Social, or sociopolitical, considerations as well as economic considerations, enter into the determination of optimum design probabilities. Where a major flood can cause catastrophic property damage and human death, the design flood to be used is the probable maximum flood. (Probable maximum floods are discussed in Chapter 4, Section 10.) For areas with a lesser potential for flood damage, the design flood to be used is one whose probability of exceedance is such that the project meets the following criteria:

1. The structure will be economically feasible; that is, the construction and maintenance costs of the structure will not exceed the direct and indirect costs of possible property damage and inconvenience to the public during the life of the structure. In other words, a \$1 million structure should not be built to protect a \$100,000 property investment.
2. Average annual costs chargeable to the structure will be minimized. The average annual costs include the following: (a) annual cost of construction of a soundly engineered structure, prorated over the years of economic life of the structure; (b) annual operation and maintenance cost of the structure; (c) average annual monetary flood damage under project conditions (structure installed or in operation), including the cost of rehabilitating the structure if damaged by flood.

Sociopolitical considerations sometimes override economic considerations. For example, a project that is barely economically feasible may be authorized for construction in an area that is economically depressed, with the idea that the project will stimulate the economy of the area.

1.2 Determination of optimum design probability by analytical methods

This section of the report discusses the details of design practice in the U.S.S.R., United States and France, in determining the optimum peak flood discharge to be used in the design of hydraulic structures or projects. The optimum design discharge is the peak flow rate corresponding to an annual exceedance probability¹ whose use in the project design will minimize the average annual cost of the project.

1.2.1 U.S.S.R. practice

In the U.S.S.R. method the average annual cost (U) of the project includes the three following elements, as explained above.

First, U_1 , the annual cost of construction of the project, prorated over the economic life (T years) of the project.

$$U_1 = \frac{K_0 + \alpha Q_P}{T}, \quad (1.1)$$

where:

K_0 = portion of project construction cost that is independent of the design discharge;

α = a coefficient that represents the increase in construction cost for each increment of discharge;

Q_P = peak discharge corresponding to an annual exceedance probability, P .

Second, U_2 , the annual cost of operation and maintenance of the project. (U_2 is considered to be proportional to the total construction cost, $K_0 + \alpha Q_P$.)

$$U_2 = r(K_0 + \alpha Q_P), \quad (1.2)$$

where:

r = the constant of proportionality between annual cost of project operation and total cost of project construction.

Third, U_3 , the average annual damage cost under project conditions, including damage to the structure.

$$U_3 = P[Y_0 + \eta(K_0 + \alpha Q_P)], \quad (1.3)$$

where:

P = the exceedance probability of peak discharge Q_P ;

Y_0 = the annual damage cost, exclusive of damage to the project structure, attributable to a peak discharge of the design probability;

η = the constant of proportionality between the cost of rehabilitating the project structure (if damaged) and the total cost of project construction.

1. The terms 'exceedance probability' and 'probability of annual exceedance' are used interchangeably in this report; they refer to the probability of a given discharge being exceeded as an annual maximum event.