

MODELLING OF NONLINEAR BEHAVIOUR OF DRAINAGE BASINS

BY

RAO, P. RAMAKRISHNA, B.E.(Civil), D.H.E.(Delft)

A thesis submitted to the Indian Institute of Technology  
Delhi for the award of the degree of

DOCTOR OF PHILOSOPHY

Department of Civil Engineering  
Indian Institute of Technology Delhi

April, 1975

## C E R T I F I C A T E

This is to certify that the thesis entitled  
"MODELLING OF NONLINEAR BEHAVIOUR OF DRAINAGE BASINS",  
which is being submitted by RAO P. RAMAKRISHNA to the  
Indian Institute of Technology Delhi for the award  
of degree of Doctor of Philosophy, is a bonafide  
research work carried out by him under our guidance  
and supervision. His thesis has reached the standard,  
fulfilling the requirements of the regulations relating  
to the degree.

The results contained in this thesis have not  
been submitted in part or in full to any other University  
or Institution for the award of any degree or diploma.

*Chander*

(Dr. S. CHANDER)  
Professor,  
Civil Engg. Dept.,  
IIT Delhi,  
NEW DELHI-110029.

*Amurthy*

(Y.K. MURTHY)  
Chairman, CW&PC,  
(Ex-officio) Secretary to the  
Govt. of India  
NEW DELHI-110011.

### ACKNOWLEDGEMENTS

This investigation was carried out by the author at the Indian Institute of Technology Delhi under the supervision of Dr. S. Chander, Professor, Civil Engineering Department and Mr. Y.K. Murthy, Chairman, Central Water and Power Commission and Ex-officio Secretary to the Government of India.

The author would like to express his sincere gratitude to the supervisors for their keen interest, guidance and encouragement in all aspects of the work. The benefits derived from the constructive discussions on the study with Dr. P.B.S. Sarma, Sr. Hydrologist, Water Technology Centre, Indian Agricultural Research Institute and Mr. S.K. Spolia, Sr. Research Scholar, I.I.T. Delhi are gratefully acknowledged.

The cooperation extended by Central Water and Power Commission in permitting the author to carry out this study is acknowledged.

The author is deeply indebted to his colleagues and staff of his Division in Flood Estimation Directorate of Central Water and Power Commission for their assistance that was so generously given during the preparation of the thesis.

  
(RAO P. RAMAKRISHNA)

## V I T A

RAO P. RAMAKRISHNA was born at Kakinada, Andhra Pradesh, India on February 15, 1935. He completed his High School Education in 1950 from the Pittapur Rajah's Collegiate High School, Kakinada. He joined the Pittapur Rajah's College, Kakinada and passed the Intermediate Examination in Science of the Andhra University in the First Class with distinction in Mathematics, Physics and Chemistry in 1952. On the basis of merit, he was admitted to the Government College of Engineering, Kakinada in 1952. He qualified for the degree of Bachelor of Engineering (Civil) of the Andhra University with a First Class in 1956.

He worked for the Government of Andhra Pradesh from May 1956 to November 1956 as Junior Engineer in the Tungabhadra Hydro-electric Scheme. He then joined the Central Water and Power Commission of the Union Government as Design and Engineering Assistant at New Delhi. On selection through the Union Public Service Commission, he was promoted to the post of Extra Assistant Director in January 1959. He was awarded the Netherlands Govt. Fellowship which enabled him to attend the Technological University at Delft from October 1961 to September 1962. During his stay in Netherlands, he

studied Reclamation Engineering under Professor Volker and obtained the Post-Graduate Diploma in Hydraulic Engineering with additional endorsement for special studies in Ground Water Recovery. On his return to India, he was elevated to the post of Assistant Director and was engaged on Designs and Research pertaining to many Major Irrigation and Power Projects.

He was deputed to the Department of multipurpose Projects and Power, Government of Himachal Pradesh, Simla, from September 1967 to April 1969 to assist in the establishment of a Design and Planning Cell. On his return to the Central Water and Power Commission in April 1969, he was posted as Deputy Director (Instrumentation) and he held this post till February 1970. During this period, he brought out a research report entitled "Prediction of Creep Characteristics of Rubble Concrete of Koyna Dam". From February 1970, he has been conducting hydrological research as Deputy Director (Flood Estimation). A research report entitled "Estimation of Design Flood Peak for Design of Bridges" prepared by him has been recommended for the use of field engineers as a Standard Code of Practice.

After a three months training, from May to August 1971, at Computer Centre, Department of Statistics,

Government of India, he qualified for the Certificate of Proficiency in Computer Technology. He set up a library of software for processing of hydro-meteorological data and for simulation of hydrologic systems. He guided a thesis entitled "Study of the Generation of Streamflow Sequences" by S.L. Pahuja submitted to Roorkee University in October 1974 for the degree of Master of Engineering.

He was Secretary to the Committee of Experts on "Utilisation and Development of the Ravi and the Beas Waters" from April 1970 to February 1971. He was Member-Convener for two Sub-Committees of the National Committee of Science and Technology to formulate R and D Plans for Water Resources Sector and two reports covering the following aspects were submitted in February 1973:

- (i) Computerisation, Mathematical Modelling and Simulation
- (ii) Evapo-transpiration, Runoff, Recharge and Floods.

The Central Water and Power Commission permitted him to undertake the present investigation in addition to his official duties. Since March 1970, he has been working on his Doctoral Thesis under the supervision of Dr. S. Chander, Professor, Civil Engineering Department, Indian Institute of Technology, Delhi and Mr. Y.K. Murthy, Chairman, Central Water and Power Commission and Ex-officio Secretary to the Government of India, New Delhi.

## S Y N O P S I S

This study is devoted to the Simulation of Surface Runoff Systems with a view to organize the research results systematically for practical applications.

The runoff dynamics of the drainage basins is briefly reviewed and a model of complex network of non-linear reservoirs with appropriate areas and storage-discharge relationships is found to preserve the essential information of the prototype. An equivalent model, parsimonious in number of parameters, is evolved for achieving computational efficiency and for facilitating its use in the solution of engineering problems. Theoretical studies on the performance of the model are made and then the model is tested with natural catchment data. The model is capable of representing both lumped as well as distributed systems.

The properties of the network model, which would help in the representation of drainage basins with such network models, are presented. It has been found that the dimensionless instantaneous unit hydrograph is unique for a given non-linear network model. The relationship between the response of the non-linear network model and that of a single non-linear reservoir, both having same area and recession parameters,

has been worked out; this relationship helps in predicting, for any input, the values of lag, peak and weighted mean discharge of network model representing the catchment, through the single reservoir model.

The sensitivity of the network model to the different empirical/subjective techniques of baseflow separation and rainfall excess evaluation is examined and the significance of the results for practical application is evaluated. It is observed that, if the baseflow separation is effected by a horizontal line, the maximum error is involved only in the rising limb of the outflow hydrograph, whereas the peak and the recession part are not significantly affected. The shape of the input hystograph is found to have no significant effect on the outflow hydrograph under certain conditions and the  $\phi$ -index method can be adopted in such cases to evaluate the time-distribution of rainfall excess. These conditions have been identified.

To extend the applicability of the principle of superposition to the non-linear reservoirs, a new method based on the concept of linearised input has been introduced. The process of transformation of input into output by non-linear reservoirs can be decomposed, according to this concept, into two elements with memory, a non-linear lag-one element and a linear time-lag element. The method is shown to be simpler than, but as accurate as, the method of numerical integration of the differen-

tial equation of the system and hence, can be adopted for ~~day-to-day~~ design practice where accessibility to sophisticated electronic computers is extremely limited.

The relationship between the parameters of a network of linear reservoirs to those of a network of non-linear reservoirs, both networks having practically the same response when fed with the same input, is investigated. This relationship enables the application of the theory of linear systems in the analysis of non-linear systems.

The concepts developed in the study are tested with observed hydrologic data of a few catchments. General conclusions are summarised and the scope for further work is indicated.

## TABLE OF CONTENTS

CERTIFICATE

ACKNOWLEDGEMENTS

VITA

SYNOPSIS

|                                                          | Page   |
|----------------------------------------------------------|--------|
| CHAPTER I : OBJECT AND SCOPE                             | 1 - 7  |
| 1.1 THE PROBLEM                                          | 2      |
| 1.2 SPECIFIC OBJECTIVES OF THE<br>PRESENT STUDY          | 5      |
| 1.3 OUTLINE OF THE STUDY                                 | 6      |
| 1.4 NOTATION                                             | 7      |
| CHAPTER II : HYDROLOGIC SYSTEMS -<br>A BRIEF REVIEW      | 8 - 51 |
| 2.1 INTRODUCTION                                         | 9      |
| 2.2 HYDROLOGIC SYSTEMS                                   | 10     |
| 2.2.1 Classification of Systems                          | 13     |
| 2.3 TYPES OF PROBLEMS IN HYDROLOGIC<br>SYSTEMS           | 16     |
| 2.4 ELEMENTS OF CONCEPTUAL MODELLING                     | 18     |
| 2.4.1 Reservoir Concept                                  | 18     |
| 2.4.2 Linear Reservoirs in Series                        | 20     |
| 2.4.3 Non-linear Reservoir                               | 21     |
| 2.4.4 Linear Channel Concept                             | 26     |
| 2.4.5 Linear Channels in Series                          | 28     |
| 2.5 HYDROLOGIC SYSTEM SIMULATION BY<br>CONCEPTUAL MODELS | 31     |
| 2.5.1 Linear Conceptual Models                           | 31     |
| 2.5.2 Non-linear Conceptual Models                       | 39     |
| 2.6 CRITIQUE AND MOTIVATION                              | 48     |

|                                                                                             |           |
|---------------------------------------------------------------------------------------------|-----------|
| CHAPTER III : CHOICE OF MODEL FOR THE<br>PRESENT STUDY                                      | 52 - 63   |
| 3.1 CRITERIA FOR THE CHOICE OF MODEL                                                        | 53        |
| 3.2 RUNOFF DYNAMICS                                                                         | 55        |
| 3.3 SIMULATION OF CHANNEL NETWORK                                                           | 59        |
| 3.4 CHOICE OF MODEL                                                                         | 61        |
| CHAPTER IV : MODEL OF NETWORK OF RESERVOIRS                                                 | 64 - 103  |
| 4.1 RESERVOIR                                                                               | 65        |
| 4.2 NETWORK OF RESERVOIRS                                                                   | 65        |
| 4.3 CLASSIFICATION OF RESERVOIRS                                                            | 66        |
| 4.4 CONCEPT OF EQUIVALENCE BETWEEN<br>RESERVOIRS                                            | 67        |
| 4.5 CONCEPT OF EQUIVALENCE BETWEEN<br>NETWORK AND SINGLE RESERVOIR                          | 69        |
| 4.5.1 Network of Two Reservoirs                                                             | 70        |
| 4.5.2 Network of n-Reservoirs                                                               | 72        |
| 4.6 EQUIVALENCE BETWEEN NETWORKS                                                            | 73        |
| 4.7 REPRESENTATION OF COMPLEX NETWORKS<br>BY SIMPLER 2-RESERVOIR NETWORKS                   | 81        |
| 4.8 PROPERTIES OF THE MODEL OF RESERVOIR<br>NETWORK                                         | 86        |
| 4.8.1 Repetition of Recession                                                               | 88        |
| 4.8.2 Effect of change of $C_e$ -value<br>on $C_n$                                          | 91        |
| 4.8.3 Variation of Lag, Peak Discharge<br>and Weighted Mean Discharge                       | 94        |
| 4.8.4 Relationship between a Single<br>Reservoir Model and a Network<br>of Reservoirs Model | 97        |
| 4.8.5 Variability of Unit Responses                                                         | 100       |
| 4.8.6 Dimensionless Unit Responses                                                          | 101       |
| CHAPTER V : ROUTING THROUGH NONLINEAR<br>RESERVOIRS-A LINEAR APPROACH                       | 104 - 142 |
| 5.1 DIFFERENTIAL EQUATION FOR A RESERVOIR                                                   | 105       |
| 5.1.1 Operational Approach                                                                  | 106       |
| 5.1.2 Functional Approach                                                                   | 107       |

|                                                                                                                        |                                                                                    |           |
|------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|-----------|
| 5.2                                                                                                                    | LINEARISED INPUT CONCEPT                                                           | 111       |
| 5.2.1                                                                                                                  | Estimation of b-value                                                              | 114       |
| 5.3                                                                                                                    | APPLICATION                                                                        | 115       |
| 5.3.1                                                                                                                  | Inputs of Short Duration                                                           | 115       |
| 5.3.2                                                                                                                  | Inputs of Long Duration                                                            | 117       |
| 5.4                                                                                                                    | STRUCTURAL RELATIONSHIP BETWEEN NETWORKS<br>OF NONLINEAR AND LINEARISED RESERVOIRS | 125       |
| 5.4.1                                                                                                                  | Relationship Between the Parameters<br>of Nonlinear and Linearised<br>Networks     | 126       |
| 5.5                                                                                                                    | ESTIMATION OF PARAMETERS OF LINEARISED<br>NETWORK                                  | 133       |
| 5.5.1                                                                                                                  | Method of Regression                                                               | 134       |
| 5.5.2                                                                                                                  | Method of Auto-correlation                                                         | 140       |
| CHAPTER VI : BASEFLOW SEPARATION AND RAINFALL<br>EXCESS EVALUATION TECHNIQUES -<br>SENSITIVITY OF THE NETWORK<br>MODEL |                                                                                    | 143 - 161 |
| 6.1                                                                                                                    | GENERAL                                                                            | 144       |
| 6.2                                                                                                                    | SEPARATION OF BASEFLOW                                                             | 144       |
| 6.2.1                                                                                                                  | Separation of Baseflow in<br>Non-linear Systems                                    | 146       |
| 6.2.2                                                                                                                  | Assumptions                                                                        | 147       |
| 6.2.3                                                                                                                  | Model set-up                                                                       | 148       |
| 6.2.4                                                                                                                  | Effect of Baseflow on Recession                                                    | 149       |
| 6.3                                                                                                                    | ESTIMATION OF RAINFALL EXCESS HYETOGRAPH                                           | 153       |
| 6.3.1                                                                                                                  | Effect of Time Distribution of<br>Input on the Outflow of the Model                | 154       |
| CHAPTER VII : APPLICATION TO FIELD DATA                                                                                |                                                                                    | 162 - 230 |
| 7.1                                                                                                                    | SELECTION OF DRAINAGE BASINS                                                       | 163       |
| 7.2                                                                                                                    | DATA USED                                                                          | 163       |
| 7.3                                                                                                                    | CRITERIA FOR VALIDATION                                                            | 164       |
| 7.4                                                                                                                    | BINTLIFF DITCH BASIN                                                               | 167       |
| 7.4.1                                                                                                                  | Drainage Area Features                                                             | 167       |
| 7.4.2                                                                                                                  | Flood Data                                                                         | 167       |

|                                                                        |                                                         |           |
|------------------------------------------------------------------------|---------------------------------------------------------|-----------|
| 7.4.3                                                                  | Rainfall Data                                           | 169       |
| 7.4.4                                                                  | Estimation of Parameters of<br>the Model                | 170       |
| 7.4.5                                                                  | Computed Hydrographs                                    | 171       |
| 7.5                                                                    | BERRY BAYOU BASIN                                       | 175       |
| 7.5.1                                                                  | Drainage Area Features                                  | 175       |
| 7.5.2                                                                  | Flood Data                                              | 175       |
| 7.5.3                                                                  | Rainfall Data                                           | 176       |
| 7.5.4                                                                  | Estimation of Parameters of<br>the Model                | 177       |
| 7.5.5                                                                  | Rainfall Excess Hyetographs                             | 180       |
| 7.5.6                                                                  | Computation of Hydrographs                              | 181       |
| 7.6                                                                    | HUNTING BAYOU BASIN                                     | 181       |
| 7.7                                                                    | CLEAR CREEK TRIBUTARY BASIN                             | 188       |
| 7.8                                                                    | COLE CREEK BASIN                                        | 191       |
| 7.9                                                                    | EVALUATION OF THE PERFORMANCE<br>OF THE MODEL           | 193       |
| CHAPTER VIII : SUMMARY OF CONCLUSIONS AND<br>PROPOSALS FOR FUTURE WORK |                                                         | 231 - 244 |
| 8.1                                                                    | SUMMARY OF CONCLUSIONS                                  | 232       |
| 8.2                                                                    | DISCUSSION ON THE STUDY -- PROPOSALS FOR<br>FUTURE WORK | 237       |
| APPENDIX A : NOTATION                                                  |                                                         |           |
| B : REFERENCES                                                         |                                                         |           |