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HYDROLOGY REVIEW

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HIGH LEVEL TECHNICAL COMMITTEE ON HYDROLOGY
NATIONAL INSTITUTE OF HYDROLOGY, ROORKEE

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CONTENTS

TECHNICAL PAPERS

1. EDITORIAL

From times immemorial floods have been a recurring menace in every country of the world and have been responsible for loss of crops and valuable property and untold human misery in the world. India, which is traversed by large number of river systems has been no exception. It has been the experience that floods occur almost every year in one part or the other of the country. The rivers of North and Central India are prone to frequent floods during the South-West monsoon particularly during July to September. Excessive rainfall in the river catchments is the main cause of floods and their magnitude and severity depend upon the nature and extent of rainfall as well as physical characteristics of the specific watersheds. Although floods occurred since ancient times, the impact of flood is felt to an increased extent due to rapid increase in population and consequent increase in the activities of man leading to encroachments in flood plains. Torrential rains associated with cyclones and depressions fill rivers with flows far in excess of their conveyance within banks and cause large scale inundation of the adjoining low lands. The destruction of the forest areas has also led to changes in river regime and led to increased fury of floods. Flash floods constitute one serious aspect of the floods and are generally caused by very heavy rainfall, particularly in the mountaineous areas.

The Rashtriya Barh Ayog has estimated that the area liable to floods in the country is about 40 million hectares. Susceptibility to flood damage can be reduced by timely forecasts of flood and issue of warnings, regulation of land use in flood plains and disaster preparedness.

Research on flood control has been only concentrated on physical modelling. Flood control, not only involves structural measures but non-structural techniques also. The quality of the flood forecast so far has depended on the ability and experience of the forecaster which is generally subjective. With the advance of science, new approaches came to be adopted.

Simulation of flows by mathematical modelling is a relatively new approach and holds promise for future needs of flood estimation and forecasting. The modelling approach involves discretization of the catchment into various sub-basins, estimation of floods from these sub-basins, routing them and combining them with flows in the main channel and routing along the channel to the forecast point. In spite of the best forecasting models being available, the forecasts of flood could go wrong because of the necessary input data not being available in time. It is peremptory to have timely and reliable forecasts of rainfall based on sound physical and mathematical reasoning.

This issue of "Hydrology Review' is dedicated to the theme of 'Precipitation and Floods'.

2. NATIONAL ACTIVITIES

2.1 (A) High Level Technical Committee on Hydrology (HILTECH)

The fifth meeting of HILTECH was held on 16th May 1985 at Delhi. The terms of reference and constitution of panels on i) Water Resources System ii) Surface Water iii) Snow and Ice iv) Hydrometeorology v) Ground Water and vi) Water Quality, Sedimentation and Erosion were approved. The sixth meeting of HILTECH was held first time in a State at Hyderabad at the invitation of A.P. Government on 19th August, 1985. Amongst other important decisions, the committee approved the institution of HILTECH Scholarship maximum upto two candidates for attending five international hydrology courses abroad. The seventh HILTECH meeting was held at Delhi on 3rd Dec. 1985. This meeting identified the specific areas ot hydrology which will need international/foreign support. The respective institutions are also identified and were requested to prepare the lead papers on these areas

The first meetings of the panels on i) Water Resources System, (2.8.85) ii) Hydrometeorology (9.9.85), iii) Surface Water (3.10.85), and iv) Snow and Ice (25.11.85) were held during the year. Actions have been initiated to prepare the state of art papers under various themes in most of the subject matters. Various subcommittees like i) Steering Committee ii) Draft Country Plan iii) Expert Review Group for IHP Phase III, iv) Education and Training v) Incentive to P.G. Courses vi) Man power Assessment vii) Editorial Board of Hydrology Review journal viii) Training Course for hydrological technicians also met and made important recommendations.

HILTECH hosted the 3rd meeting of ARCCOH Steering Committee which was held in New Delhi during Sept 18-20, 1985. The combined volume of Hydrology Review (1981-83) and 1984 volume of Hydrology Review were published and circulated. The rules and regulations for funding Seminar/Short Course/research project by HILTECH have been finalised, approved and circulated. Those who are interested may contact HILTECH Secretariat for copy of the rules.

HILTECH has approved and funded the research project "Development of generalised software on HP-1000 computer for unit Hydrograph forecast model and its application" to IIT, Delhi. The work has already been started by Prof. Subhash Chander, Project Investigator. A short course on "Stochastic methods in hydrology and water resources with computer applications" was funded by HILTECH and was held at IIT, Kharagpur in June 1985, Besides, following seminars / Symposia / Workshops were also sponsored and funded by HILTECH.

- (i) International Workshop on rural hydrogeology and hydraulics in fissured basement zones, Dept. of Earth Sciences, University of Roorkee, March, 1985.
- (ii) Seminar on Hydrology with colloquium on impact of Water Resources in agriculture at Hissar, June 1985.
- (iii) International workshop on alluvial river problems, Deptt. of Civil Engineering, University of Roorkee, October, 1985
- (iv) Symposium on Inadequacy of existing run off formulae for Surface and Subsurface drainage, Indian Association of Hydrologists, Roorkee, Oct 1985.

HILTECH Secretariat which has been functioning under the administrative control of

National Institute of Hydrology has been shifted from R.K. Puram, New Delhi to Roorkee towards the end of the year. The new address of the Secretariat is :

HILTECH Secretariat,
National Institute of Hydrology,
Jal Vigyan Bhawan,
Roorkee-247667, U.P.

2.1 (B) ARCCOH Secretariat

ARCCOH Secretariat which is functioning with the Secretariat of the High Level Technical Committee on Hydrology (HILTECH) at National Institute of Hydrology, remained very active during the year. Actions were taken on various recommendations of ARCCOH meetings held during the previous years and response from the member countries was encouraging.

During the Second meeting of ARCCOH it was decided to prepare a directory indicating education, training & research facilities and expertise on Hydrology in Asian Region. The questionnaires for compiling such directory were finalised during the Steering Committee meeting of ARCCOH which was held in Kathmandu during March, 1984. The questionnaires were sent to all member countries and to the various concerned organisations in India by the ARCCOH Secretariat and UNESCO regional office at Delhi. A good number of completed questionnaires were received at the Secretariat. The questionnaires were compiled on the VAX-11/780 Computer System of the Institute and the directory has been published. The directory contains bio-details of hydrologists from various member countries of the ARCCOH including India, Pakistan, Bangladesh, Malaysia, Sri Lanka and Afghanistan.

The ARCCOH Secretariat also revived the publication of ARCCOH Newsletter which was held-up earlier due to some unavoidable circumstances. The ARCCOH Newsletter is being brought-out from the Secretariat regularly on a quarterly basis and is circulated to various member countries and also to various concerned organisations in India. The items which are covered in the ARCCOH Newsletter are as follows :

(i) News from IHP Secretariat, UNESCO, Paris
(ii) ARCCOH regional activities
(iii) UNESCO publications in hydrology and IHP publications.
(iv) Actions taken on various ARCCOH recommendations
(v) Excerpts concerning IHP from Nature and Resources and Courier (UNESCO) publications
(vi) News, if any from ARCCOH Secretariat
(vii) Information on International Courses Seminars, Symposia, Workshops to be held.
(viii) ARCCOH meetings.
(ix) Progress of IHP projects executed by the countries in the region.
(x) Activities regarding hydrologists of the International Organizations like WMO, FAO and World Bank.

During the year four Newsletters were brought-out and widely circulated. A good response on the contents of Newsletter was observed at the Secretariat. The queries made by various organisations regarding various kinds of information included in the Newsletter are replied regularly by the Secretariat.

During the month of Sept. 1985, the ARCCOH Secretariat organised the 3rd Steering Committee meeting of ARCCOH which was hosted by HILTECH, India in New Delhi. Delegates from Nepal, India, Malaysia, representatives of UNESCO, Paris and its regional offices at Jakarta and New Delhi and observers from Iran and India participated in the three day long meeting. At this meeting the progress made by ARCCOH in the past was reviewed and recommendations for further strengthening its activities were made. The representatives of

UNESCO, Paris expressed satisfaction over the past activities of ARCCOH and assured UNESCO's cooperation in widening the activities of ARCCOH. It was decided to appoint "National Coordinator" in various member countries for coordinating various activities of ARCCOH. Action on this recommendation has been taken and a very encouraging response has been received at the Secretariat. The National Committees of India, Maldives, Pakistan, Papua New Guinea, Malaysia, New-zealand, Mangolia have already appointed National Coordinators. The committee also discussed to launch the second phase of Major Regional Project (MRP) for a group of countries experiencing similar hydrological conditions in South and Central Asia. The areas of activities for such a project were finalised and it was decided that the secretariat would make the proposal for second phase of MRP and would circulate the same to the participating countries and after receiving comments from them a preparatory meeting of participating countries would be convened towards end of 1986. The proposal is being finalised at the Secretariat. The Committee also discussed at length on the issue of compilation of Hydrological map for Asian Region for which a Hydrogeological expert of India was made the overall convenor who will coordinate this mission with the help of National Coordinators from various participating countries. The countries were divided into two major groups and it was decided that the overall convenor would visit all participating countries and with the help of the various National Organisations hydrogeological map would be compiled for Asian Region. The Govt. of India has already accorded approval for the Indian expert to take-up this mission which is likely to start very soon.

It was also decided to publish an Annual Bulletin of ARCCOH which would cover Hydrological activities of member countries for a calendar year. The Secretariat has requested various member countries to send details of Hydrological activities during 1985 to it for publication of such a bulletin and it has started receiving response from the countries. Also during the meeting the lists of activities including Seminar /Symposium / Training Courses/ Workshop were also decided which would be held in ROSTSCA and ROSTSEA regions of UNESCO during year 1986-87. It was also felt that the ARCCOH has been quite instrumental in implementing various programmes of IHP in various Asian countries and was suggested by representative of UNESCO that the member countries should back/support the activities of ARCCOH during the session of IHP council and bureau to make ARCCOH a more established and recognised body. The rules and regulations of ARCCOH are also being formulated at the Secretariat which would be circulated to the members for their comments and suggestions. In summary, successful attempts were made at the Secretariat during the year to implement various hydrological activities under IHP-III on a regional scale.

2.2 National Institute of Hydrology

The Institute completed its first phase of establishment and development during 1979-85 which also involved UNDP assistance. The main emphasis during this period had been on creation of some of the essential infrastructural facilities like buildings, recruitment and training of manpower, provision of computer and library facilities.

During 1985-86, the Institute has started its activities for the consolidation, expansion and diversification as proposed during Seventh Plan period (1985-90). While continuing with the computer oriented research and studies in different components of hydrologic cycle, their interaction as well as their quantitative assesment; laboratory and field oriented research has been considered equally necessary. Steps have been taken to create necessary infrastructural facilities by setting up laboratories and field stations.

For dissemination of the results of the research studies carried out in the Institute and transfer of technology developed, implemented and tested in the Institute to various state and central government organisations, the reports under various categories have been prepared and are being widely circulated.

The scientists and scientific staff of the Institute have contributed to and participated in a number of national and international workshops and seminars in India and published a number of papers in scientific journals.

Towards achieving the envisaged objectives of the Institute, efforts of technology transfer to states have been initiated by conducting five workshops at Roorkee and one each at Guwahati and Calcutta. A number of state and central government organisations have deputed their engineers and scientists to these workshops. Efforts are on way for setting up regional centres for greater interaction and understanding of the problems in the different regions of the country.

Seven regional centres were proposed in the following regions :

1. Deccan region
2. Deltaic region
3. Himalayan region
4. Semi arid region
5. North Eastern region
6. Ganga Plains region, and
7. Western and Southern coastal region

To start with it was planned to have four regional centres for the Deccan, Deltaic, Himalayan and Semi arid regions. Efforts have been initiated to locate these regional centres in one of the States in each of these regions. It is also proposed to undertake representative basin studies under one or more of these regional centres.

The studies and research activities of the Institute encompass different phases and the component processes of the hydrological cycle, their interaction and the influence of human activities on the quantity and quality of water resources. The research activities in the Institute were undertaken in following scientific divisions which include 3 new divisions namely; Remote Sensing Applications, Hydrological Investigations and Drought Studies, which were added during 1985-86 :

A. Surface Water Analysis
B. Surface Water Synthesis
C. Integrated Planning
D. Ground Water Analysis
E. Ground Water Synthesis
F. Hydrological Investigations
G. Remote Sensing Applications.
H. Drought Studies
I. Information System

The results of studies and research work have been brought in the form of Review Notes, Technical Reports, Case Studies, User's Manuals, and Manuals; and these have been circulated to various state and central government organisations. A list of scientific and technical reports prepared during the year under report is given at 2.2.12

2.2.1 Surface Water Analysis

The research activities in this division were carried out in the areas of stochastic hydrology, hydrometeorology and hydraulic and hydrologic routing. A number of review notes, case studies and user's manuals have been prepared covering important areas such as time series analysis, forecasting models, hydrometeorological studies, network design, effect of flood plain and channel process on flood routing. Further studies have been initiated in the areas of atmospheric - land surface process modelling, estimation of snow cover and snow melt runoff modelling, overland flow, modelling of moving storms etc.

(i) Statistical approach

In the flood frequency analysis approach for estimation of design flood, annual series is generally used. Recently many technical articles have indicated advantages in using partial duration series approach particularly for situations where available data is limited. A case study for comparison of annual flood series and partial flood series approaches using 32 years data of Mortakka site in Narmada Basin was attempted. It has been seen that the results obtained by using a partial duration series model with exact theoretical approach are quite promising and have smaller sampling variance in comparison with annual flood series.

Time series analysis models and forecasting models are two very important areas of stochastic hydrology. Considerable research activities and applications to actual field problems have been reported in technical literature in recent years. To carry out systematic study of these developments, review of literature in these two areas was taken up. Review of time series models indicates that for application of such models for Indian conditions (wherein non-monsoon flows in many rivers are almost negligible), it would be necessary to incorporate suitable modifications. Forecasting techniques have considerable potential for application particularly for real time operation of water resources systems and flood control operation of reservoirs. In this case also, it may be necessary to incorporate suitable modifications due to typical seasonal nature of flow in India rivers.

(ii) Hydrometeorological studies

Statistical analysis of long term monthly and annual rainfall data in Belgaum district were performed using serial correlation, polynomial regression and cross correlation techniques. The analysis generally did not reveal any trend or periodicities in the full series. However, some falling trend was noticed in the rainfall series of Belgaum station in recent years.

To examine the suitability of recording raingauges for providing short duration precipitation data, a review of the available recording raingauges was undertaken. The vibrating wire strain gauge developed in Denmark seems to be quite promising for this purpose.

The raingauge network designed for climatological purposes are sometimes found to be inadequate to provide realistic areal estimates of rainfall for hydrological purposes especially in regions of high spatial variability of rainfall. In view of this, at the request of Rajasthan Irrigation Department network design of raingauges in Rajasthan has been undertaken and the rainfall normals updated using rainfall data upto 1980. Some of the latest techniques like cross correlation were used to determine an adequate network.

(iii) Rainfall runoff relationship

A number of empirical and semi-empirical approaches have been in use in India for the estimation of runoff from rainfall for the estimation of dependable water yield, design flood peak etc. A review of the available rainfall-runoff relationships has been made to assess their reliability for estimation of runoff from unguaged catchments and those with inadequate data.

(iv) Channel routing

Review notes on two important aspects of channel routing have been prepared, namely, effect of flood plain on flood routing, and effect of channel processes on flood flow and routing. Though different approaches were available for treating the effect of flood plain, the complexity involving meandering rivers makes modelling a complicated process. Some of the available models are applicable only to the rivers for which they were developed. Five channel processes namely, resistance to flood flow; general aggradation or degradation; planform modifying the characteristics; stage discharge relations; and shape of the hydrograph were identified. The review revealed that the river environment undergoes changes at varying rate and the changes may be seen in 10 to 30 years. A single high flood could change the river's shape significantly. A user manual for using the Kalinin-Milyukov flood routing procedure which takes the slope of water profile also into account was prepared.

2.2.2 Surface Water Synthesis

The research activities in this division were carried out in the areas of flash flood studies, hydrologic routing, hydrological data processing, unit hydrograph studies and watershed modelling. A number of review notes, case studies and User's manuals have been prepared on the problems related to the above areas.

(i) Flash flood studies

For many parts of the country particularly for small basins, flash floods pose serious problems. Many aspects are required to be studied for understanding this phenomena. These include meteorological and hydrological factors, man made activities etc. A review note has been prepared for bringing together all relevant information on the subject.

(ii) Dam break analysis

With the increasing encroachments of flood plains, the consequences of failures of dams become serious as was experienced in the case of Machhu-II dam failure in Gujarat. The DAMBRK programme of National Weather Service, U.S.A. has been used for the analysis of this dam failure. Suitable failure pattern has been assumed and simplifications have been made with regard to gate openings. Two reports have been prepared dealing with data requirement and preparation, and application of programme.

(iii) Flood routing

The conventional flood routing procedures like Muskingum method generally available in text books do not have specific provision for incorporating the lateral flow in a river reach. A simple method based upon least squares technique has been developed to directly take into account the lateral flow and its validity has been demonstrated using test data.

(iv) Hydrological data processing

In dealing with hydrological data for different purposes one encounters various data related problems such as inconsistency, missing data, systematic and random error, broken records, outliers etc. For processing of such data, a systematic approach is necessary. A user manual has been prepared which provides details of the steps involved in processing of hydrologic data.

(v) Unit hydrograph studies

For dealing with ungauged and limited data situations in hydrologic design, it is necessary to develop suitable relationships between parameters of hydrological model e.g. unit hydrograph and catchment and climatic characteristics such as length, area, slope, mean annual rainfall etc. In the hydrological literature many such studies and approaches have been reported. These have been reviewed and classified and presented in two review notes.

(vi) Tank model

Tank model for analysis of daily and flood flow is a simple conceptual rainfall-runoff model developed in Japan. Such models are used for both humid and non humid basins. Tank model for daily analysis is capable of simulating the snow melt runoff. Two users manuals have been prepared for the application of these models.

(viii) Regional flood frequency analysis

The study of three different techniques of regional flood frequency analysis viz., index-flood method, method based on the application of power transformation technique and the method based on regional parameters of Wakeby distribution and James-Stein corrected means have been made. The data of 18 stations of sub-zone 3-d, Mahanadi basin have been used in this study.

2 2.3 Integrated Planning

The division is assigned to work in the areas of reservoir operation, optimal allocation of water resources in a basin, resources management modelling in a watershed, forest influences on hydrologic cycle, sediment yield studies and water quality modelling studies. A number of technical reports, users manuals, and revivew notes were prepared.

(i) Operation of reservoirs

Streamflow varies in space and time. However, the demand exceeds the streamflow not only during non-monsoon season but also during the pre-monsoon, break monsoon and post monsoon seasons. Accordingly it becomes imperative to store the available water during monsoon for purposes like irrigation, power generation, water supply etc. Hence it will be necessary to optimally operate the reservoirs for beneficial uses. A manual on multi-purpose operation of a reservoir was prepared. A computer model for the optimum reservoir operation using dynamic programming approach was developed and documented. A users' manual for this study was prepared which would be of use for field engineers. Review notes on sedimentation in reservoirs was also prepared. A project proposal for the operation of Sabarmati system was prepared on the request of Government of Gujarat.

(ii) Water quality modelling

DOSAG model which was developed by Texas Water Development Board was procured and was implemented and tested on VAX-11/780 system The model can calculate the BOD and the minimum DO concentration in a particular stream system. An Indian river is considered for a case study and the data is being procured A water quality laboratory for conducting water quality surveys and analysis for generating data to be used in modelling, was established.

(iii) Forest influence on hydrological parameters

The manipulation of forest vegetation in upland watersheds may be one way to alter the water budget of a catchment. The report brings out status of important research works done so far in India on the hydrological behaviour of forested catchments. Attempts have been made to review the effect of forests and forest management practices on hydrological parameters. The report attempts at emphasising the future research needs also. The influence of forests on their environment forms part of a vast and complex relationship between environment and forest vegetation. In this context, forests influences on various hydrological parameters, viz., rainfall, interception, infiltration, evapotranspiration, ground water, water yield, floods, water quality etc. have been described in the report which are based on studies conducted in India and abroad.

(iv) Sediment yield from different land uses

The problems of erosion and subsequent sediment yield are very wide spread and are of great concern to hydrologists and water resources engineers. The phenomena of sedimentation affects the reservoirs, lakes, rivers and other water bodies. In this report, an attempt has been made to present the results of various experimental studies conducted by researchers in India for the amount of soil loss/ sediment yield for different land uses. From the results of various studies a summary table has been derived which specifies ranges of sediment yield for each land use.

2.2.4 Ground Water Analysis

The research activities in this division were carried out mainly in the area of ground water balance (determination of elements), soil water accounting, return flow from irrigation, canal and stream, groundwater analysis in hard rock areas and stream aquifer interaction.

(i) Estimation of evapotranspiration

Many investigators have studied rate of evaporation from soils where water table is at shallow depth. The rate of evaporation may be controlled by either the capacity of the atmospheric environment to evaporate water or the capacity of the soil to transmit water to the surface. A review note has been prepared which gives in detail the methods for estimation of evapotranspiration which consider both the soil properties and meteorological factors. It has been found that evaporation rete decreases with water table depth more steeply in coarse textured soil than in fine textured soils.

(ii) Soil water accounting

The Soil Conservation Service method is the most widely used method for soil moisture accounting and estimating runoff amounts from agricultural watersheds. The soil type, land use and the hydrologic conditions of the cover are the various watershed factors that have been considered in this procedure. Further, the relationship between rainfall and runoff for three antecedent moisture conditions are presented in the form of curve numbers. In light of the SCS method, a technical note has been prepared which examines the validity of this method for soil moisture accounting in basins of different land use.

(iii) Seepage study from parallel canals

Analytical solution has been derived for prediction of rise in water table due to seepage from two parallel canals For this study it has been assumed that the water table is at large depth below the canal beds. It has been found that in the absence of any natural drainage the water table rise is conspicuous upto large distances from the canals. The zone in between the canals becomes stagnant and is vulnerable to water-logging problems.

(iv) Parameterisation of hydrological factors

Relationship of transmissivity with specific capacity for wells having negligible storage has been given by Walton. These graphs are used for estimation of transmissivity provided storage coefficients are known apriori. In the present study similar graphs have been developed considering well storage and variation of pumping rate with drawdown. The following cases have been considered : Case 1-the pumping rate is independent of drawdown and is constant, Case 2-the pumping rate is a linear function of drawdown. A set of type curves for a two aquifer system separated by an aquiclude has been presented. Use of the type curves for parameter estimation has been demonstrated using synthetic drawdown data. It has been shown that these type curves can provide a fairly accurate means for determining transmissivity and storage coefficient of individual aquifer from pump test conducted in a well open to two aquifers.

(v) Performance of large-diameter well

Unsteady flow to a large-diameter well in a confined aquifer has been analysed for the case where the pumping rate is a quadratic function of drawdown. Results have been presented for variation of well discharge with drawdown and recovery of well storage with time. Variation of specific capacity of large-diameter well with time for different well storage has been studied. The relationships between transmissivity and specific capacity at various times after the onset of continuous pumping have been presented for different values of well storage and specific yield which can be used for estimating transmissivity.

(vi) Duration of test pumping

An attempt has been made to establish useful guidelines and procedures to decide the minimum and maximum duration of the test pumping. It has also been attempted to give the details of the parameters which may influence the decisions regarding the length of the pumping test.

2.2.5 Groundwater Synthesis

The research activities in this division were carried out in the areas of Water Balance Studies, Groundwater Modelling and development of type curves for large diameter wells which have adequate storage in them. A number of Review Notes, Case Studies and User's Manuals are being prepared covering these important areas.

(i) Water balance Studies

The water balance studies serve as a means of solution to improve theoretical and practical hydrological problems. On the basis of water balance approach, it is possible to make a quantitative evaluation of water resources and their change under influence of man's activities. Hence such studies are important part of water resources planning and management of river basins as they identify and quantify these resources. A case study for the water balance studies in the Upper Ganga Canal Command Area was taken up on the request of UP Govt. The data that are required for the study are being procured. The data requirements have been formated and format has been provided to UP Irrigation Department for providing the necessary data in the required format. With the available data at the Institute, the work in this direction has been initiated.

(ii) Groundwater Modelling

With the advent of fast computers numerical modelling using the finite difference approach has become more popular in view of its advantages. The US Geological Survey has developed a 'Modular Three Dimensional finite difference Groundwater flow model'. This model was procured and was implemented and tested on VAX-11/780 computer system. The modular structure of the programme consists of a main programme and a series of highly independent modules grouped as packages. Each package deals with a specific feature of hydrologic system which have to be simulated, like the flow from rivers, recharge from rainfall etc. or specific method of solving linear equations which describe the flow system. This programme being very versatile, is being used for the ground water studies in the Upper Ganga Canal Command area.

(iii) Analysis of pump test data from large diameter wells

Large diameter wells with huge amount of storage are pre-dominant in the country. Use of Thies/Hantush curve for the analysis of pump test data from these wells gives erroneous values for aquifer parameters. Suitable type curves for wells with storage are, hence, necessary. The type curves were developed using the finite element technique and a technical note on "Flow towards well with storage in leaky aquifers" was prepared. The parameters on which these type curves depend were identified. From the analysis of type curves, the storage affected zone both in space and time were demarcated. The determination of transmissivity of the aquifer from the early time pumping history is indicated.

2.2.6 Hydrological Investigation

The activities of this new division were many fold viz. applications of nuclear techniques, geophysical methods, data acquisition system, telemetry systems and signal analyser for data transmission, and applications of microprocessors for hydrological studies.

In the field of nuclear hydrology, neutron moisture probe is being employed for soil moisture movement studies in the unsaturated zone. A research paper and a technical report were published. Literature was reviewed and a review note on environmental isotopes for hydrological studies was prepared. In order to relate moisture content to the resistance of soil layers, geophysical surveys were initiated in the campus of the institute. Initially terrameter and meggar were employed. A review note on geophysical investigations for hydrological studies and one technical report on geophysical investigations for soil moisture studies were prepared. Technical notes on data acquisition system, telemetry systems and signal analyser for data transmission were prepared for developing microprocess or based hydrologic data acquisition systems.

(i) Soil Moisture studies

The studies of soil moisture movement were carried out in the campus of National Institute of Hydrology with the aim to assess the variability of soil moisture storage over the area, to provide regular measurements of the changes in soil moisture storage for hydrological water balance and to get semi quantitative information concerning evaporation rates and recharge through the soil. The soil moisture profiles were taken at few sites, different depths and times which enable a study of field capacity and vertical movement of water during redistribution. The knowledge of spatial distribution of soil moisture have yielded information on the water movement as well. An attempt has also been made to review the status and potentialities of the neutron probe.

(ii) Nuclear applications

The review report on the applications of environmental isotopes for hydrological investigations describes the status and potentialities of environmental isotopes in relation to the various hydrological and hydrogeological problems. The report deals with the applications of Tritium, Carbon-14, naturally occuring isotopes and stable isotopes Deuterium and Oxygen-18 particularly for water balance studies of lakes and reservoirs

(iii) Data acquisition systems

Microcomputer and microprocessor are increasingly being used in a number of hydrometeorological sensors. Signal analyzers also comprise of these microprocessor circuits. Keeping in view the latest developments in instrumentation technology, the Institute has taken up the design and development of a general purpose data acquisition system which ultimately will be used for collection of hydrometeorological data.

2.2.7. Remote Sensing Applications

Remote Sensing Applications Division has been set up in this year. Initial thrust of research activity has been contained in two areas, viz. i) snow line and snow cover mapping, and ii) land use and land cover mapping. An 'Image Processing' software available from Space Application Centre, Ahmedabad has been implemented and tested in the Institute's VAX-11/780 computer. Peripherals which are required to make it efficiently operational are earmarked. The studies are being carried out under following main heads.

(i) Snow cover mapping

Snow and ice constitute to be major component of world water resources and it is very relevant for India because the major northern rivers originate from the glaciers in the Himalayas. Location, recognition and measurement of the snow and ice by conventional means is a time consuming and hazardous job. Remote sensing methods have unique detection capabilities to overcome these problems because of high albedo of snow in the visual portion of the electromagnetic spectrum. Further snow's albedo is reduced substantially in near infrared spectrum. Using these properties and using remote sensing technique, snow has been conveniently identified and used for snow melt runoff studies and flow forecasting by hydrologists. A review note has been prepaid in order to take stock of the state of art in this area.

(ii) Land use and land cover mapping

Land use plays a major role in determining the various hydrologic processes after the incidence of precipitation. All the major components of hydrologic cycle viz, runoff, evapotranspiration, infiltration are influenced by the prevailing land use of a catchment. Land use map prepared from remotely sensed data could be prepared conveniently and be used as an input data for runoff modelling. Repeativity of remotely sensed data admirably suited for change detection of land use in an area. A review note has been prepared to collate the state of art in land use mapping by using remote sensing technique. A visual interpreted map of upper Yamuna catchment upto Tajewala has been prepared using satellite with the equipment so far procured in the laboratory. Limited digital checking has been made in this interpretation with the help of image processing software procured from SAC, Ahmedabad. A report on this case study has been prepared.

2.2.8 Information System

The management of computer centre with VAX-11/780 computer system and its peripherals form one of the main activities of this division. Efforts have been made to obtain hydrological data and computer programmes on magnetic tapes. The research activities of this division are mainly in the area of data storage and retrieval system, software for microcomputers and accounting system. Computer software for BBC microcomputers has been developed in BASIC language for various hydrological problems, which has been transmitted to the Brahmaputra Board, Guwahati for their own use.

(i) System specific programe inputs for documented programmes

FORTRAN is now used on all major computer systems. Major versions in vogue are FORTRAN, FORTRAN II and FORTRAN IV. A FORTRAN developed for a particular computer can not be executed as such on other type of computers. This report describes various modifications necessary for successfully implementing a FORTRAN program on DEC-2350, PDP-11 and UNIVAC-1100 which was originally developed on VAX-11 and vice versa.

(ii) Development of management information system

This research work is aimed to design and implement a Management Information System for the employees of National Institute of Hydrology, Roorkee. This utility package computerises the whole process of pay roll accounting and personal information. The tasks which the package performs are : validation of incoming raw data (available on disk), its organisation and thereby creation of master files, information retrieval from the master files and maintenance of the master files. The work provides a useful accounting package for NIH which prepares a concrete platform for building up a complete Management Information System.

2.2.9 Consultancy

The institute has been carrying out research studies under two projects sponsored by Narmada Cell and National Water Development Agency. The final report of the project ' Narmada design flood studies' was submitted in July 1985 and that of the project 'Water availability studies of three sites in Mahanadi basin' is under preparation.

Discussions have been held with Brahmaputra Board for taking up the 'Hydrological Studies for Barak Basin'. Punjab Government has desired that 'Flash Flood Studies for Punjab' may be taken up by NIH and analysis of data supplied so far is under progress.

2.2.10 Laboratories

To initiate laboratory oriented studies, the following laboratories have been made operational :

(a) Water Quality Laboratory

(b) Remote Sensing Laboratory

(c) Instrumentation Laboratory

(d) Hydrologic Laboratory

The above laboratories have the following capabilities :

(a) Water quality laboratory

The Water quality laboratory has the capability of doing routine water quality sample analysis, monitoring of river water quality and survey lines of water bodies.

(b) Remote sensing laboratory

This laboratory is working for remote sensing applications in hydrology. Visual interpretation for Upper Yamuna catchment and part of upper reach of Ganga catchment has been done and land use maps have been prepared. Image processing software has been installed in VAX-11/780 computer system of NIH which is being used for image analysis, processing and land use classification of Upper Yamuna Catchment. Further studies for other areas have been planned to be undertaken soon.

(c) Instrumentation laboratory

The Service and Instrumentation Workshop is developing a microprocessor based data acquisition system for hydrological studies. It would also cater to the day-to-day needs of various equipment in different laboratories of the Institute.

(d) Nuclear hydrologic laborstory

Soil moisture profiles using Neutron Probe have been carried out in the NIH campus which can be later extended to the field.

A field station to measure the parameters of meteorological and hydrologic data using the conventional equipments has already been installed in the campus. To enhance the capabilities of this station, an Automatic Hydrologic Station (AHS) with data acquisition system for obtaining the real time data and processing the same through a microprocessor is planned and the equipment was ordered under UNDP grants. Further, a lysimeter to study soil moisture, soil temperature, percolation loss in the irrigated fields and evapotranspiration losses, is being procured.

2.2.11 Workshops and Seminars Organised by NIH

Towards fulfilling the objective of technology transfer and having interaction with States and Central Government Organisations dealing with water resources, the Institute organised a series of workshops at Roorkee and in some States on the following important areas :

1. Unit Hydrograph Techniques
2. VAX-11/780 Computer System
3. Flood Frequency Analysis
4. Ground Water Modelling

These workshops provided the practicing engineers and scientists of various organisations an opportunity to learn the tehniques and methods of analysis which have been implemented and developed at the Institute.

The Institute also organised a one day seminar on Flood Frequency Analysis at CBIP, New Delhi on 30th September, 1985. The main purpose of this seminar was to provide a forum for discussions on the recent development and advances made in this important area. Discussions and deliberations in the seminar provided useful ideas for identification of areas for further studies.

2.2.12 Papers Published During the Year 1985

1. Bhar, A.K.: 'Soil Moisture Monitoring' Accepted for publication in J. Indian Association of Hydrologists.

2. Bhatia, K.K.S. and A.K. Sikka: 'Various Procedures for Environmental Impact Assessment', Accepted for Publication in Proc. of the Seminar on 'Environmental Considerations in Planning of Water Resources Projects' to be held at Roorkee, April, 1986.

3. Chachadi, A.G. & Ralph Phraner: 'Analysis of Recovery', J. Indian Association of Hydrologists, Vol. VIII, No. 4, Dec. 1985.

4. Chandra S.: 'Recent trends of Water conservation in drought prone areas', J. Institution of Engineers (India), V. 66, Part CI 1, July, 1985.

5. Dhason, S.R.B.: 'Multi-reservoir Operation J. Indian Association of Hydrologists, Vol. VIII, No. 4, Dec., 1985.

6. Ffolliott, P., M. Fogel and A.K. Sikka: 'Impact of Upstream vegetative management on water yield improvement' Accepted for publication in Proc. of the Seminar on 'Environmental considerations in Planning of Water Resources Projects' to be held at Roorkee, April, 1986.

7. Goel, N.K. and S.M. Seth: 'Tentative Spillway design flood estimation for Narmada Sagar Project - A case study', Seminar on Flood Frequency Analysis, New Delhi, Sept. 30, 1985.

8. Goel, N.K. and S.M. Seth: 'Data related problems in Frequency Analysis', Seminar on Flood Freqучу Analysis, New Delhi, Sept. 30, 1985.

9. Goel N.K.: 'Outliers in Frequency Analysis', Seminar on Water Resources-Role of Proper Investigation, Institution of Engineers (India), Jabalpur, Sept. 2 to 3, 1985.

10. Goyal, V.C., S.M. Seth, V.K. Bansal and H. Sinvhal: 'Microprocessor based instrumentation for Soil Resistivity Studies, XIth Annual Convention of Association of Exploration Geophysicists (India) Bhubaneshwar, Nov. 22-24, 1985.

11. Jain, S.K. and R.D. Singh: 'Stochastic Approach to Reservoir Capacity Computation' I·A.H. Journal of Hydrology, Vol. VIII, No. 4, Dec. 1985.

12. Jain, S.K., V.K. Lohani and G.C. Mishra: 'Water resources planning with environmental considerations', Accepted for

publication in Proc. of the Seminar on 'Environmental Considerations in Planning of Water Resources Projects' to be held at Roorkee, April, 1986.

13. Jayaseelan, A.T.: 'Application of Kinematic Cascade model for overland Flow-A case study', J. Hydrology of Indian Association of Hydrologists, Vol. VIII, No. 3, August 1985.

14. Lohani, V.K. and Satish Chandra: 'Resources Management Model' Accepted for publication in Proc. of the Seminar on 'Environmental Considerations in Planning of Water Resources Projects' to be held at Roorkee, April, 1986.

15. Mishra, G.C. and A.G. Chachadi,: 'Analysis of flow to a large diameter well during the recovery period', J. Ground Water Vol. 23, No. 5, Sept.-Oct. 1985.

16. Mishra. G. C., M. D. Nautiyal and S. Chandra: 'Unsteady flow to a well tapping two aquifers separated by an aquiclude', J. Hydrology, V. 82 (3—4), 1985.

17. Perumal, M: 'Stability criteria of conventional Muskingam method' Hydrology J. Indian Association of Hydrologists, Vol. VIII, Dec., 1985.

18. Perumal, M. and S.M. Seth: 'Need for uniform procedure of Flood Frequency Analysis' Seminar on Flood Frequency Analysis, New Delhi, September 30, 1985.

19. Perumal, M., P. Nirupama and S.M. Seth: 'Some studies on parameter estimation methods of Gumbel EV-I distribution using Monte Carlo Tests', Seminar on Flood Frequency Analysis, New Delhi, Sept. 30, 1985.

20. Perumal, M., S.M. Seth and B. Dutta: 'Tentative spillway design flood estimation for Sardar Sarovar Project-A case study', Seminar on Flood Frequency Analysis, New Delhi, Sept. 30, 1985.

21. Perumal, M. and S.M. Seth: 'Regional Flood Frequency Analysis using Power Transformation-A case study', Seminar on Flood Frequency Analysis, New Delhi, Sept. 30, 1985.

22. Ramasastri, K. S., Pratap Singh and S.M. Seth: 'Computerized processing and analysis of rainfall data, J. Hydrology, Indian Association of Hydrologists, Vol. VIII, No. 3, August, 1985.

23. Seth, S.M. and N.K. Goel: 'Regional Flood Frequency Analysis', Seminar on Flood Frequency Analysis, New Delhi, Sept. 30, 1985.

24. Sikka, A.K.; 'Budyko-Sellers Water Balance Approach-A case study', Accepted for publication in J. Indian Association of Hydrologists.

25. Singh, R.D. and S.M. Seth: 'Regional Flood Frequency Analysis for Mahanadi Basin using Wakeby Distribution', Seminar on Flood Frequency Analysis, New Delhi, Sept. 30, 1985.

26. Singh, R. D. : 'Application of efficient smoothed least square technique for unit hydrograph derivation', J. Hydrology Indian Association of Hydrologists, V. VIII, No. 3, August, 1985.

27. Singh, R.D.; 'Estimation of parameters of discrete cascade model using quasi Newton method', Accepted for publication in J. Indian Association of Hydrologists.

28. Singhal, D.C. and A.G. Chachadi: 'Hydrological Investigation in the Sohna Block, district Gurgaon, Haryana-A case study', J. Hydrology, Indian Association of Hydrologists, Vol. VIII, No. 3, August, 1985.

29. Soni, B.: 'A rainfall-runoff model for the Hupselse beek catchment in the Netherlands' Seminar on water resources development Role of proper investigation, Institution of Engineers (India), Jabalpur, Sept. 1 to 3, 1985.

30. Soni, B. and V.K. Lohani: 'Soil water accounting models-A Review', Hydrology J. Indian Association of Hydrologists, Vol. VIII, No. 1 and 2, April; 1985.

31. Soni, B., S.S. Sahay and Jaswant Singh: 'A goal programming approach for water resources management-A case study', Vth world Congress, Brussels, Belgium, June 9-15, 1985.

32. Soni, B.: 'Guidelines for estimating interception losses', Accepted for publication in J. Indian Association of Hydro logists.

2.2.13 Scientific and Technical Reports Prepared During 1985

REVIEW NOTES

1. Use of Catchment Characteristics for Unit Hydrograph Derivation
2. Estimation of ET for Variable Water Table Situation
3. Conjunctive Use of Surface and Ground Water
4. Time Series Analysis Model
5. Comparative Study of Self Recording Raingauges
6. Rainfall-Runoff Relationship
7. Effect of Flood Plain on Flood Routtng
8. Effect of Channel Processes on Flood Routing
9. Return Flow from Irrigation
10. Environmental Isotopes for Hydrological Investigation
11. Range Analysis for Storage
12. Sedimentation in Reservoirs
13. Hydrological Applications of Microprocessors
14. Geophysical Investigations for Hydrolocical Studies
15. Snowline and Snowcover Mapping
16. Land use/Land cover Mapping
17. Flash Flood Studies
18. Atmospheric General Circulation Model
19. Forecasting Models
20. Regional Unit Hydrograph

TECHNICAL NOTES

1. Rainfall Studies of Belgaum District
2. Determination of Seepage from Water Bodies
3. System Specific Programme Inputs for Documented Programmes
4. Drought Analysis Using Soil Moisture Simulation Approach
5. Parameterisation of Hydrological Factors in Ground Water Study
6. Duration of Pumping Test for Determination of Aquifer Parameters
7. Scientific Information System
8. Data Acquisition System
9. Data Requirement and Data Preparation for Dam Break Analysis
10. Flood Routing with Lateral Flow
11. Exchange of Flow Between a River and an Aquifer System
12. Vegetative Management for increasing water yield
13. Guidelines for Sample Survey for Minor Irrigation Works
14. Optimal Reservoir Operation Using Dynamic Programming
15. Telemetry System and Signal Analyser for Data Transmission

16. Soil Moisture Using Neutron Probe
17. Conjunctive Use of surface and ground water
18. Estimation of ET Under Variable Soil Moisture Situation.
19. Design and Performance of Large Diameter Wells in Hard Rock Areas
20. Watershed Resources Management-Development of sub-model 'WATER'
21. Development of Data Storage and Retrieval System
22. Data Base Management
23. Software for Micro-computer

CASE STUDIES

1. Regional Frequency Analysis
2. Water Balance of Upper Ganga Canal
3. Partial Duration series Model
4. Network Design Studies for Raingauges in Rajasthan
5. Application of Muskingum Cunge Method
6. Land Use and Land cover mapping for Yamuna
7. Soil Water Accounting by SCC
8. Flood Control Operation of Reservoir
9. DOSAG Model
10. Finite Difference Model for UGC

STATUS REPORT

1. Forest Influences on Hydrological Parameters
2. Status of Hydrological Studies in Forested Catchments
3. Sediment Yield from Different Land Uses

USER'S MANUAL

1. Kalinin Milyukov Method
2. Application of Tank Model for Daily Analysis
3. Application of Tank Model for Flood Analysis
4. Single Purpose Reservoir Operation for Irrigation
5. Hydrological Data Processing

MANUAL

1. Multipurpose Operation of a Reservoir

2.3 Central Water Commission

2.3.1 Hydrology I Directorate

1. The Hydrology I directorate in CWC deals with various hydrology related aspects in all river basins other than Ganga, Brahmaputra and Indus. Besides the project appraisal work, the directorate is also engaged in activities connected with rendering technical advise, consultancy and developmental work in hydrology and does liaison work with other Indian as well as outside agencies like WMO dealing in Hydrology and Water Resources.

2. Hydrological aspects of 20 New projects including aspects like water availability, design flood, reservoir sedimentation, evaporation etc. were examined. Several procedural and other deficiencies in the hydrological studies were noted and suggestions made to affect improvements in Project hydrology. Further comments were offered on the state replies of some of the ongoing projects. Special assistance has been provided in 11 cases.

3. The directorate rendered special advise on
   —Design flood estimate of Naradi Barrage-Vamsadhara Stage II Project.

   —Methodology for estimating design floods for cross drainage works of Sardar Sarovar Canal

   —Water balance study for Dudhna

   —Subbasinwise studies of Mahi basin Mahi Water Dispute

4. assistance to ISI continued through participation in various BDC meetings. A draft standard 'Fixation of spillway capacities of dams' prepared by the Directorate was discussed and approved for printing without any modifications. Draft standard on 'Reservoir sedimentation' was attended and the draft guidelines for determination of effects of sedimentation in planning and performances of reservoir-DOC BDC 48 (3461) was under examination. Draft of guidelines for determining the adequacy of spillway and surcharged capacity of existing dams were prepared.

5. In connection with Bodhghat flood studies, the directorate has developed a flood hydrograph computer package capable of computing floods simultaneously at several locations of the main river and one location each of tributaries. This model incorporates computation of Unit hydrograph using Clark's IUH concept, Muskingum channel routing, addition of subarea hydrographs and diversion of flow from the main stream. It has a plotting sub-routine and prints out several goodness of fit indices. The model could be used for calibration as well as flood estimation given the rainfall excess and other input data.

2.3.2 Hydrology II Directorate

1. The directorate has carried out technical examination of hydrological aspects of 57 water resources projects in Brahmaputra, Indus and Ganga basins and river systems in north eastern states relating to water availability, design flood, sedimentation and reservoir evaporation.

2. The directorate has provided consultancy on project hydrology and other specific hydrological problems connected with planning, design and operation of water resources projects referred by central/state Government public undertakings and corporations.

3. Special Studies have been carried out in respect of

- — Non monsoon Water availability at Okhla in connection with sharing of Yamuna Water
- — Economic analysis for determining optimum design flood for Khanpur Barrage across Ganga
- — Design flood studies for Meja Dam
- — Hydrological studies for Bussar Dam in J and K and Khowai dam in Tripura.

4. Development activities in Hydrology included

- — Collaboration with ISI on evaluation of draft standards connected with hydrology
- — Preparation and review of design criteria, manuals and guidelines and technical papers.

5. Presented the following technical papers :

(i) 'A study for optimum utilisation of the Damodar Water Resources' in the proceedings of the Indian Academy of Sciences.

(ii) 'Investigations for accelerated construction of Hydropower station' at the seminar on Water Resources Developments, Jabalpur.

2.3.3 Hydrology (Small Catchments) Directorate

Hydrology (Small Catchments) Dte. of Central Water Commission is engaged in the preparation of flood estimation reports programme. The flood estimation reports provide a methodology for estimation of 50-yr. flood for fixing the waterway of bridges on rivers having small and medium catchments. 50-yr. flood for ungauged catchments is estimated by the application of 50-yr. storm rainfall with its areal and time distribution factors to synthetic unitgraph based on established synthetic relationships between physiographic and unitgraph parameters of the representative unitgraphs of the gauged catchments. The design loss rates and base flow are also suggested in the report.

In addition to the above, the report contains 25-yr. and 100-yr. isopluvial maps of the subzone to compute 25-yr. and 100-yr. flood which may be used for the design of minor cross drainage structures and safety of minor dams respectively. The report also contains the flood formula to estimate the 25-yr., 50-yr. and 100-yr. flood using the physiographic parameters of catchment area (A) in sq. km., length of longest main stream (L) in km., length of main stream opposite the centre of gravity of the catchment to the point of study/ (L_c) in km., equivalent slope of the main stream (S_{eq}) in m/km and meteorologic parameters of 50-yr. stream rainfall for design storm duration (T_D) or 24-hr. rainfall (R_{TD} or R_{24}) in cm. These formulae are suggested for ready use of the field engineers for preliminary studies. The design flood (25-yr., 50-yr. or 100-yr. flood) estimated by both the detailed studies suggested in the subzonal reports and the flood formulae are within the permissible limits of variation. Flood estimation reports subzonewise is a joint work of Central Water Commission, Research Designs & Standards Organisation of the Ministry of Transport (Railways), India Meteorological Department and Roads Wing of the Ministry of Transport (Surface).

During the year 1985, Flood Estimation Report for Upper Godavari Subzone-3 (e) has been finalised and approved in the 43rd Planning and Coordination Committee meeting for publication. Flood Estimation Report for Mahi and Sabarmati Subzone-3 (a) pertaining to H (SC) Dte. was submitted to 43rd PCC meeting which was noted. This report will be completed after the receipt of Design Storm Rainfall Chapter from IMD.

Besides the above reports, printed copies of Flood Estimation Report for Middle Ganga Plains subzone-1 (f) have been circulated to various state and central agencies, and the Flood Estimation Report for Kaveri subzone-3 (i) is under printing in CWC Publication Division for circulation.

Printed copies of the report for South Brahmaputra Subzone-2 (b) and upper Indo-Ganga Plains Subzone-1 (e) are being circulated to user agencies.

2.3.4 Statistics Directorate

1. Daily stage-discharge data have been processed and stored in the 'Data Bank' for about 400 site years for Godavari basin, 300 site years for Krishna basin, 100 site years for Sabarmati basin and 80 site years for West flowing rivers between Tapi and Kanyakumari.

2. A Data Base Information System for inventory of Hydrological sites has been developed in collaboration with National Information Centre.

3. Computerisation of sediment load data for 80 site years in respect of Godavari basin has been completed.

2.4 Central Water and Power Research Station (CWPRS), Khadakwasla

2.4.1 Hydrological Studies for Narmada Basin

The CWPRS was commissioned to estimate the design floods of Narmada river at five different project sites by the Government of Madhya Pradesh and Gujarat. These projects are : Bargi, Narmada Sagar, Omkareshwar, Maheshwar and Navagam. Hydrometeorological and statistical procedures were adopted for the purpose. Hydrometeorological evaluation of design flood requires routing of the specified design storm through the drainage basin. In the case of Narmada basin, this routing was carried out by modelling the watershed as a series of linked subwatersheds and routing elements.

(a) Flood Studies for Navagam and Narmada Sagar Dams :

Narmada basin was modelled using the hydrologic model OPSET, a self-calibrating version of Stanford Watershed Model. For the purpose, the basin was subdivided into twenty subbasins delineated by drainage divides between tributaries. The subbasins were calibrated with OPSET for as many years of past data as possible. To combine the flows from the subbasins and route them down the main stem of Narmada to desired locations, both kinematic wave routing and Muskingum routing procedures were used. Validity tests of the modelling system were also carried out to confirm the applicability of the system. Superimposing the specified design storm over each of the calibrated subbasins, the resultant floods for the subbasins were evolved. Above mentioned routing procedures were used to route the floods to those locations on Narmada river at which design flood estimates were needed.

Two alternative probable maximum precipitation (PMP) estimates were specified by the project authorities for Navagam Project. The probable maximum flood (PMF) hydrographs at the dam site corresponding to each of the design storms were evolved using the aforesaid procedure.

In the case of Narmada Sagar Project, the PMP and SPS (standard project storm) estimates were specified by the Government of Madhya Pradesh. The PMF and SPF hydrographs corresponding to these storms were also determined using Kinematic wave routing models.

The basic equations solved are :

$$\frac{\partial Q}{\partial x} \times \frac{\partial A}{\partial t} = q \text{ (Continuity equation)} \quad ..(1)$$

$$A = \propto Q^{\beta} \text{ (Rating curve function)} \quad ..(2)$$

where

A = Cross-sectional area

Q = Discharge

$\propto$ and β are routing parameters

q = lateral inflow per unit distance

x = distance along reach

t = time in seconds

Probability analysis and modelling of recorded floods of Narmada river gave flood estimates of the river at Narmada Sagar and Navagam dam sites for different design frequencies. The studies concerning the hydrological studies of Narmada have won the acclaim of the World Bank, which is funding part of the cost of the projects .

(b) Bargi Flood Studies :

Calibration of the OPSET model for the basin was done using hydrometeorological data for four consecutive years. The input data for calibration comprised streamflow, precipitation, evaporation and various catchment characteristics. Model validation was done using recorded hydrometeorological data of the basin for one year.

For PMF and SPF studies for the project, two PMP and SPS alternatives were considered. Superimposing these hypothetical storms over the calibrated basin, the PMF and SPF hydrographs that can result from the respective PMP and SPS estimates were determined. The spillway outflow peak for each of the PMF and SPF hydrographs was arrived at by routing the respective inflow hydrographs through Bargi dam under the assumption of the reservoir at full reservoir level (FRL). In the statistical approach, two alternative distributional models viz., Log Pearson Type III and Gumbel, were used to estimate the flood magnitudes for different return periods, together with the 95 per cent confidence limits.

(c) Flood Studies for Omkareshwar and Maheshwar Projects :

Omkareshwar and Maheshwar dams are proposed to be located downstream of Narmada-Sagar dam. For determining the PMF flow into the Omkareshwar reservoir, the outflow hydrograph of Narmada Sagar was combined with the PMF flow contributed by the partial catchments downstream of Narmadasagar extending upto Omkareshwar on an hour-to-hour basis. Similarly, PMF inflow hydrograph for Maheshwar was obtained as a combination of the PMF outflow hydrograph of Omkareshwar and inreach addition contributed by the partial subcatchment between Omkareswar and Maheshwar dams for the respective PMP component. The project authorities specified the PMP applicable to each of the two partial subcatchments, downstream of Narmada Sagar dam, contributing their waters to Omkareshwar and Maheshwar dams respectively. Using a comparable procedure, the SPF hydrographs were also worked out for each of the two projects. In both the cases, two alternative PMP and SPS estimates were considered. The spillway outflow peak for each of the design flood hydrographs was arrived at by routing the inflow hydrographs through the respective dams under the assumption of the reservoir at FRL.

2.4.2 Firm Power Potential and Flood Moderation for Brahmaputra System

Studies are being conducted at CWPRS for determination of firm power potential at various sites in the Brahmaputra valley. The studies also include determining the effects of the various reservoirs on the river system in abating the floods all along the valley. The power potential at Dihang and Subansiri dam sites were determined for various combinations of FRL, MDDL and tail water elevations. The effects of the dams, either singly or in combination, on the flood moderation along the valley were also determined.

2.4.3. Yield Studies of Godavari River Basin

The CWPRS took up the work of determination of yields at some identified points in Godavari basin at the instance of the National Water Development Agency (NWDA). The study is intended for assessment of possible inter-and intra-basin transfer from the specified points. The basic methodology for the studies adopted by CWPRS is that of calibrating the basin using a hydrologic model, and using the model subsequently to generate long term streamflow sequences. With the help of the generated series, yield at each of the specified sites are estimated to an acceptable degree of dependability. The hydrologic model used for calibration is the Kentucky Watershed Model (KWM); the set of watershed parameters for the basin are optimised using the OPSET program. Calibration of the model is done using past hydrometeorological data for concurrent years. The major data inputs are : streamflow, precipitation, evaporation and different basin characteristics.

The dependable yield of Wainganga river at Garchiroli, a proposed diversion point on the river, was required to be estimated. However, gauging of the flows is done at Ashti located downstream of Garchiroli. Accordingly, the yield at Ashti was determined first. On prorata basis, yield was calculated for Wainganga at Garchiroli. The 75 percent dependable yield at Ashti worked out to 21, 850 $\times 10^6 m^3$ and at Garchiroli 18, 850 $\times 10^6 m^3$. The prorata computation has been extended both on precipitation depth and area. The above yields were determined based on 60 years of rainfall data.

The Indravati subcatchment up to Pathagudem of Godavari basin was calibrated using concurrent data of five years. For the calibration, withdrawal of water upstream of the gauging station as well as diversion of flow into the Jauranalla connecting Indravati basin with Sabri basin were considered in order to obtain the parameters for the virgin condition of the catchment. Using the available hydro-meteorological data for the years 1939-40 to 1980-81, streamflows were generated using the model in order to obtain the runoff at Patha gudem. Since the yield at Dudhme, the proposed point for locating the diversion in the basin, is required, a prorata-basis computation was made for the purpose. While doing so, both the variabilities in the area as well as precipitation between Pathagudem and Dudhme have been considered. Accordingly, the yield at Pathagudem works out to 19, 455 × $10^6 m^3$. At Dudhme the value is 15, 613 × $10^6 m^3$.

2.4.4 Study of Back-Water Effects of Srisailam Reservoirs by Electronic Analogue Method :

The study of backwater effects of Srisailam reservoir by electronic analogue method was taken up at the instance of the Government of Andhra Pradesh. The backwater profile of Srisailam reservoir has an important bearing in deciding the magnitude of protection works to Kurnool and Alampur towns which lie on the foreshore of the Tungabhadra arm of the reservoir. The water-spread of the reservoir extends to about 165.73 km. upstream of the dam along Krishna river up to Godwal railway bridge and for about 136.77 km upstream of the dam along the Tungabhadra river up to the railway and road bridges across Tungabhadra.

In the methodology adopted for study, Srisailam reservoir was split into several segments starting from the dam site to the upstream sections. The backwater profile was also computed. Under the assumption of the same friction slope to be applicable for different discharges, the rating curves which would be applicable on filling up of the reservoir, were constructed for all the requisite sections. Utilising these rating curves, the flood routing was carried out through the reservoir from section to section by the specific-purpose electronic analogue computer, designed and developed at CWPRS. This Computer was developed based on kinematic wave routing. Thus, the methodology adopted in the study is that of superimposing the effect of backwater over flood routing to obtain more accurate results. The analogue computer is fabricated and calibrated to give the discharges and levels at the requisite sections.

2.4.5 Synthetic Streamflow Sequences : of Narmada at Mortakka

Studies were undertaken for generation of annual, monthly and ten-daily synthetic flow sequences for Narmada river at Mortakka site. The generated data are intended to facilitate testing of alternative designs and policies against the range of flow sequences that are likely to occur in the future. The stochastic modelling approach, adopted for flow generation, made use of Markovian modelling technique. The technique uses the information content in the historical record, and creates new ensembles of flows that are statistically analogous to the observed flow sequences of a river. Annual and monthly flows of Narmada were initially generated under normal and lognormal distiibutional assumptions. Each sequence generated was of 50 years. A total of 500 such likely flow ensembles were generated for the river. With the computational scheme for generating monthly flows as basic, ten-daily flows were also generated by additionally incorporating the following computational procedure.

Based on the recorded flood data of Narmada river for the period 1948-1979, the average flow volumes (q_{ij} ; $i=1,2......12$; $j=1,2,3$) for the three ten-day periods (with adjustments on the number of days wherever necessary) of each month were computed initially. Weights (w_{ij} ; $j = 1.2,3$) for each month i was calculated as $w_{ij} = qij / \sum_{j=1}^{3} qij$. The ten-daily flow $Q_i (P_j)$ for month i and period j for a given year (with i varying from I to 12 and j from 1 to 3) is given by $Q_i (Pj) = w_{ij} M_i$ where M_i : is the generated monthly flow for that particular year. An algorithm written as per the procedure afore described was written and the resultant computer program used to generate the ten-daily flows.

2.4.6. Regional Training Course Organised At CWPRS

Under the sponsorship of the United Nations Educational, Scientific and Cultural Organisation (UNESCO), a regional training course on Application of Computers to Hydrological Studies' was organised at the CWPRS, Khadakwasla Pune from 7-25 January 1985. The primary aim of the course was to help the participants of the course to gain a comprehensive understanding of computer applications to hydrological studies; also covered was computer programming. Emphasis was given to surface water hydrology. The course was formally inaugurated by Shri B. Shankaranand, Honourable Minister for Irrigation (now Minister for Water Resources), Government of India. Eminent scientists and engineers from various organisations attended the inaugural function. The participants for the course were selected by the UNESCO from amongst the applicants from India, Sri Lanka, Afghanistan, Nepal and Maldives. The lectures, demonstrations and workshops were conducted by the CWPRS staff.

2.5 Central Ground Water Board (NW Region)

The Central Ground water Board is the apex National Organisation engaged in Ground Water Resource Evaluation of the country. The North Western Region is one of the 9 regions of this Board covering the States of J & K, Himachal Pradesh, Punjab, Haryana and the Union Territories of Delhi and Chandigarh.

The main activities of this region during 1985 were in the spheres of hydrogeological surveys, ground water exploration through drilling and testing, construction of piezometers monitoring the ground water regime, short term water supply investigations for augmenting the water supplies to defence establishments. Urban and rural habitations as also for industries. The department also gave assistance to various state departments in finalising their schemes for ground water development.

1. Areas in the high hilly regions of the States of Jammu & Kashmir and Himachal Pradesh were systematically surveyed for the first time from the point of view of ground water resources. During this year the work was completed in parts of the districts of Rajauri, Baramulla, Kupwara of J & K and Kangra, Una, Chamba and Kinnaur of Himachal Pradesh. Work was continuing in the districts of Kargil of J & K, Sirmur, Solan and Shimla of H.P.

2. The entire states of Punjab and Haryana and parts of J & K have already been systematically surveyed for determining the hydrogeological conditions. However, ground water being a dynamic resource, the need for resurveying the areas arises with the change in the regime and increasing pace of development. With this in view, reappraisal surveys were conducted in some parts of these States in the year 1985. Such studies were completed in the districts of Doda and Udhampur of J & K, Hissar districts of Haryana and were continued in Rajauri and Punch districts of J & K, Bhiwani and Rohtak districts of Haryana and Ropar district of Punjab.

3. Exploratory drilling for studying the subsurface geology was carried out at 35 sites all over the region. 25 piezometers tapping different aquifer groups were also installed in the States of Punjab and Haryana, where rapid ground water development is taking place, in order to continuosly monitor the ground water

body. The geophysical properties of the subsurface strata were also studied as a part of this work.

In all the above spheres of activity, the chemical quality of ground water was studied simultaneously.

4. The Regional office in consultation with the various state govenment also carried out ground water resource and balance estimation for the states of Haryana and Punjab.

5. The Region continued to issue scientific reports on the analysis of systematic and reappraisal surveys, as on the monitoring of behaviour of ground water regime. Reports on the exploratory wells as also for piezometers were also issued.

2.6 National Water Development Agency

The main functions of National Water Development Agency comprise of carrying out :

(i) detailed studies about the quantum of water which is surplus in various peninsular river systems and which can be transferred to other basins/States after meeting reasonable needs of the basin states in the foreseeable future, i. e. about 2025 AD;

(ii) detailed surveys and investigations of possible storage reservoir sites and inter-connecting links in order to firm up the proposals drawn by Central Water Commission and Ministry of Irrigation;

(iii) and to prepare feasibility reports of various components of the schemes.

The National Water Development Agency field unit at Hyderabad headed by Chief Engineer (South) was formed in August 1983 with 2 circles at Hyderabad and Bangalore. Four divisions have been established at Hyderabad, Pune, Rajamundry under Hyderabad Circle and three divisions were formed with Headquarters at Bangalore, Madras and Trivandrum under Bangalore Circle.

There are 89 Nos. of river basins and 47 diversion points to be studied in the jurisdiction of this unit covering six states viz., Maharashtra, Madhya Pradesh, Andhra Pradesh, Karnataka, Tamilnadu and Kerala.

Basin data required for carrying out hydrological and water balance studies had been collected for 67 subbasins and preliminary report on water balance studies for 22 sub-basins have been prepared and are under various levels of scrutiny. These would be circulated to the members of the Technical Advisory Committee of National Water Development Agency and the concerned State Governments for their views. So far 3 water balance reports have been circulated to TAC and State Governments and comments have been received. The preliminary water balance reports of sub-basins of Godavari River basin/ diversion points so far finalised are :

(1) Indravati (G-11) upto the diversion point at Dudhme

(2) Wainganga (G-9) upto the diversion point of Garchiroli

(3) Wardha (G-8)

(4) Maner (G-6)

2.7 India Meteorological Department

1. Design storm values and return period values in respect of Patiala - Ki-Rao catchment, Ropar, Punjab were supplied to the Director, Kandi watershed Designs Directorate, Chandigarh.

2. Design storm studies for Kutch region were carried out and rainfall depths upto 1000 sq. km along with the time distribution of storm rainfall were made available to the superintending Engineer, Central Designs Organisation, Gandhinagar.

3. Design storm studies were carried out and the Standard Project Storm and Probable Maximum Storm values for Bargi Dam, Budha Irrigation project, and Karwa Project, Maharashtra were supplied to the project authorities.

4. Extreme rainfall studies were carried out for Mand Project in Madhya Pradesh and 100 year storm values for 1-day and 2-day durations were supplied to the project authorities.

5. 24 hour Isopluvial maps of 50 and 100 year return period for sub-zone 3 g (Indravati Basin) have been finalised.

6. Short duration rainfall study of Cauvery Basin sub-zone 3 (I) were carried out and the final report was supplied to the Planning and Coordination Committee (P.C.C.).

7. Isopluvial analysis of past 25 years for Cauvery Basin (sub-zone 3i) was carried out and maps prepared.

8. On request from Superintending Engineer, Narmada Projects, Gandhinagar, Gujarat time distribution of storm rainfall in respect of catchment areas between 50 to 200 sq. miles of Gujarat region for 24 hour period was computed and results communicated to the project authority.

9. On request from the Executive Engineer, Bhakra Beas Management Board, Nangal, design storm values for one day and two day durations in respect of Pong Dam site on river Beas were supplied to the project authorities. 24 hrs isopluvial maps for 100 years return period for sub-zone 4 a (Coromandal Coast) and sub zone 4 b (Coromandal coast) have been completed.

10. The following papers were contributed

(i) A study of rainfall distribution during SW monsoon to identify deficient rainfall districts in West Bengal during recent years-SR Puri, SC Sharma & PK Dutta Roy, National Seminar cum-workshop on Atmospheric Science and Engineering held at Jadavpur University 20-23 Feb. 1985.

(ii) 1-day generalized rainfall frequency maps for lower Gangetic plains-SR Puri, SC Sharma & SN Kathuria, National Seminar cum workshop on Atmospheric Science and Engineering held at Jadavpur University, 20-23 Feb. 1985.

(iii) Trend in rainfall-DS Upadhyay, Surinder Kaur, Rajeev Kumar Rajput and MS Misra, National Seminar cum workshop on Atmospheric Science and Engineering held at Jadavpur University 20-23 Feb., 1985.

(iv) On Short-duration rainfall for lower Godavari basin-SR Puri, RN Adhikari and AD Ravishankar, International Seminar on concepts and Techniques of Applied climatology at Andhra University, Waltair, 18-21 March, 1985.

(v) Papers presented at National Seminar on "Estimation of Runoff for Surface and sub-surface Drainage" held at New Delhi from 9-10 Dec., 1985.

(vi) "Generalised charts of Maximum one day rainfall for different return periods for the state of Haryana" by SR Puri, SC Sharma & AK Mehra.

(vii) Rainfall depth-duration-frequency studies for design of urban drainage system in New Delhi by SC Sharma Surender Kaur & AK Mehra.

2.8 Indian Institute of Tropical Meteorology, Pune

1. A detailed hydrometeorological study of the Karanja catchment was made to estimate the design storm depths for different return periods and the probable maximum rainfall likely to be experienced by the catchment, using long period rainfall data. It was found that the catchment experienced maximum rainfall of 193 mm, 258 mm and 312 mm during 1, 2 and 3 days period respectively during the last 94 years of record. The PMP for 1, 2 and 3 days duration, was found to be 339 mm, 406 mm and 424 mm respectively which are about 1.4 to 1.8 times the corresponding maximum raindepth experienced by the catchment.

The hourly distribution of rainfall during intense storm periods of I-day duration in the Karanja catchment was also studied. The analysis showed that during 1-hour period as much as 56% of 1-day rainfall can occur and the two consecutive hours may account for 73% of 1-day total rainfall.

2. The rainstorm of 28-30 August, 1982 over the uncontrolled catchment of the Mahanadi river which produced an unprecedented peak discharge of 4430 m^3/sec at Naraj was analysed. The study revealed that the rainstorm of August, 1982 was not so severe as compared to the past rainstorm of the catchment, though it produced maximum peak discharge. The unprecedented peak discharge resulted due to antecedent wet conditions of the soils as a result of heavy rainfall which occurred 10 days prior to this storm.

3. A study was conducted to determine the relationship between the rainfall and the available moisture content in the atmosphere. For this purpose daily surface dew point temperatures and rainfall data of stations in Narmada catchment for the period 1961-1970 were used. The day to day variability in precipitable water during monsoon season was found to be low (5 to 10%) whereas rainfall showed high variability (50 to 100%).

4. The extreme 24 hour persisting dew point temperatures are required for PMP studies. An attempt has, therefore, been made to prepare a generalised chart of annual extreme dew point temperatures for the Indian region. The extreme 24 hour persisting dew point temperatures along the Arabian sea and the Bay of Bengal coasts are found to be 29°C and 30°C respectively. The chart of extreme dew point temperatures can be used for assessing maximum moisture content at any location required for PMP studies.

5. A linear regression of S.D. on the mean annual rainfall has been estimated using data of 462 stations uniformly distributed in India. Regional regression functions of similar form have also been obtained separately for northern and peninsular India lying north and south of 20°N. The study showed that the variability of annual rainfall is more in north India than in peninsular India.

6. Normal distribution has been fitted to the actual, square-root, cube-root and log-transformed values of the annual rainfall (1901-81) data of 26 stations in Rajasthan. It has been seen that by and large, cube-root transformation for stations in west Rajasthan and square-root for stations in east Rajasthan are normally distributed.

2.9 Geological Survey of India

1. The snow cover studies in Dhauliganga Basin, U.P., were carred out during April, 1985. Due to lean winter, the area became snow free

quite early. The snow was present only on steep shaded parts of the valley slopes and on the northern faces of the slopes. The average thickness of the snow ranged from 30 to 60 cms. upto Dubter. The data is being processed.

2. Snow cover assessment studies were carried out during April, 1985, in Sind River Basin, Kashmir. An area of 30 sq. km. was covered in the E-W trending valley between Sonamarg and Bharari Marg, District Srinagar, J & K. The studies involved delineation and plotting of various snow layers, density measurements of snow pack, its ablation and thickness measurements at various places. The mean elevation of transient snow line was demarcated and major avalanches were studied.

3. Routine glaciological studies pertaining to flood season 1984-85 were taken up commencing June, 1985.

2.10 Research, Designs and Standards Organisation, Ministry of Transport (Railways)

1. Hydrometeorological studies based on representative small and medium size catchments being carried out jointly by RDSO, CWC, IMD and Ministry of transport with a view to rationalise and simplify the approaches for estimation of design flood of different return periods were continued during 1985. Exhaustive literature survey was undertaken to rationalise the method of fixing the waterway when the design floods were known.

2. An interim methodology for estimation of flood of 100 year return period has been developed for cyclone-affected coastal region utilising the unit hydrograph approach for 50 year flood and the flood frequency approach for the ratio between 50 year and 100 year return period floods.

3. Regional flood frequency studies, based on limited data were carried out for Kaveri basin. A regression formula was also developed correlating time of concentration with catchment characteristics using selected catchments with areas upto 100 sq. km.

4. Observation of flood stage, discharge and concurrent rainfall data was collected at 45 railway bridges, 208 raingauge stations. Daily peak flood stages at 256 other railway bridge sites were also collected.

2.11 Bhakra Beas Management Board, Chandigarh

The Bhakra Beas Management Board is responsible for the administration, maintenance and operation of Bhakra Dam and Reservoir, Pong Dam and Reservoir, Pandoh Dam Reservoir and the Beas Sutlej Link Water Conductor System. One of the main functions of the Board is the regulation of supplies of water from the above Projects. The Bhakra and Pong Reservoirs are operated in a planned manner and the supplies are regulated taking into account the available storage, the likely pattern of inflows and the requirements for both irrigation and power. This can only be possible if we have at our command the various inputs required for the same.

Bhakra Beas Management Board has therefore established a comprehensive net work of discharge sites both on the main rivers and their important tributaries, rain gauges, snow gauges, snow observatories and evaporimeter sites as these form an important input for reservoir operations. Some of the important sites have been connected with wireless communication for quick transmission of hydrological data. Bhakra Beas Management Board has a total of 14 discharge sites on main rivers and another 14 on important tributaries. There are 43 rain gauge stations, 17 snow gauge stations, 4 snow observatories and 11 evaporimeter sites. About 18 sites are connected by wireless.

The hydrological activities during 1985 were mainly connected with the maintenance, operation, collection and analysis of data at the various sites. All this data is also sent to various States and Central Government Agencies for information as per their requirements.

The average rainfall observed in the catchment area on river Sutlej and Unit I and Unit II of Beas Project for the period January to June, 1985 and also comparison with the normal rainfall is given in Table (a) :

The mean monthly maximum and minimum temperature (in °C) observed at 4 number snow observatories from January to June, 1985 is given in Table (b) :

On the basis of observations made at evaporimeter sites in the Bhakra Reservoir area, it has been observed that there was a total evaporation of 0.8433 metres during the period January to June, 1985. Similarly in the case of Pong Reservoir the total loss in depth of water during the period January to June, 85 worked out to be 0.7033 metres.

Table (a)

Month	Sutlej (in MM)		Beas (in MM)			
			Unit-1		Unit-II	
	Normal	Actual	Normal	Actual	Normal	Actual
1985						
January	56	45	104	66	70	68
February	55	10	88	29	79	12
March	56	11	94	45	53	13
April	27	44	66	71	29	56
May	42	31	61	46	35	34
June	141	81	121	66	173	86

Table (b)

Month	Kaza (3639 m.)		Namgia (2910 m.)		Kalpa (2439 m.)		Racksham (3130 m.)	
	Max. °C	Min.	Max. °C	Min.	Max. °C	Min	Max. °C	Min
January, 1985	— 5.7	—22.7	0.3	—8.3	0.3	—6.6	2.2	—12.8
February	—15.2	—28.4	7.2	—5.0	7.9	—3.5	7.1	— 8.2
March	—14.5	—25.2	14.4	2.6	13.6	2.3	10.7	— 1.2
April	1.7	— 8.6	17.1	4.9	16.7	4.6	13.5	1,9
May	17.1	6.7	19.9	6.7	20.5	6.9	17.8	4.9
June	19.3	8.3	25.1	11.4	23.8	10.5	20.5	7.0

In addition to the above activities, Bhakra Beas Management Board in collaboration withSnow and Avalanche Study Establishment (SASE) under the Ministry of Defence, have undertaken snow studies in two small basins in river Beas near Manali for the forecast of snow melt. Under this scheme, discharge measurements at two selected sites—Kulling and Palchan are being taken by Bhakra Beas Management Board and SASE is observing snow fall and other meteorological data at two selected sites in the basin.

2.12 Damodar Valley Corporation, Maithon

1. Computation work and preparation of report of fifth sedimentation survey of Panchet Hill Reservoir conducted in 1984-85 was completed.

2. Publication of water Data for Hydrologic computations for Panchet Tail Pool Dam Project and Damodar Diversion Project was completed.

3. Preparation of report in respect of change in the Lower Damodar River regime below dams was taken up and was in progress.

2.13 National Geophysical Research Institute, Hyderabad

1. A programme to study the interface dynamics of coastal aquifers of Pennar Delta (A.P) is initiated with the objective to improve the monitoring system of interface movement. Hydrogeological and hydrochemical studies have been carried out.

2. Detailed well inventory, air photo studies, geophysical investigations, recharge measurements and aquifer tests have been carried out in Avurpalli basin (A.P.) Recharge studies have indicated an average recharge of 3.1 cm in the year 1984-85. Ten exploratory drilling sites have been suggested based on geophysical surveys. Pump tests have been carried out on 18 large diameter wells to estimate aquifer parameters.

3. Tracer injections have been carried out in Manila basin to estimate recharge. Tracer injections have also been carried out near Shringeri (Karnataka) to study the effect of vegetation on recharge.

4. Environmental tracer studies have been carried out in Pondichery to estimate recharge and specific yield using environmental chloride as natural tracer. A suitable method was evolved for determination of low level chloride concentration of soil sample.

5. The sonde for groundwater velocity probe has been designed, fabricated and tested for vacuum and pressure leaks. The gamma ray spectrometer has been tested for energy resolution and energy linearity. The design of a vertical probe is in progress. Experiments have been carried out in wells to study dilution using tritium tracer.

6. Computer program using universal kriging technique has been suitably modified and adapted on VAX - 11/750 computer. A computer program using bivariate interpolation technique for sparse hydrogeological data has been adapted for execution on VAX-11/750. A computer program has been developed to simulate mass transport in porous media using finite difference method.

Numerical modelling was carried out for interpretation of data on pump test in a large diameter well in a granite formation incorporating the effect of incomplete recovery prior to pump test.

A preliminary groundwater flow model of Vaippar Basin (Tamilnadu) was prepared and the data gaps were identified and suggestions finalised for additional data collection.

A numerical model of typical alluvial basin was constructed with simplified boundary conditions for evolving a conjunctive utilization scheme of surface and groundwater resources.

2.14 Central Soil Salinity Research Institute, Karnal

With the introduction of irrigation in semi-arid and arid regions, the problem of waterlogging and consequently of secondary salinisation is arising and has already reached serious proportions offsetting the benefits accrued from irrigation. As the ground waters are saline, the high water table situations have resulted in secondary salinization and nearly 0.5 m ha area is severely affected with this problem. To evaluate the techno-economic feasibility of sub-surface tile drainage, studies were taken up at village Sampla in Rohtak Distt. in area of 10 ha. A sub-surface drainage system, comprising of three spacings of 25, 50 and 75 m in highly saline area, was installed in 1984. The depth of the tile drains adopted was 1.75 m. The length of each lateral drain was 200 m. Cement concrete tiles of 30 cm length and 10 cm internal dia and a natural well graded gravel with gravel size ranging from 20 to 0.2 mm as envelope material were used in the installation. The soil is sandy loam in texture with salinity (ECe) ranging from 50 mmhos/cm in the surface 20 cm layer to about 19 mmhos/cm at 100 cm depth. The installation of tne drainage system was completed in April 1984 and the pumping of drainage effluent started.

By the begining of monsoon (first July) the water table was at drain level none of the drains were flowing. The drains started functioning with the first rain in the begining of July. In the monsoon season about 57.8 cm of rainfall occurred out of which nearly 38.7 cm was received in seven storms. The maximum rain storm was 15 cm in 4 days in the last week of August. Throughout the season the water table remained within a depth range of 1.3 to 1.6 m except for five days from 28th August to Ist September during which the water table was within 20 cm. However it again dropped to depths beyond 0.8 m within seven days. In case of undrained area, the water table which reached the ground surface at the end of August, continued to remain within a depth of 0.8 m even after one month. A total depth of about 28 cm of effluent was drained out from the area in the period in 3 months time. The salinity of the drainage effluent ranged from 10 to 30 mm hos/cm.

The salts in the soil profile were leached down considerably with rain water, reaching ECe values in the range of 5 to 8 mmhos/cm by the first week of October from an initial value of about 50 mmhos/cm in the surface 20 cm layer. There was a decrease in all layers of soil upto a depth of 120 cm. Salts at the rate of about 25.5 t/ha were leached out from plots provided with 25 m spacing, 17.7 t/ha from plots with 50 m spacing and about 11.3 t/ha from plots with 75 m spacing. With the reduction of salinity, bajra crop in kharif season and wheat, mustard and barley were grown in winter. The average yield obtained in different spacings were satisfactory. In drain spacings of 25 and 50 m the yields were as good as in the normal soils and the yields with 75 m spacing also are expected to reach the same level in 2-3 years with a gradual reduction in profile soil salinity.

2.15 Physical Research Laboratory, Ahmedabad

(i) A New approach to analysis of pumping test data in Semi-confined aquifer

A pumping test is one of the most useful means of determining hydraulic properties of water bearing layers and confining beds. Semi-confined (or leaky) aquifers are a common feature of many alluvial areas such as deltas, coastal plains, low lands and river valleys, former lake basins, etc.

The well-known methods of analysing pumping test in a semi-confined aquifer are of two types, viz. (i) based on steady state condition; and (ii) based on unsteady state condition. Amongst the former, De Glee's method is based on curve matching procedure while the Hantush Jacob method is based on the straight line portion of the distance draw-down plot. De Glee's curve matching method is very subjective, particularly if only a few observation wells are available. The Hantush-Jacob method on the other hand is restricted to small values of radial distance (r) to leakage co-efficient (L) ratio (i.e. $r/L < 0.05$).

It has now been shown that the ratio of steady state draw - down to its gradient over a log - cycle in radial distance from the pumping well, uniquely determines transmissivity (T) of the aquifer. A new method based on this result has been proposed for evaluation of aquifer parameters, viz. transmissivity, leakance and hydraulic resistance of semi-pervious confining layer. The method avoids the subjectivity inherent in curve matching procedure and also does not involve any approximation in the formulation.

A procedure for evaluating errors in estimated aquifer parameters has also been developed. The method has been verified by applying to field data.

Publications :

S.K. Gupta and P. Sharma (1985) : Analysis of steady-state flow in semi-confined aquifers : a new approach, Ground-Water Vol. 23, No. 2, pp. 227-232.

(ii) Soil moisture movement in arid regions of Thar desert

Soil moisture movement in the arid region of Thar desert, Rajasthan, has been studied using the tritium tagging method. It was found that groundwater recharge in the areas varies between 5-14% of the precipitation input. The important factors which control the groundwater recharge are : (i) vegetation cover; (ii) nature of surface soil; and (iii) topography. It was found that groundwater recharge is higher in the regions of shifting unconsolidated sands as compared to established sand dunes having vegetation cover. In addition, a slight ($\sim 5°$) inclination of the land surface results in considerable reduction in the soil moisture transfer as compared to flat areas or areas which are situated in slight depression. This occurs because of high intensity of rainfall in the desert region which results in higher run-off from the slopes.

A simple conceptual model has been employed to understand the mechanism of soil moisture movement. The model involves estimation of precipitation excess for individual months taking into account the requirement of soil moisture storage and evapotranspiration. Using this model, the computed groundwater recharge for the semi-arid regions of Gujarat has been found to be in very good agreement with the experimental values obtained by the tritium tagging method.

Publications :

S.K. Gupta (1984) : A Radiotracer of Soil Moisture Movement During Groundwater Recharge, Hari Om Ashram Prerit Vikram Sarabhai Award Lectures, Physical Research Laboratory, Ahmedabad. pp. 57-76.

P. Sharma and S.K. Gupta (1985) : Soil Water Movement in Semi-arid Climate-An Isotopic Investigation. Final Report of the IAEA Research Project on studying the Physical and Isotopic Behaviour of Soil Moisture in the Zone of Aeration, IAEA, Vienna.

(iii) Mathematical modelling of aquifers in Ahmedabad

A mathematical model of aquifers in Ahmedabad city has been developed. The model considers the aquifer system consisting of an upper unconfined aquifer and a lower semiconfined aquifer. The model has been calibrated using water level, pumping rate and river discharge data for the period 1952-1972. The second calibration check Is provided by comparing the water level changes at three stations in Ahmedabad during the period of heavy concentrated pumping operation in the summer of 1975.

The calibration and the operational runs indicate that of the 132 million cubic metres (MCM) of water pumped out in 1984 within the municipal limits nearly 25 MCM was contributed by induced leakage from the Sabarmati River alone. Another 57 MCM was derived from the induced leakage from the rest of the city. Sub-surface inflow from the surrounding areas contributed another 47 MCM due to fall in water level in the city area. The balance was derived from aquifer storage resulting in water level fall. For the projected groundwater pumpage of 225 MCM for year 2000, the induced leakage from river and from the rest of the city area are estimated to 56 and 72 MCM respectively, with the water levels in the western, central and eastern parts of the city falling to 70, 85 and 125 m respectively.

The study brings out the importance of artificial groundwater recharge in the city and also suggests that instead of direct recharging of confined aquifers in the city (as previously thought) recharging of unconfined aquifers may be easier and more effective and even desirable for minimising the risk of pollution of the deeper aquifers.

Publications :

S. K. Gupta (1985). Water for Ahmedabad : Perspective for 2001, Report PRL/HYD/85/1, Physical Research Laboratory, Ahmedabad. (Summary at 2.15.1)

S.K. Gupta (1985). Scenario of Groundwater Development in Ahmedabad : Environmental Considerations. Proc. Int. Symp. Environmental Impact Assessment of W.R. Projects, Roorkee 12-14 December, 1985.

(iv) Stable isotopic study of ground and river water

A comprehensive set of measurements of Oxygen and Hydrogen isotopic ratios in groundwaters as well as waters from rivers, lakes, hot springs etc. taken from a variety of locations in north and central India has been carried out. Most depleted samples occur in high altitude precipitations in Himalayas e.g. in lakes in Bhutan and source waters of Ganga. The shallow groundwater data display a continental effect where the heavy isotope content decreases with distance from coast (approx. 4 to 6 per mil decrease in 18_0 per 1,000 km). The δD and δ 18_0 of these fresh waters are linearly related and an analysis of this relation vis-a-vis the meteoric water line shows unambiguous effect of enrichment due to evapotranspiration from soils.

Publications :

S. K. Bhattacharya, S. K. Gupta and R. V. Krishnamurthy (1985): Oxygen and Hydrogen Isotopic Ratios in Groundwater and River Waters from India Proc. Ind. Acad. Sci. Earth & Planet Section, Vol. 94, No. 3.

(v) Glaciology :

Five ice samples collected by GSI from a shallow ice core (0-3 m) from Dakshin Gangotri Station were analysed for 210 Pb and 18_0 for studying ice accumulation and past climates. The total beta radioactivity suggests the presence of nuclear debris. The stable isotope analyses indicate the mean surface air temperature at Dakshin Gangotri of - 10°C during the past decade.

Dating of ice and study of flow dynamics for CK glacier has been completeted based on 210 Pb, 82 Si and TL methods.

Publications :

N. Bhandari, D.I. Bhatt, V.N. Nijampurkar, R.K. Singh, D. Srivatsava and C.P. Vohra (1981): Radiometric age of the snout ice of Nehnar glacier, Proc. Ind. Acad. Sci., Vol. 90, No. 3, pp. 227-235.

V. N. Nijampurkar, J. M. Martin and M. Maybeck (1983) : Silicon-32 as a tool for studying silicon behaviour in estuaries, Limnol. Oceanogr. 28 (6), pp. 1237-1242.

N. Bhandari, V. N. Nijampurkar and C.P. Vohra (1983) : Radiometric chronology of some Himalyan glaciers, in A. Street-Perrot (ed.) in the Global Water Budget, D. Reida Publishing Co., pp. 207-216.

P.N. Shukla, N. Bhandari, V.N. Nijampurkar, D. Kameswara Rao, V.M.K. Puri and Sanjiv Sharma (1983): Ice accumulation rate in Changme-Khangpu glacier, Sikkim, Proc. Ind. Acad. Sc. pp. 225-260.

N. Bhandari, S.K. Bhattacharya, V.N. Nijampurkar, D. Sengupta, V.G. Shah, A.K. Singhvi, P.N. Shukla, K.M. Suthar and C.P. Vohra (1984): Isotopic and related studies of Antarctic ice samples, Proc. Ind. Acad. Sci. (Earth Planet. Sci.), Vol. 93, No. 2, pp. 135-140.

V.N. Nijampurkar, N. Bhandari and V.M.K. Puri (1984) : Ice Dynamics and Accumulation Rates on Changme-Khangpu Glacier, Sikkim, by Radioisotopic Methods, Isotope Hydrology 1983, pp. 31-41.

V.N. Nijampurkar and N. Bhandari (1984) : Oxygen isotopic ratios of some Himalayan glaciers, Tellus, Vol. 36B, pp. 300-302.

V.N. Nijampurkar (1985) : Basal flow rate of Changme-Khangpu glacier, Sikkim Himalayas based on 32 si and 210 pb chronology, Proc. Ind. Acad. Sci. Vol. 94, No. 2, pp. 83-89

2.15.1 Summary of Water for Ahmedabad: Perspective for 2001

Groundwater development in Ahmedabad city has now reached a level where it becomes necessary to investigate possible dangers of excessive exploitation. Rapidly falling water levels in the city have not only resulted in increasing pumping cost but have also rendered shallow tubewells inoperative. Large scale dewatering of aquifers is also fraught with danger of land subsidence known to have occurred in several parts of world. The area around Ahmedabad has been an important oil producing region now for almost two decades Exploitation of oil too leads to reduction in hydrostatic pressure in rocks/sediments and in some cases to land subsidence. Fortunately, no land subsidence has so far been reported from anywhere in and around the city. This aspect has, however, not been considered in the present study. Water quality aspects too have not been considered.

As a first step towards investigation of possible geological hazards of over exploitation of aquifers, the focus of the present study has been to understand the systematics of aquifer system in and around Ahmedabad and to predict the likely change in water levels and hence the extent of dewatering in different parts of the city. Data of aquifer juxtaposition as observed from driller's logs of several tubewells in the city indicated that there are six to seven lenticular aquifers down to a depth of 250 m. Over large areal extent these seem to comprise two major aquifer groups, viz., an upper phreatic aquifer separated from the lower artesian aquifer by a layer of semi-permeable aquiclude. For the purpose of mathematical modelling this two aquifer grouping was considered adequate. Further vertical subdivision of the model into multiple aquifers was not considered feasible in view of the limited historical data with which to calibrate the model. In the model, direct groundwater recharge due to deep percolation of rainwater to the upper phreatic aquifer is assumed to be 15% of annual precipitation. This is based on extensive tritium tracing experiments for groundwater recharge estimation in and around Ahmedabad in the Sabarmati basin (Gupta and Sharma, 1984) and the model calibration experiments. Indirect recharge to phreatic aquifer is due to sub-surface inflow from the surrounding regions in response to steep cityward groundwater gradient in all directions. Artesian aquifer receives indirect recharge from induced leakage of phreatic aquifer caused by reduction of artesian head due to pumping from artesian aquifer (no significant pumping is believed to be taking place from phreatic aquifer in Ahmedabad). Sub-surface inflow of artesian water from surrounding regions contributes to indirect recharge of artesian aquifer in the same manner as the phreatic aquifer. While the quantum of direct rainwater infiltration is fixed (10.5 MCM/yr), the amount of indirect recharge from various sources is controlled by i) the rate of groundwater pumpage; ii) the tranmissivity of artesian aquifer; iii) the permeability of phreatic aquifer; iv) the leakage coefficient of the semi-pervious aquiclude; and v) the saturated thickness of the phreatic aquifer, which in its turn varies with water table fluctuations,

The model has been calibrated using water level, pumping rate and river discharge data of Patel and Shah (1973) for the period 1952-1972. The second calibration check is provided by comparing the water level changes at three stations (Dudheshwar, Jupiter Mills and L.D. Engineering) in Ahmedabad during the period of bank bore operation in the summer of 1975.

The calibration and operational runs indicate that of the 132 MCM of water pumped out in 1984, within municipal limits, nearly 25 MCM was contributed by induced leakage from the Sabarmati river alone. Another 57 MCM was derived from the induced leakage from the rest of the city. Sub-surface inflow from the surrounding areas contributed and 47 MCM due to fall in water level in the city area. The balance (3 MCM) was derived from aquifer storage resulting in water level fall. The study also brings out the importance of induced leakage from Sabarmati river and explains the observed reduction in summer discharge of river in spite of releases from Dharoi reservoir.

If the average per capita daily water consumption is assumed to rise linearly so as to reach a level of about 310 litres from the present level of about 180 litres, the projected groundwater requirement for the year 2001 is 222 MCM in Ahmedabad city alone. This Is based on the assumption that AMC would be utilising its full quota of 249 MCM of surface water from Sabarmati river. For the projected groudwater pumpage of 222 MCM for the year 2001 (increasing linearly from 1985), the induced leakage from the river and from rest of the city are estimated to be 56 and 72 MCM respectively, with water levels in western, central and eastern parts of the city falling to approximately 70, 85 and 125 m respectively. This, in addition, will raise the cost of water supply and can result in serious pollution hazard if appropriate drainage works are not ready in time.

It is, however, quite likely that even at the turn of century, people in Ahmedabad city will be restricted in their daily water consumption to an average per capita limit of 180 litres as at present. The groundwater requirement assuming full utilisation of surface water resources in this case would be substantially less (62 MCM instead of 135-140 MCM at present). However, because of increased groundwater requirement outside AMC, sub-surface inflow will be substantially lower and the water levels in western, central and eastern zones of the city are estimated to between 45-60 m, 57-70 m and 80-90 m respectively.

What can the city do to increase its per capita daily water consumption, without in any way endangering the aquifer system that was inherited ? Other than long distance import of water through possibly Narmada Canal, which will pass north of Ahmedabad and may be ready by 2001, artificial recharging of aquifers in Ahmedabad appears to be a very attractive alternative.

The present study is very significant in the context of designing an economical artifical recharge scheme for the city. It is shown that even though all the groundwater from the lower artesian aquifer, is pumped the induced leakage very significantly contributes by way of indirect recharge to the artesian aquifer. This suggests that by recharging the unconfined aquifer during rainy season when Sabarmati river still has considerable surplus water, the objective of storing the run-off underground for later use. may be acyiened Artificial recharging of phreatic aquifer, that has very significantly higher storage coefficient, is believed to be technically easier than injection recharge of artesian aquifer. This would also save the artesian aquifer, which now supplies drinking water to the city, from pollution threat because of time required and filtration during leakage through the semi-pervious layer.

Present work did not concern with the design of an artificial recharge scheme but it is worth mentioning that in May 1977, the author in collaboration with Gujarat water Resources Development Corporation Ltd. (GWRDC Ltd.) had successfully conducted a pilot artificial experiment using siphon principal at Hansol, little north of Ahmedbad (Desai et al, 1970). The experiment suggested the feasibility of one of the several possible ways of recharging aquifers in Ahmedabad.

It was suggested that both Ahmedabad Municipal Corporation (AMC) and the Ahmedabad Urban Development Authority (AUDA) should initiate detailed project planning and feasibility studies for artificial recharging and close monitoring of aquifers in the entire metropolitan area.

2.16 Hydrology & Tracers Section, Isotope Division, Bhabha Atomic Research Centre, Bombay

(i) Isotope study on the salinisation of coastal Minjur aquifer near Madras

Environmental isotopes D, 18_0, 3_H alongwith major, minor and trace chemical species were used to study the salinization of the coastal aquifer near Madras. The study shows that the salinity of the deep zone groundwaters near the coast have been derived by sea water ingress. Hypersaline groundwaters encountered in certain pockets near the salt pan area have possibly derived their salinity through leaking of salts and not due to connate sea water.

(ii) Isotope study to determine inter connection between shallow and deep groundwater in the Cavery delta area near Tanjaur

Stable isotopes D and 18_0 samples collected from the shallow and deep groundwaters in the Cavery delta area interpreted along with the geochemical data unambiguously indicated that the two zones were distinctly different and not inter connected. They derive waters from two different sources.

2.17 Indian Institute of Technology, Bombay

(i) Studies in drainage system

This project deals with two problems which have been solved by analytical and experimental methods. In analytical study of seepage, the solution of Glover for unsteady flow towards the drains in horizontal impervious bed is extended for solution of unsteady seepage flow in inclined impervious bed. Glover's solution for seepage flow in drains with infiltration is solved by taking horizontal water table above the drain. In this project parabolic water table is taken. This equation is solved by fourier series. It has been noticed that with increase in drain diameter, there was no effect on seepage discharge. In the other study, the effect of leterals in augmentation of seepage flow in drain pipe is shown with 3 dimensional model.

(ii) Watershed modelling

A precalibrated catchment of Nepa river was selected for simulation of water balance using Stanford watershed model-IV. Two parameters namely infiltration parameter CB and upper zone nominal capacity UZSN were selected to study the catchment responses namely variations in evapotranspiration, overland flow, interflow, groundwater flow, groundwater storages etc. The model was used to simulate daily stream flow and water balance of the catchment at every weekend over a period of six months.

(iii) Multi objective analysis for optimal reservoir operation

The maximisation of two objectives, namely (i) the net benefits from Irrigation and hydropower use of the reservoir and (ii) the flood space, with the reservoir during the monsoon months was sought to arrive at an optimal release schedule (monthly) for the Girna Reservoir, across river Girna, in Maharashtra.

Constraint method was adopted for the multiobjective analysis. The flood space to be allocated was parametrically varied from zero to 200 million cubic meter (at intervals of 20 MCM) and for each specified value of the second objective, the first objective was optimized. Dynamic programming was adopted for the optimization.

In addition to the objective constraint, the other constraints, to be satisfied were (i) the continuity constraint (ii) the storage constraint and (iii) the irrigation demand. The demand and the benefits per unit of water supplied was considered to be varying throughout the year, in accordance with the crop pattern.

Three sets of inflows, i.e. (i) maximum (ii) mean and (iii) minimum were considered out of the generated inflow data for the next 15 years using the available 16 year record and Fiering's model for future generation of flow.

For each inflow pattern trade-offs were established (i.e., the gain in the first objective per unit loss of the second objective); The various alternatives for specified limits on the second objective) and the trade-off information was passed on to the decision maker; in turn would put some weights on the objectives considering the preferences of the different social groups and then select an alternative at the best. This was a preferred solution and corresponding to this, it was possible to give the trade off information, the net benefits, the release shedule, monthly levels of the reservoir to be maintained, the monthly power production etc. The same problem can be extended to the decision making with Game theory.

(iv) Studies in water resources systems

Tidal estuaries are terminating stretches of rivers, before they join the sea, significant to power resources engineers for their potential for waste disposal, economic navigation and availability of water for domestic and agricultural use. The last usage warrants a through analysis of interaction of seaward freshwater flows and landwards saline tidal flows, and thus determination of space-time distribution of salinity in the reach. The said interaction essentially implies the dispersion of salinity brought by landward sea water. Dispersion has hitherto been studied in tidally-averaged steady-state perspective, or even transient dispersion coefficients derived from steady-state parameters, and the same can't be expected to give accurate salinity distribution in intra-tidal computations. The present study will evolve a fresh formulation of dispersion coefficient freely varying with space and time dimensions of numerical computations, and will thus result in more accurate salinity concentration determination.

2.18 School of Hydrology, University of Roorkee

1. The 13th International Postgraduate Course in hydrology in which 29 trainee officers including 17 foreign nationals from 12 countries participated was completed. 24 trainee officers including 11 foreign nationals were admitted to the 14th International Postgraduate Course.

2. Twenty trainee officers including eleven foreign participants did Master's degree. Mr. H.D. Nautiyal and Mr. D.C. Singhal, Reader were awarded Ph D. degree for their respective thesis 'Flow to a well in Multiple aquifer system' and 'Hydrogeological and geoelectrical studies of southeastern parts of Banda district, U.P.'

3. Dr. Raj Khalil, Assistant Professor of Hydrology, New Mexico Institute of Mining and Technology, Socorpo, USA visited the School as an expert and consultant in water quality modelling under the UNDP/UNESCO project 'Post Graduate Hydrological Educational and Research'. The project ended in Decemer, 1985.

4. Work on 'Study of Sone River Hydrology' sponsored by Sone River Commission was carried out.

5. An educational film on 'Floods and their computations' prepared by Dr B.S. Mathur, Professor and Coordinator was televised UGC programme in the month of July.

2.19 Centre for Water Resources, Anna University, Madras

1. The centre offers courses both at the under graduate and post graduate levels. Presently, two post graduate degree courses of one and a half year duration in the area of hydrology and water Resources Engineering for 10 students and Irrigation Water Management for 16 students (Nine from India and seven from Indonesia) and International post graduate Diploma course of one year duration in Hydrology and Water Resources Engineering for 14 students (10 from Indonesia, 1 from Srilanka, 1 from Nepal and 2 from India). are being offered.

2. Some of the ongoing research and consultancy projects were

(i) Erodability of soils (funded by CBIP)

(ii) Flood routing studies of Indian rivers funded by (CBIP).

(iii) Back water studies for a reach in the river Cauvery near Kattalai for micro power plants (sponsored by Tamilnadu Electricity Board).

3. The centre had conducted the following training programme/workshops

(i) National workshop on "The present state of modelling for managing groundwater aquifers in India" from 15 to 19 April, 1985.

(ii) Two Training programmes on "Improved Irrigation management of Tank Irrigation system in Tamilnadu" 29 April to 3 May, 1985.

4. Two professors of the center for water resources attended the Short course in 'Diagnostic analysis of irrigation system' conducted at WALMI, Aurangabad from 27 May to 6 July 1985.

2.20 Institute of Hydraulics and Hydrology, Poondi

1. Basic and applied research studies in Hydrologic engineering were being carried out on the following problems.

    (i) Stochastic hydrological study of Tamilnadu.

    (ii) Developing rainfall runoff model for Kasathalaiyar basin at Kesavaram Anicut and Poondi Regulator.

    (iii) Infiltration characteristics of catchment.

2. Nine automatic raingauges were installed in the Poondi basin and were being maintained by the research station.

3. Two micro catchments have been created on the hilly slopes of Poondi reservoir. The reservoir is located across river Kasathalaiyar. An ogee weir was used to measure the runoff from the catchment of area 0.0486 sq. km. and another narrow crested rectangular weir is used to measure the runoff from the catchment of area 0.00475 sq. km. Hourly levels of Poondi reservoir were being recorded since October, 1984.

4. A well maintained data room with a DCM 1121 micro-system and IBM 029 key punch are available with the institute.

2.21 Irrigation Department, Madhya Pradesh

1. Most of the Major rivers in central India rise in Madhya Pradesh. With the increase in the population and Industrialization, there is an ever rising demand and river water both from within and outside the State for Irrigation, power development, industry and various other uses. Since the river in peninsular India run full only during monsoon season, dwindling down to in significant streams in the dry season, dams are needed to store surplus monsoon runoff for use in the non-monsoon period. Many dams have already been constructed, since the advent of the five years plan, but many more are needed in the near future so that the valuable water wealth, a scarce natural resource, can be effectively utilized & Irrigation potential of state which is more than 21% by end of VIth plan can be increased to National Level of 36%. The construction of such dams and other hydraulic structures calls for proper and detailed hydrometeorological and Hydrological studies, so that the structures are adequately designed and are also economical.

In accordance with above, a proposal for setting up of Hydrometeorological network in M.P. (phase-I) under World Bank assistance (and 100% reimbursible under I.D.A. credit No. 1177-IN) amounting to Rs. 84,8 Millions was approved by State Government vide memo No. 118/MPS/CP/31/81/110/dtd.15/2/82. The Phase, I proposal includes the following :

1. Etablishment of 225 Ordinary Rainguge Stations.

2. Establishment of 56 New Self Recording Raingauge Stations.

3. Conversion of 111 existing gauge station into current meter discharge stations.

4. Establishment of New 165 current meter Gauge Discharge stations.

5. Establishment of 14 New gauge discharge and silt observations stations.

For implementation of the above grogramme the government of Madhya Pradesh has sanctioned a seperate Directorate along with 4 Dy. Director's office and 12 Nos. Sub-Divisional offices under administrative control of the Chief Engineer (Invn) Irrigation Department (M.P.) Bhopal in year 1982. The complete work is divided into 5 year time slices i.e. 1981-82 to 1985-86 only and functions are also divided into three parts :

1. Procurement of Equipments.

2. Selection of sites.

3. Installation.

(i) Procurement of Equipments :

This part includes the procurement of all essential equipments for setting up of Hydro-meteorological stations, such as ordinary Rain-gauge, S.R.R.G., currentmeter, Wading rod, Measuring reel, Measuring crane, Automatic Gauge Recorder, Boats, Fish weight. Cable way, Echo sounder, 1 Second Theodolite, Distomats, Silt laboratory equipments, Surveying & Station operating equipments, etc. The total cost of the above equipments is about Rs. 2.379 crores and G.O.M.P. has given the permission to purchase vide memo No. 118/MPS/CP/31/81/828 dated 6/11/82 and revalidated to balance every year for procurement of these equipments. The tenders were invited (giving sufficient publicity & biddlng time) on L.C.B. (Local competitive bidding) forms, approved by the World Bank. Most of the equipments were procured. Only few items have to be procured, which are imported and sophisticated in nature like echo sounder, 1 second theodolite, and Distomats, import and out board motor engine etc., These are also in process. This part may be completed before June 1986.

(ii) Selection of sites :

The norms adopted for selection of Raingauge sites are as per I.M.D. i.e.

1.	Ordinary Rain-gauge stations	:	One for every 500sq. km area.
2.	Self Recording Raingaues station.	:	One for a cluster of 10 ordinary raingauge (or in 5000 Sq. Km. area).

For gauge discharge and gauge discharge silt observation station, at present there is no Indian standard for the intensity. Hence normal practice of C.W.C. is adopted i.e.

3.	Gauge discharge stations	:	One for every 750 Sq. Km. of catchment area. However, lateron it was rivised to WMO (World Meteorological Orginisation) norms i.e. one for every 1000 to 1500 Sq. Km. of C.A.
4.	Gauge discharge & silt observation stations.	:	A percentage distribution between gauge discharge station & gauge discharge silt observation station has been adopted as 95% However the same percentage are allowed with the WMO, norms.

As per above norms a detailed report alongwith a separate map for Raingauge & River-gauge stations were prepared and sent to the Director, India Meteorological Department, Poona and Director Central water commission, New Delhi for asking their comments/Suggestions. After receiving the same and incorporating their suggestions, the net work has been finalized by the Chief Engineer (Invn) Irrigation Department M.P. Bhopal and sent to the all basin formation (basin Chief Engineers) for implementation.

(iii) Installation

Most of the equipments required for the establishment of the Hydrometeorological net work has been received and the procurement of the balance is under process and is in various stages and may be completed, during the year, 1985-86. The raingauge & gauge discharge stations to be established have been selected. Typical design & Drawings as well as Typical estimates have been prepared. Some of the sites have been surveyed, some sites finally selected, for which estimates prepared and sanctioned. The following stations have so for been established

(i) New ordinary rainguage starions : 21 Nos.

(ii) New self recording raingauge stations : 2 Nos.

(iii) New gauge discharge stations : 8 Nos.

(iv) New gauge discharge and silt observations station : Nil.

The progress of installation is being constantly reviewed and it is anticipated that sizeable number of stations would be established before June 1986.

The installation maintenance of these stations, will be done under the administrative control of basin Chief Engineers, who will also collect the data of rainfall, gauge discharge and gauge discharge silt observation stations and supply those to the Director, Hydrometeorology for its compilation.

The Director, Hydrometeorology has also taken up compilation of the data of raingauge, gauge discharge stations located in the state,

2.22 Irrigation and Flood Control Department, Manipur

2.22.1 Irrigation

Manipur State, although small in geographical area, has been gifted with immense water resources specially for surface water. An outline plan for Water Resources Development in the State has been formulated. The total surface water resources of the 2 major river basins namely the Barak and Imphal, have been roughly estimated to be 1.8487 Million Hectare Metres in the form of average annual yield against the requirement of 1.1121 Million Hectare Metres for Irrigation, Water Supply and Power Generation upto 2000 A.D. However, the Water potential is very much limited and is estimated to be only about 44 million cubic-meters per annum. Existence of gas pockets is another problem in the extraction of ground water. The State cannot, therefore, rely on ground water resources for irrigation purposes except for limited domestic uses. While the need for harnessing available water resources for Irrigation, Water Supply and Hydro Power generation has always been considered to be very important factor for a State like Manipur, the projects under Irrigation Programme were taken up at a very late stage. It was only in the year 1973-74 when Manipur had attained Statehood that the first Major Irrigation Project namely the Loktak Lift Irrigation Project was started. This is a prestigious project for Manipur and is one of the highest of its kind in the North-Eastern Region. Within a decade, the state has taken up 7 projects under the Major & Medium Irrigation Programme, most of which are now in the advanced stage of construction and some are being completed. Out of the 7 projects now under execution 3 are multipurpose one is major and the remaining 3 are medium irrigation projects. These are Singda Multipurpose Project, Thoubal Multipurpose Project, Khuga Multipurpose Project, Loktak Lift Irrigation Project, Khoupum Dam Project, Imphal Barrage Project and Sekmai Barrage Project. These 7 projects, on completion, will give an ultimate annual irrigation benefit of 1,03,900 Hectares with water supply and power Component for 19 m.g.d. and 9 MW respectively. Besides these 7 ongoing projects, another medium project on Iril river at Dolaithabi having an ultimate annual irrigation benefit of 8000 hectares is being taken up during the Seventh Plan. Formulation of Project Report and Estimate for Chakpi Multipurpose Project is also being completed shortly. Besidees these, there are 15 other projects under investigation. The state irrigation & flood Control Department has also investigated a Medium Irrigation Project on Jiri River under H.E.C. Programme at Jiribam which will benefit 8000 Hectares.

By 2000 A.D. the state may be able to

create a total annual irrigation potential to the extent of 1,59,000 Hectares under Major & Medium Irrigation Programme. Over and above this, water supply system will be augmented to the extent of 45.5 m.g.d. and also provide hydro power for a total installed capacity of 47 MW from the Multipurpose Proiects under Major & Medium Irrigation Programme. By the season ending 1984-85 cumulative annual irrigation potential to the extent of 40,000 Hectares has been created from the ongoing projects and partial storage has been created in Singda Dam for supply of 1.5 m.g.d. Additional irrigation potential of 9,700 Hectares has been created during 1985-86. It is expected that during the Seventh Five Year Plan, additional irrigation potential for 23,900 hectares may be created and we shall be able to provide water supply facilities to the extent of 4 m g.d.

2.22.2 Flood Control

Flood Control has been a major worry for the State. Due to the geographical position of the State, rapid concentration of heavy rainfall in the catchment area and deforestation in the upper reaches has subjected the valley to frequent heavy floods, damaging crops and properties. While the construction of multipurpose reservoir projects on the upper reaches of major rivers would be able to moderate the flood to a great extent, the State Government has been executing flood control measures like construction of new embankments, strengthening of the existing ones, construction and improvement of drainage channels, construction of sluices etc. The State Government has also started formulation of a Master Plan on Flood Control as well as river-wise Flood Control Projects as long term measures.

The Merakhong Flood Control Project, having an estimated cost of Rs. 1.16 crores, has been sanctioned by the Planning Commission and is now under execution. Another Flood Control Project on Wangjing River has also been cleared by the State Technical Advisory Committee and State Flood Control Board and the State IFC Department is taking action for obtaining the sanction of the scheme early. Riverwise Flood Control Prjects for other major rivers such as Imphal, Iril, Thoubal, Nambul etc. are also under preparation and being taken up in a phasewise manner.

The total expenditure on Flood Control upto the end of Sixth Plan was Rs. 912.55 lakhs. The approved outlay for Seventh Plan is Rs. 500 lakhs. An Amount of Rs. 130 lakhs has been allotted for 1985-86 and Rs. 115.10 lakhs has been spent. The amount earmarked for 1986-87 is Rs. 140.00 lakhs,

3. NEWS

3.1 First Meeting of National Water Resources Council

The National Water Resources Council was set up under Government of India Resolution No 6/1/79-pp dated 10th March 1983. The functioning of the Council as set forth in the Government resolution included "to lay down the national water policy and review it from time to time". The first meeting of the Council was held at Vigyan Bhawan, New Delhi on 30th October 1985 under the Chairmanship of the Prime Minister, Shri Rajiv Gandhi.

In his address, the Prime Minister and the Chairman of the Council, after welcoming the Chief Ministers and Members of the National Water Resources Council, stated that many problems in India centered around water. On account of the variations in precipitation in space and time, some parts of the country received too little rainfall while the others received considerably more, resulting in the occurrence of droughts and floods in different parts of the country. In irrigation, although tremendous strides had been made, the problems of water logging and salinity in the irrigated areas had arisen. The Prime Minister felt that the precious resource of water was not being used to the best of our ability, and that so far there was no specific policy for the use of water, nor was there proper coordination. He further stated that there were inter-state problems regarding the sharing and allocation of water. The quantum of water being used so far was about 40% of the utilisable resources, but with the increasing demand for water for various uses, the utilisable water resources were likely to be more or less fully utilised by the turn of the century. On account of the increasing demand from industries, the present balance in the utilisation of water was likely to shift during the next 10-15 years. It was, therefore, absolutely necessary that water should not be wasted as was happening at present in irrigation systems through over-irrigation, and in urban water supply through leaking taps and through a lack of a sense of economy in the use of water. In this connection he cited the example of other countries where water was being used both for agricultural and industrial purposes far more economically than in India. He felt that the importance of this precious resource had not yet been fully realised in the country.

The Prime Minister further stressed the need to adopt an integrated approach in planning for the development of water resources right from the watershed and suggested that a complete monitoring of the use of water was absolutely necessary. He further suggested that it might be necessary to modify existing agricultural practices to suit the avaliability of water by changing cropping patterns and the crop calendars. The question of recycling and re-use of water also needed to be examined. He also emphasised the importance of formulating a plan for the utilization of water for various purposes; such a plan in his opinion should not be constrained by artificial barriers like State boundaries, but should aim at the maximum good of the country as a whole, though the reasonable present and future needs of the States should certainly be taken care of. In this connection he also drew attention to the neglect of water transport and inland navigation which was the cheapest mode of transport particularly for bulk goods. He, therefore, stressed the importance of laying down a constructive national water policy for the optimal utilisation of water. He expressed the hope that the deliberations at the first meeting of the Council would mark an important stage in that direction and wished the meeting all success.

3.2 Address of Shri B. Shankaranand Hon'ble Union Minister for Water Resources at the Sixth Annual General Meeting of National Institute of Hydrology Society. 15th November, 1985.

I am very happy to be present here this morning and welcome you all to the Sixth Annual General Meeting of Ihe Society. The Ministry has now been renamed as "MINISTRY OF WATER RESOURCES" to achieve the effective coordination of all the water related activities. It is imperative that in the Society for NIH also we reorient our policies and programmes so as to deal with all the water resources in an integrated manner.

A couple of days back the first meeting of National Water Resources Council has taken place, when we have taken stock of the large number of issues connected with the development of water resources. Efforts are already afoot to evolve a national water policy. I am happy to inform you that there has been a large measure of consensus for treating water as a national asset and for developing its uses in an integrated manner. It is in the light of the deliberations at the meeting of the National Water Resources Council, that the Society will have to redefine its goals and plans of action.

Water is our most precious natural resource. Though India is endowed with substantial water resources, on account of limitations of physiography, topography, geology, dependability and the present state of technology, only a part of this can be utilised. Indications are that we will not be able to provide irrigation to more than 50% of our agricultural land, even after developing all the feasible reservoirs. As such, the water available for the country will have to be very carefully used. Water is used not only for irrigation, but it is also an important resource for hydroelectric power generation, inland navigation, industrial processes and domestic purposes. Efficiency in water use is of paramount importance. There is, therefore, a need for use of modern scientific techniques like remote sensing, mathematical modelling, digital computers and the systems approach so as to improve our planning, design, construction and operation of the water resources. I wish the Society's National Institute of Hydrology becomes a forerunner in adopting the latest modern techniques in the field of water resources.

India's vast water resources are unevenly distributed in time and space. Severe droughts and heavy floods are quite common. They can occur at one and the same time in the different parts of the country or may occur at the same place in the different periods of the Hydrologic year. But we have tended to develop water resources without a clear understanding of the effect of vegetal cover, and land use characteristics on the hydrologic processes. Our country has a variety of physiographic and climatic conditions widely different from each other e.g. we have very high snow covered mountains and also the low lying coastal areas and islands. We have thickly wooded forests and also completely barren areas. We have very big rivers with large catchments as also small flashy rivers. We have also highly developed river basins as also nearly virgin river basins like Narmada. Hence it would not be correct to generalise any practice and make it applicable to all regions. Proper scientific studies of the hydrologic processes in areas of differing characteristics are essential to understand the processes in a clearer manner and to develop appropriate methodologies for dealing with water of that region.

Most of our planners involved with the preparation of water resources projects are not able to prepare comprehensive proposal due to the limited data. We have to remember that our data base is not as extensive as that in the advanced countries where data collection activities have continued over centuries. The sophisticated technology developed by the advanced countries generally assume availability of adequate data base and may not fit in exactly in the Indian context. Though we are making efforts to establish additional gauging station throughout the country, it will take sometims to improve the data base. Hence we will have to develop suitable techniques and methods for planning of our projects on the basis of limited data for different regions.

It is, therefore, necessary to undertake urgently representative basin studies in the different regions of our country to understand the interaction of the various components of the hydrologic cycle. Through these representative studies, the National Institute of Hydrology should make efforts to suggest scientific regional formulae for estimation of water resources and floods in different regions. By the end of the 7th Plan we should be able to develop formulae besides the existing empirical formulae which ware developed over a century ago on the basis of very limited data available then. I would suggest that the Institute should give an overriding priority for this work, and rationally define and state appropriately the relationship between the different contributary factors and the end result of a hydrologic phenomenon—may it be the annual runoff, sediment load, flood peak or the evaporation losses.

During my last visit to the Institute I had emphasized that the Institute should take effective steps to develop regional centres for studying specific hydrologic problems of the different regions in the country. I understand that the Institute has already made some efforts in this direction. But no regional centre has yet been established. I would, therefore, like to stress once again that the Institute should take up the regional studies without further delay.

I had also emphasized the urgent need for improving the methodologies for predicting the calamities like droughts and floods. I find that the Institute's Annual Report does not yet reflect adequate concern for the issues. I would suggest greater attention to these areas of study.

Huge amounts are being invested in the construction of irrigation and hydroelectric projects. We have to make efforts to maximise the benefits from these projects. It has not been possible to account properly all the water handled through these projects because of the gaps in our knowledge. Large unaccounted quantities of water are just taken as a loss. A proper scientific account of water of our river valley projects is necessary. The Institute should direct itself to this problem and may adopt a few projects from different regions to develop methodologies for water accounting in scientific manner. The Institute should also take the initiative of its own and approach the project authorities rather than wait for a reference from the project authorities.

Environmental considerations and attention to the water quality in our streams have gained considerable importance recently. Through the initiative and guidance of our beloved Prime Minister, an ambitious project for cleaning the Ganga River has been already taken up. Similar projects for other rivers will be necessary. Since the quality of water in the streams closely linked with the quantity of flow, the Institute will have an important role to play in this area. We have to reveiw the Institutes set up and programmes of activities to see if the Institute is equiped or is trying to get equiped for meeting these new challenges.

In the management of the rivers, quality of flow and the quantity of flow cannot be separated. Both ought to be dealt with together. The Institute will have to develop appropriate methodologies for the different river basins for securing a coordinated effective management To this end the Institute will have to bring together the different organisations we have been so far working separately in isolation e.g. the organisation controlling the discharge of effluents into the streams, the organisations monitoring the quality of the stream flows and the organisations managing the quantities of river flows will have to sit together and decide upon the future strategies. Let the National Institute of Hydrology play a catalytic role in this context.

The interaction proposed by the Institute with the State Governments and the Institute's involvement in the solution of their field problems is a step in the right direction. It is encouraging that Hon'ble members from the States are participating in this meeting.

It is necessary that besides working for improvement of methodologies and technologies for field use, the Institute should continue to work in frontier areas also. With the accelerated pace of development in the country, the problems that will be encountered in future will be more complex and the Institute should be well prepared and equiped to meet the new challenges. I am glad to note that the Institute is establishing its own laboratory. I feel that during the 7th five year plan period, the activities of the Institute would also gain momentum so that it can contribute significantly to the development of water resources of the country.

Jai Hind

1985 'OLYMPIA' AWARD TO K.K. FRAMJI

K.K. FRAMJI

K.K. Framji, the Secretary-General of the International Commission on Irrigation and Drainage, has been awarded the 'OLYMPIA' PRIZE FOR 1985. The 'OLYMPIA' Prize (Man and his Environment) is conferred by the Alexander Onassis Public Benefit Foundation of Greece annually on persons or institutions who have made a notable contribution to the preservation of nature or the safeguarding of our cultural inheritence or scientific progress connected therewith. Framji gets this award for his important contribution in world-wide efforts for the protection of the Environment, and more especially, for his activities in promoting the important changes in the concepts of water resources planning on our planet. The Prize is US $ 100,000, which he shares ithw world renowned Royal Academy of the Netherlands for their complete and authentic edition of the works of Erasmus.

"Man and humanity are at the core of the interest of the three International Prizes awarded by the Foundation, *thus constituting, after the Nobel Prizes,* the only other distinction of such magnitude putting emphasis on the all-round humanistic approach to man's problems and fate."

An independent International Awards Committee comprising pre-eminent professionals from different walks of life and different countries, such as the former World Bank President Mr. Robert McNamara; Mr. Hammarskjold Knut, Director General of I.A.T.A.; Monsieur Ahrweiler Gllykatzi Helene, Professor and Rector of Paris University; and Mr. Georgakis Ioannis, Honorary Professor, Ambassador H.C., are amongst its members, and the International Committee's selections are approved by the Boards of Directors of the Foundation with Mme. Christina Roussel (nee Onassis) as president and fourteen other high Greek dignitaries as members.

Such eminent personalities as Sir Harold MacMillan, former Prime Minister of United Kingdom (1979), the International Union of Conservation of Nature (IUCN) (1980), Prince Sadruddin Agha Khan (1982) and Dr. Dillon Ripley, Secretary of the Smithsonian Institution (1984), were the previous laureates of the 'OLYMPIA' Prize honoured by awards of the Foundation.

Framji is an eminent Indian Water Resources Engineer of International repute. He has extensively contributed to the International community for over two decades by promoting the economic use of natural waters through scientific management to enhance the world-wide supply of food and fibre for all people. His policy as Secretary-General resists the implementation of the "trickle down theory" where a self-sufficiency in production of grains and food restricted to the DEVELOPED Countries, who would export the surpluses to DEVELOPING Countries having scarce foreign exchange to be able to afford the cost of the imports. He urges a policy of complementarity of vigorous, development of water resources with progressive (but hastening slowly) anti-pollution, anti-erosion measures. He views the urgent needs of food of the developing countries (DCs) in the field of water resources development in global perspective in that the developed countries can greatly assist the DCs with their resources, transfer of knowledge, expertise and experience in optimum management, conservation and utilisation of water resources.

Framji's eminence in the field of irrigation has already been recognized by grant of quite a few awards in the early part of his career and the recent past, the notable ones being the M.B.E. from U.K. (1943), the ISI Award of K.L. Moudgill Prize (1979) for distinguished services for over two decades in advancing the discipline of standardization of liquid flow measurements at both national and international levels, and 'Chevalier du Merite Agricole' (1982) of the Government of France for his distinguished services in the cause of agriculture.

The profession and the international irrigation community recognise Framji not only on account of all the above, but also for his ably steering the affairs, as the Secretary-General for over 20 years, of the International Commission on Irrigation and Drainage (ICID), which was established in India in 1950. ICID honoured him recently by inviting him to deliver the Second Gulhati Memorial Lecture for International Cooperation in Irrigation in 1984 at the 12th ICID Congress in Fort Collins, U.S.A.

The Alexander S. Onassis Public Benefit Foundation Awards and Prize Winners were announced at a Press Conference in Paris on 28 March, 1985.

ESTIMATION OF AREAL RAINFALL

By

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1. Introduction :

Rainfall over a region varies both in time and space. Averages taken over a temporal data set provide normals, whereas those taken over the observations recorded at various points in a region give the volume of water fallen during a particular rainfall event. Hydrologists are generally interested in second type of averages which is termed as areal rainfall. In absolute sense, areal rainfall over an area $A(R_A)$ may be given as

$$R_A = \int_A R(x, y)\, d_A$$

Where $R(x, y)$: point rainfall recorded at location (x, y) of the given area.

Practically, R_A is estimated by averaging point rainfall values observed at n raingauge stations. Error in this estimation depends upon n. To minimise the error, n should be very large. But due to the limitation of resources required for maintenance of a very large number of raingauges in an area, one has to manage with an optimum network density of the raingauges which provides a satisfactory estimate of areal rainfall. The evaluation of network density itself is a complicated problem because of the following reasons.

(i) inter-relationship between rainfall series recorded at two places.

(ii) uneven topography.

(iii) interpolation techniques.

(iv) scarcity of long term rainfall observations.

This problem will be discussed in Sec. 5 after summerizing the various techniques available for the estimation of areal rainfall.

2. Methods :

(i) Arithmatic Mean : If over an area A, n point observations of rainfall are available, the areal rainfall is estimated by

$$P_A = \frac{1}{n} \sum_{i=1}^{n} P_i$$

This technique gives fairly satisfactory estimates of P_A if the area has good network density and the raingauges are uniformly distributed over the area. For mountainous terrain, this method is generally not recommended.

(ii) Weighted Mean : If the i th raingauge represents an area A_i, P_A may be estimated by

$$P_A = \frac{1}{A} \sum_{i=1}^{n} p_i A_i \quad \text{where } A = \sum_{i=1}^{n} A_i$$

There are a number of techniques suggested for the evaluation of weights A_i under different conditions.

(a) Thiessen Polygon : Wher the distribution of raingauges is not uniform over the area

A, this method may be applied. Here we assume that the weight alloted to the i th observation P_i in the area enclosed by a polygon which is constructed by the perpendicular bisectors of the lines joining the i th station with all the neighbouring stations, The area in each polygon is practically evaluated by using planimeter. The method is again not suitable for mountaineous regions. But it has an advantage in the sense that the information contained with the stations lying outside the region also become available.

(b) Isohyetal Method : In this method, all the point rainfall recorded inside the region and the neighbouring stations are plotted on a suitable map of the area and the isohyets (lines of equal rainfall) are drawn freehand taking into consideration orography and storm orientation. In this case the isolines should run parallel to mountain ranges and should usually be elongated along the storm track. The area between two consecutive isohyets is taken as the weight to the mean isohyetal value within the enclosed area. Though a bit of subjectivity is involved in the isohyetal analysis, this method is generally more useful than other methods. It has least estimated error and is not much affected by missing observations. Orographic features are partially taken care of in the analysis itself.

(c) Isopercental Method : This method is more appropriate for mountaineous terrain than those described earlier. Here instead of point rainfall, ratios (expresed in %) of observed rainfall to the normal seasonal rainfall at all locations, are plotted on a suitable map and isolines are drawn, the idea in this method is to involve influence of orography into the feature of rainfall events. Further computation procedure is similar as that in the isohyetal method.

(iii) Polynomial Method : These methods may be applied when quick results are desirable, e.g. in catchment modelling. The weight alloted to each station is considered as the function of their location and network density. But the technique needs periodical verification of the results by comparing with standard method.

The polynomial method is based on the presumption that the point rainfall (R) can be expressed as a polynomial function of its location vector (x, y). As an example, assuming a second degree polynomial

$$R = a_1 x + a_2 x^2 + a_3 xy + a_4 y + a_5 y^2 + a_6$$

In a third degree polynomial there will be ten constants which can be estimated by

(i) solving a system of n equations obtained by computing volume of rainfall over a given regular area

(ii) by minimising sum of the squares of residual i.e.

$$\Sigma \left(R_{\text{Computed}} - R_{\text{Observed}} \right)$$

3. Concept of Correlation Structure :

If the rainfall series recorded over two stations has significant correlation, the information of one station is contained in the observation of the other. Hence, the evaluation of correlation structure of an area is important. From a catchment having n stations, n_{C_2} correlation coefficients can be derived. It has been found from the studies conducted by various researchers (Rodriguez, 1974; Kagan 1972, Ramanathan et.al 1981) that the correllation r(s) decreases as the distance (s) between two stations increases. It may follow exponential law

$$r(s) = r(o)\, e^{-s/s_0}$$

in most cases, where S_0 is theoretical distance at which correlation reduces to r(o)/e.

's' itself is a random variable following a distribution function f(s). The form of f(s) has been derived by some authors Eagleson (1967).

Thus the mean correlation of rainfall field is given by

$$\overline{r} = \int_{O}^{L} r(s)\, f(s)\, ds$$

Where L is the maximum possible distance between two stations. This concept can be used in

(i) estimating areal rainfall from point rainfall.

(ii) determining optimum network density.

(iii) Interpolating missing observations and generation of data

Upadhyay etal (1982) suggested the relationship.

$$R_A = R_O\, \overline{r}^{\,e}.$$

4. Error of Estimation :

Kagan (1966) showed that in estimating mean rainfall over an area 'a' with one station at the centre the variance of estimate can be given by

$$\sigma_1^2 = \sigma_0^2[1 - r(o) + .23\sqrt{a}/S_o]$$

If there are n stations distributed evenly over an area A (A=na), then

$$\sigma_n^2 = \frac{\sigma_o^2}{n}\left[1 - r(o) + .23\, \frac{\sqrt{A}}{S_o\sqrt{n}}\right]$$

where σ_o^2 is the variance of point rainfall. r (o) can be theoretically estimated by r—s plot.

We illustrate this exercise with the following fictitious data. Catchment area (A) = 10,000 Sq. Km.

No. of evenly distributed raingauge (n)=5

a=2000 Sq. Km.

From the past records at such stations it has been calculated that the pooled variance of annual rainfall in the catchment=25 Cms. Mean annual rainfall as recorded over 5 stations = 20 Cms.

The correlation structure as obtained from 5_{C_2} (=10) values of r is

$$r = 0.8\, e^{-s/100}$$

Therefore r(o)=0.8 and S_o=100.

It can be seen that σ_n^2=1.5

Therefore σ_n=1.2, C.V.=6%

5. Network Design :

Designing of network is required for 3 specific purposes.

(i) Climatological or water-balance studies

(ii) Flood forecasting

(iii) Weather modification evaluation

In general, the variance (e^2) of estimate of areal rainfall can be expressed as a function of location vector q, number of observation point n and weight factor W. Thus, we can write

$$e^2 = f(q, n, w)$$

The design of optimal network consists of minimizing the function f. This is normally done in two stages i) for fixed weight w, f can be minimised with reference to q and n, i.e. keeping $w = \frac{1}{n}$, obtain the values of q and n say q* and n* for which f is minimum. We can now minimise f' (q*,n*,w) with reference to w. This can be done by solving for w_i, the system of equations

$$\frac{\partial f'}{\partial w_i} = O$$

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ARTIFICIAL MODIFICATION OF PRECIPITATION

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1. Need for Artificial Modification of Precipitation

Water is an essential element for, inter alia, human consumption, agricultural purposes and non-polluting methods of power production. In the near future with the growing world population, the problem of water resources required to support the human race may well assume similar proportions to the problem of energy resources.

In some parts of the world withdrawals of water from underground storage have exceeded the natural recharge during the past 2 to 3 decades. In some areas withdrawals of water from underground storage resulted in the rapid fall (10 to 15 m/yr) in the water tables and in some agricultural zones intrusion of seawater into the aquifers has caused a decrease in water available for irrigation. The above situation has become more acute during the years of monsoon failures.

The principal means of conventional water augmentation are (i) re-use of waste water, (ii) desalination of water (iii) reforestation for enhancement of convective precipitation by mesoscale variations in vegetative covering in semiarid regions (Anthes, 1984) and (iv) rain stimulation. Items (i) and (ii) are based on water treatment and distribution technology which are at present uneconomical in view of the huge cost involved in the operations. Items (iii) and (iv) are less direct in outcome. The rain stimulation through artificial modification of clouds is the only one of the unconventional approaches which is promising and at increasing the volume of water falling on the surface and helps in the augmentation of both surface run-off and ground-water recharge.

The physical basis for the formation of clouds and precipitation and the scientific status of rain stimulation from warm and cold clouds are reviewed in this paper.

2. Formation of Clouds and Precipitation

Cloud droplets are formed around microscopic particles consisting of dust, smokes, salt crystals, soil and other materials which are always present in the atmosphere. These particles are generally known as cloud condensation nuclei (radius range 0.01—0.1 μm). Among these particles in the atmosphere there are a few special kinds known as ice nuclei on which cloud droplets freeze or ice crystals form directly from the water vapour. Generally there is an abundance of condensation nuclei in the air but a scarcity of the special ice-forming nuclei. The sizes, types and concentration of the nuclei present in the atmosphere play an important role in determining the efficiencies with which a cloud system forms and ultimately produces either rain or snow.

Clouds are made up of billions of these tiny water drops (~ radius 10 μm) or ice crystals (length 0.5 mm), sometimes combinations of both. The cloud droplets are so small that it may take a million or more to produce a single raindrop (~ radius 100 μm). There are two types of clouds, cold and warm. The clouds with their tops below the freezing level or 0°C level (3.3 to 5.4 km a.s.l.) in the atmosphere called 'warm clouds'. The clouds with their tops extending above the freezing level are called 'cold clouds' or supercooled clouds. In these clouds water droplets can exist at temperatures lower than 0°C and these droplets are called 'supercooled droplets'.

There are two basic mechanisms by which precipitation forms in clouds. These are sometimes called warm rain and cold rain processes. Warm rain process takes place in warm clouds and cold rain process takes place in cold clouds.

In warm clouds rain is formed when larger drops (~ radius 50 μm) collide and collect smaller cloud droplets through a process known as coalescence. Giant size (radius $r > 1$ μm) nuclei mostly composed of sea salt absorb water from the atmosphere and transforms into a cloud drop.

In cold clouds both ice crystals and supercooled water drops are present. The ice crystals grow rapidly drawing moisture from the surrounding supercooled cloud drops due to the difference in saturation vapour pressure over the ice crystals and the supercooled cloud drops. Bergeron in 1933 pointed out the importance of this process in the formation of precipitation in cold clouds. Some ice crystals grow into snow-flakes solely by continued sublimation but snow flakes grow in part by overtaking cloud drops which then freeze on collision. When the ice crystals attain the size of a few millimeters they fall under the influence of gravity. These falling ice crystals may melt and join with smaller liquid cloud droplets, growing to rain drops in a manner similar to warm rain process. If the ice crystals do not melt they may grow to large snow flakes by agglomeration and reach the ground as snow. The major types of precipitating elements, and the physical processes through which they originate and grow are shown in Figure 1 (Braham, 1975).

3. Physical Aspects of Artificial Precipitation

3.1 Warm Clouds

The sizes, types and concentration of nuclei present in the atmosphere play an important role in determining the efficiency with which a cloud system forms and ultimately produce precipitation. For instance, salt crystals acting as giant size condensation nuclei are abundant in the oceanic regions. These allow larger cloud drops to form and subsequent coalescence process initiates rainfall well within the life time of the clouds. The growth of rain by the collision-coalescence mechanism can be stimulated by the introduction of giant size hygroscopic particles or water drops into warm cumulus clouds. The introduction of water drops into the tops of the clouds it not a very efficient method for producing rain since large quantities of water are required to be carried by aircraft. A more efficient technique is to introduce hygroscopic particles (like salt particles) into the base of the cloud, these may grow by condensation and then by the collision-coalescence process.

An exciting aspect of the coalescence process with enormous effect on warm cloud modification is the so called 'Langmuir Chain Reaction'. According to this concept, drops can grow by coalescence until they reach a size at which they become unstable and break-up into smaller fragments (Langmuir, 1948). Each of these fragments in turn can grow by coalescence until the unstable size is reached and it too disintegrates. This process may continue

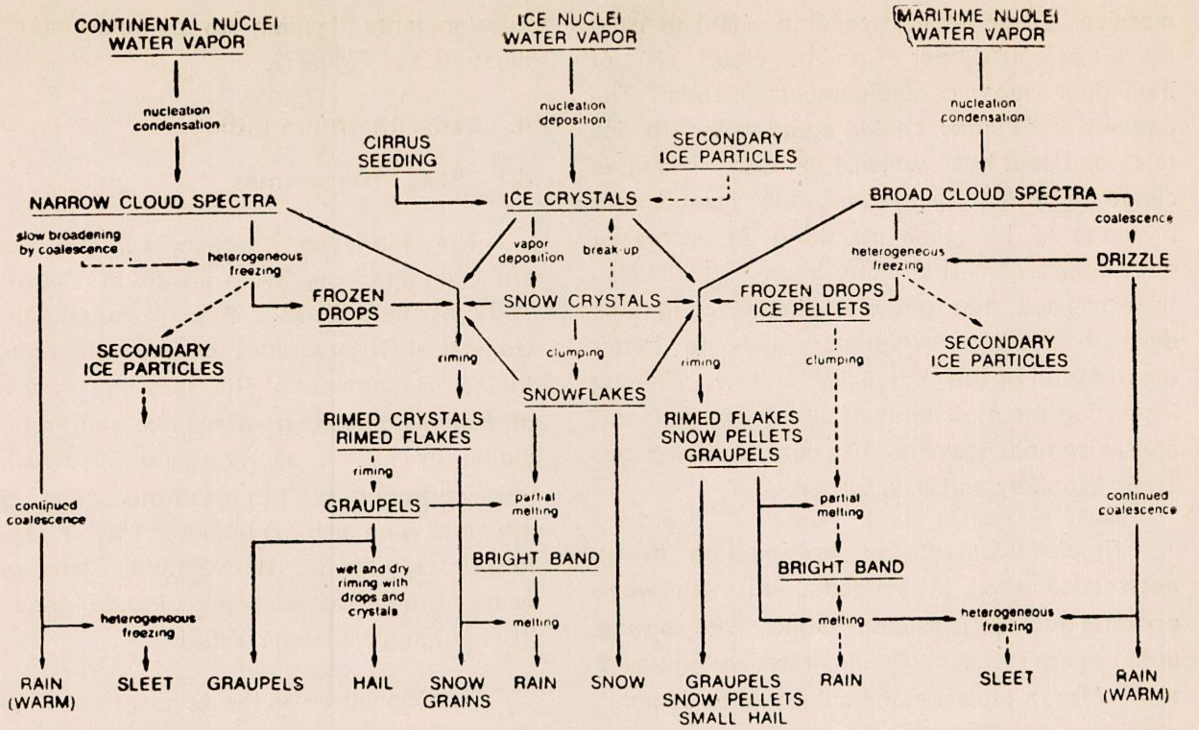


Figure 1 : Major types of precipitation elements and the physical processes through which they originate and grow (after Braham, 1974)

several cycles. Langmuir noted that high vertical velocity is the primary necessary condition for the purpose. High liquid water content is also important. The chain reaction is also dependent on the size distribution of the fragments resulting from drop break-up. Salt seeding experiments carried out in isolated warm clouds at South Dakota, USA, showed that rain formation could be accelerated through Langmuir chain reaction mechanism (Biswas and Dennis, 1971, 1972).

The progress made in warm cloud modification is very slow. Historically ice phase seeding was discovered first and has been practised more extensively. More attention should be drawn towards warm cloud seeding because of its potentialities for drought mitigation in tropical countries like India (Ramana Murty, 1984).

3.2 Cold Clouds

3.2.1 Static Approach

Precipitation enhancement efforts from supercooled clouds rest upon the hypothesis that there is deficiency of ice crystals and this deficiency can be corrected by the introduction of artificial ice nuclei like Silver Iodide to produce ice crystals. Conventionally, it is considered that one nucleus per litre or cloud air is required for an efficient precipitation process. Since the discovery of the ice nucleating property of Silver Iodide in 1946 by Dr. Bernard Vonnegut, numerous attempts were made notably in Israel, Australia, and USA where significant increases in precipitation on seeded days were noted (Hess, 1974; Gagin and Neumann, 1980; Smith et al., 1979; Simpson, 1976; Braham, 1979; Hsu and Huff, 1985).

3.2.2 Dynamic Approach

An alternate approach to cloud seeding for precipitation enhancement is directed at the buoyancy forces and circulations that sustain the clouds. This method is known as 'Dynamic Cloud Seeding'. This approach involves massive Silver iodide seeding (100 to 1000 nuclei at—10°C per litre of cloud air) of individual super cooled cumulus clouds. The conversion of super cooled liquid water to ice releases latent heat which, in turn, increases cloud buoyancy, invigorates the cloud and prolongs its life time resulting in increased convergence at the cloud-base. It is also hypothesised that under optimum conditions dynamic seeding eventually leads to better organisation of the low level inflow, thereby increasing the probability of cloud merger and area-wise enhancement of rainfall (Simpson, 1976; Woodley and Sax, 1976).

The developments of precipitation in (i) not-seeded cloud, (ii) seeded cloud with weak updrafts and (iii) seeded cloud with strong updrafts are respectively illustrated in Figures 2 to 4. Also, a typical cloud subjected to dynamic seeding in the Florida region and the progressive developments leading to cumulonimbus are illustrated in Figure 5.

4. Experiments in India

4.1 Past Programmes

The pioneering attempts in the field of artificial rainmaking were made at Calcutta in 1952 by Late Dr. S.K. Banerji, retired Director General of Observatories of the India Meteorological Department. The technique consisted of dispersing seeding agents like salt and Silver Iodide by means of Hydrogen filled balloons released from ground to reach the clouds. Some attempts were also made in 1951 by Tata firms to seed clouds in the Western Ghats region using ground-based Silver Iodide generators (Banerji and Mukherji, 1955).

The Committee on the Atmospheric Research of the CSIR recommended in 1953 that a Rain

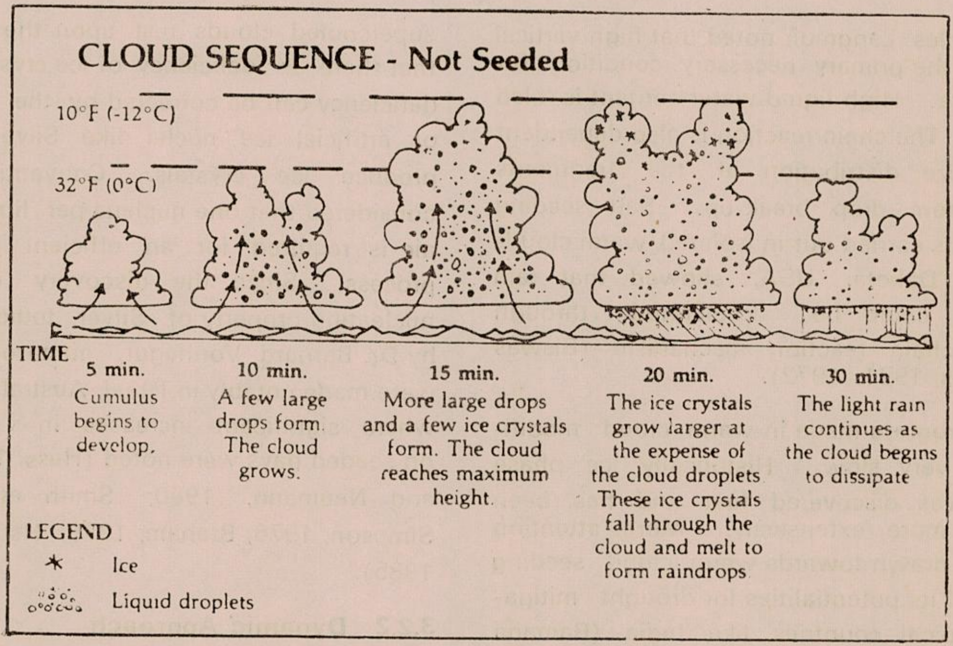


Figure 2 : Precipitation development in a not-seeded cloud

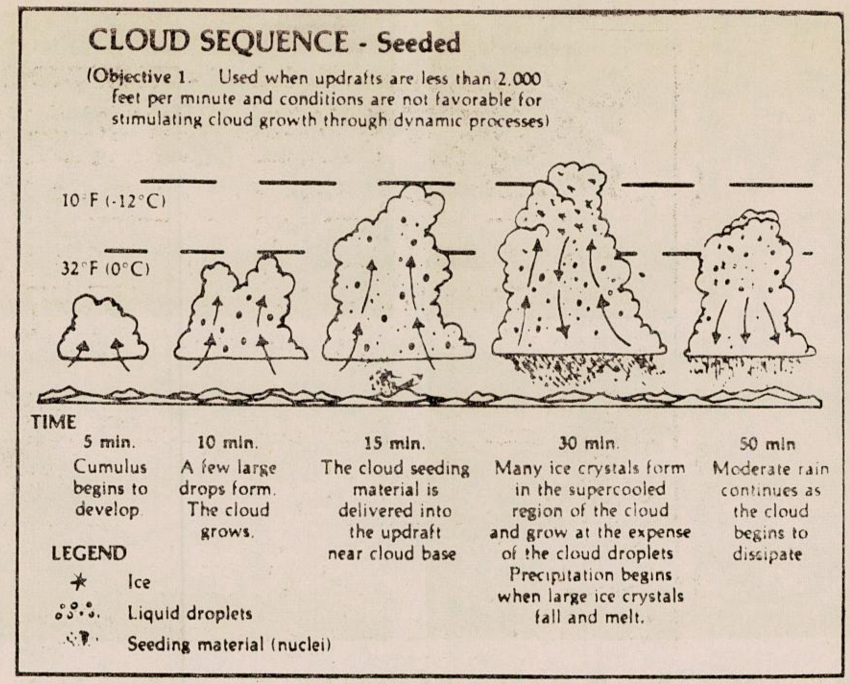


Figure 3 : Precipitation development in a seeded cloud with weak updrafts. Such clouds are not suitable for dynamic seeding

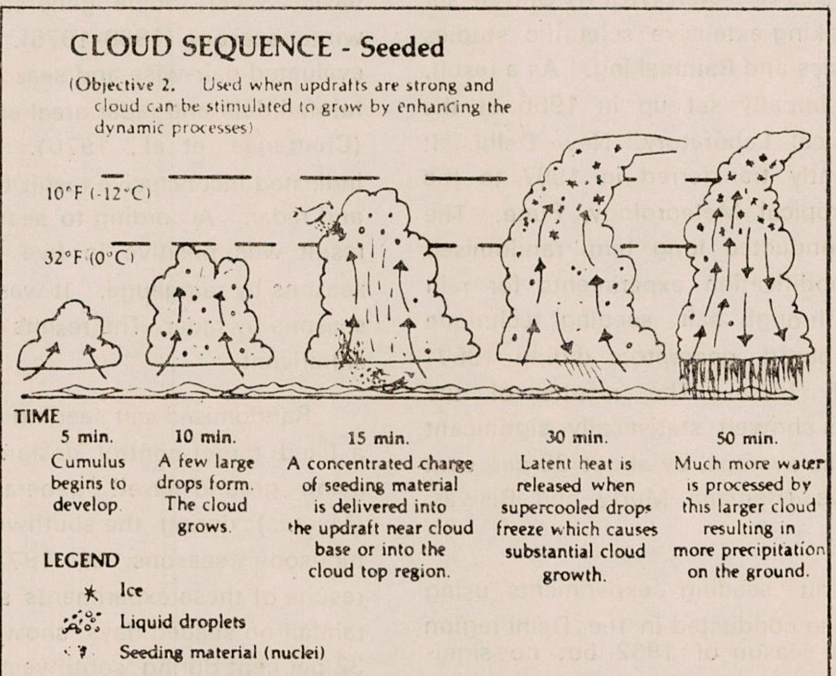


Figure 4 : Precipitation development in a seeded cloud with strong updrafts. Such clouds are ideal for dynamic seeding

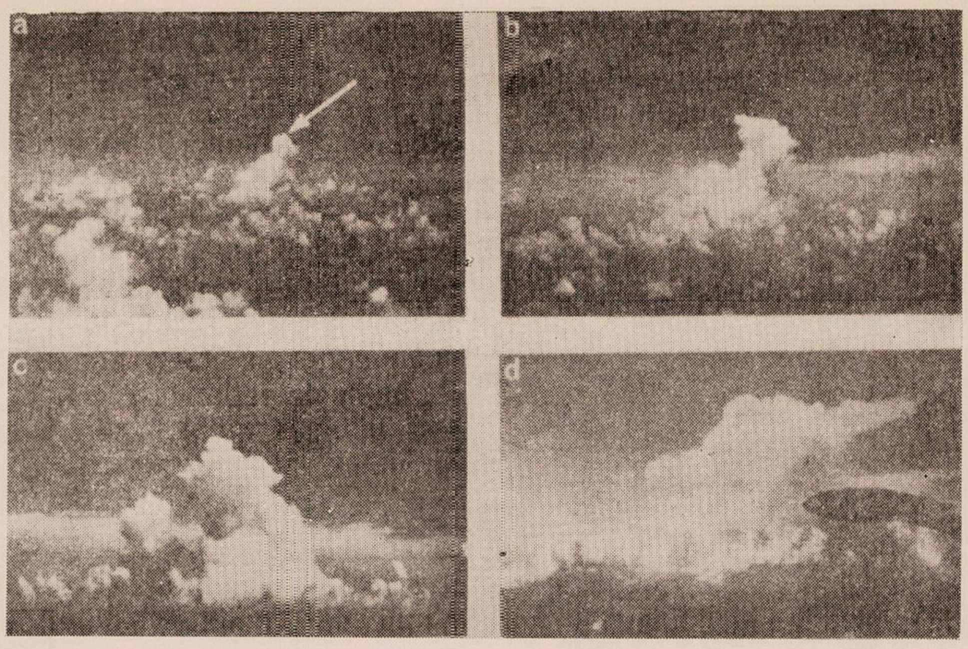


Figure 5 : The "explosive" growth of a cumulus cloud following seeding with Silver Iodide. (a) A typical cloud shown by the arrow chosen for dynamic seeding in Florida, USA; (b) 9 minutes after seeding; (c) 19 minutes after seeding; (d) 38 minutes after seeding when the cumulonimbus is fully developed (Photo : Dr. J. Simpson)

and Cloud Physics Research (RCPR) Unit be set up for undertaking extensive scientific studies on Cloud Physics and Rainmaking. As a result, the Unit was initially set up in 1955 at the National Physical Laboratory, New Delhi. It was subsequently transferred in 1967 to the Institute of Tropical Meteorology, Pune. The RCPR Unit conducted long term randomised warm cloud modification experiments for rain enhancement through salt seeding technique using ground-based generators during 1957-1966 in north India. The results of the rainfall analysis showed statistically significant increases, on the average, by about 20 per cent on seeded days (Ramana Murty and Biswas, 1968).

Limited salt seeding experiments using aircraft were also conducted in the Delhi region in the monsoon season of 1962 but no significant results were obtained.

Also, cold cloud seeding experiments were undertaken in the Delhi region using ground-based Silver Iodide generators during seven winter seasons (1968-1975). The results were evaluated pair-wise and season-wise using the rainfall data and radar areal echo coverage data (Chatterjee et al., 1976). Pair-wise analysis indicated inconclusive result both by raingauge and radar. According to season-wise analysis, result was positive in five out of the seven seasons by raingauge. It was positive in three seasons by radar. The results are not statistically significant.

Randomised salt seeding experiments with a fixed target-control design were conducted using ground-based generator at Tiruvallur (Madras) during the southwest and northeast monsoon seasons of 1973, 1975-77. The results of these experiments suggested that the rainfall on seeded days showed an increase of 32 per cent during southwest monsoon and a decrease of 17 per cent during the northeast monsoon season. The results are not statistically significant. The experiment was subsequently discontinued due to operational difficulties (Pillai et al, 1981).

The effect of massive salt seeding on warm maritime cumuls clouds was studied. A few clouds were seeded using aircraft within 50 kms off the coast at Bombay during the monsoon seasons of 1973 and 1974. During these experiments radar and in-cloud electrical, microphysical and dynamical observations of seeded (target) and not-seeded (control) clouds were made (Chatterjee et al., 1978). The radar observations indicated increases in areal echo coverage, vertical extent and echo intensity following the release of salt particles into the clouds. The variations noticed in the electrical, microphysical and dynamical conditions of clouds following seeding are consistent with the warm cloud modification hypothesis.

4.2 Current Programmes

The salt seeding experiment referred to earlier was conducted in north India during 1957-1966 using ground-based salt seeding generators. Evcn though the experiment was statistically well designed and the result obtained was statistically significant at less than 0.5 per cent level, physical evaluation could not be carried out for lack of cloud physical observations. In view of this limitations, as well as for precise targetting of seeding material, a salt seeding experiment using the instrumented aircraft with a randomised cross over design has been launched in 1973 in Maharashtra State by the Indian Institute of Tropical Meteorology, Pune.

The experimental area consists of north and south sectors of each 1600 sq. km and a buffer sector of 1600 sq. km area. The raingauge in the experimental area is one per 40 sq. km. The seeding material used consists of pulverised mixture of salt (Sodium Chloride) & soapstone in the ratio 10 : 1 with the model size of the particle being 10 um. A specially designed seeding gadget fitted to the aircraft is used for spraying the seeding materilal. Seeding is carried out inside clouds at a height of a few hundred metres above the base of the cloud during aircraft penetrations into clouds. The material is dispersed at the rate of 10 to 30 Kg per minute of aircraft flight path (3.2 km) depending upon the depth of seeded clouds. Higher seeding rates are used when the cloud depth is more (>1.5 km.)·

The aircraft used for seeding has instruments for making the following observations :

(1) cloud droplet size distribution, (2) liquid water content (3) electric field, (4) electric charges of cloud drops and raindrops, (5) electrical conductivity, (6) Corona discharge current, (7) vertical air velocity, (8) temperature, (9) dew point temperature, (10) pressure altitude, (11) cloud condensation nuclei, (13) giant size condensation nuclei and (13) Aitken nuclei. Also, a specially designed gadget for collection of cloud and rain-water samples has been fitted to the aircraft and water samples from seeded and not-seeded clouds are collected and analysed for their chemical composition. Further, rain water samples at the surface are also collected from the target and control areas during the period of the experiment and their chemial composition is determined. The cloud microphysical, dynamical and electrical observations and the data of the chemical composition of cloud and rain water obtained from the seeded and not-seeded clouds are used for the physical evaluation of the warm cloud responses to salt seeding (Murty et al., 1985 c, d, e, f).

The above aircraft salt seeding experiment has been so far conducted during the 10 summer monsoon seasons (1973, 1974, 1976, 1979-85). The results of the rainfall analysis relating to the 9-year (1973, 1974, 1976, 1979-84) experiment showed a positive trend (Murty et al., 1985 a,b). The effects of the seeding are found to depend on (i) type of clouds/monsoon activity existing on the day of seeding and the type of seeding technique (area seeding/massive seeding of individual clouds) used during the experiment. The aspects are being critically examined. The preliminary results indicated that on days with isolated and scattered rainfall activity (days with moderate activity) there was a 31 per cent increase in rainfall and on days with scattered to fairly widespread rainfall activity (days with strong monsoon activity) there was a 10 per cent decrease in rainfall (Murty er al., 1985 b). These results are not statistically significant.

4.3 Dynamic Effect of Salt Seeding

The effect of massive salt seeding on the dynamical conditions was detected from the cloud physical observations made during the warm cloud modification experiment which is in progress in Maharashtra State (Murty el al , 1976). The results of the experiment showed (i) a rise in temperature of cloud air by about 1-2°C, (ii) increase in the cloud liquid water content up to 200 per cent before the onset of rain and (iii) increase in the vertical thickness of the clouds up to 60 per cent in all the seeded clouds whose initial thickness was more than 2.5 km at the time of seeding. The above features may be attributed to the invigoration of updraft in clouds resulting from the latent heat of condensation liberated due to condensation of water vapour on the salt particles released into the seeded clouds. The rapid formation of large drops in clouds seeded with massive doses can be due to the Langmuir chain reaction mechanism. The dynamic effect of salt seeding may be smaller than that which can be produced by massive silver iodide seeding of supercooled clouds. In the former case invigoration of the cloud buoyancy is partly retarted by the evaporation of water droplets.

4.4 Warm Cloud Electrical and Microphysical Responses to Salt Seeding

The warm cloud responses to salt seeding (physical evaluation) were documented from the observations made in several seeded (target) and not-seeded (control) clouds (Murty et al., 1985 c,d, e). Cloud drop size distributions in seeded clouds showed increases in the mean volume diameter up to 478 per cent and the computed liquid water content upward of 60 per cent (Kapoor et al., 1976).

The electric field in the maritime warm cumulus clouds which developed rain following seeding showed a sign reversal, from the initial negative to positive occasionally preceded by intensification (Murty et al.. 1976). The field reversal noticed was attributed to the transport of large positive charges from the upper levels of the cloud to the base through raindrops which will initially form at the higher levels in the vigorous updraft region. The intensification of the electric field was attributed to the invigoration of the updraft produced by massive salt seeding since the electric activity is closely related to the convective activity in warm clouds. The above observations are consistent with the warm cloud modification hypothesis and lend support for establishing the feasibility of increasing rainfall through salt seeding on a scientific basis.

4.5 Chloride and Sodium Ion Concentrations in Cloud and Rain Water Samples

Information on the Chloride and Sodium ion concentrations in cloud and rain water samples collected from seeded and not-seeded could benefitially be used for evaluating the warm cloud responses to salt seeding. This aspect has been examined from the chemical analysis of the cloud and rain water samples collected during the warm cloud seeding experiment in Maharashtra State. Chloride and Sodium ion concentrations in cloud water samples collected from seeded clouds are respectively higher by 273 per cent and 305 per cent respectively as compared to the concentrations in the samples collected from not-seeded clouds. The differences are signifiant at less than 5 per cent level (Murty et al., 1985 f). Similarly in rain water samples collected, the Chloride and sodium ion concentrations are higher by 238 per cent and 133 per cent. The differences are significant at less than 5 per cent level. These results indicate that the giant size salt particles released clouds have entered the cycle of warm rain process i.e., acceleration of the coalescence process due to formation of precipitation size embryos on the salt particles released into the clouds.

Results of simultanious cloud physical observations made in the seeded and not-seeded clouds corroborate the above hypothesis (Murty et al., 1985 c,d,e).

4.6 Numerical Simulation of Cloud Seeding Experiments

The chances of detecting prescribed increase in rainfall due to seeding with specified degree of confidence can be investigated by numerically simulating the experiment (computer simulation) using the historic rainfall data. Such numerical experiments require a great deal of computer time even with the use of high speed computers.

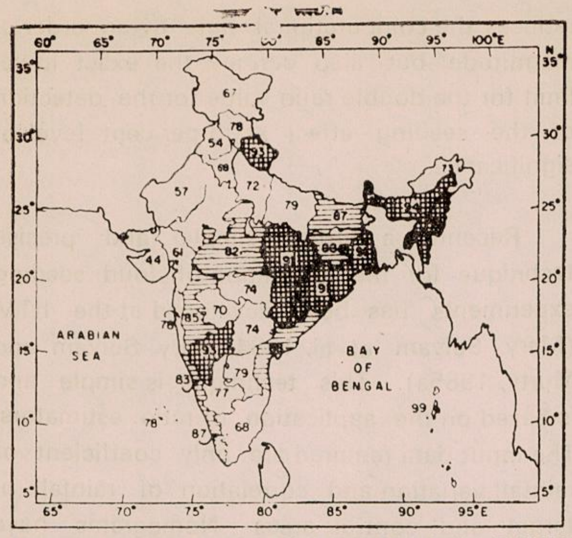
Numerical experiments for selected areas in Australia were reported (Twomey and Robertson (1973). In the numerical simulation technique of Twomey and Robertson an experiment was judged a success if the increase detected was significant at the specified signi ficance level and was between 0.5 and 1.5 times the mean increase for the hypothesised random seeding effect. This arbitrary condition used for detecting the seeding effect is not satisfactory (Das, 1976),

A new numerical technique for the simulation of cloud seeding experiment has been developed at the Indian Institute of Tropical Meteorology (IITM) Pune (Mary Selvam et. al., 1978; b 1979). The new technique not only reduces the computational time by an order of magnitude but also defines the exact lower limit for the double ratio value for the detection of the seeding effect at 5 per cent level of significance.

Recently a further simpler and precise technique for the simulation of cloud seeding experiments has been developed at the IITM (Mary Selvam et al. 1984, Mary Selvam and Murty, 1985a). This technique is simple and is based on the application of ratio estimators. The input data required are only coefficient of rainfall variation and correlation of rainfall of target and control areas. Nomograms have been prepared for specified sets of input data and these can be easily used anywhere in the world for identifying regions suitable for undertaking weather modification experiments.

Percentage probabilities of detection for 15 per cent increase in rainfall due to seeding were computed using the 5 year (1976-80) summer monsoon rainfall data for different meteorological sub-divisions in India. The results are given in Figure 6. It is considered that for the successful detection of the seeding effect, the probability of detection should be more than 80 per cent (Smith and Shaw, 1976). Based on this criteria the regions in India which are suitable for undertaking weather modification experiments have been identified (Figure 6). These are (i) northeast India, (ii) central India, (iii) west coast and (iv) south India.

Numerical simulation experiments for the Maharashtra State have been carried out for evaluating of the minimum period required for the actual cloud seeding experiment to ect specified increase in rainfall due to seeding. Increases in rainfall exceeding 10 per cent can only be detected successfully. For the detection of 10, 15 and 20 per cent increase in rainfall the experiment is required to be conducted for a minimum period of 14, 7 and 5 years respectively (Mary Selvam and Murty, 1985a).



FIGURES IN THE MAP INDICATE PERCENTAGE PROBABILITY OF DETECTION OF 15% INCREASE IN RAINFALL DUE TO SEEDING FOR THE EXPERIMENT WITH DOUBLE-AREA-CROSSOVER DESIGN

EXPERIMENT DURATION 5-YEARS (1976-80)

▦ ≥ 90% ▤ ≥ .80 < 90%

Figure 6

5. Hydrological Evaluation of Precipitation Enhancement

Many investigators have attempted to use hydrological methods for the evaluation of precipitation enhancement projects (Kahan, 1977) in addition to the meteorological/classical statistical design and evaluation methods adopted for precipitation modification experiments. Out of the hydrological methods the use of streamflow in evaluating the effectiveness of precipitation enhancement effort is nearly as long as the modern day history of cloud seeding (Thom, 1957; Crawford and Linsley, 1963; Yevdejevich 1955; Marmovic, 1966; Hastey and Gladwell, 1968; Watson and Denny, 1971; Morel-Seytoux, 1972; Henderson, 1981; Harpaz and Benjamini, 1985). The approach has been used in some long established operational projects, as well as in some randomised experiments. The advantages and disadvantages of hydrological approaches to evaluation were discussed by a number of investigators (Crawford and Linsley, 1963; Watson and Denny, 1971; Morel Seytoux, 1972). The study of the Crawford and Linsley, (1963) have shown that a given increase in precipitation may produce a greater percentage increase in streamflow, thus making the detection of the increase in rainfall due to seeding much easier. There are, however, disadvantages to the use of streamflow for evaluation that outweigh the advantages in some circumstances. Inaccuracy of discharge measurement, high variability of natural flows, and time dependence of successive river flows has been identified (Thom, 1957; Marmovic, 1966) as the main disadvantages.

6. Present State of art of Modifying Precipitation by Cloud Seeding

Seeding clouds with a view to stimulating additional rainfall over areas of a few thousand square Kilometers has been practiced for over three decades and many programmes have been in the regular operation on the assumption that cloud seeding is successful. However there is no general agreement among the scientific community as to whether, or in what condition, it is possible to increase rainfall through cloud seeding (Warner, 1973). The major problem has been the tremendous natural variability of rainfall which introduces the basic difficulty in evaluating the effect of seeding. If one understands the physical and the dynamical processes that control the intensity, duration and distribution of precipitation well enough to be able to predict them to even moderate accuracy it would be a simple matter to assess the results of the cloud seeding experiments. In the absence of the physical understanding, one is forced to rely heavily on statistical evaluation of the experiment. It has been recognised in the recent past that the in-cloud microphysical and dynamical observations are very essential for a detailed physical study of the cause and effect relationship of the events and to confirm the statistical results.

The state of art of precipitation modification as stated in the report of the Eleventh Session of the Executive Council (EC) Panel of Experts on Weather Modification/Commission for Atmospheric Sciences (CAS) Working Group on Cloud Physics and Modification of the World Meteorological Organization (WMO) held at Geneva, Switzerland during 11-16 May 1981, is reproduced below.

I. Supercooled Clouds

(i) "Several major experiments have been conducted in various types of cloud systems including orographic, winter convective, and summer convective clouds. Some of these have provided either statistical or physical indication that seeding may have affected precipitation. To date only one cloud seeding experiment has combined physical evidence in support of a seeding hypothesis persuasive evidence of increase in precipitation over an area. That project, carried out on winter convective clouds in Israel during two consecutive experiments over a 15-years period, resulted in an apparent precipitation increase of about 15 per cent.

(ii) There is evidence that certain sub-tropical convective clouds became taller and larger when they are heavily seeded to release latent heat. In view of the high correlation between the size of convective clouds and the rainfall from them, the seeded clouds presumably give more rain than if they had been unseeded. Confirmation that areal precipitation can be increased in this way is required from suitably designed experiments.

II. Warm Clouds

A few encouraging (but not conclusive) experiments have been carried out. None have the requisite combination of successful rainfall increases based on physical and statistical evidence.

7. Outlook

Weather modification research in recent years has greatly increased the physical understanding of cloud and precipitation processes (Mary Selvam et al., 1980, Murty and Mary Selvam, 1985) and the effects of various cloud seeding treatments. There is significant progress in the development of numerical models that simulate the behaviour of clouds and predict probable seeding effects (Mary Selvam and Murty, 1985b). Also, new numerical techniques have been developed for the statistical simulations (computer simulation) of weather modification experiments (Mary Selvam et al., 1984; Mary Selvam and Murty, 1985 a).

The salt seeding experiments conducted in north India using groundbased seeding generators provided the statistical evidence to show that areal precipitation can be increased through artificial modification of monsoon clouds. The warm cloud modification experiment undertaken by the Indian Institute of Tropical Meteorology in the Pune region in 1973 has sound scientific cloud physics programme and seeding is being carried out by aircraft for better targetting and distribution of the seeding material (salt particles) in the clouds. The results of the cloud physical observations made in about 100 pairs of seeded (target) and not-seeded (control) clouds have provided the vitally needed physical evidence to show that salt seeding enhances the coalescence process in warm clouds. These observations are most important for establishing the efficacy of artificial modification of precipitation on a scientific basis. Also, the rainfall analysis of the above experiment indicated that areal precipitation could be increased through salt seeding of warm clouds. The effects of seeding have been found to depend on the type of clouds (synoptic conditions) and the type of technique used for seeding. These aspects are being examined critically from a wealth of observational data obtained during the experiment conducted during the 10-summer monsoon seasons (1973, 1974, 1976, 1979-85). When the results of the rainfall analysis are established this experiment would have the requisite combination of successfull rainfall increases based on physical and statistical evidence. The results of the above warm cloud modification experiment will have great applicational value for the designing and the planning of warm cloud modification operations in many of the tropical countries where potential form cloud modification exists.

Long term cold cloud modification experiments have not been undertaken in India so far. The dynamic seeding technique appears to be promising and its potentialities are to be explored by undertaking suitably designed experiments over a period of 10 years in a suitable region in India.

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SEVERE RAIN-STORMS OF INDIA

by

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1.0 Introduction :

There have been many dam failures due to inadequate spillway capacity. There are some examples of this even in our country. To avoid such disasters it is essential that the spillway capacities should be based on proper and careful analysis of past rainstorm data in and near the basin. As such the hydrologist looks to the science of Meteorology for information on severe storms. If the storms are to be used to derive river flows, then they should be analysed in such a way that the results can be applied directly by the hydrologist. The form of information required, is of depth of rainfall which falls during specific time intervals and over specific areas. That is rainfall data should be expressed in terms of depth-duration and area (DDA).

Luckily, rainfall data are available for the last 100years or so for about 3000 stations uniformly distributed all over India.

2. Analysis of severe rainstorms :

The Depth-Area-Duration (DAD) analysis of most of the severe rainstorms of this country was carried out by the Hydrometeorology Division of Indian Institute of Tropical Meteorology, Pune in a systematic manner and this analysis has shown that the following 3 rainstorms were the most severe rainstorms of India :—

(i) 17 to 18 September, 1880 over northwest Uttar Pradesh, (ii) 24 to 29 July, 1927 over north Gujarat and (iii) 1 to 5 July, 1941 over south Gujarat-North Konkan.

These rainstorms yielded the highest average raindepths over different areas and durations. The brief description of these three severemost rainstorms are given in this article.

3. Frequency of Cyclonic Disturbances :

In India severe rainstorms are generally associated with tropical disturbances (depressions and cyclonic storms) which form in the neighbouring Bay of Bengal and Arabian seas. The Indian sub-continent experiences such disturbances in all the months of a year except February. Table 1 gives the total number of these disturbances in the different months of the year during the 90 year period from 1891-1980.

Table 1, shows that during the period of 90 years nearly 900 cyclonic disturbances moved through the Indian sub-continent, of which the southwest monsoon months of June-September, accounts for about 70% of these disturbances. It is further observed that on an average one disturbance occurs in June and about two each in July, August and September months.

4. Meteorological causes of severe rainstorms of 1880, 1927 and 1941 :

4.1 September, 1880 rainstorm :

The rainstorm of September, 1880 was associated with the Bay of Bengal depression

Table 1 : Number of cyclonic disturbances which moved through the Indian sub-continent during the period 1891-1980

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Total during 1891-1980	6	0	2	6	36	105	166	182	176	115	86	16	896
Average per month	0.07	0	0.02	0.07	0.40	1.17	1.84	2.02	1.96	1.28	0.96	0.18	9.96

which crossed the Orissa coast on 14th September near Gopalpur. On 17th September morning this depression was located near Neemuch in Madhya Pradesh. From here, the depression recurved in a north-easterly direction and was centred near about Agra on 18th September morning. According to Blanford (1888), while recurving it apparently reinforced a disturbance in northwest Uttar Pradesh due to which some rain had been falling for a day or two previously. The depression dissipated finally between 19th to 20th September over the submontane districts of northwest Uttar Pradesh. Stations which recorded rain amounts of 75 cm and above in the storm area are given below.

4.2 July 1927 rainstorm :

The 6-day rainspell over Gujarat from 24th to 29th July was caused by the Bay of Bengal depression which formed near Saugor Island on the morning of 23rd July. On 25th July morning it moved near Jabalpur and besides causing heavy rains along its track, it stimulated the activity of the Arabian Sea monsoon over Gujarat. The depression intensified further and by the morning of 26th July, it moved near Guna, and then to the neighbourhood of Mount Abu on 27th July, where it intensified further. From here, instead of moving in westerly direction, the depression turned to northwards. During the next two days it moved very slowly and was centred near about Jalore on 28th and near Jodhpur on 29th. From Jodhpur the depression moved rapidly and weakened considerably and by the morning of 30th July, it lay near Bikaner. On 31st July it got dissipated over the east Punjab hills. Fig. 1 shows the track of the depression between 23rd July to 29th July over the north Indian plains. Stations which received rain amounts of more than 110cm in 5 days in the storm area are given

Stations	Rainfall in cm		Total 2 days rainfall in cm
	17th Sept.	18th Sept.	
Hardwar	30.5	49.5	80.0
Jaolijansath	40.6	37.1	77.7
Nagina	21.8	82.3	104.1
Dhampur	22.1	77.2	99.3
Najibabad	25.7	72.4	98.1

Stations	Rainfall in cm for July, 1927						
	Dates						
	24	25	26	27	28	29	Total
Dakor	6.1	26.5	29.2	45.7	54.0	4.0	165.5
Ahmadabad	12.5	15.2	13.3	41.3	28.7	12.9	123.9
Mehmadabad	13.6	17.4	16.8	32.3	28.2	4.7	113.0
Nadiad	9.5	25.7	17.2	27.3	21.8	8.5	110.0
Kalol	5.6	14.4	36.2	25.0	39.1	7.7	128.0
Halol	7.2	17.9	46.1	20.2	23.8	4.1	119.3
Matar	6.4	28.1	21.5	30.2	22.4	3.4	112.0

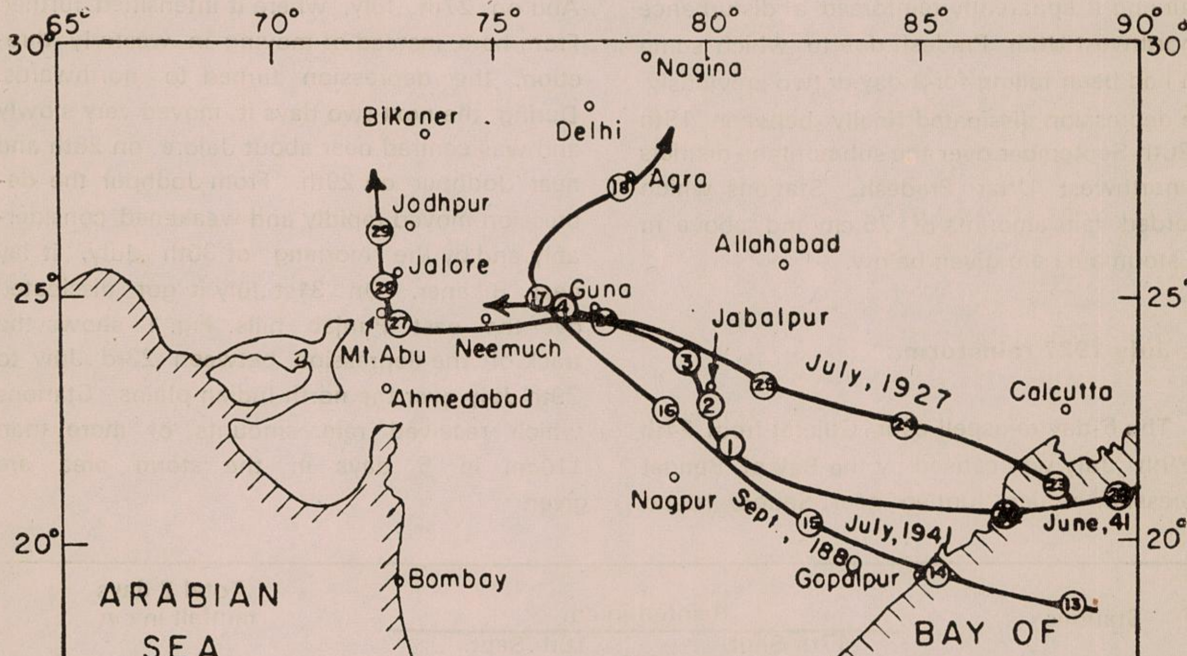

Fig. 1 Tracks of September, 1880, July, 1927 and July, 1941 Monsoon Depressions

4.3 July 1941 rainstorm :

The rainstorm of July 1941 was caused by the depression which formed in the head of the Bay on 28th June. By 1st July it crossed the Orissa coast near Chandbali. After crossing the coast, it moved westnorthwesterly direction and filled up over south Rajasthan on 4th July. In association with the movement of this depression the monsoon current from the Arabian sea got strengthened which resulted in heavy to very heavy rainfall over the coastal plains of south Gujarat-north Konkan region. Dharampur station in Surat district recorded 99cm of rainfall in 1-day which is a record rainfall for plain area station. The track of this depression is also shown in Fig. 1. Stations which recorded rain amounts of 120 cms and above in the storm area are given below :

5. Depth-area-duration (DAD) analysis :

5.1 Depth-area-duration analysis of 1880, 1927 and 1941 rainstorms

The Depth-area-duration analysis of the above storms was carried out which occurred over different regions of the country (Dhar et al 1975, 1980, 1984). For this purpose daily and total storm isohyetal maps were prepared and planimetered. The DAD statistics of these three storms are given in Table 2 for different durations.

5.2 Comparison of areal raindepths of September, 1880. July, 1927 and July, 1941 rainstorms :

A comparison of areal raindepths given in Table 2 brings out that for all the 5 days durations the July, 1941 rainstorm exceeded the average areal raindepths obtained in the other two rainstorms of Sept., 1880 and July, 1927. Thus, so far Indian sub-continent is concerned, the July, 1941 rainstorm was found to be the most severe rainstorms. The 3-day isohyetal pattern of July, 1941 rainstorm is shown in Fig. 2.

6. Comparison of Highest Indian areal raindepths with similar data from USA and Australia :

A comparison of areal raindepths of the July, 1941 rainstorm was made with the most severe rainstorms of the USA (Shipe and Riedel, 1976) and Australia (M.R. Kennedy, Personal communication). The DAD data for these 3 areas are shown in Table 3 for selected areas and duration of one to three days. Table 3 shows that with the exception of a few areas in the range from 100 to 1000 sq. miles, the areal raindepths obtained in July, 1941 rainstorm were the highest as compared to USA and Australia raindepths. It may be mentioned that areal raindepths for other tropical countries are not readily available and as such it may not be said whether the July, 1941 rainstorm was or was not the world's most severe rainstorm.

Stations	Rainfall in cm. during 1-5 July, 1941					
	Dates					
	1	2	3	4	5	Total
Navasari	46.0	78.3	1.7	14.1	7.1	147.2
Jalalpur	6.9	35.9	63.7	0.9	12.6	120.0
Waghai	39.4	42.4	35.7	3.6	7.0	128.0
Peint	35.3	47.4	25.5	11.6	3.8	123.6
Dharampur	19.2	98.7	27.3	4.2	3.5	152.9

Table 2 : Maximum areal raindepths (mm) for most severe rainstorms of India

Rainstorms	Duration (days)	Area (mi²)							
		Point Value	100	1000	2000	5000	10,000	20,000	25,000
September	1	823	813	711	622	478	366	259	224
1880.	2	1041	1029	935	864	726	564	409	361
July	1	541	523	429	385	316	274	234	218
1927.	2	998	914	686	628	533	465	401	378
	3	1290	1219	1031	935	790	671	546	512
	4	1554	1450	1159	1065	950	838	685	635
	5	1615	1525	1270	1165	1053	941	771	713
	6	1656	1610	1307	1210	1091	960	799	742
July	1	987	945	737	640	498	386	272	240
1941.	2	1270	1248	1070	965	775	595	425	375
	3	1448	1410	1245	1170	985	797	580	525
	4	1499	1435	1275	1205	1045	875	660	605
	5	1524	1485	1340	1270	1117	935	730	670

Table 3 : Depth-area-duration (DAD) statistics of July, 1941 rainstorm and their comparison with the most severe raindepths of USA and Australia.

Area (Sq. miles)	1-day duration (cm)			2-day duration (cm)			3-day duration (cm)		
	India	USA	Australia	India	USA	Australia	India	USA	Australia
Point value	98.7	98.3	—	127.0	109.5	—	144.8	114.8	—
100	94.5	89.4	82.0	124.8	98.8	126.0	141.0	103.1	161.0
500	82.5	83.1	73.0	115.8	91.4	102.5	131.5	94.7	134.0
1000	73.7	76.7	64.0	107.0	85.6	88.5	124.5	88.6	116.0
2000	64.0	63.0	—	96.5	72.1	—	117,0	75.4	—
5000	49.8	39.4	43.5	77.5	52.6	52.5	98.5	62.0	64.0
10,000	38.6	30.7	32.0	59.5	44.2	41.0	79.7	54.1	50.0
20,000	27.2	24.4	12.0	42.5	35.1	17.0	58.0	44.7	23.0

(i) 1-5 July, 1941 with centre at Dharampur, India

(ii) 3-7 Sept., 1950 with centre at Yankeetown, Florida, USA

(iii) 13-15 March, 1929 with centre at Elba, Alabama, USA

(iv) 27 June-1 July, 1899 with centre at Hearne, Texas, USA

(v) DAD data of USA & Australia are not available for duration of 4 and 5 days.

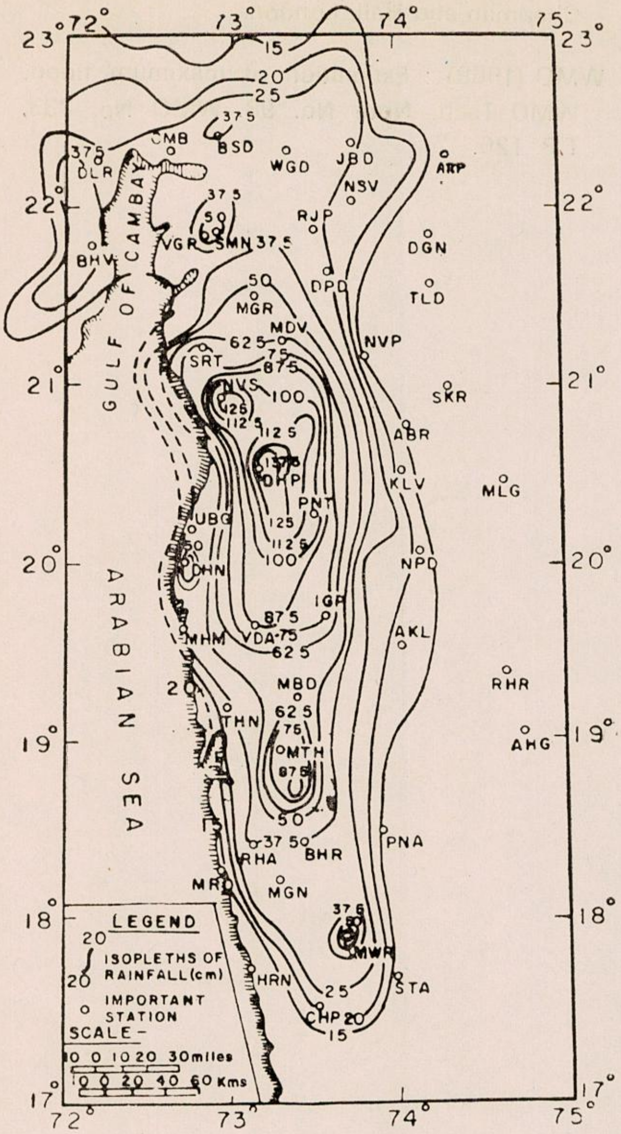

Fig. 2 Rainstorm Isohyetal Pattern of 3 Days (1-3 July, 1941) Over South Gujarat-North Konkan.

7. Efficiency of Rainstorms :

The storm efficiency (E) of a rainstorm is defined as the ratio of the observed rainfall (P) for a given duration and area to the available water (M) in the moist air over the storm area (US Weather Bureau, 1963; WMO, 1969). The ratio P/M is an index of the dynamic process which takes place within the storm to convert water vapour present in and near the storm area into precipitation. Wiesner (1970) described the procedure about the efficiency of the storm. Using this procedure Dhar and Rakhecha (1973) and Dhar et al (1984) have obtained storm efficiency ratios for all the most severe rainstorms of the Indian plains.

It was found that July, 1941 rainstorm gave the highest efficiency of the order of 23% (Dhar et al, 1984). Wiesner (1970) has mentioned that among the severe rainstorms of USA, the rainstorm of 3-7 Sept., 1950 (Hurricane Easy) gave the highest efficiency ratio of 21%. Thus the July, 1941 rainstorm was considered to be more efficient than the severe rainstorms of USA.

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PROBABLE MAXIMUM PRECIPITATION FOR DESIGN PURPOSES

by

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1. Introduction :

With optimum utilisation of water resources of the river systems by the construction of many medium and large dams for irrigation, hydropower generation, flood control or multipurpose projects, a rational study for a realistic assessment of hypothetical flood that have to be adopted for the design of such projects and any of their hydraulic structure has assumed great importance and significance. Since rainfall and runoff are inter-related, the long term rainfall data are made use for the designing of the hydraulic projects in the absence of long term discharge data. For this purpose "rainstorm analysis" is a prerequisite.

The purpose of rainstorm analysis is to evaluate the "Design Storm", the value of which is adopted for designing structure.

1.1 Design Storm :

It is an estimate of magnitude and spatial distribution of maximum rainfall over a project basin and its true distribution which can be used for obtaining the design of the hydraulic structure.

The estimation of design storm involves the determination of the following :—

(i) Maximum depth of precipitation

(ii) Duration of storm

(iii) Time distribution of storm rainfall

The design storm values adopted depend on the type of hydraulic structure of the project and the charateristics of the catchment involved together with the degree of safety or calculated risk envisaged in working out the design flood. Generally speaking, there are three types of design storms depending upon the degree of safety required for the hydraulic structure :

(i) Standard Project Storm (S.P.S.)

(ii) Probable Maximum Storm (PMS) also called Probable Maximum Precipitation (PMP)

(iii) Statistical Storm

1.2 Standard Project Storm (SPS) :

The standard project storm (SPS) is adopted for the design of such hydraulic structures where absolute safety may not be necessary but high degree of safety is necessary to avoid loss of property. The standard project storm (SPS) is defined as that historical rainstorm which is the heaviest rainstroms so far on record that has actually occurred in the records or is reasonably capable of occuring over the problem basin. Generally, all the major recorded rainstorms in the region of the problem basin are analysed and the most severe storm is selected as the SPS. However, rainstorms of extraordinary severity may be eliminated as they happen to be too unusual and extreme to adcpt as SPS. SPS is not maximised for the most critical atmospheric conditions but in order to obtain maximum raindepths over the problem basin, the storm pattern may be transposed from an adjacent homogeneous region to the problem basin.

1.3 Probable Maximum Precipitation (PMP) :

The determination of probable maximum precipitation (PMP) estimates is a time consuming and complex procedure. In spite of the availability of lengthy and explicit instructions on the topic, for specific projects or areas of interest unique questions which require an in-depth knowledge of meteorology invariably arise. For this reason, it is strongly recommended that a meteorologist be used for PMP determination.

1.4 Definition of PMP :

The American Meteorological Society "Glossary of Meteorology" (Huschke, 1959) defines probable maximum precipitation (PMP) as "the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage basin at a particular time of year." The terms "maximum possible precipitation" and "extreme rainfall" have historically been used with approximately the same meaning. The term "probable" in PMP refers to the uncertainties introduced by the imperfect techniques used to determine the PMP estimate and in no way is meant to imply any knowledge about the probability of occurrence of the event. The change in PMP values due to climatic change is unknown but is generally considered small, compared to other uncertainties in estimating these values and is therefore ignored.

The procedure for estimating PMP is documented in great detail in two World Meteorological Organization Publications (WMO 1969 and WMO 1973). The IMD closely follows the procedures described in these and the hydrometeorologist is urged to seek them out for the details necessary to properly determine PMP Values.

1.5 Causes of Heavy Rainspells Over India :

(a) Passage across the country of tropical disturbances originating from the Bay of Bengal or the Arabian Sea;

(b) Active monsoon conditions prevailing over different parts of the country.

(c) Land lows and low pressure areas moving westwards across the country during the monsoon months;

(d) Northward shift of the axis of the monsoon trough causing 'break monsoon" conditions and;

(e) Severe thunderstorm activity for short duration intense rainfall.

2. Depth-Duration (DD) Method :

Depth-Duration analysis gives the storm distribution characteristics of the catchment under study and is best suited to orographic catchments where application of D.A.D. or storm transposition technique is not advised in spite of meteorological homogenity. In this method, all the major rainstorms which have already been experienced by the catchment taking catchment area as unit for study, are analysed for various storm durations and maximum depth of rainfall computed by isohyetal method for different durations. Enveloping depth-duration curve gives the maximum depth for storm rainfall recorded in the catchment.

Generally the network of raingauges in hilly catchment is inadequate. In such cases isopercental technique of storm analysis is applied provided there is adequate raingauge network reflecting the variation of rainfall with elevation.

For all the rainstorms that occurred over the study area, with catchment area taken as a unit the average depth of precipitation for various durations (3, 6, 12, 24, 48, 72 etc. hours) in respect of each storm is obtained and plotted on a graph against duration. Such a curve is called Depth-Duration Curve. The curve enveloping all such depth-duration curves is then drawn. It gives the maximum precipitation depth tor various durations over the catchment, area.

3. Depth-Area-Duration (D.A.D.) Method :

This method is used when the catchment is situated in a meteorologically homogeneous region that is a region in which a major storm can be expected to centre anywhere in it. Secondly, the shape of the catchment is regular and is more or less similar to the isohyetal patterns of the typical major rainstorms in the region. Thirdly, the catchment size is such that the same can be easily covered by the storm isohyets.

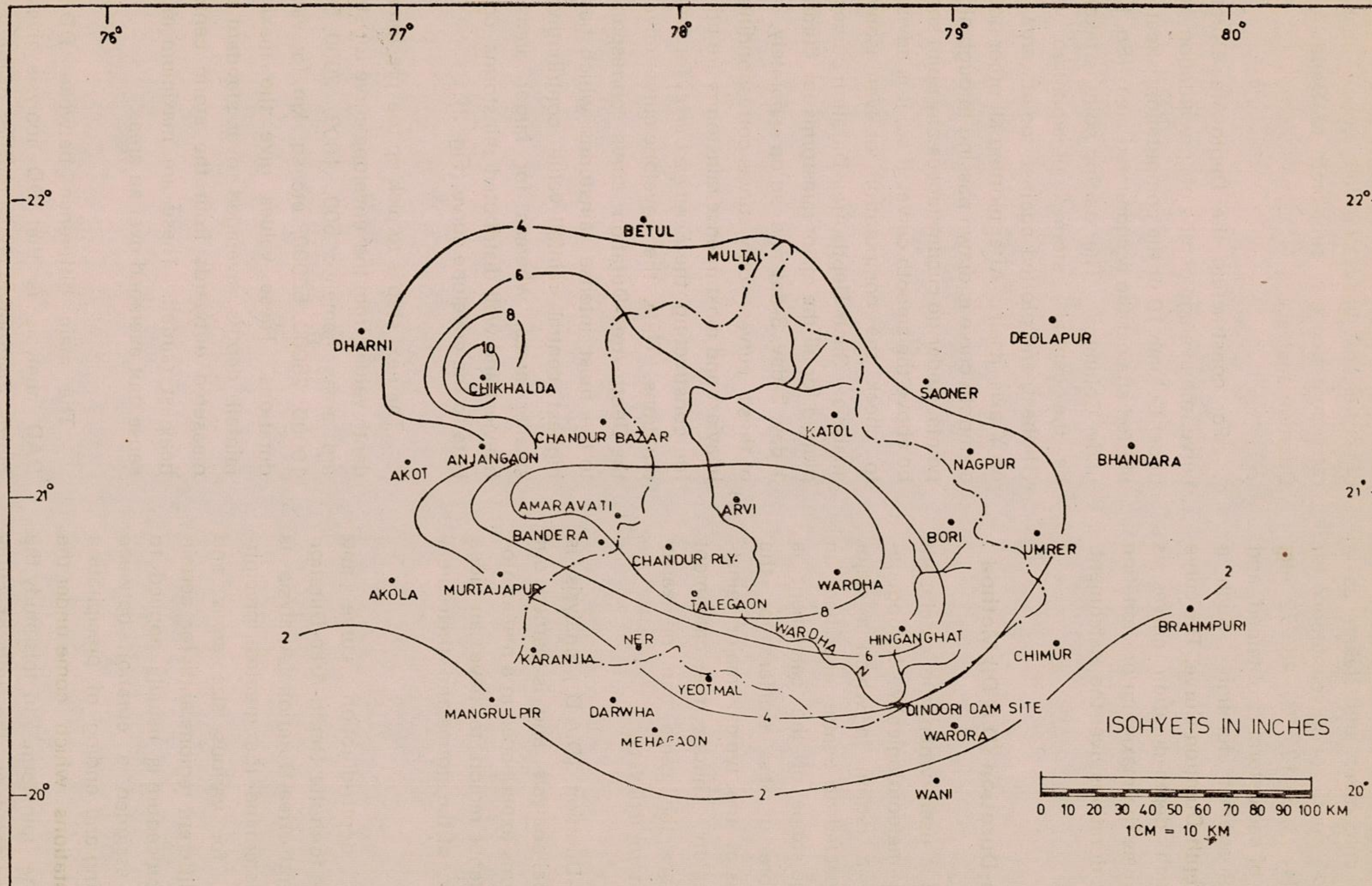
Depth-Area-Duration (D.A.D.) analysis is actually a regional analysis and is carried out for all major srorms experienced in a meteorologically homogeneous region to have an idea about the severity of the storms and their areal extent.

Collectively depth-duration curve and depth-area curve form the Depth-Area-Duration array. The Depth-Area-Duration Analysis is carried out to determine the greatest precipitation amounts for various size areas and durations over different regions and for certain seasons. This procedure is usually applied to storm which is assigned a duration between times of beginning and ending of precipitation at all those stations which come under the influence of the rainstorm. In this study the rainstorm is considered as the unit of study and its boundary is specified by the peripheral isohyet satisfying the criterion for storm selection. Only the major rainstorms with centre or centres of heavy rainfall over or near the catchment area are subjected to Depth-Area-Duration analysis.

For constructing the Depth-Area-Duration curve, the average depths of precipitation (cm) under Column 10 of the computation sheet are plotted against the accumulated area (Sq. Km.) under Column 7. The starting point is taken to be the central storm precipitation value (Highest) and plotted against 'point' area, i. e. on Y-axis itself. After plotting all other points, a smooth curve is drawn passing through all the points. Under no circumstances any point should be above the smooth curve. If so, it is advisable to check the computation or even isohyetal analysis. Such Depth-Area-Duration curves are plotted for all the major rainstorms for durations 1-day, 2-day, 3-day and so on separately. Out of these curves, only curves corresponding to heaviest and most intense rainstorms are utilised for constructing the *Envelope Curves* for various durations. Thus, the envelope curve envelops the Depth-Area-Duration curve corresponding to the most intense rainstorms which has the highest central rainfall value contributing for smaller areas, whereas for larger areas, the heaviest and well distributed rainstorms contribute to the envelope curve (Fig. 2).

The next step is to pick up the precipitation depth values from the envelope curve for standard areas namely : 500, 1000, 2000, 5000, 10000, 25000, 50000, etc. sq. km. for various durations. These values give the maximum rainfall depths averaged over standard areas measured outwards from the storm centre of heaviest rainfall. These are maximum in time sense, but averaged over an area.

The main difference between DD and DAD analysis is that DD analysis gives the storm distribution characteristics of the catchment whereas DAD analysis ensures that the possibility of occurrence of the severest neigh-



ISOHYETAL PATTERN OF THE STORM OF 15-SEPT. 1933 FOR DINDORI CATCHMENT OVER RIVER WARDHA

Fig. 1

Name of the Catchment Dindori

Date of Period of Storm 15-Sept. 1933

Isohyetal Range (In./) From	Isohyetal Range (In./) To	Mean Rainfall (In./)	Area in Sq. In	Area in Sq. Kms.	Accumulated Area in Sq. Kms.	Volume in In/ Sq.Kms. (Col.3 × Col.5)	Accumulated Volume	Average Rainfall in Inc./ Cms. (Col.8/6)	
1	2	3	4	5	6	7	8	9	In Cms.
10.85	10.0	10.42	0.25	250	250	2600	2600	10.42	26.5
10.0	8.0	9.0	0.55	550	800	4950	7550	9.43	23.9
9.1	8.0	8.5	5.50	5500	6300	46750	54300	8.61	21.9
8.0	6.0	7.0	8.70	8700	15000	60900	115200	7.68	19.5
6.0	4.0	5.0	16.55	16550	31550	82750	197950	6.27	15.9

Name of the Catchment Dindori

Date of period of Storm 14-15 Sept. 1933

Isohyetal Range (In./) From	Isohyetal Range (In./) To	Mean Rainfall (In./)	Area in Sq.In/	Area in Kms.	Accumulated Area in Sq.Kms.	Volume in In/ Sq.Kms. (Col.3 × Col.5)	Accumulated Volume	Average Rainfall in Inc./ Cms. (Col.8/6)	
1	2	3	4	5	6	7	8	9	In Cms.
14.65	14.0	14.30	1.30	1300	1300	18590	18590	14.3	36.3
14.0	12.0	13·0	5.20	5200	6500	67600	86190	13.26	33.7
12.0	10.0	11.0	9.90	9900	16400	108900	195090	11.89	30.2
10.0	8.0	3.0	9.70	9700	26100	87300	282390	10.8	27.5

Computation Sheet

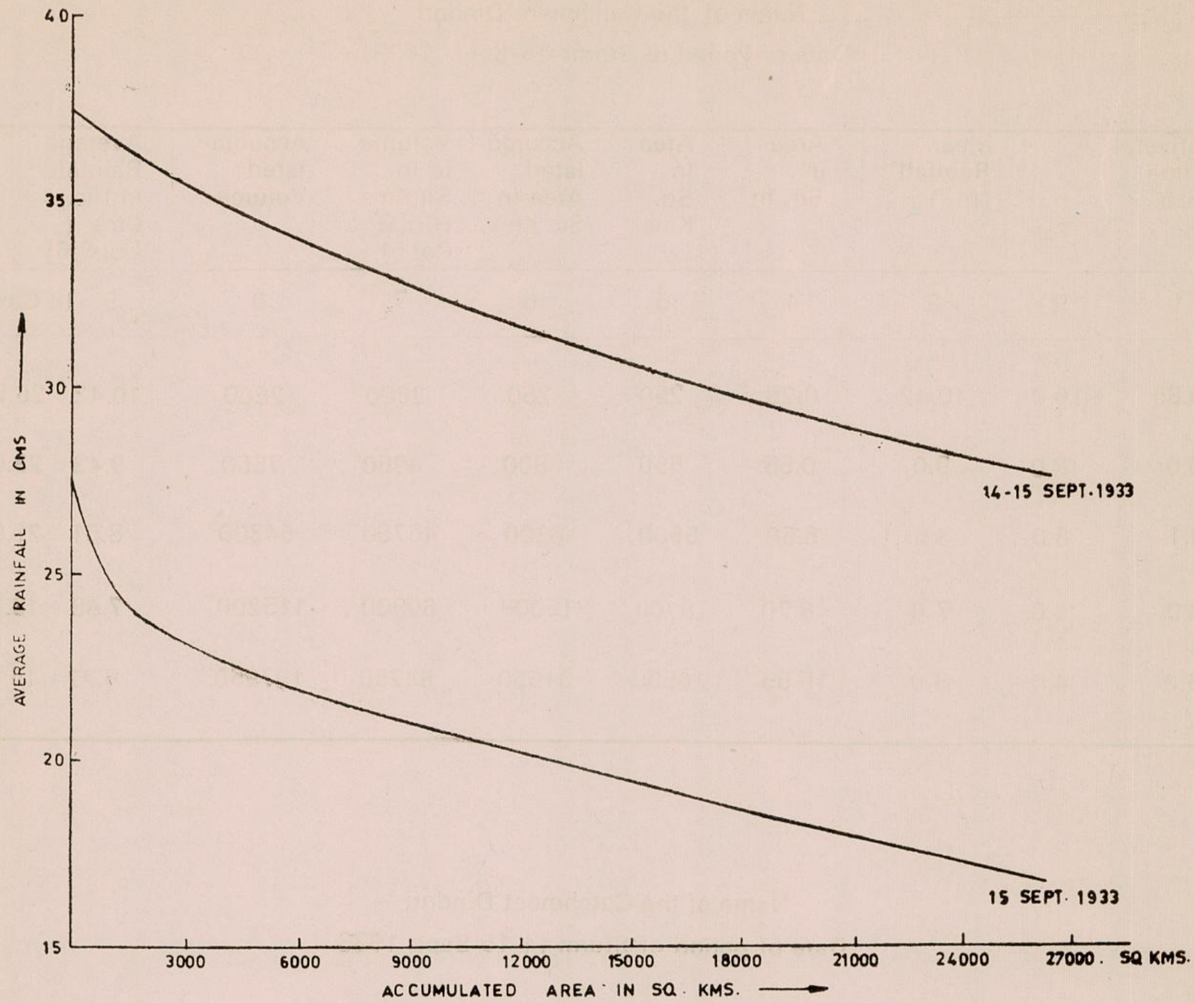


Fig. 2 Depth-Area-Duration Curves for Dindori Catchment

bouring storm over the catchment area is taken care of through storm transposition. DAD value is maximum in time but averaged over the area.

Such analysis ensures better results for estimating the time and areal distribution of the storm rainfall that has occured within the catchment than to transpose which has occured away from the catchment area. However, if the entire region is meteorologically homogeneous, then the transposition of the severest rainstorm over the area under study is advisable. While bodily transposing the rainstorm, due regard should be given to the orientation of the rainstorm with respect to the basin and if necessary a tilt in the orientation of the storms (major) axis to a maximum of 30° may be given in order to contain the entire or major portion of the rainstorm within the basin.

4. Storm Transposition :

The storm transposition technique is applied to those project areas which have inadequate rainfall data and/or no severe storm has occurred over the project area and at the same time the basin has marked irregular shape which does not generally confirm to the isohyetal patterns of major storms on record in the region.

Storm transposition means application of a storm from one area to another area in the same meteorologically homogeneous region. In effect it means that the synoptic situations associated with the storms which have already occurred in the surrounding meteorologically homogeneous region are also possible in the problem basin in due course of time (Fig, 3 & 4).

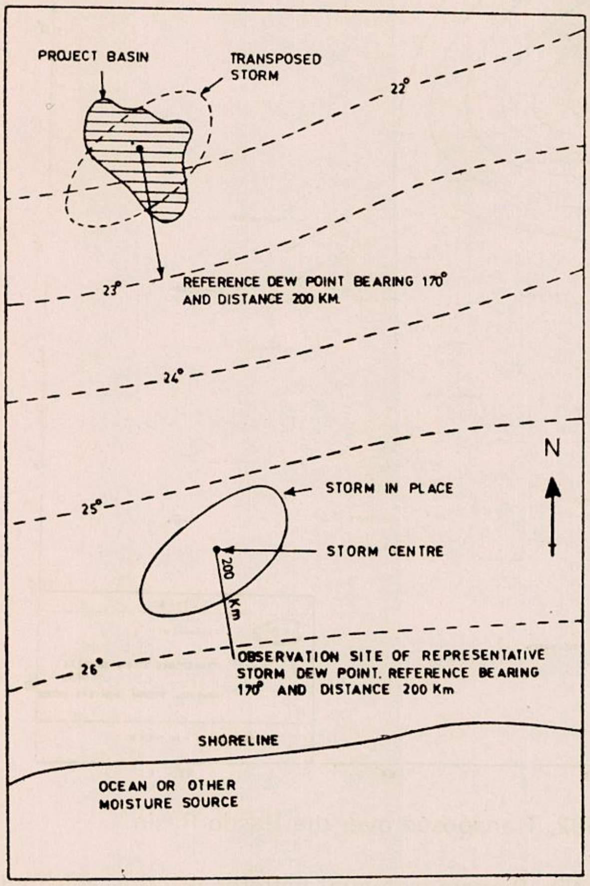


Fig. 3 Example of Storm Transposition. Long Dashed Lines Indicate Maximum Persisting 12-Hours 1000 mb dew Points (°C) for the Same Time of Year the Storm Occurred or Within 15 Days According to Common Practice.

The purpose of storm transposition is, therefore, to increase the storm experience of the basin by considering not only storms which have occurred directly over that basin but also those which have occurred within the surrounding meteorologically homogeneous region.

4.1 Meteorological Homogeneity :

Broadly speaking, a meterologically homogeneous region is one which is affected by the same moisture source, experiences the same type of storms and associated with same type or combination of same types of synoptic situations and where the major topographic features are the same.

For the purpose of storm transposition, a meteorologically homogeneous region is the one in which the probability of occurrence of rainstorms of a given intensity is the same or likely to be the same at every point in the area. It can thus be said that in such an area frequency of occurrence of rainstorms of different intensities is practically the same at all points over *a very long period of years.* As such, in such regions the normal/monsoon seasonal rainfall should also be more or less of the same order. However, the converse of this may not always be true i e. different areas having the same mean annual rainfall need not necessarily be meteorologically homogeneous.

The chief features which affect the homogeneity of an area are :

(a) Distance from the sea

(b) Direction of the prevailing winds

(c) Mean annual temperature

(d) Topography

It is evident from the above that the deleneation of areas of meteorological homogeneity can at best be done in a rather broad sense.

Other factors which can be considered from the hydrological point of view are :

(i) If run-off data are available for the catchment where the storm has occurred and the catchment in which the storm is to be transposed, then their average annual peak discharge data be comparable.

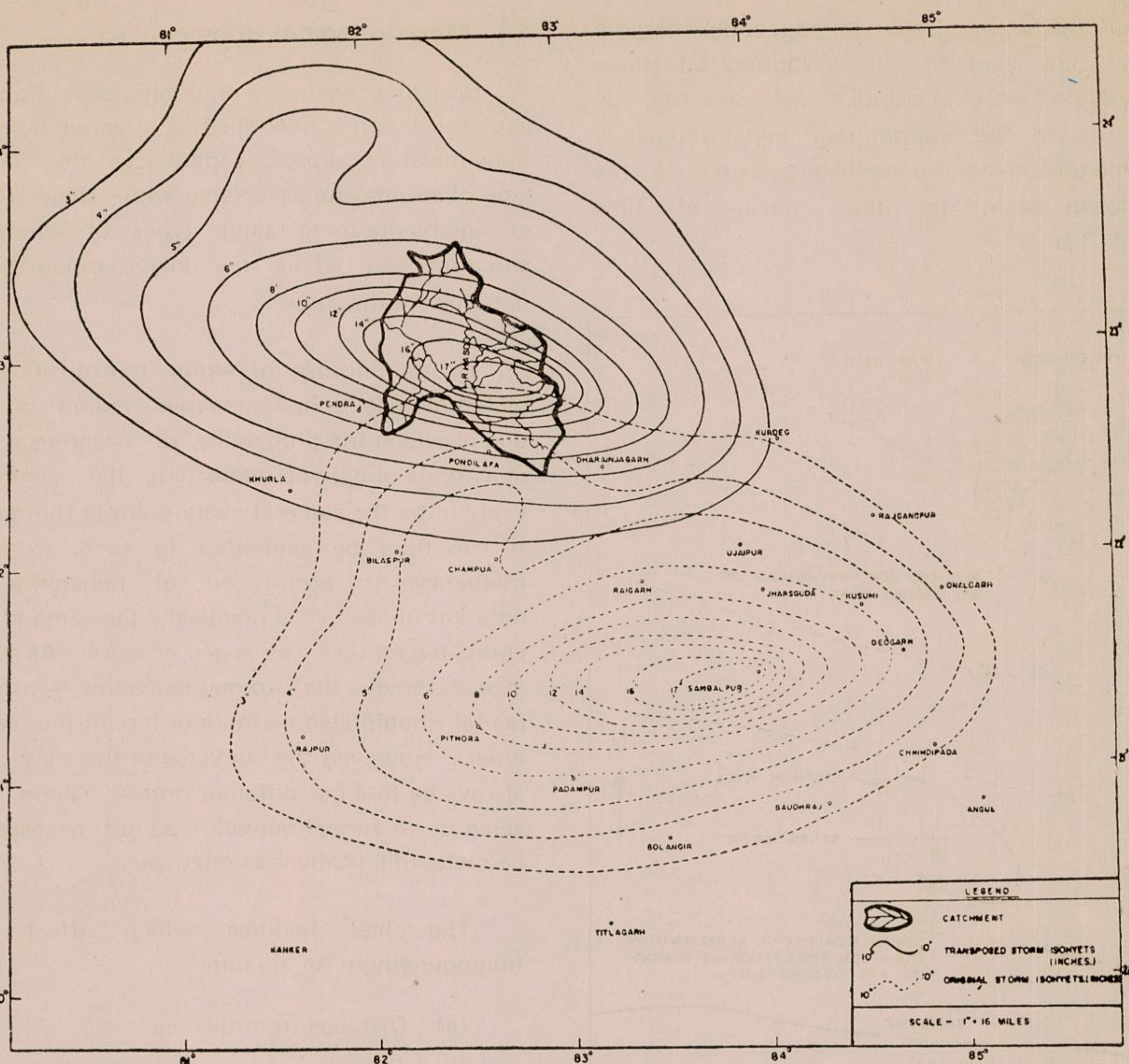


Fig. 4 Rain Storm of 22nd-23rd July, 1892, Transposed over the Hasdo Basin.

(i i) The catchment characteristics like vegetal cover, nature of soil etc. should also be examined from the hydrological point of view.

4.2 Steps in Storm Transposition :

(i) The first step in storm transposition is to identify when and where the heaviest storm occurred in the meteorologically homogeneous region of the project catchment. Next step is to identify the synoptic situations associated with that particular storm.

(ii) Prepare isohyetal patterns of the selected rainstorms.

(iii) General layout of the storm isohyetal pattern over and near the problem basin. This information is pre-requisite in the final selection of storms for transposition from the neighbouring homogeneous areas. For example, major/heavy rainstorms that have occurred near the basin or the region of similar rainfall regime should be analysed vis-a-vis the shape of the catchment. If the major axis of the rainstorm depict east-west orientation, and the catchment area is having north-south orientation, then it will not be advisable to transpose such rainstorms which have never been experienced over the basin in the past.

(iv) The fourth step is to delineate the region in which the meteorological storm type identified in step 1 is both common and important as a producer of precipitation. The locations of such storms as are comparable with the storm of type identefied in step 1 are marked on a map. A boundary around these locations is drawn to delineate the tentative region or zone where this particular type of storm can be expected to occur again. Those storms whose transposition limits do not include the problem basin need not be considered for transposition.

(v) The effect of topography or the nature of underlying surface on ralnfall distribution has to be taken into account while transposing storms.

(vi) Generally, transposition involving large changes in latitude (i.e. over 10° of latitude) are avoided.

4.3 Transposition technique :

Having selected a rainstorm for transposition over a given basin in accordance to guidelines stated above, an outlay of the storm pattern is prepared on a transparent plastic sheet. This outlay is superimposed on the problem basin in a most critical manner so as to yield maximum depths of rainfall over the basin. Care should be taken that the orientation of the storm pattern should not be tilted by more than 30° and in accordance with the normal direction of the storm axis occuring over and near the problem basin. Next is to work out the depth duration values for the basin rain in respect of the transposed storm. Similarly depth-duration values are worked out for other storms transposed to the problem basin.

4.4 Storm transposition Adjustments :

Having transposed a rainstorm from the homogeneous region to the problem basin, there are certain adjustments which are usually applied to obtain the most representative raindepths of the design storm for the problem basin.

5. Storm Maximisation :

The method generally adopted for a storm maximisation is the moisture maximisation method which is applied to individual storms. The purpose of moisture maximisation is to determine as to how much storm precipitation would have been higher under the most critical atmospheric conditions regarding moisture availability in storm region. The Moisture Adjustment Factor (MAF) for the storm is defined as the ratio of maximum total moisture that could be available in the storm area under the most critical atmospheric conditions to the total moisture that prevailed during the storm period. In order to obtain these values, the 'Identifier' commonly used is the "Dew point" temperature. Both the storm and maximum dew points from representative stations are reduced to a standard isobaric level of 1000 mb. While selecting these stations, care should be taken that the representative stations or set of stations lie between the moisture source and the rain area in the region of inflow of warm moist air into the system causing the rainstorms.

Based on the values of maximum dew point and prevailing dew point for the storm period and reduced to 1000 mb. isobaric level, the atmosphere upto a level of 200 mb. is obtained with the help of a graph showing the depth of precipitable water in a column of air of given height above 1000 mb. The ratio of the maximum moisture content 'd_1' to the prevailing moisture content 'd_2' during the storm gives the moisture maximisation factor d_1/d_2 for the rainstorm.

Care should be taken that the maximum dew point pertains to the same period of the year to which the storm pertains. The prevailing dew point data is generally compiled for both the principal synoptic hours for the period from a day prior to the day after the occurrence of the mainstorm and so-called highest persisting 12-hr. or 24-hr. dew point is generally used.

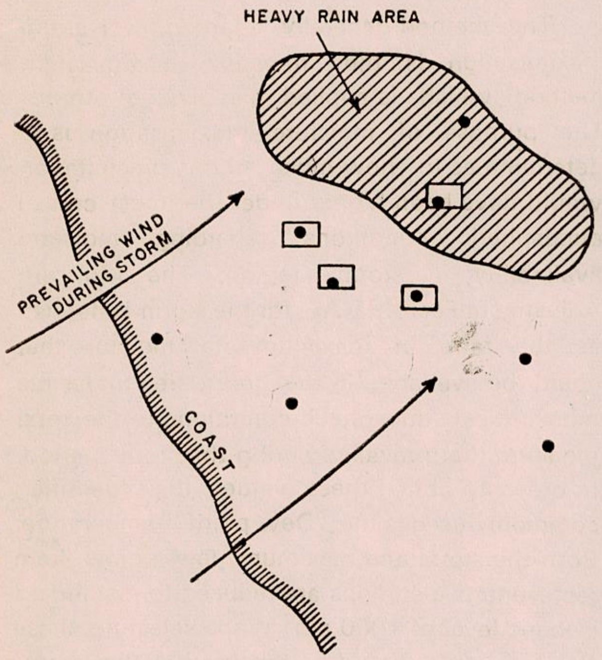


Fig. 5 Determination of maximum dew point in a storm.

5.1 Moisture adjustment for re-location :

It is well known that the areas near the coast are more damp than those inland and the moisture parameter varies from region to region and from season to season. It is likely that the transposed location may be an area either in proximity of the moisture source or be away from it and hence in the transposed position of the storm the moisture content entering the storm will accordingly change and a suitable adjustment has to be made for this change assuming that the storm mechanism remains the same at the transposed locations.

Moisture adjustment due to transposition is derived from the charts of maximum dew point temperatures reduced to 1000 mb. level for the fortnight/month to which the storm pertains. If D_1 is the maximum dew point at location A where the storm actually occurred and D_2 is the maximum dew point at location B to which the storm has been transposed and if W_1 and W_2 are the corresponding precipitable water, then the transposition adjustment factor $K_t = W_2/W_1$, where W_2 is max. precipitable water at location B to which storm has been transposed and W_1 is max. precipitable water at location A where the storm actually occurred. K_t will be greater or less than unity depending upon whether the transposition is carried out towards or away from the moisture source.

The average basin depth obtained by the transposition of the storm from location A to location B will then be multiplied by transposition adjustment factor to obtain representative basin raindepths. The enveloping depth-duration curve to the adjusted raindepths may be taken as standard project storm values for various durations for the project basin.

5.2 Storm Maximisation and Transposition adjustment for PMP :

If it is desired to obtain PMP depths from a transposed storm, then the storm is first adjusted for moisture charge at its original location before it is transposed to the new location. The adjustment factor K_m at the original location of the storm is equal to the ratio of precipitable water corresponding to the maximum persisting dew point for the fortnight (month) in which the storm occurred to the precipitable water corresponding to the highest persisting dew point. If W_1 is the precipitable water corresponding to the maximum persisting dew point at the location of the storm and W_3 is the precipitable water corresponding to the persisting storm dew point, then $K_m = W_1/W_3 = \dfrac{\text{Max. precipitable water on record at storm location}}{\text{Persistent Strom precipitable water}}$

Having adjusted the storm at its original location of occurrence the storm is then transposed to the problem basin. At its transposed location it is again adjusted for change of moisture at the new location. The transposition factor K_t for change in location $= W_2/W_1$

The combined storm adjustment factor

$$K_c = K_m \times K_t = \frac{W_1}{W_3} \times \frac{W_2}{W_1} = \frac{W_2}{W_3}$$

$$= \frac{\text{Precipitable water for the maximum dew point at the transposed location}}{\text{Precipitable water for the representative storm dew point}}$$

5.3 Barrier Adjustment :

Storm transposition across mountains of lesser elevation become unavoidable because basins upstream from a proposed dam site are often rimmed by mountains or hills. Transposition of storm across barriers higher than about 700 mb. (3 km.) above the elevation of the observed storm site is generally avoided because of their dynamic influence on storms. Barriers adjustment is carried out in storm transposition for low elevation barriers. In case of such low elevation barriers, the storm potential is decreased by a certain percentage while crossing these barriers as mountain ranges block off a certain percentage of moisture inflow into the transposed storm. Storm potential may be assumed to have decreased by the ratio the precipitable water in a column of air at the mountain crest to the precipitable water at the foot of the mountain.

If the precipitable water in a column of air at the crest of the barrier is say W_4 and the precipitable water in the column of air at the foot of the barrier is W_5 then the transposition adjustment for the barrier

$K_b = W_4/W_5 = \dfrac{\text{Precipitable water at the crest}}{\text{Precipitable water at the foot of the barrier}}$

6 0 PMP by Statistical Method :

An interesting variation of the foregoing PMP method is an attempt to approach the PMP statistically. This idea comes from Hershfield (1961). He proposes that the 24-hr. PMP at a precipitation observing point be estimated from the generalised frequency equation (Chow, 1964) in the from :

$$X_{max} = \bar{x} + KS_n$$

The data required for this evaluation are the maximum observed daily precipitation during each year of record. $\bar{x}$ is the mean of this series and Sn is the standard deviation of the series. X_{max} is the desired PMP. K is a constant to be determined emperically by an enveloping process.

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TIME DISTRIBUTION OF RAINSTORMS OVER THE INDIAN REGION

By

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1. Introduction :

The choice of design rainfall is a basic step in any method for estimation of design flood. It is however, important to recognize that the shape and magnitude of the flood hydrograph is very much affected by the distribution of rainfall within the storm period. In nature a wide range of storm patterns are possible. Some storms have their peak intensity occurring early while other storms have the peak rainfall intensity occurring towards the end of the storm and some have a tendency for the peak to occur more or less centrally. In some other situations the rainfall may be uniformly distributed. As such, knowledge of the amount of temporal variation of rainfall intensity throughout a storm period and of the peak intensity is of great interest to hydrologists concerned in the application of the design rainfall to design flood estimation.

A few studies on time distribution of Indian rainfall were carried out in the Hydrometeorology Division of I. I. T. M. This is based on data of rainstorms occurring during the monsoon months of June to September. Salient features and some results of these studies are given in the succeeding sections.

2. Short duration rainfall analysis of Calcutta (Dum Dum) :

A study of autographic rainfall records of Dum Dum observatory (Calcutta) for a period of 18 years (1948 to 1965) was made by Dhar and Ramachandran (1970). The observed extreme annual rainfall amounts recorded during each of the durations of 1. 2, 3, 6, 12,18 and 24 hours were extracted from the hourly rainfall tabulations. Using Gumbel (1954) technique, the extreme annual values for 2 to 25 years return period for different durations were calculated. The maximum rainfall intensity for different durations and return periods worked out by the authors are given in table 1.

Table 1 : Maximum rain intensity (inches/hr) for different durations and return periods.

Duration (hrs)	2-year	3-year	5-yr	7-yr	10-yr	15-yr	20-yr	25-yr
1	1.84	2.05	2.27	2.40	2.55	2.73	2.85	2.93
2	1.20	1.37	1.57	1.70	1.85	2.00	2.10	2.19
3	0.90	1.03	1.18	1.27	1.35	1.46	1.52	1.57
6	0.53	0.60	0.67	0.73	0.78	0.83	0.88	0.92
12	0.31	0.36	0.42	0.45	0.49	0.53	0.55	0.57
18	0.23	0.27	0-31	0.34	0.37	0.40	0.42	0.44
24	0.18	0.21	0.25	0.27	0.29	0.33	0.34	0.36

Table 2 : Mean percentage ratios of different durations to 24-hr and 48-hr maximum rainfall.

	Duration (hours) of							
	1	2	3	6	12	18	24	36
Mean % ratios of 24-hr rainfall.	27	39	46	58	75	87	—	—
Mean % ratios of 48-hr rainfall.	17	25	30	39	50	59	71	91

This study is useful for the design of local drainage works, road culverts and railway bridges and also estimating peak discharge for small basins.

The authors also studied the actual distribution of rainfall during some of the rainstorms whose total duration was 24 hours or more and which yielded 3 inches or more of rain. In all 25 such spells of rain were experienced and the maximum rainfall recorded during different durations of 1, 2, 3, 6, 12, 18, 24 etc. in each of these 25 rainspells were extracted. Percentage ratios of maximum rainfall recorded in each of these durations to that recorded during 24 and 38 hours were then worked out for each rainspell. The mean percentage ratios for different durations are given in Table 2 :

3. Time distribution of 10-12 August, 1979 rainstorm which caused the Morvi dam disaster in the Saurashtra region:

Dhar et al (1981) studied in detail the rainstorm which caused the Morvi dam disaster on 11th August, 1979. The autographic records of Bhavnagar, Porbhandar and Veraval stations, which were close to the rainstorm area were used to determine the time distribution of 10-12 August, 1979 rainfall. Fig. 1 shows the time distribution curves of these stations for 2-day duration. Maximum basin raindepths for short durations for 72-hour are given in Table 3.

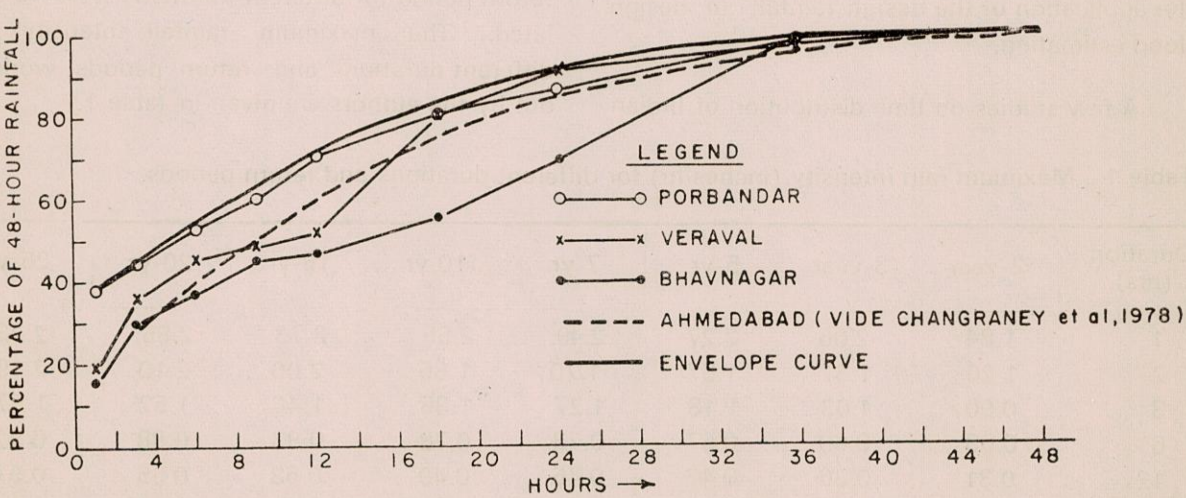

Fig. 1 Time Distribution of 48-Hour Rainfall of Self Recording Rainfall Stations Near the Rainstorm of August, 1979 Over Saurashtra Region.

Table 3 : Maximum basin rain depths for short durations for the 10-12 August, 1979 storm

Hours	1	3	6	12	18	24	36	48	72
Rainfall (cm)	14.1	16.7	20.8	26.8	31.2	34.2	36.4	37.2	44.7

4. Time distribution of unprecedented rainfall at Sambalpur in August, 1982 :

Dhar et al (1985) studied the time distribution of the unprecedented rainfall of 58 cm recorded at Sambalpur in Orissa on 19th August 1982 by using autographic data of Hirakud and Jharsuguda stations. Time distribution of these stations is shown in Fig. 2. From the slopes of rainfall curves of these two stations, it appeas that rainfall intensity was maximum at Hirakud which recorded about 29 cm in 6 hours.

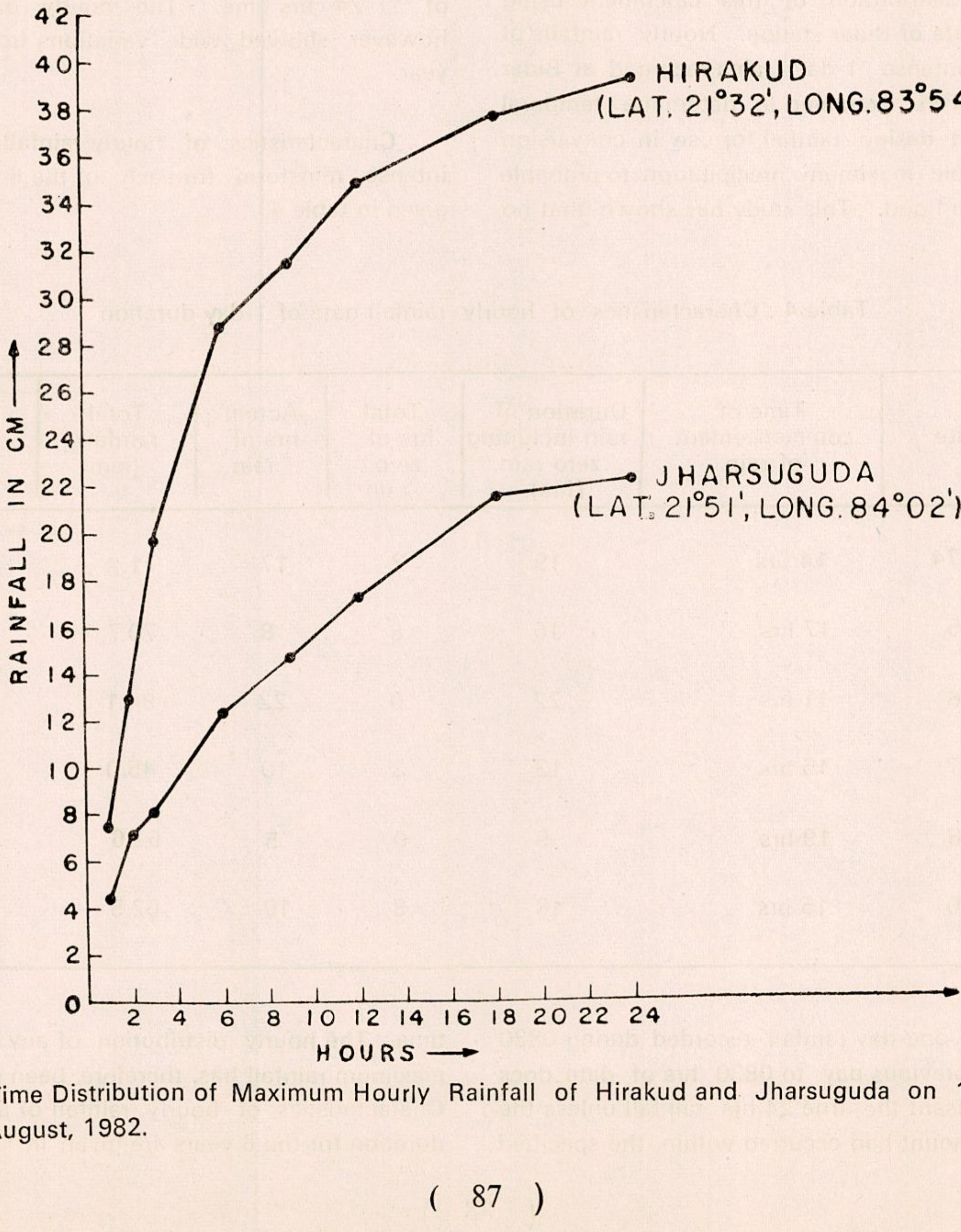

Fig. 2 Time Distribution of Maximum Hourly Rainfall of Hirakud and Jharsuguda on 18th-19th August, 1982.

5. Analysis of hourly rainfall distribution of Karanja catchment :

A hydrometeorological study of the Karanja catchment upto the Halhalli dam site (area 2025 km^2) located in the northern part of Karnataka and adjoining Andhra Pradesh was studied by Ramana Murthy et al (1985) in order to estimate the design raindepths.

Rakhecha et al (1985) studied the hourly rainfall distribution of this catchment using hourly data of Bidar station. Hourly rainfalls of 6 most intense 1-day rains recorded at Bidar station were examined to determine temporal pattern of design rainfall for use in conversion of probable maximum precipitation to probable maximum flood. This study has shown that no single typical storm pattern exists for the catchment. Two common patterns could be recognized, one with a peak intensity occuring early in the storm and other with peak intensity just after the middle of the storm. The average variability method has been applied to derive the design temporal patterns. It was found that during 1-hr as much as 56% of 1-day rainfall can occur and the two consecutive hours may account for 73% of total 1-day rainfall. The general occurrence of greatest inter hourly intensity however seemed to be during periods of 17-24 hrs time. The hourly distribution, however showed wide variations from year to year.

Characteristics of hourly rainfall of 1-day intense rainstorm for each of the 6 years are given in table 4.

Table 4 : Characteristics of hourly rainfall data of 1-day duration

Storm date	Time of commencement of rain	Duration of rain including zero rain (hrs)	Total hrs of zero rain	Actual hrs of rain	Total rainfall (mm)	mean Intensity mm/hr
23.10.1974	14 hrs	19	2	17	71.3	4.2
4.10.1975	17 hrs	16	8	8	70.7	8.9
21.7.1976	11 hrs	22	0	22	84.1	3.8
29.9.1977	15 hrs	13	3	10	45.0	4.5
2.10.1978	19 hrs	5	0	5	67.6	13.5
20.8.1980	15 hrs	18	8	10	62.5	6.3

The one-day rainfall recorded during 0830 hrs of previous day to 0830 hrs of date does not represent the true 24 hrs rainfall unless the entire amount had occurred within the specified time. The hourly distribution of any 24 houss maximum rainfall has, therefore, been examined. Characteristics of hourly rainfall of any 24 hrs duration for the 6 years are given in Table 5.

Table 5 : Characteristics of hourly rainfall data of any 24 hours duration.

S.No.	Rain period (in hrs)	Total 24-hr rainfall (mm)	Mean intensity mm/hr	Max. 1-hr intensity mm/hr	% of 24-hr rainfall
1	14th of 22-10-1974 to 13th of 23.10.1974	71.8	2.99	8.8	14
2	17th of 3-10-1975 to 16th of 4.10.1975	70.7	2.95	32.5	46
3	12th of 20-7-1976 to 11th of 21.7.1976.	97.3	4.05	16.5	17
4	15th of 28-9-1977 to 14th of 29-9-1977	45.0	1.87	17.2	38
5	19th of 1-10-1978 to 18th of 2-10-1278	77.6	3.23	31.7	41
6	15th of 19-8-1980 to 14th of 20.8.1980	65.7	2.74	35.0	53

The average patterns of 1-day and any 24 hrs heaviest rainfall obtained from 6 most intense storms are shown in Figs. 3 and 4 respectively.

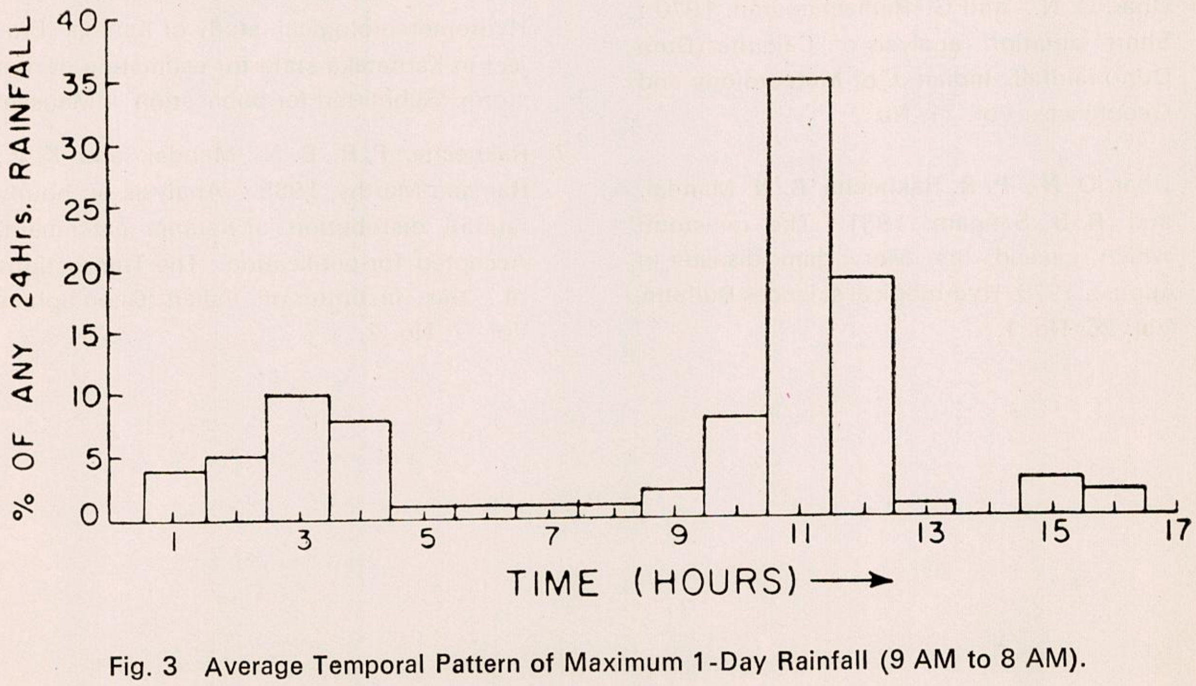

Fig. 3 Average Temporal Pattern of Maximum 1-Day Rainfall (9 AM to 8 AM).

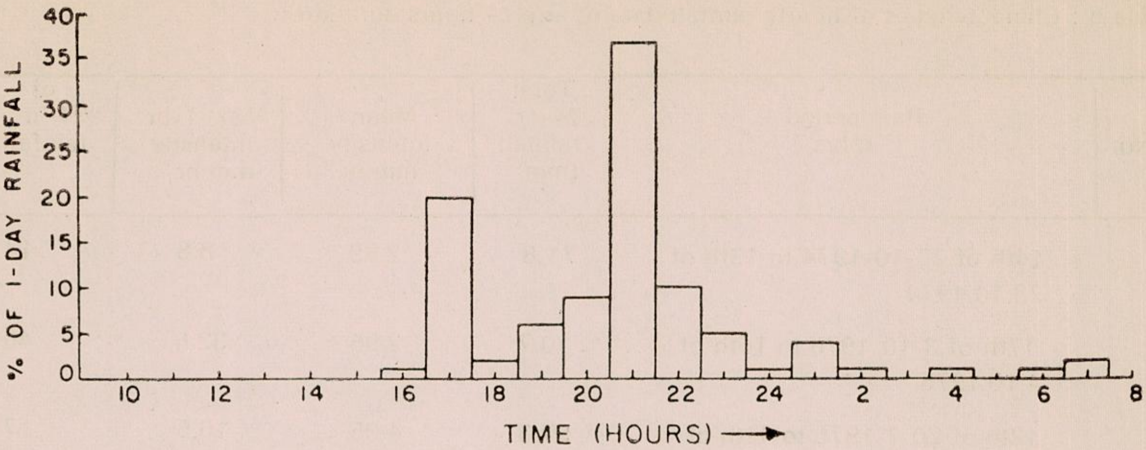

Fig. 4 Average Temporal Pattern of Maximum 24 Hours Rainfall

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METEOROLOGIGAL FORECASTING

by

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1. Introduction :

The atmosphere is always in a state of constant motion. The ultimate energy source for this is derived from the Sun. Since the atmosphere is transparent to most of the wave lengths of the solar radiation, the solar beam is received at the earth's surface without much attenuation while passing through the atmosphere. The underlying surface of the earth absorbs the solar radiation and gets heated up. Hence the source of heat for the atmosphere is at the earth's surface. This energy at the earth's surface is unevenly distributed, both in space and time, in view of (i) uneven distribution of the land and sea areas (ii) their varying capacities of absorption and of reflection of the short wave radiation from the Sun (iii) the apparant migration of the Sun and (iv) the rate of evaporation from the water bodies. The atmospheric motion, therefore, results in redistribution of energy from the source region i.e. equatorial belt to the regions of heat sink i.e, the polar regions. The capacity of the water vapour in the atmosphere, to be present in its three phases, namely vapour, liquid and ice, adds the complexity of the atmospheric motion while redistribution of energy within the atmosphere takes place. In spite of this complexity, the atmospheric motion field, viewed from a long term basis, results in well defined climatic flow patterns, known as the general circulation of the atmosphere. Short period fluctuations result in weather producing systems in the atmosphere. Thus the study of energetics of the atmosphere shall form the basis for weather prediction. The scales of the atmospheric motions and their mutual interaction need be understood to predict the future state of the atmosphere from a given state of initial conditions,

2. Climatology and weather :

The general circulation of the atmosphere may be considered as a gross picture of the global circulation pattern required for transporting of excess solar energy received in the tropics to the polar regions. The general circulation may be looked upon from two different angles. Firstly, it may be considered as the most representative average of all circulation patterns covering the entire globe, the average being worked out for a fairly long enough period, say 30 years, but not so long as to include climatic changes. Here we take advantage of the fact that the climate of a place is fairly constant over short periods though it may change completely during the course of several centuries. The concept of treating general circulation as a gross average picture of all circulation patterns has led to the development of climatology. If physical processes leading to temporary changes are understood or observable, then the large scale and persistent deviations from the mean pattern can be associated with subsequent changes. This concept provides us a basis for long range weather prediction i.e forecasting of weather conditions months or seasons ahead. Secondly, the general circulation may be considered as a basic motion on which transient motion fields associated with weather are superimposed. There is a large spectrum of such fields of motion. They range from those associated with characteristic bulging or contracting changes of the semipermanent anticyclones and their temporary shift from their mean position, mid-latitude cyclones, tropical depressions and cyclonic storms to smaller scale systems down to whirls and dust devils. This view has given rise to look upon these phenomena as embedded eddies of different sizes in the general flow pattern of the global circulation. Concentrating our attention on these eddies and their evolution i.e. origin, development, and decay in relation to the other eddies and flow patterns, we shall have a basis of weather forecasting whose validity could extend from a few hours to a few days. These constitute short range and medium range forecasts. These two views are complementary. In both the cases climatology plays an important role in weather forecasting.

Even though the weather at a given locality at any instant of time can result from a specific weather system, the system by itself is not independent of the influence of other synoptic scale or even global scale weather systems. There is a large spectrum of atmospheric motion fields with specific mutual interactions some of which are yet to be understood fully.

3. Scales of atmospheric motion systems

The spectrum of the horizontal scales of atmospheric motion ranges from the size of the planet earth to that of molecular motion. However, most of the atmospheric motion systems are clustered around the following four scales :

3.1 Planetary Scale

These are the atmospheric motion systems of horizontal dimensions that are comparable to the size of the major continents and oceans. These systems appear to be semi-permanent for over a period of a month to a season. Monsoons, jet streams, slow moving waves in the mid latitude westerlies known as Rossby Waves, subtropical anticyclones over oceans are examples of horizontal motion in the atmosphere coming under the planetary scale. Hadley circulation is an example of both horizontal and vertical circulation field in the atmosphere which is large enough to be considered under this scale.

3.2 Synoptic Scale

The synoptic scale systems are the waves or vortices in the atmosphere of horizontal size of about a few thousand kilometers which are large enough to be studied by conventional meteorological data gathered from a network of meteorological stations with spacing of about a few hundred kilometers. The life cycle of synoptic scale system is normally about a week. Depressions and cyclones, easterly waves, east moving troughs in westerlies associated with frontal depressions arising out of imbalance in pressure and density fields within the atmosphere (baroclinic waves), and western disturbances are some examples af this scale. The phenomena associated with some of these systems like cold and heat waves depending on their horizontal extent may also be treated as synoptic scale systems.

3.3 Meso-Scale

Atmospheric systems with horizontal size ranging from a few tens to a few hundred kilometers come under the meso - scale. Conventional meteorological data are not adequate to study these systems. Either special network of observatories are to be established or more sophisticated meteorological equipments like radars and satellites need be employed in delineating meso-scale systems. Life time of such systems is hardly a few hours. Frontal zone, squall lines, rain bands associated with severe cyclonic storms and mountain and lee waves are a few examples of meso-scale systems.

3.4 Small Scale

Still smaller ranges of atmospheric motions give rise to small scale weather systems of the size of a few kilometers or even less. The life cycle of such systems may be of the order of an hour or less. Ground frost, thunder storms, tornadoes, dust devil, thermals and turbulence may be cited as examples coming under this scale.

4. Basis of Meteorological Forecasting :

All the above scales of motion covering entire spectrum of the atmospheric motion field is simultaneously present. Different scales of motion, exhibit mutual interaction among themselves. The future evaluation of weather systems depend on their state. Hence in order to be able to predict weather over a given area one has to understand the weather systems affecting that area at a given time. Further, a knowledge of such of those systems that are likely to affect the forecast area in course of time is also necessary. For this purpose a large number of meteorological observations recorded at a specified hour are plotted on a chart and analysed. During this process, the analyst delineates various weather systems and visualises the weather at the time of observation as well as the physical processes responsible for them. He gets a full insight into the evolution of different synoptic systems by comparing present weather chart with the preceding one. Continuity of weather systems has to be kept in his analysis. A series of weather charts starting from the one at the earth surface to high levels extending to stratosphere are generally prepared and analysed. Such analysed charts are known as synoptic weather charts. The main purpose of weather analysis is to predict weather. By taking into consideration of the relevant laws governing the initial atmospheric flow patterns it should be possibl e to determine its future state. This thinking has led to the concept of Numerical Weather Prediction (NWP). However, the equations governing the atmospheric motion field are nonlinear. These are to be taken together with other physical laws that determine the energy and mass conservation. Thus, when the full set of equations which can completely specify the initial state of the atmosphere, consistent with a given set of synoptic observations are developed, they can only be solved with specific boundary conditions by numerical integration techniques on large computers. The change of state of water in the atmosphere leading to local heat changes within the atmosphere, the influence of the land topography, the energy exchange between the sea/land surface and the lower layers of the atmosphere, and the radiation balance at the earth's surface and the influence of the clouds on the same are a few physical processes which need be parameterised and suitably incorporated in the numerical models of the atmosphere. In recent years considerable work has been done in this area and as such it can optimistically be hoped that in very near future it should be possible to predict the atmospheric flow patterns for periods of about ten day's validity Such models are routinely available for extratropical regions. However, mainly due to poor corialis balance and intense convection modelling of the tropical atmosphere is more complicated.

While NWP is fast developing and holds much promise, the conventional synoptic method of weather forecasting is mostly used for short range weather prediction. In the synoptic approach weather producing systems are identified and their evolution is assessed taking physical processes involved into consideration in somewhat a subjective manner. Hence, this approach calls for considerable experience on the part of the forecaster.

Low pressure systems are the areas of precipitation. In the regions of anticycones fine weather prevails. Since vertical ascent of the air is a prerequisite for the formation of clouds and precipitation, the low pressure areas and upper air cyclonic circulations should be associated with vertical upward motion, while descent of air should occur in the regions of high pressure and or upper air anticyclonic circulations. The vertical component of the wind velocity is very small compared to the horizontal motion field. Hence it cannot be measured. Its presence is assessed from the apparent horizontal wind circulation. Here the concepts of vorticity and divergence play an important part. Both these parameters can be obtained from the horizontal motion field. Vorticity and divergence are not independent of each other. These parameters can be computed from the observed wind field. The horizontal divergence/convergence gives an idea of the type of vertical motion field in the atmosphere. Similarly, magnitude and sign of vorticity and its changes are again related to vertical motion field. Though these parameters are not routinely calculated in a synoptic laboratory, they are kept in view in weather forecasting.

From the hydrological point of view, forecasting of occurrence of rainfall and its intensity is very important. Now, with this background we can visualise weather forecasting as consisting of the following steps :—

(i) Identification of weather producing systems.

(ii) Forecast of their intensity changes.

(iii) Forecast of movement of the systems.

(iv) Forecasting the area and duration of precipitation and

(v) Forecasting intensity of precipitation.

Identification of weather producing systems like low pressure areas, troughs etc. is done through the analysis of weather charts. Forecast in change of intensity of weather systems is possible by considering several factors. If the surface pressure is falling or shows large departures from the normal then the system is likely to intensify. A low level convergence or a high level divergence or both, and increasing positive vorticity indicate the deepening of the system. A series of vorticity, divergence, vertical velocity charts derived as NWP products read together with the current weather charts will give a good insight into the possible intensity changes of synoptic scale systems:

Weather systems generally move towards areas of pressure fall. Sometimes the direction of movement is towards an area where advance rainfall would have occurred. Often satellite cloud pictures indicate characteristic clouding a head of the system thereby suggesting the possible movement towards that area. Dynamically, a weather system can be considered as a superimposed synoptic scale circulation on the general flow pattern of the atmospheric motion field. Hence the synoptic system should move with the mean flow within which it is embedded, so long as its interaction either with the mean flow or with other synoptic scale systems in its vicinity is ignored. If this interaction can be assessed, then taking into consideration of the mean flow, the movement of the system can be predicted. A single system cannot be considered in isolation. Its interaction with other systems on the chart should be fully understood. Upward motion of airmass ahead of a weather system is a strong indication of its movement towards it,

From the present and past weather, the extent of precipitation associated with a system is assessed. An analysis of the cloud patterns, source of moisture supply, and consideration of its likely movement, intensification or otherwise enables the forecaster to indicate the future area likely to be affected. The past history of the system is always kept in view. The forecaster's experience in dealing with similar situations is very vital, as no forecasting rules can be enumerated to cover all possible synoptic combinations. The duration of precipitation is dependent on the stage of development of the system, its earlier history and its interaction with other weather disturbances. A climatic knowledge of the behaviour of similar systems is highly useful.

Precipitation is not evenly distributed around a synoptic weather system. There are generally small areas of concentrated heavy rain associated with each type of weather system. The climatology and persistence of weather is helpful for intensity forecasts. The intensity forecast has to be consistent with other aspects described above. In addition, frequent monitoring of intensity of rainfall through a network of automatic weather stations together with frequent observations from sophisticated aids like radar or satellite will be necessary to monitor the intensity changes of weather systems and to update the forecast.

5. Data requirements :

Initial inputs of a large amount of synoptic data from an adequate area is the starting point for meteorological forecasting. For different ranges of forecasts, different areal coverages of the atmosphere need be studied. For long range we need hemispherical or global atmospheric sampling and analysis. For medium range forecasting covering a period of the order of about a week, the atmospheric conditions over a vast area are required so as to cover a large number of migrating weather systems that could affect the forecast area. For making short range forecasts of the order of a day or so the areal coverage is much less but it should cover all weather systems likely to move and affect the forecast region. For ultra short range forecasts or nowcasting having a period of validity of few hours, we need purely local observations at frequent intervals together with a knowledge of the weather system affecting the area. For this purpose conventional meteorological data need be supplemented with frequent radar and geostationary satellite observations. For short range weather predictions made at intervals of 3 to 12 hours may be sufficient. However the data requirements depend on the variability of the parameter to be observed. Further, the frequency also depends on the life history i.e. the genesis, development, maturity and decay of the weather system under consideration. Based on these considerations a broad classification of weather systems, data requirements for their analysis and forecast, types of forecasts and their utility are given in Table I. In all these cases the vertical air column to be sampled may be roughly taken as the troposphere and sometimes the lower stratosphere. For forecasting certain special phenomena, even surface and low level observations may be sufficient.

Forecast needs are different for different human activities. But in all cases, the basic parameters to be monitored are essentially the same. They are atmospheric pressure, temperature, humidity, wind speed and wind direction. For general purposes, forecast of temperature, wind and rainfall is a regular requirement.

Weather warnings against severe adverse weather conditions are needed for taking appropriate precautions. The horizontal extent of a particular weather phenomenon naturally depends on the size of the system that produce it. The intensity of weather is related to the intensity of the weather system. Thus, a forecaster should identify weather systems from a mass of meteorological observations, gauge their intensity, understand the state of their development and finally assess their likely changes subsequent to the time of observation before he finally makes a weather forecast.

TABLE I

Classification of weather system data requirements and weather analysis and forecasts and their utility

System	Horizontal scale	Observation needs	Type of analysis and forecasts	Significance
Planetory scale eg. Macro-scale-General circulation Trade winds, continental anticyclones, large scale perturbations in general circulation	Very large - thousand of Kms often hemispherical	Means and departure from climatic averages of meteorological parameters for seasons/months/weeks	Statistical synoptic and NWP methods long range forecasts valid for months or seasons ahead and medium range valid for a week or 10 days	For long term planning
Synoptic scale eg. depressions, cyclones etc.	Hundred to thousands of Kms.	Observations several times daily	Synoptic supported by N W P techniques. Short range valid 2 to 5 days	For basic weather sensitive operations and for taking precaution against adverse weather
Meso-scale eg. Thunderstorms	Tens of Km. around the station	Continuous watch to $\frac{1}{2}$ hourly observations plus radar and geostationary observations	Detailed meso-scale analysis and extra polation based on physical and climatic reasoning very shorts : upto half a day validity (Now casting)	For taking precautions in all weather sensitive operations
Micro-Scale Small-scale eg. Tornadoes. squalls, local fog etc.	One Km. or less	Continuous and special type of observations from radars satellites and other special instruments	Time section analysis extra-polation of instrumental observations to together with guidance from synoptic climatological emperical relationship nowcasting for a few hours ahead	—do—

MODELLING OF PRECIPITATION

by

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1.0 Introduction

The principal use of meteorological forecasts in operational hydrology is as input to hydrological forecasting systems. Meteorological forecasts could be used to prolong the lead time of the forecast and enhance the accuracy and reliability of hydrological forecasts. Short term hydrological forecasts are generally based on precipitation forecasts for periods ranging from 6 to 48 hours. For other activities such as agriculture, water management and reservoir operation etc., the forecasts are required over longer periods of time (medium and long range forecasts).

The W M O Commission for hydrology at its sixth session held in 1980 has identified the following meteorological forecasts for use in operational hydrology :

—Quantitative precipitation forecasts (QPF) for 6, 12, 24 and 48 hours.

—Forecasts of maximum and minimum air temperature and dew point, wind and sky conditions for three to five days.

—Long range forecasts of precipitation and temperature for 30 days or more.

—Forecasts of hourly wind speed and direction for 24 hours or more.

Considering the current trend towards using rainfall-runoff models to simulate a catchments response from precipitation input, improvements in the timeliness of hydrological forecasting will depend largely on the progress made in rainfall prediction. Reliable precipitation forecasts are also the basic and most important input to operational on line forecasting schemes used in short term computerized control strategies for the management of multipurpose reservoir systems and river regulation works. Also, there is need for precise forecasts of short duration high intensity rainfall which is known to cause flash floods in small catchments and urban storm water drainage systems.

With the increased use of more complex hydrological models in operational practice, the demand for more reliable precipitation forecasts is increasing.

2.0 Formation of Precipitation

Precipitation results from the lifting of air mass, resultant cooling and saturation of moist air. Rainbird (1968) had listed four conditions as necessary for the production of heavy rainfall

(i) a lifting mechanism to produce cooling of the air,

(ii) a mechanism to produce condensation of water (cloud) droplets,

(iii) a mechanism to produce growth of cloud droplets to sizes capable of falling to the ground against the lifting mechanism,

(iv) a mechanism to produce sufficient accumulation of moisture to account for observed rainfall rates

Individual rainstorms contribute widely differing amounts of rain. The variation of precipitation in space and time is largely determined by spatial and temporal variations in the vertical motion of air. This vertical motion results from processes within the atmosphere and interaction between the atmosphere and underlying surface of the earth. Both types of processes operate on small (mesoscale) medium (sub-synoptic scale) and large (synoptic scale) scales.

Systematic observations on diverse storm types indicated the consistent occurence of certain sub-synoptic features with similar characteristics and behaviour. Austin and Houze (1972) reported some of these sub-synoptic features.

Precipitation areas of synoptic scale (areas greater than 1000 km^2) contain sub-synoptic precipitation areas (large meso scale areas). While the synoptic areas have a life span of one to several days, the life span of the large mesoscale areas was found to be within the order of several hours and their number within a synoptic area has been observed to be ranging from one to six. The large mesoscale systems move in relation to a synoptic area. The precipitation intensity inside a large mesoscale system is always high than the region surrounding it. The small mesoscale areas build and dissipate within a large mesoscale area with an average life span of a few hours (Figure 1). These mesoscale systems contain regions of cumulus convective precipitation, commonly known as 'convective cells'. The cells build and dissipate within a few hours and generally occur in clusters.

Convective vertical motion occurs in the convective cells with a diameter of about 1.5

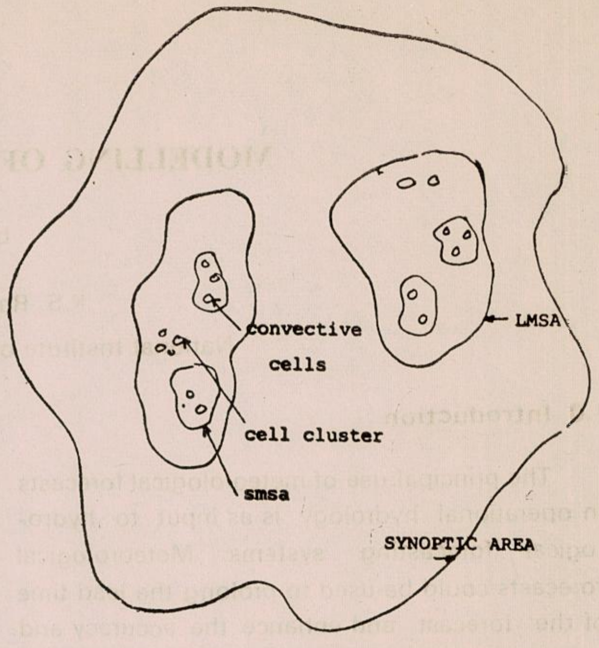

Fig. 1 A schematic depiction of subsynoptic rainfall features (Waymire and Gupta, 1981)

to 8 km and a vertical extent from about 1000 m to more than 15000 meters. The amount of rainfall they yield is closely related to their vertical extent and the amount of water vapour in the air. The convective cell mechanism predominates in tropical regions' rainfall and in the warm season rainfall of many higher latitude regions.

Banded vertical motion is usually associated with a front or other zone of convergence or is the result of orographic lifting. The upward motion of air generally occurs over a band from a few kilometers to about 80 kms in width and several hundred kilometers in length. Spatial variability of rainfall resulting from a banded system depends to a large extent on the stability of the lifted air.

General vertical motion is associated with large scale synoptic features such as depressions and upper level cold lows. Organised convection bands are known to occur in extra-tropical storms.

3.0 Precipitation Forecasting

Depending on the type of activity for which they are issued precipitation forecasts could be broadly grouped under the following time scales :

(i) Short-range prediction

(ii) Medium-range prediction and

(iii) Long-range prediction.

Short range forecasts ranging from 6 to 48 hours are given for flood forecasting purposes. Medium range forecasts of at least 3-7 days validity are required for agricultural purposes, reservoir operation and drought management.

Long range forecasts are issued for planning purposes. For example monsoon season rainfall forecasts are issued in India before the monsoon season to help the government organisations for planning agricultural and other socio-economic activities.

Different varieties of models have been developed and tested the world over for predicting precipitation over different ranges of time periods. Some of these models and techniques are reviewed here. The review is only indicative and not exhaustive.

4.0 Modelling of Precipitation

Models of precipitation in space and time can be grouped into three broad categories.

The first category consists of the numerical modelling of space time rainfall on the basis of the principle of fluid mechanics and thermodynamics.

The second category includes numerical simulation of rainfall on the basis of certain empirical regularities which space time rainfall has been observed to exhibit.

The third category includes analytical modelling of rainfall as a random field.

4.1 Numerical Modelling

In the numerical modelling generally known as Numerical Weather Prediction (NWP), given the initial state of the atmosphere, its future state is determined through time integration of the mathematical equations governing the physical laws of the atmosphere. Tremendous strides were already made in NWP at advanced research centres in USA, Japan and other European countries during the last three decades.

Noting the great potential offered by the NWP and its relevance to day to day forecasting of tropical weather systems, the India Meteorological Department, Indian Institute of Tropical Meteorology, Poona and Indian Institute of Technology, New Delhi have also inititated the numerical modelling studies and had made considerable progress in developing simple models for short range precipitation prediction.

A description of some of the NWP models and their later day modifications could be seen in Lighthill and Pearce (1981) and Rama Sastri and Pratap Singh (1985-86).

Fairly simple models which ignore or grossly simplify some parts of the problem can be used to explore specific aspects. One dimensional models which treat the atmosphere as a single vertical column do not take cognizance of the influence of atmospheric motions and provide no information on the geographical distribution of climatic parameters. Two dimensional models which assume that complex atmospheric motions can be represented by averages over latitude bands are more realistic than one-dimensional models. By far, the most promising are the three dimensional numerical models which treat the atmosphere as a vast, turbulent, rotating fluid heated by the Sun and exchanging heat, moisture and momentum with the underlying continents and oceans and which allow for monthly and seasonal changes in solar radiation, ocean surface temperatures, ice cover etc.

These models provide prognostic charts of vorticity, divergence and vertical motion and prognostic charts of wind field. They depict large scale flow patterns of the atmosphere which in turn are used by the analyst meteorologist to predict weather in general and possible areas of precipitation occurrence. The model outputs of the NWP scheme are thus more of qualitative nature rather than quantitative as far as precipitation forecasting is concerned.

4.2 Quantitative Precipitation Forecasting

To make accurate flood forecast an idea of the rainfall that is expected to occur in the catchment area during the next 24 or 48 hours is essential. The quantitative precipitation forecasting as is applied in hydrology, assumes great importance even when no flood is involved because these forecasts enable one to conserve and utilise the available water resources.

Attempts at computing precipitation rates were originally carried out by Fulks (1935) and Takahashi (1935).

Rainbird (1968) and Rao (1973) reviewed some of the methods of estimating qnantitative precipitation which include :

(i) subjective forecasting techniques

(ii) statistical forecasting techniques

(iii) dynamical approach based techniques

Subjective techniques rely on the experience, skill and insight of the forecaster. The statistical techniques relate expected rainfall amounts over a particular locality or river basin to meteorological parameters using statistical procedures which include graphical and mathematical correlation and regression techniques. The dynamical approach use equations involving evaluation of moisture and vertical motion fields. Simplifying assumptions were sometimes made for establishing the relationships describing the rate of rainfall.

4.2.1 Statistical approach

Initially studies were carried out by IMD using statistical methods applying Brier's (1946) method. In this method an area was selected for the purpose of calculating rainfall about 24 hours in advance. The meteorological parameters were selected on the basis of study of synoptic situations during a period of 30 years. The parameters selected were :

(i) 0830 hrs. Pressure at Station A (X_1)

(ii) 1730 hrs. Pressure of Previous day A (X_2)

(iii) 0830 hrs. Pressure at Station B (X_3)

(iv) 1730 hrs. Pressure of Previous day at B (X_4)

(v) 0830 hrs. Dew point at Station C (X_5)

(vi) 0830 hrs. Dew point at Station A (X_6)

(vii) 0830 hrs. surface wind at Station D (Y_1)

(viii) 0830 hrs. surface wind at Station C (Y_2)

(ix) Difference between 0830 hours pressures at Station A and Station B (Y_3)

(x) Difference between 0830 hours pressures at Station B and Station D (Y_4)

The solution for the above was obtained by successive coaxial graphical method. The verification of forecast and actual rainfall was done by considering another set of values which were not used in developing the coaxial diagram.

Using similar parameters as in the graphical method, multi valued linear regression equations were developed which is of the form as below (Narasimha Rao, 1973)

$$Y=\bar{y}+b_1(X_1-\bar{X}_1)+b_2(X_2-\bar{X}_2)+\ldots\ldots b_8(X_8-\bar{X}_8) \qquad \ldots(1)$$

Where

X_1 = 0830 hrs. pressure at Station A

X_2 = 0830 hrs. pressure at Station B

X_3 = 0830 hrs. dew point at Station C

X_4 = 0830 hrs. dew point at Station A

X_5 = Pressure difference between Stations A and B

X_6 = Pressure difference between Stations B and D

X_7 = Northerly component of surface wind at Station C

X_8 = Easterly component of surface wind at Station C.

Charba (1977) had developed an operational system for predicting probabilities of thunderstorm occurrence for square areas 40-45 nautical miles in the United States east of Rocky mountains.

The probabilities were produced by multiple linear regression equations. The independent variables or predictors in these equations were derived from routinely observed surface atmospheric variable, manually digitized radar data, localized climatic frequencies of thunderstorms and large scale numerical model output. Verification of 2½ months of operational spring season forecasts showed the forecasts as having considerable skill.

4.2.2 Dynamical approach

Efforts towards development of a model for making objective quantitative precipitation forecasting by an appropriate mathematical solution of basic equations of motion under specified assumptions have been initiated by Fulk (1935) in U S A and Takahashi (1935) in Japan and studies for improvement of the techniques have been going on in the developing as well as developed countries.

4.2.2.1 Fulk's method

Fulks estimated hourly rates of precipitation as that represented by the loss of moisture from the ascending air

$$I=\frac{3.6\,\epsilon\,10^{10}}{RT}\left(\frac{de}{dT}\cdot\frac{dT}{dh}+\frac{eg}{RT10^{3}}\right) \ldots\ldots(2)$$

Where,

I = the rate of preciptiation (mm/hrs) in a 100 m column of air rising with a vertical velocity of 1m/sec.

$\frac{dT}{dh}$ = adiabatic lapse rate

$\frac{de}{dt}$ = Rate of change of saturated vapour pressure with temp. in (mb/°C)

h = height in cms.

dh = thickness of layer in cms.

T = absolute temperature

ϵ = 0.6221, the ratio of densities of water vapour and dry air at same temperature and pressure.

e = saturation vapour pressure

R = gas constant for dry air

g = acceleration due to gravity.

4.2.2.2 Storage function

The storage equation is a balance of the rate of inflow and rate of out flow in a column of unit cross section and is equal to the rate of storage of moisture which in turn could be considered as approximately equal to the rate of precipitation.

$$I=(W_o\,\rho_{wo}-W_1\,\rho_{w1})\,\frac{3600}{10^4}\times 0.3937\ldots(3)$$

Where

ρ_w = absolute humidity g/m³, and

ρ_w = $x\rho$

ρ = density of air g/m³,

x = humidity mixing ratio.

w = vertical velocity m/sec

Subscript 0 and 1 refer to the bottom and top of the column of air.

$$I = \frac{w_o \rho_{wo} - w_1 \rho_{w1}}{7} \text{ inch/hour} \quad \text{........(4)}$$

Showalter (1946) assumed that no convergence or divergence occurs between top and bottom of the column.

i.e. $w_o \rho_o = w_1 \rho_1$

and $\rho w_o = x_o \rho_o$, $\rho w_1 = x_1 \rho_1$ and so on.

The formula expressed in mixing ratio X becomes

$$I = \frac{w_o \rho_o (x_o - x_1)}{7} \text{ inch/hr.} \quad \text{.........(5)}$$

$\rho_0 = 348.4 \left(\frac{p_o}{T_o}\right)$ where p_o is in mb

and T in absolute units.

The assumption of non-existence of divergence and convergence within the layer is, however the serious objection in this approach.

Benon (1948) has considered the rate of decrease of water vapour content as nearly equivalent to the rate of precipitation. The rate at which a column of unit cross section is losing moisture (all of which is supposed to come as precipitation) is calculated as

$$I = \rho w \left[\tau \left(\frac{r}{T} + \frac{dr}{dT} \right) - \frac{gr}{RT} \right] dz \quad \text{.........(6)}$$

Where,

I is the rate of precipitation mm/hrs

w is the vertical velocity in cm/sec

The two important parameters thus are

(i) moisture distribution in the vertical and

(ii) vertical velocity distribution.

Several methods are available to estimate the precipitable water from dew point temperature. Similarly the vertical velocity could be determined from data of wind vector at different standard pressure levels.

Narasimha Rao (1973) summarised the results of using dynamical approach for continuous days during the monsoon months of 1962, 1963 and 1964. The findings were as follows :

(i) The intensity of precipitation was found to be directly proportional to vertical velocities.

(ii) The computed precipitation rates were generally overestimates over observed values.

(iii) The computations indicated a layer of 2-3 km height which contributed about 35 per cent of total rainfall.

(ix) Below 903 mb very little contribution to the total precipitation was found.

Georgakakos and Bras (1982) formulated a station precipitation model in state-space form. Based on the surface pressure, temperature and dew point temperature, their model gives precipitation rate as output. The model formulation was based on pseudoadiabatic ascent of the air masses and on simplified cloud microphysics with exponential particle size distribution and linear dependance of the particle terminal fall velocity on the particle diameter.

Bennets and Bader (1982) had simulated the convective rainfall through a numerical model with the aim of understanding some aspects of extreme rainfall. A three-dimensional pressure coordinate model of deep convection has been extended to simulate mid-latitude clouds by the inclusion of a parameterised ice phase. The model domain was 16 x 16 km in the horizontal with 1 km grid resolution and 950 mb deep with a 50 mb resolution in the vertical. The model was integrated using as input the radiosonde information appropriate to midnight, midday and the mean of these two soundings. The magnitude of the simulated and observed precipitation rates were found to be of the same order. This model has further been extended to merge two isolated single cloud cells to achieve enhancement of precipitation for PMP.

Using the wind field and 12 hourly change in absolute vorticity Rao et al (1983) located areas of positive vorticity changes and in conjunction with other meteorological parameters used it as a criteria for forecasting heavy rainfall in Bhagirathi catchment. It was suggested by the authors that positive vorticity changes may be taken as a guide to forecast areas of precipitation 12 to 15 hrs in advance while monitoring the possible lateral shift of forecast areas of precipitation.

4.2.3 Moisture Transport

The moisture transport forms a very useful tool for quantitative forecasting purposes by monitoring the level of moisture transport.

Moisture transport studies have been made by a number of authors. Fugiwara (1956) and Osawa (1963) made the initial attempts in this direction.

Start and Peixoto (1958), Rasmusson (1967) and Palmen (1967) used the moisture transport to study the atmospheric water balance. Rama Sastri (1976) studied the net water vapour flux in a polygon formed by upper air observatories at New Delhi, Allahabad, Calcutta, Visakhapatnam and Nagpur for estimating atmospheric water balance over Bihar and neighbouring areas. Assuming hydrostatic equlibrium, the atmospheric water vapour balance equation for a column of air extending from the surface P_s to a pressure P_u was written as

$$E - P = \frac{1}{g} \int_{P_u}^{P_s} \frac{\partial q}{\partial t} dp + \frac{1}{g} \int_{P_u}^{P_s} \nabla . q V dp \qquad \ldots\ldots\ldots (7)$$

The first right hand term in equation 7 is the rate of change of water vapour content per unit area and the second one is the divergence of the horizontal water vapour flux.

The mean monthly vertical distribution of water vapour flux divergence was computed for different layers of the atmosphere during the monsoon months for two drought years 1965, 1966 and a non-drought year 1967. It was found that during drought months, the net inflow into the polygon was small whereas outflow was observed in the severe drought months.

Saha and Bavadekar (1977) computed the net total flux of water vapour entering the land, across a vertical section along the West Coast of India treating the part of the section north of Bombay as meridional and that south of Bombay as inclined to the meridion of Bombay at an angle of about 12.5·. The computations were done for monsoon months (Jan-Sep.) during nine years from 1964 to 1972 and related to average total seasonal rainfall over the West Coast region during ditfferent years (1965-1972). Good correlation was noticed between the combined Vapour Flux (North and south section) and rainfall. Good correlation was also noticed to exist between the flux across south sector and rainfall over the peninsular region.

4.3 Orographic Models :

An increase in rainfall amounts, over hills of the order of a few hundred metres high is very apparent in certain synoptic situations when compared with rainfall in the adjacent valleys. Bergeron suggested that this enhancement of rainfall was due to the formation of low level, orograpically produced clouds which are washed out by raindrops falling from a higher level cloud layer. The low level clouds are formed of droplets large enough to be subsequently removed by precipitatlon falling from above but too small for independent rain formation. Attempts to demonstrate this low level growth have been made by a number of workers by construsting numerical models. (Bader and Roach, 1977 etc).

The Bader and Roach model was essentially two-dimensional, using grid lengths of 100 m in the vertical and 2 km in the horizontal, sufficient to cover the low level cloud. They derived equations to calculate the accretion growth of an individual rain drop falling through the orographic cloud and also, the water content of the cloud. Using the calculated values of the water content of the low level cloud in each layer of the model, the accretion growth on the rain drops as they fell through each layer was determined.

The orographic model described by Miller (1972) treats the precipitation resulting from forced ascent of moist air over an unbroken mountain ridge as a simplified two dimensional model. The air passing over the mountain would accelerate as the air from deep upwind layer has to pass through a relatively shallow layer at the peak. The model thus, assumed the air to be lifted over the mountain ridge as a laminar flow. A simple diagram of inflow and outflow winds over the mountain barrier as given by Miller is shown in figure 2.

The model considers the flow of air in a vertical plane at right angles to a mountain chain or ridge. The plane has a Y coordinate

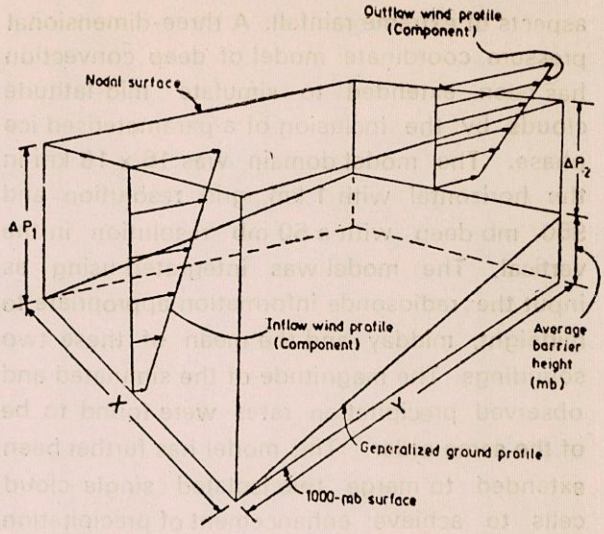

Fig. 2 Schematic Wind-flow Model for Orographic Precipitation (Reproduced from Paper of Miller, 1972)

in the direction of flow and a Z coordinate in the vertical. The flow may represent an average over a few kilometers of stretch in transverse or X direction. The wind at ground level is assumed to move along the surface. The slope of the air stream lines above a given point on the mountain slope decreases with height, becoming horizontal at the nodal surface.

The model divides the complete column of air into several layers of flow. The rate of precipitation from each of these layers is given by the equation

$$R = \frac{\overline{V}_1 \, p_1 \, (\overline{q}_1 - \overline{q}_2)}{y} \; \frac{1}{g\rho} \qquad \text{.......(8)}$$

Where

R = the rainfall rate in cm/sec

$\overline{V}_1$ = the mean inflow windspeed in cm/sec through the layer

p_1 = the thickness of the air in mb at inflow

$\overline{q}_1$ = the mean specific humidity in g/kg at inflow

$\overline{q}_2$ = the mean specific humidity in g/kg at outflow

ρ = the density of water in g/cc

y = the horizontal distance in cm.

A dynamical model for orographic rainfall with particular reference to the Bombay-Poona region in the Western ghats was developed by Sarker (1967). The model was based on steady state, two dimensional linearised equation and a saturated atmosphere with pseudo adiabatic lapse rate. Vertical velocities were computed analytically.

From a given characteristic of the air stream on the windward side, the terrain induced vertical velocity was computed from the equation

$$\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial z^2} + f(z)\, w = 0 \quad \text{.........} \quad (9)$$

by a quasi-numerical method. In the above equation f(z) is a function of wind speed, wind shear and stability of the undisturbed air stream.

The distribution of computed rainfall intensity showed reasonable agreement with the distribution of observed rainfall. Other important conclusions of the study were :

i. The model computed orographic rainfall increased from West Coast to inland along the slope of the ghats and reached a maximum before the crest of the mountain was reached after which it decreased sharply.

ii. The contribution of orography to coastal rainfall was only about 20% indirectly suggesting that the observed heavy rainfall along the coast is caused largely by synoptic scale convergence.

iii. The observed maximum in rainfall close to the peak of the mountain was almost completely accounted for by the orographic model.

Sinha Ray et al (1982) had studied the contribution of orography on the total rainfall in the western ghats and Khasi Jayantiya hills of Assam. An attempt was made to isolate the relative importance of the orographically induced vertical motion in terms of the flow characteristics like wind speed, direction, shear and stability of air and the role of the synoptic and convective factors also.

Hobbs et al (1975) had carried out a detailed analysis of orographically enhanced rain over the cascade mountains in the western Washington state of USA. Direct measurements of the wind field and inference based on the shape of the frontal cloud indicated that as the front approached the mountain the horizontal winds aloft were faster than the average velocity of the front while the lower level winds were considerably slower. The authors attributed the slowing of the low level winds due to the friction caused by local small scale topography.

Marwitz (1980) described the type of orographic precipitation obtained in the San Juan mountains in south west Colorado, USA where orographic rain was said to be usually associated with the approach of the baroclinic zone. As the zone approached, the air was stably stratified and the low level flow was entirely blocked by mountain. During this time, cold air advection occurred aloft and after several hours when air upstream of the mountain has been stabilised precipitation was produced in large parts by embedded convection in a deep layer of cloud.

Smith (1982) proposed a orographic model in which the blocking of low level air by a mountain has caused approaching cold air to override the warm air, producing an unstable layer upstream of the mountain. Smith concluded that under some conditions it was the blocking action of the mountain rather than the forced ascent which cause the enhanced precipitation.

Porch and Mechrez (1984) had studied the combined effect of wind and topography on rainfall distribution analytically and numerically. A general solution for the trajectories of the raindrops in two dimensional equilibrium flows in terms of the stream function describing the wind motion was presented. Though the model could not predict the distribution of rainfall as it has occured in nature, the analysis was used to demonstrate the basic features of the combined effect of wind and topography.

4.4 Models of Medium and Long Range Forecasts

A weather forecast whose period of validity is three to five days is known as medium forecast. Forecasts for durations beyond this period are long range forecasts. The techniques and models used for short range forecast are generally not valid for the medium and long range forecast. Since the weather systems are migratory in nature and their life cycle is much shorter than the period of validity of medium range forecasts, the mutual interaction of these systems, the complexity of their genesis, evolution and decay could not be forecasted for durations longer than a day or two with the numerical models. For issue of medium and long range forecasts there are two different approaches. They are

(i) Use of physical-cum-statistical relationships,

(ii) Use of empirical statistical relationships between the elements to be predicted.

Saha and Mooley (1968) presented some of the methods for medium range forecasting. They used the concurrent relationship between

(i) contour height anomaly over a region and the latitudinal position of the monsoon trough axis across the central longitude of the region.

(ii) contour anomaly and the rainfall character

(iii) monsoon trough axis location and rainfall character

(iv) contour height anomaly and trough axis location on the one hand and the rainfall character on the other.

For each pentad rainfall of 29 contiguous regions in India. Significant parameters from the above mentioned pentad charts and the charts for the last day of the pentad were used to prepare the forecasts of the probability of occurence of different terciles over a number of stations, river catchments and the meteorological sub-divisions using the contingency technique. The potential predictors were determined from the composite charts antecedent to abnormal and subnormal rainfall over the region of interest and on physical reasoning. The forecasts on independent data showed significant skill.

Mooley (1976) examined the relationship, concurrent as well as with lag, between the monthly mean sea level pressure difference of Aden and Zanzibar and the monthly rainfall at 25 stations along the Indian west coast and one station along the west coast of Sri Lanka. In addition, the relation between monthly sea level pressure at each of the two stations Aden and Zanzibar and the rainfall at the 26 stations was also studied. Significant relationship was noticed along some sections of the west coast.

Sikka (1977) carried out a diagnostic study of the large scale rainfall over India during the summer monsoon and its relation to the lower and upper troposphere vorticity. By analysing the daily variation of the lower and upper troposphere wind field for the monsoon season of 1972 (drought year) and 1973 (good monsoon year) it was shown that the changes in the large scale rainfall were directly related to those in the large scale vorticity above the frictional boundary layer on a day to day basis. The major difference in the upper tropospehreic wind field between the two seasons was in the meridional component which was southerly to the north of 23° N in 1972 and northerly during 1973.

Banerjee et al (1977) related the mid tropo sphere circulation anomaly in April to the south-west monsoon rainfall over India. It was found that the total monsoon rainfall over the country was significantly correlated with the latitudinal position of the sub-tropical ridge on the mean circulation chart of April at 500 mb level. A regression equation was developed with a sample data of 27 years (1950-70) and tested with data for the period 1939-49 (11yrs) and 1971-75 (5 yrs). It was observed that the average deviation between computed and actual south-west monsoon seasonal rainfall distribution was 6%. Years when the sub-tropical ridge at 500 mb in April was poleward of the normal position were followed by good monsoon rainfall and when the ridge was equatorial of the normal position they were followed by poor monsoon rainfall.

Thapliyal (1979) studied the relationship of easterly quasi biennial oscillation (QBO) and westerly QBO in January with the subsequent monsoon season rainfall. It was noticed that easterly QBO in January was followed by good monsoon in 75% occasions and westerly QBO was followed by bad monsoon rains in 50% occasions.

Since 1973, a group at the University of Wisconcin, Madison, USA has been trying to identify physical processes that produce inter-annual variation of the climate. The purpose was to increase the possible lead time of long range forecasts and identify mechanisms which might be combined with those in general use to give better overall accuracy. (Bryson, 1982). Actual forecasts with lead times of a year or more were made and several real time forecasts were verified. The best forecasts were said to have been achieved for seasonal patterns of monsoon rainfall in India. Forecasts for the monsoon season of 1986 and 1987 have also been issued by the group.

4.4.1 Analogue modelling Synoptic Typing method

In this technique all the historical synoptic situations are typed into some categories depending on their intensity, location and similarity of their flow patterns so that a particular range of rainfall and spatial distribution can be associated with each type of synoptic situation. These are known as analogues. The technique was applied by Narasimha Rao (1973) for a selected area in Northeast India. It was found that broadly the following four synoptic types could be identified.

Type I : Passage of depression through the area of concern

Type II : The southward or northward shifting of eastern end of monsoon trough

Type III : Low pressure area formed at the head Bay and affecting the area

Type IV : Movement of lows in westerlies

Out of 25 cases chosen for study, 14 cases happened to be of Type II, 5 of type I and 5 of type III. Only 1 was of type IV.

Paul et al (1982) had categorised daily weather charts for the sea level and two upper levels for the months of July and August for 30 years (1946-1975) for different features. The results of a forecasting experiment conducted during the monsoon season of 1978, 1979 and 1980 showed that the distribution of 24 hour rainfall over different parts of India could be forecasted upto 40% accurately and upto 82% fairly accurately.

4.5 Stochastic Modelling

The general concept underlying the stochastic modelling of precipitation is not new. The most basic description of rainfall can be obtained by viewing it as a random field in the space time continum. The stochastic modelling of precipitation was motivated by the observed regularities in the evolution of space time rainfall from diverse storm types. The importance of specifying the stochastic structure of a rainfall intensity field comes from the fact that the structures of various space-time averages of rainfall intensity can then be obtained as mathematical approximations of the basic rainfall field. Given that a synoptic disturbance has originated, the main problem in modelling rainfall is to describe the mathematical structure of the random field intensity resulting from the disturbance.

Chow and Ramaseshan (1965) represented the annual storms for the French Broad River Basin at Brent Creek, North Carolina by a first order non-stationary Markov model in log-normally distributed random ccmponents. Since the storm time distribution patterns were different, they carried out a 'storm Shifting' procedure to obtain the best storm orientation so that the mean, standard deviation, trend and components of the hourly rainfall became regular and consistent. The storms were assumed to have the same duration which was approximately equal to the longest duration of the storm under consideration. They successfully applied a first order autoregressive model to generate sequentially the hourly rainfall depths within the annual storms having constant duration.

Ramaseshan (1971) further revised these studies and concluded that

(i) storm precipitation could be conceived of as a finite duration, quantitized data, continuous-variable, nonstationary, stochastic process. For the river basin studied, a simple Markov model with log normally distributed random components was found to be satisfactory.

(ii) detailed steps in the mathematical modelling of the process could be standardised to yield consistent results.

(iii) shift analysis is useful in generating sequential data of storm precipitation in a basin and subsequently verifying the data. Such data may be used in the analysis and design of water resources system by simulation.

Yevjevich and Karplus (1973) had carried out structural analysis of monthly precipitation at 41 raingaguge stations in North Dakota and Minnesota and 29 raingaguge stations in the eatern Nebraska of USA. The analysis was based on the concept that the monthly precipitation was composed of

(i) a deterministic component specified by periodic parameters and

(ii) a stationary stochastic component with the coefficients of the periodic parameters following regional trends.

Mathematical models for the periodicity and trends were inferred with five regional constants and three regression coefficients for each of the two regions. when the periodicity and regional trends in parameters are removed (filtered), the stationary stochastic process components of monthly precipitation were found to be approximately time independent process and closely follow the three parameters gamma probability distribution. The independent stationary stochastic components of monthly precipitation were highly cross correlated with lag zero cross correlation found to be primarily a function of interstation distance.

Gupta (1973) considered the cumulative rainfall within a season and the maximum cumulative rainfall per rainfall event within a season for space time modelling of rainfall. An approach was given to determine the cumulative distribution function (c. d. f) of the cumulative rainfall per event, based on a particular random structure of space-time rainfall. The first two moments of the cumulative seasonal rainfall were derived based on a stochastic dependence between the cumulative rainfall per event and the number of rainfall events within a season. A theorem was then proved on the exact c.d.f. of the seasonal cumulative rainfall upto the ith year to its limiting c. d. f. Use of the limiting c. d. f of the maximum cumulative rainfall per rainfall event upto the ith year within a season was given for the determination of 'design rainfall' which could be useful in the design of hydraulic structures. A numerical application of this approach was demonstrated on the Atterbury watershed in the southwestern USA.

Amorocho and Wu (1977) developed two mathematical models for the simulation of cyclonic storm and precipitation fields. The first a storm sequence model uses the Monte Carlo simulation technique to generate storm sequences from the probability distributions of storm characteristics analysed included time between storms, number of bands within a storm, time between bands, band duration, band depth and band velocity. The second model which simulate a spatially distributed precipitation field, used a randomization process to generate clusters of short lived and high intensity rain cells within a storm band. The apparent sizes, life cycles and space distribution of rain cells were determined from the properties of historical data. The two models could be used either together or in succession to generate precipitation sequences for any sampling time interval and at any ground location in the path of a storm.

Richardson (1977) has modelled the stochastic structure of the time area daily precipitation process. The daily precipitation at a point was considered as a continuous random variable that has been turncated at zero. The zero daily precipitation amounts were considered as negative precipitation amounts of unknown quantity. The multi variate normal distribution was used to describe the time-area variation of daily precipitation over an area. Precipitation sequences were generated for two areas in the study region (Texas, USA) using the truncated multi-variate normal distribution model. Parameters of the model were defined using the latitude and longitude of each station. The new sequences closely resembled the observed sequences in

(i) the periodic daily means and standard deviation

(ii) the lag one auto correlation coefficient

(iii) the lag zero cross correlation coefficient

(iv) the Markov chain wet dry transition probabilities

(v) the mean, standard deviation and skewnes coefficients of annual precipitation.

Creutin and Obled (1980) had proposed a hourly stochastic precipitation model which could provide some conditional distribution of the next hourly flows.

The model uses a rainfall event as split into periods of uninterrupted rain seperated by a rain free period af atleast 12 hr, which could be described by a few simple and independent variables. The distribution functions of these variables were adjusted on a sample of 135 events and at two stations seperately. The statistical dependence of these variables was tested and verified so that the model could be used for simulation with a random number generator to generate likely rainfall events.

The following characteristics needed to be defined

(i) inter arrival time of storm events

(ii) number of storm segments inside the event

(iii) duration of a given storm segment

(iv) time interval between a given storm and the previous one

(v) total accumulation of water for the storm considered

(vi) ratio of the hourly maximum to the hourly average of the storm

(vii) location of the peak inside the storm period

Most of these variables fit the simple exponential density functions or log normal distributions.

Marshall (1980) described a method for estimating the speed and movement of storm rainfall pattern from a network of continuously recording raingauges. An analysis of cross correlations between all pairs of raingauges of the network was made for different time lags. Besides giving an estimate of the storm motion, the method indicates the temporal and spatial structure of the storm. Similar analysis were carried out by Ramasastri (1983) for storms in Narmada basin in India using the hourly rainfall recorded at the self recording raingauge stations in the catchment of Narmada.

Srikanthan and Mc Mahon (1983) had developed hourly and six minute interval models to stochastically generate sequences of rainfall depths. Hourly rainfall data was generated in two stages. In the first stage, a daily transition probability matrix (TPM) was used to determine the state of a day (wet or dry). If the day was wet, rainfall depths were generated at hourly in the second stage.

Several models including many variations were successively tested for their ability to generate hourly rainfall depths on wet days. These included

(i) Hourly rainfall depths were generated on wet days using an hourly TPM.

(ii) Two state second order Markov chain was used to determine the wet hours on a wet day and then wet hours were generated using a TPM.

(iii) Wet and dry spells were obtained from fitted distributions and an hourly TPM was used to generate rainfall depths during wet tpells.

(iv) Two sets of hourly TPM based on the type of wet day (low or high rainfall) were used to generate hourly rainfall.

(v) Two state second order Markov chain with an hourly TPM corresponding to each type of wet day.

Results from models (i) to (iii) were found to be unsatisfactory. Results from (iv) and (v) indicated dividing a wet day into two types produced satisfactory annual rainfall parameters. However model (iv) did not take into account the variations in probability of rainfall throughout a day. Model (v) was used with a time dependent Markov chain to generate hourly rainfall. The daily, monthly and annual rainfall parameters obtained by aggregating the hourly rainfall were satisfactorily reproduced.

Six minute rainfall generation was an extension of hourly generation. It was found that the six minute model reproduced most of the characteristics of the six minute rainfall.

Johnson and Bras (1980) had developed a rainfall prediction model which simultaneously predicts rainfall rates at multiple locations for multiple values of prediction lead. The model included velocity and direction of storm movement as explicit parameters. The storm arrival time at each predicted point was also explicit parameter which was estimated apriori for each station. The mean and variance of rainfall rate was modelled as being non-homogeneous spatially and non-stationary with time. The model parameters were estimated solely from telemetered raingauge data for the event being predicted.

Eagleson (1984) has modelled the occurrence of wetted storm area within a catchment as a Poisson process in which each storm is composed of stationary, nonoverlapping, independent random cell clusters whose centres are Poisson distributed in space. The model was used to estimate the spatial properties of tropical stroms on six tropical catchments in sudan.

Chang et al (1984) had constructed a discrete autoregressive moving average structure and applied it to the daily precipitation in Indiana, USA. The Indiana daily precipitation sequence were transformed into a multistate discrete precipitation sequence by discretizing the daily precipitation sequence into a number of magnitude states. The stochastic process of the daily precipitation sequence was analysed in terms of the locally stationary seasons. In each season the candidate DARMA models were identified in terms of the covariance function within the season. The parameters of the models were estimated by fitting their theoretical auto correlation function to their empirical counterparts and the state probabilities were obtained through the multistate mean runlengths.

Singh and Kripalani (1982) studied the dependence of daily rainfall of 12 stations and daily rainfall in 10 meteorological sub-divisions of India during the summer monsoon by

(i) analysing the rainfall as stochastic point process by fitting several types of models like log model and Markov chain of 1st and 2nd order

(ii) fitting autoregressive and autoregressive moving average models to spatially averaged data.

The significant conclusion was that the Markov chain of order 1 fits the runs of wet spells and autoregressive model of order 1 fits the spatially averaged data satisfactorily.

5. Operational forecasting with numerical models

Several countries especially USA, Canada, United Kingdom, USSR, Australia, Japan etc. have been using prognosis from numerical models for forecasting of weather two to three days in advance. It is generally the practice to work with models of two different space scales, a global model and a regional model.

In the United States of America and Canada, the quantitative precipitation forecasts are issued by the National Meteorological Centre at Suitland, Maryland by using rigorous barotropic or baroclinic models. The model uses a grid size of 160 km and is called limited fine mesh (LFM) model. For initialising certain parameters, radiation data from satellite and precipitation data are used.

Model outputs from statistical analysis using multiple regression techniques (Charba, 1977) are also used as additional information by the local weather service offices for issue of quantitative precipitation forecasts.

The Meteorological Office, U. K. uses two models; one eleven layer model and the other a five layer General Circulation model. The models have a horizontal resolution of 220 and 330 km respectively. The cloudiness is implicit in the models and the radiation is absorbed by three gases namely carbon dioxide, water vapour and Ozone. The fluxes of momentum, heat and water vapour at the earth's surface are calculated in terms of the surface roughness, wind at lowest level and potential temperature gradient.

The hydrometeorological centre of USSR issues short range forecasts using a regional numerical primitive equation model with a grid of 250 km $\times$ 250 km. The operational model was an adiabatic model, the only non-adiabatic processes considered being the friction and orography. The forecasts were said to be accurate in comparison to the forecasts based on quasigeostrophic models. The forecasts of the regional model were valid only upto two to two and half days Though the precipitation forecasts were good, temperature forecasts were said to be relatively better. Statistical models were used for forecasts of medium range i.e. 3 to 7 days. The forecasts included total precipitation for 5 days, five day forecasts of temperature and their departures from normal.

5.1 Use of numerical models for forecasting of precipitation in India.

Conventionally the weather forecasting in India is done based on the inference drawn by experienced meteorologists from analysis of surface and upper air meteorological data.

Attempts at forecasting weather and precipitation using numerical models began around 1970 in India.

Das (1962) used a 10 layer quasi geostrophic model (QGM) to compute vertical motion (w) field. This study showed that QGM could be used in tropics in a monsoon regime.

Das, Datta and Chhabra (1971) used a 10 layer quasi geostrophic model to compute the vertical motion which led to the extensive use of quasi-geostrophic models in India.

Mukerji and Datta (1973) made the first attempt in India to develop a quantitative precipitation forecast technique based on a 4 layer diabatic quasi geostrophic model. The main problems, besides other inherent limitations which affected the accuracy of quasi geostrophic models over Indian sub continent were :

(i) not very satisfactory input to the model especially over the oceanic regions and Himalayas,

(ii) lack of proper understanding of the influence of Himalayas, and

(iii) limited knowledge of cumulus convection and monsoon circulation and their interaction.

The primitive equation models because of the basic advantage of not assuming geostrophy were found to be better suited over the Indian region.

Ramanathan and Saha (1972) used a barotropic 'primitive equation' model to forecast the movement of western disturbance. However, for using the primitive equation model for quantitative precipitation forecasting, Bedi et al (1976) used a baroclinic primitive equation model. The atmosphere was divided into four layers, the lower layer being always considered as constant (850 mb) and the pressure at the top of the atmosphere taken as 200 mb. Orography was used in the model. Besides diabatic heating and orography, the prediction equation for specific humidity needed to be added.

Das and Bedi (1978) extended the above study and were able to simulate the monsoon trough. The study also indicated possibility of using the model for QPF purpose. Bedi (1985) reported of the development of a primitive equation spectral model for global use.

5.2 Long range forecasting of monsoon

Sir Gilbert Walker formerly Director General of observatories introduced the testing of relationship beetween Indian rainfall and preceding conditions by correlation coefficients. South American pressure (April to May) and South Rhodesian (Zimbabwe) rainfall (October to April) have been important factors in the seasonal forecast formulae. Later, upper wind flow in preceding months over India itself was correlated with the monsoon rains. Northerly winds in April at Bangalore were positively correlated with peninsular monsoon rain. The India Meteorological Department issues seasonal forecasts of monsoon rainfall every year for official pur poses.

6.0 Remarks

The structure of rainfall in different parts of the world and even in different parts of a large country like India, Australia or USA exhibits large variation. Therefore, the development of a single model which incorporates all these variabilities is a difficult task and probably impossible. Although many types of numerical and mathematical models have been proposed on the structure of rainfall, there is no unified approach to the problem of modelling of precipitation. Since rainfall is a space time phenomenon, its representation (modelling) requires conceptualisation of its physical characteristics on the one hand and its randomness on the other.

Development of the Numerical Weather Prediction techniques for short range weather prediction and statistical and climatological studies for forecasting the precipitation on medium and long range time scales (monthly or seasonal) have resulted in objective methods for weather prediction which have practical application. In India, these have helped in the better understanding of short term climatic fluctuations and about vagaries of monsoon and better planning.

The utility of statistical techniques using correlation approach has, however, limited application as the validity of such methods diminishos as years pass by. These would need constant updating and an improvement in the knowledge of the General Circulation of the atmosphere would enable in the better choice of the meteorological parameters that influence the rate of precipitation.

With regard to stochastic modelling the main difficulty arises out of the lack of appropriate mathematical tools which could be used to define the dependence which the precipitation phenomenon seems to exhibit.

The few remarks made above indicate the obvious difficulties which hydrologists and meteorologist in general and modellers in particular faced during the last few decades in trying to design a unified dynamical and mathematical approach towards precipitation modelling. The future, however, holds lot of promise for the numerical modelling for forecasting of short range precipitation distribution and stochastic models for medium and long range precipitation prediction and its distribution in time and space.

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HYDROLOGICAL FORECASTING

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1. General :

Human nature as always been concerned with the prediction of future events. Apart from pure curiosity, security reasons and scientific interest, modern economic societies need the prediction of the main factors in the economy for efficient performance and substantial economic gains.

Water resources development programme forms an important sector in the national five-year plans launched by our country. The planning of river valley projects envisages optimum utilization of the available surface flows. The design and operation of multi-purpose projects are based on the estimates and forecasts of the future pattern of inflows of the reservoir and the highest floods that are expected to be handled by the project.

Hydrological forecasts (or flow forecasts) are among the most important aspects of water resources development. They are necessary for the rational regulation of runoff to meet the various requirements of flood control, hydro-power generation, irrigation, inland navigation, water supply, water quality management etc.

The tools of the flow forecaster include rainfall runoff relations, unit hydrographs, routing methods, recession curves and stage-discharge relations. Methods for collection and handling of basic data, preparation of forecasts and dissemination of these forecasts must be carefully organised.

2. Classification of hydrological forecasts :

The period covered by forecasts refers to the period from the time the forecast is issued to the time the predicted event takes place. Depending on the length of this period, flow forecasts may be classified as (a) short-term forecasts or (b) long-term forecasts. Most short-term forecasts include those covering a period of several hours or days while long-term forecasts may cover a period of one to six months or upto one year. Short-term forecasts predict the magnitude and time of occurrence of peak flows or stages and provide flood warnings. They are used to warn the people likely to be affected by inundation, to operate dams and emergency flood-ways and to keep vigil on the engineering works on and along the rivers. Long-term flow forecasts are used to plan seasonal utilisation of Water likely to be available and for chalking out appropriate and periodic regulation schedule to match with the the plan of utilisation. Forecasts of inflow for a season or specific periods of time are of great importance to hydro-electric power plants. Long-term forecasts of the streamflow for the entire growing season are of considerable importance in connection with irrigation.

3. Requirements and collection of basic data :

The development of the flow forecasting procedure requires adequate lengths of historical hydrologic data, while the preparation of operational forecasts requires reliable information on current hydrologic conditions over fhe drainage basin, augmented by weather reports and forecasts,

3.1 Data for developing forecast procedure :

The first step in the development of any procedure for estimating runoff resulting from rainfall is the collection of adequate basic data from a basin which has hydrologic characteristics similar to those of the area requiring forecast. This involves the selection of the basin to be used in the study, the selection of the specific past storms to be studied, and the evaluation of rainfall, runoff and other variables such as antecedent conditions and duration of each of the storms selected.

In general, selection of smaller basins is preferable as the concentration times are normally shorter for a small basin and the problem of relating streamflow to the storm which caused it is considerably simpler than for larger basins. Besides, a small basin should have less areal variations in rainfall, making estimates of basin precipitation simpler. No specific rules can be set down on the proper size for a basin to use in a runoff study, but in general basins having drainage areas of 100 to 1000 sq. km. usually work out best.

As a generalization it can be said that it is necessary to have a minimum of 10 years of stream flow and precipitation records for the basin to be studied and to have 50 to 100 storms, covering a wide range of hydrologic conditions available in order to develop adequate forecasting procedures. Short records with a limited range of stream flows make it necessary to extrapolate the relations, with a probable loss of accuracy. Storms with significant rainfall but little runoff should be considered as well as those which produce appreciable runoff in order to avoid a bias in the resultant procedures. Storms with very uneven areal distribution of precipitation should not be used. Complex hydrographs resulting from long sporadic rainfall should also be avoided.

Rainfall records should be adequate to provide reasonable estimates of the average precipitation over the area under study. The density of rainfall stations required varies with basin topography, meteorological factors and hydrologic need.

The frequency of reports is a function of basin characteristics. Forecasts for small basins with rapid concentration times may require reports at intervals of 6 hours or even less, during high flow conditions. For the development of a flow forecasting procedure it is essential for a proportion of the rainfall stations to be equipped with recording gauges, approximately 1 in 5.

3.2 Operational data acquisition :

The primary data required for operational purposes are amount and areal distribution of rainfall, water equivalent and areal distribution of snow, if any, river discharges, reservoir storages, soil conditions etc. River/reservoir stage reports are also required as a check on other data.

The collection of the necessary data is accomplished through telephone, telegraph or wire-less communication systems from the organised network of reporting stations.

4. Short-term forecasting :

Short-term forecasts, which are usually flood forecasts, constitute a direct means for the reduction of flood damage and loss of life. Rainfall-runoff relations are used to estimate the amount of water expected to appear in the streams, while unit hydrographs, streamflow routing procedures are utilised to determine the time distribution of this water at a forecast point. Stage-discharge relations are utilized to convert these flows into stages, if necessary.

4.1 Rainfall-runoff relations :

The rainfall-runoff relation correlates storm rainfall, antecedent basin conditions, storm duration and the resulting storm runoff. Such a relation is developed by coaxial graphical method using data from one or more headwater areas in the basin for which forecasts are required, Studies must be limited to areas for which the runoff can be evaluated (from the hydrograph) for each individual storm event. Storm runoff can be estimated for the local inflow areas and tested in the relation.

In this rainfall-runoff relation the antecedent basin conditions are represented by two variables. The first is antecedent precipitation index (API) which is essentially the summation of the precipitation amounts occuring prior to the storm weighted according to time of occurrence. The API for today is K times the API for yesterday plus the average basin precipitation observed for the intervening day. Generally the value of K is taken as 0.9.

The second variable is the week of the calendar year in which the storm occurs. Week of the year introduces the average inteiception and evapotranspiration characteristics of each season, which, when combined with the API provides an index of antecedent soil conditions.

The value of storm duration used in the runoff relation is not critical and can be adequately derived from 6 hourly precipitation records. One method defines the duration as the sum of those 6 hourly period with more than 5 mm of rain plus one-half the periods with less than 5 mm.

The storm precipitation is the average over the basin. If a sufficient number of uniformly distributed precipitation stations are available, an arithmatic mean is usually sufficient although the Thiessen weighing method or isohyetal maps can be used for more accuracy.

The storm runoff in most river forecasting relations is direct runoff. It is composed of surface runoff, channel precipitation and interflow. The ground water flow (or base flow) is discharged to the stream over a much longer period of time. Any of several methods of hydrograph analysis may be employed to seperate the base flow, but care must be taken to use the same method operationally as was used in development. The storm runoff is usually expressed as an average depth, in mm, over the basin.

4.2 Unit hydrograph :

The rainfall-runoff relation provides an estimate of the volume of water which will runoff for a given storm situation. It is necessary to determine the distribution of this water with respect to time at the forecast point. The unit hydrograph is a simple and generally effective method of accomplishing this. In order to deal effectively with uneven distribution of runoff in time, unit hydrographs for short periods are used, very often for 6 or 12 hours durations. The increment of runoff is estimated for each time period, with the contributions from each interval superimposed upon the previous contributions.

4.3 Stream flow routing :

The next basic problem is to predict the movement and change in shape of the flood hydrograph as it moves downstream from one forecast point to another after being modified by lag and storage in the reach between the points. Numerous routing procedures are available; ranging from very complex storage functions to simple lagging procedures. The Muskingum type of routing is one of the commonly used procedures. In preparing a forecast for the downstream point, it is also necessary to determine the contribution of flow from the local drainage area between the two points

5. Long-term forecasting :

Long-term forecasts of the flow and its distribution during periods of low water are of great interest for hydropower plants, navigation and irrigation. The flow during low-water period depends on three basic factors : (i) Water storage in the basin at the beginning of the dry season. (ii) the rate at which this storage is depleted and (iii) additional contribution resulting from intermittent precipitation. In the absence of quantitative precipitation forecasting methods, the feasibility of low-flow forecasts depends on the relative role of the additional contribution and the extent to which it varies from year to year and from month to month.

The river runoff regime during the dry season in characterised by a gradual decline in discharge. The rate of the decline diminishes exponentially as the seasonal storage in the river basin is depleted, until discharge reaches a minimum value. This minimum is ensured by a relatively stable supply from ground water. In some basins minimum discharge does not remain constant from year to year, reflecting changes in ground water storage. It varies according to runoff during the previous high-water season.

In Central Water Commission, presently long-term forecasts are not being undertaken as a routine. Only inflow forecasts for some reservoirs on the river Damodar and its tributaries are being issued. For issue of forecasts of inflows to reservoirs, mean areal rainfall at an interval of three hours are calculated based on the information received from reporting stations of the sub-basins of the reservoirs through CWC HF wireless grid. Theissen Polygon method is used to calculate the mean areal rainfall. A set of correlation graphs have been developed considering antecedent precipitation index (API) for computation of runoff from rainfall. Different unit hydrographs have been developed for each reservoir sub-basin for different durations. Finally the runoff derived from the application of unit hydrograph is added to the base flow to get the total inflow forecast. The D. V. C. reservoirs are currently operated according to the regulation manual. The manual prescribes two sets of guidelines in flood situations, one for use in flood control operations from June to September and the other for October. In addition to the flood control guidelines the manual provides guide curves for reservoir levels during draw down period and filling period outside flood situations.

FLOOD ROUTING-HYDROLOGIC METHODS

by

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1.0 Introduction :

A great many different methods and procedures for solving flood routing problems have been described in engineering literature. In general, those methods that attempt a strict mathematical treatment of the many complex factors affecting flood wave movement are not easily adaptable to the practical solution of problems of routing floods, as they demand high computer resources as well as quantity and quality of input data. In order to keep the amount of computation within practical limits and to conform to limits ordinarily imposed by the type and amount of basic data available, it is generally necessary to use approximate flood routing methods that either ignore some of the factors affecting flood wave movement or based on simplifying assumptions in regard to such factors. Approximate methods produce results at considerably less expense but are limited in generality and accuracy (U.S. Army Corps of Engineers, 1960).

Methods of flood routing are broadly classified as empirical, hydraulic and hydrological (Fread, 1981). Empirical methods are limited in application with sufficient observations of inflows and outflows to calibrate the essential coefficients. The classification as hydraulic or hydrological depends on whether or not the St. Venant's equations are employed in the derivation of the model structure (Whitehead et al., 1979). However, this classification is more artificial as the so called hydrological methods can also be derived from the St. Venant's equations (Price, 1973; Weinmann and Laurenson, 1979). The Kalinin-Milyukov method (Kalinin and Milyukov, 1957) is a particular example of such a case. However, the weight of empirical evidence tends to substantiate the claim that simple routing methods are adequate for most purposes, particularly in the planning stages of flood control and multi-purpose projects, and in real time forecasting. (Price, 1975; Keefer, 1976; Weinmann and Laurenson, 1979). Keefer (1976) compared the solutions of various linear hydrological flood routing models with that of St. Venant's solution obtained using implicit method. He found linear hydrological models are more cost effective from the consideration of computer resources and data needs. He found for many practical purposes the application of linear models is justified. In general, the more complex the model, the higher the price in terms of data and computer time. This is particularly true of accurate finite difference models, which may require frequent cross sectional and roughness information along a stream reach. Stability requirements often require tight time steps and thus high computer cost. Finite difference models, for many cases, represent a form of overkill, in that predicted output is required only at one or two points. To get this prediction it may require data from two or several hundred points. Thus, for many problems, a simple hydrologic model which treat the stream reach as a lumped system may be of advantage. Such type of hydrologic models are abundant in literature. Muskingum method introduced by Mc Carthy (1938) and modified by many researchers, lag and route method (Meyer, 1941), the diffusion analogy method (Hyami, 1951), Kalinin-Milyukov method (Kalinin and Milyukov, 1957), the complete linearized model (Harley, 1967), multiple linearization form routing method (Keefer and McQuivey, 1974), the simple non-linear model (Mein et al., 1974) etc. are some specific examples of hydrological models. The diffusion analogy model can be solved either by lumped linear system approach (Hyami, 1951; Harley 1967, Dooge, 1973) or by numerical method approach (Thomas and Wormleaton, 1970). The former approach in which the reach being studied as a single unit can be regarded as a hydrological approach and the latter approach where the cross section information is required at short intervals may be regarded as a hydraulic approach. Therefore it may be considered, at this point, that hydrologic routing methods, in general, treat the channel or river reach as a single unit or a series of single units, and as such information within this unit can not be obtained. In this paper, only the literature on hydrologic flood routing methods has been reviewed. An exhaustive review of hydrologic flood routing methods has been recently brought out by National Institute of Hydrology (1985).

The hydrologic method of routing can be broadly classified as 1) storage routing method, and 2) complete linearized method and its simplifications although, there are some methods like that of HYMO flood routing method introduced by Williams (1975) which do not fall in the above two categories and yet considered as hydrologic methods. The storage routing method may deal with linear, quasilinear and nonlinear flood routing problems. In linear routing the parameters of the model are kept constant throughout the routing operation. Examples are the conventional Muskingum flood routing method, lag and route method, Kalinin-Milyukov method etc. In quasi-linear routing some or all the parameters of the model change from one time step to another. The variable parameter Muskingum-Cunge method (Ponce and Yevjevich, 1978), the variable lag and route method introduced by Quick and Pipes (1975) are the specific examples of such category. The method proposed by Mein et al. (1974) and Rockwood (1958) form the class of nonlinear storage routing method.

All the above categories of hydrologic flood routing methods have been reviewed in this paper with reference to the aspects of mathematical development, advantages and limitations and comparison among themselves. The paper ends with the remarks for further work to be carried out on the hydrologic flood routing area.

2.0 Review

2.1 Storage Routing Models

All the storage routing models are based on the continuity equation in lumped form which can be written for a channel reach as :

$$I(t) - Q(t) = \frac{dS(t)}{dt} \qquad \text{......(1)}$$

where, I (t) and Q (t) are inflow and outflow respectively, and S (t) the storage in the reach under study at time t. Since there are two unknowns viz. Q (t) and S (t) and only one equation, the solution for Q (t) can not be obtained. In order to eliminate one of the unknowns, expression for storage S (t) in terms of I (t) and Q (t) or Q (t) is used. The storage equation may be linear or nonlinear in form. The following are the commonly used forms of storage equations in flood routing :

$$S(t) = K\,Q(t) \qquad \text{......(2)}$$

$$S(t) = K\,Q(t+\tau) \qquad \text{......(3)}$$

$$S(t) = K\,[\theta\, I(t) + (1-\theta)\, Q(t)] \qquad \text{......(4)}$$

$$S(t) = a_0\, Q(t) + a_1 \frac{dQ(t)}{dt} + a_2 \frac{d^2 Q(t)}{dt^2} \qquad \text{......(5)}$$

$$S(t) = a_0 Q(t) + a_1 \frac{dQ(t)}{dt} + b_0 I(t) \quad (6)$$

$$S(t) = a_0 Q(t) + a_1 \frac{dQ(t)}{dt} + b_0 I(t) + b_1 \frac{dI(t)}{dt} \quad \text{......(7)}$$

$$S(t) = K [Q(t)]m \quad \text{..... (8)}$$

For the sake of brevity the time functions attached with the notations for inflow, outflow and storage would be dropped here after-wards except for the case of equation (3) which represents the storage of the lag and route model. Equation (2) represents the storage of a Single Linear Reservoir (SLR) model proposed by Zoch (1934). Using a series of n-SLRs Nash (1957) conceptualised the catchment behaviour for a unit impulse input and derived the Instantaneous Unit Hydrograph (IUH) for the catchment. Dooge (1973) pointed out the same can also be used for modelling the flood in a river reach. Equation (3) forms the basis of the lag and route model proposed by Meyer (1941). It relates the outflow of time $(t + \tau)$ storage at time t. The term τ represents the response delay time or the time taken for the leading edge of the flood wave to reach the outflow section. Equation (4) forms the basis of the classical Muskingum flood routing method proposed by Mc Carthy (1938). Equations (5) – (7) were studied by Kulandaiswamy et al. (1957) as particular cases of general linear storage routing model applied to route floods in channels and river reaches. Equation (8) represents the nonlinear relationship between storage and discharge and it has been employed by Rockwood (1958) and Mein et al. (1974) for channel routing. The work based on each of the above equations have been reviewed.

2.1.1 Single linear reservoir (SLR) model and its variations

(a) The SLR model

The storage equation for SLR Model is given above as :

$$S = KQ$$

combining equation (1) and (2) and solving for Q, for the Dirac-delta input gives the response as :

$$U(o, t) = \frac{1}{K} e^{-t/K} \quad \text{......(9)}$$

where,

u (o, t) = the IUH

K = the storage constant of SLR

The form of the impulse response suggests that it can represent only the attenuation effect of the flood wave.

(b) Nash model

To overcome the deficiency of SLR Model, Harley (1967) and Dooge (1973) suggested the use of n-SLRs in series to partially simulate the translation behaviour of the flood wave in a channel reach. The form of IUH of such a model is given as :

$$u(o, t) = \frac{1}{K\sqrt{n}} \left(\frac{t}{K}\right)^{n-1} e^{-t/K} \quad \text{......(10)}$$

in which,

n = the number of SLRs, in series

Equation (10) represents Nash model (1958). The parameters n and K can be determined from the inflow and outflow hydrographs using the moments theorem (Nash, 1958).

(c) Kalinin-Milyukov model

This model proposed by Kalinin and Milyukov (1957) and widely used in USSR is a physically based n-linear reservoirs model. It is physically based because the length of the reach which can be modeled by a SLR is given in terms of the channel and flow characteristics of the reach. They computed the length of the reach assuming that there is a single value relationship between the downstream discharge and the stage at the middle of the SLR reach. The characteristic unit reach length is given as :

$$\triangle x = \frac{Q_o}{s_o BC} \quad .....(11)$$

in which, Q_o, the reference discharge about which the unsteady behaviour of the flood flow is linearised; So, the bed slope; B, the channel width, and C, the wave celerity. The lag time of the characteristic unit reach length is given as :

$$K = \frac{\triangle x}{C} \quad ......(12)$$

where, $\triangle x$ is the reach length under consideration. Using the characteristic unit reach length, the number of reservoirs required for routing floods in a given reach can be computed. Miller and Cunge (1975) explained the procedure of this method for use in practice.

It can be seen now, that the black box modelling of flood flow in a river reach using Nash model given by equation (10) has physical basis through Kalnin-Milyukov model. Whereas in the case of Nash model the parameters n and K are estimated by the method of moments (Nash, 1958) using the past recorded inflow and outfow information, they are estimated in the case of Kalinin-Milyukov model based on the physical consideration. Thus, the Kalinin-Milyukov model enables one to compute the parameters of the model for those floods which are greater in magnitude than the past observed floods. However, both the Nash model and Kalinin-Milyukov model treat the entire flow at a particular section including the flood plain flow as a single channel flow.

2.1.2 Lag and route models

The simple lag and route model is a two parameter model on the following input-storage-output relationship as given in equations (1) and (3) :

$$I - Q = \frac{ds}{dt}$$

$$S = KQ\ (t+\tau)$$

in which, τ is the travel time of the leading edge of the flood wave to arrive at the outlet section and K, the storage constant of the linear. reservoir. The concept of lag and route model was based on intuition (Meyer, 1941) and thus it has been considered for a long time as an empirical model (Harley, 1967; Doog, 1973). This model attempts to duplicate the complex action of a channel by a simple combination of a linear channel and a linear reservoir in series. The impulse response function of this particular system is as follows :

$$u\ (o,\ t) = \frac{1}{K} e^{-(t-\tau)/K} \quad \text{for } t > \tau \qquad (13)$$
$$u\ (o,\ t) = 0 \quad \text{for } t > \tau$$

A similar unit response approach for routing through a SLR was reported by Saur (1973). Quick and Pipes (1975) have proposed a nonlinear lag and rout model which is based on the physical characteristics of the channel and flow characteristics. However Keefer et al. (1976) criticised the approach of Quick and Pipes as it has been developed based on daily flows only, and the method itself is derived from Hyami's theory (1951) which could have been applied directly incorporating the nonlinear behaviour of flood wave. Recently Perumal (1984) has given physical justification for the lag and route method based on a consideration which is different from that of Quick and Pipes (1975). He showed that the parameters K and τ of equation (13) can be estimated using the channel and flow characteristics. The parameter τ has been kept constant and the parameter K can be either constant or varying. Perumal (1986) demonstrated his approach using two hypothetical problems and found that the solution obtained is comparable with that of St. Venant's equations solutions.

Instead of using one SLR in the lag and route method, Harley (1967) proposed a n-multiple SLR in series along with a single linear reservoir. Such a model has the flexibility of applying it to long river reaches and its IUH form is given as :

$$u\,(o,t) = \frac{1}{K\sqrt{n}} \left(\frac{t-\tau}{K}\right)^{n-1} e^{-(t-\tau)/K}$$

$$\text{for } t < \tau \qquad \ldots(14)$$

Equation (14) reveals that the model is a combination of n-linear reservoirs in series alongwith a linear channel whose characteristic is to translate the flow to downstream end of the reach without any modification. Equation (14) represents the three parameter Gamma distribution. The parameters n, τ and K of this model can be estimated using moments theorem.

2.1.3 Conventional Muskingum method and its variations

(a) The conventional Muskingum method.

The Muskingum method is the widely used method for routing floods in rivers and channels. Mc Carthy (1938) introduced this method as a storage routing method, in connection with studies of the Muskingum Conservancy District Flood Control Project. The method employs the lumped continuity equation given at 1)

$$I - Q = \frac{ds}{dt}$$

and the storage equation given at (4)

$$S = K\,[\theta\, I + (1-\theta)\, Q\,]$$

in which Q is the weighting parameter and all the other notations being as defined earlier. The conventional or classical Muskingum routing equation is obtained by expressing equation (1) and (4) in the finite difference form and their simplification leads to :

$$Q_2 = C_o I_2 + C_1 I_1 + C_2 Q_1 \qquad \ldots(15)$$

in which, Q_1, Q_2 and I_1, I_2 respectively are the outflow and inflow at the beginning and end of the routing interval, $\triangle t$.

The coeffients C_o, C_1 and C_2 are expressed as ;

$$C_o = \frac{-K\,\theta + \triangle t/2}{K\,(1-\theta) + \triangle t/2} \qquad \ldots(16)$$

$$C_1 = \frac{K\,\theta + \triangle t/2}{K\,(1-\theta) + \triangle t/2} \qquad \ldots(17)$$

$$C_2 = \frac{K\,(1-\theta) - \triangle t/2}{K\,(1-\theta) + \triangle t/2} \qquad \ldots(18)$$

The sum of C_o, C_1 and C_2 are equal to 1.0. Since I_1, I_2 and Q_1 are known for every time increment, routing is accomplished by solving equation (15) recursively. The Muskingum solution can also be obtained using electronic analogue formulated on the basis of equations (1) and (4). Ramanamurthy (1965) has formulated such an electronic analogue model for the reach between Baramul and Kaimundi on the river Mahaadi.

For the numerical solution of the Muskingum flood routing method, it is generally recognised in the standard text books (Viessman et al., 1977) that for some particular values of the Muskingum parameters K and θ (when $\triangle t = K$ and $\theta = 0.5$) the outflow hydrograph is the same as the inflow hydrograph, but lagged in time by K. Substituting these particular values of $K = \triangle t$ and $\theta = 0.5$ in equation (16), (17) and 18 leads to the solution of equation (15) as :

$$Q_2 = I_1 \qquad \ldots\ldots(19)$$

However this is a misleading conclusion since routing of the inflow hydrograph by these constants does not reproduce the outflow hydrograph adequately. (Hopkins, Jr., 1956; Nash, 1959; Singh and Mc Cann, 1980). The error lies in violating the condition that $\triangle t$ must be small relative to K. Where this condition is relaxed, as in the case of modified

Muskingum method, it can be shown that equation (19) is not obtained.

(b) The modified Muskingum method

Because of the condition that $\triangle t$ should be small relative to K in the conventional Muskingum method, Nash (1969) linearised the inflow over the time interval Δt and solved the basic equations (1) and (4) using linear system approach. Nash's solution is given as :

$$Q_2 = C'_0 I_2 + C'_1 I_1 + C'_2 Q_1 \qquad \text{......(20)}$$

in which

$$C'_0 = 1 - (1 - c) K/\triangle t \qquad \text{......(21)}$$

$$C'_1 = (1 - c) K/\triangle t - c \qquad \text{......(22)}$$

$$C'_2 = c = \exp(\triangle t/K (1 - \theta)) \qquad \text{......(23)}$$

Here the $\triangle t$ is restricted only from the consideration of adequately describing the inflow and outflow, and not with reference to K as in the conventional Muskingum method. Substituting $K = \triangle t$ and $\theta = 0.5$ in equation (20) does not show pure translatory characteristics :

(c) Further studies on the Muskingum method

Kulandaiswamy (1966) studied the translatory characteristics of the Muskingum method and for this purpose he derived the following exact solution of the Muskingum method using the initial condition

$$Q_o = I_o \text{ at } t = 0;$$

$$Q(t) = -\frac{\theta}{1-\theta} I(t) + \frac{e^{-t/K(1-\theta)}}{K(1-\theta)^2} \int_0^t I(t) e^{t/K(1-\theta)} dt + \frac{I_o}{(1-\theta)} e^{-t/K(1-)} \qquad \text{.........(24)}$$

The same solution was also independently derived by Diskin (1967). Kulandaiswamy pointed out that when $\triangle t = K$ and $\theta = 0.5$, equation (24) does not lead to translatory solution. However he pointed that the Muskingum solution is approximately translatory if the third and higher order derivatives of the inflow are negligible. In his controversial paper Gill (1979a) stressed that the Muskingum solution is purely translatory under the condition laid out by Kulandaiswamy (1966). As a response to this conclusion Singh and Mc Cann (1980) proved unequivocally that the pure translatory solution is a myth. Strupczewski and Kundzewicz (1980), and Kundzewicz and Strupczewski (1982) showed by systems approach that for $\theta = 0.5$, the Muskingum solution is approximetly translatory when compared with the other value of θ. Based on these works, one can conclude that the Muskingum solution does not exhibit the pure translatory characteristics.

One of the disturbing fact of the Muskingum method is the formation of negative outflow in the beginning of the solution. Nash (1959) recognised this defect and recommended the use of lag and rout method especially for steep rising rivers, wherein this defect is prominent. However, Nash pointed out that the negative outflow is mathematically correct. Venetis (1969) explicitly brought out this defect in the form of IUH of the Muskingum reach as:

$$u(o,t) = -\frac{\theta}{(1-\theta)} \delta (0_+) + \frac{1}{K(1-\theta)^2} e^{-t/K(1-\theta)} \qquad \text{......(25)}$$

in which, δ is the Dirac-delta function. The development of negative outflow has even led to the suggestion of rejecting the Muskingum method for the field use other than for mere academic interest (Meehan, 1978; Meehan and Wiggins, 1979). Gill (1979a, 1979b) argued that the negative outflow development is due to the adoption of wrong initial conditions and suggested a new set of initial conditions as:

$$Q(\tau) = I(0) \text{ when } \tau > 0 \qquad \text{.........(26)}$$

and quoted that Q is undefined for $t < \tau$. Gill's (1979a) initial conditions as proposed above created a lot of controversies in the literarure of Muskingum method, (Singh and McCann, 1980; Strupczewski and Kundzewicz, 1980, 1981) and it was emphasised that the use of initial condition $Q(o) = I(o)$ at $t=0$, for solving the Muskingum equation is correct. Singh and McCann (1980) argued that when $Q(t)$ is undefined for $t<\tau$, then it leads to inconsistency in the mass balance of the Muskingum method and therefore such an initial condition is not suitable. In a reply to the discussion of Strupczewski and Kundzewicz (1980), Gill (1980) changed his previously stated initial condition and modified it as $Q(t)=I_o$ for $t<\tau$.

His argument in favour of the modified initial condition is quite physically based. But he did not explain the impact of that inflow which enters the reach between time 0 and τ on the outflow. This made the researchers not to heed much attention to his concept. In a recent paper Gill (1984) has convincingly clarified his concept on the modified initial conditions. It is worthwhile to mention that the concept proposed by Gill (1980) had been employed much earlier by Pitman and Midgley (1966). However, they accounted the travel time of the leading edge of the wave as a time varying parameter. An indirect support to the concept of Gill's modified initial conditions has been given by Comer et al. (1981) when they suggested the modified ATTKIN routing model. The basic concept behind the ATTKIN Model is that proper unsteady flow models describing the passage of flood hydrograph, through a reach must atleast be a combination of both kinematic characteristics for translation and storage characteristics for attenuation. While the full dynamic equations simultaneously account for both effects in a distributed manner, the hydrologic models should account for them in a lumped fashion.

(d) Parameter estimation :

Most hydrology text books (Linsley et al., 1949; Viessman et al., 1977) present the graphical technique for estimating the parameters K and θ using observed inflow and outflow data with no lateral flow. Although the graphical method is generally satisfactory, it certainly is not the most convenient method to work with Harley (1967) and Dooge (1973) estimated these parameters using the method of moments. Gill (1978) proposed the least squares method to estimate the Muskingum parameters. Stephenson (1979) proposed a direct optimization method for parameter estimation. Singh and Mc Cann (1980), and Singh and Choudhury (1980) studied five different methods of estimating the parameters of the Muskingum method. These methods include (1) graphical method (2) least squares method (3) method of moments, (4) method of cumulants and (5) direct optimisation method. However, the inclusion of method of moments, and method of cumulants as separate methods of parameter estimation is not correct, as the method of cumulants has to be reduced to method of moments before computing the parameters and thus they would give the same parameter values (Dooge, 1973). Singh and McCann concluded that these methods of parameter estimation are comparable and one method does not have a particular advantage over the other. Laurenson (1959) investigated the parameter estimation of the Muskingum method for long river reaches and found that the linear storage relationship given by equation (4) is no more valid. He suggested that long reach has to be sub-divided into smaller reaches, such that the travel time K of the small reach is less than half the time of rise of the inflow hydrograph.

(e) Range of parameters

The parameter K signifies the average travel time of the flood wave between upstream and downstream section of the reach (Dooge, 1983). The value of K for practical purposes may range between $\triangle t$, the time interval used for routing the flood, and half the time of rise of the inflow hydrograph as suggested by (Laurenson (1959).

The weighting parameter θ ranges between 0 and 0.5, The lower limit of θ corresponds to linear reservoir case and the upper limit corresponds to the non-attenuation of the inflow hydrograph. Using Fourier transform analysis, Strupczewski and Kundzewicz (1980) demonstrated that $\theta > 0.5$ leads to inflow hydrograph amplification which is not a desired result in the routing.

2.1.4 Muskingum-Cunge method and its variations

Since the flood characteristics are likely to vary from one flood to another, it would be rash to assume that the parameters determined from one set of flood records could be used to predict the behaviour of an altogether different flood. This, in effect, limits the predictive capability of the method to floods similar to that used in the calibration, and any attempt at extrapolation is unwarranted. The use of constant parameters in the classical Muskingum method is tantamount to an assumption of linearity, and this is in contradiction with the quasilinear property of flood waves.

(a) The Muskingum-Cunge method

The Muskingum-Cunge method (Cunge, 1969), considerably enhances the predictive capability of the Muskingum method, while remaining within the same computational framework. Cunge related the parameters of the method K and θ with the channel and flow characteristics using the analogy between the finite difference approximation of the conventional Muskingum difference scheme derived using the Kinematic wave theory concept, and the linear convection diffusion equation or the diffusion analogy model. Cunge's approach essentially converts the conventional Muskingum difference scheme being hydrological in theory into a method based on hydraulic principle. Cunge's relationship between model parameters, and channel and flow characteristics are given as ;

$$K = \triangle x/C \quad \text{...... (27)}$$

$$\theta = \frac{1}{2}\left(1 - \frac{Q_o}{S_o\, BC \triangle x}\right) \quad \text{......(28)}$$

in which Q_o the reference discharge about which the unsteady flow is linearized; S_o, the bed slope; C, the wave celerity, and $\triangle$ x the channel reach length.

Muskingum-Cunge method employs equation (15) with the coefficients C_o, C_1, and C_2, given by equations (16) (17) ,and (18) respectivel y,being computed using the parameters estimated through equations (27) and (28). Following Cunge's study a number of papers and reports have been added to the literature of Muskingum method, based on the principle of diffusion analogy (Miller and Cunge, 1975; NERC 1975; Koussis, 1976, 1978, 1980, 1983; Weinmann, 1977; Ponce and Yevjevich, 1978; Ponce et, al, 1978, 1979; Ponce, 1979; Ponce and Theurer, 1982; Weinmann and Laurenson, 1979; Cameron, 1980; Smith, 1980; Jones, 1981; Chang et al, 1983; Ferrick et al 1984). Ponce and Yevjevich (1979) improved the Muskingum-Cunge method by varying the parameter K and θ in time and space, and showed that the use of variable parameters computed based on an iterative four point approach simulates the flood flow accurately. Cameron (1980) developed a Kalman filter application based Muskingnm-Cunge method for real time application to flood forecasting. Cunge's work (1969) and its derivatives basically try to mimick the physical diffusion present in the flood routing using the numerical diffusion.

(b) Muskingum-Koussis method

Koussis advocated (Koussis, 1976, 1978, 1980, 1983) an alternate finite difference scheme of Muskingum method, obtained through the space averaged continuity and linear storage weighted discharge equations after linearising the inflow hydrograph over the routing time interval. He named the scheme as more refined scheme (1978) and related the parameters K and θ with the channel and flow characteristics in a similar manner as Cunge had done for the conventional scheme. The more refined scheme was also derived by Nash (1959): The scheme reads as :

$$Q_2 = C_o' I_2 + C_1' I_1 + C_2' Q_1 \quad \text{......(29)}$$

The coefficients C_o', C_1' and C_2' remain same as that of equations (21)-(23). The weighting factor of the Koussis scheme is given as:

$$\theta_k = 1 + r/\ln((1+\lambda-r)/1+\lambda+r) \quad \text{......(30)}$$

$$r = \triangle t/K \quad \text{......(31)}$$

and $$\lambda = Q_o/(S_o BC\triangle x) \quad \text{......(32)}$$

However in both the schemes the travel time K is given as:

$$K = \triangle x/C \quad \text{......(27)}$$

Koussis (1980) noted that the numerical experimentation could not conclusively prove the superiority of his scheme over the Cunge's scheme and noted that more refined scheme, however, is less prone to the well known dip at the beginning of the outflow hydrograph. Perumal (1984) showed by theoretical analysis that both the schemes yield the same coefficients of the routing scheme. He reasoned that both the schemes, by appropriate selection of their respective weighting factors afford a second order, approximation of the same physically based convection-diffusion equation.

(c) Weighting parameter θ

Cunge (1969) limits the value of θ to 0.5 at the upper end from the numerical stability point of view and to zero at the lower end. However, Perumal (1985) has shown using discrete impulse response analysis that there is no numerical instability even if $\theta > 0.5$, but points out that the value of θ has to be limited to 0.5 to avoid amplification down the channel. The numerical values of θ_k of the Koussis method can be greater than 0.5 without affecting the stability of the solution and at the same time maintaining the attenuation of the flood wave down the channel (Chang et al; 1983). Note that in contrast to weighting factor of the conventional scheme (Cunge's scheme), the Koussis θ_k depends on the time step $\triangle t$. However, as pointed out by Perumal (1984), the coefficients of both the schemes are exactly the same in terms of the physical and flow characteristics of the channel reach.

(d) Time and spatial resolution

The problem of negative outflow exists, whether one is dealing with the conventional Muskingum method or with that of diffusion analogy based Muskingum method. U.S. Army Corps of Engineers (1960) suggest that the routing time interval $\triangle t$ should be greater than 2 $K\theta$ in order to avoid negative value of C_o which causes negative outflow in the beginning. Weinmann and Laurenson (1979) suggested that for practical purposes, these negative outflows are small enough and sufficiently short lived to be ignored if the following inequality is satisfied:

$$\frac{\triangle x}{C} \leqslant \frac{T_r}{2\theta} \quad \text{......(33)}$$

in which, T_r = period of rise of inflow hydrograph. Chang et al (1983) arrived at the lower limiting condition on $\triangle t$ based on the Koussis scheme, which eliminates the dip of the outflow hydrograph using the implicit equation:

$$t^* = \triangle t = K(1-\theta) \ \ln\ [(1-\Delta t/K)]^{-1} \quad \text{...(34)}$$

Kundzewicz (1984), and Perumal and Seth (1984) emphasized that by taking a minimum value of Δt, the problem of negative outflow or reduced outflow in the beginning of the outflow hydrograph is not really solved and it is simply skipped.

Ponce and Theurer (1982) have suggested, based on their experience with the diffusion analogy method, that the upper limit of the spatial resolution Δx can be limited to:

$$\Delta x < \left(\frac{q_o \Delta t}{S_o \epsilon}\right)^{1/2} \quad \text{.........(35)}$$

in which, q_o being the reference discharge per unit width and $\epsilon = 0.25$. They found that there is no theoretical limit on Δx: However, Jones (1983) argued that the accuracy criterion proposed by Ponce and Theuret is not correct due to the unusual way the finite difference scheme is constructed to match the convection-diffusion equation in which the amount of diffusion is assumed to be small. He emphasized, therefore, that it is not possible to use consistency or convergence of the finite difference-scheme as accuracy criterion in this case. He pointed out based on his earlier studies (Jones, 1981) on the Muskingum - Cunge method, that the time resolution should be based on the following criteria.

$$\frac{T_r}{5} > \Delta t > 1.43 \left(\frac{q_o}{2S_o C}\right) \quad \text{.........(36)}$$

and the space resolution being equal to the channel length:

(e) Reference discharge

The reference discharge used in the diffusion analogy model for determining K and θ is based on the representative value of discharge both for the length of each considered and for range of discharges encountered. Price (1973) used the average peak discharge of inflow and outflow as a representative value.

(f) Diffusion analogy model corrected for dynamic effects

The Muskingum-Cunge method and the Koussis method described earlier, use the kinematic wave speed parameter C for determining the travel time of flood in a given river reach. This parameter C is a function of depth only as this is viewed through a kinematic wave model and this implies a single valued rating curve. A number of attempts have been made to make these models more general by allowing for a looped rating curve, rather than a single valued rating curve characteristic of the kinematic wave model in determining the travel speed parameter. Koussis (1976) has used "Jones formula" (Henderson. 1966) to obtain the travel speed of the flood wave based on the loop rating curve. The Jones formula used for establishing loop rating curve at a particular section in a river is given as:

$$Q = Q_n \left(1 + \frac{1}{BC^2 S_c} \frac{\partial Q}{\partial t}\right)^{1/2} \quad \text{.........(37)}$$

in which Q_n corresponds to the normal flow at a section.

The advantage of this model is that it not only takes care of the variation in C, but the effect of loop rating curve on C is also taken into account in a more rational manner than the method proposed by Ponce and Yevjevich (1978).

2.1.5 Kulandaiswamy's general storage equation based model

Kulandaiswamy et. al (1967) studied some particular forms of the general storage equation (Kulandaiswamy, 1964) for use in the flood routing problem. The particular forms of the storage equations studied are :

$$S = a_o Q \quad \text{...(38)}$$

$$S = a_o Q + a_1 \frac{dQ}{dt} + a_2 \frac{d^2 Q}{dt^2} \quad \text{...(39)}$$

$$S = a_o Q + a_1 \frac{dQ}{dt} + b_o I \quad \text{...(40)}$$

$$S = a_o Q + a_1 \frac{dQ}{dt} + b_o I + b_1 \frac{dI}{dt} \quad \text{...(41)}$$

Each of the above equations was studied in conjunction with the space averaged continuity equation for its suitability to describe the flood movement, using the data of three floods. They found that the form of storage equation given by equation (40) gave satisfactory results. In all the three floods studied, 'a' and 'b' cefficients were determined by the method of least squares. The coefficients a_o, a_1 and b_o have been assumed to be constants for a given flood.

2.1.6 Nonlinear storage routing model

This model is based on the space averaged continuity equation given by equation (1) as :

$$I - Q = \frac{dS}{dt}$$

and the non-linear storage equation given by equation (8) as :

$$S = K\,Q^m$$

Equation (1), written in finite difference form for routing reach of length $\triangle x$ and a time interval, $\triangle t$ may be combined with equation (8) to yield :

$$\frac{Q_2}{2} + \frac{KQ_2{}^m}{\triangle t} = \frac{I_2 + I_1 - Q_1}{2} + \frac{KQ_1{}^m}{\Delta t} \quad ...(42)$$

where, the parameters K, m and the terms on the right hand side are known. This equation can be solved for Q_2 by an iterative procedure such as the Newton-Raphson procedure. The details of the model solution procedures and methods of parameter evaluation are described by Laurenson et al. (1975). Rockwood (1958) has also used the same form of the model described by equations (1) and (8), but with a different solution procedure. Napiorkowski and O' Kane (1984) have presented a non-linear lumped conceptual model which is composed of a cascade of equal nonlinear storage elements preceded by an element of pure delay, and this model depends on four parameters only.

2.1.7 Modified puls method for flood routing through a river reach

The Hydrologic Engineering Center uses in their HEC-1 'flood hydrograph package' (HEC, 1981), the modified Puls method as one of the method for routing floods in river reaches. Routing in river using the modified Puls method is same as reservoir routing, except for the method of developing storge outflow curves. The method consists of repetitive solution of the space averages continuity equation and is based on the assumption that outflow at the end of the river reach considered is a unique function of storage within that river reach.

Using the developed storage discharge relationship and the space averaged continuity equation, the following recursive equation required for modified Puls method of routing is obtained.

$$\left(\frac{S_2}{\Delta t} + \frac{Q_2}{2}\right) = \left(\frac{S_1}{\Delta t} + \frac{Q_1}{2}\right) - Q_1 + \left(\frac{I_1 + I_2}{2}\right) \quad ..... (43)$$

Where, S_1 and S_2 are storage at the beginning and end of the time step, Δ t.

2.2 Complete Linearized Model and its Simplifications

2.2.1 Complete linearized model

Harley (1967) obtained a general linear solution to the flood routing problem by solving the linearized equation of motion described by the St. Venant's equation, for a semi-infinite uniform open channel subject to a direc-delta function input at the upstream end. The linearization of St. Venent's equation about a reference discharge q_o, applied to a unit width of channel carrying a unit discharge leads to the following linear form :

$$(gy_o - u^2{}_o)\frac{\partial^2 q}{\partial x} - 2u_o\frac{\partial^2 q}{\partial x\,\partial t} - \frac{\partial^2 q}{\partial t^2} = 3gS_o\frac{\partial q}{\partial x} + \frac{2gs_o}{u_o}\frac{\partial q}{\partial t} \quad ......(44)$$

in which,

q = the discharge/unit width of the channel

u_o = the velocity corresponding to the reference discharge, q_o

y_o = the depth corresponding to the reference discharge, q_o

g = acceleration due to gravity

x = the distance from upstream end of the reach.

Harley obtained the following unit response function due to the dirac-delta function as input at the upstream end of the reach :

$$u(x, t) = e^{-px}\delta\left(t - \frac{x}{C_1}\right) + h\,(x/C_1 - x/C_2)$$
$$e^{sx-rt}\, I\,(2hm)/m \quad \text{......(45)}$$

where

$$C_1 = u_o + \sqrt{gy_o}$$
$$C_2 = u_o - \sqrt{gy_o}$$
$$F = u_o / \sqrt{gy_o}$$
$$p = S_o\,(2 - F)\,/\,2\,y_o\,(F^2 + F)$$
$$r = S_o\,u_o\,(2 + F^2)\,/\,2\,y_o\,F^2$$
$$s = S_o/2\,y_o$$
$$h = S_o\,u_o\sqrt{(4 - F^2)\,(1 - F^2)/4\,y_o\,F^2}$$
$$m = \sqrt{(t - x/C_1)\,(t - x/C_2)}$$

and I (2 hm) is a first order Bessel function of ths first kind and δ is the Dirac-delta function.

This model's accuracy is very much dependent on the reference discharge magnitude. The moments of the linear channel response are related with the channel and flow characteristics of the complete linearized solution model (Harley, 1976) as :

$$U'_1 = x/C \quad \text{......(46)}$$

$$U_2 = \tfrac{2}{3}\,(1 - F^2/4)\,(y_o/S_o\,x)\,(x/C)^2 \quad \text{......(47)}$$

$$U_3 = 4/3\,(1 - F^2/4)\left((1 + \frac{F^2}{2}\right)(Y_o/s_o\,x)^2$$
$$(x/1.5\,u_o)^3 \quad \text{......(48)}$$

in which, U'_1 is the first moment about the origin and U_2 and U_3 are the second and third moments respectively about the mean; C, the wave celerity obtained using Chezy's coefficient. As this is a three parameter model the first three moments are sufficient to estimate the parameters of the model.

2.2.2 The diffusion analogy model

By neglecting the last two terms on the left hand side, equation (44) can be reduced from hyperbolic to parabolic equation of the following form:

$$\left(gy_o - \frac{u_o^2}{4}\right)\frac{\partial^2 q}{\partial x^2} = 3\,gS_o\,\frac{\partial q}{\partial x} + \frac{2gs_o}{u_o}\frac{\partial q}{\partial t} \quad \text{.........(49)}$$

Rearrangement of equation (48) to the form of convection diffusion equation proposed by Hyami (1951) reduces to:

$$\frac{\partial q}{\partial t} + \frac{3}{2}\,u_o\,\frac{\partial q}{\partial x} = \frac{q_o}{2S_o}(1 - F^2/4)\frac{\partial^2 q}{\partial x^2} \quad \text{......(50)}$$

The wave celerity is given as:

$$C = 1.5\,u_o \quad \text{.........(51)}$$

and the hydraulic diffusivity is given as:

$$D = \frac{q_o}{2S_o}\,(1 - F^2/4) \quad \text{.........(52)}$$

when the Froude number is less than one-half, it may be neglected and D is expressed as :

$$D = \frac{q_o}{2S_o} \quad \text{.........(53)}$$

Equation (50) with D expressed as in equation (53) may be traced back to Hyami (1951). The linear channel response of equation (50) at distance x, is given for a Dirac-delta input as Harley, (1967):

$$U(o, t) = \frac{X}{\sqrt{4\,\pi D t^3}}\exp\left(-(x - ct)^2/4Dt\right) \quad \text{......(54)}$$

By convoluting the unit discharge at x = o with equation (54), the response of channel at any x and t may be determined. As long as q (t) does not vary greatly from q_o, the reference discharge, or atleast in a range in which C and D do not vary greatly with discharge, equations (54) is a satisfactory routing model.

The relationship between the first two moments of the impulse response function and the channel and flow properties are given as (Harley, 1967) :

$$U'_1 = x/C \qquad \ldots\ldots(55)$$

$$U_2 = 2\,Dx/C^3 \qquad \ldots\ldots(56)$$

Using the above two equations, the parameters C and D can be determined from the known input and output. The parameters C and D of the model ere related with the channel and flow characteristics as indicated by equations (51) and (52) based on the assumption of wide rectangular channel. While applying this model for flood routing in natural channels, equations (55) and (56) can be used to find the equivalent wide rectangular channel characteristics for the given reach with past flood data. The equivalent parameters arrived in such a manner can be used for routing floods in the same reach of the natural channel for those input which were not used for calibration of the model.

2.2.3 Multiple linearization model

Keefer and McQuivey (1974) realized that the complete linearized model and the diffusion analogy model, linearizes the flow behaviour in a channel about a single discharge which forces all the blocks of discharges of a hydrograph to travel at a single velocity. They argued that the stream channels behave very nearly as linear systems over small ranges of discharge and so they divided a single block of discharge, say over the routing interval △ t, in different ranges, in such a manner that there is a unique unit response for each range of flow. These unit responses are convoluted with the discharges according to the range they belong to, and then these convoluted discharges are summed up to give the outflow hydrograph. Keefer and McQuivey's apıoach can be used with any of the methods of generating response functions such as complete linearized model, diffusion analogy model etc. Keefer and McQuivey (1974) evaluated the performance of their multiple linearization model for four river reaches in U.S. using the response functions of the complete linearized model as well as that of diffusion analogy model. They found that, multiple linearization model performs much better than a single linearization model. They also found that complete linearized model proved difficult to apply to actual data when compared with the diffusion analogy model.

Eventhough the method proposed by Keefer and McQuivey yield acceptable results from the practical consideration, their approach of dividing a single block of discharge into different ranges for the purpose of linearization seems to be artificial. Instead if they had adopted a single response function for a single block of discharge, but varying with different ranges of single discharge, then the nonlinearities would have been taken realistically.

2.2.4 Comparison of two parameter models

Dooge (1973) compared the performance of the two parameter models like diffusion analogy model, Muskingum model, lag and route model, and Kalinin-Milyukov model with reference to the solution of the complete linearized model. He found the diffusion analogy model and the Kalinin-Milyukov model predict discharges which are graphically indistinguishable from the complete linear solution. The lag and route method predicts the travel time to a fair degree of accuracy, but underestimates the degree of attenuation. The Muskingum method is seen to predict negative ordinates for a considerable period and a higher peak discharge with a 50% small time to peak. Dooge found that for the short channel lengths the Muskingum method performs as satisfactorily as the other methods and found for long reaches the method fails as noted by Laurenson (1959).

2.2.5 Comparison of three parameter models

With the above consideration Dooge (1973) studied the performance of three parameter models like, diffusion plus lag, multiple Muskingum method, and three parameter gamma distribution model with that of complete linearized solution. The diffusion plus lag model is a combination of diffusion analogy model and linear channel which simply translates the hydrograph in time. Dooge found that a change in the length of the channel considered does not result in any change in the value of convective velocity, C or the hydraulic diffusivity, D, but the third parameter, the lag, varies in order to maintain the optimum solution and is directly proportional to the length of channel. In the case of three parameter gama model, the reservoir lag time, K remains constant as in the two parameter Kalinin-Milyukov model, but both the number of reaches, n and lag of the linear channel, τ vary directly with the length to maintain similarity with the complete linear solution. Doog found that both diffusion plus lag model and three parameter gamma distribution model are well able to simulate the complete linearized solution. In the case of the multiple Muskingum model, the values of K ane θ are independent of the reach length and the complete linearised solution is matched by using a number of Muskingum reaches which is proportional to the length.

2.3 Physically Based Hydrologic Flood Routing Models

Many of the hydrologic flood routing models discussed above are semi-empirical in nature. The semi-empiricism arises, because the parameters involved in the mathematical formulation of the flood movement phenomena by various models are estimated from the past flood data. Application of such models for input whose magnitude is greather than the recorded input, which was used for calibration of the model, is not warranted. However, some of the models described above are physically based, in the sense that the parameter of the models are related with the measurable channel and flow characteristics. Such models can be used with confidence, for inflow which had not been recorded in the past or used for calibration of the model. Models like Kalinin-Milyukov method, Muskingum-Cunge method, complete linearized model and diffusion analogy model fall under this category. The Muskingum-Cunge method, although relates the parameters of the model with flow and channel characteristics, their derivation is based on mimicking the numerical diffusion with the physical diffusion. The other three models are based on approximations of the St. Venant's equations which governs the one dimensional flow in channel and river reaches. On the same lines, recently Pernmal (1985) has related the parameters of the lag and route model with the channel and flow characteristics.

An entirely different approach has been proposed for routing floods in channels by williams (1975) which forms a component of the HYMO Watershed model. He has proposed a Variable Travel Time (VTT) flood routing method which takes into account the variation in travel time of the discharge with stage and water surface slope. Williams has shown that by accounting the variation in water surface slope, the VTT method yields results that are comparable to the accurate results obtained with an implicit solution of the unsteady flow equations of continuity and motion. The basic equations employed in this method are the space averaged continuity equation and the travel time equation.

$$T = 2S/(I+Q) \qquad \ldots\ldots(57)$$

in which, S, the storage within the reach and T, the travel time through the reach. By expressing equation (57) in terms of normal flows at both ends of the reach and the corresponding depths, Williams was able to get the solution of outflow using iterative procedure. He found the method is well suitable for inbank as well as flows within flood plain, and demonstrated the applicability of the method to channel reaches of Brushy creek in U.S.A.

2.4 Wave Speed-Discharge Relationships

Most of the physically based models employ either Chezy's or Manning's formula to estimate the wave speed required to determine the average travel time of the flood wave movement from upstream to downstream of the reach under consideration. For example, Kalinin-Milyukov method, Muskingum–Cunge method, and diffusion analogy method determine the travel time as :

$$K = \Delta x/c \qquad \ldots\ldots(12)$$

In general, travel time varies nonlinearly with discharge. Since single valued stage (and therefore storage) versus discharge relations are assumed in most of the hydrologic models, this propogation speed is called the kinematic wave speed. Wave speed-discharge investigations carried out by Wong and Laurenson (1983 a, 1983 b, 1984) on six Australian river reaches, which include in bank as well as flood plain flow, show consistent variations of wave speed with discharge and show that the wave speed first increases rapidly with discharge, then decreases sharply and finally increases at a slower rate. The establishment of such empirical relationships between wave speed and discharges are immensely useful for application of physically based hydrologic flood routing models to field problems.

2.5 Accounting of Lateral Inflow

One of the factors which affects the accuracy of flood forecasting is the magnitude of lateral inflows to the channel. If lateral inflows to the channel are ignored in routing the flows from upstream to downstream of the reach, then the computed flows at downstream point would be smaller than the observed flows. These errors propagate as floods are routed down the stream. Consequently, estimating lateral flows would improve the routing accuracy. Estimation of lateral inflows has not received much attention. Infact the development of different flood routing techniques has been investigated more than the lateral inflow estimation. Nevertheless attempts have been made to estimate the lateral inflow in a meaningful manner. In 'HEC-1 flood hydrograph package' (HEC, 1981) the lateral inflow is estimated based on the supplied pattern of lateral inflow hydrograph and the volume difference between outflow and inflow hydrograph of the given reach. To determine the lateral inflow contribution in a more rational manner, Mimikov and Rao (1976) have proposed a model in which the lateral inflow volume of each storm is distributed over time equal to storm duration in a manner similar to the time distribution of rainfall of the storm within the intervening catchment of the reach. They have applied their model for daily flow and daily storm and therefore the application of such a concept to estimated lateral inflow based on hourly data is questionable due to its dynamic nature than that of daily data. Slocum and Dandekar (1975) have estimated the lateral inflow hydrograph by subtracting the outflow hydrograph estimated using different K and θ values of the Muskingum method, from the observed outflow hydrograph. The lateral inflow hydrograph which does not contain even a single negative ordinate has been considered as the correct one. Using Muskingum - Cunge model, Price (1973) has taken into account the lateral inflow assuming a uniform contribution along the channel reach. However, such assumptions are more valid for the urban storm sewer system rather than to natural river system. Recently 0 'Donnell (1985) has suggested the estimation of lateral inflow hydrograph from the given inflow and outflow data using the method of least squares technique based on the matrix method. In all these approaches the influence of addition of lateral inflow on the wave speed characteristics of the flood has not been considered,

3.0 Remarks

The hydrologic approach to flood routing is based on the consideration that in a large number of practical cases, the inertia terms of the equations of motion play an exceedingly small role. Such methods have advantages and disadvantages from the practical consideration. Miller and Cunge (1975) have listed the advantages and disadvantages in detail. Some of them ars listed below :

3.1 Advantages

(1) Hydrologic methods may provide answers in much less time than solution procedures based on the complete equations.

(2) The channel geometry need not be described in detail.

(3) Computation cost is less; programming for solution is simpler.

(4) Hydrologic flood routing models probably can be more easily integrated with rainfall-runoff models.

(5) The uses of the results from mathematical modelling often do not require the accuracy provided by the complete model.

3.2 Disadvantages

(1) Hydrologic methods do not have the accuracy of a solution procedure based on the complete equations. Probably a hydrologic routing model may give sufficiently accurate results for a particular application, but there is often considerable doubt as to how accurate the results are for any application.

(2) Considerable amount of past data, especially of inflow and outflow is required for reliable estimation of the parameters involved in the model.

(3) Backwater effect can not be accounted for by hydrologic methods as they are single characteristic passing only the upstream disturbance to downstream.

(4) The impact of lateral inflow on the parameters of the hydrologic models can not be taken into account due to longer length of reach usually considered.

(5) Solutions of simplified equations may lack desired generality.

Although current interest in the field of flood routing seems to be in methods utilizing numerical solutions of the complete equations of continuity and momentum, hydrologic methods are still useful, and may be preferable in some circumstances. The limitations of each technique must be thoroughly understood so that an intelligent choice of method to be used may be made.

3.3 Choice of Methods

The final choice of the best method of flood routing ultimately depends on the factors such as accuracy, the type and availability of data, the available computational facilities, the computational costs, the extent of flood wave information desired, and the familiarity of the user with a given model (Fread, 1981). Taking for granted that the modeler is well versed with all the techniques and there is no dearth for required data and computational facility, the important factors which influence the appropriate flood routing method are :

(1) The objective of the flood routing exercise, and

(2) The nature of available data.

If flood routing is to be done on a real time basis as part of a flood forecasting scheme, then what is required is a simple model in which the flood forecast at the downstream end of the channel reach can be updated at hourly or lesser intervals. If on the other hand, the flood routing is to be carried out as part of the design of a large scale hydraulic engineering project, then it may be more appropriate to use a more accurate method because of the potential savings resulting from the analysis (Dooge, 1980). If more flow data are available than the channel characteristic information like cross sectional area, wetted perimeter, roughness information etc., then the hydrologic method is best suited. Even when there is less flow information, but more channel characteristic information are available, one can still prefer the hydrologic methods which are physically based, for computing the parameter of the method using the channel characteristics.

Having decided to adopt the hydrologic method one is faced with the problem of selecting the best among them. Perhaps the conclusions arrived at by Dooge (1980) in this aspect may be worth considering. Based on the comparative study of various two parameter models with reference to complete linearized solution of the St. Venant's equation Dooge (1980) indicated that the diffusion analogy model appeared to give better simulation than any other two parameter model studied. Accordingly there seems no reason to prefer either the Muskingum method or the Kalinin-Milyukov method. In a similar manner he also concluded that among the three parameter models studied, the Kalinin-Milyukov method with pure lag added performs better. However, he has restricted his studies to physically based linear models and the performance of the simple nonlinear models such as proposed by Mein et al. (1974), Multiple linearized model (Keefer and McQuivey, 1974), HYMO flood routing model, Muskingum-Cunge model (Cunge, 1969) and Muskingum-Koussis model corrected for dynamic effects has not yet been studied with reference to complete linearized solution model. NERC (1975) has recommended the use of Muskingum-Cunge method over the diffusion analogy model as the former can take into account the lateral inflow explicitly. However it should be remembered that the Dooge's (1980) recommendations on the choice of 2 and 3 parameter models are based on the use of hypothetical data like sinusoidal input applied to a wide rectangular channel reach. He has used the chezy's resistance equation in his studies, and accordingly for wide rectangular channels the wave celerity is of the magnitude of 1.5 V, where V is the average mean velocity in a cross section. Keefer and McQuivey (1974) pointed out while applying their multiple linearization flood routing model to the reaches of Catawba river in U. S. A., that the wave celerity was 4V rather than 1.5 V meant for wide rectangular channels. Therefore Dooge's (1980) conclusions should not be taken as the ultimate rule, but only as a suggestion for a better method to begin with.

3.4 Further Research Needs

Future work on the hydrologic flood routing methods need to be focussed on improving the existing methods to suit the practical needs rather than to develop new methods. More attention should be paid in studying the physically based flood routing models for their field application, so that the parameters of the modles are evaluated from the known charactersitics of the channel reach and the flow characteristics. Attempts should be made to find a method to vary the parameters in time depending on the flow magnitude and the conveyance of the channel. Perhaps the studies conducted by Wong and Laurenson (1983a, b; 1984) may be of much use in this direction, for modelling the flood flow including the flood plain flow. Although their study is site specific, no doubt, they throw more light on the possibility of adopting same procedure for rivers in any other part of the world. Little attention has been paid for modelling the lateral inflow in a river reach. Although the backwater effect created by the bulk addition of lateral inflow, such as from a tributary to the main channel, can not be modelled by a hydrologic method, its impact on the wave speed of the main channel flow can be studied. Such a study would be of immense use for real time forecasting. Studies in the direction of finding the suitability of applying the hydrologic methods to alluvial rivers should be made. This would be useful in real time forecasting of floods in rivers like Ganga and Yamuna where the channel cross sections get modified during the progress of flood wave due to sediment transportation.

The hydrologic flood routing methods are most suitable for use in forecasting in Indian rivers due to the lack of cross sectional information and the gauging stations being located far apart. The central water commission has recommended (CWC, 1969) the use of Muskingum method for flood routing. It would be desirable to use methods like Muskingum-Cunge (Cunge, 1969), variable parameters Muskingum-Cunge (Ponce and yevjevich, 1978) etc. which are based on physical considerations, but at the same time maintain the simplicity of the conventional Muskingum method. The magnitude of flood problem in Indian rivers, especially the Himalayan rivers, is increasing day by day due to increased upland activities such as deforestation, changing land use, water resources development works etc. Rather than continuing the use of empirical methods, such as the gauge relationship, peak travel time relationship for forecasting floods, it is better to adopt simple, but rational methods of flood routing like hydrologic flood routing for flood forecasting. For this purpose the problems of lateral inflow and the sediment transportation have to be studied in detail, as indicated earlier. Literature survey indicates that there are few studies in our country on flood routing problems in river reaches. It is high time a systematic study of flood routing problems in each of the flood prone rivers in our country is carried out using hydrologic flood routing methods for the purpose of forecasting floods.

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HYDRAULIC ROUTING-A REVIEW

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1.0 Introduction

As the demand for water increases, there is greater pressure to regulate flow in natural streams. In India, there are now only few rivers that have not been affected in one way or other by artificial controls. There is, therefore, a strong need for accurate and economic methods to predict time varying flows and levels in a river, both for design and real time operations. Because of differing situations, the choice of method will vary according to application. This paper reviews the existing techniques for routing unsteady flow in streams and is concerned primarily with one dimensional modelling of unsteady and gradually varying flow in open channels. Approximate methods like hydrologic methods are not covered. However, a simple comparision of hydrologic methods with hydraulic methods has been given.

2.0 Physical aspects of flood flow

The river flow is contributed by tributaries and small gullies which are fed by rain or through sub surfaces. Large floods overflow the banks to occupy the floods plains. These flood plains are encroached because of urban development and hence affected. Therefore, these floods inundate unprotected areas. Such submergence reduces the flood peak and thus indirectly protects downstream areas naturally. In almost all the cases the river bed adjusts itself and accomodates the flood flow. However, an assumption of rigid bed will not be far from realistic except in the cases of alluvial rivers. The flow in a river is generally changing with time, and also varies spatially, leading to three dimensional flow behaviour. But bulk of the flood flow generally moves in one direction and hence one dimensional models are considered sufficient for engineering applications.

Some Indian rivers like Kosi, Brahmaputra present some problems in routing. Excessive sediment load is a problem in both these rivers. The river Kosi has steep gradient and rapid changes of the same. Due to these special aspects of Kosi the usual flood routing methods can only be a gross approximation of the reality. There is no model in the literature as on to day to formulate sediment movement and the energy slope in these rivers.

Besides, the river training works like construction of embankments etc have changed the river environment altogether as seen by Kosi river bed aggradation. Break of embankment is a problem of serious concern during floods. At the confluence, the back water effects are noticed over a long distance in the tributaries.

In almost all the rivers in India flow is highly variant comparing monsoon and non-monsoon season flows. The magnitude of flood changes considerably from year to year. and hence parameters found for one flow situation are not are not equally applicable for other flood flows. Floods which are confined within the banks are to be treated seperately than the floods which just crossed the banks or flowing much above the banks. At least three situations are to be distinguished in Indian rivers. Much of the works are yet to be done in this regard.

3.0 Mathematical model :

The law of conservation of mass and momentum are two basic principles with which a flow can be described mathematically. The St. Venant equations as given below are widely used in unsteady flow computations.

Continuity equation :

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \qquad \ldots\ldots\ldots(1)$$

Momentum equation:

$$\frac{\partial A}{\partial t} + \frac{Q}{A}\frac{\partial Q}{\partial x} + Ag\left(S_f - S_o + \frac{\partial y}{\partial x}\right) = 0 \qquad \ldots\ldots\ldots(2)$$

Where,

- A is the wetted area of cross section of flow (m^2)
- Q is the discharge (m^3/S).
- g is the acceleration due to gravity (m/S^2)
- q is the lateral flow per unit length (m^3/S)
- S_f is energy slope
- y is depth of flow (m) and
- x is the distance in general flow direction (m).

These equations are generally recognized as providing an accurate description of flood flow which can be assumed to be one dimensional. These flows are assumed to have negligible vertical accelerations as is usually the case for most natural river channels. These equations may still be applied to over bank flooding provided the lateral drainge of the flood-plain is small (Walton et al 1975). It is well known that flow in flood plain (with small depth of flow) will be much different from relatively large depth of flow in the adjacent channel. A more elaborate model is required in this case. The equation (2) assumes hydrostatic pressure distribution. This is not valid for very rapid flows like dam break wave. The energy slope S_f cannot be formulated from first principles because of the complex interactions of the flow and geometry of the river. This has been treated seperately in later section.

To completely define the mathematical model boundary conditions are to be specified. There are two kinds of boundary conditions for the one dimensional routing (Chen 1977) models.

(i) Exterior Boundary Conditions :

If the flow is sub critcal, the routing solution is possible only when one condition is specified at the downstream end assuming a uniform flow in the upstream end. In case of non uniform flow at the upstream site a boundary condition need tobe specified in addition. There are three different ways of specifying this boundary condition : (1) the stage hydrograph (2) the discharge hydrograph (3) the rating curve. If there is a disturbance (R. K. Price 1974) such as from a tributary or from a tide downstream of the boundary, it is preferable to define either the discharge or the stage at this boundary. Price, R. K. (1974) discussed about the boundary conditions and stated them to be dependent upon the method of solution. But it is well known that the number of boundary conditions are independent of method of solution.

(ii) Interior Boundary Conditions :

They are usually concerned with continuity of discharge or water level or energy balance. For example at tributary junction the following should be satisfied.

$$Q_3 = Q_1 + Q_2 \qquad \ldots\ldots 3$$

$$h_1 + V_1^2/2g = h_3 + V_3^2/2g + h_{f1-3} \qquad \ldots\ldots 4$$

$$h_2 + v_2^2/2g = h_3 + v_3^2/2g + h_{f2-3} \qquad \ldots\ldots 5$$

Where Q, h, v are discharge, waterlevel and velocity respectively. The h_f is head loss in the reach. Flow through control structures also forms internal boundary conditions. The equation 3 expresses continuity and the other two about the total head. For derivation of the above equation, one may refer any standard text book on Hydraulics.

4.0 Methods of solution :

In many situations the continuity equation and the rating curve in a different form as storage equation is solved instead of full Saint Venant equations given earlier. These methods are approximate and are known as hydrologic flood routing. A comparison of these methods with that of hydraulic routing is given in the Table 1. Hydraulic methods use full equations. These are non linear partial differential equations and hence can not be solved analytically for the given boundary conditions. Numerical methods form efficient solution techniques. Subramanya, K. (1984) has classified the numerical methods used in flood routing as follows :

I Direct Methods (FDM) (a) Implicit (b) Explicit

II Method of characteristic (MOC) (a) characteristic nodes (b) rectangular grid.

III Finite Element method.

In case of method of characteristics, he has further classified them into implict methods.

Table 1 — Comparison of simplified Vs. Complete Models

No.	Simplified Model (Hydrologic Routing)	Complete Model (Hydraulic Routing)
	Advantages	
1.	Computationally easy	Relatively difficult
2.	Many problems can be solved even without recourse to a digital computer,	A computing machine is very essential.
3.	Provides answer in much less time	Takes time
4.	Computational cost is less	More
	Disadvantages	
5.	Normally do not have necessary accuracy	Desired accuracy can be obtained depending upon the uncertainties involved.
6.	Large amount of past flood records are needed.	Model calibration requires only few.
7.	Tributary flows and other controls can not be modelled, in general.	Can be modelled.
8.	Accuracy of the results very much depends on the length of reach.	The reach length is normally discretised.
9.	All acceleration terms are excluded.	Included.
10.	Does not require data on cross-section etc.	Needs data on cross-sections, Manning 'n' at all discretised points.

Numerical solution approximates the continuous (defined at every point) partial differential equations with a set of discrete equations in time and space. The region of interest is usually divided into discrete nodes and the nodes will be used to make algebraic equations for each sub region and time step. These equations are assembled and solved. While applying numerical methods, three aspects needs attention. They are : (1) accuracy 2) efficiency and 3) stability. Accuracy deals with how well the discretized solution approximates the true solution to the continuous problems. Efficiency is a measure of how much computational work and computer resources are required to obtain a solution. Stability addresses the question of whether or not a solution is possible at all. These definitions are over simplifications for practical purposes. The various methods are briefly given below.

4.1 Method of characteristic (MOC)

This method converts the Saint-Venant equations into a set of ordinary differential equations in characteristic form and then they are solved by finite difference methods either by implicit or by explicit scheme. The courant condition required for stability ($\Delta t \leqslant | \Delta x/(v+c) |$) is automatically satisfied by MOC. This method was proposed for integration of the shallow water equations by Massau in 1905. Explicit schemes were used by Liggett and Woolhiser (1967), Streeter and Wylie (1967). This method has been applied to non-prismatic channels by Ellis (1970). He has used the scheme to study flows in Rhu Narrow at Clyde sea area (Scotland). The grid used by him is very similar to that of Hartree who first developed it (Fox 1962). Amein (1966) used MOC with implicit scheme. It can be seen from Ellis (1970) work and others that the method of characteristic is accurate. This method generally and automatically makes a closer mesh in area of rapid change and sparse in other regions of the problem domain. This is a favourable capability of the method. The main disadvantage of this method is that it requires cross sectional data and roughness character etc. at different locations at different time steps. These data are not available in practice. Hence this method did not gain importance. However Wylie, E. B., (1980) developed an alternate formulation where this requirement was avoided by interpolations in time.

4.2 Implicit Method :

Stoker and his colleagues (1953) first anticipated the need for an implicit method for flood routing. Later Isacson (1954) applied to river problems. In implicit method, two or more unknowns at the upper time level are related to one another in a single equation. Since time step size is not a limitation, the use of this method is preferred.

Among various implicit schemes used in open channel flows the four point scheme of Amien (1970) are mentionable. In a comparative study Price, (1974) has concluded that implicit scheme of Amien to be the most efficient one. Amien (1975) presented a modified version of his earlier work. He used a non-uniform rectangular grid on x-t plane. The weighting factor was defined to be $\Delta t/\Delta t$ Amein concluded that for this weighting factor equal to 1, the method can take flow problems ranging from abrupt to slowly varied. Implicit methods have been used in solving various field problems and found to take much less computer time than explicit methods. Another advantage of this method is that the time step can be selected in accordance with the physical requirements of the problem rather than that of numerical stability. For example, the speed of the flood wave, Crossing the bank above can be considerably lesser than the speed of a flood peak which is just within the banks of the same river. The accuracy of the numerical solutions can be improved with appropriate time steps dictated by the physical situation. However, implicit method can not be explained physically.

4.3 Explicit method ;

Although one of the simplest possible schemes this method is not useful because it always has large error due to truncation.
The following finite difference is general explicit scheme.

$$\frac{\partial h}{\partial t} = \frac{h_j^{n+1} - h_j^n}{\Delta t} \qquad \ldots\ldots\ldots 6$$

Where $h_j^n = \frac{1}{2}\,a\,(h_{j+1}^n + h_{j-1}^n) + (1-a)\,h_j^n$,
h is any variable.

Special schemes may be obtained by varing a. These schemes are constructed in such a way that each new value h_j^{n+1} can be found directly if the values at a certain time level n are known. In the case of explicit methods the time step is very important inorder to avoid instability. This restriction has led many modeller to choose implicit methods explained below.

4.4 The finite element methods :

The ability to model curved boundaries and to represent nonlinear variation easily makes it an important technique to solve many engineering problems. Among various methods in FEM, Galerkin technique is popular in solving complete St. Venant equations. In this method algebraic approximation to the variables appearing in complete equations are made. This produces residual error. By using certain mathemathical criterion each of the FEM method forces the residual to zero. In the process of making the residual vanish the method produces a set of algebraic equations. These are solved by appropriate matrix solvers after imposing boundary conditions. Fread (1981) commented that the mathematical basis for finite element solution shemes is not as easily understood as finite difference approcah. The use of finite element method to route floods in channels and natural streams is presented by Colley and Moin (1976). A variance of conventional FEM method was proposed by Katopodes (1984). He concluded that the cost of computation using above approach is comparable to that of an implicit finite difference scheme using same number of grid points. The relative merits and demerits of finite difference and finite element methods are given in Table 2.

Table—2 Comparison of Finite Difference Methods (FDM) and Finite Element Methods (FEM)

No.	FDM	FEM
1.	A difference approach	An integral approach
2.	Approximation by grid points	Approximation is by finite elements
3.	Non linear variation between grid points are not possible.	Non linear variation adds no complexity.
4.	Curved boundaries require larger grid points.	Curved boundaries can be represented with few curved elements.
5.	Grid formation is simple	Needs greater care to discretize
6.	Unit cost of computation (Per node per time step) is independent of the overall size of the problem.	Unit cost increases with size of the problem.
7.	Matrix techniques are not a must.	Matrix techniques are generally required.
8.	Accuracy is comparatively less (in few cases)	High order accuracy can be achieved.
9.	Hand computations are possible	Computer is a must
10.	Problem formulation and subsequent computer programs are relatively simple.	Both formulation and computer program development are formidable task.

4.5 Energy slope :

This term present in the momentum equation 2 is an important component to be determined before further solving the equations. This represent the energy loss caused by the frictional resistance produced by bed and banks. The prediction of this, still poses a problem to engineers. The Manning's equation provides a means of formulation of this term. Most of the well known river models like HEC-2, HEC-2 SR etc. use this equation only as follows

$$S_f = (nQ / AR^{2/3})^2 \qquad \ldots\ldots(7)$$

Where, R is hydraulic radius, n is the Manning's roughness coefficient and Q, A are as defined earlier. Einstein and Barbarossa (1952) recommended the use of Manning's—Strickler equation.

$$V/V_* = 7.66\ (Y/K_s)^{1/6} \qquad \ldots\ldots(8)$$

Where $V_* = (g\ RS_f)^2$ and is known as shear velocity, K_s is sand grain diameter taken as bed sediment size such that 65% of the materials are finer. These equations 6 or 7 can be used with confidence in the case of rigid bed channels and also alluvial stteams with flat bed.

However, when undulations are present the Manning's n is found (Garde, etal 1977) to be a function of discharge Q. In the model MOBED Krishnappan. B G (1985) used the following formulations based on the works of Kishi and Kuroki (1974).

$$S_f = \text{Const.}\ (R/D)^M \quad (V/gR)^N \qquad \ldots\ldots(9)$$

Where, V is average velocity, M, N are constant parameters and other terms are as defined earlier.

5.0 Conclusions :

Hydraulic routing techniques have been reviewed. Only those methods which are used in practice are included. It is seen that one dimensional models are sufficent to route the flow. However, when large flood plain is involved this is not possible.

The complete equations 1 and 2 are sufficiently accurate in describing the flow. It is only the supplementary equations like equations for energy slope etc. require considerable attention and further research.

The method of characteristics uses finite difference approximations and hence both MOC and FDM require similar efforts. Curved boundaries produce difficulties in both the methods. The FEM has admirable quality of modelling curved boundaries and non linear properties, but it invariably requires computers. The finite difference methods can be adopted for hand computations also. It is to be understood that no numerical method is best for all applications. The personal preference based on familiarity of the model developer is the determining factor in selecting particular method.

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FLOOD MODERATION

by

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Central Water Commission

1. Introduction

Floods in the rainfed rivers of India depend in respect of their magnitude and duration almost wholly on the intensity, areal distribution and duration of the rainfall over the catchment. If the entire catchment would receive copious rainfall, the situation in the rivers become critical, resulting in high discharge and corresponding high water levels. Several low lying areas along the river get submerged causing damage to properties and loss of lives. If there could be possibilities of absorbing the high and flashy floods and dissipation in a gradual manner we could mitigate, if not avoid flood catastrophies. Flood forecasting and warning also comes to great assistance in the absence of adequate flood protection and moderation to the extent required.

2. Flood Pattern

Floods form the major source of the run-off of a river. This is particularly so in the non-perennial rivers of peninsular India, which are not snow-fed and have, therefore, little or no flow in the non-monsoon season of the year. In order to make optimum use of the water resources of a basin it is indispensable to go in for storage reservoirs which could store the flood flows during the rainy season and make the stored waters available for various uses like irrigation, water supply, hydropower etc. in regulated quantities during the later part of the water year. While flows of a river could thus prove to be extremely important and a vital necessity for beneficial uses of the precious water resources of the nation, the other side of the coin represents floods which cause a major disaster and damage and lead to colossal loss of human lives and property in several parts of the country. While total flood prevention would be neither economical nor practicable, some means of reducing the flood damages are essential. In order to mitigate the tremendous losses caused by floods year after year various structural and non-structural measures of flood control have been undertaken in the several five year plans. Amongst the different flood-control measures, one of the most advantageous is construction of storage reservoirs. Since constructing storage reservoirs merely for flood control purpose could prove to be uneconomical, it is the usual practice to combine the element of flood-control with other aspects like irrigation, hydropower generation etc. through multi purpose reservoir projects. Even where specific flood reserve storage is not incorporated, it would still be possible to draw down the reservoir level before the commencement of the flood season and to have a reservoir filling schedule such that sufficient storage space would be available in the reservoir for absorption of excessive flood flows during the flood periods and, by proper regulation, endeavour to have the reservoir full by the close of the monsoon season for use during lean period.

Forecasting had been considered as an immediate measure to help the public to safeguard themselves and move to safer places with advance warning to them. Forecasting also gains importance with the growth in population and gradual inhabitation in the low lying areas without concern even for their lives, in case of flooding. Flood forecasting and warning therefore was started in respect of some interstate rivers by Central Water Commission to help evacuation of these areas. Even where some flood protection works are in existence, forecast and warning enable the engineers take requisite care during the flood peak travel.

3. Moderation and its necessity :

Flood moderation is the process through which the intence flood is absorbed by natural or artificial mechanisms and allowed to pass further downstream in an even manner. Every river channel has a limited capacity and as long as the flow is contained within that, severity of the situation would be reduced. Flood moderation aims at containing the sudden gushing of water, slowing down the flow so not to exceed the channel capacity of river. The over bank spread, if allowed could damage habitation and lands along the banks of the river.

The human activity like cultivation along adjoining banks, or sometimes, even inside the river bed is causing serious impedance to natural flow of rivers. Apart from the problem of public encroaching into the flood banks, there is also geological phenomenon at places reducing the channel capacities. Deforestation and subsequent severe soil erosion in upstream catchments is resulting in silting of channels. Thus, the area available for natural flow being reduced, the possibility of over bank spilling has increased considerably. Hence it is essential on the part of the Government or any administration to mitigate the floods, by artificial means. For this man made moderation techniques are used to store the excess flood water and utilise it in lean season for irrigation and drinking purposes.

4. Natural moderation :

Flood moderation takes place in nature by various processes. The intensity of the first flood often is severe and usually flashy in nature in upstream reaches and this flood generally is moderated by nature itself. The flood waters are absorbed by unsaturated river beds and adjoining natural banks and the floods disappear after some distance as moderated flows. The premonsoon floods are created in unsaturated basin. Soil absorbs a part of the discharge of major river and slowly relases later for days together. If there are more tributaries merging at a point, due to the moderation process i.e. formation of temporary pooling, absence of peaks is commonly observed in one or two. Even the non-synchronisation of peaks in these tributaries amounts to moderation of the floods to certain extent. In this, a double or multipeak flood may be observed at downstream areas with lesser intensity.

5. Moderation techniques :

While the natural moderation takes care of floods of particular circumstance the dependable and definite protection to the habitation is possible, by scientific planning. Man-made structures are a correct solution to moderation of the floods. Various existing structures like reservoirs (with larger areas/capacities of man-made lakes) with controlled releases, through dams, weirs (uncontrolled flow over the crest), barrages or artificial lakes (in which flood water can be temporarily stored), under ground reservoirs are some of the techniques adopted in this respect.

These projects apart from serving in power generation, irrigation, water supply etc. benefit us greatly in absorbing large quantities of water. The downstream are safe unless unexpected flood of very high magnitude occurs on the upstream. However, there are limits of resources, utilisation, economy which are to be

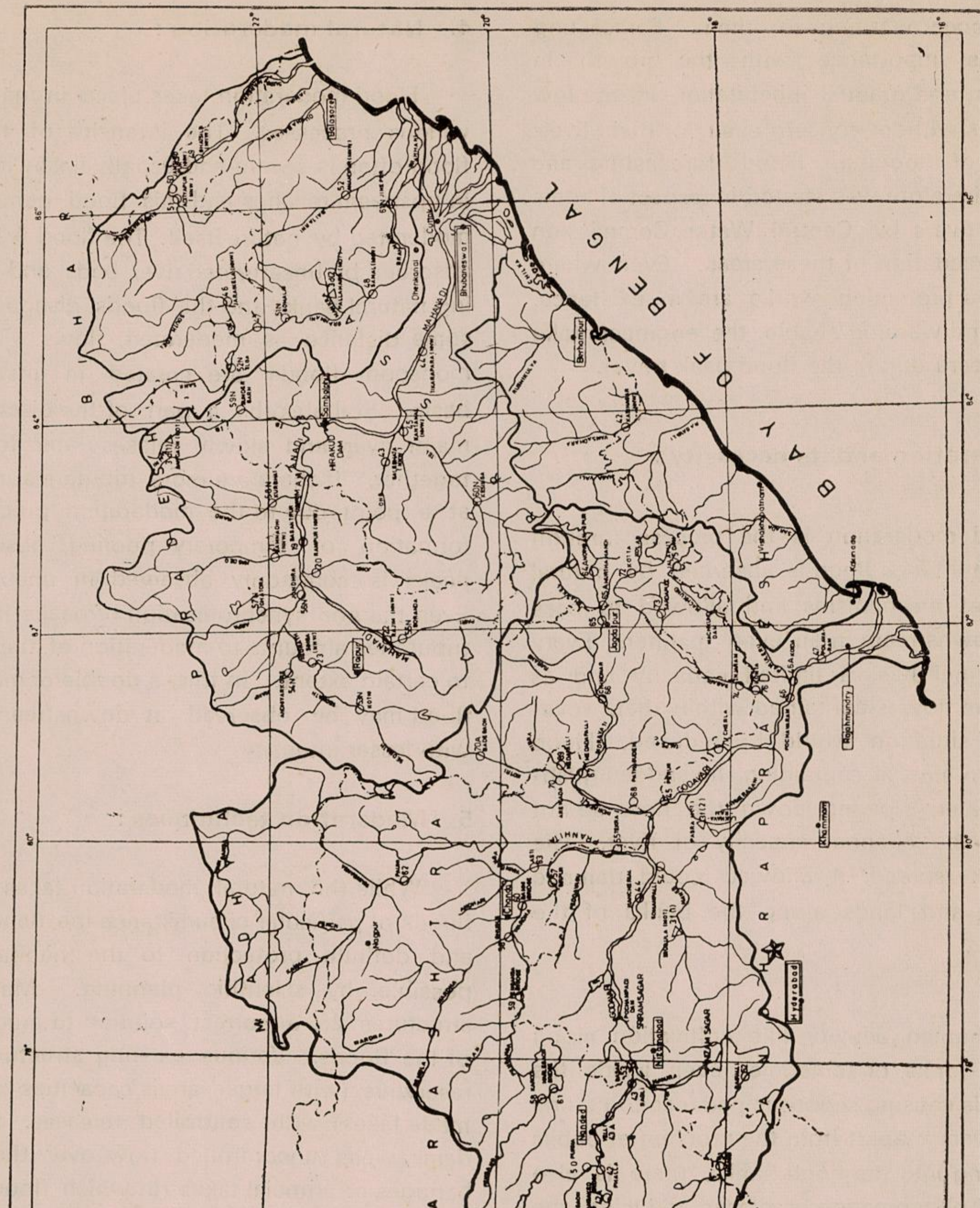

Fig. 1 Irrigation Structures in Godavari and Mahanadi Basins

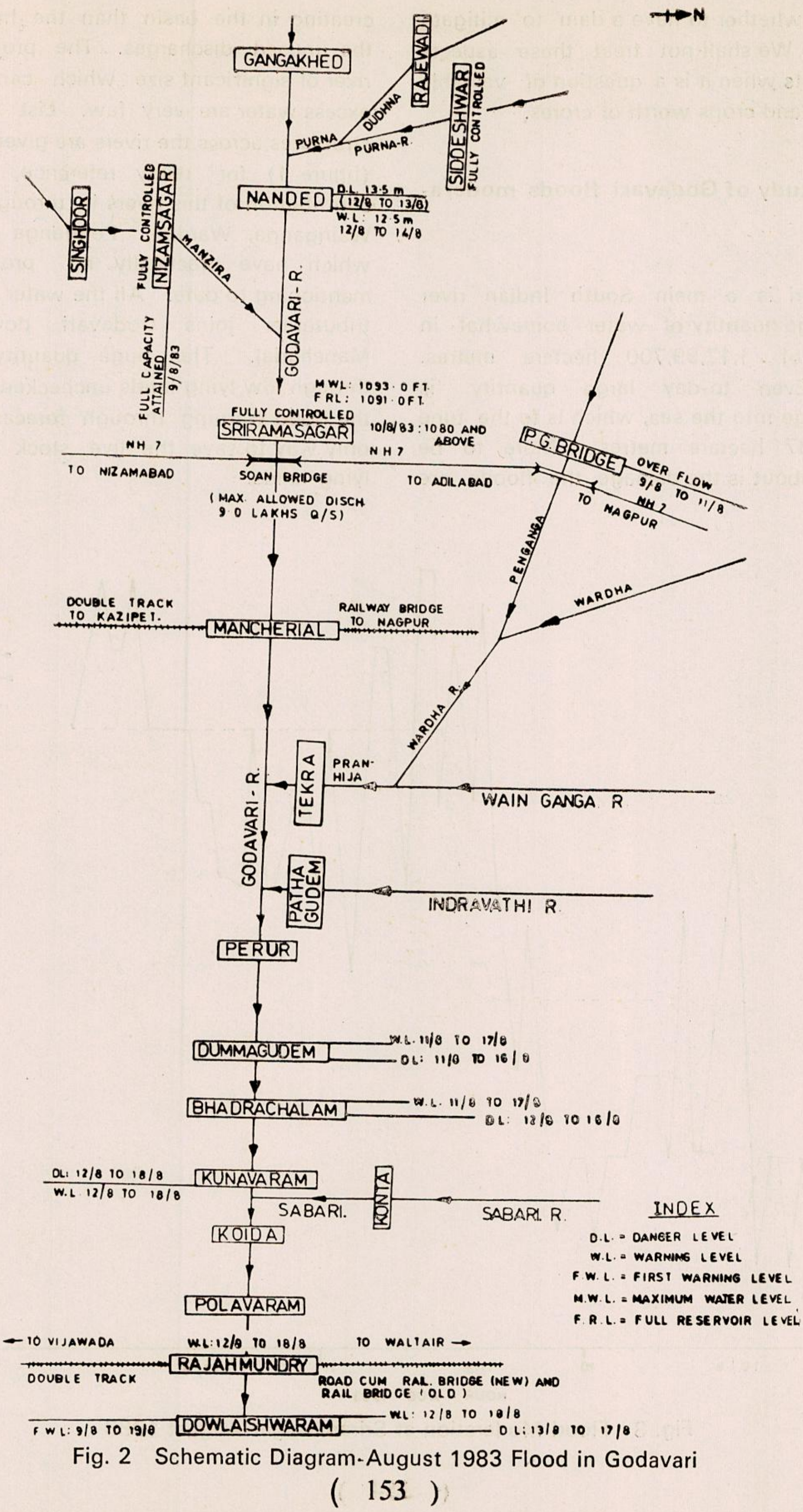

Fig. 2 Schematic Diagram-August 1983 Flood in Godavari

considered, whether to have a dam to mitigate the floods. We shall not treat these aspects as constraints when it is a question of valuable lives, cattle and crops worth of crores.

6. Case study of Godavari floods moderation :

Godavari is a main South Indian river carrying huge quantity of water somewhat in the order of 1,17,99,700 hectare metres. annually. Even to-day large quantity is allowed to go into the sea, which is to the tune of 87,78,237 hectare metres. More to be concerned about is the damage the floods are creating in the basin than the harnessing of the unused discharges. The projects on this river of significant size which can store this excess water are very few. List of irrigation structures across the rivers are given in the map (figure 1) for ready reference. The major contribution of this rivers is through Indravathi, Wainganga, Wardha, Penganga and Sabari which have practically no projects worth mentioning to date. All the water from these tributories joins Godavari downstream of Mancherial. This huge quantity then passes through low lying lands unchecked. Presently, the flood warning through forecasting is the only way to save the live stock of the low lying lands.

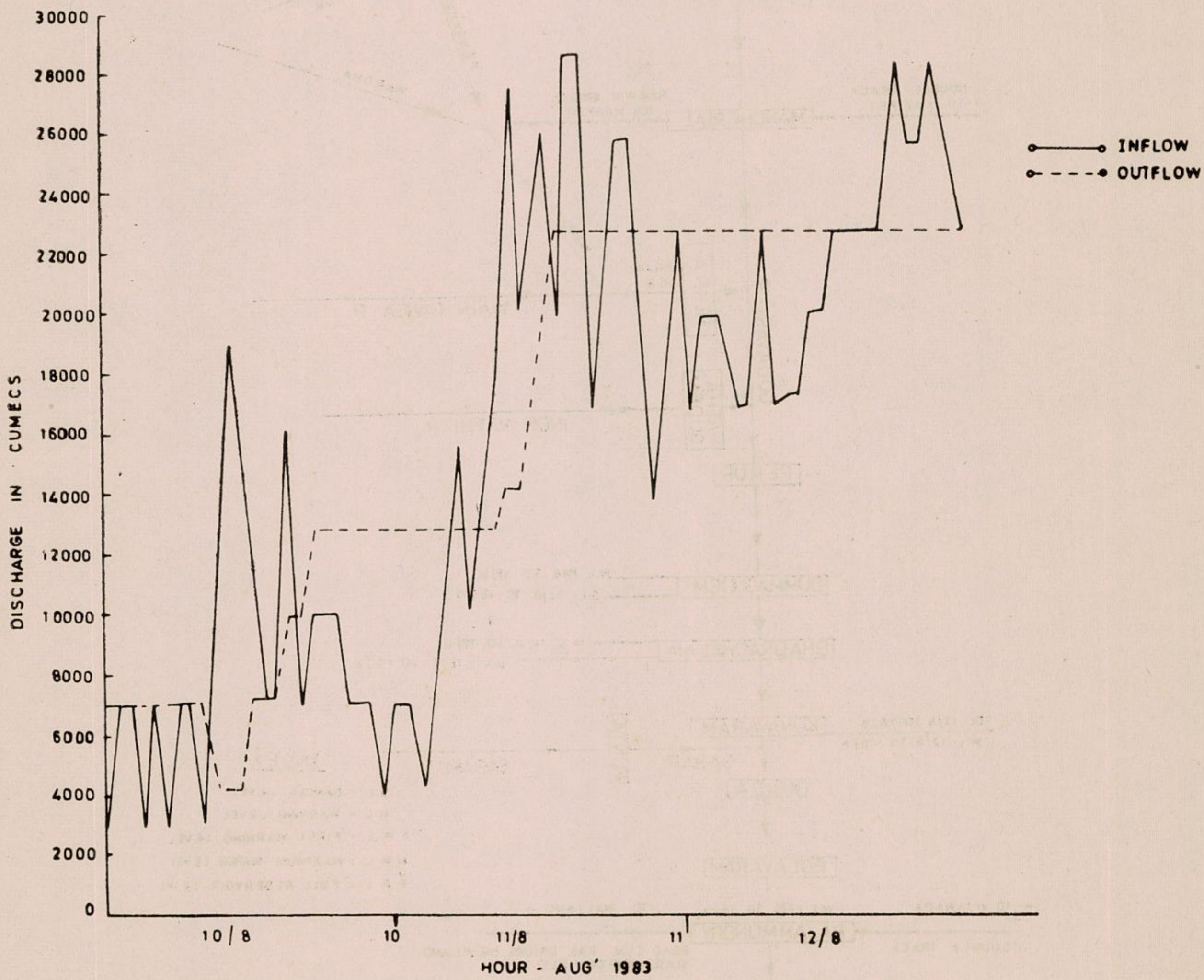

Fig. 3 Flood Moderation at Sriramasagar-August 1983

Sriramasagar project, a project that came up recently during 1983 is a relief to some extent. It takes care of the incoming floods of the upper reaches and moderates the floods of the downstream reaches upto Mancherial (before the confluence of other major tributaries. Just after the completion of the project (i.e.) 1983, the project has received a test flood of record magnitude. It is because of the presence of this project, the downstream areas have been free from serious floods during 1983, August floods. A schematic diagram showing the flood situation during August, 1983 is shown in Figure 2.

The bridge just downstream of the project (viz) Soan Bridge on N.H.-7, was protected by regulating the outflow from the Dam. The capacity of Soan Bridge is 9 lakhs Cft/Sec and it was possible to moderate the downstream flood with the help of the Sriramasagar gates operation at the dam. The railway bridges at Mancherial also could safely pass the floods becaus of this relation and maintained the traffic undistrubed for all the days. The maximum flow could have been 29,000 M^3/s if the flood was not moderated, which is beyond the capacity of these bridges. The gate operation at this project and corresponding flood moderation are given in figures 3 & 4 for the August and October floods.

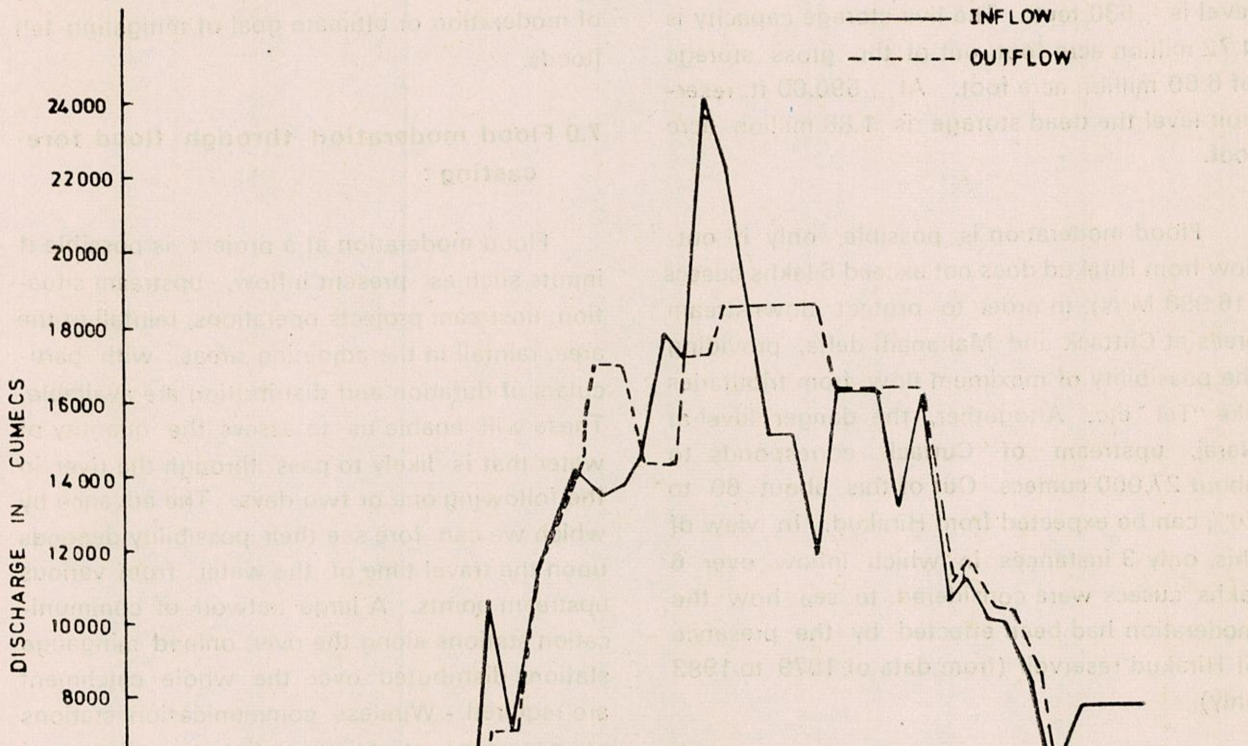

Fig. 4 Flood Moderation at Sriramasagar-October 1983

6.1 Case study of mahanadi floods moderation :

Hirakud Dam across Mahanadi near Hirakud in Sambalpur District, Orissa, was completed during the year 1958. The total length of the Dam is (15748 ft) 4800 meters, of which, length of concrete and masanory dam is 1148 metres (3768 ft.) It has 64 Nos. of under sluices of size each 12 ft. by 20 ft. 4 inches. The crest level as well as maximum reservoir level of spillway is at + 610.0 ft. It has 34 crest Bays, the size of each spillway crest gate being 51 ft. by 20 ft. The maximum designed discharge is 15 lakh cusecs. The full reservoir level is +630 feet. The live storage capacity is 4.72 million acre foot, out of the gross storage of 6.60 million acre foot. At +590.00 ft. reservoir level the dead storage is 1.88 million acre foot.

Flood moderation is possible, only if outflow from Hirakud does not exceed 6 lakhs cusecs (16,990 M^3/s), in order to protect downstream areas at Cuttack and Mahanadi delta, providing the possibility of maximum flow from tributaries like "Tel" etc. Altogether, the danger level at Naraj, upstream of Cuttack corresponds to about 27,000 cumecs. Out of this about 60 to 70% can be expected from Hirakud. In view of this, only 3 instances in which inflow over 6 lakhs cusecs were considered to see how the moderation had been effected by the presence of Hirakud reservoir (from data of 1979 to 1983 only).

In case of No. 1, during 18-21 September 1980, the maximum flood of about 33000 M^3/s to 36 000 M^3/s was moderated to about 34,000 M^3/s with a time delay introduced due to passage in live storage of the reservoir. The outflow could not be limited to 17,000M^3/s, as the level of the Hirakud was about FRL & MWL itself (i.e.) +630 ft., and the flood occured at the fag end of the season. The excess quantity above 17,000M^3/s was 1.278 thousand million cubic metres. If this amount can be stored upstream of HiraKud or itself, the floods could have been avoided (Figure 5)

In the case of No. 2 during 18-21 August '82 and No. 3 during 30th August-2nd September '82 the moderation was completely achieved as the water levels of the reservoirs were in the range of 617-622 ft. & 624-629 ft. respectively and the outflow was limited to around 16,000 M^3/s.

Thus it can be seen that a dam like Hirakud with huge capacity or a number of reservoirs with medium capacities are possible solutions of moderation or ultimate goal of mitigating teh floods.

7.0 Flood moderation through flood forecasting :

Flood moderation at a project is possible if inputs such as present inflow, upstream situation, upstream projects operations, rainfall in the area, rainfall in the adjoining areas, with particulars of duration and distribution are available. These will enable us to assess the quantity of water that is likely to pass through the river in the following one or two days. The advance by which we can fore see their possibility depends upon the travel time of the water from various upstream points. A large network of communication stations along the river, onland raingauge stations distributed over the whole catchment are required. Wireless communication stations are necessary at various points to collect and pass on the above data. The present network of Central Water Commission is able to forecast the inflow even upto two days in advance to Sriramasagar and one day to Hirakud by which tha projects can comfortably regulate the releases. Forecast is an essential work to moderate the flood releases, in the absence of which, the project may be compelled to release the flood excesses, all at a time, due to any sudden inflow rush.

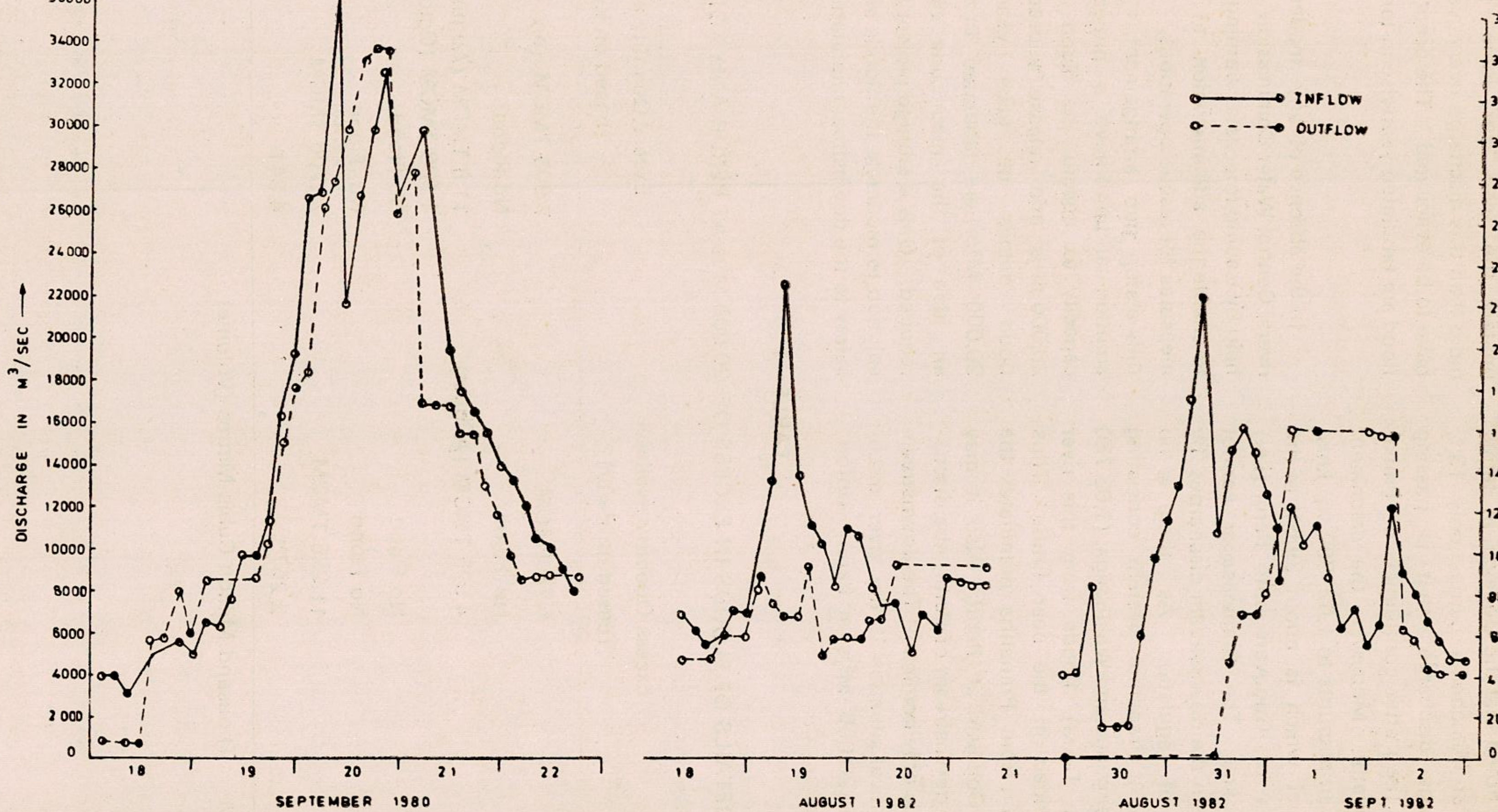

Fig. 5 Flood Moderation at Hirakud

It may be noted that the Godavari in terms of discharges at Mancherial carries only 13% on the average discharge that is passing through Perur (i.e.) after confluence of Pranahita and Indravathi. Moreover, the catchment area of Godavari amounts to 1,02, 900 sq. kms. upto Mancherial which is about 39.5% of the catchment area of Godavari upto Perur (i.e.) 2,60,200 sq. kms. The Sriramasagar cannot therefore govern the downstream discharges by any amount of regulation. As there is no dam in the entire Pranahita system consisting of Wardha, Penganga and Wainganga, (1,08 780 sq. kms upto Tekra), floods from this river cannot be avoided in the near future. Thus the contribution from Pranahita dominates the discharges of Godavari at Perur. Also it may be noted that downstream of Perur, the discharges increase is only nominal. The downstream areas are in critical situation if the river discharges exceed 20,000 M^3/s at Perur. Unfortunately the river for some period carries more than this discharge every year and people have to be evacuated. The occurrences of such flood are tabulated yearwise in table 1.

In the absence of any moderation of the rivers, Central Water Commission has come to help by issuing forecasts, warnings in advance to enable the administration to take suitable measures for rescue operations. This can be only a stop gap arrangement. A fool proof solution can be to have a project of required capacity to absorb the flood waters above 20,000 m^3/s and release subsequently. The flood details of each year in excess 20,000 M^3/s are tabulated in table I to give an idea of the magnitude of the storage required. Only a storage project is a permanent solution to moderate the floods and to provide safety to the downstream habitation.

TABLE—1

DETAILS OF FLOODS IN EXCESS OF 20,000 M^3/s AT PERUR AND KOIDA

Year	Excess Quantity available (based on Perur)	Excess Quantity available (based on Koida)
1981	6.76 TMCM	7.908 TMCM (on 4 occasions)
1982	No Flood	No Flood
1983	4.525 TMCM (August)	11.8 TMCM (August) 1.998 TMCM (October)
1984	No Flood	No Flood
1985	No Flood	No. Flood
Total	11.285 TMCM	21.706 TMCM
Average	2.257 ,,	4.341 ,,

NOTE : TMCM = Thousand Million Cubic Metres (Volume)

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