Journal of Indian Water Resources Society
Vol. 1 No. 2, 3 & 4 June, July & Oct., 1995

PHYSICALLY-BASED DISTRIBUTED MODELLING OF NARMADA (UPTO MANOT) BASIN USING THE SYSTEMS HYDROLOGIQUE EUROPEAN

C.P. Kumar
Scientist 'C'

National Institute of Hydrology
Roorkee - 247667 (U.P.)

ABSTRACT

The systeme Hydrologique Europeen (SHE), a physically-based, distributed, catchment model has been implemented for Narmada (Upto Manot) basin in Madhya Pradesh. The calibration and validation of the model was achieved on the basis of physical reasoning and through consideration of the variation of runoff response from the basin. The calibration was carried out for the period 1982-84 by varying only a few of the parameters and was then validated against 1985 and 1987 hydrographs, on the basis of changes in the initial level of the phreatic surface. Some deficiencies in the simulations were noted but, in general, there were good agreement between observed and simulated responses.

INTRODUCTION

The increasing rate of water resources development activity and utilization of water for various uses have focused attention of development and application of physically based hydrological models to deal with constantly changing hydrological environment. When the hydrological system is subject to change or when a realistic physical representation of flow in space and time is required for studies of water quality or soil erosion, the conceptual representation of traditional rainfall runoff models with lumped approach are not suitable. Due to its general formulation and physical basis, the SHE may be able to give a very detailed and to a large extent physically correct description of the water flow processes. The Narmada (uptoManot basin was selected for model application since this basin is undergoing large scale water resources development with complex environmental repercussions.

THE SHE

The Systeme Hydrologique Europeen (SHE) is an advanced, physically-based, distributed modelling system developed by the Danish Hydraulic Institute, the British and France responsibilities for the SHE lies with the University of Newcastle upon Tyne (UK) and the Laboratoire d'Hydraulique de France respectively.

Within the SHE, each of the major components of the land phase of the hydrological cycle (snowmelt, canopy interception, evapotranspiration, overland and channel flow, unsaturated and saturated subsurface flow) is modelled either by finite difference representations of the theoretical partial differential equations of mass, momentum and energy conservation or by empirical equations derived from independent experimental research. The spatial distribution of catchment parameters, rainfall input and hydrological response is achieved in the horizontal through the representation of the catchment by an orthogonal grid network and in the vertical by a column of horizontal layers at each grid square. Rivers channels are superimposedon the grid element boundaries. Parameters must be evaluated as appropriate for each grid element, river link and subsurface layer.

The physical processes considered in the SHE are schematized in figure 1. The SHE software is structured so that each hydrological process is allocated its own component and the simultaneous operation of each component is controlled by a central frame component. For flexibility, the components can be modified or omitted (to be replaced by dummy exchange components) in any given application, depending on the hydrological conditions and availability of data. Each of the primary processes of the land phase of the hydrological cycle is modelled as follows -

Interception	:	Rutter accounting proc edure or based upon interception storage and leaf area index.
Evapotranspiration	:	Penman-Monteith equa tion orKristensen and Jensen (1975) method based upon leaf area index and soilmoisture content in the root zone.
Overland and channel flow	:	Simplifications of the st. Venantequations.
Unsaturated zone flow	:	One-dimensional Rich ards'equation
Saturated zone flow	:	Two-dimensional Bous sinesq equation
Snowmelt	:	Energy budget method.

The SHE is designed as a practical system for application in a variety of water resource problems. In particular, its physical and spatially distributed basis gives it an advantage over simpler regression and lumped models in simulating land use change impact ungauged basins, spatial variability in catchment inputs and outputs, ground water and soil moisture conditions, and the water flows controlling the movement of pollutants and sediments. However, the distributed and physically-based nature of the SHE requires that in each application study, a vast amount of data and parameters describing the physical characteristics of the catchment are available. The data availability will in any case determine the degree of reliability which can be put into the simulation results.

THE STUDY AREA

The Narmada is a major west-flowing river in Central India running through the states of Madhya Pradesh, Gujarat and Maharashtra. The Narmada basin (upto Manot) lies between each logitudes 80° 24' to 81° 47' and north latitudes 22° 26' to 23° 18', most of the part lying in Mandla district and some part in Shahdol district of Madhya Pradesh. The river rises in the Maikala range near Amarkantak in the Shahdol district, at an elevation of 1,057 m at north latitude 22° 40' and east longitude 81°45'. It flows in a generally northwesterly direction but turns in a loop to the south upstream of Manot. The basin comprises the 4980 sq. km. head water catchment of the Narmada defined by the Central Water Commission gauging site at Manot, where the river length is about 269 km. (figure 2). The basin has a hilly terrain and is heavily dissected by the stream network. The largest tributary in the basin has a length of approximately 90 km.

Topography of the Narmada basin above Manot is hilly with forest cover, especially in the upper reaches. Flat

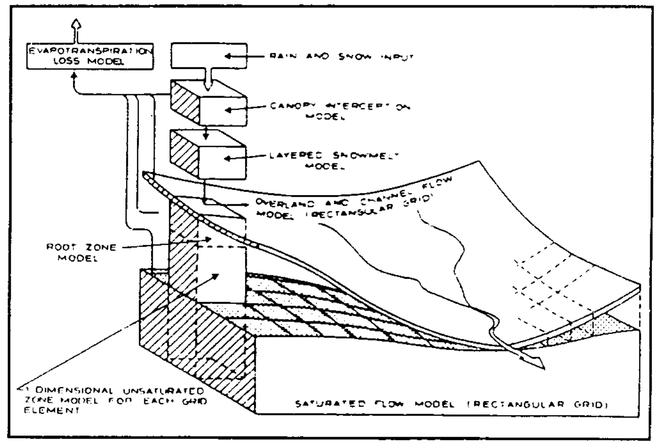

Fig. -1 Schematic representation of the European Hyrologic System (SHE)

farmland is more evident in the lower reaches. Flat agricultural areas containing bunded fields are interrupted by low hills with a medium to dense forest cover. Topographically, the basin was divided into three distinct levels - low land areas (below 640 m), hill slopes or semi-hilly areas (640 m to 810 m), and upland or hilly areas (above 810 m). The topographic elevations in the basin ranges from 450 m near the Manot gauging site to 1110 m in the upper part of the basin.

Four basic land covers were identified as agricultural land (51.89%), dense mixed forest (17.19%), thin forest (17.67%) and waste land (13.25%). The soil types identified in the basin were medium black, shallow black and laterite. Three categories of soil depth were defined, for low land areas (7.0 m), semi-hilly areas (2.5 m), and hilly areas (1.5 m).

DATA PROCESSING

Application of the SHE involves three phases - data preparation, execution of the SHE, and retrieval and graphical display of the SHE results. In connection to the SHE, a suite of service routines are used in the data preparation phase and the presentation of the SHE results.

All the data processing, including transfer of the rainfall, discharge and evaporation records to computer files, detailed evaluation of the hydrometeorological records and other data records assembled and corrections for errors and incompatibilities, digitization of the river system etc., were carried out prior to model setup and simulation work. A large number of reports were referred

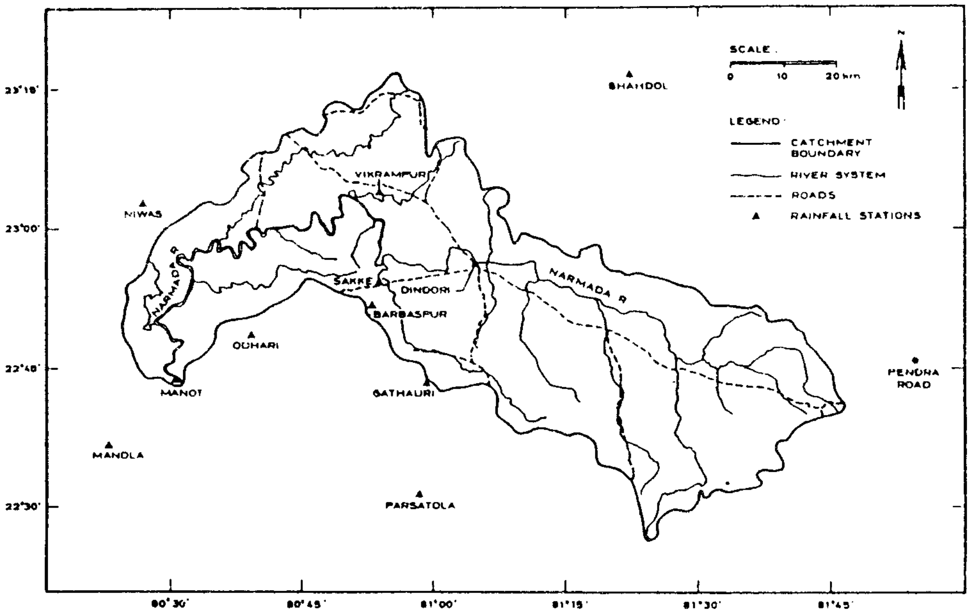

Fig. -2 The Narmada basin upstream of the Manot gauging site

for obtaining the relevant information on basin properties.

There are seven ordinary raingauge stations within or near the basin and only one hourly station (SRRG) lying outside the basin. The spatial distribution of ordinary raingauge stations is uneven with upland are poorly represented. The daily rainfall records were distributed on an hourly basis according to the pattern measured at the nearest recording gauge (Mandla). Discharge data are available only at the basin outlet (Manot). Hourly discharge values were obtained from the measured stage values with the help of rating curves derived by the Central Water Commission for each monsoon. Potential evaporation was assumed to be given by the daily pan evaporation data of Pendra Road (located outside the basin) multiplied by a factor (0.7) and to apply uniformly in the basin.

Land and channel elevations in the basin where taken from 1:50,000 scale contour maps. Land use map was prepared from satellite imagery and the 1:250,000 topographic maps. The soil distribution was obtained from 1:2,000,000 scale map in the 'Agricultural Atlas of India'. Data on topography, river network, soil type and land use were read from maps using a digitizer and transformed into discretized representation at the model grid scale.

There is a general lack of direct information on soil and vegetation properties, root zone depths, vegetation growth and cropping patterns , soil depths, soil moisture and aquifer properties. The model parameters and their spatial variations were, therefore, evaluated from the available information obtained indirectly from the literature on neighbouring areas. The same oil retention curve, typical of black cotton clays, was used throughout. For want of information ,the overland flow resistance coefficient was assumed to be spatially uniform into he basin. The channel flow resistance coefficient was evaluated using measured flow and channel data at the basin outlet. Cross-sectional dimensions were available at the basin outlet (Manot) only. A series of rough cross-sectional surveys made in the Hiran basin, were used to derive relationships between channel dimensions and upstream channel length which were then applied to provide cross-sectional data as required throughout the system.

MODEL SETUP

Model setup is the process of preparing the data in the correct format and entering them into the SHE data files, which represent the catchment characteristics. The first stage in the model setup was the construction of the computational grid network and channel system used to represent spatial distribution. For the basin, an array for parameter evaluation and distribution was prepared with grid squares of 2 km x 2 km. A topographic evaluation, land use type code, soil type code and a meteorological station code were then assigned to each square on the basis of available map information. Within the SHE, the network is mapped by a series of channel links superimposed on the grid square boundaries. The basin was represented by 1245 grid squares and 455 river links representing the river system. With the model data sets established, initial test runs were carried out using hypothetical input data of check for errors in the grid arrangements, river links and topographic representations and to ensure that surface flows (overland and channel flows) within the basin could be modelled realistically. With the errors eliminated, the way was open to make simulations based fully on the measured data and evaluated parameters.

CALIBRATION AND VALIDATION

Model calibration in general involves manipulation of a specific model to reproduce the response of the catchment under study within some range of accuracy. In a calibration procedure, an estimation is made of the parameters which can not be assessed directly from field data. The fully distributed, physically-based models contain only parameters which can be assessed from field data so that in theory, a calibration should not be necessary if sufficient data are available. However, for all practical purposes the distributed, physically-based models also require some kind of calibration although the allowed parameter variations are restricted to relatively narrow intervals compared with those for the empirical parameters in empirical or lumped, conceptual models.

It is evident from the previous description that the comprehensive field data covering model parameters was not available, therefore a degree of calibration or optimization of parameter values was needed to minimize the differences between observed and simulated hydrographs. The following calibration procedure was used for the basin :

(i) A split sample test was defined by dividing the available time series record in two parts. Calibration was carried out using the first period (March 1982 to February 1985) covering three successive monsoon seasons and the intervening dry seasons. Validation was then performed for the following period (March 1985 to February 1986 and March 1987 to December 1987). The data of 1986-87 was not used due to inconsistency detected in water balance computations. Each simulation period began on 1st March and the initial phreatic surface levels were therefore defined from consideration of pre-monsoon well levels.

(ii) The basis of the calibration was comparisons between simulated and observed monthly outlet hydrograph volumes, outlet peak discharges and outlet baseflow discharges. Some calibration against phreatic surface elevations at well sites was also possible in a more qualitative sense.

(iii) Calibration was carried out by adjusting a few key parameters and examining their effects on the simulated hydrographs. Several trial-and-error runs were carried out. The Strickler roughness coefficients for overland and channel flow were used principally to calibrate hydrograph peaks, the saturated conductivity for the unsatured zone determined the amount of infiltration and thence the runoff hydrograph volume, the saturated zone conductivity affected base flow discharges, while the soil crack and surface detention submodels were used to moderate the amount of infiltration and runoff in the early stages of the monsoon. In general , adjustments to parameter values were kept within physically realistic limits. Table 1 shows the final calibrated parameter values.

Table 1 : Calibrated Parameter Values

S.No.	Parameters	Calibrated value
1.	Strickler Roughness Coefficient for overland flow	2.5 $m^{1/2}/s$
2.	Strickler Roughness coefficient for Channel Flow	30 $m^{1/3}/s$
3.	Detention Storage	0.02 m
4.	Saturated Conductivity (Unsaturated Zone)	0.1 m/day
5.	Saturated Zone Conductivity	7.5 m/day

Figures 3 and 4 show a comparison of the observed and the simulated hydrographs for the basin during the calibration and validation periods respectively. The figures show that the observed and the simulated hydrographs match reasonably well. The base flows and the small peaks at the beginning of the monsoon are generally less well simulated than the remaining part of the hydrographs. The validation results show a better simulation of peak discharges but a poorer simulation of the monthly runoff volumes as compared with the calibration results.

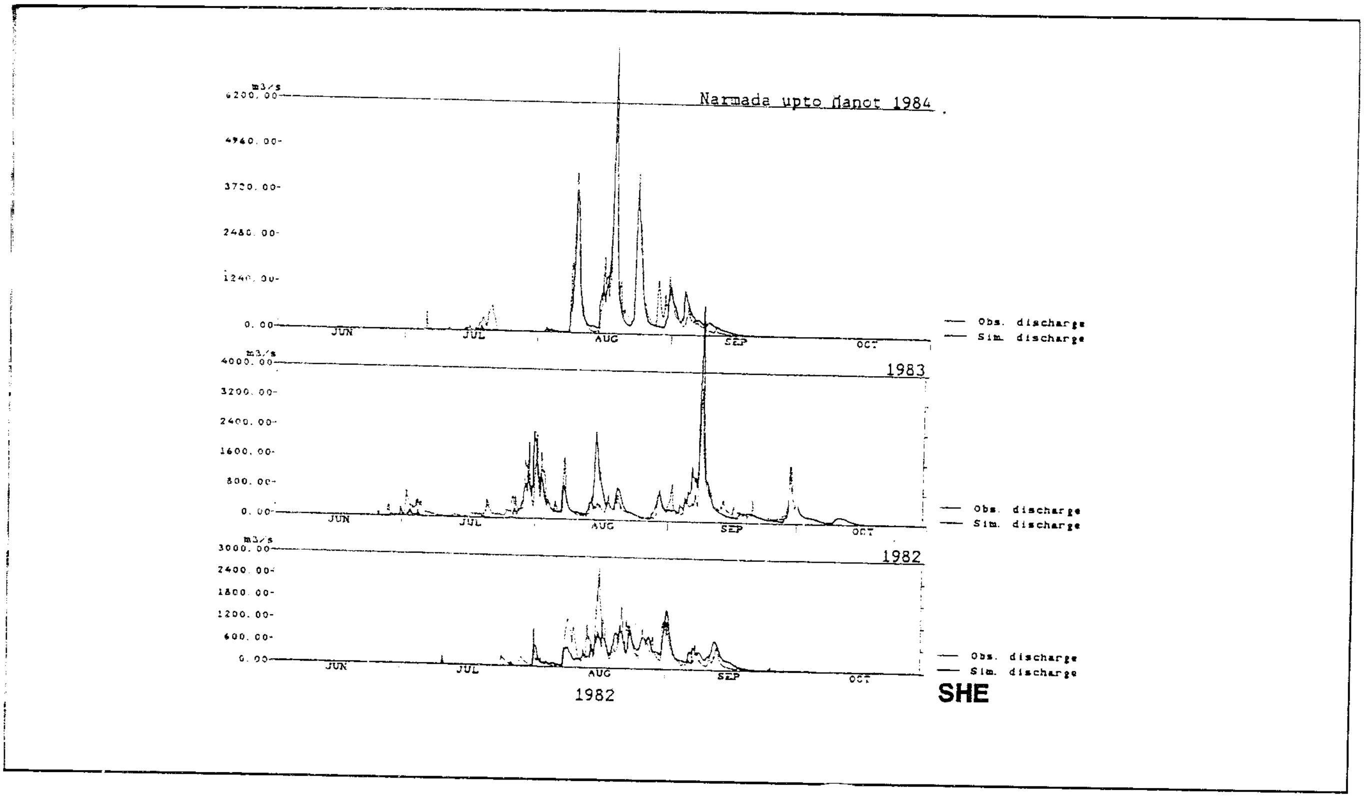

Fig. - 3 Observed and simulated hydrographs for the Narmada at Manot during the calibration period 1982-84

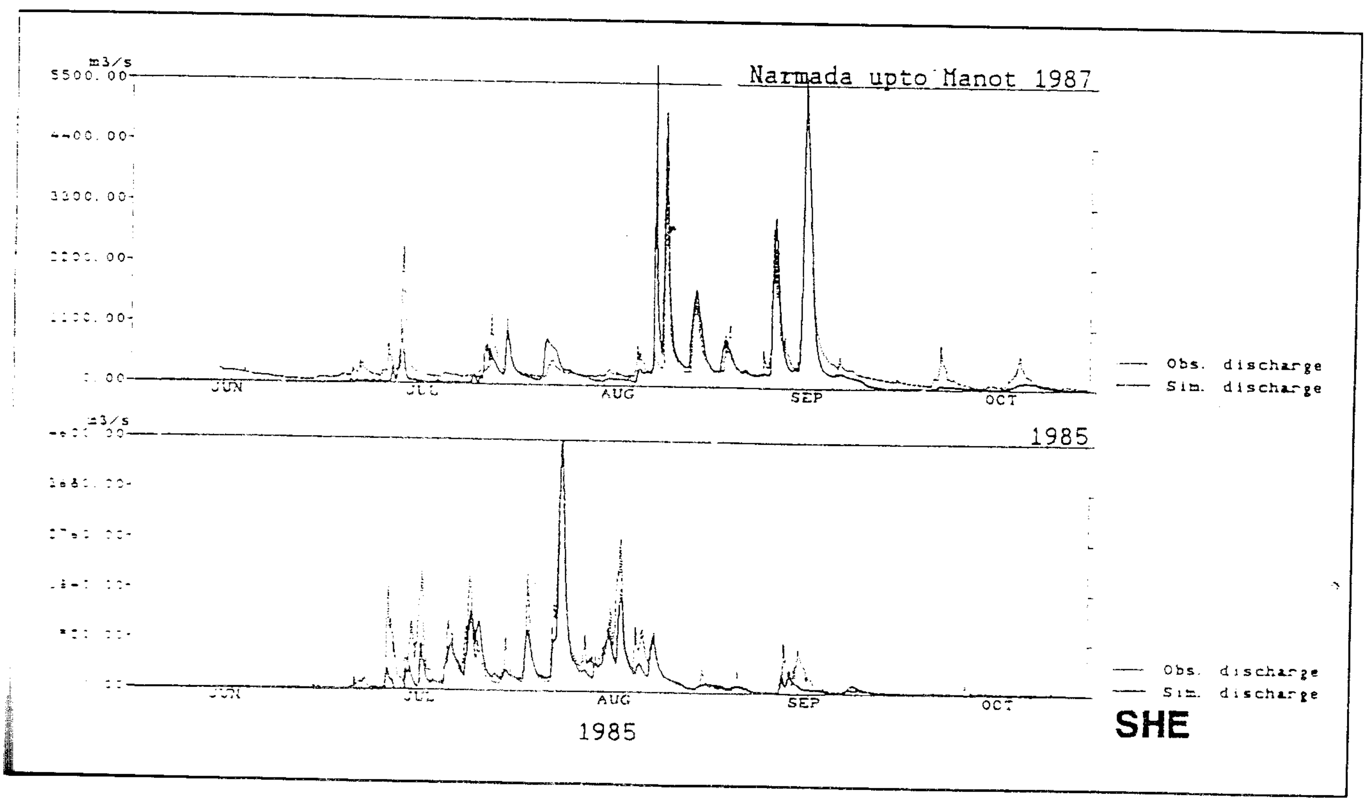

Fig. - 4 Observed and simulated hydrographs for the Narmada at Manot during the validation period 1985 and 1987

[illegible] Resources Society Vol. I (2, 3 & 4) 1995

CONCLUSIONS

The modelling results are considered satisfactory taking into account the data availability. The main source of uncertainty with regard to runoff simulations is the limited amount of rainfall data. The uncertainty in the basin rainfall input data is generating an uncertainty in the simulated runoff, which can not be reduced by collection of other field data. The rainfall-runoff simulation results are of the same degree of accuracy as would have been expected with simpler hydrological models of the lumped, conceptual type. However, in addition to the runoff simulations, the SHE modelling provides detailed simulations of the various hydrological processes within the basin by use of all existing data on topography, soil, vegetation, geology, meteorology, etc.

There are fundamental problems in the application of physically based models for practical prediction in Hydrology. In most current applications, physically based models are used as lumped, conceptual models at the grid scale. Some degree of lumping and conceptualization has taken place at the grid scale of the present model application, with the result that some model parameters had to be assessed through calibration. Still the present basin model is much more physically based and distributed than the traditional lumped, conceptual models and is therefore well suited for modelling studies, for which no real alternative to a physically based, distributed modelling approach exists.

ACKNOWLEDGMENTS

The study described was a part of the project carriedout under the ALA/86/19 financial agreement between the Government of India and the Commission of the European Communities. The author wishes to express his deep sense of gratitude to Dr. Satish chandra, Director, NIH for his inspiring and able guidance and Dr. S.M. Seth, Scientist F', NIH for his constant encouragement and direction of study at every stage of this work. The author is also thankful to the consultants from the Danish Hydraulic Institute (Denmark), the University of New castle upon Tyne (U.K.) and SOGREAH (France) for close interaction during author's training in Denmark.

REFERENCES

1. M B Abbott, J C Bathurst, J A Cunge, P E O'Connell and J Rasmussen. 'An Introduction to the European Hydrological System - Systeme Hydrologique European, SHE, 1 : History and Philosophy of a Physically-based, Distributed Modelling System' Journal of Hydrology, Vol. 87, 1986, pp. 45-59.
2. M B Abbott, J C Bathurst, J A Cunge, P E O'Connell and J Rasmussen. 'An Introduction to the European Hydrological System - Systeme Hydrologique Europeen, SHE, 2: Structure of a Physically-based, Distributed Modelling System'. Journal of Hydrology, Vol. 87, 1986, pp. 61-77.
3. James C Bathurst 'Physically-based Distributed Modelling of an Upland Catchment using the Systeme Hydrologique Europeen'. Journal of Hydrology, Vol 87, 1986, pp. 79-102.
4. James C Bathurst 'Sensitivity Analysis of the Systeme Hydrologique Europeen for an Upland catchment'. Journal of Hydrology, Vol. 87, 1986, pp. 103-123.
5. 'Hydrological Computerized Modelling System (SHE)'. Lecture Notes and Exercises, Training Course 1989, Danish Hydraulic Institute, Denmark.
6. 'Hydrological Computerized Modelling System (SHE)'. User's Guide and Documentation, 1989, Danish Hydraulic Institute, Demark.
7. K J Krishtensen and S E Jensen. 'A Model for Estimating Actual Evapotranspiration from Potential Evapotranspiration'. Nordic Hydrology, Vol. 6, 1975, pp. 70-88.
8. C P Kumar. 'Application of SHE Model to Narmada (upto Manot) Basin'. National Institute of Hydrology, Case Study Report No. CS29, 1990, 158 pp.
9. J C Refsgaard, S M Seth, J C Bathurst, M Erlish, B Storm, G H Jorgensen and S Chandra. 'Application of the SHE to Catchments in India, Part 1. General Results'. Journal of Hydrology, Vol. 140, 1992, pp 1-23.