System Memory Based Rainfall-Runoff Models for the Shakkar River Watershed of Narmada Basin

THESIS

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In

AGRICULTURAL ENGINEERING
(SOIL AND WATER ENGINEERING)

By

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2015

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This is to certify that the thesis entitled ***“System Memory Based Rainfall-Runoff Models for the Shakkar River Watershed of Narmada Basin”****submitted in partial fulfillment of the requirement for the degree of* ***“MASTER OF TECHNOLOGY IN AGRICULTURAL ENGINEERING”*** *of the Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur, is a record of the bonafide research work carried out by* ***Miss Neha Dwivedi*** *under my guidance and supervision. The subject of the thesis has been approved by the Students Advisory Committee and the Director of Instruction.*

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Jabalpur

Date : (Neha Dwivedi)

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LIST OF ABBREVIATIONS

%	:	Percentage
Agril	:	Agricultural
APE	:	Absolute Prediction Error
API	:	Antecedent Precipitation Index
AQI	:	Antecedent runoff index
CAE	:	College of Agricultural Engineering
CE	:	Coefficient of efficiency
Contd	:	Continued
DPQNM	:	Daily rainfall-runoff non-linear model
Engg.	:	Engineering
e.g.	:	Exempli Gratia (for example)
et al.	:	And others
etc.	:	Etceteras (and so on)
eq.	:	Equation
Fig.	:	Figure
i.e.	:	That is
ISE	:	Integral square error
JNKVV	:	Jawaharlal Nehru KrishiVishwaVidyalaya
mm	:	millimeter
M.P.	:	Madhya Pradesh
m^3/s	:	Cubic meter per second
No.	:	Number

NORW	:	Number of rainy days in a week
P_d	:	Daily rainfall
P_w	:	Weekly rainfall
Q_d	:	Daily runoff
Q_w	:	Weekly runoff
R^2	:	Coefficient of multiple determination
sq. km	:	Square kilometer
viz	:	Namely
WPQLM	:	Weekly rainfall-runoff linear model
WPQNM	:	Weekly rainfall-runoff non-linear model

CURRICULUM VITAE

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INTRODUCTION

Water is one of the most important natural resources available to mankind. It has unique role as a natural resource. It deserves special attention of researchers and planners because of its multiple benefits and the problem created by its excess, shortage and quality deterioration. The water on earth, whether in form of water vapour in the atmosphere, as surface water in the streams or lakes, as salt water in seas and oceans, or as ground water in the interstices of the subsoil; is not at rest, but in a continuous circulatory movement and never ending transformation from one state to another called the “hydrologic cycle” with sun as its driving force. It undergoes various complicated process of interception, infiltration, unsaturated flow, saturated flow, evaporation, transpiration, overland flow, channel flow etc. All these process depend on space and time.

The hydrologic response of catchment to rainfall estimates the catchment yield, and runoff data are of vital importance for hydrological analysis necessary for water resource planning, flood forecasting, pollution control and many other applications (Shamsudin and Hashim, 2002). Most of the river catchments in India are ungauged and the runoff information is not available for those catchments. Under such circumstances rainfall-runoff model can be developed to simulate the natural hydrological processes for estimating runoff from the catchment. The rainfall-runoff process is most important hydrological process considered during watershed management studies in humid and semiarid areas. It is a complex process as it is influenced by a number of implicit and explicit factors, such as precipitation distribution, evaporation, transpiration, abstraction, watershed topography and soil types. The runoff discharges and flow rates at a river site varies greatly throughout the course of a year, depending on seasonal rainfall, watershed characteristics and many other parameters. These variables greatly influence modelling effort and time which in turn provide opportunities for research endeavours.

Hydrological modelling is a simplified description of hydrological cycle to imitate the natural system. Rainfall- runoff modelling is simplified representation of real world system, and consists of a set of simultaneous, equations or logical set of operation with the aim of simulating the end result of hydrological cycle which is runoff. Many hydrologic models are available; varying in nature, complexity and purpose (shoemaker et al.,1997). Rainfall-runoff modelling is an important tool to deal with various practical problems in water sector such as water resources assessment, design of engineering channels, flood forecasting, predicting population incidents and many other purposes. Water resources development and management in the river basin can be planned by making use of appropriate model.

Runoff water is usually the medium involved in the sediment generation and its transporting processes. The rainfall-runoff process is most important hydrological process considered during watershed management studies. In the formulation and operation of soil and water resource management and erosion control programmes, it is necessary to ascertain the probable amount of runoff and sediment yield from a watershed on sequential and integrated time scale basis. Watershed runoff and sediment yield models are yet in the stage of infancy and therefore more serious studies and regress efforts are required to develop various mathematical models based on the processes such as rainfall-runoff, runoff-sediment and rainfall-runoff-sediment in watershed system.

Hydrological models can be grouped as statistical regression models, system models, parametric models, stochastic models, dynamic models. Statistical regression models are invariably location specific and used for prediction of one variable from one or more other variables. Regression models provide us with powerful tools allowing predictions to be made about past, present or future events to be made with essential information about the same. In system models the system concepts are introduced for planning, analysis, design, implementation, development, behaviour, input data and output data views. The parametric models are having numeric values called parameters to quantify the factors affecting the process. Most of the simulation models for hydrological studies are based on parametric modelling approach. Stochastic models are not the input-output models, but are governed by the laws of probability and predict future events based on a time series data of the variables under consideration.

Dynamic models are the input-output models which consider the effect of the memory of the system. The hydrologic processes are dynamic in nature where antecedent conditions of input and output affect the present output. Therefore, dynamic models are a better and more appropriate representation of the hydrological process. In most of the studies on hydrological dynamic models (Sharma et al. 1979, Kumar 1993, Sharma et al. 1993, Ranjan et al. 2010) equal impact was assigned to each of the past successive events which were considered affecting the present event. This approach appears to be a gross simplification of the natural process. There is a every likelihood that each prior event may not be affecting the present event with same magnitude. That is, the first preceding event may have more effect on the output than the second preceding event and so on. Thus, it can be hypothesized that if independent variables, namely, antecedent precipitation index (API), antecedent runoff index (AQI) are introduced in dynamic models of runoff, then these parameters are expected to account for varying impacts of preceding events on the present output.

With this concept in mind, an attempt was made to develop memory based runoff models for Shakkar river watershed of Narmada basin on sequential and integrated time scale basis for the simulation and prediction of runoff data with following objectives:

1. Determination of appropriate number of preceding events and their magnitude affecting the present output.
2. Development of system memory based runoff prediction models on daily and weekly basis for the rainfall-runoff process.
3. Qualitative evaluation and validation of developed models at (2) for their prediction performance.

REVIEW OF LITERATURE

2.1 Rainfall-Runoff Process

Lee and Bray (1969) derived the runoff prediction equations for regions within the province of New Brunswick. The prediction equations were based on the storm rainfall, antecedent precipitation index, base flow and week number in which storm occurred. The equation proposed by them is as follows

$$RO = 0.51\,P + 0.34\,P_a + 0.051\,N - 1.051 \qquad \text{.............} \; 2.1)$$

Where RO is the estimated runoff in inch, P is the observed precipitation in inch, P_a is the antecedent precipitation index in inch and N is the week number.

Bonne (1971) developed a model for simulation of monthly stream flow series, which includes both precipitation and flow, instead of the simple regression Markovian model based only on the antecedent flow alone. The variables in the regression function represent the previous month's flow, current precipitation, antecedent month's precipitation and the accumulated precipitation as independent variables, while the dependent variable is the current stream flow. Three watersheds with different physiographic characteristics were selected and stream flow for each basin were simulated and compared with the measured records. The results were also compared with those obtained by the simple regression Markovian model. In most cases a definite improvement was achieved over the simple regression model. He proposed the following model,

$$Q_t = A + BQ_{t-1} + CP_t + DP_{t-1} + E \sum_{i=t-j}^{t-1} Pi$$

Where, Q_t is the current month flow in inch, Q_{t-1} is the previous month flow in inch, P_{t-1} is the previous month precipitation in inch, j = 1,2,3,……..12, a water year month counter,

$\sum_{i=t-j}^{t-1} Pi$ is the accumulated precipitation and A, B, C, D, E are the multiple regression coefficients. He concluded that the previous flows and precipitation account for the storage in the basin, whereas significant current precipitation is the reason for an immediate increase in flow rate and the accumulated precipitation is an important parameter in high lying basin, where melting of snow provide the major portions of the flow during spring and early summer.

Babu and Dhruvnarayana (1983) developed a runoff prediction equation on the rainfall-runoff data of 180 storm events from five experimental watersheds at Dehradun. They developed both linear and non-linear models and found that a simple linear model is better than the non-linear inspite of the fact that rainfall-runoff relationships are generally non-linear. The liner and non-linear model proposed by them are respectively as follows,

$$Q = 2.15 + 0.172 A - 4.705 L + 0.779 D + 0.163 P - 0.025P_{30} - 0.10 API$$

$(R^2 = 52\%)$

$$Q = 0.33 A^{-0.003} L^{1.115} D^{0.136} P^{0.153} P_{30}^{0.545} API^{0.096}$$

$(R^2 = 40\%)$

Where, Q is the runoff volume in mm, P is the total rainfall in mm, P_{30} is the maximum rainfall occurring in 30 min interval in mm, API is the antecedent precipitation index in mm, A is watershed area in ha, L is the main cannel length in km and D is the duration of storm in hour.

Pathak et al. (1984) developed a model to predict runoff volume from small watershed which was based on the modified soil conservation services curve number technique and on a soil moisture accounting procedure. This model was tested with data from seven vertisol watershed at ICRISAT centre. The model simulated daily, monthly and annual runoff volume quite accurately. The model also predicted runoff fairly accurately from big runoff events.

Kumar and Rastogi (1989) developed a mathematical model of the instantaneous unit hydrograph based on time area histogram for a small watershed at Pantnagar. The instantaneous hydrograph was used for generation of runoff hydrograph.

Schroeder et al. (1990) observed that the antecedent moisture condition of a region for the prediction of runoff is determined from the previous five day rainfall totals which were grouped qualitatively for runoff predictions. Frequency distribution for the three AMC groups (AMCI: lowest runoff potential, AMCII: average condition, AMCIII: highest runoff potential) during the North Dakota growing season were developed to determine their validity in a semi-arid climate. Long-term average five day precipitation totals at the 50% probability level were compared for growing and dormant seasons and found that AMC groups were not applicable for semi-arid climates as for humid climates which endure frequent and larger rainfall.

Yu and Wang (1990) proposed a rainfall-runoff model which combines an ARMA (autoregressive- moving average) and phillip's infiltration models. The model parameters were estimated by using a non-linear minimization technique with the estimated parameters for a given watershed. The model can be used to compute the runoff hydrograph directly from rainfall hyetograph.

Lungu (1991) developed a relationship between effective rainfall as the input and runoff as the output for the Metsemotlhaba and the Notwane basins in Botswana on monthly basis. Effective rainfall was calculated as the difference between monthly rainfall and monthly evapotranspiration. The linear transfer function model was used and result showed that a memory less model was adequate to Metsemotlhaba and that a model with first order memory was required for the Notwane.

Murphree and McGregor (1991) developed linear relationship between runoff and rainfall values on monthly and storm basis for the soybean crop for flatland watershed in Mississippi Delta. They found that monthly runoff as a function of monthly rainfall was well fitted both on an annual basis as well as for the April-June, July-October and November-March periods.

Wang et al. (1992) developed a rainfall-runoff model for small watershed of Loess Plateau of China by combining the excess rainfall and the runoff concentration processes. The excess rainfall was modeled by using two parameters Green-Ampt infiltration approach. A six parameter was used to model the runoff hydrographs. They found that the model which simulated runoff hydrographs were in close agreement with the observed hydrographs. The proposed model is,

$$Q(t)= a_1Q(t-1) + \dots + a_pQ(t-p) + b_0I(t) + b_1(t-1) + \dots +b_qI(t-q)$$

Where Q(t) and I(t) are direct runoff in m^3/sec and excess rainfall in mm respectively at time t, and $a_1, a_2, \ldots\ldots a_p$ and b_1, $b_2, \ldots.. b_q$ are the time invariant parameters.

Jakeman et al. (1993) developed a method for rainfall-runoff modeling and hydrograph separation by assessing the dynamic response characteristics of river flow. They adopted the unit hydrograph and system identification techniques for rainfall-river flow modeling on daily basis. This approach separates the quick and the slow flow components of stream flow over annual period using daily data. Estimation of parameters and approximate uncertainties was performed using an instrumental variable method.

Kumar (1993) development a non-linear (log-log transformed) dynamic model for the Naula watershed of Ramganga river catchment for estimation and generation of daily data of runoff. He concluded that linear models do not represent the rainfall-runoff process. The non-linear model proposed by him is as follows,

$\ln Q_t = 0.372 + 0.120 \ln R_t + 0.712 \ln Q_{t-1} + 0.192 \ln Q_{t-5} + e_t$

where $R_t$is the daily rainfall in mm for time t, Q is the daily runoff in ha-cm at corresponding time t, t-1,....t-5 in days. The e_t is the error term of model.

Ahsan and O' Connor (1994) developed a nonlinear rainfall-runoff model by incorporating a variable gain factor dependent on the prevailing soil moisture state of the catchment. The simulation model output of an auxiliary simple linear model was used as an index of soil moisture state, and simple and realistic functional relationship between the gain factor and the prevailing catchment wetness index was assumed. The resulting model, called the variable gain factor model, was tested on the data of five catchments, assuming two different functional forms of gain factor variation with the catchment wetness index. The results indicated significant improvement over the performance of the simple linear model for the test catchments.

Ojasvi et al. (1994) developed a weekly rainfall-runoff model for hilly catchment in Tripura by considering the weekly rainfall, antecedent precipitation index, number of rainy days in a week and respective week number as input parameters. The model is of the form-

$RO = 1.182 + 0.055\ API + 0.078\ WEEK - 2.713\ NORW + 0.317\ PR$ ....2.2)

Where RO is weekly runoff in mm, API is the antecedent precipitation index in mm, WEEK is the calendar week number, NORW is the number of rainy days in the week under consideration and PR is the weekly rainfall in mm.

Nien et al. (1995) developed a hydrologic process based daily stream flow forecasting model with a built-in parameter estimation routine. The model closely captures the physical reality while maintaining the robustness of statistical model, both of which were required to be considered in day-to-day operations of a reservoir. Several equations were used to describe various hydrologic processes, such as direct runoff, baseflow, infiltration, evapotranspiration and change in ground water storage. They assumed that these equations can generate total daily stream flow from precipitation forecasts and initial conditions. The model parameters were automatically determined by a built-in Gauss-Newton algorithm. Model performance was analysed by five statistical error measurements including correlation coefficient, coefficient of efficiency, relative error, standard error and volume error. The proposed model was calibrated and verified using historical stream flow data from three gauging stations in Taiwan. The results indicated that the daily model for stream flow forecasting was satisfactory for use in daily operations of reservoir.

Ye et al. (1995) used a conceptual or lumped parameter rainfall-runoff model to analyse daily rainfall, temperature and stream flow time series from an Australian bench mark catchment. The catchment has seasonal storage dynamics, caused by evapotranspiration losses in summer being much higher than in winter. It behaves more like a semi-arid zone than a temperate zone catchment in summer. This additional non-linearity of response was characterized quite well by the introduction of one extra parameter in the model’s loss component previously used for temperate humid catchments.

Buchtele et al. (1996) used the conceptual soil moisture accounting model (SACRAMENTO) and also the physically based forest hydrological model (BROOK) for simulation of runoff for small and medium sized basins in the Czech Republic to investigate the contributions of different runoff components to the overall runoff.

Kuchment et al. (1996) applied physically based distributed rainfall-runoff model to the River Quse basin, UK, with a catchment area of 3315 km^2. The model includes a description of overland flow, subsurface flow, vertical water transfer in the soil, evapotranspiration and channel flow in the river network. Parameters of the model were determined on the basis of the topography, soil characteristics, 15 minutes rainfall intensity, flow data for six flood events, daily rainfall and runoff data for 1986. He compared the simulated data with daily flow measured values for the years 1987-1990 and found that the model can simulate catchment outflow satisfactorily.

McIntyre et al. (2007) tested the capability of simple regression models and analysedhourly data from 36 rainfall–runoff events in WadiAhin, a 734 km^2 catchment in the Sultanate of Oman. Runoff volumes and peaks were regressed against descriptors of rainfall characteristics and antecedent conditions. The controls on runoff were found to be: rainfall volume, rainfall peak, rainfall spatial location and variability, and antecedent wetness. Simple linear relationships between runoff peak and volume, and rainfall volume produce the best predictions, along with robust prediction confidence limits. We speculate that application of physically-based models will not produce better predictions, but will allow us to test hypotheses about the underlying hydrological processes.

Ranjan et al.(2010) Developed dynamic model of runoff sediment yield for the Kashinagar watershed of Vamsadhara river catchment, Orissa. He found that nonlinear form of model for daily data sequence was valid for the study area and linear relationship didn't give satisfactory results. The study indicated that assigning varying weightage to antecedent events was found to be suitable for study area. The conclusion was that the Kashinagar watershed fluvial system exhibits a strong memory on daily basis. Dynamic models are the input–output models which consider the effects of past events, which are in the memory of the system. Past studies on hydrological dynamic models have been performed considering equal effect of previous successive events on current events. (Sharma et al., 1979; Kumar, 1993; Sharma et al., 1993). However,each prior event may not be producing the effect ofsame magnitude on the present event. The firstimmediately preceding event may have more effect onthe output than the second preceding event and so on. Two antecedent indices viz. antecedent runoff index (AQI) and antecedent sediment index (ASI) havebeen taken as independent variable in the present studyto define the varying impacts of consecutive priorevents.

Ramana GV. (2014) formulated regression analysis for rainfall-runoff models and found that the advantage of formulating this regression analysis for the watershed was that it enabled to generate the runoff. Once the regression analysis is formulated the same can be applied to any watershed to estimate the runoff, even if the sub catchment is ungauged.

MATERIAL AND METHODS

This chapter deals with the details of study area, data collected and methods employed to fulfil the objectives.

3.1 General description of study area

3.1.1 Study area

The study was carried out in the Shakkar river watershed, geographically located between 22°20' N to 23°00' N latitude and 78°40' E to 79°20' E longitude. The Shakkar river originates in the Satpura range, east of the Chhindi village Chhindwara district, Madhya Pradesh. The major portion of watershed lies in Narsinghpur district and some part in Chhindwara district. Shakkar river is a left bank tributary of Narmada river. Main town near its confluence with Narmada is Gadarwara. Area is studied upto Gadarwara. The area of the watershed is about 2223 km^2 up to the gauge discharge site. Length of the river is 161 km. The maximum and minimum elevations of the watershed are respectively 314 m and 1154 m above MSL (mean sea level).

3.1.2 Climate

The average annual rainfall of study area is about 1245 mm. The rainfall in the area is due to southwest monsoon which starts from middle of June and ends in last of September. The climatic conditions of the study area in December and January are severely cold, whereas summer month of May and June are intensely hot. The minimum mean air temperature in January is around 8°C while the maximum mean air temperature in the hottest month (May) is around 42.5°C. The relative humidity is low in May (less than 33%) and high in August (more than 87%).

3.1.3 Soil

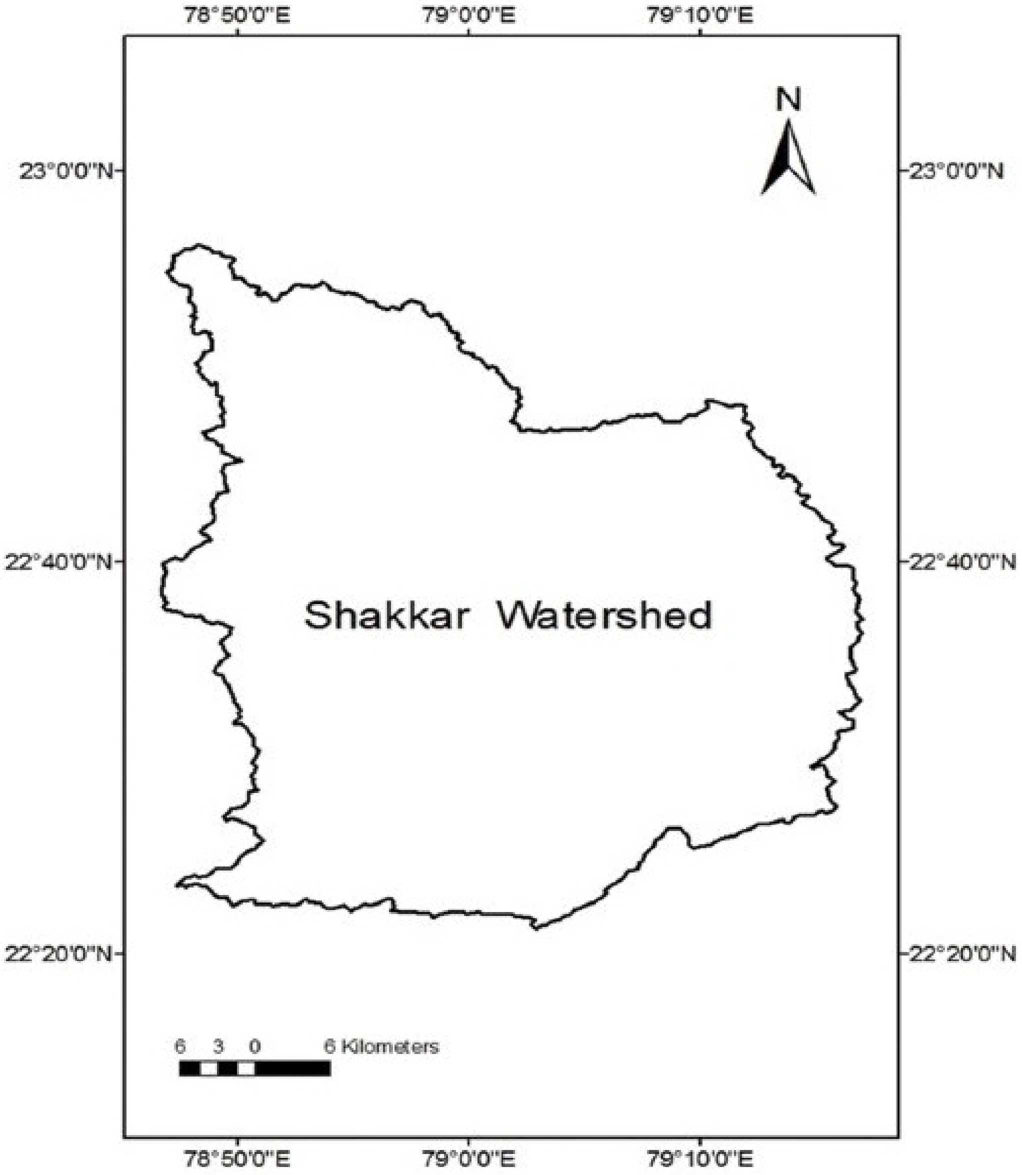
Soils are mainly clayey to loamy in texture with calcareous concretions invariably present. They are sticky and, due to shrinkage, develops deep cracks in summer. They generally predominate in montmorillonite and beidellite type of clays .In rest of alluvial areas mixed clays, blackish brown to reddish brown in colour, derived from sandstones and traps is observed which is sandy clay in nature with calcareous concretions. Near the banks of the rivers and at the confluence, light yellow to yellowish brown soils are noticed which were deposited during the recent past. These soils were clayey to silt in nature (Gajbhiye et al.2013).

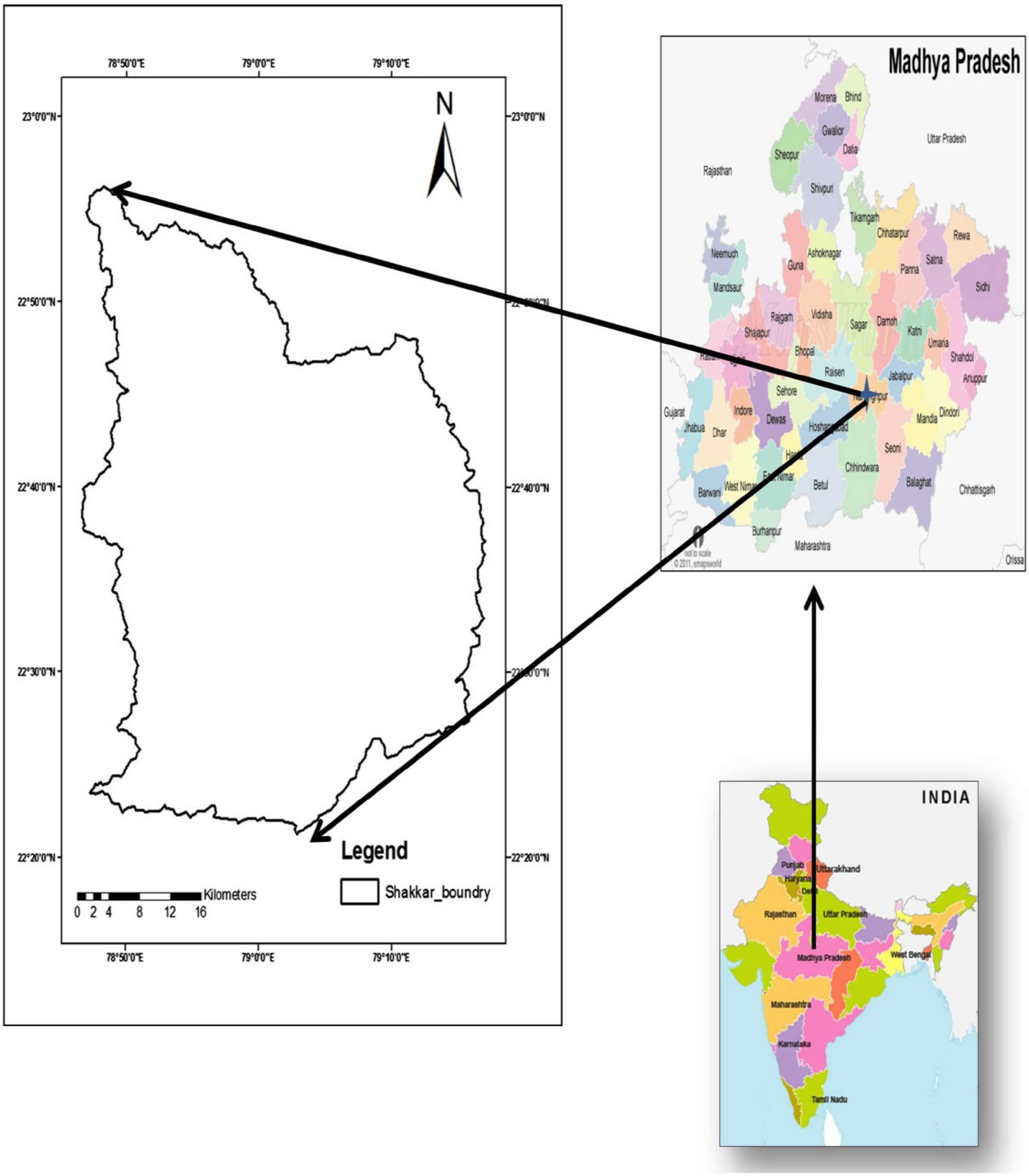
3.1.4 Land use pattern

Table 3.1: Land use pattern of Shakkar river Watershed

Land Use pattern	Area (sq. km)	Percentage of total area
Water body	32.456	1.46
Agricultural land	1217.537	54.77
Forest	876.084	39.41
Waste land	96.923	4.36

3.1.5 Location map of study area





3.2 Data used

3.2.1 Rainfall data

The daily rainfall data of three rain gauge stations namely Gadarwara, Amarwara and Harrai for the period of 20 years that is from 1994 to 2014 were used. The rainfall data was collected from Land Record Department, Collectorate, Narsinghpur and Land Record Department, Collectorate, Chhindwara.

Estimation of average rainfall

The recorded daily rainfall data at different stations of watershed were converted into weighted average rainfall data by the Arithmetic mean method.

The average rainfall depth over the watershed was calculated by the following relationship,

$$\overline{P} = \frac{1}{m}(P1 + P2 + ... + Pj + ... + Pm) = \frac{1}{m}\sum_{1}^{m} Pj$$

Where $\overline{P}$ = mean precipitation, P_1,P_2,….P_m = respective rainfall values in a given period at m stations within a catchment.

3.2.2 Runoff data

The daily runoff data of Gadarwara site was collected from Central Water Commission, Narmada Division, ParyavasBhawan, Bhopal. The daily data of runoff in m^3/s were collected from the year 1994 to 2014. These data were converted into millimeter for their use in development of different models.

3.3 Model development

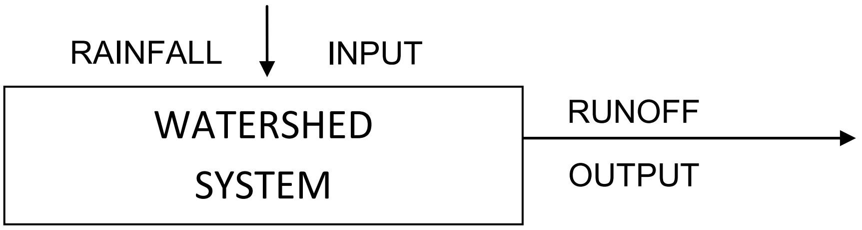
Under Indian conditions the occurrence of rainfall is confined to four month monsoon season, i.e., June to September. Therefore rainfall and runoff data for only these four months was used for the development of models. Runoff producing characteristics of a watershed are greatly affected by the antecedent conditions of input and output which are dependent on previous rainfall and runoff. The antecedent hydrological events of more than 5 days are not likely to have significant effect on the present event (Ojasvi*et al.*,1993 and Kumar, 1993). In the present study of Shakkar river watershed m values ranging from 2 to 7 were tried to arrive at the appropriate value of m, where m represents the number of successive past events affecting the present event. A significant amount of sediment yield get deposited within the catchment while routing through rills and gullies, and may reach the outlet in addition to the runoff resulted from the subsequent day’s event of rainfall and runoff. In almost all earlier research studies in the area of dynamic modelling of runoff on sequential and integrated time scale basis, equal impact was assigned to each preceding event in determining their impact on the present event (Sharma et al.,1979; Kumar, 1993 and Sharma et al., 1993). However it was felt that each prior event may not produce the effect of same magnitude on the present event. That is, the first prior event may have more effect on the current event than the second preceding event and so on. With this hypothesis in mind an attempt was made to introduce the antecedent precipitation index (API) and the antecedent runoff index (AQI) as independent variable in the present study, which is believed to account for varying impact of preceding events on the present event in developing memory based runoff dynamic models.

3.3.1 Model Hypothesis

The model building process involves system identification, parameter estimation, and qualitative checking. This section mainly deals with the development of memory based runoff prediction models on the daily and weekly time scale basis for the Shakkar river watershed. The runoff prediction models was obtained by modelling the rainfall-runoff process.

3.3.1.1 Rainfall-runoff process

The rainfall-runoff process through a watershed system can be described as,



That is, the process may be functionally represented, respectively on sequential and integrated (weekly) time scale basis as,

$Q_d = f(P_d, Y_1P_1, Y_2P_2, \ldots, Y_jP_{dj}, \ldots, Y_mP_{dm}, \ldots Y_1Q_{d1}, Y_2Q_{d2}, \ldots, Y_jQ_{dj}, \ldots, Y_mQ_{dm})$ …….(3.1)

$Q_W = f(P_w, Y_1P_{w1}, Y_2P_{w2}, \ldots, Y_jP_{wj}, \ldots, \mathrm{WEEK}, \mathrm{NORW},$

$Y_mP_{wm}, \ldots Y_1Q_{w1}, Y_2Q_{w2}, \ldots, Y_jQ_{wj}, \ldots, Y_mQ_{wm})$ …….(3.2)

Where, Q is the present runoff in mm, P is the present rainfall in mm, Q_j and P_j, j= 1,2,3,.....m represents respectively the runoff and rainfall values for the j^{th} event prior to the current event. That is j = 1 represents the first event immediately preceding the current event. Y_j is the weightage assigned to the j^{th} preceding event, m is an integer also called memory parameter. Week is the calendar week number and NORW is the number of rainy days in a week.

The suffix d and w indicate respectively daily and weekly values of respective variables. Weights are assigned in such a way that

$$\sum_{i=1}^{m} Yj = 1$$

The antecedent precipitation index (API) and the antecedent runoff index (AQI) estimated by the following equations,

$API = Y_1P_1 + Y_2P_2 + Y_3P_3 + \ldots\ldots\ldots + Y_jP_j + \ldots\ldots\ldots + Y_mP_m$

$$\mathrm{API} = \sum_{i=1}^{m} \mathrm{YjPj} \qquad \ldots\ldots\ldots(\ (3.3)$$

$AQI = Y_1Q_1 + Y_2Q_2 + Y_3Q_3 + \ldots\ldots\ldots + Y_jQj + \ldots\ldots + Y_mQ_m$

$$\mathrm{AQI} = \sum_{i=1}^{m} \mathrm{YjQj} \qquad \ldots\ldots\ldots(3.4)$$

The weight of different preceding events, Y_j, j = 1,2,3,…….m was estimated by following equation proposed by Ojasvi et al. (1994),

$$Yj = \frac{\exp[-(j-1)/m]}{\sum_{i=1}^{m} \exp[-(j-1)/m]} \qquad \ldots\ldots\ldots(3.5)$$

The appropriate value of m for the study area was worked out by trial and error. The value which gives highest value of coefficient of multiple determination (R^2) was selected for the study area. Now by substituting the antecedent parameters, API and AQI the equations (3.1) and (3.2) can respectively be written in compact form as,

$Q_d = f\ [P_d, (API)_d, (AQI)_{d]}$ ....(3.6)

$Q_W = f\ [P_w, (API)_w, NORW\ , WEEK\ (AQI)_w]$ ....(3.7)

The above equations indicate that output of runoff is in response to more than one output variables. This relationship can be classified as multiple input and single output (MISO) type models and the multiple regression can be applied to obtain functional relationships between corresponding input and output variables.

An attempt was made to develop both linear and non linear relationships on sequential and weekly time scale basis to model rainfall-runoff process in the present study.

The equation (3.6) and (3.7) can be structured in their linear and non-linear forms.

Linear form

$Q_d = \alpha_0 + \alpha_1(P_d) + \alpha_2(API)_d + \alpha_3(AQI)_d$ ....(3.8)

$Qw = \alpha 0 + \alpha 1(Pw) + \alpha 2(API)w + \alpha 3(NORW)w + \alpha 4(WEEK)w + \alpha 5(AQI)w$

.........(3.9)

Non-linear form

$Q_d = \alpha_0 \times (P_d)^{\alpha 1} \times (API)_d^{\alpha 2} \times (AQI)_d^{\alpha 3}$ ....(3.10)

$Q_w = \alpha_0 \times (P_w)^{\alpha 1} \times (API)_w^{\alpha 2} \times (NORW)_w^{\alpha 3} \times (WEEK)_w^{\alpha 4} \times (AQI)_w^{\alpha 5}$ ....(3.11)

where α's are the regression coefficient.

The non-linear equations were linearised for performing further analysis. The non-linear equation linearised by log transformation given below,

$\ln (Q_d) = \ln \alpha_0 + \alpha_1 \ln (P_d) + \alpha_2 \ln (API)_d + \alpha_3 \ln (AQI)_d$ ....(3.12)

$\ln (Q_w) = \ln \alpha_0 + \alpha_1 \ln (P_w) + \alpha_2 \ln (API)_w + \alpha_3 \ln (NORW)_w + \alpha_4 \ln (WEEK)_w + \alpha_5 \ln(AQI)_w$

.........(3.13)

The least square technique has been advocated by number of researchers [Schermerhorn and Barton (1968), Zuzel and Cox (1978), Wang and Yung (1986), Stedinger et al. (1988), Wang et al. (1991), Garren (1993), Ojasvi et al. (1994), and Kumar (1995)] for estimation of various regressions and owing to its inherent advantages, it was adopted in the present study as well.

3.4 Parameter Estimation

The determination procedure of various parameters used in the above linear and non-linear models on daily and weekly time scale is described in subsequent sections.

3.4.1 Antecedent Precipitation Index and Antecedent Runoff Index (API and AOI)

The values of API and AQI for different days were determined respectively by using equations (3.3) and (3.4) Weightage Y_j, j = 1,2,3,………m, assigned to the different preceding events affecting the current event were determined by the equation (3.5). The appropriate value of m was determined by trial and error. In the present study m ranging from 2 to 7 have been tried and m=3 has been found to yield highest value of coefficient of multiple determination (R^2). Thus the weights assigned to precedingthree daily or weekly events prior to the day or week under consideration, as the case may be, came out to be 0.448, 0.321 and 0.230 respectively.

3.4.2 Number of rainy days in the week under consideration (NORW)

The number of rainy days in a week (NORW) was obtained by adding the number of days receiving rainfall in that week. Variable NORW indirectly accounts for the total duration of rainfall during the seven days period.

3.4.3 Calendar week number (WEEK)

Runoff greatly varies from week to week and a number of regression equations were required to describe runoff for respective weeks. To reduce the number of parameters, all equations can be lumped by introducing meteorological week number as an independent variable.

3.5 Memory Based Runoff Models

In this section the daily runoff prediction models for the study area were developed.

3.5.1 Daily runoff models

3.5.1.1 Linear models

Three years active period data were selected for the development of model of the form as expressed by eq. (3.8). Three different range of three consecutive years, viz., 1994-96, 1997-99 and 1998-00 were tried in the present study. However, the model developed using the data series of the year 1994-96 was found to yield the highest value of coefficient of multiple determination (R^2), which has been finally selected for further testing and verification for the study area under the present study. The daily runoff prediction linear model obtained through the analysis is expressed as,

$$Q_d = -0.04 + 0.4\,(P_d) - 0.16\,(API)_d + 0.58\,(AQI)_d \qquad (R^2=0.67) \qquad ....(3.14)$$

3.5.1.2 Non-linear models

The same sets of three years data, as expressed in 3.5.1.1, were used for development of a non-linear model of the form shown in equation (3.10). However, the data of 1994-96 was again found to yield a better model in terms of higher R^2 value. The developed non-linear model is of the form,

$$\ln(Q)_d = -0.2 + 0.27\,\ln(P_d) - 0.12\,\ln(API)_d + 0.89\,\ln(AQI)_d \qquad (R^2=0.86) \qquad ....(3.15)$$

3.5.2 Memory based weekly runoff models

Due to absence of recording type rain gauges in most of the watersheds in India, it is not possible to obtain the data of rainfall duration and intensity and as such it is difficult to go for base flow separation etc. To overcome this problem, it is plausible to develop a rainfall-runoff model on an integrated time scale (weekly) basis.

3.5.2.1 Linear model

The weekly runoff model of the form eq. (3.9) was obtained by considering rainfall and runoff records for the active weeks (23rd to 39th meteorological week) during the period 1994-96. Two runoff models, viz., one with NORW and other without NORW were tried to observe the significance of this particular variable on the plausibility of the model. The final form of the models obtained with and without the variable, NORW are respectively as follows,

$$Q_w = -9.46 + 0.26\ P_w + 0.13\ (API)_w - 0.47\ (WEEK) + 0.01\ (NORW) + 0.21\ (AQI)_w \quad (R^2=0.86) \qquad ....(3.16)$$

$$Q_w = -17.17 + 0.26\ P_w + 0.14\ (API)_w + 0.43\ (WEEK) + 0.14\ (AQI)_w \quad (R^2=0.87) \qquad ....(3.17)$$

It can be seen that the value of coefficient of multiple determination (R^2) is same for both the models. Since the coefficient of NORW is negligible in equation (3.16), therefore, with a view to reduce the number of independent variables and to make the model more compact and simpler, the model eq. (3.17) without NORW variable was selected for further testing and verification in the study area.

3.5.2.2 Non-linear model

The non-linear weekly runoff model of the form represented by the equation 3.13 was also tried by considering same data range as expressed above (1994-96) and procedure described under section 3.5.2.1. The final form of the model obtained with and without the variable NORW are respectively as follows,

$$\ln(Q_w) = -4.7 + 0.72\ \ln(P_w) + 0.43\ \ln(API)_w - 0.29\ \ln(NORW) + 1.06\ \ln(WEEK) + 0.01\ (AQI)_w \quad (R^2=0.96) \qquad ....(3.18)$$

$$\ln(Q_w) = -6.519 + 0.6\ \ln(P_w) + 0.45\ \ln(API)_w + 1.65\ \ln(WEEK) - 0.07\ (AQI)_w \quad (R^2=0.96) \qquad ....(3.19)$$

Here again the coefficients of multiple determination (R^2) values for both the models with and without the NORW variable (eq. 3.18 and eq. 3.19) were found to be equal, which clearly shows that there is no significant effect of NORW variable on the R^2 value and thus, on the model performance. Therefore, the non-linear model (eq. 3.19) without NORW variable was selected for testing and application in the study area.

3.6 Models Selected for Testing and Verifications

The various memory based models selected on the basis of R^2 values for the study area for prediction of runoff on daily and weekly time scale basis are listed as below.

Rainfall-Runoff process

(1) Daily rainfall-runoff non-linear model (DPQNM)

$$\ln(Q)_d=-0.2+0.27\ln(P_d)-0.12\ln(API)_d+0.89\ln(AQI)_d \quad (R^2=0.86) \qquad ....(3.20)$$

(2) Weekly rainfall-runoff linear model (WPQLM)

$$Q_w= -17.17+ 0.26\, P_w + 0.14\, (API)_w + 0.43\, (WEEK) + 0.14\, (AQI)_w \quad (R^2=0.86) \qquad ....(3.21)$$

(3) Weekly rainfall-runoff non-linear model (WPQNM)

$$(Q_w) = -6.519 + 0.6 \ln(P_w) + 0.45 \ln(API)_w + 1.65 \ln(WEEK) - 0.07\, (AQI)_w \quad (R^2=0.96) \qquad ....(3.22)$$

3.7 Qualitative Evaluation of Model Performance

The acceptability of a model was judged by the goodness of fit between measured value and the values estimated or generated by a model. For qualitative comparison between measured and estimated or generated values, the following statistical measures have been employed in this study.

3.7.1 Absolute prediction error (APE)

Absolute prediction error values are determined by the following equation proposed by the World Meteorological Organization Statistics (1975),

$$APE = \frac{\sum_{i=1}^{n}(Mi - Ei)}{\sum_{i=1}^{n} Mi} \times 100 \qquad ......(3.23)$$

Where, APE is the absolute prediction error in percentage, and M_i and E_i are measured and estimated values.

3.7.2 Integral square error (ISE)

The goodness of fit between measured and estimated values by of a model was also determined by the integral square error, given by the following equation (Diskin et al., 1978).

$$ISE = \frac{[\sum_{i=1}^{n}(Mi - Ei)^2]^{1/2}}{\sum_{i=1}^{n} Mi} \times 100 \qquad \text{......(3.24)}$$

Where, ISE is the integral square error in percentage, M_i and E_i are measured and estimated values.

3.7.3 Coefficient of efficiency (CE)

The coefficient of efficiency for evaluating the model performance has been recommended by many researchers in the field of hydrology [Nash and Sutcliffe, (1970); Mutreja, (1992); Basu, (1993); and Nien et al., (1995)]. The coefficient of efficiency is defined by Nash and Sutcliffe (1970) as the proportion of the initial variance accounted for by the model. The coefficient of efficiency is determined by the following equation,

$$CE = \frac{\sum_{i=1}^{n}[Mi - \overline{M}]^2 - \sum_{i=1}^{n}[Mi - Ei]^2}{\sum_{i=1}^{n}[Mi - \overline{M}]2} \times 100 \qquad \text{......(3.25)}$$

Where, CE is the coefficient of efficiency in percentage, M and E are measured and estimated value at corresponding time and $\overline{M}$ is the mean of measured values.

RESULT AND DISCUSSION

This chapter deals with the application of different models developed in this study for the Shakkar river watershed for prediction of runoff data on daily and weekly basis. The Shakkar river watershed, comprising an area of 2223 km^2 is located in the Narmada catchment, Madhya Pradesh, India. The prediction performance of models was ascertained by verifying with the data of the Shakkar river watershed for all the years individually from 1994-2014. Accurate runoff recording for watershed is a difficult process. With this in view an attempt was made to predict runoff data series on sequential and integrated time scale basis for different years, by using developed prediction models in the study. The plausibility of various types of models were verified at various stages for the data series. A period of four month from June to September of each year in case of daily and 23rd-39th week in case of weekly runoff models were considered as the active period.

The qualitative performance of different models was checked by estimating the value of absolute prediction error (APE), integral square error (ISE) and the coefficient of efficiency (CE). In the present study the permissible limits for APE, ISE and CE were taken respectively as 30%, 10 % and 60% that means the prediction should satisfy the criteria of APE less than 30%, ISE less than 10% and CE more than 60%.

4.1 Memory Based Runoff Models

4.1.1 Daily Runoff Prediction Models

4.1.1.1 Testing and Verification

Two runoff models, viz., linear and non-linear were developed as per procedure detailed under section (3.5), chapter 3, by using the daily data of active periods only in series during the period of 1994-96. The linear model gave the coefficient of multiple determination (R^2) 0.67. Whereas non-linear model gave the coefficient of multiple determination (R^2) 0.86. The developed non-linear model was tested on the same data individually for each year from 1994 to 1996. The predicted values of daily runoff for the years 1994 and 1995 were presented in Tables 4.1.

From visual comparison shown in Figs. 4.1 and 4.2 respectively for non-linear model for the year 1994 and 1995, a good degree of closeness between measured and predicted values of daily runoff can be observed. The values of qualitative parameters for the years 1994 and 1995 are shown in Table 4.2 which confirm the plausibility of model for the study area.

4.1.1.2 Prediction Performance

The non-linear model was applied on the daily data individually for all the years from 1994 to 2014, to establish their applicability for the study area. The model gave fairly accurate prediction of runoff volume for the entire monsoon season (i.e. June-September) in a stretch for all the years. The qualitative performance of non-linear model is also shown in Table 4.2. From the table 4.2, it can be observed that in case of non-linear model the values of APE, ISE and CE for all the year are well within the permissible limits adopted in the present study. For better understanding, predicted values of daily runoff using the runoff prediction non-linear model for years 1996, 1998, 2002, 2008, 2010 and 2013 were shown in Table 4.3, 4.4 and 4.5. The graphical comparison of measured and predicted values of daily runoff with time for non-linear model is shown in Figs. 4.3, 4.4 and 4.5 respectively for years 1996, 2002 and 2010. From these figures, a good degree of closeness between the measured and the predicted values can be seen. However, the values of coefficient of multiple determination (R^2) for linear and non-linear models were found to be equal to 0.67 and 0.86respectively; on the basis of prediction performance and R^2 value the non-linear model was found more appropriate for the Shakkar river watershed. Hence, the rainfall-runoff process for the watershed was found non-linear.

Table 4.1 Measured and Predicted values of daily runoff (mm) by runoff prediction non-linear model for year 1994 and 1995

Month/date		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1994																																
JUNE	**M**	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	3.12	3.12	0.12	0.12	0.13	0.13	0.13	0.15	0.14	0.13	0.13	6.16	9.3	1.71	1.62	4.67	
	P	-	-	-	0.1	0.07	0.14	0.1	0.1	0.14	0.13	0.12	0.08	0.1	0.11	0.15	1.63	1.4	1.62	0.92	0.2	0.29	0.22	0.19	0.07	0.13	0.27	4.3	5.19	4.8	3.15	
JULY	**M**	1.34	7.07	15	6.48	5.24	1.95	0.6	0.34	0.27	0.31	1.23	2.95	5.29	5.28	3.95	4.94	14.1	18.7	14.1	15.7	26	24.6	13.2	11.4	7.43	7.09	6.39	5.56	4.97	4.21	5.34
	P	1.39	5.91	13.6	7.67	8.71	3.2	1.82	1.29	0.73	0.44	0.57	1.06	2.35	4.51	3.3	4.58	11.5	13.6	17	12	25.3	24.1	9.9	11.7	6.03	5.36	5.54	5.47	5.34	2.13	4.45
AUG.	**M**	12.3	11.8	5.79	12.1	15	14.4	20.2	22.2	11.1	7.94	6.1	5.53	11.1	8.09	5.67	4.38	3.76	6.06	15.7	18.8	9.55	7.25	5.8	6.19	7.38	16.5	15.8	8.01	14.9	16.6	14.3
	P	10.1	12.5	4.56	11.9	10.3	9.78	16.3	23.7	10.6	6.98	8.18	6.46	7.16	4.02	4.34	5.76	3.95	2.84	10.9	12.6	7.63	5.42	5.46	8.2	7.77	12.7	12.6	8.93	13.7	15.2	14.8
SEP.	**M**	11.7	17.4	23.7	28.7	23.3	20.1	15.5	8.91	6.62	6.11	7.55	5.65	4.26	3.31	5.79	2.52	2.44	2.4	2.35	2.28	2.19	2.07	1.9	1.82	1.81	1.75	1.67	1.57	1.53	1.5	
	P	12.6	15.3	24.8	24.4	27.6	23.2	11.2	7.24	6.3	5.94	9.01	4.99	4.23	3.51	4.19	3.55	2.03	3.19	2.91	1.42	1.44	1.54	1.62	1.53	1.45	1.4	1.36	1.33	1.27	1.22	
1995																																
JUNE	**M**	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	1.06	4.06	1.09	0.09	0.09	0.09	0.1	0.09	0.09	1.38	1.11	1.4	3.3	
	P	-	-	-	0.07	0.07	0.08	0.08	0.08	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.08	0.12	0.13	0.73	1.58	1.56	1.25	0.33	0.05	0.09	0.18	0.09	0.76	0.68	2.44	
JULY	**M**	2.36	0.31	0.1	0.19	0.17	1.16	1.15	0.1	0.1	1.1	4.91	3.16	4.83	4.72	3.68	2.02	1.69	1.6	3.59	5.8	4.57	5.84	5.8	12.3	10.1	5.06	3.58	5.3	9.1	6.77	3.6
	P	1.47	1.38	1.02	0.64	0.16	0.37	0.44	0.66	0.34	0.74	0.93	2.96	3.67	3.23	3.88	3.29	2.08	2.17	2.41	3.82	3.34	5.03	5.19	13.6	9.01	3.99	3.55	5.59	7.06	2.95	3.28
AUG.	**M**	2.11	0.78	6.41	3.12	5.88	4.23	3.6	3.18	2.03	6.24	4.47	1.63	1.17	0.72	0.73	0.73	0.81	0.92	3.22	5.33	6.22	5.79	5.53	3.23	3.03	2.61	6.89	4.36	2.84	3.53	9.76
	P	2.79	3.39	3.57	2.36	3.89	3.25	3.16	3.01	2.75	4.48	3.96	2.28	1.93	1.57	0.69	0.68	0.87	0.89	1.37	2.6	3.14	2.58	4.24	2.74	2.93	2.51	5.88	2.34	2.18	3.08	6.29
SEP.	**M**	8.69	7.97	7.37	6.2	4.2	3.42	2.82	2.78	0.16	0.64	0.15	0.6	1.47	2.92	5.68	1.63	1.24	1.52	1.41	1.22	1.13	1.14	1.06	0.97	1.07	0.75	0.75	0.72	0.7	0.74	
	P	6.79	7.66	8.78	7.82	3.25	2.84	2.54	2.37	2.12	1.25	0.8	0.29	0.41	1.1	2.16	3.04	1.75	2.84	1.3	0.93	0.94	1.02	0.93	0.8	0.97	0.98	0.91	0.68	0.62	0.61	

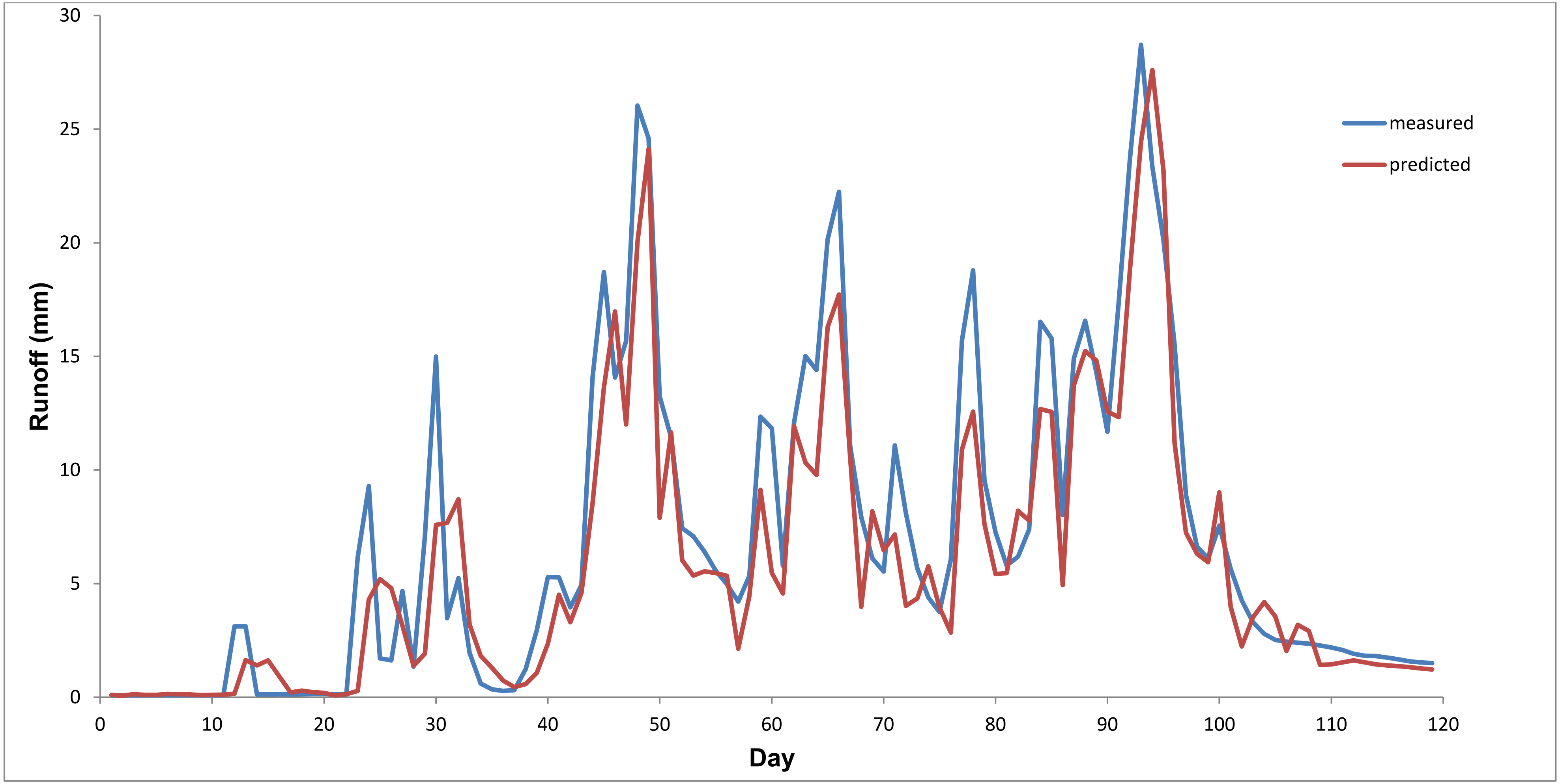


Fig. 4.1 Comparison of measured and predicted values of runoff for daily runoff prediction non-linear model (DPQNM) for the year 1994

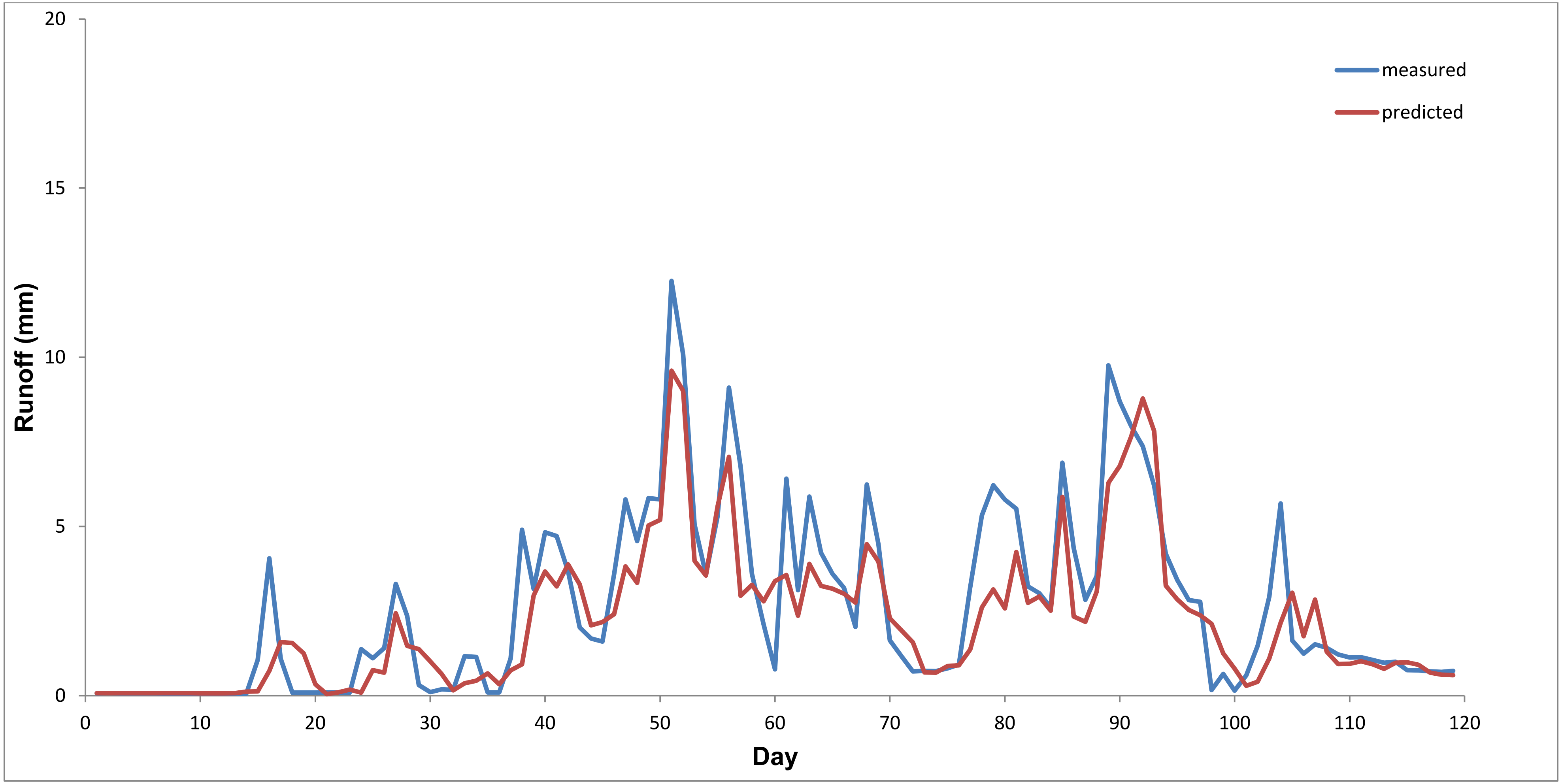


Fig. 4.2 Comparison of measured and predicted values of runoff for daily runoff prediction non-linear model (DPQNM) for the year 1995.

Table 4.2 Qualitative comparison of daily runoff prediction non-linear model during year 1994-2014

Year	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2006	2007	2008	2009	2010	2011	2012	2013	2014
APE(%)	15.2	16.23	18.41	9.33	13.31	9.49	15.86	11.66	10.15	13.68	11.54	18.83	16.31	16.33	10.31	15.46	10.51	18.79	15.54	16.99
ISE(%)	3.48	4.46	4.35	4.04	3.94	4.21	5.1	5.75	4.9	3.98	5.22	4.74	3.63	5.08	4.19	3.6	3.65	3.52	2.77	4.35
CE(%)	85.16	76.28	70.2	74.49	75.09	80.07	68.97	63.3	82.57	73.69	72.29	71.88	79.76	63.35	79.85	74.82	74.44	81.26	85.86	76.89

Note : (i) Data of the year 2005 were not available at source

Table 4.3 Measured and Predicted values of daily runoff (mm) by runoff prediction non-linear model for year 1996 and 1998

Month/Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1996																															
JUNE M	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	3.01	1.01	1.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
P	-	-	-	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.36	0.9	0.74	0.79	0.82	0.82	0.81	1.85	1.17	1.22	0.98	0.53	0.26	0.01	0.01	0.01	0.02	0.01	0.01	
JULY M	0.01	0.01	0.02	4.02	4.04	3.06	4.1	2.15	4.14	1.13	4.12	3.15	5.13	4.19	4.34	3.45	2.1	1.92	4.97	6.24	5.08	2.15	1.14	5.59	4.04	4.99	12.6	9.06	4.89	3.61	2.45
P	0.01	0.01	0.01	0.05	0.84	1.73	3.51	2.41	3.95	1.5	3.3	2.87	3.79	3.96	4.12	3.41	2.96	1.81	3.7	4.23	4.36	4.28	1.57	3.58	2.63	4.62	7.8	5.01	3.61	3.65	3.54
AUG. M	2.44	9.79	6.67	4.33	3.35	5.31	3.11	3.22	6.69	4.65	3.14	2.03	1	1.8	1.71	2.12	5.63	4.94	3.59	4.99	5.11	2.95	1.42	1.28	1.09	1.95	1.41	1.02	1.23	2.75	6.02
P	1.72	5.15	5.95	3.17	4.33	5.72	1.15	2.22	5.62	2.41	2.61	2.45	1.85	1.64	2.32	1.69	2.5	3.4	3.17	4.56	5.36	2.12	3.8	2.29	1.49	1.38	1.36	1	1.06	1.23	3.19
SEPT. M	4.12	3.88	5.09	2.86	3.3	5.86	7.28	6.06	5.51	2.96	5.05	2.92	1.11	3.27	2.66	3.05	2.7	1.53	2.28	1.09	0.92	1.22	0.79	0.74	0.67	0.65	0.62	0.6	0.58	0.55	
P	1.9	2.54	4.78	2.73	2.24	4.94	5.89	4.79	4.29	3.07	5.74	3.05	2.07	2.93	2.23	2.56	1	1.68	1.56	1.35	1.07	1.02	0.88	0.79	0.72	0.61	0.58	0.55	0.53	1.06	
1998																															
JUNE M	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	1.01	1.01	0.01	0.01	1.01	1.01	0.02	1.02	1.02	0.02	0.02	0.02	1.03	2.03	3.03	5.01	5.44	2.37	
P	-	-	-	0.02	0.02	0.02	0.03	0.03	0.03	0.01	0.02	0.02	0.04	0.36	0.6	0.59	0.36	0.53	0.56	0.74	0.51	0.61	0.47	0.31	0.02	0.86	0.8	3.37	4.38	3.96	
JULY M	2.38	1.12	5.36	7.22	10.5	9.98	6.91	5.86	4.29	2.94	5.52	3.65	8.03	7.37	3.89	3.66	2.24	1.13	1.62	5.89	4.9	2.94	1.7	1.66	1.54	0.49	0.49	0.44	0.4	0.4	1.34
P	2.09	1.73	3.39	4.26	8.03	9.11	6.48	6.49	3.84	3.89	5.13	2.35	6.53	6	3.04	5.91	2.37	1.84	1.35	3.04	2.63	2.32	2.31	2.07	1.48	1.25	0.88	0.62	0.42	0.5	0.47
AUG. M	2.89	5.93	6.92	7.43	3.03	1.23	4.07	3.62	3.58	1.55	1.44	2.9	5.56	6.99	6.27	3.38	1.97	2.39	1.38	1.29	4.29	4.18	3.3	1.53	1.36	3.48	2.42	1.36	3.34	3.19	1.39
P	1	4.95	5.22	6.06	3.04	2.6	4.26	2.65	3.77	2.58	1.76	2.09	4.2	5.46	4.78	2.87	2.66	2.36	1.93	1.2	2.85	3.23	2.95	2.7	1.16	2.93	1.66	2.57	2.36	2.14	2.44
SEPT. M	1.63	1.67	1.08	1.59	1.99	3.64	3.17	3.18	2.1	3.09	3.78	2.77	3.75	9.68	7.73	6.75	3.74	1.48	1.46	1.59	2.13	6.11	4.5	3.49	3.49	4.48	0.47	0.44	0.43	0.41	
P	1.45	1.57	1.2	1.28	1.63	1.94	2.68	3.15	2.68	3.01	1.5	3.32	3.89	5.37	6.29	6.11	3.77	2.9	2.14	2.1	1.64	7.92	4.36	3.3	1.92	3.08	2.6	1.23	0.33	0.34	

Table 4.4 Measured and Predicted values of daily runoff (mm) by runoff prediction non-linear model for year 2002 and 2008

Month/Date		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2002																																
JUNE	M	0.02	0.02	0.02	0.02	0.02	0.02	0.14	0.07	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	2.02	0.02	1.03	1.03	2.03	1.91	1.97	3.78	2.58	1.93	1.06	0.95	1.72	2.58	
	P	-	-	-	0.02	0.02	0.02	0.05	0.07	0.07	0.06	0.04	0.03	0.04	0.03	0.02	0.04	0.04	0.73	0.81	0.81	1.14	1.33	1.61	2.45	3.15	1.65	1.88	1.56	1.35	1.77	
JULY	M	1.58	0.32	0.28	0.23	0.21	0.2	0.11	0.07	0.05	0.05	0.05	0.04	0.04	0.05	0.04	1.04	0.04	4.04	3.27	3.27	0.97	0.73	0.59	0.45	0.4	0.35	0.29	0.19	0.26	0.24	0.23
	P	1.14	1.07	0.86	0.57	0.32	0.22	0.2	0.16	0.12	0.08	0.06	0.06	0.05	0.05	0.11	0.05	0.45	0.63	2.66	2.38	1.33	1.2	1.02	0.71	0.61	0.41	0.36	0.31	0.25	0.23	0.23
AUG.	M	3.41	3.44	1.08	6.5	3.51	1.84	2.68	3.54	2.41	0.35	0.28	0.3	0.11	0.11	3.22	8.13	9.51	14.8	13.9	14.4	9.75	6.92	10.3	11.3	4.19	5.69	4.11	3.49	8.91	5.44	11.8
	P	0.53	1.5	2.55	3.51	3.84	4.36	3.94	3.47	1.76	1.75	1.04	0.76	0.35	0.17	0.35	2.63	6.61	0.93	13.4	11.3	9.91	10.4	8.98	9.93	7.79	4.78	3.64	4.36	6.84	6.06	9.85
SEPT.	M	5.63	4.95	6.09	6.51	9.74	13.9	11.4	9.66	4	3.56	3.4	3.55	4.24	2.66	2.3	2.8	2.36	2.04	1.92	1.67	1.32	1.75	1.13	1.74	0.95	0.83	0.66	0.63	1.17	0.58	
	P	7.32	7.26	6.43	3.39	8.2	10.8	10.5	8.59	7.55	4.47	5.54	2.48	2.06	2.35	2.62	2.08	1.91	1.83	1.72	1.52	1.55	1.4	1.48	1.08	1.32	1.14	1.04	0.66	0.59	0.73	
2008																																
JUNE	M	0	0	0	0	0	0	0	0	0	0.01	0.01	0.01	0.23	0.2	3.17	2.03	1.03	0.03	0.03	0.03	0.03	0.14	0.03	1.03	3.2	4.23	5.04	5.03	5.04	7.23	
	P	-	-	-	0.13	0.56	0	0	0	0.01	0	0.01	0.01	0.01	0.22	0.14	1.01	1.52	1.51	1.05	0.35	0.04	0.04	0.09	0.13	0.84	2.66	2.68	3.14	5.81	4.45	
JULY	M	5.23	5.11	6.03	4.8	1.7	0.47	0.23	0.14	1.11	3	3.36	6.8	5.56	5.23	2.11	0.03	0.03	0.03	0.03	0.01	0.01	0.11	0.04	0.03	1.03	2.2	4.23	0.23	5.2	8.75	7.48
	P	3.74	6.64	5.3	2.83	2.83	2.38	1.59	0.92	0.31	2.15	2.63	3.21	2.89	3.31	2.82	3.42	2.03	0.47	0.04	0.04	0.02	0.03	0.08	0.09	0.09	0.72	1.13	3.2	3.02	4.9	5.22
AUG.	M	7.16	11	12.6	11	9.52	7.06	5.58	5.35	4.83	4.02	5.96	3.61	3.18	2.53	2.46	1.3	3.96	3.2	2.9	1.85	3.8	0.7	0.7	0.7	0.65	1.65	4.65	6.6	6.6	5.56	3.69
	P	8.61	9.12	9.51	9.33	8.06	9.41	4.39	3.77	3.6	5.73	5.21	5.33	3.73	1.75	1.62	3.51	2.02	1.61	1.82	4.61	1.48	1.79	0.95	2.12	0.69	0.79	2.01	2.56	4.68	2.95	3.82
SEPT.	M	2.16	2.01	2.61	2	3.52	6.06	7.58	5.35	4.83	4.02	3.96	3.61	3.18	2.53	1.46	3.3	3.96	3.9	5.9	6.85	3.8	5.7	4.7	1.7	1.09	0.65	0.65	0.3	0.3	0.26	
	P	2.92	5.34	2.05	1.54	2.25	3.99	5	3.94	3.12	3.18	3.15	3.51	2.71	2.33	2.23	3.83	3	2.55	5.16	5.01	3.46	2.65	3.05	3.58	2.53	1.59	0.84	0.63	0.44	0.35	

Table 4.5 Measured and Predicted values of daily runoff (mm) by runoff prediction non-linear model for year 2010 and 2013

MONTH/DATE		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2010																																
JUNE	M	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.02	0.02	0.02	0.02	0.02	0.02	1.02	1.02	0.02	0.04	0.04	0.04	2.05	1.07	2.08	
	P	-	-	-	0.82	0.82	0.03	0	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.06	0.05	0.33	0.53	0.45	0.29	0.05	0.11	0.6	1.71	
JULY	M	1.09	0.15	1.45	4.75	4.36	1.37	2.7	5.81	5.96	2.74	1.54	1.57	1.6	1.54	1.89	2.14	2.23	2.26	2.37	5.6	3.38	5.31	5	3.2	3.2	7.85	4.68	4.81	4.55	4.38	7.77
	P	1.57	0.85	1.27	1.48	2.32	3.52	3.81	3.75	3.58	2.5	2.39	2.95	2.21	1.14	1.77	1.1	2.4	1.29	1.88	3.86	2.7	4.69	2.96	2.5	2.4	6.61	3.06	2.07	5.03	2.98	6.06
AUG.	M	7.77	4.82	9.16	8.28	6.36	5.44	10.9	11.7	7.17	5.45	4.64	3.32	3.19	4.72	9.54	12.7	9.77	5.4	5.7	7.16	8.32	11.7	7.2	5.45	4.83	6.59	4.7	4.8	6.17	8.84	8.83
	P	7.53	5.91	8.15	7.52	3.48	6.6	10.4	8.25	4.47	4.12	3.91	4.24	5.26	3.31	6.97	7.81	5.67	4.5	8.38	4.49	9.92	9.8	4.1	4.02	7.13	5.14	3.17	7.58	5.59	5.95	6.15
SEPT.	M	10.8	12.9	9.95	9.28	9.72	4.5	4.35	4.49	4.51	4.26	3.81	4.34	4.3	4.2	4.13	4.74	5.58	4.3	5.44	4.39	4.79	4.38	4.2	3.63	4.01	3.81	2.33	2.13	1.55	1.46	
	P	8.86	13.9	8.17	7.86	11.5	5.35	3.54	6.44	5.32	3.89	2.24	2.3	2.72	2.92	4.65	5.81	2.77	5.16	4.2	3.96	2.59	2.92	3.16	3.04	2.78	2.75	2.69	2.29	1.89	1.45	
2013																																
JUNE	M																															
	P	0	0	0	0	0	0	0.01	0.01	0.01	0.01	0.1	0.1	0.1	0.22	1.28	2.21	0.13	0.08	0.03	0.12	0.18	3.41	3.46	4.17	5.22	7.74	8.13	3.11	2.7	2.81	
		-	-	-	0.17	0.29	0.05	0.03	0.01	0.01	0.01	0.02	0.05	0.17	0.14	0.22	1.28	1.65	0.86	0.76	0.07	0.15	0.2	2.13	4.09	3.66	6.79	5.8	6.07	2.62	2.22	
JULY	M																															
	P	2.45	6.92	6.47	5.38	7.47	6.82	6.53	6.05	5.73	5.33	4.76	4.38	5.67	7.97	6.91	8.14	7.7	5.26	7.33	12	9.21	8.48	11.7	13.3	12.4	11.7	13.6	14	15.8	16.1	14.3
		3.68	4.37	5.48	5.02	3.33	6.33	8.5	5.95	6.66	2.87	2.31	6.23	3.66	3.29	6.8	10.1	6.67	6.91	3.13	8.16	8.07	5.34	9.16	11.3	11.3	11.1	13.5	11.5	13.6	15.3	12.5
AUG.	M																															
	P	22.3	17.7	16.8	10.9	10.7	10.2	10.1	10.6	15.7	16.4	13.1	13.5	14	13.2	13.4	9.02	5.56	4.88	8.01	10	10.9	14.9	21	22.4	15.9	8.17	6.46	9.08	6.97	5.56	5.87
		18.9	13.4	16.5	7.43	6.77	7.43	10.1	5.77	15.1	13.9	8.91	12	15.6	8.85	12.5	5.99	5.77	7.3	10.9	7.33	8.3	12.1	17.2	16.2	12.8	6.57	6.36	10	4.33	4.27	4.07
SEPT.	M																															
	P	5.21	5.21	5.48	5.55	5.04	5.74	4.85	4.1	3.34	3.15	3.05	2.51	2.36	2.33	2.1	2.08	2.1	1.99	1.94	1.88	2.38	3.08	3.56	3.24	2.72	2.4	2.28	2.9	2.41	2.34	
		4.01	3.7	3.62	3.6	3.67	3.59	3.69	3.51	3.23	2.75	2.44	2.26	2.41	2.36	1.68	2.38	1.88	1.42	2.58	1.98	1.71	2.53	2.38	1.8	2.06	2.07	2.09	1.89	2.23	2.28	

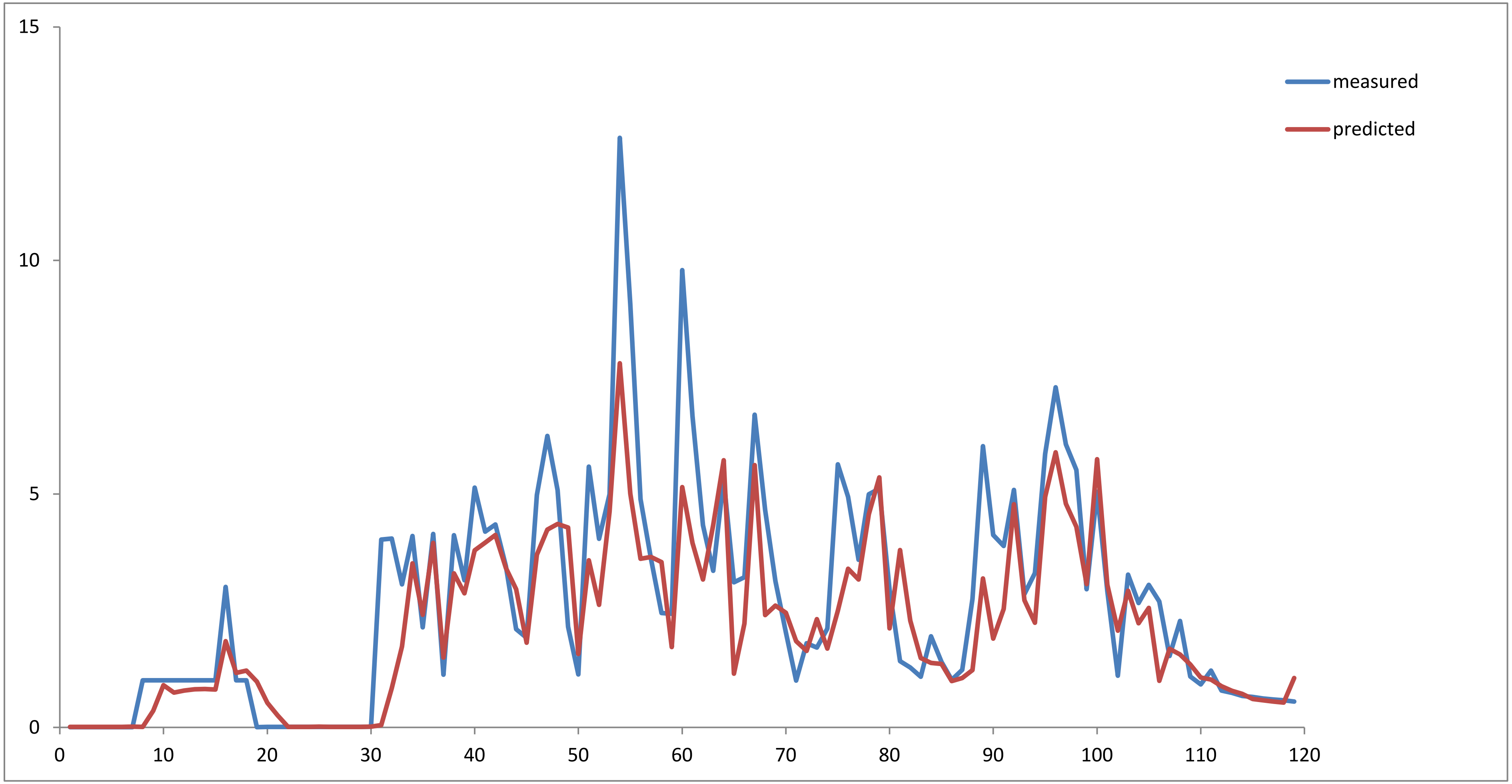


Fig. 4.3 Comparison of measured and predicted values of runoff for daily runoff prediction non-linear model (DPQNM) for the year 1996

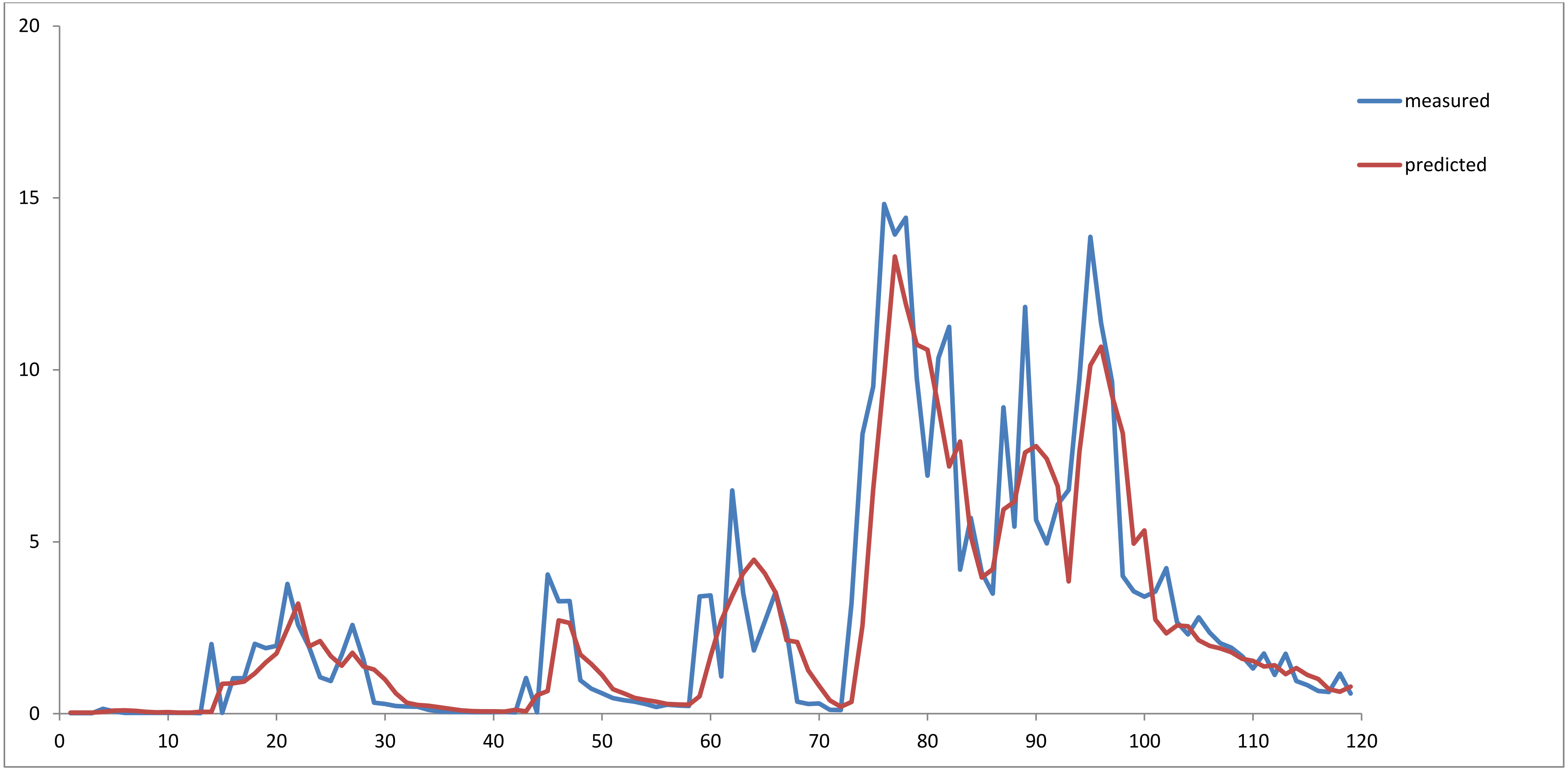


Fig. 4.4 Comparison of measured and predicted values of runoff for daily runoff prediction non-linear model (DPQNM) for the year 2002

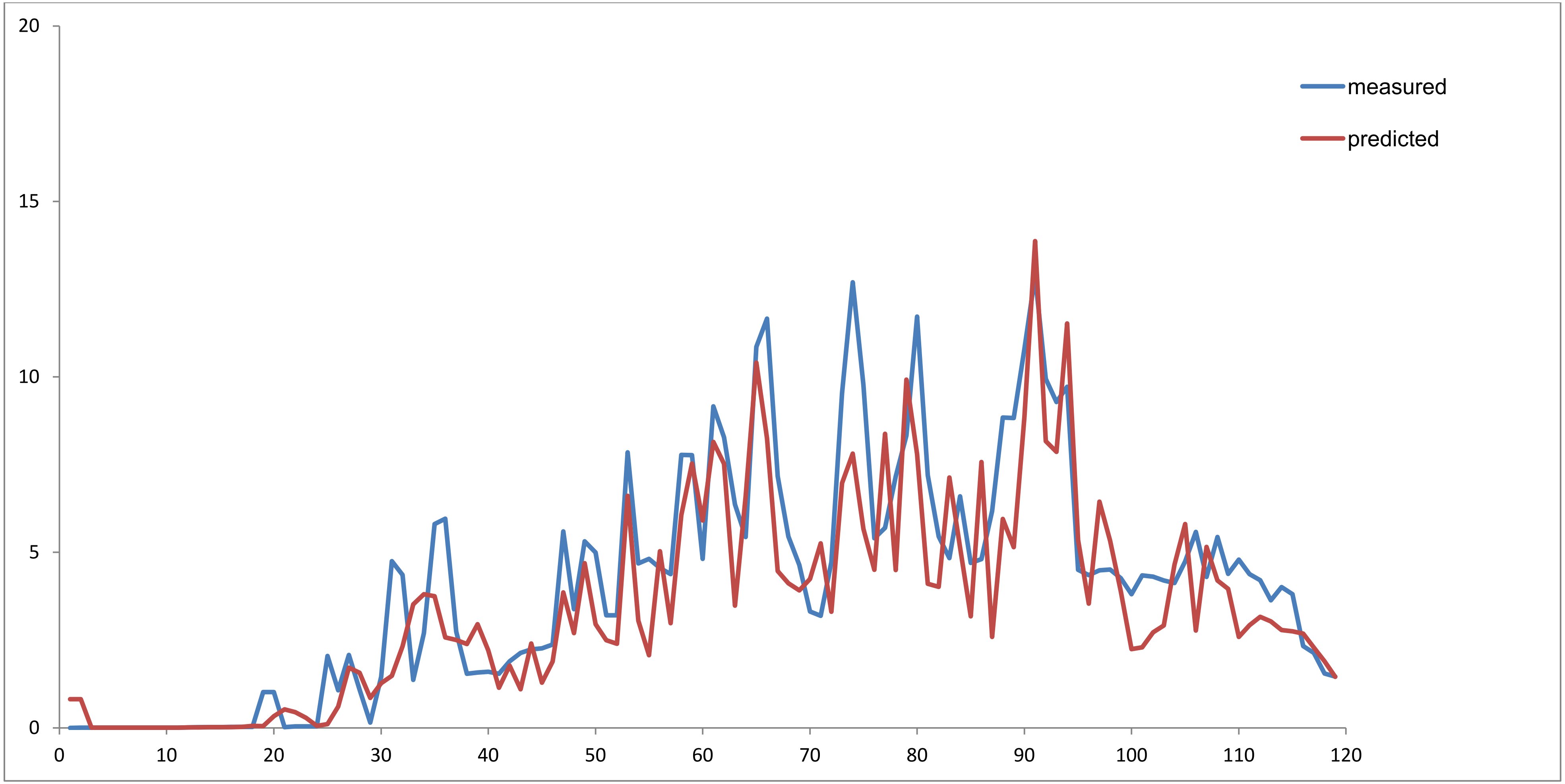


Fig. 4.5 Comparison of measured and predicted values of runoff for daily runoff prediction non-linear model (DPQNM) for the year 2010

4.1.2 Weekly Runoff Prediction Models

4.1.2.1Testing and verification

Two runoff models viz., linear and non-linear were developed for the Shakkar river watershed following the computational procedure described in section 3.5.2, Chapter 3, considering a time series of weekly runoff data of active weeks only during the years 1994-1996. The plausibility of both the developed models was verified on measured weekly runoff data series of active weeks of each year individually from 1994-1996. The results were presented in the Tables 4.6 and 4.7 alongwith the values of qualitative parameters, respectively, for the linear and non linear models. The Tables reveal that in case of linear model and non-linear model the values of APE, ISE and CE are well within the permissible limits adopted in the study. From this it can be inferred that the memory based non-linear model is more appropriate for the study area as compared to the linear model. Moreover, the R^2 value in case of developed non- linear model is also more (0.96) than that for linear model (0.86). The visual comparison of the measured and the predicted values of runoff for the years 1995 and 2009 were shown in Figs. 4.6 and 4.7 for the linear model and in figs. 4.8 and 4.9 for non-linear model. From the figures, a good degree of closeness can be seen between the measured and the predicted values. Hence, the rainfall-runoff process for the watershed is non-linear on aggregate time scale basis also.

4.1.2.2 Prediction performance

From the plausibility test performed on both the models under section 4.1.2.1, the non-linear model was found performing better for the study area. The validity of memory based models was established for the study area by applying it on the measured weekly runoff data of different individual years under consideration (1994-2014).The result along with the values of qualitative parameters are presented in tables 4.6 and 4.7 for all the years. From which it can be observed that the values of APE, ISE and CE for all the years are well within the permissible limits adopted in the present study. Thus, this confirms that the non-linear model is more appropriate and realistic for prediction of weekly runoff for the Shakkar river watershed. To have a better interpretation, a comparison between measured and predicted values of runoff was shown in Figs. 4.6, 4.7, 4.8 and 4.9, wherein a good degree of closeness can be observed between the values.

Table 4.6 Measured and linear model predicted values of weekly runoff (mm) during 1994-2014

YEAR/WEEK		26	27	28	29	30	31	32	33	34	35	36	37	38	39	APE(%)	ISE(%)	CE(%)
1994	M	24.9	33.7	29.3	138	56.1	66.6	67.5	54.8	71.5	98.7	107	32.2	15.6	11.7	-	-	-
	P	27.7	27.1	35	153	58.2	74.7	61.3	47.2	82.2	86.2	102	47.8	32.6	15.1	4.16	4.08	92.72
1995	M	9.73	3.18	22.5	25.1	71.2	38.7	25.4	18.3	30.2	44	27	13.1	8.72	5.63	-	-	-
	P	7.89	2.97	18	24.6	60.3	45.8	33.5	24.5	17	33	21.9	14.9	11.6	4.34	6.46	7.33	85.14
1997	M	2.44	46.7	14.6	17.4	66.6	37.6	21	12.1	43.2	27.4	19.6	41.8	33.5	29.7	-	-	-
	P	0.46	52.1	22.5	30.4	69.6	36	26.2	18.2	36.1	18.9	23.2	37.6	33.5	31	7.46	6.41	80.89
1998	M	11.3	46.9	35.7	22.4	6.7	28	18.4	27.9	29.4	15	16.7	37.5	31	19.2	-	-	-
	P	13.4	52.8	35.9	28.2	13.6	27.3	13.7	27.5	26.3	19.9	19.3	36.9	26.9	20	4.5	2.2	87.47
1999	M	9.92	18.4	15.5	23.5	31.8	42.8	62	15.9	20.5	23.8	29.5	64.6	133	64.5	-	-	-
	P	8.16	12.4	9.13	19.1	38.5	46.6	54	24.2	15.4	19.8	14.9	74.9	118	65	6.48	5.36	93.64
2000	M	1.99	17.1	30.4	37.6	53.9	21.1	26.3	22.5	19.4	17.7	7.57	5.25	7.83	5.68	-	-	-
	P	5.58	15.8	33.6	44.5	62.2	34.6	25.4	31.4	11.2	20.4	10.2	4.47	6.73	4.68	12.45	8.43	79.43
2001	M	8.68	9.12	27.3	16.1	21.3	6.99	18.3	44.8	46.9	11.3	10.3	4.04	3.18	2.44	-	-	-
	P	10.3	10.1	28.9	25.6	23.6	13.5	20.8	44.5	39.1	20.9	16.8	5	2	1.6	15.06	8.23	86.43

Contd…….

Table 4.6 contd…….

YEAR/WEEK		26	27	28	29	30	31	32	33	34	35	36	37	38	39	APE(%)	ISE(%)	CE(%)
2002	M	12.4	1.416	0.332	13.37	2.536	18.4	11.41	59.84	52.58	44.37	61.22	22.51	12.19	6.569	-	-	-
	P	11.65	1.945	2.939	11.23	0.452	18.93	13.71	72.89	41.82	51.86	60.63	26.62	16.24	9.028	9.45	7.35	91.25
2003	M	21.24	21.5	13.29	24.34	53.33	21.16	24.71	34.57	26.11	27.74	34.82	55.44	40.37	55.25	-	-	-
	P	19.45	16.35	11.46	23.23	56.17	17.92	31.49	30.57	21.85	29.19	32.73	48.35	38.97	47.69	10.79	5.01	80.36
2004	M	31.58	22.57	62.78	54.41	43.45	32.96	62.02	16.41	23.94	49.93	21.44	42.69	28.06	13.99	-	-	-
	P	25.13	22.58	64.42	60.32	45.53	31.44	54.33	24.76	27.03	44.85	25.74	35.17	20.31	10.37	2.81	3.94	86.7
2006	M	5.083	12.64	5.068	44.08	28.04	33.51	30.32	49.32	38.11	38.96	50.5	25.76	19.97	12.8	-	-	-
	P	3.418	9.462	6.477	34.74	33.72	30.54	34.29	52.14	27.09	41.78	44.63	23.54	17.1	11.28	3.63	5.31	88.02
2007	M	19.34	44.56	32.86	21.36	46.76	57.67	50.4	16.4	22.38	27.21	52.04	23.9	22.01	39.39	-	-	-
	P	16.81	53.08	26.56	21.05	47.41	58.57	43.11	23.68	19.71	20.32	51.61	20.72	24.02	31.58	1.73	4.25	86.31
2008	M	25.01	18.48	28.17	10.25	22.97	57.54	36.4	19.53	10.04	31.27	31.96	22.06	24.8	8.95	-	-	-
	P	23.97	13.62	20.74	9.644	25.93	54.25	27.41	22.5	8.26	32.32	30.63	13.31	23.89	9.33	10.96	6.9	74.59
2009	M	4.69	15.54	43.58	66.98	57.48	18.31	27.12	17.85	23.28	39	43.12	39.72	11.61	7.027	-	-	-
	P	5.641	21.72	36.2	74.82	61.63	29.26	28.64	14.74	15.72	40.05	41.53	36.32	19.23	9.781	8.75	6.03	87.49
2010	M	6.404	20.59	16.85	23.29	13.3	28.54	38.52	51	48.28	57.02	46.79	29.79	23.08	8.915	-	-	-
	P	7.639	27.55	11.41	23.53	17.01	33.36	36.83	46.24	42.41	55.72	43.86	28.23	21.31	9.471	1.8	3.37	94.48

Contd…….

Table 4.6 contd…….

YEAR/ WEEK		26	27	28	29	30	31	32	33	34	35	36	37	38	39	APE (%)	ISE (%)	CE (%)
2011	M	29.58	22.57	58.78	54.41	43.45	32.96	62.02	26.41	23.94	49.93	31.44	42.69	28.06	7.989	-	-	-
	P	25.13	22.45	64.33	59.99	45.35	31.56	54.4	24.8	27.72	45.31	26.07	35.82	23.34	11.34	3.23	3.33	90.71
2012	M	0.044	20.36	21.65	20.16	24.27	30.57	66.07	30.37	65.77	43.45	51.44	44.8	20.59	9.974	-	-	-
	P	1.571	14.63	15.57	13.06	18.16	27.71	66.95	30.99	62.34	38.52	46.86	38.85	24.35	14.18	7.85	3.79	94.29
2013	M	32.16	45.65	40.74	48.12	52.52	58.67	56.59	51.12	83.27	44.37	17.11	17.57	16.93	12.28	-	-	-
	P	40.59	48.18	35.39	40.28	47.99	52.75	49.43	48.92	80.73	45.82	24.5	16.89	14.04	10.24	3.69	3.27	93.24
2014	M	3.168	2.111	10.1	26.65	47.76	53.5	41.53	19.27	21.28	34.07	43.25	46.11	29.13	16.61	-	-	-
	P	0.663	0.42	11.31	33.97	45.54	50.13	35.89	24.3	25.56	30.52	40.11	38.89	23.38	13.89	2.59	4.63	92.1

Note: (i) Data for the year 2005 were not available at the source

(ii) M: measured, P: predicted

Table:4.7 measured and non-linear model predicted values of weekly runoff (mm) during 1994-2014

YEAR/WEEK		26	27	28	29	30	31	32	33	34	35	36	37	38	39	APE(%)	ISE(%)	CE(%)
1994	M	24.93	33.66	29.28	138.1	56.11	66.61	67.45	54.75	71.47	98.68	106.9	32.19	15.63	11.65			
	P	28.87	28.42	34.73	115.4	34.67	73.44	58.43	47.72	86.41	102.2	125.6	25.38	20.25	13.26	5.02	6.51	84.59
1995	M	9.731	3.179	22.47	25.11	71.18	38.67	25.39	18.29	30.23	44.04	26.96	13.1	8.72	5.628			
	P	10.98	6.285	19	25.79	63.91	47.26	32.39	23.14	27.07	35.19	25.52	13.11	11.73	7.518	4.9	7.59	84.05
1996	M	0.069	12.4	26.21	25.93	42.33	32.64	28.15	20.8	18.8	20.43	35.96	21.02	10.53	14.42			
	P	1.391	9.701	21.87	22.03	39.57	31.67	25.16	20.51	21.76	18.83	29.96	24.09	10.92	11.81	5.81	5.25	86.34
1997	M	2.44	46.75	14.56	17.44	66.63	37.59	20.99	12.14	43.24	27.39	19.57	41.79	33.47	29.72			
	P	1.903	31.94	17.92	32.07	67.7	36.36	22.21	14.52	44.57	21.4	28.49	47.82	40.72	32.21	7.04	7.51	73.81
1998	M	11.29	46.94	35.7	22.39	6.702	27.96	18.39	27.94	29.44	14.99	16.74	37.54	31	19.21			
	P	12.62	37.71	35.51	25.69	4.484	26.34	16.05	30.83	32.32	21.92	24.74	44.97	36.89	23.15	7.8	5.62	75.66
1999	M	9.924	18.37	15.47	23.48	31.83	42.85	61.99	15.91	20.52	23.78	29.45	64.55	133	64.51			
	P	7.716	13.48	10.81	18.08	35.84	49.78	60.33	17.07	18.65	22.25	17.52	66.54	152.2	70.33	2.71	5.45	93.43
2000	M	5.987	17.07	30.39	37.64	53.9	21.06	26.35	22.46	19.44	19.74	7.568	5.247	7.832	6.875			
	P	6.121	16.72	30.99	43.51	62.85	30.47	24.17	35.63	15.91	24.53	10.22	2.419	6.825	4.286	11.42	9.02	76.49
2001	M	8.68	9.124	27.34	16.15	21.3	6.988	18.27	44.83	46.94	11.35	10.3	4.039	3.184	2.438			
	P	12.23	12.58	25.53	21.84	26.84	12.45	24.99	46.21	48.37	12.44	16.13	7.719	1.517	1.679	9.75	7.82	87.79

Table:4.7 contd….

YEAR/WEEK		**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**APE(%)**	**ISE(%)**	**CE(%)**
2002	M	12.4	1.416	0.332	13.37	2.536	18.4	11.41	59.84	52.58	54.37	61.22	22.51	12.19	6.569			
	P	13.8	1.228	6.44	13.49	1.573	19.58	18.61	71.22	48.64	63.44	76.13	18.98	13.21	2.582	15.6	10.75	81.45
2003	M	21.24	21.5	13.29	24.34	53.33	21.16	24.71	34.57	26.11	27.74	34.82	59.44	40.37	55.25			
	P	15.06	17.74	12.66	23.47	48.44	18.49	30.73	35.38	25.52	35.56	41.2	61.1	35.94	57.64	2.6	5.76	74.08
2004	M	31.58	22.57	62.78	54.41	43.45	32.96	62.02	16.41	23.94	49.93	21.44	42.69	28.06	13.99			
	P	24.2	22.4	52.47	57.53	43.28	25.14	53.52	20.6	30.82	53.02	30.57	46	18.71	11.75	4.98	5.18	80.52
2006	M	5.083	12.64	5.068	44.08	28.04	33.51	30.32	49.32	38.11	38.96	50.5	25.76	19.97	2.798			
	P	6.436	11.91	10.12	30.77	35.68	33.55	37.77	56.66	26.63	49.28	55.32	22.46	13.88	9.614	4.15	7.03	79.01
2007	M	19.34	44.56	32.86	21.36	46.76	57.67	50.4	16.4	22.38	27.21	52.04	13.9	22.01	39.39			
	P	16.12	40.07	23.73	17.97	44.63	56.89	45.56	7.884	19.83	22.69	49.75	12.72	30.87	44.02	7.2	4.69	87.44
2008	M	25.01	18.48	28.17	10.25	22.97	57.54	36.4	19.53	10.04	31.27	31.96	22.06	24.8	4.95			
	P	21.26	15.29	21.86	7.128	24.01	50.68	26.83	19.6	18.74	24.94	26.38	13.25	29.51	2.742	11.99	6.28	78.99
2009	M	0.69	15.54	43.58	66.98	57.48	18.31	27.12	17.85	23.28	39	43.12	39.72	11.61	7.027			
	P	2.461	24.61	36.54	67.16	61.94	13.3	28.31	14.79	17.63	48.78	55.06	46.67	14.74	4.751	2.29	7.15	82.44
2010	M	6.404	20.59	16.85	23.29	13.3	28.54	38.52	51.77	48.28	57.02	46.79	29.79	23.08	8.915			
	P	10.79	24.97	12.63	25.42	18.85	33.45	42.48	53.35	49.53	65.59	52.14	27.89	21.53	2.589	6.99	4.1	91.8

contd…..

Table 4.7 contd….

YEAR/WEEK		26	27	28	29	30	31	32	33	34	35	36	37	38	39	APE(%)	ISE(%)	CE(%)
2011	M	29.58	22.57	58.78	54.41	43.45	32.96	62.02	26.41	23.94	49.93	31.44	42.69	28.06	7.989			
	P	24.2	22.46	52.55	57.72	43.34	25.62	53.66	20.63	30.64	52.7	30.45	45.63	24.71	2.861	5.26	3.56	89.37
2012	M	0.044	20.36	21.65	20.16	24.27	30.57	66.07	30.37	65.77	43.45	51.44	44.8	20.59	9.974			
	P	2.78	18.5	18.45	15.15	19.87	28.62	62.03	26.56	71.06	40.93	55.61	46.39	25.08	6.658	2.62	3.03	94.02
2013	M	32.16	45.65	40.74	48.12	52.52	58.67	56.59	51.12	83.27	44.37	17.11	17.57	16.93	12.28			
	P	40.17	46.35	32.88	38.19	45.7	52.25	51.26	52.27	86.5	46.52	3.699	10.58	15.11	12.39	7.49	4.21	88.79
2014	M	3.168	2.111	10.1	26.65	47.76	53.5	41.53	19.27	21.28	34.07	43.25	46.11	29.13	6.61			
	P	5.865	5.12	13.6	29.79	48.01	54.49	35.21	20.53	28.63	35.48	49.86	51.16	20.57	3.158	4.41	4.44	92.72

Note: (i) Data for the year 2005 were not available at the source

(ii) M: measured, P: predicted

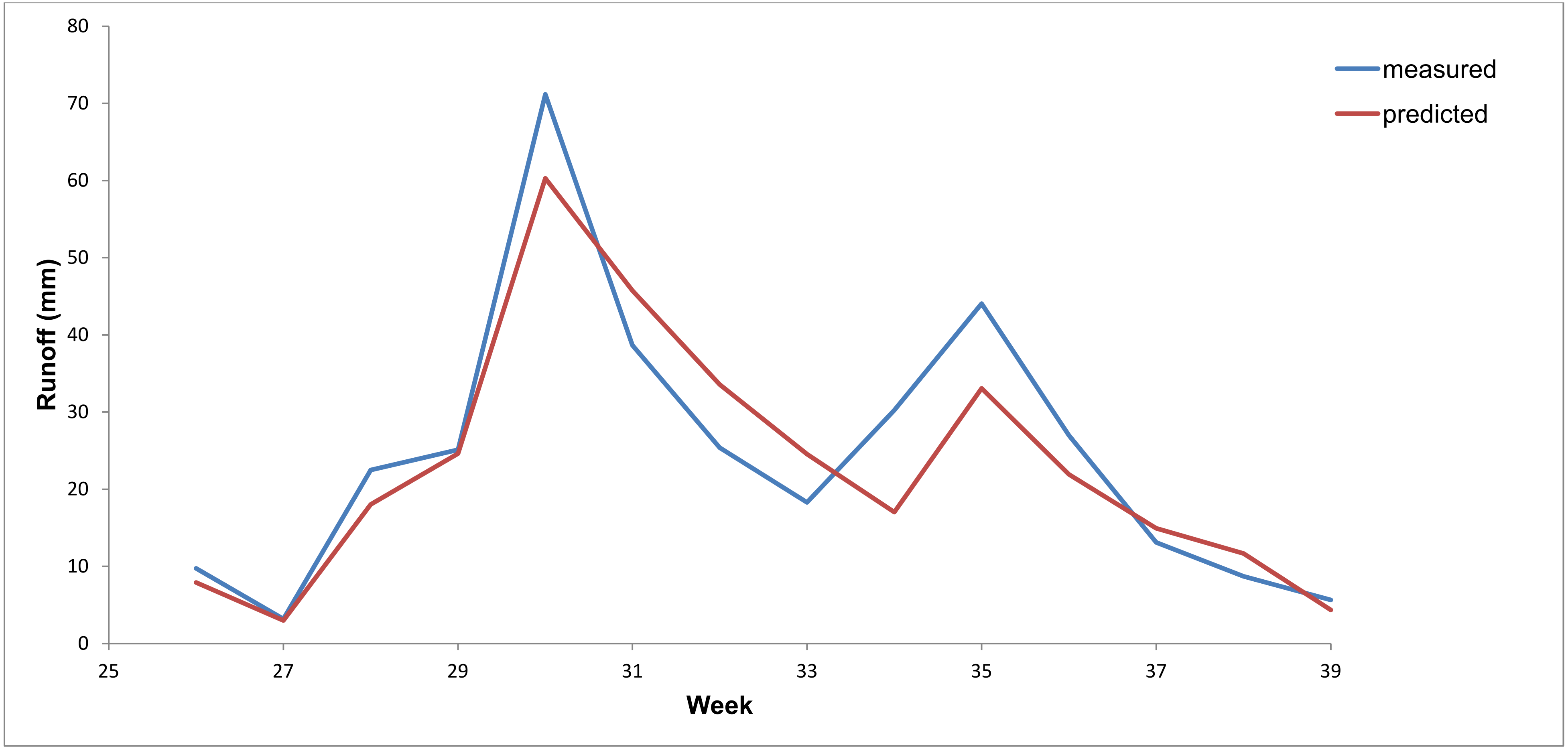


Fig. 4.6 Week wise comparison of measured and predicted values of runoff for weekly runoff prediction linear model (WPQLM) for the year 1995

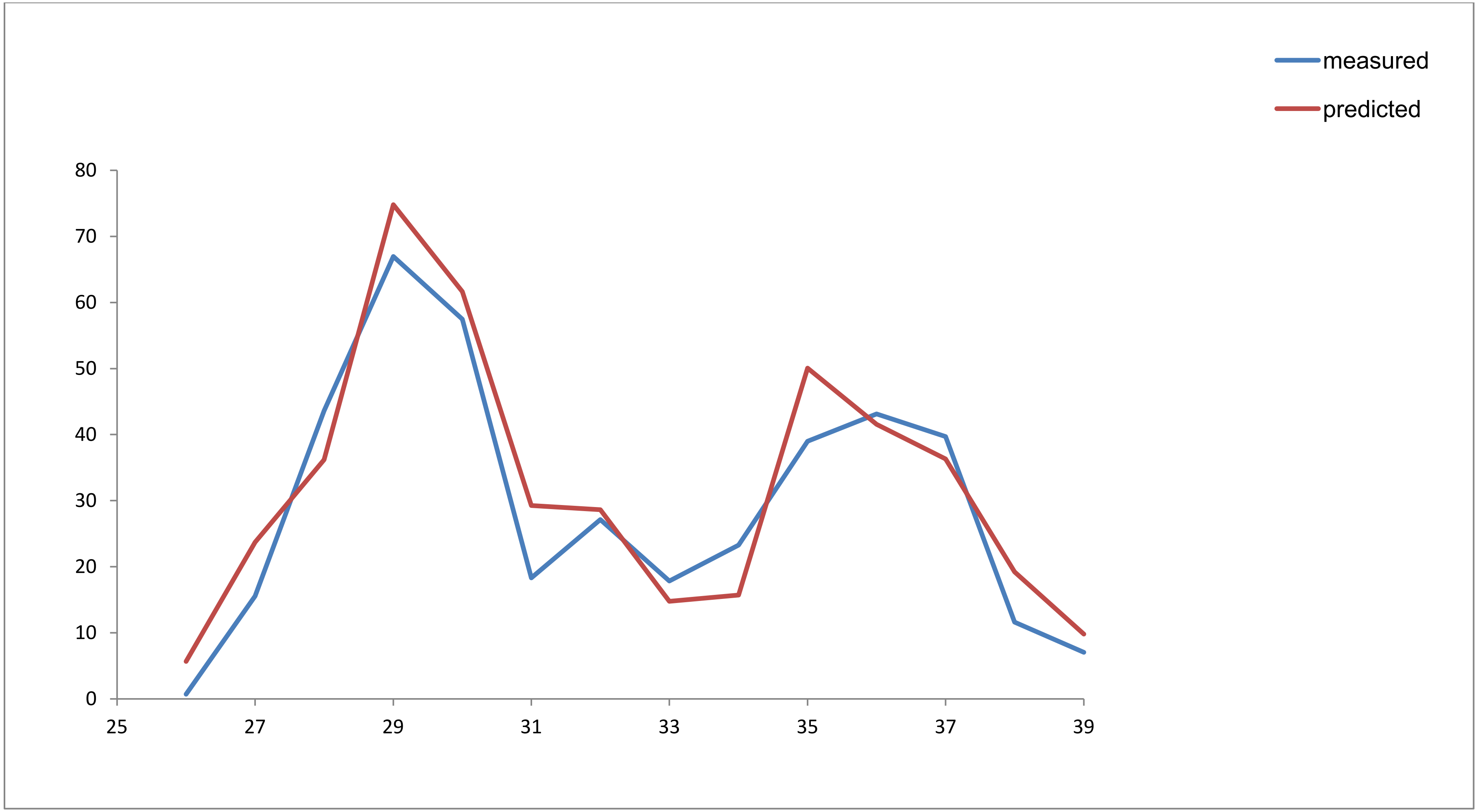


Fig. 4.7 Week wise comparison of measured and predicted values of runoff for weekly runoff prediction linear model (WPQLM) for the year 2009

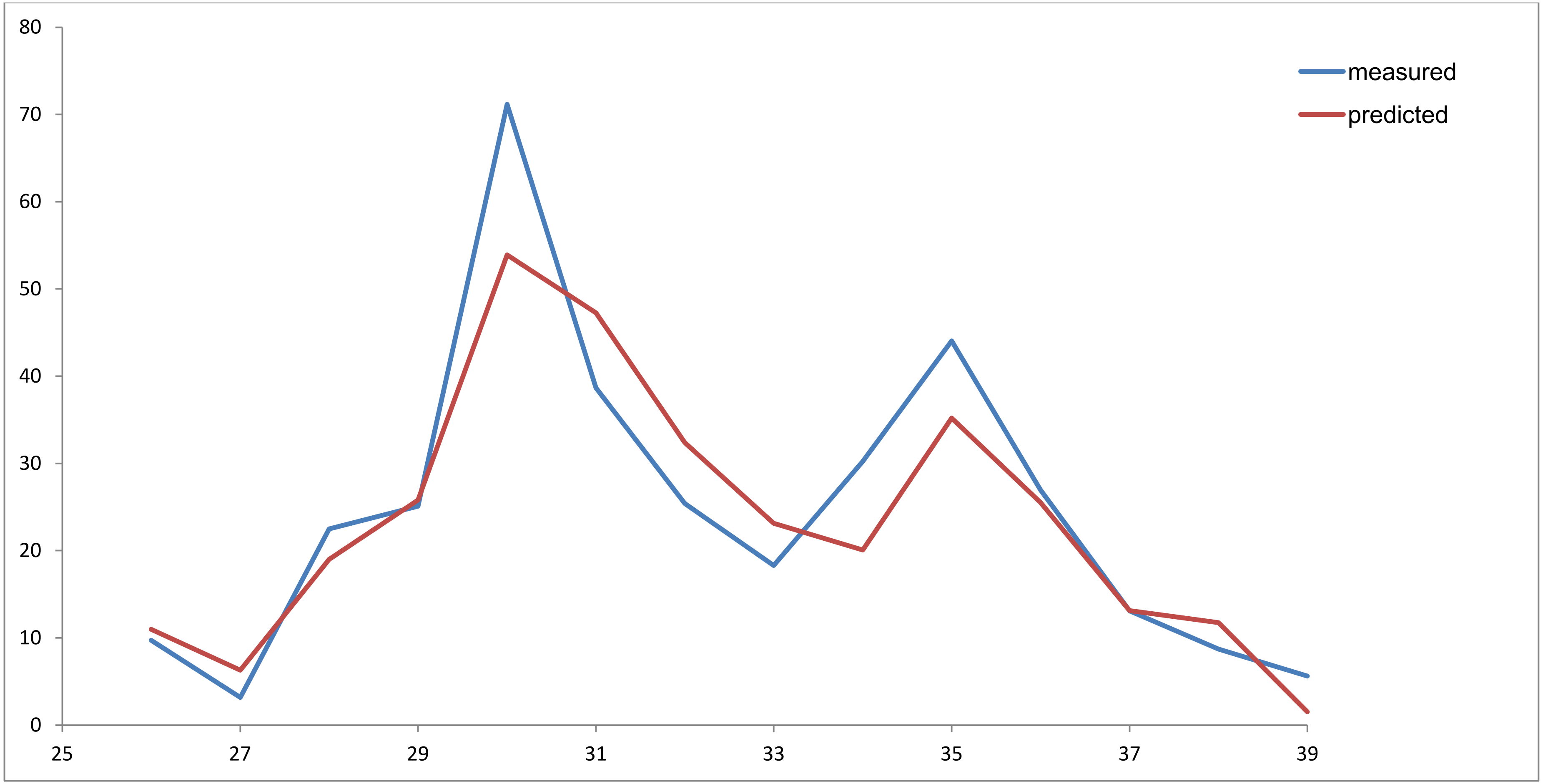


Fig. 4.8 Week wise comparison of measured and predicted values of runoff for weekly runoff prediction non-linear model (WPQNM) for the year 1995

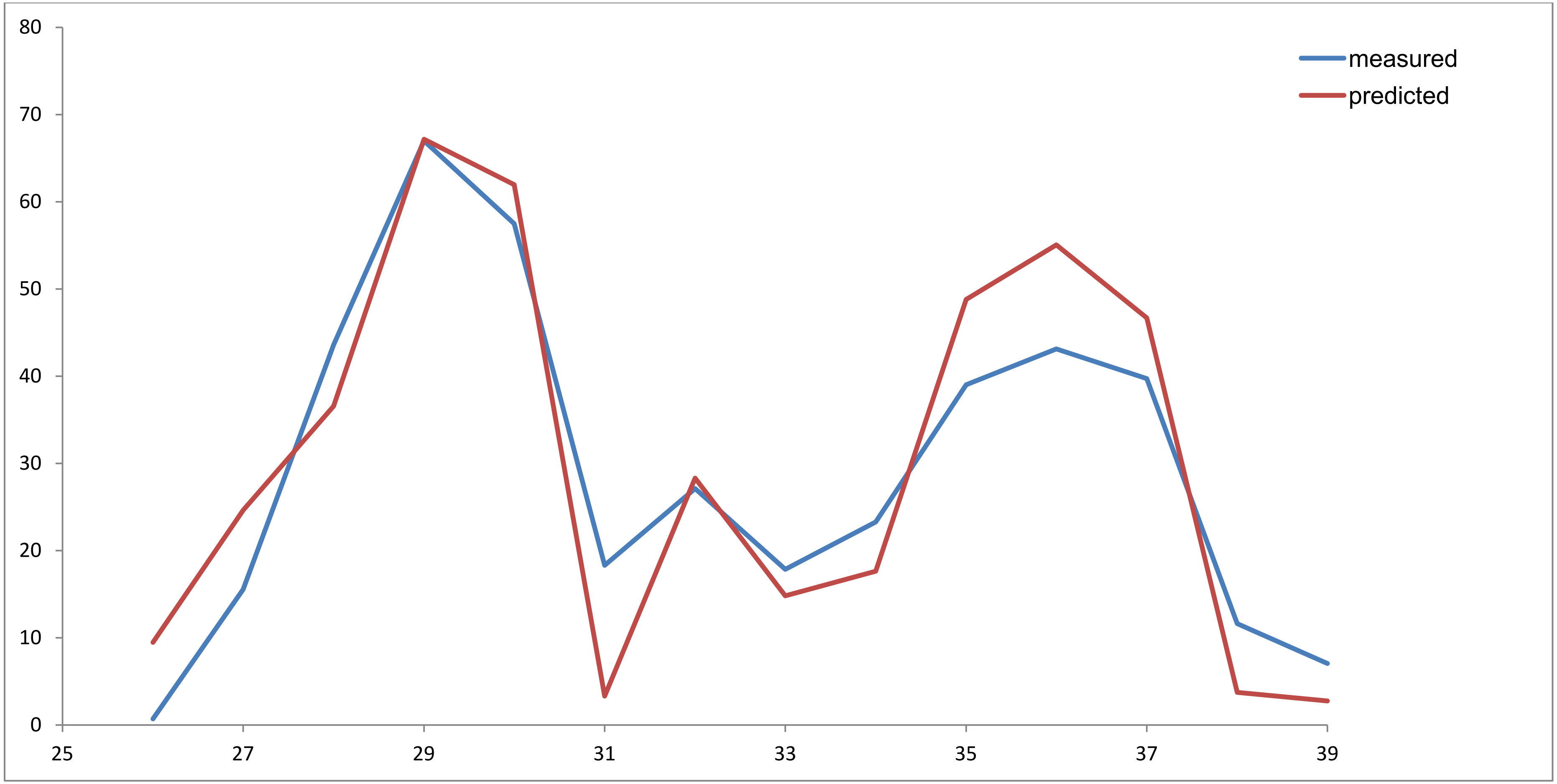


Fig. 4.8 Week wise comparison of measured and predicted values of runoff for weekly runoff prediction non-linear model (WPQNM) for the year 2009

SUMMARY AND CONCLUSION

5.1 Summary

The principle objective of this study was to develop and verify the system memory based runoff prediction models on sequential and integrated time scale basis as per the hypothesis described in chapter 3, for Shakkar river watershed, comprising an area of 2223 sq. km, of the Narmada basin, M.P., India. The watershed has maximum and minimum elevations respectively 314 m and 1154 m above MSL (mean sea level). The average annual rainfall is about 1245 mm. The daily rainfall data was collected from Land Record Department, Collectorate, Narsinghpur and Land Record Department, Collectorate, Chhindwara for the years 1994 to 2014. The daily runoff data was collected from Central Water Commission, Narmada Division, Paryavas Bhawan, Bhopal. The runoff data were converted into millimeter before subjected to analysis.

The dynamic models based on rainfall-runoff processes of a watershed fluvial system was developed in the present study on sequential and integrated (weekly) time scale basis. The qualitative performance of models were ascertained by estimating the values of absolute prediction error (APE), integral square error (ISE) and the coefficient of efficiency (CE). In the present study the permissible limits for APE, ISE and CE were taken respectively as 30%, 10% and 60%, that is the prediction should satisfy the criteria of the APE less than 30%, ISE less than 10% and CE more than 60%.

The runoff prediction models developed on daily and weekly basis for the study area can be summarized as,

(1) Two types of memory based runoff prediction models viz., linear and non-linear were developed by using the daily data series of three consecutive years from 1994 to 1996 of active period (June to September) only. Both the models consider the present rainfall, antecedent precipitation index (API), antecedent runoff index (AQI) as input. The values of coefficient of multiple determination (R^2) for the linear and non-linear models were found equal to 0.67 and 0.86 respectively, on the basis ofR^2value and prediction performance, the non-linear memory based model was found considered more

appropriate than the linear model for the study area. The Qualitative performance of non-linear model as tabulated in table 4.2, confirm the applicability of the model for all the years (1994-2014) under study.

(2) Memory based linear and non-linear weekly runoff prediction models were developed by using only active weeks' (23^{rd}-39^{th} meteorological weeks) data series of three years, ranging from 1994-1996. The coefficient of multiple determination (R^2) values were found equal to 0.86 and 0.96 respectively. The values of APE, ISE and CE for different year used for verification under study, reveals that the weekly non-linear runoff prediction model is better than the linear model.

Rainfall-Runoff Process

(1) Daily runoff prediction model:

a) Linear model

$$Q_d = -0.04 + 0.4\ (P_d) - 0.16\ (API)_d + 0.58\ (AQI)_d \quad (R^2=0.67) \quad …….(5.1)$$

b) Non-linear model

$$\ln(Q)_d = -0.2 + 0.27 \ln (P_d) - 0.12 \ln (API)_d + 0.89 \ln (AQI)_d \quad (R^2 = 0.86) \quad ……..(5.2)$$

(2) Weekly runoff prediction models:

a) Linear model

$$Q_w = -17.17 + 0.26\ P_w + 0.14\ (API)_w + 0.43\ (WEEK) + 0.14\ (AQI)_w \quad (R^2 = 0.86). \quad ..…….(5.3)$$

b) Non-linear model

$$\ln(Q_w) = -6.519 + 0.6 \ln(P_w) + 0.45 \ln (API)_w + 1.65 \ln(WEEK) - 0.07\ (AQI)_w \quad (R^2 = 0.96) \quad ……...(5.4)$$

5.2 Conclusion

The following are the salient conclusions obtained from the present study,

1. The fluvial system of Shakkar river watershed exhibits a strong memory on both the sequential and integrated time scale basis, and only past three successive events were found to influence the present event.

2. The first event, immediately preceding the current event was found to have more impact on it, in comparison to other preceding event, and the weights determined for the three successive antecedent events affecting the current event were 44.84%, 32.13% and 23.03% respectively.
3. The non-linear memory based daily runoff prediction model was found more appropriate than the linear model for the Shakkar river watershed of Narmada basin on the basis of coefficient of multiple determination (R^2) and prediction performance.
4. The memory based weekly rainfall-runoff non-linear model was found more appropriate than the weekly linear model for prediction of daily runoff volume for the study area, the inclusion of variable NORW (number of rainy days in a week) was not found to show any significant impact on the value of coefficient of multiple determination (R^2) and thereby on the performance of the model.

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ABSTRACT

Part 1: Front page of the abstract

Title of the thesis : **“System Memory Based Rainfall-Runoff Models for the Shakkar River Watershed of Narmada Basin”**

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ABSTRACT

The principle objective of this study was to develop and verify the system memory based runoff prediction models on sequential and integrated time scale basis as per the hypothesis, for Shakkar river watershed, comprising an area of 2223 sq. km, of the Narmada basin, M.P., India. The watershed has maximum and minimum elevations respectively 314 m and 1154 m above MSL (mean sea level). The average annual rainfall is about 1245 mm. The daily rainfall data was collected from Land Record Department, Collectorate, Narsinghpur and Land Record Department, Collectorate, Chhindwara for the years 1994 to 2014. The daily runoff data was collected from Central Water Commission, Narmada Division, Paryavas Bhawan, Bhopal. The runoff data were converted into millimeter before subjected to analysis. The dynamic models based on rainfall-runoff processes of a watershed fluvial system was developed in the present study on sequential and integrated (weekly) time scale basis. The qualitative performances of models were ascertained by estimating the values of absolute prediction error (APE), integral square error (ISE) and the coefficient of efficiency (CE). In the present study the permissible limits for APE, ISE and CE were taken respectively as 30%, 10% and 60%, that is the prediction should satisfy the criteria of the APE less than 30%, ISE less than 10% and CE more than 60%.

The runoff prediction models developed on daily and weekly basis for the study area can be summarized as,

Two types of memory based runoff prediction models viz., linear and non-linear were developed by using the daily data series of three consecutive years from 1994 to 1996 of active period (June to September) only. Both the models consider the present rainfall, antecedent precipitation index (API), antecedent runoff index (AQI) as input. The values of coefficient of multiple determination (R^2) for the linear and non-linear models were found equal to 0.67 and 0.86 respectively, on the basis of R^2 value and prediction performance, the non-linear memory based model was found considered

more appropriate than the linear model for the study area. Memory based linear and non-linear weekly runoff prediction models were developed by using only active weeks' (23rd-39th meteorological weeks) data series of three years, ranging from 1994-1996. The coefficients of multiple determination (R^2) values were found equal to 0.86 and 0.96 respectively. The values of APE, ISE and CE for different year used for verification under study, reveals that the weekly non-linear runoff prediction model is better than the linear model.

The following are the salient conclusions obtained from the present study,

1. The fluvial system of Shakkar river watershed exhibits a strong memory on both the sequential and integrated time scale basis, and only past three successive events were found to influence the present event.

2. The first event, immediately preceding the current event was found to have more impact on it, in comparison to other preceding event, and the weights determined for the three successive antecedent events affecting the current event were 44.84%, 32.13% and 23.03% respectively.

3. The non-linear memory based daily runoff prediction model was found more appropriate than the linear model for the Shakkar river watershed of Narmada basin on the basis of coefficient of multiple determinations (R^2) and prediction performance.

4. The memory based weekly rainfall-runoff non-linear model was found more appropriate than the weekly linear model for prediction of daily runoff volume for the study area, the inclusion of variable NORW (number of rainy days in a week) was not found to show any significant impact on the value of coefficient of multiple determination (R^2) and thereby on the performance of the model.