Runoff Modeling for a Watershed in Pothowar Region of Pakistan

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ABSTRACT

Floods are among the most devastating natural hazards in the world. Pakistan has big rivers and flood planning and management is mainly concentrated on riverine floods occurring during monsoon. However, flash floods in hilly and Pothowar (semi-hilly) area are also common with demonstrated damage potential. This study was taken up to thoroughly investigate flood mechanism and inundation behavior in a watershed in Pothowar region by use of computer modeling with the Lai Stream as a case study. The Lai Stream Basin with an area of 235 km^2 is located in northern part of Pakistan. Lai is the main stream passing through Rawalpindi city with a flood damaging history of almost once in every three years. 2001-Flood has been the largest among recorded events claiming 74 human lives, affecting 400,000 people and inflicting a capital loss of USD 0.25 billion. Thorough data analysis was performed to select most suitable data for computer modeling. The whole basin was divided in to fifteen (15) sub-basins and their respective yields were generated and subsequently incorporated in to river network of Lai Stream. Calibration was achieved successfully along the river profile with 2001 flood as target followed by the estimation of standard flood discharge for Lai stream. Thereupon useful recommendations have been made to utilize the model for mitigating flash flood events in urban/inhabited Pothowar (semi-hilly) region of Pakistan in particular and world over in general.

Key Words: **Flood, Modeling, Pothowar, Runoff, Watershed.**

1. INTRODUCTION

Floods are one of the most dramatic interactions between man and his environment, emphasizing both the sheer force of natural events and man's inadequate efforts to control them [1]. Flood is defined as any high stream flow which overtops natural and artificial banks of a stream [2]. Floods are among the most devastating natural hazards in the world, claiming more lives and causing more property damage than any other natural phenomena [3]. Flooding is one of the major natural disasters that affect many parts of the world including developed nations. Besides losing billions of dollars in infrastructure and property damages, hundreds (sometimes thousands) of human lives are lost each year due to flooding [4]. With the increasing impacts of climate change and the more recent flood events throughout the world, there is a need to establish more useful flood risk management plans and strategies [5]. The science and technology of flood disaster mitigation addresses policy, planning, design, and operational aspects. Good policy and planning can reduce the exposure to flooding through control of land management and housing development whilst well-designed flood defence schemes will alleviate

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the impact of flooding. However, complete protection from flooding is rarely a viable goal [6]. Flooding can be partially avoided by adequate mitigation techniques, however, flood hazards can never be ruled out. Future flood prevention and reaction measures will require a stronger stress on integrated approaches incorporating flood forecasting and risk uncertainties [7].

The damage by flash floods is a universal episode. Flash floods can happen everywhere, independently of altitude, longitude or latitude, when large volumes of rainfalls happen within a short period of time in the same area [8]. Urban areas, where much of the land surface is covered by impervious material, are characterized by reduced infiltration and accelerated runoff which causes flooding unrelated to a flood-plain. Historically, riverine flooding and flash flooding along flood-plains have received considerable attention, whereas flooding in the urban setting has not [9].

Pakistan has big rivers and floods are mainly caused by heavy south-westerly monsoon showers and rapid snow melting in the Northern Alpines. However, flash floods occurring in natural streams (called Nullahs/Kas) as a result of localized intense rains in hilly and pothowar (semi-hilly) areas are also very common. Such flash floods have remarkably demonstrated their damage potential in the last few years. Also with the development in urban areas the frequency of urban flood damage is increasing. Flooding problem in Lai Stream, originating from Margalla foot hills in Islamabad area and passes through the center of Rawalpindi City, has been under discussion for the last 60 years. Floods in the Lai Stream Basin occur during the monsoon season (July-September). On average there are flood damages almost once every three years in the Rawalpindi. Extreme flood years were 1981, 1988, 1997 and 2001. Flood of 2001 has been the largest among the recorded events so far and considered as a national disaster. on 23rd July, 2001, the rainfall depth was recorded at 620 mm in 10 hours from 0600-1600 hours and tragically, 74 human lives were lost while 3,000 houses were completely or partially damaged [10]. Estimates indicate that almost 400,000 people were affected by 2001 flood alongwith a loss of more than USD 0.25 billion to infrastructure, government and private property [11].

A representation of the real world into a simple form can be considered a model. There are two types of models, namely static models and dynamic models [12]. Static models generally represent a single state of affairs while dynamic models put emphasis on changes that have taken place, are taking place, or may take place. Models can also be defined according to their form, namely scale, conceptual, and mathematical model. Scale models are representation of real world physical phenomena. Conceptual models use a quasi-natural language or flowchart to outline the components of the system under investigation and highlight the linkage between them. Mathematical models operationalize the conceptual models with mathematical formulations [13]. Computer model is the sophisticated form of mathematical model. Recent years have seen an explosion in the development and use of spatially distribute models in hydrology. For the particular case of flash flood forecasting their merits are obvious [14].

Engineering studies in river hydraulics make extensive use of numerical modeling for various purposes, from environmental applications to flood applications, like flood risk assessment or flood forecasting [15]. Worldwide, many cities are facing the issue of developing methods to address coexisting water shortages and flood-inundation, especially cites in semi-arid regions and semi-humid continent monsoon climate zones. Rainfall-runoff prediction and real-time water resources assessment is essential for addressing such situations [16]. Nowadays computer-modeling techniques have ably assisted scientists and engineers with determining floods as well as flood assessments. Computer models for the determination of flooding effects generally require four parts [17] the hydrological model which develops rainfall-runoff relationship from a design storm or historic storm event, (2) the hydraulic model which routes the runoff through stream channels to determine water surface profiles at specific locations along the stream network, (3) a tool for floodplain mapping and visualization, and (4) the extraction of geospatial data for use in the model(s). However, point measurements of stage or discharge are more compatible with 1D models [18].

This investigation is intended to provide useful technical information for flood management planners to help in the selection and design of flood mitigation measures as well as in the involvement of flood risk management strategies to avoid flood damages by flash floods in general and by Lai Stream flood in particular.

2. PHYSICAL CONDITIONS OF THE STUDY AREA

2.1 Topography

Having a catchment area of 234.8 km^2 Lai Stream Basin is located between 33°33' and 33°46' North and 72°55' and 73°07' East. The upper part of 161.3 km^2 (69%) falls in Islamabad Capital Territory, and the rest area of 73.6 km^2 in Rawalpindi City and its suburbs.

In view of topography, the Lai Stream Basin might be broadly divided into four areas. They are the Margalla range, the higher plain, the lower plain and the valley area in the north to south direction. The longitudinal river profile is shown in Fig. 1.

2.2 Climate

The Study Area might be classified as "Subtropical Triple Season Moderate Climate Zone", which is characterized by single rainfall season from July-September and its moderating influence on temperature. The rainfall-temperature pattern of the area based on the record of last 60 years, obtained from PMD (Pakistan Meteorological Department), is shown in Fig. 2.

Although rains occur in all seasons but the monsoon rain is pronounced and constitutes a definite rain season between July and September. The total rainfall during the rain season is about 600mm, accounting for 60% of the annual rainfall of about 1,000mm. These monsoons bring heavy downpours in the Lai Stream Basin, resulting in

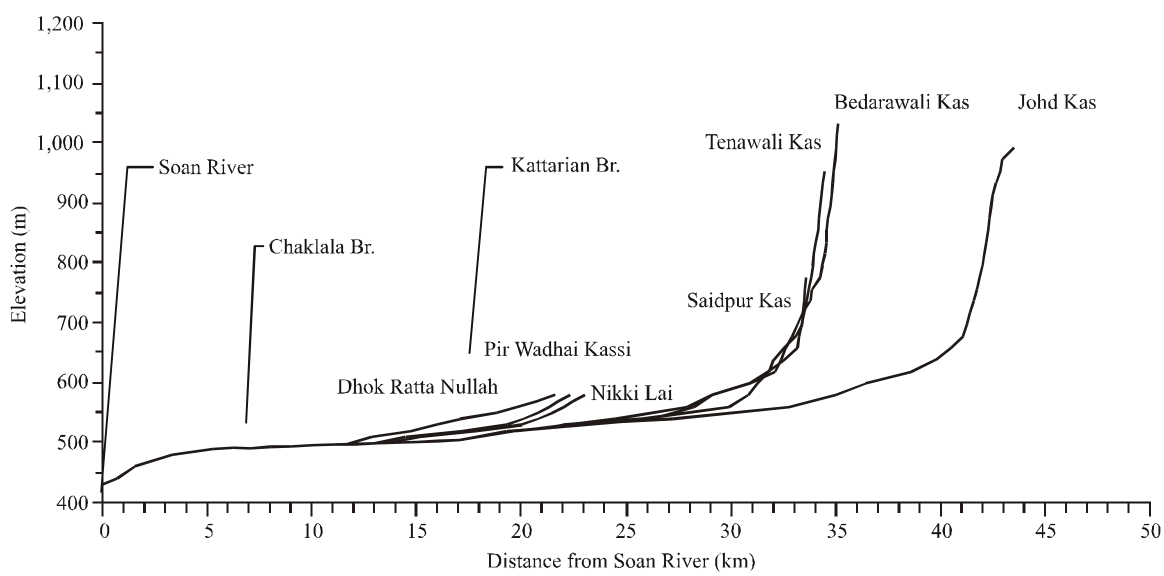

FIG. 1. LONGITUDINAL RIVER PROFILE OF LAI STREAM BASIN

flooding of Lai Stream and the tributaries. According to several study reports, flood damage broke out almost once in every three years.

3. RAINFALL ANALYSIS

3.1 Rainfall Observation and Data Availability

The four (4) rain gauge stations line up along the eastern boundary of the Lai Stream Basin with an order of Saidpur, Islamabad, RAMC, and then Chaklala in the north to south direction. The Chaklala and Islamabad Stations have comparatively long operation period of more than 35 years, but the Saidpur and RAMC Stations are so new that they started measurement only 13 and 19 years back respectively. Locations and main features of the existing four rain gauge stations are presented in Fig. 3 and Table 1 respectively.

Efforts were made to collect short-time rainfall data such as hourly and 3-hourly data recorded during selected heavy rainstorms as well as all available daily rainfall data, visiting PMD Headquarters in Islamabad, Regional Meteorological Center in Lahore and the four stations. Unfortunately the data availability does not correspond to the operation periods of the stations and considerable parts of precious old data were missing or were already lost.

The Chaklala Station is the richest in rainfall data with daily data of 63 years, 3-hourly data of 38 years, and hourly data of 26 years, followed by the Islamabad Station for which daily and 3-hourly data are available since 1983. The RAMC Station has daily rainfall data and self-recorder charts of 18 years since 1989. The new Saidpur Station is the poorest with daily data of 12 years.

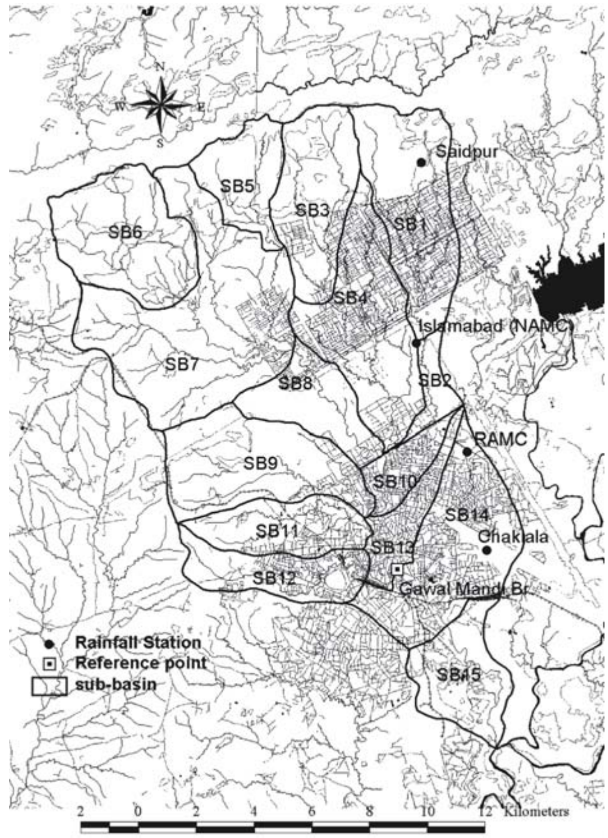

FIG. 3. SUB-BASIN DIVISION AND LOCATION OF RAIN GAUGE STATIONS FOR LAI STREAM BASIN

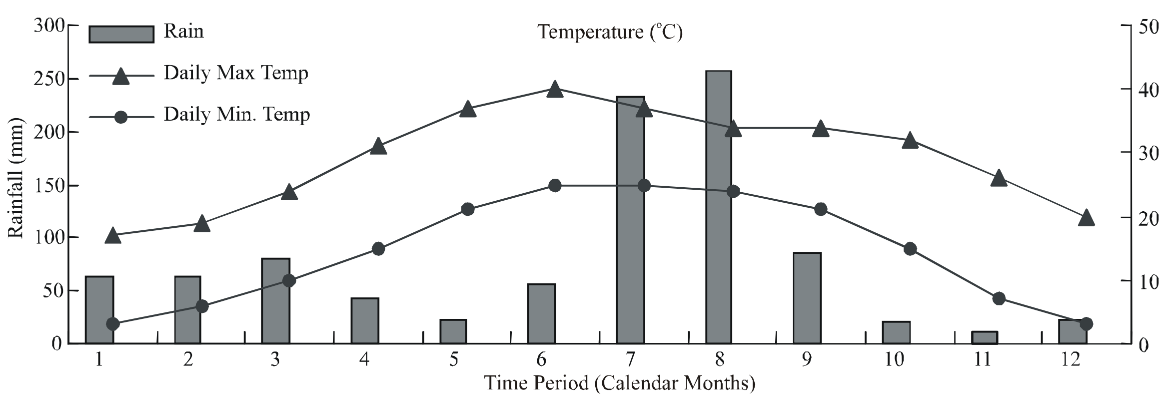

FIG. 2. RAINFALL AND TEMPERATURE PATTERN OF THE AREA

The short-time rainfall data was initially focussed, especially hourly data during heavy rainstorms that are indispensable for analyses of flash floods like the 23rd July, 2001 flood,. However, the data availability was too low, mostly due to instrument troubles caused by such rainfall intensities. Hourly data were available only for a few rainstorms among the selected 53 storms since 1970. Due to inadequacy of the hourly rainfall data, the rainfall analyses was alternatively based on the 3-hourly rainfall data as described hereinafter.

3.2 Rainfall Characteristics

Using the collected rainfall data, rainfall analyses was made to know general characteristics of the rainfall in the Study Area in terms of duration and distribution in space and time.

3.2.1 Duration

To judge the general duration of rainfall, significant past rainfall events were studied based on the records of Islamabad and Chaklala rain gauge stations. It was concluded from the records that the rain duration was generally short. Almost all the rainstorms ended within 12 hours.

3.2.2 Spatial Distribution

The investigation of spatial distribution of storm rainfall in the Study Area was based on the rainfall records of the recent floods on 29th July, 1996, 27th August, 1997 and 23rd July, 2001. It is obvious that the three floods show different rainfall distribution patterns. The 1997 flood rainfall was fairly uniform along the eastern basin boundary. The 1996 flood rainfall was biased towards the south. In the 2001 flood, the rainfall of 620.7mm at Islamabad Station overwhelmed those at the other three stations located within a radius of only 8 Km. The differences were as big as 300-450mm.

For analysis of flash flood rainfall data with shortest duration of measurement is ideally desired. However, due to inadequate availability of hourly rainfall data, the analysis was based on 3-hourly rainfall data only. Accordingly, the 3-hourly rainfall data of the Islamabad Station was plotted against that of the Chaklala Station to examine correlation between the two stations as shown in Fig. 4. The plotting scatter of Fig. 5 revealed that no correlation exists between the two most rich rainfall data stations in the Lai watershed. Thus plotting for correlation for other durations and other stations was not focused. From the above analyses, it might be concluded that the localization of rainfall is quite significant and the spatial distribution pattern is different from flood to flood.

3.2.3 Temporal Distribution

The hyetographs were also drawn for the recent three floods as shown in Fig. 4 to know rainfall distribution in time. The hydrographs were based on the collected 3-hourly data except at the Chaklala Station for the 1997 flood and at the Islamabad Station for the 2001 flood for which hourly data are by chance available. The same scales of graph axes were commonly employed for the three floods to facilitate comparison of the rainfall intensities.

TABLE 1. EXISTING RAINFALL STATIONS IN LAI STREAM BASIN

Station	Location			Year of Establishment	Frequency of Measurement
	Latitude (North)	Longitude (East)	Altitude (m)		
Chaklala	33°37'	73°06'	500	1931	Every 3 hours
Islamabad	33°41'	73°04'	520	1967	Every 3 hours
RAMC	33°39'	73°05'	500	1989	Three times a day
Saidpur	33°45'	73°04'	660	1994	Once a day

Surprisingly intensive rainfall is found at the Islamabad Station in 2001 flood. Intensive rainfall over 130 mm/hr continued 3 hours between 1000 and 1300 hours on 23rd July, 2001. The hourly rainfall intensity of 180mm between 1200 and 1300 hours is the recorded maximum in Pakistan according to PMD. Intensity of 90mm/hr was also recorded between 1300 and 1400 hours at the RAMC Station during the same period. As for the other floods, the rainfall intensity was quite lower than the exceptional 2001 flood, while the intensive 3-hourly rainfall of more than 25mm/hr (corresponding to 105mm in three hours) was also observed in the 1996 flood at the Chaklala Station and in the 1997 flood at the Chaklala and RAMC Stations.

3.3 Frequency Analysis of Rainfall

As the spatial distribution pattern of rainfall in watershed varies from flood to flood, therefore, in order to correctly evaluate such rainfall in relation to flood discharges in Lai Stream, basin mean rainfalls are more important than point rainfalls observed at each station. In this sense basin mean rainfalls were estimated based on the collected rainfall data, and then a frequency analysis was made to estimate probable basin mean rainfalls for several return periods, as:

3.3.1 Reference Point

To begin with, Gawal Mandi that is located in the middle of the habitual flood inundation area between Gunj Mandi and Railways Bridges was defined as a reference point for the estimation of the basin mean rainfalls. In other words,

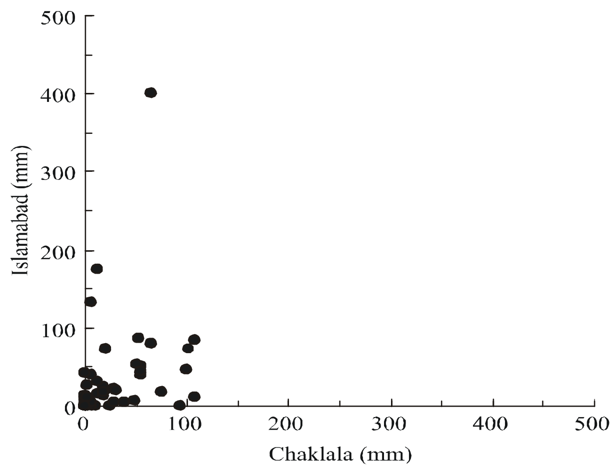

FIG. 5. CORRELATION OF 3-HOURLY RAINFALLS

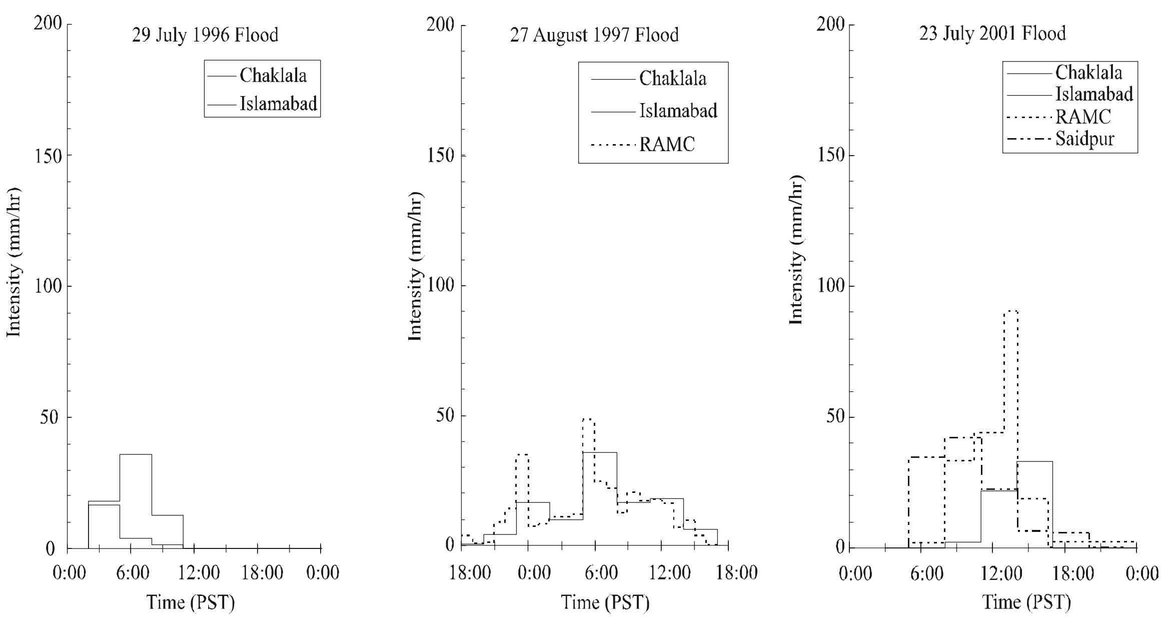

FIG. 4. HYDROGRAPH DURING RECENT THREE FLOODS

the basin mean rainfalls were estimated not for the whole river basin of 234.8 km^2 but for the catchment area of 199.2 km^2 (85% of the whole basin catchment area) upstream of the bridge, taking it into consideration that flood discharges in the habitual flood inundation area are mostly generated by rainfalls falling in the 199.2 km^2 area. Gawal Mandi Bridge is very meaningful for the conventional flood warning system of TMA (Tehsil Municipal Administration) too. The water level at this bridge is an indicator for the flood warning issuance. Once the water level rises over the 18 feet level, sirens are to be blown at several warning posts in Rawalpindi.

3.3.2 Basin Mean Rainfall

The estimation of basin mean rainfall was made by applying Thiessen Polygon Method. Divisions from the Lai Stream Basin by the Thiessen polygon lines according to the rainfall data availability, and the Thiessen coefficients are summarized in Table 2.

The collected 3-hourly data observed at the stations was used to calculate 3-hourly basin mean rainfall data in order to create a basin mean rainfall database for the selected heavy rainstorms of 38 years from 1970-2007.

3.3.3 Probable Rainfalls

For the estimation of probable basin mean rainfalls, the annual maximum basin mean rainfalls of four (4) different durations (3,6,9, 12-hourly rainfalls) were extracted from the basin mean rainfall database Different probability distribution curves including the Gumbel, Long-normal, Pearson Type 3 and Log-Pearson Type 3 were tried. From the results, it was evaluated that the Log-Pearson Type 3 gives good fitting to all the four extreme rainfalls and selected as the optimum distribution and data plotted for four durations as shown in Fig. 6.

The probable basin mean rainfalls were thus estimated through the Log-Pearson Type 3 and are summarized in Table 3, which also shows the actual basin mean rainfalls of the 2001 flood, the probable basin mean daily rainfalls were additionally estimated so as to facilitate the comparison with the obtained probable rainfalls. Design hyetographs with different return periods are created from these probable 3,6,9 and 12-hourly rainfalls.

The evaluation of the exceptional flood on 23rd July, 2001 in terms of return period of rainfall. shows that the 3,6,9 and 12-hourly rainfalls of the 2001 flood are all slightly smaller than those of the 100-year return period, and the flood could be evaluated at 75-90 years of return period.

4. RUNOFF MODELING IN LAI STREAM BASIN

4.1 Description of Model Set Up

Flood simulation has been made in two steps, namely calculation of runoff from the sub-basins and flood routing along the rivers. Mike11 software that is an integrated software developed by DHI (Denish Hydraulic Institute) Water & Environment for river management was used for all the above procedures, selecting appropriate methods for each procedure among a variety of optional methods provided in the software.

TABLE 2. THIESSEN COEFFICIENTS

Station	Number of Stations of which Rainfall Data are Available			
	4 Stations	3 Stations	2 Stations	1 Station
Saidpur	0.30	N/A	N/A	N/A
Islamabad	0.47	0.77	0.85	N/A
RAMC	0.12	0.13	N/A	N/A
Chaklala	0.11	0.10	0.15	1.00

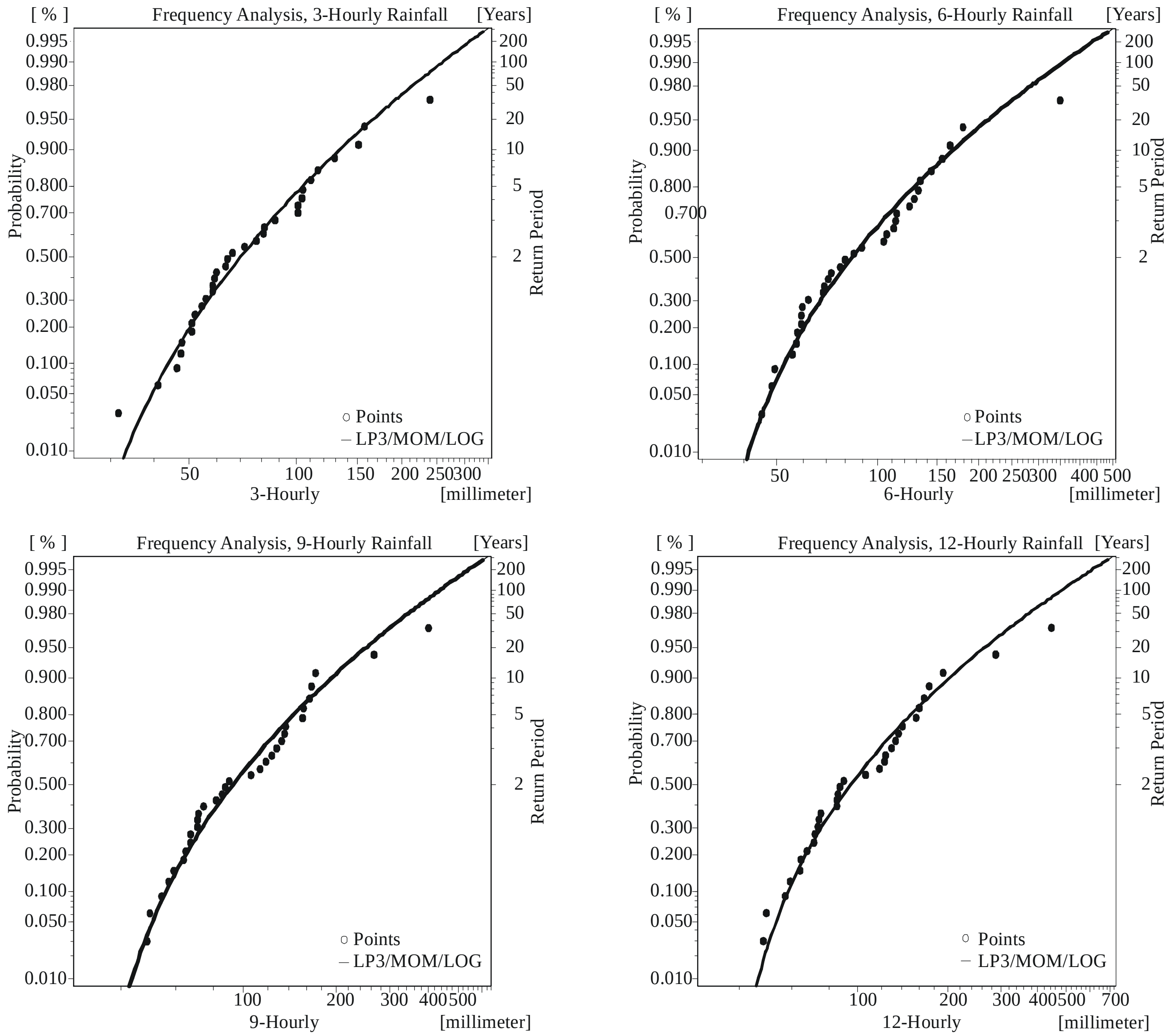

FIG. 6. PROBABILITY PLOTTING OF RAINFALL FOR DIFFERENT DURATIONS

TABLE 3. PROBABLE RAINFALLS (mm)

Rainfall	Data Period	Return Period (years)						2001 Flood
		5	10	25	50	100	200	
3-Hourly	38 Years (1970-2007)	105	134	177	216	260	311	239
6-Hourly	38 Years (1970-2007)	128	167	230	287	355	437	349
9-Hourly	38 Years (1970-2007)	146	194	272	346	435	542	401
12-Hourly	38 Years (1970-2007)	151	203	291	376	481	611	444
Daily	38 Years (1970-2007)	152	196	263	324	395	478	411

SCS (Soil Conservation Service) curve number method has been effectively used for runoff assessment in the past studies on Lai flooding. This method has been developed by USA Soil Conservation Service in 1972. This method incorporates all the important parameters influencing runoff generation from a watershed such as soil, land use and antecedent moisture conditions etc. Therefore ,in this study, the runoff discharges from 15 sub-basins were estimated by Unit hydrograph method based on the SCS curve number. The estimated runoff discharges were further used as inflow data to the river network for the flood routing as shown in Fig. 7.

The main Lai Stream, and its four major tributaries, Saidpur Kas, Tenawali Kas, Bedarawali Kas and Johd Kas were considered to build the river network for the flood routing. A dynamic one-dimensional flow model of Mike11 that can stimulate hydraulic phenomena more precisely was applied to estimate discharges and water levels in the river network.

4.2 Runoff Calculation by SCS Unit-Hydrograph Method

This method is developed by the USA SCS for computing abstraction from storm rainfall, introducing a concept of

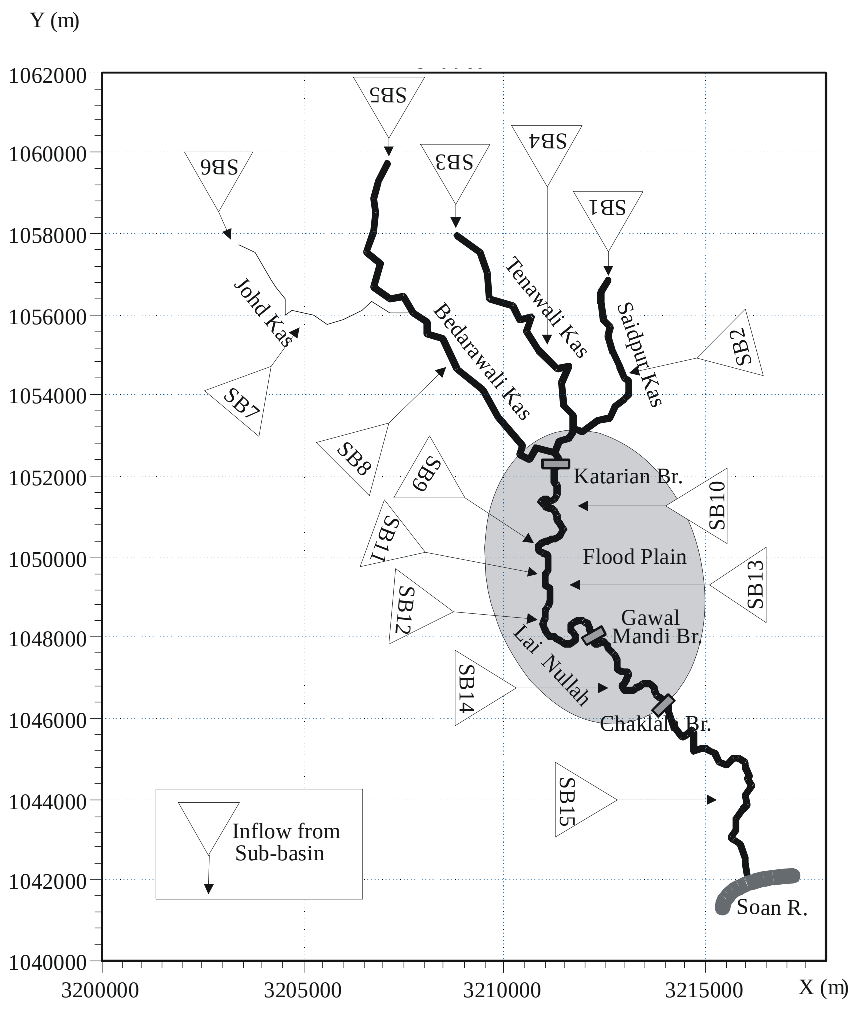

FIG. 7. RIVER NETWORK OF LAI STREAM BASIN

the CN (Curve Number). The CN represents various runoff influencing parameters. Using the CN, the depth of excess precipitation is calculated. The excess precipitation is converted into runoff discharge by the SCS triangular unit-hydrograph. The lag time is calculated from the catchment characteristics using the standard SCS formula [19].

4.3 Dynamic One-Dimensional Flow Calculation

The core of Mike11 is the dynamic one-dimensional flow calculation module that is based on the 'Saint Venant' equations. The equations of continuity and momentum are [20]:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \qquad (1)$$

$$\frac{\partial Q}{\partial t} + \partial \frac{\alpha Q^2 / A}{\partial x} + \frac{gA\partial h}{\partial x} + \frac{gQ|Q|}{C^2} AR = 0 \qquad (2)$$

Where q is discharge per unit width, Q is discharge, A is flow area, Q is lateral inflow, h is water level, C is Chezy resistance coefficient ($C=R^{1/6}/n$), n is Manning roughness coefficient, R is hydraulic radius, and α is momentum distribution coefficient.

The flood routing is made along the river network consisting of the five rivers as detailed in Table 4. Pre-defined water levels at the confluence with Soan River and the estimated runoff discharge from the sub-basin at each of the four upstream ends are given as the boundary data of the river network for flood routing.

TABLE 4. RIVERS IN THE NETWORK

River	Stretch	Length (Km)
Lai Stream	Kattarian Branch to Soan River	17.5
Saidpur Kas	Zero Point to Tenawali Kas	5.8
Tenawali Kas	Jinnah Avenue to Bedarawali Kas	8.7
Bedarawali Kas	E-9 to Lai Nullah	12.7
Johd Kas	Golra Village to Bedarawali Kas	7.3

4.4 Model Calibration

The flood on 23rd July, 2001 that could provide the richest hydrological data, was selected as the target flood for the model verification, and reproduced to clarify the flood mechanism.

The river cross-sectional data was availed from the results of survey by the ADB (Asian Development Bank) Project and the JICA (Japan International Cooperation Agency) Study. The survey by the ADB Project, which was carried out immediately after the 2001 flood covers the stretch between Kattarian and Chaklala Bridge on Lai Stream. In JICA Study, the supplementary cross-sectional surveys were conducted between October and November 2002 for lower Lai Stream downstream of Chaklala Bridge, its several tributaries and Soan and Kurang Rivers.

To express the retarding effects by flood inundation, additional off-stream storage areas, of which area-elevation data were extracted from the generated DEM, were connected to the Lai Stream cross sections between Kattarian Bridge and Chaklala Bridge, where inundation was so extensive in the 2001 flood.

The rainfall data observed at the four stations were applied for the runoff calculation of the 15 sub-basins. The basin mean rainfalls were firstly estimated for each of the sub-basins based on the Thiessen polygons, and the basin mean rainfalls were input to the SCS unit-hydrograph method.

The trial runs of runoff calculation were made until acceptable accuracy was attained, changing and adjusting model parameters including the SCS CNs and the Manning's roughness coefficients of the rivers. The SCS CN by land use was finally determined as given in Table 5. The roughness coefficients of all the rivers were determined at 0.035 for the low water channels and at 0.050 for the high water channels.

Fig. 8 presents the discharge and water level hydrographs at Kattarian, Gawal Mandi and Chaklala Bridges. As shown in Fig. 8, the temporal variation of the water level and discharge in hydrographs is gradual, which could be attributed to the flood retarding effects of the river basin. The peak water level appears around 1400 hours at Kattarian Bridge and around 1800 hours at Gawal Mandi and Chaklala Bridges. The duration of flood inundation around Gawal Mandi Bridge is estimated at about 10 hours judging from the temporal variation of water level in the hydrograph. These timings and the inundation duration agree with the memories of inhabitants and officials concerned.

TABLE 5. SCS CURVE NUMBER BY LAND USE

Land Use	Curve Number CN*
Agricultural Area	70
Residential Area (Densely Populated)	90
Residential Area (Moderately Populated)	75
Residential Area in the Suburbs	70
Forest (Mountain Area)	70
Forest (Flat Area)	65
Green and Grass Area	65
Water Body	100
*Under Normal Antecedent Moisture Condition (AMC II) [19]	

Fig. 9 compares the estimated maximum water levels along Lai Stream with the elevations of flood marks left at several bridges. It can be said that the estimated water levels match the flood marks very well.

It is evident from the above results that the reproduction of the 2001 flood is satisfactory enough and the established model is considered acceptable and applicable for estimation of the standard flood discharge.

4.5 Flood Simulation for Future Scenarios

Using the established simulation model, the standard flood discharge was estimated as described hereinafter:

4.5.1 Simulation Conditions

4.5.1.1 Rainfall

100, 50, 25, 10 and 5-year design hyetographs with 12 hours of duration were created as shown in Fig. 10 for the future scenario flood simulation, based on the frequency analysis of 3, 6, 9 and 12-hourly rainfalls.

4.5.1.2 Land Use

The 2012 land use condition was applied for this calculation. The SCS CNs of the sub-basins were modified accordingly.

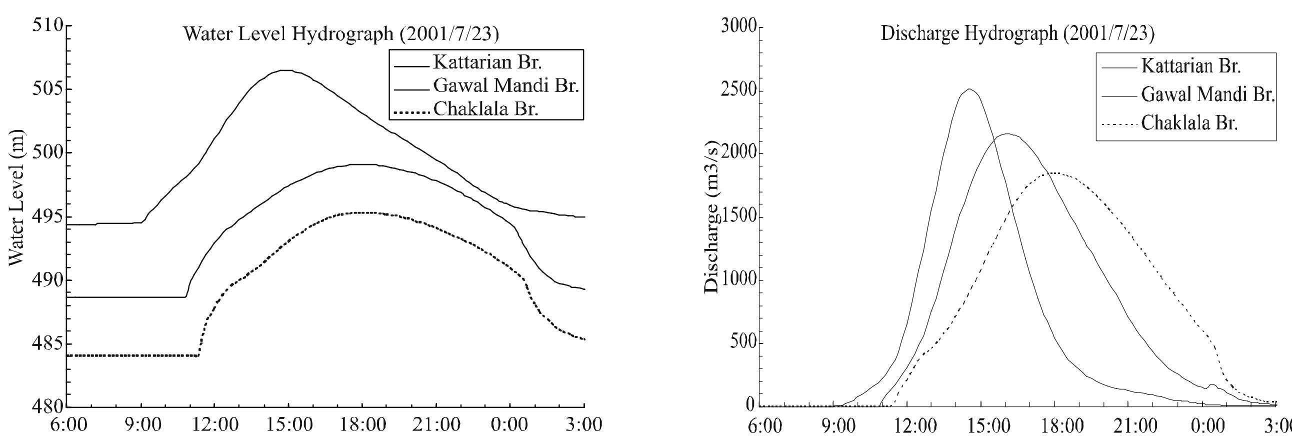

FIG. 8. REPRODUCED WATER LEVEL AND DISCHARGE HYDROGRAPHS DURING 2001 FLOOD

4.5.1.3 Consideration of ADB River Improvement Project

The Lai Stream improvement project was completed in early 2003 by ADB and Lai Stream was widened by 20-30m. The completion of this river improvement was premised for the flood simulation, and the existing cross sections of Lai Stream that were used for the reproduction of the 2001 flood were replaced by the cross sections designed for the ADB project with roughness coefficient designed as 0.030.

4.5.1.4 Confinement of Flood Discharges in Rivers

The additional off-stream storage areas connected to the cross sections of the simulation model for the 2001 flood were removed to confine all the flood water in the rivers

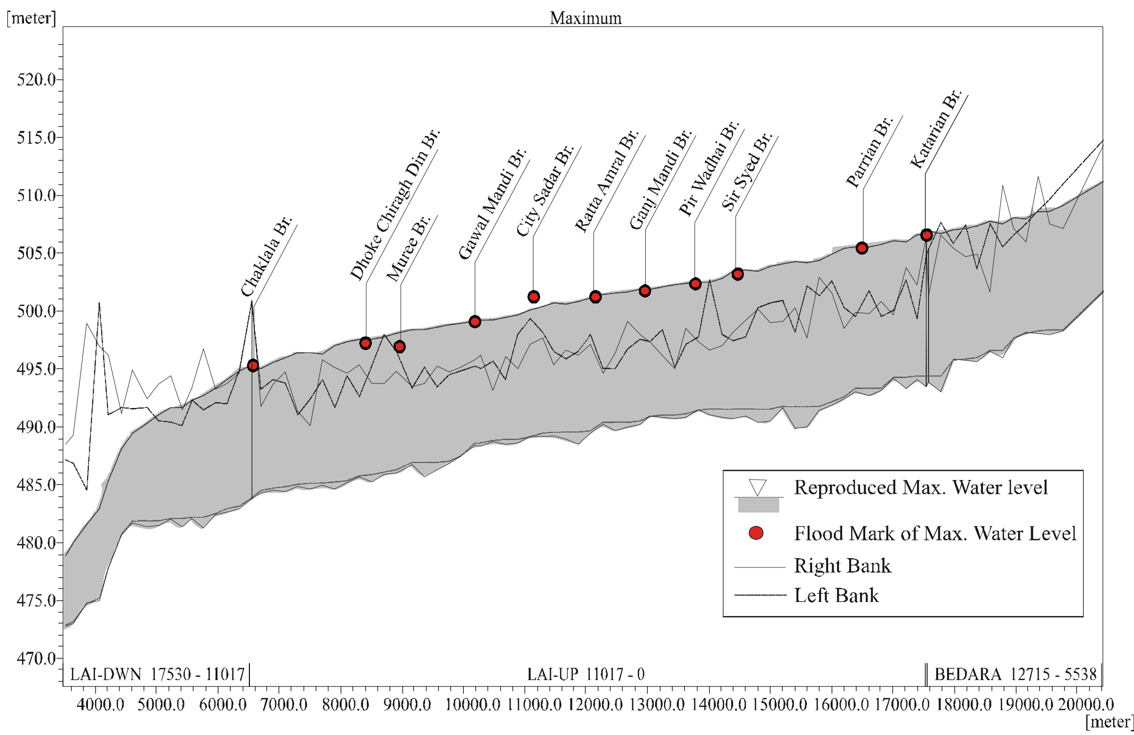

FIG. 9. COMPARISON OF REPRODUCED AND OBSERVED MAXIMUM WATER LEVELS DURING 2001 FLOOD

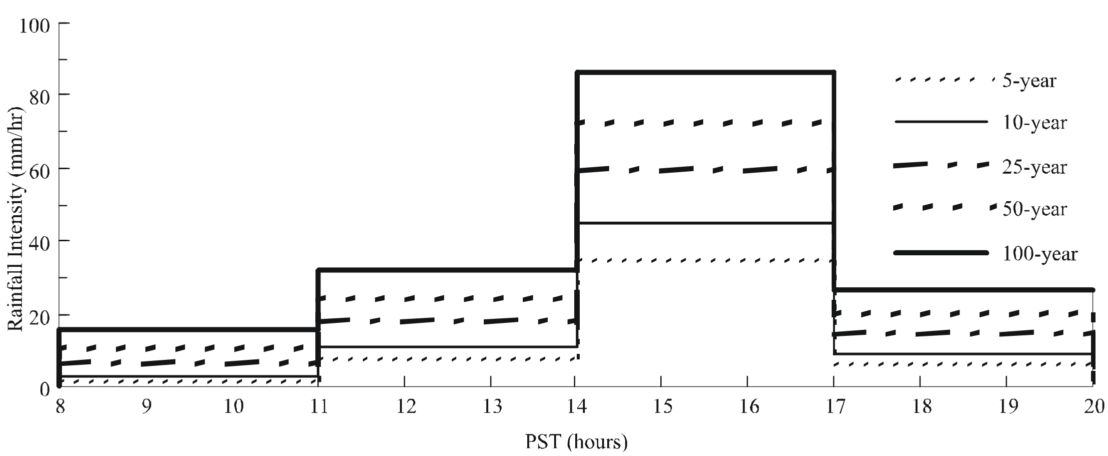

FIG. 10. DESIGN HYETOGRAPHS

not allowing any spillage because this future scenario simulation is aimed to estimate river discharges under no flood inundation.

4.5.2 Simulation Results of the Standard Flood Discharge

The aforesaid standard flood discharges were estimated through a model slightly modified from the simulation model for the 2001 flood. The standard flood discharges thus estimated at the principal reference point, namely Gawal Mandi Bridge are compared with the probable discharges estimated from the observed water level as shown in Table 6.

By statistical analysis, goodness of fit was checked on both the simulated as well as observed discharge data sets for the five different return periods. For model simulated values R-Square is 0.9869 and for those observed from water levels R-Square is 0.9833. Therefore, it is confirmed that the trend of two data sets is similar. In order to further explore the correlation, the correlation coefficient which is a normalized measure of the strength of the linear relationship between two variables was worked out for the above data. The correlation coefficient comes out to be 1 which clearly indicates that there is a strong linear correlation between the two values; one observed and the other simulated for the five return periods. Therefore, it could be concluded that the values simulated as the standard flood discharge well accord with the values estimated from the observed water levels. However, the simulated values obtained from model run are slightly lower than those obtained from observed water levels using the H-Q rating curve at Gawal Mandi Bridge. After ADB improvement project, completed in early 2003, there has been no de-silting activity so far and bed of Lai stream has been continuously rising mainly due to garbage dumping. Therefore, the high values observed by water levels may be attributed to silting up of the river bed.

5. CONCLUSIONS

(i) The existing hydrological gauging data including the rainfall and water level data in Lai Stream Basin is quite inadequate and less orderly prepared, which is a great hindrance for formulation of the flood mitigation plan in the area.

(ii) The data availability of short time rainfall, especially hourly data during heavy rainstorms which is indispensable for analysis of flash floods like the 23rd July, 2001 flood, is too low, mostly due to instrument troubles caused by such rainfall intensities. Due to inadequacy of the hourly rainfall data, the rainfall analysis is alternatively based on the 3-hourly rainfall data in this study.

(iii) It might be concluded that the localization of rainfall is quite significant and the spatial distribution pattern is different from flood to

TABLE 6. STANDARD FLOOD DISCHARGE BY RETURN PERIOD

Reference Point	Description	5 Years (m^3/s)	10 Years (m^3/s)	25 Years (m^3/s)	50 Years (m^3/s)	100 Years (m^3/s)
Gawal Mandi Branch	Simulated as Standard Flood Discharge	390	720	1,340	1,940	2,640
	Estimated from Observed Water Levels	490	840	1,500	2,200	3,000

flood. Therefore, basin mean rainfall is more important than the point rainfalls for runoff assessments.

(iv) It might be concluded from the records of significant past rainfall events that the rain duration was generally short. Almost all the rainstorms ended within 12 hours.

(v) It has been observed that Kattarian Bridge falls at a crucial location in the catchment because this is the point at which all the tributaries join up to form the main Lai Stream and also it is the point from where the flood plain consisting of low lying urban areas of Rawalpindi starts and also another crucial point in the center of severely affected urban area is Gawal Mandi Bridge.

(vi) Gawal Mandi Bridge which is located in the middle of the habitual flood inundation area was defined as a reference point for the estimation of the basin mean rainfalls. Accordingly, the basin mean rainfalls were estimated not for the whole stream basin of 234.8 km^2 but only for the catchment area of 199.2 km^2 (85% of the whole basin catchment area) upstream of the bridge, taking into consideration that flood discharges in the habitual flood inundation area are mostly generated by rainfalls falling in the 199.2 km^2 area.

(vii) It is evident from the model results that the reproduction of the 2001 flood is satisfactory enough and the established model is considered acceptable and applicable for estimation of the standard flood discharge.

(viii) It is important to evaluate the exceptional flood on 23rd July, 2001 in terms of return period of rainfall. The 3,6,9 and 12-hourly rainfalls of the 2001 flood are all slightly smaller than those of the 100-year return period and the flood could be evaluated at 75-90 years of return period.

6. RECOMMENDATIONS

It is recommended that:

(i) More rainfall gauging stations in western part of the catchment be established and at the same time proper attention should be given to orderly arrange the gauged data.

(ii) A water level gauging station preferably with automatic recorder be installed at Kattarian Bridge. Also a similar state of the art water level gauging station be installed at Gawal Mandi Bridge to replace the present manual and occasional recording by TMA Rawalpindi.

(iii) An efficient Flood Forecasting & Warning System be established in the area to safeguard the public life and property in the event of flood in the Lai Stream.

(iv) An elaborate flood warning code be set, taking due advantage from this runoff model, so that alert and evacuation warnings are issued well advance of the high flood occurrence in urban areas of Rawalpindi.

(v) Based on the results of runoff modeling the preparation of flood hazard map be taken up for the central urban part of Rawalpindi city for planning flood risk reduction measures.

(vi) Runoff modeling of various streams be taken up to avert flood damages due to flash floods in other parts of Pakistan especially in Mardan District of NWFP, and Dera Ghazi Khan District of Punjab.

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