Arab J Sci Eng (2012) 37:945–954
DOI 10.1007/s13369-012-0227-0

RESEARCH ARTICLE - CIVIL ENGINEERING

Habib-ur-Rehman · Usman Ali Naeem · Hashim Nisar · Naeem Ejaz

Development of Empirical Equations for the Peak Flood of the Chenab River Using GIS

Received: 12 February 2010 / Accepted: 7 October 2010 / Published online: 18 April 2012

Abstract Estimation of flooding is indispensable for the design of hydraulic structures such as dams, especially when there are many potential small dam sites available, but no flow data is being measured at these sites. If stream gauging stations are present upstream and downstream of the proposed dam site, empirical relationships can be developed for the site. The equation development process becomes more difficult when lateral flow releases are considered at various locations in a river reach. This issue is addressed in the present study, in which empirical equations are developed for flood prediction in the upper reaches of the Chenab River, between Marala Headworks and Qadirabad Headworks. The purpose is to predict flood magnitudes within selected reaches of the Chenab River. The selected gauging stations are Marala Headworks, Alexandra Bridge, Khanki Headworks and Qadirabad Headworks. To develop the equations, a multiple nonlinear regression analysis is used. Average river and watershed slopes for four watersheds are extracted from a digital elevation model, using geographic information systems software. The developed peak flood equations for the region are tested with observed flood data, and results show that these equations estimate peak floods within an acceptable range of accuracy. The developed empirical equations are region-specific, so their application to other areas requires discretion. However, these equations can be used to approximate floods in other regions with similar climatic and physiographic characteristics.

Keywords Flood estimation formula · Chenab River · GIS · Average watershed slope · Multiple nonlinear correlations

الخلاصة

إن تقدير الفيضانات هو أمر لا غنى عنه لتصميم المنشآت المائية مثل السدود، وبخاصة عندما تكون هناك العديد من المواقع المحتملة للسدود الصغيرة موجودة، ولكن من دون قياس تدفق البيانات في هذه المواقع. وإذا كانت محطات قياس التدفق متاحة على المنبع والمصب من موقع السد المقترح، فإنه يمكن بعد ذلك تطوير علاقات تجريبية لهذه المواقع. إن عملية تنمية المعادلة تصبح أكثر صعوبة عندما يكون تدفق الإصدارات الجانبية في مواقع مختلفة متوفرا في امتدادات النهر.

تتناول هذه الدراسة مشكلة مشابهة حيث وضعت معادلات تجريبية للتنبؤ بالفيضانات في الروافد العليا لنهر تشيناب بين أشغال مارالا الرئيسية وأشغال قاديراباد الرئيسية. إن الغرض من هذه الدراسة هو التنبؤ بأحجام الفيضانات في امتدادات مجموعة مختارة من نهر تشيناب. كانت محطات القياس المختارة هي أشغال مارالا الرئيسية، وجسر الكسندرا، وأشغال خانكي الرئيسية وأشغال قاديراباد الرئيسية. لقد تم استخدام تقنية تحليل الانحدار غير الخطي المتعدد لوضع المعادلات. وتم استخراج المتوسط النهري و منحدرات نقاط التحول لأربعة مستجمعات مياه من DEM باستخدام برمجيات نظم المعلومات الجغرافية. وتم اختبار معادلات ذروة الفيضان المطورة في المنطقة مع بيانات الفيضانات المرصودة وأظهرت النتائج أن المعادلات وضعت تقديرات ذروة الفيضانات ضمن نطاق مقبول من الدقة. إن المعادلات التجريبية المطورة هي محددة للمنطقة وتطبيقها في مناطق أخرى يحتاج إلى عناية خاصة. ومع ذلك، يمكن تطبيق هذه المعادلات التقريبية للفيضانات في مناطق أخرى لها خصائص مناخية وجغرافية مماثلة.

Habib-ur-Rehman (✉)
Civil Engineering Department, UET Lahore, Lahore, Pakistan
E-mail: mughalhabib@uet.edu.pk

U. A. Naeem · H. Nisar · N. Ejaz
Civil Engineering Department, UET Taxila, Taxila, Pakistan

1 Introduction

Recently, data-based and empirical analyses have led to important advances in understanding how large-scale climate anomalies extend over large areas and significantly alter rainfall and stream flow patterns. Statistical models have been developed that directly link the hydrologic variable of interest (e.g., stream flow) with external forcing (i.e., climate predictors). These empirical models have proven successful in predicting stream flow and rainfall patterns [1]. However, these models are site-specific and require discretion when being applied to other regions.

A flood is an unusually high stage on a river, normally the level at which it overflows its banks and inundates the adjoining area. Damages caused by floods in terms of loss of life, property, and economic loss from disruption of economic activity, are all too well known [2].

Flood estimation is a necessary input to the viable design of any hydraulic structure, ranging from small reservoirs to large dams. Many approaches are available, such as the unit hydrograph, past flood marks, flood frequency analysis and empirical formulas. Regardless of the manner in which ensemble flood forecasts are communicated, it is questionable whether hydrologists would be able to find probabilistic information useful for what is, in operational terms, typically a binary decision (or set of decisions), i.e., whether or not to issue a flood warning. Recent studies by Rayner et al. [3] and Morss et al. [4] have documented significant cultural and institutional constraints on water resource managers making the best use of innovative decision-support technologies. In the present study, empirical equations for estimation of flood peaks on the Chenab River are developed, as a function of average watershed slope and area. A multiple nonlinear regression analysis technique is used to develop these equations.

Canal releases from three headworks complicate the development of flood discharge formulae in the river reaches under consideration. This problem is first tackled by adding canal releases to the observed instantaneous flood peaks, and developing a general equation. Then, three equations are developed that are applicable to the three reaches, by subtracting the cumulative canal releases.

1.1 Empirical Approaches

A number of empirical formulae have been developed for estimation of flood peak. These are essentially regional formulae, based on statistical correlation of the observed peak and important catchment properties. To simplify the form of the equation, only a few of the many parameters affecting the flood peak are used. For example, almost all formulae use the catchment area as a parameter affecting the flood peak, and most neglect flood frequency as a parameter. In view of this, the empirical formulae are applicable only in the region for which they were developed. When applied to other areas, limitations of each equation must be kept in mind. Compared to objective forecasting methods, intuitive forecasting produces a higher average error. Nevertheless, the range of error may be narrower than the very large, albeit rare, errors that can result from a model being applied outside the range of conditions for which it has been tuned [5,6].

By far the simplest of empirical relationships are those that relate the flood peak to the drainage area. The maximum flood discharge Q_p from a catchment area A is given by these formulae as

$$Q_p = f(A) \tag{1}$$

While there are vast numbers of formulae of this kind proposed for various parts of the world, only a few popular formulae are given below:

(a) Dickens formula (1865)
Dickens proposed the following formula for estimation of peak flood discharge as a function of watershed area.

$$Q_p = C_D A^{3/4} \tag{2}$$

where Q_p is the maximum flood discharge (m^3/s), A is the catchment area (km^2) and C_D is the Dickens constant that varies from 11.45 to 24.97, depending on rainfall magnitude and topography of the watershed. The formula was derived for Northern India.

(b) Ryves formula (1884)
This formula was originally developed for the Tamil Nadu region of India, and is in use there and in parts of Karnataka and Andhra Pradesh.

$$Q_p = C_R A^{2/3} \tag{3}$$

where Q_p is the maximum flood discharge (m^3/s), A is the catchment area (km^2) and C_R is the Ryves coefficient whose value ranges from 6.8 to 10.2, depending on the available topography. The formula is derived from the study of river basins in South India.

(c) Inglis formula (1930)
This formula is based on flood data from catchments in the Western Ghats in Maharashtra, India. The flood peak Q_p in m^3/s is expressed as

$$Q_p = \frac{124A}{\sqrt{A + 10.4}} \tag{4}$$

where A is the catchment area in km^2. Equation (4), with small modifications to the constant in the numerator (124), is used in Maharashtra for design in small catchments.

(d) Bransby-Williams formula
The following relationship was proposed by this equation:

$$Q_p = 4{,}600A^{0.52} \tag{5}$$

where A is the catchment area and Q_p is the maximum flood magnitude. The equation is applicable to catchments in Western India.

(e) Dredge and Burge formula
The formula is given below:

$$Q_p = 1{,}300WL^{1/3} \tag{6}$$

where Q_p is the maximum flood discharge, W is the average width of the basin, and L is its length. The formula is derived from records of Indian river discharges, but is not in use.

(f) Fanning formula
This formula was derived from data from New England and Appalachian basins in the United States, and is of local application. The formula is expressed as

$$Q_p = CA^{5/6} \tag{7}$$

where A is the catchment area and Q_p is the maximum flood magnitude. The average value of C is taken as 254.

(g) Chamier formula

$$Q_p = 640CRA^{3/4} \tag{8}$$

where R is the average rate of greatest rainfall, C is constant and ranges from 0.25 to 0.35 for flat terrain, sandy soil or cultivated land; from 0.35 to 0.45 for meadows, gentle declivities and absorbent ground; from 0.45 to 0.55 for wooded hill slopes and compact or stony ground; and from 0.55 to 0.65 for mountainous and rocky terrain and non-absorbent surfaces.

(h) Bürkli-Ziegler formula

$$Q_p = 296A^{3/4} \tag{9}$$

where Q_p is the peak flood discharge and A is the catchment area. This formula is applicable to American catchments.

(i) Metcalf and Eddy formula

$$Q_p = 440A^{0.73} \tag{10}$$

where Q_p is the flood discharge and A is the catchment area. The formula was developed in the United States and is applicable to local areas over 518 km^2.

(j) Jarvis formula
Jarvis presented the flood discharge formula as

$$Q_p = C\sqrt{A} \tag{11}$$

where Q_p is the flood discharge, A is the catchment area, and the value of C ranges from 1.76 to 176.

(k) Myers modified formula

$$Q_p = 10{,}000p\sqrt{A} \tag{12}$$

where Q_p is the flood discharge, A is the catchment area, and the value of p depends on flood frequency and drainage factors. The formula is based on long-term data observed along rivers in the United States.

(l) Lane formula (1914)
Lane presented the following formula for flood discharge estimation.

$$Q_p = K(\log I + B)A \tag{13}$$

where Q_p is the flood discharge, A is the catchment area, K is constant for the stream, B is constant for the region and I is the return period.

(m) Fuller's formula (1914)
The formula was derived for catchments in the United States, and is given as

$$Q_{TP} = C_f A^{0.8}(I + 0.8\log T) \tag{14}$$

where Q_{Tp} is the maximum 24-h flood with a frequency of T years in m^3/s, A is the catchment area in km^2 and C_f is a constant, with values between 0.18 and 1.88.

Spatial variations in flow statistics are closely related to variations in regional physiographic and climatic factors. Making use of this observation, regional regression models are often used to estimate flow statistics for un-gauged sites [7–9].

In the present study, empirical equations for estimation of flood discharges are developed by using multiple nonlinear regression analysis. The goal of this analysis is to evaluate the relationship between several independent or predictor variables and a dependent or criterion variable [10].

2 Study Area

The selected river reach begins at Marala Headworks and ends at Qadirabad Headworks. The origin of the Chenab River is in India. Therefore, some of the catchment area of the selected reach lies in India. The shaded area in Fig. 1 shows the study area.

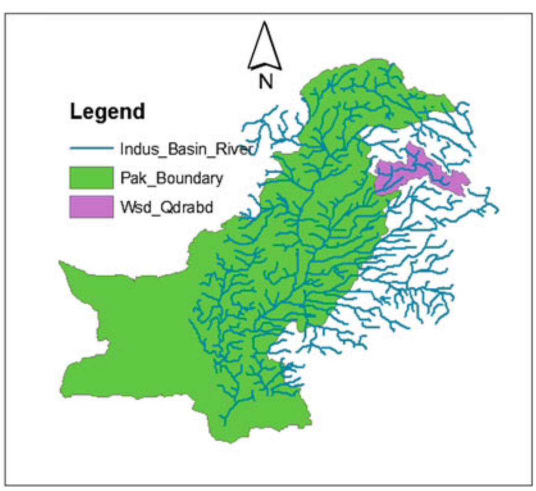

Fig. 1 Pakistan map showing location of the study area

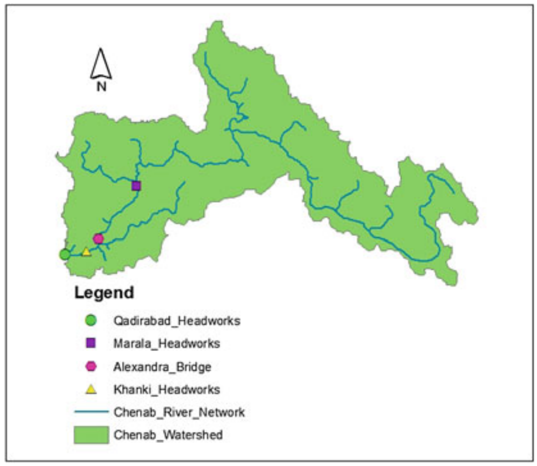

Fig. 2 Catchment of Qadirabad Headworks, with river network and locations of four stream gauging stations

The catchment areas of the Chenab River at Marala Headworks, Alexandra Bridge, Khanki Headworks and Qadirabad Headworks are 25,000, 29,302, 30,155 and 32,685 km^2, respectively. The runoff potential of the watershed is high. The river carries monsoon rainfall-induced runoff. There is moderate to high vegetation cover in the watershed. The major land use type is grassland. This is because the watershed receives rainfall nearly all months of the year, which keeps vegetation growing on the hill slopes. The Qadirabad Headworks watershed, with its river network and locations of four stream gauging stations, is shown in Fig. 2.

3 Data Sources

Data from four stream gauging stations, that is, Marala Headworks, Alexandra Bridge, Khanki Headworks and Qadirabad Headworks, was collected by the Discharge Division of the Irrigation and Power Department, Punjab in Lahore. These data comprise daily discharges and instantaneous flood peaks, from 1991 to 2003. Help in this regard was also given by the Hydrology Directorate Drainage and Flood Zone, Canal Bank Ferozepur Road in Lahore. Hydrographs for every station in each year were developed. Figure 3 shows the trend of runoff and flood peaks in the Marala Headworks hydrograph, for the year 1996. The maximum observed peak was 21096 cumecs, in August. The figure shows that floods at this site are highly flashy in nature. Peak discharges in each year at every station were identified. Figure 4 shows instantaneous flood peaks observed at Qadirabad Headworks over a period of 13 years. The representative trend line shows a significant reduction in flood peaks with time. Releases from the headworks into the canals were taken from a publication of Pakistan Engineering Congress [11]. For the generation of watershed boundaries at four locations along the Chenab River, a GTOPO30 digital elevation model (DEM) of 1 km × 1 km resolution was used.

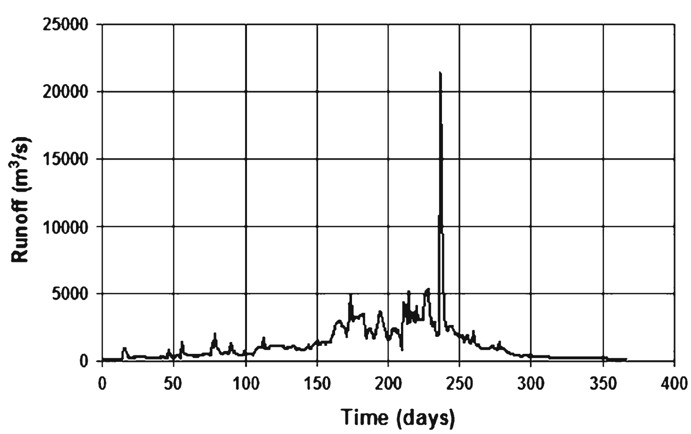

Fig. 3 A typical flood hydrograph for Chenab River at Marala Headworks, for the year 1996

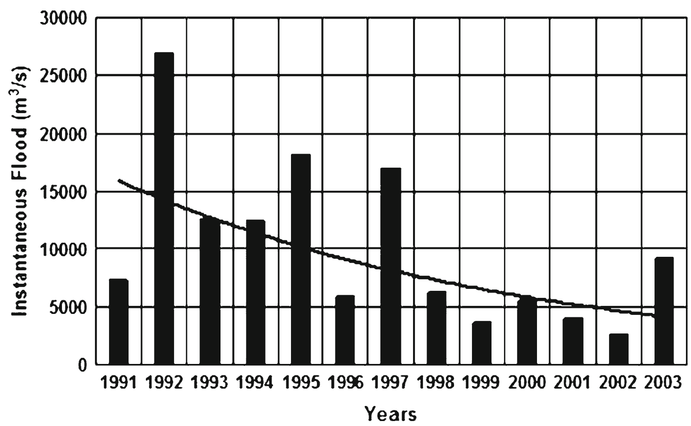

Fig. 4 Temporal distribution of instantaneous floods at Qadirabad Headworks

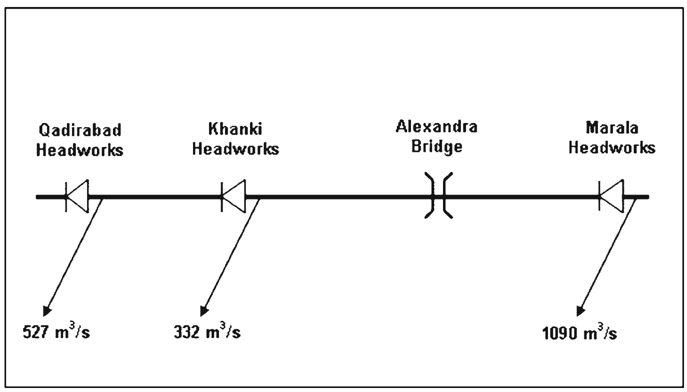

Fig. 5 Stream flow gauging stations and canal releases

4 Methodology

The Chenab river network was generated using geographic information systems (GIS) software, using an appropriate threshold value to initiate the river network. Watersheds for the four stream gauging stations were delineated, and the average slopes of the watershed areas were determined.

Using the data gathered from the Discharge Division of the Irrigation and Power Department of Punjab in Lahore, instantaneous flood peaks for a period of 13 years were found for each station. The average of the peaks was then calculated for the four stream gauging stations. Flow measurements on these headworks are made on the downstream side of the barrages, and hence do not represent canal releases. To obtain river-like flow (without considering lateral outflows), average canal releases from the headworks were added to the observed instantaneous peaks. A schematic diagram showing the locations of stream flow gauging stations and canal releases is presented in Fig. 5.

Using these modified instantaneous flood peaks along the river at the four stream gauging stations, a general multiple nonlinear regression equation was developed. Then, by subtracting cumulative canal releases at the headworks, three more equations were developed that are applicable to three river reaches, i.e., the Marala–Khanki reach, the Khanki–Qadirabad reach, and the reach downstream of Qadirabad Headworks.

After developing the four equations for flood peaks, they were tested for the four stream gauging locations by comparing equation results with observed instantaneous flood peak values (Figs. 6, 7, 8, 9).

5 Results

Using GIS software, the average watershed slopes of Marala, Alexandra, Khanki and Qadirabad Headworks were determined as 22.18, 19.88, 18.01 and 17.18 %, respectively.

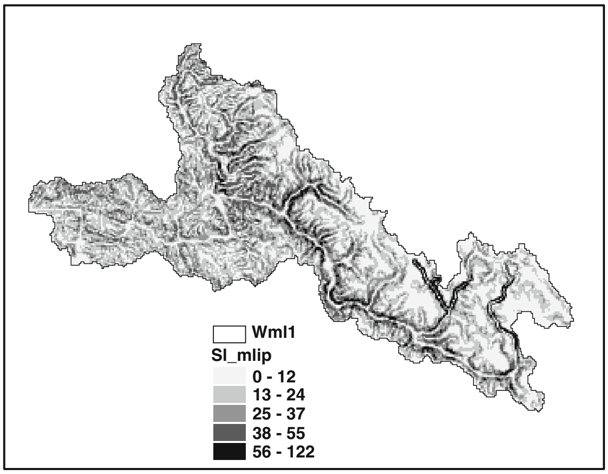

Fig. 6 Slope map for Marala watershed

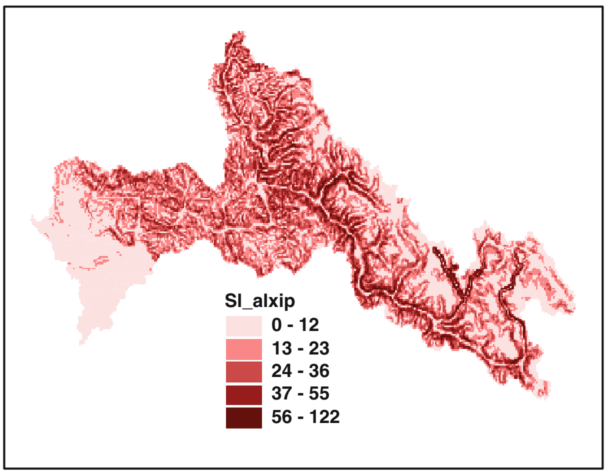

Fig. 7 Slope map for Alexandra watershed

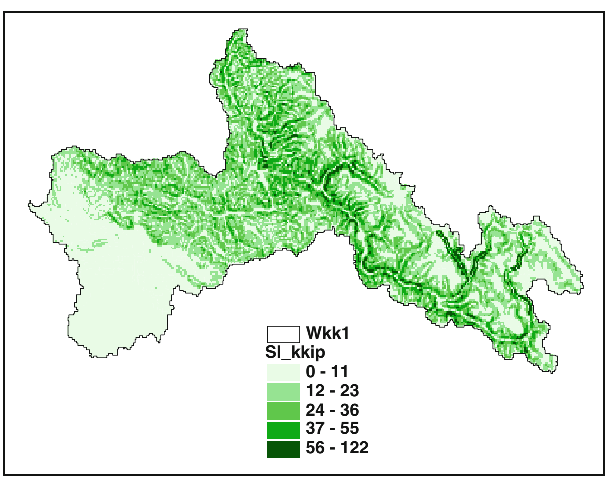

Fig. 8 Slope map for Khanki watershed

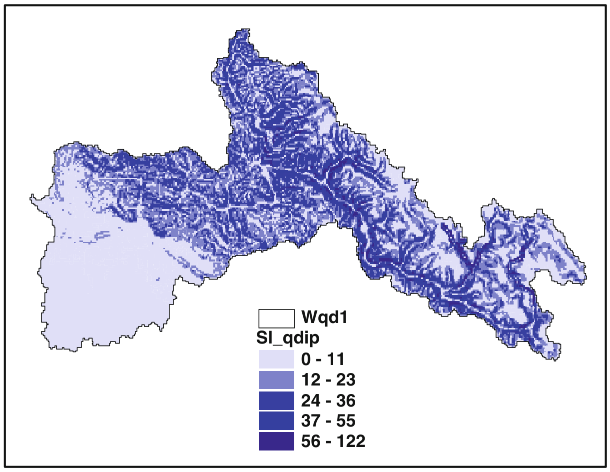

Fig. 9 Slope map for Qadirabad watershed

Table 1 Comparison between computed and observed flood peaks

Sr. No.	Stream gauging station	Watershed area (km^2)	Computed peak flood (cumecs)	Observed peak flood (cumecs)	Difference (%)	Confidence level (%)
1	Marala	25,000	10,406	10,418	0.1	2
2	Alexandra	29,302	11,766	11,350	−3.7	43
3	Khanki	30,155	12,833	12,849	0.1	2
4	Qadirabad	32,685	13,582	13,693	0.8	12

The developed general multiple nonlinear regression equation for the peak flood discharge of the Chenab River reach under consideration is given by Eq. (15). This general equation is applicable for the river reach upstream of the Marala Headworks.

$$Q_p = K A^{0.2837} S^{-0.746} \tag{15}$$

where Q_p is the peak flood discharge in m^3/s, A is the catchment area in km^2, S is the average watershed slope in percent and K is the coefficient of the equation, with a value of 5,943 for the region considered.

The developed equation for the Marala to Khanki river reach is below.

$$Q_p = K A^{0.2837} S^{-0.746} - 1{,}090 \tag{16}$$

The developed equation for the Khanki to Qadirabad river reach is below.

$$Q_p = K A^{0.2837} S^{-0.746} - 1{,}422 \tag{17}$$

The developed equation applicable downstream of the Qadirabad river reach is below.

$$Q_p = K A^{0.2837} S^{-0.746} - 1{,}949 \tag{18}$$

6 Testing of Developed Equations

Empirical equations for peak flood estimation along the Chenab River (Equations 16–18) were tested by computing the peak flood discharges, substituting the respective watershed areas and average watershed slopes. Table 1 shows the comparison between computed and observed flood peaks, as well as the percentage differences and confidence levels at four stream gauging stations.

The percentage differences between observed and computed flood peaks were 0.1, −3.7, 0.1 and 0.8 for Marala, Alexandra, Khanki and Qadirabad gauging stations, respectively. The developed equations underestimated the flood peaks at Marala, Khanki and Qadirabad gauging stations, whereas peaks were overestimated at Alexandra station. The reason for this overestimation is perhaps the unavailability of instantaneous peak

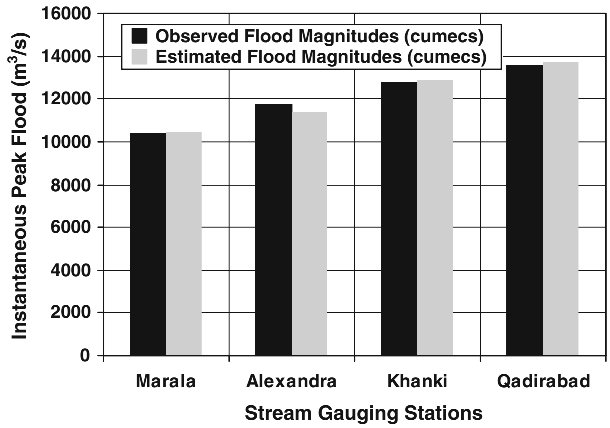

Fig. 10 Testing of developed multiple nonlinear regression equation results for the four stream gauging stations

flood values for 2 years, i.e., 1986 and 1987. This lowered the observed flood peak value at Alexandra, since 1986 experienced above average flooding on the river. The confidence levels computed along the Chenab River for Marala, Alexandra, Khanki and Qadirabad gauging stations were 2, 43, 2 and 12 %, respectively. The reasoning for these values is the same as explained above. Comparison between results of the developed equations and observed peak floods at the four sites is shown in Fig. 10. The results reveal that the developed equations can predict flood peaks with reasonable accuracy.

7 Conclusions

Empirical equations were developed in the form of multiple nonlinear regression models, for inferring flood peaks in the upper Chenab River as a function of watershed area and average slope.

The developed equations can be used with confidence to predict the peak flood discharges in the upper Chenab River, without collecting any flow data. These empirical equations are region-specific, and should be modified if applied in different climatic and physiographic conditions.

The concept used in developing these equations can be constructive for developing similar equations for river reaches with several lateral inflows and outflows.

Acknowledgments The authors would like to thank Executive Engineer, Mr. Muhammad Hanif Khalid from the Discharge Division, Irrigation and Power Department, Lahore, whose personal efforts are highly appreciated for gathering the data on instantaneous maximum discharges. We would also like to thank Mr. Asghar Shah, Chief Drafts man, Drainage and Flood Zone of the Hydrology Directorate, Canal Bank, Ferozepur Road Lahore, for providing the hydrologic data of the missing years.

References

1. Lima, C.H.R.; Lall, U.: Climate informed monthly stream flow forecasts for the Brazilian hydropower network using a periodic ridge regression model. J. Hydrol. **380**, 438–449 (2010)
2. Chow, V.T.: Handbook of Applied Hydrology. McGraw-Hill, New York (1964)
3. Rayner, S.; Lach, D.; Ingram, H.: Weather forecasts are for wimps: why water resource managers do not use climate forecasts. Clim. Change **69**, 197–227 (2005)
4. Morss, R.E.; Wilhelmi, O.V.; Downton, M.W.; Gruntfest, E.: Flood risk, uncertainty, and scientific information for decision making: lessons from an interdisciplinary project. Bull. Am. Meteorol. Soc. **86**, 1593–1601 (2005)
5. Doswell, C.A. III.: Weather forecasting by humans—heuristics and decision making. Weather Forecast. **19**, 1115–1126 (2004)
6. Stewart, T.R.; Sarewitz, D.; Pielke, R.A. Jr.; Byerly, R. (eds.): Uncertainty, judgment and error in prediction. In: Prediction: Science, Decision Making, and the Future of Nature, pp. 41–57. Island Press, Washington, DC (2000)
7. Thomas, D.M.; Benson, M.A.: Generalization of stream flow characteristics from drainage-basin characteristics. US Geological Survey, Water Supply Paper (1970)
8. Vogel, R.M.; Kroll, C.N.: Generalized low flow frequency relationships for ungaged sites in Massachusetts. Water Resour. Bull. **26**(2), 241–253 (1990)

9. Tasker, G.D.; Hodge, S.A.; Barks, C.S.: Region of influence regression for estimating the 50-year flood at ungaged sites. Water Resour. Bull. **32**(1), 163–170 (1996)
10. Sahoo, G.B.; Schladow, S.G.; Reuter, J.E.: Forecasting stream water temperature using regression analysis, artificial neural network, and chaotic non-linear dynamic model. J. Hydrol. **378**, 325–342 (2009)
11. Izhar ul Haq: Barrages and dams in Pakistan. In: Pakistan Engineering Congress, p. 130. Allahwala Printers, Lahore (1990)