IMPACT OF GLOBAL WARMING ON FLOWS IN THE RIVER INDUS AND THE RIVER JHELUM IN PAKISTAN

By

Ishtiaq Hassan[1], Abdul Razzaq Ghumman[2] and Hashim Nisar Hashmi[3]

ABSTRACT:

Analysis of inflows in the river Indus at Tarbela and the river Jhelum at Mangla has been carried out to see the evidence of impact of climate change on run-off of these rivers. Time series analysis has been executed using inflow data from 1971 to 2000. It indicated increases in decadal monthly river run-off by 1.31% to 6.24% for Indus at Tarbela and by 8.24% to 10.19% for Jhelum at Mangla. Simulations for river inflows at these two locations for 21st century have been performed by applying IHACRES stream flow modeling software. The precipitation, temperature, river discharges and catchment data required for the software was collected from the Meteorological Department, Islamabad. The simulations have shown increases of approximately 21.07% in inflows at Tarbela and 22.50% in inflows at Mangla. These increases are indicative of improvements in water sources of Pakistan in terms of surface waters.

KEY WORDS:

Global Warming, Precipitation, Temperature, Flow, IHACRES.

INTRODUCTION:

Pakistan is basically an agricultural country which is heavily dependent on its water resources. The waters in the Indus River System play an important role in this regard (Snow and Ice Hydrology Project, 1990). The country is facing the issue of water and energy crises these days. The present energy crises are very much related to lack of water resources. Planning and management of water resources is dependent on estimation of runoff from the precipitation. Precipitation is directly related to variations in the temperature. It is, thus, clear that temperature and precipitation changes cause variations in flow of rivers. The changes in temperature are attributed to the global warming due to which regional and area temperatures are either increasing or decreasing depending upon the geographical location and other environmental characteristics of that region. The global warming has significant impact on the hydrologic cycles (*Arora et. al., 2008, Vicuna et. al., 2006*, *Veijalainen et. al., 2010*). The IPCC reports (2001 & 2007) indicate that the surface temperature is expected to undergo an increase of 1.1 to 6.4 °C during the twenty-first century. The uncertainties in range of these changes in temperatures are attributed to sensitivity of Greenhouse

---

1. Ph.D. in Water Resources and Irrigation Engineering and a practicing professional Consultant Engineer NESPAK; eishtiaq@yahoo.com; 0092-0300-8525881.
2. Professor (PhD), Department of Civil Engineering, University of Engineering and Technology, Taxila, (Pakistan (Permanent), abdulrazzaq@uettaxila.edu.pk, 0092-0300-5223338.
3. Professor (PhD), Department of Civil Engineering, University of Engineering and Technology, Taxila, Pakistan, dhn@uettaxila.edu.pk, 0092-0321-5570450.

Gases (GHGs) and the approximations of Global Climate Models (GCMs). The *major effects* of climate change are observed in terms of global dimming, rise in mean sea level by 1.8mm/year *(Bruce, 1997)* during 20th century and 2.8mm to 3.1mm per year during 1993-2003 *(Bindoff, 2007; Chambers, 2003),* decrease in ocean acidification i.e. pH value decreased from 8.179 in 1751 8.104 in 1994 *(Orr et al., 2005 and Key et. Al., 2004),* extinction of species, pollinator decline etc.

There are various steps involved in estimation of river flows which include: (i) modeling of basic hydrological parameters like precipitation and temperature on the basis of historic data, for which global climate models (GCMs) have been found the best tool; (ii) simulation of these hydrological parameters for the internationally-defined (IPCC reports 2001 & 2007) scenarios for required time period; (iii) downscaling of the model output to required stations of interest; (iv) modeling of river flows on the basis of base period records of temperature, precipitation and river flows and (v) simulation of river flows for the simulated precipitation and temperature values obtained in step (i).

As explained above, the Global Climate Models (GCMs) are applied to simulate the climate change in terms of temperature and precipitation etc. These models involve understanding of physical, chemical and biological processes which govern the climate. Future climate prediction is associated with the study and input of historical and present data of the all components which are responsible for climate and its change. All climate models use these data for future climate prediction. These GCMs apply four fundamental equations of Physical processes i.e. conservation of momentum, conservation of mass, conservation of energy and ideal gas law. These equations are complex in nature and they require explicit modeling of physical processes in climate system, natural treatment of interactions and feedbacks among the parts of the system. Hence, it is not an easy job to apply these equations directly for simulation. These equations and their solution is explained in detail by Hansen et al. (1983) and by Aarnout V. D. (2010) in the book titled “Dynamical Meteorology” (chapter 10).

There are many techniques which are applied for downscaling the results of GCMs to the station of interest. These techniques involve statistical and dynamical techniques. Ishtiaq et al. (2010 and 2011) introduced and applied graphical-output methods of downscaling i.e. eagle point surface modeling and AutoCAD2000i Quick Surf.

Similarly, there are various models available for river flow modeling. IHACRES is a Catchment-scale rainfall – stream flow modeling software developed collaboratively by the Institute of Hydrology (IH) UK and Center for Resource and Environmental Studies (CRES) the Australian National University. The software is PC version 1.03 released in April 1997 and updated in 2003. This model was applied in present study.

ESTIMATION OF RIVER FLOWS USING IHACRES:

IHACRES software requires time series data of three components i.e. rainfall, stream flow and temperature. Evapo-transpiration effects are estimated by the model itself. Another input is the catchment area. The time steps for simulation can be selected from 6 minutes to one month. IHACRES performs modeling as catchment-scale rainfall-runoff behaviour rather than the small-scale hydrological processes by which rainfall causes the stream flow generation. The software incorporates a sound conceptualization of relevant large-scale catchment processes. The concept of Unit Hydrograph (UH) theory to estimate the stream flows is applied. The software takes into account all non-linearity, that is otherwise commonly observed between the rainfall and the stream flow, by applying effective rainfall concept. The percentage of rainfall that becomes effective varies between 0% and 100% as the catchment wetness index varies between zero and unity. The model has two modules*. There are three {any three of* $a^{(q)}$, $a^{(s)}$, $b^{(q)}$, $b^{(s)}$*} parameters in linear module and another three (f,* τ_w *and C) in non-linear loss module, making overall six parameters* which are applied in this model.

a) Non-linear (loss) module:

This module takes into account the non-linearity in the catchment-scale rainfall-runoff process. It is easy to understand that a catchment that is already wet will always generates more stream flow for a given amount of rainfall than it generates from the same amount when the catchment is initially dry. This observation is applied in the form of a catchment wetness index, s_k, ideally $0 < s_k < 1$. The index s_k takes into account the soil moisture effects for the catchment. For this module, the following three equations are applicable:

$$\mathbf{Pe_k = Po_k.s_k} \qquad \text{………..} (1)$$

$$s_k = C.Po_k + s_{k-1}.\{1 - 1/\tau_w.(t_k)\} \qquad s_o = 0 \qquad \text{………..} (2)$$

$$\tau_w(t_k) = \tau_w.e^{0.062f(R-t_k)} \qquad \tau_w(t_k) > 1 \qquad \text{………..} (3)$$

where:

τ_w = catchment drying time constant,

R = Reference temperature (=20°C).

$\tau_w(t_k)$ controls the rate at which the catchment wetness index (s_k) decays in the absence of rainfall.

f = temperature modulation factor that controls the sensitivity of $\tau_w(t_k)$.

Po_k = observed rainfall at time step k.

Pe_k = effective rainfall at time step k.

s_o = wetness index at time zero

C = Volume forcing constant is the proportion of rainfall r_k that gives an increment to s_k during the rainfall when it s_k is still going down as per set up. The model itself, calculates the value of C during the calibration process so that volumes of effective rainfall and observed stream flow over the model calibration period are equal.

b) Linear UH module:

Consider a scheme of UH as shown in Figure-I below. In order to find relation for the three parameters of linear module, let:

b (<1) = stream flow over the data time step that is produced by the unit hydrograph by unit effective rainfall.

and

a (<1) = proportion of stream flow in subsequent time step that decays exponentially (at a rate determined by a).

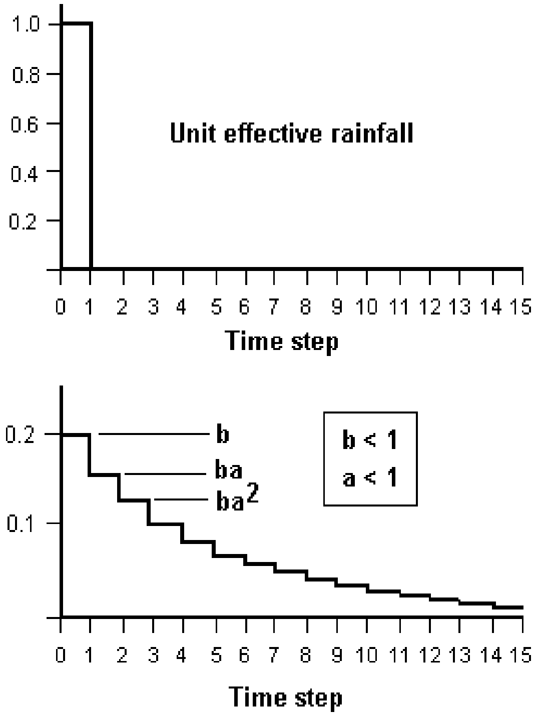

Figure I: Typical UH scheme (after Figure-2 of user guide of IHACRES).

The area under the resultant UH = volume of flow = sum of the infinite series = b + ab + a^2b + a^3b + ……

With 0 < a < 1, we have this infinite geometric series sum equal to b / (1-a) i.e. we have two equations (4) and (5). The shape of UH is completely defined by one parameter (either ‘a’ or ‘b’).

$b(1 + a + a^2 + a^3 + \ldots\ldots\ldots) = b / (1-a)$ ……. (4)

and $b = 1 - a$ ……. (5)

Convolution of UH with effective rainfall excess (……Pe_{k-2}, Pe_{k-1}, Pe_k, Pe_{k+1}, Pe_{k+2}, ………), to generate an estimate of stream flow (……Q_{k-2}, Q_{k-1}, Q_k, Q_{k+1}, Q_{k+2}, ………) can be achieved by applying equation 6,

$$\mathbf{Q_k = a.Q_{k-1} + b.Pe_k} \qquad \text{…….} \ (6)$$

i.e. Flow at present time step = a.(previous time step flow) + b.(present time step effective rainfall).

where ‘a’ and ‘b’ are the parameters for contribution of previous stream flow and present effective rainfall, respectively.

In principal, any number of these simple UHs can be configured in series or in parallel to represent the catchment-scale rainfall-runoff process. IHACRES has three options: single, two in series and two in parallel. In 2nd and 3rd options, UH of total stream flow is the sum of UH for quick (q) stream flow and UH for slow (s) stream flow. Hence, the model uses equation (7) that has just three parameters *{any three of* $a^{(q)}$, $a^{(s)}$, $b^{(q)}$, $b^{(s)}$*}* which is another form of equation (4):

$$b^{(q)}/(1-a^{(q)}) + b^{(s)}/(1-a^{(s)}) = 1 \qquad \text{………} \ (7)$$

and eq. (6) is applied to estimate Q values given in equations (8), (9) and (10),

$$Q^{(q)}_k = a^{(q)}.Q^{(q)}_{k-1} + b^{(q)}.P^{(q)}e_k \qquad \text{………} \ (8)$$

$$Q^{(s)}_k = a^{(s)}.Q^{(s)}_{k-1} + b^{(s)}.P^{(s)}e_k \qquad \text{………} \ (9)$$

$$Q_k = Q^{(q)}_k + Q^{(s)}_k. \qquad \text{………} \ (10)$$

Where $Q^{(q)}_k$ *represents quick flow at time step k,* $Q^{(s)}_k$ *represents slow flow at same time step k and* Q_k *is the estimated total flow at the same time step k.* The parameters of the linear module (a & b) are calculated by applying Simple Refined Instrumental Variable (SRIV) technique. The SRIV algorithm applies an Instrumental Variable approach to find out estimated values of the constant parameters and linear transfer function.

c) Dynamic Response Characteristics (DRCs) loss module:

Parameters such as τ_w, f, and C are the DRCs which apply to the loss module of the overall model.

d) Calibration and simulation of Model:

In run time options, catchment drying time constant (τ_w), temperature modulation factor (f) and time delay (δ), reference temperature and pre-filter selection are known. Reference temperature is always kept as 20°C and pre-filter selection is kept de-selected. *Other three parameters are adjusted by the operator by performing various combinations so that the model performs calibration process and develops the plot option as well.* It is simplified by entering data ranges for τ_w and f with different δ values. That combination of these three factors is selected that gives maximum value of D and least value of %ARPE where *D is co-efficient of determination* and *%ARPE is the percentage average relative parameter error*. “D” is the proportion of initial variance in the observed flow that the models takes into account. The following expression (equation 11) is used to find out the value of D (or Dc) by the model (Littlewood, 2002):

$$D_c = 1 - \frac{\left(\hat{\sigma}\,\xi\right)^2}{\left(\hat{\sigma}_y\right)^2}$$

(after equation A1 of Littlewood, 2002) ………. (11)

Where σ denotes standard deviation, and ξ and y denote model residuals and observed stream flow respectively. ARPE for a ‘two in parallel’ UH module (Littlewood, 2002) is given by equation (12). Jakeman et al. (1990).

$$\text{ARPE} = \left[\left(\frac{\hat{\sigma} a_1}{\hat{a}_1}\right)^2 + \left(\frac{\hat{\sigma} a_2}{\hat{a}_2}\right)^2 + \left(\frac{\hat{\sigma} b_0}{\hat{b}_0}\right)^2 + \left(\frac{\hat{\sigma} b_1}{\hat{b}_1}\right)^2\right] / 4$$

(after equation A1 of Littlewood, 2002) ………. (12)

STUDY AREA AND DATA ANALYSIS:

Pakistan owns the best irrigation system consisting of three major rivers (western rivers the Indus, the Jhelum and the Chenab) and three minor rivers (eastern rivers the Sutlej, the Bias and the Ravi). Eastern rivers are mainly under the control of India and remain dry unless fed by the western rivers through link canals. The western rivers are the most important ones out of which two rivers, the Indus and the Jhelum, have been selected in this study. The country has two larger dams; Tarbela dam on the river Indus and the Mangla dam on the river Jhelum. These are backbone of its irrigation and power generation systems. This study aims at investigating river flows at these two locations. Inflow data for Indus at Tarbela; and for Jhelum at Mangla for the period of 1971-2000 have been obtained from the Indus River System Authority (IRSA) Islamabad. For each month, three records on the basis of 10 day’s mean have been provided. These inflow data have been analysed by calculating their respective standard deviations which are 1205.8 and 485.1 for the Indus at Tarbela and the Jhelum at Mangla, respectively. Additionally, analysis of observed and modeled flows in IHACRES indicates a uniformity in monthly flows as the hydrograph ascends and descends. Hence, the data has been found satisfactory for further analysis.

Average temperature and precipitation data, for the period of 1971-2000, was collected from the Meteorological Department Islamabad (Pakistan) for four stations Islamabad, Kakul, Cherat and Jhelum. These data have been transferred to the stations of interest (Tarbela and Mangla) by applying the distance weightage techniques. For temperature, a standard deviation of 0.51 for Pakistan as a whole has been found within the acceptable limits. Similarly, a standard deviation of 7.44 mm/day in precipitation for Pakistan as a whole suggests that the data is within the acceptable limits for Pakistan.

METHODOLOGY:

Modeling of basic hydrological parameters like precipitation and temperature on the basis of historic data, for which EdGCM (Educational Global Climate Model) have been applied. The results were calibrated by applying Nash and Sutcliff (1970) relative volume error technique. Temperature results have been obtained by Ishtiaq et al. (2010). Same procedure was applied to simulate precipitation results.

Changes in flows of the two most important rivers (the Indus at Tarbela and the Jhelum at Mangla) of Pakistan have been studied with respect to: (a) evidence of changes in the recorded flows by performing the time series analysis and (b) simulation of river flows for the expected changes in precipitation and temperature. The first part of study has been carried out by finding average of monthly flows for the three decades i.e. 1971-1980, 1981-1990 and 1991-2000 and comparing the second and third decade average monthly flows with the first decade average monthly flows. The second part of the study deals with simulation of future flows by IHACRES model.

RESULTS AND DISCUSSION:

(a) TIME SERIES ANALYSIS FOR TARBELA AND MANGLA:

Figure-II(a) and II(b) show ten-daily inflow hydrographs of Indus at Tarbela and Jhelum at Mangla. In Figure-II(a) the rising limb of the hydrograph starts in the beginning of May as a result of snow-melt in the catchment ***(Jain et. al., 2010)***. The peak reaches in the start of August after due to glacial-melt ***(Jain et. al., 2010)*** after which the recession starts. It is observed that the inflows have increased in Indus at Tarbela in all months except June and July. For Tarbela, the maximum increase in inflows is 682cumecs (11.02%) during 1981-1990 in August and 491cumecs (17.3%) during 1991-2000 in September as compared to the first decade of 1971-1980. The decadal comparison for Tarbela shows that yearly average flows have increased by **1.31**% during second decade (1981-1990) and **6.24**% during third decade (1991-2000) as compared to the first decade (1971-1980).

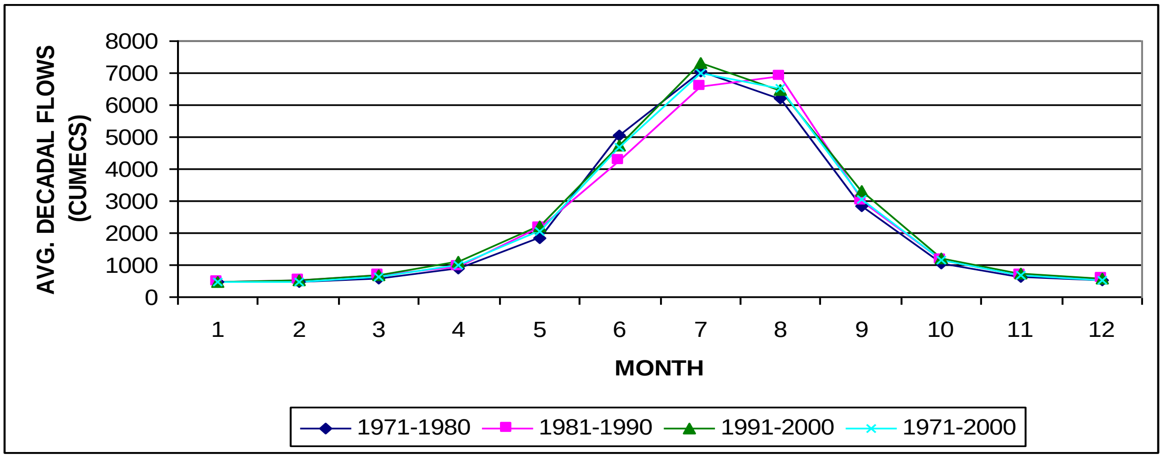

Figure II(a): Inflow hydrograph in Indus at Tarbela during the decadal periods of 1971-1980, 1981-1990, 1991-2000 and base period 1971-2000.

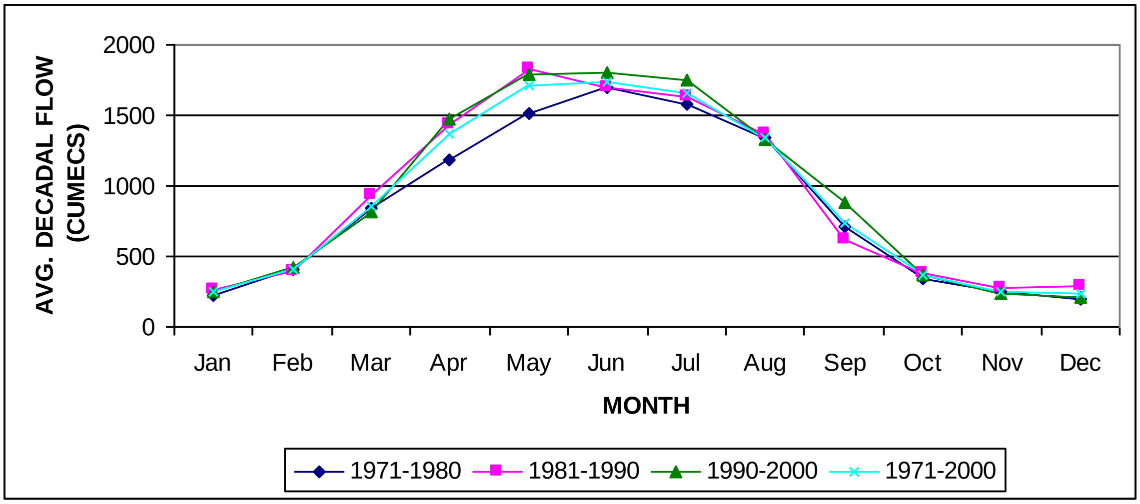

Figure II(b): Inflow hydrograph in Jhelum at Mangla during the decadal periods of 1971-1980, 1981-1990, 1991-2000 and base period 1971-2000.

In Figure-II(b), the rising limb of the hydrograph starts in the beginning of February. The peak reaches in the start of June after which the recession starts. The inflows are result of snow-melt ***(Jain et. al., 2010)*** during the months of February while during May and June the inflows are resultant of glacial-melt ***(Jain et. al., 2010)***. Comparison of last two decades (1981-1990 & 1991-2000) with the first decade (1971-1980), as given by data, indicates that the inflows have increased at Mangla in all months except February, March, September and November. For Mangla, the maximum increase in inflows is 325cumecs (21.52%) during 1981-1990 in May and 289cumecs (24.45%) during 1991-2000 in April as compared to the first decade of 1971-1980. The decadal comparison for Mangla shows that yearly average flows have increased by **8.24**% during the second decade (1981-1990) and **10.19**% during the third decade (1991-2000) as compared to first decade (1971-1980) of base period.

(b) FUTURE SIMULATIONS:

IHACRES has been applied to simulate flows for both Indus at Tarbela and Jhelum at Mangla by the end of 21st century. Figure-III(a) and Figure-III(b) show plots (graphical comparison) of the observed rainfalls and the effective rainfalls for Indus Catchment at Tarbela and Jhelum catchment at Mangla, respectively, as modeled by IHACRES. In Figure-III(a), about 31.43% of the observed rainfall contributed to the stream flow whereas in Figure-III(b), about 56.50% of the observed rainfall contributed to the stream flow.

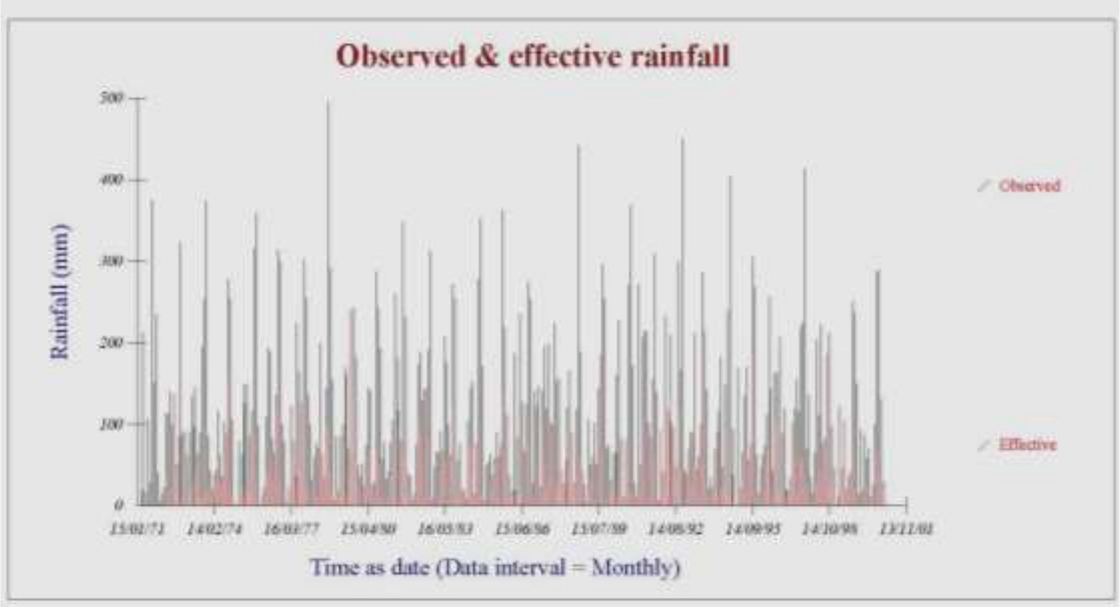

Figure III(a): Plot of Observed and effective rainfall for Indus at Tarbela during 1971-2000 modeled in IHACRES.

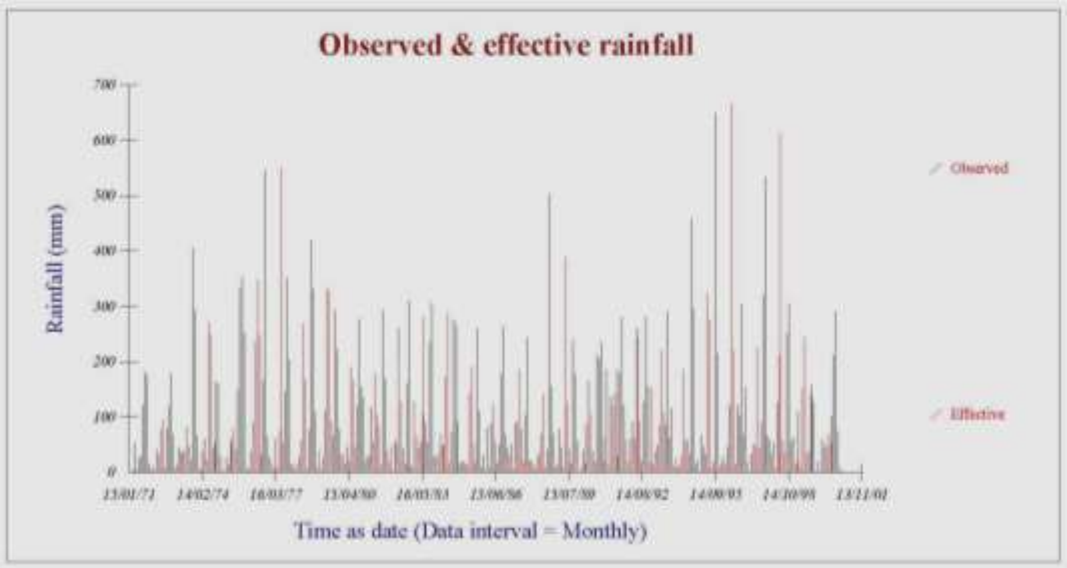

Figure III(b): Plot of Observed and effective rainfall for Jhelum at Mangla during 1971-2000 modeled in IHACRES.

Figures-IV(a) and IV(b) show plots of observed and modeled stream flows developed by IHACRES for the Indus catchment at Tarbela and Jhelum catchment at Mangla, respectively. The visual comparison also indicates that IHACRES has modeled the flows closer to the observed flows.

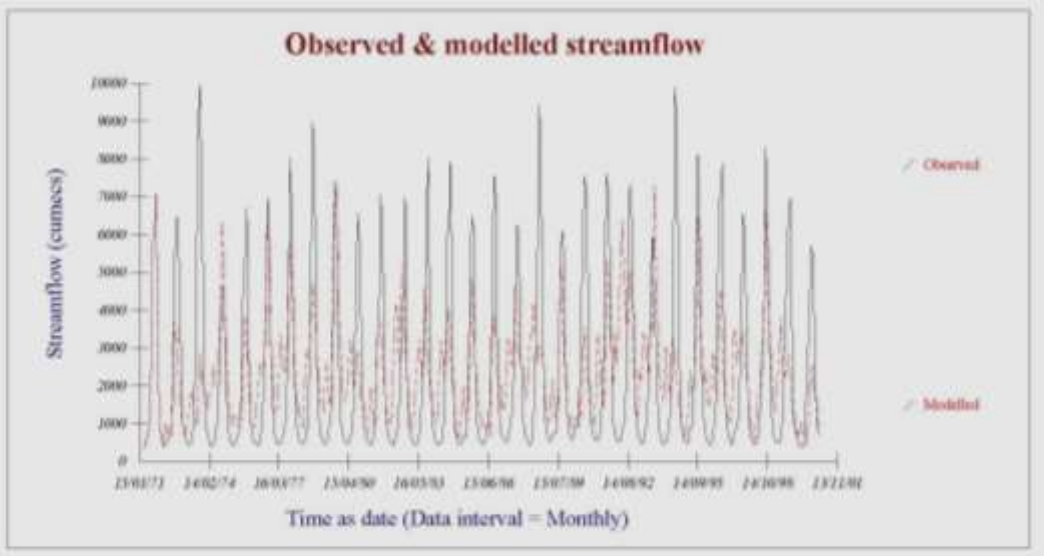

Figure IV(a): Plot of Observed and Modeled river flows for Indus at Tarbela during 1971-2000 using IHACRES.

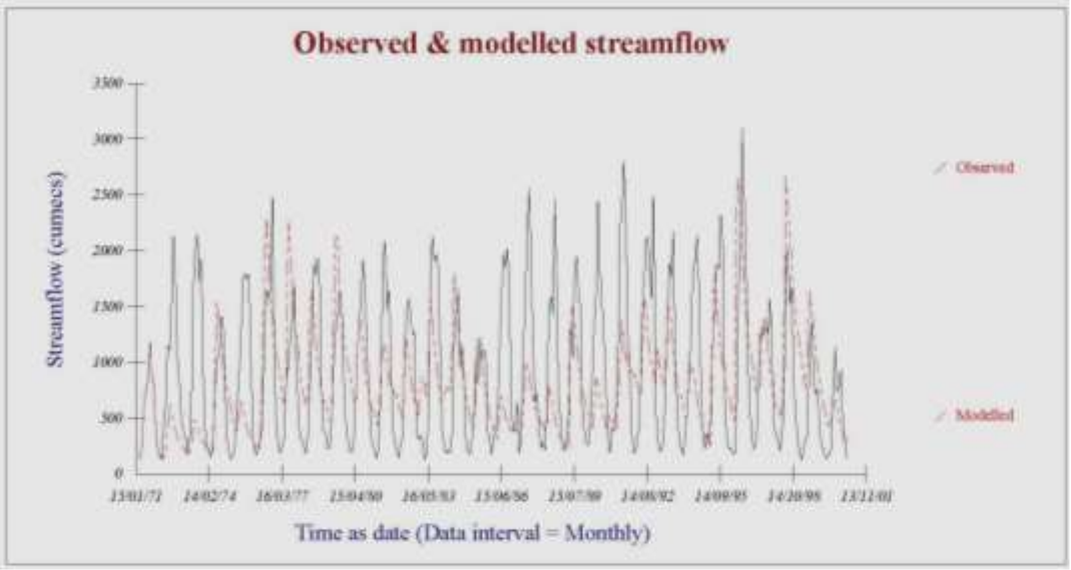

Figure IV(b): Plot of Observed and Modeled river flows for Jhelum at Mangla during 1971-2000 using IHACRES.

These modeled flows have been utilized by the software to develop a unit hydrograph (UH) for the average flows in the catchment. Figures-V(a) and V(b) show unit hydrographs for Indus at Tarbela and Jhelum at Mangla, respectively.

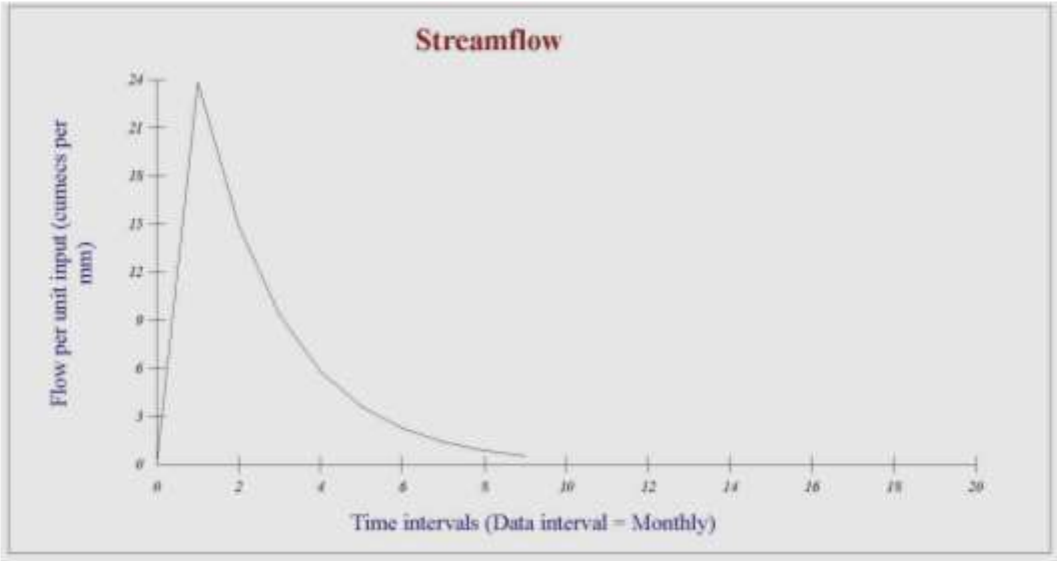

Figure V(a): Unit Hydrograph for Indus at Tarbela average annual flows using IHACRES.

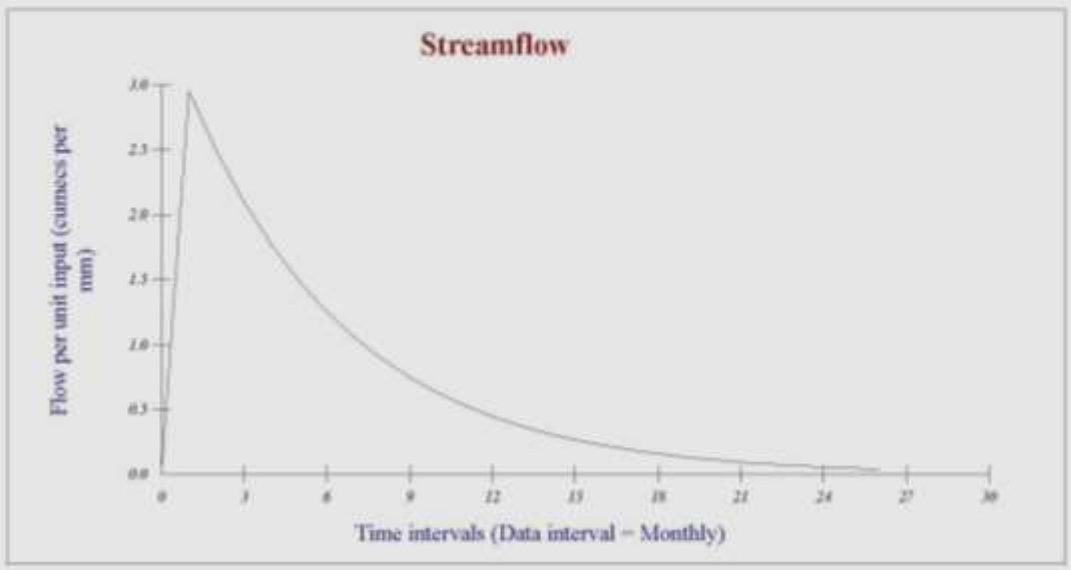

Figure V(b): Unit Hydrograph for Jhelum at Mangla average annual flows using IHACRES.

These unit hydrographs, UHs, (Figures-V(a) & V(b)) have been used to find out hydrographs of direct runoff (DRO) for annual average flows after applying a check on validity of these UHs. Validity of each has been checked by finding DRO for the observed average meteorological values of annual precipitation and temperature at these two locations.

Calibration and Validation of IHACRES modeled flows:

Calibration and validation checks for IHACRES modeled flows have been carried out by applying Nash and Sutcliff (1970) efficiency co-efficient (NS) and the Relative Volume Error (RE) calculations. The flows have been finally calibrated and validated by finding factors for each flows calculations. Table-I and Table-II show NS and RE value of the simulated (Qs) and observed flows (Qo) for Indus at Tarbela and Jhelum at Mangla, respectively. Each Qs has been calculated for the tabulated respective observed precipitation (Po) and observed temperature (To). For this purpose, ten observed values have been selected from the base period records and the factors for correction have been found as 0.95 and 0.97, respectively for Indus at Tarbela and Jhelum at Mangla.

Table I: Calibration and Validation of IHACRES model flows for Indus at Tarbela.

Before Calibration

P_o (mm/day)	**T_o (Deg C)**	**Qs (cumecs)**	**Qo (cumecs)**	**(Qs-Qo)^2**	**(Qo-Qo')^2**	**NS**	**RE**
2.51	19.14	2620	2053	321489	91809	-2.50	0.28
2.60	18.77	2576	2292	80656	4096	-18.69	0.12
2.67	19.02	2615	2252	131769	10816	-11.18	0.16
2.80	19.17	2645	2258	149769	9604	-14.59	0.17
3.57	18.61	2622	3201	335241.00	714025	0.53	-0.18
3.97	18.94	2697	2830	17689.00	224676	0.92	-0.05
3.17	18.26	2545	2126	175561.00	52900	-2.32	0.20
3.74	17.88	2531	2124	165649.00	53824	-2.08	0.19
2.74	14.64	2017	2414	157609.00	3364	-45.85	-0.16
3.45	17.59	2471	2425	2116.00	4761	0.56	0.02

After Calibration

Factor for correction of Q		**Qs (cumecs)**	**Qo (cumecs)**	**(Qs-Qo)^2**	**(Qo-Qo')^2**	**NS**	**RE**
	0.79	2069.8	2053	282	91809	1.00	0.01
	0.89	2292.64	2292	0	4096	1.00	0.00
	0.86	2248.9	2252	10	10816	1.00	0.00
	0.85	2248.25	2258	95	9604	0.99	0.00
	1.2	3146.4	3201	2981	714025	1.00	-0.02
	1.04	2804.88	2830	631	224676	1.00	-0.01
	0.83	2112.35	2126	186	52900	1.00	-0.01
	0.84	2126.04	2124	4	53824	1.00	0.00
	1.2	2420.4	2414	41	3364	0.99	0.00
	0.98	2421.58	2425	12	4761	1.00	0.00
Average	**0.95**	2389.12	2397.50	424.26	116987.50	1.00	0.00

Table II: Calibration and Validation of IHACRES model flows for Jhelum at Mangla.

Before Calibration

P_o (mm/day)	T_o (Deg C)	Qs (cumecs)	Qo (cumecs)	(Qs-Qo)^2	(Qo-Qo')^2	NS	RE
1.73	23.76	926	527	159201	146689	-0.09	0.76
2.73	23.73	944	1032	7744	14884	0.48	-0.09
3.44	23.22	936	988	2704	6084	0.56	-0.05
2.60	23.67	939	809	16900	10201	-0.66	0.16
2.97	22.73	909	831	6084.0	6241	0.03	0.09
2.59	22.84	906	1090	33856.0	32400	-0.04	-0.17
1.86	23.45	916	960	1936.0	2500	0.23	-0.05
3.31	23.78	957	1070	12769.0	25600	0.50	-0.11
3.22	23.3	936	1090	23716.0	32400	0.27	-0.14
1.75	24.61	960	563	157609.00	120409	-0.31	0.71

After Calibration

Factor for correction of Q		Qs (cumecs)	Qo (cumecs)	(Qs-Qo)^2	(Qo-Qo')^2	NS	RE
	0.59	546.34	527	374	146689	1.00	0.04
	1.1	1038.4	1032	41	14884	1.00	0.01
	1.05	982.8	988	27	6084	1.00	-0.01
	0.86	807.54	809	2	10201	1.00	0.00
	0.92	836.28	831	28	6241	1.00	0.01
	1.21	1096.26	1090	39	32400	1.00	0.01
	1.05	961.8	960	3	2500	1.00	0.00
	1.12	1071.84	1070	3	25600	1.00	0.00
	1.17	1095.12	1090	26	32400	1.00	0.00
	0.6	576	563	169	120409	1.00	0.02
Average	**0.97**	901.24	896.00	71.31	39740.8	1.00	0.01

Sensitivity Analysis:

The sensitivity analysis has been carried out on the observed values of temperature and precipitation (as given in the following section above Tables-III and IV). Three cases have been checked for sensitivity of flow variations due to change in observed precipitation and temperature for both catchments. These cases include flow checks for: (i) 1% change in observed precipitation only for no change in temperature, (ii) 1 °C change in observed temperature only with no change in precipitation and (iii) 1% change in observed precipitation and 1 °C change in observed temperature. The outcome of these three cases has shown changes of 0.96%, 1.00% and 1.01% in observed flows, respectively for each case, for the river Indus at Tarbela. Similarly, the outcome of these three cases has shown changes of 1.00%, 1.04% and 1.04% in observed flows, respectively for each case, for the river Jhelum at Mangla. The comparison of each case for Tarbela and Mangla shows good working of IHACRES for both catchments because of almost the same percentage increases in the river flows.

Simulation for 2091-2100:

Two sets of calculations have been performed on the UHs of Figure-V (a & b) to find an expected change in stream flow by the end of 21st century. These sets of calculations are given below:

(i) Determination of average annual DROs (stream flows) during the base period (1971-2000) for recorded (observed) precipitation and temperature values have been carried out as follows:

Table-III shows that river Indus at Tarbela has an average flow of 2401 cumecs for observed precipitation value of 3.21 mm and temperature value of 18.15 °C as modeled in IHARES. Similarly, Table-IV shows that river Jhelum at Mangla has an average flow of 897 cumecs for observed precipitation value of 2.57 mm and temperature value of 23.52 °C as modeled on the basis of UH developed by IHARES.

Base data for Table-III is as follows:

Period of Interest for which average is given below = 1971-2000
Observed Average Precipitation, P_O (mm) = 3.21
Observed Average Temperature, T_O (Deg. C) = 18.15
Model (IHACRES) Average Temperature, T_m (Deg. C) = 16.59

TABLE-3: Flow determination for Terbela during base period by applying IHACRES model results.

Time (months)	Interval (months)	Ordinate* of UH cumecs	RO for Po cumecs	Approx. base flow cumecs	DRO Po cumecs	Volume of Flow (cumecs)
0		0	0.00	235	235.00	-
1	1	24	77.04	235	312.04	273.52
2	1	15	48.15	235	283.15	297.60
3	1	9.4	30.17	235	265.17	274.16
4	1	6	19.26	235	254.26	259.72
5	1	3.35	10.75	235	245.75	250.01
6	1	2.11	6.77	235	241.77	243.76
7	1	1.4	4.49	235	239.49	240.63
8	1	0.8	2.57	235	237.57	238.53
9	1	0.6	1.93	235	236.93	237.25
				Total Flow for P_o value =		2315.18
			Total Flow for P_o & T_o value =			**2532.88**
		Total Flow after applying correction (validation) factor =				**2401.17**

**taken from unit hydrograpgh developed by IHACRES modelling software.*

Base data for Table-IV is as follows:

Period of Interest for which average is given below = 1971-2000
Observed Average Precipitation, P_O (mm) = 2.57
Observed Average Temperature, T_O (Deg. C) = 23.52
Model (IHACRES) Average Temperature, T_m (Deg. C) = 23.52

TABLE-4 : Flow determination for Mangla during base period by applying IHACRES model results.

Time	**Interval**	**Ordinate* of**	**RO for**	**Approx.**		**Volume**
(months)	**(months)**	**UH**	**Po**	**base flow**	**DRO Po**	**of Flow**
		cumecs	**cumecs**	**cumecs**	**cumecs**	**(cumecs)**
0		0	0.00	95	95	
1.2	1.2	2.935	7.54	95	102.54	118.53
3	1.8	2.153	5.53	95	100.53	182.77
6	3	1.283	3.30	95	98.30	298.25
9	3	0.772	1.98	95	96.98	292.92
12	3	0.49	1.26	95	96.26	289.87
15	3	0.261	0.67	95	95.67	287.90
18	3	0.165	0.42	95	95.42	286.64
21	3	0.087	0.22	95	95.22	285.97
24	3	0.044	0.11	95	95.11	285.51
26	2	0.043	0.11	95	95.11	190.22
				Total Flow for P_o value =		**2518.56**
			Total Flow for P_o & T_o value =			**2518.56**
		Total Flow after applying correction (validation) factor =				**896.61**

**taken from unit hydrograpgh developed by IHACRES modelling software.*

(ii) Determination of average annual DRO (stream flow) for Indus at Tarbela and Jhelum at Mangla by the end of 21st century for simulated precipitation and temperature values has been carried out as follows:

Table-V shows that river Indus at Tarbela has an average flow of 3067 cumecs for observed precipitation value of 3.50 mm and temperature value of 23 °C as modeled in IHARES. Similarly, Table-VI shows that river Jhelum at Mangla has an average flow of 1098 cumecs for observed precipitation value of 2.95 mm and temperature value of 28.73 °C as modeled on the basis of UH developed by IHARES.

Base data for Table-V is as follows:

Period of Interest for which average is given below = End of 21st century.
Simulated Average Precipitation, P_s (mm) = 3.5
Simulated Average Temperature, T_s (Deg. C) = 23
Model (IHACRES) Average Temperature, T_m (Deg. C) = 16.59

TABLE-5 : Flow determination for Terbela during simulated period by applying IHACRES model results.

Time	**Interval**	**Ordinate* of**	**RO for**	**Approx.**		**Volume**
(months)	**(months)**	**UH**	**Ps**	**base flow**	**DRO Ps**	**of Flow**
		cumecs	**cumecs**	**cumecs**	**cumecs**	**(cumecs)**
0		0	0.00	235	235.00	-
1	1	24	84.00	235	319.00	277.00
2	1	15	52.50	235	287.50	303.25
3	1	9.4	32.90	235	267.90	277.70
4	1	6	21.00	235	256.00	261.95
5	1	3.35	11.73	235	246.73	251.36
6	1	2.11	7.39	235	242.39	244.56
7	1	1.4	4.90	235	239.90	241.14
8	1	0.8	2.80	235	237.80	238.85
9	1	0.6	2.10	235	237.10	237.45
				Total Flow for P_s value =		2333.26
			Total Flow for P_s & T_s value =			3234.78
		Total Flow after applying correction (validation) factor =				**3066.57**

**taken from unit hydrograpgh developed by IHACRES modelling software.*

Base data for Table-VI is as follows:

Period of Interest for which average is given below = End of 21st century.
Simulated Average Precipitation, P_s (mm) = 2.95
Simulated Average Temperature, T_s (Deg. C) = 28.73
Model (IHACRES) Average Temperature, T_m (Deg. C) = 23.52

TABLE-6 : Flow determination for Mangla during simulated period by applying IHACRES model results.

Time	**Interval**	**Ordinate* of**	**RO for**	**Approx.**		**Volume**
(months)	**(months)**	**UH**	**Ps**	**base flow**	**DRO Ps**	**of Flow**
		cumecs	**cumecs**	**cumecs**	**cumecs**	**(cumecs)**
0		0	0.00	95	95	
1.2	1.2	2.935	8.66	95	103.66	119.19
3	1.8	2.153	6.35	95	101.35	184.51
6	3	1.283	3.78	95	98.78	300.20
9	3	0.772	2.28	95	97.28	294.09
12	3	0.49	1.45	95	96.45	290.58
15	3	0.261	0.77	95	95.77	288.32
18	3	0.165	0.49	95	95.49	286.89
21	3	0.087	0.26	95	95.26	286.12
24	3	0.044	0.13	95	95.13	285.58
26	2	0.043	0.13	95	95.13	190.26
				Total Flow for P_s value =		**2525.75**
			Total Flow for P_s & T_s value =			3085.23
	Total Flow after applying correction (validation) factor =					**1098.34**

**taken from unit hydrograpgh developed by IHACRES modelling software.*

The values of DRO for observed and simulated stream flows worked out in Tables-III and IV have been applied to find change in flows. It is found that stream flow in Indus at Tarbela is expected to experience an increase of **21.07**% in annual average flows by the end of 21st century as compared to the annual average flows of the base period (1971-2000). This increase is related to 9% in precipitation (change from 3.21 to 3.50mm) and to 4.85°C rises in temperature (change from 18.15 to 23 °C).

The values of DRO for observed and simulated stream flows worked out in Tables-V and VI have been applied to find change in flows. It is found that stream flow in Jhelum at Mangla shall experience an increase of **22.50**% in annual average flows by the end of 21st century as compared to the annual average flows of the base period (1971-2000). This increase is related to 14.59% in precipitation (change from 2.57 to 2.95 mm) and to 5.21°C rises in temperature (change from 23.52 to 28.73°C).

CONCLUSIONS AND RECOMMENDATIONS:

The time series analysis of the two important rivers (Indus, and Jhelum) of Pakistan indicates that the inflows have increased overall during the base period. The pattern of hydrograph for river inflows has remained almost the same in time series analysis. It is also concluded that the increase is not continuous but there do occur increases as well as decreases in the inflows. It means that effects of changes in global warming have experienced more increases at one time and less increases at other time. The flow modeling of the river Indus at Tarbela and the river Jhelum at Mangla by using IHACRES modeling software has shown average increases of approximately 21.07% in river Indus at Tarbela and 22.50% in river Jhelum at Mangla by the end of 21st century. These increases are positive signs of increases in water resources of Pakistan. There is need to develop more water storage reservoirs at various locations on the courses of these rivers to fulfill irrigation and power demands of the country.

ACKNOWLEDGEMENTS:

Acknowledgement is made to “National Agro met Center (NAMC) of Pakistan (Meteorological Department)” who provided the weather data for 1971-2000 free of cost. Acknowledgments are also extended to Mr. Muhammad Khalid Idrees Rana, Deputy Director (Operations), IRSA whose valuable data on Tarbela and Mangla Inflows helped to make a time-series and prediction analysis of the river flow. Acknowledgement is also extended to owners of IHACRES stream flow modeling software at the Institute of Hydrology (IH), UK and at the Center for Resource and Environmental Studies (CRES), Australia, who made the PC version software available on internet free of cost. The flows of river Indus and river Jhelum have been modeled by using this well known software.

REFERENCES:

Aarnout V. D.; updated 2010, Dynamical Meteorology, Atmospheric Dynamics – Chapter 10 (Models); pages 228-246; Department of Physics and Astronomy, Utretcht University, Netherlands.

Arora M., Singh P., Goel N. K.; 2008; Climate Variability Influences on Hydrological Responses of a Large Himalayan basin; Journal of Water Resource Management, DOI 10.1007/s11269-007-9237-1.

Bindoff, NL et al.; 2007; Observations: Oceanic Climate Change and Sea Level, Climate Change: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press

Bruce C. D; 1997; Global Sea Rise: A Re-determination; Surveys in Geophysics 18: 279–292 doi:10.1023/A:1006544227856

Chambers, D. P.; 2003; Calibration and Verification of Jason-1 Using Global Along-Track Residuals with TOPEX; Marine Geodesy 26: 305. doi:10.1080/714044523.

Hansen J. et al., 1983. Efficient Three-Dimensional Global Models for Climate Studies: Model I and II. NASA/Goddard Space Flight Center., Institute for space studies, New York, NY 10025; Vol. III No. 4.

Ishtiaq Hassan , Abdul Razzaq Ghumman, Hashim Nisar Hashmi; Jan 2011; “Impact of Environmental Changes and Global Warming on Temperature in Pakistan”, Mehran University Research Journal of Engineering & Technology; Volume 30, No. 1 Pages 1-14.

Ishtiaq Hassan, Abdul Razzaq Ghumman, Hashim Nisar Hashmi, Abdul Sattar Shakir; 2010, “Investigation of Impact of Global Warming on Precipitation Pattern of Saudi Arabia”, Civil Engineering and Environmental Systems; Volume 27, Pages 365-376.

Key, R. M.; Kozyr, A.; Sabine, C. L.; Lee, K.; Wanninkh of, R.; Bullister, J.; Feely, R. A.; Millero, F.; Mordy, C. and Peng, T.-H.; 2004; A global ocean carbon climatology: Results from GLODAP; Global Biogeochemical Cycles 18: GB4031. doi:10.1029/2004GB002247.

Nash, J. E. and Sutcliffe, J. V., 1970. River flow forecasting through conceptual models 1: a discussion of principles, J. Hydrol., 10, 282–290.

Orr, James C.; et al.; 2005; Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms; Nature 437 (7059): 681–686. doi:10.1038 / nature04095.

Veijalainen, N., Dubrovin, T., Marttunen, M., Vehvilainen, B.; published online 2010; Climate Change Impacts on Water Resources and Lake Regulation in the Vuoksi Watershed in Finland; Journal of Water Resource Management, (2010)24:3437-3459.

Vicuna S. and Dracup J. A., 2007. The evolution of climate change impact studies on hydrology and water resources in California. University of California, Berkeley, CA. 947210-1710.