FLOOD FORECASTING FOR THE SUPER FLOOD 2010 IN SUKKUR-KOTRI REACH OF INDUS RIVER

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ABSTRACT

The worst flood disaster in the history of 80 years of Pakistan which occurred in July 2010 following heavy monsoon rains, which has resulted in loss of life and substantial damage to property, infrastructure and agriculture. UNESCO supported the national efforts to cope with the flood disaster in Pakistan. UNICEF Pakistan has also responded quickly and effectively when the floods began to make their way down the length of the country. Keeping in view above situation, the proposed finite element model has been applied for the Super Flood 2010 of the Indus River. The semi-implicit Taylor-Galerkin Predictor-Corrector (TGPC) scheme based on Finite Element Method has been adopted for computing flood routing. The presented numerical model is the best technique of flood forecasting for any reach of river channels. In this paper, the model has been applied for Sukkur-Kotri reach, computing peak flow attenuation and time lag between inflow (i.e. at downstream of Sukkur barrage) and outflow (i.e. at upstream of Kotri barrage) of the River Indus. The accuracy of the presented model has been observed through comparing the numerical prediction at upstream of Kotri barrage of Indus River against the observed data. The statistical comparison also demonstrated that the numerical simulation of model has a good agreement with observed flow at upstream of Kotri barrage. The stability of the model has also been observed during simulation of the flood discharge between the selected reach. The observed and computed lag times are calculated for the maximum flood peaks of various periods (2009, 2010 and 2011), which show almost good agreement. The observed minimum lag time is about 4 to 5 days for normal flood; however, the maximum time lag was observed during Super Flood of 2010 i.e. about 16 days.

Keywords: FEM, Flood routing, Time Lag, Super Flood, Sukkur-Kotri reach, Indus River

1 INTRODUCTION

River floods occur naturally on rivers, and these floods result from heavy rain, sometimes combined with melting snow, which causes the rivers to overflow their banks. Pakistan has a long history of flooding from the Indus River and its tributaries due to heavy rainfall mostly occurred in the monsoon season (Memon, 2004). These high floods subsequent loss of human lives, crops and livestock, damages of infrastructures and extensive erosion.

In July 2010, following heavy monsoon rains, Indus River rose above its banks and flooded surrounding areas. With rains continued further two months, large areas of Pakistan were affected in various degrees. As mid of August, the heaviest flooding moved Sindh province along the Indus River for out-falling to the Arabian Sea (Health Cluster-Pakistan, 2011).

Flooding routing is a modeled either by hydraulic routing or by hydrologic routing procedures. Hydraulic routing is based upon the equation of motion of unsteady flow, along with the equation of continuity. The differential equation which describes this flow is known as the St. Venant equation whereas hydrologic routing is based on the equation of continuity. Generally, in hydraulic studies, the models of hydraulic flood routing are used (Das, 2004).

Flow in a river channel is often considered to be one-dimensional in the direction of flow; this assumption allows simplified mathematical analysis of the flow. Multi-dimensional flows require accounting for the physics (mass and momentum conservation) of the flow in two and sometimes three dimensional (Abbott et al., 1979 and Cunge et al., 1980).

One-dimensional numerical models have extensively been used to compute unsteady free surface flows of flood wave generated by torrent rains and flows produced by the operation of control structures, the first attempt was made by Stoker et al. (1953) . Since then, a variety of numerical techniques have been used to solve shallow water wave equations (Cunge et al., 1980 and Chaudhry, 1993).

In most of numerical models, the finite difference method has been used as it requires small space and time steps, but which decreases its efficiency. On the contrary, the finite element method (FEM) is not only accurate and efficient method but also flexible in handling general shapes of domain and boundary conditions, which is vital for fluid dynamic problems that often require the calculation of flows in complex geometrical phenomenon (Delphi et al., 2010 and Donea et al. 1984).

The Taylor-Galerkin scheme generates an accurate time-marching technique in accordance with high spatial resolution, which results from a Galerkin approximation (Qureshi & Baloch, 2013) Therefore, in this paper, the finite element model using two-step Taylor-Galerkin Predictor-Corrector (TGPC) scheme is used to develop one-dimensional numerical model for the computation of flood routing.

2 GOVERNING EQUATIONS

The flood routing modeling is based on the dynamic of Saint -Venant equations which consist the continuity and momentum equations. After neglecting terms related to inertia and momentum in Saint–Venant system, the following equation is derived at.

$$\frac{\partial Q}{\partial t} = -C\frac{\partial Q}{\partial x} + D\frac{\partial^2 Q}{\partial x^2} \tag{1}$$

Where, Q is the Discharge, C is the Wave celerity, D is the Diffusion Coefficient, t is the time and x is space in longitudinal direction.

Non-Dimensionalization of above governing equation is made using non-dimensional variables: space $x^* is \frac{Cx}{D}$, time $t^* is \frac{C^2 t}{D}$, inflow characteristics, $Q^* is \frac{Q}{Q_0}$ (where Q_o is initial discharge). Where, * is denoting the non-dimensionalized value.

Dropping the asterisks for simplicity and brevity, the non-dimensionalized equation be written as:

$$\frac{\partial Q}{\partial t} = -\frac{\partial Q}{\partial x} + \frac{\partial^2 Q}{\partial x^2} \tag{2}$$

The diffusive wave equation describes both convection and diffusion terms depend on two parameters, celerity and diffusivity, which are functions of the discharge. The resolution of this equation depends also on initial conditions, input hydrograph, lateral inflow/outflow hydrographs and geometric characteristics of the channel (Moussa & Bocquillon, 2001).

Diffusion Coefficient is an important parameter for rivers and streams, for Indus River it is as follows (Mahessar et al., 2013). $\text{Diffusion Coefficient} = D = \frac{0.058Q}{BS}$; Where, S is longitudinal bed slope and B is channel width.

3 NUMERICAL TECHNIQUE

The importance of numerical scheme for numerical simulation hinges on the accuracy, efficiency and stability of the algorithm. Literature shows that an explicit scheme requires small time steps (Δt) for convergence in computation so that the alternate approach is adapted, i.e. implicit and semi-implicit technique. The implicit schemes enhance stability but computational is more costly. However, semi-implicit scheme can be applied with the large time-steps are numerical stability and efficiency (Mahessar et al. 2013).

In step-1, predict the discharge Q at half time step (n+1/2) level using following equation:

$$\left(\frac{2M}{\Delta t} + \frac{SQ}{2}\right)\left(Q_j^{n+\frac{1}{2}} - Q_j^n\right) = -\left(N(C) + SQ\right) Q_j^n + b.t. \tag{3}$$

Using the above information from eq. (3), correct the second order accurate Q at full time (n+1) level in step-2 using following equation.

$$\left(\frac{M}{\Delta t} + \frac{S_Q}{2}\right)\left(Q_j^{n+1} - Q_j^n\right) = -N(C)Q_j^{n+\frac{1}{2}} - S_Q Q_j^n + b.t. \tag{4}$$

Where, M, N(C) and S_Q are matrices and b.t. is boundary terms. For details refer Cuvelier et al. (1986)

4 INDUS RIVER: SUKKUR TO KOTRI REACH

Indus river system comprises of seven rivers including the River Indus itself. The five rivers of Punjab i.e. Bias, Sutluj, Ravi, Chanab, and Jehlem discharge in Indus at Mithan Kot and the Kabul river from Afghanistan at Attock (Memon, 2004). The catchment of Indus is most unique in the sense that it contains seven (7) of the world's highest ranking peaks, after Mount Everest. These include K-2, Nanga Parbat and Rakaposhi etc. Likewise, barring the polar areas, seven glaciers situated in the Indus catchment are amongst the largest in the world, namely Siachan, Hispar, Biafo, Batura, Balttoro, Barpu and Hopper. This river is perennial having annual volume of water more than 125 billion cubic meter (BCM). The average peak flow of this river is 14,000 cumecs. There are six head works at Indus River but out of them three Barrages Guddu, Sukkur and Kotri are in Sindh province territory.

The daily discharge data for the year 2009, 2010 and 2011 at downstream of Sukkur barrage and upstream of Kotri barrage has been collected from Irrigation Department, Government of Sindh. The problem statement is shown in Fig. 1.

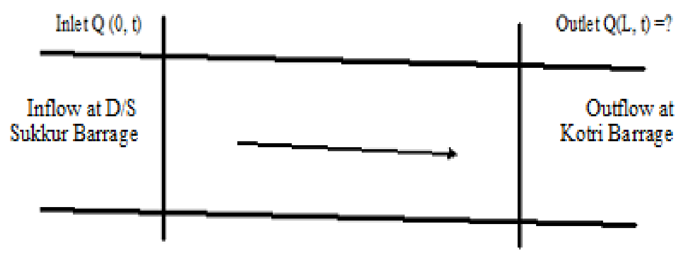


Figure 1. Problem statement: Sukkur -Kotri reach

The total length of Indus in Sindh is 864 km having Sukkur-Kotri reach 400 km (see Fig. 2). The Sukkur barrage is located at altitude 27^o 40’ 44” N and longitude 68^o 50’ 42” E and Kotri barrage is located at altitude 25^o 26’ 33” N and longitude 68^o 18’ 54” E.

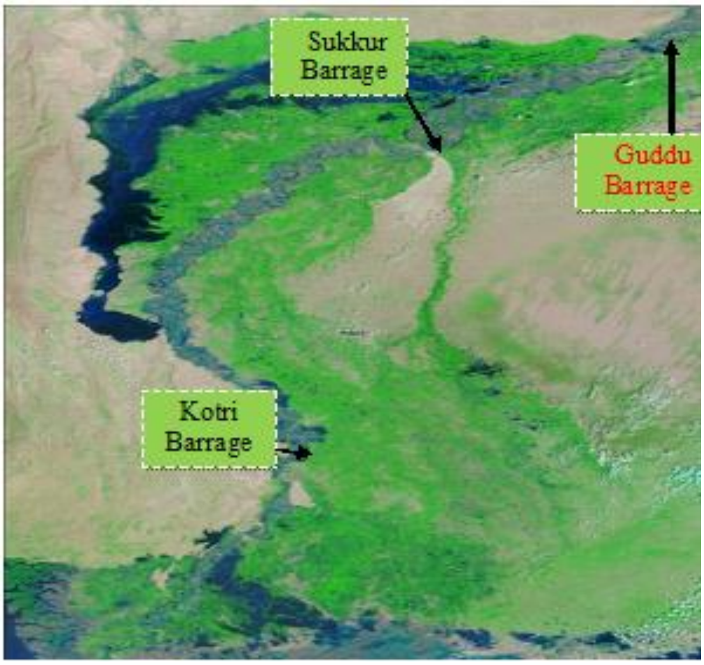
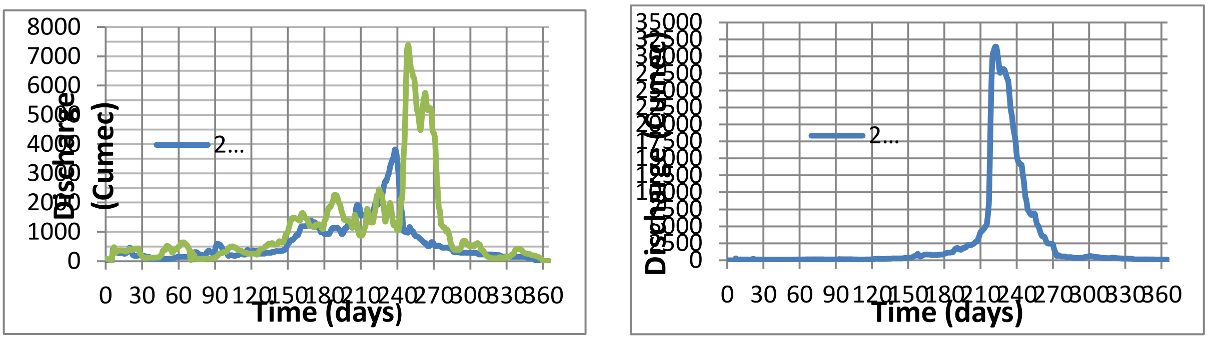


Figure 2. Satellite imagery of study area (Indus River: Sukkur-Kotri reach)

Floods for three years 2009, 2010 and 2011 have been taken for the study, which are categorized as Normal, Super and Low flood in terms of peak discharge during flood conditions. Hydrographs described in Fig. 3 for three years 2009, 2010 and 2011 at downstream of Sukkur barrage of Indus River are used as inlet boundary condition for the model. The numerical scheme presented above is employed to forecast hydrograph at upstream of Kotri barrage. No lateral inflow or outflow between Sukkur and Kotri reach has been assumed.



(a) Normal Flood 2009 and Low Flood 2011 (b) Super Flood 2010

Figure 3. Observed annual flow for year 2009, 2010 and 2011 at downstream Sukkur barrage

5 RESULTS AND DISCUSSIONS

Comparison of the observed and computed hydrographs at u/s of Kotri barrage for year 2009 is shown in Fig. 4 along with observed and computed four peaks; their comparison show a good agreement. Out of four peaks, there is only one major peak. These peak discharges show matching of observed with predicted ones. The error between observed and simulated high peak flow is only about 4.8%. The absolute relative error is varying for different months; however, the average annual relative error is about 13%.

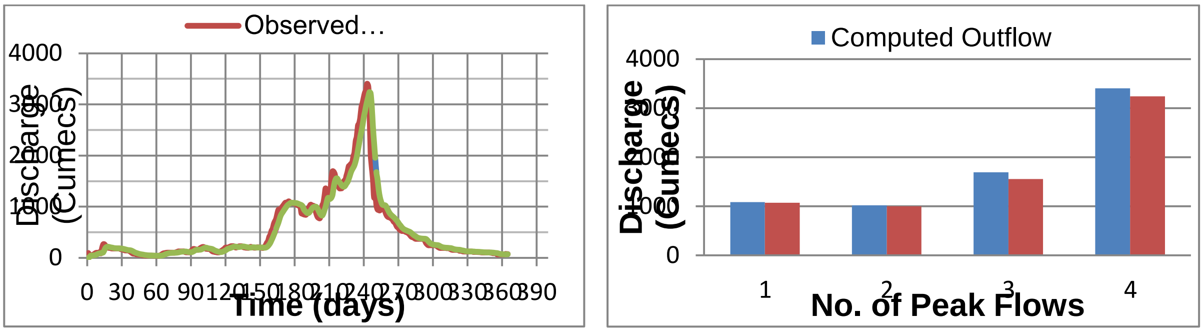


Figure 4. Computed and observed hydrographs at upstream of Kotri barrage along with peaks in 2009

The correlation coefficient R^2 of measured and predicted values of total volumes was calculated which comes 0.85; this shows a good agreement between observed and simulated results.

The observed and computed lag times for year 2009 are calculated for the peak flows. The observed minimum lag time is three days. For the major peak flow, the observed lag time is 6 days, whereas the computed lag time comes 8 days. Meanwhile, the average lag time is calculated which is seven to eight days.

For the Super Flood of 2010, the behavior of water flows at upstream of Kotri Barrage was computed. In this year, a super flood flow observed in the month August (i.e. from 210 to 240 days) that is due to monsoon abnormal rainfall and snow melting (see Fig. 5). In this year, there is only one peak which continuously move for about one month starts from low, to medium, then high and finally became Super flood just in 15 days, remain almost same in more than 10 days.

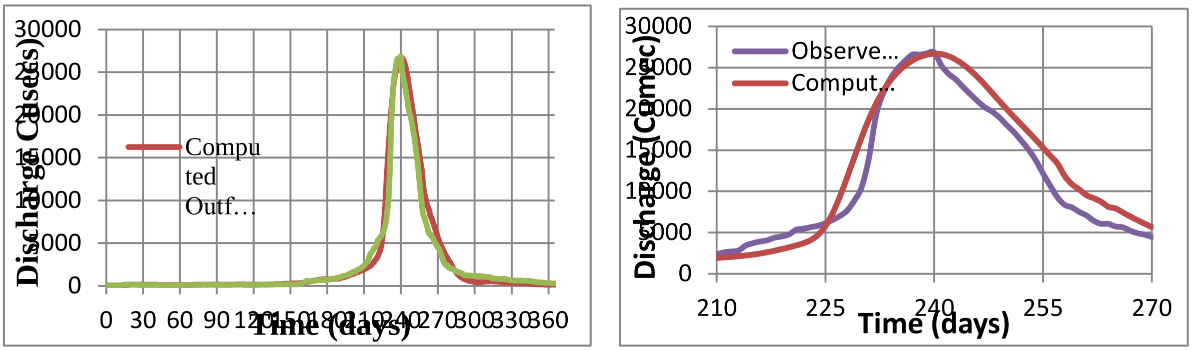


Figure 5. Computed and observed outflow hydrograph at upstream of Kotri barrage in year 2010

The hydrograph at u/s of Kotri barrage was computed through the model and was compared with the observed one (see Fig.5), which shows a good agreement. The absolute relative error for different months is not varying too much. The observed and computed highest peak flows show relatively realistic matching with each other (Fig. 5). The annual volume error (described in Table 1) is 5.7%, whereas, the peak flood error is about 2.4%., which is evidence of better agreement.

The observed and computed lag times for this Super flood 2010 are 16 and 17 days respectively; that is only one day variation; this matching clearly demonstrate the accuracy of the present model.

Now, for the year 2011, hydrograph at u/s of the Kotri barrage was computed; the comparison of observed and computed is shown in Fig. 6. There are total six peaks, one small, three medium and two high; these two high peaks observed continuously in the month of September 2011 are also shown in Fig. 6. Comparison of the model results against the observed data of annual hydrograph and especially two major peaks shown in bar chart demonstrate nice matching with each other. The peak flow variation of computed with respect to observed ones is 2 and 3% respectively; their average comes 2.5%.

The observed and computed lag times are also calculated and are shown in Fig. 7. There is variation between observed and computed time leg. The observed minimum lag time is four days (see Peak # 4); however, the computed minimum lag time is two (see Peak # 5). On the other hand, the maximum lag time for observed and computed is seven and nine days respectively. Meanwhile, the average lag time is calculated which comes five to six days. The measured and predicted values volumes were calculated, their error is 17.085 %, whereas the peak error is about 2.165%.

The evaluation of simulated results against measured data (see Table 1) reveals that there is good agreement between them. Model is efficient and accurate which proves good application of this reach of the Indus river.

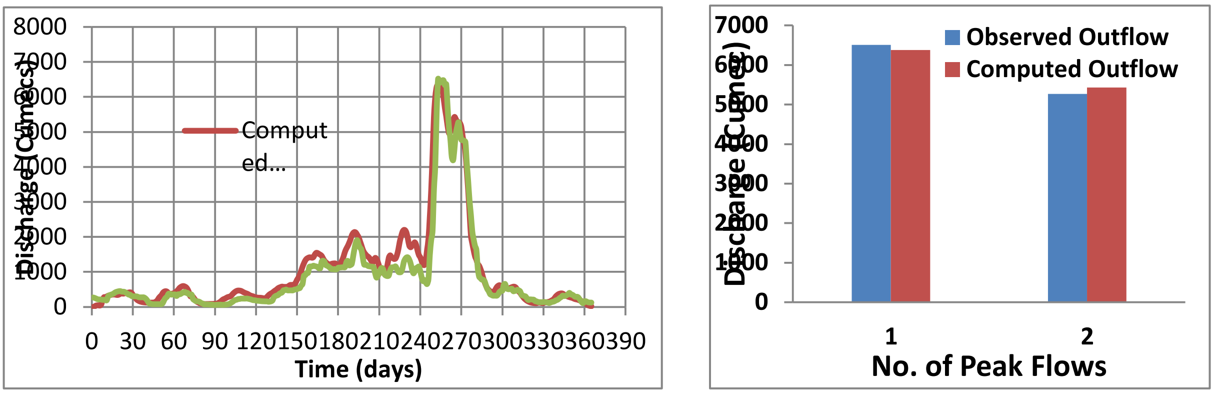


Figure 6. Computed and observed outflow hydrograph and two major peaks for the year 2011

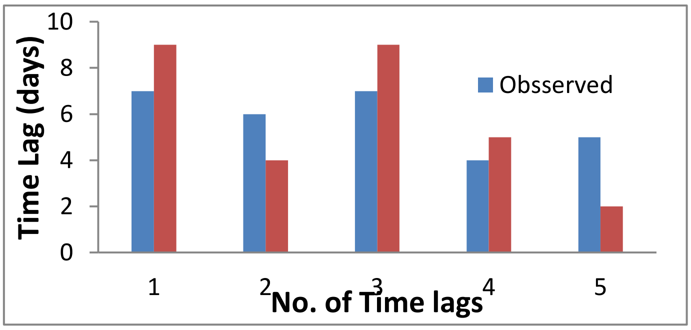


Figure 7: Computed and Observed Time Lag (days) at u/s of Kotri barrage for Year 2011

Table-1: Evaluation of Measured Data against Simulated results

Description	**Values for the**		
	Normal Flood 2009	**Supper flood 2010**	**Low Flood 2011**
Observed Peak Flow (m^3/sec)	3404.849	26688.909	6512.221
Computed Peak Flow (m^3/sec)	3241.642	27328.773	6380.898
Error (%)	4.793	2.397	2.01655
Average Error (%)	**3.07**		
Volume of observed flow (BCM)	16.465	78.456	28.0658
Volume of simulated flow (BCM)	19.488	82.921	32.861
Volume error (%)	18.36	5.6913	17.085
Maximum positive difference b/w observed & computed flow (m^3/sec)	466	1585	927
Minimum negative difference b/w observed & computed flow (m^3/sec)	-0.66	-0.67	-7.04

6 CONCLUSIONS

The developed finite element model using semi-implicit TGPC scheme has been applied for the simulation of flood routing of Sukkur-Kotri reach of the Indus River for Normal, Low and Super floods (www.pmd.gov.pk). The observed and computed hydrographs at upstream of Kotri barrage having average error of about 3% provides an accurate resolution of the model under field conditions. Hence, it is concluded that this model is capable of computing accurate results for various floods stages. The model calculates peak flow attenuation and time lag which is vital to be computed for flood routing.

The observed lag time for the normal flood 2009 is 6 days and for low flood 2011 comes five to six days; however, for the Super flood 2010, it is 16 days. The observed and computed lag times for this Super flood 2010 are 16 and 17 days respectively; that is only one day variation; this matching clearly reveals the accuracy of the present model.

Applicability and accuracy of this model has also been evaluated. The model shows accurate prediction with peak error of 4.8, 2.4 and 2.02% and maximum positive and negative difference of peak flow attenuation are 466, 1585, 927 m^3/sec and -0.660, 0.666 and -.7.04 m^3/sec respectively. This validates that the model demonstrate the conformity of the scheme suitable for lower Indus region.

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