Journal of Himalayan Earth Sciences Volume 48, No. 2, 2015 pp.129-138

Flood hazard assessment using hydro-dynamic model and GIS/RS tools: A case study of Babuzai-Kabal tehsil Swat Basin, Pakistan

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Abstract

Flooding is the most recurrent and devastating phenomenon around the globe. Heavy precipitation in the monsoon season especially in south Asian countries like, Pakistan, Bangladesh and India coupling with snow melting, generates, overflow in the river channels. This overflow in the river channel ravages the downstream areas and cause damages to both life and property. Due to the frequent flooding and its destruction, the demand for flood hazard assessment using GIS and RS, has tremendously increased. In the present study the river channel in the district Swat, northern Pakistan was modeled through the integration of field data, HEC-RAS, ASTER DEM and GIS. GIS and HEC-GeoRAS were used for the geospatial analysis of the study using ASTER DEM (30 m). The river geometry data was obtained through the field survey using Total Station (Sokkia, Model No= CX105). HEC-RAS has been used for the simulation of the hydrological data. The HEC-RAS model was calibrated by known water discharge (4971 m^3/s) for the peak flood of 2010 with the support of Manning's 'n' values and contraction and expansion of the river channel. The overall model results show an average difference of 0.36 m, which is in the acceptable limits. To validate the results against known water surface (HFL) for the year 2010, a correlation curve was developed. The curve indicated best correlation (R2= 0.99) between known and computed water surfaces. However, due to the relatively coarse resolution of the ASTER DEM, the development of flood hazard map was limited. Further, the study suggested that the integration of GIS, RS and HEC-RAS play a vital role in the prediction of future floods and its spatial inundation in the nearby floodplains.

Keywords: Remote sensing; Floods; Hydrodynamic model; Swat.

1. Introduction

Natural hazards are intense conditions that exist inside the natural environment (atmosphere, biosphere, hydrosphere and lithosphere) and have diverse capabilities of causing damages to both life and property. These extreme events have significant impact on the socio-economic system of the human settlement (Alexander, 1993). Like other natural hazards, hydro-meteorological hazards such as floods and storms, dominated major portion in the mass of natural disasters. It was found in the year 2010, that natural disaster including floods and storms displaced about 42 million people around the world (UNEP/OCHA, 2010). According to the disaster statistical report for the year 2013 by the Centre for Research on the Epidemiology of Disasters (CRED), showed that hydrological events (floods and mass movement (wet)) still claim the largest (48.2%) share in comparison to other natural disasters (Fig. 1).

Pakistan is a disaster–prone country due to its geo-physical and climatic conditions. The country is severely affected and still prone to different natural hazards i.e. hydro-meteorological, geo-physical and biological (NDMA, 2013). Among the natural hazards, flood's is the most frequent and complex natural disaster in the country followed by earthquakes, cyclones and drought (ADB, 2008; UNEP/OCHA, 2010). In the last 65 years the Pakistan economy has set back with a cumulative financial shock of more than US$ 39.055 billion due to different flood disasters (GoP, 2012). The floods of 2010, was ever worst in the history of the country, which caused widespread damages across the Pakistan, killing about 1985 people, 2,946 got injured, over 1.6 million homes were destroyed and 20 million people were seriously affected (NDMA, 2010; GoP, 2012). The number of people affected was high in comparison to other disasters such as the 2004 Indian Ocean Tsunami, the 2005 Kashmir Earthquake, Cyclone Nargis 2008 and the 2010 Haiti Earthquake (Table 1).

Swat district located in the northern part of the country is vulnerable to frequent floods (Nasir and Khan, 2011). In the area, floods are mainly induced by rainfall in the form of erratic and cloud burst and summer snow-melt especially in the late monsoon season i.e. July to September. This heavy downpour of the rain also aggravate secondary hazards such as landslides, mudslides, soil erosion and sediment deposition downstream (Rahman and Khan, 2011; PDMA, 2015). Moreover, due to high gradient of the river, the virulent flow often caused severe damages to the nearby properties and infrastructure (PDMA, 2015). The district has suffered a number of disastrous floods in the year 1973, 1992, 1993, 1994, 1995, 1996, 2001 and 2010 (Table 2).

However, the flood of 2010 had caused severe damages to both life and property. It caused the death of 86 people; loss of 9800 animals, damaged more than 4000 houses and uprooted dozen of bridges (Rahman and Khan, 2011). According to various studies (Nawaz, 1987; EPS, 2003; Rahman and Khan, 2011), the frequent floods in the area had posed damages to the inhabitants and posing a serious threat to the socio-economic development.

Geographic Information System (GIS) and Remote Sensing are frequently and effectively used for flood hazard forecasting and mapping (Dewan et al., 2006; Bhatt et al., 2014). Similarly, the applications of hydrodynamic models are also quite obvious in flood management studies and are used as a decision support tool. However, these models require proper characterization of the channel and adjacent floodplain. HEC-Geo RAS, an extension used in the ArcGIS, to process geospatial data for use with the Hydrological Engineering Centre River Analysis System (HEC-RAS). HEC-RAS is a 1D hydrodynamic model, used to simulate river flood phenomena and the results can be presented in geospatial format (Ahmad et al., 2010). Sanaullah (2011) applied HEC-RAS one-dimensional model in combination with the ASTER DEM for flood modelling in the Kalpani river reach in Khyber Pakhtunkhwa, Pakistan. Similarly, Solaimani (2011) also utilizes a hybrid approach of HEC-RAS and GIS to determine vulnerable localities along a 5 km long Nike river channel in northern Iran. This computer based 1-D hydrodynamic model possess some advantages like, modeling single reach or whole basin, steady flow and unsteady flow computations, water quality analysis, graphical user interface (GUI), separate analysis component and tabular representation of the analysis (HEC, 2010). Being 1D in nature it is generally very efficient, but posing limitations like the inability to simulate the lateral diffusion of flow, the representation of topography in the form of cross-sections rather than as a surface and in steady flow, some constraint seen like gradual variation, longitudinal simulation and channels with small slopes (Cook, 2008). With the developments in integrating capabilities of Remote Sensing (RS) (satellite imagery, Digital Elevation Models (DEMs)), GIS and Hydrodynamic modelling have provided opportunities for quantitative analysis of flood events, from local to regional scales (Johnson et al., 2001). The aim of this study is to apply GIS/RS, field data and Hydro-dynamic modelling for flood hazard assessment in the study area.

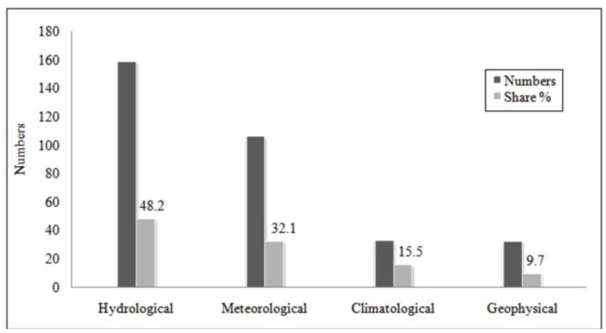

Fig. 1. Numbers and share % of different natural disaster in the year 2013 (Source: Guha-Sapir et al., 2014).

Table 1. Comparison of 2010 floods with other major disasters in the world.

	Pakistan Floods 2010	Kashmir Earthquake 2005	Katrina Cyclone USA 2005	Nargis Cyclone Myanmar 2008	Indian Ocean Tsunami 2004	Haiti Earthquake 2010
Population Affected (No.)	20,251,550	3,500,000	500,000	2,420,000	2,273,273	3,200,000
Area Affected (Km^2)	132,000	30,000	NA	23,500	NA	13,226
Death (No.)	1985	73,338	1,836	84,537	238,000	23,000
Injured (No.)	2946	128,309	NA	19,359	125,000	300,000

Table 2. Flood damages in district Swat, 1992-2010

Year	Discharge in cumec (m^3s^{-1})	Affected area	Type of damages
August 1992	3587	Khwazakhela & Matta	Protective Embankment of bridge connecting Khwazakhela and Matta was washed away along with standing crops and orchards
July 1993	728	Swat district	Damages to crops worth more than 3 million Pak rupees*
July 1995	1474	Mingora	Protective embankments and bridge near Mingora washed away as well as drowning of four people and damage to standing crops. The cost of embankment reconstruction was more than 1 million Pakistani rupees
August 1995		Swat district	Damages to only crops were more than 2 million Pak rupees
July 1996	1073	Khwazakhela & Matta	Road between Khwazakhela and Matta washed away and communication link was cut off for 2 months
August 1996		Swat district	Standing crops and fruit orchards lost with an estimated loss of 3 million Pak rupees
July 2010	4971	Swat district	86 Death casualties, loss of 9,800 animals, 4,000 houses washed away and dozens of bridges were uprooted

2. Study area

District Swat stretches in the northern region of Pakistan (Fig. 2) with a total area of 5,337 km^2 (GoP, 1999). The elevation of the area ranges from 733 to 5670 m mean sea level (Rahman and Khan, 2011). Topographically, Swat lies between the western and eastern mountain ranges of Hindukush. The western part of the mountain range divides Swat and Dir districts (Swat-Dir divide) whereas, the eastern part of the mountain range marks the boundary between Swat and Indus river watershed (GoP, 1999). Climatically, Swat is influenced by various factors such as latitude, altitude, summer monsoon and the wind current coming from the Mediterranean sea in winter. The overall climatic prospect of the area is divided into semi-arid, sub-humid and humid (Khan et al., 2010). Tectonically, the study area belongs to the Indian Plate, Melange Zone and the Kohistan Island Arc (Afridi et al., 1995). However, major part of the study area is covered by unconsolidated Quaternary stream channel deposits. The Swat valley consists of another physiographic portion, known as the Swat basin which is drained by Swat river and its tributaries (Rahman and Khan, 2011). The Swat river emerges in the region of Kalam from three main tributaries the Gabral, Bhandra and Ushu (EPS, 2003). The river is recharged by rain and summer snowmelt. Major tributaries of the river inside the Swat district are Ghail, Mankial, Daral, Chail, Haronai, Kokarai, Marghazar and Hazara (Shah, 2013; PDMA, 2015).The total length of Swat river from Kalam to river Kabul is 250 Km. Before merging in river Kabul, it drains about 14,000 km^2 areas up to Munda headwork (EPS, 2003). The River and its tributaries are famous for summer floods. Almost every year, during the month of June, July and August the recurrent floods occur that causes potential damages to life and property (Rahman and Khan, 2011). The study area spread over parts of the Babuzai and Kabal Tehsils of district Swat (Fig. 2). The selected strip (6 Km) is a part of the Swat river that marks boundary between the two Tehsils i.e. Babuzai and Kabal, and is longitudinally extend from upstream Sangota to downstream Ayub bridge (Fig. 2).

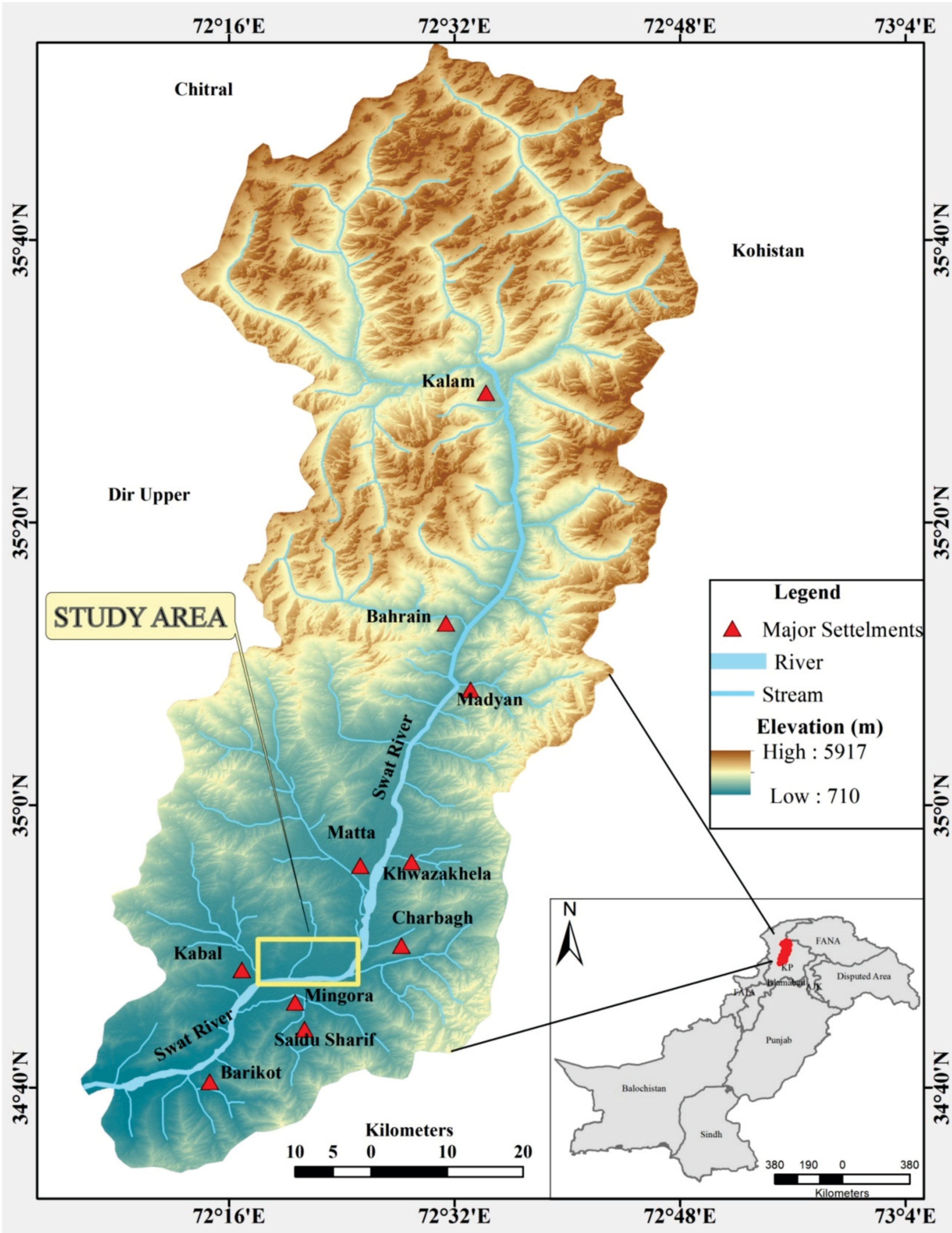

Fig. 2. Location map (ASTER DEM) of the study area.

3. Methodology

The overall methodology of this research study comprised of five phases namely; 1) preparation, 2) fieldwork and data acquisition, 3) river flood modelling 4) validation of model results and e) conclusion (Fig. 3).

Geospatial data and river discharge data were collected during the field visits from concern organizations and other relevant sources (Table 3).

ArcGIS (9.3) and HEC-GeoRAS were used for the geospatial analysis of the study. Google Earth and Quantum GIS (1.7.4) were utilized for the development of land use map of the study area. HEC-RAS (4.1), a1-D flood model were used for hydrological simulations. The river geometry data (river cross-sections & cross profiling) is important to understand the hydraulic geometry of river system and how the width, depth and velocity of natural rivers change in a downstream direction. It is also the main input parameter for HEC-RAS model. Before starting the cross-sectional survey of the proposed river reach, two control points were recorded using GPS (Garmin, Model No: eTrex-2000). These points were used as a reference for the rest of the field survey. Between the upper and lower reach of the selected river channel, total of 12 cross-sections were drawn at 500 m interval (Fig. 4). Additionally, during the field thorough observations were made to observe the land use pattern in the floodplain on both sides of the river channel for hydraulic roughness determination. However for obtaining Manning 'n' both field base data and the reference table of Chow (1959) were used. Total Station (Sokkia, Model No: CX105) available at the National Centre of Excellence in Geology, University of Peshawar, was used in the field for obtaining the geometry data of the selected river reach (Fig. 5).

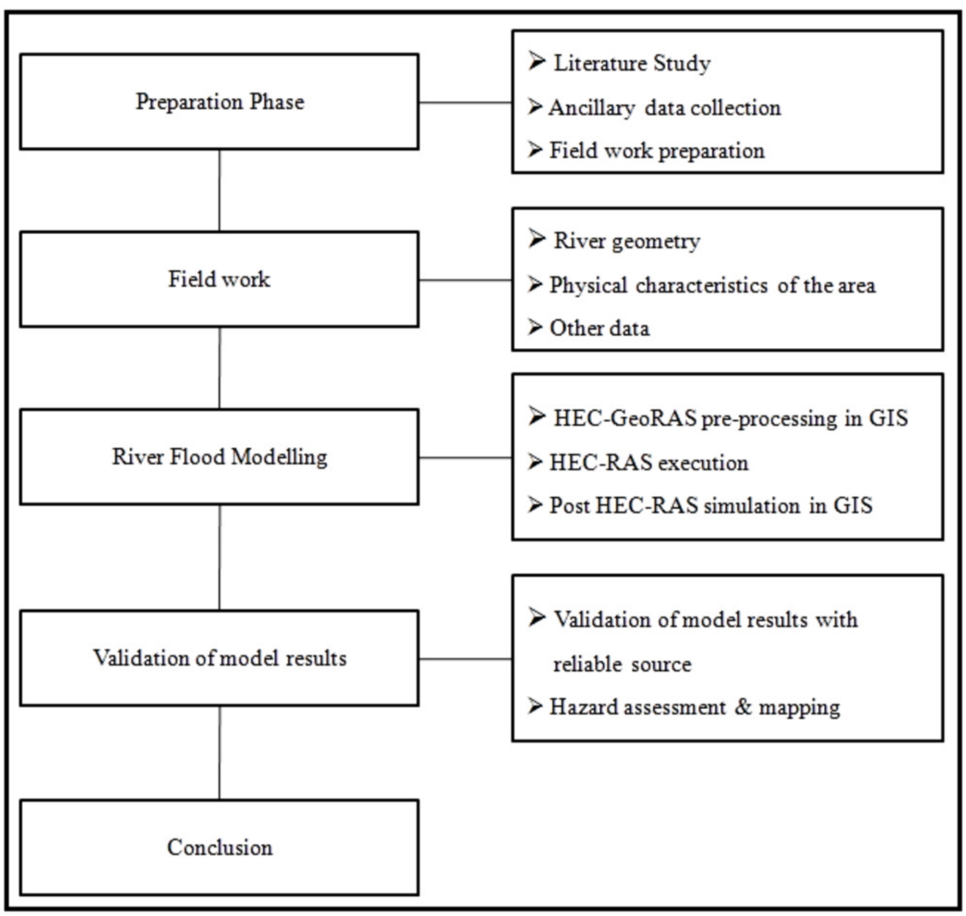

Fig. 3. Research methodology adopted for the study.

Table 3. Different data and their sources used in the research study.

S.No	Data	Sources
1	Digital Elevation Model DEM (30 m)	From Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)
2	Discharge normal and Peak (m^3s-1)	Hydrology wing, Irrigation Department, Peshawar, Khyber Pakhtunkhwa.
3	Administration map 1: 169000	Survey of Pakistan
4	Landuse map of the proposed area	Prepared from Google earth
5	Manning, n Values	Adopted from Chow (1959)

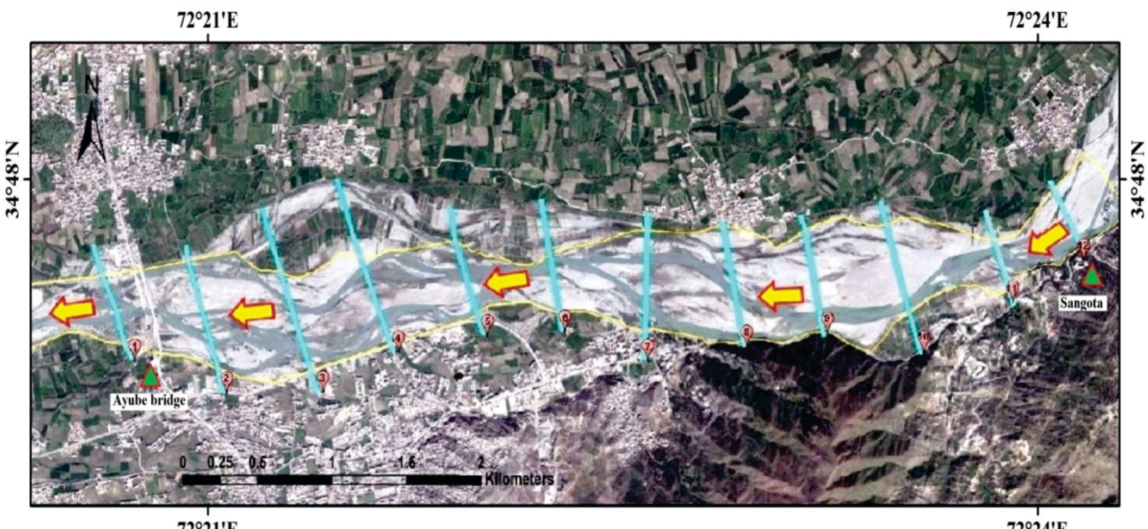

Fig. 4. Location of cross-sections on Google-Earth image at the proposed river reach.

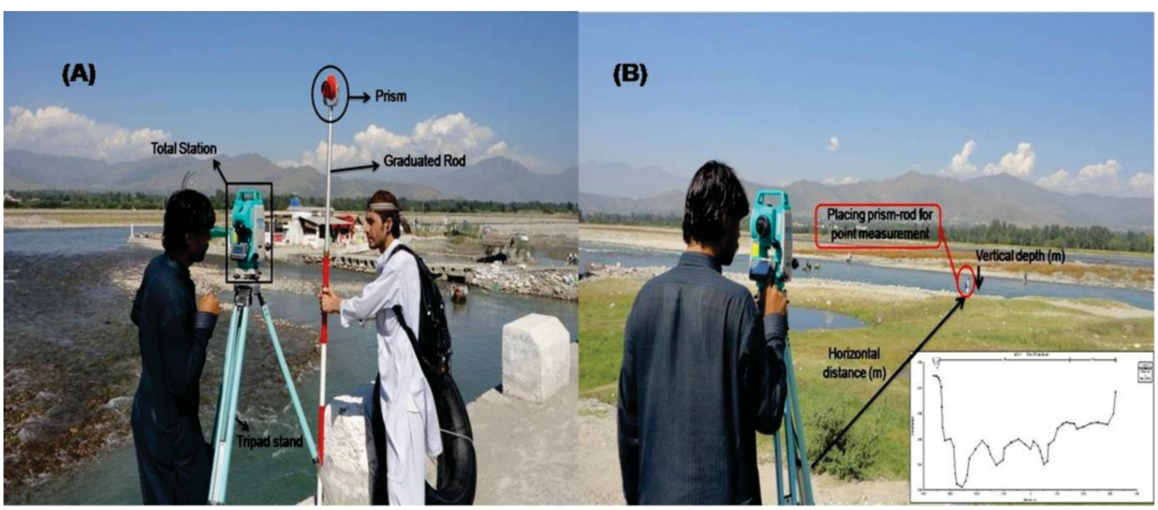

Fig. 5 (a). Point measurement during the field survey at the left bank of the Swat River.
(B) A view of the cross-section on the Swat River.

The next phase is the river flood modelling (Fig. 3) through HEC-RAS one dimensional flow model. In order to simulate the flood phenomenon, HEC-RAS need two types of data i.e. geometric data and hydrological data for river channel modelling. Geometric data was acquired from 30m ASTER DEM as a base and is supplemented by river cross-sections data, landuse map and topographic map at a scale of 1:250000. The geometric data is the pre-simulation requirement of the hydrodynamic modelling software. It was created through HEC-GeoRAS program in the ArcGIS environment. For generating the hydrological data, the HEC-RAS program was used. However, for the discharge data the return periods were estimated by using Weibull formula (Eq. 1) and the related exceedance probability in percentage were calculated by an inverse of the Weibull formula (Eq. 2) (UCAR, 2010).

$$T = \frac{n+1}{m} \text{ ---------------------------- Eq. 1}$$

$$\text{Prob. (\%)} = \frac{m}{n+1}(100) \text{ ---------------------- Eq. 2}$$

Where T is the returned period, N is the number of observation and m is the rank. The probable peak discharge for the hydrological data is given in the table 4.

Table 4. Probable peak discharge for Swat river at Khwazakhela station.

Returned period (year)	Probable peak discharge (m^3sec^{-1})
5	2378
10	3341
25	4644
50	5606
100	6513

4. Results

The HEC-RAS model was calibrated using known water discharge (4971 m^3/s) for the peak flood year of 2010 with the incorporation of Manning's 'n' values (0.013, 0.025, 0.04, 0.05 and 0.06) and contraction and expansion data. The water surface computed from the model calibration for the peak flood year of 2010 is given in Figure 6.

Figure 6. Water surface generated during the model calibration for the year 2010.After the calibration of model it was simulated for whole of five different returned periods (05, 10, 25, 50 and 100 years) with normal depth and boundary condition. The water surfaces computed from HEC-RAS for all the returned periods are given in the Figure7.The HEC-RAS computes water level at every river station that can be viewed both in graphical and tabular format for understanding the model hydraulic behavior. The three dimensional perspective plot of the total surface area resulted from the model for the 100-year returned period is also given in Figure 8.

4.1. Results validation

The model was validated for 2010 peak flood using calibrated model values and the observed HFL points. The results computed by the hydrodynamic model were slightly higher (0.4-0.5 m) for some of the river stations (02, 04 and 07) but in comparison to overall the results show an average difference of 0.36 m which is nearly to the acceptable limits (as determined by FEMA (± 0.2 m) incorporated by Sanaullah, 2011). To evaluate the model reliability, the computed water surface is compared with the known water surface (HFL) (Fig. 9), showing the R2= 0.99, indicating the quality of the model.

5. Conclusion

The river channel spread over parts of the Babuzai-Kabal tehsil (from upper reach Sangota to lower reach Ayub bridge) of the Swat basin was successfully modeled through HEC-RAS 1-D. The selected river channel is passing laterally from the main town of Mingora. The integration of GIS/RS and Hydro-Dynamic model (HEC-RAS) were successfully simulated for flood hazard modelling. The model results were validated with the field based data that were collected with each river station (cross-section) for the peak flood of 2010. The validation results were nearly to the acceptable limits of (± 0.2m) as determined by the FEMA for geospatial data. However, due to the relatively coarse resolution of the ASTER DEM that is used in this research study, the post processing of the model results in ArcGIS were not possible for the creation of flood hazard map. It is concluded from the proposed study, that the integration of GIS, RS (ASTER DEM) and Hydro-dynamic model (HEC-RAS) play a vital role in predicting of future floods and its spatial inundation in the nearby floodplains.

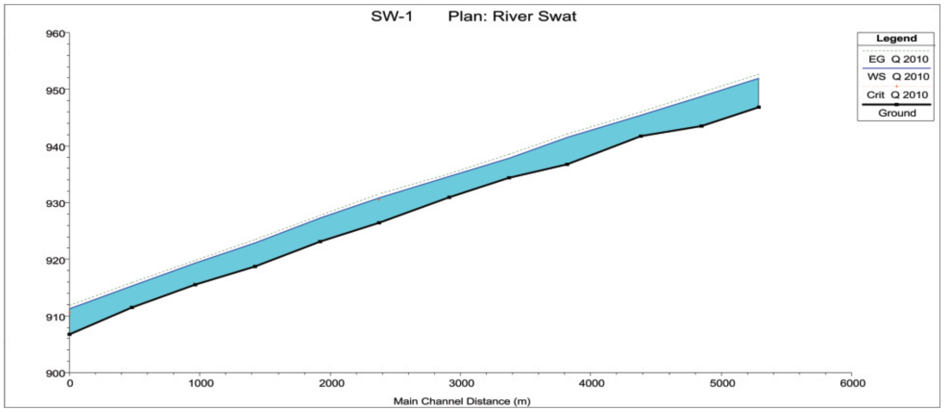

Fig. 6. Water surface generated during the model calibration for the year 2010.

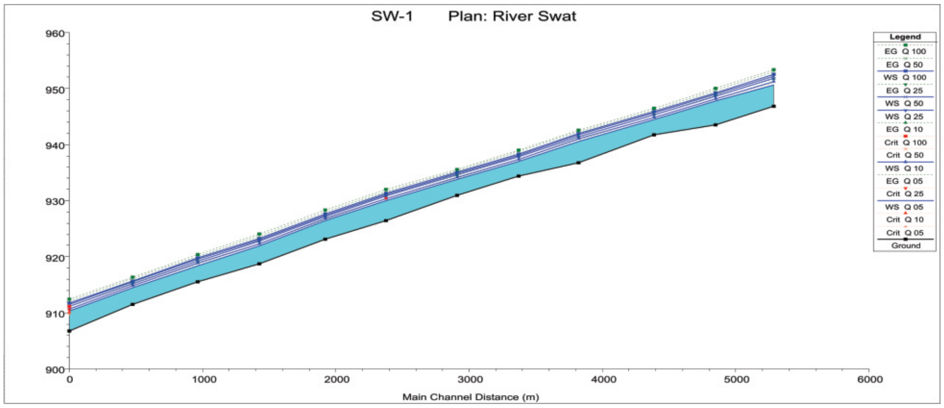

Fig. 7. Water Surface profile for all returned periods.

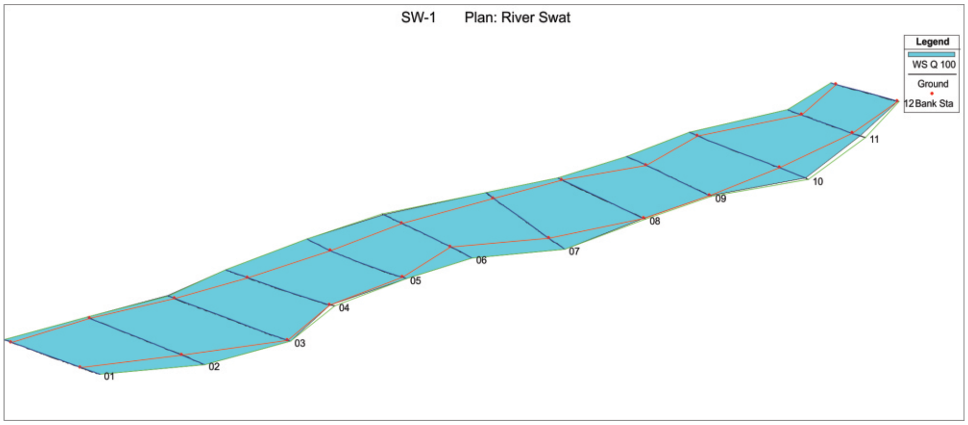

Fig. 8. 3D view of total SA of the long term 100-years returned period.

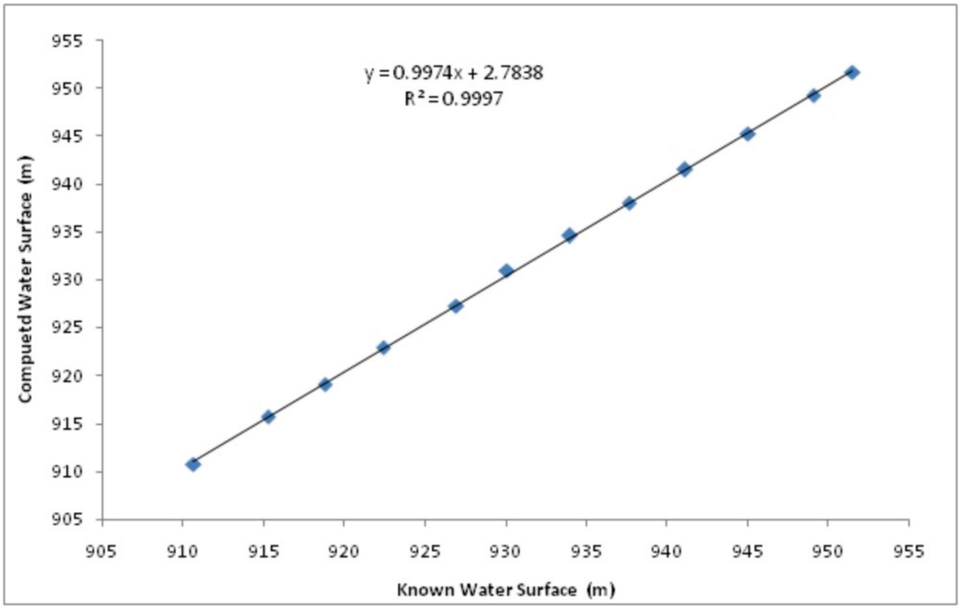

Fig. 9: Known and computed water surfaces for model validation output.

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