

HYDROLOGICAL MODELLING AND FLOOD HAZARD MAPPING OF NULLAH LAI

Bashir Ahmad^{*1}, Muhammad Shumail Kaleem², Mohsin Jamil Butt³, Zakir Hussain Dahri¹

¹Pakistan Agricultural Research Council (PARC), Islamabad, Pakistan, ²Pakistan Poverty Alleviation Fund, Islamabad, Pakistan, and ³Department of Meteorology, COMSATS, Islamabad, Pakistan

Received Dec.2009, accepted August 2010

Abstract: Floods are among the most devastating natural hazards in the world causing huge losses of lives and infrastructure. Flooding can be partially avoided but flood hazards can never be ruled out. However, future flood prevention measures require a stronger stress on integrated approaches incorporating flood forecasting and risk uncertainties. Therefore, an appropriate flood modeling and mapping approach is needed to assess the potential damages. This study is carried out by integrating hydrological models with GIS to estimate the flood zone of Nullah Lai in Rawalpindi. HEC-RAS and HEC-GeoRAS hydrological models have been used to delineate the areas vulnerable to flood at different discharge values. A topographic survey of fine resolution of the target area (Kattarian to Gawalmandi Bridges) was used to generate the DEM of the area. Krigging was used to interpolate the elevation data. GIS technology has been used to delineate the variation of topography and to find the inundation depths at various locations in the study area. Inundation area estimated at the discharge value of 3000 m³/sec is 3.4 km² out of which 2.96 km² is occupied under the inundation depth from 1 to 5 meters. Maximum inundation depth can go up to 20 meters for this discharge value. Output of the study using HEC-RAS shows that inundated areas and inundation depths are in close approximation with survey based inundation results obtained by JICA. This shows that the integrated modeling approach used in the present study works well in order to delineate areas vulnerable to flood with a good estimation of inundation depths at a specific discharge value.

Keywords: Hydrological modelling, risk assessment, hazard mapping, satellite remote sensing

Introduction

In many regions and countries floods are the most devastating natural hazards affecting the social and economic aspects of the population [1] and claiming more lives than any other natural phenomena [2]. The frequency with which floods occur is increasing in many regions of the world [3]. With the increasing impacts of climate change and the more recent flood events throughout the world, there is a need to establish more useful flood risk management plans and strategies [4]. The quality of flood forecasting systems depends mainly on the quality and the amount of basic collected data about hydrology and the hydrological yield of the corresponding watershed.

The application of predictive models in flood inundation assessment is already widespread and is well-accepted decision support tool. However, two main approaches

in fluvial hydraulic modeling happen to be the most popular: 1D modeling and 2D modeling. 1D modeling approach is based on the one dimensional solution of the Saint-Venant equation [5] like the models MIKE-11 and HEC-RAS [6]. These models require the characterization of the terrain through a series of cross-sections perpendicular to the direction of flow for which the average water depth and velocity of flow are calculated.

In near flat-terrain with complex topography it can not be assumed that all flow will be parallel to the river. Models are required that calculate flow in both spatial dimensions, in X- and Y- directions, such models like Delft-FSL [7,8], Telemac 2D [9] and MIKE21 [10] are based on the two dimensional solution of the De Saint Venant equations. They require a continuous representation of the topography in the form of a digital surface model.

Modern hydrological modeling techniques

* Email: bashirad@hotmail.com

have assisted scientists and engineers with determining floods as well as flood assessments. According to Snead, [11] computer models for the determination of flood's effect generally require four parts, i.e. 1) the hydrological model which develops rainfall-runoff from a design storm or historic storm event, 2) the hydraulic model which routes the runoff through stream channels to determine water surface profiles at specific locations along the stream network, 3) a tool for floodplain mapping and visualization, and 4) the extraction of geospatial data for use in the model(s).

In the field of flood zone mapping such integration provides valuable basis for assessment of flood prone area and spatial analysis and modeling of flood hazard phenomenon. Flood map hazard is also one of the important steps in non-structural flood control. In recent decades, non-structural flood control methods have been noticed as effective and economical methods in decreasing flood effects. These methods try to match flood condition and manage damage reduction. Non-structural methods have less cost in compare to structural methods and could show more effects besides each other [12].

Recent advances in Geographic Information Systems and hydrological modeling techniques allow their powerful integration. Since flood modeling has greatly improved in recent years with the advent of Geographic Information Systems (GIS), radar-based, high-resolution Digital Elevation Models (DEMs), distributed hydrologic models and delivery systems on the internet [13]. It is believed that these advances will provide for a more efficient and a more accurate alternative to traditional methods for studying watersheds [14].

As high-resolution digital elevation models (DEMs) become more readily available, it is

possible to map not only flood extents but also flood depths for a given event. Complementary to the remote-sensing observations, a DEM can also be used to extract flooding under dense vegetation and forest cover and within residential areas [15,16]. From a disaster management point of view, water depth information for a given flood event as well as flood visualization within urban areas is of paramount importance for obvious reasons such as property loss and damage, health issues related to standing waters, and the assessment of socioeconomic damages.

The study employed HEC-GeoRAS, which works as ArcGIS extension specially designed to process geospatial data for use with the Hydrological Engineering Centre River Analysis System (HEC-RAS). HEC-RAS can be used to perform river flood using floodplain encroachment analysis and the results can be presented in a geospatial format [17].

Several studies pertaining to the flood hazard problem of Nullah Lai, Islamabad-Rawalpindi were conducted. However, research on the integration of GIS and hydrologic modeling for flood hazard assessment and mapping has not been done in the area. Present study is an attempt to bridge this gap and evaluate the usefulness of GIS technology and DEM data for flood hazard assessment and mapping. This study may provide useful suggestions to identify and delineate areas vulnerable to flood by integrated use of GIS and hydrological modeling.

Objectives of this research work are:

- River flood modeling within the GIS environment
- Assessment of flood water depth and delineation of vulnerable areas
- Risk assessment and hazard mapping for different scenarios

Materials and Methods

Study area

The Lai Nullah Basin is located in the northern part of Pakistan between $33^{\circ} 45' 00''$ and $33^{\circ} 32' 30''$ North and $72^{\circ} 57' 30''$ and $73^{\circ} 07' 30''$ East, with a basin area of 235 Km². The upper basin covering 161.3 km² (69%) falls in Islamabad city and the lower basin covering 73.6 km² falls in Rawalpindi city and its suburbs. The drain has a length of about 30 Km and has six major tributaries, three originating at the foothills of Islamabad in the higher altitude area; and remaining three at the lower altitudes. The elevation of the Lai Nullah Basin ranges from 420 m at the confluence of Soan River to almost 1200 m at mountain top in the Margala range as shown in Figure 1. Four major tributaries are Saidpur Kas, Tenawali Kas, Bedarawali Kas and Johd Kas finally flow into Lai Nullah just

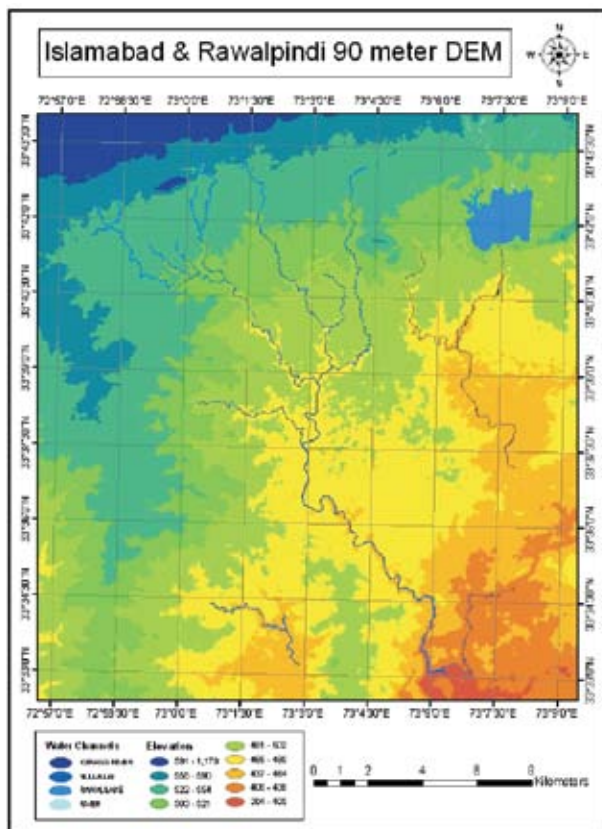


Table 1. Spatial data and source

No	Spatial Data	Source
1	Digital Elevation Model (DEM)	Prepared by Topographic survey based elevation data and modified using different Interpolation techniques
2	Topographic Map (Scale 1: 50,000)	Acquired from Survey of Pakistan (SOP)
3	Land Use Map of Rawalpindi & Islamabad	Japan International Cooperation Agency (JICA 2002)
4	Administration Map (Scale 1:50,000)	Tehsil Municipal Administration (TMA) Rawalpindi. Capital Development Authority (CDA) Islamabad
No	Hydrological data	Source
1	Climatic Data	Pakistan Meteorological Department (PMD)
3	Peak Discharge (100 year return period)	Japan International Cooperation Agency (JICA)
4	River Cross-Section	Japan International Cooperation Agency (JICA)
5	River Cross-Profile (upstream to downstream)	Japan International Cooperation Agency (JICA)

Table 2. Existing rainfall stations in study area

Station	Location			Year of establishment	Frequency of measurement	Year of Installation of Self-recorder
	Latitude (North)	Longitude (East)	Altitude (m)			
Chaklala	33°37'	73°06'	500	1931	Every 3 Hrs	(1951)**
Islamabad	33°41.00	73°03.87	520	1967*	Every 3 Hrs	1999
RAMC	33°38.88	73°05.13	500	1989	3 Times a Day	1989
Saidpur	33°44.56	73°03.91	660	1994	Once a Day	N/a

of spatial and hydrological data including 90 m resolution DEM from SRTM; topographic maps acquired from survey of Pakistan; land use map, peak discharge, drain cross-section and drain cross-profile developed by JICA; climatic data from Pakistan Meteorological Department (PMD); and administration maps from Capital Development Authority (CDA).

There are seven gauges for rainfall measurements in the Nullah Lai Basin as shown in Table 2 alongwith latitude and longitudes. Most of them record data after every three hours at 0200, 0500, 0800, 1100, 1400, 1700, 2000 and 2300 hours (PST) at the Chaklala and Islamabad Stations, three times a day at 0800, 1400 and 1700 hours at the RAMC Station, and once a

day at 0800 hours at Saidpur Station. A self-recording rain gauge is annexed to two stations, Islamabad and RAMC. Water measuring stations are at Katerian and Gawalmandi Bridges.

Hydrological modeling

This phase consists of implementing the river flood models for specific data inputs. The flood modeling gives more focus in the low-lying areas, where most of the commercial and residential areas are located. An integrated approach using hydrological modeling and GIS softwares has been used for river flow modeling. The HEC-RAS software has been used to perform, calculate and analyze the hydrological factors, as well as to generate the 3D perspective

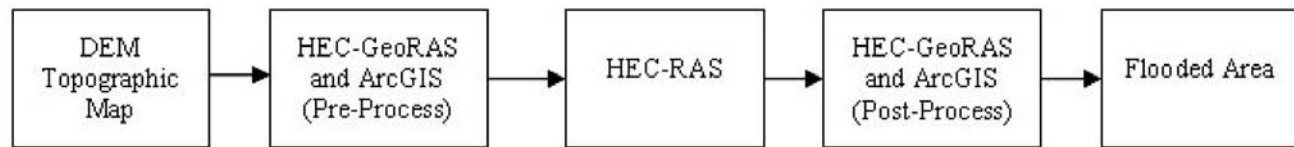


Figure 2. Conceptual flow chart for river flood modelling

for floodplain analysis. For geometric data, which is data to perform the spatial analysis, the HEC-GeoRAS software has been applied. The conceptual and detailed technical approach for river flood modeling is described in Figure 2.

i. HEC-GeoRAS application

HEC-GeoRAS uses the functions associated with Spatial Analyst and 3D Analyst extensions of ArcGIS. It is specially designed to process the geospatial data. It is used to create a HEC-RAS import file containing geometric attribute data from an existing digital elevation model (DEM) and complimentary data sets. The geometric data developed in HEC-GeoRAS includes; stream centre line, reaches (tributaries), cross sectional cut lines, cross sectional surface lines, cross sectional bank stations, downstream reach lengths, main channel, right over bank, left over bank. This data is exported to HEC-RAS.

The RAS themes are created and organized as line and polygon and are used for geometric data development. The line themes are: stream centerline, main channel banks, flow path centerlines, and cross-section cut lines.

ii. HEC-RAS application

The HEC-RAS is comprised of graphical user interface (GUI), separate hydraulic analysis components, data storage and management capabilities, graphics, and reporting facilities. One of the hydraulic analysis components in the HEC-RAS is steady flow water surface profile. This component of the modeling system

is intended for calculating water surface profiles for steady gradually varied flow. The steady flow system is also designed for application in floodplain management and to evaluate flooded area.

All the geometric data developed in HEC-GeoRAS is exported to HEC-RAS, which is prosecuted for a variety of discharge data at different locations of the river. The results exported from HEC-RAS are further processed within the GIS environment to assess the areas inundated by floods and flood depths.

iii. Analysis of river flow data

A selected number of profiles, the peak flow data, and boundary conditions are needed in order to analyze the river flow in HEC-RAS. To perform the flood scenario, two different conditions are required. One is the condition of the normal discharge and the other is the 100-year return period of flood discharge. Discharge data have been obtained from the Pakistan Meteorological Department (PMD). Measurements are being taken at the Kattarian Bridge and Gawalmandi Bridge by gauges installed to measure water depth. Probable peak discharges estimations of the 100-year return period for Kattarian Bridge and Gawalmandi Bridge. As the 2001 flood was the most severe flood in the history of Lai Nullah. That is why the peak discharge observed during the 2001 flood has been put into the HEC-RAS model. Peak discharge estimated during 2001 flood was 2870 m³/s.

iv. Steady flow modeling

The simulation is performed based on the geometric data, flow data and boundary conditions in a steady flow analysis. Steady flow describes condition in which depth and velocity at a given channel location do not change rapidly with time. Gradually varied flow is characterized by minor changes in water depth and velocity from cross-section to cross-section. The primary procedure used by HEC-RAS to compute water surface profiles assumes a steady, gradually varied flow scenario and is called the direct step method. This method computes water surface profiles at the adjacent cross sections.

Results and Discussion

Floods cause severe consequences as they happen. This study employs hydrological flood models and procedures to estimate the propagation of river flood; assess the areas vulnerable to flood; and to map areas inundated by flooding at specific discharge values to find potential flood hazards. The advanced GIS technology is employed into the model operations and flooding simulations to test the effectiveness of flood mitigation measures for giving recommendations to solve or compensate the flooding problems in urban catchments, or for developing plans to rebuild the affected areas or developing new areas.

Increase in Discharge by Urbanization

Land use also acts as an important factor affecting flood discharges. Urbanization that is generally accompanied by pavement, building and drain installation leads to an increase of flood discharges. Land use of the basin has been presented for 2001 and projected land use for 2012 and 2030 by JICA in their study as shown in Figure 3.

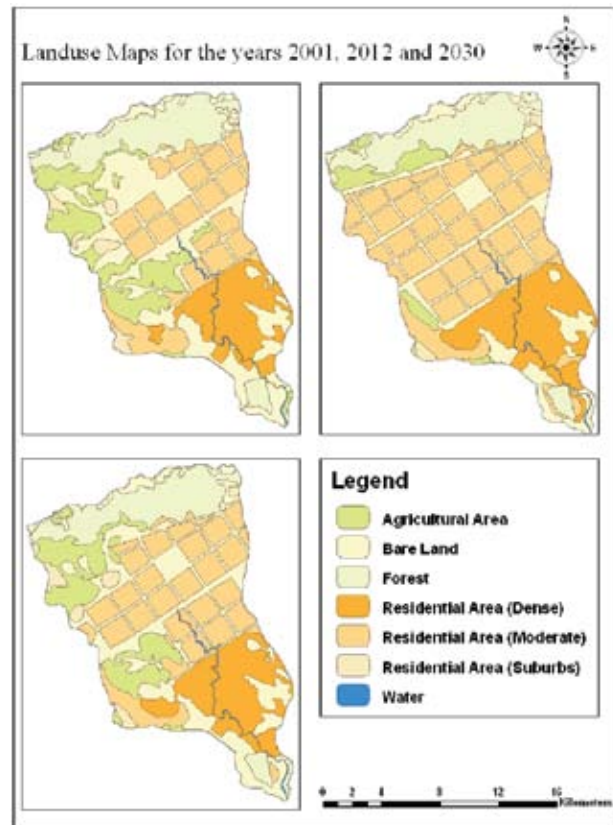


Figure 3. Land use maps for Rawalpindi and Islamabad for years 2001, 2012 and 2030 (Source: [19]).

As an overall trend, it can be clearly seen that the built up area or residential area is increasing fairly rapidly from 2001 until the 2030. In 2001, 38.6 % of basin area was built up. This number increases up to 58.0 % until 2030. In contrast, non built up area was 61.3 % in 2001 and continued to decrease up to 42.0 % until 2030. Maximum discharge increases from 1260 to 1375 m³/sec for Kattarian Bridge and 2551 to 2711 m³/sec for Gawalmandi Bridge for 2001 and 2030 land uses respectively.

Elevation Data Preparation and Analysis

The elevation dataset for DEM generation is derived through the integration of various elevation data sources. The DEM data was acquired by WASA (Water and Sanitation



Figure 4. Natural surface elevation points.

Authority) Rawalpindi. This DEM was generated from topographic survey, conducted from October 2006 to July 2007 for drainage and sewerage maintenance purposes. About 23000 Natural Surface Elevation points were collected using total station as shown in Figure 4. This survey was conducted along the roads and streets of Rawalpindi to assess the elevation trends of the city. This survey gives only the elevation trends of the ground surface but the inside parts of all the streams which are passing through the Rawalpindi city, have been skipped. Natural surface elevation points are not uniformly distributed on the map. In order to get a smooth surface, kriging interpolation technique is used to create a DEM of 1meter resolution.

The DEM for Nullah Lai was made using contour of 1meter resolution from survey data conducted by NESPAK for Lai Express

Highway. So the both types of data, i.e. the point elevation data in Nullah's surroundings and the contour data of the inside of the Lai stream were converted into an integrated DEM, using 3D-Analyst and Spatial-Analyst extensions in ArcGIS.. Integration of elevation data from different sources with different scales and accuracies is a big problem to handle. This work is essential to fill the gaps between the elevation points to create a smooth DEM for river flood modelling. In the present study, ordinary Krigging method has been used to create a surface after Demirhan *et al.*, (2003) [18] and this surface has then been converted to raster DEM having 1meter pixel size.

Simulated Standard Flood Discharges

JICA and PMD in their flood forecasting project of the Lai Basin used 100 years return period to estimate flood discharges at the two locations using MIKE-11 model. The discharges at the same locations were also estimated from the observed water levels. These flood discharges are presented in the Table 3 and have been compared with the discharges estimated from runoff analysis of study conducted by the ADB (Asian Development Bank). The simulated flood discharges at 100-year return period by JICA are 2270 and 2640 m³/sec while by ADB project these are 784 and 1264 m³/sec at the Kattarian and Gawalmandi Bridges respectively It can be observed that the standard flood discharge simulation values by JICA are in better accordance with the estimated values from the observed water level. However, the discharge values as estimated by the ADB are three times less than the JICA estimates. Flood discharge of 2,870 m³/sec for Gawalmandi Bridge has been observed in 2001 and this value has been used in our calculations.

Table 3. Standard flood discharge by return period

Reference Points	Source	Description	05 Years	10 Years	25 Years	50 Years	100 Years
Kattarian Bridge	JICA	Simulated Standard Flood Discharge	330	620	1,150	1,660	2,270
	ADB Project	Estimated by Runoff Analysis	324	425	571	682	784
Gawalmandi Bridge	JICA	Simulated as Standard Flood Discharge	390	720	1,340	1,940	2,640
		Estimated From Observed Water Levels	490	840	1,500	2,200	3,000
	ADB Project	Estimated by Runoff Analysis	563	719	942	1,109	1,264

Modeling Results

To assess inundated areas, HEC-RAS has been simulated for a variety of probable discharge values at Kattarian and Gawalmandi Bridge, estimated by Japan International Cooperation Agency (JICA) of 25, 50 and 100 year return periods. GIS based preliminary

flooding analysis delineates the flood risk zones for specific discharge values which are valuable for making flood development plans and for further demanding flood simulation in future and have been demonstrated in Figure 5 for various discharges of returns periods of 25, 50 and 100 at Gawalmandi and Kattarian Bridges.

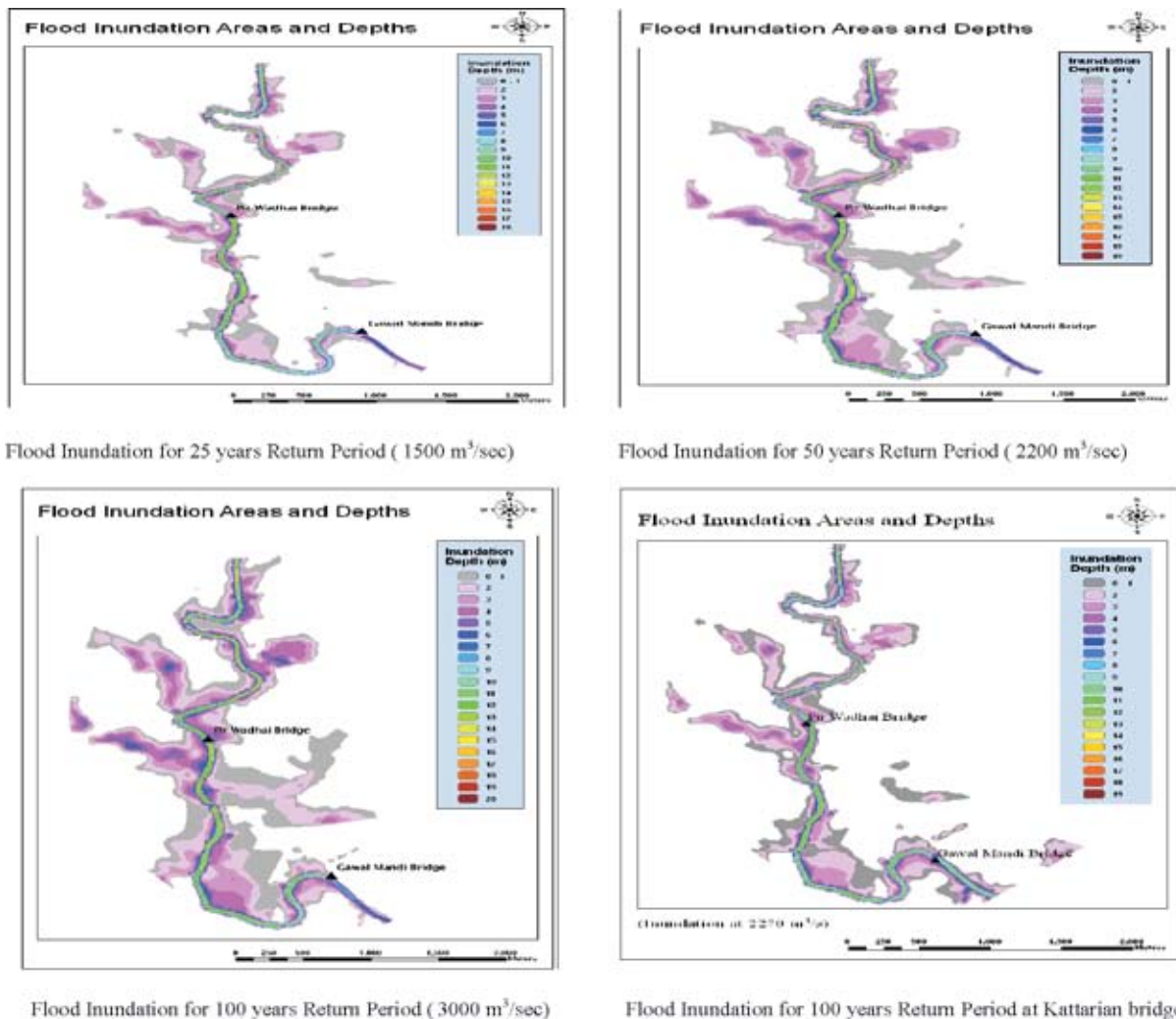


Figure 5. Flood inundation for 25, 50 and 100-year return periods at Gawalmandi Bridge

In the present study, the output map of flood inundation areas and depths has been prepared by simulating HEC-RAS and HEC-GeoRAS on the basis of Digital Elevation Model (DEM). To validate model's results, a map for the discharge value of 2870 m³/s estimated for 2001 flood at Kattarian Bridge, has been shown in Figure 6. To validate the model's output, the only source available is the 2001 flood map prepared by JICA based on interview survey in 2002-2003 in the fringes of Lai Nullah. Not only the inundated areas were estimated but inundation depths were also measured and then displayed thematically on high resolution satellite imagery as shown in Figure 7 [19].

The visual comparison of Figures 6 and 7 depicts a strong correlation and close approximation between the survey based profile of inundated areas and depths prepared by

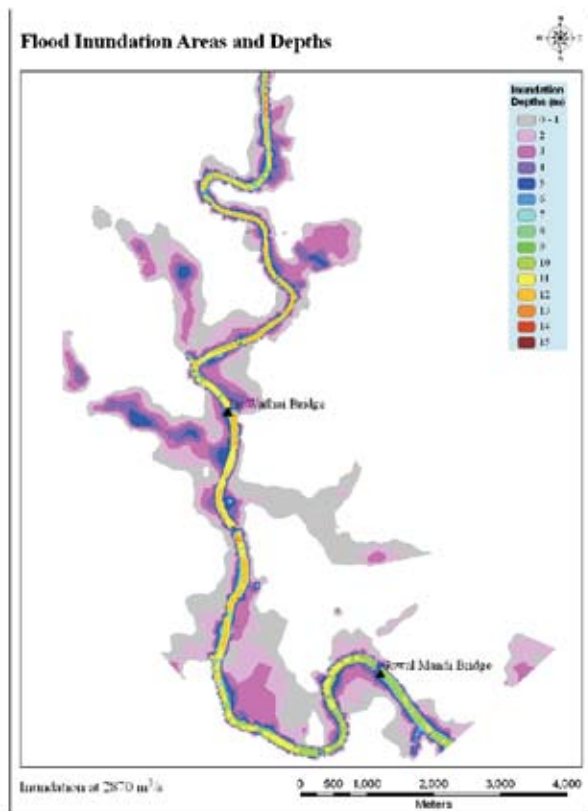


Figure 6. Inundation areas and depths at the estimated discharge for 2001 flood

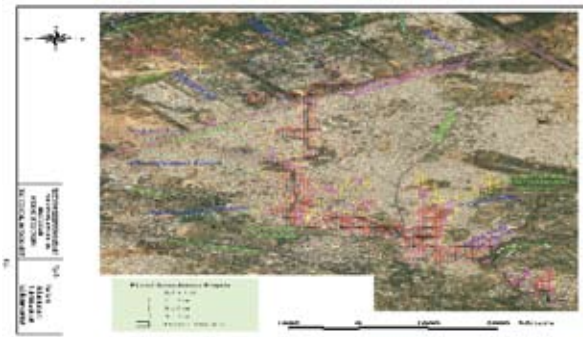


Figure 7. Survey based inundation map developed by JICA for 2001 flood. (Source: JICA [19]).

JICA, and inundation areas and depths prepared by current study. This shows that the integrated models work well in order to locate areas vulnerable to flood with a good estimation of inundation depths at a specific discharge value.

Flood Hazard Assessment

Flood hazard assessment is the evaluation of potential damage due to flood. It involves the calculation of water depth and land use affected by floods. Firstly, the flooded area has been calculated for different water depth classes using river flood model's results. Secondly, the impact of the flood on land use has been determined. Different water depths on different land use have a different impact in term of damage and cost.

Water Depth Distribution of Flood

The distribution of water depth can be calculated by subtracting grid maps of water surface and terrain. The calculation of the flooded area per water depth class is done by histogram analysis using a raster class map with the distribution of water depth. Figure 8 shows the raster class map with the distribution of water depth having 1meter pixel size. The flooded area per depth class has been shown in Table 4.

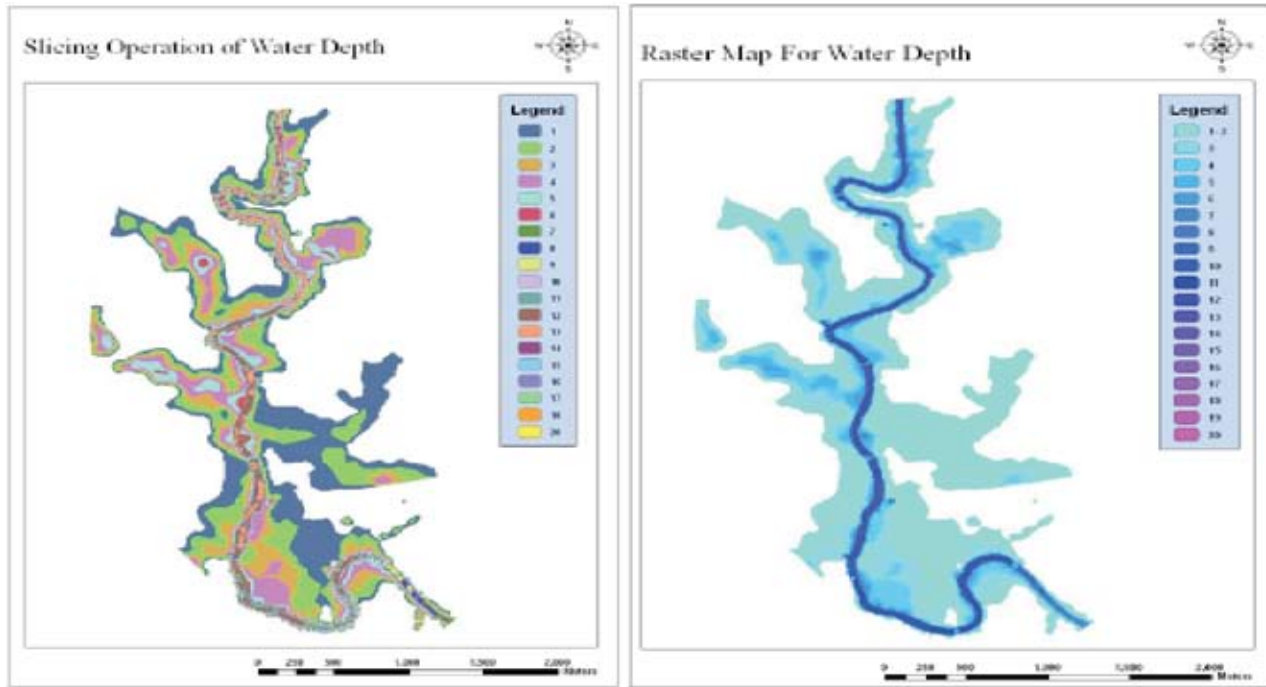


Figure 8. Distribution of flood depths

Table 4. Area per class of river flood depth

Depth Classes (m)	Number of Pixels	Area (m ²)	%
1	1084895	1084836.8404	31.95
2	759708	759700.0329	22.37
3	509294	509345.5173	15.00
4	397917	397865.3958	11.72
5	210916	210993.0210	6.21
6	86613	86596.4366	2.55
7	44337	44258.6544	1.30
8	36186	36107.6810	1.06
9	29869	29912.0043	0.88
10	30071	30047.5699	0.88
11	57659	57682.1266	1.70
12	94338	94334.6880	2.78
13	52334	52373.9770	1.54
14	1830	1823.9594	0.05
15	22	22.0188	0.00
16	16	14.8549	0.00
17	6	6.1520	0.00
18	1	0.6404	0.00
19	1	1.0000	0.00
20	1	1.0000	0.00
Total	3396013	3395922.5707	100

Using histogram analysis, the number of pixels for each class has been calculated. Table 4 shows that one meter inundation depth contains 1084895 numbers of pixels; consequently, the total inundation area having one meter water depth at different locations will be 1084836.8404 m². The inundated area has been disseminated into twenty depth classes. The total flooded area is 3395922.5707 m² (nearly equal to 3.4 km²).

Impact of Flood on Land Use

The impact of flood on land use has also been determined by crossing both the maps (the land use map and flood inundation map) as shown in Figure 3. The land use map was developed by JICA. By superimposing the flood inundation map over the land use map as shown in Figure 9, it is clear that the residential area (dense) class is mainly affected by flood. Residential Area (dense) class could also be grouped into some sub-classes like, residential areas, commercial areas, schools, parks, banks, Mosques etc.

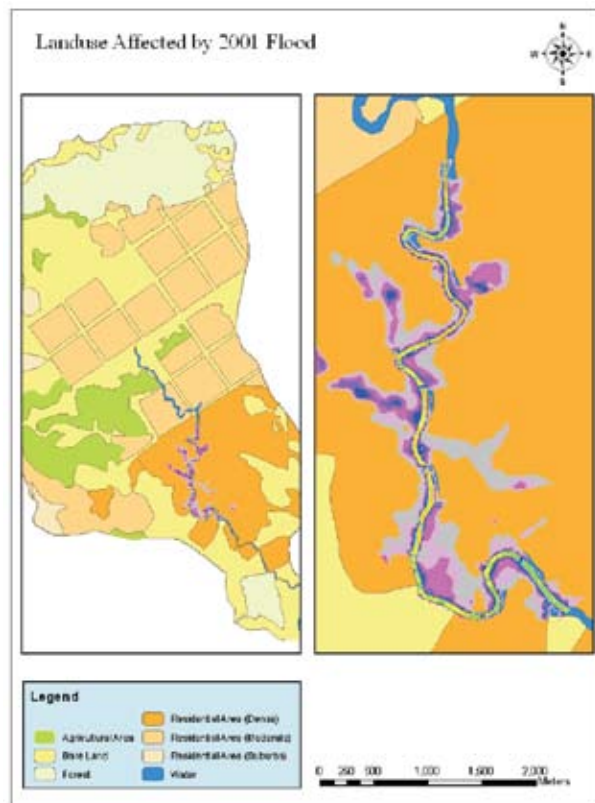


Figure 9. Land use affected by flood

Conclusion

In the present research, coarse DEM and hydrological data have been used and obviously the result would have been different if the detailed complete hydrological data were used. Inundation area estimated at the discharge value of 1500 m³/sec at Gawalmandi Bridge is nearly about 1.8 km² out of which 1.4 km² is lying under the inundation depth from 1 to 4 meters. Inundation area estimated at the discharge value of 3000 m³/sec is 3.4 km² out of which 2.96 km² is occupied under the inundation depth from 1 to 5 meters. Maximum inundation depth can go up to 19 meters for this discharge value. Output of the study using HEC-RAS and HEC-GeoRAS Models shows that inundated areas and depths are in close approximation with survey based inundation results obtained by JICA. The mapping of inundated areas from Kattarian Bridge to Gawalmandi Bridge is satisfactory, as

it is validated using high resolution inundation map developed by JICA. This shows that the integrated modeling approach used in the present study works well in order to locate areas vulnerable to flood with a good estimation of inundation depths at a specific discharge value. The results obtained will have widespread applications for city planners, environmental planners, flood control administration, policy makers, emergency manager and totally will help flood hazard mitigation.

Recommendations

- To find the areas vulnerable to flood, high resolution Digital Elevation Model (DEM) for Lai Nullah including all of its tributaries from foothills of Margala to the Soan River is needed to get better results.
- Use of hydrological models to find flood vulnerable areas and flood hazard mapping is a cost effective approach which gives a high quality output. This methodology could be used in large river floods vulnerable areas also.
- Water discharge data for the main Lai Nullah with all of it's tributaries at specific locations and especially at confluences will give better results.

References

1. **Smith, K, and Ward, R.** 1998. *Floods: Physical Processes and Human Impacts*. John Wiley and Sons, Chichester, USA.
2. **Dilley, M., Chen, R.S., Deichmann, U., Lerner, A.L., and Arnold, M.** 2005. *Natural Disaster Hotspots: A Global Risk Analysis*, The World Bank, Washington DC, US, 150 pp.
3. **Drogue, G., Pfister, L., Leviandier, T., Idrissi, A., Iffly, J.F., Matgen, P., Humbert, J., and Hoffmann, L.** 2004. Simulating the spatio-temporal variability of stream flow response to climate change scenarios in a mesoscale basin. *J. Hydrology* 293: 255–269.
4. **Institution of Civil Engineers (ICE), UK.** 2001.

- Learning to live with rivers, *Final report of the ICE Presidential Commission to review the technical aspects of flood risk management in England and Wales*. 87 pp.
5. **Fread, D.L.** 1992. Flow routing. In: Maidment, D.R. (Ed) *Handbook of Hydrology*. pp: 10.1-10.36. McGraw-Hill, Inc. NewYork, USA.
 6. **Brunner, G.W.** 2002. HEC RAS River Analysis System; Hydraulic Reference Manual. US Army Corps of Engineers, Davis, USA.
 7. **Stelling, G.S. Kernkamp, H.W.J. and Laguzzi, M.M.** 1998. Delft Flooding System, a powerful tool for inundation assessment based upon a positive flow simulation. In: *Hydroinformatics*. Eds. Babovic and Larsen. pp. 449-456. Balkema; Rotterdam, The Netherlands.
 8. **Hesselink, A.W., Stelling, G.S., Kwadijk, J.C.J. and Middelkoop, H.** 2003. Inundation of a Dutch River Polder, sensitivity analysis of a physically based inundation model using historic data. *Water Resources Res.* 39, art.no.1234.
 9. **Hervouet, J.M. and Van Haren, L.** 1996. Recent advances in numerical methods for fluid flows. In: *Floodplain Processes*. Eds. Anderson, M.G., Walling, D.E. and Bates, P.D. pp. 183–214. John Wiley and Sons, England.
 10. **Abbott, M. B. and Price, W.A.** 1994. *Coastal, estuarial and harbour engineer's reference book*. E. and FN Spon, London. UK.
 11. **Snead, D. B.** 2000. *Development and application of unsteady flood models using Geographic Information Systems*. Departmental Report, Master of Science in Engineering, University of Texas at Austin, USA.
 12. **Sadrolashrafi, S. S., Thamer A. M., Ahmad R. B. M., Majid K. K., and Amir S.** 2008. Integrated modeling for flood hazard mapping using watershed modeling system. *American J. Engg. Appl. Sci.* 1:149-156.
 13. **Garrote, L. and Bras, R.L.** 1995. A distributed model for real-time flood forecasting using digital elevation models. *J. Hydrology*. 167:279-306.
 14. **Johnson, C.A., Yung, A.C., Nixon, K.R. and Legates, D.R.** 2001. The use of HEC-GeoHMS and HEC-HMS to perform grid-based hydrologic analysis of a watershed. Dodson and Associates, Inc. - Houston, Texas, USA - www.dodson-hydro.com
 15. **Wang, Y., Colby, J.D. and Mulcahy, K.A.** 2002. An efficient method for mapping flood extent in a coastal flood plain using LANDSAT TM and DEM data. *Internat. J. Remote Sensing*. 23:3681–3696.
 16. **Guy, S., Renaud, H., Christian, P., Lucien, H., Patrick, M., Florian, P. and Laurent, P.** 2007. High-Resolution 3-D Flood Information from Radar Imagery for flood hazard management. *IEEE Transactions on Geo-science and Remote Sensing*. Vol.45, No.6.
 17. **US Army Corps of Engineers (USACE).** 2001. *HEC-RAS, River Analysis System, User's Manual Version 3.0*. Hydrologic Engineering Centre, Davis, CA, USA.
 18. **Demirhan, M., A. Ozpinar, and L. Ozdamar.** 2003. Performance evaluation of spatial interpolation methods in presence of noise, *Internat. J. Remote Sensing*. 24: 1237-1258.
 19. **JICA.** 2007. *The project for strengthening of flood risk management in Lai Nullah Basin* Expert Team. *Inception Report*. Japan International Cooperation Agency (JICA).