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Optimization of Model Parameters of HEC-RAS 2D Model on Flood Inundation Mapping: A Case Study of Kankai River Basin

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Abstract
Among different natural hazards, floods are the most common and disastrous around world. Flood simulation model are used to predict the consequences of probable flood by estimating inundation area, depth and velocity of flow. US Army Corps of Engineering Hydrologic Engineering Center (HEC) has developed HEC-RAS which performs one dimensional (1D) steady and unsteady flow calculation, as well as two dimensional (2D) unsteady flow calculation. In this study HEC-RAS 2D model is used to predict flood inundation of Kankai River originating from mid-hills and further sensitivity of model parameter are evaluated. In order to accurately represent the hydraulic processes happening in the river, selection of appropriate model parameter is most important. This study is focused on evaluation of those model parameter sensitivity on Inundation Area, Water Surface Elevation and Computational Time. Sensitivity of Mesh geometry, Time step, Equation set and Theta weighing factor for 2D model are evaluated in detail and with selection of optimal parameters, inundation map of Kankai River is obtained. Based on sensitivity analysis, this study aims to provide general recommendation on selection of optimal model parameter for 2D flood modeling using HEC-RAS. For 100 years return period of flood, 65.5 km^2 of area got inundated, which represent 4.36% of catchment area of Kankai River Basin.

Keywords
HEC-RAS , Flood Inundation, Kankai River

1. Introduction

A flood can be defined as a massive water flow exceeding the river capacity. The water from the main channel overflows and inundate the flood plains bordering with the main channel. The consequences of flood disaster directly or indirectly affect human life, property, infrastructure, agriculture, wildlife, and environment. Major flood disaster around the world has created social and economic impact upon the countries [1]. Flood is common disaster which occurs in the rainy season in Nepal. It has been most frequent, highly damaging and wide spread natural hazard. The flood of Koshi River in 2008 killed 250 people and affected nearly 3 million people from their homes in Bihar, more than 300,000 houses were destroyed and at least 340,000 hectares (840,000 acres) of crops were damaged. Also in Nepal, 6 districts were affected causing approximately 53,800 Nepalese (11,572 households)[2].

Hydraulic modeling and flood inundation mapping are performed to provide important information from a flood event including inundation area, depth and water surface elevation within the study area. A hydraulic simulation model is a mathematical representation of the physical hydraulic processes that occur during a flood event. Such processes can be described by conservation of Mass, conservation of Momentum, and conservation of Energy equations posed in either one, two or three dimensions [3]. Determination of floodplain inundation generally consist of construction of a physically-based fully 2D hydrodynamic model, calibration of the model using historical flood data, use of the best-fit model to simulate synthetic design flood events and interpretation of the model results to generate flood-hazard maps in a Geographical Information System (GIS) [4].

HEC-RAS one dimensional (1D) modelling was performed for Bishnumati River and the flood vulnerability was assessed with regard to land use pattern of the study area. Maximum of the inundated area lies under urban area in different flood frequencies. The analysis showed that for all the return periods, maximum area under flood has inundation depth between 0.5 m to 1.5 m [5]. A study was made on effect of flooding on Karnali basin. The extent of the flood hazard in the downstream region of the Karnali River for the various return period shows that the total hazard area increases as the return period increases. High-intensity rainfall across the basin leads to flooding associated with high discharge in Karnali River. Hydraulic simulations performed for different return period showed that a rapidly increasing area of fertile land will be inundated, thereby threatening the food security of the river basin [6].

It is stated that the stability and accuracy of result depends on selection of model parameters. The study is made on finding the importance of selecting appropriate model parameter on accuracy of result and model stability[7]. This study is therefore focused on the finding the suitable model parameter for the selected river. To find the suitable model parameter, sensitivity analysis of the parameter is carried out.

The objective of this study is to evaluate how the selection of model parameters affects the stability, computational resources and output accuracy of results from 2D HEC-RAS model and then select the optimal parameters to obtain the flood inundation map of Kankai Basin.

2. Study Area

The study area is a Kankai watershed of Eastern Nepal. The Kankai River is rain fed Perennial River. It originates from Mahabharat range at Phakphokthung Rural Municipality in Ilam district. Deumai, Puwa, Mai, Jogmai are the tributaries of Kankai River.

The catchment area of basin is 1384.9 km^2, length of major stream is 120.7 km and average channel slope is 0.02. The altitude of its origin is about 1820m above the mean sea level. It has tropical and sub-tropical climate regime [8].The topography of Kankai watershed is highly varied. The upper part of the watershed lies in hilly region with steep terrain while the lower part of basin lies in flat plains with mild slope.

The climatic condition varies in different season. There is hot and dry in the period from March to June, hot and humid from July to August, pleasant from september to october and cold from November to February. During summer and winter the temperature ranges from 46°C to 2°C. The mean daily temperature at observed at Gaida meteorological station (25.58° N, 87.90° E, elevation 143m) is 24.5°C, relative humidity (RH) is 75% and vapour pressure is 23.79. The annual mean precipitation in the study area ranges from 2000 to 3000mm. The average annual precipitation at Gaida station is 2734 mm, Damak station is 2369 mm, Sanischare station is 2794 mm and Ilam Tea state is 1574 mm. The annual average discharge at Mainachuli gauging station (Station no. 975) is 58.9 m^3/s. The stream flow record from 1972 to till date can be obtained from DHM in this station.[9]

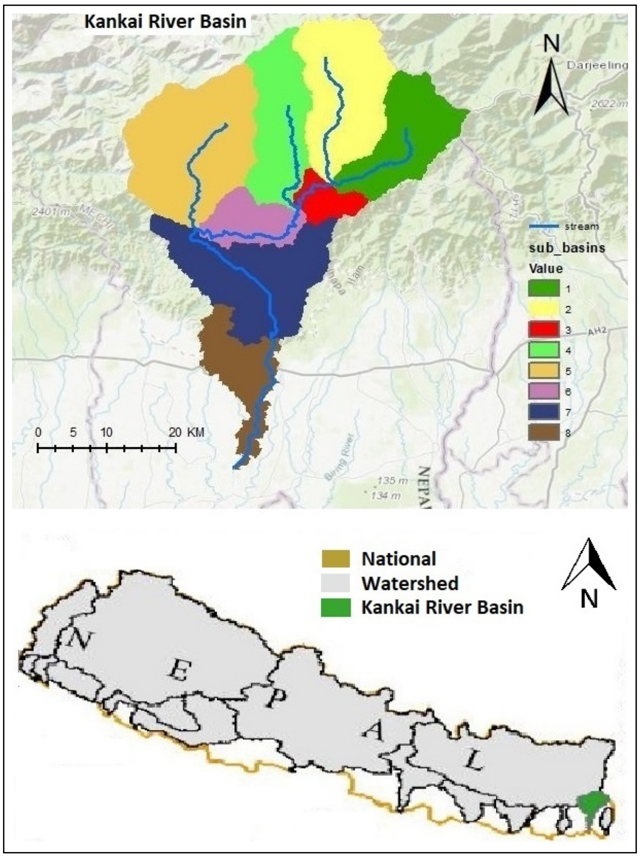

Figure 1: Study Area

3. Methodology

Data collection, model setup, sensitivity analysis of model parameters, evaluation and selection of model parameters, validation of result and development of flood inundation map are the major steps involved in this study. The detail methodology adopted for developing HEC-RAS 2D model, sensitivity analysis of model parameters and flood inundation mapping of the Kankai river are summarized in a flow chart and described here.

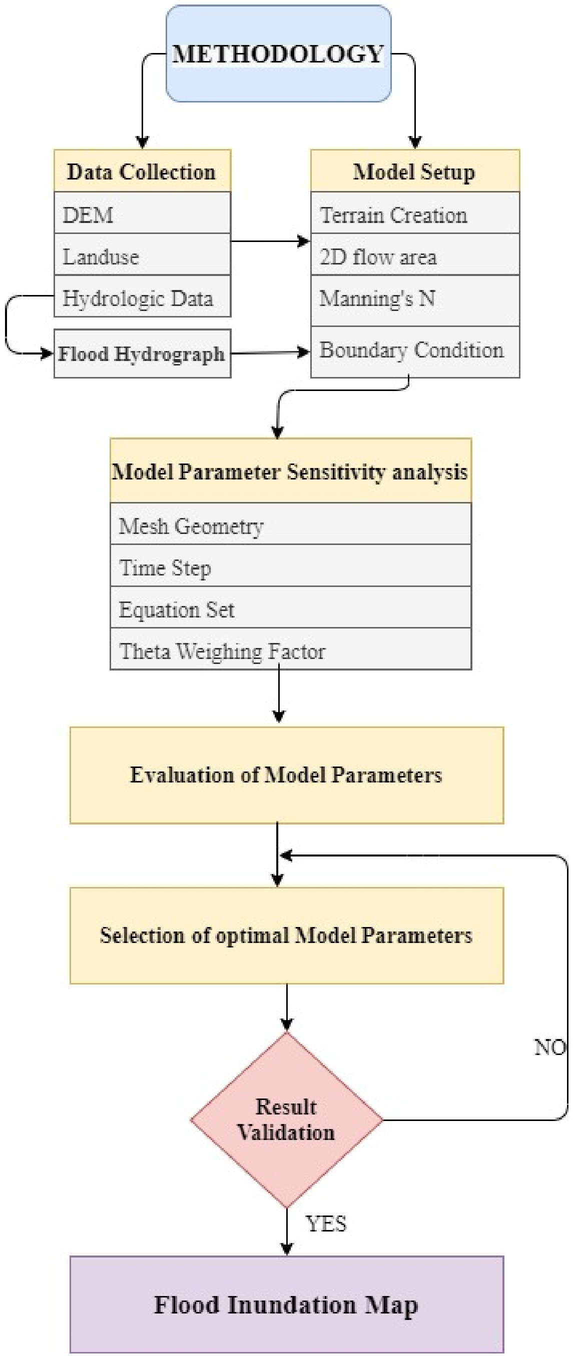

Figure 2: Methodological Flowchart

3.1 Data Collection

In order to develop the mathematical flood model, various kinds of data, recent and past several years have been collected and compiled. These data also form the basis for further analysis and interpretation of the model results leading to accurate assessment of hydrological condition of study area. According to the modeling requirements, a significant amount of data includes terrain information in the form of digital elevation model, rainfall data, land use data, satellite data of flooding extent delineation, etc. The data requirement and its sources are summarized in Table 1.

Table 1: Summary of Data

SN	Data Type	Data Source	Remark
1	Rainfall Data	DHM	1991-2015
2	DEM	SRTM	30m Resolution
3	LandUse	ICIMOD	2010
4	Satellite Images	Google Earth	1990-2015

3.2 Hydrologic Analysis

Though the selected river is gauged river, detail data for hydrological modelling is not available. Reviewing different empirical equations, Snyder's Unit Hydrograph (SUH) was found to be best. A hydrological analysis was done using standard Snyder's Unit Hydrograph (SUH) and frequency analysis for 100 year return period.

3.2.1 Estimating Precipitation Gauge Weight

To estimate the gauge weights of selected precipitation stations for each basin, Thiessen polygons are created using create Thiessen polygon tool in ArcView GIS. The intersected area of Thiessen polygons in each sub-basin are calculated using Geo-processing extension in ArcView GIS.

3.2.2 Flood Frequency Analysis

As flooding is an extreme hydrological event, frequency analysis for floods are done using Extreme Value (EV) distributions [10]. The maximum value data was selected for individual years from the hydrological and rainfall data sets at the required stations. For estimation of extreme hydrological event 24 hour maximum rainfall data of past 25 years are collected from the DHM. Using Gumbel's distribution method, 24 hours maximum rainfall values at each sub-basin has been estimated for different return period.

3.2.3 Development of Snyder's Unit Hydrograph and DRH

The Snyder unit hydrograph is a synthetic unit hydrograph which is based on relationship between three characteristics of a standard unit hydrograph and descriptors of basin morphology. The hydrograph characteristics are the effective rainfall duration, peak runoff rate, and basin lag time. From these relationship, five characteristics of a required unit hydrograph for a given effective rainfall duration can be calculated. The peak discharge per unit of watershed area, the basin lag, the base time and the widths of the unit hydrograph at 50% and 75% of the peak discharge are those five characteristics. [11].

Once required unit hydrograph is prepared, unit hydrograph is converted to direct runoff hydrograph (DRH) for 100 years return period of rainfall intensity calculated from Gumbel's method. The prepared DRH is used as flood hydrograph boundary condition at inlet of 8 different sub basin shown in Figure 3. Flood Hydrograph of 100 years return period is used for sensitivity analysis.

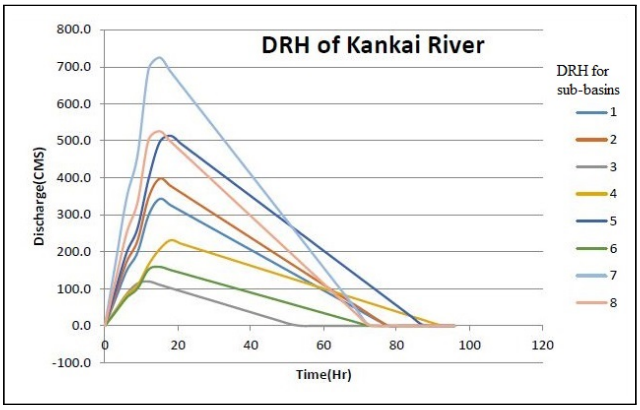

Figure 3: Direct Runoff Hydrograph of Sub Basin for 100yrs return period

3.3 HECRAS 2D model setup

3.3.1 Creating Terrain Layer

Terrain is created by SRTM 30m resolution DEM. With the help of RAS Mapper, One or more terrain models can be created in HEC-RAS and can be associated with a specific geometry input file or a specific result output file. DEM is imported, spatial reference projection system of the data frame is given and terrain data set is created.

3.3.2 2D Flow Area and Mesh Construction

The 2D flow area defines the boundary of computational mesh. Initially 2D flow area is created to cover the possible flooding extend, which is further modified as per flow condition. Within the 2D flow area computational mesh is created, and each computational mesh have cell center, cell faces, and cell face points.

3.3.3 Defining Manning's Roughness

Manning's roughness is important parameter in calculating flow resistance and conveyance of the cell in HEC-RAS 2D, which need to be accurately define for better accuracy of the result. In current version of HEC-RAS, manning's n can be defined with in geometry by creating manning's n layer by using previously created land use map and assigning manning's n for each land use type. In this study land use map obtain from ISIMOD is used. Manning's n value for different Land use type used in the model is shown in Table 2.

Table 2: Manning's n for different Land use

Land Use	Manning's n
Forest	0.05
Shurbland	0.04
Agricultural area	0.045
Barren Area	0.015
Water Body	0.025
Builtup Area	0.1

3.3.4 Defining Boundary Condition

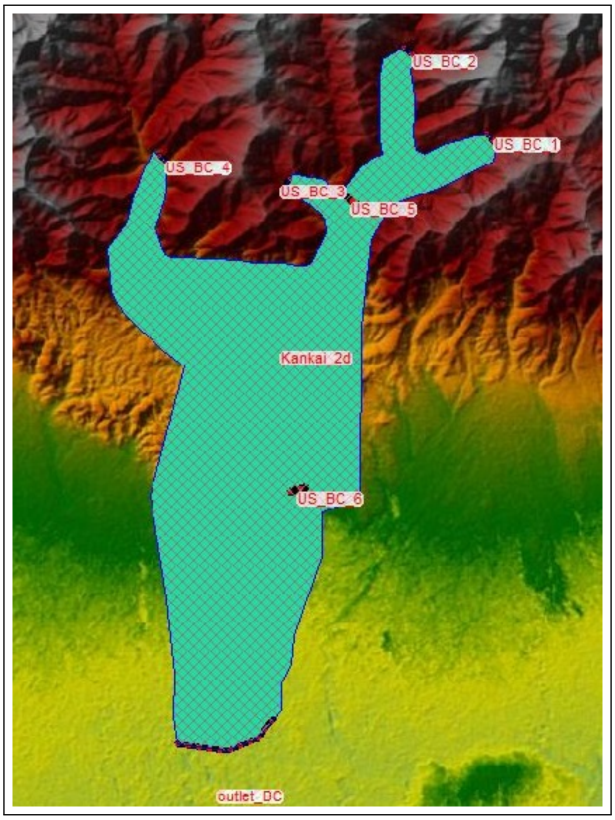

Figure 4: 2D mesh and Boundary Condition in Modelling

For this study flow hydrograph is used as upstream and normal depth is used for downstream boundary condition. HEC-RAS has the capability of defining both internal and external boundary condition. The use of internal boundary condition makes it easier to add overland flow joining the river stream at intermediate point. For each sub basin flood hydrograph calculated from hydrologic analysis is defined as upstream boundary condition. A typical condition of flood hydrograph defined as upstream boundary condition is shown in Figure. River outlet is defined as normal depth; the slope of river near outlet is used for normal depth as boundary condition.

3.4 Sensitivity Analysis

3.4.1 Mesh Geometry

The sensitivity of mesh size is carried out on 4 different geometries to find out the optimal geometry that represents the topography and optimal computational time. For sensitivity analysis diffusive wave equation is used with time step controlled by courant condition.

3.4.2 Computational Time Step

HEC-RAS uses temporal and spatial discretization of governing equation. Time steps directly affects how the temporal derivatives of governing equation are approximated. Choosing appropriate time steps depends on how the hydraulic properties between two consecutive time steps are changing. Choosing too large time steps, the change in hydraulic property between two consecutive time steps might be too large causing the instability problem. Too small computational time step will increase the computational time. The thumb rule for selecting the time step is that the courant number is kept close to 1 and not larger than 5 for diffusive wave equation and 3 for full momentum equation [7]. HEC-RAS let user to manually select computational time step or user can apply the courant condition to select the optimal time step. This sensitivity analysis will evaluate the effect of computation time step on model stability and simulation results.

3.4.3 Equation Set: Full Momentum and Diffusive Wave Approximation

The HEC-RAS solves continuity and momentum equations (2D Saint-Venant equation) and HEC-RAS 2D modelling can be done by using both full momentum and diffusive wave equation. In Diffusive wave approximation gravity and friction are assumed to be dominating forces acting on control volume. This sensitivity analysis is focused on the numerical stability, computation time and result sensitivity between two governing equation.

3.4.4 Theta Weighting Factor

Theta weighting factor is related to accuracy and stability of the model. This study is focus on finding, at what cost of accuracy, stability of model can be achieved by using higher theta weighting factor. For the study, the model is run for theta weighting factor of 0.6, 0.8, and 1 using diffusive wave equation.

3.5 Flood Inundation Mapping

The model is run for different model parameter, change in inundation area, water surface elevation and computational time for each model parameters are evaluated. For selection of optimal mesh size and computational time step, maximum mesh size and time steps below which the inundation area and WSEL are less sensitive is selected. For selection of Equation sets and theta weighing factor, improved in accuracy on inundation area and WSEL calculation is compared over computational time step and model stability. Optimal model parameter based on the sensitivity analysis are selected for flood modeling of entire reach of selected rivers. The result is further validated by comparing simulated inundation area with inundation area of flooding extend obtained from satellite images. The validation is done based on percentage of area inundated. To analyze the impact of the flood of 100 years return period on study catchment, flood inundation map was prepared using optimal model parameter selected from the sensitivity analysis. The impact of flood on different land use is further categorized based on inundation depth. For inundation mapping, inundation depth raster exported from RAS-Mapper is mapped over topographic map from open street map using Arc-GIS.

4. Results and Discussion

The selected portion of the river is studied in detail for sensitivity analysis using the flood discharge calculated for 100 years return period of flood using Gumbel and Snyder's unit hydrograph method. The sensitivity of the parameter is studied keeping all other parameter to be same to determine the impact of model parameter on simulation result. The parameters that were investigated are mesh geometry, computational time step, governing equations, theta weighting factor for 2D model. After sensitivity analysis optimal model parameter selected for portion of River were applied for whole river stretch and inundation mapping for different return period is prepared.

4.1 Result on Sensitivity Analysis

4.1.1 Mesh Geometry

This study is focused on finding the optimal mesh geometry to describe the hydraulic properties of the study area perfectly keeping in the reasonable computational time. The different geometry are compared for inundation area, water surface elevation and computation time and result are compared. The summary of sensitivity analysis is shown in Table 3.

Table 3: Sensitivity analysis on Mesh Size

SN	Mesh Size	% change in Inundation Area	change in WSE(m)	Computational Time (hh:mm:ss)
1	100	-3.4	2.5	00:24:17
2	80	-1.8	1.7	00:27:06
3	50	-1.2	0.3	00:38:16
4	30	-1.2	0.3	00:45:08

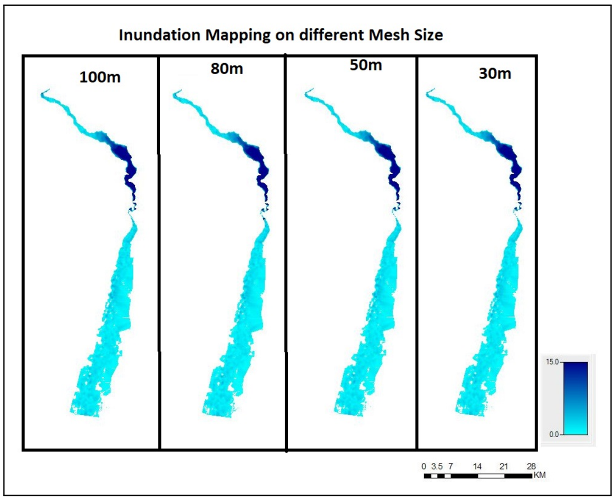

Figure 5: Inundation on different Mesh Geometry

Evaluating the relative change in inundation area relative change in water surface elevation level for different mesh geometry there is no significance change below the mesh size of 50m.

4.1.2 Computational Time step

While running the HEC-RAS with higher time step, model runs smoothly without showing any computational error massage but inaccurate result.With selection of larger time step, model gives the overestimation of both inundation area and WSEL. It's because, in rising limb of flood hydrograph the hydraulic conveyance of a mesh will raise rapidly, which is not perfectly accounted by selected time step.

Table 4: Sensitivity analysis on Time Step

SN	Time Step	% change in Inundation Area	change in WSE (m)	Computational Time (hh:mm:ss)
1	30min	57.9	7.5	00:15:38
2	15min	47	5.6	00:36:29
3	5min	7	3.8	02:38:16
4	1min	-1.2	0.7	03:18:22
5	30sec	-1.2	0.6	05:06:27
6	15sec	-1.6	0.5	08:05:17

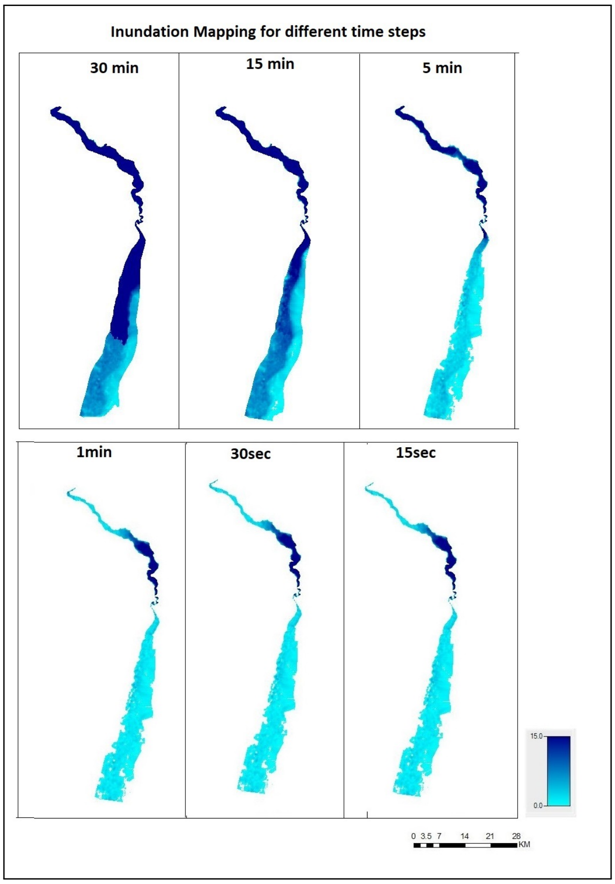

Figure 6: sensitivity of time step on Inundation Area

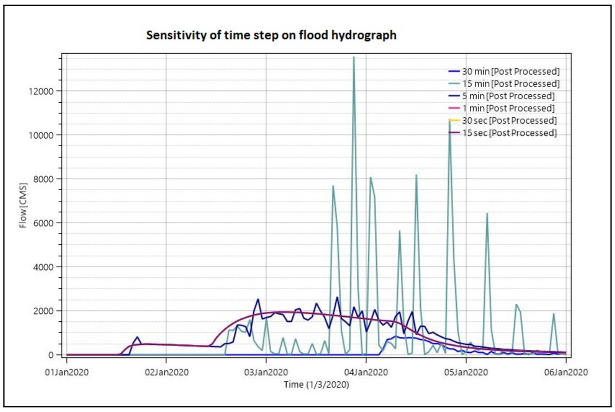

Figure 7: Sensitivity of time step on Flood Hydrograph

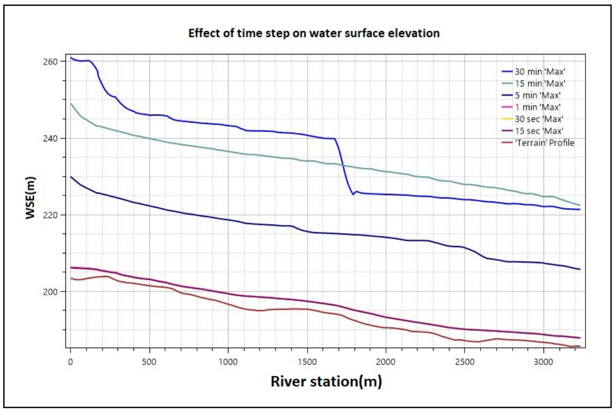

Figure 8: Sensitivity of time step on WSEL

4.1.3 Equation Set

Evaluating the relative change in inundation area relative change in water surface elevation level for different equations, there is less significance change for full momentum equation then Diffusive wave equation. But the computational time for Full momentum Equation is larger than that of diffusive wave equation.

Table 5: Sensitivity analysis on Equation Set

SN	Equation Set	% change in Inundation Area	change in WSE (m)	Time (hh:mm:ss)
1	Diffusive wave	-9.6	1.6	01:126:02
2	Full Momentum	-2.6	0.94	03:36:08

4.1.4 Theta Weighing Factor

In this study theta weighting factor of 0.6, 0.8 and 1 are used to evaluate its effect on simulation result and model stability. The summary of the sensitivity of theta weighting factor is presented in Table 6.

Table 6: Sensitivity analysis on Theta Weighing Factor

SN	Theta Weighing Factor	% change in Inundation Area	change in WSE (m)	Computation Time (hh:mm:ss)
1	1	0	0	01:06:02
2	0.8	0.8	0.18	01:32:57
3	0.6	1.2	0.21	01:56:51

There is no significant difference in result for different theta weighting factor. So for the flood inundation mapping in selected river the theta weighting factor was found to be less sensitive, also the numerical instability increases by using theta factor of 0.6. So for this study theta factor of 1 is found to be perfect parameter, as theta factor of 1 give most stable solution with no significant change in accuracy of the result compared to lower theta factor.

Table 7: Selected Optimal Parameters

Mesh Geometry	50m x 50m
Time Step	30 sec
Governing Equation	Full Momentum
Theta Weighing Factor	1

4.2 Validation and Flood Inundation Mapping

Using the selected optimal model parameter, flood inundation mapping for 100 years return period was prepared. The results are validated by capturing flood marks from satellite images. It is assumed that, those flood mark are of recurrent flooding event and considered as 2 years return period of flood. Model Validity from satellite images was found to be 85%. Effect of flood inundation on different land use category is presented below. For 100 Years of flood. 4.31% of catchment area gets flooded for Kankai River basin.

Table 8: Flood Inundation area on Land Use

Land Use	Inundation Area (km^2)
Forest	2.65
Shurbland	29.3
Agricultural Land	23.16
Barren Area	0.15
Water Body	8.34
Builtup Area	0.01
Total Inundation Area	63.5

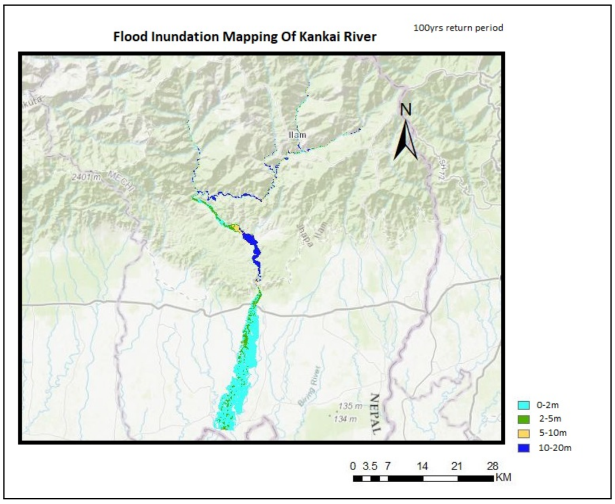

Figure 9: Flood Inundation Map of Kankai River

5. Conclusion and Recommendation

On the basis of inundation area, water surface elevation level and computational time required, this study gave the idea of model parameter sensitivity on result with some guidelines for selecting optimal model parameter.

1. The effect of theta weighting factor on result is very small so theta weighting factor of 1 can be used as it gives most stable numerical model.

2. For flood inundation mapping in flat terrain, diffusive wave approximation is not validated. So full momentum equation must be used.

3. Time step was the most sensitive factor among all four factors. For the time step above 1 minute, error in result increases exponentially with increase in time step and the result are less sensitive for time step below but computational time will increase with use of lower time step.

4. Mesh size is also highly sensitive for obtaining WSE and inundation area.

Selection of model parameters affects highly the overall accuracy of result and computational time, so for selecting the optimal model parameter following recommendation are made based on this study. While selecting optimal mesh size, selection should start with larger mesh size and change in WSEL must be observed by reducing the mesh size. Once the minimum change in WSEL observed, refinement of mesh geometry to capture the topographical features must be done. Use of too small mesh size is not recommended, as that will increase the computational time.

Time step must be selected using courant condition of 1 for maximum velocity and mesh size of critical location, which need an approximation of the maximum velocity. While modeling the moderate slope and steep slope river diffusive wave equation also gives accurate result with better numerical stability and lower computation time. In case of rapidly changing flow, comparison between full momentum and diffusive wave equation must be done.

In Terai region of Kankai River, proper flood protection measures such as construction of levees and flood wall, improvement of river channels, river bank stabilization are recommended. Settlement on inundation area should be restricted to minimize vulnerability to flood.

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