Paper 5-4-3

DEVELOPMENT OF A 1D HYDRAULIC MODEL FOR FLOOD INUNDATION MAPPING ALONG THE ANABRANCHED MEKONG RIVER, SIPHANDONE, LAO PDR, AS AFFECTED BY RECENT LAND USE CHANGES

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ABSTRACT

Development of a suitable digital elevation model (DEM) of the bathymetry of a remote river channel, which could then be used for hydraulic modeling, was challenging. This paper presents a method to derive a pseudo-bathymetry using a SPOT (Satellite Pour l'Observation de la Terre) images for channels within an anabranching network of the Mekong River where there were no surveyed bathymetric data. The derived information was then integrated with the available bathymetry from a hydrographic atlas to create a complete DEM of a complex anabranching river networks. A one dimensional (1D) hydraulic model - Hydrological Engineering Centre River Analysis System (HEC-RAS) - was applied to calculate the wetted section throughout a multi-channel network where a detailed DEM was available for the date of the SPOT image and for the in-bank discharge that day recorded at Pakse. The wetted sections obtained from the HEC-RAS model were compared to those in the SPOT image to identify the acceptability of the modelled results. Land cover maps for the last decade showed significant changes in the land cover pattern. The HEC-RAS model then was run for overbank flood flow conditions and the effect of spatial and temporal changes in land cover roughness were determined. It was found that the lateral extent of flooding was not significantly affected by the land cover changes (leading to the hydraulic roughness changes) but the reduction in flow resistance as natural forest was cleared might lead to faster near-bank flows and increased bank erosion.

INTRODUCTION

Many numerical hydraulic models have been developed to explore different aspects of natural channelized river flows. Perhaps the most important input data for a numerical hydraulic model is the geometry of a channel system. However, the geometry data are not always available at a sufficient resolution and indeed, in some cases, there may be no channel geometry data. Collet *et al.* (2000) developed an approach to determine bathymetric maps using SPOT (Satellite Pour l'Observation de la Terre) images to estimate water depths. However, this particular model was developed in the case of non-turbid water. It is still a significant challenge to apply remote-sensing techniques to explore the bathymetry of a deep, highly turbulent, turbid river.

In recent times, the land cover along the Mekong River, especially in the Siphandone wetlands, Lao PDR has changed significantly from dry forest and mixed forest to dry scrub and agriculture, especially rice paddy. Such changes result in alteration of the hydraulic natures of the flow during the flooding period within the study area and may have significant impact on the downstream channels as well. However, the influence of land cover change on the flooding pattern is not clear, especially in the case of a multi-channel network with a combined bedrock and alluvial river bed. In addition, apart from the choice of the dimensionality of a model, the selected roughness values of the riparian land surfaces are important for estimating the flooding pattern during overbank discharges. The roughness values mainly are influenced by the land cover pattern which can be derived from satellite images (Wilson and Atkinson, 2007).

According to previous studies, there are still uncertainties about the suitability of hydraulic models of different dimensionality for modelling flooding extent. Even though HEC-RAS is a one dimensional (1D) hydraulic model, it may be used effectively to calculate the water surface elevation (WSEle) at each cross-section and therefore in principle can be used to estimate the flooding pattern along a multi-channel network (Horrit and Bates, 2002). A 1D hydraulic model is most suitable in those situations where input data are limited in both quality and quantity, as is the case with poorly gauged rivers in developing countries.

This study is done to: (i) Develop a semi-quantitative bathymetry of a complex anabranching river network; (ii) Calculate the hydraulic roughness at each cross-section along the multi-channel network; and, (iii) Determine the planview of the wetted multi-channel network during low discharge and the flooding patterns resulted from an extreme high discharge by using a 1D hydraulic model (HEC-RAS) in the case of different scenarios of land cover change.

STUDY AREA AND SPATIAL MATERIAL

A mixed bedrock – alluvial anabranching river network of the Mekong River located in the Siphandone wetlands, Lao PDR (Figure 1) was chosen for this study. Within the Siphandone wetlands, a multi-channel network can be found in the north (Box b, Figure 1) while in the south, a complex anabranching river network can be observed. Because there was no discharge data collected at any gauging station near the study area, the discharge recorded from the Pakse gauging station was used as the upstream boundary condition for the 1D hydraulic models. Two stage board records at Channoi and Hatxaykhoun were used to constrain the upstream and downstream boundary conditions of a 1D hydraulic model of the studied multi-channel network, respectively.

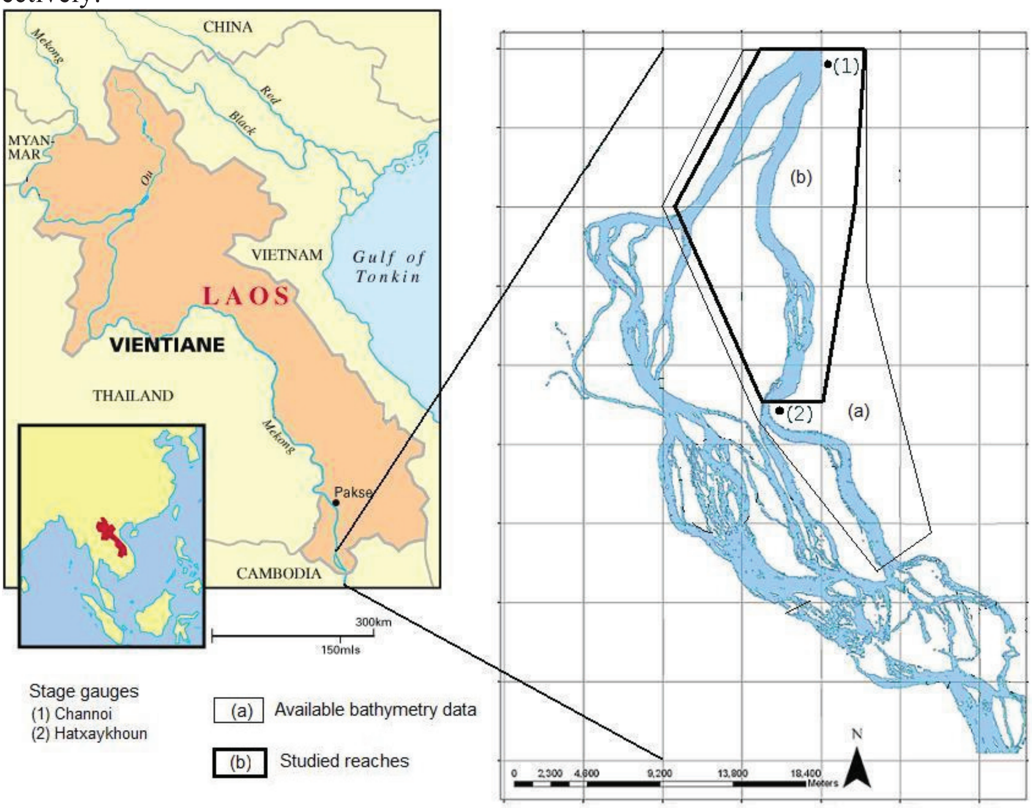

Figure 1. The Siphandone wetlands, Lao PDR

The SPOT images (20 m resolution) taken on 3 March, 2001 and 18 February, 2005 were used to acquire the spatial changes of the land cover pattern over a 4-year period. However, both SPOT 2001 and 2005 did not cover the entry channel at Channoi therefore the SPOT image taken on 30 March, 2003 was used to calculate the hydraulic roughness at each cross-section and therefore applied to validate results obtained from the HEC-RAS model. In addition, to classify the land cover pattern on the SPOT images, a land cover map produced by the Mekong River Commission (MRC) in 2006 was used. Furthermore, the DEM of the study area was available according to: (i) The available DEM (30 m resolution) partly covering the Siphandone wetlands (including bathymetric data), and (ii) the Shuttle Radar Topography Mission (SRTM) data (90 m resolution) to create a new DEM which covered the land surface of the whole Siphandone wetlands.

METHODOLOGY

To create a pseudo-bathymetry of the riverbed where there were no available bathymetric data, a SPOT image was used with reference to the digital Hydrographic Atlas (dHA) sounding data (Box (a), Figure 1). A semi-quantitative approach describing the river bathymetry within the river network was developed by matching the SPOT image reflectance band data with the available measured bathymetric data. To simplify the applied method, the assumption was that where the water column was deepest in the main channels, the flow velocity would be higher and the total suspended sediment concentration would be higher, which resulted in less reflectance (*i.e.* darker colour in the image) at the water surface (WS). The following classification of the water depth was proposed: very deep water (11 - 20 m), deep water (6 - 11 m), average (4 - 6 m) and shallow water (0 - 4 m).

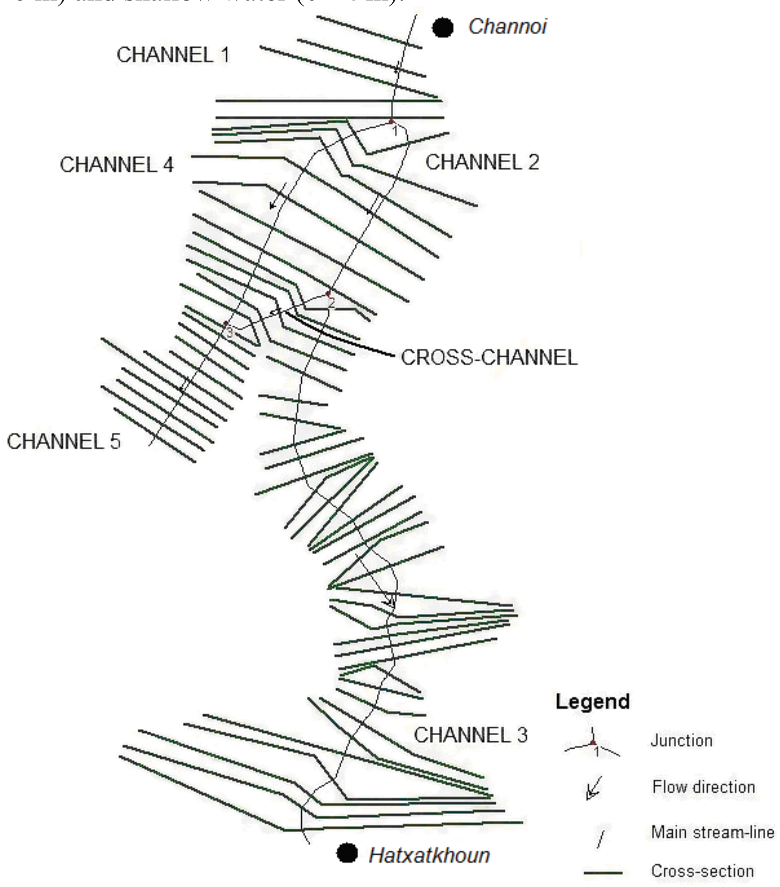

Figure 2. Cross-section alignment developed for both low and flooding discharge scenarios

To classify different land cover patterns in the study area during the studied period, the available data (*i.e.* a digital land cover map and the SPOT images taken in 2001 and 2005) were analyzed using the supervised classification technique.

For the low discharge scenario (6,450 m^3s^{-1}), with the interpolated top-width derived from the SPOT image (taken in 2003), the WSEle at the first cross-section of channel 1 and the last ones of channel 3 and 5 were 84.09 m+MSL (mean sea level), 80.30 m+MSL and 80.98 m+MSL, respectively. During the flooding period, there was no specific information which could help to determine the WS slopes of channels within the multi-channel network. According to the local people, with the peak discharge (56,000 m^3s^{-1}) in 1978, the WSEle's at Channoi and Hatxaykhoun were about 2.50 m and 2.00 m above the left bank respectively. With the elevation of the left bank in Channoi and Hatxaykhoun of about 86.00 m+MSL and 85.50 m+MSL, the WSEle's at each location were about 88.50 m+MSL and 87.80 m+MSL, respectively. In addition, it is assumed that the water surface slope along the multi-channel network in the flooding period was similar; the WSEle at the end of Channel 5 was estimated at 88.00 m+MSL. The WSEle's at each location in two scenarios were summarised in Table 1.

Table 1. Boundary conditions of the multi-channel network at different scenarios of the entry discharge

Channel	WSELe (M+MSL)	
	Low discharge	Flooding discharge
Channel 1 (Upstream boundary condition)	84.09	88.50
Channel 3 (Downstream boundary condition)	80.30	87.50
Channel 5 (Downstream boundary condition)	80.98	88.00

Zavadil *et al.* (2007) used the ratio of cross-sectional areas of the first cross-section of each downstream channel to examine the changes of geometry of the multi-channel network at each confluence. In this paper, such the ratio was used as an indicator to identify the splitting discharge at each junction. In other words, the ratio of splitting discharge at each junction was defined by the ratio of cross-sectional areas between the first cross-sections of the two channels downstream.

To calibrate the HEC-RAS model in the low discharge scenario (Figure 3), the top-width at each cross-section was identified according to the SPOT image. By using Winxspro, a software package designed to analyze stream channel cross section data for geometric and hydraulic parameters, the WSEle and cross-sectional area at each cross-section corresponding to the top-width were identified. In addition, the initial values for the WS slope between cross-sections were identified according to the average WS slope of each channel which was the ratio of the difference in the WSEle and the distance between the first and last cross-section of a channel. The Manning's *n* roughness parameter was calculated at each cross-section in MS Excel according to the Manning's equation and then applied in HEC-RAS. The hydraulic nature at each cross-section was modelled using HEC-RAS. If the differences of simulated WSEle's between the last cross-section of the upstream channel and the first two cross-sections of the two downstream channels were acceptable (less than or equal to 0.003 m), the water-way along the multi-channel network was identified; otherwise, the WS slope at each channel in MS Excel was adjusted (to match the SPOT channel width and to minimize the differences of the WSEle's of the cross-sections at the junctions) leading to the change of the hydraulic roughness at each cross-section and the simulated water-way.

In the flooding scenario (Figure 4), to identify the hydraulic roughness value at each cross-section in MS Excel, an initial WS slope ($S = 4.5 \times 10^{-5}$) was applied to all channels. The WSEle at each cross-section was calculated from the downstream to the upstream cross-section of each channel according to the initial slope. With the defined WSEle, the cross-sectional area and top-width at each cross-section were identified by using Winxspro. The Manning's *n* at each cross-section was calculated (in MS Excel) and applied in HEC-RAS. If the differences of the WSEle's between the last cross-section of the upstream channel and the first two cross-sections of the two downstream channels were acceptable (less than or equal to 0.003 m), the flooding pattern along the multi-channel network was identified; otherwise, the initial WS slope along the channels would be adjusted.

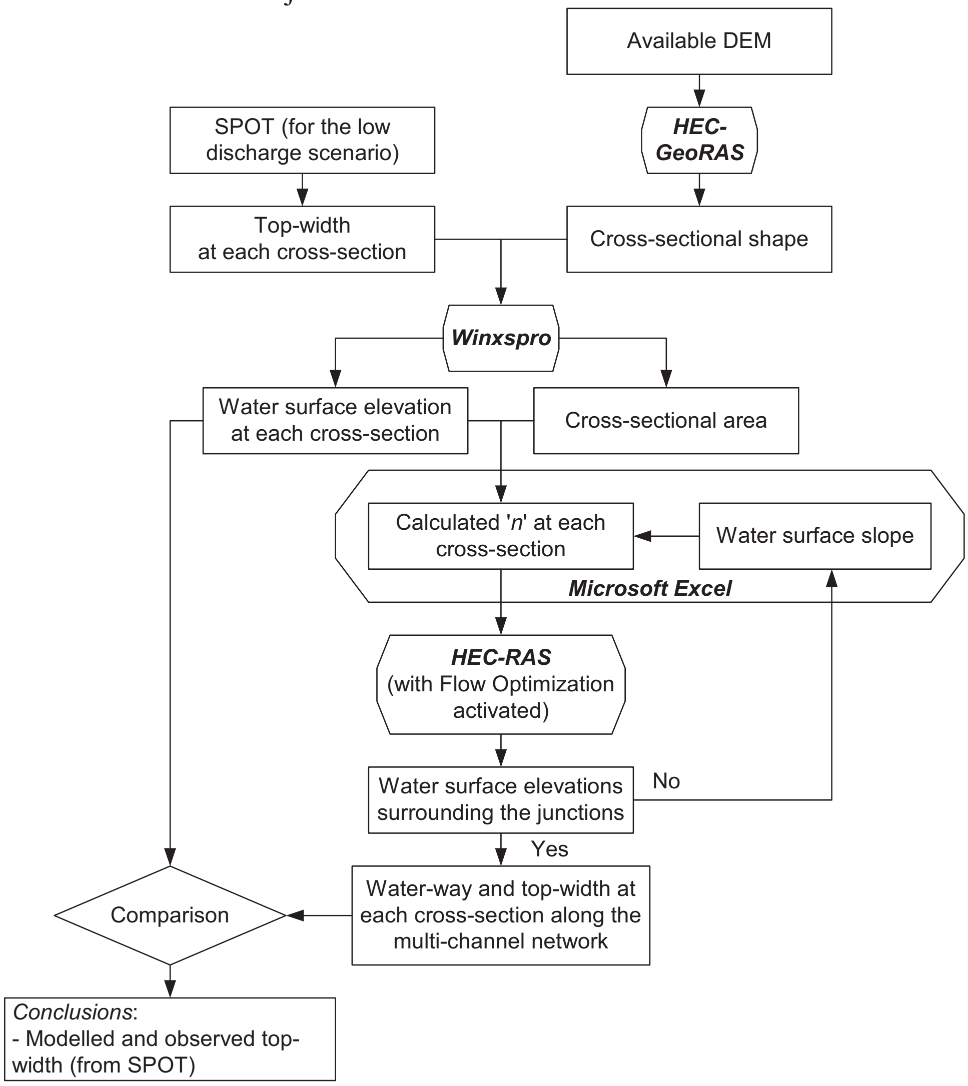

Figure 3. Routine to calibrate the HEC-RAS model for the low discharge scenario

To account for rapid changes of the land cover within the study area, three scenarios of land cover pattern were developed to model the flooding patterns. The first scenario (scenario 1) was of the current land cover pattern for the year 2005. The second and third scenarios were hypothetical cases in which all areas were covered by dry forest and rice paddy, respectively.

RESULTS

Land cover change over the Siphandone wetlands

Within the study area, the main land cover types (*i.e.* outcrops of rock and sand bars, dry shrub, bamboo/mixed forest, dry forest and rice field) could be recognized in both of the two SPOT images (taken in 2001 and 2005) (Figure 5). Between the two dates, the spatial pattern of the location and the proportion of each land cover type over the study area have changed significantly. Significant changes had occurred in the areas of dry forest and bamboo/mixed forest; dry forest had been cut mainly for commercial purposes and had not been re-planted but replaced by degraded forest of bamboo/mixed forest or dry scrub. This feature was most noticeable in the west of the study area. In the east of the study area, apart from the change of dry forest into bamboo/mixed forest, more rice fields could be found as well. In addition, the land cover change could also be recognized by an increasing proportion of dry scrub from 2001 to 2005. The wetted-area was slightly different due to different entry discharges of the multi-channel network at the time the SPOT images were taken.

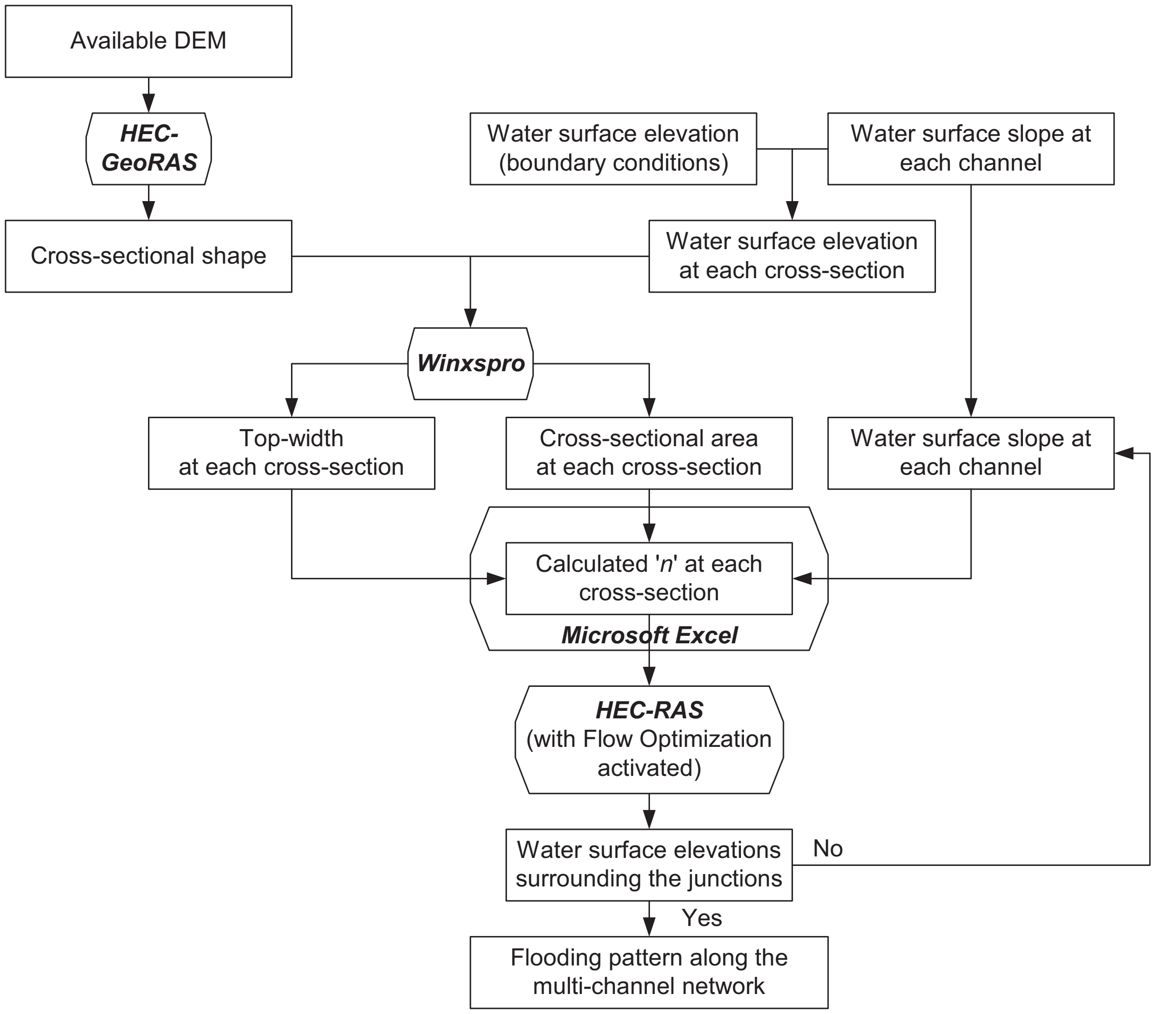

Figure 4. Routine to calibrate the HEC-RAS model for the flooding scenario

The integrated DEM

There were about one-hundred pairs of points (created by interpreting the SPOT image and derived from the dHA) available to develop a relationship between spectral reflectance and bathymetry. The correlation coefficient, $R^2 = 0.742$, for the relationship (between the reflective combination of the three bands in SPOT and the range of water depth) confirmed that the ranges of water depth derived from the SPOT image were relevant to the range of classified depths derived from the dHA. The newly developed DEM (with the integration of the available DEM. SRTM, dHA and SPOT) is presented in Figure 6. There are some errors (presented in ellipses) but these are few and mostly remote from the river network and require correction in due course.

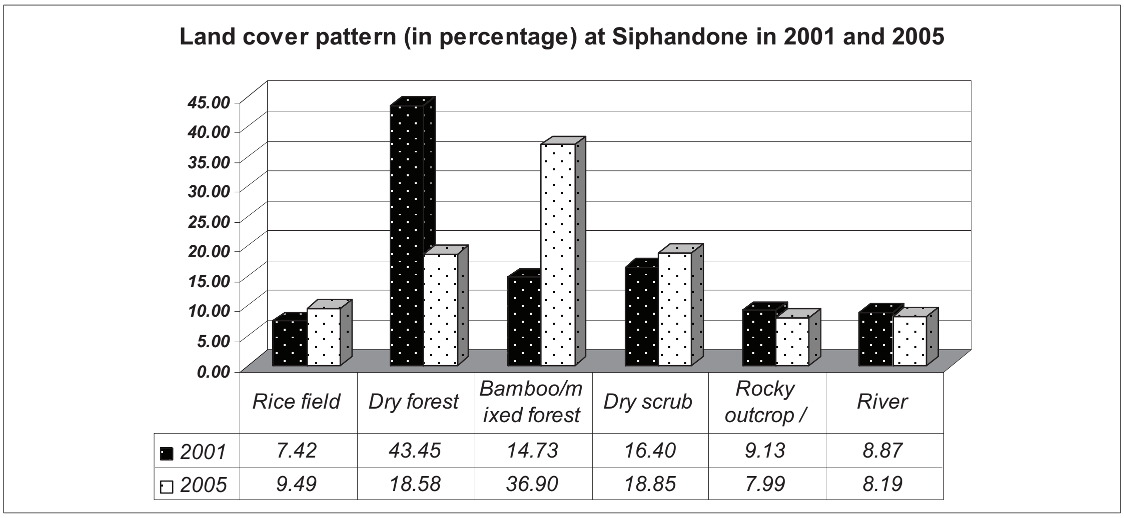

Figure 5. Percentage of each land cover type of the year 2001 and 2005

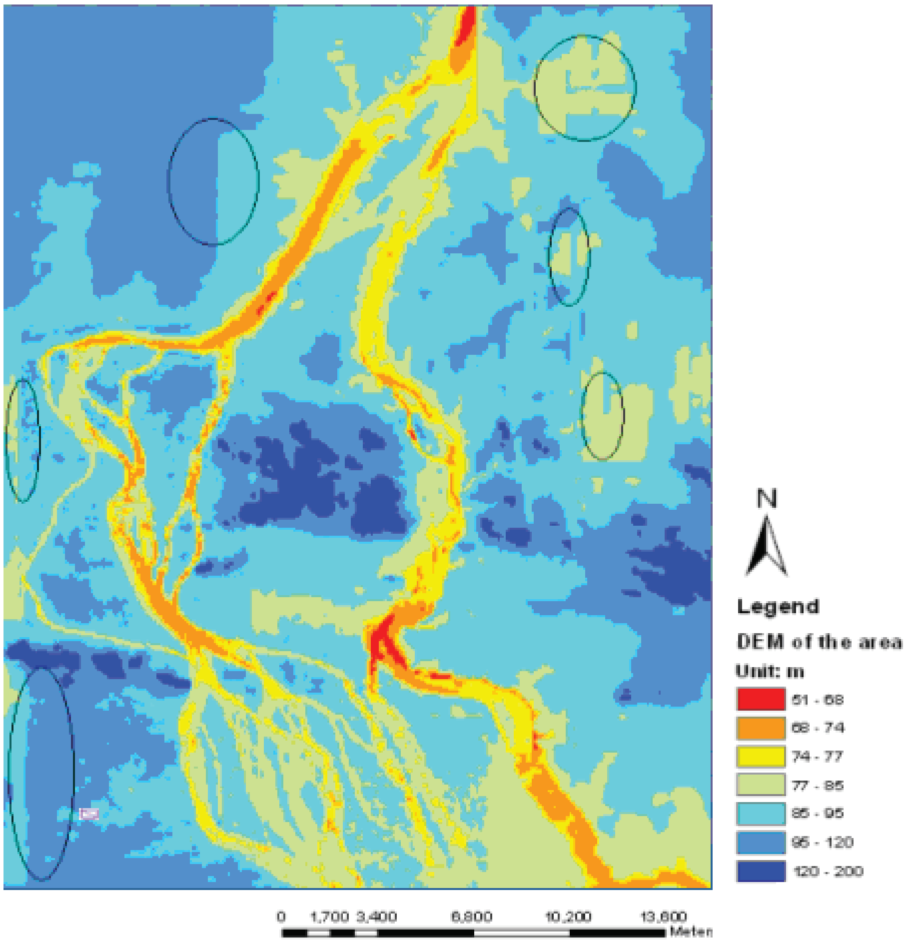

Figure 6. The newly developed DEM of the Siphandone wetlands, Lao PDR

The application of HEC-RAS for the multi-channel river network

Figure 7 illustrates the distribution of the in-channel hydraulic roughness (Manning's *n*) at each cross-section along the multi-channel network. It can be seen that the Manning's *n* coefficients along channel 4 and 5 was higher than those along channel 2 and 3. The comparison between the SPOT image and the modelled wetted section in HEC-RAS is presented in Figure 8; in this figure, the positive percentage indicates that the wetted area in the SPOT image was wider than in the HEC-RAS results and the negative percentage indicates the wetted area in HEC-RAS was wider than in the SPOT image. The differences between the modelled top-width and the SPOT image was within the range of (-27%: +17%) and most of the significant differences came from Channel 3. WSEle at the first cross-sections of each channel and the splitting discharge ratio at each bifurcation are presented in Table 2.

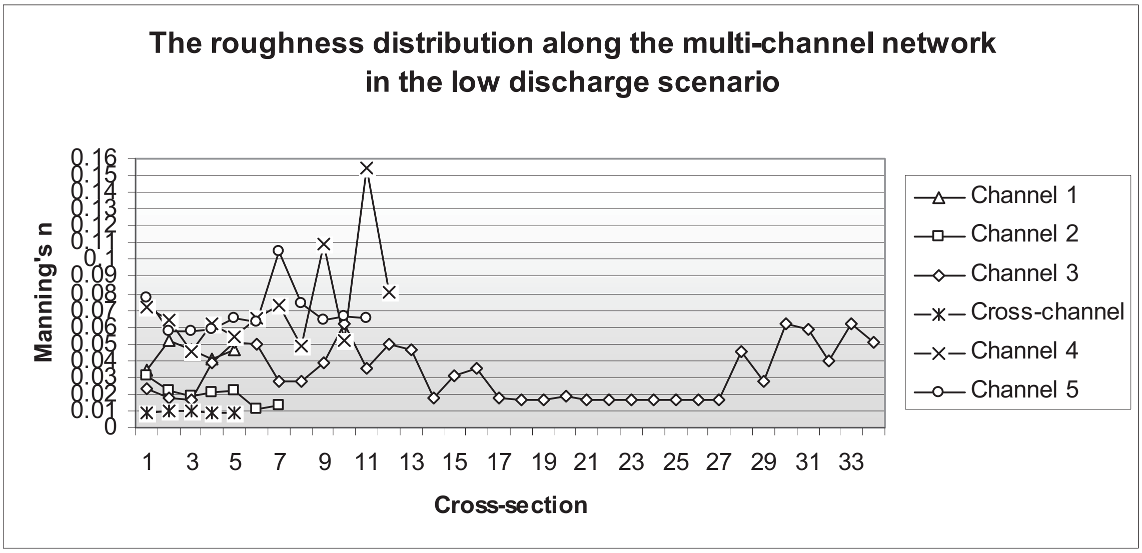

Figure 7. The hydraulic roughness distribution along the multi-channel network in the low discharge scenario

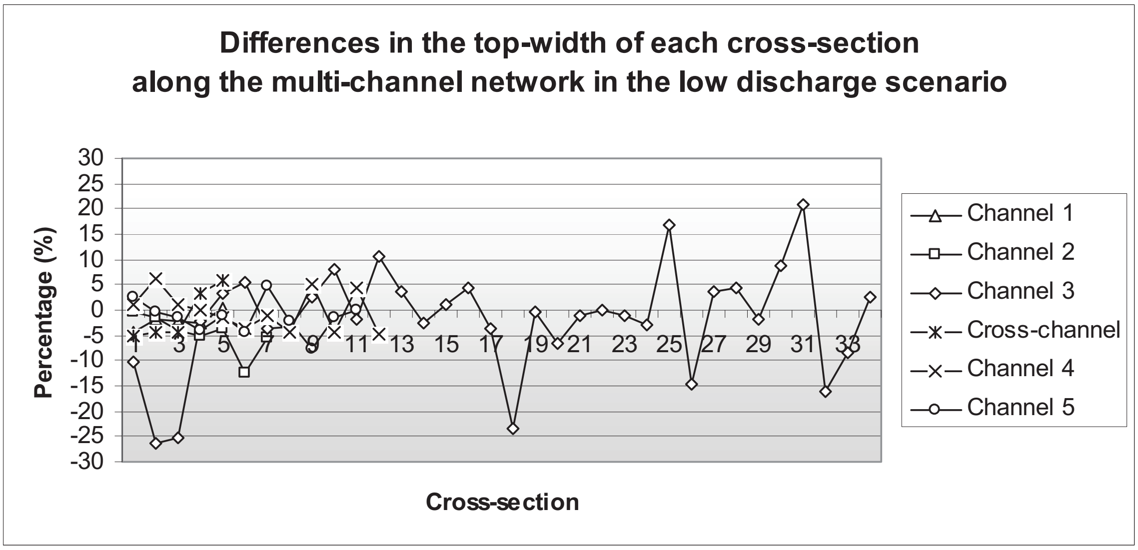

Figure 8. Comparison between the top-width derived from the HEC-RAS result versus SPOT image in the low discharge scenario

For the flooding scenario, each cross-section was divided into three main parts, including two sections of the floodplain and a channel section. To identify the hydraulic roughness of the floodplain sections, the land cover map produced by the MRC in 2006 was used and the referenced hydraulic roughness values of each land cover type were identified according to literature (Table 3).

Table 2. Water surface elevation at first cross-sections and the entry discharge of each channel

Channel	WSEle (m+MSL)	Discharge (m^3s^{-1})	Ratio of splitting discharge at the junction (%)	
			Junction 1	Junction 2
Channel 1	84.09	6,450		
Channel 2	83.92	3,278	50.8	
Channel 3	83.41	3,119		95.1
Cross-channel	83.40	159		4.9
Channel 4	83.93	3,172	49.2	
Channel 5	82.89	3,331		

Table 3. Roughness value of each riparian land cover type in the Siphandone wetlands.

No.	Land cover type	Referenced roughness
1	Outcrops of rock and sand bar (low flow only)	0.050 (**)
2	Dry shrub	0.300 (*)
3	Bamboo/mixed forest	0.200 (**)
4	Dry forest	0.800 (*)
5	Rice field	0.220 (*)

(*) Marsik and Waylen (2006); (**) Arcement and Schneider (2008).

Figure 9 illustrates the hydraulic roughness distribution along the channels of the multi-channel network and Figure 10 shows the flooding pattern for the current land cover scenario with WSEle at the upstream boundary condition found to be 89.09 m+MSL, which was 0.59 m above the predefined boundary condition. The hydraulic roughness at all cross-sections in the flooding scenario was lower than in the low discharge scenario, except the hydraulic roughness along the cross-channel because in the cross-channel the WS slope increased when the upstream boundary discharge increased. With different scenarios of land cover change, the simulated WSEle at each channel was similar therefore the flooding extents were not different according to land cover change. However, the land cover change led to change of hydraulic roughness of the floodplain and therefore resulted in the change of the velocity of the floodplains (Figure 11) leading to changes of discharge flowing through the floodplain. In fact, there were no significant differences in flooding area according to different land cover scenarios.

DISCUSSION

The SPOT image can be used together with the measured bathymetry to create a pseudo-bathymetry of a large river network where there was no measured data and should be similar according to the hydraulic properties and sediment transport pattern to the neighbour channels. However, in the case of a highly turbulent channel, the obtained result might be able to reflect ranges of the bathymetry with a certain level of uncertainty. The pseudo-bathymetric data has not been used in the hydraulic modelling reported in the 'Results'. The approach needs to be further studied so that it can be used to develop a more precise pseudo-bathymetry of a large river network and therefore useful for a 1D hydraulic modelling. To advance this aspect of the study, it is planned to use the pseudo-bathymetry DEM to extend the hydraulic model further to the south. For the present, the HEC-RAS model has been developed for the northern multi-channel network alone (Box b, Figure 1) using the dHA and the DEM developed by the MRC.

By using MS Excel and Winxspro, the hydraulic roughness (within the channel) at each cross-section could be identified and the wetted section along the multi-channel network identified for low discharge by using HEC-RAS and matching the water levels to the SPOT image. Once this procedure was developed successfully, the similar procedure was applied to the less-well constrained flooding scenario. Even though the Flow Optimization function (to minimize any hydraulic jump or drop by adjusting the splitting ratio at each junction) in HEC-

RAS was used to identify the ratio of splitting discharge at each junction, the ratios of the cross-sectional areas of the first cross-sections after each junction were used to provide guidance on splitting the discharges proportionately to the area ratios for both low and flooding flows.

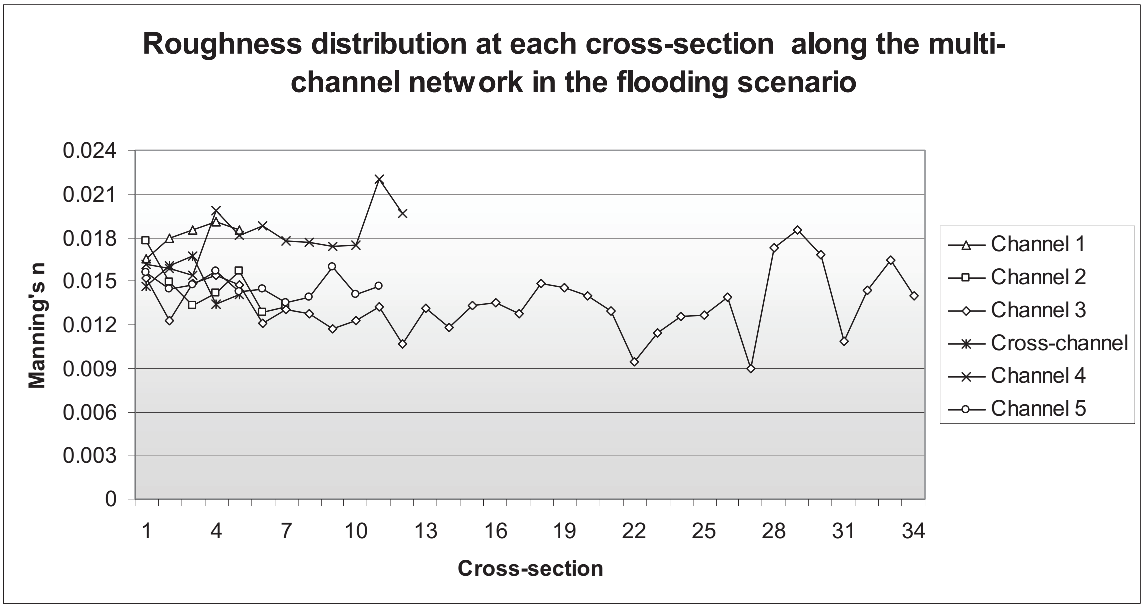

Figure 9. Hydraulic roughness distribution along the multi-channel network in the flooding scenario

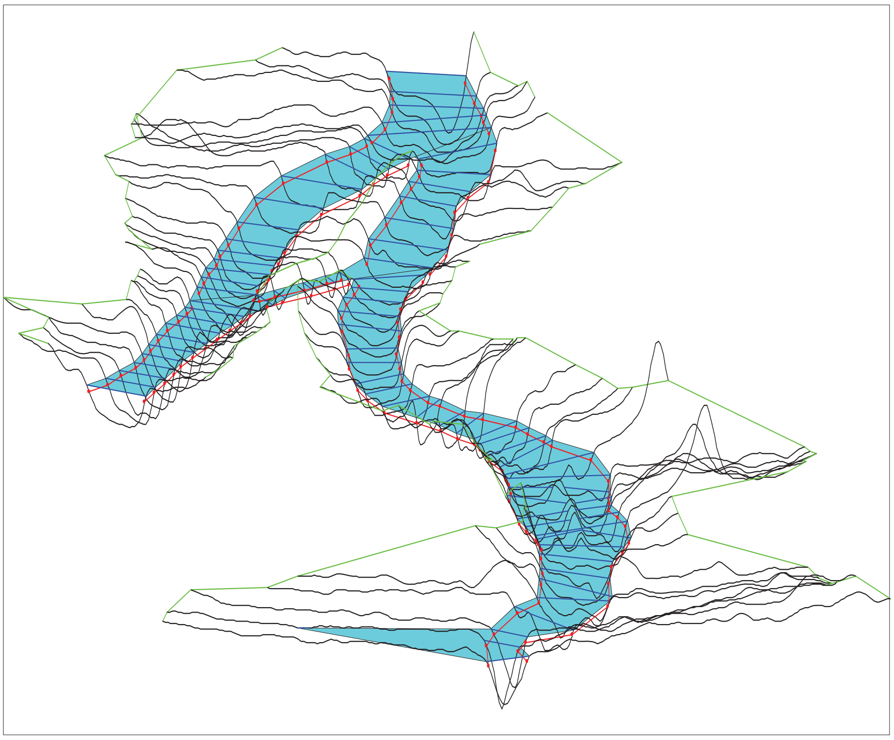

Figure 10. Flooding pattern according to three scenarios of the land cover pattern. Blue colour is the modelled channelized flow, the green lines indicate expected floodplain and red lines indicate the channel banks

The hydraulic roughness along channel 4 and 5 was higher than that of channel 2 and 3 in both scenarios of the entry discharge. Such differences might be explained by differences in the physical roughness of each channel bed; a topographically-rough bedrock channel might have higher hydraulic roughness than one with an alluvial fill within the bedrock channel. The hydraulic roughness of the cross-channel remains low, as the cross-channel is largely alluvial.

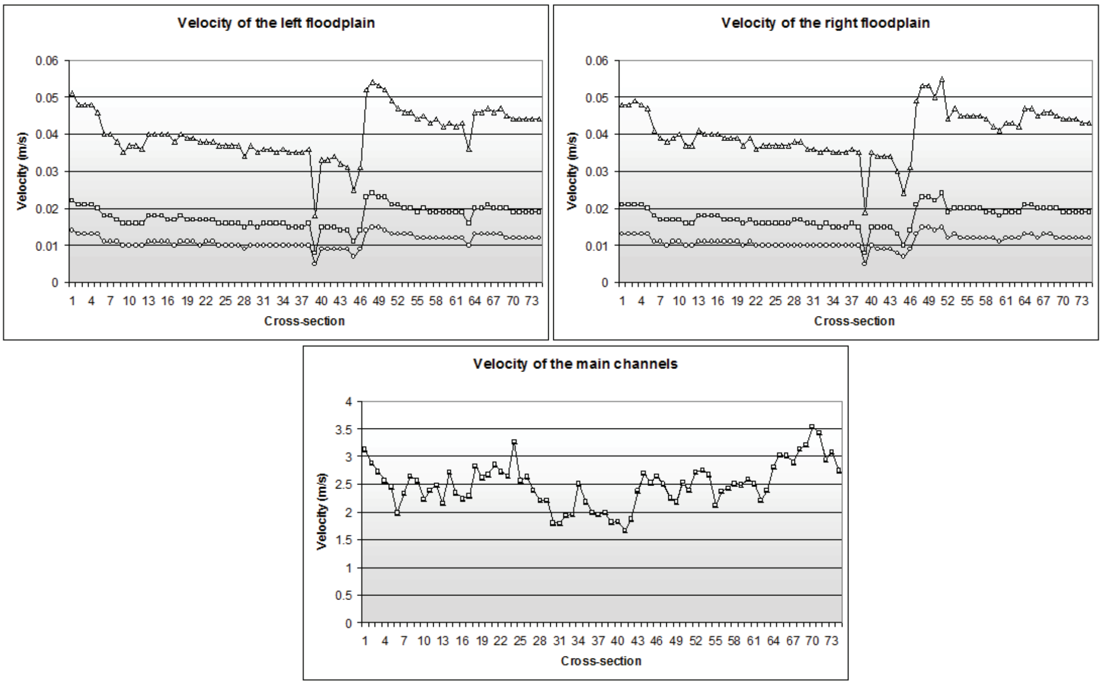

Figure 11. Velocity of the left-floodplain, channel and right-floodplain in different scenarios of the land cover pattern along the multi-channel network; square-symbol represents the present-day hydraulic roughness of the floodplain while triangle- and round-symbol represent the hypothetical cases where all areas were covered by rice paddy and dry forest, respectively

With different scenarios of the land cover pattern, even though the flow velocity along the floodplain changed significantly, the flow velocities within the main channels were similar when comparing the simulations for the three land cover patterns. In addition, the proportion of discharge flowing through the floodplain was small compared to that of the channels. Given the spatial resolution in the GIS model, land cover change had no effect on flooding extent but the presence of riparian vegetation slowed the main channel flow slightly so increasing water levels slightly. Additional unsteady flow simulations are required to investigate the effects of land use change on the dynamic progress of the annual peak flow and flooding patterns. Future work will also consider the changes in proportions of the land uses inundated given the effects of climate change scenarios on river discharge.

CONCLUSIONS

The SPOT image can be used to derive the pseudo-bathymetry of the river network based on the supervised classification technique. Due to the limitation of the information extracted from the SPOT images in the context of determining water depths, the results do not show a continuous range of bathymetry values but are rather grouped semi-quantitatively to create a pseudo-bathymetry that replicates the known range of bathymetric values. The approach potentially is valuable especially in the case of a complex anabranching river network where not all channels can be observed in the field.

The ratio of cross-sectional areas (defined according to the available dHA) after a bifurcation can be used to set the initial ratio of splitting discharge in the case of lack of field discharge data in individual channels. Subsequently, using MS Excel and Winxspro, the optimized hydraulic roughness at each cross-section along the network can be identified iteratively. Consequently, the HEC-RAS model can be used to simulate the multi-channel network with different upstream boundary discharges and limited additional parameter information.

Land cover change does not have significant impacts on the flooding extent over the study area. In addition, the land cover change along the floodplain does not have any impact on the velocity of the channel itself but the velocity of the floodplain (*i.e.* the lower the roughness floodplain, the faster the flow in the floodplain). Such the consequent changes of the flow rate according to the land cover change could cause major modifications of geomorphological features within the river network.

ACKNOWLEDGEMENT

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