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OPTIMIZED FLOOD INUNDATION MAPPING USING INTEGRATED GIS AND HYDRAULIC MODEL FOR UNGAUGED RIVER BASIN

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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May 2018

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Flood inundation mapping is one of the efficient methods for prediction of flood hazard and risk areas for emergency response and city development planning. River discharge and flood depth are critical parameters in hydraulic modelling for accurate flood hazard estimation. However, limited availability of observed discharge and river morphologies data results in the erroneous calculation and imprecise flood simulation and forecasting. Several empirical equations have been developed in order to predict the discharge. But, the impact of flood inundation mapping via minimum hydraulic variables has not been widely investigated. In addition, resampling techniques have been applied in order to increase the flood prediction; however, studies on the effect of resampled data with respect to the elevation of different land-use categories are limited.

This study attempts to determine a suitable discharge equation and assess the errors of flood inundation mapping at the ungauged station. The study was carried out along Padang Terap River, Kedah Malaysia using Interferometric Synthetic Aperture Radar (IFSAR) and light detection and ranging (LiDAR) DEMs. Through utilisation of this dataset water surface elevation (WSE) was delineated via Manning, Dingman and Sharma, and Bjerklie's equations. The Dingman and Sharma's equation which employs observed data presented a significantly noble agreement with measured and predicted WSE, followed by Manning and Bjerklie equations with the similarity of 80%, RMSE value of 2% and relative error of around 13%.

Next, the uncertainty of hydraulic variables was investigated via Bjerklie's equation, while the sensitivity analysis was evaluated through Monte Carlo simulation. Furthermore, a method for calculation of discharge without ground data via GIS technique was proposed. In addition, the effect of applying normal depth and known water surface (W.S.) boundary conditions were examined and the flood extent was verified with TerraSAR-X and historical flood marks. The F-statistics value was found to be 0.64-0.66 for normal depth and known W.S. boundary condition, respectively. By utilising modified IFSAR and known W.S. boundary condition, the mean absolute error

(MAE), root mean square error (RMSE) and Nash–Sutcliffe efficiency (NSE) were found to be 0.261, 0.365 and 0.808.

Quality of the IFSAR elevation data was assessed by comparing the output with observed Global Positioning System (GPS) and 15 cm resolution LiDAR on different land-use types. Results indicated that the LiDAR, original and the resampled IFSAR DEMs are correlated in elevation value about 90%. The equation was interpolated on the original and resampled IFSAR DEMs to improve the medium-resolution data for WSE delineation. Then, an additional sensitivity analysis was carried out at 95% confidence interval. The findings revealed that the optimize $IFSAR_{5m}$ is superior to the original DEM based on the MAE and RMSE values of 0.785 m and 1.071 m, respectively. WSE generated in HEC-RAS via different cross-section intervals (50, 100, 150 and 200 m) revealed that 100 m cross-section of the modified IFSAR DEM (MID1m) is the most suitable for flood extent mapping with MAE of 1.053 m.

Overall, the novelty of this is attributed to its evaluation of the performance discharge equations for flood mapping, especially in a spatial context. Furthermore, the uncertainties obtained from the hydraulic variables utilised in the discharge equation should be recognized. Consequently, by considering that these errors contributed to the flood hazard maps, the prediction of the inundated area and water depth could be produced accurately, especially at the data-scarce areas. Moreover, this study contributes to development of novel methodological approach by estimating discharge without ground data observation on optimized DEM with limited data available. The outcome of this research may support the current flood modelling in mitigation planning and strategies.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMETAAN GENANGAN BANJIR TEROPTIMUM MENGGUNAKAN INTEGRASI GIS DAN MODEL HIDRAULIK UNTUK LEMBANGAN SUNGAI TANPA TOLOK

Oleh

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Pemetaan banjir adalah salah satu cara yang berkesan untuk meramalkan bahaya banjir dan kawasan berisiko untuk tindak balas kecemasan dan perancangan pembangunan bandar. Pelepasan sungai dan kedalaman banjir adalah parameter penting dalam pemodelan hidraulik bagi membuat anggaran bahaya banjir dengan tepat. Walau bagaimanapun, pengehadan pelepasan air yang dicerap dan data morfologi sungai menyebabkan pengiraan yang salah dan simulasi banjir dan peramalan tidak tepat. Beberapa persamaan empirikal telah dibangunkan untuk meramal pelepasan air. Walau bagaimanapun, kesan pemetaan banjir menggunakan pembolehubah hidraulik secara minimum tidak diselidik dengan meluas. Di samping itu, teknik *resampling* telah digunakan untuk meningkatkan ramalan banjir, namun, kajian mengenai kesan data resampled berkenaan dengan ketinggian jenis penggunaan tanah berbeza adalah terhad.

Kajian ini dijalankan untuk memastikan pemodelan pelepasan air yang sesuai dengan menilai kesilapan dalam menganggarkan aliran air di kawasan tanpa stesen cerapan. Kajian ini dijalankan di sepanjang Sungai Padang Terap, Kedah Malaysia menggunakan *Interferometric Synthetic Aperture Radar (IFSAR)* dan *light detection and ranging* (LiDAR). Dengan ketinggian permukaan air dataset ini (WSE) telah digambarkan menggunakan persamaan Manning, Dingman dan Sharma, dan Bjerklie. Persamaan Dingman dan Sharma yang menggunakan data yang dicerap menunjukkan persetujuan yang sangat baik diikuti Manning dan Bjerklie dimana WSE yang diukur dan diramalkan mempunyai persamaan 80%, RMSE 2% dan ralat relatif sekitar 13%.

Seterusnya, Untuk menyiasat ketidakpastian mengenai pembolehubah gabungan hidraulik yang digunakan dalam persamaan Bjerklie, simulasi Monte Carlo telah dilaksanakan. Tambahan lagi, kaedah untuk mengira pelepasan air tanpa data cerapan menggunakan teknik GIS dicadangkan. Selain itu, kesan penggunaan kedalaman biasa dan permukaan sempadan air yang diketahui (WS) diperiksa dan tahap banjir telah disahkan dengan TerraSAR-X dan tanda banjir bersejarah. Nilai F-statistik didapati 0.64-

0.66 bagi kedalaman biasa dan permukaan sempadan air yang diketahui (W.S.) masing-masing. Menggunakan IFSAR yang diubahsuai dan keadaan sempadan WS yang diketahui, kesilapan mutlak bermakna (MAE), kesilapan akar min kesilapan (RMSE) dan kecekapan Nash-Sutcliffe (NSE) didapati 0.261, 0.365 dan 0.808.

Kualiti data ketinggian IFSAR dinilai dengan membandingkan output dengan sistem kedudukan global (GPS) bersama LiDAR resolusi 15 cm pada jenis guna tanah yang berlainan. Hasilnya menunjukkan bahawa LiDAR asal dan *resampled* IFSAR DEMs mempunyai korelasi dalam nilai ketinggian kira-kira 90%. Persamaan itu diinterpolasi pada data asal dan *resampled* IFSAR DEMs untuk memperbaiki data resolusi sederhana untuk penentuan WSE. Kemudian, analisis sensitiviti lain dilakukan pada selang keyakinan 95%. Penemuan menunjukkan bahawa pengoptimuman $IFSAR_{5m}$ lebih baik daripada DEM asal berdasarkan MAE dan RMSE masing-masing sebanyak 0.785 m dan 1.071 m. WSE yang dijana di HEC-RAS menggunakan selang rentas (50, 100, 150 dan 200 m) yang berlainan yang mendedahkan bahawa keratan rentas 100 m dari IFSAR DEM (MID_{1m}) yang diubahsuai adalah yang paling sesuai untuk pemetaan luas banjir dengan MAE sebanyak 1.053 m. Hasil kajian ini dapat menyokong pemodelan banjir semasa dalam perancangan dan strategi mitigasi.

Keseluruhan, novelti bagi tesis ini adalah kajian komparatif untuk menilai prestasi model pelepasan untuk pemodelan banjir, terutama dalam konteks spatial. Selain itu, dengan menentukan ketidakpastian pemboleh ubah hidraulik yang digunakan dalam persamaan pelepasan, kesilapan dalam menyediakan peta bahaya banjir di kawasan yang terhad mungkin dikurangkan. Selain itu, tesis ini menyumbang pendekatan metodologi baru dengan menganggarkan pelepasan tanpa pemerhatian data tanah pada DEM yang dioptimumkan dengan data terhad yang tersedia.

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I certify that a Thesis Examination Committee has met on 18 May 2018 to conduct the final examination of Ernieza Suhana binti Mokhtar on her thesis entitled "Optimized Flood Inundation Mapping Using Integrated GIS and Hydraulic Model for Ungauged River Basin" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

1D	One-dimensional
2D	Two-dimensional
DEM	Digital Elevation Model
DGPS	Differential Global positioning System
DID	Department of Irrigation and Drainage
DSM	Digital Surface Model
ETM+	Enhanced Thematic Mapper Plus
GCP	Ground Control Point
GIS	Geographical Information System
GLUE	Generalized likelihood uncertainty estimation
HEC-HMS	Hydrologic Modelling System
HEC-RAS	River Analysis System
IFSAR	Interferometric Synthetic Aperture Radar
LiDAR	Light Detection and Ranging (LiDAR)
MAE	Mean Absolute Error
MSS	Multispectral Scanner
NRCS-CN	National Soil Conversion Service (NRCS) Curve Number (CN)
NSE	Nash–Sutcliffe efficiency
ORI	Orthorectified Radar Image
R2	coefficient of determination
RCM	Rating curve model
RE	Relative error
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
SPOT	Satellite Pour l'Observation de la Terre
SWAT	Soil and Water Assessment Too
TIN	Triangular Irregular Networks
TM	Thematic Mapper
W.S.	Water Surface
WSE	Water Surface Elevation

CHAPTER 1

INTRODUCTION

1.1 Background of Study

At the present time, natural disasters such as landslides, earthquakes, drought, and floods have turn into catastrophic phenomena in different parts of the world, resulting in causalities and property damages. These events are unpredictable since they occur unexpectedly. According to Pradhan and Youssef (2011), floods are the most devastating disasters occurring in rural and urban areas, typically with severe damages. A flood occurs when riverbanks are over-spilled and the water diverted to the floodplain zones in residence area, which is known to be damaging for public facilities and agricultural lands. Flood is categorised into three main types: coastal flood, flash flood, and river flood. Differentiating the type of flood depends on the rainfall, duration, and size of flood extent (Opolot, 2013). It is on record that floods in India occurred continuously with magnitude of more than 35,000 m^3/s due to extreme precipitation, resulting in economic losses of over US$ 400 million in 2008 and 2011 (Jena et al., 2016). Due to the heavy rainfall and inadequate drainage design for the purpose of holding water in high volume, the water overflow from channel to dry surface was submerges underwater (Kaveckis and Bechtel, 2014).

Common triggering factors such as storm surge, typhoon and tropical low pressure result in intense rainfall in the central and south region of Vietnam (Ho et al., 2010). In addition, it has been reported that sea levels are rising due to global warming (Obanawa et al., 2010), climate change, uncontrolled human activities such as deforestation, while rapid development escalates the flood risk and coastal erosion due to the rise of discharge and surface runoff (Chen et al., 2016; Tehrany et al., 2015; Wu et al., 2015). Every year, natural disasters lead to hundreds of deaths and cost billions of dollars in disaster aid, disruption of socioeconomic activities, and damages the buildings and critical infrastructure. According to the Malaysian Department of Irrigation and Drainage (DID), it has been estimated that more than 2.7 million people live in flood-prone areas while the average annual flood damages amount to RM200 to RM300 million per year (Pradhan et al., 2009). In addition, DID reports that in 2010 most of the flood events in Kedah were attributed to water overflowing from Padang Terap River. For instance, around 5,615 residents and a large expanse of paddy fields and cultivated land were affected by a flood event in the state of Kedah between 2005 and 2010 (Said et al., 2013). The property loss was also estimated to be around RM17.81 million in 2010, in comparison to RM3.126 million in 2009 (DID, 2009, 2010).

Although the damages produced by the flood have reduced to about RM12.685 million in 2014, however, flood continues to wreak havoc on the communities along Padang Terap River annually, arising from heavy rainfall and water overflowing of the river banks. Several efforts have been executed by the Ministry of Natural Resources and

Environment Malaysia (2011) towards enhancing flood mapping and forecasting by utilising structural methods such as flood protection and nonstructural methods which include preparation of hazard maps, flood warning, and forecasting systems. Between 2010 and 2012 alone, about 25 flood hazard maps were produced to assist the state government in flood mitigation planning.

Flood inundation maps are important for flood hazard and risk assessment (Merwade et al. 2008a). Several attempts have been performed in order to improve and produce accurate flood hazard maps (Getahun and Gebre, 2015; Nor Aizam et al., 2014; Pradhan et al., 2014; Turner et al., 2013); via different hydraulic models such as Hydrologic Engineering Centre River Analysis System (HEC-RAS) (Brandimarte and Di Baldassarre, 2012; Getahun and Gebre, 2015; Knebl et al., 2005; Salimi et al., 2008), Hydrologic Modelling System (HEC-HMS) (Tripathi et al., 2014), Natural Resources Conservation Service Curve Number (NRCS-CN) (Gholami et al., 2010; Ibrahim et al., 2014), MIKE 11 (Alam et al., 2014) and Soil & Water Assessment Tool (SWAT) (Ahn and Merwade, 2017; Wu et al., 2015). These hydraulic models are integrated with GIS and remote-sensing datasets where river discharge is vital for water inundation extraction, flood risk, hazard mapping, and surface runoff monitoring (Alaghmand et al., 2010; Ali et al., 2011; Ibrahim et al., 2014; Jung et al., 2014; Jung et al., 2012; Tarpanelli et al., 2013a). River discharge can be obtained from gauge station (Jung et al., 2014; Salimi et al., 2008; Tarpanelli et al., 2013a) or by empirical equation (Bjerklie, 2007; Dingman and Sharma, 1997; Riggs and Reston, 1976; Robert, 1897). Other parameters such as surface roughness, cross-section depth, boundary condition and river width are required as well for simulation of inundated area and flood depth (Brunner, 2010; USDA, 2007). For this purpose, low-high resolution DEM, optical and SAR imageries have been widely utilised to enhance the flood inundation mapping. GIS and remote-sensing data integrated with hydraulic models have been resourcefully employed in hydrology and hydraulic modeling for estimation of discharge, model calibration, and surface runoff characteristic based on land-use variations, uncertainties of hydraulic variables, flood hazard, flood risk, flood susceptibility and land-use.

Enhancement of flood inundation mapping is essential for assessing and accurately locating potential areas at risk of flooding. However, uncertainties in hydraulic variables and geospatial data are required to be eliminated for accurate deriviation offlood hazard maps. Therefore, this study aims to enhance the current methods and identify uncertainties in flood hazard mapping by optimizing IFSAR dataset to derive flood extent and water surface elevation accurately. This study is of importance to government agencies such as DID and the Department of Town and Country Planning for effective flood monitoring and management.

1.2 Research Questions

Related research questions that will be answered in this research are:

i. How discharge value could be obtained for the area of the ungauged station?
ii. Which statistical equation is appropriate for river discharge estimation?

iii. What are the uncertainties in the proposed equation and how could utilised hydraulic variables be minimized at the ungauged station in flood modeling?
iv. Is it possible to forecast the flood extent and water surface elevation without ground data observation?
v. How IFSAR DEM could predict water surface elevation more accurately?
vi. What is the most suitable cross-section interval to delineate the water surface elevation?

1.3 Research Hypothesis

This research tests the following hypothesis:

i. Estimating flood extent and depth at the ungauged station can be determined precisely by reducing observed hydraulic parameters and minimizing geospatial data available.
ii. Optimization medium-resolution DEM can determine flood hazard area as provided by high-resolution DEM

1.4 The Motivation behind the Thesis

Recognition of error contributions in flood inundation mapping processes is the main consideration in this research. Due to the existence of uncertainties in different parameters in hydraulic variables on discharge prediction and geospatial data, the inundated area and flood depth cannot be predicted accurately. Considering the absence of the observed discharge data and river geometric, it is vital to make certain that the existing discharge equation is carefully selected in order to obtain the minimum error. Especially for areas that cannot be accessed due to unfavorable factors such as topography, weather condition, high cost, and non-availability or incomplete ground data observation. Hence, obtaining several variables such as wetted perimeter, cross-section depth, and the cross-section area of the river is known to be challenging. It is, therefore, necessary to improve the quality of IFSAR DEM. This research was performed in order to reduce the uncertainties that occurred due to selection of suitable values for the hydraulic variables, land-use surface roughness, which proposes the appropriate DEM data characteristic for flood modeling. Flood hazard maps could be precisely produced even for areas with limited data availability.

1.5 Problem Statement

The northern state of Kedah has been suffering from flooding, while approximately 5,615 residents and a massive portion of paddy field areas of 8,500 (2007) and 49,529 (2010) hectares were badly affected by flood. In 2010, severe flooding submerged the lands with flood depth in average 1 to 2 m in the catchment of Padang Terap River for five to six days due to overspill of the river's bank in 2005 and 2010. In the context of flood incidents, a loss of RM 3.126 million was reported in 2009, which pales in comparison to another major flood disaster in 2010, which disclosed an estimated staggering property loss of RM17.81 million. Specifically, during the major floods in 2010, an hourly record of the water level was captured by Muda Agriculture Development Authority (MADA) automatic telemetry station located at Kuala Nerang. The telemetry data indicated that the water level reached about 4 - 9 m from 31st October to 4th November.

Recently, Ministry of Natural Resources and Environment Malaysia (2011) has improvised several flood hazard maps as a reference for effective development planning which propagates the information regarding the inundated area for authorities responsible for flood operation (Jung et al., 2012; Merwade et al., 2008b). However, discharge data was unavailable in a certain area, which makes it difficult to map the inundated area accurately in hydraulic perspectives to prevent or at least minimise the damages to people and properties. According to Grimaldi et al. (2016), limited gauge stations are accessible in the developing countries, while the traditional methods labor intensive as well as being costly. In addition, it is challenging to quantify an accurate estimation of discharge at ungauged sites (Jung et al., 2013). Therefore, empirical equations have been developed to overcome the challenges with discharge data measurement (Barnes, 1969; Bjerklie et al., 2003; Brunner, 2016; Dingman and Sharma, 1997; Jarret and Asce, 1984). Furthermore, due to problems associated with observation of water discharge during unfavorable weather conditions, estimation of river flow via remote-sensing based techniques has attracted the attention of researchers (Birkinshaw et al., 2014). Therefore, the main goal of this study was to identify the existing discharge equation that could be appropriately utilised on the natural river in the Malaysian environment. In addition, based on the previous studies, no comparative study has been performed to evaluate the performance of the discharge equation for flood modeling, especially in a spatial context. Consequently, the selected discharge equations are proposed by considering the limited observed hydraulic data.

Flood inundation mapping can be provided accurately if the observed hydraulic data are available. Unfortunately, due to non-existence of ground observation data and difficulties in obtaining the high-flow condition, it can contribute to uncertainties in discharge and boundary condition, which leads to major challenge in prediction of inundated areas and flood depths (Bjerklie, 2007; Grimaldi et al., 2016; Jung et al., 2012; Pappenberger et al., 2006; Pappenberger et al., 2005). Furthermore, uncertainties are contributed by the complexity of flow equations, input flow values, model parameters, boundary condition, and river profile (Mason et al., 2015; Pappenberger et al., 2006; Yan et al., 2013). In addition, errors arise from model parameters assumption, uncertainties in Manning-*n* and wrong calibration due to assignment of a constant value as the roughness coefficient (Merwade et al., 2008a; 2008b; Pappenberger et al. 2005; Di Baldassarre et al., 2010). The uncertainties of the parameters may lead to inaccurate flood inundation mapping. Elimination or identification of the impact of uncertainties could significantly enhance the decision-making for present and future forecasting (Savage et al., 2016). Although several studies (Grimaldi et al., 2016; Lin et al., 2013; Merwade et al., 2008b; Tarpanelli et al. 2013b; Xie and Lian, 2013; Yan et al., 2013) have investigated the uncertainties of some parameters such as hydraulic model, discharge equation, and digital elevation model (DEM) on flood mapping, however, the existing uncertainties of the hydraulic variable utilised in the discharge equation at data-scarce area for flood inundation mapping require further exploration. Furthermore, evaluation of the impact of flood extent and depth with or without observed hydraulic variables by means of existing discharge equation requires to be performed in order to overcome the non-availability of data.

Additionally, uncertainties could be found in GIS-based mapping in terms of horizontal and vertical resolution, topographic data, interpolation algorithm, classification method, satellite equipment, surface roughness and image quality (Casas et al., 2006; Eleuterio, 2012; Jung, 2011; Md Ali, 2018). Quality of elevation data, cross-section extraction and integrating of surveyed and existing DEM data may influence the flood mapping, as it is the main concern which may affect the prediction of inundated area and flood depth (Ahn and Merwade, 2017; Md Ali, 2018; Md Ali et al., 2015; Merwade et al., 2008b). Merwade et al. (2008a) and Yan et al. (2013) reported that the performance of the integration of two different data format is necessary for reliable hydraulic modeling in flood profiles simulation. Although few researchers (Brandimarte and Di Baldassarre, 2012; Lin et al., 2013; Lumbroso and Gaume, 2012; Teng et al., 2017) have discussed the uncertainties of elevation data in hydraulic approach, the capability of the IFSAR DEM for flood modeling has not been widely explored. Therefore, this study examines the effects of resampled DEM data, establishes the relationship between LiDAR and IFSAR DEMs and enhances the quality of IFSAR DEM.

In this study, flood hazard map for Padang Terap River was enhanced to present the estimated inundated area and flood depth by minimizing errors that contributed to hydraulic variables utilised in the discharge equation and geospatial data. Then, the hazard area could be determined accurately to address the aforementioned gaps. Furthermore, several standards and the most relevant practices for data acquisition and processing were performed in order to improve the data quality for enhanced flood hazard mapping.

1.6 Aim and Objectives

The main aim of the study is to estimate the uncertainties in flood inundation mapping based on hydraulic characteristics and land-use via GIS techniques.

To achieve this aim, the specific objectives are:

i. To determine suitable discharge equations and assess errors in estimating water flow at the ungauged station on flood inundation mapping.
ii. To investigate uncertainties of hydraulic variables and influences of inundation areas delineated from estimated discharge without ground observation data and different boundary conditions.
iii. To examine the accuracy of DEM for different land-use types and optimize IFSAR DEM with various vertical resolutions and cross-section intervals.

1.7 The scope of the research

This study focuses on Padang Terap River, which connects three major areas, Kuala Nerang, Kampung Kubu and Kampung Kuala Pai, Kedah, Malaysia. Historically, communities along this river are known for frequent flooding, while one of the worst occurred in 2010. These areas are selected mainly due to their location which is in the low land area and are typically submerged due to the river overflow of channel. This study is purely data-driven, while several remote-sensing data including TerraSAR-X, and historical flood marks were utilised in order to analyse and verify the efficiency of the proposed method for flood inundation prediction and to enhance flood detection without hydraulic data. In this study, flow hydrograph was not considered; therefore, the new empirical equation for discharge estimation was not of importance. Furthermore, dam operation and the river sub-tributaries were not considered in the analysis.

1.8 Thesis Outline

This thesis is divided into five chapters. Chapter 1 explains, in brief, the introductory part, which includes the background of the study, problem statement, research motivation, research question, aim and objectives as well as scope of work. The Chapter 2 highlights the definition of flood inundation mapping, description of hydraulic variables and land-use concept. Furthermore, a thorough discussion of existing discharge models and the effect of uncertainties on water surface elevation and flood depth are presented. The chapter concludes with DEM quality assessment and the current trend in flood modeling using GIS and Remote Sensing techniques. The detailed methodology utilised in this study is presented in Chapter 3. The chapter describes the study area, gives details of the data used and methodology employed. In Chapter 4, the results are presented with elaborate discussion and implications of the findings according to the sequence of the methodological workflow. Issues of importance include discharge model assessment, determination of uncertainties of inundation area. Also a proposed approach to cross-section depth measurement, DEM quality assessment and appropriate cross-section intervals for forecasting inundated area is presented and discussed. Finally, the thesis concludes with Chapter 5, which summarizes the overall findings and suggests recommendations for future research.

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