RESEARCH ARTICLE | DECEMBER 07 2023

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AIP Conf. Proc. 2680, 020019 (2023)
https://doi.org/10.1063/5.0126176

Estimation of River Bathymetry and Spatial Distribution of Precipitation and Their Uncertainties

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Abstract. Hydrological modeling required essential input data such as river bathymetry, discharge, topographic and floodplain elevation values, manning's n values, and precipitation. In this study, river bathymetry and spatial distribution of precipitation were focused because of challenges in their estimation and associated uncertainties. These input data are also important in accurate flood risk and vulnerability assessment. Previous studies developed several models for their estimation using remote sensing and GIS. However, further improvement is required for their accurate estimation. This study will be helpful in accurate spatio-temporal estimation of these two input data. Furthermore, it was suggested the use of machine learning approaches to handle big data obtained from satellite images for further improvement in the spatio-temporal estimation.

INTRODUCTION

Increasing urbanization in valleys and anthropogenic activities at rivers and streams causing flooding during medium to high precipitation [1]. The continuous construction of dams to meet the requirement of agriculture and industries leads to an increase in sedimentation and flooding events during precipitation and hence changes in the river course [2]. Due to changes in river course, every year during monsoon in a tropical climate, the number of people effecting, losing their livelihood and lives. The impact and risk of flooding in these conditions can be minimized by

Proceedings of the 4th Tarumanagara International Conference of the Applications of Technology and Engineering (TICATE) 2021
AIP Conf. Proc. 2680, 020019-1–020019-6; https://doi.org/10.1063/5.0126176
Published by AIP Publishing. 978-0-7354-4698-4/$30.00

accurate flood forecasting and vulnerability assessment. These actions can provide sufficient time for planning and implementation of mitigation measures (for both short- and long-term measures) to maintain sustainability [3].

Several physically-based hydrological models, provide a realistic view of flooding, have been developed which required a large number of data that need to be entered [4]. The most important input data in most of the flood models are river geometry, precipitation, discharge, topography, and roughness values. Generally, precipitation and discharge data can be obtained from gauge stations, topography data from Digital Elevation Models (DEM), roughness values from land use land cover maps, and river geometry during field surveys. Uncertainties in flood modeling arise due to low density of gauge stations, coarse resolution of DEMs, sensitivity of roughness values, and limited field surveys [5,6]. There are alternative solutions for the coarse resolution of DEM and the sensitivity of roughness values. For instance, the use of DEM with a resolution ≤ 2.5 m and a range of roughness values in hydrological models can improve the associated uncertainties. However, the use of alternative approaches for low-density gauge stations and river geometry due to limited field survey is limited.

Several methodologies and models have been developed for the alternative approaches which showed that remote sensing and GIS techniques play a major role in the alternative approaches. How remote sensing and GIS techniques are useful in improving uncertainties associated with the spatial distribution of precipitation and estimated river bathymetry. Therefore, the focus of this study is to review the developed methodologies of the spatial distribution of precipitation and the estimation of river cross-sections in the last decade. Also, current scenarios in this field of research. The objectives of this study are (i) to review developed methodologies for estimation of the spatial distribution of precipitation and river bathymetry using remote sensing and GIS and (ii) to explore possibilities of future research and improvement in the input data uncertainties. This review would be helpful in Spatio-temporal estimation of input data for hydrological modeling in the absence or limited in-situ data. Furthermore, the effect of changes in river course and flooding could be accurately assessed and predicted.

ESTIMATION OF RIVER BATHYMETRY USING REMOTE SENSING AND GIS

During field surveys, measurement of river bathymetry for long reaches at a watershed scale is difficult, costly, and time-consuming. For accurate flood modeling, cross-sections at every few meters are necessary which is almost impractical during field surveys. Remote sensing and GIS techniques are useful for the estimation of river cross-sections at fine spatial resolution. Mapping of river bathymetry using remote sensing has some limitations [7]. First, greater sensitivity of red band to water depth which restricts it to penetrate the deeper water column. Second, the relationship between depth and watercolor is site-specific which needs calibration using in-situ data. Third, heterogeneities in spectral reflectance of river water due to the presence of different substrate materials, vegetation, surface waves, and shadows of nearby objects.

In the estimation of river bathymetry using remote sensing and GIS, the role of the Digital Elevation Model (DEM) is important which can map river bathymetry through shallow water. Publicly available the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global DEM of 30 m resolution can be used for wide rivers at plain topographic areas. However, ASTER GDEM has vertical errors reported in the literature. Light Detection and Ranging (LiDAR) based DEMs of high resolution (≤ 2.5 m) have been used to map river bathymetry with limited in-situ data. LiDAR-based DEM can measure accurate river bathymetry up to water surface level while the submerged part of the bathymetry is undetected due to the above-mentioned limitations (Figure 1). The undetected part of the bathymetry arises the discontinuity between measured bathymetry from LiDAR-based DEM and in-situ data which leads to uncertainty in hydrological models.

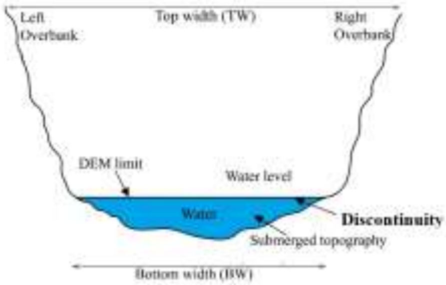

FIGURE 1. It is showing DEM limit in extracting river cross section up to surface water level and unknown submerged topography. Discontinuity also showing between river cross section extracted from DEM and the cross section measured from field survey.

To improve the discontinuity, Landsat images of 30 m resolution and also higher resolution images such as SPOT 5 can be used in the absence of in-situ data. Legleiter and Roberts [8] used forward modeling in which image-derived river information is based on the pixel-based spectral response of the image to assess the depth retrieval accuracy and precision. Legleiter [9] developed a framework using passive optical image data in which an alternative approach based on linear regression were used for river bathymetry estimation in the absence of in-situ data. Pilotti [10] used one-dimensional shallow water equations and DEM resolution of 16 m to extract river cross-sections at varying sinuosity of the thalweg. He observed limitations due to the sensitivity of DEM resolution and the requirement of some basic engineering common sense in the extraction of river cross-sections. Almeida et al. [11] used inverse modeling to shallow water equations and developed a framework to estimate river bathymetry using surface velocity data. Legleiter et al. [12] developed a framework of optimal band ratio analysis to relate imaged derived quantity and submerged river cross-section depth across a range of depths. They found that accuracies of depth estimate were effected by truncation or sampling. Overall, recent development in the estimation of river bathymetry using remote sensing indicating the requirement of further improvement using multiple approaches including remote sensing and GIS.

ESTIMATION OF SPATIAL DISTRIBUTION OF PRECIPITATION USING REMOTE SENSING AND GIS

Precipitation is also one of the most important input parameters in flood modeling. Accurate flood modeling required Spatio-temporal precipitation data which can be simulated generally in physically-based models. Accuracy of Spatio-temporal distribution of precipitation depends on the density of gauge stations which effected mostly in highly irregular topography. Several interpolation techniques have been used for Spatio-temporal distribution of precipitation such as Thiessen polygons (Thiessen 1911), Inverse Distance Weightage (IDW), kriging, multiple linear regression (MLR) and locally weighted polynomial regression (LWP). These interpolation techniques are divided into conventional and geospatial [13]. However, their performance is quite uncertain due to spatial discontinuities and topographic influence [14].

Various models have been developed for the accurate spatial distribution of precipitation using different parameters. Guan et al. [15] developed a geostatistical model based on orographic and atmospheric effects. In mountainous areas, the distribution of precipitation is heterogeneous. The orographic effect causes more precipitation at a higher elevation and on the windward side while less precipitation at the leeward side. Here also, the role of DEM with the appropriate resolution is important to analyze orographic as well as atmospheric effects on the spatial distribution of precipitation. For instance, Castro et al. [14] develop an interpolation methodology based on slope orientation and prevailing wind direction. In this case, slope orientation at both windward and leeward sides was assessed using DEM while wind direction data was obtained from gauge stations (Figure 2).

However, wind characteristics data can be obtained from satellite imageries such as the Geostationary Operational Environmental Satellite (GOES), ERDDAP, NCEP/NCAR Reanalysis 1, NCEP-DOE Reanalysis 2, Global wind Atlas and ERA-Interim. Hawang et al. [13] improve the conventional interpolation method using easting, northing, and elevation as predictor variables. They found that topography was the dominant factor in the spatial distribution of precipitation and parameter uncertainties can be better understood with the knowledge on parameter behavior. Anees et al. [16] used latitude, longitude, elevation, slope, and wind speed as a predictor variable in the estimation of the spatial distribution of precipitation using remote sensing, GIS, and MLR. Overall, these studies contribute to improving the spatial distribution of precipitation. However, further, improvement is required using an integrated approach coupled with remote sensing and GIS.

FUTURE STUDIES FOR FURTHER IMPROVEMENT OF INPUT DATA UNCERTAINTIES

Satellite images have many pixels that contain lots of spectral information. Generally, flood modeling is conducted on a large spatial scale which covers a large number of pixels. In this regard, remote sensing data should be considered big data. Big data generally analyzed through widely used tools such as Artificial Intelligence (AI), Fuzzy logic, and deep learning. In terms of river bathymetry estimation using remote sensing data, the relationship between the spectral response of the image and the depth retrieval should be analyzed using big data. This relationship coupled with the varying sinuosity of thalweg will be helpful to develop a framework for Spatio-temporal river bathymetry estimation. Furthermore, the developed framework could be linked with other information such as the amount of suspended sediment in the river and its effect of depth retrieval and effect of river morphology on depth retrieval.

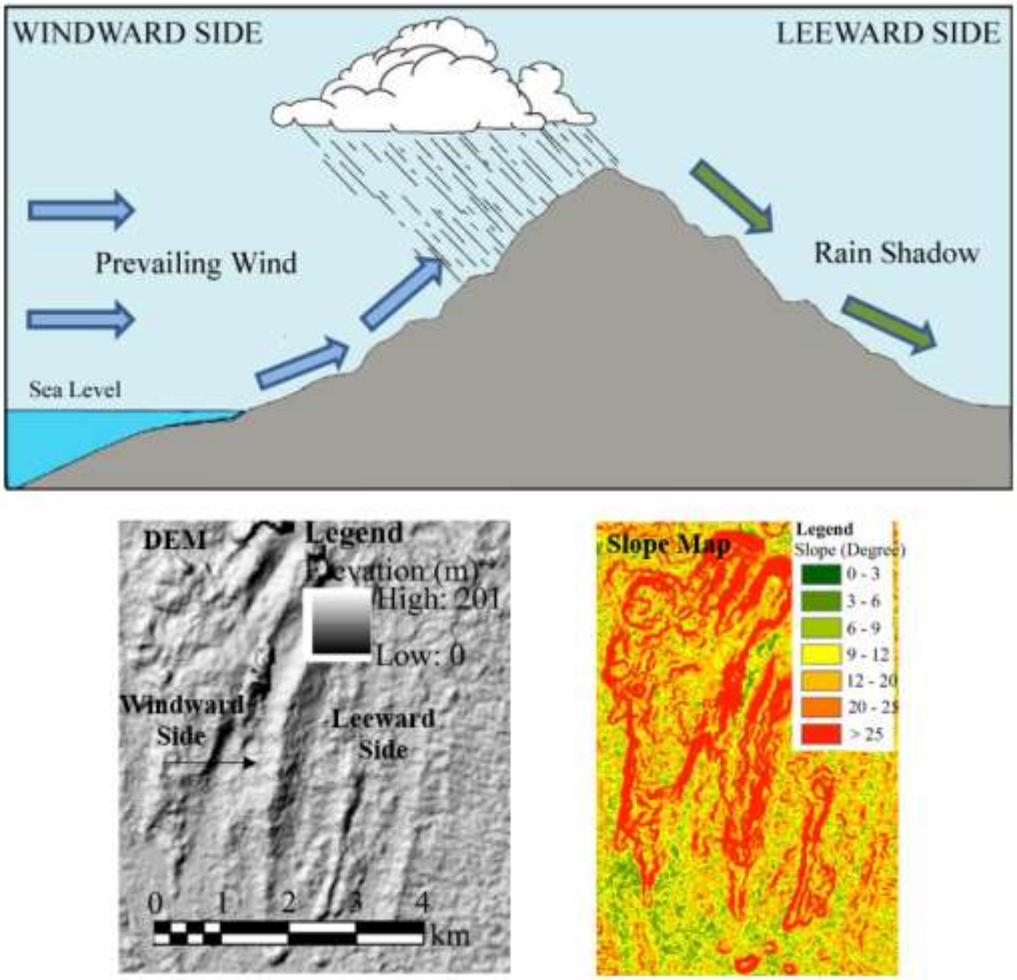

FIGURE 2. Figure 2A showing orographic effect in spatial distribution of precipitation. Figure 2B showing windward and leeward sides in ASTER GDEM of 30 m resolution. Figure 2C showing slope map showing slope orientation extracted from the DEM.

In terms of the spatial distribution of precipitation using remote sensing data, predictor variables such as latitude, longitude, elevation, slope characteristics, wind characteristics, and meteorological variables should be linked together and analyzed as a big data. This framework will help in Spatio-temporal estimation of precipitation of at catchment and watershed scale with the effect of orographic, atmospheric and meteorological and topographical. Furthermore, the developed framework could be linked with rates of evapotranspiration, soil erosion, and infiltration.

CONCLUSION

The present study reviewed input data uncertainties in hydrological modeling. Estimation of river bathymetry and spatial distribution of precipitation in the absence or limited in-situ data using remote sensing and GIS as an alternative approach were examined. Remote sensing and GIS techniques can extract surface topographic variation and identification of different objects based on elevation and spectral reflectance respectively. It was concluded that remote sensing data have lots of spectral information which have been used to estimate topography submerged in water. Factor affecting the spatial distribution of precipitation such as orographic, topographical, and meteorological can be examined spatially and temporally using remote sensing and GIS. Moreover, further improvements are suggested based on research gaps in previous studies which showed big data analysis of remote sensing data using tools such as Artificial Intelligence, Fuzzy logic image processing, and deep learning. As a future work perspective, the authors will deploy parallel image processing technique to analyse the big size aerial image hydromorphological study data to reduce the processing time [17-22].

ACKNOWLEDGMENT

We gratefully acknowledge the Universiti Sains Malaysia for providing financial support through RUI grant 1001.PAERO.8014035 to carry out this work. The authors would also like to acknowledge the technical lab staff of Geology Department of University of Malaya.

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PUBLICATION TYPE

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0094243X, 15517616

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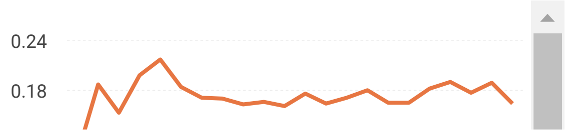

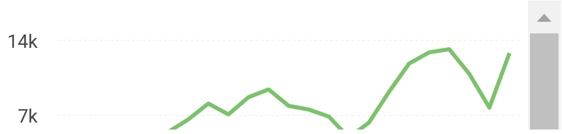

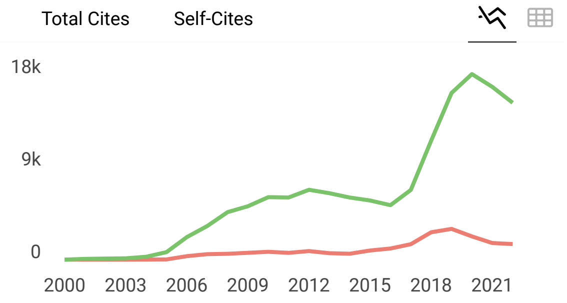

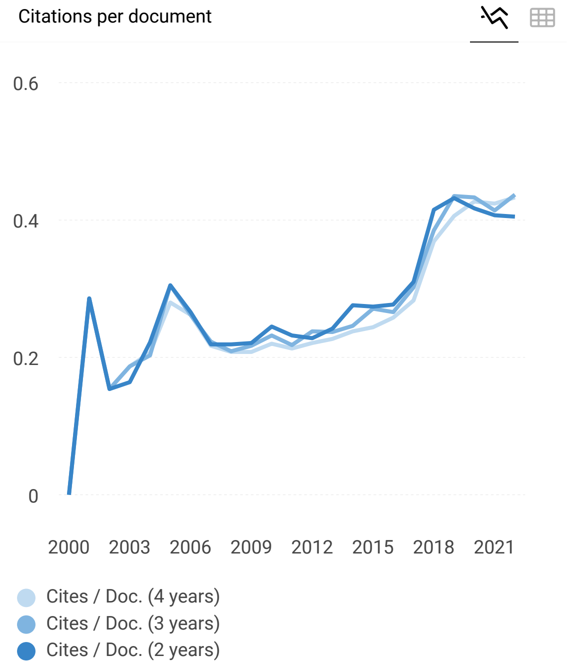

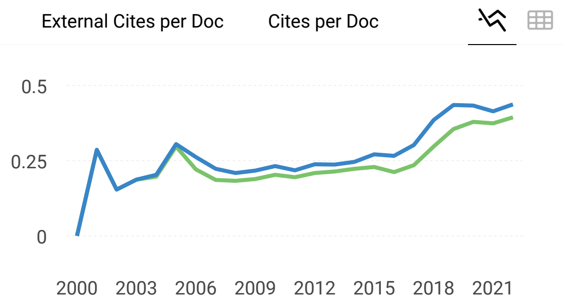

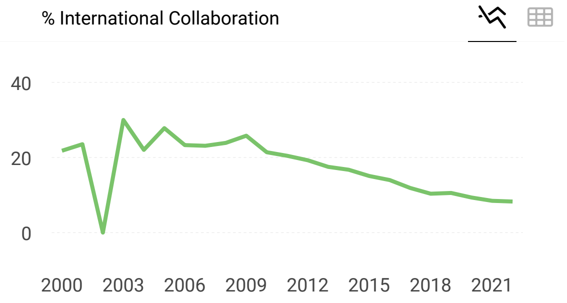

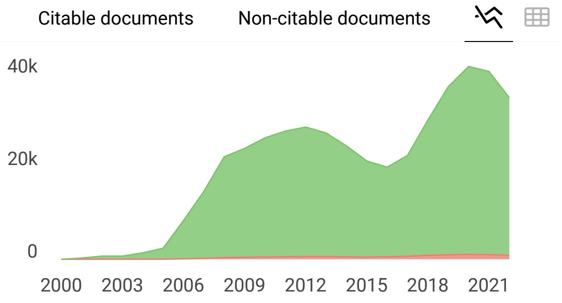

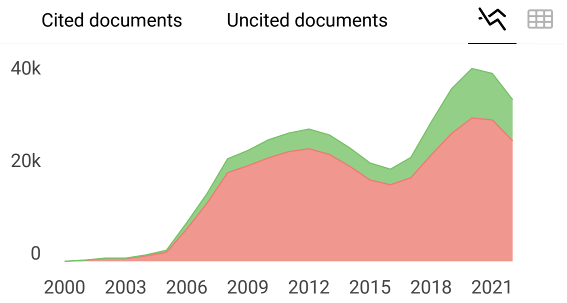

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