Exploring the Potential of Spaceborne Techniques for Mapping of River Hydraulics and Discharge

Abstract

Reliable estimation of river discharge is fundamental to hydrological science, water resources planning, flood risk management, and climate change adaptation. However, the global availability of in-situ discharge observations is declining due to financial, logistical, and institutional constraints, leading to significant spatial and temporal data gaps, particularly in developing and hydro-geomorphologically complex regions. In this context, satellite remote sensing provides a compelling alternative by offering consistent, spatially extensive, and repeat observations of river systems. This thesis investigates the potential of spaceborne techniques for mapping river hydraulics and deriving river discharge through the integrated use of multi-satellite observations, hydro-geomorphological characterisation, and machine learning–based modelling frameworks.

The study employs a comprehensive suite of satellite datasets, including optical imagery from Landsat and Sentinel-2, Synthetic Aperture Radar (SAR) data from Sentinel-1, and radar altimetry from Sentinel-3A/B, to retrieve river width and water level across major tropical river basins in peninsular India. Satellite-derived hydraulic parameters were systematically validated against in-situ discharge records from more than 140 hydrological observation stations. Width-based discharge estimation demonstrated strong to good correlations at approximately 43% of stations, including several river reaches narrower than 100 m, indicating that spaceborne width retrievals can reliably capture discharge variability even in relatively small channels. Altimetry-based water level–discharge relationships showed strong to good performance at about 36% of virtual stations, confirming the utility of contemporary altimetric missions for inland river monitoring despite inherent footprint and orbit constraints.

A key contribution of this research lies in the explicit evaluation of hydro-geomorphological (HGM) controls on the accuracy and spatial variability of satellite-derived discharge estimates. A broad set of hydrological, topographical, morphological, meteorological, and land-use parameters was compiled and analysed to explain observed performance differences across river reaches. The results demonstrate that hydrological variability, channel slope, elevation, maximum historical water extent, and rainfall exert dominant control on the strength of satellite–discharge relationships. Based on these controls, river reaches were clustered into distinct HGM regimes, revealing systematic, flow-regime-dependent biases in both width- and level-based discharge estimates and highlighting the limitations of uniform correction strategies across heterogeneous river systems.

To address these biases, the thesis develops machine learning–based correction frameworks that explicitly incorporate HGM characteristics and flow regimes. Ensemble learning approaches using Random Forest algorithms, were shown to significantly improve discharge estimates by reducing underestimation during high flows and balancing errors across low- and moderate-flow conditions. Extending this framework to a large-scale spatial assessment, more than 6,000 river reaches were classified for satellite suitability, identifying approximately 21% of the network as favourable for reliable satellite-based joint estimation of river width and water level.

Building on these findings, a multi-satellite fusion framework was developed for joint discharge estimation by integrating river width and water level within unified empirical and machine learning models. The joint approach consistently outperformed single-parameter models, particularly in river reaches where individual width- or level-based estimations showed only moderate skill. Machine learning–based joint models effectively captured non-linear hydraulic relationships and demonstrated robust performance across hydro-geomorphologically diverse and ungauged basins, supporting the feasibility of discharge estimation using satellite-derived data alone.

In this regard, this thesis attempts to establish a scalable and transferable framework for satellite-based river discharge estimation that explicitly accounts for hydro-geomorphological diversity and flow-regime dependence. The findings demonstrate that combining multi-sensor satellite observations with HGM-informed machine learning and joint estimation substantially enhances the robustness, accuracy, and generalisability of spaceborne discharge models. Future research should focus on integrating emerging high-resolution missions such as SWOT, incorporating anthropogenic regulation and hydrodynamic constraints, and advancing operational implementation for flood forecasting, water resources planning, and climate resilience. Collectively, this work contributes toward the development of reliable, satellite-driven discharge monitoring systems for data-scarce and ungauged river basins worldwide.