COMMENTARY

Observing river discharge from space: Challenges and opportunities

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Inland rivers serve as the primary source of freshwater for human use and regulate hydrological and ecological cycles. They play a unique role in supporting global biodiversity, biogeochemical cycles, and human societies. River discharge integrates all hydrological processes in the upstream basin, reflecting the carrying capacity of rivers, and is the most important indicator to assess river conditions. Observing river discharge and monitoring its dynamics are critical to water resource management, ecological health, and maintaining ecological flow for biodiversity within the watershed.

Traditional discharge observations primarily rely on standard hydrological gauge stations, but this approach is time-consuming and labor-intensive. The establishment and maintenance of these stations are costly, and they are mainly located in the main stems of rivers, resulting in sparse distribution and a lack of observation data for many inaccessible small to medium-sized rivers and tributaries. The challenge is using limited stations to reflect the diversity of river network attributes and the impact of human activities accurately and comprehensively. Therefore, discharge observation and estimation have been a focal point in hydrological research. Enhancing the capability to monitor and predict dynamic water resources is crucial to support sustainable societal development in a changing environment. It represents a major objective of the International Association of Hydrological Sciences (IAHS) Prediction in Ungauged Basins (PUB) initiative (2003-2012). It is also a key component of the Panta Rhei initiative (2013-2022).

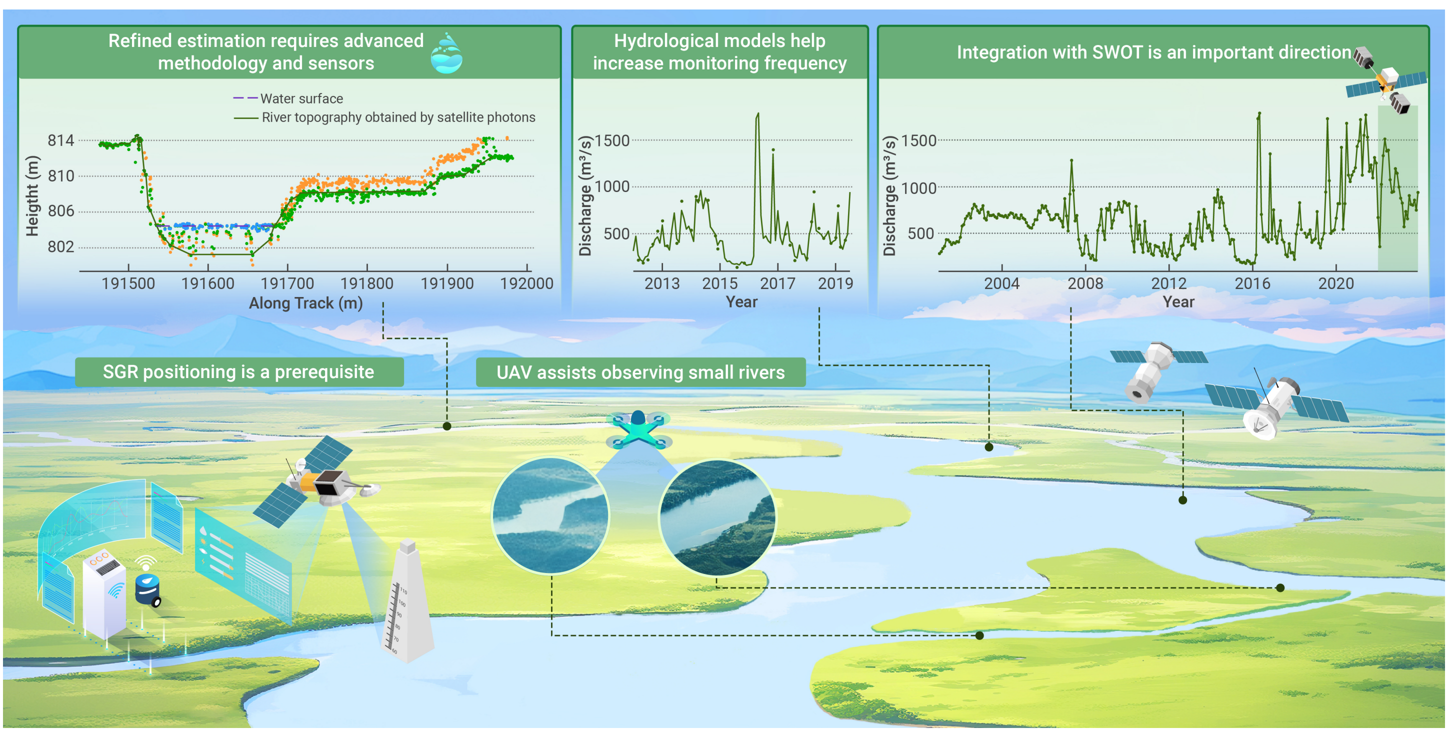

Figure 1. Challenges and opportunities in the field of remote sensing of river discharge.

Remote sensing technology is an advanced means of Earth Observation. It possesses advantages such as multiscale, multispectral, and high efficiency. It serves as an effective supplement to traditional river discharge observations. Numerous studies have emerged for estimating river discharge using remotely sensed imagery as a vital aspect of river observations. In the early stages, remote sensing estimation of river discharge was primarily conducted in basins with some discharge observation data, used to extend the temporal or spatial scales of station observations. Traditional river discharge estimation obtained the water area or water level of rivers at different times through remote sensing and then establishing statistical relationship models with measured discharge, or adopted remotely sensed hydraulic parameters as inputs for hydrodynamic models. They rely on substantial requirements on measured data (such as observed discharge and underwater topography) to achieve high accuracy. This limits their applications in data-scarce or less accessible regions.

In recent years, to address the challenge of river discharge estimation in data-scarce basins, an increasing number of studies have focused on purely remote sensing-based methods. These methods typically require establishing a Satellite Gauging Reach (SGR) in specific river sections. Multiple remote sensing data, including optical and microwave imagery and altimetry, are integrated to obtain hydraulic parameters such as water surface width, water level, water surface slope, and flow velocity. Subsequently, hydraulic equations or flow laws are used to estimate the discharge. For these methods, the prerequisite for successful discharge estimation through remote sensing is a higher hydraulic visibility[1] of the river section, indicating the sensitivity of remote sensing to hydrological responses and hydraulic changes under varying flow conditions. Recent efforts have accelerated the diversification of approaches for estimating discharge from space due to improvements in satellite sensors, which produces a range of opportunities for this field, while also creates a series of issues and challenges (Figure 1).

ACHIEVING REFINED DISCHARGE ESTIMATION

River discharge equals to the product of flow velocity and cross-sectional area. Although there are already some exploratory studies that utilized satellite video remote sensing to map river water surface velocity,[2] flow velocity is generally considered difficult to be directly observed through remote sensing. However, flow velocity is usually related to water surface slope, which could be calculated from water level difference at two cross sections. Water level can be acquired using altimetry satellites, or inferred by combining water surface width and Digital Elevation Model (DEM). Cross-sectional area depends on water surface width (or water level) and underwater topography. While water surface width can be obtained from most remote sensing images, changes in water surface width are the most intuitive reflection of natural river flow fluctuations in remote sensing images. Therefore, further development of methods based for extracting river boundaries and achieving high-frequency, high-resolution, and high-precision water surface width through techniques like image fusion and deep learning is an important direction for future research. In addition, the unknown nature of underwater topography has been a key constraint for precisely quantifying the volume of discharge. Mass-conserved Flow Law Inversion (McFLI) techniques provide a possible solution for this.[3] McFLI combines the measurements of time-varying hydraulic parameters with flow laws to set bounds on water discharge without having to rely on direct measurements of depth. However, the natural changes in river morphology, such as channel shifting and bed erosion, can further pose challenges in consistently monitoring discharge. Advanced sensors with the ability of detecting water velocity and river bathymetry may be a solution for this. For example, satellite photons can be used to extract river topography, even underwater topography for clear and shallow rivers.

SELECTING OPTIMAL SATELLITE GAUGING REACH

Hydraulic visibility is mainly constrained by two factors: whether remotely sensed data cover the target river section; and whether remote sensors can observe changes in hydraulic parameters due to flow variations and support discharge estimation. The hydraulic visibility varies from different river sections of the same river, indicating that the sensitivity of remotely sensed images to flow changes differs. Consequently, the accuracy of discharge estimation results derived from remote sensing observations varies significantly in different river sections. Therefore, it is a prerequisite for the successful implementation of discharge estimation to select an ideal river section with the best hydraulic visibility for SGR based on river morphology parameters and available remotely sensed imagery.

NEW APPROACHES NEEDED IN SMALL AND MEDIUM RIVERS

As water level is a key parameter for discharge estimation, satellite water level data are frequently used in related studies. However, due to limitations in the resolutions of remote sensing data and the coverage of altimetry satellite data, these methods face challenges when applied to small and medium-sized rivers. These rivers are numerous, widely distributed, and their hydrological conditions are more significantly influenced by various factors, necessitating urgent and essential monitoring. Therefore, for small and medium-sized rivers, it is imperative to further utilize high-resolution satellite imagery, or explore sub-pixel-scale water fluctuation information. Some attempts have been already implemented by examining the Near InfraRed reflectance signal of multispectral images at medium and high resolutions.[4] The near-daily availability of images, thanks to the multi-mission approach, is advantageous for monitoring rivers at subpixel level, but cannot yet solve the limitation of cloud cover during flood events, which still remains underestimated. Only the combination with radar sensors, such as the altimeter, in a fusion method can address this limitation. However, processing radar altimetry data for narrow rivers with low-resolution mode altimeters is not easy, and taking advantage of off-nadir measurements is a common solution for this. Therefore, fusion of multiple missions and multiple sensors with elaborate designed methods is an important direction to address the monitoring of river discharge from space. Moreover, Nanosatellite constellations have provided the ability to frequently update high-resolution information about the Earth's surface, which can make it critical for monitoring highly variate river discharge, even for small rivers. In some cases, conducting unmanned aerial vehicle (UAV) surveys in river sections to obtain high-precision digital elevation models for improved hydraulic visibility would be extremely beneficial for successful discharge estimation.

ACHIEVING DAILY OR SUB-DAILY DISCHARGE MONITORING

Many rivers exhibit changes in discharge on daily or hourly timescales, particularly during flooding periods. These cases require daily or even sub-daily intensive discharge monitoring. However, most remote sensing-based methods find it challenging due to the limitations of current satellite observation cycles. Capturing flood flow peaks is especially difficult, because optical sensors are usually unable to work due to weather conditions, leaving microwave sensors (SAR sensors in particular) the only manner that can be relied on. To address this limitation, hydrological models or data assimilation models are typically integrated with remote sensing techniques to extend instantaneous satellite observations to daily or even sub-daily frequency.

NEW HYDROLOGY-ORIENTED SATELLITE MISSIONS

The Surface Water and Ocean Topography (SWOT) mission will vastly expand measurements of global rivers, providing critical new data sets for both gauged and ungauged basins. SWOT measurements of rivers include water surface elevation, river width, and slope, each of which is invaluable in estimating river discharge. A framework for estimating global river discharge from the SWOT Mission is referred to Durand et al. (2023).[5] SWOT discharge products will provide discharge for all river wider than 100 m using several algorithms that were developed from hydraulic equations and flow laws. However, based on its orbital parameters and designed lifespan, its river discharge observations are limited in terms of both time span and temporal resolution. How to integrate SWOT official discharge products with long-term and high-frequency discharge estimation obtained by other satellites, especially for ungauged rivers, is a question worthy of further research.

Remote sensing has the potential to democratize essential and new river discharge observing tools, enhancing water security and flood forecasting capability. However, while Earth Observation through satellites has provided breakthrough scientific advances on the comprehension of river discharge world-widely, it is still a challenge to translate knowledge and information from remote sensing into continuous and valuable information and indicators that can assist decision makers to support the water resource governance and related fields. If remote sensing of river discharge can be developed into an operational component of a gauging program, it could serve to augment and economize the current streamflow information network and facilitate the expansion of the network into ungauged basins.

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DECLARATION OF INTERESTS

The authors declare no competing interests.