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Editorial

Editorial for the Special Issue "Remote Sensing of Flow Velocity, Channel Bathymetry, and River Discharge"

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1. Introduction

River discharge is a fundamental hydrologic quantity that summarizes how a watershed transforms the input of precipitation into output as channelized streamflow. Accurate discharge measurements are critical for a wide range of applications including water supply, navigation, recreation, management of in-stream habitat, and prediction and monitoring of floods and droughts. However, the traditional, in situ stream gage networks that provide such data are sparse and declining, even in developed nations, and absent in many parts of the world (e.g., [1]). Moreover, establishing and maintaining these gages is expensive, labor-intensive, and can place personnel at risk (e.g., [2]).

For all these reasons, remote sensing represents an appealing alternative means of obtaining streamflow information. Potential advantages of a remote sensing approach include greater efficiency, expanded coverage, increased measurement frequency, lower cost, and reduced risk to field hydrographers. In addition, remote sensing techniques provide exciting opportunities to examine not just isolated cross sections but long segments of rivers with continuous coverage and high spatial resolution. To realize these benefits, further research is needed to focus on the remote measurement of flow velocity, channel geometry, and, most critically, their product – river discharge.

This special issue was motivated by our desire to foster the development of novel methods for retrieving discharge and its components and thus stimulate progress toward an operational capacity for streamflow monitoring. Our goals as guest editors were to encourage studies on this topic and to compile high-quality, peer-reviewed articles in a special issue of *Remote Sensing* dedicated to this theme. We solicited manuscripts concerned with all aspects of the remote measurement of streamflow—including estimation of flow velocity, channel bathymetry (or water depth), and discharge—from various types of remotely sensed data (active or passive) acquired from a range of platforms (manned or unmanned aircraft, satellites, or ground-based imaging systems). Papers describing past, present, or future missions devoted to various aspects of fluvial remote sensing were welcomed.

A total of 16 manuscripts were submitted to this special issue and subjected to a rigorous peer review process that involved a total of 41 anonymous, conscientious reviewers. Of these 16 manuscripts, 10 papers achieved the level of quality and innovation expected by *Remote Sensing* and ultimately were published in this special issue. A total of 53 authors contributed to these 10 articles and hailed from six different nations: Germany (one author), Italy (one), the United Kingdom (two), Austria (five), the Netherlands (five), and the United States of America (41).

2. Themes Represented in this Special Issue

The papers published in this special issue span a wide range of topics, from specific measurement techniques [3] and rigorous evaluation of a particular sensor [4] to studies illustrating the diversity of ways in which fluvial remote sensing can be applied [5,6]. We identified five emergent themes from the work presented in this special issue and allocated each of the published papers to one or more of these themes, as some articles addressed more than one of the following topics:

1. Measuring surface flow velocities via various non-contact methods [3,7,8]
2. Mapping water depth using both active and passive remote sensing approaches [4,8,9]
3. Deriving estimates of river discharge from various types of remotely sensed data [7,8,10]
4. Characterizing flow frequency and flooding using image-derived data products [11,12]
5. Applying remote sensing techniques to characterize flow-related spatial and temporal heterogeneity of key river attributes [5,6]

In addition to this special issue focused on discharge and its components, we also want to direct the reader's attention to another special issue on "Remote Sensing of Large Rivers" published in *Remote Sensing* in 2020. This editorial was inspired by and is modeled after the overview of "Remote Sensing of Large Rivers" presented by Alcantara and Park [13].

2.1. Surface Flow Velocities

Beginning with the velocity theme, Fulton et al. [7] described a near-field remote sensing approach to measuring surface flow velocities using Doppler radars. In this context, the term near-field refers to fixed, ground-based platforms such as bridges; such techniques thus are well-suited for deployment at established stream gages and can be readily incorporated into operational streamflow monitoring programs. Radar-based measurements of surface flow velocity were made at 10 U.S. Geological Survey (USGS) gaging stations and a probability concept used to estimate the cross-sectional mean velocity on the basis of a single surface velocity measurement at the cross-channel location where the maximum velocity occurs. Mean velocities computed using this method agreed closely ($R^2 = 0.993$) with observations from conventional, in situ instrumentation, with an average error of −1.1%.

Another paper in this special issue also focused on measuring surface flow velocities at a local scale, but from a mobile airborne platform rather than a permanent installation. Kinzel and Legleiter [8] used a small unmanned aircraft system (sUAS) equipped with a cooled, mid-wave infrared camera to acquire thermal image time series from which surface flow velocities were inferred via particle image velocimetry (PIV). This technique involved tracking the motion of turbulent structures expressed at the water surface as small differences in temperature and thus did not require seeding the flow with artificial tracers or assuming the presence of floating foam or debris, as in typical PIV applications based on optical images. Comparison of image-derived velocity estimates with field measurements yielded good accuracy ($R^2 = 0.82$) at one cross section and a moderate level of agreement ($R^2 = 0.64$) at another transect. A significant source of uncertainty was the velocity index used to convert remotely sensed surface velocities to depth-averaged velocities comparable to those measured in situ.

A third velocity-themed paper further increased the scale of observation by using image sequences acquired from a helicopter deployed above two large rivers in Alaska, USA. Rather than thermal data, Legleiter and Kinzel [3] showed that surface flow velocities could be inferred from standard red-green-blue (RGB) images in sediment-laden rivers, again without introducing tracers to facilitate PIV. In this case, plumes of suspended sediment upwelled from within the water column produced boils and vortices that were expressed as differences in water color trackable via PIV. A parameter optimization framework was used to demonstrate that, for a 200-m-wide channel imaged from approximately 600 m above the river, relatively large PIV interrogation areas of 9.6–48 m and modest frame rates of 0.5–2 Hz were sufficient to yield strong agreement ($R^2 > 0.9$) between remotely sensed velocities and field measurements. Similarly, examining the effect of image sequence duration indicated that a high level of accuracy could be maintained with dwell times as short as 16 s at 1 Hz or as little as 8 s at 2 Hz. This study demonstrated that data from inexpensive video cameras could enable reach-scale mapping of flow fields and introduced a modular workflow to support such analysis.

Also note that in addition to the three papers published in this special issue, non-contact measurement of flow velocities has garnered increased coverage in *Remote Sensing* recently. For example, Tauro et al. [14] chose this journal to introduce an optical flow-based technique for detecting, tracking, and filtering feature displacements. Similarly, several studies focusing on PIV algorithms [15], their application [16], and their refinement [17] have already appeared in *Remote Sensing* in 2020.

2.2. Bathymetry (Water Depth)

Our second theme, remote sensing of river bathymetry, was specifically addressed by three of the papers appearing in this special issue. Two of these studies employed an active form of remote sensing that has drawn considerable interest in recent years: topo-bathymetric lidar [4,8]. These systems feature water-penetrating green wavelength lasers and have been miniaturized to such a degree as to enable deployment from sUAS platforms. For example, Mandlburger et al. [4] described a novel lightweight laser scanner and assessed its ability to measure submerged elevations along a gravel-bed river in Austria. A pulse repetition rate of up to 200 kHz yielded point densities as high as 50 points/m^2 and full laser waveforms were captured for both online and post-flight processing. Laser pulses penetrated up to two times the Secchi depth, but a depth-dependent bias was reported and attributed to forward scattering of the laser beam by suspended materials. Overall, the system's high spatial resolution and depth measurement accuracy lead the authors to conclude that the new laser scanner is well-suited for a range of river-oriented applications.

The second paper to evaluate a novel bathymetric lidar deployed from a sUAS was that of Kinzel and Legleiter [8]. In this case, the lidar system considered not only the travel time of laser pulses but also their polarization state. This additional source of information allowed returns from the channel bed to be distinguished from pulses reflected from the water surface. This approach enabled more precise depth measurements in shallower water than conventional bathymetric lidars. Comparison of lidar-derived and field-surveyed depths was favorable for a relatively shallow cross section with a maximum depth of 0.7 m ($R^2 = 0.95$) but less encouraging for a transect with greater depths, up to a maximum of 1.2 m ($R^2 = 0.61$).

The third paper focused on remote sensing of water depth using a different, passive optical approach that has seen increasingly widespread application in river research: Structure-from-Motion (SfM) photogrammetry. Woodget et al. [9] used a sUAS to acquire multiple, overlapping images from a small river in the United Kingdom for two different time periods and showed that the level of topographic accuracy achieved in submerged areas was similar to that in exposed areas, even without separate calibration data and different SfM processing methods for within the wetted channel. Importantly, these findings imply that multiple techniques are not required to map both the subaqueous channel bed and dry bar surfaces, nor are extensive in-channel survey data. Moreover, the selection of a refraction correction method had little impact on results derived from near-nadir imagery. Instead, Woodget et al. [9] identified improved estimation of water surface elevations as the most direct means of increasing the accuracy of SfM-based bed elevation measurements. The paper also introduced a machine learning framework for producing continuous, high-resolution maps of geomorphic change that include spatially variable error estimates. This approach could facilitate efforts to characterize channel morphodynamics in shallow, clear-flowing streams.

2.3. River Discharge

The third theme is the primary, unifying topic of this special issue: remote sensing of river discharge. All of the papers in this special issue involved both remote sensing and river discharge (or one of its components) in some capacity, but three papers directly focused on this subject. Of these three, two were discussed previously in the context of inferring surface flow velocities but also went on to estimate river discharge. First, in addition to evaluating the utility of Doppler radars for velocity measurement as described above, Fulton et al. [7] applied the probability concept described above to infer cross-sectional mean velocities and compute river discharge. Because the data were collected at established gaging stations, information on channel geometry was available from prior field surveys used to define the rating curves that relate water level (i.e., stage) to discharge for each gage. For the 10 sites evaluated by Fulton et al. [7], observed discharges ranged from 0.17 to 4890 m^3/s and agreement between radar-derived and conventional in situ discharges was very strong ($R^2 = 0.999$), with an average error of −1.1%. The radars also were deployed in a continuous mode to provide time series with a 15-min resolution, implying that this approach could be used for real-time streamflow monitoring on an operational basis.

A second paper in this special issue also performed discharge calculations, but the analysis presented by Kinzel and Legleiter [8] was based entirely on remotely sensed data collected from two sUAS. In this case, discharges were computed by combining surface flow velocity estimates inferred via PIV of thermal image time series with information on cross-sectional area derived from the polarizing bathymetric lidar. Compared to direct field measurements made with an acoustic Doppler current profiler, the remotely sensed discharge estimates were 22% greater than the field observations at one cross section and within 1% at a second transect. Although acquiring useful thermal images required collecting data at dawn to maximize the air-water temperature contrast and the bathymetric lidar had limited penetration, important advantages of this approach include the ability to perform PIV under natural conditions without seeding the flow and to obtain information on channel geometry without field measurements of depth for calibration.

The third paper to explicitly consider remote sensing of river discharge (RSQ) did so in a comprehensive and thought-provoking manner. The review contributed by Gleason and Durand [10] points out that although widespread innovation has allowed RSQ to advance rapidly, this new subfield has become somewhat non-cohesive, leading to confusion amongst the broader hydrologic community regarding the role of RSQ and its potential to contribute to the discipline. Gleason and Durand [10] attempt to provide clarity by summarizing the literature and organizing work on RSQ first by application area and then by methodology. More specifically, a distinction was made between methods appropriate for gaged, semi-gaged, regionally gaged, and totally ungaged basins, but categorization by sensor was not considered useful. Instead, Gleason and Durand [10] emphasize the need to provide proper context for research on RSQ as a means of fostering hydrologic understanding. For example, clarifying what the term 'ungaged' means as it relates to RSQ and defining which techniques are appropriate for such basins would be helpful. The review concludes by lauding the diversity that has become a hallmark of RSQ and encouraging further 'methodological proliferation'.

2.4. Flow Frequency and Floods

The fourth theme addressed within this special issue involves using remotely sensed data to characterize the frequency with which different river discharges occur and to provide critical information on rare but important flow events. The first paper in this category sought to answer a key question regarding the ability of remote sensing to yield hydrologic insight: to what degree do archived satellite data effectively capture the overall population of river flow frequency? Allen et al. [11] used archives of Landsat data to determine when cloud-free images were available over USGS gaging stations on rivers large enough to be observed by Landsat. The flow frequency distributions derived from the cloud-free Landsat overpasses were then compared to those from the in situ stream gages. This analysis indicated that these two frequency distributions were not significantly different from one another except for hydrologic extremes, such as the maximum flow. Allen et al. [11] also reported that the degree to which a Landsat-based sample can be used to characterize the flow frequency distribution varies by location but concluded that the Landsat archive is, on average, representative of the temporal frequencies of discharges along large rivers.

The second paper within this theme focused on documenting the impacts of the extreme events that might not be captured by satellite archives. Forbes et al. [12] established the need for basic information on inundation extent and peak flood stage to support analysis of flood events by providing compelling statistics on the loss of life and property due to flooding. The study then demonstrated the potential of sUAS and close-range remote sensing techniques to identify high-water marks (i.e., indicators of peak stage) after a flood and to obtain the topographic input data required for hydraulic modeling. Remotely sensed data were compared to traditional, ground-based Global Positioning System (GPS) surveys of two small streams, one in a semiarid and the other in a temperate environment. Mean elevation errors were greater in the more humid setting (0.14 m), due to the presence of vegetation that obscured the ground surface, than in the drier climate (0.07 m), but these results were similar to the accuracy that can be achieved via GPS surveys. Forbes et al. [12] thus concluded that sUAS-based identification of high-water marks and measurement of channel cross sections can be an efficient and effective alternative to conventional field methods of characterizing flood impacts.

2.5. Broader Applications

The fifth and final theme covered in this special issue is concerned with the application of remote sensing techniques in the broader context of river systems. For example, by examining the effects of dam operations on spatial and temporal thermal heterogeneity, Mejia et al. [5] illustrated the significance of flow management, which must be informed by reliable discharge data that in turn could be obtained via remote sensing. More specifically, Mejia et al. [5] focused on cold-water refuges for salmonids in a large, regulated river in the northwestern USA and used thermal image data and generalized additive models to characterize the occurrence of cool-water areas. Importantly, a remote sensing-based approach allowed this analysis to be conducted across scales ranging from reaches to sub-catchments. The results of this study indicated that lateral contributions from tributaries were the primary control on thermal heterogeneity, which thus peaked at confluences, and that cool areas were associated with channel morphology and distance from the dam. These insights, along with remotely sensed information on river discharge and spatial patterns of flow velocity, could help to guide habitat management for salmonids.

A second application-oriented paper in this special issue further illustrates the many ways in which remote sensing can contribute to our understanding of river systems, all the way to their termini in estuaries. Leuven et al. [6] focused on intertidal areas where human activities and rising sea levels impact the distribution of depths and thus habitat conditions. Although numerical modeling can provide information on the spatial pattern and duration of inundation, as well as peak flow velocities and salinity, the requirements of these models in terms of both data and computing power can be prohibitive. As an alternative, Leuven et al. [6] presented a Python-based software tool that predicts hydrodynamics, bed elevations, and the distribution of channels and bars at minimal computational expense. These predictions are based on empirical relations derived from natural estuaries and the only inputs required to use the tool are an along-channel width profile and tidal amplitude, both of which can be derived from remotely sensed data. The approach is thus useful for rapid assessment of potential habitat when only images of the estuarine environment are available.

3. Concluding Remarks

We wish to extend our sincere gratitude to all 53 authors who elected to contribute their research to this special issue. Similarly, we want to explicitly thank the 41 reviewers for performing such an essential, but all too often, thankless task. The thoughtful, timely comments provided by the reviewers improved each of the papers published in this special issue, which came to fruition only because they were willing to volunteer their time and attention. Finally, we appreciate the efforts of Nelson Peng and the entire MDPI editorial team to support the guest editors in efficiently processing each manuscript.

Remote sensing of flow velocity, channel bathymetry, and river discharge is an important and timely topic in the fields of hydrology and geomorphology and although the 10 papers compiled in this special issue represent some meaningful progress, additional work in this area is needed. We hope that the studies published herein will help the river research and management communities to more effectively characterize and more thoroughly understand river systems through the informed use of remote sensing technologies.

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