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Estimation of discharge from braided glacial rivers using ERS 1 synthetic aperture radar: First results

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Abstract. Using multitemporal ERS 1 synthetic aperture radar (SAR) satellite imagery and simultaneous ground measurements of streamflow, a strong correlation ($R^2 = 0.89$) was found between water surface area and discharge for a braided glacial river in British Columbia, Canada. Satellite-derived effective width (W_e) was found to vary with discharge (Q) as $W_e = 27.5Q^{0.42}$, where W_e is defined as the total water surface area within a 10 km × 3 km control section, divided by the section length. This "area/discharge rating curve" yields instantaneous discharge estimates with a mean error of ±275 m^3/s for ground-measured flows that ranged from 242 to 6350 m^3/s.

Introduction

Increased interest in the hydrologic processes of the cryosphere has been stimulated by general circulation model (GCM) modeling, which predicts amplification of a CO_2-induced global temperature increase toward the poles [*Manabe and Wetherald*, 1980; *Manabe et al.*, 1991]. This widely accepted premise is supported by a recent small increase in northern hemisphere high-latitude temperatures [*Folland et al.*, 1990]. It has also been suggested that early indication of a global temperature change may best be observed in the cryosphere because of the sensitivity of snow and ice to climate [*Hall*, 1988]. River discharge measurements are essential for detecting such effects, as runoff is the primary mechanism by which mass is removed from snowpacks and glacier ice. Glaciers adjust to climate changes by storing or releasing water, producing higher mean streamflows during recession [*Young*, 1985; *Lawson*, 1993]. *Meier* [1984] suggested that the current global sea level rise of 1–1.5 mm/yr may be partly explained by the observed shrinkage of the world's small glaciers. Runoff modeling for a glacierized Himalayan basin predicted at least a 30% increase in summer streamflows as a result of a simulated 2°C increase in temperature [*Fukushima et al.*, 1991]. However, efforts to characterize river flows for most glacierized basins have been severely restricted by a paucity of discharge observations. This problem is due to a combination of (1) harsh weather conditions and low accessibility, (2) high costs associated with maintaining stream gauges in these remote areas, and (3) typical conditions of high bed load and rapid discharge fluctuations that create shallow, shifting braided systems that are virtually impossible to gauge using traditional stage-recording devices. In recognition of these difficulties, *Lawson* [1993] concluded that in order to understand the relationships among climate, glacier mass balance, and hydrology, new remote-sensing techniques are needed to replace expensive, labor-intensive ground measurements. Development of such techniques would also permit study of remote, high-latitude rivers for industrial or water supply purposes.

The complex hydrologic and sedimentologic processes that interact to form a braided channel configuration are topics of ongoing research [*Krigstrom*, 1962; *Fahnestock*, 1963; *Church*, 1972; *Mosley*, 1983; *Young and Davies*, 1990; *Maizels*, 1993; *Warburton and Davies*, 1994], but the end result of these processes is a relatively flat, unrestricted surface covered with multiple shallow channels that maintain similar geometries and flow depths despite frequent lateral shifting. Unlike single meandering channels that adjust primarily through flow depth (unless their banks are overtopped), braided streams accommodate changes in discharge through channel widening and adding or subtracting channels to the braid complex. Field measurements in small braided streams indicate that channel widths vary strongly as a function of discharge [*Rice*, 1979; *Mosley*, 1983; *Leopold*, 1985], a relationship also observed in experimental flume studies [*Schumm et al.*, 1987].

Advances in satellite technology have sparked efforts to assess river hydrologic conditions from space. *Bryan* [1981] identified lakes, wetlands, and rivers using Seasat and airborne synthetic aperture radar (SAR) imagery. *Koblinsky et al.* [1993] used Geosat radar altimeter waveform data to measure river stage in the Amazon. *Solomon* [1993] recommended the use of ERS 1 SAR for delineating river networks in densely forested areas, while *Brakenridge et al.* [1994] used ERS 1 to obtain stage estimates from the 1993 flooding along the Mississippi River. Although braided rivers are not well suited for traditional stage-recording devices, their spatial sensitivity makes them highly amenable to using remote sensing to detect changes in discharge. In this study, total water surface area within a 10 km × 3 km control section on a braided glacial river in British Columbia was repeatedly measured using multitemporal SAR imagery acquired by the first European Remote Sensing Satellite (ERS 1) in 1992 and 1993. These satellite-derived values were then compared to field measurements of river discharge measured by a Water Survey of Canada gauge located 10 km downstream from the control section. Their strong correlation indicates that it is possible to obtain good estimates of flow rates from space using this approach.

ERS 1 Satellite and the Study Site

ERS 1 was launched July 17, 1991, by the European Space Agency. In image mode its C band (5.3 GHz) SAR produces an 80–103 km swath with a processed pixel spacing of 12.5 m. ERS 1 is placed in a near-circular, polar, and Sun-synchronous orbit with 3-, 35-, and 168-day repeat cycles during its various

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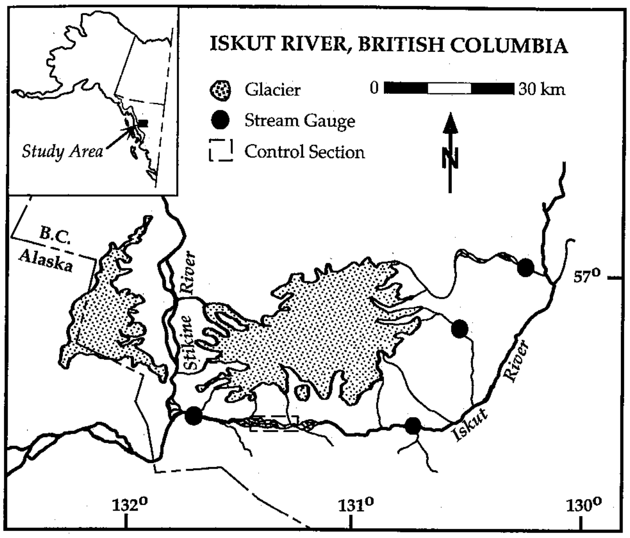

Figure 1. Map of the study area: Iskut and Stikine Rivers, British Columbia.

mission phases. SAR sensors are well suited for multitemporal hydrologic studies owing to their cloud-penetrating capability and strong sensitivity to surface moisture conditions. The former is a tremendous asset in chronically cloudy regions such as the Coast Mountains along the Alaska/British Columbia border. The Iskut River (approximately 57°N, 131°W) drains 9350 km^2 of this heavily glacierized area (Figure 1). Five helicopter-serviced stream-gauging stations have been installed in nonbraided reaches by the Water Survey of Canada. One of these stations is located only a few kilometers downstream of the prominent braid complex used for the control section in this study. Using two overlapping repeat pass orbits, ERS 1 SAR images were acquired over the control section from April 1992 to December 1993 by the NASA Alaska SAR Facility (ASF) in Fairbanks.

Data Processing

Using an ASF-provided program, each ERS 1 image was radiometrically calibrated to permit comparison of actual backscatter (σ^o) values between multitemporal images and also within a single scene. The calibration process removes variations in backscatter caused by sensor antenna pattern, range to target, and incidence angle for each image, using a satellite-derived noise versus range function and three calibration coefficients [*Bicknell*, 1992]. This information is provided in the Committee on Earth Observation Satellites (CEOS) format header file that accompanies each ERS 1 data take processed by ASF. All radiometric and geometric corrections are fitted to the ellipsoidal surface of the Goddard Earth Model (GEM06) geoid model. Surface elevation or departures of the true geoid from the ellipsoid are not considered, producing small but uncertain errors in mountainous regions.

Unlike lakes which can return a wide range of radar backscatter intensities with varying surface wind conditions [*Olmsted*, 1993; *Hall*, 1995], rapidly flowing streams such as the Iskut tend to have backscatter values that are spatially and temporally consistent. An upper threshold of −10.5 dB was used for classification of the water surface. This value approximately coincides with the mode of a right-skewed Gaussian distribution of data values typical for the control section. Although a bimodal distribution distinguishing water from gravel was not observed, the mode tends to behave as an inflection point, with distribution density to the left of the mode increasing with water surface area. Its relatively stable position at −10.5 dB permitted uniform application to all images acquired over the control section. From visual assessment, thresholds set lower than −10.5 dB tend to miss some water surface area; higher thresholds classify noncontiguous patches that do not appear to be channels.

Speckle was reduced using a 3 × 3 bimodal majority filter that was applied to each image to remove anomalous bright pixels from the channels and dark nulls from the surrounding floodplain surface; this approach is similar to that used by *Kellndorfer et al.* [1993]. Following calibration, classification, and filtering of each image (Figure 2), total water surface area within the control section was computed from a simple pixel count of cells classified as water. Division by the length of the control section (10 km) was used to normalize these areas, yielding an "effective width" (in meters) of the total water surface for each ERS 1 image.

Results

Twenty-eight ERS 1 SAR images were acquired over the Iskut River control section from 1992 to 1993. Hourly streamflows measured simultaneously on the ground ranged from 242 to 6350 m^3/s, including an extreme flood event on October 27, 1993, the largest recorded in the 34-year history of the gauging station. Peak annual flows normally do not exceed 2000 m^3/s. Effective width of the braided channel network grows or contracts in response to changing river discharge, as can be seen from three sample images in Figure 3. Satellite-derived effec-

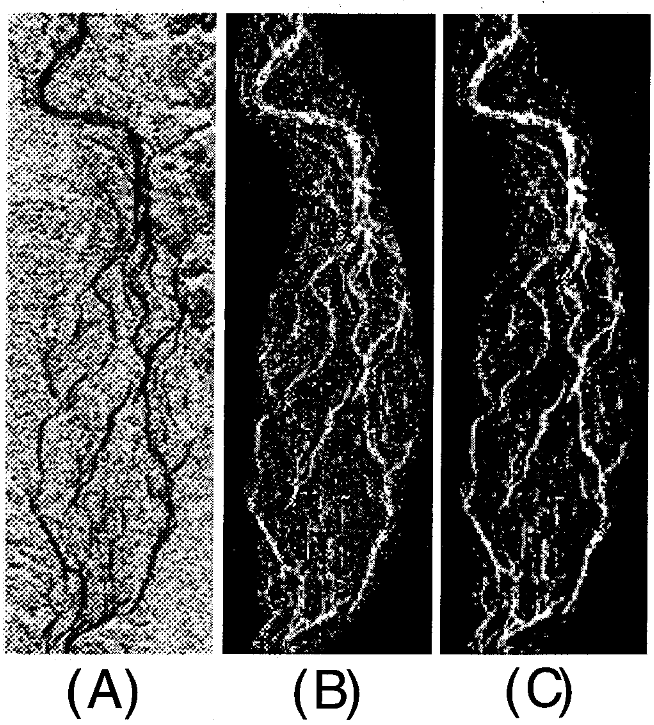

Figure 2. Processing of ERS 1 SAR data: (a) radiometric calibration; (b) water classification (−10.5 dB); and (c) speckle filtering. Braid complex is approximately 10 km × 3 km.

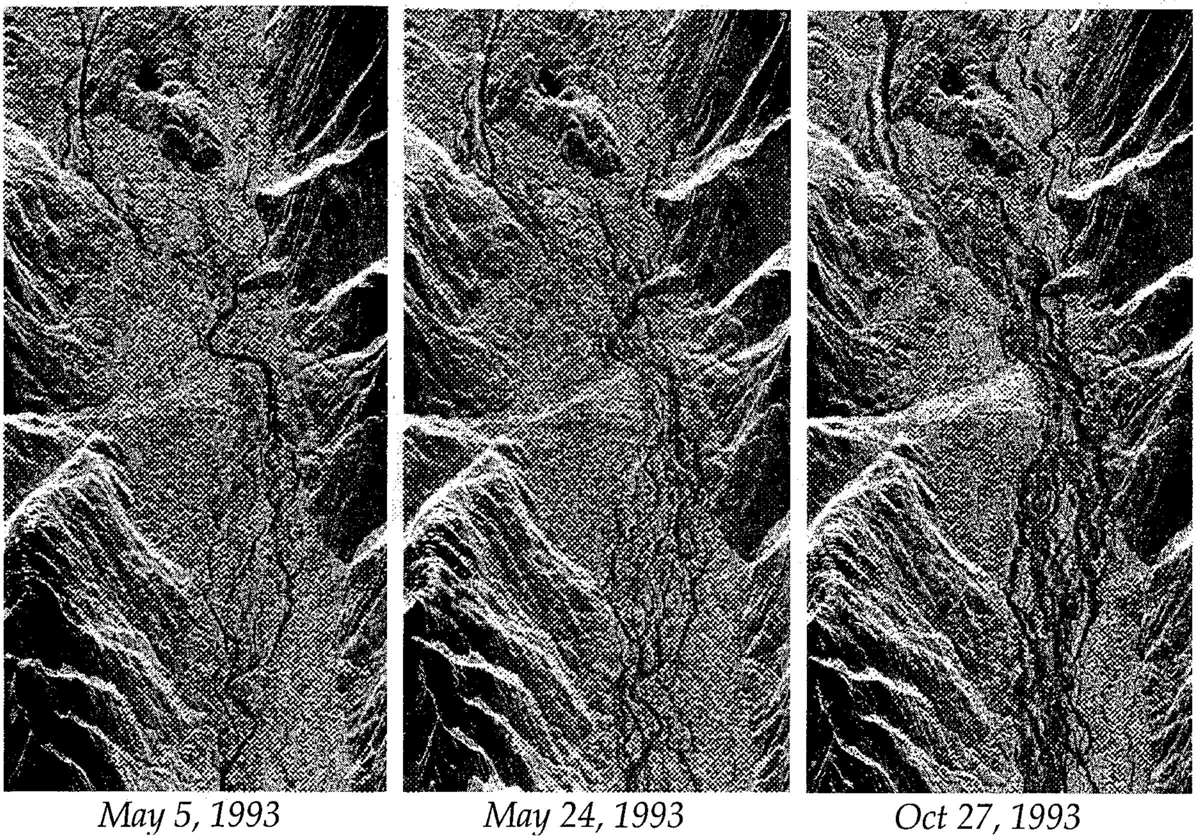

Figure 3. Three ERS 1 SAR images acquired over the Iskut River in 1993. Water surfaces are dark; river discharge increases from left to right. May 5 and May 24 are typical; October 27 was an extreme flood event. Each image is approximately 15 km × 8 km.

tive widths and actual river discharges are plotted in Figure 4. The relationship is log linear with 89% of the variation explained by the equation $W_e = 27.5Q^{0.42}$, using a 95% confidence interval. This plot constitutes a satellite-derived "area-discharge rating curve" for the control section with a mean error of ± 275 m^3/s.

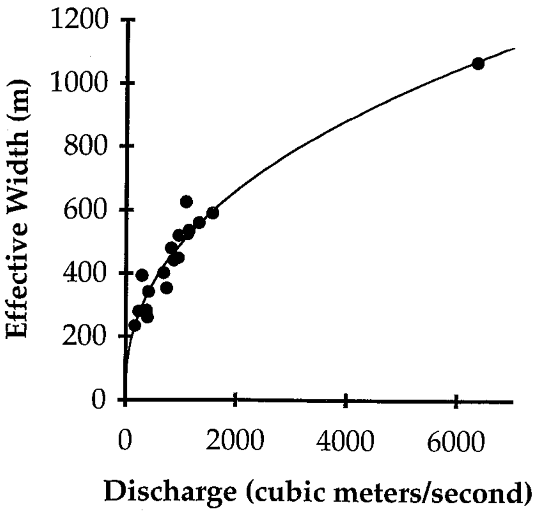

Figure 4. Relationship between satellite-derived effective width (W_e) and river discharge measured on the ground. The equation of the best fit curve is $W_e = 27.5Q^{0.42}$ ($R^2 = 0.89$). Each point is determined from a single ERS 1 SAR image. Outlier is an extreme flood event; maximum annual flows do not normally exceed 2000 m^3/s.

Changes in the braided network can be tracked through time. Although the main channels of the Iskut appear to be relatively stable, secondary channels appear and disappear, often with a new configuration. River ice can also be monitored, but this technique can not be applied during winter conditions because there is no unique relationship between river ice area and discharge. Ground discharge measurements, when available at all, are also of poor quality during winter conditions. Frozen channels typically appear bright instead of dark, but melting snow and ice during March and April cause low backscatter returns from much of the floodplain, including areas between channels. The extensive dark patches that result have low backscatter values and are easily misclassified as open water. For these reasons, only ice-free images (Table 1) were used to produce Figure 4.

Discussion

Previous studies have noted the strong correlation between channel width and discharge in the braided fluvial environment [*Rice*, 1979; *Mosley*, 1983; *Leopold*, 1985; *Schumm et al.*, 1987, chapter 5]. The relationship is typically described as a function of the form

$$W = aQ_c^b$$

where W is braid channel width, Q_c is channel discharge, and a and b are constants. The responses of channel depth and

Table 1. ERS 1 Synthetic Aperture Radar Scenes Used to Produce Figure 4

ERS 1 Orbit	ASF ID	Date
4424	75634	May 20 1992
4696	27431	June 08 1992
5197	83322	July 13 1992
5426	77526	July 29 1992
5698	75759	Aug. 17 1992
6199	81831	Sept. 21 1992
6428	81861	Oct. 07 1992
6929	81981	Nov. 11 1992
9434	83388	May 05 1993
9706	83425	May 24 1993
9935	83435	June 09 1993
10207	83458	June 28 1993
10436	83488	July 14 1993
10937	83530	Aug. 18 1993
11209	83565	Sept. 06 1993
11438	83606	Sept. 22 1993
11939	83833	Oct. 17 1993
12211	86023	Nov. 15 1993

ASF ID is Alaska SAR Facility (ASF) image identification number, and date is Greenwich Mean Time date of acquisition.

flow velocity are described by similar functions. The value of the width exponent b is an indicator of the sensitivity of a channel's width to changing discharge. Field measurements in small braided channels (with flows of the order of 1–15 m^3/s) and flume studies have yielded width exponents that range from 0.07 to 0.58, with typical values around 0.22–0.45 [*Fahnestock*, 1963; *Church*, 1972; *Cheetham*, 1979; *Rice*, 1979; *Mosley*, 1983]. The satellite-derived width exponent of 0.42 for the Iskut River is similar, despite the much larger scale (flows of hundreds to thousands of cubic meters per second) and integration over all channels in an entire braided reach. Width-depth ratios also tend to be similar among rivers of similar scale [*Fahnestock*, 1963; *Church*, 1972], but more comparative studies are needed to assess the potential of this technique for application to ungauged braided systems. Construction of effective width/discharge curves for other gauged watersheds will permit comparisons with the one derived in this study.

Layover, foreshortening, and radar shadow are common effects in SAR images acquired over areas of steep topography. Radar returns from the glaciers and mountain slopes surrounding the Iskut River valley are significantly affected by satellite position, requiring the use of repeat pass imagery for study of their changing surface conditions. However, minimal topographic distortions were found over the flat, wide floodplains of the Iskut and Stikine Rivers. Changes in viewing geometry do not significantly affect the detection of water surfaces, permitting the use of overlapping orbits to increase the temporal resolution of a monitoring program over these low-relief valley floors. The presence of river ice, however, presents a severe difficulty for both satellite and ground-based discharge estimates. This problem is mitigated by the fact that as much as 95% of the total yearly discharge for glacierized basins is released during the summer [*Lawson*, 1993], making winter measurements less critical to the assessment of annual water cycles. For the Iskut River, winter contribution to total annual streamflow is consistently less than 10% each year.

Annual streamflows in glacierized basins follow a predictable pattern, unlike watersheds dominated by stochastic rainfall events. Mean discharges swell over a period of months during the summer melt season with small, highly random deviations superimposed on a larger, relatively smooth trend that is remarkably similar from year to year. For this reason, discontinuous instantaneous discharge estimates tend to approximate the annual hydrograph more closely for snowmelt and ice melt rivers than for rainfall-controlled watersheds. It is hoped that future work will indicate some transferability of satellite-derived rating curves from gauged watersheds to ungauged rivers of similar morphology. If not, potential still exists for inferring relative changes in streamflow for a particular ungauged site, even if absolute values are not obtainable without a period of ground calibration.

Spaceborne SAR's such as the currently operating ERS 1 and Japanese Earth Resources Satellite (JERS) 1, and the anticipated ERS 2, JERS 2, and Canadian RADARSAT, are excellent sensors for multitemporal hydrologic studies due to their cloud-penetrating capability, high spatial and temporal resolution, and strong sensitivity to water. While it is not suggested that satellite-derived values will ever approach the accuracy or sampling frequency of traditional gauging methods, approximate and intermittent estimates of discharge from braided glacial outwash streams will provide assessment of hydrologic conditions at a regional scale not currently possible for these remote, climatically sensitive watersheds.

Conclusion

With our rapidly improving satellite technology and the prospect of abundant multitemporal data in the next century, new spatially based discharge estimation techniques show great potential for improving our understanding of hydrologic regimes in remote areas. ERS 1 SAR classifications of water surface area correlate well with ground discharge measurements for a braided river in British Columbia, indicating that approximate discharge estimates can be made from space. Potential exists for satellite monitoring of large remote or high-latitude glacial rivers, where flows may be sensitive indicators of regional or global climatic conditions.

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