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Remote sensing of stream depths with hydraulically assisted bathymetry (HAB) models

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Abstract

This article introduces a technique for using a combination of remote sensing imagery and open-channel flow principles to estimate depths for each pixel in an imaged river. This technique, which we term hydraulically assisted bathymetry (HAB), uses a combination of local stream gage information on discharge, image brightness data, and Manning-based estimates of stream resistance to calculate water depth. The HAB technique does not require ground-truth depth information at the time of flight. HAB can be accomplished with multispectral or hyperspectral data, and therefore can be applied over entire watersheds using standard high spatial resolution satellite or aerial images. HAB also has the potential to be applied retroactively to historic imagery, allowing researchers to map temporal changes in depth.

We present two versions of the technique, HAB-1 and HAB-2. HAB-1 is based primarily on the geometry, discharge and velocity relationships of river channels. Manning's equation (assuming average depth approximates the hydraulic radius), the discharge equation, and the assumption that the frequency distribution of depths within a cross-section approximates that of a triangle are combined with discharge data from a local station, width measurements from imagery, and slope measurements from maps to estimate minimum, average and maximum depths at a multiple cross-sections. These depths are assigned to pixels of maximum, average, and minimum brightness within the cross-sections to develop a brightness–depth relation to estimate depths throughout the remainder of the river.

HAB-2 is similar to HAB-1 in operation, but the assumption that the distribution of depths approximates that of a triangle is replaced by an optical Beer–Lambert law of light absorbance. In this case, the flow equations and the optical equations are used to iteratively scale the river pixel values until their depths produce a discharge that matches that of a nearby gage.

R^2 values for measured depths versus depths estimated by HAB-1 and HAB-2 are 0.51 and 0.77, respectively, in the relatively simple Brazos River, Texas. R^2 values for HAB-1 and HAB-2 are 0.46 and 0.26, respectively, in the Lamar River, a complex mountain river system in Yellowstone National Park. Although the R^2 values are moderate, depth maps and cross-sections derived from the HAB techniques are consistent with typical stream geomorphology patterns and provide far greater

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spatial coverage and detail than could be achieved with ground-based survey techniques. Improved depth estimates can be achieved by stratifying the river into different habitat types that normalize for differences in turbulence and substrate.

Keywords: Remote sensing; Depths; Bathymetry; Streams; Rivers; Optical

1. Introduction

Detailed depth maps of streams can be a valuable tool for characterizing stream hydraulics (Waddle et al., 2000; Lane and Chandler, 2003), modeling flow dynamics and forecasting flood hazard (Brunner, 2002; Steffler and Blackburn, 2002), modeling pollutant dispersion (Coles and Wells, 2003), predicting channel change (Lane et al., 2002), documenting instream habitats (Whited et al., 2002; Marcus et al., 2003), and evaluating potential effects of management decisions. At present, accurate depth maps are generated from ground-based surveys, but these surveys are time consuming, costly, difficult to conduct in inaccessible areas, and require surveyors be in the field at the time of depth measurements. Ground-based depth surveys are therefore generally spatially limited to single reaches of a stream or to several cross-section locations throughout a watershed, and are temporally limited to periods when surveyors can be in the field, as well as to locations of known bed constraint.

Optical remote sensing of stream depths provides a useful, complementary alternative to ground-based surveys. Remote sensing-based depth maps could provide spatial coverage across entire watersheds and temporal coverage on a year-round basis, so long as the water column is not obstructed by trees, clouds, shadows, overhanging materials, ice, or significant turbidity. Indeed, accurate maps of stream depths (Lyon and Hutchinson, 1995; Winterbottom and Gilvear, 1997; Marcus et al., 2003) and marine bathymetry (e.g., Lafon et al., 2002; Liceaga-Correa and Euan-Avila, 2002; Louchard et al., 2003) have been generated by coupling remote imagery with ground measurements. However, the need for ground-based measurements imposes the same general constraints associated with field mapping of depths and reduces the relative advantages of these remotely sensed approaches.

In this article, we develop and evaluate two remote sensing models for estimating stream water depths without the use of ground crews. The two models are based on simple concepts of open-channel flow and require only slope data for the stream bed and discharge data from a nearby gaging station at the time of image collection. Because these hydraulically assisted bathymetry (HAB) models do not require ground data on depths or water optics, they remove the logistical obstacles associated with field surveys and radiometric calibration and enable depth estimates using historical and modern photos and digital data.

2. Background

Remote sensing of water depths dates at least to World War II, when photogrammetric techniques were used with aerial photos to measure near-shore depths in the Pacific (Lundahl, 1948). Likewise, some of the earlier work on use of digital imagery addressed techniques for estimating depth (Poclyn and Sattinger, 1969). Since these early studies, the large majority of research relevant to optical remote sensing of depth has focused on documenting and modeling optical characteristics of water (e.g., Gordon and Brown, 1974; Mobley, 1994; Gould and Arnone, 1997; Woodruff et al., 1999; Herlevi, 2002; Holden and LeDrew, 2002; Louchard et al., 2003—to list just a few) and using variants of these radiant transfer models to estimate near-shore marine or lake depths (e.g., Lyzenga, 1978; Sandidge and Holyer, 1998; Roberts and Anderson, 1999; Lafon et al., 2002).

Similar radiant transfer models have generated useful depth estimates in large and relatively clear rivers. Lyon et al. (1992) and Lyon and Hutchinson (1995), for example, developed an optical model that, when coupled with ground-based measurements, estimated five depths classes with 95% accuracy in the St. Mary's River of Michigan. While of value, these models do not readily transfer to the more spatially and temporally heterogeneous turbulent environments of relatively smaller and more shallow streams, where