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Satellite-based remote sensing of running water habitats at large riverscape scales: Tools to analyze habitat heterogeneity for river ecosystem management

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ABSTRACT

We illustrate an approach to quantify patterns in hydraulic habitat composition and local heterogeneity applicable at low cost over very large river extents, with selectable reach window scales. Ongoing developments in remote sensing and geographical information science massively improve efficiencies in analyzing earth surface features. With the development of new satellite sensors and drone platforms and with the lowered cost of high resolution multispectral imagery, fluvial geomorphology is experiencing a revolution in mapping streams at high resolution. Exploiting the power of aerial or satellite imagery is particularly useful in a riverscape research framework (Fausch et al., 2002), where high resolution sampling of fluvial features and very large coverage extents are needed. This study presents a satellite remote sensing method that requires very limited field calibration data to estimate over various scales ranging from 1 m to many tens or river kilometers (i) spatial composition metrics for key hydraulic mesohabitat types and (ii) reach-scale wetted habitat heterogeneity indices such as the hydromorphological index of diversity (*HMID*). When the purpose is hydraulic habitat characterization applied over long river networks, the proposed method (although less accurate) is much less computationally expensive and less data demanding than two dimensional computational fluid dynamics (CFD). Here, we illustrate the tools based on a Worldview 2 satellite image of the Kiamika River, near Mont Laurier, Quebec, Canada, specifically over a 17-km river reach below the Kiamika dam. In the first step, a high resolution water depth (*D*) map is produced from a spectral band ratio (calculated from the multispectral image), calibrated with limited field measurements. Next, based only on known river discharge and estimated cross section depths at time of image capture, empirical-based *pseudo-2D* hydraulic rules are used to rapidly generate a two-dimensional map of flow velocity (*V*) over the 17-km Kiamika reach. The joint distribution of *D* and *V* variables over wetted zones then is used to reveal structural patterns in hydraulic habitat availability at patch, reach, and segment scales. Here we analyze 156 bivariate (*D*, *V*) density function plots estimated over moving reach windows along the satellite scene extent to extract 14 physical habitat metrics (such as river width, mean and modal depths and velocity, variances and covariance in *D* and *V* over 1-m pixels, *HMID*, *entropy*). A principal component analysis on the set of metrics is then used to cluster river reaches in regard to similarity in their hydraulic habitat composition and heterogeneity. Applications of this approach can include (i) specific fish habitat detection at riverscape scales (e.g., large areas of riffle spawning beds, deeper pools) for regional management, (ii) studying how river habitat heterogeneity is correlated to fish distribution and (iii) guidance for site location for restoration of key habitats or for post regulation monitoring of *representative* reaches of various types.

Abbreviations: 2D, two-dimensional; α, constant depending on the local value of river slope; γ, unit weight of water; y_0, river bed roughness constant for vertical velocity profiles; ρ_w, water volumetric mass density; σ, standard deviation; τ_0, shear stress; *A*, cross-sectional area; AOI, area of interest; B1, B2,…,, spectral band 1, 2, …; BP, bivariate plot (= density function plot); CI, confidence intervals; CEHQ, Centre d'expertise hydrique du Quebec; CFD, computational fluid dynamics; CV, coefficient of variation; COV, covariance; *D*, water depth; D_{av}, mean water depth; D_{md}, modal water depth; DEM, digital elevation model; DF, density function; e, base of natural logarithm; *Entrp*, entropy; *FastShlw*, fast-shallow; *HHI*, habitat heterogeneity index; *HMID*, hydromorphological index of diversity; *k*, Von-Karman constant; Lidar, Light detection and ranging; *ModalBox*, modal box (= modal density); N, number of samples; NDWI, normalized difference for water index; NIR, near-infrared; PC-1, PC-2, …,, principal component axis 1, 2, …; PCA, principal component analysis; *Q*, river discharge; R^2, statistical coefficient of determination; RS, remote sensing; *S*, water surface slope; *ShoreLength*, shore length; *SlwDeep*, slow-deep; *SlwShlw*, slow-shallow; u^*, shear velocity; UTC, coordinated universal time; UTM, Universal Transverse Mercator; *V*, Flow velocity; V_{av}, mean flow velocity; V_{md}, modal flow velocity; VAR, variance; Vis–NIR, visible and near-infrared; W_{av}, mean river width; W_{bkf}, bankfull river width; WD_{ratio}, width to depth ratio.

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1. Introduction

1.1. The riverscape challenge in river science

Geological and geomorphic legacies along fluvial corridors play a major role in shaping riverine landscapes (Richards et al., 2002; Ward et al., 2002); and the resultant multiscale heterogeneity has long posed a challenge for river habitat characterization (Carbonneau et al., 2012). The river itself can be seen as heterogeneous succession of reaches of various character, encompassing alluvial sections of different energy, sedimentology, and pattern, interspersed with reaches under stronger nonalluvial (or bedrock) control. At finer scales, each reach can also be described as a sequence of multiple mesohabitats types with contrasting hydraulic conditions (Harper et al., 1992).Finally longer river segments can be defined between *nodes* where major tributaries reset water discharge and sediment load conditions, and often also alter water temperature and chemistry (Rice et al., 2006). Yet, the connectivity of hydrology, sediments, pollutants, and biotic populations along a river requires that river ecosystems be managed at the watershed scale.

Describing habitat heterogeneity (diversity in habitat conditions over various distance scales) over an extensive river ecosystem is a key requirement for river management. In particular, the details of spatial organization among complementary riverine fish habitats (such as distinct adult spawning and juvenile rearing habitats) over significant river segments can affect fish production rates and the distribution of fish biomass. In a study of regional variations in Atlantic salmon (*Salmo salar*) production, Kim and Lapointe (2011) showed how variability in along-river separation between three geomorphologically distinct types of reaches, each providing only one of the complementary habitats required for salmon production (summer refugia for adults in canyon reaches with deep holding pools, fall spawning habitat in cobble gravel bar reaches, and good rearing habitats for older juveniles in boulder rapid reaches)explain significant interriver differences in salmon production across 14 Quebec Appalachian watersheds. Similarly, Torgersen et al. (1999) showed how the coincidental occurrence of deeper pools that also happen to be set within river reaches with cooler water temperatures explains Chinook specie abundance patterns along northern Oregon streams.

Given the movement and migration ranges of many river fish and their requirements for various complementary riverine habitats, very detailed studies of habitat availability that are limited to short, accessible river reaches are often insufficient to understand the health of fish populations in a river. Consequently, a broader-scale *riverscape* approach has been promoted (Fausch et al., 2002) to reveal multiscale patterns in fish-habitat relationships (Torgersen et al., 2006). As a corollary, low cost tools are needed to generate habitat heterogeneity and habitat composition metrics over very large river extents. Remote sensing is a natural approach to this challenge. Such tools are described here, based on satellite high resolution, multispectral products. For illustration, insights into habitat patterns and spatial variations in reach-scale habitat heterogeneity or complexity are presented here, with application to a 17-km-long segment of the Kiamika River in Canada. Longer river segments can easily be studied with the same approach.

One key tenet of the riverscape approach is that, in the absence of a detailed and extensive river analysis encompassing large spatial extents, classic study reach selection exercises (often heavily determined by access constraints) can severely bias representations of a river ecosystem (Fausch et al., 2002). These authors concluded that the development of high resolution, large spatial extent characterization tools based on remotely sensed (RS) data are needed to fill the data gaps in decision making projects at riverscape scales and efficiently conserve stream fish populations. The approach proposed here addresses such needs.

1.2. Remote sensing tools for riverscape scale analyses

Fluvial geomorphologists have shown great interest in the use of airborne photogrammetric or satellite images to study riverine structure (Legleiter et al., 2004) and in ecohydraulic modeling for fish habitat mapping (Bergeron and Carbonneau, 2012). While remote sensing tools to characterize emergent bar and floodplain features are well developed (Wiederkehr et al., 2010),the characterization using RS imagery of underwater hydraulic habitats (in particular, planwise or two-dimensional velocity patterns) is more challenging, especially over distances exceeding hundreds times the mean river width. Carbonneau et al. (2012) reviewed the different techniques currently used in river studies to map habitat variables associated with riverine landscape ecology. They demonstrated the use of high resolution, low elevation airborne imagery to quantitatively map primary fluvial variables (e.g., river bathymetry, substrate grain size, water temperature) and inferred hydraulic variables (e.g., flow velocity). Yet for surveys over larger river networks, the costs of purpose flow manned or unmanned coverage remain a practical limitation to uniform data acquisition at riverscape scales. When centimeter- or decimeter- scale resolutions are not required, or where funding is insufficient for purpose-flown low elevation image acquisition, commercially available satellite imagery with submeter resolution (panchromatic) and 2-m resolution (multispectral), such as provided by WorldView, Geoeye, and Quickbird, can be used. Satellite coverage can cover hundreds of river kilometers at submeter resolution at much lower cost than airborne – or boat – based surveys, particularly in remote regions with poor or no access nor close by airfields.

1.3. Objectives

Where project budgets permit, very high resolution computational fluid dynamics (CFD) and remote sensing methods including Lidar are already available to fully characterize with high precision river channel topography and hydraulics (Alsdorf et al., 2007; Mandlburger et al., 2009). However, two-dimensional-CFD remains impractical at riverscape scales where simulation domain lengths are often measured in multiples of thousands of channel width. The methods proposed here have a different aim and application: to generate at much lower cost than state-of-the-art river CFD, over large watersheds and broad regional scales, and longitudinal and transverse characterization along rivers of the main features of habitat variability. Where resources are available to acquire field and airborne data needed for more exacting approaches to mapping channel depths and velocities, the latter simulations can simply be incorporated to generate more precise estimates of the various metrics developed here.

The approach presented incorporates well-known methods of depth interpretation (based on a calibration of spectral band ratios) combined with existing, *pseudo-2D* hydraulic computation approaches (Maddock et al., 2013), the latter adapted to situations where minimal field calibration data are available. The aim is to generate original insights into riverscape-scale habitat zonation and locations of hotspots of reach heterogeneity. The innovation proposed here thus lies, rather than in the choice of specific depth or velocity interpretation tools used, in the definition of metrics and the interpretation of large-scale patterns that is demonstrated using satellite-based coverage.

The specific goals are (i) to illustrate how RS-based approaches with minimal field data can help characterize river habitat zonation and detect reaches with highest heterogeneity scores along the Kiamika River, using a suite of physical habitat variables computed in the model; (ii) to analyze the sensitivity of key habitat metrics to uncertainties in depth and velocity in the RS-derived interpretations;(iii) to analyze the effects of the choice of reach window scale over which habitat metrics are calculated on the resultant interpretations; and (iv) to describe and compare three heterogeneity metrics in terms of their sensitivity to different channel morphologies.