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Semi-automated analysis of high-resolution aerial images to quantify docks in glacial lakes ☆

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ABSTRACT

Lake resources can be negatively affected by environmental stressors originating from multiple sources and different spatial scales. Shoreline development, in particular, can negatively affect lake resources through decline in habitat quality, physical disturbance, and impacts on fisheries. The development of remote sensing techniques that efficiently characterize shoreline development in a regional context could greatly improve management approaches for protecting and restoring lake resources. The goal of this study was to develop an approach using high-resolution aerial photographs to quantify and assess docks as indicators of shoreline development. First, we describe a dock analysis workflow that can be used to quantify the spatial extent of docks using aerial images. Our approach incorporates pixel-based classifiers with object-based techniques to effectively analyze high-resolution digital imagery. Second, we apply the analysis workflow to quantify docks for 4261 lakes managed by the Minnesota Department of Natural Resources. Overall accuracy of the analysis results was 98.4% (87.7% based on $\widehat{K}$) after manual post-processing. The analysis workflow was also 74% more efficient than the time required for manual digitization of docks. These analyses have immediate relevance for resource planning in Minnesota, whereas the dock analysis workflow could be used to quantify shoreline development in other regions with comparable imagery. These data can also be used to better understand the effects of shoreline development on aquatic resources and to evaluate the effects of shoreline development relative to other stressors.

1. Introduction

The increasing presence of permanent or seasonal homes on lake shorelines has been a cause for concern among lake managers given the potential impacts of human activities associated with these properties. Home-owners can alter shoreline characteristics by preferential removal of aquatic vegetation or through the addition of unnatural structure (e.g., docks, rip–rap). The potential effects of shoreline development may contribute to declines in habitat quality (Christensen et al., 1996; Radomski and Goeman, 2001; Jennings et al., 2003; Marburg et al., 2006; Radomski, 2006), having associated effects on fish spawning success and population structure (Jennings et al., 1999; Garrison et al., 2005; Wagner et al., 2006; Reed and Pereira, 2009; Gaeta et al., 2011). Although the potential effects of shoreline development have been recognized, the precise implications for the protection of lake resources is unclear in the context of whole-lake management. For example, the relative effects of both shoreline development and watershed-based stressors is unclear considering potential interactions among factors that influence water quality. Additionally, researchers have not extensively evaluated the cumulative effects of shoreline development on whole-lake condition relative to site-level impacts (but see Jennings et al., 1999; Marburg et al., 2006). Lack of quantitative information describing shoreline development across broad areas has been a primary research limitation.

The use of Geographical Information System (GIS) and remote sensing technologies to quantify environmental stressors of lakes has importance given the potential to accurately quantify information across multiple spatial scales. Several techniques using GIS or

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remote sensing approaches have been proposed for evaluating lake resources in the Upper Midwest United States (Sawaya et al., 2003; Host et al., 2005; Olmanson et al., 2008; Chipman et al., 2009; Olmanson et al., 2011). Olmanson et al. (2008) developed an approach for evaluating water clarity using imagery from the Landsat satellite. Water clarity for more than 10,500 lakes in Minnesota was determined by developing linear regression models of *in situ* measurements of water clarity compared with surface radiance values obtained from Landsat imagery. Additionally, Sawaya et al. (2003) described the development and application of remote sensing techniques to quantify information relevant for lake management at the local scale. The application of GIS and remote sensing technologies for the management of aquatic resources has shown promise and should be further investigated to determine whether additional techniques can be developed.

Most remote sensing techniques for lake management have primarily focused on assessing lake condition prior to the implementation of management actions (e.g., Host et al., 2005; Olmanson et al., 2008) but have not focused on the explicit quantification of relevant stressors. More importantly, available data that can be used to quantify stressors, such as satellite-derived land use information, have inadequate spatial resolution to characterize shoreline development. Specifically, Landsat-derived products describe land use in 30 m grid cells that cover 900 m^2, whereas most docks typically do not exceed 15–20 m^2 (MNDNR, 2011). In the absence of sufficient or appropriate data, researchers are limited to manual techniques or *in situ* assessments for quantifying information (e.g., Radomski et al., 2010; Perleberg et al., 2012), although these techniques cannot be practically applied to regional evaluations. Additionally, efforts to quantify stressors of aquatic systems must consider appropriate surrogate measures (Danz et al., 2007; Wang et al., 2010), such as indicators for multiple shoreline-based stressors. Docks are potentially useful indicators because they can directly impact habitat Garrison et al. (2005); Radomski et al. (2010) and are indirectly associated with other stressors (Jennings et al., 2003; Radomski, 2006), such as recreational activity at the site-level, or housing density at the whole-lake spatial scale. Ease of identification in aerial imagery further supports their use as a surrogate measure (Radomski et al., 2010).

Image classification techniques for quantifying shoreline development have not been extensively developed despite the increasing availability of high-resolution (1 m or better) digital imagery. Traditional approaches for image classification have relied on pixel-based techniques where individual pixels are assigned to classes defined by clustering (Richards and Jia, 2006a,b; Homer et al., 2007; Jensen et al., 2009). Ideally, classes should correspond to thematic categories of interest in the image, such as land use or cover. Pixel-based classifiers can be used with high-resolution imagery but problems are encountered when the pixel size is significantly smaller than the classes of interest. Multiple pixels with different spectral properties may describe a single object or the dependence among neighboring pixels may introduce bias in the classification (Townshend et al., 2000; Blaschke and Strobl, 2001). Object-based image analysis has been proposed as an alternative approach that seeks to identify objects defined by groups of pixels with similar spectral and spatial characteristics (Hay and Castilla, 2008; Lang, 2008; Blaschke, 2010). Image objects (i.e., vector polygons) define the fundamental units of interest for identifying real-world objects. Object-based image analysis applied with more traditional methods of image classification could provide a powerful approach for quantifying stressors in nearshore environments.

The goal of this study was to develop a cost-effective approach for quantifying and assessing the extent of shoreline development of glacial lakes in the Upper Midwest United States. First, we describe a dock analysis workflow that can be used to quantify docks using high-resolution digital imagery. This workflow combines elements of traditional pixel-based classifiers with object-based approaches to create a semi-automated analysis for enumerating docks and estimating dock area. We focused on the development of techniques that can be applied across broad regions rather than methods with limited spatial scope. Accordingly, our second objective was to use the workflow to quantify the extent of shoreline development in Minnesota using images for 4261 lakes that are managed by the Minnesota Department of Natural Resources (MNDNR). These results have immediate relevance for MNDNR planning, whereas the dock analysis workflow could easily be extended to other states or regions with comparable imagery. This study also considers docks to be adequate indicators of a majority of stressors that result from shoreline development (Garrison et al., 2005; Radomski et al., 2010). Here and throughout, 'docks' refer to docks, boat lifts, trampolines, fishing piers, and other structures on or in the water that do not naturally occur in nearshore environments.

2. Material and methods

2.1. Data and software

Digital aerial images from the 2008 National Agricultural Imagery Program (NAIP) were used for the development and application of our dock analysis workflow described below. NAIP images are leaf-on images (May through September) with 1 m resolution and are available annually for the entire United States (USDA, 2011). The 2008 images also contain a near infrared (NIR) spectral band, in addition to the standard red, green, and blue spectral bands, which was useful for removing vegetation from images and improving identification of relevant classes during analysis. Each pixel in each band has an 8-bit digital number (DN) value as a measure of surface radiance ranging from 0 to 255. NAIP images were obtained as ortho-rectified county mosaics for 84 of Minnesota's 87 counties that contained our study lakes. Image acquisition dates varied such that 12% were in May, 9% were in June, 28% were in July, 47% were in August, and 4% were in September. The county mosaics were obtained in the JPEG 2000 (.jp2) format and included 87.8 Gb of data.

The workflow was implemented using the ArcGIS (v9.3) (ESRI, 2009) geo-processing object in the programming language Python v2.6.5 (http://www.python.org/). The use of Python to write scripts specific for ArcGIS improved efficiency of the analysis by combining all components of the workflow in a single script file. This utility provides a major advantage of using ArcGIS for image analysis. Potential users of the dock analysis workflow are also more likely to have access to ArcGIS rather than more specific image analysis software.

2.2. Description of the dock analysis workflow

The dock analysis workflow consists of three separate processes: (1) shoreline correction; (2) dock extraction; and (3) manual post-processing (Figs. 1 and 2). Individual images bounded by the minimum and maximum Universe Transverse Mercator coordinates for each lake are used as input for the analysis workflow. The following describes each process of the workflow in more detail.

The dock analysis workflow begins with the *shoreline correction process* (Figs. 1 and 2). We adopt an approach similar to Liu et al. (2011) by using pixel-based classifiers and object-based techniques to extract shoreline areas from remotely sensed data. However, the goal of our process is to create a lake polygon that can be used to clip the input image in the beginning of the dock extraction process. The resulting polygon may not always be an accurate representation of the shoreline but is sufficient for isolating docks