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Airborne hyperspectral remote sensing to assess spatial distribution of water quality characteristics in large rivers: The Mississippi River and its tributaries in Minnesota

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ABSTRACT

Aircraft-mounted hyperspectral spectrometers were used to collect imagery with high spatial and spectral resolution for use in measuring optically active water quality characteristics of major rivers of Minnesota. Ground-based sampling undertaken concurrent with image acquisition provided calibration data for chlorophyll, suspended solids, turbidity and other measures of water clarity. Our approach identified the spectral characteristics that distinguish waters dominated by several inherent optical properties (IOPs), and we used those characteristics to develop models to map water quality characteristics in optically complex waters. For phytoplankton related variables (volatile suspended solids (VSS) and chlorophyll *a* (chl *a*)), the ratios of the scattering peak at the red edge (~700 nm) with the reflectance troughs caused by chlorophyll absorption at ~670 nm and other plant pigment absorption peaks at 592 and 620 nm all were strong predictors of chl *a* and VSS (r^2 values of 0.73–0.94). The scattering peak at ~700 nm was a strong predictor of variables related to water clarity (total suspended solids (TSS), turbidity and turbidity tube (T-tube)) (r^2 values of 0.77–0.93). For mineral-based variables (nonvolatile suspended solids (NVSS) and the ratio NVSS:TSS), combinations of the TSS and chl *a* relationships described above were strong predictors (r^2 values of 0.73–0.97) and the most robust because this model corrects for the scattering of phytoplankton at ~700 nm. Application of the methods to quantify spatial variations in water quality for stretches of the Mississippi River and its tributaries indicate that hyperspectral imagery can be used to distinguish and map key variables under complex IOP conditions, particularly to separate and map inorganic suspended sediments independently of chlorophyll levels.

1. Introduction

Minnesota has 93,000 miles (150,000 km) of rivers and streams. They are highly important as transportation corridors and recreational resources that contribute significantly to the state's economy and tourism. Of the 17% of the state's river and stream miles assessed for the 2010 Impaired Waters List, 40% were found to be impaired (Minnesota Pollution Control Agency, 2011). We explored the use of aircraft-mounted remote sensing systems as a cost-effective way to gather information to measure optically active water quality properties of rivers relevant to the issue of river water impairment. This paper describes a general approach, as well as specific predictive relationships, that can be used for such measurements.

We have had success previously using multispectral radiance information from Landsat imagery (e.g., Olmanson et al., 2008) to measure lake water clarity. More recently, we showed that other satellite sensors (MERIS and MODIS) can provide accurate estimates of chlorophyll levels in large and moderately sized lakes (Olmanson et al., 2011). We expect that similar relationships exist in flowing waters, but compared with lakes, rivers and streams pose a more challenging set of problems in applying remote sensing techniques to assess water quality. First, conditions in rivers and streams are temporally more dynamic and often spatially more heterogeneous than those in lakes. Second, small rivers and streams may be so shallow that light penetrates to the bottom, such that reflectance from the water is a function of bottom conditions in addition to that of the water itself. Third, the spatial resolution of most satellite sensors, including Landsat, is too coarse for small rivers and streams. Finally, to measure water quality conditions other than clarity, a better set of spectral bands is needed than what Landsat provides. Although the MERIS and MODIS satellite sensors provide such bands, their coarse spatial resolution makes them suitable only for very large rivers or impoundments of large rivers.

Hyperspectral sensors, mounted in small aircraft can collect landscape images with high spatial and spectral resolution. Such airborne systems have been available for over two decades and have been used for mineralogical exploration (e.g., Abrams et al., 1977; Clark et al., 1990; Goetz & Srivastava, 1985), as well as to determine the type, health and condition of vegetation for environmental quality, forestry and agriculture purposes (e.g. Carroll et al., 2008; Gitelson & Merzlyak,

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1996; Gitelson et al., 2002; Haboudane et al., 2002, 2004; Shah et al., 2002, 2004; Wessman et al., 1988). Several publications have described the application of such systems to measure water quality conditions in lakes (e.g., Ammenberg et al., 2002; Chipman et al., 2009; Hakvoort et al., 2002; Hoogenboom et al., 1998 and Moses et al., 2011), but only a few publications (e.g., Senay et al., 2001 and Shafique et al., 2003) have focused on potentially more complex river systems. Phytoplankton, mineral suspended sediment, humic color or combinations of these constituents may dominate the optical properties of rivers depending on watershed and flow conditions. Strong relationships were found in previous studies between chlorophyll concentrations and turbidity or suspended solids concentrations and reflectance data, but none attempted to separate competing inherent optical properties (IOPs).

In this paper we describe the use of aircraft-mounted hyperspectral sensors on three major rivers in Minnesota (Mississippi, Minnesota, and St. Croix) and some associated floodplain lakes with distinct and competing IOPs. Sufficient information was acquired in three separate aerial data acquisitions to evaluate the usefulness of aircraft-mounted remote sensing as a supplement/complement to conventional ground-based river monitoring programs. For calibration purposes, water samples were collected concurrently with the remote sensing data acquisition, and in order to obtain a range of conditions for calibrations, we focused our measurements around the confluences of river systems that have different water quality characteristics. Imagery was collected during August of 2004, 2005 and 2007, and each period represented different flow and water quality regimes.

The overall goal was to develop reliable techniques for synoptic measurements of key indicators of river water quality that can be used to complement data obtained by conventional ground-based methods. Our specific objectives were to: (1) identify spectral characteristics that distinguish waters dominated by different IOPs indicative of important water quality characteristics; (2) develop predictive relationships for these characteristics based on their individual spectral (reflectance) characteristics (or combinations thereof); (3) determine whether and how accurately chlorophyll *a*, total suspended solids (TSS), and nonvolatile suspended solids (NVSS) can be mapped independently when competing IOPs are dominant and whether the proportion (NVSS/TSS) can be identified and mapped quantifiably; (4) develop an overall approach to measure and map water quality variables using aircraft-mounted spectrometers; and (5) evaluate the accuracy and usefulness of aircraft-based hyperspectral remote sensing for water quality studies of rivers. The work was conducted using images collected under clear (cloudless) conditions and processed by methods similar to those developed for regional assessments of water clarity and chlorophyll *a* from satellite imagery (e.g., Olmanson et al., 2008, 2011).

2. Background information: major rivers in Twin Cities Metropolitan Area

The Mississippi River, which originates in Lake Itasca in northern Minnesota, is a moderate sized river (average flow of 11,700 cfs (3163 $m^3\ s^{-1}$), Table 1) by river mile 871, where it reaches the Minneapolis–St. Paul (Twin Cities) Metropolitan Area (TCMA). The drainage basin of the Mississippi River above the TCMA (~49,000 km^2 in area) includes much of central and north central Minnesota. Land cover in the basin is mixed (37% forest and 21% cropland). In the TCMA (7700 km^2) the land cover is 40% agricultural row crops, 30% urban and 13% forest. The Minnesota and St. Croix Rivers are large tributaries that flow into the Mississippi in the TCMA and increase the total river flow on average by more than a factor of two (Table 1).

The drainage basin of the Minnesota River covers 42,000 km^2, including large portions of south-central and southwestern Minnesota, as well as small portions of Iowa and South Dakota. The basin has relatively flat to gently rolling hills with highly productive soils and is primarily (75%) row-crop agricultural land. The river carries a high burden of suspended solids from stream bank and soil erosion that is attributed to a combination of artificial drainage and steep slopes from deep incising of the Minnesota River Valley by Glacial River Warren (Belmont et al., 2011; Gran et al., 2009; Thorleifson, 1996).

The drainage basin of the St. Croix River covers 20,000 km^2 in eastern Minnesota and northwestern Wisconsin. The basin is the least developed of the three considered here and consists of 50% forest, 15% grassland or pasture, and 15% agricultural row crops. Among the three rivers, the St. Croix has the lowest nutrient and suspended solids concentrations but has higher levels of natural colored dissolved organic matter (CDOM).

Aside from their commercial and recreational importance, the rivers play important roles in transporting pollutants downstream. Most of the treated wastewater from the TCMA enters the Mississippi River downstream of a major treatment plant in St. Paul; among other consequences, this leads to high nutrient (nitrogen and phosphorus) concentrations that promote summertime algal blooms in the river and downstream Lake Pepin (Engstrom et al., 2009).

The water chemistry/quality of these rivers is more complex than that of most lakes. Dominance by both phytoplankton, usually measured in terms of chlorophyll *a* concentrations (sometimes called green phase) and inorganic sediment, sometimes called brown phase and measured in terms of Secchi depth, turbidity, or suspended solids concentrations, may occur depending on flow and seasonal dynamics. Typically, the Mississippi River accounts for 40–45% of flow and 20% of incoming TSS load; the Minnesota River accounts for 25–30% of flow but 75% of incoming TSS; and the St. Croix River accounts for 25–30% of flow but only 5% of the incoming TSS load (Metropolitan Council, 2004). Water quality conditions in the three rivers are highly diverse, and conditions in the Mississippi River downstream of the confluences with the two tributaries depend on the relative flows of the rivers and the degree to which mixing of the waters has occurred.

Water quality impairment issues occur in the Mississippi River as a consequence of urban and agricultural runoff and inputs of treated municipal wastewater as the river flows through the TCMA. Major concerns exist about the effects of suspended solids and nutrient loadings on Lake Pepin, a natural lake in the main channel of the river ~40 miles (70 km) downstream of the TCMA (Belmont et al., 2011; Engstrom et al., 2009; Mulla & Sekely, 2009). At a larger scale, there also is concern about contributions from Minnesota to the total nutrient load of the Mississippi River to the Gulf of Mexico (Goolsby et al., 2001; Rabalais et al., 2002a, b; Turner & Rabalais, 1994). Under normal conditions Minnesota contributes ~3% of the total nitrogen flux and 2% of the phosphorus flux delivered to the Gulf of Mexico by the Mississippi River (Alexander et al., 2008).

Table 1
River discharge for Minnesota, Mississippi and St. Croix Rivers in the TCMA.

River	Site	Mean discharge (cfs) 26,604	August 19, 2004 discharge (cfs) 9130	August 15, 2005 discharge (cfs) 7370	August 30, 2007 discharge (cfs) 8070
Minnesota	Jordan	8810–33%	3190–35%	1840–25%	4160–52%
Mississippi	Anoka	11,700–44%	2770–30%	4100–56%	1930–24%
St. Croix	Stillwater	6094–23%	3170–35%	1430–19%	1980–24%