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The new Landsat 8 potential for remote sensing of colored dissolved organic matter (CDOM)

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ABSTRACT

Due to a combination of factors, such as a new coastal/aerosol band and improved radiometric sensitivity of the Operational Land Imager aboard Landsat 8, the atmospherically-corrected Surface Reflectance product for Landsat data, and the growing availability of corrected fDOM data from U.S. Geological Survey gaging stations, moderate-resolution remote sensing of fDOM may now be achievable. This paper explores the background of previous efforts and shows preliminary examples of the remote sensing and data relationships between corrected fDOM and Landsat 8 reflectance values. Although preliminary results before and after Hurricane Sandy are encouraging, more research is needed to explore the full potential of Landsat 8 to continuously map fDOM in a number of water profiles.

Introduction

1.1. CDOM and water quality

Colored dissolved organic matter (CDOM) is the humic-rich, optically active fraction of dissolved organic matter that is present in natural waters from the decomposition of detritus and other organic material. Also known as chromophoric dissolved organic matter, yellow substance, humic color, and gelbstoff (Hoge et al., 1995), CDOM is an important measure of water quality and has important implications for drinking water (Evans et al., 2005; Herzsprung et al., 2012), aquatic ecosystems (Häder et al., 2007), and metal transport (Bergamaschi et al., 2011). For example, CDOM reduces the available light in the water column and tends to impede biological activity such as photosynthesis, thereby inhibiting growth in phytoplankton populations, which are fundamental to aquatic food chains (Häder et al., 2007). Understanding the spatial and temporal variability of CDOM is important to the study of water quality, global carbon budgets, and climate change.

CDOM is increasingly being monitored at U.S. Geological Survey (USGS) gaging stations. Although naturally occurring, CDOM can also be increased by anthropogenic activities such as agricultural runoff, sewage treatment plant discharge, and runoff from confined animal feeding operations (Hudson et al., 2007). CDOM can also be elevated by extreme weather events, such as storms and hurricanes that cause massive overland flow and washing of surface material into estuarine waters. This effect of increased CDOM from the Hurricane Sandy event was the catalyst for this research review and analysis.

Dissolved organic matter (DOM) is an important component of the total dissolved carbon pool in surface waters. Functionally, CDOM behavior is complex and affects the productivity of the water column by both blocking ultraviolet radiation in the upper layer while blocking sunlight and limiting production at depth. The photobleaching that accompanies the photochemical modification of DOM affects the optical properties of seawater and influences penetration of ultraviolet and photosynthetically active radiation (PAR) wavelengths (Moran et al., 2000). CDOM absorbs varying amounts of ultraviolet to blue light whereas pure water absorbs red light, which is why pure water appears blue while with varying amounts of CDOM, water color will range through green, yellow-green, and brown as CDOM concentration increases (Nelson and Coble, 2009).

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CDOM is often estimated in remotely sensed data as part of surface reflectance models when quantifying chlorophyll and suspended sediment concentrations in surface waters. However, several recent studies have also attempted to estimate surface water CDOM from multispectral satellite remote sensing with limited success. A major challenge has been the lack of standard methodologies required to generate atmospherically corrected data (Kutser et al., 2009). For example, interferences from atmospheric moisture and gases complicate reflectance measurements by introducing increased interference and variability in the spectral signal. However, Kutser et al. (2005a) demonstrated it was feasible to estimate CDOM from the EO-1 Advanced Land Imager (ALI) when the ALI data were atmospherically corrected.

CDOM is optically measurable and therefore an excellent candidate for quantification by remote sensing techniques. Although several researchers have approached the issue of measuring CDOM from multispectral satellite remote sensing, no uniform methodology has been widely accepted in part because of the lack of atmospherically corrected data (Kutser et al., 2005b). The advent of Landsat 8, with the new band in the blue portion of the electromagnetic spectrum, increased radiometric resolution, coupled with the associated USGS surface reflectance product (USGS, 2015b), has made measuring CDOM feasible. However, several challenges still need to be addressed to unlock the potential for remotely sensed CDOM data. In particular, the ability to correlate remotely sensed measurements with ground-truth surface water data for CDOM requires carefully timing field sampling with satellite overpasses (e.g., every 16 days for Landsat 8), or relying on data collected on nearby dates. The ability to develop a remotely sensed, continuous model of CDOM would have important advantages to the scientific community. The purpose of this paper is to explore the possibility of measuring CDOM from the Landsat 8 Operational Land Imager (OLI) using the surface reflectance data product that is now being produced by the USGS Earth Resources Observation and Science (EROS) Center, the USGS science center that collects, stores, processes and distributes all Landsat data (USGS, 2015b).

1.2. CDOM measurements and Hurricane Sandy

In the wake of Hurricane Sandy, October 22–31, 2014, damages to buildings and infrastructure mobilized a variety of contaminants into the local rivers and bays of New York and New Jersey, with visible contaminant plumes reported weeks after the storm (Kenward et al., 2013, Reilly et al. this issue). As part of the response to Hurricane Sandy, the USGS employed remote sensing data to detect and map wastewater and sediment plumes in the receding storm waters. Pre- and post-Sandy Advanced Land Imager (ALI) scenes were used to compare relative CDOM levels with the goal of detecting wastewater and sediment plumes that resulted from infrastructure damage in the wake of the storm. However, the available data had insufficient temporal resolution to develop meaningful calibration curves for plume detections. This realization highlighted an outstanding need for new methods of water quality parameter extraction from sensors with more regular return intervals, such as the recently launched Landsat 8, which because of its increased radiometric resolution, similar to the prototype ALI sensor, offers the potential to more accurately derive ocean and near-coastal water quality parameters. The initial attempt to extract plume waters from ALI data, and preliminary results of a study investigating the utility of improved Landsat 8 data for CDOM detection are detailed below, followed by a discussion of the current capabilities and future needs to accurately predict CDOM in open waters using Landsat 8 data. The preliminary results from the Hurricane Sandy data, gathered by the ALI sensor, showed promise and led to the collection and study of CDOM data from three individual gaging stations where corrected CDOM data were available.

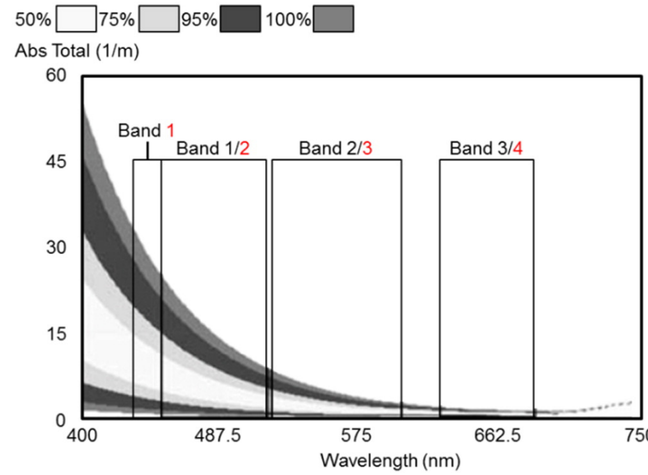

Fig. 1. The gradually decreasing absorbance of CDOM in the electromagnetic spectrum and the band location of typical multispectral satellite sensors. Dark numbers represent earlier Landsat sensors and red numbers indicate Landsat 8 bands and the improvement of Band 1 relative to the available energy. The shaded intervals represent typical ranges of 500 simulations. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)
(After Kutser et al., 2005b).

2. Background

2.1. Measuring and reporting of CDOM in water

CDOM reflectance occurs in the ultraviolet-blue part of the electromagnetic spectrum, but has no unique identifying spectral absorbance or reflectance features. Instead, CDOM exhibits a gradually decreasing slope from the ultraviolet through the blue regions (Fig. 1).

CDOM is typically derived using absorbance or fluorescence techniques. Spectral absorbance is a measure of how much light at a specific wavelength (typically 254 nm or 440 nm) is absorbed over a range of wavelengths. Fluorescence is a process where a substance emits longer wavelength light when exposed to short wavelength light depending on the amount of absorbing material, the absorbance characteristics of the material and the optical path-length the light must travel through the sample. CDOM sensors typically use fluorescence to characterize CDOM in situ rather than absorbance given the lower cost and higher sensitivity of field fluorometers. Fluorescent dissolved organic matter (fDOM) refers to the fraction of CDOM that fluoresces and is generally accepted as a surrogate for CDOM.

One of the research problems related to CDOM is that it is not measured nor reported uniformly. CDOM is sometimes expressed as a function of color at 440 nm (C_{440}) (Brezonik et al., 2005). Similarly, Aiken (Aiken, 2014) observed that marine chemists often express absorption coefficients in Naperian (spectral absorbance coefficient) units, whereas the freshwater and wastewater communities usually express decadal absorption coefficients. CDOM is also sometimes measured by absorbance spectra ranging from 240 to 800 nm with a peak around 355 nm (Zhang et al., 2007). Stedmon et al. (2000) found that the absorption at 375 nm was the optimum measure of CDOM concentration using both linear and non-linear regressions that included a coefficient for the spectral slope between the ultraviolet and the red, and absorption spectra between 300 and 650 nm (Stedmon et al., 2000). CDOM light absorption is sometimes expressed in terms of PCU color (Platinum-Cobalt units). Others studies have reported CDOM relative to other materials such as color from chloroplatinate units (Brezonik et al., 2005). CDOM fluorometers typically report measurements in relative fluorescence units (RFUs). Many USGS gaging stations measure CDOM via fluorescence techniques and report CDOM concentrations as units of a Quinine Sulfate Equivalent (QSE). Quinine is a highly fluorescent alkaloid that absorbs ultraviolet light, has a very high quantum fluorescence yield, and has often been used as a standard in fluorometric analyses. Further, quinine has a maximum absorption wavelength of 350 nm and a maximum emission wavelength of 450 nm, and has become a de facto standard for in situ reporting of CDOM fluorescence. CDOM research in the future could benefit from the adoption of standard reporting units of CDOM and the establishment of quantitative equivalencies for alternate measurement units.

One of the research challenges for remote sensing of CDOM is that surface water CDOM measurements used to calibrate imagery are not reported uniformly in the literature. For example, CDOM has been reported as absorption at wavelengths ranging from 254 nm to 440 nm (Spencer et al., 2012), with one study suggesting that absorption at 375 nm was the optimum measure of CDOM concentrations (Stedmon et al., 2000). While absorbance at these wavelengths tend to be strongly correlated, the absolute values reported as absorption coefficients (normalized to the cell path length in meters) or unit-less absorbance values (A) will differ and may result in discrepancies. The inconsistencies in reporting units, including the differences in the Naperian absorption coefficients (α) commonly used by marine scientists, and the decadal absorption coefficients (a) commonly used by the freshwater and wastewater communities (Aiken, 2014), can result in confusion over the appropriate values for calibration.

Another source of potential confusion is the analysis of CDOM by absorbance versus fluorescence. It should be noted that older literature often refers to measurement of CDOM by absorbance or fluorescence in the same way, while more recent literature commonly uses fDOM to describe the fluorescence-based measurements with maximum excitation and emission wavelengths around 370 and 450 nm, respectively. Laboratory measurements of CDOM and fDOM are often strongly correlated (Ferrari and Dowell, 1998). However, differences between CDOM and fDOM have been observed (Spencer et al., 2007; Stedmon et al., 2000) and may be indicative of changes in DOM composition that affect the ratio of absorbance to fluorescence (e.g., relative fluorescence efficiency).

One important distinction between fDOM and CDOM is the emergence of relatively low cost, low power fluorometers for in situ fDOM measurements in rivers, streams and estuaries. As noted by Brezonik et al. (2015), the temporal variability in DOM – particularly in some rivers and lakes – necessitates that water samples to calibrate satellite imagery are collected within days of satellite acquisition. Continuous fDOM measurements alleviate this issue as data are measured at a high frequency (e.g., many measurements per hour or day) and can be transmitted in real-time to publicly accessible data portals. While in situ spectrophotometers are available for absorbance measurements in the ultraviolet and visible range, they tend to be more expensive (e.g., >$20,000) and are often less amenable to long-term unattended monitoring in freshwater and coastal systems. The use of fDOM sensors as continuous surrogates for CDOM as suggested by Ferrari and Dowell (1998) is now becoming more feasible given recent increases in the number and spatial distribution of in situ sensors.

However, challenges remain for the collection of comparable and accurate in situ fDOM data. In particular, the need to compensate for temperature effects and correct for interferences from suspended particles and highly colored waters presents a major challenge for the current generation of sensors. Recent studies have shown that the magnitude of these effects can be large in many freshwater systems (Downing et al., 2012; Saraceno et al., 2009) with >90% of the fluorescence signal lost under particularly challenging matrix conditions. Future work to characterize and correct sensor output based on these effects remains critical for correlating remotely sensed data with surface water fDOM measurements, particularly in rivers and lakes, which may experience high turbidity (e.g., 100–1000+ Formazin Nephelometric Units) and inner filter effects from highly colored waters (Downing et al., 2012).

2.2. Fluorescence measurements of water quality

Fluorescence is the property of a substance that absorbs incoming energy and emits longer wavelength energy. The shorter incoming radiation, such as natural light or ultraviolet radiation serves to bombard atoms, molecules and ions, which cause a release of energy that ceases as the incoming radiation source ceases. Fluorescence has been developed as a unique form of spectroscopy and used extensively in laboratory chemical testing such as biomedical applications.

Fluorescence techniques have gained widespread acceptance in water quality monitoring such as determining the amount of dissolved organic matter (DOM) in a water sample. The amount and type of DOM in a local watershed is an important factor in understanding the sources of organic compounds and their effect on biological systems.

Dissolved organic matter includes a broad range of organic molecules of various sizes and composition that are released by all living and dead plants and animals. Measuring the fraction of DOM that absorbs light at specific wavelengths and subsequently release it at longer wavelengths (i.e. fluorescence) is diagnostic of DOM type and amount (Aiken, 2014). Measurements of CDOM fluorescence (i.e. fDOM) have a long history in oceanography as an indicator of terrestrial humic substances in the coastal ocean (Coble, 2007). Advances in field-deployable optical sensor technology over the past 20 years have led to the routine use of compact and relatively inexpensive fluorometers in situ in coastal environments (Chen, 1999; Coble et al., 1998; Vodacek et al., 1995) and more recently in freshwaters. For example, fluorescence sensors have been used as high resolution proxies to better understanding the transport of dissolved organic carbon (DOC) from watersheds (Pellerin et al., 2012; Saraceno et al., 2009; Spencer et al., 2007), internal sources of DOC to drinking water reservoirs (Downing et al., 2008), the formation of disinfection by-products following drinking water treatment (Carpenter et al., 2013), and the transport and cycling of other constituents including methylmercury (Bergamaschi et al., 2011; Bergamaschi et al., 2012). Traditionally, DOM fluorescence (e.g. fDOM) has been measured at an excitation wavelength around 370 nm and an emission wavelength around 450 nm, which is most closely related to terrestrial, humic-like organic matter (Coble et al., 2014). These wavelengths for field fDOM instrumentation were historically determined by the availability of stable light-emitting diodes (LEDs) with wavelengths in an excitation range that provided a measurable response (e.g., a fluorescence emission band not susceptible to ambient light interference). While the fluorescent properties of DOM in natural waters have been known for more than 60 years (Kalle, 1949), the first reports of in situ fDOM measurements were not published until the early 1990s (Coble et al., 1991). Advances in field-deployable optical sensor technology since then have led to the routine use of compact and relatively inexpensive fluorometers in situ in coastal environments (Chen, 1999; Coble et al., 1998; Yamashita et al., 2015); and more recently in freshwaters. For example, fluorescence sensors have been used as high resolution proxies to better understand the transport of DOM from watersheds (Gannon et al., 2015; Pellerin et al., 2012; Saraceno et al., 2009; Spencer et al., 2007; Wilson et al., 2013), sources and cycling of DOM in lakes and reservoirs (Downing et al., 2008; Watras et al., 2015), the formation of disinfection by-products following drinking water treatment (Carpenter et al., 2013), and the transport and cycling of other constituents including methylmercury (Bergamaschi et al., 2011; Bergamaschi et al., 2012; Fichot et al., 2015).

2.3. Satellite remote sensing of water quality and atmospheric corrections of spectral reflectance

Over the years, the use of satellite remote sensing data has become increasingly commonplace for deriving water quality information from estuarine and freshwater systems. The consistent temporal coverage and broad spatial extent of satellite data provide a cost effective solution for frequent, synoptic water quality measurements. Numerous empirical, semi-analytical, and analytical models have been developed to estimate a range of parameters including chlorophyll *a* concentrations, total suspended solids (TSS), colored dissolved organic matter (CDOM), salinity, and temperature (Fan, 2014; Senay et al., 2002). Remotely sensed water quality measurements typically utilize empirical relationships between the spectral features of water reflectance and discrete in situ water samples, quantifying the water quality parameter(s) of interest (Fan, 2014).

However, to develop these quantitative models, remotely sensed data must first be corrected for the effects of absorption, emission and scattering of electromagnetic energy through atmospheric moisture and gases. In order to make these corrections, the effects of these processes have been mathematically modeled in a process known as *radiative transfer*. The science of remote sensing centers around modeling relationships between transformations in electromagnetic energy and measured chemical, biological, or physical characteristics of objects (e.g., building, tree, and waterbody) or phenomena (e.g., temperature, soil moisture, and biomass) on Earth. Electromagnetic energy can be transmitted, absorbed, reflected, scattered, or emitted by an object, and the nature and magnitude of these transformations is dependent on the properties of that object and/or phenomena. For any given object the amount of emitted and/or reflected energy varies by wavelength, and thus exhibits a characteristic spectral signature when the observed reflectance is plotted against wavelength along the electromagnetic spectrum. These spectral characteristics can be used to identify and/or quantify an object or phenomena if their spectral fingerprints are known. Satellites such as Landsat house passive sensors that capture reflected and/or emitted energy from Earth in various wavelengths of the electromagnetic spectrum across numerous sensor bands. Measured reflectance values for each band are stored digitally as a composite pixel or raster image of the Earth's surface, which can be used in tandem with in situ samples to develop models to predict various phenomena (NASA, 2000).

A number of environmental factors may influence the accuracy of remotely sensed data including atmospheric influences such as cloud cover, air moisture content, and aerosol content. These factors may interfere with the reflected or emitted energy as it travels from the object under study to the satellite sensor, and in some cases may limit the usability of the data or cause data gaps. Additional limitations include the temporal and spatial resolution of the data collected by satellite systems. While their consistent return intervals and broad spatial coverage allow for unparalleled analytical capabilities, they do not provide a means to detect short-term phenomena, or objects with a small spatial footprint. Therefore, it is critical that studies are designed and proper data processing guidelines are followed to accommodate these limitations.

Previously, atmospheric corrections to Landsat data required researchers to correct individual scenes, a time and labor intensive process. However, with the new Surface Reflectance products developed by the National Aeronautics and Space Administration (NASA) and the USGS, corrected data are now routinely delivered to any researcher and can be obtained by download thought the USGS EarthExplorer website (http://earthexplorer.usgs.gov). This greatly enhances the potential for remote sensing research of water quality.

2.4. Remote sensing of CDOM

Interest in the remote sensing of CDOM dates back to the 1980s when researchers realized that CDOM interferences had to be accounted for before phytoplankton, chlorophyll, and suspended sediment measurements could be accurately made from reflectance remote sensing data (Ferrari and Tassan, 1992; Karabashev et al., 1993; Tassan, 1988). As a result, this opened up the possibility that CDOM could be directly measured from remotely sensed data (Ferrari et al., 1996; Hoge et al., 1993).

Remote sensing of CDOM to assess DOC in aquatic systems has been successfully demonstrated by several researchers (Del Castillo and Miller, 2008; Menken et al., 2006; Vignudelli et al., 2004). The most successful satellite application to address CDOM directly to date has been demonstrated by Kutser et al. (2005a) who showed that a band 2/band 3 ratio from atmospherically corrected Advanced Land Imager (ALI) data could reasonably estimate CDOM in small lakes. ALI is NASA's experimental prototype for Landsat 8. Other coarser spatial resolution sensors, such as MODIS (Moderate Resolution Imaging Spectroradiometer), and SeaWiFS (Sea-Viewing Wide Field-of-View Sensor), have been used to quantify CDOM in oceanic and coastal waters (Antoine et al., 2008; Brown et al., 2008). However, the spatial resolution (250 m/1.1 km, respectively) of these sensors is too coarse to deal with rivers, coastal outfalls and small lakes.

It is important to note that there are three different forms of spectral data typically involved in CDOM calculations. Laboratory methods generally involve measurements of ***absorbance*** at a specific wavelength between 250 and 440 nm. In situ sensors of the type that are currently being utilized at USGS gaging stations are based on ***fluorescence*** measurements where the excitation wavelength is around 350 nm and the emission wavelength is around 450 nm (Brezonik et al., 2015). Successful overhead remote sensing applications are based on ***reflectance*** measurements generally at wavelengths greater than 500 nm (Brezonik et al., 2015; Kutser et al., 2005a; Menken et al., 2006). Cross walking among these different remote sensing units and equivalencies remains a major challenge.

Hyperspectral remote sensing (HRS) of CDOM has great information potential. Although generally not practical in large-scale field efforts, using the entire solar-reflected spectrum has decided advantages. HRS has been addressed by several researchers who have greatly improved the understanding of CDOM from reflectance measurements. Vertucci and Likens (1989) used spectroradiometer measurements of Adirondack lakes and showed the spectral reflectance relationships between plant pigments, dissolved organic carbon, and suspended material. They showed that these factors were negatively correlated between 400 and 600 nm and positively correlated between 600 and 750 nm. They also developed a reflectance ratio of 525 nm/554 nm and regression models for estimating total pigments and dissolved organic carbon (DOC).

Stedmon et al. (2000) utilized spectral absorbance data of 586 CDOM samples in Danish fjords to develop a new method for estimating spectral slope coefficients, which enabled the identification of CDOM based on different land use types and demonstrated that the optical properties of CDOM could be used in regional scenarios. Mobley et al. (2005) used mobile hyperspectral images to develop spectral matching look-up tables of inherent optical properties of the water column, including CDOM. Yu et al. (2010) developed a functional linear model of CDOM using hyperspectral reflectance that also provided coefficient curves to estimate and remove the interferences from turbidity and chlorophyll. Kutser et al. (2001) developed special absorption, scattering coefficients, and backscattering probabilities for turbid lakes utilizing airborne spectrometer data after finding that previous absorption and scattering coefficients were not optimal. Kallio et al. (2001) used airborne hyperspectral to estimate water quality parameters in 11 Finnish lakes. They found that seasonal differences were important and that apparent reflectance, instead of radiance, improved estimation of total suspended solids and turbidity.

2.5. Landsat 8 and remote sensing of CDOM

Assessment of water quality has long been of interest in the remote sensing community, with applications of remote sensing of CDOM dating back to the 1980s. Satellite remote sensing data have been successfully used to predict a variety of water quality parameters, including total suspended solids, turbidity, chlorophyll-*a*, and colored dissolved organic matter (CDOM) (Vincent et al., 2004). The consistent return intervals and synoptic coverage of satellite sensors have become increasingly appealing for event responders and change detection research. Handheld instruments measuring reflectance have been successfully utilized to estimate CDOM (Arenz et al., 1996; Hirtle and Rencz, 2003; Kutser et al., 1998; Vertucci and Likens, 1989). Handheld and airborne spectrometers have similarly proven that high spectral resolution reflectance measurements can be used to quantify CDOM (Brando and Dekker, 2003; Kallio et al., 2001; Lee et al., 1994; Mobley et al., 2005; Vahtmäe et al., 2006). Most remote sensing satellites, such as SeaWiFS

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and MODIS lack the spatial resolution to map small lakes or lack the spectral and/or radiometric resolution to sufficiently address CDOM parameters (Kutser et al., 2005a). Earlier Landsat sensors such as the Thematic Mapper on Landsats 5 and 7, lacked the radiometric resolution to fully address CDOM measurement, (Kutser et al., 2005b). Another major problem for satellite remote sensing of CDOM has been the lack of adequate atmospherically corrected reflectance data. Atmospheric gases and particles alter the radiance and reflected energy signal significantly, and most images collected by satellites are substantially contaminated by the effects of atmospheric constituents through absorption and scattering of light. While the images can be used for interpretation of morphological characteristics, and the atmospheric interferences can be mitigated by scene-specific target corrections, band ratios, and indices, rigorous spectral measurements require atmospheric corrections for consistent results.

The synoptic and repeat coverage of the Landsat sensors, coupled with recent data processing improvements, make them desirable for climate data records. Landsat 8 was launched on February 11, 2013, and was placed into operational service on May 30, 2013. The two-sensor payload includes the Operational Land Imager (OLI) and the Thermal InfraRed Sensor (TIRS). The OLI is based on the prototype Advanced Land Imager (ALI) that was part of the EO-1 mission and represents substantial improvements for addressing CDOM and related water issues as compared to the Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM), which were the imaging sensors on Landsat 5 and Landsat 7, respectively.

The first major improvement was the increased radiometric sensitivity from 8-bit to 16-bit data. In 2005, Kutser et al. (2005b) showed that the 8-bit radiometric resolution of Landsat 7 was inadequate to address CDOM under high concentration conditions. They went on to suggest that the 16-bit radiometry and improved signal-to-noise ratio of the ALI and OLI sensors were capable of addressing CDOM under a wide range of water quality conditions.

A second major improvement of the OLI sensor in relation to CDOM is the addition of a new band 1 for coastal/aerosol sensing. The 433 nm–453 nm spectral range is centered near the 440/443 nm absorbance band that has been utilized by several researchers for estimating CDOM concentrations among other water quality parameters (Bowers et al., 2004; Brando and Dekker, 2003; Brezonik et al., 2005; Chen et al., 2007; Lee et al., 1994; Menken et al., 2006; Mobley et al., 2005; Zhu et al., 2011). This band is an important new capability for water quality remote sensing.

A third major improvement is the release of a surface reflectance data product by the USGS EROS Center in 2015 (USGS, 2015a,b). Atmospherically corrected data for Landsats 4, 5, and 7 were generated from the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) developed by NASA. The LEDAPS is specialized software that applies MODIS atmospheric correction routines to Level-1 data products. Water vapor, ozone, geo-potential height, aerosol optical thickness, and digital elevation information are input with Landsat data to generate top of atmosphere (TOA) reflectance, surface reflectance, brightness and temperature, along with masks for clouds, cloud shadows, adjacent clouds, land and water (USGS, 2015a). Landsat 8 Surface Reflectance data are generated from the Landsat 8 Surface Reflectance (L8SR) algorithm – this is not the same algorithm used for Landsats 4, 5 and 7 data – instead, this new method currently uses the scene center for the sun angle calculation and then hardcodes the view zenith angle to 0. The solar zenith and view zenith angles are used for calculations as part of the atmospheric correction (USGS, 2015b).

The combination of Landsat 8 sensor improvements and the Surface Reflectance product create a data environment where previous limitations to addressing CDOM have been, at least potentially, largely removed. Based on the earlier work by Brezonik et al. (2005); Kutser et al. (2005a,b), and Griffin et al. (2011), mapping CDOM from satellite data may now be possible.

3. Material and methods

The initial investigation involved Advanced Land Imager (ALI) multispectral data that were utilized to extract Colored Dissolved Organic Matter (CDOM) values for the estuarine waters of New York and New Jersey. Pre- and post-Hurricane Sandy ALI scenes were downloaded from the USGS Hazards Data Distribution System Explorer (http://hddsexplorer.usgs.gov) for 9/12/2011 and 11/21/2012. Scenes were then atmospherically corrected and processed for CDOM following methods detailed in Brezonik et al. (2005); Kutser et al. (2005a), and Griffin et al. (2011).

Kutser et al. (2005a) mapped CDOM values for ALI water pixels utilizing a simple power function:

$$a_{CDOM}(420) = 5.20x^{-2.76}$$

where x is the ratio of ALI bands 2 (565 nm) and 3 (660 nm), and $a_{CDOM}(420)$ is the absorption coefficient of CDOM at 420 nm. By using a negative power function, a lower ratio value x would indicate greater CDOM levels, which are assumed in this study to represent waters with humic-rich organic material. Kutser et al. (2005a) demonstrated strong

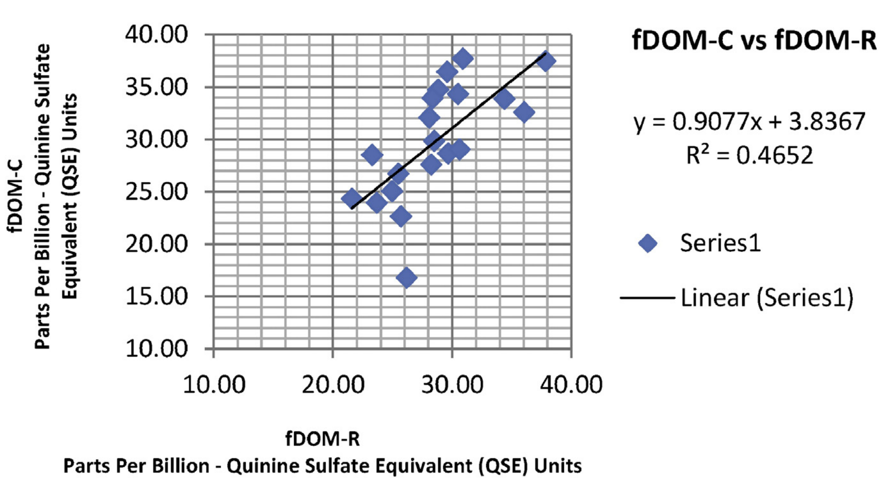

Fig. 2. The difference between the raw (−R) and corrected (−C) fDOM values at the Middle Haddam, CT, gage for the values corresponding to the OLI satellite overpasses. The relationship shows the importance of correcting CDOM data.

correlations between in situ CDOM measurements and the ALI band ratio ($R^2 = 0.84$). For this study in the New York-New Jersey coastal area, in situ data were not available for dates coinciding with the ALI scenes, therefore, making absolute CDOM levels impossible to estimate. Instead, differences in the resulting band ratios were assumed to represent relative differences in CDOM concentrations.

Extracted plumes of elevated CDOM levels were compared against known wastewater effluent locations whose facilities were overwhelmed during Hurricane Sandy (Kenward et al., 2013). Pre- and post-storm comparisons were also made to highlight any CDOM changes from the baseline (pre-storm) conditions.

Relatively clear, atmospherically corrected Landsat 8 scenes over three gaging stations were also identified and downloaded from the USGS EarthExplorer site. These stations were: Middle Haddam Connecticut (01,193,050), Potomac River at Little Falls (01,646,500), and the Susquehanna River at Darlington, Maryland (01,579,550). The reflectance values for each of seven Landsat 8 bands were individually recorded at or near the gage location, and the CDOM and other water quality parameters for 10:30 A.M. (time of the sun-synchronous overpass of Landsat 8) were recorded. CDOM values reported at most of the gaging stations are preliminary and require a series of corrections before accurate CDOM values can be reasonably extracted (Downing et al., 2012; Pellerin, 2013). In general, CDOM values need corrections for temperature, turbidity, and inner filter effects from highly colored water. Corrected CDOM values were obtained for the USGS gaging stations based on the procedures outlined in Downing et al. (2012). The fluorometer at the Middle Haddam site is a Turner Designs C-7 CDOM Fluorometer (Turner Designs, Sunnyvale, CA); at the Little Falls and Darlington Sites, the fluorometer is a YSI EXO CDOM Fluorometer (YSI, Yellow Springs, OH). At USGS gaging sites the fDOM sensors are typically deployed at a depth of approximately 2–3 ft below the average water surface. Fig. 2 shows the linear relationship between the raw fDOM values, as would be preliminarily reported in the USGS National Water Information System (NWIS), and the corrected values for temperature, turbidity, and color in the Connecticut River. The corrected data are reported as fDOM, the portion of CDOM that fluoresces, and is generally regarded as a surrogate measurement for CDOM and an easier means of tracking DOM in natural waters in situ.

4. Preliminary results

CDOM extraction methods detailed in Kutser et al. (2005a) were successfully applied to ALI scenes for both pre- and post-Hurricane Sandy (Fig. 3a and b) to detect elevated CDOM gradients assumed to be indicative of plumes of humic rich water. The diagonal lines represent the edge of the image as taken from the orbital platform. Comparisons of pre- and post-Hurricane Sandy results appear to highlight potential plume waters at or around locations of known wastewater infrastructure failures resulting from Hurricane Sandy (Fig. 3). However, a number of outfall locations with reported plumes (see Kenward et al., 2013) were not detected from the ALI data. This observation may reflect the time elapsed between the 11/21/2012 scene used in this analysis and the recession of the majority of the flood waters. Further, repairs to a number of the locations damaged during Hurricane Sandy were staggered, with some occurring immediately after the storm and others occurring weeks after. Plumes remaining in the 11/21/2012 scene may reflect infrastructure that had not undergone repair and was still releasing untreated wastewater and contaminants.

Elevated CDOM levels observed in the Hudson River for the pre-Hurricane Sandy data likely reflect elevated humic concentrations in the river resulting from Tropical Storm Lee, which had rainfall totals upwards of 13 in. on September 8th, (Fig. 3a) just 4 days before the ALI acquisition (Lumia et al., 2014). While not useful as a baseline condition to compare against the post-Hurricane Sandy CDOM levels, the elevated pre-Hurricane Sandy CDOM levels in the Hudson suggest that ALI data, with Kutser's equation applied, are detecting elevated CDOM concentrations.

A major limiting factor in this study was the lack of in situ corrected CDOM/fDOM measurements concurrent with the ALI acquisition dates.

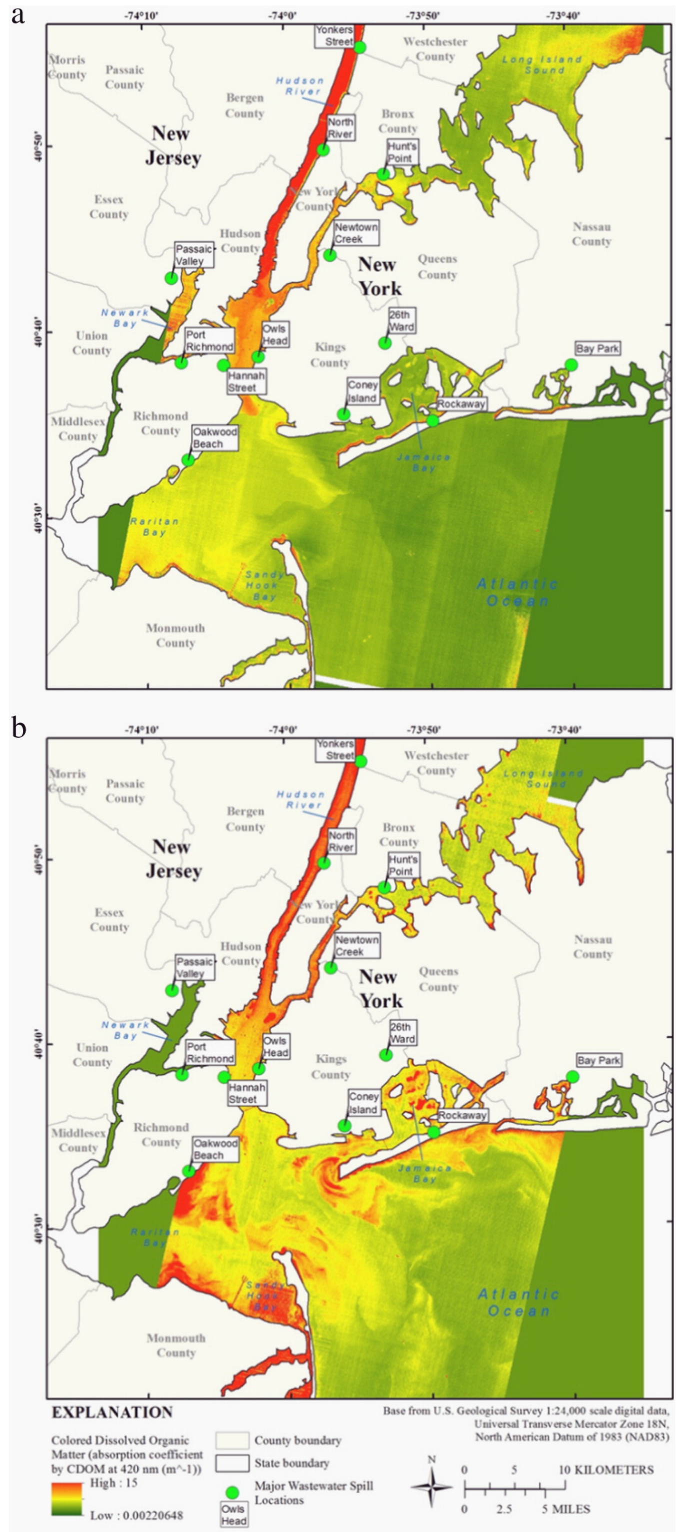

Fig. 3. Colored Dissolved Organic Matter (CDOM) gradients extracted from Advanced Land Imager (ALI) multi-spectral data for 9/12/2011 (a) and 11/21/2012 (b). Points indicate locations of wastewater treatment facilities that failed during Hurricane Sandy, releasing untreated and partially treated sewage into the New York and New Jersey Bays. Red areas indicate high levels of CDOM.

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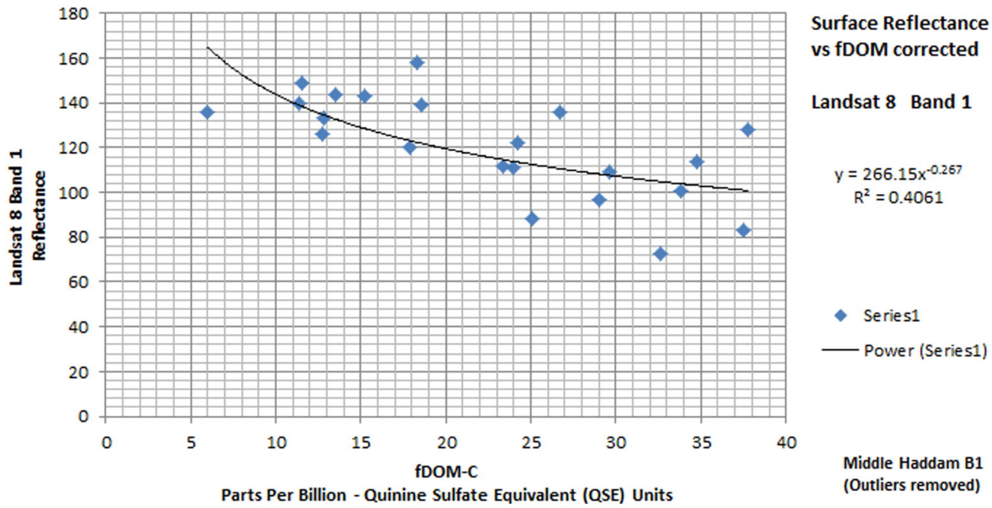

Fig. 4. A weak power relationship between fDOM-C and band 1 at the Middle Haddam site.

Without the in situ data it was impossible to generate quantitative CDOM measurements from the ALI data. Further, variability in circulation and currents both daily and seasonally make comparative CDOM measurements across dates difficult without first having a base of in situ measurements against which to compare observed satellite trends. This highlights the need for more real-time water quality monitoring in vulnerable bays (particularly CDOM), coupled with rapid-response water quality grab sampling, ahead of and during storms.

Of the USGS gaging stations that report CDOM in the on-line NWIS data, most have not been corrected for inner filtering due to color, turbidity, and temperature. Data from three gaging stations on the East Coast (Middle Haddam, Connecticut (01,193,050), Potomac River at Little Falls (01,646,500), and the Susquehanna River at Darlington, Maryland (01,579,550) were gathered to coincide with clear Landsat 8 scenes that were corrected to surface reflectance. This resulted in 53 raw fDOM readings, which were then corrected according to the methods outlined in Downing et al. (2012). Band 1 (433 nm–453 nm) on Landsat 8 is a new addition to the Landsat suite of bands and could be potentially important to CDOM research as it is fairly narrow and centered in a part of the spectrum that is sensitive to coastal phenomena. Fig. 4 shows a weak statistical power relationship between fDOM and band 1 observed at the Middle Haddam sites. The other two sites showed almost no relationship, in part due to a low number of observations at both sites.

The band 3/band 4 relationship (560 nm/655 nm) on the OLI sensor also shows a weak but potentially important power relationship with fDOM (Fig. 5). This is similar to the band 2/band 3 relationship reported by Kutser et al. (2005a). In addition, the band 2/band 3 relationship (480 nm/560 nm) on the Landsat 8 OLI sensor shows a potentially important relationship with respect to fDOM remote sensing (Fig. 6).

5. Discussion

Post-Hurricane Sandy modeling of fluorescing organic matter plumes in the bay and estuarine waters of New York and New Jersey reflect known humic-rich plumes resulting from failed infrastructure that were observed in the field weeks after the storm receded (Kenward et al., 2013). Despite a lack of in situ monitoring data required for calibration and quantification of the remotely sensed predictions, these results do suggest that the Landsat 8 Operational Land Imager data are capable of detecting plume waters. However, in situ data are required to account for site-specific conditions that may influence DOM spectral signatures, and to generate empirical equations to convert from DOM reflectance into DOM concentrations. Future efforts

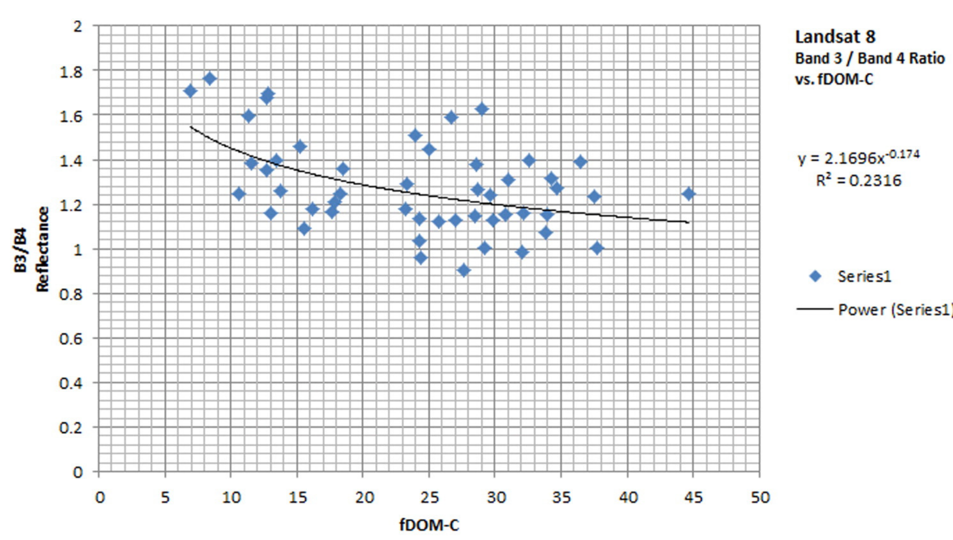

Fig. 5. A weak power relationship exists between the remote sensing reflectance blue/red band ratio and fDOM-C at all three sites and would be consistent with the results of Kutser et al. (2005a). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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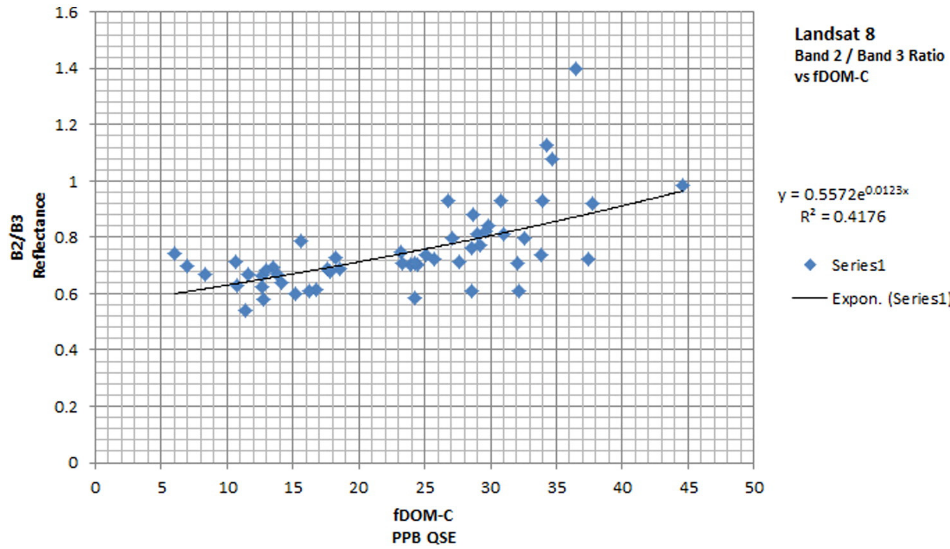

Fig. 6. A log relationship between the Landsat 8 OLI sensor reflectance band 2/band 3 ratio and fDOM-C at all three sites.

should seek to couple in situ measurements of CDOM/fDOM and other water quality parameters with timely remote sensing acquisitions.

Initial results of the Landsat 8 DOM extractions reveal a promising relationship between DOM and various combinations of bands 1, 2, 3 and 4. While overall regressions yielded relatively weak correlations, it is important to note that key ancillary variables that have been shown to exert a significant influence on the fluorescent properties of DOM, such as salinity, turbidity, and temperature (Bowers and Brett, 2008; Brezonik et al., 2015; Downing et al., 2012; Hudson et al., 2007; Matthews, 2011; Saraceno et al., 2009), were not factored into the remotely sensed reflectance analyses, although turbidity and temperature were factored in when correcting the fDOM. For example, Saraceno et al. (2009) showed that increased turbidity levels in post-storm waters decreased the ability to accurately detect DOM levels due to the increased optical signal scatter. Similarly, in a study of freshwater lakes, Brezonik et al. (2005) observed that CDOM levels are difficult to discern in waterbodies with high algal abundance due to algae exhibiting a higher radiance than CDOM. More research is needed to articulate the relationship between the various Landsat 8 bands and the CDOM/fDOM signature in open waters. Specifically, the suite of environmental variables shown to influence the relationship need to be explored using in situ measurements coupled with the Landsat acquisitions, thereby allowing direct comparisons of observed and modeled CDOM/fDOM.

The relationships between remote sensing data and CDOM/fDOM documented in this study highlight new and exciting capabilities provided by Landsat 8. The increased spectral resolution and synoptic coverage provide a means to more accurately detect and quantify changes to water quality parameters in major rivers and waterways. Although currently limited, the increasing automation of instrumentation at USGS gaging stations around the nation will generate a dense dataset of continuous in situ monitoring records, thereby facilitating calibration of remotely sensed data. Future work is still needed to establish the fundamental equations linking the remotely sensed data to the in situ measurements. Some specific research considerations include:

1. More direct comparisons between in situ sensors and Landsat 8 overpasses, especially for lakes. Small, relatively inexpensive fluorescence sensors are now available and could provide a wealth of data for calibrating Landsat 8 reflectance values.
2. Additional corrections for Landsat 8 Surface Reflectance product. There is still a high degree of variability in Landsat 8 reflectance values that could potentially be adjusted by additional spectral and atmospheric corrections. Further reflectance corrections for salinity, turbidity, and temperature, for the Landsat 8 OLI data should be explored and developed.
3. Standardization of CDOM/fDOM measurements, and equivalencies in units, would be of great benefit for the entire community involved in remote sensing of water quality.
4. Comparison studies of CDOM/fDOM in lakes, rivers, estuaries, and coastal environments are needed to understand critical differences, especially in terms of remote sensing capabilities.

This paper was intended to initiate a discussion and perhaps provide a framework for research that would lead to a method for continuous mapping of CDOM/fDOM by overhead remote sensing methods, and specifically from the improved Landsat 8 sensor and data products now being provided by the U.S. Geological Survey. The relationships demonstrated here are meant only to show that some basic connections exist and show promise for further development. With the emergence of new fluorescence sensors and data, improved imagery extraction methods, and more sophisticated analyses, *continuous* mapping of CDOM/fDOM, instead of point samples, may now be possible.

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