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Use of satellite imagery for water quality studies in New York Harbor

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Abstract

The utility of satellite imagery for water quality studies in New York Harbor is investigated. Ground data from a routine sampling program (New York Harbor Water Quality Survey) are compared to imagery from the Landsat Thematic Mapper (TM) and Terra Moderate Resolution Imaging Spectroradiometer (MODIS) sensors. New York Harbor is a challenging environment for remote sensing because of the complex hydrography and strong tidal influence. Using a time-averaged spatial analysis it is shown that turbidity as determined from Secchi depth correlates with Landsat TM red reflectance in regions affected by the Hudson River sediments ($N = 21$, $R^2 = 0.85$). Based on this correlation the estuarine turbidity maximum of the Hudson River is mapped. Landsat TM red reflectance is also used to identify and map plumes of increased turbidity caused by rainfall runoff and/or spring tide resuspension in Newark Bay. Chlorophyll *a* concentration correlates with the ratio of Landsat TM green to red reflectance in the eutrophic East River and Long Island Sound ($N = 16$, $R^2 = 0.78$). Terra MODIS estimates of chlorophyll *a* show no correlation with ground observations, are biased towards low values and are therefore not directly useable for New York Harbor.

Keywords: remote sensing; satellite imagery; water quality; estuary turbidity maximum; Landsat TM; Terra MODIS; New York Harbor

1. Introduction

The optical properties (i.e. reflectance) of water depend on the concentration and character of suspended sediments, phytoplankton and dissolved organic matter ("yellow substance", gelbstoff). Sensors aboard satellites can measure the amount of solar radiation at various wavelengths reflected by surface water, which can be correlated to water quality parameters (e.g. total suspended solids, TSS). This constitutes an alternative means of estimating water quality, which offers three significant advantages over ground sampling. First, the near-continuous spatial coverage of satellite imagery allows for synoptic estimates over large areas. Second, the global coverage of satellites allows for the estimation of water quality in remote and inaccessible areas. Third, the relatively long record of archived imagery (e.g. Landsat since the early 1970s) allows estimation of historical water quality, when no ground measurements can possibly be performed. However, there are also significant disadvantages of satellite estimates. First, the ability to distinguish among the various constituents of the water is limited. Second, the sampling depth is limited to the surface, varies with water clarity and is not controllable. Third, the spatial and temporal resolution can be inadequate and is not controllable. Whereas

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either of these approaches can be used alone, the combination of ground and satellite estimates is often the most effective approach. As an example, satellite imagery can be used to extrapolate ground measurements to areas and times with little or no coverage. This reduces the number of ground samples and increases the spatial and temporal coverage of the estimates.

Satellite estimates of water quality have found widespread application, especially in oceanography. A total of 38 parameters including total suspended solids, chlorophyll *a*, dissolved organic matter, diffuse attenuation coefficient and calcite are estimated using the MODIS sensor onboard the Terra and Aqua satellites. The accuracy can be very high with errors of less than 30% for chlorophyll *a* concentrations from MODIS (Carder et al., 1999). For the open ocean (Case 1 waters), reflectance is primarily affected by chlorophyll and related degradation pigments, and global relationships can be applied universally. For inland, estuarine and near-shore ocean waters (Case 2 waters), reflectance is affected by site-specific factors, such as the geology of the watershed, which affects the type of suspended sediments. As a result, site-specific relationships are generally developed for these types of waters. Such relationships have been developed for many water bodies as summarized in Table 1. Baban (1997), for example, used Landsat Thematic Mapper (TM) images to produce maps of TSS, turbidity, chlorophyll *a* and other parameters for the Breydon Water Estuary. Ruhl et al. (2001) used Advanced Very High Resolution Radiometer (AVHRR) images to estimate TSS in San Francisco Bay.

Remote sensing water quality studies have been carried out before in New York Bight (e.g. Wezernak et al., 1975), but so far the use of satellite imagery in water quality studies has not been reported for New York Harbor. The objective of this contribution is to determine the feasibility of using satellite imagery for water quality studies in New York Harbor. The general strategy is to correlate satellite reflectance to ground observations. First the sources of ground and satellite data are presented, followed by an outline of the methodology. Then the results are presented and discussed. Finally the conclusions and recommendations of the study are summarized.

2. Data

2.1. Ground data

Water quality data were collected as part of the New York Harbor Water Quality Survey program (NYC DEP, 1996, 2001). The purpose of the program is to characterize coarse-scale spatial and long-term temporal trends in water quality in New York Harbor. It is used to evaluate the effectiveness of pollution abatement measures (e.g. wastewater treatment plants). Parameters measured include fecal coliform, dissolved oxygen, nutrients, plankton, chlorophyll *a*, Secchi depth, temperature, salinity, pH and TSS. We included Secchi depth (SEC), TSS and chlorophyll *a* (CHL) in this study, because they have been successfully correlated to reflectance in satellite imagery (Table 1). For TSS and CHL only surface samples, collected 1 m below the water surface, are included. Ground stations used in this study are presented in Fig. 1a (the satellite image will be discussed later). Station locations are defined by description rather than coordinates. Station N3B in the Hudson River, for example, is defined as ''one-third of the distance from the Manhattan shore at West 125th Street to the New Jersey shore''. The exact location where samples are taken is therefore expected to vary considerably. As a result it is difficult to quantify the spatial accuracy of the water quality measurements. The average sampling period for each station is about 20 days.

2.2. Satellite data

Many satellites orbit the earth with sensors potentially suitable for estimating water quality parameters. A useful basis for sensor comparison and selection is the spectral, spatial and temporal resolution. Higher resolution is better in most cases, but signal-to-noise requirements of current sensor technology impose limitations on the combined (spectral + spatial + temporal) resolution, and no sensor can have a high spectral, high spatial and high temporal resolution. If the pixel size of a sensor is small (high spatial resolution), the spectral bandwidth has to be large (low spectral resolution) to capture sufficient light energy for an acceptable signal-to-noise ratio. There is a tradeoff in spectral, spatial and temporal resolution and the best combination depends on the intended use of the sensor.

Based on primarily the literature survey presented in Table 1, a short list of sensors was compiled. The sensors along with their spectral, spatial and temporal resolutions are summarized in Table 2. The resolutions of the sensors vary by up to three orders of magnitude (e.g. AVHRR vs. IKONOS spatial resolution), which is a reflection of their intended use. A high spectral resolution is desired to differentiate substances (i.e. suspended sediments vs. chlorophyll *a*) based on their reflectance spectrum. Sensors specifically designed for this purpose, like MODIS, therefore have many bands with narrow wavelength ranges. Due to the signal-to-noise requirements, they have low spatial resolution. A high spatial resolution is desired for many land applications (e.g. urban mapping) and sensors designed for this purpose, like IKONOS, have a fine ground resolution. However,

Table 1
Satellite measurements of water quality in inland, estuarine and near-shore ocean waters

Location	Sensor(s)[a]	Parameter(s)[b]	Reference
Inland waters			
Lakes in Minnesota	TM, MSS, IKONOS	SEC, CHL, TUR	Lillesand et al. (1983), Kloiber et al. (2002a,b), Sawaya et al. (2003)
Flaming Gorge Reservoir	MSS	SEC, CHL	Verdin (1985)
Lake Kasumigaura	TM	TSS, CHL	Baruah et al. (2002)
Norfolk Broads	TM	SEC, TSS, CHL	Baban (1993)
Lake Chicot	MSS	TSS	Schiebe et al. (1992)
Lake Iseo	TM	TSS, CHL	Giardino et al. (2001)
Lake Erken	TM	TSS, CHL	Oestlund et al. (2001)
Lakes in Nebraska	TM	TUR	Fraser (1998)
Frisian Lakes	TM, XS	TSS	Dekker et al. (2001, 2002)
Lake Garda	TM	CHL	Brivio et al. (2001)
Lake Kinneret	TM	CHL	Mayo et al. (1995)
Black Sea	CZCS, MOS	CHL	Barale et al. (2002)
Yellowstone Lake, Jackson Lakes, Green Bay, Lake Michigan	TM	SEC, TSS, CHL, TUR	Lathrop and Lillesand (1986), Lathrop (1992)
Estuarine waters			
Gironde Estuary	XS	TSS	Doxoran et al. (2002)
Pamlico Sound	AVHRR	KE	Woodruff et al. (1999)
Neuse River Estuary	MSS	CHL, TUR, TSS	Khorram and Cheshire (1985)
Chesapeake Bay	AVHRR, CZCS	CHL	Stumpf and Tyler (1988)
Delaware Bay	AVHRR, TM	KE, TSS, CHL	Stumpf and Pennock (1989, 1991), Keiner and Yan (1998)
Breydon Water Estuary	TM	TSS, TUR, CHL	Baban (1997)
San Francisco Bay	AVHRR	TSS	Ruhl et al. (2001)
Near-shore ocean waters			
Gulf of Maine	AVHRR	TSS	Stumpf and Goldschmidt (1992)
North Sea	TM, AVHRR	TSS	Baban (1995), Van Raaphorst et al. (1998)
Gulf of Mexico	AVHRR	KE	Gould and Arnone (1997)
Florida Bay	AVHRR	KE	Stumpf et al. (1999)
Bay of Biscay	AVHRR	TSS	Froidefond et al. (1999)
Adriatic Sea	TM, CZCS	CHL, TSS	Tassan (1987)

[a] See Table 2 for sensor characteristics.
[b] SEC = Secchi depth, TSS = total suspended solids, KE = light extinction/attenuation coefficient, CHL = chlorophyll or chlorophyll *a*, TUR = turbidity. Parameters without obvious direct effect on optical properties of the water (e.g. phosphate) are omitted in this summary.

due to the signal-to-noise requirements their spectral resolution is low. Within these extremes, there are sensors like MERIS and MOS that provide a combination of medium spectral and spatial (and temporal) resolution. Also, some sensors provide a range of spatial resolutions (e.g. MODIS 250, 500, 1000 m). The predominant use of high spatial resolution sensors (e.g. TM) in inland waters and low spatial resolution sensors (e.g. AVHRR) in near-shore ocean waters is evident in the applications summarized in Table 1.

In this study, a high spectral resolution is desired because we are concerned with characterizing water quality. Also, a high spatial resolution is desired to resolve spatial gradients within New York Harbor and avoid interference from non-water features. As illustrated in Fig. 2, the AVHRR, CZCS, MODIS and SeaWiFS sensors have spatial resolutions close to the scale of the major hydrographic features in New York Harbor. For those sensors it would be very difficult to get pixels that are not "contaminated" by non-water features. However, single point estimates can be obtained for Upper and Lower New York Bay (see Fig. 1). The MSS, TM and XS sensors have the necessary spatial resolution to resolve spatial gradients within most of the study area. Finally, a high temporal resolution is desired because New York Harbor is a tidally dominated system, where the water quality can change at a time scale of hours (discussed in more detail later in the paper). Unfortunately, none of the sensors in Table 2 have the temporal resolution to resolve these dynamics.

Two sensors, selected to span a range of spectral and spatial resolutions, were included in this study. TM is selected as a low spectral/high spatial resolution sensor because it has a higher temporal and/or spectral resolution than MSS and XS. MODIS is selected as a high spectral/low spatial resolution sensor, because it has a higher spectral resolution than AVHRR, CZCS and SeaWiFS.

The TM satellite imagery used in this study consists of seven mostly cloud-free scenes from Landsat 5 for 1996.

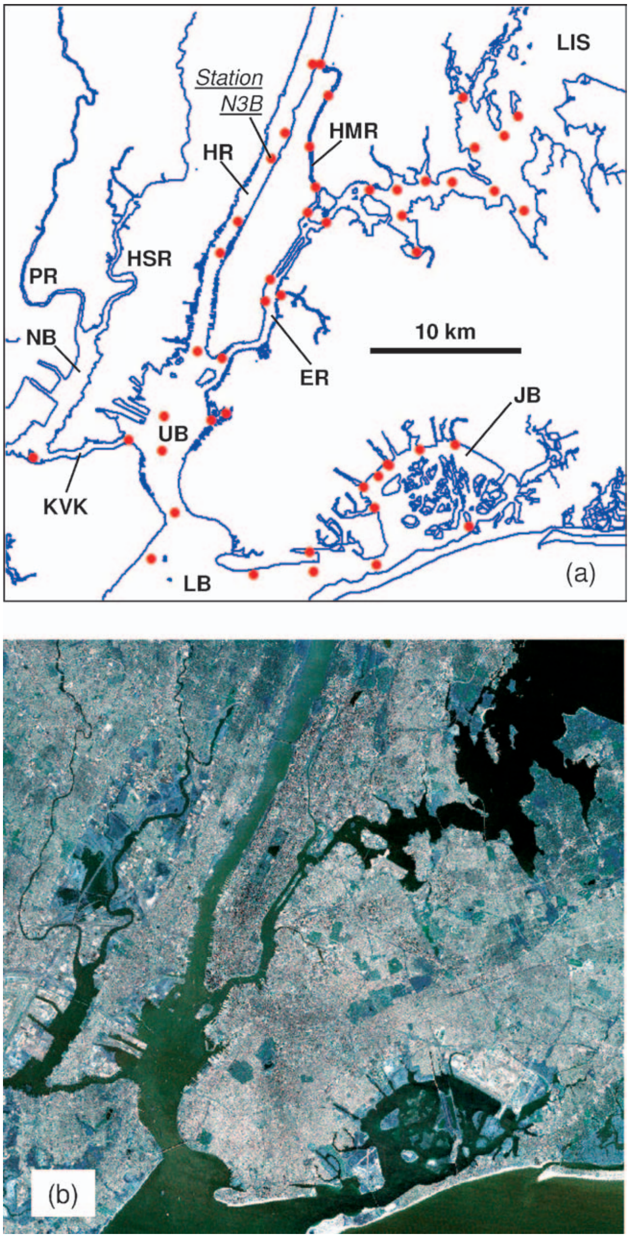

Fig. 1. New York Harbor. (a) Hydrography and New York Harbor Water Quality Survey stations (ER = East River; HMR = Harlem River; HR = Hudson River; HSR = Hackensack River; JB = Jamaica Bay; KVK = Kill van Kull; LB = Lower New York Bay; LIS = Long Island Sound; NB = Newark Bay; PR = Passaic River; UB = Upper New York Bay). (b) True color Landsat TM image for 4/15/96 9:20 AM.

It should be noted that a set of cloud-free days is not a representative sample of average water quality conditions. That is because water quality is affected by rainfall, which occurs under clouds. To spatially relate the images to ground sampling stations they were geo-referenced based on prominent features, like the northwest corner of Central Park. Since this procedure is based on visually identifying features in the satellite images, the error is estimated to be at least 2 pixel sizes, or 60 m. To eliminate any temporal variation in satellite-measured radiance due to atmospheric turbidity and solar illumination the images were radiometrically rectified as described in detail by Small (2002). Briefly, this consists of identifying features with pseudoinvariant (PIV) radiance. Any temporal difference in satellite-measured radiance from these PIV features is assumed to be due to differences in atmospheric turbidity and solar illumination. Based on the measured reflectance of these features, the reflectance of all the pixels in the image is "corrected".

The MODIS sensor is onboard the Terra and Aqua satellites. At the time of this study, the relevant data from Aqua MODIS sensor were not available and only imagery from the Terra MODIS sensor is included. The MODIS satellite imagery used here consists of 16 scenes (granules) for 2001, coincident with the dates of water quality measurements in Upper and Lower New York Bay. The MODIS images are processed by NASA to calculate a number of water quality parameters. Chlorophyll *a* is calculated using two different algorithms specifically designed for Case 2 waters. Those parameters are selected for this study. Since we are only able to obtain single point estimates in the study area (due to the low spatial resolution), the images do not have to be geo-referenced.

3. Methods

3.1. Interference from non-water features

3.1.1. TM

Several of the ground sampling stations are located close to static non-water features (e.g. land, piers, bridges). Reflectance from these features can affect ("contaminate") the reflectance of the pixel corresponding to the ground station. This represents a significant problem when using historical data from routine sampling programs. For example, bridge piers are convenient landmarks for locating stations (for the sampling crew and data user), but they are unsuited for remote sensing projects. To avoid using pixels "contaminated" by non-water features, ground data from stations within a buffer distance of static non-water features were compared to satellite reflectance just outside the buffer distance. The buffer distance was set at 200 m, which was selected to account for (a) pixel size, (b) effect of shallow water near land, and (c) any geo-referencing error. Stations in water bodies less than 200 m wide, like the Harlem River, were moved to the center to minimize the probability of land effects. In shallow water, the sediment bed can affect reflectance. Whether bottom effects are important will be a function of the water column depth and water clarity. Baban (1993) used a depth criteria based on the Secchi depth. He discarded measurements with Secchi depths greater

Table 2
Spectral, spatial and temporal resolution of satellite sensors commonly used for water quality studies

Sensor	Satellite(s)	Resolution		
		Spectral # bands/min Δλ (nm)	Spatial[a] (m)	Temporal[b] (days)
AVHRR (1978–)	TIROS and NOAA series	5/100	1100	0.5
CZCS (1978–1986)	Nimbus-7	6/20	825	1
MERIS (2002–)	ENVISAT	15/2.5	300	3
MODIS (Terra: 1999–) (Aqua: 2002–)	Terra and Aqua	36/10	250-1000	0.5
MOS (1996–)	IRS-P3	18/1.4	520	5
MSS (1972–)	Landsat series	5/100	80–240	16 (8 for NYC)
IKONOS (1999–)	IKONOS	5/70	0.8–3.2	~3
SeaWiFS (1997–)	Orbview-2/SeaStar	8/20	1100	1
TM (1984–)	Landsat series	7/60	28.5–120	16 (8 for NYC)
XS (1986–)	SPOT series	3/70	20	26

AVHRR = Advanced Very High Resolution Radiometer; TIROS = Television and Infrared Observation Satellite; NOAA = National Oceanic and Atmospheric Administration; CZCS = Coastal Zone Color Scanner; MERIS = Medium Resolution Imaging Specrometer Instrument; MODIS = Moderate Resolution Imaging Spectroradiometer; MOS = Modular Optoelectronic Scanner; IRS = Indian Remote Sensing Satellite; MSS = Multispectral Scanner; SeaWiFS = Sea-viewing Wide Field-of-view Sensor; TM = Thematic Mapper; SPOT = Systeme Pour l'Observation de la Terre.

[a] For nadir viewing. For sensors with variable resolution the resolution of the bands appropriate for water quality estimates is underlined.

[b] Estimate for sensors on multiple satellites. Depends on how many satellites are operational at a given time.

than half the water column depth. In this study, the water column depth at low tide of all the stations is well above twice the Secchi depth for all stations. This is because most of the stations are located in waters easily navigable by the relatively large survey vessel. Therefore, although bottom effects are not important at any of the stations, they will affect the reflectance at other shallower areas of the system. Interference can also be caused by dynamic non-water features (e.g. clouds, ships, ice, shadows). Clouds and ships are plentiful in New York Harbor. Clouds mask the water below and their shadow affects the reflectance of the water. Ships and more importantly the rough water they leave in their wake change the reflectance of the water. The shadows from the skyscrapers of Manhattan also affect the reflectance, as illustrated in Fig. 3, which shows the shadow of the late World Trade Center towers over the Hudson River. Each image was examined visually and observations found to be affected by dynamic non-water features were omitted from the analysis.

Even in the absence of any of the static and dynamic interferences discussed above, the reflectance of the water can be affected by factors other than water quality. Currents and wind affect the roughness of the water surface. This can lead to changes in reflectance over time at a particular location, or spatially at one time. The complex hydrography of New York Harbor

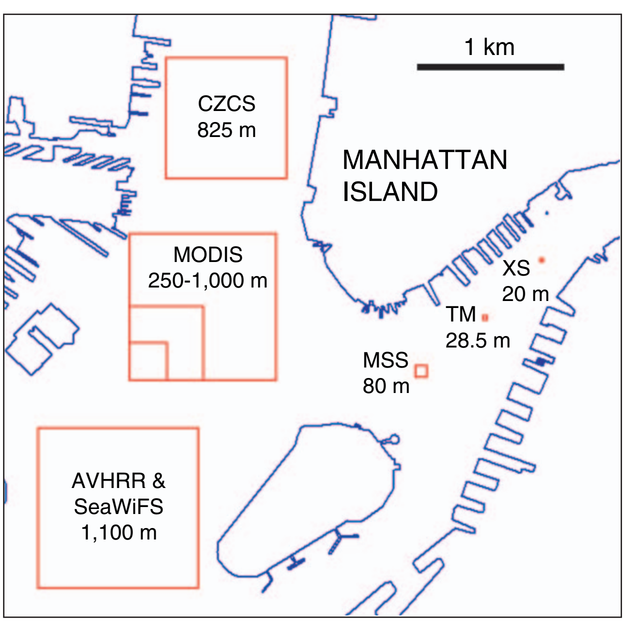

Fig. 2. Comparison of New York Harbor hydrography with the spatial resolution of various satellite sensors. Area shown is the confluence of the Hudson and East Rivers at the southern tip of Manhattan Island. Each box corresponds to one pixel. See Table 2 for sensor characteristics.

Fig. 3. Landsat TM image of southern Manhattan Island (1996) for 12/27/96 9:20 AM. The shadow of the late World Trade Center towers is visible on the Hudson River. The image width is 7 km.

leads to significant horizontal structure in the tidal currents. Also wind gusts moving over the water or calm areas in the lee of the skyscrapers of Manhattan or the Palisades Cliff are present.

3.1.2. MODIS

The MODIS images include land and "no data" masks, which in theory eliminate the problem of interference by non-water features. However, there remain problems for this application including (a) spatial accuracy of the land mask, (b) bottom reflection in near-shore shallow water, and (c) dynamic non-water features (e.g. ships and their wake, see Fig. 1b). The MODIS land mask has a 900-m resolution and is applied at the center of the pixel. That means as long as the center of the pixel is over water, the pixel is judged water, even if a significant fraction is over land. Therefore, the possibility of interference from non-water features remains high even for the pixels not identified as land or "no data". Given the available data, it is difficult to identify pixels that are contaminated or quantify the effect of the contamination, and therefore the MODIS data were used as long as they were not identified as land or "no data".

3.2. Matching ground and satellite observations

3.2.1. Space

Water absorbs visible light more strongly than most non-water features. As a result, the reflectance of water is more subject to random errors, also called noise. The image of the area south of the Verrazzano Narrows Bridge (Fig. 4) shows significant structure in reflectance indicative of differences in water quality. However, the spatial variability in reflectance is low and comparable to the noise, which in this case is represented by the near-diagonal lines in the image ("striping problem", Algazi and Ford, 1981; Pan and Chang, 1992). It should be noted that the Enhanced Thematic Mapper sensor onboard Landsat 7 has a higher signal/noise ratio, which reduces this problem. The effect of sensor noise can also be seen in processed MODIS images (Fig. 5), where a discontinuity is evident every 10 rows. One option to reduce the effect of noise is to spatially average reflectance over a number of pixels. In New York Harbor the number of pixels used in the averaging (e.g. 3×3) is limited by the hydrography. A 5×5 box corresponds to a size of 150 m, which is about the width of the Harlem River. Several spatial averaging schemes were tested. The difference in reflectance for the various schemes is low compared to the difference in reflectance at various times. The noise should therefore not significantly affect the results of this study. To minimize the effect of interference by non-water features a single pixel value is used in this study.

Due to the low spatial resolution of MODIS, only estimates for Upper and Lower New York Bay can be obtained. The corresponding pixels were identified based on the land masks in the MODIS image (Fig. 5). Pixel locations were verified using the latitude/longitude values included in the MODIS images. The

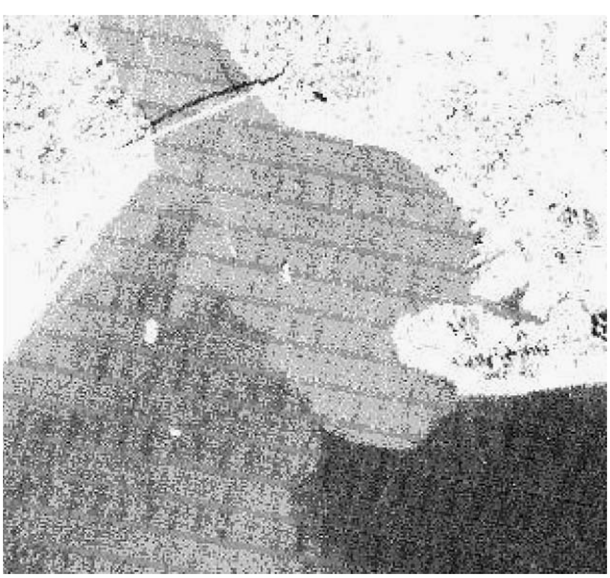

Fig. 4. Landsat TM red (TM3) reflectance south of the Verrazzano Narrows Bridge for 12/27/96 9:20 AM. The image contrast is "stretched" to highlight the variability in the reflectance from water. The regular pattern of near-horizontal lines in reflectance is sensor noise. The image width is 9 km.

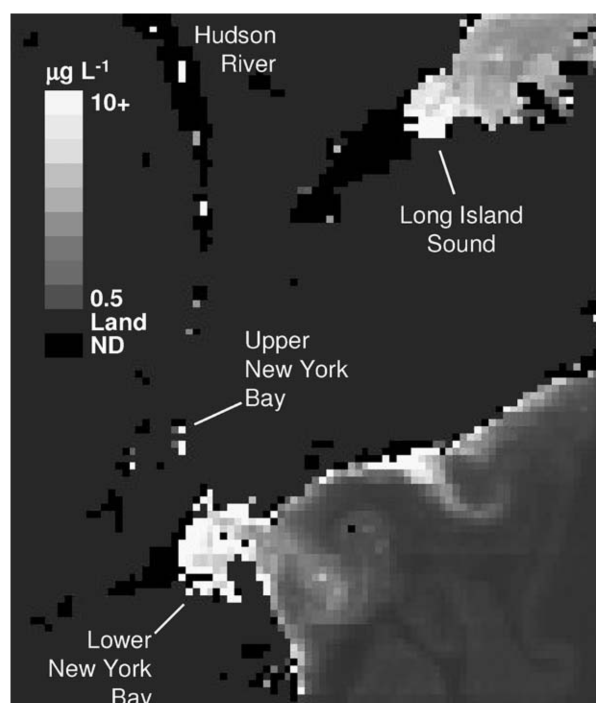

Fig. 5. MODIS chlorophyll *a* concentration (SeaWiFS analog algorithm) on 9/19/01. Lighter shading corresponds to higher concentration. Dark gray and black are land and "no data" masks, respectively. The image width is 90 km.

chlorophyll *a* concentrations were then read off manually. If more than one pixel was available in an area, the concentration of the pixels was averaged. The average number of pixels in Upper and Lower New York Bay was 3 and 20, respectively.

3.2.2. Time

The time difference between ground and satellite observations is important, because in the time gap the water quality can change. This can occur gradually due to seasonal effects (e.g. spring snowmelt), or more abruptly due to short-term meteorological events (e.g. rainfall runoff). It also has to be considered that New York Harbor is a tidally influenced system. The allowable time difference between ground and satellite observations is significantly shorter for tidal systems than for non-tidal systems, where time differences of seven days (336-h time window) have been found to yield reasonable results (Kloiber et al., 2002a). The M_2 tide with a 12.42-h period is dominant, causing typical tidal velocities of 50–100 cm s^{-1} (Blumberg et al., 1999). As a result, water particles can travel a distance of over 10 km (350 pixels) within one tidal cycle. This spatial translation can be accounted for by moving the sampling location, as was done for Delaware Bay by Stumpf and Pennock (1989). Stumpf and Pennock used a maximum time difference of 3 h (6-h time window) and suggest a maximum of 1–2 h (3-h time window) if no tidal translation correction is applied. Another effect of the tides is currents that can resuspend sediments. Fig. 6 shows that the TSS concentration in the Hudson River by Manhattan can vary over almost an order of magnitude within one tidal cycle. This is consistent with the observations of Geyer et al. (1998), who found that in this area of the estuary "virtually all of the sediment settles during slack water". For Landsat TM only 1% of the observations have a time difference of less than 1.5 h (Fig. 7). For Terra MODIS, which has a daily return period, 23% are within 1.5 h.

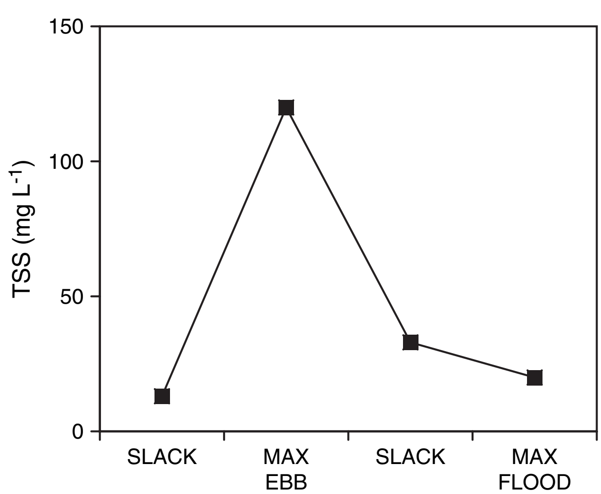

Fig. 6. Total suspended sediments in the Hudson River by Manhattan (close to Station N3B, see Fig. 1a) during the course of one tidal cycle. Data are surface samples collected in May 1991. Source is HydroQual (1995).

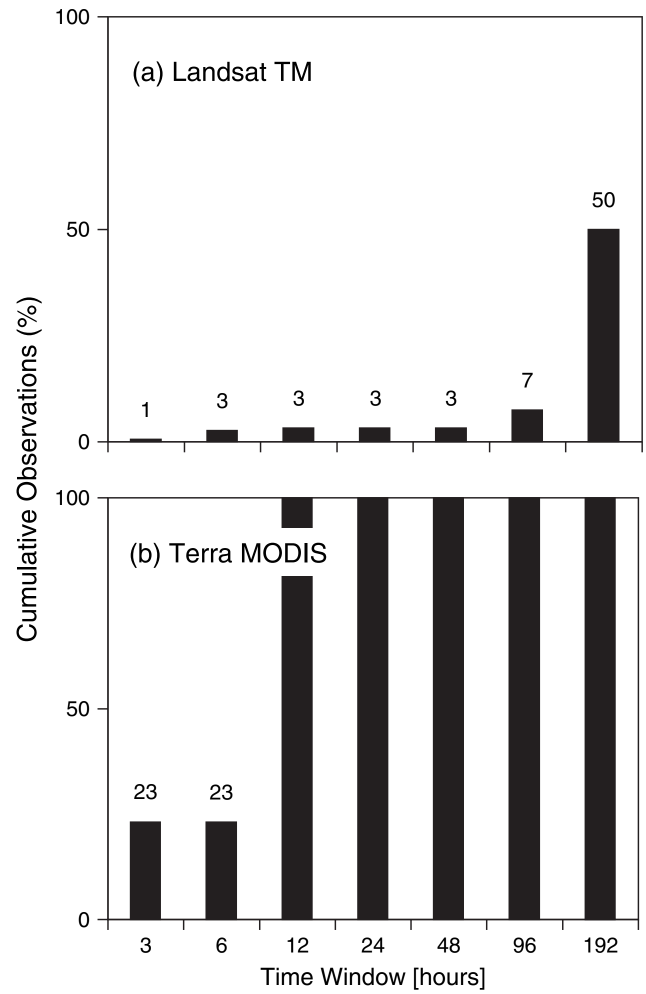

Fig. 7. Cumulative number of observations as a percentage of the total vs. time window for (a) Landsat TM and (b) Terra MODIS.

4. Results and discussion

4.1. Low spectral/high spatial resolution sensor (Landsat TM)

As a result of the low number of coincident satellite and ground observations, a real-time comparison is not feasible given the available data. One feature clearly visible in satellite images of New York Harbor is the different "color" of the Hudson River compared to other areas, such as Long Island Sound or Jamaica Bay (see Fig. 1b). This is undoubtedly caused by the suspended sediments carried by the Hudson River. To investigate if this general spatial pattern can be quantified using satellite imagery, a time-integrated, spatial comparison was performed. The average Secchi depth is compared to average Landsat TM reflectance in the red band (TM3) at all stations. It should be noted that there is no consistent correlation between Landsat TM reflectance and water quality parameters in the literature surveyed in Table 1. The same water quality parameter is correlated to reflectance in different bands, and in some cases the equations show opposite trends (i.e. Baban, 1993 vs. Baruah et al., 2002). This analysis was done for all combinations of water quality and satellite reflectance. None of the variables show a good correlation (results not presented). However, a pattern emerges if the stations are differentiated by region, as shown in Fig. 8a. Reflectance in the red band (TM3) at stations affected by the Hudson River (Hudson River, Harlem River, New York Bay) generally decreases with Secchi depth. The correlation can be used to estimate Secchi depth and turbidity. Compared to water, sediment has high reflectance in all visible bands. However, the correlation between Secchi depth and blue and green reflectance is weaker than that for red

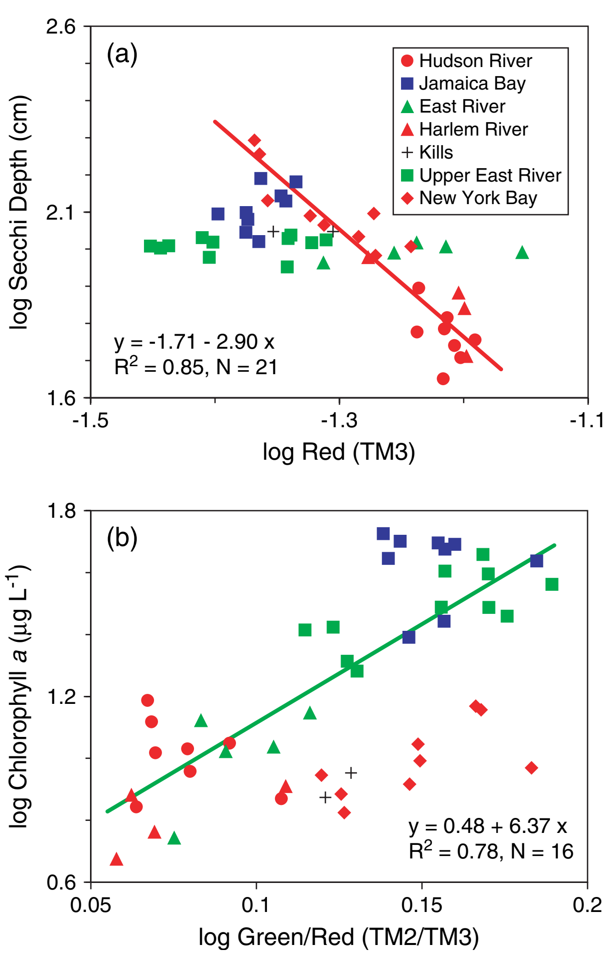

Fig. 8. Time-averaged water quality vs. Landsat TM reflectance for each station. (a) Secchi depth vs. red band (TM3) (only red stations are included in regression) and (b) chlorophyll *a* vs. green/red band (TM2/TM3) (only green stations are included in regression).

(results not presented). This is probably at least in part because atmospheric scattering is less prominent for red than for blue and green light. In other areas, not affected by Hudson River sediments, red reflectance does not vary with Secchi depth. Jamaica Bay and the Upper East River do not receive significant river runoff, and the reflectance there is probably predominantly affected by phytoplankton concentration. Fig. 8b shows that the chlorophyll *a* concentration for those stations varies with the ratio of green to red reflectance (TM2/TM3). This is consistent with the optical properties of chlorophyll *a*, which has high reflectance in green and low reflectance in red. In the absence of substances that have high red reflectance, the red reflectance is relatively constant and close to that of pure water. Then the ratio of green to red reflectance correlates to the concentration of chlorophyll *a*.

The correlation analysis showed that in areas affected by river runoff, red reflectance (TM3) correlates positively with turbidity. A significant amount of sediment is transported by rivers during runoff events and as a result turbidity increases at the river mouth in the days after rainfall. It is possible that this is the cause of the higher reflectance on 10/24/96 in Newark Bay, as shown in Fig. 9. However, turbidity in Newark Bay also increases during the spring tide (K. Rankin, personal communication). Spring tide occurred on 10/25/96, close to the date of satellite acquisition, which could also be the reason for the increased turbidity. The structure in reflectance, indicative of suspended sediments, is useful information for hydrodynamic and sediment transport studies. The temporal resolution of Landsat (8 days in NYC, further reduced when cloud cover is considered) limits its usefulness for these types of studies. It also has to be considered that Landsat TM images have to be processed before they are available for download. This takes several days and limits the usefulness of Landsat TM imagery for real-time monitoring applications. However, selected images can be used to calibrate and validate sediment transport models, which can then be used for that purpose. Another application of the turbidity to reflectance correlation is presented in Fig. 10a, which shows higher reflectance indicative of turbidity along the western shore of the Hudson River by Manhattan. Higher suspended sediments are routinely observed in this area along the western shore (Geyer et al., 1998). This is the area of ''estuarine turbidity maximum'', which can be reproduced using numerical models (Geyer et al., 1998) and delineated using shipboard sidescan sonar (Fig. 10b) (Woodruff et al., 2001). The Landsat image of the Hudson River estuary turbidity maximum area highlights the advantage of the continuous spatial coverage of satellite imagery over discrete ground samples. The low number of ground stations (see Fig. 10a) is not able to resolve the pronounced spatial structure of turbidity in the area.

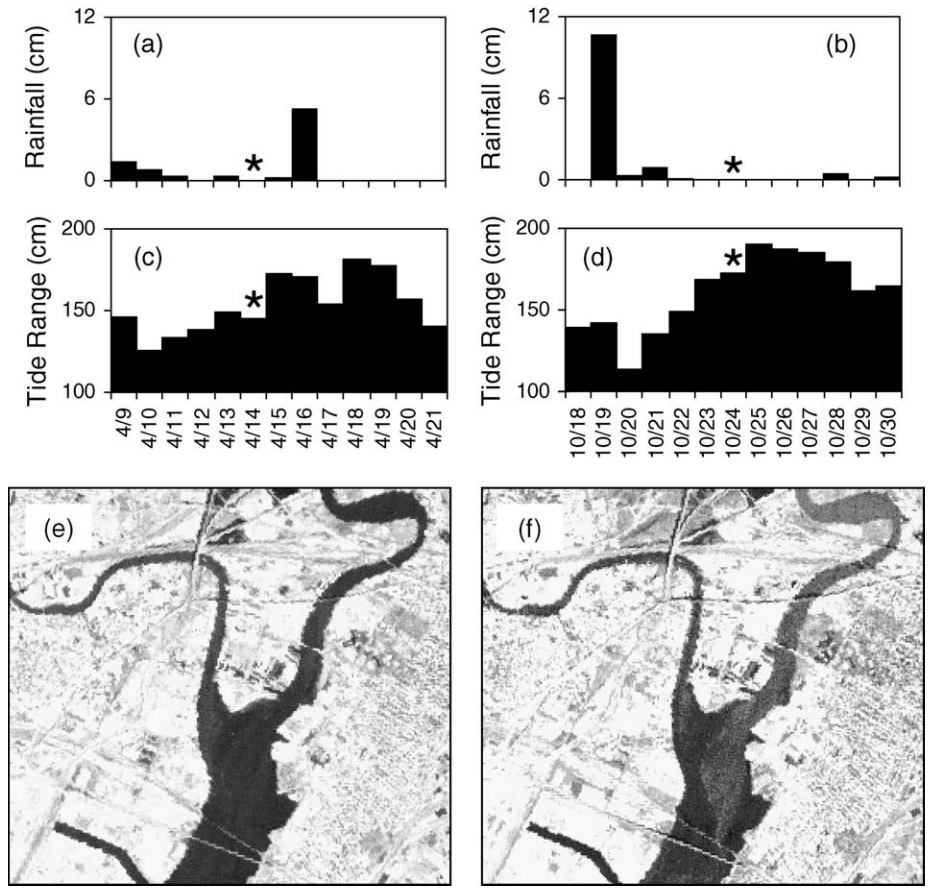

Fig. 9. Reflectance affected by rainfall and/or spring tide resuspension in Newark Bay. (a and b) Rainfall in Central Park, New York. (c and d) Mean daily tidal range at the Battery, New York Harbor, New York. (e and f) Landsat TM reflectance in the red band (TM3) in northern Newark Bay at the confluence of the Passaic and Hackensack Rivers. The image contrast is "stretched" to highlight the variability in the reflectance from water. Date of satellite acquisition is marked with * in panels a–d (9:20 AM). The images are 8 km wide.

Turbidity derived from the satellite image, even with a relatively large uncertainty introduced by a reflectance-to-turbidity algorithm, would be vastly superior to discrete ground samples for some applications. Even in the absence of a quantitative algorithm, the satellite imagery can help visualize the spatial heterogeneity in the turbidity and help design ground sampling programs.

4.2. High spectral/low spatial resolution sensor (Terra MODIS)

Spatial average chlorophyll *a* concentrations from ground and MODIS are compared in Fig. 11. There is no correlation between the MODIS estimates and ground measurements within Upper or Lower New York Bay. Data are matched based on a 12-h time window and the low correlation could be due to changes in chlorophyll *a* concentration within that time. Data are also averaged by region (Upper and Lower New York Bay), which introduces an error. For Lower New York Bay, however, the MODIS estimates are biased towards low values, especially at the higher concentrations. This is unlikely a result of the spatial or temporal mismatch. It is possible that interference by non-water features (as discussed in Section 3) is responsible for the discrepancy. Nevertheless, it does appear that the MODIS estimates of chlorophyll *a* are not directly applicable to New York Harbor.

Although the MODIS chlorophyll *a* estimates are not directly useable, it may be possible to derive acceptable estimates from the reflectance values. If the discrepancy is due to site-specific reflectance properties, it might be possible to develop a site-specific algorithm or correction for New York Harbor. If the discrepancy is due to interference from non-water features, then it is likely that the 1000-m resolution is not suitable for this area. However, the 500-m bands of MODIS might be used to develop site-specific algorithms, as was done with the TM data.

5. Conclusions and recommendations

In this study the feasibility of using satellite imagery for water quality studies in New York Harbor was

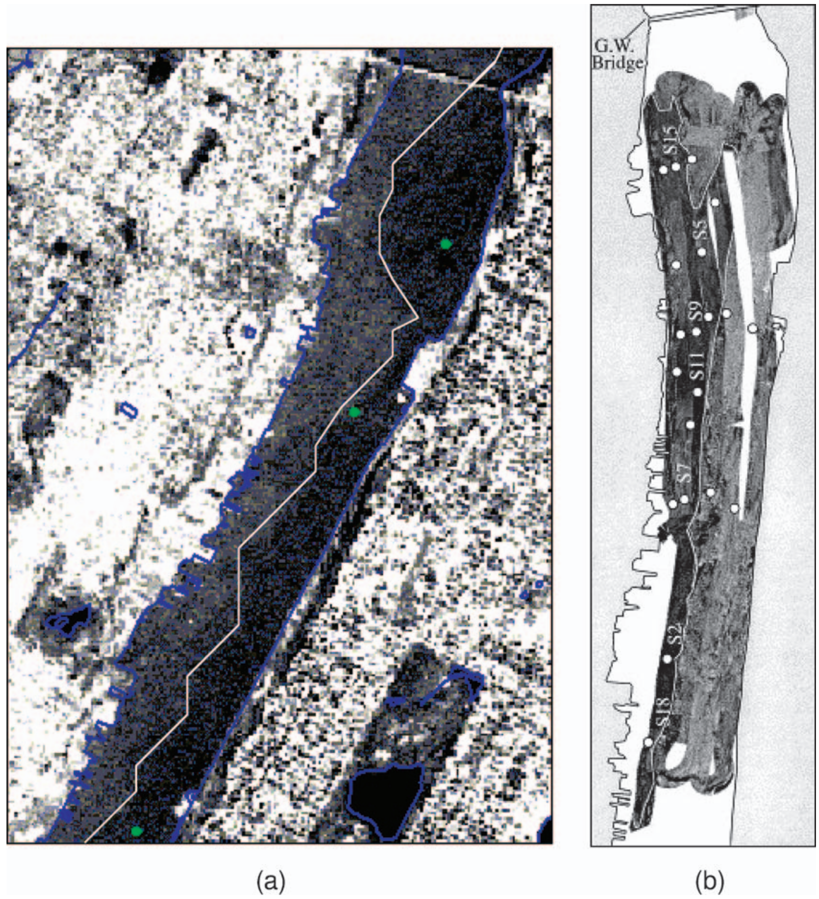

Fig. 10. Estuary turbidity maximum of the Hudson Estuary by Manhattan. (a) Landsat TM reflectance in the red band (TM3) for 4/15/96 9:20 AM. The image is contrast "stretched" to highlight the variability in the reflectance from water. Green points mark ground sampling stations. The thin white line outlines the high turbidity area. (b) Sidescan sonar mosaic for 6/23/98–6/25/98 from Woodruff et al. (2001). Areas of low side-scan backscatter appear dark in the figure while high side-scan backscatter areas appear light. The thin white line identifies the visual delineation between low and high side-scan backscatter environments. The average width of the estuary in the area shown is 1.3 km.

investigated. It is concluded that this technology is useful for water quality studies. In the Hudson River and areas affected by its sediments (New York Bay, Harlem River), the Secchi Depth correlates with Landsat TM red reflectance. In the East River and Long Island Sound, chlorophyll *a* concentration correlates with the ratio of green to red reflectance. Therefore, Landsat TM images can be used to estimate these parameters. With the high spatial resolution of Landsat TM, it is possible to resolve sub-kilometer scale variability in water quality. This is not possible using the present set of ground sampling stations of the New York Harbor Water Quality Survey program. Therefore, Landsat TM should be a valuable addition to that program. MODIS-estimated chlorophyll *a* concentrations do not correlate with ground measurements. Those estimates are not directly useable in New York Harbor. However it is possible that acceptable estimates can be derived from the reflectance data using a site-specific algorithm. It is recommended that further research be conducted to identify the most useful sensor(s) for water quality studies in New York Harbor. This should include investigating the use of medium spectral/medium spatial resolution sensors (e.g. MERIS and MOS) and higher spatial resolution bands of variable resolution sensors (i.e. 500 m bands of MODIS). Those alternatives might be most useful for areas like Upper and Lower New York Bay.

Turbidity correlates positively with Landsat TM red reflectance. This allows for the delineation of sediment plumes caused by rainfall runoff events or spring tide resuspension. Landsat TM images can be used to calibrate and/or validate hydrodynamic and sediment transport models. Also, the Landsat TM images clearly show the estuarine turbidity maximum. The outline of this feature visible in the Landsat images is consistent with that obtained using other techniques (i.e. discrete samples, sidescan sonar). Because of the high spatial resolution, Landsat TM images can provide useful information in studying this phenomenon. However, the low temporal resolution does limit the utility of Landsat TM in studies of dynamic processes.

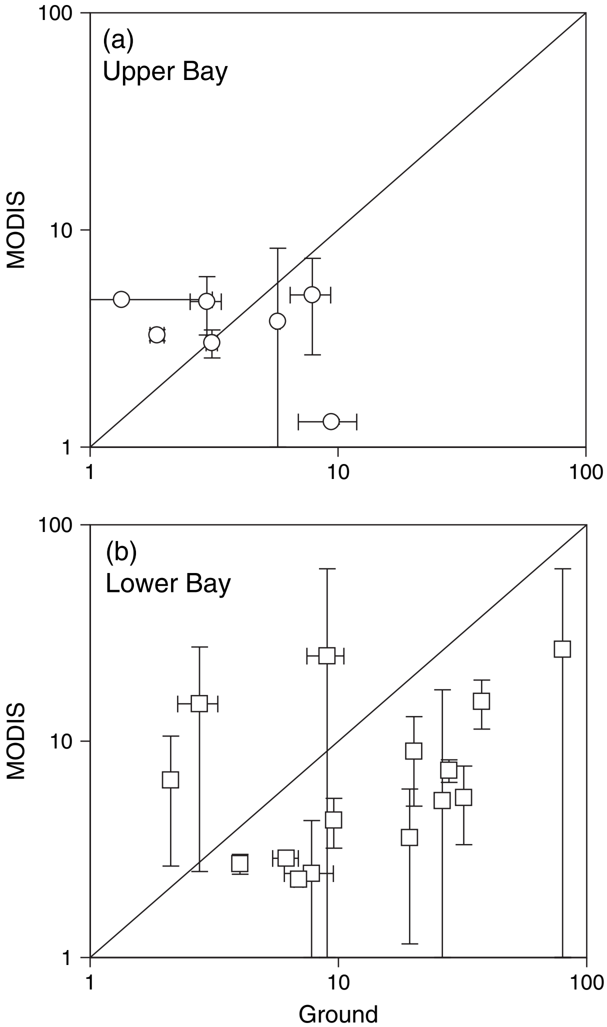

Fig. 11. MODIS estimated vs. ground measured chlorophyll *a* concentration (μg L^{-1}). Symbols are average ± 1 standard deviation of all samples or pixels in the specified area (Upper or Lower New York Bay). Data are matched in time using a 12-h window (i.e. same day). MODIS estimates are from Semianalytic algorithm. Agreement using estimates from SeaWiFS analog (OC3M) algorithm is similar.

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