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Relationship Between Watershed Land-Cover/Land-Use Change and Water Turbidity Status of Tampa Bay Major Tributaries, Florida, USA

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Abstract The extent and change of land cover/land use (LCLU) across the Tampa Bay watershed, Florida, was characterized for the time period between 1996 and 2006. Likewise, the water turbidity trend was determined at a site near the Bay for each of four major tributaries to Tampa Bay (Hillsborough River, the Alafia River, the Little Manatee River, and the Manatee River). This study identifies consistent changes in LCLU across the Tampa Bay watershed and a decrease in water turbidity. LCLU change analysis as a percent of the total Tampa Bay watershed revealed an increase of 2.6% in developed area followed by a 0.9% in bare land and a 0.6% in water cover. A decrease of 1.8% of the total Tampa Bay watershed was found in agriculture, followed in order by 1.1% in wetland and 1.4% in scrub/shrub. Other land classes changed less than 0.2% of the total watershed. A linear mixed model (SAS procedure PROC MIXED) revealed an overall decreasing trend in water turbidity ($p=0.003$, slope estimate$=-0.02$) across the four major Tampa Bay tributaries considered. This study suggests that development (urbanization) could be associated with decreasing water turbidity in Tampa Bay. Finally, although these results may help explain similar effects on other water bodies with similar conditions of adjacent urbanization and low slope, more analysis are needed considering a larger number of watersheds with similar scales and longer time period in order to confirm that the findings of this study are generally evident.

Keywords Remote sensing · Geographical information systems · Water quality · Developed · Agriculture · Wetland · Bare land · Scrub/shrub · Forest · SAS · Urbanization

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1 Introduction

There is a worldwide tendency for population to increase faster in coastal (Nixon 1995; Valiela et al. 1992) and urban (Rast and Thornton 1996; Vorosmarty et al. 2000) areas, with the consequent change in land cover/land use (LCLU), which leads to concerns about the potential degradation of water quality in coastal ecosystems (Basnyat et al. 2000; Beckert et al. 2011). Water turbidity (measure of cloudiness in the water column), which is one of the most common parameters used to estimate surface water quality, has been generally reported to increase with urbanization of watersheds (Coulter et al. 2004; Nelson and Booth 2002), as more impervious area increases runoff and sediment fluxes. In general, it is understood that alterations of any of the processes taken place in a watershed will affect loading of sediments and associated nutrients (Beckert et al. 2011; Peterjohn and Correll 1984). In fact, population growth and watershed development have been often associated with an increased loading of nutrients in coastal waters (Basnyat et al. 2000; Bennett et al. 2001; Smith et al. 2003; Valiela and Bowen 2002; Valiela et al. 1992; Xian et al. 2007), leading to phytoplankton abundance and further exacerbating turbidity problems. This in turn, affects biological and physical processes in coastal estuaries by interfering with the penetration of sun light to benthic algae and sea grass, and may even affect public health (FDEP 2004; Olsen et al. 1982; Ufnar et al. 2006). By contrast, some forms of development may be associated with lower sediment loads and further lower turbidity as the imperviousness, typical of urbanization, isolates the soil from the water runoff (Estes et al. 2009). Storm water runoff causing lower turbidity has also being reported from watersheds draining organic enriched material (Miller et al. 2011, 2009).

Due to the coastal and growing urban conditions of the Tampa Bay watershed, in Florida (Greening and Janicki 2006) and the great amount of data available, this watershed offers a good case to study a relationship between LCLU change and the effects in coastal aquatic ecosystems. Accurate monitoring on the status and trends of LCLU on watersheds as well as the water quality of the receiving water bodies are required for analysis of possible relationships between the two and in general for environmental management leading to sustainable development. Use of remote sensing (RS) technology provides a great benefit for both fields of study, facilitating monitoring of changes in a timely and cost effective manner. Satellite sensors can cover wide areas with long term measurements. Such technology is applied in this study to LCLU analysis while *in situ* data are used for water turbidity analysis.

Advantages of RS to study LCLU changes have been widely capitalized (Gomarasca et al. 1993; Kam 1995; Ridd and Liu 1998; Sohl 1999; Xian and Crane 2005; Xian et al. 2007). There are however, some limitations with the use of RS due to the reliability of target surfaces to draw inferences and resulting in LCLU misclassification (Gove et al. 2001; Snyder et al. 2003) as satellite sensors may not provide the desirable spatial resolution or sensibility required to detect some particular features. Xian and Crane (2005) monitored the percent of impervious surfaces (rooftops, roads, and parking lots) to infer LCLU change on Tampa Bay watershed and added normalized difference vegetation index to correct for miscalculations. The authors used Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) and found that urban LCLU in the Tampa Bay watershed increased almost 3-fold from 1991 to 2002. Several studies have elaborated on the importance of imperviousness as estimator of the effect of urban LCLU in regard to health of water resources (Arnold and Gibbons 1996; Schueler 1994). Xian et al. (2007) further confirmed with a cross-sectional analysis of the water quality that urbanization as estimated by imperviousness in the Tampa Bay watershed was closely associated with annual pollutant loadings in runoff. Several studies have reported similar positive relationship between remotely sensed LCLU and general water quality in other watersheds (Buck et al. 2004; Gove et al. 2001; Snyder et al. 2003; Tong and Chen 2002).

Among other LCLU studies using satellite remote sensing imagery on the hydrographic basin of the Gulf of Mexico, percent developed land (including urban and agricultural) has been found directly related with mean annual stream flow (Laymon and Cruise 2004) and increasing sediment loads and associated nutrients in surface runoff and streams (Basnyat et al. 2000). Despite related research conducted, the longitudinal relationship between multiple LCLU changes and water turbidity of Tampa Bay tributaries still needs attention. The present paper examines for possible relationships between multiple LCLU change and water turbidity of tributaries to Tampa Bay, during the time interval 1996 and 2006, using remotely sensed data from the Coastal Change Analysis Program (C-CAP). This is a standard Landsat-derived regional land cover and change analysis data on the coastal zone along the USA, which is freely available and comes ready for use. This advantage not just provide data accessibility but also avoid the technical procedures needed for sensor calibration and expensive image processing softwares that although routine for satellite data users, may be very complicated and cumbersome for potential new users.

2 Common Causes of Turbidity

The shift from rural to sub-urban or urban land use that has been taken place in the Tampa Bay watershed during the last decades has caused more impervious cover thus increasing hydrological activity and subsequent rainfall runoff (Xian and Crane 2005). This is of special interest in regard to alteration in the sediment budget as a result of increased water flow along creeks and channels. Because much of the Tampa Bay watershed is underlain by karst geology (van Beynen et al. 2007), soils should be naturally well drained under natural conditions, consequently with less surface runoff and transport of sediments. Therefore, impacts exerted by imperviousness are a more important factor to consider when analyzing this type of soils, as imperviousness more drastically changes the natural conditions of the ecosystem as opposed to poorly drained soils, which saturate more easily making surface runoff a more normal feature in such ecosystems (Reistetter and Russell 2011).

Nutrients enrichment can contribute to water turbidity by stimulating phytoplankton growth in receiving water bodies; in fact, it is among the most important causes of algae blooms (Paerl 1988). In addition to sediment transport, increased storm water runoff is also associated to increased transport of nutrients hence favoring phytoplankton growth (Johnes et al. 1996; Reddy et al. 1999; Soranno et al. 1996). Changes such as the urbanization of previously agricultural land has been reported as a major cause of nutrients mobilization as these are transported by suspended sediments resulting from increased runoff and erosion caused by urban LCLU (Bennett et al. 2001). The potential increase in the loading of associated nutrients and pollutants to Tampa Bay is a matter of special concern as a result of the continuing conversion of wetlands and agriculture to residential development. Pollutants, nutrients, and water-borne pathogens associated with suspended sediments are also of particular concern to public health (Olsen et al. 1982; Ufnar et al. 2006). Besides the widely known adverse effects of nutrients enrichment in the ecosystem, it represents also a serious threat to public health (FDEP 2004). Changes in LCLU can alter the amount and chemical composition of compounds released from electrical utilities, industry, and transportation to the atmosphere, subsequently changing atmospheric deposition of nutrients to bodies of water or adjacent drainage basins (Paerl 1997; Poor et al. 2005). LCLU change can affect nutrient inputs and subsequently water turbidity also via groundwater (Paerl 1997; Valiela et al. 1990; Valiela et al. 1992). Facilitated by the soil porosity in the Tampa Bay watershed, nutrients can find their way through groundwater transport into natural waters and into the bay (Swarzenski and Kindinger 2004). This is of particular concern when considering that an important portion of the population in the Tampa bay watershed still relies on septic systems for household sewage treatment (Schmidt and Luther 2002) and leakage may not be an uncommon phenomenon.

As urban sprawl is more commonly becoming a dominant feature in coastal areas, urban wastewater is increasingly becoming a major nutrients source (Valiela and Bowen 2002). Twentieth century human settlement within the Tampa Bay watershed was linked to a dramatic mid-century decline in bay water quality and loss of seagrass areas. Decades of direct and indirect nutrient discharges to the bay from phosphorus mining, fertilizer manufacturing, and wastewater treatment, as examples, impaired the estuary. During the last decades, however, regional stakeholders have worked successfully to improve the bay water quality by reducing point and non-point source nutrient loading to the bay (Tampa Bay Estuary Program (TBEP) 2006). The upgrade to tertiary level in the Tampa waste water treatment plant since 1979 (Garrity et al. 1982) has been one of the key measures in these management efforts. Results of such efforts have shown that with effective watershed management, the process of eutrophication in estuarine waters can be reversed even with increasing population on the watershed (Greening and Janicki 2006).

3 Methods

3.1 Study Area

Tampa Bay is located on the west-central coast of the Florida Peninsula between 27.5–28.08° N and 82.36–82.75° W (Figs. 1 and 2). Air temperatures in the area range between about 4°C in the winter and 39°C in the summer. About 60% of the annual precipitation occurs during summer (approx. 76 cm) (NOAA 2010). Based on data from the Environmental Protection Commission of Hillsborough County (EPCHC) at 54 fixed stations in Tampa Bay, the overall mean values of turbidity, concentration of chlorophyll-α, TN, and TP in Tampa Bay water during the time period between 1996 and 2006 were 3.5 nephelometric turbidity units (NTU), 8.4 $\mu g\ l^{-1}$, 0.65 $mg\ l^{-1}$, and 0.19 $mg\ l^{-1}$, respectively. Discharges are mainly received from four major rivers: the Hillsborough River, the Alafia River, the Little Manatee River, and the Manatee River. The bay is the largest open-water estuary in the state of Florida, covering 1,030 km^2 at high tide with an average of 3.4-m water depth. The 6,600-km^2 Tampa Bay watershed lies within the Counties of Hillsborough, Pinellas, and Manatee and extends to parts of Sarasota, Pasco, and Polk Counties (Fig. 1).

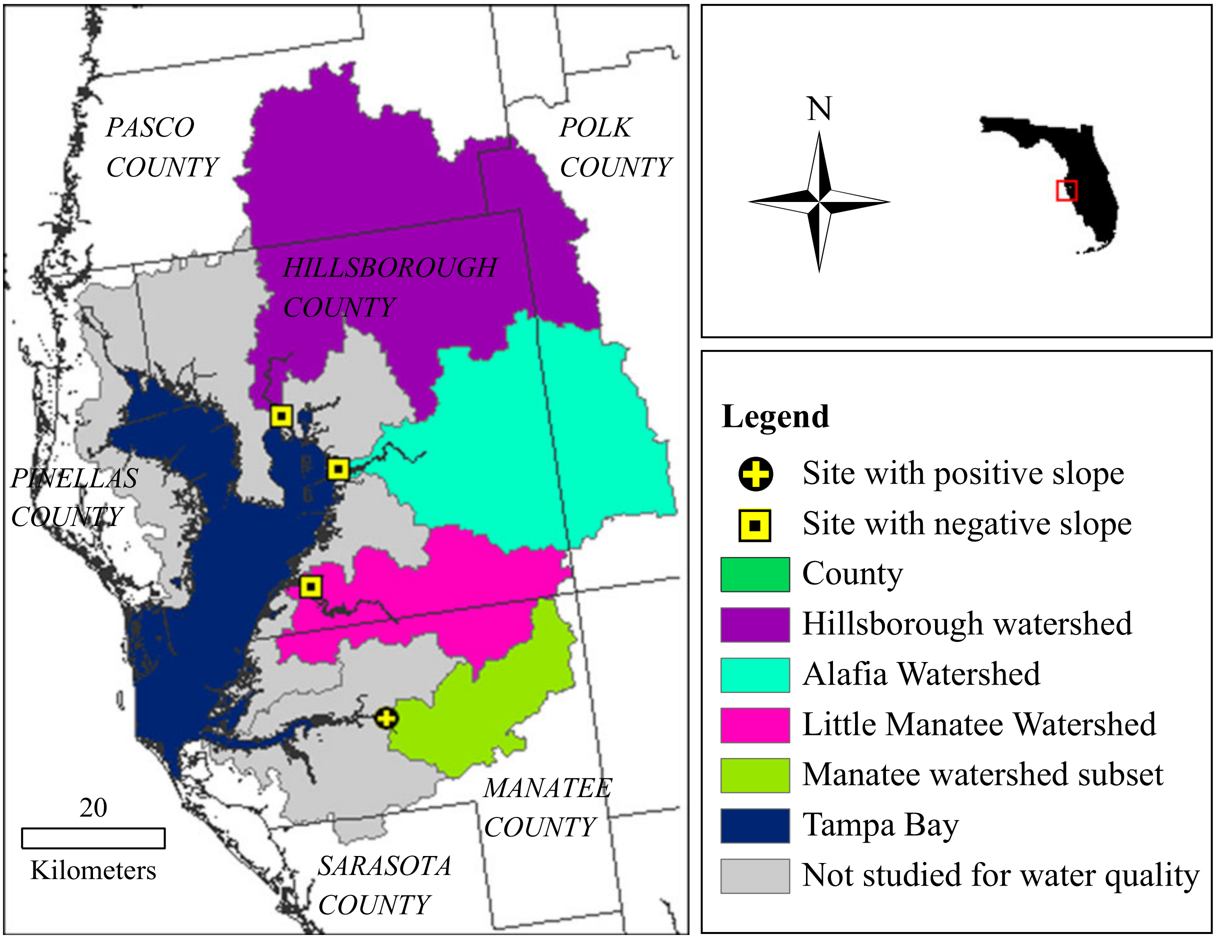

Fig. 1 The Tampa Bay watershed and five sub-watersheds, with four monitoring stations used to study the water turbidity trend line

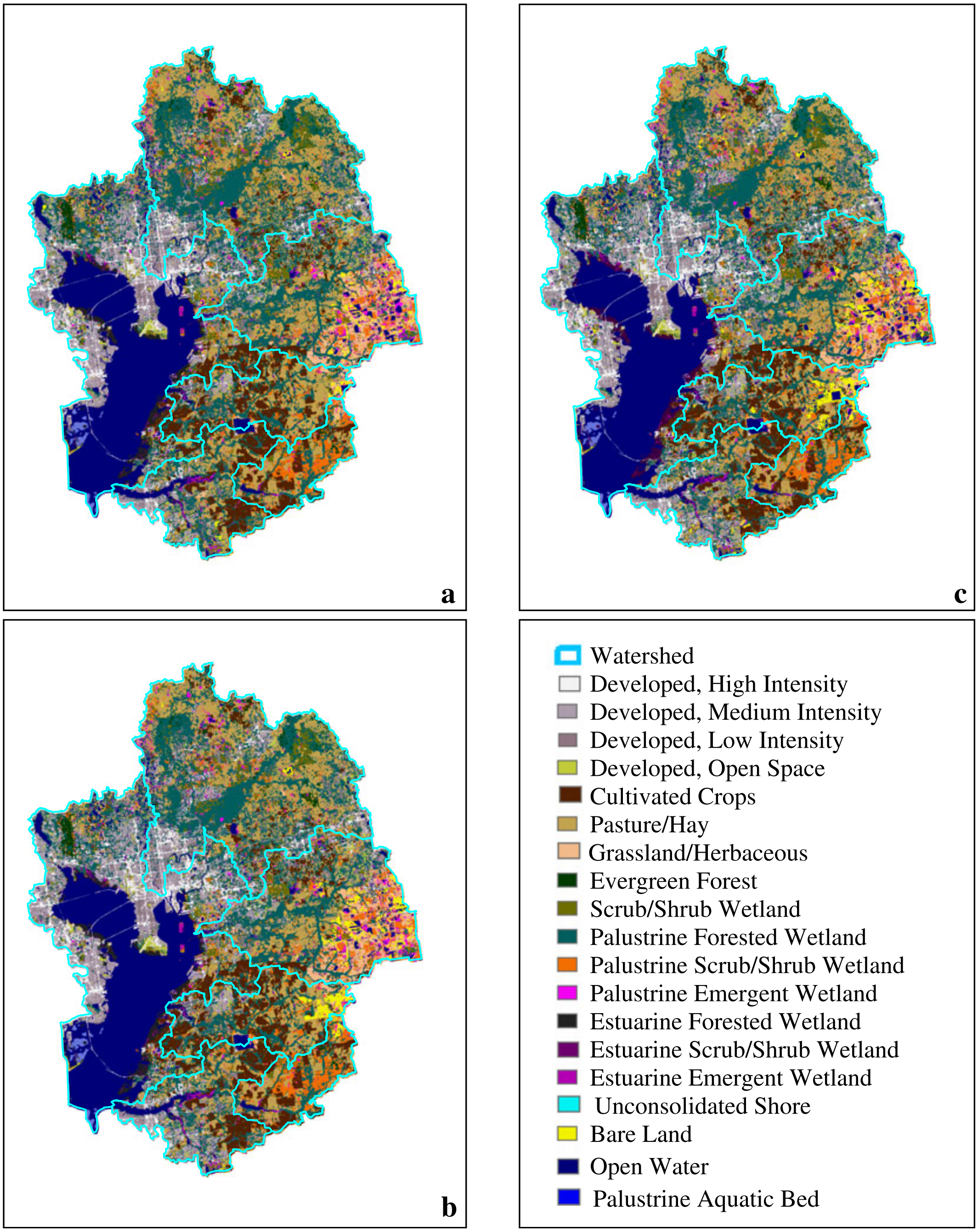

Fig. 2 Distribution of land classes, from C-CAP, used in this study: **a** 1996, **b** 2001, and **c** 2006. For identification of sub-watersheds please refer to Fig. 1

The watershed contains most of the Tampa Bay Metropolitan Area, which includes the cities of Tampa, St. Petersburg, and Clearwater, in four counties: Hillsborough, Pinellas, Manatee, and Pasco (Fig. 1). This is the second largest metropolitan area of Florida and the 21st largest in the USA, with a growing population of about 2.7 million inhabitants. Population growth between 1990 and 2006 was about

30% (US Census 2007). This was higher than the approximate 20% growth of the total USA population for the same time period.

3.2 Spatial Data

The satellite data used in this study come from a standard database on land cover and change in the coastal regions of the USA, developed by the C-CAP program. C-CAP is part of the Estuarine Habitat Program, which in turn is included within the Coastal Ocean Program of the National Oceanic and Atmospheric Administration (NOAA). These data are produced primarily with NASA Satellite imagery from Landsat TM in combination with aerial photography and fieldwork. The data are interpreted, classified, analyzed, and integrated with other digital data in a geographic information system (GIS). The resulting data are projected into the US Contiguous Albers Equal Area Conic USGS version and are made available in digital form at no cost on NOAA's website (2007).

The completed C-CAP land-cover data encompass five regions of the coastal USA. The US Southeast coastal region includes North Carolina, South Carolina, Georgia, and Florida. These data were produced using a composite of 30-m resolution Landsat TM and ETM satellite imagery around years 1996, 2001, and 2006. These available time sets of land-cover data were the criteria used for selecting the time period 1996–2006 of this study. Florida data were downloaded and subset for the Tampa Bay watershed with ArcGIS 9.3. Spatial data on rivers and major watershed boundaries (Hillsborough River, Alafia River, Little Manatee River, Manatee River) were registered to the GCS North American 1983 HARN geographic coordinate system and obtained from the Florida Geographic Data Library (FGDL) at the University of Florida's GeoPlan Center (UF 2010). Watershed boundaries data were projected into Albers Conical Equal Area (Florida Geographic Data Library). A subset of the Manatee River watershed was manually digitized in ArcGIS using the detailed streams network data that were also obtained from the FGDL. This subset was delineated to engulf the maximum possible portion of the Manatee River watershed that drained into a given monitoring site in order to use such site for water turbidity analysis. Only the Manatee River watershed required this extra subset within its total area because of its long-shaped estuary, which prevents drainage into a specific site but rather multiple sites along the shoreline. Streams data were projected with NAD 1983 HARN State Plane Florida West FIPS 0902 Feet. Boundaries of Tampa Bay watershed and sub-watershed boundaries considered in this study are depicted in Figs. 1 and 2a–c.

C-CAP classifies land-cover types into 22 standardized classes that include forested areas, urban areas, and wetlands. Of those, only 20 classes were present in the Tampa Bay watershed. The C-CAP data for each one of the 3 years available was linked to the studied watersheds using the Spatial Analyst tool of ArcGIS 9.3. This revealed the area covered by each one of the 20 classes (Table 1) present in the watersheds and subsequently the change from year to year could be calculated. After presenting a general view of the LCLU change throughout the entire Tampa Bay watershed during the time period 1996–2006, Sub-watersheds from the major tributary watersheds within the Tampa Bay watershed (as described in the previous paragraph) were independently analyzed for LCLU change. To facilitate the analysis, the process was simplified by grouping those classes more related into a bigger unified class. This resulted in nine classes (Table 2); where developed land included high, medium, and low intensity of development as well as open space development. Agriculture included cultivated crops and pasture/hay. Evergreen forest was the only dry land forest present in the area and is called here as forest. Three types of wetlands (forested, scrub/shrub, emergent) for both estuarine and palustrine ecosystems were joined here into one class called wetland. Open-water, palustrine aquatic bed, and estuarine aquatic bed are all considered open water. Grassland/herbaceous and scrub/shrub are kept the same. The area covered by unconsolidated shore was not considered in the analysis for being too small.

3.3 Water Turbidity Data

This study used water turbidity data from major rivers in Hillsborough and Manatee Counties. Data were collected by the Environmental Protection Commission of Hillsborough County (EPCHC) and the Manatee County Environmental Management Department (MCEMD), respectively. Data were collected monthly as part of routine water quality monitoring programs

Table 1 Area in km^2 per C-CAP land class for 1996, 2001, and 2006 and area increase in km^2 (for the entire Tampa Bay watershed)

Summary Tampa Bay watershed		Area per year in km^2			Change in km^2		
Class name		1996	2001	2006	1996–2001	2001–2006	1996–2006
Developed	High intensity	185.5	223.6	230.5	38.1	6.9	45.0
	Medium intensity	482.1	530.1	540.5	48.0	10.4	58.4
	Low intensity	441	492.8	499	51.8	6.2	58.0
	Open space	155	162.9	168.6	7.9	5.7	13.5
Agriculture	Cultivated crops	484.1	500.7	481.1	16.6	−19.5	−3.0
	Pasture/hay	867.7	791.4	753.4	−76.3	−38.0	−114.3
	Grassland/herbaceous	265.6	279.1	278.3	13.5	−0.9	12.7
	Evergreen forest	47.8	51.3	49.8	3.5	−1.5	2.0
	Scrub/shrub	246.6	155.9	152.3	−90.6	−3.7	−94.3
Wetland	Palustrine forested	1,479.9	1,419.0	1,393.8	−60.8	−25.2	−86.1
	Palustrine scrub/shrub	522.7	555.5	548.5	32.7	−7.0	25.7
	Palustrine emergent	231	225.1	216.2	−6.0	−8.9	−14.9
	Estuarine forested	77.7	78.1	77.9	0.4	−0.1	0.3
	Estuarine scrub/shrub	11.4	10.8	10.9	−0.6	0.0	−0.6
	Estuarine emergent	25.4	25.2	25	−0.2	−0.2	−0.4
	Bare land	67.4	93.8	126.2	26.4	32.4	58.8
Water	Open water	1,003.8	999.1	1,043	−4.7	43.9	39.3
	Palustrine aquatic bed	1.7	2.0	1.6	0.4	−0.4	0.0
	Estuarine aquatic bed	20.1	20.1	20.1	0.0	0.0	0.0
	Unconsolidated shore	0.5	0.4	0.4	−0.1	0.0	−0.1
Total area in km^2		6,617	6,617	6,617			

from numerous sampling stations distributed throughout Hillsborough and Manatee Counties respectively. In this study, we used 510 measurements of water turbidity from 4 monitoring sites (one site per tributary, Fig. 1) that were measured during the time period between 1996 and 2006 (uninterruptedly). The only monitoring site used per tributary, was chosen for being the one closest to the discharge point into Tampa Bay. This was done to include the largest portion of land within that watershed that drains into that site. As anticipated in the spatial data section, the monitoring site used for the Manatee River watershed

Table 2 Area increase in square kilometers and relative increase as a percent of the total Tampa Bay watershed per grouped land class

Class group	Change in km^2			Percent change
	1996–2001	2001–2006	1996–2006	1996–2006
Developed	145.7	29.2	174.9	2.6
Agriculture	−59.7	−57.6	−117.3	−1.8
Grassland	13.5	−0.9	12.7	0.2
Forest	3.5	−1.5	2.0	0.0
Scrub	−90.6	−3.7	−94.3	−1.4
Wetland	−34.4	−41.5	−75.9	−1.1
Bare land	26.4	32.4	58.8	0.9
Open water	−4.3	43.5	39.2	0.6
Unconsolidated	−0.1	0.0	−0.1	0.0

provided water turbidity data representative of only a portion of this sub-watershed. Although there are five major sub-watersheds within the Tampa Bay watershed, only four sites (four sub-watersheds) were selected meeting the above criteria because the fifth sub-watershed is rather a union of all remaining minor sub-watersheds within the Tampa Bay watershed.

US EPA (1993) 180.1 and SM (1995) 2130B were the sampling methods used by EPCHC and MCEMD, respectively. The samples were taken at mid-depth, read directly using the meter at room temperature and reported in NTU. Laboratories from both environmental agencies used a Hach Model 2100N turbidimeter. Both laboratories are certified by the Florida Department of Health for Nonpotable Water General Chemistry and Microbiology and are compliant with the National Environmental Laboratory Accreditation Program. Data were uploaded to the Storage and Retrieval Data Warehouse on an annual basis and made available through the Watershed Atlas (USF 2010). Data from Manatee River were retrieved from the mentioned website and those from Hillsborough Rivers, Alafia River, and Little Manatee River were directly provided by EPCHC.

3.4 Statistical Analysis

Baseline conditions of LCLU in the Tampa Bay watershed and water turbidity of tributaries were described in different tables (Tables 1, 2, 3, 4, and 5). LCLU data were expressed as numbers and percentages while water turbidity data as numbers and summary statistics. In visual inspection, histogram analysis was used to assess the proportions and changes in LCLU across the Tampa Bay watershed (Fig. 3).

A visual inspection of time-series during the study period was conducted by plotting monthly median values of water turbidity from the four sites studied against their respective months for the time period between 1996 and 2006 (Fig. 4). The preliminary conclusions were compared with further statistical analysis. A linear mixed model, SAS procedure PROC MIXED, was first performed to analyze more rigorously for a trend in water turbidity across the four sites. Since there was no data for comparison from undisturbed watersheds where conditions other than LCLU were similar to those in our study, comparisons were done among the four sub-watersheds within the Tampa Bay watershed.

Turbidity was chosen as dependent variable in the analysis and log transforms were applied so that the data more closely meet the assumptions of normality. Time as independent variable was considered as fixed effect in the model and the variability among the four sites was considered as random. To further investigate trends within each sub-watershed, a generalized linear regression model, SAS procedure PROC GLM, was used to analyze for trends in every monitoring site separately.

Simple linear regressions (SAS procedure PROC REG) were conducted choosing the slopes estimates from each site as the dependent variable, while the values of percent LCLU change per class as the independent variable. LCLU change was expressed for each class as the areal change of that particular class relative to the area of the tributary watershed. Statistical analyses were performed using SAS (V9.2,

Table 3 Percent of grouped class change between 1996 and 2006 in each sub-watershed studied, relative to the total area of the sub-watershed

Watershed	Percent change								
	Developed	Agriculture	Grassland	Scrub/shrub	Wetland	Bare Land	Water	Forest	Unconsolidated
Hillsborough River	3.0	−1.3	0.5	−1.9	−1.0	0.4	0.2	0.1	0.0
Alafia River	1.7	−1.0	−0.3	−1.5	−1.9	1.9	1.2	0.0	0.0
Little Manatee River	0.8	−6.1	0.9	−1.2	−1.6	5.1	2.0	0.0	0.0
Manatee River	4.2	−2.9	−0.2	−1.4	−1.0	0.5	0.7	0.0	0.0
Manatee River (subset)	0.3	0.0	−0.8	−0.7	−0.5	0.9	0.7	0.0	0.0
Tampa Bay (minor watersheds)	2.6	−1.0	0.2	−1.1	−0.8	−0.1	0.2	0.0	0.0

Table 4 Area of each grouped LCLU class in 2006 in each sub-watershed studied

Watershed	Area (km^2)								
	Developed	Agriculture	Grassland	Scrub/shrub	Wetland	Bare land	Water	Forest	Unconsolidated
Hillsborough River	383.6	400.5	43.9	66.4	792.7	13.3	21.5	28.0	0.0
Alafia River	155.0	172.0	149.4	29.7	471.7	56.6	57.8	0.7	0.0
Little Manatee River	47.6	223.3	31.2	5.8	200.2	37.6	29.7	0.2	0.0
Manatee River	164.0	305.1	25.1	17.7	359.2	10.6	49.0	2.7	0.0
Manatee River (subset)	7.3	141.3	9.4	9.9	166.8	4.9	8.0	2.6	0.0
Tampa Bay (minor watersheds)	688.2	133.5	28.6	32.5	448.4	8.1	907.0	18.2	0.4

SAS Institute, Cary, NC) for windows. Two-sided *p* values of ≤0.05 were considered as statistically significant.

4 Results

4.1 Land Cover/Land Use

Maps depicting the geographic distribution of the 20 LCLU classes present in the entire Tampa Bay watershed for years 1996, 2001, and 2006 are shown in Fig. 2a–c, respectively. The area values of these classes as well as the change for each interval (1996-2001and 2001–2006) and for the overall study time period (1996–2006) are provided in Table 1. Most of the developed land corresponded to medium intensity followed in order by low intensity, high intensity, and open space. All developed land classes increased in coverage during the study period. The proportion of developed land was higher toward the bay shoreline, although Hillsborough River watershed also showed important proportions of developed land covering upstream areas. The watershed of Manatee River presented the greater proportion of developed land followed by Hillsborough River, minor watersheds all together, Alafia River, and Little manatee River (Fig. 2). In general developed land grew mainly at the expense of wetlands particularly palustrine forested, which nevertheless was the land class with the greater coverage within the Tampa Bay watershed in 2006, especially in the headwaters of the Hillsborough River watershed and along the Alafia River (Fig. 2). Developed land also gained coverage to scrub/shrub and cultivated crops. Palustrine wetlands showed greater coverage than estuarine wetlands. All except palustrine scrub/shrub wetlands and estuarine forested wetlands showed a decrease in land coverage during the study period (Table 1).

Most of the decrease in agricultural land corresponded to pasture/hay, while cultivated crops decreased just slightly. Both lost ground to bare land, which also gained to grassland/herbaceous. Watersheds of Manatee River and Little manatee River presented the highest proportions of cultivated crops; while that of pasture hay and grassland/herbaceous were highest in Hillsborough River and Alafia River respectively. Open water increased at the expenses of bare land followed by pasture/hay,

Table 5 Summary for monitoring sites: slope estimates of the water turbidity trend line, statistics, and geo-location

1996–2006	Turbidity trend		Salinity (ppm)	Turbidity (NTU)					
	p value	Slope	Median	Median	Mean	SD	*N*	Latitude	Longitude
Hillsborough River	<0.001	−0.03	19	3	3.3	1.8	132	27.9408	−82.4579
Alafia River	0.001	−0.05	13.2	4.4	5.5	3.5	132	27.859	−82.383
Little Manatee River	0.001	−0.04	12.9	2.85	3.1	1.5	132	27.7043	−82.4487
Manatee River subset	<0.001	0.07	0.1	2.8	3.7	2.8	116	27.51417	−82.3668

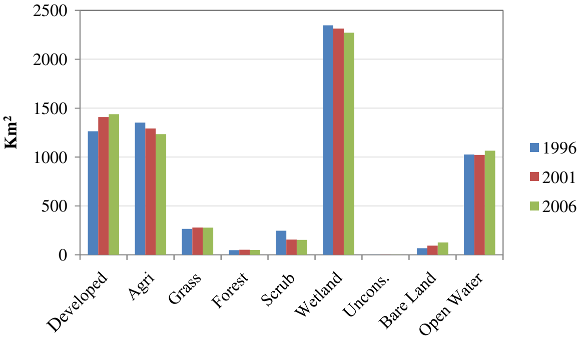

Fig. 3 Change in spatial extent of grouped land class from 1996 to 2001 and 2006 in the entire Tampa Bay watershed

palustrine crub/shrub wetland, and palustrine emergent wetland.

Overall, after grouping related land classes into bigger simplified ones; by 2006 the largest land-cover class in the Tampa Bay watershed was wetland (34.3%), followed by developed (21.7%), agriculture (18.7%), and open water (16.1%). Minor proportions of the watershed were covered by grass land (4.2%), scrub (2.3%), bare land (1.9%), forested (0.8%), and unconsolidated (<0.1%). Histogram analysis proportions of LCLU classes for the entire Tampa Bay watershed is provided in Fig. 3. LCLU changes by grouped classes in absolute area and as a percent of the total Tampa Bay watershed area are shown in Table 2. Developed land presented the most gain followed in order by bare land, open water, and grassland. Lost in LCLU were noted for agriculture, followed in order by scrub/shrub, and wetland. Forest and unconsolidated land did not present a noticeable change. Table 3 considers LCLU change for each sub-watershed (within the Tampa Bay watershed) during the study time period as a percent of the total area of the sub-watershed. This analysis indicated that the proportion of developed land increased in the four major sub-watersheds within the Tampa Bay watershed as well as in all remaining watersheds considered together. Except for Little Manatee River watershed, this LCLU class had the most proportional areal gain during this study period as compared with all other LCLU classes. The watersheds of Manatee River and Hillsborough River presented the greatest proportional increases of developed land, while Little Manatee River watershed and the subset of the Manatee River watershed (used for water quality analysis) had the lowest. Conversely, the proportion of the sub-watersheds covered with agriculture, scrub/shrub, and wetland decreased in all sub-watersheds. Proportionally, the watersheds of Little Manatee River followed by Manatee River and Hillsborough River had the most areal lost in agriculture, while Hillsborough River and Alafia River watersheds did in scrub/shrub and wetland, respectively. These two LCLU classes decreased their areas in all sub-watersheds. Surface area covered with water slightly increased in all sub-watersheds especially in Little Manatee River watershed. Grass land and bare land increased and decreased across the different sub-watersheds. Forest only had a very slight increase in Hillsborough River watershed and remained the same in all other sub-watersheds. No change in unconsolidated shore was noted. Table 4 shows the absolute extent of all the studied LCLU classes for the different sub-watersheds at the end of the study period.

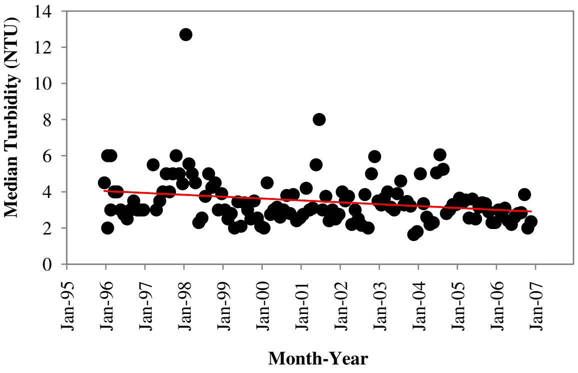

Fig. 4 Temporal trends of monthly median values in water turbidity across Hillsborough River, Alafia River, Little Manatee River, and Manatee River. For each river, the data correspond to the monitoring site closest to the bay

4.2 Water Turbidity

Temporal trends of monthly median values across stations for the period 1996–2006 suggested a decreasing trend line in water turbidity (Fig. 4). These results align well with the turbidity trend analysis conducted with SAS procedure PROC MIXED, during the same time period. Such results showed a significant decreasing turbidity trend (p=0.003, slope estimate=−0.01993, and n=510).

Results from running SAS procedure PROC GLM are displayed in Table 5 showing the turbidity trend slope and level of significance for each site. Table 5 also shows the geo-location and a summary statistics for the four monitoring sites. The slope signs of the three sites by the Bbay suggest a tendency for a decreasing turbidity trend but the site located farther from the Bay (Manatee River site), which monitors water drained from land with lower development intensity, shows an increasing water turbidity trend line.

The geographic distribution of the four stations studied, along with information about the sign of their slopes, is displayed in Fig. 1. The site with the largest mean turbidity value for the 1996–2006 period was located in Alafia River (5.5 NTU), followed by Manatee River (3.7 NTU), Hillsborough River (3.3 NTU), and Little Manatee River (3.1 NTU). Overall, water turbidity was low over the 6-year study period, averaging 3.8 NTU (n=510; SD=2.5).

4.3 Relationship Between LCLU Change and Water Turbidity

Regressions between the slopes estimates of water turbidity obtained at each site (Table 5) and the percent change of their watersheds for each LCLU class considered (Table 3) were not significant (p>0.05) presumably due to the small number of sub-watersheds considered (4). However, the plots for developed land and scrub/shrub (Figs. 5 and 6, respectively) agree with possible relationships between water turbidity and these two LCLU classes. A line suggesting an inverse relationship between the slope estimates of water turbidity and the percent change of developed land for four sites and tributaries (Fig. 5a) maintains an inverse position even if the Manatee River site is removed. Similarly, a direct relationship line between the slope estimates of water turbidity and the percent change of scrub\shrub land continue suggesting a direct relationship after removing the same site.

5 Discussion

Conditions where a growing urban population coincides with coastal areas are increasingly more common (Nixon 1995). As such conditions characterize the Tampa Bay watershed, the results from this case study could help explain an increasing number of cases worldwide. Although geologic and climatic factors might differ, and the social, economical, and political constrains might determine different water management in different geographical locations; some features of LCLU like the imperviousness resulting from urbanization would be associated with similar effects.

LCLU change analysis conducted with C-CAP data clearly shows patterns of increase in developed areas and decrease in agriculture, scrub/shrub, and wetlands across the different sub-watersheds within the Tampa bay watershed. In general, this pattern is consistent when considering the common situation of many metropolitan areas (Carlson and Arthur 2000; Yuan et al. 2005). There was an increase in water covered areas across the major Tampa bay sub-watersheds, which is likely due to water surface increase in inland lakes because of the higher annual precipitation in 2006 as compared with 2001 and 1996 as registered by NOAA at the Tampa International

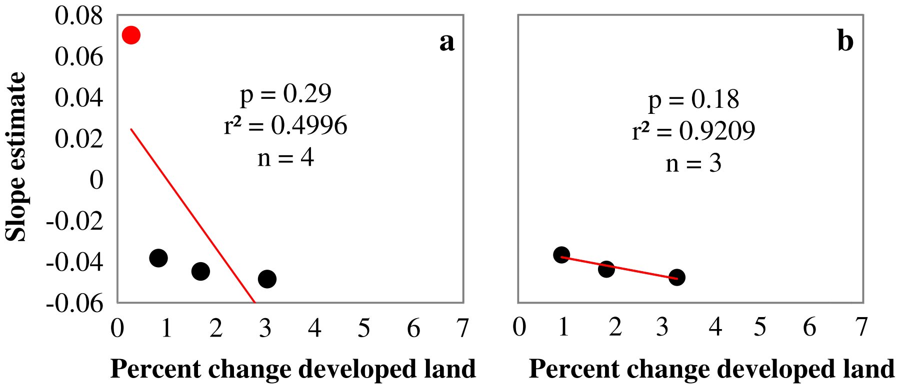

Fig. 5 Plots between the slope estimates of water turbidity trends (for Hillsborough River, Alafia River, Little Manatee River, and Manatee River) and the percent of change in developed LCLU in their watersheds: with (**a**) and without (**b**) Manatee River (the *red dot* corresponds to Manatee River). All water turbidity trends correspond to the monitoring site closest to the bay in each river

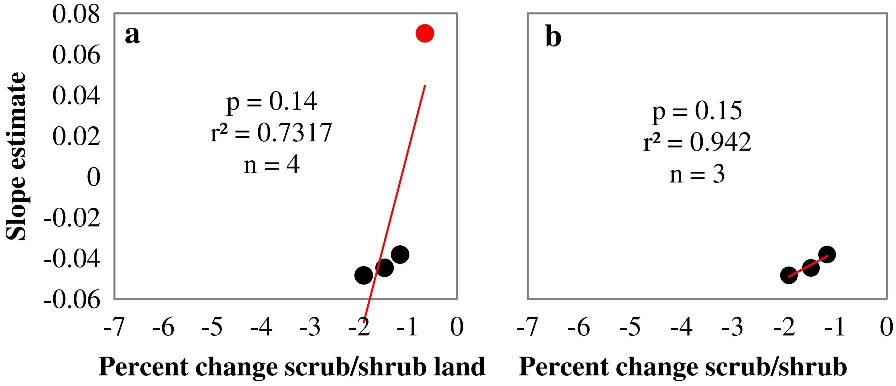

Fig. 6 Plots between the slope estimates of water turbidity trends (for Hillsborough River, Alafia River, Little Manatee River, and Manatee River) and the percent of change in scrub \shrub LCLU in their watersheds: with (**a**) and without (**b**) Manatee River (the *red dot* corresponds to Manatee River). All water turbidity trends correspond to the monitoring site closest to the bay in each river

Airport station; data downloaded from the Water Atlas (USF 2010). Other contributing factor may be the construction of aesthetics lakes and storm water retention ponds along with the increasing number of residential complexes and other sub-urban developments. Other LCLU classes did not present consistent changes across the four sub-watersheds.

A preliminary analysis for the time period 1996–2006, seems to suggest a decrease in water turbidity (Fig. 4) with the increase in developed land (Tables 2 and 3; Fig. 3). Such relationship could apparently be supported by a of growing imperviousness associated with urbanization (Estes et al. 2009) and composed by paved roads, parking lots, roofing, and concrete areas, more intense toward the shoreline. This reduces bare land area which might be more susceptible for erosion. Additionally the prevalent implementation of storm water retention ponds across the Tampa Bay watershed and especially in urban and sub-urban areas impede direct discharge of storm water carrying sediments into streams and rivers. Likewise, some of the rivers studied have dams along their courses, which slow down the flowing water subsequently allowing for sedimentation of suspended solids.

Accordingly, although not statistically significant ($p>0.05$), the negative regression slope in Fig. 5a, b suggests a decrease in water turbidity with an increase in developed land. Note in Fig. 5a that the regression slope is negative in despite of one positive slope estimate that corresponds to the site in a subset of the Manatee River watershed. The watershed draining into this site presents a low increment and extent in developed land as compared with the other three watersheds (Tables 3 and 4, respectively). The lower intensity of developed LCLU in this subset of the sub-watershed may explain the increasing water turbidity slope measured at its site. Such possibility is consistent with a slightly but significantly higher turbidity ($p=0.04$) reported by the authors in Tampa Bay water with eight or more days after low-intensity rainfall as compared with the same day of rainfall (Moreno Madrinan et al. 2010). A likely explanation for such effect was the increased dilution of sediments as a consequence of moderate rain events on an urbanized watershed followed by the subsequent concentration of sediments with more days after the rain event. This is also in agreement with literature generated from other watersheds (Estes et al. 2009; Miller et al. 2011, 2009). An opposing view, as it has been suggested from other watersheds, would expect that the increased runoff normally resulting from urbanization associated imperviousness could accelerate erosion from agricultural areas downstream, thus increasing the rate of transport of sediments (Bennett et al. 2001). Nevertheless, such situation may not apply under the conditions of the Tampa Bay watershed since most urbanized areas are concentrated toward the Bay shoreline thus not having agricultural areas between the Bay and the urbanized areas.

Contrary to the hypothesis of direct inverse association between development and water turbidity, the lower salinity median (0.1 ppm) at the Manatee River site, as compared with the other three sites (>12 ppm), which can be explained by its location further away

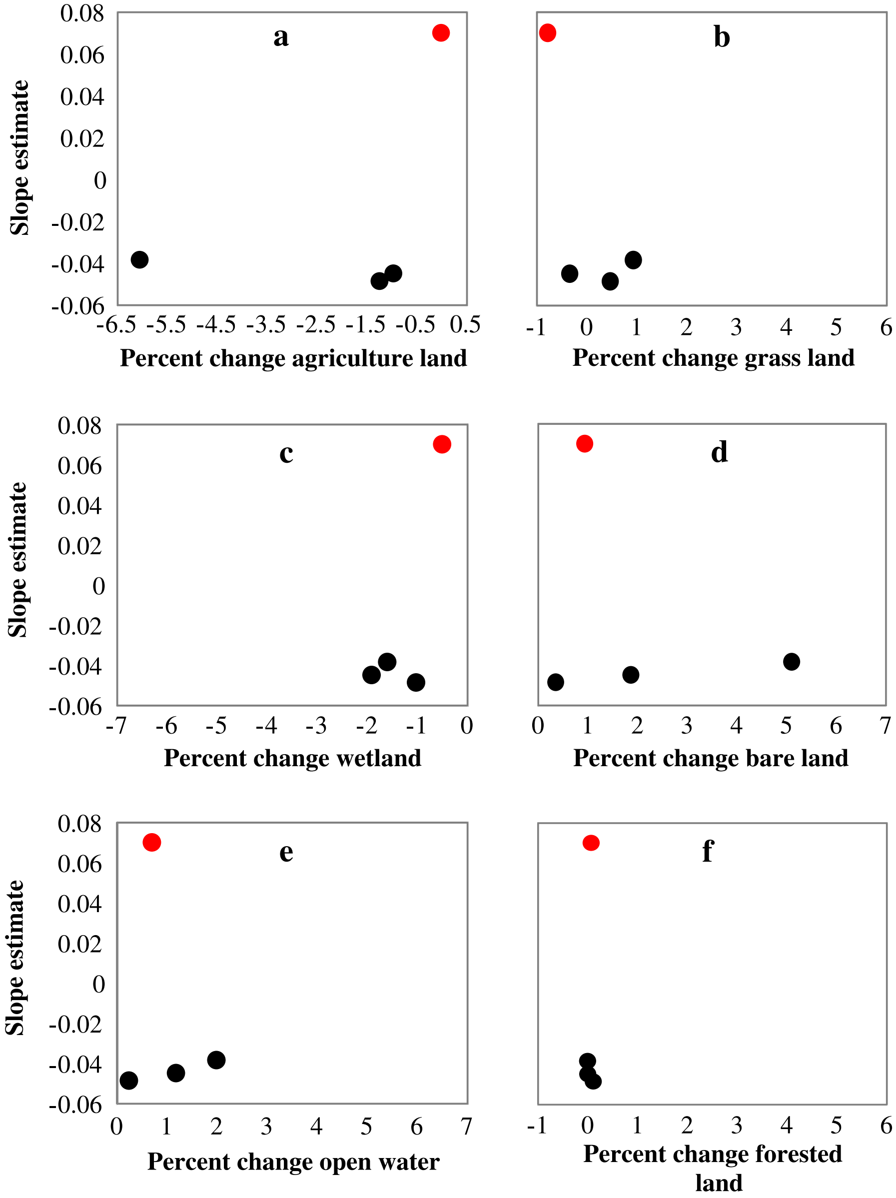

Fig. 7 Plots between the slope estimates of water turbidity trends (for Hillsborough River, Alafia River, Little Manatee River, and Manatee River) and the percent of change in LCLU in their watersheds: **a** agriculture land, **b** grass land, **c** wetland, **d** bare land, **e** open water, and **f** forested land. All water turbidity trends correspond to the monitoring site closest to the bay in each river. For each graphic, the *red dot* corresponds to Manatee River

from Tampa Bay, may suggest that it is the influence of Tampa Bay water intrusion what brings turbidity down rather than the effect of urbanization. After all, the water turbidity in Tampa Bay is also presenting a decreasing trend (Dixon et al. 2009), although it seems logical to expect a receiving water body to be influenced by the tributaries as opposed to the other way around. Nevertheless, when this dot is removed from the plot, the negative regression line fits better (Fig. 5b).

Remaining sub-watersheds within the Tampa Bay watershed could not be brought to this analysis to increase *n* because they were too small as compared with the four major sub-watersheds used. The influence of LCLU on longitudinal water quality trends varies with scale (Buck et al. 2004; Gove et al. 2001; Pan et al. 2004). With different scales may be also different interactions among LCLU classes that may cause conflictive effects. Table 4 puts into context the different LCLU classes in the different sub-watersheds and their absolute areas in 2006 compared with each other. The effect of development in an area with large agricultural or bare land can be different from that in another area with small agricultural or bare land and this difference can further vary with the scale of the watershed. Furthermore, the ratio of width to length of the watershed is also important when considering the relationship between LCLU and water quality (Gove et al. 2001).

The increasing bare land in the study area (Table 2 and Fig. 3), which could be expected to be associated with erosion and sediment release, does not agree with the decreasing trend line in water turbidity (Fig. 4). Similarly, the loss of wetlands in the Tampa Bay consistent with the tendency in Florida and the entire USA (Dahl 1990) is not consistent with the decrease in water turbidity of Tampa Bay tributaries. In the absence of other competing factors, the increase in bare land and decrease in wetlands would be expected to be associated with an increase in water turbidity since bare lands are more susceptible to erosion and wetlands behave as filters and sedimentation traps (Faulkner 2004). Such association was not observed in this study (turbidity did not increase) indicating that other additive factors exerted more influence compensating for the increase in bare land and the loss of turbidity reducing effect of wetlands (for example, the reduction of agricultural areas).

The decreasing trend in water turbidity (Fig. 4) along with the increase in open-water land cover in the watersheds (Table 2; Fig. 3) may be explained in part by more settling down of sediments due to increasing number of retention ponds and artificial lakes that act as sediment traps and filters of the water draining down toward the bay tributaries. Considerable efforts are taking place in environmental management and restoration programs of Florida lakes, in general (Coveney et al. 2002; Poor 2010). Similarly, such practices are being undertaken in lakes within the Tampa Bay watershed (Southwest Florida Water Management 2003) benefiting not just the water in the lake but also that of Tampa Bay tributaries as they receive the lake water outflow. Especial attention has been placed on the reestablishment of aquatic vegetation as it greatly contributes to water transparency in lakes and further outflow into the bay (Bachmann et al. 2002, 2004; Moreno Madriñán 2010, 2011).

As it is widely reported in literature, agriculture is a major factor causing increased water turbidity (Harding et al. 1999; Schlosser and Karr 2007; Sharpley et al. 1994); therefore, the decrease in agricultural land in the watershed seems to agree with the overall decreasing water turbidity trend (Fig. 4). Such decrease in water turbidity also coincides with a consistent decrease in Scrub\shrub land across all major sub-watersheds (Tables 2 and 3; Fig. 3), which seems further supported by a positive regression slope between these two parameters in Figs. 6a, b, that nevertheless is not statistically significant ($p>0.05$) due, as discussed earlier, to a low n available for the analysis. Other plots between water turbidity and the remaining LCLU classes studied did not show any type of pattern (Fig. 7).

6 Conclusions

Based on observations made in this study, characterization of LCLU across the entire Tampa Bay watershed for the time period between 1996 and 2006 revealed an increase in developed area followed by bare land and water. An area decrease was found in Agriculture, followed by scrub/shrub and wetland. Other LCLU classes showed less clear patterns. By the end of the study period, the predominant LCLU classes in the Tampa Bay watershed were wetland (34.3%), developed (21.7%), agriculture (18.7%), and water (16.1%). In less magnitude, other LCLU classes were grassland, scrub, bare land, forested, and unconsolidated (4.2%, 2.3%, 1.9%, 0.8%, and <0.1%, respectively). Comparisons between the different Tampa Bay sub-watersheds revealed some patterns that support what was observed when considering the entire Tampa Bay as a whole. An increase in developed area together with a decrease in agriculture, scrub\shrub, and wetland was consistent in all sub-watersheds (as in the entire Tampa Bay watershed).

Overall trends in water turbidity between 1996 and 2006 in four Tampa Bay major tributaries, as measured by monitoring sites near the point of discharge into the Bay, showed a decline in water turbidity. Yet, this result was not consistent in the monitoring site used for Manatee River presumably because the land draining into this site is just a subset of the Manatee River watershed that does not include the development land prevalent along the shoreline of the rest of this sub-watershed. Although there were important changes in LCLU in the Tampa Bay watershed, such changes cannot be explicitly ascertained as the primary cause for the declining trend in water turbidity, as no significant linear regressions were obtained in the expected relationships. This was presumably due to the small number of sub-watersheds with similar scales within the Tampa Bay watershed available for the study (n=4) and perhaps also conflicting effects between the different land classes. Nevertheless, the consistent increase in developed land and the reduction of agriculture and scrub\shrub seems to align well with the reduction in water turbidity.

In summary, this work identifies consistent changes in LCLU across the Tampa Bay watershed and decrease in water turbidity. This study suggests that development land (urbanization) on land adjacent to Tampa Bay and with low slope could be associated with decreasing water turbidity in Tampa Bay. Interference by competing factors may have been aggravated because the representation of some classes in the total area was too small, the opposing effects of some classes were mutually neutralized, or because of factors not related to LCLU. Water turbidity decreased despite the decrease in wetland and the increase in bare land, which could be due such competing factors. The theoretical effect of wetlands reducing water turbidity and that of bare land increasing it may have been counteracted by the consistent decrease in agriculture and in less extent by the increase in inland water and constructed lakes. The areas of forest and unconsolidated land compared with the total area as well as their changes seem to be too small to have a noticeable effect. Finally, although these results may also explain similar effects on other water bodies with similar conditions of adjacent urbanized areas with low slope, more analysis are needed considering a larger number of watersheds with similar scales and longer time period in order to confirm that the findings of this study are generally evident.

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