CHAPTER 7

Effects of changing land use on nutrient loads and water quality in a Southeastern US Blackwater River Estuary

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Abstract

Nutrient enrichment in the coastal zone is a world-wide phenomenon, driven by consistent increases in population and land development. In order to counteract the effects of eutrophication, it is important to use historical records to first determine baseline conditions within the affected water body. Then the sometimes difficult and expensive process of constructing a nutrient budget must be completed, which will account for the within-basin point and nonpoint-source nutrient loads. Once this has been achieved, environmental managers will have the information to effectively target point source reductions through regulation and nonpoint-source reduction through best management practices. We take the reader through this process using the Lower St. Johns River Estuary, Florida as a model system to show degradation of water quality over time concomitant with increases in population and changes in land use, culminating in a determination of both the anthropogenic nitrogen and phosphorus loads.

1 Introduction

Continual increases in population density in the coastal zone have had a dramatic effect on both the land use and consequent resultant water quality of many estuarine systems. Changes in land use not only lead to increased nutrient loading, but also shifts to increasing bioavailable nutrient forms. Eventually, the nutrient status of the water body increases to a point where it is difficult for water-resource

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managers to mitigate expressions of eutrophic conditions including algal blooms, low dissolved oxygen (DO) and resulting fish kills. We have used the Lower St. Johns River Estuary, Florida to demonstrate how coupled population increase and land-use change can affect water quality. Land-use change can affect the overall nutrient loads but also the proportion of bioavailable nutrients. Finally, we have constructed a nitrogen and phosphorus budget for the basin and compare current loads with a historical on (estimated predevelopment) to determine the anthropogenic nutrient load to the system.

The St. Johns River (SJR) is one of the largest blackwater rivers of the southeast U.S. A blackwater river has water whose color ranges from clear tea to coffee. The river is located in northeast Florida and drains about 1/5th of the state, encompassing a 9562 square mile drainage area. The river is slow moving, with a slope of only 1.4 in/mile [1], and is essentially at sea level for its final 125 mi. The lower St. Johns is the estuarine portion of the river, formed at the confluence of the middle St. Johns and the Ocklawaha River, and encompassing a 2750 square mile area (Fig. 1). Within this reach, the St. Johns River is slightly more that 100 miles long and has a water surface area, including tributary mouths below head of tide, of 85,000 acres. Major centers of population within the LSJRB include Palatka, a city of 10,700 at the southern entrance to the basin; Green Cove Springs, a city of 4700 at the midpoint; and the Orange Park, Middleburg, and Jacksonville metropolitan area, with a population of over 1 million, in the northern portion of the basin [2]. The LSJR is a sixth-order, blackwater river estuary, and, along its length, it exhibits characteristics associated with riverine, lake, and estuarine aquatic environments [3].

The LSJR is divided into three ecological zones based on salinity. The three zones are as follows: 1) a predominantly freshwater, tidal lake-like zone that extends from the city of Palatka north to the mouth of Black Creek; 2) an alternately freshwater and marine, oligohaline zone extending from Black Creek northward to the Fuller Warren Bridge in Jacksonville; and 3) a predominantly marine and much narrower zone downstream from I-95 to the mouth [4]. The slow moving, lacustrine nature of the river facilitates phytoplankton primary production, and spring and summer algal blooms in this nutrient-rich river often exhibit chlorophyll *a* concentrations exceeding 100 μg/L.

The southern portion of the lower basin is largely rural, with predominant land uses in forestry and row-crop agriculture. The northern portion of the basin is distinguished by the heavily urbanized cities of Jacksonville, Orange Park and Middleburg. Roughly three quarters (64–82 per cent) of the basin's highly developed land uses (medium and high residential, high-intensity commercial and industrial) drain to the oligohaline and mesohaline lower St. Johns. In contrast, 62 to 98% of the basin's agricultural land uses drain to the fresh tidal reach.

1.1 Water-quality problems

Due to a long history of development within the basin, and its associated water-quality problems dating back to at least 1947 [5], the LSJR was one of the State's originally identified Surface Water Improvement and Management Act [6] water bodies for restoration, and has been identified as a high-priority water body for the

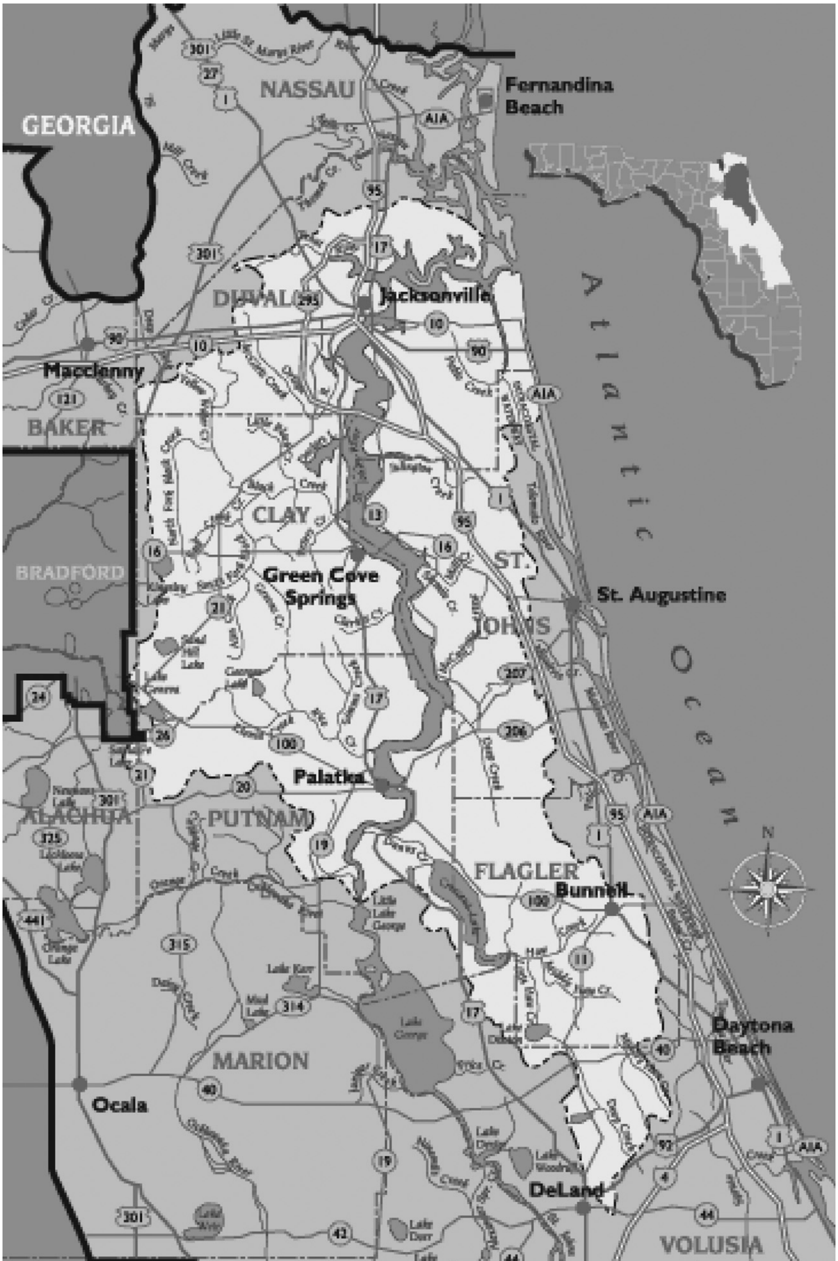


Figure 1: The Lower St. Johns River Basin showing population centers. The river flows through a series of connected lakes from south to the ocean outlet at Jacksonville, FL.

establishment of total maximum daily loads (TMDL) and pollutant-load-reduction goals (PLRG) to limit nutrient pollution.

Comprehensive external nutrient load assessments have been performed twice previously for the LSJR. In 1976, the firm of Atlantis Scientific [7], under authorization of the 1972 Clean Water Act Section 315, undertook a computation of the external load and concluded that point source comprised the majority of this load. Hendrickson and Konwinski [4] also computed the external load to the river for 1993–94, and concluded that nitrogen and phosphorus were 2.5 and 6 times greater than natural background respectively, with augmented nutrient loads (that load above natural background) approximately evenly split between point and nonpoint sources.

Accelerated eutrophication due to nutrient enrichment of estuaries represents one of the most significant water-quality problems faced by near-coastal waters world-wide [8]. Investigation into the effects of nutrient enrichment and elevated levels of algal biomass in the LSJR has, however, revealed noteworthy departures from the eutrophication paradigm established for other estuaries. The LSJR is, first, a blackwater river, with large amounts of allochthonous organic carbon and, at times, substantial light limitation to primary production imparted by colored dissolved organic matter. Also, in most river-mouth estuaries, algal production peaks in the broad, shallow zones that exist in the mesohaline reach, and is typically marine diatom-dominated. In contrast, the LSJR, due to its unique morphology, exhibits maximum algal standing stock in the upper, freshwater and oligohaline reaches. This morphology also results in a very different pattern in the zone of oxygen depletion; the most often cited manifestation of estuarine eutrophication [9]. Instead of the mesohaline zone vertical oxygen stratification typical of most eutrophic estuaries, the LSJR "dead zone" exhibits a stronger longitudinal character, with strong vertical mixing and top to bottom, long duration, and low oxygen levels.

Because of its broad, shallow shape and low flow – long residence time co-occurrence with spring and summer enhanced algal growth – the LSJR can exhibit prodigious amount of seasonal algal productivity and biomass. River flow, tide, and wind currents continually advect, disperse and diffuse algae, nutrients and salinity, with the result that the manifestations of nutrient loads frequently occur far from the source of entry. Changes in nutrient status, salinity, water-column light availability and water temperature bring about changing environments that seldom favor one particular algal group, so a succession of plankton communities is typically observed through the spring and summer growth seasons. Environmental stressors can at times be abrupt enough to lead to mass death in the algal community, leading to a sequence of water-quality characteristics with important implications for nutrient recycling, community change, and water-quality effects.

In addition to the elevated chlorophyll *a* values (algal blooms) and low DO levels, a number of widespread water-quality problems have been identified throughout the river that are indicative of an imbalance in the flora and fauna of the LSJR [10]. These problems include the following: a) fish kills; b) submersed aquatic shoreline vegetation covered in algal mats; c) excessive epiphyte growth further blocking light from submerged aquatic vegetation, d) anecdotal accounts of shoreline vegetation losses and reduced recreational fishing quality; e) river sediment conditions indicative of low benthic animal diversity; f) excessive organic matter sedimentation and prolonged anoxia; and g) the presence of potentially toxic dinoflagellates such as the *Pfiesteria*-like *Crytoperidiniopsoids* [11, 12], and *Prorocentrum minimum* [3], often co-occurring with fish kills or ulcerative disease syndrome in fish. All of these problems are connected by a common thread – they indicate accelerated eutrophication in an estuarine environment.

Numerous other studies have identified either high nutrient concentrations or eutrophic conditions [13–15] in the LSJR. In their assessment of nutrient loads to the LSJR and their potential effects, Hendrickson and Konwinski [4] determined the following: A combination of point- and nonpoint-source pollution has increased within-basin nutrient load to the LSJR 2.5 times over natural background for total nitrogen (TN) and 6 times higher for total phosphorus (TP). The areal nutrient loading is at 9.7 and 2.1 kilograms of nitrogen and phosphorus per hectare of watershed contributing area per year in the LSJRB, is one of the highest reported from studies in the southeastern United States.

It is clear that the LSJR receives high nutrient loads and is nutrient enriched, and that it exhibits the symptoms of estuarine eutrophication. While nutrient enrichment is not the only problem leading to impaired water quality in the LSJR, it is probably the most widespread and multifaceted.

2 Long-term water-quality trends

Few water-quality data exist for the St. Johns River prior to substantial levels of development. It is difficult to ascertain the point at which the St. Johns River Basin became developed to a degree that it exerted a significant effect on water quality. However, the sharp increase in the State's population that began subsequent to World War II appears to correspond to the earliest reports of water quality degradation (Fig. 2). Population density within the Basin upstream of Jacksonville remained relatively low until 1940. Between 1940 and 1950, the population within the basin increased by 39% [16].

By the time of the earliest, regular surface water quality monitoring efforts, beginning in the late 1960s, water quality in the middle St. Johns River appears to have already declined. Moody attributed this decline in Lake George to the occurrence of regular, severe algal blooms [17]. The principle factors leading to these algal blooms were believed to be: 1) upstream development and its concomitant nutrient enrichment through point- and nonpoint-source pollution, and 2) aquatic weed spraying to eliminate floating water hyacinth. There were clearly higher concentrations of blue-green algae in 1967 [17] than reported in an earlier study in 1939–40 (by Pierce [18]). Two water-quality sample events for Lake George, which were collected in July of 1967 and December of 1969 reported that in July, the sample contained 2.28 mg/L TN and 0.13 mg/L TP, while the December sample contained 1.3 mg/L TN and again, 0.13 mg/L TP.

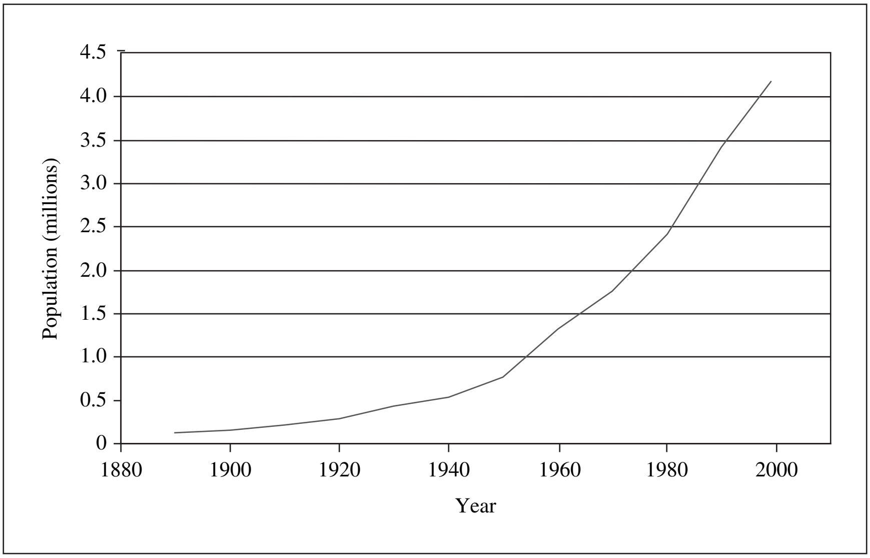


Figure 2: Population growth within the 14 Counties of the St. Johns River Basin, 1890–2000. Data from Dietrich [19] and University of Florida [20].

Three data sets have been identified that can help in understanding the nutrient status and hence open water ecology of the St. Johns prior to substantial development. The first of these is a study conducted by Pierce [18] reporting on several aspects of the water quality and plankton in the St. Johns River at locations in the Ocklawaha River mouth, in the river upstream and downstream of the Ocklawaha from September 1939 to November 1940. The second is the work of Odum [21] characterizing the phosphorus concentrations of waters of the State. The third study was published by the Florida State Board of Health in 1948 to determine the effect of untreated waste discharge in and around the City of Jacksonville.

The objective of the Florida State Board of Health study was to determine the effect of the discharge of untreated sewage in the vicinity of Jacksonville, and sampling stations were established in the St. Johns River near the city of Green Cove Springs to characterize upstream, background conditions. Two surveys were performed, the first conducted in May and June of 1945, and a second conducted from September 1945 to May of 1946. Though nutrient analysis was not performed, biological oxygen demand (BOD) and DO were examined and may be used to infer trophic status. Many of the reports' sampling stations were located in Jacksonville, which at the time was already significantly impacted, principally from the discharge of raw sewage. However, comparing the report's BOD data from the upstream, "un-impacted" site near the Shands Bridge to present-day concentrations at the same location suggests that water-column biodegradable organic matter has increased over time. The May–June survey produced what was referred to as a "highest average" (statistical methods were not explained in the report) of 0.83 mg/L; in comparison, the May–June mean BOD concentration at Shands Bridge from 1996 to 2000 was 2.14 mg/L. The September. 1945 to May 1946 survey produced a highest average concentration of 0.82 mg/L, while the 1996–2000 average is 1.43 mg/L for DO.

Under present-day conditions in the LSJR, algal biomass accounts for the majority of labile organic carbon in the river, and the relationship between BOD and chlorophyll *a* is highly significant, with chlorophyll *a* concentrations explaining over 70% of the variation in BOD (Chl-a = 14.39*(BOD) – 4.11; $R^2 = 0.71$). Based on this relationship, the 0.83 mg/L BOD measured in 1945 corresponds to a chlorophyll *a* of about 8 mg/m^3. Converting the present-day mean river color for this location to refractory organic nitrogen (assumes color has not changed; in reality, river color probably has declined somewhat due to basin development), and adding in the nitrogen content of algal biomass at 8 mg/m^3 chlorophyll *a*, a mean total organic nitrogen content of 0.48 mg/L can be calculated. With the inclusion of inorganic nitrogen, it would be expected from these BOD data that total nitrogen was in the neighborhood of 0.6 mg/L, comparable to the reconstructed historic Buffalo Bluff mean TN concentration of 0.687 mg/L.

The Odum [21] report to the Florida Geological Survey extensively surveyed orthophosphate and TP in surface waters around the State of Florida. Samples were collected at one time from many different locations, so annual trends cannot be inferred. These data for locations in the St. Johns River and its contributing streams are listed in Table 1. These data must be viewed selectively for the potential of anthropogenic nutrient contamination. For locations that likely still represented unimpacted reaches of the lower St. Johns River in 1952 (Lake George and Crescent Lake), these data suggest a concentration of TP of around 0.04 mg/L. Upstream of Lake Monroe (Brevard and Orange counties), the Odum data suggests a St. Johns River that was remarkably low in phosphorus.

Table 1: Total phosphorus concentrations determined for selected locations in St. Johns River Basin in 1952. Data from Odum [21].

Location	Date	TP, mg/L
Black Creek, Route 17	Aug. 9, 1952	0.04
Deep Creek, Hastings, Route 207	Jul. 14, 1952	0.54
Crescent Lake, Andalusia	Jul. 19, 1952	0.033
Doctor's Lake, Route 17	Aug. 9, 1952	0.065
Lake George at Silver Glen Springs	Aug. 14, 1952	0.044
Lake Monroe, Sanford	Jun. 23, 1952	0.18
Ortega River, Route 21	Aug. 9, 1952	0.044
St. Johns R., Crows Bluff, Volusia Co.	Sep. 3, 1952	0.117
St. Johns R., Palatka	Jul. 19, 1952	0.061
St. Johns R., Route 192 (Brevard Co.)	Jun. 23, 1952	0.007
St. Johns R., Route 50 (Orange Co.)	Jun. 23, 1952	0.015
St. Johns R., Green Cove Springs	Jul. 16, 1952	0.119

The data of Pierce [18], due to the length of his study and the comparatively large suite of measurements, provide compelling evidence of a river that was dramatically lower in nutrients and algal biomass. In 1939–40, Pierce reported blue-green algae (of the genera *Anabaena*, *Raphidiopsis* and *Microcystis*) ranging from too few to count for most months, to 36,000 cells/ml in August of 1940. In comparison, the annual mean peak blue-green cell count exiting Lake George for 1997–2000 [22] was significantly higher at 518,893 cells/ml. The Pierce [18] study also suggests a shift in the dominance of phytoplankton groups, with diatoms (primarily the genera *Coscinodiscus* and *Melosira*) formerly making up a much greater relative portion of the plankton.

The Pierce [18] study also provides data on nitrogen forms throughout the year (analysis for phosphorus was not performed) Due to some differences in methodology and uncertainties regarding sample handling and preservation techniques, only TN concentrations are compared. Pierce reported mean annual TN as 0.41 mg/L in Little Lake George (upstream of the Ocklawaha mouth), and 0.37 mg/L at Welaka (downstream of the Ocklawaha), values that are roughly one quarter of present-day concentrations. The Pierce TN numbers are similar to the present day estimated mean concentration refractory total organic nitrogen at Buffalo Bluff, of 0.46 mg/L.

Unaccounted for in the water-column measurements of these studies is the sequestration of nutrient in water hyacinth *(Eichornia crassipes)*. Water hyacinth, introduced to the St. Johns shortly before 1900, quickly spread through the river, and anecdotal accounts prior to 1940 indicate widespread coverage. Annual reports to Congress on the progress of hyacinth control in the St. Johns [23] indicate that between 3000 to 13,000 acres of hyacinth were removed annually, suggesting that at least 5 to 10% (based on the sum of lake surface areas of the St. Johns from Lake Winder through Little Lake George) of the rivers water surface area typically may have been covered.

These studies suggest substantially lower water-column nitrogen and algal biomass, and marginally lower phosphorus concentrations prevailed in the predevelopment St. Johns River. If the concentrations of TN of 0.6 mg/L and TP of 0.04 mg/L are accepted as representative of water column (including floating macrophytes) natural background levels, then nutrients flowing into the lower St. Johns River from the upper and middle St. Johns and Ocklawaha Rivers today appear to be elevated between 1.5 to 4 times above predevelopment conditions.

Persistent, low concentrations of dissolved oxygen in the meso/polyhaline reach of the LSJR are a well-documented but poorly understood phenomena. First studied intensively in the 1950s, these occurrences were attributed to the discharge of untreated domestic sewage and industrial waste [24]. Despite large improvements in point-source treatment, the occurrence and severity of these episodes has remained unchanged over time.

3 Nutrient sources within the Basin

3.1 Point sources

Domestic wastewater facilities that discharge to surface waters are concentrated along the St. Johns River from Green Cove Springs to its mouth north of Jacksonville, and farther south near Palatka (Fig. 1). The largest domestic treated wastewater dischargers in the basin are the wastewater treatment facilities associated with the city of Jacksonville in the northern (downstream) end of the basin, including the Buckman Street, Arlington East, JEA District II, Southwest District, and Mandarin wastewater treatment facilities. Several of these facilities participate in reuse programs, and most are actively seeking ways to either include or improve nutrient-removal treatment [4, 25].

All domestic wastewater facilities discharging to the St. Johns River are required, at a minimum, to monitor for conventional pollutants such as total suspended solids (TSS), carbonaceous biological oxygen demand ($CBOD_5$), and fecal coliforms bacteria [25]. While most permits do not include nutrient effluent limits, nutrients must be monitored in many systems because of their potential negative effects on surface water, including their role in the formation of nuisance and harmful algal blooms.

Large industrial dischargers in the basin include power plants, pulp and paper mills, chemical plants, and manufacturing plants. The majority of industrial plants send their process wastewater through pretreatment facilities to publicly owned treatment works (POTWs). Facilities with significant nutrient discharges to the main stem of the LSJR include the Georgia-Pacific Corporation (which produces bleached and unbleached pulp and paper), Stone Container (which changed from a pulp and paper mill to a recycling mill in the 1990s, reducing the volume of discharge), and Anheuser-Busch (a brewery). Remaining discharges include nonprocess wastewater such as cooling water, softener regenerate, and boiler blowdowns, which do not contribute a significant nutrient load.

3.2 Nonpoint sources

Nonpoint sources of nutrient loading to the LSJR include septic tanks, marinas, silviculture, row-crop agriculture, dairies, stormwater from urban development and tributaries (including Black Creek, Dunns Creek, Deep Creek, Rice Creek, Julington Creek, Trout Creek, Sixmile Creek, Governors Creek, Clarkes Creek, Cedar Creek, Camp Branch, Mill Branch, and Dog Branch). Unlike traditional point-source effluent loads, nonpoint-source loads enter at so many locations and exhibit such large temporal variation that a direct monitoring approach is infeasible, except for the largest, most significant inputs. Those largest inputs are the upstream boundary of the LSJR at Buffalo Bluff, Dunns Creek, and the downstream boundary at the Atlantic Ocean.

4 Population trends

Between 1940 and 1950, the population within the basin increased by 39% to approximately 0.75 million people [16] (Fig. 2). Since 1950, the population has increased by an average of 0.7 million per decade rising to the year 2000 total of approximately 4.2 million. Such a dramatic increase in population is going to invariably lead to changes in land use as well as increased nutrient runoff associated with point and nonpoint discharges.

5 Land use and effects on water quality

Since 1973, there has been a pattern of shifting land use from more rural to more urban land use (Fig. 3). There has been a steady decline in forested/undeveloped land which comprised the majority of the land use in the basin at 73%. By 2005, this land-use category has declined to 59% of the basin in 1973. The land-use categories of both urban and agricultural lands made up similar percentages (13–14%) (Fig. 3). However, due to the increase in population, the urban land use has increased dramatically and comprised 32% in 2005. Approximately 5% of the land was conversion from agriculture to urban land use with the remainder coming from the forested/undeveloped category. In tracking land-use changes based on the 1973 survey, we can see that% urban has steadily increased to 120% more with no indications that this conversion has peaked (Fig. 4). It is likely that this trend will continue.

Land development influences the delivery of water-quality constituents to surface waters in two fundamental ways. Through fertilization, lawn maintenance, manure spreading, septic-tank operation, vehicular use, etc., nutrients and other pollutants are added to the land surface or to shallow groundwater in excess of natural land-cover conditions (i.e. native forest, wetland). Unlike the situation that tends to predominate on developed lands, natural land covers are highly conservative of

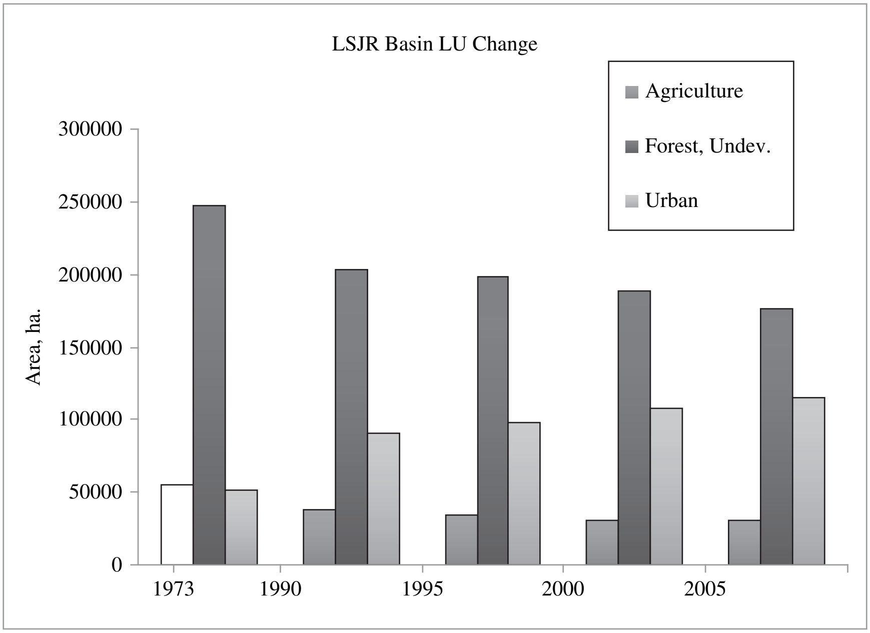


Figure 3: Land use (LU) changes from 1973–2005 for the Lower St. Johns River Estuary from 1973–2005.

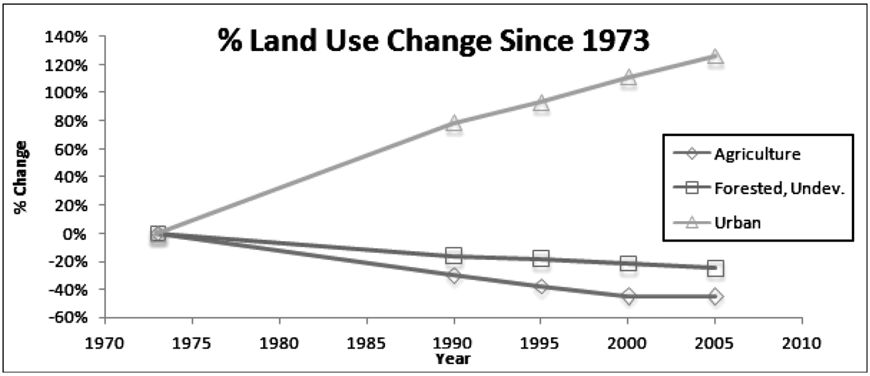


Figure 4: Percentage land-use change for agriculture, urban and forested/undeveloped. Percentage increase is based on the 1973 land-use assessment.

essential growth nutrients, and thus labile nutrient forms tend to be retained within these terrestrial ecosystems. In addition, the creation of impervious surfaces, drainage development, and the destruction of near-stream wetlands increases the amount of rainfall that ultimately ends up as runoff, thus increasing the pollutant-exporting capability in developed landscapes. Thus, the process of nonpoint-source pollution has both chemical and hydrologic components.

The effects of changing land use on both total and bioavailable nutrients is best demonstrated in a comparison of TN, which includes total inorganic N, labile organic N and refractory organic N components. Consider the basin comparison between natural forested land and mixed urban/commercial/residential watersheds. The difference may be a concentration increase of 214% from natural to urban land use (Fig. 5). However, the relative proportion of the total N has also changed such that when you pool the bioavailable pools (total inorganic + labile organic N), you have a net increase of 663% in the bioavailable pool [26]. This pool of N is what leads to expression of eutrophic conditions in coastal areas. Due to the higher relative amounts of labile nutrients in developed landscapes, deleterious nutrient load often exceeds that which would be inferred by absolute increases in nutrients alone.

6 Determination of a nitrogen and phosphorus nutrient budget

There are several components of the nutrient load that need to be assessed to determine the overall nutrient budget (the basin point-source load, the basin nonpoint-source load, and the upstream nutrient load). This is a vital first step in any eutrophic coastal area, especially for water management to determine the best course of action in mitigating nutrient loads. Once the source loads are identified, there will need to be a determination as to which loads can be most readily decreased in a cost-effective manner to yield the greatest benefit on the resultant water quality.

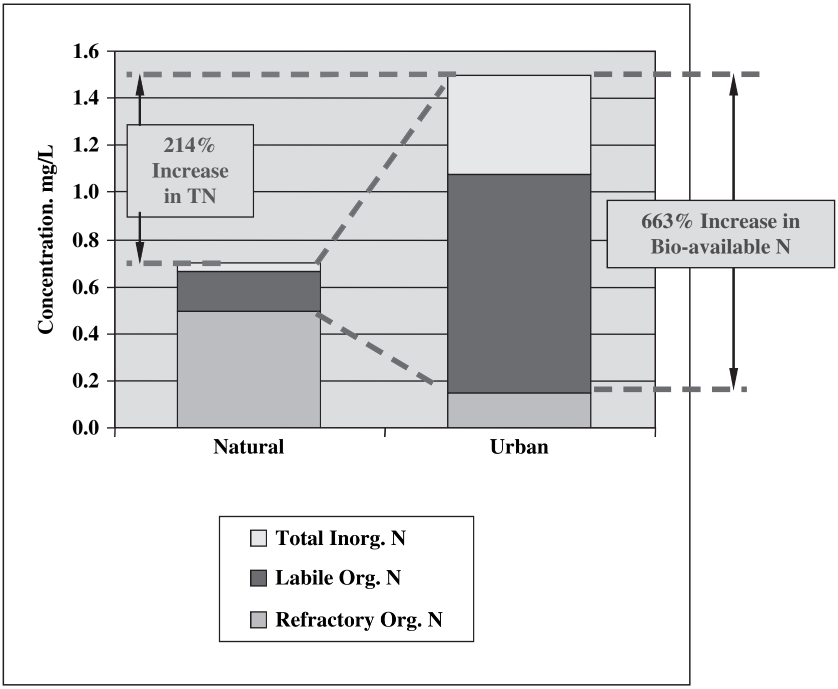


Figure 5: Comparison of total and bioavailable nitrogen forms in runoff from natural forested and mixed urban/commercial/residential watersheds.

While nitrogen is the primary nutrient of concern in coastal eutrophication, the morphology and hydrodynamics of the Lower St. Johns River estuary are such that there are regions of saline, fluctuating saline-oligohaline, and tidal-influenced freshwater zones. Therefore, phosphorus, which is generally limiting in freshwater systems, is likely an important contributor to the eutrophication status of the estuary and should therefore be accounted for in the nutrient budget.

6.1 Point sources

For the Lower St. Johns River Estuary, the point-source load estimation was performed using six separate data sets to gain available information on concentration, flow, point of discharge and service area. These data sets included 1) hard copy monthly operating report files maintained at the Florida Department of Environmental Protection (FDEP) Northeast District Office; 2) National Pollutant Discharge Elimination System (NPDES) electronic files obtained from FDEP Tallahassee; 3) Discharge quality data maintained by the Jacksonville Electric Authority; 4) Fifth-year synoptic surveys performed by FDEP or by contractor as part of permit renewal process; 5) a special 2-year sampling program conducted jointly by FDEP and Saint Johns River Water Management District (SJRWMD), and 6) a GIS data base of locational information.

6.2 Nonpoint sources

Unlike point-source effluent loads, nonpoint-source loads enter at so many locations and exhibit such large temporal variation that a direct monitoring approach is infeasible except for the largest, most significant inputs. At all other nonpoint entry points, statistical watershed modeling was relied upon to complete the external load budget. The watershed modeling approach used utilizes the relationship between land-use development and alteration in water quality and quantity to perform a spatial extrapolation of whole-basin nonpoint-source load. The formulation of this statistical model has its roots in the spreadsheet watershed load screening model, referred to as the pollution-load-screening model, which utilizes a computer-driven geographic information system framework to calculate constituent loads as the product of water-quality concentration associated with certain land-use practices, and runoff water volume associated with those same practices. The model's nonpoint-source pollutant export concentrations are specific to one of 15 different land-use classes. Water quantity is determined through a hybrid of the Soil Conservation Service (SCS) curve number method, and is the product of rain volumes and a coefficient (referred to as the runoff coefficient, or RC, with values ranging from 0 to 0.9) relating the propensity of various land-use and soil hydrologic group combinations to generate runoff. The computational approach of the PLSM is similar to that of the surface-water-management model (SWMM) screening level tool.

6.3 Upstream load

The upstream load is composed of the three large tributaries that make up the lower St. Johns: the middle St. Johns River, the Ocklawaha River, and Dunns Creek. These three tributaries make up approximately 61, 21, and 18 per cent of the long-term annual mean river discharge at Palatka. Because of autochthonous production in upstream lakes, the upstream load differs greatly from watershed loads that enter within the LSJR basin.

Because of the large amount of the entire LSJR flow that enters upstream (roughly 60%), a direct monitoring approach, featuring continuous measurement of discharge, and biweekly collection of water-quality samples, has been used to determine its constituent load. This is in contrast to the aforementioned watershed modeling approach that has been used to develop the downstream tributary load.

6.4 Nutrient budget

Compiling all available historical data and results of recent nutrient assessment, we can begin to understand the Lower St. Johns River Estuary nitrogen and phosphorus

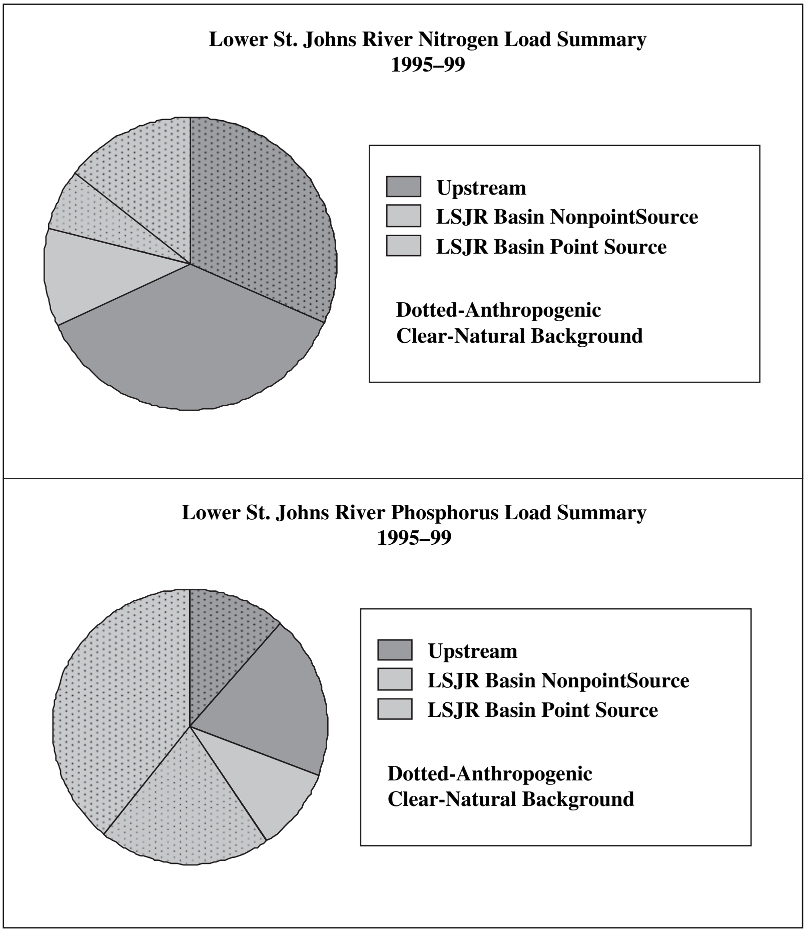


Figure 6: Nitrogen and phosphorus budgets for the Lower St. Johns River Estuary including the within basin point- and nonpoint-source loads and the upstream contributions.

budgets. For nitrogen, the largest component enters from upstream at 69% (Fig. 6). The within-basin contributions are split between point source (24%) and nonpoint-source (17%). From modeling efforts and historical data sets, we have been able to reconstruct the historical N loads. It is estimated that 50% of the upstream load is anthropogenic, due to human affects on the system. All the point-source additions are anthropogenic and approximately 55% of the nonpoint-source is anthropogenic. Consequently, 58% of the total nitrogen load to the Lower St. Johns River estuary is due to the additive effect of the human population and associated land-use changes to support that population.

The phosphorus budget has a different overall proportion when compared to the nitrogen budget. Only 31% of the phosphorus budget enters the basin from upstream. Another 30% includes the nonpoint-source contribution and the final 39% makes up the point-source discharges (Fig. 6). Clearly, reducing phosphorus concentrations may prove to be an easier task as municipalities generally have greater control and restrictions on point-source pollution.

The anthropogenic component of the phosphorus load includes 100% of the point sources, 33% of the nonpoint-source additions and 39% of the upstream load. Overall, the population and land-use changes have more than doubled the phosphorus load to the Lower St. John River estuary.

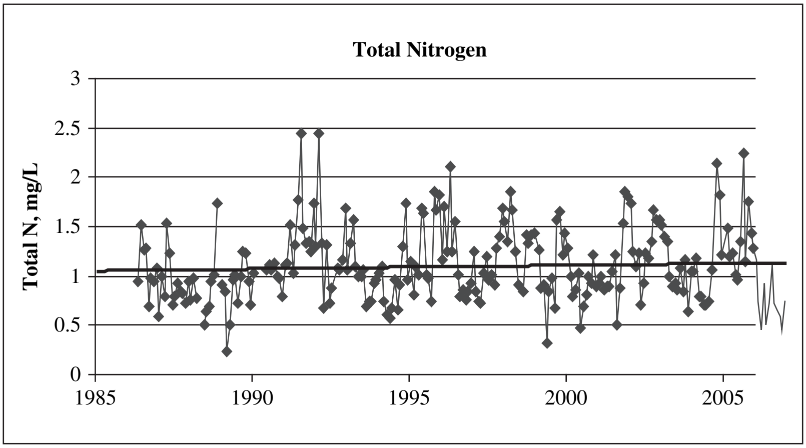
6.5 The internal or sediment load

The sediments of the Lower St. Johns River Estuary have become enriched with N and P as organic material associated with repeated algal blooms has settled to the bottom. Consequently, over time, there will be a release of N and P through mineralization or decomposition of this organic material that will continue to be a source of bioavailable nutrients to the water column. In a recent study, it was determined that the potential for sediment released NH_4-N was 2066 Mg/yr and 330 Mg/yr for dissolved reactive P [27]. Based on previously published nutrient load calculations [4], the sediment can potentially produce 28% of the total N loading and 21% of the total P loading from the watershed. Since this internal load is entirely in the bioavailable form, this internal load might exert an even greater influence on the nutrient dynamics of the estuary over time.

7 Effects of oceanic dilution on water quality

There have been numerous initiatives over time to counteract the changes in land use, high nutrient concentrations and the eventual expressions of eutrophication in the Lower St. John River Estuary including tighter permit restrictions on point source for both nitrogen and phosphorus and best management practices for agricultural lands in order to intercept nutrient runoff. When examining data on the total N and P of the estuary at Jacksonville, Fl, we observe no discernable increase in either N or P over the past 20 years, suggesting that initiatives to reduce loading have been successful in spite of the ever-present changes in land use and increases in population over that time (Fig. 7). The data show dramatic variability due primarily to the episodic nature of the rainfall patterns, where approximately 75% of the precipitation falls within about 5 months, which will affect both the upstream and nonpoint-source nutrient loads.

However, evidence suggests that this period of record is a particularly dry one with precipitation well below normal. Consequently, as an estuary, the ocean can exert significant influence due to the higher tidal amplitude and the very slow slope of the land and river. With low freshwater flows, a greater dilution by seawater can



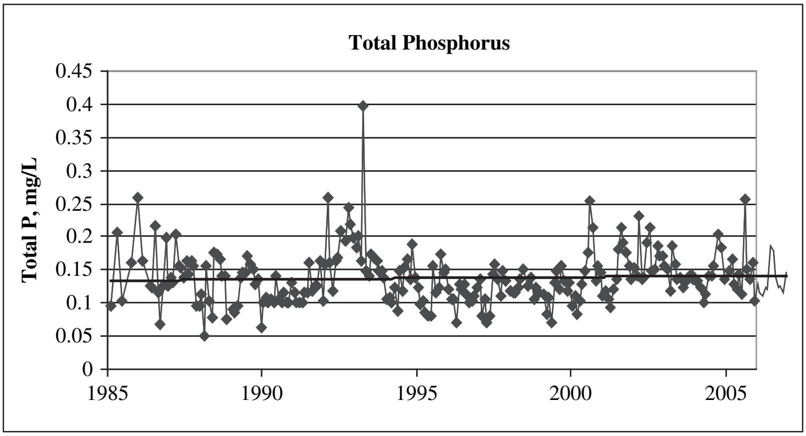
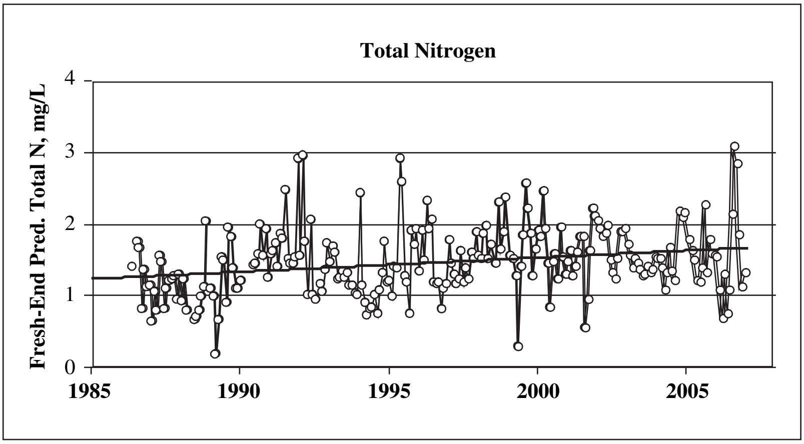


Figure 7: Total nitrogen and phosphorus for water samples collected at Jacksonville, Florida from the Lower St. Johns River estuary.

occur that can confound interpretation of the effectiveness of nutrient mitigation protocols on the nutrient status of the river.

In order to investigate this particular possibility, we have attempted to determine the effect of dilution of the river water by seawater over this 20-year timeframe. Using a fairly stable ocean concentration of N and P of the oceanic end member of the water and determining the amount of mixing within the estuary based on the salinity over time, we have been able to determine the concentration of the freshwater runoff from the basin into the river. In fact, when we subtract out the ocean mixing end member and plot the predicted freshwater end member for both N and P, we can see a more predictable pattern of increasing concentrations associated with the aforementioned changes in population and land use (Fig. 8). This trend suggests



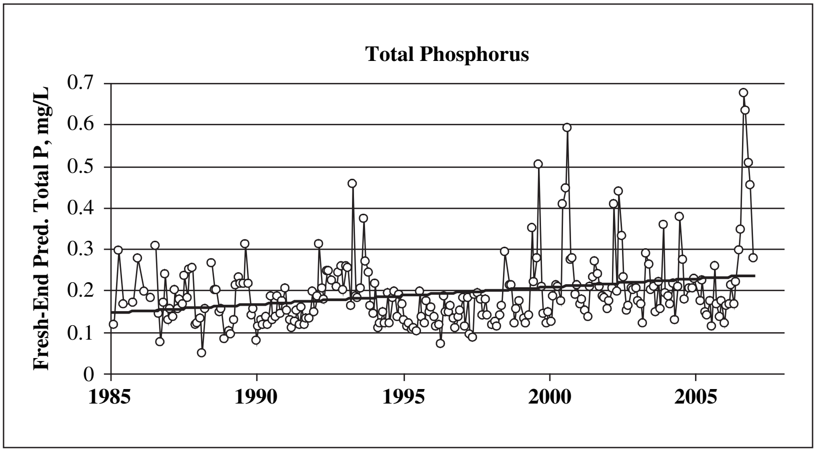


Figure 8: Calculated freshwater total nitrogen and phosphorus concentration for water samples collected at Jacksonville, Florida from the Lower St. Johns River estuary. The *y*-axis is the freshwater end-member predicted concentration for the watershed point- and nonpoint-source contributions subtracting out for dilution by the ocean tidal pulses and upstream contributions.

that despite best efforts to reduce nutrient loading to the estuary, the N and P concentrations of the runoff continues to increase.

8 Conclusions

The ever-increasing population in the coastal zone has had a marked effect on estuarine water quality around the globe. A concentration of people and associated land-use changes lead to anthropogenic point- and nonpoint-source discharges of nutrient into adjacent surface waters. These aquatic systems respond very quickly to these nutrient additions with similar expressions of eutrophication found in the St. Johns River Estuary including, low DO, increased algal blooms and associated fishkills.

In order to restore water quality back to some preimpact level, quantifying the contributions of the various nutrient sources in the coastal zone is an important step. This can be a difficult, time-consuming and expensive process. However, it is a critical first step in attempting to reverse the effects of eutrophication. Once both the source and forms of nutrients are known, efforts can be focused on those sources over which we have the greatest control and can make the largest impact. Specific land uses can be managed to reduce the increasingly bioavailable nutrient load. Additionally, as the population continues to increase and land use is impacted in the coastal zone in the future, the ability to identify and target specific nutrient loads may prove valuable in maintaining or improving water quality in the face of significant population pressure.

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