Annual Salinity and Nutrient Budget of Lake Pontchartrain and Impact of the Proposed Bonnet Carré Diversion

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ABSTRACT: A nutrient mass balance identifies the total mass load of the nutrient entering a waterbody, loss across the downstream boundary, and the rate at which the material is synthesized or lost within the waterbody. Nutrient budgets for total phosphorus (TP) and total nitrogen (TN) were developed, along with budgets for lake salinity and volumetric water flows. The analyses reported here were initiated to support the evaluation of a proposal to divert a small fraction of Mississippi River discharge through Lake Pontchartrain. These analyses determine the sensitivity of Lake Pontchartrain to nutrient loading, and provide a basis for development of more complex hydrologic and water quality models. Discharge and nutrient loading data have been analyzed using simplified formulas which predict annual average nutrient concentrations within the Lake. For other aquatic ecosystems, this simplified analytical approach has often proven to be a valuable management tool in support of environmental decision making. Total freshwater inflow, Q_T, is estimated to be 13.2 km^3 yr^{-1}, or an annual average inflow of 419 m^3 s^{-1} (14,800 cfs). The proposed diversion would increase freshwater inflow by 6.6 km^3 yr^{-1}. Average residence time is projected to drop from 102 d to 76 d following implementation of the diversion. In Lake Pontchartrain, projected annual average TP and TN concentrations without the proposed river diversion project are 0.060 mg-P l^{-1} and 0.65 mg-N l^{-1}. With the proposed diversion these concentrations are projected to rise to 0.071 mg-P l^{-1} and 0.86 mg-N l^{-1}.

Introduction

There is a need for simple quantitative assessment tools for evaluating the impact of nutrient additions on lakes and estuaries. In the U.S., the Clean Water Act requires the determination of the total maximum daily load (TMDL) of nutrients and other potential pollutants, and the allocation of these loads among point and nonpoint sources within a watershed. To this end, EPA has developed wasteload allocation guidance for TMDL determinations for control of eutrophication in lakes and impoundments (Mancini et al. 1983). This EPA guidance reviewed and was based on the extensive earlier work of Vollenweider (1976) and others. Here, as far as possible, we have followed this guidance. This study provides a case study for the application of these techniques to an estuary, and illustrates which factors must be included to extend the procedures of Mancini to coastal waters.

A proposed Mississippi River diversion at the site of the existing Bonnet Carré Floodway led to public concerns about the potential eutrophication of Lake Pontchartrain. This river diversion was designed to reduce salinities in oyster beds near the Mississippi State border, beyond the downstream

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boundary of this study. Although alternative diversion discharge schedules have been considered during project re-evaluation, only the monthly diversions proposed in the general design memorandum (GDM) are analyzed in this paper (United States Army Corps of Engineers 1990). Monthly GDM diversion discharges from January through December are 0, 0, 306, 850, 473, 413, 91, 74, 57, 156, 91, and 0 $m^3 s^{-1}$. The GDM discharges are higher than those proposed in other plans which have been considered since the publication of the GDM. Thus, the GDM provides a maximum diversion scenario, and diversions of smaller size should have proportionately smaller impacts.

Ideally, a nutrient budget analysis considers total nutrient concentration, incorporating all biologically available forms of the nutrients, including nutrient which has been sequestered or incorporated into planktonic biomass. Total phosphorus (TP) analysis (American Public Health Association 1992) provides such an estimate, but may in some instances also include P which is unavailable. Total nitrogen (TN) is not directly measured, and must be calculated as the sum of measured components. Total Kjeldahl nitrogen (TKN) measures the concentration of organic nitrogen and ammonia nitrogen (Metcalf and Eddy Inc. 1991; American Public Health Association 1992). Therefore, TN is estimated as the sum of TKN, and nitrate plus nitrite N. In rivers and estuaries with short displacement time, both TP and TN may often be adequately modeled as conservative materials. In lakes and estuaries with long displacement time, it is unlikely that such a conservative model would be adequate because both TP and TN loss within the waterbody are significant relative to hydraulic displacement.

Methods

Site Description

Lake Pontchartrain is located in southeastern Louisiana. Lake Maurepas, a smaller coastal lake, lies upstream of Lake Pontchartrain. These lakes are hydrologically connected by a short waterway named Pass Manchac. At its downstream boundary, Lake Pontchartrain connects to Lake Borgne and the Mississippi Sound through Chef Menteur Pass and Pass Rigolets. Circulation is driven primarily by wind, rather than by river discharge or tidal exchange (Stone et al. 1972; Gael 1980). The long retention time of Lake Pontchartrain compared to other Gulf Coast estuaries (Solis and Powell 1999) and limited tidal exchange (Swenson 1980) reduce the spatial variation of salinity and nutrients within Lake Pontchartrain. These characteristics make Lake Pontchartrain well suited for the analytical methodologies developed for lake nutrient budget analysis. The Lake Pontchartrain watershed (14,490 km^2) drains a large area of southeastern Louisiana and a smaller area of Mississippi. The potential sources of freshwater input, including drainage basins, open water areas, pumped stormwater from the New Orleans area, and the proposed diversion were numbered (Figure 1). Sub-basin drainage areas were reported by Sloss (1971) and Earl (1992).

Freshwater Inflows

The U.S.G.S. maintains continuous discharge records on the major streams in the Lake Pontchartrain Basin (Arcement et al. 1993). Monthly mean gaged discharges for the period-of-record were used as the basis for monthly discharge estimates. The period-of-record for these discharge statistics ended with water year 1992. Stream gaging stations used in this study are located on the Amite River near Denham Springs, the Tickfaw River at Holden, the Tangipahoa River at Robert, and the Pearl River near Bogalusa. Drainage areas associated with these gaging sites are respectively 3,315 km^2, 640 km^2, 1,673 km^2, and 17,024 km^2. Conventional discharge gage sites must be located where a stable and sensitive stage-discharge relationship exists, often well upstream of the mouth. Additionally, small drainage sub-basins have no appropriate gaging site. Thus, gaged discharge from the Lake Pontchartrain Basin (excluding the Pearl River Basin) represents only 39% of the total Basin area. Runoff, stream discharge per unit of watershed drainage area, is commonly used to extrapolate discharge to ungaged areas. Average monthly runoff calculated for each gaging station provides a basis for estimating average monthly discharge from each Lake Pontchartrain sub-basin by multiplying the most appropriate gaged runoff by the sub-basin drainage area.

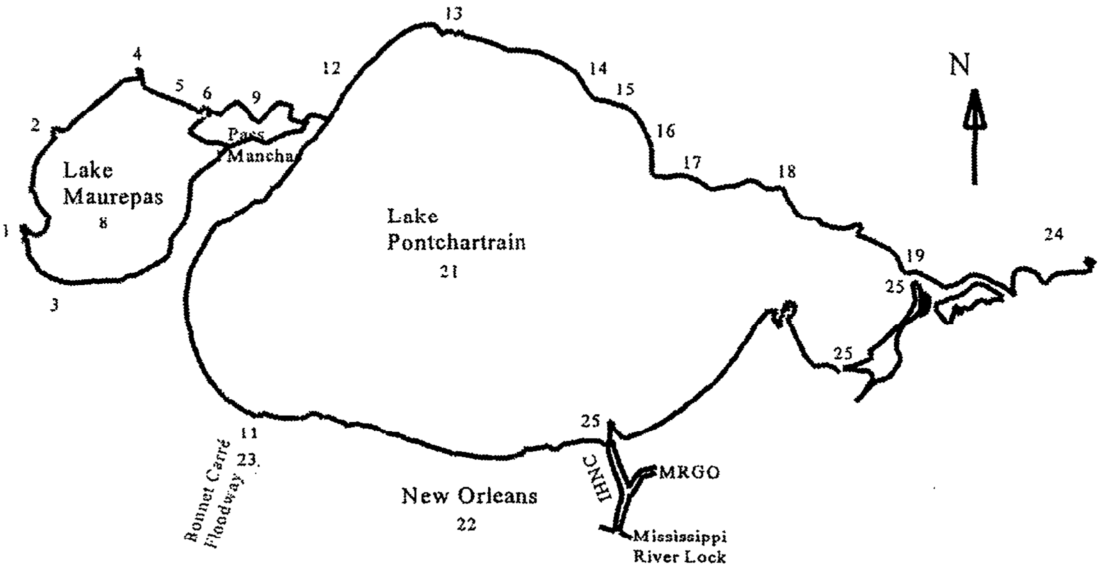

Figure 1. Map of Lake Pontchartrain system with loading sources indicated by numbers.

Freshwater inflow to Lake Pontchartrain must include not only all tributaries, but also some fraction of the Pearl River flow (Sikora and Kjerfve 1985). The mouth of the Pearl River is located just outside of Lake Pontchartrain at Pass Rigolets, and therefore contributes a part of its flow to the Lake during each tidal cycle. Assuming a symmetrical tide cycle, this fraction must be less than half, and for the purposes of this analysis one third of the Pearl River flow was assumed to contribute to the freshwater inflow and nutrient loading of Lake Pontchartrain.

Discharge from leakage through the existing Bonnet Carré spillway structure was estimated to be 15% of the flow and load of the proposed diversion. Nutrient loading from the proposed structure has been adjusted to include the anticipated load reduction that will result from operation of the sedimentation basin (Benndorf and Klaus 1987; Putz and Benndorf 1998). Based on an estimate that 30% of the sediments will be removed within the sedimentation basin, it is assumed here that this will result in a 20% reduction in TP, and a 10% reduction in TN loading from the proposed Mississippi River diversion.

An alternative method was used to estimate pumped urban stormwater inflow. The runoff coefficient is the ratio of runoff to rainfall, and can provide an estimate of runoff in ungaged watersheds (Mancini et al. 1983). Runoff coefficients typically vary between 0.1 and 0.6, with increasing values being associated with increased impervious ground cover in the drainage basin (Bowie et al. 1985). Total annual runoff values indicate that considerably less than half of the average annual rainfall of 156 cm (Louisiana Office of State Climatology) is discharged as runoff from the watershed. East Bank Jefferson Parish stormwater pumping stations records for 1988 indicate an annual runoff coefficient of 0.5 (Earl 1992, Volume 2, page 5-22). Total average monthly discharge from the New Orleans area pump stations were therefore estimated as 50% of the average monthly rainfall falling over the pumped drainage areas (Earl 1992, Volume 2, page A7). Estimated drainage areas (Jefferson Parish 131 km^2, Orleans Parish 134 km^2) and water quality of pumped runoff were also obtained from Earl (1992, Tables 5-6 and 5-7).

Nutrient Concentration and Loading

The Office of Water Resources of the Louisiana Department of Environmental Quality (LDEQ) maintains a statewide water quality monitoring network. This fixed station, long-term surface water quality monitoring network currently provides data from 186 monitoring sites. Sampling and laboratory procedures follow extensive quality assurance plans available from LDEQ. Field measurements and samples are collected at one meter or, in shallow streams, at half depth. Laboratory nutrient analysis is performed on whole water samples and generally follows Standard Methods (American Public Health Association 1992). Data from 28 of these sites were used in this assessment. Most sites have more than 10 years of data, and many have been monitored for more than 20 years. Most sites are monitored on a monthly basis, however some newer sites are monitored on a bimonthly basis. The period-of-record utilized here ends in August 1993.

An environmental organization voiced a concern during comments on the early plans for the reevaluation of the Bonnet Carré diversion project. It was suggested that pollutant levels may have increased over past decades, and load calculations in this study should be representative of present conditions. Bahr (1983) also concludes that P loading has increased over past decades. Therefore, in this study, monthly mean concentrations, used here in load calculations, were calculated from observations more recent than January, 1985. This should both provide an adequate number of monthly observations, and also reduce the influence of any long-term trends in concentration which may exist because of land use changes or other historical factors.

The term load or loading rate is the rate at which mass of substance is entering a waterbody through point sources, nonpoint sources, or tributary inflow. Regardless of temporal, spatial, or dynamic complexity, all models of nutrients and eutrophication require the development of nutrient load estimates. The load (mass/time) of a substance entering a system through water inflow is calculated from concentration of the substance (mass/volume) multiplied by the stream discharge (volume/time). Concentration and volumetric inflow or stream discharge for each source of water entering the waterbody are necessary components of a load estimate. It must also be noted that average values for concentration and discharge must be used with some care in calculating loads because, in general, the average of the product of two variables does not equal the product of their averages. Consequently, the product of average annual discharge and average annual concentration may provide inaccurate estimates of average annual load. In order to reduce this undesired effect, monthly average loads were here calculated and summed to develop annual average load estimates.

Simplified Model Analysis

Following Mancini et al. (1983) we represent Lake Pontchartrain as a single well-mixed compartment. Assuming a first order loss term corresponding to net sedimentation:

$$\frac{d(c_t V_t)}{dt} = W_t - (Q_t + K_s V_t)c_t \qquad (1)$$

where t = time and subscript t denotes time dependent variables;
c = concentration within the waterbody;
V = volume;
W = sum of all mass loads including all internal waterbody sources;
Q = total of all volumetric flows into the waterbody;
and K_s = net sedimentation rate.

The long-term average value of the left hand side of Eq. 1 should approach zero. This yields a result analogous to the steady-state solution of Eq. 1:

$$c = \frac{W}{Q + K_s V} = \frac{W/V}{\rho + K_s} \qquad (2)$$

where ρ = Q/V, the hydraulic displacement rate; and all variables in Eq 2 are averaged over a period which is long relative to $1/(\rho + K_s)$.

The hydraulic displacement time, $\tau = 1/\rho$. Loading rate comparisons among waterbodies is facilitated by normalizing Eq. 2 for water surface area:

$$c = \frac{w'/z}{\rho + K_s} \qquad (3)$$

where w' = load divided by surface area;
and z = mean waterbody depth.

The occurrence of salinity within Lake Pontchartrain demonstrates that in addition to the freshwater inflows, there is a net saltwater inflow, Q_B, entering from the downstream (seaward) boundaries. The method applied here to estimate Q_B is a variation of the "fraction of freshwater method" reviewed in Bowie, et al. (1985, page 43-44) and by Solis and Powell (1999), and utilized by Swenson (1980) in estimating Lake Pontchartrain retention time. Average salinity, S, represents a special case of Eqs. 1-3, with K_s=0, and the salinity load W= Q_BS_B. where S_B is the boundary water salinity. This assumes that the salinity of the freshwater inflow is negligible. Average total inflow, Q, equals the sum of the average total freshwater inflow, Q_T, and Q_B. From Eq. 2, average salinity is:

$$S = \frac{Q_B S_B}{Q_B + Q_T} \qquad (4)$$

Results

For Lake Pontchartrain, area (A) is 1637 km^2 (Sloss 1971), mean depth (z) is 3.4 m (Stone et al. 1972), resulting in volume (V) of 5.56 km^3. Including inflows as described earlier, Q=19.653 km^3 yr^{-1} under current conditions, and Q=26.252 km^3 yr^{-1} after the proposed diversion. Thus, τ= 0.28 yr (102 d) without the proposed diversion, and τ= 0.21 yr (76 d) after the proposed diversion.

Boundary salinity and nutrient concentrations can be estimated from the highest salinity values observed at the Lake Pontchartrain outlet monitoring sites, Chef Menteur Pass and Pass Rigolets. Over a period-of-record beginning in 1978, maximum salinity observed at these sites was 12.9 ppt, and the 95th percentile salinity was 9.8 ppt. It is assumed that the characteristics of the boundary waters entering the lake are similar to those which are present at the outlet sites under these conditions of elevated salinity. An estimate of the boundary salinity and concentrations was performed by averaging observations where salinity met or exceeded 9.8 ppt. Average salinity under this constraint was 10.8 ppt, and average nutrient concentrations were: TP=0.082 mg-P l^{-1}, nitrate plus nitrite=0.037 mg-N l^{-1}, and TKN=0.669 mg-N l^{-1}. Since 1985, average salinity was 3.6 ppt at the Lake Pontchartrain monitoring stations.

Average annual seawater inflow, Q_B, is estimated using Eq. 4 to be 6.44 km^3 yr^{-1}, or 33% of total inflow. Annual average total discharge is estimated to be 19.65 km^3 yr^{-1} (Table 2). Tributaries flowing from the watershed provide 36%, and the Pearl River is estimated to provide 20% of total inflow. The remaining 11% of flow is divided between urban pumped stormwater discharge, direct net precipitation, and leakage from the Mississippi River. With these results, the average salinity in Lake Pontchartrain after diversion can be estimated by including the diversion discharge in a recalculation of Eq. 4. Under the GDM diversion scenario average Lake Pontchartrain salinity is projected to decrease from 3.55 to 2.66 ppt.

Annual Loading and Areal Loading

Average annual TP and TN loads total 3,300 and 35,700 metric tons yr^{-1}, respectively (Table 2). Loading from the diversion is estimated to add 1,050 and 17,030 metric tons yr^{-1} of TP and TN. The TN:TP mass ratio of total nutrient source loadings is thus estimated to be 10.8 without the diversion, and 12.1 following the proposed diversion. A characteristic inflow concentration may be calculated by dividing total load by total discharge. For TP and TN this is 0.168 and 1.82 mg l^{-1} without diversion, and 0.166 and 2.01 with diversion. Areal loading is loading divided by waterbody surface area. Areal loading of TP rises from 2.02 to 2.66 g m^{-2} yr^{-1} after diversion, and TN rises from 21.82 to 32.22 g m^{-2} yr^{-1}.

Annual average LDEQ TP and TN observations (Table 1) in Lake Pontchartrain were 0.060 and 0.65 mg l^{-1}, respectively. A TP net sedimentation rate, K_s, of 6.4 yr^{-1} was determined by model calibration using Eq. 2 and substituting values of volume, discharge, TP load, and average Lake Pontchartrain TP concentration. Equation 2 then projects TP concentration following diversion implementation to be 0.071 mg l^{-1}. Simplified

Table 1. Average parameters at DEQ monitoring sites (1985-1993) by class (L. PON.=Lake Pontchartrain, M. RIV.=Mississippi River, OUTLET=Lake passes, TRIB.=tributaries).

		CLASS			
Parameter	Units	L. PON.	M. RIV.	OUTLET	TRIB.
NO_x	mg-N l^{-1}	0.054	1.363	0.051	0.226
TKN	mg-N l^{-1}	0.60	0.94	0.77	0.94
TN	mg-N l^{-1}	0.65	2.30	0.82	1.17
TP	mg-P l^{-1}	0.060	0.241	0.091	0.187
TN:TP (mass)		10.9	9.6	9.0	6.2
TOC	mg-C l^{-1}	5.84	5.78	6.44	8.97
Temperature	deg C	21.0	18.8	21.3	20.8
DO	mg-O l^{-1}	8.51	8.48	8.34	6.17
Conductivity	µmho	5478	369	7965	1589
Secchi disk	cm	94.4	23.8	64.0	55.6
Salinity	ppt	3.40	0.15	5.00	0.92

Table 2. Annual discharge and nutrient loading values.

SOURCE	Q km^3 yr^{-1}	TP kg yr^{-1}	TN kg yr^{-1}
Tributaries	7.178	1,366,926	8,377,933
Pearl River	3.944	345,037	3,84,112
Stormwater	0.104	292,562	322,863
Precipitation	1.000	65,484	0
Saltwater Inflow	6.436	1,036,235	6,256,029
Mississippi River	0.990	196,362	2,837,906
N-fixation			14,100,000
Total without diversion	19.651	3,302,606	35,708,843
Diversion	6.598	1,047,263	17,027,437
Total with diversion	26.249	4,349,869	52,736,280

modeling approaches for TN have not been as extensively studied and tested as those for TP. Mancini et al. (1983) suggest that an approach similar to that used here for TP should also be adequate for other nutrients. Calibration of Eq. 2 for TN results in an estimate of $K_s = 2.5$ yr^{-1}, and a projected average TN lake concentration of 0.972 mg l^{-1} after diversion. However, this calibration neglects an estimate of load from N fixation (as well as precipitation load of TN to the lakes surfaces). Calibration for TN is therefore deemed to be inappropriate here. Mancini et al. (1983) notes that both TN and TP are removed from the system by permanent burial following settling of particulate organic materials, and conjecture that because this mechanism of loss is the same for TN and TP, it is reasonable to assume that the K_s value for TN is equal to that for TP. Assuming $K_s = 6.4$ yr^{-1} for TN as well as TP, a N fixation term may be added to the TN load such that Eq. 2 is calibrated. This gives a N fixation load estimate of 14,100 metric tons yr^{-1}. This estimated load is greater than any other single load source listed in Table 2, and 65% of the total load from all other existing sources combined.

Discussion

Isphording et al. (1989), and Flowers and Isphording (1990) report freshwater discharge to Lake Pontchartrain to be 6.8 km^3 yr^{-1} (7600 ft^3 s^{-1}) and volume of Lake Pontchartrain to be 5.77 km^3 (2.038 10^{11} ft^3). This compares favorably with the estimates presented here (7.18 km^3 yr^1 and 5.49 km^3). Argyrou et al (1997) estimate a similar total volume, 6.58 km^3, but estimate annual average discharge of rivers into the Lake Pontchartrain Estuary to be only 4.48 km^3 yr^{-1} (142 m^{3}s^{-1}). Swenson (1980) concluded that gaged discharge must be scaled by an average factor of 2.4 to provide an appropriate freshwater discharge. This compares closely with the value of 2.6 used here. Swenson also estimated a comparable displacement time in Lake Pontchartrain, 105 d, using the "fraction of freshwater method" which reduces the waterbody volume to the equivalent freshwater volume. The displacement time of Lake Pontchartrain is estimated here to be 102 d. Sikora and Kjerfve (1985) also recognized the need to scale gaged discharges to estimate total tributary discharge. They applied scaling factors ranging from 1.06 to 2.4 to their tributary inflows. Solis and Powell (1999) present displacement times of Gulf Coast Estuaries in graphical format, with Lake Pontchartrain residence time near 140 d. Argyrou et al. (1997) estimate hydraulic residence time to be 537 d. This anomalously high estimate results primarily from an underestimate of freshwater inflow and also from failure to consider saltwater inflow or volume.

Bianchi and Argyrou (1997) estimate watershed nutrient loading of phosphate, ammonium, and nitrate plus nitrite. Because those nutrients are components of the TP and TN loads, we anticipate that their associated loads should be less than the total nutrient loads estimated here. Although the total tributary inflow estimate of 142 m^{3}s^{-1} used by Bianchi and Argyrou is somewhat lower than the value used here, their published load estimates are anomalously high and appear to be in error. Loads can be calculated from nutrient concentrations presented by Bianchi and Argyrou, and these loads are consistent with loads calculated here.

Areal *nutrient loading rate (loading per unit* of lake surface) in Lake Pontchartrain is estimated to be 2.02 and 21.82 g m^{-2} yr^{-1} for TP and TN. These values generally fall within the range of values which have been reported for lakes (Reckhow 1979; Mancini et al. 1983). Bahr (1983) projected a P load of 2 g m^{-2} yr^{-1} near the year 2000.

Ryding and Rast (1989) state that it is rare that available nutrient sampling data will produce nutrient load estimates within ±25%. In the case of Lake Pontchartrain, uncertainty involving the Pearl River, N fixation, and the saltwater load contributions add uncertainty to the load estimates. However, for the purposes of this trophic comparison and comparison of projections with and without the implementation of the proposed diversion, these load estimates should be adequate.

Calculations presented here illustrate the importance of incorporating the seaward boundary contributions in estuarine budgets. Even in the case of Lake Pontchartrain, with a relatively limited seaward exchange, the magnitude of net saltwater inflow and total nutrient loading was nearly as large as freshwater runoff and nutrient loading (Table 2). Failure to incorporate this flow and load source can result in over estimation of estuarine displacement time and sensitivity to loading for nutrients and other substances.

The Lake Pontchartrain seaward boundary is complicated by the location of the Pearl River at one seaward boundary channel. For the purposes of the comparison of diversion project alternatives, it is not critical to exactly identify the fraction of the Pearl discharge and load that should be incorporated with other tributary inflow. However, this is one source of uncertainty, and determination of the amount of the Pearl River flow and load entering Lake Pontchartrain is worthy of further study. Both the Pearl River contribution and the more general seaward boundary exchange should be quantified in future hydrodynamic computer modeling studies.

In this model, over 39% of present N loading results from fixation (or other unaccounted inputs such as dry deposition or precipitation). There is great uncertainty in this estimate because this loading was estimated through an indirect calculation, and is based on Mancini's conjecture that the same K_s value is adequate to model net sedimentation loss of TP, TN, and other total nutrient concentrations, such as total organic carbon (TOC). Future research in the Lake Pontchartrain Estuary, as well as other lakes and estuaries, should be directed toward obtaining a better estimate of K_s for total nutrient concentrations, and testing Mancini's conjecture. For nutrients with allochthonous sources and sinks, this will necessitate more direct estimation.

Although the stormwater discharge and load estimates are uncertain, they are small relative to the total estuary discharge and load (0.5% of discharge, 9% TP load, and 0.8% of TN load). This suggests that the urban stormwater pumps have little impact on estuary trophic state. This conclusion is likely true, but it does not follow that these nutrient sources are environmentally benign and need not be considered in a Lake Pontchartrain pollutant management plan. The pumped stormwater load likely plays an important role in the reduction of near-shore water quality, and the pulsed nature of the input may promote local algal blooms uncharacteristic of lake-wide events. Both of these potential consequences illustrate limitations of the average annual nutrient load and steady-state modeling approach presented here. More study is needed to determine the impact of these urban sources and other sources near their points of discharge. This should include application of dynamic modeling with spatial resolution adequate to identify local impacts.

The annual steady-state nutrient modeling approach presented here has clear value in support of environmental management planning. This includes plans for evaluation of overall nutrient control from point and nonpoint sources and TMDL determinations, and comparison of some impacts of alternative designs. The approach also provides a background for comparison in studies utilizing more temporally or spatially complex modeling. The modeling approach requires limited effort and computer resources relative to more complex methodologies, and provides simple straightforward predictions which support comparison of alternatives. It is essential, however, that the projections of this simple approach not be applied inappropriately. For example, this approach can not predict impacts resulting from changes in seasonal nutrient patterns, or local impacts of discharges. Applied with care, the approach is a valuable tool for environmental analysis, management, and decision support.

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