Environmental Review of Florida's Indian River Lagoon System

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EXECUTIVE SUMMARY

The Indian River Lagoon System (IRLS) includes about 156 miles of open estuarine water which runs from north to south along Florida's east coast. The IRLS developed over the past 5,000-7,000 years as a low nutrient, (oligotrophic) estuarine system with a surface water area of about 353 square miles and a limited watershed area of only 893 square miles. The lagoon itself was, and remains, restricted from significant tidal influence by a series of barrier islands. These barriers were interrupted by four inlets (now five) along the length of the lagoon. The pre-development IRLS relied largely upon direct atmospheric input (rainfall and dry deposition) as the major nutrient source. These nutrients which found their way into the lagoon waters through groundwater seepage and small surface creeks were captured by expansive seagrass lawns and associated epiphytes, both serving as the primary producers. Because of the low nutrients, the IRLS generated little net ecosystem production (NEP), i.e., excess production. Consequently, accretion of organic residual was low, which facilitated the establishment of a stable quasi-steady state dynamic.

The ecology of the IRLS changed dramatically with extensive development of a technological society during the twentieth century. By the year 2000 as a result of canalization; watershed expansion; and urban, residential, industrial and agricultural development, the IRLS had become a eutrophic (highly productive) system which was trending towards a shift from seagrass dominated primary production to phytoplankton (suspended algae) dominated primary production. With this shift, and the subsequent decline in seagrasses, combined with disruption in hydrologic and nutrient dynamics, ecological degradation began to impose upon the local economy and the quality of life.

In 2009 a TMDL for nutrient loading was established by the Florida Department of Environmental Protection (FDEP) for the three impaired segments of the IRLS—these being the North IRL, Central IRL and Banana River Lagoon. As part of the TMDL development, a direct relationship was established between seagrass coverage, as determined through average maximum depth of seagrass growth, and nutrient mass loading to the lagoon segments. This relationship was used to determine nutrient loading limits (TMDL). The original model used in projecting stormwater loading was later replaced with an improved model, the Spatial Watershed Iterative Loading or SWIL, and the TMDL was adjusted accordingly. The present TMDL as noted in the 2021 Basin Management Action Plans (BMAP) is 1,975,106 pounds per year total nitrogen and 224,319 pounds per year total phosphorus for the three segments.

In 2011 the IRLS experienced an extensive algae bloom, and unprecedented blooms followed in subsequent years, often accompanied with fish kills and excessive loss of seagrass—about 50% loss of seagrass coverage occurred from 2011 to 2018. As a consequence of reduced seagrass coverage, per the Florida Fish and Wildlife

Conservation Commission (FWC) in 2021 the IRLS experienced "*unprecedented manatee mortality due to starvation".*

Following the 2011 bloom, it became clear that the IRLS was shifting from a seagrass dominated system to a suspended algae (phytoplankton) dominated system, resulting in serious ecological disruption and impairment of major natural and economic resources. In addition, changes in a common Dinoflagellate alga known as *Pyrodinium bahamense* var *bahamense* which generates bioluminescence in the water during the summer months, appeared to facilitate an increased rate of production of saxitoxin—a toxin dangerous to humans as well as other organisms. Some described this ecological shift within the IRLS as a "tipping point", and it became clear that seagrass losses were the result of more than just external nutrient loading, and that the relationship between external nutrient loading and seagrass coverage was no longer sufficient to project seagrass recovery.

Research conducted by the Florida Institute of Technology (FIT) located in Melbourne, in cooperation with Brevard County and the State of Florida, as well as others, clearly showed that internal nutrient and solids loading from accumulated "muck" sediments, or "muck flux", had become a major contributing factor to phytoplankton blooms and seagrass losses. As much as 30% of the total nutrient loads to the lagoon--what are often called legacy loads--were found to be generated by nutrient flux from the muck sediments. These nutrients contributed to the explosion of phytoplankton populations into Harmful Algal Blooms or HAB. Not only did these HAB's reduce the penetration of light so essential to seagrasses, they also competed for nutrients, collapsed dissolved oxygen levels, and often released powerful toxins. In addition to providing the nutrients for HAB development, the muck sediments created turbid conditions when re-suspended through wind and current action, contributing significantly to light attenuation and seagrass loss. In fact, research has shown most of the light attenuation in IRLS is attributable to sediment particles—known as tripton.

The ecological shift within the IRLS threatens the very social and economic foundation of the region, particularly within Brevard and Indian River Counties. Convinced that muck removal was essential for ecological recovery Brevard County has moved quickly to implement muck removal projects. While not considered in the TMDL development, the legacy nutrients from "muck flux" have been deemed eligible for nutrient reduction credits by FDEP.

Managing "muck flux" either through actual dredging or other means such as sand capping or long-term removal through "kidney" type continuous treatment systems, is critical to achieving a desired level of IRLS reclamation. However, reduction of external sources must be done concurrently. This reduction can be done through institutional means e.g., fertilizer ordinances and public education, or through active projects including shoreline restoration; street sweeping; stormwater flow diversion; baffle boxes to capture solids and nutrients from stormwater; chemical injection systems; and the use of specialized media to facilitate nutrient removal. Larger scale initiatives for reducing external nutrient inputs should be adequately funded and prioritized as follows:

1. Treatment upgrade for all Wastewater Treatment Facilities to AWT standards, including effluent for irrigation reuse.
2. More aggressive implementation of agricultural BMP's, including verification of efficacy.
3. Expedite elimination of all septic tanks on less than one acre of land through extension of sewage collection and treatment capabilities.
4. Alternatively, replace septic tanks with advanced Onsite Sewage Treatment and Disposal System (OSTDS) which provide Advanced Wastewater Treatment (AWT) effluent quality.
5. Implement flow diversion projects which result in reduction of nutrient inputs to the IRLS while avoiding deleterious impact on other water resources.
6. Establish "kidney" type treatment systems to intercept and treat waters from nutrient laden tributaries and canals, and possibly from the lagoon directly, such as the Managed Aquatic Plant Systems (MAPS) used by Indian River County (https://vimeo.com/375731448?ref=fbshare&fbclid=IwAR1fCVnlhNdI33XZXBu3MkXkrJv8sJF_q2yg1-j1ng8R0w19TQFSwmyoM6o) or the chemical/filtration system (see https://phosphorusfree.com/) being tested by the St. Johns River Water Management District (SJRWMD) on Lake Apopka.
7. Restore or create wetlands which can intercept stormwater and groundwater seepage.
8. Ensure wet and dry ponds for stormwater are properly maintained to include provisions which deter the production of blue-green algae (Cyanobacteria) while promoting the recovery of nutrients.
9. Employ aquatic plant harvesting where feasible, with the commensurate reduction of herbicide use.
10. Ensure any stormwater management systems within new developments are designed and maintained to avoid increased nutrient and sediment loading to the IRLS.

It is suggested that preference be given to cost effective projects that actually recover and reuse nutrients from the various pollution sources. In addition, more extensive monitoring of the nature and behavior of muck sediments; the water quality and ecology of the lagoon itself; and external nutrient inputs, including both groundwaters and surface waters, is essential.

INTRODUCTION:

The Indian River Lagoon System (IRLS) can be described as a series of shallow interconnected bar-built estuaries that run parallel to Florida's East Coast. The designated northern extreme is just south of Ponce Inlet in Volusia County[1] with the designated southern terminus at Jupiter Inlet in Palm Beach County. The IRLS total length is about 156 miles, with the open water area approximately 353 square miles and the natural watershed area circa 1913--prior to extensive disruptions associated with urban and agricultural development--noted as about 893 square miles[2]. The pre-development watershed area to surface water area for the IRLS therefore was approximately 2.5, indicating a comparatively small contributing land mass. The watershed area has since been expanded to about 2,284 square miles primarily through canalization which connects the IRLS natural watershed with major basins to the west—e.g., the C-54 connection to the St. Johns River Basin and the St. Lucie canal connection to Lake Okeechobee. As a result of this expansion, the watershed to surface water ratio has increased to about 6.5.

The IRLS during the last glacial period—about 20,000 years before the present (ybp) --when sea levels were about 300 feet below present level, was likely a dry grassy/shrubby plain located between a series of beach dunes/shoreline relicts. As sea levels rose, and reached near present levels about 5,000-7,000 ybp, the IRLS developed as an estuarine system influenced by its relatively small watershed area, warming temperatures and limited influx of tidal waters. Many of the dune areas became barrier islands which served to protect the lagoons from extensive tidal flows and forces.

Unlike the estuaries on Florida's West Coast such as the Suwanee Sound, Tampa Bay and Charlotte Harbor, the IRLS is not associated with major rivers which would provide extensive hydrologic and material influx from the interior of the State. This is particularly true of the northern reaches of the IRLS, which includes the Mosquito Lagoon, the Banana River Lagoon and the main body of the Indian River Lagoon from Titusville to just north of Melbourne in southern Brevard County. To the south of Melbourne, the IRLS does receive some flow from associated tributaries which drain lands west of the lagoon, such as the Eau Galle River, Crane Creek, Turkey Creek, and the Sebastian

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[1] The designated area for the National Estuary Program (NEP) was extended about 25 miles north to include the Halifax River area near Daytona Beach

[2] https://www.epa.gov/sites/default/files/2018-01/documents/58692_an_river_lagoon_an_introduction_to_a_natural_treasure_2007.pdf pg. 16.

River. These are comparatively minor, whose watersheds do not naturally extend west of Interstate Highway 95 (I-95). Further south the St. Lucie River and the Loxahatchee River at the very southern reaches of the IRLS are larger and do impose a greater influence on the system's dynamics. The extension of the St. Lucie River to connect the IRLS to Lake Okeechobee has been particularly problematic. However, even these two rivers do not compare in magnitude or impact to the Florida West Coast Rivers, such as the Suwanee, Hillsborough, Peace, or Caloosahatchee.

The natural ridge upon which much of I-95 is built roughly marks the pre-development watershed boundary for the IRLS north of Vero Beach. Lands west of I-95 from Vero Beach to Ponce Inlet typically fall within the St. Johns River Basin, which is naturally separated from surface water connections to the IRLS. South of Vero Beach there are some areas west of I-95 that are within the St. Lucie and Loxahatchee River watersheds. Both rivers are managed to direct flow into the IRLS.

NUTRIENT DYNAMICS:

As noted, the pre-development IRLS estuaries were effectively isolated from most of interior Florida or from any major river systems which might provide alluvial material whose origins were considerable distant from the surface waters into which they flow (e.g., Suwanee River). In addition, again unlike much of the west-central portions of the Florida peninsula, there are no substantial deposits of phosphate bearing mineral associated with the IRLS watershed[3]. Consequently, pre-development phosphorus input was limited to atmospheric deposition; minor upward leakage from the Floridan Aquifer; birds and wildlife immigration; and tidal flow from the four natural inlets—Ponce Inlet, Indian River Inlet (later dredged as Ft. Pierce Inlet), St. Lucie Inlet, and Jupiter Inlet[4]. Nitrogen inputs were similarly restricted, except for the additional influence of nitrification, denitrification and nitrogen fixation[5]. Shown in Figure 1 is an approximation of nutrient (N and P) dynamics for a pre-development IRLS.

Because of the length of the IRLS, and the distance between inlets, the tidal flushing rate (% replenished per day) is low in several segments, particularly in the north and north central stretches of the IRLS, which includes the Mosquito Lagoon, the Banana River Lagoon, and much of the Indian River Lagoon. This flushing rate has probably been reduced to some degree by the flow impediments imposed by the numerous causeways/bridges—there are 20 along the 156-mile length. Some higher flushing rates in sections just north of Vero Beach however are associated with the construction of

[3] There are some phosphatic clays within the confining Hawthorne formation at about 100 feet below surface, but these appear to be sufficiently sequestered from the surface and groundwater associated with IRLS.
[4] Periodically both the Indian River and Jupiter inlets would be shut off through sand accumulation
[5] Nitrification-denitrification is a biological process facilitated by specialized bacteria within highly aerobic environments and anoxic environments respectively with ultimate release of elemental nitrogen back to the atmosphere. Nitrogen fixation is a biological process that allows capture of atmospheric nitrogen and conversion to biologically available ammonia. Nitrogen fixation is associated with specialized bacteria, including certain species of Blue-Green algae known as Cyanobacteria.

Sebastian inlet in 1923. South of Vero Beach, tidal flushing is much more consequential because of the proximity of the Ft. Pierce, St. Lucie and Jupiter Inlets.

The pre-development flow and nutrient dynamics of the IRLS depended largely upon freshwater influx from a limited watershed and tidal waters moving through the four inlets—which at times may have been only two inlets (see footnote 4). Tidal flushing in the northern reaches of the IRLS approach one renewal per year (0.27% renewal per day), indicating tidal water inputs and exports of nutrients from tidal exchange are minimal[6]. South of Sebastian Inlet tidal flushing rate is around 1-6 days (17 to 100% renewal per day), and nutrient flux through tidal exchange is much more relevant to nutrient dynamics. It would be reasonable however to expect tidal export of nutrients from a pre-development IRLS in these southern areas would be greater than the nutrient influx from influent waters from the Atlantic, and that tidal contribution of nutrients was more than off-set by tidal exports. If wildlife nutrient imports and exports are close to a balance, and tidal nutrient inputs are negligible, then atmospheric deposition may be considered the dominant pre-development source of phosphorus and nitrogen.

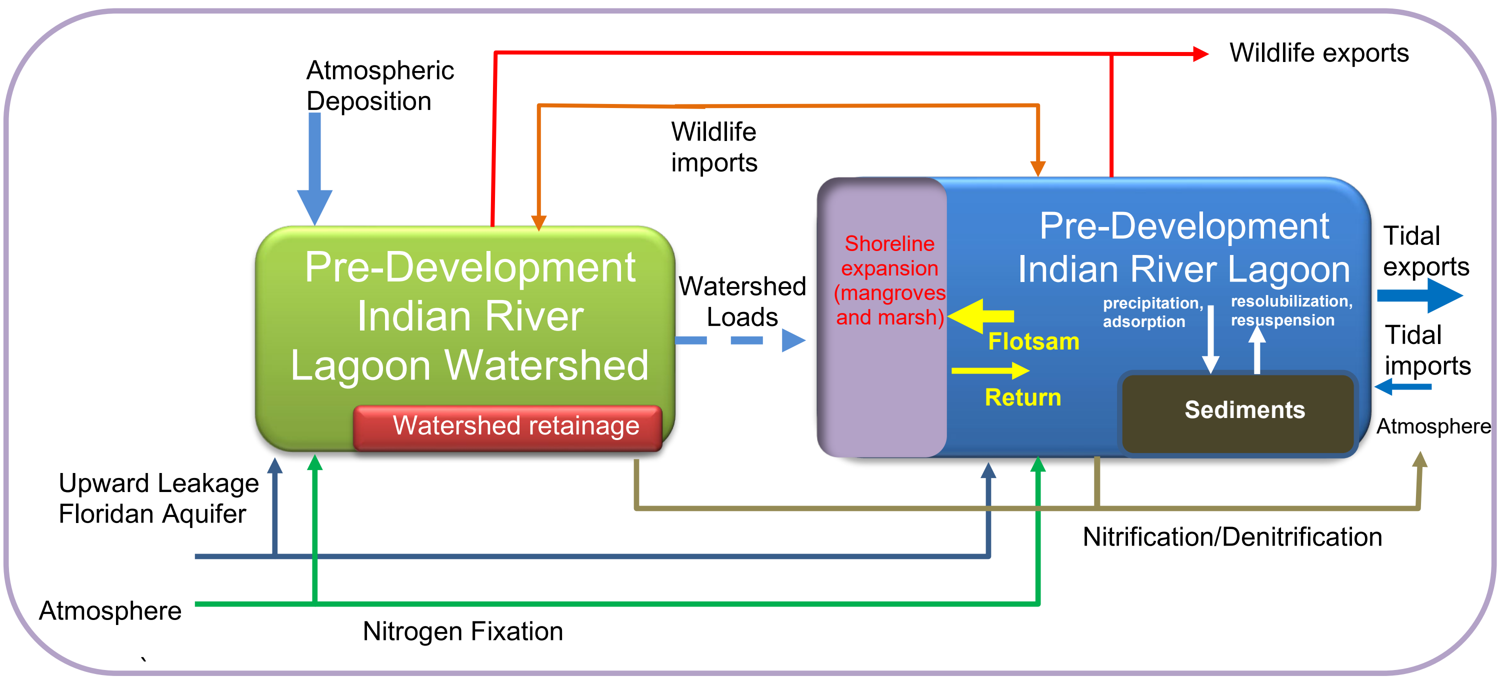

Figure 1: General pre-development nutrient dynamics IRLS (nitrogen and phosphorus)

[6] Smith, N. P. (1993). Tidal and nontidal flushing of Florida's Indian River Lagoon. *Estuaries*, 16(4), 739-746. doi:10.2307/1352432

Historically it appears the northern and central IRLS as well as the BRL were oligotrophic systems which were able to sustain a high level of stability, i.e., a near steady-state, even though they were quasi-isolated from tidal flushing and vulnerable to extensive nutrient loading and accumulation of net ecosystem productivity (NEP)[7]. This stability is related largely to a balance between the comparatively low NEP and the rate of removal of any organic accumulations either through tidal action; sequestration within the sediments; encroachment of mangrove and wetlands built largely upon decomposed flotsam and shifting sand; and perhaps through net export attendant with wildlife migration and visitation. The NEP was kept low because of the paucity of available nutrients, which allowed this balance to be maintained and kept the system in an oligotrophic state. One can imagine through time the pre-development IRLS, particularly in the northern reaches, slowly shifting to shallow wetlands, with the open water areas retracting. This successional process was comparatively slow because of the low NEP. In addition, succession would be disrupted through major storm events which could shift inorganic and organic accumulations as well as open inlets to the Atlantic. These storm events could help stabilize the overall dynamic and prolong the successional process—a phenomenon termed pulse stabilization by the Ecologist Eugene Odum[8]. Considering this model, it is not difficult to visualize any substantial increase in nutrient loading as a destabilizing disruption which would increase NEP, largely through increased drift algae and phytoplankton production, and hence increase the rate of accumulation of organic matter--that is to say accelerating the rate of succession.

To further evaluate the impact of changes in nutrient dynamics within the IRLS, consider the loading analyses included in the 2009 TMDL report[9]. The scope of this report is limited to the impaired segments within the northern and central IRL and the Banana River Lagoon, with a total watershed of area of 467,167 acres and a total lagoon surface water area of 153,241 acres, or a total IRLS area of 620,399 acres. Included in the report are estimated atmospheric deposition rates[10] of 4.0 lb/acre-yr for total nitrogen and 0.09 lb/acre-yr for total phosphorus. The nitrogen rate is commensurate with data provided by the National Atmospheric Deposition Program (NADP) in Madison Wisconsin. The phosphorus rate is about half of the rate cited in the Lake Okeechobee TMDL report[11]. Applying these rates to the entire TMDL lagoon basin area (land and surface water) would provide a reasonable estimate of pre-development nutrient inputs—or about 2,481,596 lb/yr for total nitrogen and 55,836 lb/yr total phosphorus. Of

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[7] Net Ecosystem Productivity may be considered the difference between gross primary production (GPP) and total ecosystem respiration, with GPP being the amount of carbon captured through photosynthesis, and respiration is the amount of carbon converted to carbon dioxide to support the metabolic needs of the ecosystem.

[8] Odum, W.E., E.P. Odum and H.T. Odum (1995) Natures pulsing paradigm *Estuaries,* Vol 8, No. 4 pp 547-555

[9] Florida Department of Environmental Protection (FDEP) 2009, Xueqing Gao, Nutrient and Dissolved Oxygen TMDLs for the Indian River Lagoon and Banana River Lagoon

[10] Ibid. *pg. 41 through 44. "These (atmospheric deposition) rates were estimated based on data collected from an atmospheric deposition site (IRL 141) located at Sebastian Inlet between 2001 through 2006."*

[11] Florida Department of Environmental Protection (FDEP), 2001, Final Report: Total Maximum Daily Load for Total Phosphorus Lake Okeechobee, Florida

this input, a portion would be retained within the wetlands which developed between the sand ridges and along the lagoon shoreline, so the actual loading to the lagoon would likely be somewhat less than these inputs.

These values can be compared to present total annual loading estimates to the TMDL study area as reported in the TMDL report[12]. This comparison is shown in Table 1. Within the TMDL report, present loadings are estimated at 3,112,960 lb/yr for total nitrogen and 476,976 lb/yr for total phosphorus. The TMDL targets for nitrogen and phosphorus is a reduction to 1,941,787 lb/yr total nitrogen and 244,996 total phosphorus, also noted in Table 1.

Table 1: Initial Comparative nitrogen and phosphorus loadings within TMDL segments of the IRLS

	Present Total Nitrogen Loading To Lagoon Segments per TMDL lb/yr	Target Total Nitrogen Loading To Lagoon Segments per TMDL lb/yr	Reduction Total Nitrogen Loading To Lagoon Segments per TMDL lb/yr	Present Total Phosphorus Loading To Lagoon Segments per TMDL lb/yr	Target Total Phosphorus Loading To Lagoon Segments per TMDL lb/yr	Reduction Total Phosphorus Loading To Lagoon Segments per TMDL lb/yr
Northern IRL Segment	886,257	687,044	199,213	100,918	56,550	44,368
Central IRL Segment	1,961,103	962,988	998,115	314,148	165,193	148,955
Banana River Lagoon	484,462	291,755	192,707	61,900	23,253	38,647
TOTAL	**3,331,822**	**1,941,787**	**1,390,035**	**476,966**	**244,996**	**231,970**
Pre-development Basin Input lb/yr		**2,481,596**			**55,836**	
Difference lb/yr		**(539,809)**			**189,160**	

Also noted in Table 1, the TMDL target nitrogen load appears to be somewhat lower than the pre-development estimate, while the TMDL target phosphorus load is considerably higher than the pre-development estimate—by a factor of about 4.3. The implication is that phosphorus could be much more problematic, and that its comparative abundance could facilitate serious ecological shifts within these sections of the IRLS. It is noteworthy that none of the present loading estimates shown in Table 1 include release of legacy nutrients from accumulated muck within the lagoon itself-- an issue discussed later within this text.

The concentrations associated with the pre-development loadings, considering an average rainfall of 52" per year are 0.33 mg/L total nitrogen and 7.6 µg/L total phosphorus[13] [14]. If the present annual loadings for the TMDL segments are applied to a 52" annual rainfall, the concentrations would be 0.46 mg/L total nitrogen and 65 µg/L total

[12] Ibid footnote 9 -- taken from Table 5.1
[13] These estimates may be high as they do not include any attenuation within the watershed.
[14] H.T. Odum in his 1953 study for the Florida Geological Society Dissolved Phosphorus in Florida Waters in four samples in the north central IRL the total phosphorus averaged 7 µg/L. A fifth sample from the pool north of Titusville was found to have an elevated level of 72 µg/L total phosphorus.

phosphorus. Based upon data included in the TMDL report the total nitrogen within the lagoon presently averages about 1.17 mg/L total nitrogen and 58 µg/L total phosphorus within the TMDL segments. This actual total nitrogen concentration is notably higher than the calculated concentration (1.17 mg/L vs. 0.46 mg/L), which may indicate under-estimation of incoming loads; influence of nitrogen fixation; or release of legacy stores from the accumulated sediments. Note that the total phosphorus concentrations between the actual and calculated (58 µg/L vs. 65 µg/L) are similar.

Some insight into the nature of the changes in nutrient dynamics within the TMDL segments of the IRLS can be gained with comparison of the N:P ratios based upon loadings and the documented concentrations within the lagoon itself. Shown in Table 2 are the N:P ratios for loadings associated with the pre-development, present, and TMDL target scenarios. Most noticeable is the high values for the pre-development conditions, indicating a paucity of phosphorus, whereas the present and target loading N:P atomic ratio are closer to the Redfield atomic balanced N:P of 16:1[15].

The N:P ratio based upon surface water concentrations reported within the TMDL report are about 20 by weight or 45 by atomic ratio, which at first glance could be seen as an implication of phosphorus-controlled productivity, i.e., phosphorus limited. The concentration-based N:P being much higher than the loading N:P is suggestive of either disproportionate sequestration of phosphorus when compared to nitrogen within other compartments of the systems—such as the sediments or standing biomass--or as suggested previously, another source of nitrogen input such as nitrogen fixation or legacy nitrogen.

Table 2: Comparative N:P ratios of watershed loads within IRLS TMDL segments

	Present N:P ratio by weight	Present N:P Ratio by atomic ratio	Target N:P ratio by weight	Target N:P Ratio by atomic ratio
Northern IRL Segment	8.78	19.45	12.15	26.90
Central IRL Segment	6.24	13.82	5.83	12.91
Banana River Lagoon	7.83	17.33	12.55	27.78
TOTAL	**6.99**	**15.47**	**7.93**	**17.55**
Pre-development Basin Input N:P ratio			**44.44**	**98.41**

In a study by Phlips[16] involving 8 segments of the Indian River Lagoon, water samples for nutrient analysis were taken monthly at each segment from the period from July 1997 to March 2000, The mean results are noted in Table 3.

[15] Redfield ratio is the consistent atomic ratio of carbon, nitrogen and phosphorus found in marine phytoplankton, empirically found to be C: N:P = 106:16:1.
[16] Phlips, E. (2002) Factors Affecting the Abundance of Phytoplankton in a Restricted Subtropical Lagoon, The Indian River Lagoon, Florida, USA Estuarine*, Coastal and Shelf Science*. doi:10.1006/ecss.2001.0912

When the N:P atomic ratio is above 16, the system productivity may be controlled (limited) by phosphorus, while it may be controlled by nitrogen if the N:P atomic ratio is below 16. Per Table 3, sites 1 through 5, which roughly represent the TMDL segments, appear to be phosphorus limited, while sites 7-9 lean towards nitrogen limited productivity. However, if only readily available nutrient forms, which include ammonia, nitrate+nitrite and Soluble Reactive Phosphorus—or ortho phosphorus--are used in calculating N:P atomic ratios (second to last column in Table 3), the sites 1 through 5 move closer to the balanced N:P of 16, while sites 6 through 8 more clearly show nitrogen limiting conditions.

This shift however is based upon the assumption that the bioavailability of organic phosphorus and organic nitrogen is not limited, which may not always be true. Refractory Dissolved Organic Nitrogen (RDON) for example implies resistance to enzymatic influence, while much of the dissolved organic phosphorus may be rendered available through phosphatase action. RDON has been found to be associated with lignin-like molecules while labile forms of dissolved organic nitrogen are associated with proteins and lipids[17]. As organic nitrogen quite often represents the major percentage of total nitrogen—92% for sites 1 through 8 per Table 3—then its bioavailability could have profound impacts upon the nature and extent of productivity within the IRLS. This could also apply to organic phosphorus.

Table 3: Nutrient concentrations and Comparative N:P ratios within the IRLS 1997-2000[18]

Site	Total Phosphorus µg/L	Soluble Reactive Phosphorus (SRP)µg/L	Organic Phosphorus µg/L	Total Nitrogen µg/L	Nitrate + Nitrite Nitrogen µg/L	Ammonia Nitrogen µg/L	Organic Nitrogen µg/L	N:P based on atomic ratio TN:TP	N:P based on atomic ratio (Nitrate+Nitrite+ Ammonia):SRP	N:P based on atomic ratio (Nitrate+Nitrite+ Ammonia+0.048 organic N):(SRP+0.315 organic P).
1 Mosquito Lagoon	54	9	45	563	26	34	502	23	15	8
2 Titusville	35	5	30	762	7	45	710	48	25	13
3 Banana River Lagoon	54	4	50	760	5	38	717	31	24	9
4 Eau Gallie	59	4	55	667	8	18	641	25	16	6
5 Melbourne	68	5	63	667	14	29	624	22	19	6
6 Sebastian	55	13	43	366	10	18	338	15	5	4
7 Vero North	118	45	73	458	20	40	398	9	3	3
8 Vero South	101	37	64	530	18	24	488	12	3	3
Pre-Development	**8**			**330**				**91**		

As an example, consider the N:P atomic ratio shown in the last column of Table 3 in which it is assumed 4.8% of organic nitrogen is bioavailable, while 31.5% of organic phosphorus is bioavailable (see page 9). Note that the revised N:P atomic ratios show a shift from phosphorus limited or near Redfield balance to nitrogen limited for sites 1 through 5. Sites 6 through 8 remain nitrogen limited, possibly due to influence of the St. Lucie River and

[17] Osborne, D.M., D.C. Podgorski, D.A. Bronk, R. Sipler, D. Austin, J.S. Bays. And W.T Cooper (2013). Molecular-level characterization of reactive and refractory dissolved natural organic nitrogen compounds by atmospheric pressure photoionization coupled to Fourier transform ion cyclotron resonance mass spectrometry DOI: 10.1002/rcm.6521
[18] Ibid footnote 16 (nutrient data for sites 1-8 only)

its connection to phosphorus rich Lake Okeechobee, as well as other phosphorus laden flows from the expanded watershed.

The actual conditions regarding the influence of N:P atomic ratio therefore may depend significantly upon the bioavailability of organic phosphorus and organic nitrogen. If there is a significant disproportionate advantage for bioavailability of organic phosphorus, then the N:P ratio would be further reduced, pushing the system towards nitrogen limitation. As noted, as organic nitrogen is quite often the most predominant nitrogen form in Florida waters, the nutrient and productivity dynamics is often reliant upon the percentage of this organic nitrogen as RDON. In some cases, such as suggested for the brown algae 2012 bloom in the Mosquito Lagoon associated with the phytoplanktonic algae *Aureombra lagunensis,* organic nitrogen in an environment in which inorganic nitrogen (e.g., nitrate) is scarce, may offer a selective advantage to those organisms capable of exploiting organic nitrogen[19].

For Florida conditions some insight is offered from two studies in which Algal Turf Scrubbers (ATS) were used to reduce nutrients from water associated with the canal network operated by the Indian River Farms Water Control District in Indian River County[20]. These canals eventually discharge into the IRLS near Vero Beach.

The Egret Marsh Stormwater Park includes a 4.58-acre ATS that accommodates flows of about 10 million gallons per day taken from the Lateral D of the Main Canal, just east of I-95 and just south of SR60. The study was authorized through section 319(h) of the Clean Water Act (CWA) to determine system efficiency regarding nutrient removal, and involved weekly composite sampling of nitrogen and phosphorus, including nitrate, ammonia, organic and Kjeldahl nitrogen and total, ortho (SRP) and organic phosphorus from both ATS influent and effluent[21]. The results of one year's sampling are noted in Tables 4 and 5.

The other ATS study in Indian River County, known as Osprey Marsh, was conducted on the South Canal which also discharges into the Indian River Lagoon[22]. The results are shown in Tables 6 and 7.

A third project involved a one-year ATS pilot study conducted in the Everglades at STA-1W (Stormwater Treatment Area -1 West) near West Palm Beach, outside of the IRL

[19] Gobler, C.J., F. Koch, D.L. Berry, Y.Z. Tang. M. Lasi, L. Wiliams, L. Hall and J. Miller (2013) Expansion of harmful brown tides caused by the pelagophyte *Aureoumbra lagunensis* DeYoe et Stockwell to the U.S. East Coast. Harmful Algae *http//dx.doi.org/10.1016/j.hal.2013.04.004*

[20] An algal turf scrubber is a water treatment system which encourages production of periphytic and epiphytic algae within the framework of an engineered system, to facilitate nutrient uptake, removal and recovery. See www.hydromentia.com

[21] HydroMentia, Inc (2011) Egret Marsh Stormwater Park Algal Turf Scrubber® 319(h) Grant Quarterly Performance Report Quarter Four Final Report Contract # G0143 Prepared for: Indian River County and Florida Department of Environmental Protection

[22] HydroMentia, Inc (2011) PC South Canal Algal Turf Scrubber Pilot – Final Report Indian River County, Florida Stormwater Division Public Works Department

watershed[23]. The water source associated with this project was characterized by a high N:P atomic ratio (>100), indicating phosphorus limitation. The results are shown in Tables 8 and 9.

Table 4: One year nitrogen removal (2010-2011) within the Egret Marsh Algal Turf Scrubber, Indian River County

	NITROGEN									
Egret Marsh Indian River County	Total Nitrogen mg/L		Total Kjeldahl Nitrogen mg/L		Nitrate + Nitrite Nitrogen mg/L		Ammonia Nitrogen mg/L		Organic Nitrogen mg/L	
Quarter	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
Q1	0.86	0.72	0.78	0.68	0.08	0.04	0.12	0.05	0.66	0.63
Q2	0.80	0.73	0.71	0.66	0.09	0.07	0.07	0.04	0.64	0.62
Q3	0.65	0.61	0.62	0.59	0.03	0.02	0.01	0.00	0.61	0.59
Q4	1.06	1.04	0.97	0.88	0.09	0.16	0.11	0.10	0.86	0.78
Percent Reduction	Total Nitrogen		Total Kjeldahl Nitrogen		Nitrate + Nitrite Nitrogen		Ammonia Nitrogen		Organic Nitrogen	
Q1	16.3%		12.8%		50.0%		58.3%		3.0%	
Q2	8.8%		7.0%		22.2%		42.9%		2.0%	
Q3	6.2%		4.8%		33.3%		100.0%		2.0%	
Q4	1.9%		9.3%		-77.8%		9.1%		8.0%	
MEAN	***8.3%***		***8.5%***		***6.9%***		***52.6%***		***3.8%***	
sd	***6.0%***		***3.4%***		***57.6%***		***37.7%***		***2.9%***	

Table 5: One year phosphorus removal (2010-2011) within the Egret Marsh Algal Turf Scrubber, Indian River County

	PHOSPHORUS					
Egret Marsh Indian River County	Total Phosphorus mg/L		Ortho Phosphorus (SRP) mg/L		Organic Phosphorus mg/L	
Quarter	Influent	Effluent	Influent	Effluent	Influent	Effluent
Q1	0.100	0.067	0.036	0.030	0.064	0.037
Q2	0.049	0.046	0.016	0.011	0.033	0.035
Q3	0.050	0.030	0.023	0.012	0.027	0.018
Q4	0.212	0.157	0.180	0.127	0.032	0.030
Percent Reduction	Total Phosphorus		Ortho Phosphorus (SRP)		Organic Phosphorus	
Q1	33.0%		16.7%		42.2%	
Q2	6.1%		31.3%		-6.1%	
Q3	40.0%		47.8%		33.3%	
Q4	25.9%		29.4%		6.3%	
MEAN	***26.3%***		***31.3%***		***18.9%***	
sd	***14.6%***		***12.8%***		***22.6%***	

[23] HydroMentia, Inc (2009) STA-1W Algal Turf Scrubber Pilot Final Performance Report South Florida Water Management District. West Palm Beach, Florida

Table 6: Six Month nitrogen removal (2011) within the Osprey Marsh Pilot Algal Turf Scrubber, Indian River County

	NITROGEN									
Osprey Marsh Indian River County	Total Nitrogen mg/L		Total Kjeldahl Nitrogen mg/L		Nitrate + Nitrite Nitrogen mg/L		Ammonia Nitrogen mg/L		Organic Nitrogen mg/L	
Month	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
1	0.60	0.39	0.52	0.38	0.08	0.05	0.14	0.02	0.38	0.36
2	1.00	0.47	0.91	0.46	0.09	0.16	0.34	0.00	0.57	0.46
3	1.26	0.69	1.17	0.51	0.09	0.18	0.46	0.05	0.71	0.46
4	0.93	0.68	0.87	0.54	0.06	0.13	0.39	0.02	0.48	0.52
5	0.60	0.41	0.57	0.41	0.03	0.00	0.03	0.02	0.54	0.39
6	0.97	0.71	0.83	0.57	0.13	0.14	0.13	0.05	0.70	0.52
Percent Reduction	Total Nitrogen		Total Kjeldahl Nitrogen		Nitrate + Nitrite Nitrogen		Ammonia Nitrogen		Organic Nitrogen	
1	35.0%		26.9%		37.5%		85.7%		2.0%	
2	53.0%		49.5%		-77.8%		100.0%		11.0%	
3	45.2%		56.4%		-100.0%		89.1%		25.0%	
4	26.9%		37.9%		-116.7%		94.9%		-4.0%	
5	31.7%		28.1%		100.0%		33.3%		15.0%	
6	26.8%		31.3%		-7.7%		61.5%		18.0%	
MEAN	***36.4%***		***38.4%***		***-27.4%***		***77.4%***		***11.2%***	
sd	***10.6%***		***12.1%***		***85.6%***		***25.4%***		***10.6%***	

Table 7: Six Month phosphorus removal (2011) within the Osprey Marsh Pilot Algal Turf Scrubber, Indian River County

	PHOSPHORUS					
Osprey Marsh Indian River County	Total Phosphorus mg/L		Ortho Phosphorus (SRP) mg/L		Organic Phosphorus mg/L	
Month	Influent	Effluent	Influent	Effluent	Influent	Effluent
1	0.086	0.056	0.058	0.030	0.028	0.026
2	0.176	0.044	0.054	0.010	0.122	0.034
3	0.159	0.048	0.065	0.013	0.094	0.036
4	0.098	0.034	0.067	0.013	0.031	0.021
5	0.131	0.059	0.060	0.045	0.071	0.014
6	0.162	0.099	0.110	0.076	0.052	0.023
Percent Reduction	Total Phosphorus		Ortho Phosphorus (SRP)		Organic Phosphorus	
1	34.9%		48.3%		7.1%	
2	75.0%		81.5%		72.1%	
3	69.8%		80.8%		62.2%	
4	65.3%		80.6%		32.3%	
5	55.0%		25.0%		80.3%	
6	38.9%		30.9%		55.8%	
MEAN	***56.5%***		***57.8%***		***51.6%***	
sd	***16.6%***		***26.4%***		***27.3%***	

Table 8: One year nitrogen removal (2008-2009) within the STA-1W Algal Turf Scrubber Pilot, Palm Beach County

	NITROGEN									
STA-1W Palm Beach County	Total Nitrogen mg/L		Total Kjeldahl Nitrogen mg/L		Nitrate + Nitrite Nitrogen mg/L		Ammonia Nitrogen mg/L		Organic Nitrogen mg/L	
Quarter	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
Q1	2.61	2.51	2.44	2.39	0.17	0.12	0.18	0.11	2.26	2.28
Q2	2.43	2.35	2.35	2.30	0.12	0.05	0.21	0.16	2.14	2.14
Q3	2.63	2.37	2.37	2.29	0.18	0.09	0.18	0.10	2.19	2.19
Q4	2.39	2.32	2.32	2.27	0.07	0.05	0.13	0.08	2.19	2.19
Percent Reduction	Total Nitrogen		Total Kjeldahl Nitrogen		Nitrate + Nitrite Nitrogen		Ammonia Nitrogen		Organic Nitrogen	
Q1	3.8%		2.0%		29.4%		38.9%		-2.0%	
Q2	3.3%		2.1%		58.3%		23.8%		0.0%	
Q3	9.9%		3.4%		50.0%		44.4%		0.0%	
Q4	2.9%		2.2%		28.6%		38.5%		0.0%	
MEAN	***5.0%***		***2.4%***		***41.6%***		***36.4%***		***-0.5%***	
sd	***3.3%***		***0.6%***		***14.9%***		***8.8%***		***1.0%***	

Table 9: Annual phosphorus removal (2008-2009) within the STA-1W Algal Turf Scrubber Pilot, Palm Beach County

	PHOSPHORUS					
STA-1W Palm Beach County	Total Phosphorus mg/L		Ortho Phosphorus (SRP) mg/L		Organic Phosphorus mg/L	
Quarter	Influent	Effluent	Influent	Effluent	Influent	Effluent
Q1	0.046	0.035	0.031	0.017	0.015	0.018
Q2	0.030	0.018	0.012	0.007	0.018	0.011
Q3	0.025	0.019	0.010	0.008	0.015	0.011
Q4	0.038	0.022	0.010	0.008	0.028	0.014
Percent Reduction	Total Phosphorus		Ortho Phosphorus (SRP)		Organic Phosphorus	
Q1	23.9%		45.2%		-20.0%	
Q2	40.0%		41.7%		38.9%	
Q3	24.0%		20.0%		26.7%	
Q4	42.1%		20.0%		50.0%	
MEAN	***32.5%***		***31.7%***		***23.9%***	
sd	***9.9%***		***13.6%***		***30.8%***	

The percent reduction of both organic nitrogen and organic phosphorus associated with these projects provides some insight into their relative recalcitrance. Organic nitrogen in all cases appeared more resistant to enzymatic activity than organic phosphorus, with removals ranging from -0.5% to 11.2% reduction, or an average of 4.8% as compared to 18.9% to 51.6% for organic phosphorus, or an average of 31.3%. It needs to be understood that these values are indicative, but certainly not conclusive, particularly considering there is mobility between organic and inorganic forms. Nonetheless the dynamics of organic nitrogen and organic phosphorus must be considered influential in terms of productivity and species composition, and that depending upon the relative availability, the system may oscillate between nitrogen limitation and phosphorus limitation depending upon the sources, the species involved[24], light attenuation, and the climatic and water quality condition—e.g., temperature, pH, salinity, etc. The possibility of fluctuating nutrient limitations can be seen in Figures 2 and 3 set around conditions for sites 1 and 5 (see Table 3). The implication from these graphs is that if no more than 10% of the organic nitrogen is labile (not RDON), then system productivity is likely to be nitrogen controlled. The case for nitrogen limitation is strengthened by the fact that the Indian River Lagoon environment at least in the sites 1 through 5 per Table 3, are siliciclastic rather than carbonate-rich, as much of the freshwater source is from seepage through a shallow, sand dominated aquifer, meaning phosphorus may be more readily accessed when compared to carbonate-rich conditions[25].

While it may be helpful to evaluate the relative availability of nitrogen and phosphorus, the most influential factor regarding changes within the IRLS may not solely be which nutrient is controlling productivity or species selectivity, but rather the sheer magnitude of the increase in nutrient loadings when comparing present conditions to pre-development conditions—particularly with phosphorus. If the pre-development loadings projected within this text are emulative of the 5,000 +/- year successional history, then the IRLS was certainly an oligotrophic system in which the scarcity of phosphorus required a diversity of organism to facilitate access to that phosphorus which was available. With low concentrations of phosphorus within the water column, those primary producers that could exploit the phosphorus accumulated within the sediments as well as within the water column would have a selective advantage—hence the predominance of seagrasses and their associated epiphytic algae, as well the consumer populations which grazed upon them. Within the pre-development watershed itself, rainfall would tend to recharge the shallow aquifer associated with the highly permeable sands characteristic of the coastal ridge

[24] As noted, different algal species will have different capabilities to access organic nitrogen and/or organic phosphorus

[25] Lapointe, B.E., M.M. Littler and D.S. Littler (1992) Nutrient availability to marine macroalgae in siliciclastic versus carbonate-rich coastal waters. *Estuaries* **15,** 75–82 (1992). https://doi.org/10.2307/1352712

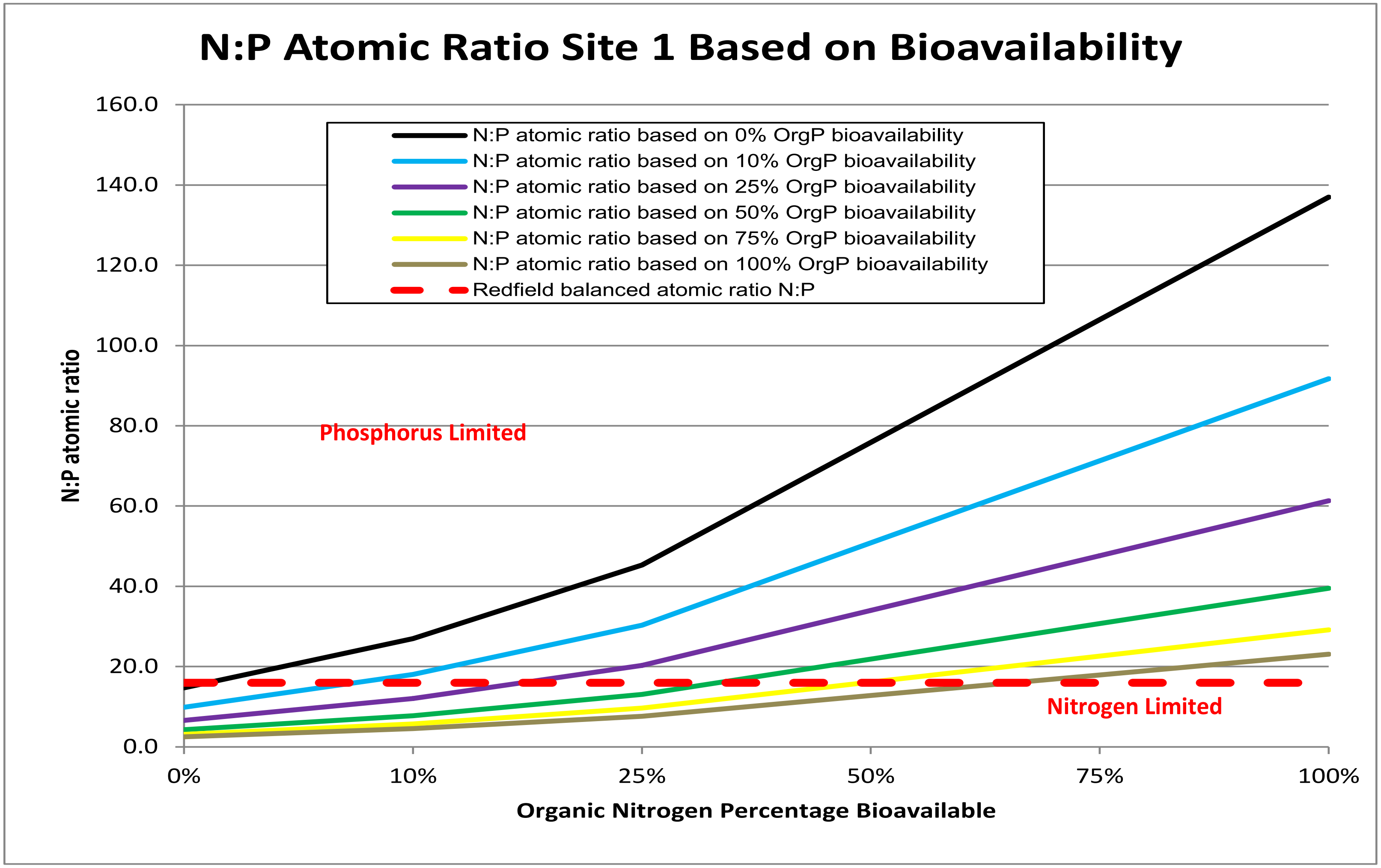

Figure 2: N:P atomic ratio Site 1 with varying percentages of bioavailability of organic nitrogen and organic phosphorus

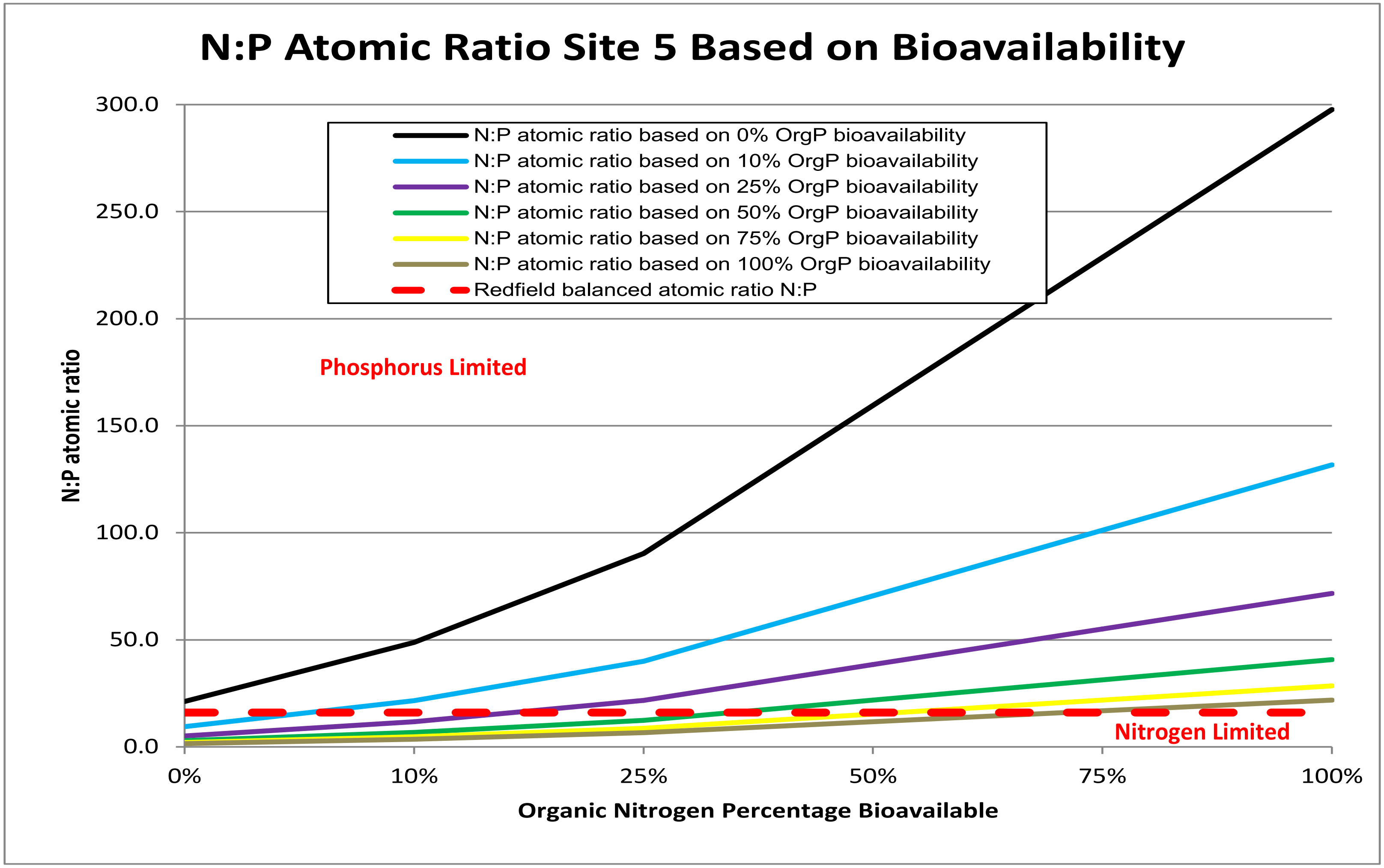

Figure 3: N:P atomic ratio Site 5 with varying percentages of bioavailability of organic nitrogen and organic phosphorus

This aquifer would then seep into downgradient wetlands and perhaps into small streams, and eventually into the lagoon itself. The rapid movement of direct surface runoff associated with a low time of concentration would be comparatively small with the groundwater seepage modulating the scheduling of freshwater flows, particularly in the northern reaches. Such modulation would also serve to avoid severe salinity flux more effectively within the lagoon and provide higher base flows than present conditions during drought periods.

Salinity trends under pre-development conditions would fluctuate based upon tidal flushing rate; influx of freshwaters primarily from direct rainfall, groundwater seepage and surface water flows in southern areas; and evaporation rate. Tidal movement would have depended significantly upon the status of natural inlets. When inlets closed because of sand build-up, the freshwater inputs could accumulate to a point of reducing salinity below the tolerance limit of many of the marine and euryhaline organisms, resulting in significant water quality changes. For example, in the late 1850s Jupiter Inlet closed off, resulting in stagnation in the vicinity of the mouth of the Loxahatchee River. The pooled water invited mosquito breeding, and the eventual onset of malaria in the region—what was then called Jupiter Fever. Most likely some of the observed stagnation was associated with a die-off of marine and many euryhaline organisms which could not survive the lower salinities created by freshwater accumulation. Historically similar conditions, including fish kills, were reported in the Sebastian area before the Inlet was opened permanently. In more recent times however fish kills and poor water quality have been associated largely with excessive nutrient loading from both external and internal sources and attendant phytoplankton blooms and sediment resuspension which interfered with light availability.

Today the IRLS is not identified as an oligotrophic system but rather as "a nutrient-rich environment"[26] disrupted by sizable increases in nutrient loading from myriad sources; expansion of the watershed and manipulation of hydrology to accelerate flow rates to accommodate agriculture and urban flooding concerns; dredging of channels which serve as depositories for flocculent organic sediments; construction of flow-impeding bridges and causeways; imposition of development upon wetlands; and increased soil loss from the watershed related to clearing for urban and agricultural development. In summary, recent manipulation of the IRLS to accommodate extensive development has introduced conditions which represent substantial departures from the historical experience of the IRLS during its successional period of 5,000 to 7,000 years. When stable, balanced ecosystems are so seriously disrupted, homeostasis is compromised, and changes are

[26] Ibid footnote 16

inevitable, although the exact nature and timing of these changes are typically not predictable[27].

Furthermore, these changes may be irreversible. This brings into question the TMDL targets, which have been set to facilitate return to conditions in which the median depth limit of seagrass development approaches conditions noted for years after 1943 up to 2009. By meeting the TMDL targets will seagrasses return, or has the IRLS been so disrupted that phytoplankton and drift algae will continue to dominate primary productivity? Certainly, making the effort to reduce nutrient loading may be helpful in slowing the rate of change, but the phosphorus loadings will remain well above the pre-development conditions. And, of course there is concern regarding the legacy accumulations within the organic sediments as discussed in the following section.

The selection of conditions beginning in 1943 is somewhat arbitrary and is recognition that establishing pre-development conditions as a baseline or target is not reasonable. Indeed, by 1943, the IRLS had been seriously disrupted through canalization, dredging of the Intracoastal Waterway; agriculture and watershed expansion; and urbanization. However, many of the desirable features of the IRLS were retained, including aesthetics, wildlife abundance, and a lucrative recreational and commercial fishing industry. Attaining the 1943-2009 seagrass coverage would represent a marked improvement in the quality and value of the IRLS. Reduction of nutrient loads and restoration of certain ecological features should facilitate some improvement, although this is yet to be field validated, and other actions may likely be required, including management of the accumulated "muck".

It is stated in the IRL 2020 final report from the National Estuary Program that "*restoration of the IRL to an idealized past reference status after removal of human induced pressure may be difficult to achieve"* [28]*.* As noted, this can be interpreted as a concession that returning the IRLS to pre-development conditions would require efforts and sacrifices which may not be acceptable, and hence not achievable. This is an accurate assessment when considering the extent of development within the watershed and the present economic paradigm to increase development as a means of "growing the economy" (however that might be defined). The clear implication is that the intent is to establish conditions in which the ecology of the IRLS is improved and emulative of conditions associated with earlier periods of the twentieth century—e.g., 1943—without serious imposition upon existing economic, social, institutional and political paradigms. The presumption of such a target is that the ecological dynamic is reversible, and that achieving the TMDL target will result in seagrass recovery and elimination of Harmful Algae Blooms (HAB's). Perhaps the biggest challenge to this presumption is the stored

[27] This is effectively explained in the book by Ilya Prigogine entitled The End of Certainty (The Free Press 1997). To quote him in his book "*I have always considered science to be a dialogue with nature. As in real dialogue, the answers are often unexpected—and sometimes astonishing."*

[28] A 10-year Comprehensive Conservation and Management Plan for the Indian River Lagoon, Florida (2020) National Estuary Program www.irlcouncil.com

nutrients associated with a growing muck layer which presently covers as much as 20% of the IRLS surface water area[29].

SEDIMENT DYNAMICS, LEGACY NUTRIENTS AND MUCK FLUX:

In recent years the term "legacy nutrients" has gained acceptance as meaning nutrients stored over the years within sediments—mostly organic sediments—associated with lakes and estuaries and their watersheds[30]. These legacy nutrients may be considered the 500-pound Gorilla in the room. The magnitude of the threats from these legacy nutrients within the IRLS are rather immense, a situation shared with a ubiquity of Florida's impaired waters. For example, consider the TMDL for Lake Okeechobee[31], which is 149 tons of phosphorus per year. This would be a reduction by at least 70% (+/-) of the present loading of over 500 tons of phosphorus per year. However, according to the University of Florida Water Institute, there is over 100,000 tons of available legacy phosphorus within the watershed, or enough to load the lake with 500 tons per year for the next 200 years, even if all other sources were eliminated[32]. The nature of legacy phosphorus in Lake Okeechobee was described in a 2021 study by Missimer et. al.[33]. They suggested that "*despite major efforts to control external nutrient loading into the lake, the high frequency of algal blooms will continue until the muds bearing legacy nutrients are removed from the lake."*

They describe the organic "muds" in Lake Okeechobee as incorporated into three layers—a consolidated bottom layer, a less consolidated mobile middle layer, and a thixotropic layer, i.e., readily fluidized, which moves both laterally and vertically under the direct influence of wind and wind-induced currents (e.g., seiches). It is this top fluid layer that apparently serves to reintroduce available nutrients to the water column, and which feeds the frequent blooms of Cyanobacteria. Its age has been estimated at 72 years, indicating it is the result of anthropogenic activities. As noted in the Missimer et. al. study *"The sediments in Lake Okeechobee (fluid mud), which have accumulated from decades of inflow from the watershed and in lake vegetation growth serve as a semi-permanent source of the key nutrients that can support and sustain these massive (Cyanobacterial) blooms."*

The conditions described for Lake Okeechobee are not dissimilar to that detailed in 1987 by Reddy and Graetz[34] for Lake Apopka, a large hypereutrophic lake in Central Florida. Legacy nutrients within Lake Apopka have facilitated a continuous bloom of

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[29] Ibid

[30] The word "legacy" can be misleading as it has a double meaning—one of which implies something of value preserved for future benefits. This certainly does not fit the deleterious threat imposed by these stored excess nutrients. Perhaps "occult nutrients" or "latent nutrients" would be more fitting terms.

[31] Ibid footnote 11

[32] University of Florida, Water Institute, W, Graham Director. (2015) Options to Reduce High Volume Freshwater Flows to the St. Lucie and Caloosahatchee Estuaries and Move More Water from Lake Okeechobee to the Southern Everglades An Independent Technical Review by the University of Florida Water Institute Gainesville, Florida

[33] Missimer, T.M.; Thomas, S.; Rosen, B.H. Legacy Phosphorus in Lake Okeechobee (Florida, USA) Sediments: A Review and New Perspective. Water **2021**, 13, 39. https://doi.org/10.3390/w13010039

[34] K. R. Reddy and D. A. Graetz (1987) INTERNAL NUTRIENT BUDGET FOR LAKE APOPKA FINAL REPORT^ Project No. 15-150-01-SWIM 1987-90 Prepared for: St. Johns River Water Management District Palatka, Florida

Cyanobacteria within the lake for over fifty continuous years, which has virtually eliminated growth of submerged aquatic vegetation.

The IRLS anthropogenic organic sediments (muck) have been accumulating for several decades, and now represent 10-20% of the area of the IRL water surface. These muck deposits collect in deeper areas, such as dredged channels, and in the vicinity of creek outlets, and become anoxic, with interstitial (pore) water[35] being high in dissolved ammonium—as much as 10-15 mg/L as ammonium nitrogen[36]. It is believed muck is formed largely by the bacterial degradation of organic matter at the transition between freshwater and estuarine waters. Therefore, external loading of organic matter and inorganic silts and clays is considered the major source of muck[37]. However, as phytoplankton and drift algal gain dominance as the primary producers, it can be expected that their excess productivity could contribute to organic sediment accumulations as well within the IRLS, much as now occurs in Lake Apopka. That is, where the high net productivity becomes a positive feedback mechanism to sustain eutrophic conditions.

It is suggested that there is well over 5 million cubic yards of muck within the lagoon, which delivers circa 30% of the TMDL calculated total nutrient load to the IRL[38]. In the dredging project at the outlet area of Turkey Creek, about 160,000 cubic meters (209,279 cubic yards) of muck was removed, with an estimated dry weight of 83,000 metric tons (91,492 tons) or 874 pounds dry per cubic yard, at 0.36% nitrogen and 0.08% phosphorus[39]. If the amount of muck throughout the IRLS is estimated at 8 million cubic yards with a dry weight of about 3.5 million tons, based upon nitrogen and phosphorus content found from the Turkey Creek muck removal project of 3.14 pounds of nitrogen and 0.70 pounds of phosphorus per cubic yard of muck, it is estimated that legacy stores in the IRLS amount to circa 25.2 million pounds of nitrogen and 5.6 million pounds of phosphorus. Considering the fluctuation of nutrients from the muck ("muck flux") of 657,953 pounds of nitrogen per year and 63,076 pounds of phosphorus per year, shown in Table 10 for Brevard County, which encompasses most of the legacy sources of nutrients within the IRLS, it could take 38 years to deplete the legacy nitrogen and 88 years to deplete the legacy phosphorus, if no additional loading to the sediments occur. These are simply calculated values based on the assumption that the extent of sediment sequestration within the muck layer does not change substantially over time during the period of depletion. While this assumption is not supported

[35] Interstitial water, or pore water in this case refers to water filling the pore space within the muck sediment
[36] Beckett, K.M. (2016) Categorizing "Muck" in the Indian River Lagoon, Florida, Based on Chemical, Physical and Biological Characteristics A Master's thesis submitted to the College of Engineering at Florida Institute of Technology
[37] Bradshaw II, D.J., N.J. Dickens. J.F. Trefy and P.J. McCarthy (2020) Defining the sediments microbiome of the Indian River Lagoon, Fl. USA https://doi.org/10.1101/2020.07.07.191254
[38] Fox, A.L. and J.H. Trefry (2017) Lagoon-wide Application of the Quick-Flux Technique to determine Sediment Nitrogen and Phosphorus Fluxes Submitted to Brevard County, Fl. Natural Resources Management Department
[39] Fox, A.L. and J.H. Trefry (2018) Environmental Dredging to Remove Fine-Grained, Organic-Rich Sediments and Reduce Inputs of Nitrogen and Phosphorus to a Subtropical Estuary *Marine Technology Society Journal July/August 2018 Volume 52 Number 4*

empirically, these calculations do provide insight into the potential magnitude of the legacy nutrient influence upon water quality and ecological stability.

The rate at which the muck sediments release nutrients is referred to as “muck flux”. A technique called Quick-Flux was developed by Austin Fox and John Trefry of the Florida Institute of Technology in Melbourne, Florida (FIT) to facilitate assessment of the nutrient releasing potential of specific muck deposits. Such assessments provide critical information in identifying specific “hot spots” related to legacy nutrient sources. The Quick-Flux method was developed around nutrient levels within the interstitial water, or pore water, associated with the muck, and the rate of molecular diffusion per Fick’s Law[40]. By collecting sediment samples and extracting interstitial water at different sediment depths a concentration gradient can be established and hence the rate at which nutrients move from the higher concentration interstitial water into the lower concentration water column of the lagoon.

The nutrient contribution from muck flux is estimated at about 150 pounds nitrogen per acre per year and 20 pounds phosphorus per acre per year, with about 6,700 acres of muck within the lagoon, or about 1,005,000 pounds of nitrogen per year and 134,000 pounds of phosphorus per year contributed through “muck flux. This is somewhat higher than the values for Brevard County segments given in Table 3.1 of the same reference[41] of 657,953 pounds of nitrogen per year and 63,076 pounds of phosphorus per year—shown here as Table 10. The “muck flux” contributions amount to 23.7% of the annual total nitrogen load to the IRLS and 24.7% of the annual total phosphorus load for Brevard County segments when the total loads are adjusted to include the muck flux, or 30.4% of the annual total nitrogen load and 32.7% of the annual total phosphorus load of the total annual loading without “muck flux contributions.

Table 10: Brevard County Nutrient Loadings from 2021 Project Update[42]

Source	Banana River Lagoon TN lb/yr	Banana River Lagoon TP lb/yr	North IRL Lagoon TN lb/yr	North IRL Lagoon TP lb/yr	Central IRL Zone A TN lb/yr	Central IRL Zone A TP lb/yr	Total Nitrogen lb/yr	Percentage of Total Nitrogen	Total Phosphorus lb/yr	Percentage of Total Phosphorus
Stormwater Runoff	119,923	15,064	328,047	45,423	279,351	43,193	727,321	25.8%	103,680	40.5%
Baseflow/Septic/Leaking Sewer/Reclaimed Water	164,225	22,613	344,111	47,383	370,129	5,096	878,465	31.1%	75,092	29.3%
Atmospheic Deposition	175,388	3,222	301,977	5,505	49,456	892	526,821	18.7%	9,619	3.8%
Point Sources	17,484	3,370	14,711	1,029	0	0	32,195	1.1%	4,399	1.7%
Muck Flux	393,948	43,216	247,078	17,583	16,927	2,277	657,953	23.3%	63,076	24.7%
TOTAL	**870,968**	**87,485**	**1,235,924**	**116,923**	**715,863**	**51,458**	**2,822,755**	**100.0%**	**255,866**	**100.0%**

[40] Fick’s law relates the rate of molecular transport via diffusion through a media driven by concentration gradients

[41] Tetra Tech, Inc. and CloseWaters LLC. (2021) Save Our Indian River Lagoon Project Plan 2021 Update for Brevard County, Natural Resources Management Department Brevard County, Florida

[42] Ibid

In has been noted that "*as ecosystem health declines, benthic fluxes become an increasingly greater source of N and P that can produce a positive feedback loop that helps sustain eutrophication"[43].* This is what has occurred in Lake Apopka, and appears to be happening in Lake Okeechobee, and is similar to the recent dynamics in the IRLS following the 2011 phytoplankton bloom and subsequent blooms and seagrass losses.

Brevard County has committed to removing enough muck to achieve 25% reduction, by volume, in an effort to substantially reduce recycled internal nutrient loads through their "Save Our Indian River Lagoon" program, funded largely by 0.5 cent sales tax increase[44]. In addition, as part of this program will be treatment of the interstitial water—the water which seeps from the removed muck. It is estimated that the total muck within Brevard County section of the IRLS is about 5,608 acres. Within the Brevard County 2021 Updated Project Plan, it is stated that nitrogen and phosphorus released each year as muck decays are now larger than any current source of nutrient pollution to lagoon waters[45]. While this is not exactly supported from data shown in Table 10. It is certainly true for the Banana River Lagoon, which has been identified as one of the "hot spots" regarding legacy sources.

While the impact of legacy nutrients in the IRLS muck is fully recognized by Brevard County in their updated Save Our Indian River Lagoon plan, it is hardly mentioned in the TMDL document, nor are the legacy loads included in either the PSLM or SWIL modeling. Consequently, it is not considered a nutrient input within the TMDL calculations of incoming nutrient loads. Some consideration to "muck flux" is included in the follow-up Basin Management Action Plan (BMAP) documents[46] [47] [48]. In this passage from the North IRL BMAP, it is inferred that implementation of other projects to reduce non-legacy loads will suffice to improve water quality:

"Legacy loading can present an additional challenge to measuring progress in many areas of Florida with adopted BMAPs. Based on research, initial verification by DEP, and long-term trends in water quality in the BMAP area, it is expected that current efforts, such as BMP implementation, will continue to provide improvements in overall water quality despite the impacts from legacy loads."

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[43] Ibid

[44] http://www.brevardfl.gov/SaveOurLagoon

[45] Ibid

[46] Indian River Lagoon Basin Central Indian River Lagoon Basin Management Action Plan. (2021) Florida Department of Environmental Protection of Environmental Assessment and Restoration Water Quality Restoration Program with participation from the Central Indian River Lagoon Stakeholders

[47] Indian River Lagoon Basin Northern Indian River Lagoon Basin Management Action Plan. (2021) Florida Department of Environmental Protection of Environmental Assessment and Restoration Water Quality Restoration Program with participation from the Central Indian River Lagoon Stakeholders

[48] Indian River Lagoon Basin Banana River Lagoon Basin Management Action Plan. (2021) Florida Department of Environmental Protection of Environmental Assessment and Restoration Water Quality Restoration Program with participation from the Central Indian River Lagoon Stakeholders

Later in the BMAP text the importance of legacy nutrients is mentioned, including the need to physically remove muck, and several projects aimed at muck removal are listed. However, as legacy inputs were not included in the TMDL, there is some question how this removal will be credited, although a mechanism is alluded to:

"The SWIL Model does not automatically take this process into account; however, guidance documentation has been developed for crediting muck removal projects specifically from the lagoon."

As with the recent Lake Okeechobee report on legacy nutrients[49], it is suggested that any meaningful restoration and sustained protection of the IRLS is not possible without addressing ways to reduce impact of legacy nutrients.

In recent correspondence with Virginia Barker, Director of Brevard County Natural Resource Management Department, she noted that there is some confusion as to how legacy loads would be included in the TMDL values. She also recognized the importance of legacy (muck) loading and that Brevard County is making progress in relating the muck loading to water quality. She admitted that the recent developments within the IRL regarding extensive seagrass losses and algal blooms have challenged the previously developed relationship between external nutrient loading and seagrass coverage, noting that the system appears to be experiencing a shift from macrophyte dominated to phytoplankton dominated, and that system response to nutrient loading in the past may not be a reliable indicator of future responses. She noted that the St. Johns River Water Management District (SJRWMD) is preparing an analysis of the recent ecological shift in the lagoon, and what factors have contributed. It is not known when this report will be completed and distributed. Ms. Barker made it clear Brevard County is moving forward with their Save Our Indian River Lagoon projects to determine system response to restorative efforts.

It is clear that muck removal is among the projects planned, and several such programs have already been implemented, e.g., Turkey Creek. Ms. Barker did note that the state has criteria for issuing BMAP credit for muck removal based not on the tons of nutrients removed, but on the change in annual "muck flux". This method developed by FDEP involves calculating nutrient reduction BMAP credits as pounds per year associated with changes in the nutrient flux within the muck. This method relies upon presumed nutrient flux as related to organic content measured as Loss on Ignition (LOI), and the muck area actually removed[50].

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[49] Ibid footnote 33

[50] INDIAN RIVER LAGOON (IRL) BASIN MANAGEMENT ACTION PLANS (BMAPS) MUCK REMOVAL PROJECT CREDIT GUIDANCE FLORIDA DEPARTMENT OF ENVIRONMENTAL PROTECTION (DEP) REVISED DRAFT OCTOBER 2019 https://publicfiles.dep.state.fl.us/DEAR/DEARweb/BMAP/BMP_Efficiencies/FDEPRevisedMuckRemovalCreditGuidance10162019%20(003).pdf

Presently 500 acres within the Banana River Lagoon and the North Indian River Lagoon are targeted for muck removal. It is projected that 2,660,000 cubic yards of wet muck will be removed to include interstitial water treatment, to result in flux reduction of 207,990 pounds of nitrogen per year and 17,815 pounds of phosphorus per year[51]. The cost per pound of nitrogen reduction is noted at $520 per year, with the cost of phosphorus reduction at $6,075 per year.[52]

The costs presented in this Project Update report[53] however are somewhat confusing, for if the project costs are one-time capital costs that facilitate annual reductions at the quantities mentioned, then the per unit ($/pound removed) costs should be evaluated as a long-term cost through a present value evaluation. For example, not considering annual operating and monitoring expenses and capital costs in present dollars are $108 million, then we can estimate the unit cost (U) at 50 years as:

$$U= \$108,000,000/ (207,990 \text{ lb-N/yr} \times 50 \text{ yr}) = \$10.38 \text{ lb-N}$$

$$U= \$108,000,000/ (17,815 \text{ lb-N/yr} \times 50 \text{ yr}) = \$121.25 \text{ lb-P}$$

This is more in line with evaluations done on other removal systems (e.g., STA's and Managed Aquatic Plant Systems or MAPS) by the University of Florida Institute of Food and Agricultural Sciences (IFAS)[54]. They found 50-year present value costs per removed pound of phosphorus to range from $10.90 to $611.08. The variability relates to treatment mode, original concentrations, and percent removal.

Dredging appears to be a viable approach if indeed it facilitates water quality enhancement, which is a reasonable expectation. Like so many treatment technologies, residual management is a challenge. Settling areas contiguous or close to the lagoon may be scarce and expensive, and finding a use for the consolidated material may be difficult. Improvements in dredging and residual and interstitial water management however should result from gained experience and reduced costs. Obviously, coordination with external pollution abatement and management is critical to preserve the benefits of dredging.

There may also be other approaches to assist in managing "muck flux", including aeration, sand capping, and other means of consolidation. In addition, continuous external "kidney" type treatment programs may be helpful in long-term reduction of turbidity, removing nutrients and enhancing oxygen levels, such as Managed Aquatic Plant Systems (MAPS) as used by Indian River County, or chemical treatment systems such as the Phosphorus Free Solutions Technology being tested by SJRWMD on Lake

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[51] Note that based upon the previous calculation, the 2,660,000 cubic yards of muck would contain over 14 million pounds of nitrogen and over 3 million pounds of phosphorus.
[52]Ibid footnote 41
[53] Ibid
[54] Sano, D.; A. Hodges and R. Degner (2006) Economic Analysis of Water Treatments for Phosphorus Removal in Florida Document FE576, Food and Resource Economics Department, UF/IFAS, Gainesville, Florida

Apopka[55]. The Algal Turf Scrubber technology, which is being applied in Indian River County, has been shown to be effective in estuarine waters[56].

SEAGRASSES, DRIFT ALGAE AND PHYTOPLANKTON:

Seven species of seagrasses occur in the IRL, a higher diversity than in any other United States estuary. It has been estimated, based upon aerial photographs that in 1943 there was nearly 30,000 ha (circa 81,000 acres) of seagrass coverage throughout the IRLS. The average maximum depth for seagrass coverage in 1943 ranged from a low of 1.1m in the south central IRL to 1.8m in the Mosquito lagoon, north IRL and north central IRL. By 1992 the coverage had reduced to about 28,400 ha (67,300 acres) and the average maximum depth had declined to about 0.8m in the north and central segments of the Indian River Lagoon[57].

From the period 1992 to 2011 a general expansion of seagrass coverage was observed. However a series of algae blooms from 2011 to 2018 resulted in substantial decreases in light penetration and 50% reduction in coverage. About 14,000 ha (33,000 acres) of seagrass coverage was lost after 2011[58]. In the IRL 2020 National Estuary Report[59] the 2011 event is suggested to be a "tipping point", delineating a shift from seagrass to phytoplankton as the primary producer—similar to that suggested by Ms. Barker. This shift as expected is attendant with some serious ecological changes, including damage to benthic communities and shifts in food availability for specialized consumers—including the Manatee, which experienced unprecedented mortality in the IRL during the first half of 2021 due primarily to starvation. This event was included in a statement by the Florida Fish and Wildlife Conservation Commission (FWC). "*Unprecedented manatee mortality due to starvation was documented on the Atlantic coast this past winter and spring* (2021)*. Most deaths occurred during the colder months when manatees migrated to and through the Indian River Lagoon where the majority of seagrass has died off. Because of the large number of manatee deaths documented in this Atlantic event, the preliminary statewide mortality number for the first half of 2021 has*

[55] Kidney type continuous treatment involves conveyance of lagoon or tributary water and in some cases interstitial water, into a land-based treatment system which facilitates solids and nutrient removal, while increasing dissolved oxygen levels, before returning the treated water back to the lagoon. The St. Johns River Water Management District presently has such a chemical/filtration based demonstration project on Lake Apopka (https://www.sjrwmd.com/streamlines/phosphorus-free-project-is-latest-step-in-lake-apopkas-recovery/) and an aquatic plant based approach is being applied by Indian River County Florida as seen in the video at https://vimeo.com/375731448?ref=fbshare&fbclid=IwAR1fCVnlhNdI33XZXBu3MkXkrJv8sJF_q2yg1-j1ng8R0w19TQFSwmyoM6o.
[56] HydroMentia, Inc. 2010, Powell Creek Algal Turf Scrubber Pilot. prepared for Lee County, Florida.
[57] Fletcher, S.W. and W.W. Fletcher (1995) Factors affecting changes in seagrass distribution and diversity patterns in the Indian River Lagoon Complex between 1940 and 1992. Bulletin of Marine Sciences 57(1):45-58
[58] L.J. Morris, L.M. Hall, J. D. Miller, M. A Lasi, R. H. Chamberlain, R.W. Virnstein, and C. A. Jacoby (2021) Diversity and distribution of seagrasses as related to salinity, temperature, and availability of light in the Indian River Lagoon, Florida. Proceedings of Indian River Lagoon Symposium. Florida Scientist 84(2-3) Florida Academy of Scientists
[59] Ibid footnote 25

surpassed the previous highest annual statewide number of 830 mortalities from 2013" [60].

In an email exchange with FWC biologists involved in the assessment of this extensive manatee die-off, it was stated that for a number of the manatees— "*we did test some animals from the current UME* (Unprecedented Mortality Event) *for multiple marine toxins including saxitoxin and they were negative."* As noted, the conclusion was that starvation was the principal cause of the mortality within the IRL.

The general opinion among the majority of investigators is that long term nutrient enrichment is the primary cause for the ecological shift from a seagrass dominated oligotrophic system to a eutrophic system in which epiphytic (attached) algae and drift macroalgae become more prevalent, and finally to a hypereutrophic stage in which phytoplankton becomes dominant[61]. While light attenuation associated with heavy phytoplankton growth is considered one cause of disruption of seagrass productivity, Phlips[62] observed that tripton—non-algal suspended solids—contributes 50.4 to 70.7% of the light attenuation, while phytoplankton contributes only 16.2%. The implication is that resuspension of the sediments—primarily the more recent "muck" sediments—are largely responsible for light starvation within the seagrass community. These re-suspended sediments also contribute "legacy" nutrients, which can promote phytoplankton development in a feedback situation.

While it has not been discussed at any length in the literature, there must be a concern regarding water quality changes beyond turbidity and light attenuation, including potential allelopathy[63]; increased temperatures; shifts in salinity profiles; and diurnal fluctuations in pH and dissolved oxygen associated with heavy phytoplankton production.

This role of sediment accumulations associated with anthropogenic nutrient loading has caused some difficulty within the institutional entities responsible for establishing water quality standards. For example, setting nutrient concentration standards has not typically included consideration of the time delay attendant (lag) with temporary sediment sequestration. When sediments reach some "tipping point"[64] and unload extensive quantities of "legacy" nutrients to the water column, responses can be

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[60] Florida Fish and Wildlife Conservation Commission, Maine Mammal Pathobiology Laboratory 2021 Preliminary Manatee Mortality Table with 5-year summary 2/2/21 through 7/30/21

[61] Lapointe, B.E., L. W. Herren, R. A. Brewton and P. Alderman (2020) Nutrient over-enrichment and light limitation of seagrass communities in the Indian River Lagoon, an urbanized subtropical estuary. Science of the Total Environment. Volume 699, 10 January 2020, 134068

[62] Ibid footnote 16

[63] Allelopathy is the release of substances, including toxins by a species which interfere with the growth or viability of another species, typically a competitive species.

[64] Ibid footnote 28

dramatic and unpredictable—such as the case of the extensive phytoplankton blooms in the IRLS beginning in 2011. As noted, when sediment release of nutrients becomes influential the relationship between watershed loading and seagrass viability appears to collapse. Perhaps a more effective regulatory strategy would be to establish standards for sediment nutrient quality, the rate of accretion, and changes in "muck flux", along with numeric nutrient concentration.

Until 2009 phytoplankton blooms were oriented around diatoms and dinoflagellates, including the long-term resident *Pyrodinium bahamense* var *bahamense. P. bahamense* var *bahamense* and other dinoflagellates have been ubiquitous within the IRLS through most of its natural history and are associated with bioluminescence during the summer months. This phenomenon has typically been considered "natural" with no obvious deleterious impacts. However, in 2006 *P. bahamense* blooms which began in the Banana River Lagoon (BRL) were much more extensive than previous events. There was noted a direct relationship between the 2006 bloom and shifts in climatic events such as the El Nino influence and associated heavy rainfall and heavy external nutrient loading. By 2011 however, phytoplankton dynamics shifted unexpectedly with an initial bloom dominated in the BRL by *Pedinophyceae sp*., which is a green alga, and the small celled cyanobacteria *Picocyanobacteria*, neither of which had previously been documented at the "bloom" level. This bloom was accompanied by noticeable declines in benthic primary producers including seagrasses, associated epiphytes, and drift algae, indicating a serious shift towards phytoplankton dominated primary production. There was indication that internal nutrient recycling from necrotic benthic producers was partly responsible for this 2011 bloom, along with winter low water temperatures. While not mentioned specifically in the article by Phlips et.al., it is suspected "legacy" nutrients released from disrupted sediments could also have contributed[65].

By 2012 a major bloom in the Mosquito Lagoon and North IRL was the first recorded major event involving the brown tide species Aureoumbras *lagunensis* in the IRLS. This "brown tide" event resulted in extensive fish kills, and again in 2016 a bloom of *A. lagunensis* triggered a larger fish kill[66]. In 2020 another bloom associated with a nanocyanobacteria resulted in an additional fish kill, and a commensurate decline in seagrasses and drift algae[67]. The substantial loss of seagrasses has led to starvation of large numbers of manatees in 2021[68].

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[65] Phlips. E.J., S. Badylak & M.A. Lasi, R. Chamberlain, W. C. Green, L. M. Hall, J. A. Hart, J. C. Lockwood, J. D. Miller, L. J. Morris and J. S. Steward (2014) From Red Tides to Green and Brown Tides: Bloom Dynamics in a Restricted Subtropical Lagoon Under Shifting Climatic Conditions. Estuaries and Coasts DOI 10.1007/s12237-014-9874-6

[66] https://www.floridatoday.com/story/news/local/environment/2016/03/23/what-we-know----and-dont-know----fish-kill/82163574/

[67] http://blogs.ifas.ufl.edu/extension/2020/12/02/irl-fish-kill/

[68] Ibid footnote 60

In addition to the increased occurrence of serious phytoplankton blooms within the IRLS, particularly in the northern and central sections, there has emerged a concern that the indigenous form of *P. bahamense* var. *bahamense* has become a serious producer of the toxin saxitoxin. Until 2002, the production of saxitoxin was believed to be limited to Indo-Pacific forms of *P. bahamense* assigned the varietal designation *compressum*. The observation of saxitoxin production coincided with reports of large blooms of *P. bahamense* in the same region and time period. These observations have heightened interest in the controversial relationships between species and varietal designations associated with *P. bahamense* from the Atlantic and Indo-Pacific. Morphologically the two variants appear quite different, and the differences appear to be genetic not environmentally induced. Whether saxitoxin is a newly acquired capability of *P. bahamense* var*. bahamense* is still being investigated. Because saxitoxin can pose a serious risk to the health of humans and other animals, this issues regarding the physiochemistry of P. *bahamense* var. *bahamense* demand expedited research efforts[69].

RESTORATIVE AND POLLUTION REDUCTION PROGRAM—BASIN MANAGEMENT ACTION PLANS:

The shift from benthic to phytoplankton dominated primary production within the IRLS, along with the toxicity concerns related to potential saxitoxin poisoning, has heightened the urgency to develop and implement serious restorative actions as well as pollution reduction programs. A blueprint for such actions is delineated within three Basin Management Action Plans (BMAP)—the Northern IRL, the Central IRL and the Banana River Lagoon [70] [71] [72]. In addition, Mosquito Lagoon programs are detailed within a 2019 Reasonable Assurance Plan[73].

Within these recent BMAP documents is included a revision to the loading and target removals of nitrogen and phosphorus based upon the updated model known as Spatial Watershed Iterative Loading or SWIL. These adjustments as noted in Table11 do not deviate significantly for the 2009 TMDL values, nor do they include internal legacy loading.

Much of the planned management for the southern IRL revolves around the control of flows into the St. Lucie River and subsequent release into the southern IRL as

[69] Badylak, S., K. Kelley, and E.J. Phlips (2004) A description of Pyrodinium bahamense (Dinophyceae) from the Indian River Lagoon, Florida. Phycologia (2004) Volume 43 (6), 653-657
[70] Ibid footnote 46
[71] Ibid foonote 47
[72] Ibid footnote 48
[73] Mosquito Lagoon Reasonable Assurance Plan (RAP) Volusia County and Mosquito Lagoon RAP Stakeholder Group (August 2019) Prepared by Jones Edmunds & Associates, Inc. 730 NE Waldo Road Gainesville, Florida 32641 PE Certificate of Authorization #1841 and Janicki Environmental, Inc. 1727 Dr. MLK St., N St. Petersburg, Florida 33704

described within the St. Lucie River and Estuary BMAP[74]. Presently the U.S. Army Corps of Engineers in cooperation with the South Florida Water Management District (SFWMD) is building the C-44 reservoir and Stormwater Treatment Area (STA) with a capacity of storing 60,500-acre feet of water which will help protect the southern IRL from the deleterious impact of discharges from Lake Okeechobee[75].

With the BMAP's and the Reasonable Assurance Plan, as well as previous efforts to protect and restore the IRLS there is stated a commitment to protecting and restoring the resource to ensure optimal benefits are received. To date, efforts to attend to this commitment have fallen short, as validated by the development of HAB's, attendant fish kills, threats to the health of humans and other animals and the starvation of over 800 manatees in one year.

Table 11: BMAP phosphorus and nitrogen loading and removal adjustments from 2009 TMDL

	Total Nitrogen Loading To Lagoon Segments lb/yr		Target Total Nitrogen Loading To Lagoon Segments lb/yr		Reduction Total Nitrogen Loading To Lagoon Segments lb/yr	
	Per 2009 TMDL	per 2021 BMAP	Per 2009 TMDL	per 2021 BMAP	Per 2009 TMDL	per 2021 BMAP
Northern IRL Segment	886,257	759,084	687,044	506,858	199,213	252,226
Central IRL Segment	1,961,103	2,211,955	962,988	1,328,244	998,115	883,711
Banana River Lagoon	484,462	271,252	291,755	140,004	192,707	131,248
TOTAL	**3,331,822**	**3,242,291**	**1,941,787**	**1,975,106**	**1,390,035**	**1,267,185**
Pre-development Basin Input lb/yr	**2,481,596**	**2,481,596**				
Difference lb/yr	**850,226**	**760,695**				

	Total Phosphorus Loading To Lagoon Segments lb/yr		Target Total Phosphorus Loading To Lagoon Segments lb/yr		Reduction Total Phosphorus Loading To Lagoon Segments lb/yr	
	TMDL	BMAP	TMDL	BMAP	Per 2009 TMDL	BMAP
Northern IRL Segment	100,918	96,224	56,550	51,090	44,368	45,134
Central IRL Segment	314,148	298,758	165,193	156,962	148,955	141,796
Banana River Lagoon	61,900	36,028	23,253	16,267	38,647	19,761
TOTAL	**476,966**	**431,010**	**244,996**	**224,319**	**231,970**	**206,691**
Pre-development Basin Input lb/yr	**55,836**	**55,836**				
Difference lb/yr	**421,130**	**375,174**				

[74] Final Basin Management Action Plan for the Implementation of Total Maximum Daily Loads for Nutrients and Dissolved Oxygen in the St. Lucie River and Estuary Basin (2013) Florida Department of Environmental Protection, Division of Environmental Assessment and Restoration
[75] https://www.saj.usace.army.mil/Missions/Environmental/Ecosystem-Restoration/Indian-River-Lagoon-South/

While there have been some good efforts put forward by talented, well-intended people and groups, these efforts have been offset by institutional delays, funding deficiencies, and inadequate technical approaches, such as presumption of treatment by stormwater and wastewater management systems, and the prolonged discounting of legacy loading. In its Consensus Report the Blue-Green Algal Task Force, which was created by Governor DeSantis to conduct a scientific assessment of the issues related to the increased frequency of HAB's, offered constructive criticism of the BMAP process as well as other efforts related to nutrient reduction within Florida's surface waters. It is worth including within this text several of their comments, as follows[76]:

"A strategic implementation of any of the DEP approved plans is hindered, in large part, however, by local funding constraints that dissuade commitments by otherwise willing partners to execute identified projects. As a consequence, delays in the anticipated time to achieve a specific restoration target within BMAP areas have occurred."

"The task force recognizes that rapidly changing demographics, alterations in land use and altered hydrology obfuscate the BMAP process. Nevertheless, projections of such changes should be incorporated, where possible, into the BMAP process to identify projects/actions that could compromise other ongoing restoration efforts".

"Moreover, the effectiveness of specific projects has not been regularly and rigorously assessed due to a lack of available monitoring data calling into question returns on investment. Such projections could be used also to inform future land use planning and permitting".

"The presumption that a stormwater treatment system constructed and permitted in compliance with BMP design criteria will not cause or contribute to violations of surface water quality standards in adjacent and/or connected waterbodies has been evaluated and challenged. Available data suggest that a substantial number of stormwater treatment systems throughout the state fail to achieve their presumed performance standards".

"The task force further recommends that projects with the demonstrated potential to expedite legacy nutrient removal merit special attention and be designated as priority projects".

"The Blue Green Algae Task Force recognizes that (Agricultural) *BMPs are necessary, but not sufficient in many areas to achieve water quality targets established within BMAP areas. Nevertheless, the task force recommends that the effectiveness of BMP's be*

[76] Blue-green Algae Task Force DRAFT Consensus Document #1 Final Draft – Revised 3 October 2019. For information on the Task Force https://protectingfloridatogether.gov/state-action/blue-green-algae-task-force

supported by adequate data to justify the presumption of compliance granted upon enrollment and implementation".

"The Department of Environmental Protection should develop a comprehensive regulatory program to ensure that onsite sewage treatment and disposal systems (septic tanks)*, where appropriate, are sized, designed, constructed, installed, operated and maintained to prevent nutrient pollution, reduce environmental impact and preserve human health".*

"The task force further recommends legislation and funding to accelerate cost-effective septic to sewer programs with the aim of reducing nutrient pollution that leads to harmful algae blooms".

"Finally, the task force encourages an investment in a program to aid in the development and/or implementation of technologies to reduce nutrients and/or harmful algae".

Considering the seriousness of the degradation of the IRLS and the magnitude of long-term economic implications, the present BMAP strategy could be assessed as timid and inadequately responsive. For example, a lack of urgency to remove septic tanks and to upgrade wastewater treatment nutrient removal capabilities; the allowance of heavy nutrient loading from wastewater reuse; the slow development of effective agricultural BMP's; the failure to included legacy loads as a nutrient input; the continued reliance upon presumption of treatment regarding stormwater ponds; and little mention of the need to consider the impacts of future developments and land use changes upon the BMAP efforts.

septic tanks

It is reported that there are about 103,000 septic tanks in the North IRL, Central IRL and BRL watershed of which over 78,000 are in the Central IRL watershed. While there appears to be a general thought that well-functioning conventional septic tanks offer effective treatment, they actually do little to reduce nutrient levels. Also, the belief that drain fields and receiving soils offer considerable reduction of nutrients is not well documented, nor is it likely to apply in the sandy soils associated with the IRLS, particularly in the northern and central watershed[77]. The problem of seepage of nutrients from septic tanks into the IRLS is exacerbated by continued loss of interceptor wetlands that historically served to enhance nutrient reduction while modulating flow rates into the lagoon.

[77] Historically in Florida there seems to have developed a great deal of confidence that once water moves into groundwater, the soils provide long term sequestration or at least significant attenuation of any nutrients associated with this water. It is now becoming apparent that the capabilities of these soils are often over-stated.

In the 1983 Water Quality Assurance Act--Ch. 83-310, 1983 Florida Law—the permitting and regulation of Septic Tanks were transferred from the Florida Department of Environmental Regulation (FDER, now FDEP) to the Florida Department of Health and Rehabilitative Services, now the Florida Department of Health (FDOH). This eliminated any serious consideration of nutrient impacts associated with septic tanks (except for nitrate-nitrogen levels exceeding 10 mg/L), with emphasis almost exclusively on human health issues. This allowed the continuation of septic tank proliferation, including allowances for new developments. The price paid for this convenient maneuvering of septic tank regulation is now apparent in the emergence of so many HAB events.

Consider a cursory calculation of potential influence of septic tanks on nutrient dynamics. Assuming daily septic tank unit flows to be 150 gpd with effluent levels of 25 mg/L total nitrogen and 6 mg/L total phosphorus—and this is likely a low estimate-- the daily load to the watershed would be 15.45 MGD and 3,221 pounds of nitrogen per day or 1,175,783 pounds of nitrogen per year and 773 pounds of phosphorus per day or 282,188 pounds of phosphorus per year. This is over 30% of the total nitrogen watershed loading and over 50% of the total phosphorus watershed loading estimates presented within the TMDL report (see Table 11).

In a septic tank study conducted for the Florida Department of Environmental Protection within the Wekiva River Basin[78], septic tank effluent averaged 85 mg/L total nitrogen, with about 40% attenuation through the shallow soils and drainfield. The residual therefore averaged about 51 mg/L total nitrogen, which is considerably higher than the calculation presented in the previous paragraph. Within the IRL TMDL and BMAP documents the loading from septic tanks are not quantified specifically. Rather they are included within the general category of non-point sources. The Pollutant Loading Screening Model (PLSM) model used to calculate the 2009 non-point source loading is based upon land use categories and loading surface runoff rates associated with each category. The model projects loadings associated with rainfall events, not with loads emanating from continual movement through the groundwater of septic tank effluent. Per the 2009 TMDL report, it was recognized that subsurface seepage and base flows are not specifically identified within the loading estimates and were considered only implicitly[79].

The SWIL model does segregate runoff from baseflow and adjusts flows by considering evapotranspiration. In the SWIL modeling applied to the Brevard County IRLS segments, baseflow loadings exceeded direct surface runoff loadings for nitrogen by about 20%, while phosphorus baseflow loadings were lower than surface runoff

[78] Wekiva-Area Septic Tank Study (2018) Division of Environmental Assessment and Restoration, Florida Department of Environmental Protection 2600 Blair Stone Rd. Tallahassee, FL 32399 www.dep.state.fl.us
[79] Green, W and Joel S. Steward (2003) The Utility of a Pollutant Load Screening Model in Determining Provisional Pollutant Load Reduction Goals Conference Proceedings of Emerging Technologies, Tools and Techniques to Manage our Coasts in the 21st Century. U.S. E.P.A. Cocoa Beach, FL.

estimates (see Table 10). The SWIL estimates for water quality and mass loading of baseflow, which includes septic tanks, reclaimed water, leaking sewer lines and other groundwater contributions, are based upon model calibration from water quality and flow data from streams (creeks) around the central IRL, such as Turkey Creek.

The baseflow and seepage loads reflect the net groundwater input to the IRLS following nutrient attenuation as the flows move through the soils. While there is documentation related to reduction of nutrients within groundwater, the rates of reduction depend not only upon soil types, vegetation, and distance of travel, but also with time. Accumulation of nutrients within soils can create a legacy condition, e.g., as documented within the Okeechobee watershed. Also, it is not clear how the interception of some of the groundwater flow within creeks and canals relate to direct groundwater seepage into the IRL itself, such as would be most prevalent in the Northern IRL as well as certain reaches of the Central IRL and the BRL. The behavior of nutrients which remain unexposed to surface conditions would not be expected to be similar to those which eventually enter stream flow before discharge to the lagoon, as stream conditions would more likely promote nitrification, denitrification, nitrogen fixation, plant uptake and other transformative reactions. In consideration of these differences, it is possible that baseflow loads as shown in Table 10 for the Brevard County Segments are low.

It is likely that septic tanks are a major nutrient contributor to the IRL, as noted in studies by LaPointe et.al.[80] who by tracing $\delta^{15}N$ (isotope ratio) provided evidence that nitrogen associated with animal (including human) waste was a major contributor to HAB's in the IRLS. Accordingly, to mitigate for septic tank loading, efforts targeting expansion of wastewater treatment and collection should be expedited and wastewater treatment standards made more stringent, as discussed in the next subsection.

Considering the magnitude of the septic tank issue, the following measures are suggested to be incorporated into the BMAP:

1. Place a moratorium on all new septic tanks, with the possible exception where a tank is installed on no less than one contiguous acre.
2. Establish and expedite a comprehensive, aggressive domestic wastewater facility plan which targets septic tank elimination.
3. Adopt strategies for securing funding for facility plan implementation. e.g., municipal bonds backed by upgraded users and impact fees and sales tax; Federal and State grants and loans; and adjustments to property taxes.
4. Accelerate interim repair to poorly functioning septic tanks and drainfields.

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[80] LaPointe,, B.E., L.W. Herren, D.D. Debortoli, M.A. Vogel (2015) Evidence of sewage-driven eutrophication and harmful algal blooms in Florida's Indian River Lagoon Harbor Branch Oceanographic Institute at Florida Atlantic University, Harmful Algal Bloom Program, 5600 US 1 North, Fort Pierce, FL 34946, USA https://doi.org/10.1016/j.hal.2015.01.004

5. In lieu of sewer hook-up, allow upgrading tanks to enhanced OTSDS (on-site sewage treatment and disposal system) which include nitrification/denitrification to ensure AWT total nitrogen standards (3 mg/L), supported by effective monitoring and O&M.
6. Restore disturbed wetlands which would intercept groundwater seepage downstream from septic tank clusters.
7. Consider groundwater treatment in specific “hot spots”, which may include engineered systems for nutrient removal.

domestic wastewater treatment

Within the 1972 Clean Water Act (PL92-500) is included section 201 which outlines Federal funding mechanisms for regional wastewater systems, with the original intent of upgrading and expanding systems when practical to meet the Advanced Wastewater Treatment (AWT) standard of 5 mg/L five-day Biochemical Oxygen Demand (BOD_5); 5 mg/L Total Suspended Solids (TSS); 3 mg/L as total nitrogen (TN); and 1 mg/L total phosphorus (TP) prior to surface water discharge. Incentivized by the possibility of Federal subsidies, there was a rush within both the public and private sectors to develop innovations which could cost-effectively meet these standards. As a result, the nation’s wastewater infrastructure was improved significantly, resulting in notable improvements in surface water quality.

However, by the early eighties the trend was moving away from AWT/direct discharge, towards methods that eliminated direct discharge. These included deep well injection, rapid infiltration systems which quickly put the effluent into shallow groundwater aquifers, and reuse of effluent largely for irrigation or industrial reuse. Over the years the reuse option often became the most preferable of these, as it was seen as an effective water conservation measure. Today wastewater reuse is ubiquitous in Florida, being used not only in public areas and golf courses, but also for private landscaping irrigation and industrial applications. The benefits of reuse beyond water conservation include lower costs than full AWT, and the opportunity to set user fees for access to the reuse water[81].

Presently, wastewater effluent which meets standards for irrigation reuse typically does not include extensive nutrient reduction. The standard nutrient requirements for advanced secondary effluent as reuse water is noted in Ch. 64E-.025 (1) F.A.C. as an annual average, ≤ 10 mg/L as carbonaceous BOD (CBOD) and TSS; TN ≤ 20 mg/L; TP ≤ 10 mg/L and nitrate nitrogen ≤ 12 mg/L. Within the BMAP documents (footnotes 46, 47 and 48), somewhat more stringent standards are suggested for effluent reuse within

[81] Brevard County charges $10 per month for each acre wetted, or a flat fee of $6.00 per month for residential users. https://www.brevardfl.gov/UtilityServices/ReclaimedWater

the IRLS, as noted in Table 12. The direct discharge standard applies to end-of-pipe, while the Rapid Rate and reuse standards apply to water quality at the compliance well at the edge of zone of discharge.

Table 12: Effluent Wastewater Effluent Phosphorus and Nitrogen Standards per BMAP for facilities greater than or equal to 0.50 MGD

Direct Surface Discharge		Rapid Rate Land Application		Reuse	
Total Nitrogen mg/L	Total Phosphorus mg/L	Total Nitrogen mg/L	Total Phosphorus mg/L	Total Nitrogen mg/L	Total Phosphorus mg/L
3.0	1.0	3.0	1.0	10.0	6.0

As with septic tanks, reuse effluent discharges to groundwater. The presumption upon which these reuse effluent standards are based is that travel through the soil, combined with plant uptake will attenuate nutrient levels to acceptable concentrations by the time the groundwater enters the lagoon via seepage. It is difficult to monitor the validity of this presumption however once the effluent enters the groundwater system.

While the concept of releasing effluent to groundwater is emulative of pre-development hydrology by which much of the watershed flow to the lagoon was modulated by movement through the shallow aquifer, the presence of such heavy nutrient loads far exceeds pre-development conditions. The extent that these loads are captured and effectively sequestered or somehow dissipated has not proven to be predictable, as noted by several situations in which nutrients from reuse waters have found their way to critical surface waters to create serious ecological disruptions. The first of such cases in Florida involved the downgradient movement of reuse irrigation seepage from the effluent sprayfield in Tallahassee into Wakulla Springs[82], with nitrate being the major concern. More recently, other systems such as Wekiwa Springs have been deleteriously impacted by nitrogen associated with rapid rate land application systems, as well as reuse and septic tank seepage, as was documented within the recent Wekiwa Springs and Rock Springs BMAP[83]. Within much of the Wekiwa and Rock Springshed, both rapid rate systems and other land application methods for wastewater effluent are now expected to meet the standard of no more than 3 mg/L total nitrogen.

[82]Davis, J.H., B.G. Katz and D.W. Griffin (2011) Nitrate-N Movement in Groundwater from the Land Application of Treated Municipal Wastewater and Other Sources in the Wakulla Springs Springshed, Leon and Wakulla Counties, Florida, Scientific Investigations Report 2010-5099 USGS https://pubs.usgs.gov/sir/2010/5099/pdf/sir2010-5099_davis_revised_3-2-2011.pdf

[83] Wekiwa Spring and Rock Springs Basin Management Action Plan Division of Environmental Assessment and Restoration Water Quality Restoration Program Florida Department of Environmental Protection with participation from the Wekiwa Spring and Rock Springs Stakeholders June 2018

To gain some insight into the extent of attenuation of nutrient loads within the shallow aquifer, consider the calculated loads of septic tanks and reuse water within the Brevard County segments. There are reported about 53,200 septic tanks within the Brevard County watershed to the IRL[84]. It is reasonable to expect these contribute about 150 gpd each or 7.98 MGD total. If the post-drainfield concentrations are 25 mg/L total nitrogen and 6 mg/L total phosphorus, then the annual septic load prior to any further attenuation is estimated at 607,298 lb-N/yr and 145,752 lb-P/yr.

The population for the Brevard County per the U.S. Census Bureau, is estimated at about 600,000 persons. If the average daily per capita wastewater generation is 75 gallons, then the total daily wastewater flow would be about 45 MGD. Subtracting from this about 0.51 MGD as direct discharge and the 7.98 MGD going to septic tanks, leaves an estimated 36.5 MGD that is applied to some form of reuse or rapid infiltration. If this reuse effluent is assumed to be at 10 mg/L total nitrogen and 6 mg/L total phosphorus, the maximum loading to the watershed from this flow then would amount to 1,111,100 pounds per year nitrogen and 666,658 pounds of phosphorus (considerably higher than the septic tank loads). Combining these reuse loads with septic tank loads amounts to 1,718,398 pounds per year total nitrogen and 806,400 pounds per year total phosphorus. As shown in Table 13, of the SWIL determined baseflow loads of 878,465 pounds per year total nitrogen and 75,092 pounds per year total phosphorus, the minimum calculated attenuation rate for baseflow and seepage would be 49% and 91% for nitrogen and phosphorus respectively. If other loads such as stormwater infiltration, sewage line leakage and fertilizer losses were to be included, then the attenuation rate would be higher. Over time, how much of these loads would find a way to the lagoon is an issue open for debate, but certainly, as soils become saturated with these nutrients, they have the potential of becoming legacy sources.

Table 13: Estimated Minimum Nutrient Attenuation within Shallow Aquifer of Brevard County Segments

Septic Tank Load lb/yr	Reuse Load lb/yr	Septic Tank + Reuse Load lb/yr	Baseflow Load per Table 10 lb/yr	Minimal Attenuation lb/yr
Total Nitrogen				
607,298	1,111,100	1,718,398	878,465	49%
Total Phosphorus				
145,752	661,658	806,410	75,092	91%

If the effluent standard for all wastewater treatment systems were upgraded to 3 mg/L total nitrogen and 1 mg/L total phosphorus, the reuse loading would be reduced to 333,330 pounds per year of nitrogen and 111,110 pounds of phosphorus per year

[84] Ibid footnote 41

before attenuation. If septic tank loadings were also eliminated, or at least significantly reduced, baseflow loadings would undoubtedly decrease significantly. Both septic tank elimination and wastewater treatment upgrade to AWT would offer extensive reduction of non-point source loading to the lagoon.

Therefore, regarding management of wastewater, the following is suggested:

1. All domestic wastewater treatment facilities be upgraded to ≥AWT standards
2. Expand treatment capacity by circa 15.5 MGD to handle flows associated with septic tank elimination.
3. Expedite repair of faulty sewer lines
4. When possible, develop infiltration basins for AWT level effluent within the ridge areas of the western periphery of the watersheds.
5. Recover and restore interim wetland systems. This should include procurement of disturbed or developed wetlands and their subsequent restoration when practical. This may also involve reclamation of flood zones.

stormwater management

The regulation and permitting of stormwater management systems in Florida include a provision for “rebuttable presumption”, as delineated by the FDEP and the Water Management Districts[85], meaning that systems designed, installed and maintained per state criteria are presumed to meet water quality standards, unless reasonable challenges show otherwise. Generally, nutrient treatment associated with the present detention and retention system designs to which the “rebuttable presumption” applies are oriented around ponds or a series of pond systems intended to capture what is typically referenced as the “first flush”, which has been documented as that portion of the runoff containing the majority of pollutants. The design criteria vary somewhat depending upon the water management district involved; rainfall patterns; site hydrology; land use categories; the extent of directly connected impervious areas (DCIA); the status of receiving waters; and the size and topography of the watershed being targeted. However, all share a common strategy, which is either a reliance upon nutrient uptake within aquatic vegetation associated with the system, or attenuation through settling and subsequent infiltration into the ground, or both. As noted in the Blue-Green Algae Task Force consensus report, this presumption of treatment and compliance is being challenged both for stormwater treatment and Agricultural Best Management Practices (BMP).

[85] ENVIRONMENTAL RESOURCE PERMIT APPLICANT’S HANDBOOK, VOLUME II: FOR USE WITHIN THE GEOGRAPHIC LIMITS OF THE ST. JOHNS RIVER WATER MANAGEMENT DISTRICT (2013) Section 4.13

As noted previously, in its Consensus Report of 2019 the Blue-Green Algae Task Force stated that:

> *". the presumption that a stormwater treatment system constructed and permitted in compliance with BMP design criteria will not cause or contribute to violations of surface water quality standards in adjacent and/or connected waterbodies has been evaluated and challenged. Available data suggest that a substantial number of stormwater treatment systems throughout the state fail to achieve their presumed performance standards."*

The two primary concerns regarding the efficacy of the present use of detention and retention ponds for stormwater treatment are 1) the too frequent lack of maintenance by the permitted entity, and insufficient oversight by permitting agencies and 2) the apparent presumption that any nutrients associated with stormwater which infiltrates into the ground are effectively removed.

The 2009 TMDL projections of stormwater runoff quantity and quality were developed around the Pollutant Loading Screening Model (PLSM). This model targeted runoff conditions without segregating baseflows and groundwater impact from surface runoff, and without consideration of evapotranspiration (ET).

The upgraded SWIL model attempts to account for groundwater quality impacts from stormwater infiltration as well as septic and reuse irrigation influences, by separating baseflow (groundwater movement) from surface runoff. It also includes ET in the model calculations, setting baseflow as rainfall minus the sum of surface runoff and ET.

The quality and nutrient loading of stormwater runoff per the SWIL model is developed from calculated runoff volumes and the Event Mean Concentration (EMC) of runoff from various land uses, corrected for presumed treatment from any stormwater management systems. The Land use acreages and associated EMC are shown in Table 14.[86] [87]

[86] Harper, H.H. and D.M. Baker (2016) – REFINING THE INDIAN RIVER LAGOON TMDL Technical Memorandum Report: Assessment and Evaluation of Model Input Parameters FINAL REPORT prepare for Brevard County Natural Resources Management Department

[87] Ibid footnote 9

Table 14: Land use and Event Mean Concentrations or the North IRL, Central IRL, and the Banana River Lagoon

			North IRL Acreage		Central IRL Acreage		Banana River Lagoon Acreage		TOTAL	
	Event Mean Concentration mg/L		132,135		283,609		51,423		467,167	
LAND USE	Total N	Total P	Percent of Total	Acreage	Percent of Total	Acreage	Percent of Total	Acreage	Percent of Total	Acreage
Urban/Built-up (Industrial/Commercial)	1.42	0.214	6.6%	8,784	9.6%	27,355	15.2%	7,825	9.4%	43,964
Low Density Residential	1.51	0.178	4.2%	5,597	5.6%	15,944	0.9%	439	4.7%	21,980
Medium Density Resdiential	1.87	0.301	6.3%	8,338	14.0%	39,626	8.6%	4,416	11.2%	52,380
High Density Resdiential	2.10	0.497	4.9%	6,449	2.8%	7,897	6.4%	3,278	3.8%	17,624
Transportation and communication	1.37	0.167	2.8%	3,710	2.2%	6,255	2.0%	1,038	2.4%	11,003
Agriculture	2.61	0.485	8.9%	11,735	26.9%	76,157	0.4%	231	18.9%	88,123
Rangeland	1.15	0.055	12.0%	15,831	11.7%	33,184	19.3%	9,921	12.6%	58,936
Upland Forest	1.00	0.034	8.9%	11,805	13.7%	38,793	19.1%	9,818	12.9%	60,416
Water (does not include Lagoon area)	NA	NA	1.9%	2,576	2.2%	6,127	7.1%	3,649	2.6%	12,352
Wetland	1.50	0.100	42.4%	56,076	10.4%	29,503	20.4%	10,509	20.6%	96,088
Barren	1.32	0.347	0.9%	1,234	1.0%	2,768	0.6%	299	0.9%	4,301
Total Annual Nitrogen Non-Point Loading lb/yr*			576,413		1,796,063		289,117		2,661,593	
Total Annual Phosphorus Non-Point Loading lb/yr*			93,507		309,007		54,981		457,495	
Loading Rate Nitrogen lb/acre-yr			4.36		6.33		5.62		5.70	
Loading Rate Phosphorus lb/acre-yr			0.71		1.09		1.07		0.98	

Baseflow water quality was developed through calibration with water quality associated with several tributaries in the Central and Northern IRL, including Crane Creek and the Fellsmere Canal, during periods in which surface runoff was minimal or absent. The geometric mean of nitrogen and phosphorus values associated with these tributaries during periods of minimal surface flow influence were used to determine loading associated with modeled baseflow volumes. As shown in Table 10 the baseflow is a major contributor of nitrogen, being higher than surface runoff. In the SWIL modeling however, the specific delineation of source of the baseflow pollution is not clearly provided, nor are the specific forms of nitrogen and phosphorus identified. As noted earlier in this text, the bioavailability of nitrogen is important to the productivity dynamics within the lagoon itself. It has been shown that seepage from septic tanks for example are largely associated with organic nitrogen and ammonia nitrogen, while seepage from reuse is represented by higher nitrate levels. The SWIL modeling does not project influence of groundwater seepage which moves directly into the IRL. This would apply for example to septic systems which are in proximity to the lagoon, particularly in regions such as seen in the North IRL where hydraulic gradients contiguous to the lagoon are comparatively high.

The SWIL model represents a significant improvement in the ability to project stormwater impact, including baseflow loadings. However, baseflow water quality data is limited. Additional monitoring of groundwater, especially in regions close to the lagoon will allow further enhancement of SWIL. Monitoring should include analysis for specific forms of nitrogen and phosphorus as well as nitrogen isotope ratios to provide insight as to the source of nitrogen pollution.

One thing that is quite noticeable is the difference between the calculated pre-development baseflow nutrient concentrations at 0.33 mg/L total nitrogen and 0.008 mg/L (8 µg/L) total phosphorus (see Table 3) and the SWIL baseflow concentrations of 0.88 mg/L total nitrogen and 0.122 mg/L (122 µg/L) total phosphorus—or a 266% nitrogen and 1,525 % phosphorus departure from pre-development conditions. Reduction of these baseflow loads then is critical to any effective restoration of water quality or seagrass recovery.

agricultural BMP's

Within the three segments addressed though the TMDL—NIRL, BRL and CIRL—the major agricultural sources are located within the CIRL. Agriculture accounts for 26.9% of the land use area within the CIRL, and 86.4% of all agricultural area within the three IRL segments. Development, implementation and regulation of agricultural pollutant contributions is the responsibility of the Florida Department of Agriculture and Consumer Services (FDACS), which is also tasked to encourage enrollment of owners of agricultural lands to the BMP program. In the CIRL presently only 25% of landowners are enrolled in the FDACS BMP program.

In addition to poor participation, there is some question, as noted by the Blue-Green Algae Task Force as to the efficacy of the agricultural BMP's:

> *The Blue Green Algae Task Force recognizes that* (Agricultural) *BMPs are necessary, but not sufficient in many areas to achieve water quality targets established within BMAP areas. Nevertheless, the task force recommends that the effectiveness of BMP's be supported by adequate data to justify the presumption of compliance granted upon enrollment and implementation."*

Agricultural nitrogen loading contributions are 21.6% of the total loading in CIRL, with phosphorus loading contributions at 16.5%, as shown in Table 15. Over the three segments, agriculture accounts for 16.0% of nitrogen loading and 12.2% phosphorus loading.

Table 15: Agricultural Nutrient Loadings

	North IRL	Central IRL	Banana River IRL	Total
Agricultural Area	**11,735**	**76,157**	**231**	**88,123**
Annual Agricultural Nitrogen Loading lb/yr	38,099	477,619	4,130	519,848
Annual Agricultural Nitrogen Areal Loading lb/acre/yr	3.25	6.27	17.88	5.90
Percentage of Total Basin Nitrogen Loading from Agriculture	5.0%	21.6%	1.5%	16.0%
Annual Agricultural Phosphorus Loading lb/yr	5,750	51,895	516	58,161
Annual Agricultural Nitrogen Areal Loading lb/acre/yr	0.49	0.68	2.23	0.66
Percentage of Total Basin Phosphorus Loading from Agriculture	0.8%	16.5%	0.8%	12.2%

Much of the agricultural loads are associated with activity well west of the lagoon, with much of this loading intercepted by drainage canals —the South and Main canals in Indian River County being examples. The flows from these canal networks can be treated through “kidney” systems, such as the Egret Marsh and Osprey Marsh facilities in Indian River County. Such treatment systems however should not be considered replacements for agricultural BMP programs.

land use changes

The TMDL removal targets are based upon present land use. As land use changes occur it is likely that nutrient and hydraulic loading rates will also change. The SWIL model is useful in being able to revise projections as these changes occur. The difficulty however lies with the fate of generated wastewater and the management of stormwater/baseflow impacts. Introducing wastewater to systems that are not presently effectively reducing nutrient loadings would interfere with restoration efforts and could exacerbate an already urgent problem. Similarly, there are serious questions related to the presumption of treatment of stormwater and agricultural BMP’s. These concerns are legitimate and require additional measures to ensure that any land use changes do not increase nutrient or hydraulic loading to the lagoon. Again, this was clearly expressed by the Blue-Green Algae Task Force

> *“The task force recognizes that rapidly changing demographics, alterations in land use and altered hydrology obfuscate the BMAP process. Nevertheless, projections of such changes should be incorporated, where possible, into the BMAP process to identify projects/actions that could compromise other ongoing restoration efforts”.*

STATUS OF RESTORATIVE AND POLLUTION REDUCTION ACTIONS TO DATE:

Within the BMAP documents for the NIRL, CIRL and BRL are calculations related to nutrient reduction progress to date, as shown in Table 1

Table 16: Nutrient Reductions Present and Future Projections

North IRL				Central IRL				Banana River Lagoon			
Calculated % reduction 2020		100% reduction 2035 lb/yr		Calculated % reduction 2020		100% reduction 2035 lb/yr		Calculated % reduction 2020		100% reduction 2035 lb/yr	
N	P	N	P	N	P	N	P	N	P	N	P
50%	49%	252,495	45,193	27%	23%	916,040	220,828	48%	38%	112,539	17,273

For the NIRL, most of the existing reductions relate to implementation of wet and dry detention facilities. Other completed and ongoing actions include baffle boxes[88], fertilization restrictions and educational programs, street sweeping, managed floating aquatic plant islands (MAPS), aquatic plant harvesting and alum injection systems. Dredging projects are listed but nutrient reduction values are not given within the BMAP.

In the CIRL, most of the existing reductions relate to redirection of canal C-1 flows to the St. Johns River Basin; Managed Aquatic Plant Systems or MAPS in Indian River County; aquatic plant harvesting on Main Canal in Indian River County; wet and dry detention ponds; deep well injection; Agricultural BMP's; baffle boxes; and education and fertilizer ordinance. Dredging projects are listed but nutrient reduction values are not given within the BMAP.

In the BRL, much of the existing reductions relate to wastewater plant upgrade and implementation of wastewater reuse programs. Other actions include wet and dry detention facilities; baffle boxes; and educational programs. Dredging projects are listed but nutrient reduction values are not given within the BMAP.

The calculated achievements to date related to nutrient reductions are largely associated with presumption of treatment, so there is some question as to the reliability of the claimed removals. Beyond the issue of level of removal, however, is the fate of nutrients which are stored rather than removed. For example, nutrients associated with seepage from detention systems escape into the groundwater compartment where their fate is typically not well documented. These nutrients are vulnerable to temporary sequestration, meaning they can become legacy sources with the potential of releasing to the lagoon at some further date. With this recognition, it would be prudent to show preference for systems that actually capture nutrients for recycling; for out-of-basin export; or for secure disposal at contained sites such as landfills. Actual nutrient capture projects would include dredging; MAPS systems such as Egret Marsh; aquatic plant harvesting; chemical precipitation (Alum) programs; and well-maintained baffle boxes. Some agricultural BMPs also involve nutrient capture and reuse.

DISCUSSION:

The original TMDL was developed from the relationship between nutrient loading and seagrass coverage as measured by the average maximum depth of seagrass growth. The stormwater loading calculations done in 2009 involved the use of the Pollutant Loading Screening Model (PLSM) which projected the quantity of surface runoff, with groundwater/baseflow being implicitly included. Later a revised model-- Spatial Watershed Iterative Loading or SWIL—was used to effectively identify surface runoff

[88] Baffle boxes are structures designed to facilitate settling and screening of intercepted stormwater. Sometimes special media is used to facilitate additional nutrient removal. The efficacy of baffle boxes depends upon frequent and effective maintenance.

and baseflow separately. In the 2021 BMAP documents the TMDL was revised, although the changes were minimal—1, 975106 pounds per year total nitrogen and 224,319 pounds per year total phosphorus.

After 2011, following a number of algal blooms and fish kills and 50% loss of seagrass, it became clear that external nutrient loading as considered in the TMDL development could not be used effectively to project seagrass coverage. The influence of the accumulating muck sediments has been identified as a major contributor to the ecological changes observed. These sediments not only return stored (legacy) nutrients into the water column—about 30% of the TMDL load--they also reduce light penetration through re-suspension of fine sediments. It is reasonable to project that any reclamation of the IRLS will require effective management of these muck sediments, and Brevard County is expediting muck dredging projects within the BRL and NIRL. Muck management projects should be top priority. While dredging is presently the selected management approach, other methods need to be considered, such as sand capping, consolidation, and long term “kidney” type treatment systems which would pull water from the lagoon, treat it for nutrients and suspended solids while adding dissolved oxygen, before returning the treated water to the lagoon. This type of “kidney” system is presently being used by Indian River County using Managed Aquatic Plant Systems (MAPS) while St. Johns River Water Management District is testing a chemical/filtration “kidney” system on Lake Apopka.[89]

Within the BMAP’s are identified a variety of actions which would reduce external nutrient loading to the lagoon. Some of these are institutional such as fertilizer restrictions and public educational programs, some are restorative such as shoreline enhancement, while some are ongoing maintenance such as street sweeping and baffle box maintenance. Suggested large scale initiatives for external nutrient load reduction include the following, listed in priority ranking:

1. Treatment upgrade for all Wastewater Treatment Facilities to AWT standards, including AWT upgrade of effluent for irrigation reuse
2. More aggressive implementation of agricultural BMP’s, including verification of efficacy.
3. Expedite elimination of all septic tanks on less than one acre of land through extension of sewage collection and treatment capabilities.
4. Alternatively, replacement of septic tanks with advanced Onsite Sewage Treatment and Disposal System (OSTDS) which provide Advanced Wastewater Treatment (AWT) effluent quality.

[89] The Indian River County Egret Marsh MAPS can be viewed at https://vimeo.com/375731448?ref=fbshare&fbclid=IwAR1fCVnlhNdI33XZXBu3MkXkrJv8sJF_q2yg1-j1ng8R0w19TQFSwmyoM6o) The Lake Apopka approach can be viewed at www.phosphorusfree.com

5. Implement flow diversion projects which result in reduction of nutrient inputs to the IRLS.
6. Establish “kidney” type treatment systems to intercept and treat waters from nutrient laden tributaries and canals, and possibly from the lagoon directly, such as the Managed Aquatic Plant Systems (MAPS) used by Indian River County, or the chemical/filtration system being tested by the St. Johns River Water Management District (SJRWMD) on Lake Apopka.
7. Restore or create wetlands which can intercept stormwater and groundwater seepage
8. Ensure that development of wet and dry ponds for stormwater are compliant with applicable standards and properly maintained to include provisions which deter the production of blue-green algae (Cyanobacteria), while promoting the recovery of nutrients.
9. Employ aquatic plant harvesting where feasible, with the commensurate reduction of herbicide use.
10. Ensure any new developments are designed and maintained to avoid increased nutrient and sediment loading to the IRLS.

It is suggested that preference be given to cost effective projects that actually recover and reuse nutrients from the various pollution sources. Concepts which recover and can reclaim nutrients such as MAPS, Aquatic Plant Harvesting, muck dredging, and some chemical treatment systems could be developed to facilitate recycling of nutrients for agriculture and should be seriously discussed with FDACS.

In addition, more extensive monitoring of the nature and behavior of muck sediments; the water quality and ecology of the lagoon itself; and external nutrient inputs, including both groundwaters and surface waters are essential for effective planning; refining projects’ design; and enhancing program efficiency.

There is an urgency associated with the ecological degradation of the IRL. All measures to reverse the present trend towards perpetual algal blooms and fish kills should be expedited and properly funded. Any perceived benefits of delaying or avoiding costs attendant with legitimate and necessary programs will be quickly negated by damage to the economy and quality of life.