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2017 Coastal Master Plan

Attachment C3-21: Nitrogen Uptake

Report: Final

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Coastal Protection and Restoration Authority

This document was prepared in support of the 2017 Coastal Master Plan being prepared by the Coastal Protection and Restoration Authority (CPRA). CPRA was established by the Louisiana Legislature in response to Hurricanes Katrina and Rita through Act 8 of the First Extraordinary Session of 2005. Act 8 of the First Extraordinary Session of 2005 expanded the membership, duties and responsibilities of CPRA and charged the new authority to develop and implement a comprehensive coastal protection plan, consisting of a master plan (revised every five years) and annual plans. CPRA's mandate is to develop, implement and enforce a comprehensive coastal protection and restoration master plan.

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- Coastal Protection and Restoration Authority (CPRA) of Louisiana - Mandy Green, David Lindquist, and Angelina Freeman

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Executive Summary

Water quality conditions, particularly processes regulating nitrogen (N) concentrations in the water column and intertidal wetlands, are expected to change as restoration projects are implemented in coastal Louisiana. There is potential for aquatic and estuarine ecosystems to mitigate increased loads of inorganic nitrogen associated with projects like river diversions. Given the importance of denitrification and associated nitrogen processes rates (fixation and nitrification) in water bodies and wetlands along hydrological gradients, it is important to assess spatial and temporal patterns in nitrogen transformations.

The nitrogen uptake subroutine of the Integrated Compartment Model (ICM) is based on previous research and work conducted to support the 2012 Coastal Master Plan. This subroutine is designed to assess potential changes in water quality dynamics resulting from various restoration projects; however, results of these analyses are not intended to establish actual 'water quality' standards.

The main objective of this subroutine is to use information derived from other subroutines within the ICM to evaluate the potential fate of nitrogen (nitrate, NO_3) in different types of wetlands and open water bodies. It uses a spatial statistical approach (SSA) that uses habitat classification (at a cell resolution of 500 m x 500 m) and site-specific denitrification rates directly measured in coastal Louisiana in combination with salinity, and temperature output from the hydrology subroutine and output from the vegetation subroutine (i.e., spatially explicit type and extent of wetlands). The subroutine estimates N removed by denitrification in vegetated areas using the information on vegetation distribution (500 m x 500 m resolution). It separately estimates nitrogen removal for benthic sediments then adds the N removal from benthic sediment to calculate the Total Nitrogen (TN) removal. The subroutine is used to calculate removal for different coastal conditions, e.g., future without action under different environmental scenarios, for comparison with with-project conditions, enabling assessment of the effects of individual projects, or groups of projects on nitrogen uptake.

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List of Abbreviations

CLEAR	Coastal Louisiana Ecosystem Assessment and Restoration
CPRA	Coastal Protection and Restoration Authority
Dn	Denitrification
ICM	Integrated Compartment Model
N	Nitrogen
N_2	Nitrogen Gas
NO_3	Nitrate
NH_4	Ammonium
NR	Nitrogen Removal
ppt	parts per thousand
SSA	Spatial Statistical Approach
TN	Total Nitrogen

1.0 Introduction

This report describes a subroutine for the 2017 Coastal Master Plan modeling that is based on a model developed to support the 2012 Coastal Master Plan (Rivera-Monroy et al., 2013). That model built on previous experimental studies and research conducted in Louisiana and elsewhere. The model was specifically designed to estimate denitrification (Nitrogen [N] loss) associated with restoration projects with various sizes, locations, and operational schemes; however, results of these analyses do not reflect and were not intended to establish actual 'water quality' standards or to predict specific water quality conditions.

2.0 Background

Water quality conditions, particularly processes regulating nitrogen (N) and phosphorous (P) concentrations in the water column and intertidal wetlands, are expected to change as freshwater diversions and other restoration projects are implemented in coastal Louisiana. The potential for aquatic and estuarine ecosystems to mitigate increased loads of inorganic nitrogen is perhaps nowhere more important than in the coastal region of Louisiana. This region encompasses the largest deltaic system, at the mouth of the Mississippi River, in the Gulf of Mexico, and one of the largest areas of wetlands in the United States. Denitrification is a major pathway for the removal of inorganic nitrogen in lakes, rivers, and coastal estuaries. This reduction is biologically mediated through a series of intermediate gaseous products to N_2 representing a direct loss of nitrate to the atmosphere. This conversion of nitrate to nitrogen gas is a critical ecological function for the removal of highly-enriched nitrogen from anthropogenic sources. Since nitrate is generally the dominant form of excessive nitrogen entering coastal regions, there is potential to ameliorate water quality problems through the reduction of nitrate via direct denitrification. As nitrate-enriched water masses flow through the landscape, the presence of riparian, headwater streams, and coastal wetlands can efficiently remove reactive nitrogen. Comparative studies of wetland and riparian ecosystems along the Mississippi River basin suggest that those habitats can retain up to 70% of nitrate inflow. However, large-scale managed input of nutrient-enriched Mississippi waters into wetlands and open waters has been controversial since its implementation in coastal Louisiana. Presently, there is no clear consensus on whether restoring wetlands with sediment diversions from the river will also enhance the capacity of nitrate removal. Given the ecological and economic importance of denitrification and associated nitrogen processes rates (fixation and nitrification) in water bodies and wetlands along hydrological gradients, it is critical to assess rates of spatial and temporal variation to select optimal values when modeling nitrogen transformations at large temporal and spatial scales. The spatial statistical approach (SSA) aims to provide denitrification data sets in several habitats in coastal Louisiana. The hydrology subroutine of the Integrated Compartment Model (ICM) uses a mass balance modeling approach to predict changes of water quality parameters for >900 compartments representing a range of estuarine and freshwater ecosystems. The nitrogen uptake subroutine focuses specifically on nitrate removal via denitrification.

The nitrogen uptake subroutine is based on previous experimental studies and work performed during the Coastal Louisiana Ecosystem Assessment and Restoration (CLEAR) Program (Rivera-Monroy et al, 2003). It was partially developed using a water quality model. This subroutine can help assess potential changes in water quality dynamics resulting from various sizes, locations and operational schemes of proposed river diversions and other projects; however, results of these analyses did not reflect and were not intended to establish actual 'water quality' standards.

The main objective of this subroutine is to use information derived from various subroutines within the ICM to evaluate the potential fate of nitrogen (nitrate, NO_3) in different types of wetlands and open water bodies. Different projects considered for the 2017 Coastal Master Plan might affect these systems. The nitrogen uptake subroutine uses output from the hydrology subroutine and the vegetation subroutine (see Meselhe et al., 2013, and Visser et al., 2013 for the basic approach, in addition, see Chapter 3, Attachment C3-5, and Attachment C3-22 for recent improvements for the 2017 Coastal Master Plan).

The subroutine aims to provide a first-rate estimation of inorganic nitrogen removal (NO_3) that can be used to assess how protection and restoration projects could affect nitrogen removal in wetlands and surrounding areas influenced by management decisions. Nitrogen removal is estimated using *in situ* values of denitrification rates. Denitrification is a major pathway for the removal of inorganic nitrogen in lakes, rivers, and coastal estuaries. This reduction is biologically mediated through a series of intermediate gaseous products to N_2 representing a direct loss of nitrate to the atmosphere and therefore a net loss of nitrogen from the system.

3.0 Subroutine Approaches

The ICM hydrology subroutine incorporates a water quality portion that includes transport and reactions that affect conventional water quality variables that are dissolved or in particulate form in the water column. The hydrology subroutine includes processes that deposit or transfer material onto the sediment bed, but it does not model the fate of any constituents once they are in the sediment bed. The water column is assumed to be aerobic at all locations and times. Therefore, in that subroutine there are no transfers of nutrients from the bed to the water column as can occur when the water column is anoxic.

In the water quality component of the hydrology subroutine the sediment denitrification (Dn) term is applied for all cells throughout the ICM, including open water and wetland. The source of NO_3 is nitrification from ammonium (NH_4), and the sinks are photosynthetic uptake and sediment denitrification. Water column denitrification is not included since it is assumed that the water column would always be aerobic. There is no process specifically for vegetation effects; all effects are lumped into a single calculation (Meselhe et al., 2012) and the hydrology subroutine does not explicitly differentiate nitrogen removal among wetland types (freshwater, brackish, and saline) and open water areas. The loss term does not distinguish the presence or absence of vegetation, rather it is applied consistently everywhere within each cell. Nitrogen removal is directly influenced by the nitrate concentration, water temperature, water depth, and algal growth (Meselhe et al., 2012). Thus the removal of nitrogen in the hydrology subroutine represents a broad average value, even for wetlands with differing vegetation types.

The approach implemented here in the nitrogen uptake subroutine is a SSA that uses habitat classification (at a cell resolution of 500 m x 500 m) and site-specific denitrification rates directly measured in coastal Louisiana in combination with salinity, and temperature output from the hydrology subroutine and output from the vegetation subroutine (i.e., spatial explicit type and extent of wetlands). The nitrogen uptake subroutine separately estimates nitrogen removal for benthic sediments. Then, the subroutine estimates N removed in vegetated areas using information on vegetation distribution (500 m x 500 m), and adds the N removal from benthic sediment to calculate the Total Nitrogen (TN) removal. This is the final value provided by the nitrogen uptake subroutine.

The Total nitrogen removal (NR) obtained represents the spatially explicit removal of nitrogen in different types of wetlands and benthic sediments, as these landscape categories change as a response to restoration actions.

4.0 Nitrogen Uptake Subroutine Inputs and Structure

The nitrogen uptake subroutine uses published denitrification rates reported for Louisiana wetlands (Table 1) and open water systems (Table 2) in fresh, brackish and saline environments. This approach explicitly partitions NR rates for vegetation and benthic sediments. Total NR is estimated by adding vegetation and benthic NR values. The subroutine uses only denitrification rates published for vegetation and open water habitats in Louisiana to avoid confounding factors (e.g., latitude, geomorphology, hydrology, water management regimes, etc.) when including rates from other coastal and freshwater ecosystems.

Table 1: Denitrification rates (Dn) (µmol m^{-2} h^{-1}) estimated in several wetland vegetation habitats throughout coastal Louisiana.

Method	Location	Habitat	Rate Min	Rate Max	Rate Avg	CF Conf. Int.	Rate Range	Enrichment	Units	Species	Ambient	Units	Species	Reference
15N	Lac des Allemands	Freshwater Marsh			4.5	NA	4.5	100	kg/ha	NH4	NA			Lindau et al. 1991
Acetylene	Atchafalaya	Bald Cypress /Tupelo Swamp	0.18	14.23	7.205	NA	.18-14.23	Background			NA			Lindau et al. 2008
Acetylene	Atchafalaya	Bald Cypress /Tupelo Swamp	0.18	77.17	38.675	NA	.18-77.17	100	mg/L	NO3	NA			Lindau et al. 2008
Acetylene	Atchafalaya	Bald Cypress /Tupelo Swamp	29	89.2	59.1	9.5	29-89.2	Background			0.2-1.8	uM	NO3	Boustany et al. 1997
15N	St. James Parish	Bald Cypress/ Water Tupelo Swamp			79.1	20.4	79.1	10	g/m2	NH4	15	g/m 2	NO3	DeLaune et al. 1998
Acetylene	Atchafalaya	Bald Cypress /Tupelo Swamp	0.18	163.6	81.89	NA	.18-163.6	100	mg/L	NO3	NA			Lindau et al. 2008
15N	Spring Bayou	Bottomland Hardwood Forest			92.2	NA	92.2	10	g/m2	NO3	NA			Lindau et al. 1994
Other	Lac Des Allemands	Freshwater Marsh			100.4	NA	100.4	NA			NA			Smith et al. 1983
Acetylene	Davis Pond	Freshwater Marsh			131.5	NA	131.5	1	mg/L	NO3	.5-2	mg/L	NO3	Gardner 2008
Acetylene	Davis Pond	Freshwater Marsh	5.7	274.9	140.3	NA	5.7-274.9	0-2	mg/L	NO3	NA			Gardner 2008
Acetylene	Atchafalaya	Bald Cypress /Tupelo Swamp	0.18	289.6	144.89	NA	.18-289.6	100	mg/L	NO3	NA			Lindau et al. 2008
Acetylene	Davis Pond	Freshwater Marsh	92	214	153	29.7 / 62.5	92-214	142.8-285.6	uM	NO3	1-1.4	mg/L	NO3	DeLaune et al. 2005
15N	Spring Bayou	Bottomland Hardwood Forest			182.9	NA	182.9	30	g/m2	NO3	NA			Lindau et al. 1994
15N	Lac des Allemands	Freshwater Marsh			193.45	NA	193.45	200	kg/ha	NH4	NA			Lindau et al. 1991
15N	St. James Parish	Bald Cypress/ Water Tupelo Swamp	66.6	335	200.8	NA	66.6-335	10	g/m2	NO3	15	g/m 2	NO3	DeLaune et al. 1998

Method	Location	Habitat	Rate Min	Rate Max	Rate Avg	CF Conf. Int.	Rate Range	Enrichment	Units	Species	Ambient	Units	Species	Reference
15N	St. James Parish	Bald Cypress/ Water Tupelo Swamp			243	31.2	243	10	g/m2	NO3	15	g/m 2	NO3	DeLaune et al. 1998
Acetylene	Atchafalaya	Bald Cypress /Tupelo Swamp	89.2	416.5	252.85	NA	89.2-416.5	3	uM	NO3	0.2-1.8	uM	NO3	Boustany et al. 1997
Other	Davis Pond	Freshwater Marsh	130.9	407.5	269.2	32.7 / 71.4	130.9-407.5	0-2	mg/L	NO3	NA			Gardner 2008
15N	Lac des Allemands	Freshwater Marsh			321.3	NA	321.3	300	kg/ha	NH4	NA			Lindau et al. 1991
15N	Davis Pond	Freshwater Marsh	0	678.6	339.3	79.9	0-678.6	3.8	g/m2	NO3	NA			Yu et al. 2006
15N	Bayou Chevrieu	Bald Cypress/ Water Tupelo Swamp	413.2	829.7	621.45	NA	413.2-829.7	10	g/m2	NO3	NA			Lindau et al. 1988
Acetylene	Atchafalaya	Bald Cypress /Tupelo Swamp	59.5	1338.6	699.05	NA	59.5-1338.6	3	mM	NO3	54-1158	uM	NO3	Boustany et al. 1997
15N	St. James Parish	Bald Cypress/ Water Tupelo Swamp	4.8	1488	746.4	NA	4.8-1488	10	g/m2	NH4	15	g/m 2	NO3	DeLaune et al. 1998
15N	Bayou Chevrieu	Bald Cypress/ Water Tupelo Swamp	601.5	898.9	750.2	NA	601.5-898.9	10	g/m2	NH4	NA			Lindau et al. 1988
15N	Lac des Allemands	Freshwater Marsh			803.2	NA	803.2	100	kg/ha	NO3	NA			Lindau et al. 1991
15N	St. James Parish	Bald Cypress/ Water Tupelo Swamp	383.7	1579.6	981.65	NA	383.7-1579.6	10	g/m2	NO3/NH 4	NA			DeLaune et al. 1998
15N	Lac des Allemands	Freshwater Marsh			1020.83	NA	1020.83	200	kg/ha	NO3	NA			Lindau et al. 1991
15N	Lac des Allemands	Freshwater Marsh			1336.31	NA	1336.31	300	kg/ha	NO3	NA			Lindau et al. 1991
Acetylene	Davis Pond	Freshwater Marsh	NA	NA	NA	NA	NA	Control	NA	NA	NA	NA	NA	Gardner & White 2010
Acetylene	Davis Pond	Freshwater Marsh	98.1	163.6	130.8	NA	98.1-163.6	0.5	mg/L	NO3	NA	NA	NA	Gardner & White 2010

Method	Location	Habitat	Rate Min	Rate Max	Rate Avg	CF Conf. Int.	Rate Range	Enrichment	Units	Species	Ambient	Units	Species	Reference
Acetylene	Davis Pond	Freshwater Marsh	196.3	368.8	282.5	NA	196.3-368.8	1	mg/L	NO3	NA	NA	NA	Gardner & White 2010
Acetylene	Davis Pond	Freshwater Marsh	336.1	478.9	407.5	NA	336.1-478.9	2	mg/L	NO3	NA	NA	NA	Gardner & White 2010
15N	Atchafalaya	Bald Cypress Swamp	49.0	138.9	88.9	NA	49.0-138.9	NA	NA	NA	NA	NA	NA	Lindau et al. 2011
Acetylene	Atchafalaya	Bald Cypress Swamp	9.8	60.3	33.3	NA	9.8-60.3	NA	NA	NA	NA	NA	NA	Lindau et al. 2011
Acetylene	Atchafalaya	Bald Cypress Swamp	21.4	35.6	28.5	NA	21.4-35.6	0	mg/L	NO3	0.31-2.8	mg/L	NO3	Scaroni et al. 2011
Acetylene	Atchafalaya	Bald Cypress Swamp	64.2	78.5	71.3	NA	64.2-78.5	1	mg/L	NO3	NA	NA	NA	Scaroni et al. 2011
Acetylene	Atchafalaya	Bald Cypress Swamp	349.8	364.1	356.9	NA	349.8-364.1	5	mg/L	NO3	NA	NA	NA	Scaroni et al. 2011
Acetylene	Atchafalaya	Bottomland Hardwood Forest	1285.0	1642.0	1570.6	NA	1285.0-1642.0	50	mg/L	NO3	NA	NA	NA	Scaroni et al. 2011
Acetylene	Atchafalaya	Bottomland Hardwood Forest	28.5	42.8	35.6	NA	28.5-42.8	0	mg/L	NO3	0.31-2.8	mg/L	NO3	Scaroni et al. 2011
Acetylene	Atchafalaya	Bottomland Hardwood Forest	49.9	64.2	57.1	NA	49.9-64.2	1	mg/L	NO3	NA	NA	NA	Scaroni et al. 2011
Acetylene	Atchafalaya	Bottomland Hardwood Forest	278.4	292.7	285.5	NA	278.4-292.7	5	mg/L	NO3	NA	NA	NA	Scaroni et al. 2011
N15	Atchafalaya	Bottomland Hardwood Forest	1142.3	1285.0	1213.7	NA	1142.3-1285.0	50	mg/L	NO3	NA	NA	NA	Scaroni et al. 2011
N15	Breton	Freshwater Marsh	496.7	568.1	532.4	NA	496.7-568.1	1.46	mg/L	NO3	NA	NA	NA	Van Zomeren et al. 2012
Other	Breton	Freshwater Marsh	18.7	24.0	21.4	NA	18.7-24.0	2	mg/L	NO3	NA	NA	NA	Van Zomeren et al. 2013
Acetylene	Four League Bay	Saline/Fresh Benthic Sediment			17.1	NA	17.1	25 & 50	uM	NO3	1-107 / 7	uM	NO3 / NH4	Smith et al. 1985
Other	Barataria	Brackish Marsh			29.8	NA	29.8	Background			NA			Smith & Delaune, 1983
Other	West of Bayou Perot	Brackish Marsh			87.1	NA	87.1	NA			NA			Smith et al. 1983

Method	Location	Habitat	Rate Min	Rate Max	Rate Avg	CF Conf. Int.	Rate Range	Enrichment	Units	Species	Ambient	Units	Species	Reference
Other	Barataria	Brackish Marsh			163.7	NA	163.7	Background			NA			Smith & Delaune, 1983
Other	Barataria	Brackish Marsh	163.7	1116.1	639.9	NA	163.7-1116.1	57 & 1469	mg/m 2	NH4	NA			Smith & DeLaune, 1984
Other	Barataria	Brackish Marsh	44.6	2157.7	1101.15	NA	44.6-2157.7	57 & 1243	mg/m 2	NH4	NA			Smith & DeLaune, 1983
Acetylene	Four League Bay	Saltmarsh			13.9	NA	13.9	25 & 50	uM	NO3	1-107 / 7	uM	NO3 / NH4	Smith et al. 1985
Other	East of Leeville, LA	Saltmarsh			56.3	NA	56.3	NA			NA			Smith et al. 1983
15N	East of Leeville, LA	Saltmarsh	28.9	395.6	212.25	NA	28.9-395.6	10	g/m2	NO3/NH 4	NA			Lindau & DeLaune 1991
Other	Davis Pond	Saltmarsh			241	110.1	241	4-Feb	mg/L	NO3	1-1.4	NO3		Delaune et al. 2005

Table 2: Denitrification rates (Dn) (µmol m^{-2} h^{-1}) estimated in several benthic sediment habitats throughout coastal Louisiana for the period 1981–2013 (modified from Rivera-Monroy et al., 2010; Lindau et al., 2009; Scaroni et al., 2011; Van Zomeren et al., 2013b).

Method	Location	Sediment Type	Dn Range	Dn Avg.
15N	Lake Cataouatche	Fresh Benthic Sediment	9.8-47.6±35.7/15.1	28.7
15N	Lac des Allemands	Fresh Benthic Sediment	64-66.1	65.05
15N	Lac des Allemands	Fresh Benthic Sediment	44.8	44.8
15N	Lake Verret	Fresh Benthic Sediment	114-154	134
15N	Lake Cataouatche	Fresh Benthic Sediment	56.15±45.73	50.94
15N	Lake Cataouatche	Fresh Benthic Sediment	47.5±31.59	39.545
15N	Little Lake	Brackish Benthic Sediment	71.5-76.9	74.2
15N	Airplane Lake	Saline Benthic Sediment	11.4	11.4
Acetylene	Big Mar	Fresh Benthic Sediment	0-2.8	1.4
Acetylene	Big Mar	Fresh Benthic Sediment	13.7-199.5	106.6
Acetylene	Big Mar	Fresh Benthic Sediment	41.9-349.8	195.85
Acetylene	Lake Cataoutche	Fresh Benthic Sediment	0.2-2	1.1
Acetylene	Lake Cataoutche	Fresh Benthic Sediment	10.7-280.1	145.4
Acetylene	Lac Des Allemands	Fresh Benthic Sediment	1-367.6	184.3
Acetylene	Lake Cataoutche	Fresh Benthic Sediment	9.8	9.8
Acetylene	Lake Cataoutche	Fresh Benthic Sediment	19.9	19.9
Acetylene	Lake Cataoutche	Fresh Benthic Sediment	137.9	137.9
Acetylene	Lake Cataoutche	Fresh Benthic Sediment	241.8	241.8
Acetylene	Offshore	Saline Benthic Sediment	58.2±9.5	58.2
Acetylene	Offshore	Saline Benthic Sediment	108.1±13.8	108.1
Acetylene	Offshore	Saline Benthic Sediment	47.9±6.9	47.9
Acetylene	Offshore	Saline Benthic Sediment	39.8±14.5	39.8
Acetylene	Offshore	Saline Benthic Sediment	103.3±14.5	103.3
Acetylene	Offshore	Saline Benthic Sediment	69.3±12.6	69.3
Acetylene	Offshore	Saline Benthic Sediment	63.1±9.6	63.1
Acetylene	Offshore	Saline Benthic Sediment	44.62-148.74	96.68
Acetylene	Airplane Lake	Saline Benthic Sediment	0.2-47	23.6
Acetylene	Four League Bay	Saline/Fresh Benthic Sediment	17.1	17.1
Acetylene	Lake Cataouatche	Fresh Benthic Sediment	104.1 - 327.2	157.7
Acetylene	Lake in Atchafalaya	Fresh Benthic Sediment	7.8 - 3569.7	1023.6
Other	Lac Des Allemands	Fresh Benthic Sediment	62.9	62.9
Other	West of Bayou Perot	Brackish Benthic Sediment	38.2	38.2
Other	Leeville	Saline Benthic Sediment	87.1	87.1
Other	Bayou in Breton	Fresh Benthic Sediment	23.8 - 32.7	28.3

Dn rates were grouped using the habitat categories shown in Table 3. For each grouping Table 3 also shows the common names of the species used in the vegetation subroutine (Attachment C3-5). Average values per grouping were derived for use when evaluating total nitrogen removal (vegetation plus benthic sediments).

Table 3: Vegetation groupings used in this subroutine referenced to the vegetation subroutine descriptions.

Nitrogen Uptake Subroutine Vegetation Grouping	Vegetation Subroutine Description
Brackish Marsh	Wire Grass
	Paspalum
Fresh Forested	Cypress
	Black Willow
	Tupelo
Bottomland Hardwood	Water Oak
	Live Oak
	Texas Red Oak
Fresh Marsh	Maiden Cane - Floating
	Pennywort - Floating
	Spike Rush - Floating
	Pennywort
	Wax myrtle
	Spike Rush
	Sawgrass
	Cutgrass
	Cattail
	Maidencane
	Arrowhead
	Bull Whip
	Bull Tongue
	Iva
	Rouseau Cane
	Baccharis
Saline Marsh	Salt Grass
	Beach Grass - Barrier Island
	Needle Grass
	Salt Grass - Barrier Island
	Oyster Grass
	Seaside Golden Rod
	Mangrove
Open Water	Open water
	Submerged aquatic vegetation

The subroutine uses two steps to estimate NR via denitrification. The first step is to estimate NR for vegetation using the groupings of vegetation shown in Table 3 and apply the median values shown in Table 4.

Table 4: Medians calculated from Table 1 for use in analysis. Ranges of the means are also shown to illustrate the effects of uncertainties.

Vegetation Type	Median	Range of Means	
		Min.	Max.
Bottomland Hardwood	182.9	35.6	1570.6
Fresh Forested	144.9	7.205	981.65
Freshwater Marsh	269.2	4.5	1336.31
Brackish Marsh	163.7	29.8	1101.15
Saltmarsh	134.3	13.9	241

Benthic rates are estimated, taking into consideration salinity output from the hydrology subroutine, and using the averages from the studies previously identified (Table 5). Salinity zones follow the classification of Penfound and Hathaway (1938):

- Fresh 0-5 parts per thousand (ppt)
- Brackish 5-20 ppt
- Saline >20 ppt

Table 5: Medians calculated from Table 2 for use in analysis. Ranges of the means are also shown to illustrate the effects of uncertainties.

Salinity Zone	Median	Dn Range	
Brackish Benthic Sediment	56.2	38.2	74.2
Fresh Benthic Sediment	64.0	1.1	1023.6
Saline Benthic Sediment	63.1	11.4	108.1

Field and laboratory experiments using sediment cores sampled in coastal Louisiana (Rivera-Monroy et al., unpublished results) show that temperature has a major role in regulating Dn rates, particularly at 10°C when rates are reduced by >50%. Thus, a temperature modifier is used in the calculations shown below. The temperature modifier is shown in Figure 1 and uses mean annual temperature from the hydrology subroutine as all calculations are made at an annual time step, and the annual mean is a way of integrating over seasonal fluctuations which cannot be captured in this approach.

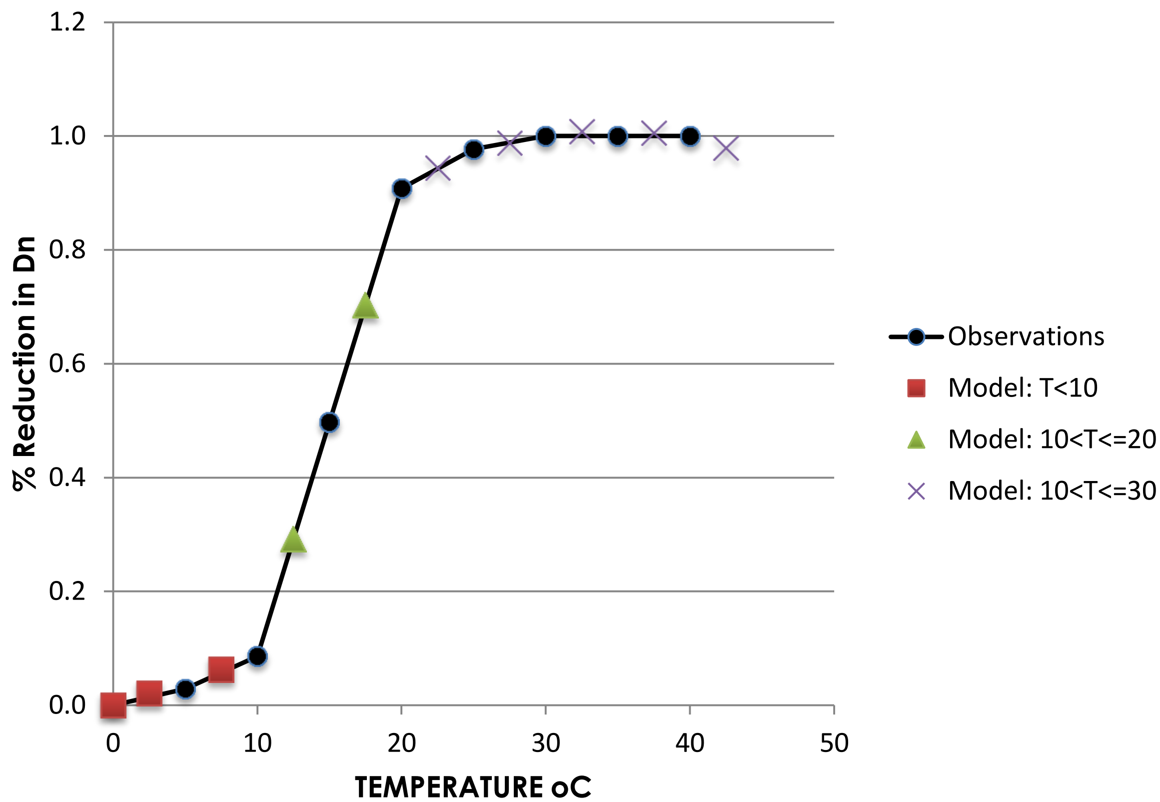

Figure 1: Temperature modifier used by Rivera Monroy et al. (2013).

The following equations are used in the subroutine calculations:

$$Total\ Nitrogen\ Removal\ =\ \ Vegetation\ Removal\ +\ Benthic\ Sediment\ Removal$$

$$Vegetation\ Removal$$
$$=Bottomland\ Hardwood\ (BLH)\ Removal\ +\ Swamp\ Forest\ Removal$$
$$+\ Fresh\ Marsh\ Removal+Brackish\ Marsh\ Removal+Saline\ Marsh\ Removal$$

$$Swamp\ Forest\ Removal=Swamp\ Forest\ Area\ x\ Swamp\ Forest\ Dn\ x\ Temp.\ Multiplier$$

$$Fresh\ Marsh\ Removal\ =Fresh\ Marsh\ Area\times Fresh\ Veg\ Dn\times Temp.Multiplier$$

$$Brackish\ Marsh\ Removal\ =Brackish\ Marsh\ Area\times Brackish\ Marsh\ Dn\times Temp.Multiplier$$

$$Saline\ Marsh\ Removal\ =Saline\ Marsh\ Area\times Saline\ Marsh\ Dn\times Temp.Multiplier$$

$$Benthic\ Removal\ =Openwater\ Area\times Benthic\ Dn\times Temp.Multiplier$$

Calculations are made for the dominant vegetation grouping and the open water area separately based on their relative cover of the 500 m x 500 m cells. The hydrology subroutine provides a temperature for use in the temperature modifier for each cell. Removal for each cell is then summed for each time step (annual) and summed for the geographic area of interest, e.g., ecoregion and basin.

5.0 Capabilities and Limitations of the Subroutine

The approach used here was evaluated using comparative analyses with other coastal ecosystems (Rivera-Monroy et al., 2013). Given that the approach used is based on other studies or models, there are no explicitly available alpha and beta tests that can be applied.

This subroutine is built on statistical analysis of nutrient removal rates and uses output from both the hydrology and vegetation subroutines applied in the 2017 Coastal Master Plan. Nitrogen removal rates are robust estimates since they take into consideration denitrification rates estimated in several types of coastal settings (e.g., different types of vegetation, open water). Results from this approach can be considered as potential values given the source of denitrification rates used for the estimation of NR (potential and *in situ* estimations). Also, it is strongly recommended to include in the evaluation of landscape nitrogen removal rates the range of values represented in the literature, as they can be used to develop confidence intervals for project evaluations.

The nitrogen uptake subroutine is prone to the same uncertainties as the hydrology and vegetation subroutines since all NR calculations are based on results from those subroutines. NR confidence intervals can be estimated for total values using the range of denitrification rates values used in the spatial calculations/extrapolations. However, these confidence interval are also dependent on uncertainties in the subroutine that provide input values.

6.0 References

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