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Dynamic model of ecological factors impacting the Gulf of Mexico dead zone

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DYNAMIC MODEL
OF
ECOLOGICAL FACTORS IMPACTING
THE
GULF OF MEXICO DEAD ZONE

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DEDICATION

When I count my blessings I count my wife and my daughter twice.

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Dr. Constant remarked that his life was dedicated to God, family and job. There are no words to adequately thank him for making part of his job guiding me. Dr. Richard L. Bengtson tireless effort to improve and to assist others is an example worth following. I thank him for assisting me. Dr. Dean Adrian is thanked for his kind assistance. Dr. John A. Pojman is most gracious with his assistance. Dr. Vincent Wilson is my minor professor and close friend to me and to my family. Thank you is small praise for his tireless efforts to encourage and guide me.

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ABSTRACT

The industrial agriculture complex of the Mississippi River Drainage Basin has the positive effect of feeding more individuals with less land via the use of chemical nutrients, pesticides and drainage. The negative effects of the agricultural nutrient load are carried by the Mississippi River to the Gulf of Mexico. After the flood of 1927 the Flood Control Act of 1928 began changing the Mississippi River into a navigation and flood control project. While successful, the river was turned into a channel where nutrient input was discharged into the Gulf of Mexico. Nitrogen compounds discharged from the Mississippi are claimed to degrade coastal fisheries and create a Gulf of Mexico hypoxia zone where aquatic life dependent on greater than 2 mgL^{-1} oxygen levels cannot survive. Stratification and nutrients are required for the production of algae blooms. Discussions continue as to whether the causes of the algae bloom are biological or due to physical changes in the river plume, wind currents and amount of river discharge. In this work, the creation of a STELLA® mathematical model correlating the "algae bloom" to the hypoxia zone in the Gulf of Mexico was developed considering numerous inputs and system variables or system data. Analysis of correlative data such as: sediment oxygen content, photosynthesis, turbidity, nutrient content and light penetration aided in defining the limits of hypoxia. Causative data such as urbanization, removal of wetlands, channelization and deforestation was found related to the causes of hypoxia. While data were limited, variables did correlate to the relative size of the hypoxia zone, but revealed no insight into direct causation. Limited data made verification of the model to acceptable standards difficult. The creation or modification of two predator-prey STELLA ® models showed that ecological changes can cause the marine inverted trophic pyramid to invert causing algae to grow out of control. This "bloom" can cause the hypoxia zone by removal of algae filter eaters. Physical factors such as mixing can

diminish or eliminate the hypoxia zone. Standardized models were employed individually and in combination to yield insight into ecological variables and those variables' contributions to causation.

CHAPTER 1. INTRODUCTION

1.1 The Balance of Nature

Organism equilibrium results from continuous interaction among other organisms and is defined by the interdependency between organisms and the relationship to their environments (Ukidwe, N. U. *et al.* 2009). The definition of balance is related to the concept of equilibrium.

1.2 Equilibrium

The American Heritage® New Dictionary of Cultural Literacy, Third Edition defines equilibrium as: "A concept in ecology that describes natural systems as being in a state of equilibrium, in which disturbing one element disturbs the entire system. The inference is usually drawn that the natural state of any system is the preferred state and that it is best to leave it undisturbed. Modern ecologists no longer believe that a balance of nature exists."(Literacy, T. A. H. N. D. o. C. 2005) There are two drivers which disturb equilibrium. There are natural drivers such as climate variability, extreme weather events, or volcanic eruptions and manmade (anthropogenic) drivers such as deforestation, urbanization (Department of Commerce Bureau of the Census 2010), channelization, fertilizers. Interactions among drivers is an important consideration (Nelsen, T. *et al.* 1994).

1.3 Biomass of Earth

The Earth's mass and its ability to support life are primary consideration of ecological discussion. The question of whether technology and informed policies will allow a large population to be supported with decent living standards and without plundering the planet has long been considered (Werbach, A. 2006). Once the volume of the Earth was calculated as (4/3) x 3.14 x $(6{,}400{,}000)^3$ m^3 and the mass of Earth being calculated as approximately 5.9742×10^{24}

kilograms(Whittaker, R. H. and G. E. Likens 1975) leading to the total world biomass being calculated at approximately 1,877.29 billion tonnes (1 tonnes = 1000 kilograms(Cutnell, J. D. and K. W. Johnson 2001)) or 1,877.29 trillion kilograms. Once this number was calculated, the thought that man's activities would have no effect on the planet Earth vanished. Man lives on a finite planet with finite resources. 'Biomass' is the total amount of living or organic matter in an ecosystem per given time (Campbell, N. A. 1996). Given that the amount of energy received from the sun (except for earth's internal heat and chemo-energy) is relatively constant an estimation of the yearly production of biomass at 164 billion tons (Whittaker, R. H. and G. E. Likens 1975) would be proportional to sunlight and relatively constant.

1.4 Solar Insolation

The amount of sunlight (insolation) is a measure of solar radiation received. The solar constant at the Earth's orbit is 1370 W/m^2 perpendicular to the solar rays (30 % is reflected back into space). Thus, the Earth receives 960 W/m^2 of its cross section ($1.27 * 10^{14}$ m^2), which is a total isolation available at the Earth's surface of $1.22*10^{17}$ W.

Distributed over the surface of the sphere, which is 4 times the cross section yields a day and night global average of 240 W/m^2 on the surface. Equatorial regions get some 400 W/m^2, while the inhabited regions in higher latitudes will receive around 200 W/m^2 on a horizontal surface (Pidwirny, M. 2006). [Sun]light, temperature and inorganic nutrients affect the biochemical process of controlling growth and thus directly affect the amount of biomass (Lee, K.-S. *et al.* 2007). This will be explored further below.

1.5 Constant Biomass?

According to physics, chemistry and biology, there can be no sustained net mass output from any ecosystem (Pimentel, D. 2008). Matter is recycled, and in a mature ecosystem one

species' waste must be another species' food. No net waste (output) is sustained (Pimentel, D. 2008). Energy flows through ecosystems, while matter cycles within them. Biomass quantum is the weight of the plants (producers) which are food to the plant eating heterotrophs [consumers and decomposers (animals, fungi and bacteria)]. Consumers dine on mostly living tissue. Decomposers consume dead organic matter (Pimentel, D. 2008).

Since biomass depends on sunlight received and the sunlight received varies according to solar cycles the amount of biomass produced per some unit of sunlight received could be considered constant (Campbell, N. A. 1996; Pidwirny, M. 2006). The natural equilibrium balance could be disrupted by natural drivers or anthropogenic drivers.

If natural drivers such as climate variability, extreme weather events, or volcanic eruptions would not result in a net output from an ecosystem and a disruption of the natural equilibrium then energy balancing and mass balancing would be possible. If manmade (anthropogenic) drivers such as deforestation, urbanization, channelization, fertilizers are a net output then an ecosystem could be disrupted from its equilibrium position with little chance of returning to equilibrium (Burkhardt, H. 2006). Energy or matter (mass) balancing would be elusive. Interactions among drivers is an important consideration (Nelsen, T. *et al.* 1994). Net outputs from an ecosystem are anthropogenic and affect energy flow and matter recycling as well as the efficiency rate of gathering energy and matter. How ecologists view ecosystems is of primary importance. While this may hold true for the entire Earth the contention of this paper is that individual ecological biomass is not constant. While energy is relatively constant, the matter cycled in an ecosystem is subject to anthropogenic inputs and outputs which disrupt the balance of an ecosystem. This disturbance in equilibrium is not manifested in a disturbance of the energy pyramid. The disruption manifests itself in the biomass pyramid which will always be balanced

but from year to year or time to time can display wide fluctuations in total biomass from pyramid to pyramid.

1.6 Food Webs — Biomass Breakdown

Ecosystem ecologists view ecosystems as energy machines and matter processors. Grouping species in a community of trophic levels of feeding relationships allows ecologists to follow the transformation of energy in the ecosystem and facilitates the mapping of movements of chemical elements used by the biotic community (Campbell, N. A. 1996). Viewing ecosystems as energy machines and matter processors creates a reasonable hypothesis that ecosystems are based on the exploitation of the energy and the matter in the ecosystem (Polis, G. A. and D. R. Strong 1996).

Matter is recycled (often many times) in the ecosystem. Energy cannot be recycled. An ecosystem must be powered by a continuous influx of new energy from an external source (the sun). Energy flows through ecosystems, while matter cycles within them (Campbell, N. A. 1996).

The "exploitation ecosystems" hypothesis proposes strong consumption leads to alternation of high and low biomass between successive levels. High levels of herbivores infer low levels of plants. If herbivores are suppressed; plants do well. The most productive systems support secondary carnivores. As many as four trophic levels could occur with a corresponding low level of plants. Low-productivity systems (e.g., tundra) support only plants. More productive habitats (e.g., forests) have three. Productivity is never high enough to support more than three effective levels on land or four in water (Polis, G. A. and D. R. Strong 1996). Hairston and Hairston disagree and argue that physical differences between habitats account more for the influence on ecosystems (Polis, G. A. and D. R. Strong 1996).

Herbivores influence ecosystems by interacting with food, habitat and predators on several levels. The feedbacks are complex with unexpected results. There is no general theory that explains how animals or man alter ecosystems as they interact with that ecosystem (Pastor, J. and R. J. Naiman 1992). The closest we can come to describing these feedbacks is with food chains, food webs and trophic pyramids (Polis, G. A. and D. R. Strong 1996).

1.7 Trophic Pyramid

Ecological systems are composed of food chains which interact to form food webs and unite to form trophic pyramids. While no general theory exists which describes these exact relationships, a general description of the components and the interactions can be formulated. The outline with a general description follows (Campbell, N. A. 1996).

1.7.1 Food Chains — Food Webs

Every form of life feeds on another form of life. Food chains show how one species is dependent on another. Food webs show how energy is transmitted through the ecosystem and matter cycles within the system (Campbell, N. A. 1996).

1.7.1.1 Food Chain

The passage of energy and nutrients from one organism to another is illustrated by a food chain. Food chains above 4 trophic levels are rare because energy diminishes when passed from one stage or tropic level to the next. Aquatic animals usually form the longest chains (Campbell, N. A. 1996). Matter cycled within a system is represented by a biomass pyramid.

Biomass pyramids are inverted and upright. Biomass pyramids consists of four basic levels, namely; primary producers, primary consumers, secondary consumers and tertiary consumers (Campbell, N. A. 1996). These pyramids will be considered later in this discussion. Another type of pyramid represents the transfer of energy through an ecosystem as shown in Figure 1.

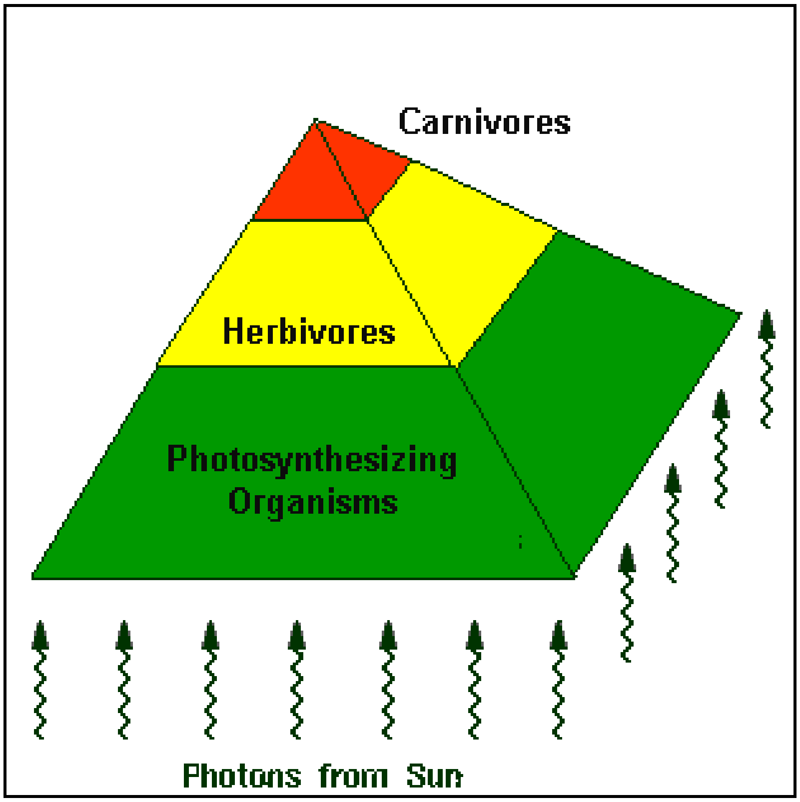


Figure 1. Energy Pyramid (Campbell, N. A. 2008)

An energy pyramid is divided into three trophic levels; namely, producers which are at the base of the pyramid, herbivores which are placed above the producers in the pyramid and carnivores which are at the apex of the pyramid. Only 1/1000 of the energy from the sun is utilized by producers in the photosynthesizing base of the pyramid. The energy pyramid represents a healthy ecosystem if producers exist in large numbers, herbivores exist in moderate levels and carnivores exist in small numbers. Energy pyramids of aquatic creatures, amphibians and etc. exist and represent energy transfers through an aquatic ecosystem (Campbell, N. A. 1996).

Ten percent of the energy received is available for the next stage. The majority is used to maintain a physical body, to move that physical body from point to point, or is lost as heat. Available energy decreases at every trophic level, and each level supports fewer individuals than

the one before. This normal terrestrial tropic pyramid has many organisms at the bottom and few at the top (Campbell, N. A. 1996).

1.7.1.2 Food Web

Food webs are complicated and may contain thousands of different species with each species involved in several food chains. Food chains interconnect to form a food web. Tropic pyramids are formed by the interconnection of food webs (Campbell, N. A. 1996).

1.7.2 Trophic Level

A species occupies a link in the chain called a trophic level. The consumer occupies a higher level than the producer. The predator occupies a higher level than the prey. The interrelationship becomes complex when you have species such as an owl, a coyote, a snake, a mouse and plants. As the owl preys on the snake, rabbit and mouse, the coyote preys on the owl, snake, rabbit and mouse. The snake can prey on the mouse and the rabbit. The efficiency of the predator, the reproductive rate of the prey and the reproductive rate and nutrients available to consumers determine the width of the base and height of the trophic level. At each trophic level corresponding to the levels in the food chain, different species may occupy different levels and move between trophic levels in different food chains (Campbell, N. A. 1996).

1.7.3 Producer

An autotroph is a producer, making the food that supports the other species in the chain. Autotrophs make their own food and form the first trophic level of a food chain. The most important producers harness the Sun's energy to make food by photosynthesis. Some species of bacteria harness the energy in chemicals to make food by chemosynthesis (Campbell, N. A. 1996). Producers are in turn consumed.

1.7.4 Consumers

A hetrotroph is a consumer. Hetrotrophs cannot make food and survive by preying on other living things. Food chains contain several types of consumers, each occupying a different trophic level.

- Primary consumers eat producers
- Secondary consumers eat primary consumers
- [Tertiary] consumers eat secondary consumers (Campbell, N. A. 1996)

At the point of death, the corporeal body of any organism begins decomposition. Various organisms assist in decomposition.

1.7.5 Decomposer

Saprotrophs are decomposers breaking down the organic compounds in dead remains to recycle their raw materials back into the environment. Bacteria and fungi are the main saprotrophs. Some organisms fulfill dual functions and an organism such as a flesh eating beetle could be a consumer or a decomposer (Campbell, N. A. 1996). Feeding off the chain of producers, consumers and decomposers (now prey) are the predators.

1.7.6 Predator—Prey

Carnivores are predators, implying an animal that catches and kills prey. The efficiency of the predator is determined by the efficiency of the prey in avoiding capture. The predator-prey relationship has been extensively studied. General observations are that plentiful resources tend to increase the amount of prey which increases the amount of predators. While numbers of prey and predator are interrelated, many species have been driven to extinction because of predation by man beyond the ability of predator and prey to sustain their numbers (Campbell, N. A. 1996; Pennsylvania State University 1998). We have considered energy as

passing through an ecosystem and matter as being cycled within a system. We must concern ourselves with the conservation of energy and mass. The laws of thermodynamics dictate that energy cannot be created nor destroyed only transformed.

1.8 Laws of Thermodynamics

The laws of physics and chemistry (thermodynamics) apply to organisms and ecosystems. Energy is gathered in the manner most efficient to each organism to ensure the survival of that organism. Natural predators and their prey gather mass and energy with varying degrees of efficiency and obey the laws of thermodynamics (Campbell, N. A. 1996).

1.9 First Law of Thermodynamics

Energy is conserved; not created or destroyed, only transformed (Cutnell, J. D. and K. W. Johnson 2001).

1.10 The Second Law of Thermodynamics

Energy transformation is not completely efficient; some energy is lost as heat. (The entropy of the universe is constantly increasing.) (Cutnell, J. D. and K. W. Johnson 2001). Thus efficiency of ecological energy conversions can be measured and discussed (Cutnell, J. D. and K. W. Johnson 2001). If the maximum efficiency is 100% (1) lesser efficiencies are designated as a fraction of the maximum. The importance of this to modeling is profound. The transfer of energy through a system and the utilization of that energy by the members of that ecosystem are subject to an elusive "mass balancing" but can be considered in terms of rates. The biomass pyramid can be explained in terms of rates of efficiency of consumers and the rates of efficiencies at which different members of the ecosystem gather or act as predators. Much of the problems concerning natural equilibrium and anthropogenic disturbance of natural systems reveal that the harvest man inflicts on the natural ecology are net output with little or no net input

to maintain equilibrium (Campbell, N. A. 1996). The questions of total biomass in a trophic pyramid and the question of total energy in a trophic pyramid are critical and will be considered. The rate at which an organism gathers energy/biomass and the rate at which a trophic level composed of one or more species gathers energy/biomass is a critical part of ecological dynamics.

1.11 Ecological Rate Dynamics

Organisms are process-oriented and efficiency is defined in terms of rates. All living systems can be understood in terms of processes reflecting the dynamics of the system in terms of the rates of change and the consumption of energy or the release of energy. While the rate at which a producer converts nutrients in the presence of sunlight into mass is critical, the relationship of predator to prey is well known and studied.

1.12 Predator Prey Relationship

The predator prey equations can be used to describe the relationships between the various components of the biomass. Alfred Lotka had the idea that successful systems maximize the flow of useful energy implying that living organisms require a source of energy to exist and evolve to maximize energy inflow (Ukidwe, N. U. *et al.* 2009). The sun provides the majority of energy which makes life possible. Development and growth are influenced by the intensity of energy or material gradients. Successful systems tend to stay far from equilibrium, minimize their entropy (disorder), maximize their energy and possibly maximize the rate of energy consumption for themselves and systems they depend on (Ukidwe, N. U. *et al.* 2009). Ecosystems are networks of energy flow converting global energy inputs such as sunlight, crustal heat and tidal forces into ecological products (Ukidwe, N. U. *et al.* 2009).

1.13 Direction of Dissertation

The intention of this dissertation is to examine the hypoxia event in the Gulf of Mexico with the skills of the modeler and the insight of one who understands the difference between correlation and causation. Data can show a correlation between one event and another without being proof that one event caused the other. While one stands at the edge of a pond and observes the presence of water lilies, the presence of water lilies correlates to the presence of water. Without the pond, you may not have the water lilies. You can have the pond without the lilies. One event does not cause the other. In the same manner the presence or absence of oxygen may correlate to surface depth, deep and bottom water photosynthesis but the increase or decrease of the ability of plants to produce oxygen may correlate to turbidity. Turbidity would be correlated to detritus in streams. Detritus would correlate to changes in land use. Changes in land use would correlate to increasing human population and the changes necessary to feed that population. The cause of decreased oxygen would be the increasing human population. Logical rigidity is not limited to equations and should extend to the definitions of correlation and causation.

Causation is but-for analysis. But for one event, you would not have the other. Understanding whether the change in a variable is caused by a direct, superseding, intervening or contributing cause aids in considering whether the cause is a singularity or a combination of events which could lead to unforeseen effects.

While stratification and nutrients are required for the growth of algae, the argument that the hypoxia zone is a physical or biological process is yet to be resolved. The knowledge that hypoxia existed prior to the presence of intensive humanization does not disprove that man is the cause of present day hypoxia.

Driven by the ease of loading data into STELLA® models, modeling will occur first and loading data into the model will be second. See Appendix A.

1.14 Organization of Dissertation

The dissertation is organized in codex or book style. A brief description of each chapter's contents is listed:

- Chapter 1 introduces the problem.
- Chapter 2 reviews the literature on the ecology from the Mississippi River Drainage Basin, Mississippi River and Gulf of Mexico.
- Chapter 3 lists the objectives of the dissertation.
- Chapter 4 describes the materials and methods.
- Chapter 5 shows results and discussion with STELLA® mathematical models to graphically display relationships of ecological elements.
- Chapter 6 lists the conclusions.
- Chapter 7 discusses recommendations for future work.

CHAPTER 2. LITERATURE REVIEW

2.1 Roll On

The immortal words of Lord Byron stated the paradigm of man’s concern with ocean pollution in the latter years of 1700. The belief that man’s insignificant activities could not affect the vast ocean was immortalized by Lord Byron:

> Roll on, thou deep and dark blue Ocean – roll!
> Ten thousand fleets sweep over thee in vain;
> Man marks the earth with ruin – his control
> Stops with the shore; -- upon the watery plain
> The wrecks are all thy deed, not does remain
> A shadow of man’s ravage, save his own,
> When for a moment, like a drop of rain,
> He sinks into thy depths with bubbling groan,
> Without a grave, unknell’d, uncoffin’d, and unknown.
>
> (From “Childe Harold’s Pilgrimage”, Canto the Second, CLXXIX.)
> George Gordon Noel Byron, Lord Byron. (1788–1824)

2.2 Solution to Pollution Is Dilution

The majority of the human population held the viewpoint that the vast clean air, fresh water and blue ocean could not be affected by the demon of pollution or alternatively pollution is acceptable if it serves the greater good of satisfying the needs of the human population. The court system reflects the view that ecology exists to satisfy the needs of the human population. The paradigm expressed by Lord Byron scarcely changed when in the United States Tenth Circuit recognized the “old rule of sanitary engineers . . . the solution to pollution is dilution.” F.E.C. v. CO. REP. FED. CAM. COM., 213 F.3d 1221 (10th Cir. 2000) No. 99-1211.

Plaintiffs in HAWAII'S THOUSAND FRIENDS v. HONOLULU alleged that the city had violated the Clean Water Act on a continuous basis since July 1, 1988 by discharging sewage into the ocean. The city's approach to sewage disposal is that "dilution is the solution to

pollution…[I]t is not the role of the court to evaluate the wisdom of the deep ocean outfall…" It is not the social paradigm to prevent all pollution, but to allow pollution to an acceptable limit. Treatment is a method to reduce pollution to acceptable levels.

The EPA defines "secondary treatment" to require the removal of 85%, of BOD and SS in the effluent, average concentrations of 30 mg/1 on a 30-day average for both BOD and SS, average concentrations of 45 mg/1 on a seven-day average for both BOD and SS, and a pH level between 6.0 and 9.0. 40 C.F.R. §§ 133.102 (a) and (b)33 U.S.C. § 1314 (d) (1) HAWAII'S THOUSAND FRIENDS v. HONOLULU (Hawaii 1993) 821 F. Supp. 1368. The social paradigm takes a back seat to costs and the aging of structures designed to treat and remove pollutants. Caring people fail to follow a desired paradigm due to economic, political and social pressures. In PLAQUEMINE v. NO. AMERICAN the impermeability of concrete was called into question. The original trial judge's reference to this facility as "the concrete of the damned" seems a more accurate description than Householder's reference to it as "adequate." The American Concrete Institute (ACI), a technical society dedicated to providing knowledge and information for the best use of concrete, produces technical reports and guides. Its Committee 350 (ACI 350) requires concrete to be strong, durable, extremely dense, and as impermeable as possible, with limited deflection and cracking. ACI 350 1.1 states: "Because of the stringent service requirements of sanitary engineering structures, they must be designed with great care. Testimony was adamant that this structure is not fit as a watertight liquid-retaining structure. Permeability is the movement of water through concrete (without cracks). Concrete cannot be completely impermeable because it is a "hard sponge" with microscopic holes that absorb fluid, but the goal here was to have the tank as impermeable as possible. PLAQUEMINE v. NO. AMERICAN, 00-2810 (La.App. 1 Cir. 11/8/02); 832 So.2d 447.

Coupling “dilution is the solution to pollution” with the engineering difficulties involved and it is easy to understand that as population pressure increases the amount of pollutants and the facilities used to treat those pollutants came under scrutiny. Court cases and judges tended to use the terms discharge and while point sources of pollution were easy to focus the attention of the enforcement arm of the government, the nebulous term non-point source was not an easy enforcement question.

2.3 Discharge from Point Source

The term "discharge" means a release of a pollutant or pollutants. 33 U.S.C. § 1362 (16). a point source discharge implies some point of discernible size. The term "point source" means "any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container . . . from which pollutants are or may be discharged." 33 U.S.C. § 1362 (14). ZANKE-JODWAY v. CITY OF BOYNE CITY (W.D.Mich. 9-28-2009) Case No. 1:08-cv-930. September 28, 2009. Concern with the purity of the nation’s waters led to legislation.

2.4 Clean Water Act

The CWA was enacted in 1972 "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters." CWA § 101; 33 U.S.C. § 1251 (a). The CWA requires, among other things, that [a]ny applicant for a Federal license or permit to conduct any activity including, but not limited to, the construction or operation of facilities, which may result in any discharge into the navigable waters, shall provide the licensing or permitting agency a certification from the State in which the discharge originates or will originate. Id. § 401 (a) (1).

Any such discharge must also comply with other provisions in the CWA that establish effluent limitations and national performance standards. Id. (citing CWA §§ 301-303, 306, 307; 33 U.S.C. §§ 1311-1313, 1316, 1317).

A dispute arose over the meaning of the word "discharge," as used in § 401. The party filing the lawsuit claims that "discharge" includes "pollutants" emitted by grazing livestock in the form of sediment, fecal coliform, and fecal streptococci. The Forest Service responds that because cattle do (Page 780) not fall under the definition of "point sources," they are not covered under § 401.

The CWA does not define "discharge," but states that "[t]he term ‘discharge' when used without qualification includes a discharge of a pollutant, and a discharge of pollutants." Id. § 502 (16); 33 U.S.C. § 1362 (16). The Act further defines "discharge of a pollutant" and "discharge of pollutants" to mean: (A) any addition of any pollutant to navigable waters from any point source, (B) any addition of any pollutant to the waters of the contiguous zone or the ocean from any point source other than a vessel or other floating craft." § 502 (12). Finally, the Act defines "point source" as "any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged. § 502 (14).

2.5 Nonpoint Sources

All other sources of pollution are characterized as "nonpoint sources." See OR. NATURAL RES. COUNCIL V. U.S. FOREST SERV., 834 F.2d 842, 849 n. 9 (9th Cir. 1987) ("Nonpoint source pollution is not specifically defined in the Act, but is pollution that does not result from the ‘discharge' or ‘addition' of pollutants from a point source.").

The CWA's disparate treatment of discharges from point sources and nonpoint sources is an organizational paradigm of the Act. From the passage of the Act, Congress imposed extensive regulations and certification requirements on discharges from point sources, but originally relied almost entirely on state-implemented planning processes to deal with nonpoint sources, later amending the Act in 1987 to include more federal review of nonpoint sources. Id. §§ 208, 319; 33 U.S.C. §§ 1288, 1329; see also William L. Andreen, Water (United States Geological Survey 2010) Quality Today — Has the Clean Water Act Been a Success?, 55 ALA. L.REV. 537, 545 n. 42 (2004). Congress primarily focused its regulation under the Act on point sources, which tended to be more notorious and more easily targeted, in part because nonpoint sources were far more numerous and more technologically difficult to regulate. See S. REP. NO. 92-414, at 39 (1972), as reprinted in 1972 U.S.C.C.A.N. 3668, 3674 (acknowledging that "many nonpoint sources of pollution are beyond present technology of control"); 118 CONG. REC. 10611, 10765 (1972), reprinted in LEGISLATIVE HISTORY OF THE WATER POLLUTION CONTROL ACT AMENDMENTS OF 1972, at 8 (1973) (noting that "we do not have the technology" to deal with nonpoint sources in the same way as industrial pollution).

In 1972, Congress passed the Clean Water Act, which made important amendments to the water pollution laws. The amendments place certain limits on what an individual firm could discharge. The Act thus banned only discharges from point sources. The discharge of pollutants from nonpoint sources — for example, the runoff of pesticides from farmlands — was not directly prohibited. The Act focused on point source polluters presumably because they could be identified and regulated more easily that [sic] nonpoint source polluters. Id. at 1096 (quoting NATURAL RES. DEF. COUNCIL V. EPA, 915 F.2d 1314, 1316 (9th Cir. 1990)).

The court further found that a cow is not a point source under the CWA, because it is "inherently mobile," and therefore directed the district court to enter judgment in favor of the Forest Service. Id. at 1099. The Supreme Court denied petition for a writ of certiorari on November 1, 1999. 528 U.S. 964, 120 S.Ct. 397, 145 L.Ed.2d 310 (1999).

“. . . [S]tates are encouraged to promote their . . .methods of tracking and targeting nonpoint source pollution.” It is generally understood among students of the CWA that "[w]hile Congress could have defined a ‘discharge' to include generalized runoff as well as the more obvious sources of water pollution, . . . it chose to limit the permit program's application to the latter [point source] category." 55 ALA L.REV. at 562. See also Marc R. Poirier, Non-point Source Pollution, in ENV'L L. PRACTICE GUIDE § 18.13 (2008).

The reason for the CWA's focus on point sources rather than nonpoint sources is simply that "[d]ifferences in climate and geography make nationwide uniformity in controlling non-point source pollution virtually impossible. Also, the control of non-point source pollution often depends on land use controls, which are traditionally state or local in nature." Poirier, Non-point Source Pollution, § 18.13. Instead, § 208 and then § 319 were designated by Congress as methods to keep states accountable for identifying and tracking non-point sources of pollution, as well as identifying "the best management practices and measures" to reduce such pollution. CWA § 319 (b) (2) (A).

2.6 Summary

In summary, while many scholars recognize the harmful effects of nonpoint source pollution, they also recognize that the CWA does not generally exercise jurisdiction over those nonpoint sources. [U]nlike the permitting and enforcement provisions for point sources, [under the CWA] EPA lacks direct implementation or regulatory authority in the face of nonexistent or

inadequate state implementation. At most, under the nonpoint source control provisions, EPA is authorized to withhold grant funding for delinquent states. This policy judgment appears consistent with Congress's reluctance, as expressed in sections 101 (b) and (g) of the Act, to allow extensive federal intrusion into areas of regulation that might implicate land and water uses in individual states. Robert W. Adler, The Two Lost Books in the Water Quality Trilogy: The Elusive Objectives of Physical and Biological Integrity, 33 ENVTL. L. 29, 56 (2003).

The doctrine of stare decisis is "the means by which we ensure that the law will not merely change erratically, but will develop in a principled and intelligible fashion." VASQUEZ V. HILLERY, 474 U.S. 254, 265, 106 S. Ct. 617 88 L.Ed.2d 598 (1986). The doctrine helps to ensure that "bedrock principles are founded in the law rather than in the proclivities of individuals." Id. OREGON NATURAL v. U.S., 550 F.3d 778 (9th Cir. 2008) No. 08-35205.

If a cow is not legally point source of pollution because it is "inherently mobile and the discharge of pollutants from nonpoint sources— for example, the runoff of pesticides from farmlands — was not directly prohibited, it is highly unlikely the law under the current legal paradigm will ever change. The rule of stare decisis will not allow the law to merely change erratically, but will ensure that the law develops in a principled and intelligible fashion." That principled and intelligible fashion will continue to focus on point sources of pollution and fail to regulate nonpoint sources of pollution because of technological, social and economic problems. One can only wonder if a tractor will be considered “inherently mobile” and fertilizer not directly prohibited. Such legal principles are not logical to the scientist, but are founded on bedrock and will not provide the legal tools necessary to reduce growth enhancing chemicals necessary to feed an ever increasing population.

2.7 Causation

The trial court gave the following instruction regarding causation: “An injury is caused by the defendant's [act] when it appears that the [act] contributed a substantial part in bringing about or actually causing the injury, disease or damage and that the injury, disease or damage was either a direct result of or the product of a natural and continuous sequence produced by the [act].” Causation may require the combination of the actions of two actors. The actions of either would not cause the harm. In combination the actions of both would cause the injury and would be the proximate cause of the injury. Intent of the parties or the knowing that the results of combined actions would be certain to cause harm could be one proximate cause or multiple causes which must combine to cause the injury.

This does not mean that the law recognizes only one proximate cause of an injury or damage, consisting of only one factor or thing or the conduct of only one person. On the contrary, many factors or things may operate at the same time, either independently or together, to cause injury or damage, and in such case, each may be a cause, so long as it can reasonably be said that, except for the [act], the injury complained of would not have occurred.
IN RE MANGUNO, 961 F.2d 533, 535 (5th Cir. 1992)

The proximate cause of an injury is where the process is an unbroken chain, without independent intervening cause up to the point of inflicting injury or damage. That is the legal technical definition of proximate cause. What the definition means is this: the law takes no cognizance of negligence which is remote to the accident or the injury. It is only the negligence which actively and directly causes the accident or the injury to which the Court recognizes and attaches legal consequences.

Olin Suggested Jury Charge No. 9: When the first actor is negligent, but a second actor's negligent conduct intervenes between the first actor's negligent act and the resulting wrong, the negligence attributable to the first actor may be come (sic) a passive cause, too remote in point of time or sequence to events to remain viable in legal contemplation. ARCADIAN CORP. v. OLIN CORP., 01-1060 (La.App. 3 Cir. 5/8/02); 824 So.2d 396

The generally accepted definition of and distinction between proximate and remote cause appears to be well stated in Am.Jur., Vol. 38, Verbo Negligence, Sec. 50, Page 695, as follows:

"Perhaps the best, as well as the most widely quoted, definition is the following: The proximate cause of an injury is that cause, which, in natural and continuous sequence, unbroken by any efficient intervening cause, produces the injury, and without which the result would not have occurred. By remote cause is intended that which may have happened, and yet no injury have occurred, notwithstanding no injury could have occurred if it had not happened; that cause which some independent force merely took advantage of to accomplish something not the probable or natural effect thereof."

Examining causation reveals the difference between proximate cause, intervening causes and remote causes must be considered before one can state affirmatively that an observed event is the “cause” of another observed event. Simply because a field is fertilized in Illinois does not establish with sufficient proof that excess fertilizer is the “cause” of hypoxia in the Gulf of Mexico. Many events could be considered co-dependent causes or contributing factors. Some events are remote and could be considered remote causes; some are intervening and could be considered intervening causes and some events may be coincidental and would not contribute to the hypoxic zone. Understanding causation is not an easy task. One unquestionable “cause” of

the deteriorating conditions in ecological systems in the world is the increasing world population as shown in Figure 2. The cause of the deteriorating conditions of the Gulf of Mexico ecology is the ever increasing human population of the United States which mirrors the world population and is shown in Figure 3.

2.8 Population

Supplying the needs of the world population impacts ecology negatively and depending on the chosen paradigm the impact can be reduced but not eliminated.

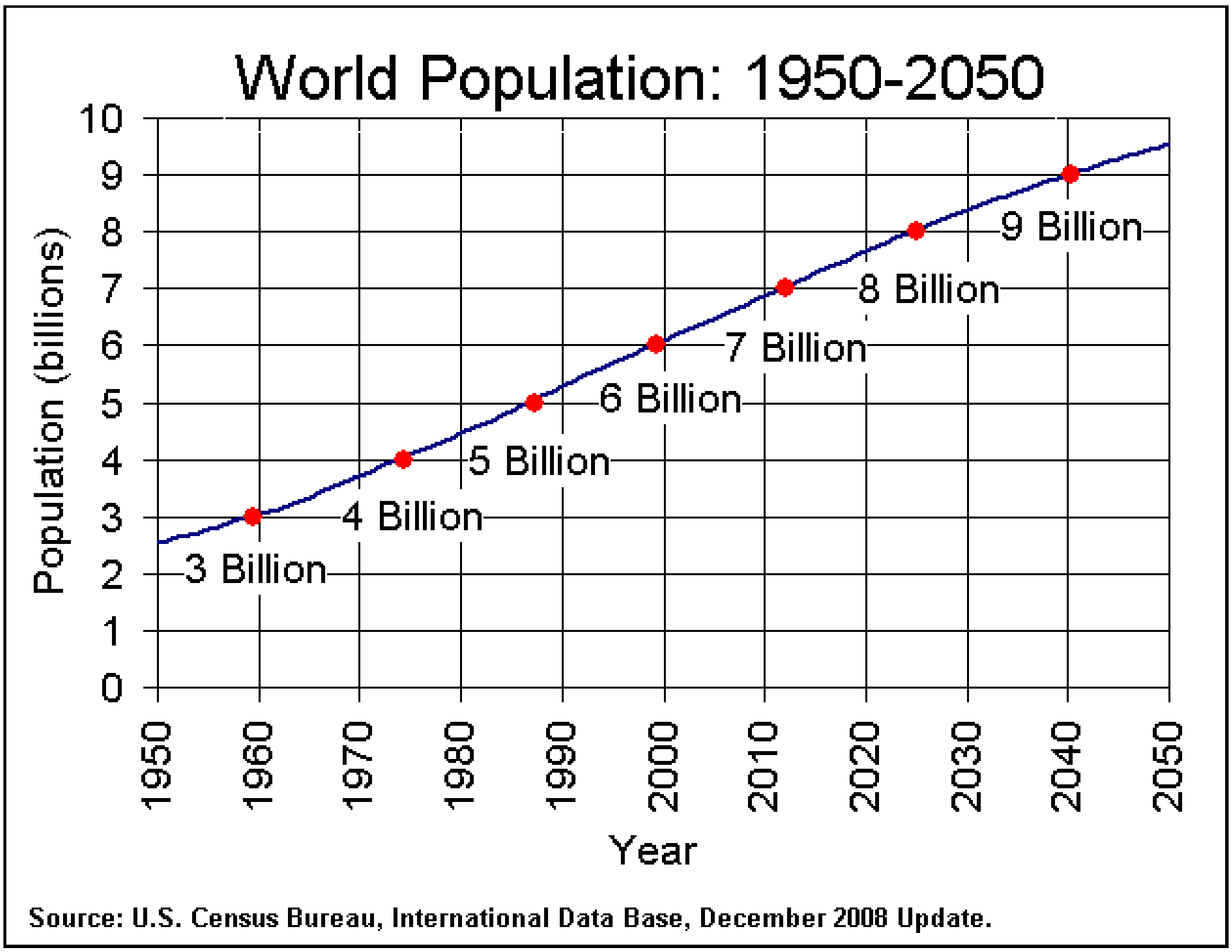


Figure 2. World Population (Department of Commerce Bureau of the Census 2008)

The population in the United States is a microcosm of global population. Note the population in the United States would have stabilized around 212 million except for immigration

and the children of immigrants as shown in Figure 3. The increased population demands increased goods and requires disposal of used items and pollutants.

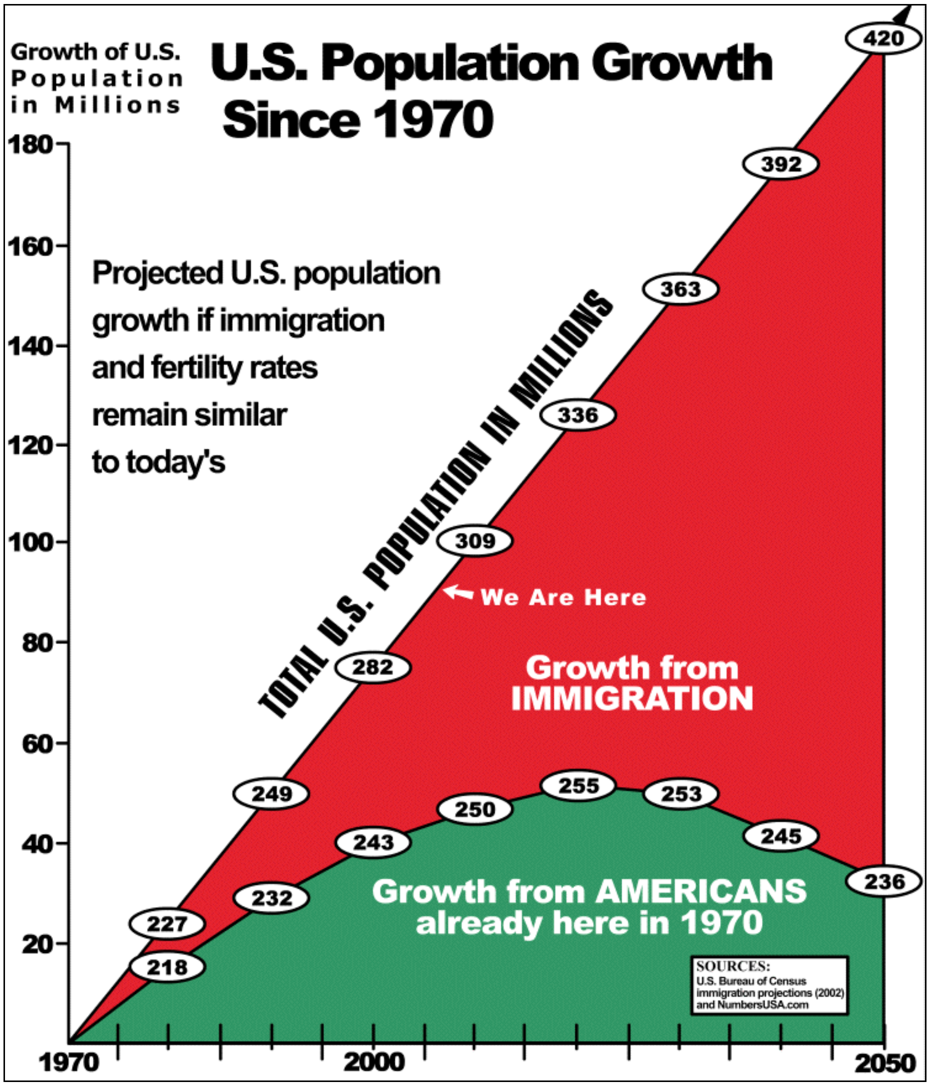


Figure 3. U. S. Population Growth (Department of Commerce Bureau of the Census 2002)

2.9 Human Causation

One acre of land is lost due to urbanization and highway construction alone for every person added to the U.S. population (Pimentel, D. and M. Giampietro 1994). Figure 4 compares population versus arable acres. Fewer acres are feeding many more people.

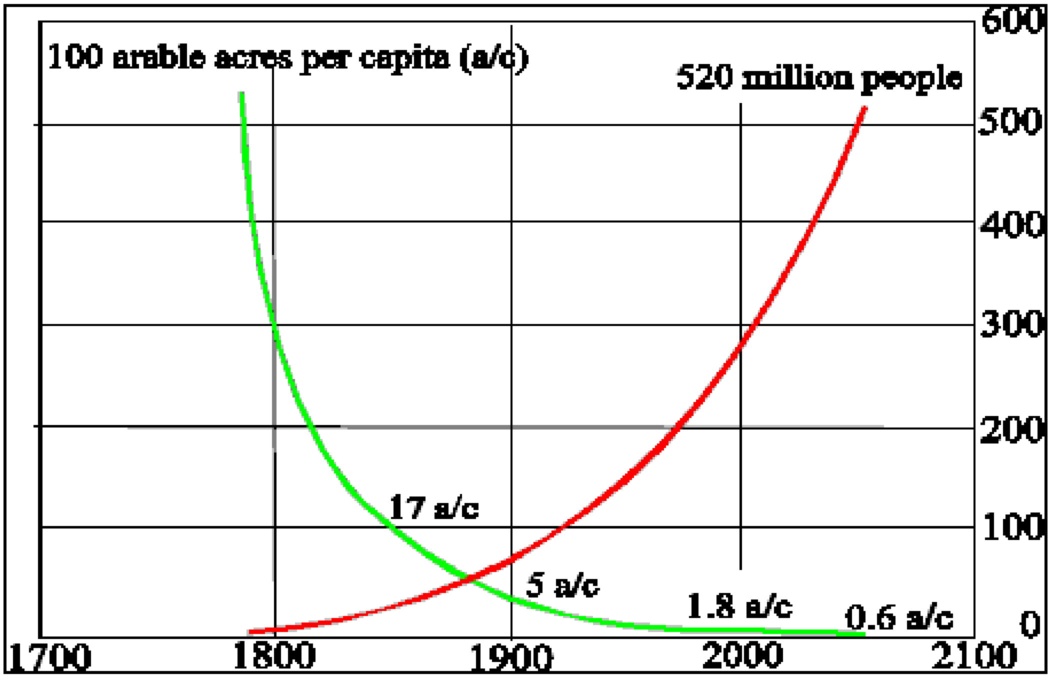


Figure 4. Acres Per Person (Pimentel, D. and M. Giampietro 1994)

2.10 Driven By

The term "driven by" is synonymous to causation. Arable land per capita decrease is driven by dividing fixed land by an ever increasing human population. To feed an increasing population from ever decreasing arable land per capita land requires increased production. Fertilizer and drainage increases farm production. A 2.5 increase in corn yield was found with application of 224 kg/ha (200 lbs/acre) of nitrogen fertilizer over corn with no fertilizer (Hoeft, R. G., Nafziger, E.D.,Mulvaney, R.L., Gonzini, L.C.,Warren, J.J., 1999). A hectare (One Hectare = 2.47 acres) (One Hectare = 10000 m^2 or 107600 f^2) (One Acre = 4050 m^2 or 43560 ft^2) without drainage might yield 2.1 m^3 (60 bushels) of corn, whereas the same hectare with a properly designed surface drainage system could yield 3.2 m^3 (90 bushels) of corn (Zucker, L. A. and L. C. Brown 1998). More production means more money. Farmers fear a reduction in the use of fertilizers and drainage is matched by a reduction in income. The correct political position may be to subsidize agriculture and regulate against pollution without consideration of the

bottom line for farmers. Past regulations have not faced economic reality (Hey, D. L. *et al.* 2005).

2.11 Fertilizer Use in Mississippi River Basin

The Mississippi River and its distributary, the Atchafalaya River, drain water from the Mississippi River Drainage Basin of nearly 3,208,700 km^2 or about 41 percent of the continental United States comprising the largest river basin in North America and the third largest river basin in the world (Battaglin, D. A. G. a. W. A. 2000). Water drained from the Mississippi River Drainage Basin contains (leached or drained) nitrogen originally purchased for use on farms in the Mississippi River Drainage Basin. Data indicates a relatively flat consumption rate of nitrogen and phosphorus in recent years as shown in Figure 5 and 6. Drainage or leached nitrogen should have a similar slope to its graph.

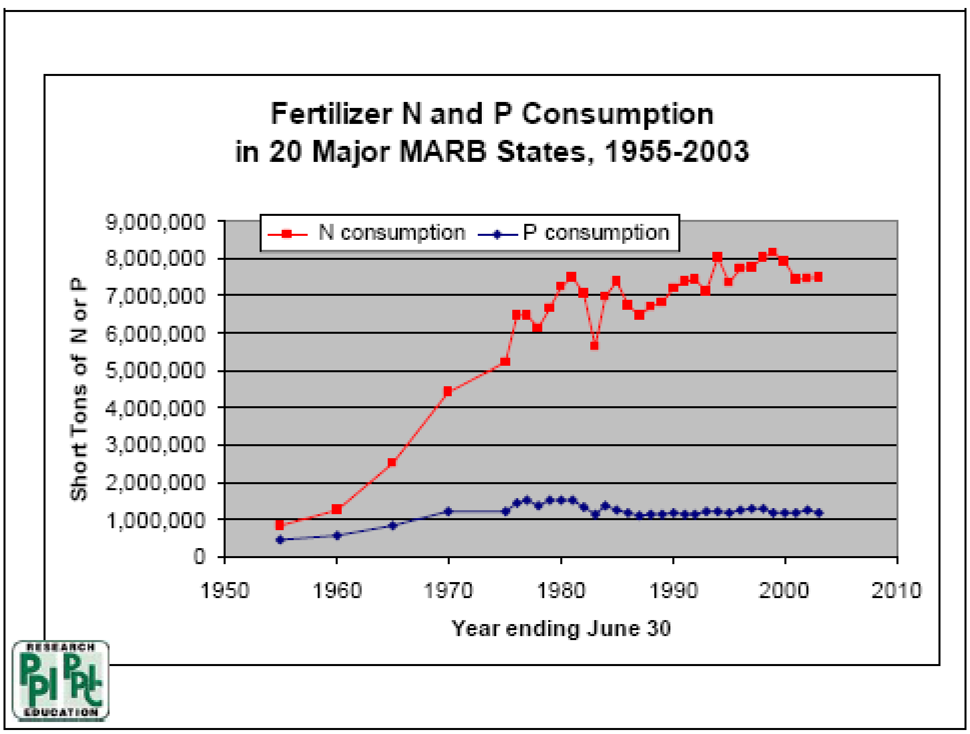


Figure 5. Nitrogen And Phosphorus Consumption (Potash & Phosphate Institute 2004)

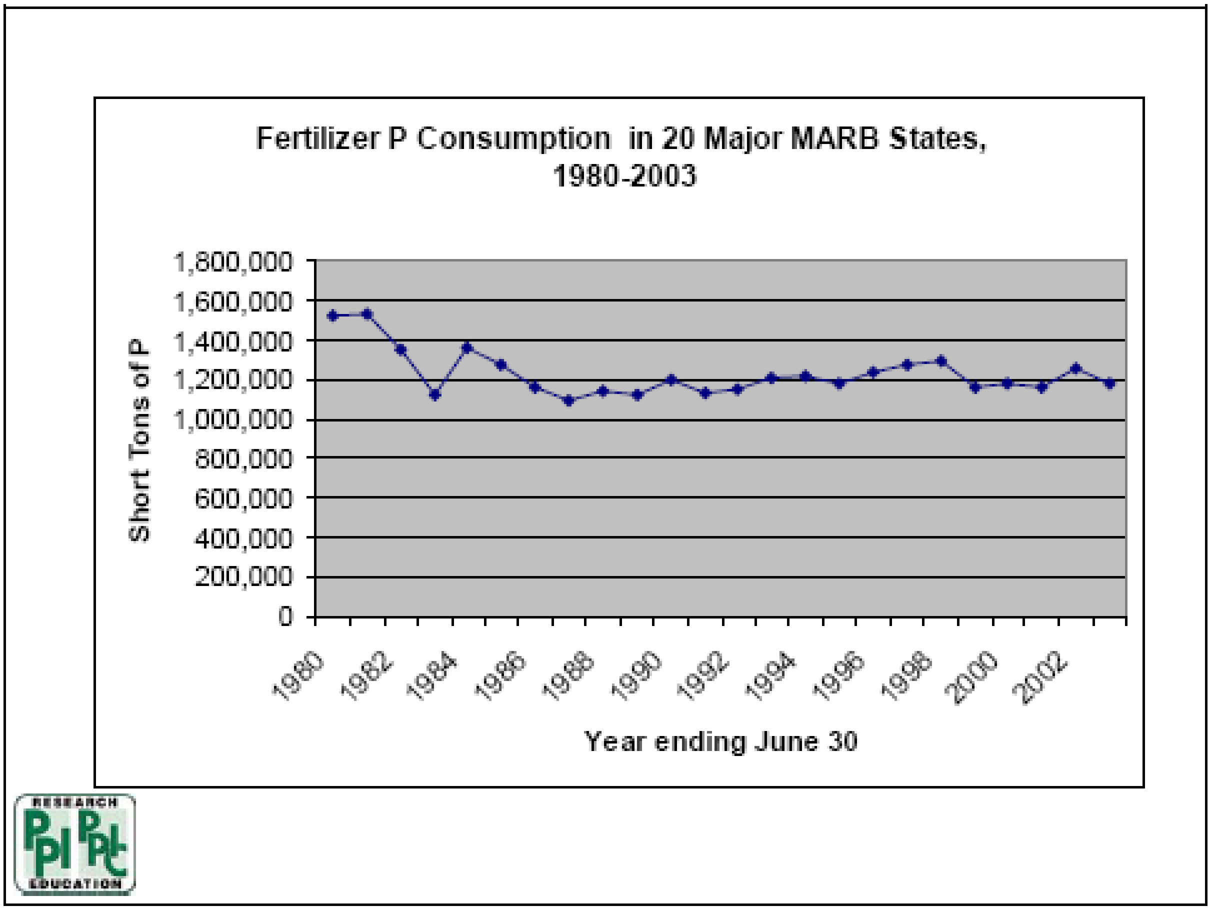


Figure 6. Phosphorus Consumption (Potash & Phosphate Institute 2004)

Fertilizer P consumption in the 20 major states in the Mississippi-Atchafalaya Basin (MARB) has declined by 23% since 1980 (Potash & Phosphate Institute 2004). Figure 6 presents a more detailed view in terms of P consumption from 1980 forward. Phosphorus limits production of algae in fresh water as shown by examining Lake Tahoe, where a once pristine lake now suffers algae blooms. The algae blooms grow (explode) until algae reaches a maximum mass, dies, sinks to the bottom where aerobic bacteria consume algae until the oxygen is consumed and then anaerobic bacteria complete the process of eutrophication. Lake Tahoe research shows eutrophication can be slowed or reversed through reduced nutrient loading,

diversion of sewage, tertiary wastewater treatment or reduction of fertilizer. Improving water quality involves one or more of the following techniques:

1. Controlling nutrients and sediment inflow;
2. Decreasing algal population by grazing, settling, or outflow;
3. Reducing sunlight available to the algae, usually by mixing; and
4. Controlling nutrient distribution in the water column and bottom sediment.

The Louisiana Universities Marine Consortium (LUMCON) researchers state that some of the major events leading to hypoxia in the Gulf of Mexico are:

1. Freshwater discharge and nutrient loading of the Mississippi River
2. Nutrient-enhanced primary production, or eutrophication
3. Decomposition of biomass by bacteria on the ocean floor
4. Depletion of oxygen due to stratification (Louisiana Universities Marine Consortium 2010)

Lake Tahoe is analogous to the Gulf of Mexico and has the advantage of being able to study a closed system. Significant nutrient flux into Lake Tahoe occurs as; surface runoff (urban and wild lands), groundwater transport and atmospheric deposition (Schuster, S. and M. E. Grismer 2002). Bioassays determine the limiting nutrient by comparing the N:P ratio in the water with the N:P ratio of algal biomass. Lake Tahoe has shifted from N limitation to N and P co-limitation then to mostly P limitation after about 1980. The average N:P ratio in Tahoe water increased from approximately three in 1973 to five in 1988, and now exceeds 20, surpassing the Redfield ratio range of 7–18 for Tahoe algae, and strongly suggest P limitation. Though initial actions to protect the Lake focused on N control through reduction of suspended sediment loading, they also had the effect of reducing P loading (Schuster, S. and M. E. Grismer 2002).

The Lake Tahoe study offers guidance to algae problems and hypoxia in the Gulf of Mexico. In fresh water phosphorus is considered the limiting factor and in salt water nitrogen is considered the limiting factor. In both, stratification of the water prevents the oxygen rich top layer from mixing with the oxygen deprived lower levels. Detritus penetrates the stratified layer, falls to the bottom to be acted on by anaerobic bacteria which exhausts oxygen causing oxygen dependent life to move or die (United States Geological Survey 2010). Nitrogen input to terrestrial systems and riverine flux to coastal waters approximately doubled in the latter half of the 20th century. Nitrogen is considered limiting to primary algae production in coastal waters (Alexander, R. B. *et al.* 2002). With stratification of fresh water over denser salt water it is suggested the limiting nutrient for the fresh water could be phosphorus and the limiting nutrient for the denser salt water is suggested to be nitrogen. The effect of the salt water on the algae growing in the fresh water is not known.

Claims that algae blooms and correlated hypoxia is driven by the introduction of excessive agriculture fertilizer would not be supported if no fertilizer were sold showing fertilizer may have a correlation to algae growth without proving causation. Algae blooms and hypoxia occurring prior to the sale of fertilizer would break the causative link.

A paleo-record of sedimentary deposits of shellfish that thrive in low oxygen water are evidence that severe hypoxia is not a new phenomenon. When oxygen uptake by respiration exceeds resupply and dissolved oxygen content drops to less than 2mg/L hypoxia occurs in continental-shelf subsurface waters. Rabalais (1999) indicates measurements of Louisiana continental-shelf waters indicate hypoxia has increased in frequency of occurrence and size of event since 1985 (Rabalais, N. N. 1999). Sediment cores (paleo data) taken from the Louisiana shelf provide a record of hypoxic (low-oxygen conditions) over time intervals of 50-100 years

(Osterman, L. E. *et al.* 2010). Relative abundance of three low-oxygen tolerant benthic foraminifers (*Pseudononion atlanticum, Epistominella vitrea, and Buliminella morgani*) [PEB] are indicators of the present hypoxic conditions on the Louisiana shelf as shown in Figure 7.

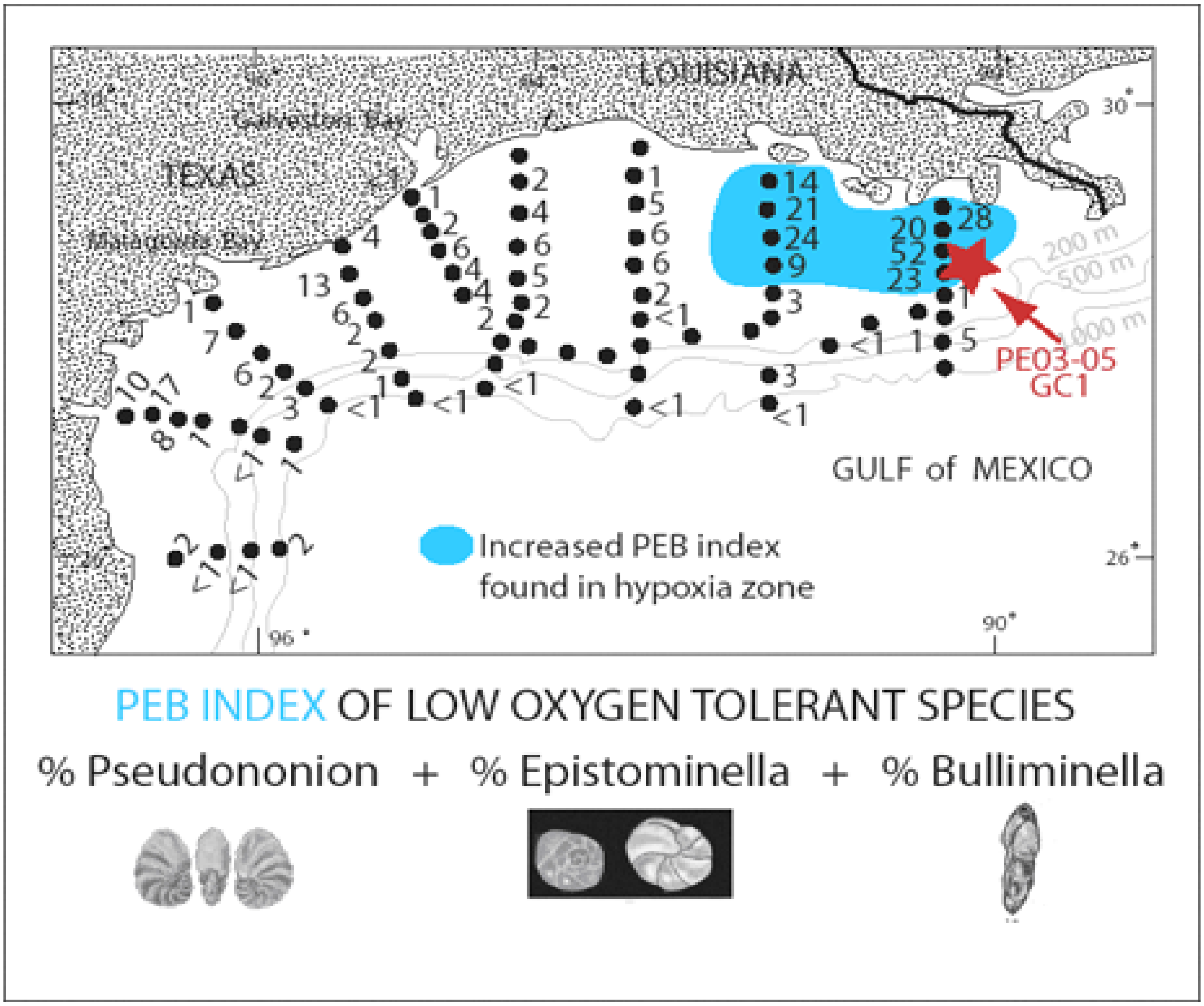


Figure 7. PEB Index Of Low Oxygen Tolerant Species (Osterman, L. E. et al. 2010)

PE03-05 GC1 is the location of the site where the data was taken to produce the PE03-05 GC1 chart which follows. Evidence shows low-oxygen events pre-date the use of commercial fertilizer in the Mississippi Basin (~1950). Between 1817 A.D. and 1910 A.D. fluctuations in the amount of these low-oxygen tolerant species correspond with increased discharge/flooding events in the Mississippi River drainage. High river discharge correlates with high percentage values of the low-oxygen tolerant PEB species (Osterman, L. E. *et al.* 2010) shown in Figure 8.

The PEB values in the lower core exceed the values that are found in the upper fertilizer-driven hypoxia interval (post 1900). Using a sedimentation rate extrapolated from ^{210}Pb data in the top 20 cm, low-oxygen events may extend back to ~1500 A.D. The PEB record from PE 03-05 GC1 shows that low-oxygen events have occurred on the Louisiana Shelf for the last several hundred years. PEB values in the older portion of the record indicate that several low-oxygen events in the 1500's to early 1700's were as severe as events occurring in the last 50 years (Osterman, L. E. *et al.* 2010) as shown in Figure 9. The sediment and the PEB are compared in Figure 10. Results indicate the development of low-oxygen bottom waters on the Louisiana shelf is a complex natural process altered by human activities (Osterman, L. E. *et al.* 2010).

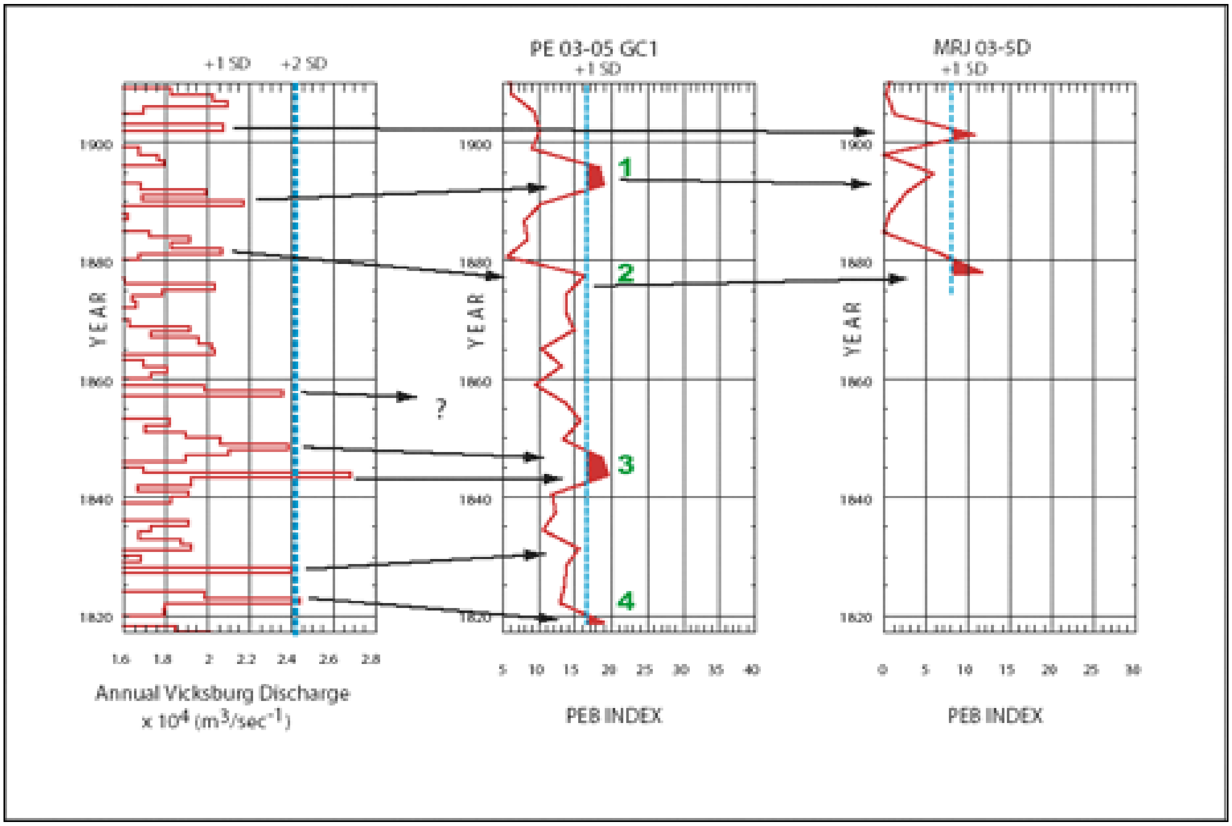


Figure 8. Annual Vicksburg Discharge and PEB Index (Osterman, L. E. et al. 2010)

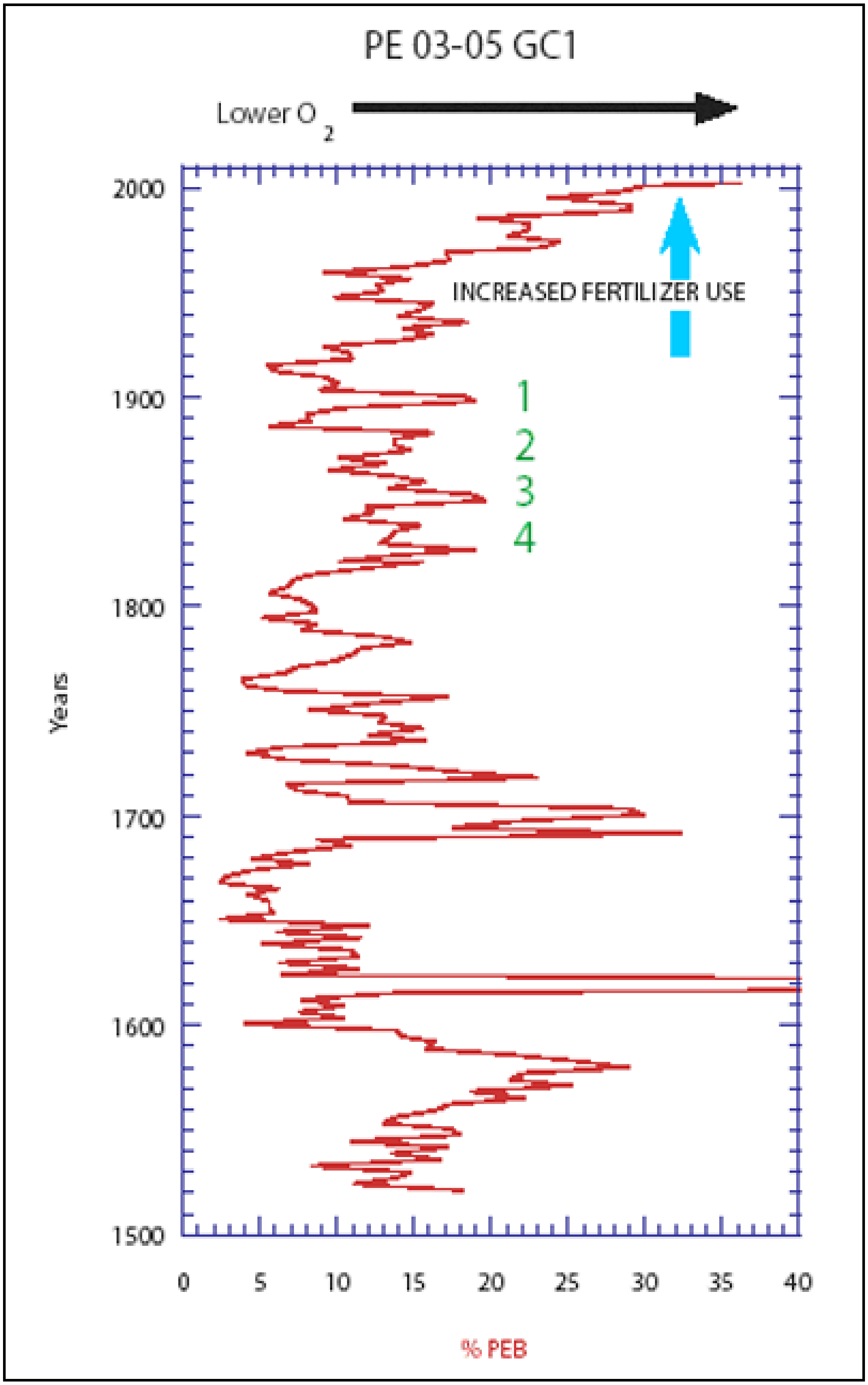


Figure 9. Variation in PEB Index in Core PE 03-05 GC1 (Osterman, L. E. et al. 2010)

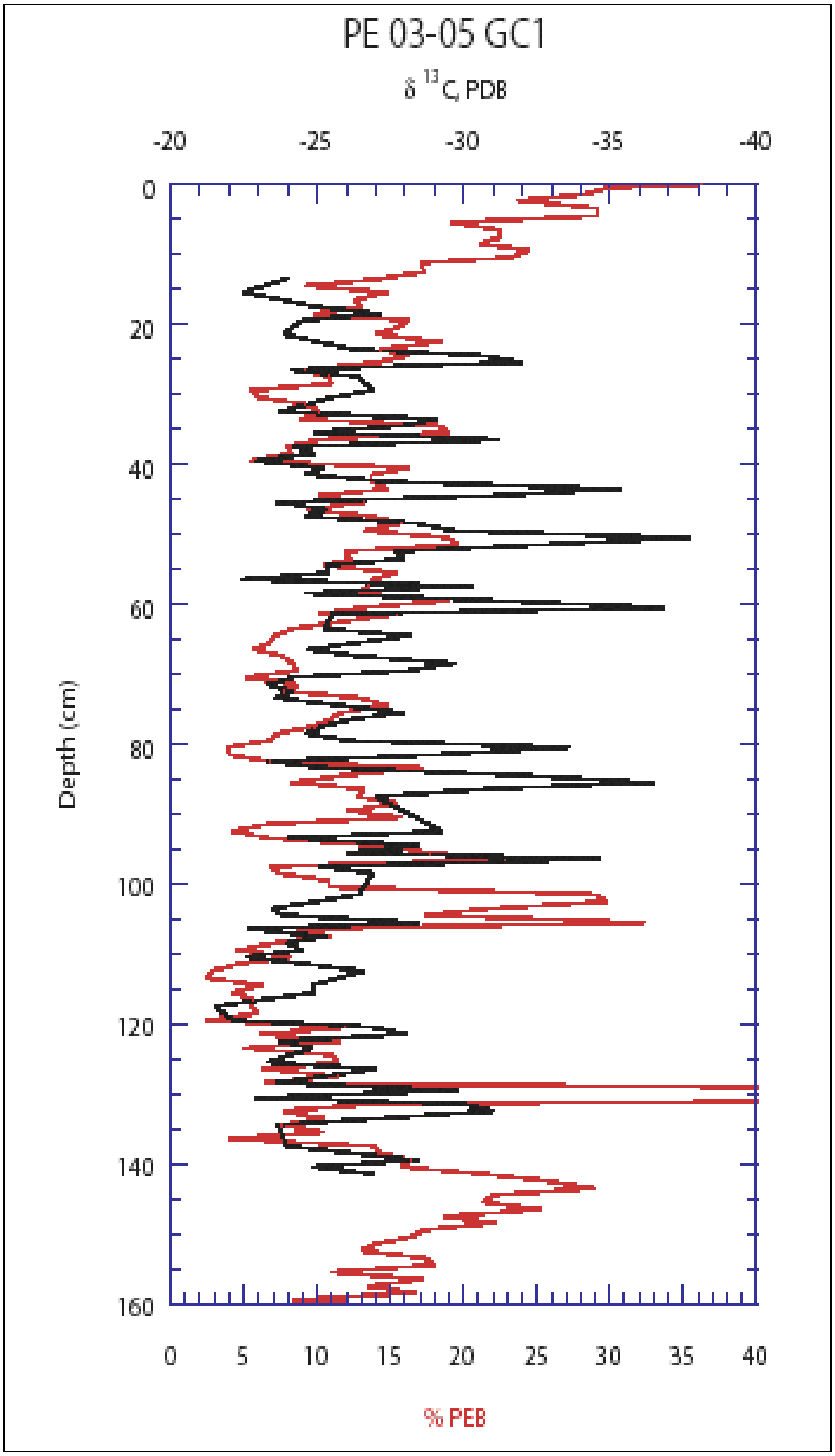


Figure 10. Record Of Bulk Sediment Δ 13C along with the PEB INDEX in Core PE 03-05 GC1 (Osterman, L. E. et al. 2010)

Nitrogen fertilizer use is an anthropogenic change and the principal sources of nitrogen to the Mississippi Basin as charted in Figure 11. Figure 11 displays soil mineralization, fertilizer, legumes and pasture, animal manure, atmospheric deposition, and municipal and industrial point source inputs into the Mississippi The production of legumes (e.g., soybeans) contributes to the increased nutrient concentrations (Goolsby, D. A. and W. A. Battaglin 2000). Annual nitrogen input has increased more than six fold since the 1950's (Battaglin, D. A. G. a. W. A. 2000). Causation of the increase in the size of the hypoxia zone is not supported by Figure 12 which indicates reduced of nitrates and increasing hypoxia zone. The nitrate discharge is supported by Figure 13 demonstrating a linear correlation.

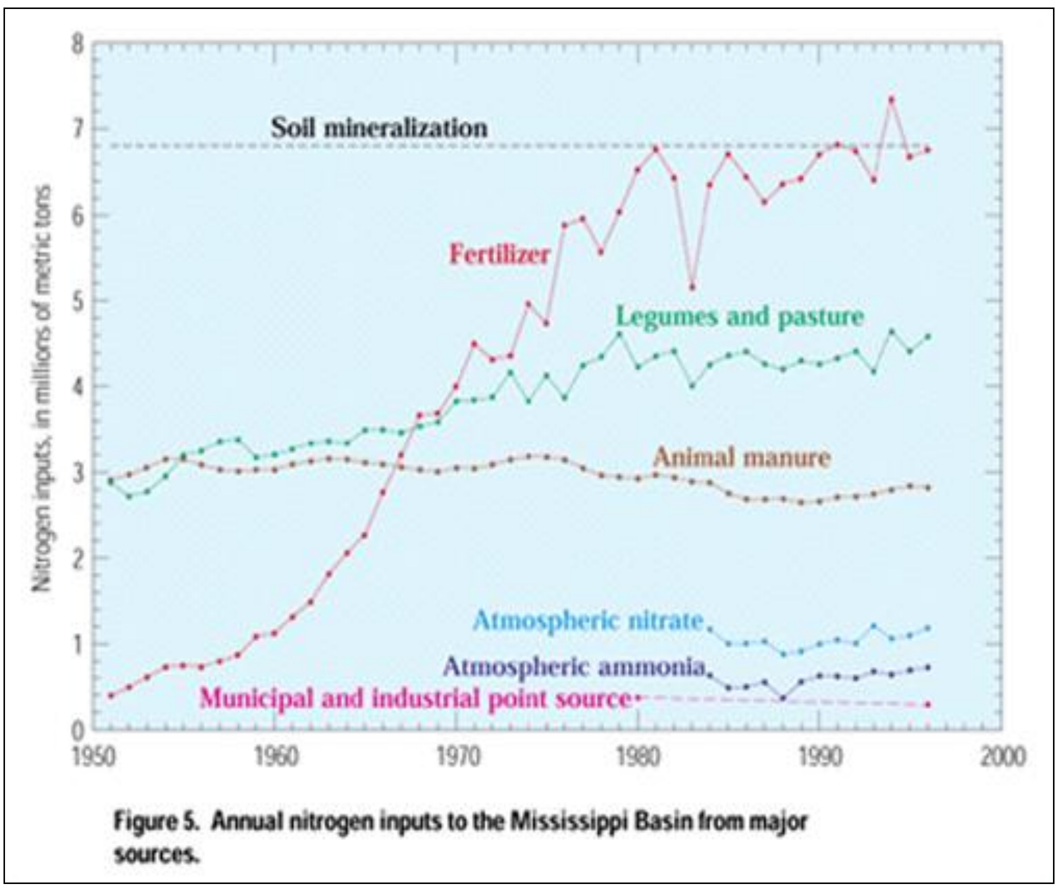


Figure 11. Annual Nitrogen Influx Mississippi River (United States Geological Survey 2008)

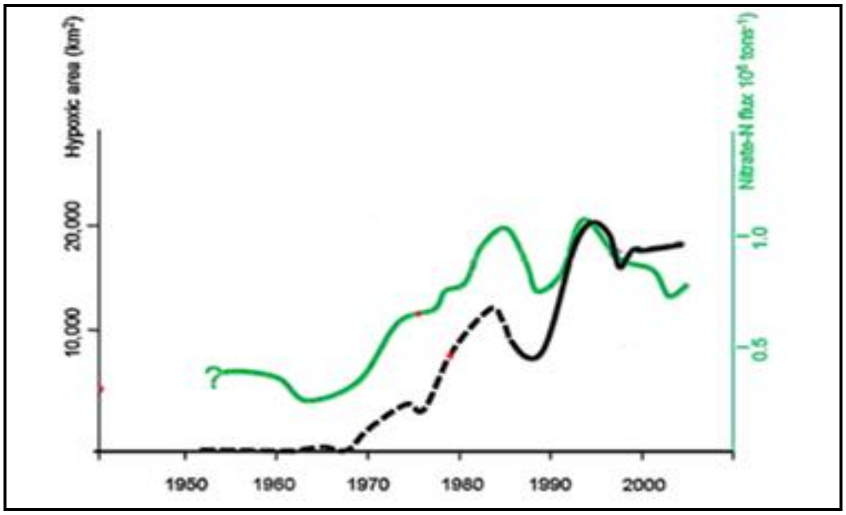


Figure 12. Nitrate Superimposed With Size Of The Hypoxia Zone In Gulf Of Mexico (Osterman, L. E. et al. 2010)

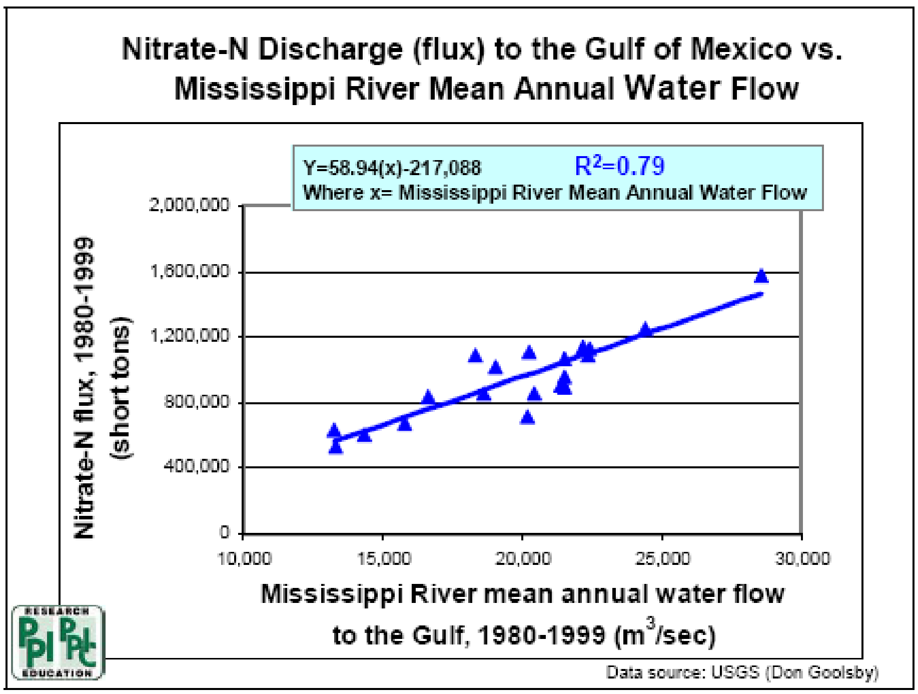


Figure 13. Nitrate Discharge To Gulf Of Mexico (United States Geological Survey 2010)

Annual Mississippi River flow to the Gulf of Mexico (Figure 13) may correlate to the variation in nitrate-N discharge (United States Geological Survey 2010) however, the transport of nitrate by stream flow of the Mississippi driving (causing) hypoxia is not supported by the paleo record (Osterman, L. E. *et al.* 2010) prior to sales of fertilizer. More than 28 million ha (70 million acre) in the Mississippi Basin had been drained by extensive systems of drain tiles and

outlet ditches by 1980 moving surface and groundwater out of agricultural fields (Zucker, L. A. and L. C. Brown 1998) into the Mississippi River Basin and through the levee system.

2.12 Levees

Extensive modification of the channel and floodplain of the Mississippi River System for the purposes of: (1) flood control and (2) commercial navigation reduced accessible floodplain area by 70% to >90%. Human settlement and use of the Mississippi River Valley altered land use, floodplain cover and drainage characteristics changing flood levels (4.1 to 6 m) and flood frequencies (Jonathan, W. F. *et al.* 2009).

Between 1929 and 1942, the river was channelized and shortened 245 km for purposes of navigation by cutting off fifteen meander bends from the main-stem channel. Between 1939 and 1955 the river was shortened 88 km by chute cutoffs. Chute cutoffs act as sediment storage locations, removing channel and point bar sediments from the main channel.

Following the 1927 flood, 3000 km of artificial levees were added or improved. construction of 1400 km of concrete revetments stabilized the channel forcing water to pass between the Mississippi River levees (Kesel, R. H. 2002) transporting nitrates to the Gulf of Mexico. The correlation between streamflow and nitrate transport was shown in Figure 13.

Agricultural drains discharge nitrate from agriculture fields in high concentrations — 20 to 40 mg/L or more (Zucker, L. A. and L. C. Brown 1998). More water correlates to more nitrate. The drought of 1988 (a 52 year record low discharge) of the Mississippi River transported less water correlating to less nitrate, higher than normal bottom oxygen concentrations and no hypoxia zone despite a continuous appearance in previous years. During the flood of 1992 (a 62 year record high discharge) a two fold increase over average hypoxia occurred (Justic, D. *et al.* 2007) as shown in Figure 14.

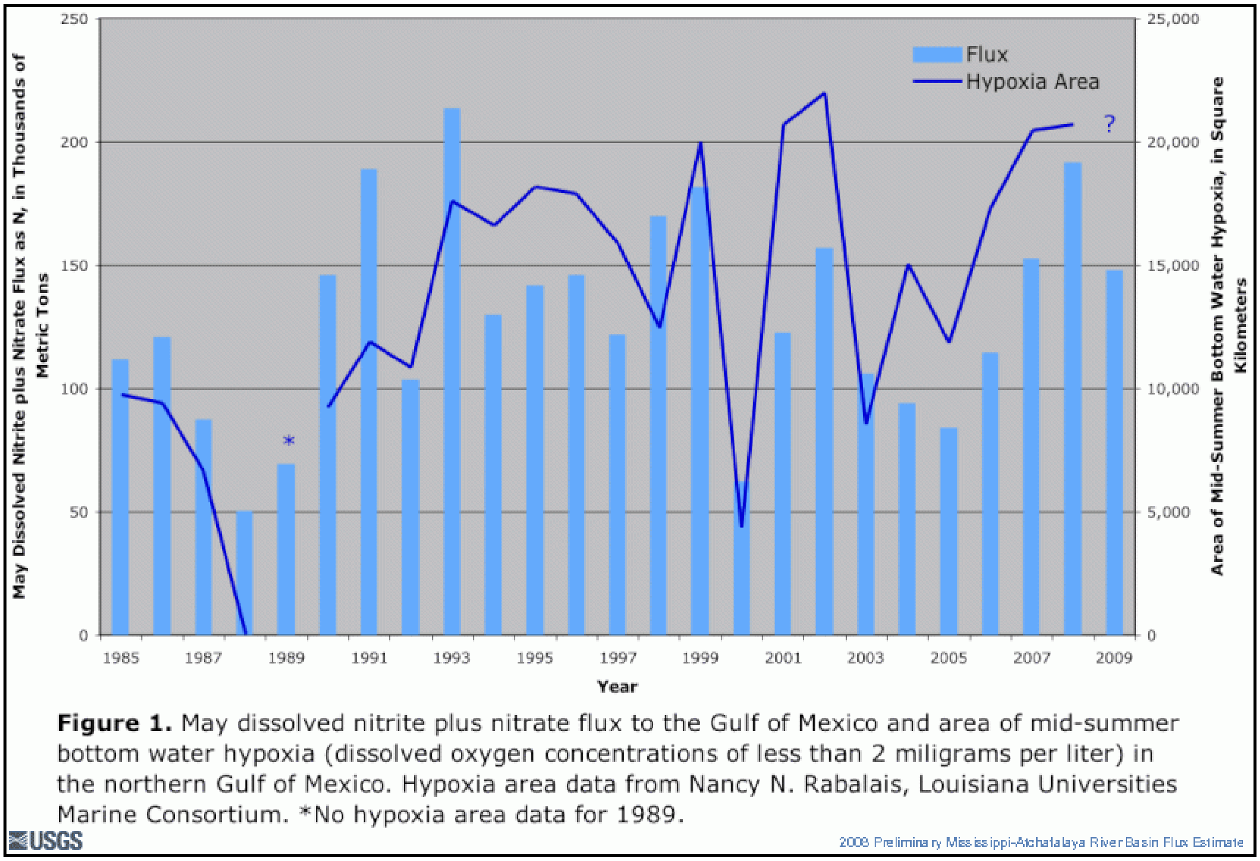


Figure 14. Stream Flow And Bottom Hypoxia (Justic, D. et al. 2007)

Figure 15 is a satellite image in ultraviolet showing oxygen levels in the Gulf of Mexico. The oxygen levels correlate to the algae mats in the Gulf of Mexico and were discussed in the 12th Biennial Coastal Zone Conference (Bierman, V. J. *et al.* 2001). Despite correlation between stream flow and nitrate transport, the paleo-record reveals hypoxia predated widespread fertilizer use. Some authors indicate Louisiana shelf bottom water hypoxia (low-oxygen) is the result of anthropogenic changes to a complex natural process including changes to the Mississippi River Drainage Basin and anthropogenic damage to the Gulf of Mexico (Osterman, L. E. *et al.* 2010).

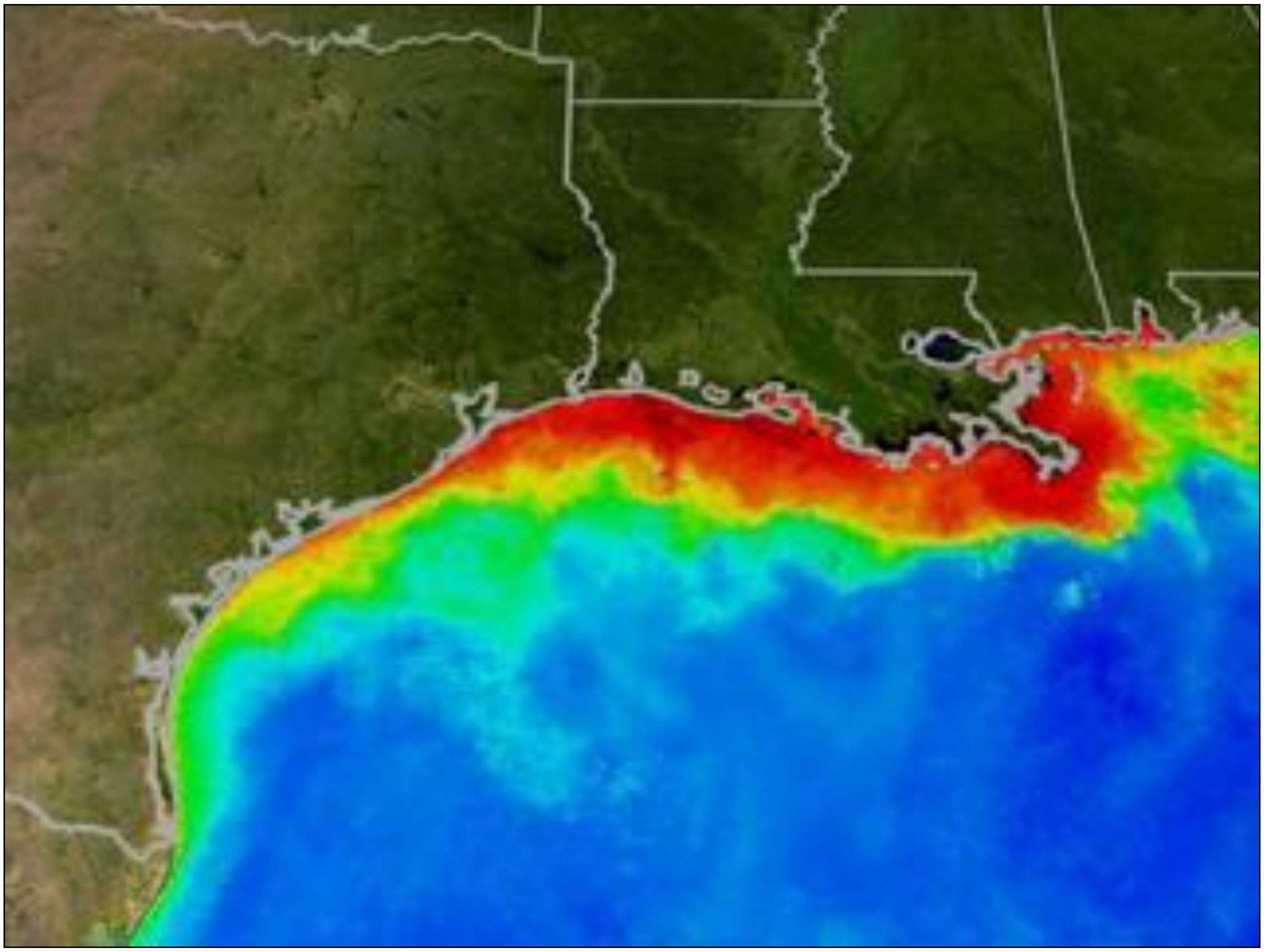


Figure 15. (Ultraviolet Satellite Image) Hypoxia Zone In Summer (NASA Goddard Space Flight Center 2004; United States Geological Survey 2008). Red represents lowest oxygen. Orange represents second lowest.

2.13 Definition of Hypoxia

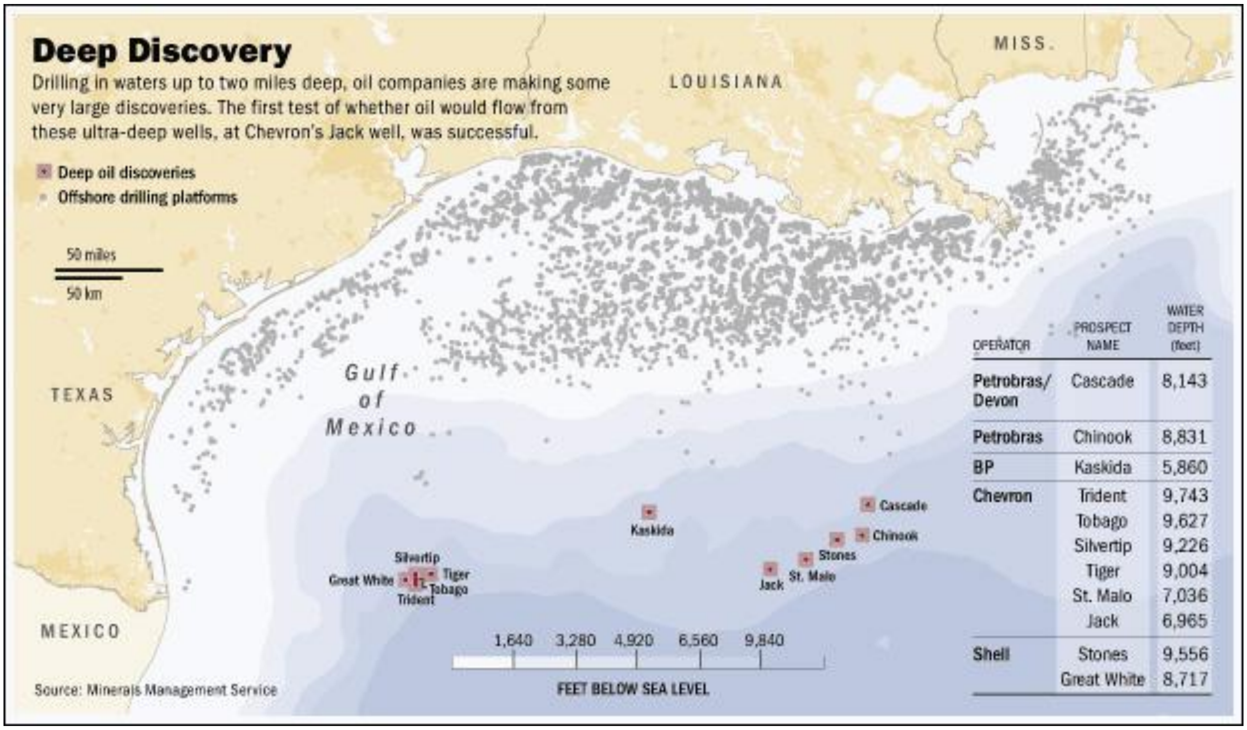
Hypoxia in the northern Gulf of Mexico is when oxygen levels are below 2mg/L (2 ppm). The upper limit for hypoxia may be as high as 3-5 mg/L (Rabalais, N. N. 2000). Hypoxia typically occurs from March through October in waters below the pycnocline extending between 5m and 60m deep is being actively studied by at least two groups (Justic, D. *et al.* 2007). Both groups claim that hypoxia depends on stratification of the water body to prevent absorption of oxygen from the surface and detritus to absorb oxygen from the bottom waters.

2.14 Hydrocarbons and Ancient Hypoxia

PEB levels were discussed in Chapter 2 (Page 29-32). The existence of ancient hypoxia zones was defined by the presence of benthic foraminifers which thrive in the presence of low oxygen conditions. The data on the presence of benthic foraminifers is gathered by drilling core samples similar to the process of drilling ice core samples. Mussel shells are then counted to determine frequency. The presence of the PEB's does not prove eutrophic conditions were caused by the increased production of algae. The presence of PEB's does show that low oxygen conditions existed. The thirty-six samples of benthic algae collected from the continental shelf along the eastern Gulf of Mexico contained [on average] 82.8 to 143 ppm aliphatic hydrocarbons by dry weight and 11.8 to 22.7 ppm aromatic and polyolefinic hydrocarbons (Lytle, J. S. *et al.* 1979). This data shows the high oil content of algae. The presence of algae correlates to hypoxia zones. The presence of hypoxic zones correlates to the presence of PEB's. The presence of algae blooms, hypoxia and increased frequency of PEB's occupy similar geographic positions as present day hydrocarbon fields (Figure 16) in the Gulf of Mexico and suggest, but do not prove oil rich algae correlate to the presence of present day hydrocarbons.

The PEB and hydrocarbon discussion demonstrates too much attention is paid to correlation and too little to causation. It was thought increasing human population would be causative to the increasing size of the hypoxia zone. The paleo-record showed hypoxia existed prior to the introduction of anthropogenic nitrogen. The theorists who indicate nitrogen introduction drives the creation of the hypoxia zone ignore: 1) sediment-water interactions, 2) natural northern Gulf of Mexico hydrometeorological variability 3) Gulf-wide circulation 4) finer horizontal and vertical spatial resolution 5) explicit representation of sediment diagenesis. Ignoring the physical elements of the Gulf of Mexico have led to postulations that a reduction in

the input of nitrogen will cause an increase in the oxygen levels in the Gulf of Mexico as shown by Figure 17. Ignoring physical factors, predictions were made based on the correlation between nitrogen transport and stream flow. The size of the hypoxia zone was smaller than predicted.



OPERATOR	PROSPECT NAME	WATER DEPTH (feet)
Petrobras/ Devon	Cascade	8,143
Petrobras	Chinook	8,831
BP	Kaskida	5,860
Chevron	Trident	9,743
	Tobago	9,627
	Silvertip	9,226
	Tiger	9,004
	St. Malo	7,036
	Jack	6,965
Shell	Stones	9,556
	Great White	8,717

Figure 16. Offshore Drilling Platforms (LoBuono, C. 2009)

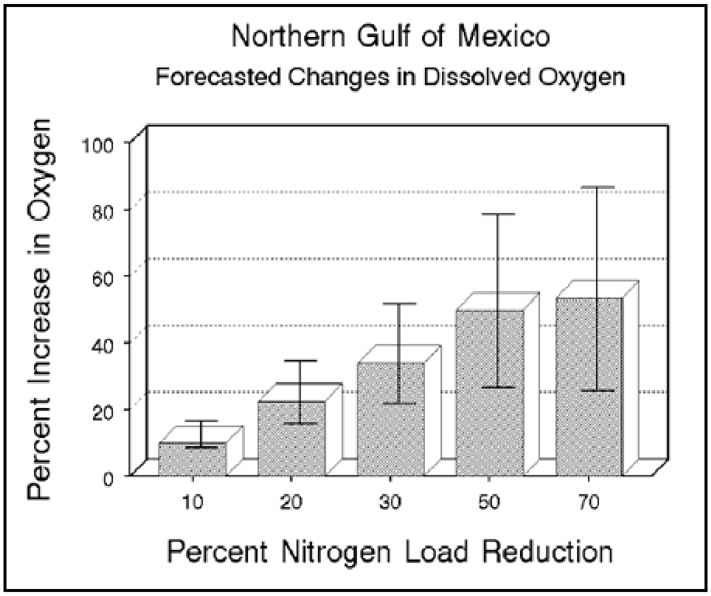


Figure 17. Nitrogen Load Reduction To Oxygen Concentration Increase (Bierman, V. J. et al. 2001)

2.15 Dead Zone Smaller Than Predicted

The University of Michigan aquatic ecologist Donald Scavia and his colleagues issued a statement, released June 18, 2009 which called for a Gulf dead zone of between 7,450 and 8,456 square miles, which is an area about the size of New Jersey (Scavia 2009). "NOAA (National Oceanic and Atmospheric Administration) supported scientists, led by Nancy Rabalais, Ph.D. from the Louisiana Universities Marine Consortium, found the size of this year's Gulf of Mexico dead zone to be smaller than forecasted, measuring 3,000 square miles." Winds and high waves west of Atchafalaya River mixed oxygen into the water (National Oceanic and Atmospheric Administration 2009). A difference in modeling forecast and reality of 100% suggests too much attention was paid to correlations and insufficient attention was paid to causation. Two conditions must exist before hypoxia will occur.

2.16 Hypoxia Depends Upon Two Conditions

Hypoxia depends upon two conditions:

1. Stratification of the water column in the Gulf which occurs when warmer, less dense fresh water overlies colder, denser salt water, and
2. The presence of organic matter (detritus) to consume oxygen.

Organic matter in the decomposition phase consumes oxygen, reducing the oxygen level to below 2 mgL^{-1}. Hypoxia can cause stress or death in bottom-dwelling organisms that can not leave the zone. The midsummer extent of the hypoxic zone has more than doubled since it was first systematically mapped in 1985 (Glover, L. K. and S. A. Earle 2004; Goolsby, D. A. *et al.* 1999; Rabalais, N. N. 1999). As in any study, opinions vary. As to the causes of hypoxia there are at least two camps of researchers supporting differing opinions with similar concepts.

2.17 History — Eastern Camp

The Eastern camp is led by Rabalais and Turner and proffers the following theory: "[N]itrate, the predominant form of nitrogen in the Mississippi river, has increased 2.5 fold since the 1950s, coincidentally with the increased use of fertilizers in the watershed." Anthropogenic nitrogen is transported down the Mississippi River to the Gulf of Mexico. The nutrient-rich water allows algae to feed, grow, reproduce at an explosive rate, die and add their bodies to the detritus load falling to the bottom of the Gulf of Mexico. Zooplankton and other species eat the algae; excrete fecal pellets and dead algae that sink to the bottom. Bacteria deplete the water of oxygen and marine life flees or dies as shown in Figure 18. Nitrogen is considered the limiting nutrient for algae blooms in the Gulf of Mexico (Bierman, V. J. *et al.* 2001; Justic, D. *et al.* 2007; Justic, D. *et al.* 1993). The Eastern camp uses empirical evidence of nutrient influx and stream flow to create an regression analysis equation to project the size of the hypoxia zone in the Gulf of Mexico (Rabalais, N. N. *et al.* 2005).

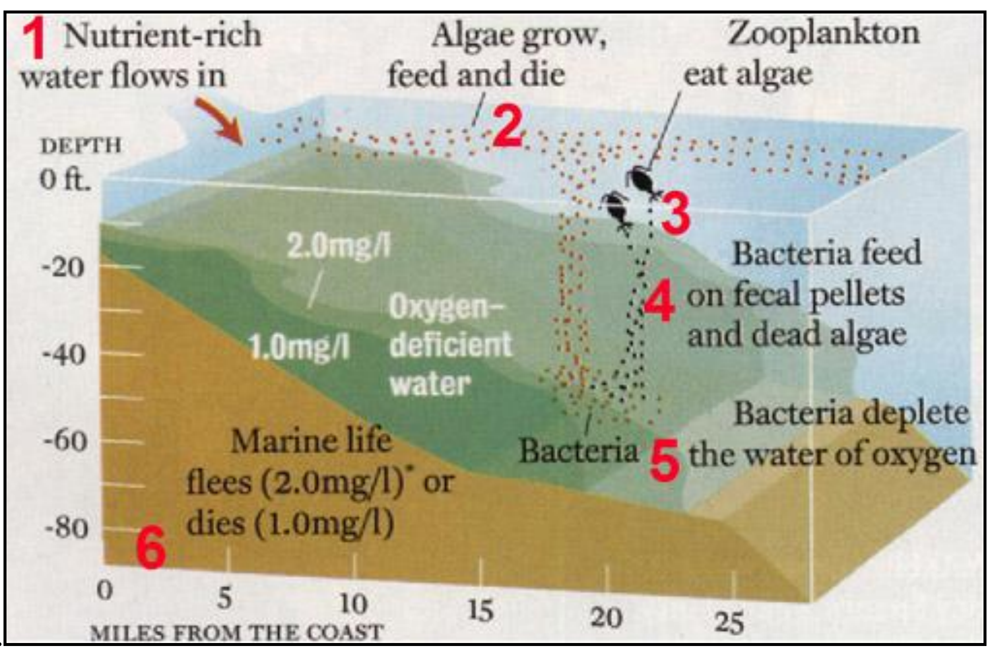


Figure 18. Nutrient-based Hypoxia Formation (Louisiana Universities Marine Consortium 2010)

2.18 History — Western Camp

The Western camp is represented by Robert D. Hetland and Steven F. DiMarco who recognize that previous studies suggest enhanced nitrogen loading may be responsible for the hypoxia zone citing work by the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2004 (Turner, Rabalais, Justic and Scavia, known proponents of the nutrient causes hypoxia theory) and works cited therein. The Western camp admits the strong relationship between river discharge and hypoxia. The Western camp explains that fresh water river discharge increases stratification over saltier denser shelf waters and increases the supply of organic matter. The physical effect of stratification is part of the hypoxia process. It is difficult to separate the physical effect from the biological effect of eutrophication (Hetland, R. D. and S. F. DiMarco 2007). The Western camp explains that a patch of low oxygen water with an initial diameter of 20 km advected by a westward flow of 0.005m s^{-1} would be diluted by a factor of four after being moved 50 km. The hypoxic patch would disperse as smoke from a smokestack. Discharge from the Mississippi River Delta is the primary influence on the Eastern region. The western regime is influenced by both the discharge from the Atchafalaya and shelf wide wind driven currents with bottom respiration being the primary cause of hypoxia (Hetland, R. D. and S. F. DiMarco 2007). The Western camp recognizes two plumes and suggests two hypoxia areas with separate causes for creation with mixing ending both hypoxia zones and suggests the creation of hypoxia may be more related to the stratification of fresh water over denser salt water eliminating respiration and inducing a hypoxic zone. The hypoxic zone and any increase in the size of the hypoxic zone would be more related to physical processes rather than biological. Any increase in respiration would decrease the size of the hypoxic zone (Hetland, R. D. and S. F. DiMarco 2007).

2.19 Regression Analysis

Excess nitrates transported by the Mississippi River drive the production of algae in the surface water of the Gulf (Rabalais, N. N. *et al.* 2005), increasing detritus, which drives (correlates to) the increasing size of the hypoxia zone. Some smaller streams show dramatic increases in average nitrate concentrations over lower Mississippi River main stem nitrate concentrations. Average nitrate concentrations increased by a factor of about 2.6 between 1905–07 and 1980–96 with the majority of nitrate concentration increase in the lower Mississippi River main stem occurring between the late 1960's and the early 1980's. Between the late 1960's and the early 1980's, the average annual nitrate concentration in water flowing to the Gulf of Mexico more than doubled (Goolsby, D. A. and W. A. Battaglin 2000). A linear regression based on the correlation of stream flow to nitrogen transport was used to estimate the size of the hypoxia zone (Rabalais, N. N. *et al.* 2005).

2.20 Differing Theories

The Eastern group proffers the following: 1) Stratification of the water column in the Gulf is a necessary condition for hypoxia. 2) The presence of organic matter (detritus composed of organic material washed downstream, dead algae or bycatch) to reduce the oxygen level. The Western group agrees with 1) and 2) and postulates physical factors such as: 3) Mixing will reduce or end hypoxia zones. 4) Any increase in respiration will decrease the hypoxic zone. These factors suggest the list is not complete. Physical factors could include changes in land use, wetland loss, levee building, and population increases.

2.21 Wetlands Decrease

It is estimated that six Upper Mississippi River Basin states—Iowa, Missouri, Illinois, Indiana, Ohio, and Kentucky (same region with the highest fertilizer usage)—lost 80–90% of their wetlands from 1780 to 1980 (Dahl, T. E. 1990). As wetland ecosystems decrease in size the potential for flooding increases. Thus, these ecosystems possess significant economic value (Parsons, C. 2006). Mean annual national flood damages now approximating US $3.4 billion despite a similar rise in control costs. Flood storage could have prevented a 1993 overtopping of the Mississippi River levee above St. Louis by relieving pressure on levees. 1993 flood losses were 16 billion in US dollars (Richards, F. 1994). The reduction in damages due to flooding could be used to offset political and social pressures regarding the costs of restoring wetlands.

An estimated 2–5.3 million ha of restored wetlands would be required to stem the flow of nitrogen to the Gulf of Mexico to diminish the hypoxic zone (Mitsch, W. J. *et al.* 2001). Currently, crops requiring less drainage and nitrogen are being actively considered. New forms of nitrogen fertilizer that attach to soil and dissolve more slowly are being developed. Cost considerations can be modeled and considered (Hey, D. L. *et al.* 2005). Nitrate accumulates in soils and underground waters during dry years and is flushed into streams and the main river channel during wet years (Goolsby, D. A. *et al.* 1999). A higher discharge decreases the water residence time in canals, lakes and small streams in the upper watershed. This reduces nitrogen loses due to denitrification (Howarth 1996). Wetlands cycles affect the amount of nitrates released as shown in Figure 19. Cahoon's 2008 conceptual wetland loss diagram considers factors which influence marsh loss, grazing of vegetation by muskrat and nutria, altered flooding and salinity patterns, annual prescribed burning of vegetation, and the rate of sea-level rise. Data collectors need to identify factors, including continued sea-level rise, which affect site plans for

successful wetland restoration. The study in St. James Parish of an enclosed wetland measuring inflows and outflows of water and nutrients has provided insight into the value of wetlands (Kemp, G. P. and J. W. Day 1981).

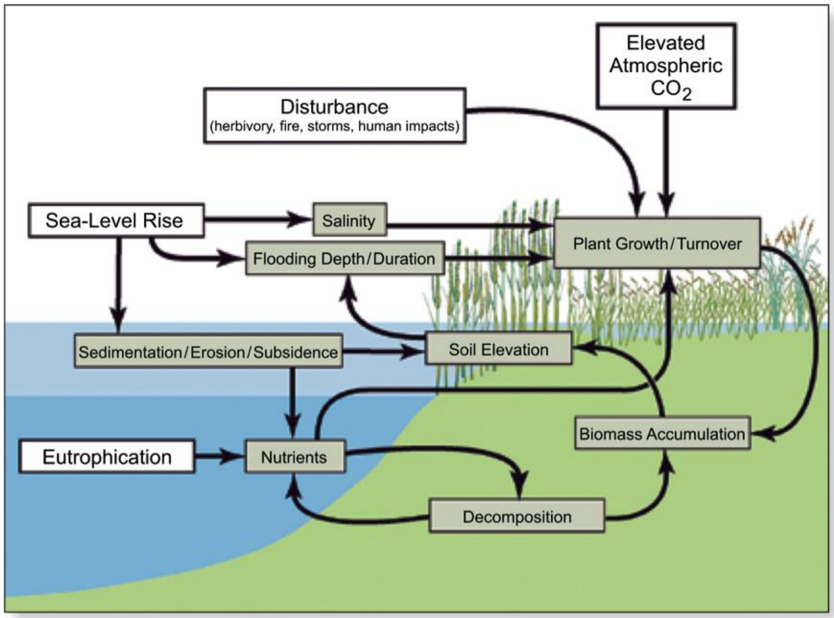


Figure 19. Wetland Loss (Cahoon, D. R. 2008)

For a year, nitrogen and phosphorus input and output of a (closed system) 64 ha swamp forest in the headwaters of Louisiana's Barataria Estuary were measured to determine the system capacity to sequester nitrogen and phosphorus. Approximately 44% of nitrogen and 40% of phosphorus introduced into the swamp forest was sequestered (Kemp, G. P. and J. W. Day 1981). More than 90% of the annual phosphorus input caused by over bank flooding in a southern Illinois cypress swamp was sequestered in phosphorus rich sediment (Kemp, G. P. and J. W. Day 1981). The Illinois swamp removes dissolved inorganic nitrogen from over bank flooding, but adds dissolved PO_4 to flood waters. N:P ratios ranged from 0.1 to 6.0:1 but clustered around a mean of 2:1 (SD = 1.8). Wetlands are nutrient sinks (Kemp, G. P. and J. W. Day 1981). Plants growing in wetlands are expressed by a broad based trophic food pyramid. Wetlands and coastal marshes display similar pyramids.

Sea grasses are sequesters of carbon and nitrogen as displayed by their Redfield ratio. The Redfield ratio for phytoplankton is generally accepted as 106:16:1 (C N P). The composition of phytoplankton is remarkably similar to the sea water where they are found (Chisholm, S. W. 1992). The Redfield ratio for sea grasses is 119:17:1. Sea grasses and other benthic marine plants possess Redfield ratios of 550:30:1 well above phytoplankton ratios. For sea grasses N:P ratios of 30:1 are considered P limiting and less than 25-30:1 are considered N limiting (Johnson, M. W. *et al.* 2006). Sea grasses are underwater wetlands. Plants use required sunlight for photosynthesis at different rates of efficiency (Campbell, N. A. 1996).

2.22 Solar Energy Efficiency

Every day the Earth receives 10^{22} joules (J) of solar radiation, (1J = 0.239 calories) varying in intensity with latitude, with the tropic receiving the highest input. Solar radiation is absorbed, scattered or reflected in an asymmetrical pattern determined by cloud cover patterns and atmospheric dust. Solar radiation variation, amount of water, temperature and nutrient availability are some of the variables which limit photosynthetic output of ecosystems (Burkhardt, H. 2006).

Only about 1% to 2% of the small amount of solar radiation striking algae and plant leaves is converted to chemical energy by photosynthesis (Campbell, N. A. 1996). The efficiency of photosynthesis varies with the type of plant, level of solar radiation and other factors such as water, temperature and nutrient availability. Primary producers create approximately 170 billion tons of organic matter each year. Sunlight does not penetrate more than approximately 120 feet through water and is limited by the amount of particulates in water and the concentration of algae. (Crater Lake in Oregon is very clear and the maximum depth a Secchi disk can be observed is 120 feet (National Park Service 2009).) The depth of the water,

the clarity and the amount of sunlight available within growing range parameters determine the efficiency of photosynthesis.

2.23 Photosynthesis

It follows that photosynthesis is the conversion of energy to matter in the presence of sunlight and chlorophyll. Photosynthesis may be represented as:

$$6CO_2 + 12H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O$$

This formula represents the reverse of cellular respiration (Campbell, N. A. 1996). It is important to note that 6 moles of water are produced in this process. Different ratios of Carbon to Nitrogen to Phosphorus are used by algae, plants, crops and aquatic biomass. The ratio indicates how much of each element must be present for a producer (organism capable of photosynthesis) to function. The ratio of 50:7:1 (Bengtson, D. R. 2009) is a ratio used for some algae. The Redfield ratio is 106:16:1 (Chameides, W. L. and E. M. Perdue 1996) and is for different species of algae and organisms. The ratio of C N P introduces concepts of limiting nutrients on growth and terrestrial plants and aquatic plants which have higher C N P ratios are potential nitrogen sinks and can be used to sequester carbon. Sustainable management should be based on a sound understanding of C N P ratios, the natural functioning of coastal ecosystems including river discharge, and the relationship between species and their utilization of energy and biomass (Kemp, G. P. and J. W. Day 1981).

Whether the ecosystem of the Gulf of Mexico is loaded with the essential elements of life waiting for the warmth of the summer sun to grow algae resident in the Gulf of Mexico or introduced by stream flow is not known and would require more research. "[T]here is overwhelming evidence supporting P-limitation of primary production in most freshwater ecosystems. [T]here is little support for P-limitation in marine ecosystems. With a few

exceptions, nutrient addition bioassays and the distribution of N : P ratios over the major oceanic basins, coastal areas and estuaries demonstrate that N, and not P, stimulates primary productivity" (Falkowski, P. G. 2001). Given available nutrients, sunlight, water temperature and algae reproduction rates, algae "blooms" occur at an explosive rate. This suggests that the initial reproduction rates are at least increased by nutrient enrichment and may be multiplied under certain conditions. While economic multipliers have been studied, it is not known if an ecological multiplier exists.

2.24 John Maynard Keynes Economic Multiplier

John Maynard Keynes first put forth a congealed version of a multiplier (Einbond, A. 1993/1994). Keynes's idea is that income will increase by a multiple of investment. The multiplier works because money invested to construct new capital does not remain in the pockets of the laborers. New income is consumed when goods are bought from others. The amount spent on consumption determines marginal propensity to consume. A marginal propensity to consume of 2/3 (meaning out of an increased income they will spend 2/3 and save 1/3), then an extra 2/3 of their salaries is added to total income. Then those who sell receive the 2/3 and will spend 2/3 of that (or 4/9 of the original investment) on goods. This continues indefinitely, greatly increasing wealth. If the original investment was one million dollars, the marginal propensity to consume was 2/3, the increase in income would be (1+2/3 + (2/3)2 + (2/3)3 + . . .) or $3 million with the multiplier being 3 (Einbond, A. 1993/1994). The concept of multiplier is well founded in economics and it is suggested to have application to ecology.

2.25 Ecological Multiplier

For example, one atom of nitrate-N can be responsible for producing 6.6 atoms of organic carbon through photosynthesis (Battaglin, D. A. G. a. W. A. 2000; Redfield, A. C. 1958).

Rabalais and others suggest that an atom of nitrogen from the Mississippi River is recycled about four times, on average, in the Gulf before it is lost from the water column (Goolsby, D. A. *et al.* 1999). The recycling of an atom, the recycling of a nutrient, and the duration of the cycling time suggest an ecological multiplier.

2.26 Variations in Nutrient Cycling Time

Nutrients cycle rates are extremely variable due to differences in rates of decomposition (Meybeck, M. 1982). Decomposition rates can vary from months to many years. Several examples are listed with the expected rates of decomposition.

1. In tropical rain forests, most organic material decomposes in a few months to a few years (Campbell, N. A. 1996).
2. In temperate forests most organic material decomposes on average in 4 to 6 years (Campbell, N. A. 1996).
3. In the tundra, decomposition can take 50 years (Campbell, N. A. 1996).
4. In aquatic ecosystems, which are often anaerobic, it may occur even more slowly (Campbell, N. A. 1996).

The temperature, the availability of water, the availability of oxygen (O_2), local soil chemistry and the frequency of fires all affect rates of decomposition and nutrient cycling times (Campbell, N. A. 1996). Almost nothing in the natural world is constant, as illustrated below even solar insolation varies.

2.27 Solar Energy

Figure 20 shows solar insolation in the Great Salt Lake Desert, chosen because of a lack of interfering factors such as cloud cover and water vapor. Solar insolation is the primary source of energy for the majority of ecological processes. Terrestrial temperatures vary directly as the amount of solar insolation striking land surface. Water temperature is one of the variables of weather and the chemical processes in the Gulf and is driven by the amount of solar insolation striking the surface of the water.

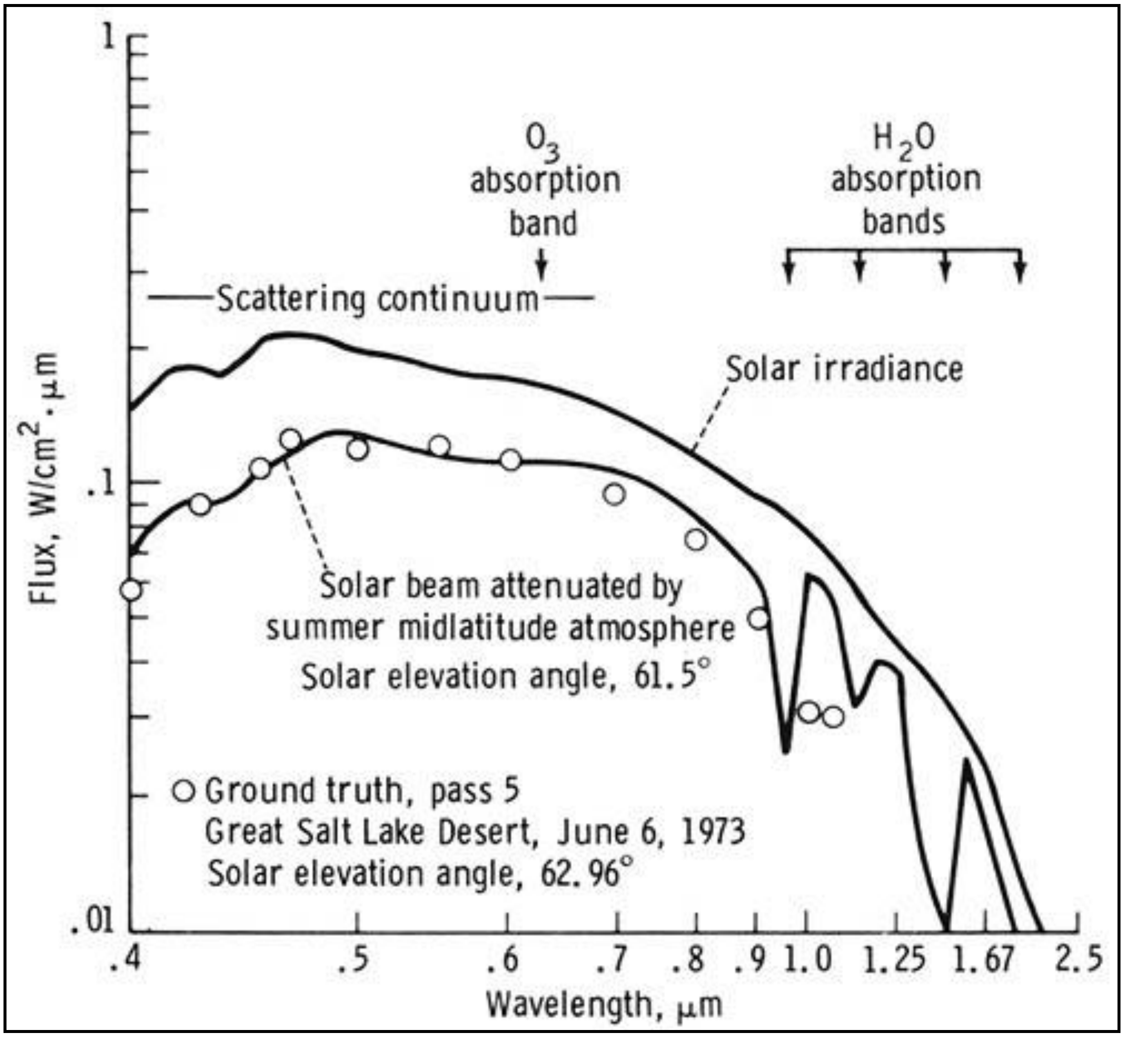


Figure 20. Example Of Solar Radiation (National Aeronautics and Space Administration 1973)

Sunlight penetration to various depths in water must be measured and considered. The Secchi disk is a device which is useful for measuring the depth to which sunlight penetrates water (Secchi, F. P. A. 1865). The penetration of sunlight would affect the temperature of the water and the photosynthesis of plant life. Solar elevation angle shall not be modeled in this discussion. The depth of the algae model was selected at 0-4 meters because sunlight observed at the various bayous and in the Gulf of Mexico did not penetrate deeper than 12- 13 feet. A white (8" diameter) Secchi disk was raised and lowered as illustrated in Figure 21 to obtain this result.

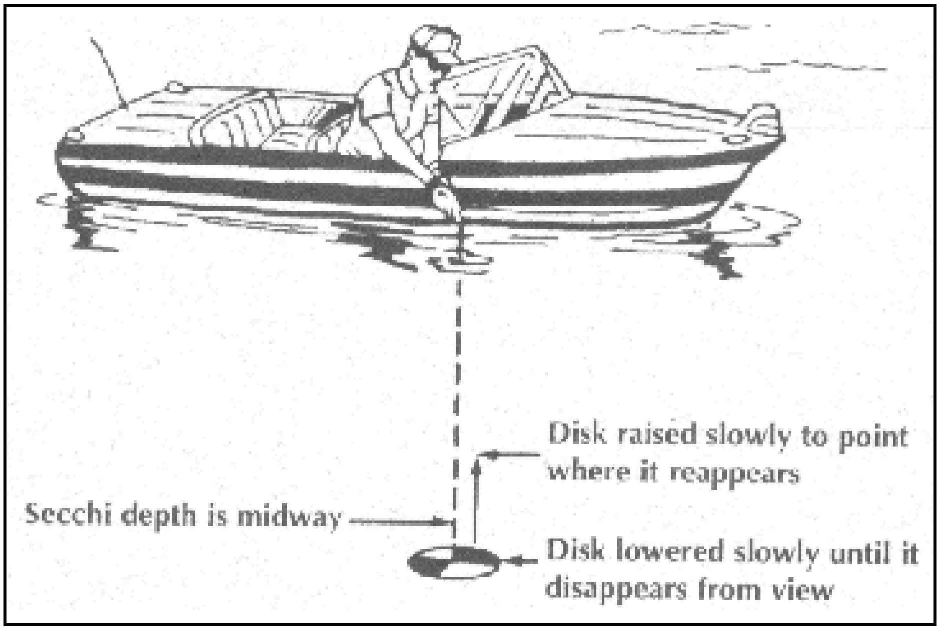


Figure 21. Secchi Disk (Secchi, F. P. A. 1865)

Stratification and nutrients are necessary elements for hypoxia. The difference in salinity of stratified water, the question of speed of algae growth, the rates of reproduction and nitrogen versus phosphorus limitation demand consideration.

2.28 Algae Grow In Fresh, Brackish and Salt Water

Given there are 7000 types of green algae alone and chlorophyta (green algae) live in both fresh and salt water (Campbell, N. A. 1996), understanding the limiting nutrients in fresh, brackish and salt water aids the understanding of the distribution of algae in the Mississippi River, the marshes and the Gulf of Mexico. Dortch and Whitledge (1992) found an important index of nitrogen limitation (the ratio of intracellular free amino acids to protein) did not support the view that nitrogen limitation was widespread. Concentrations and ratios of inorganic nutrients indicate that potential limitation by phosphorus was more likely than nitrogen limitation in areas of low salinity. Nitrogen limitation was more prevalent in higher salinity waters further offshore, especially during the late summer (Castill, M. a. M. *et al.* 2003). Redfield in 1934 and

Falkowski in 2000 stated the elemental composition of phytoplankton is remarkably similar to that of the seawater in which they are found. The ratio of C N P indicates the relative efficiency nutrients used by algae and vary from fresh water to salt water (Castill, M. a. M. *et al.* 2003). The utilization of nutrients and the accumulation of energy are indications of the efficiency of food chains (Campbell, N. A. 1996).

2.29 Efficiency of Food Chains

Of the energy fixed by photosynthesis, approximately 1/1000 flows through a food web to a tertiary consumer, such as a hawk or shark. This is why food webs usually include only three to five tropic levels. There are no predators of lions, eagles or killer whales other than humans because their mass is insufficient to support another trophic level (Campbell, N. A. 1996).

Ecology limits trophic levels and human society has a theory that everything is linked. While interesting on the socioeconomic level, the thought that ecological food links are limited offers insight into the sensitivity of the system to over harvesting. Affecting one trophic level would according to the theories of linked trophic levels thus affect many levels.

2.30 Linked

Albert-Laszlo Barabasi (2003) wrote that everything is connected by six degrees of separation. The ecological significance of this statement when considering the energy and biomass pyramids is profound. The coexistence of robustness and vulnerability plays a key role in understanding the behavior of most complex systems. If a highly connected keystone species is removed the ecosystem dramatically collapses. The sea otter in California was almost extinct because of excessive harvesting for pelts. In 1911 federal regulation protected the sea otter. The sea otter responded with a dramatic increase in numbers. The sea otter feeds on urchins which

feed on kelp. When the sea otter reduced the number of urchins, the number of kelp increased increasing the food supply for fish. The kelp protected the coast from erosion aiding the economy of the California coast. Finfish now dominate in estuaries once dominated by shellfish. This dramatic change was caused by the protection of one species (Barabasi, A.-L. 2003). Such events suggest the possibility of an inverted pyramid where a change in a keystone species would have dramatic effects.

2.31 Normal and Inverted Pyramids

The efficiencies of one level of the trophic food pyramid consuming another show the dependence of a higher level on the level below. Of primary concern is the interdependence of trophic levels. This interdependence adds complexity to the ecosystem and complexity does not add to the ease of understanding the ecosystem or modeling the system.. Terrestrial biomass pyramids decrease in biomass at successively higher trophic levels and are considered normal. Energy pyramids are always bottom heavy. If the efficiency of the terrestrial pyramid (swamps and bogs are normal terrestrial pyramids) (Campbell, N. A. 1996) was 1 to 1,000 meaning a normal terrestrial pyramid shown in Figure 22 with a base of 1,000 and an apex of 1. Careful research must be conducted to determine the exact efficiencies. Figure 23 is typical of ocean ecologies. If the efficiency of 1 to 1,000 is maintained the inverted pyramid would be illustrated by the Figure 23. An example of an inverted pyramid would be the aquatic ecosystem of the English Channel where a small crop of producers (phytoplankton) supports a larger standing crop of primary consumers (zooplankton). The zooplankton rate of consumption is greater than the rate of algae reproduction. The biomass of zooplankton (consumers) is five times the weight of phytoplankton (producers) (Campbell, N. A. 1996).

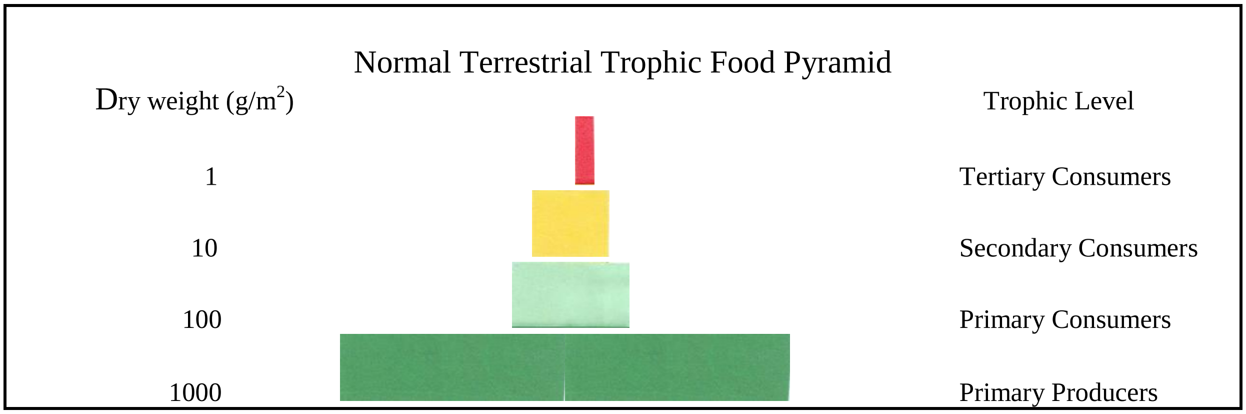


Figure 22. Normal Terrestrial Pyramid

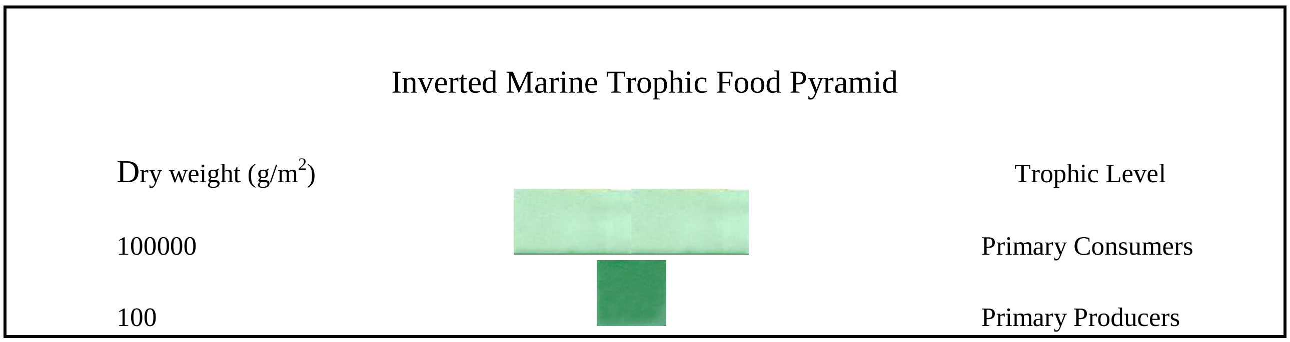


Figure 23.Gulf Of Mexico Pyramids (Campbell, N. A. 1996)

If the (predators) consume algae at a faster rate than the algae can reproduce an inverted pyramid would occur. The history of the Gulf of Mexico indicates consumers of algae existed in greater numbers in the past. The menhaden, oysters and coral no longer exist in numbers sufficient to consume algae faster than the algae can reproduce. In most real-world systems, trophic efficiencies are on the order of 10 to 40% (Begon, M. *et al.* 1990; Schmitz, O. J. and G. Booth 1997). Ten percent is conservative.

2.32 Intrinsic and Extrinsic Causes of Hypoxia

The causes of hypoxia are intrinsic and extrinsic. Intrinsic processes describe the interaction between water, the chemicals in the water, the sediment and re-suspension process that occurs. Extrinsic loadings are from nitrate, freshwater, dissolved organics and suspended

clay particles to name a few (Rowe, G. T. 2001). Therefore, the approximately 0.95 million metric tons of nitrate as nitrogen discharged annually from the Mississippi River Basin (Goolsby, D. A. *et al.* 1999) could potentially produce more than 20 million metric tons of organic carbon annually in the Gulf of Mexico (Rabalais, N. N. 1999).

2.33 Tipping Point

If one atom of nitrate-N can be responsible for producing 6.6 atoms of organic carbon through photosynthesis (Battaglin, D. A. G. a. W. A. 2000), and if as Rabalais and others (1999) suggest an atom of nitrogen from the Mississippi River is recycled about four times, on average, in the Gulf before it is lost from the water column (Goolsby, D. A. *et al.* 1999), then it is suggested the algae explosion could be the result of a combination of co-dependent ecological causes. These co-dependent ecological causes such as nitrogen introduction, channelization of the Mississippi, increasing human population, decreasing wetlands, and decreasing forests could cause the eco-system to reach a tipping point where resilience to stress is diminished and sustainable harvests are not possible. The name given to that one dramatic moment where everything changes all at once is the “tipping point” (Gladwell, M. 2002). “A ‘tipping point’ is a threshold beyond which the system goes into a disequilibrium from which return to the original condition is problematic (Cairns, J. 2004). Could co-dependent causes lead to the “tipping point” and only one more “cause” tip the system into disequilibrium? This question requires further study. Ecological systems display resilience to change. Sustainable harvests of a resilient ecological system occur without damage to the eco-system. Understanding resilience, tipping point and sustainability is essential to management.

2.34 Resilience and Sustainability

Resilience is defined as resistance to change and sustainability in the ecological sense is the ability to sustain the same harvest repeatedly (Glover, L. K. and S. A. Earle 2004; Vanderkooy, S. J. 2009). A tipping point may mark the point past which the ecosystem is not resilient and harvests can not be sustained. Man disregards the well being of his environment either because of a lack of understanding of resilience, sustainability and tipping point, or a belief that the environment will not be affected by individual actions. When the individual must satisfy his needs from the environment or fail to survive the lack of concern for the environment is acute. Maslow described the efforts of man to survive and the efforts to reach fulfillment in his hierarchy of needs.

2.35 Maslow's Hierarchy

Abraham Maslow was born in 1908 in Brooklyn, New York. Maslow was a humanistic psychologist who developed the Hierarchy of Needs with the concept that people must satisfy lower needs before they can achieve his concept of self-actualization (Maslow, A. 1943). His hierarchy of needs pyramid visually depicts his concepts as shown in Figure 24.

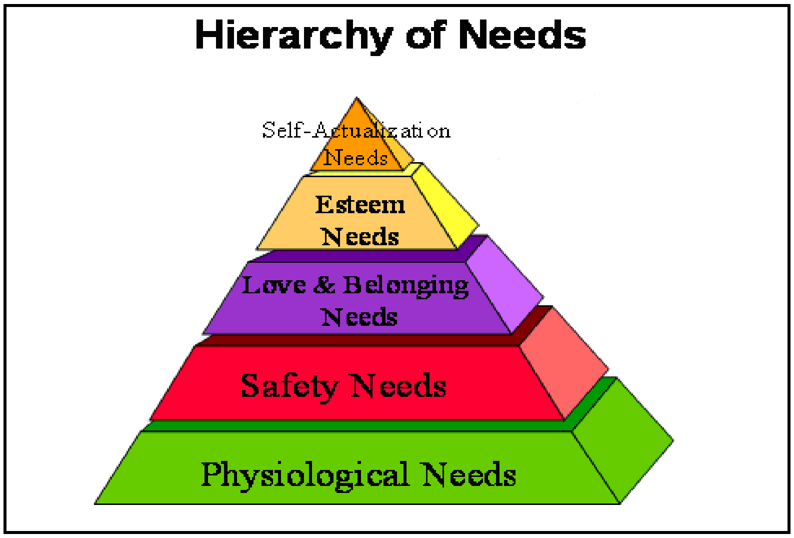


Figure 24. Maslow's Hierarchy Of Needs (Maslow, A. 1943)

Maslow's hierarchy of needs sparks a debate between those who have and those who struggle to have. Nearly all believe it is best to preserve some quantity of natural capital in order to achieve sustainable development. To accomplish preservation of "some environmental capital" stake holders advocate one of two social paradigms; the 'strong' and 'weak' paradigm. The 'weak' sustainability paradigm supporters believe depleted natural resources can be replaced by technological advances and substitutions enabling economic growth to continue. The 'strong' sustainability paradigm supporters believe technology and resource substitutions will not maintain the ability to achieve sustainable harvests from the environment and advocate limiting material utilization, economic expansion, and population increase from zero to some level. The zero growth advocates require no discussion (Udo, V. E. and P. M. Jansson 2009).

2.36 Understanding Man's Disregard of His Environment

There are conflicting views on whether poverty causes degradation of ecological systems. While some believe a degraded environment can accelerate the process of impoverishment because the poor depend directly on natural assets and impoverishment accelerates environmental degradation through over exploitation of natural resources like land and water there are researchers that present evidence that urbanization has a greater affect on ecological degradation (Satterthwaite, D. 2003). The deterioration of natural resources and unsafe living conditions affects the fertility of the urban population: the higher the urbanization, the lower the fertility (Lutz, W. and R. Qiang 2002). Regardless of the cause, ecological pressures as a result of urbanization or poverty in a particular class of people do cause adverse ecological pressures. Ecological resources will be exploited until there is no reward for exploitation (Hardin, G. 1974). This tragedy was explained by Garret Hardin when he described what would happen if individual herdsmen continued to add cattle to pasture held in commons (Hardin, G. 1968). The Gulf of

Mexico is a commons and the analogy between herdsmen and fishermen can be made (Franklin, H. B. 2007). The Marxist words, “from each according to his abilities; to each according to his needs.” lose meaning and fishermen tend to underachieve according to their ability and over demand. As James Madison said in 1788, "[i]f men were angels, no Government would be necessary" (Federalist, no. 51). In a world where all resources are limited, a single nonangel in the commons spoils the environment for all. (Hardin, G. 1974)

As herdsmen add cattle, fishermen engage in destructive trawling and damage the common fishing grounds by removing filter feeders or key species (Franklin, H. B. 2007). A model of potential managerial positions and the possible outcomes could avoid expensive and time- consuming trial and error. The model could display potential solutions and become an aid to bring the stakeholders to agreement on potential sustainable solutions.

2.37 Rowe Discusses the Eastern and Western Camps

There are divergent opinions on the causes and the cures for hypoxia in the Gulf of Mexico. The following discussions concentrate on intrinsic and extrinsic causes of hypoxia (Rowe, G. T. 2001). The intrinsic processes (biological processes) either produce or consume oxygen, often in response to the above-mentioned forcing functions and are internal processes to the Gulf of Mexico.

The extrinsic processes are external to the Gulf of Mexico and are the introduction of nitrogen-laden water. Two different explanations have emerged concerning the extrinsic causes of Louisiana hypoxia. Physicists propose the freshwater plume prevents mixing of oxygen-rich surface waters into the interior water column, where respiration dominates. Physicists demonstrate that the vertical density gradient can reach critical levels. Bottom water cannot be oxygenated and in weeks to months hypoxia occurs. Wind events cause mixing, ending the

stratification which refreshes the bottom water, and hypoxia is prevented or delayed (Rowe, G. T. 2001; Wiseman, W. J. and R. W. Garvine 1995).

2.37.1 Western Camp

Physicists propose the freshwater plume prevents mixing of oxygen-rich surface waters into the interior water column, where respiration dominates. When the vertical density gradient reaches critical levels, the bottom water can no longer be refreshed and hypoxia results in a matter of weeks to months. If the gradient is interrupted by wind events, then mixing occurs, the bottom waters are refreshed, and hypoxia is prevented or at least delayed (Wiseman, W. *et al.* 1997). Caveat: The writer proffers the opinion that the plume possesses a current strong enough to carry sediment and this plume prevents the wind from affecting the Ekman currents and prevents mixing and deep water respiration until the wind from a storm or a hurricane becomes strong enough to overcome the strength of the river plume. Page 63 to 70 will discuss this further.

2.37.2 Eastern Camp

Biologists and chemists observe that nitrate concentrations in river water increased in the past half century (Turner, E., and N. Rabalais 1991), increasing algal growth (Lohrenz, S., M. Dagg, and T. Whitledge 1990). Detritus including algal cells, cellular debris, and zooplankton feces gravitate into deep water (Redalje, D., S. Lohrenz, and G. Fahnenstiel 1994) where they accumulate (Eadie, B. *et al.* 1994) decomposing bacteria which exhaust deep water oxygen leading to hypoxia. An increase in nitrate loading might explain hypoxic expansion (Turner, E., and N. Rabalais 1991) over the last few decades (Nelsen, T. *et al.* 1994). High concentrations of nitrate in agricultural runoff are presumed to be the forcing function (Rowe, G. T. 2001).

The relationship between nitrate flux and organic matter accumulation rates in the mud were defined (Eadie, B. *et al.* 1994), based on ^{210}Pb dating (Nelsen, T. *et al.* 1994). Diminishing

the nitrate loading in the river might slow the production of phytoplankton in the plume over the continental shelf lessening the organic loading of deep water and slow (one might suspect) the net losses to respiration in deep water (Justic, D. *et al.* 1993).

2.38 Rowe Model

Rowe (2001) created a STELLA® model which did not treat the extrinsic forcing functions. The model dealt with the intrinsic processes that either produce or consume oxygen, often in response to the above-mentioned forcing functions. The model demonstrated the relationship of oxygen to photosynthesis and various elements in the water body. The oxygen model is presented in 25. The equations follow the model graphic (Rowe, G. T. 2001).

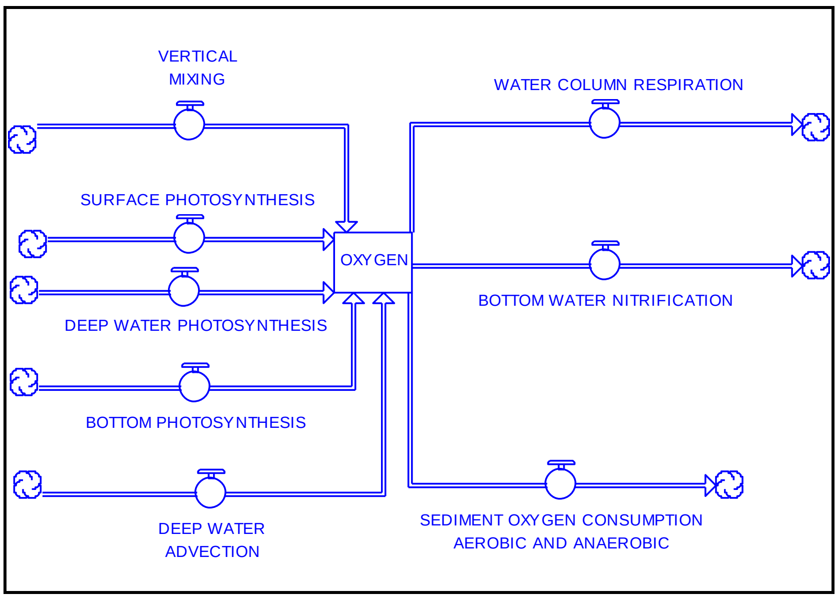


Figure 25. Rowe Oxygen Model (Rowe, G. T. 2001)

The STELLA® Equations follow:

OXYGEN (t) = OXYGEN (t - dt) + (VERTICAL_MIXING + DEEP_WATER_ADVECTION + BOTTOM_PHOTOSYNTHESIS + DEEP_WATER_PHOTOSYNTHESIS + SURFACE_PHOTOSYNTHESIS - WATER_COLUMN_RESPIRATION - BOTTOM_WATER_NITRIFICATION - SEDIMENT_OXYGEN_CONSUMPTION_AEROBIC_AND_ANAEROBIC) * dt

INIT OXYGEN = 6.3

INFLOWS:

VERTICAL_MIXING = .0038

DEEP_WATER_ADVECTION = 0

BOTTOM_PHOTOSYNTHESIS = .3

DEEP_WATER_PHOTOSYNTHESIS = .3

SURFACE_PHOTOSYNTHESIS = .0962

OUTFLOWS:

WATER_COLUMN_RESPIRATION = .19

BOTTOM_WATER_NITRIFICATION = .3

SEDIMENT_OXYGEN_CONSUMPTION_AEROBIC_AND_ANAEROBIC = .128+.0076

The STELLA® graph (Figure 26) is the graph generated by the model. Sediment oxygen consumption = 0.128 + 0.0076 x bottom water oxygen and deep water oxygen concentration initial conditions are equal to 156 mmol m^{-3} (5.0 mg L^{-1}). The diel variation (variation of sunlight because of day and night) in the photosynthesis term was parameterized as sin (π x time/12) in the Rowe model (Rowe, G. T. 2001). This parameterization would create a sine wave in the graphic solution for the model. Models should be simple as possible, but complex enough for the particular modeling task considering the ecosystem and the data available (Kimmins, J. P. H. *et al.* 2008). The complexity adds nothing to the model (Figure 26) created for this study. The background science for the oxygen model was discussed in the Global Oxygen Cycle (Chameides, W. L. and E. M. Perdue 1996). Vertical physical mixing, bottom respiration and nitrification into the bottom water were not included (Rowe, G. T. 2001) and data calibration of the Rowe model will not be explored.

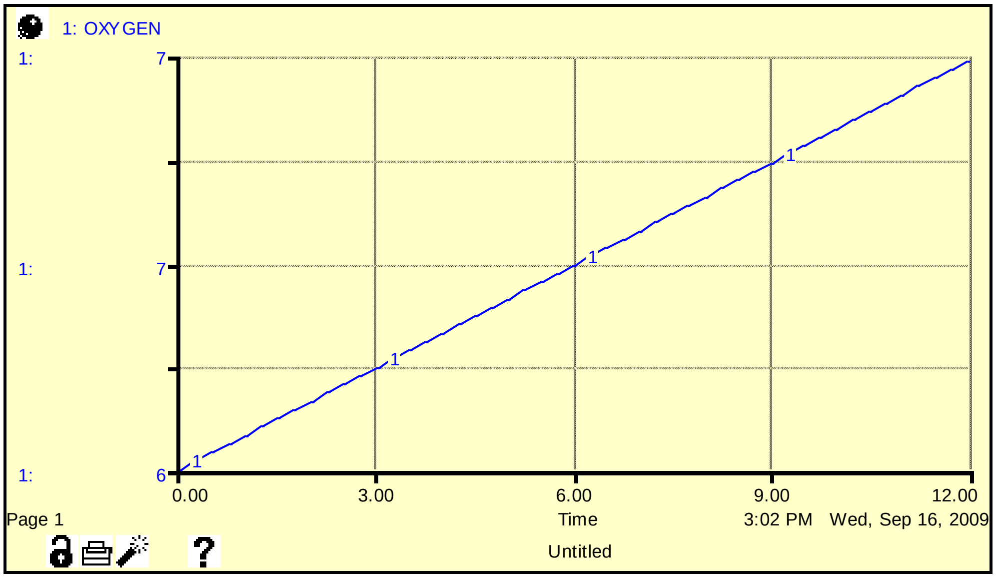


Figure 25. Rowe Shows Oxygen Increase (Rowe, G. T. 2001)

2.39 Recorded Oxygen Values

The following chart (Figure 26) was taken from Rowe's (2001) work. In May, during the spring phytoplankton bloom, oxygen surface values were supersaturated (Rowe, G. T. 2001). When surface water is supersaturated (9 mg L^{-1}, 281 mmol m^{-3}), O_2 is lost to the atmosphere (Liss, P., and L. Merlivat 1986), and the loss rate is a function of wind speed (Winninkhof, R. 1992) Oxygen declined from high values of 7 mg L^{-1} at the surface to values of 3 mg L^{-1} at the surface as shown in Figure 26 (Rowe, G. T. 2001).

2.40 Losses of Oxygen

The Rowe model is useful as a beginning. Figure 26 is an aid in understanding the oxygen at depth or Sediment Oxygen Consumption which is the part of the Gulf of Mexico considered to hypoxic. The data were gathered over three days (5, 7 and 10 of 1991) (Rowe, G. T. 2001). The respiratory metabolism of sediment-living organisms is the losses to sediment oxygen consumption (SOC). Oxidation of NH^{+}_{4}, Mn, and Fe may be appreciable, but unfortunately have not been quantified in these sediments. Figure 27 shows sediment oxygen consumption in mmol m^{-2} hr^{-1} related to temperature. Based on 10 data points a simple linear

regression was created (Rowe, G. T. 2001). Bottom water oxygen concentration is an important number, but little is known about the complex variables and how these variables affect the rise or the fall of oxygen concentration as shown in Figure 28. Solar radiation (light) is the limiting element for photosynthesis. Given adequate light bottom photosynthesis can almost equal water column photosynthesis on the inner continental shelf (Cahoon, D. R. 2008). Mixing is ignored in the original Rowe model but mixing is known to eliminate hypoxia in the Gulf of Mexico. Weather is not included in the variables. Data are not available on when and how mixing occurs or the process by which mixing eliminates hypoxia (Rowe, G. T. 2008).

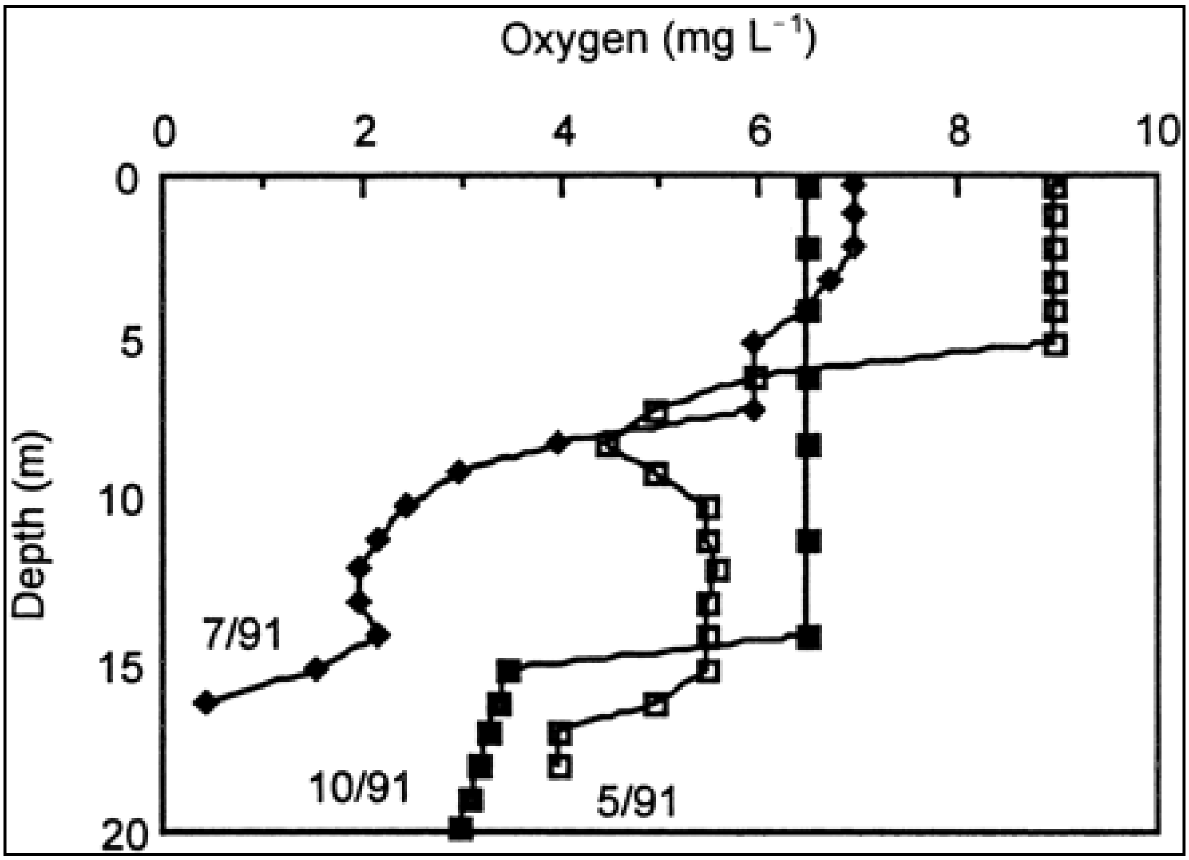


Figure 26. Oxygen At Depth (Rowe, G. T. 2001)

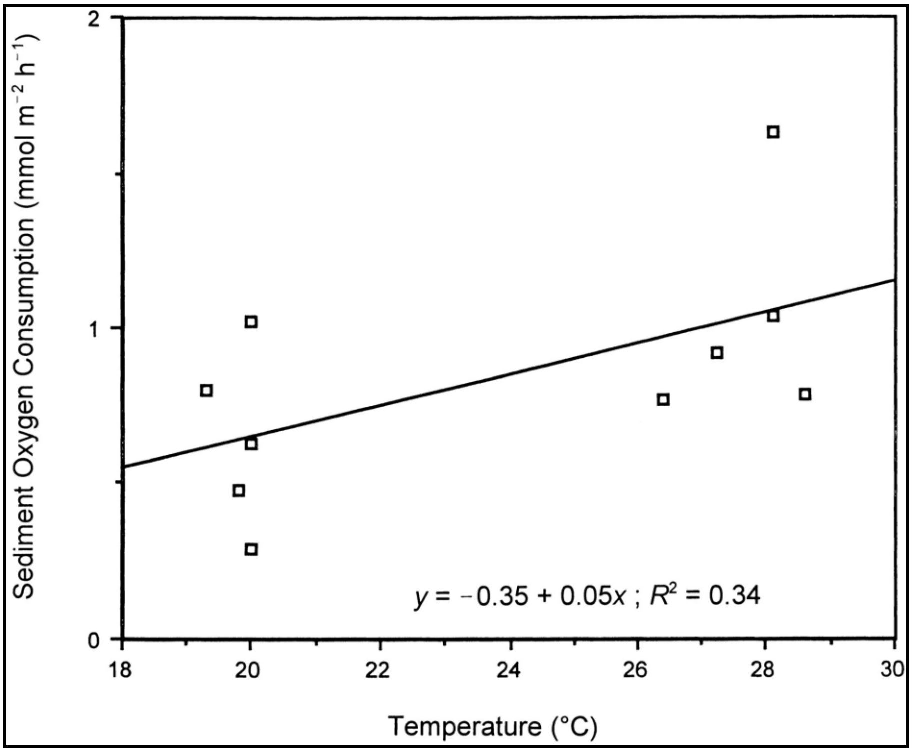


Figure 27. Sediment Oxygen Concentration (Rowe, G. T. 2001)

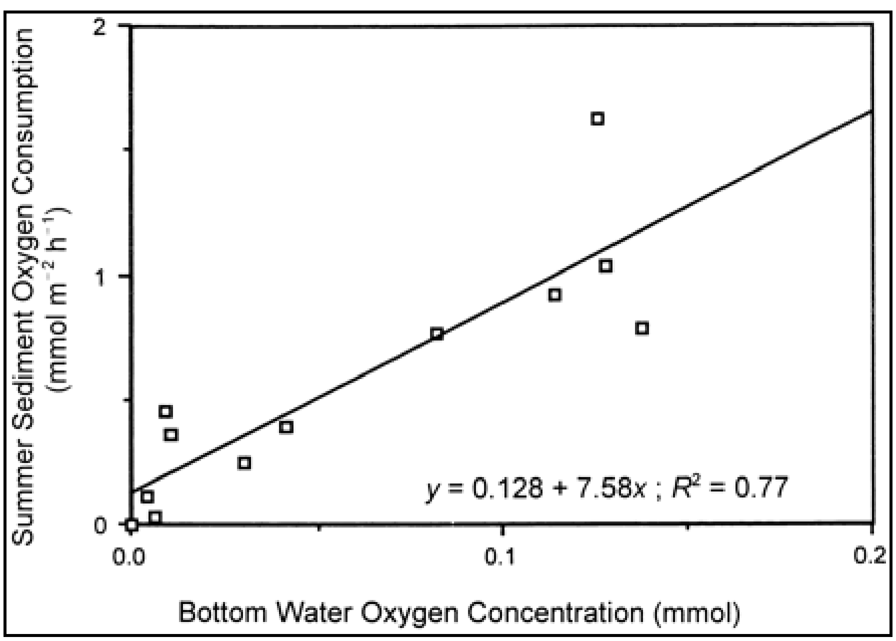


Figure 28. Bottom Water Oxygen Concentration (Rowe, G. T. 2001)

2.41 Mixing

Physical mixing increases circulation input oxygen into the system. Mixing transfers oxygen down concentration gradients either horizontal or vertically. Most vertical transfer is caused by turbulent diffusion mixing. Advective flow accounts for most horizontal exchange. Mixing or advective flow is a complex processes not well quantified on small time and space scales (Rowe, G. T. 2001) as shown by the variations in density data in Figure 29.

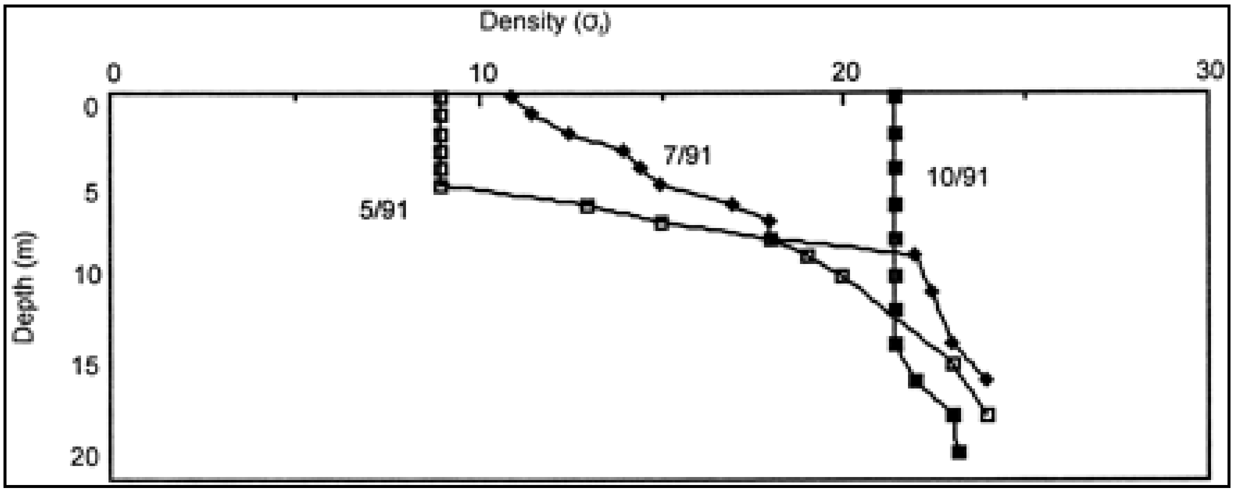


Figure 29. Density And Depth (Rowe, G. T. 2001)

The vertical transfer of oxygen to depth from surface waters can be parameterized as a Fickian diffusion, where: flux = K_d ([O_2]surface – [O_2]bottom)/depth interval where K_d has units of $m^{-2}h^{-1}$ and the flux in mmol $m^{-2}h^{-1}$. "[t]he flux is equal to concentration gradient times an eddy diffusion coefficient. The vertical gradients can be steep, and thus the intensity of the mixing or lack thereof is extremely important. Horizontal exchange of water along or across the continental shelf is equal to the concentration times the current velocity. However, concentration gradients in the horizontal are often small. Changes due to horizontal exchanges can result in lower as well as higher concentrations, depending on the relative concentrations of the water masses involved. If along shore and cross-shelf (e.g., horizontal) homogeneity is assumed, then

this term can be ignored in short time and space scales (Rowe, G. T. 2001)." "Vertical transfers are due mostly to mixing by turbulent diffusion and horizontal exchanges are related to advective flow, but both can be a mixture of complex processes that are not well quantified on small time and space scales (Rowe, G. T. 2001)." Depending on the relative concentrations of water masses horizontal exchanges can increase or decrease concentrations (Rowe, G. T. 2001).

The efforts of U. S. National Oceanic and Atmospheric Administration's Nutrient Enhanced Coastal Ocean Productivity project (NECOP), or the concomitant study conducted by the personnel of the Minerals Management Services of the U.S. Department of the Interior (called LATEX) (Rowe, G. T. 2001) will not be described in detail as this information can be obtained from original references. Raw data can be obtained electronically from National Oceanic and Atmospheric Administration's Coastal Ocean Program (COP) files at the Atlantic Oceanographic and Meteorological Laboratory (AOML) in Miami, FL (Hendee, J. 1994). These data and the data from the graphs throughout this discussion were used to establish the low and high points for sliders and knobs in the models. (Sliders and knobs are the names used in STELLA® for the input and adjustments which allow the modeler to vary values.)

Water column respiration (WCR) is the oxygen intake by heterotrophic organisms, especially bacteria with the resultant CO_2 discharge. Below surface oxygen biological sources are accomplished by photosynthesis of:

1. Bottom living micro algae, and
2. Water column phytoplankton.

Photosynthesis tends to dominate shallow ecosystem dynamics. Photosynthesis depends on solar insolation. Any physical phenomenon which reduces solar insolation reduces photosynthesis. Turbidity reduces the ability of insolation to penetrate a water column.

Turbidity is great around the Mississippi River plume and tends to diminish away from the plume. Figures 27, 28 and 29 suggest that detritus and soil particles from erosion would be transported toward shore with winds blowing south and would be transported away from shore with winds blowing north consistent with hypoxia being close to the coast of Louisiana. The Mississippi River plume begins with rain, picks up detritus and nutrients (C N P for example) and is intensified by any force or change (anthropogenic or natural) which increases the amount of water received or discharged from the Mississippi River Drainage Basin is defined by soil erosion, detritus and stream flow (Pinchot, G. 1908).

In 1989 the variability in plume area correlated with large changes in river discharge. During spring high river discharge (March/April), the Mississippi River plume averaged 4595 km^2, whereas during autumn low river discharge (October) the plume averaged 2058 km^2.

Wind was a forcing function on the location of the river plume. The east, south, and west plume parameters were maximized by winds from different directions. West of the delta, the plume area increased during episodes of eastward winds. During winter, southward winds increased the western plume area as well as the western extent of the sediment plume. Northward and eastward winds increased the size and extent of the plume east of the delta. The offshore extent of the plume was maximized by eastward winds (Walker, N. D. 1994).

During May 1993, an amazing amount of day-to-day variability in plume areas was observed which appeared to be related to wind speed. A 1826 km^2 plume on 30 May was followed by a 4822 km^2 plume the following day. The only obvious change in the environment was a decrease in wind speed suggesting a positive relationship between wind speed and plume area, particularly when winds were southward or eastward. The relationship between environmental forcing factors and plume morphology may change throughout the year.

No data on strength of stratification is readily available. But, stratification of the water column, which increases in spring and is maximized in summer (with increased solar radiation input) may have an important influence on plume dynamics (Walker, N. D. 1994). The stark contrast between the blue water of the ocean and the turbid waters of the Neuse River, a river rising in the piedmont of North Carolina and emptying into Pamlico Sound below New Bern, is shown in Figure 30.

Figure 30. Neuse River After Hurricane Floyd (National Aeronautics and Space Administration 2004)

The 1850 Federal Swampland Act sanctioned the drainage of thousands of acres of swamp land and exchanged swamp for some of the most fertile cropland in the world. In the Mississippi River Drainage Basin vast forest clearing, swamp land drainage and agricultural restoration projects were implemented. Drainage was accomplished by burying drainage pipe (tiles) in some 10 million acres, about 35% of the total agricultural area in Illinois significantly affecting the hydrology and water quality of Illinois watersheds. Improved drainage correlates to elevated nutrient transport from agriculture land. Improved drainage of a swamp or a river

decreases the amount of time a theoretical drop takes to move from the top of the drainage area to the bottom (Pimentel, D. 1982).

The rate of water erosion on agricultural soils and the efficiency of appropriate response practices are commonly evaluated with the Universal Soil Loss Equation (USLE) devised by Wischmeier and Smith (1978) and the Revised Universal Soil Loss Equation (RUSLE), proposed by Renard (1997) (Janecek, M. *et al.* 2006). Both empirical models, USLE and RUSLE, are based on the principle of tolerable soil loss per standard plot. The measurements of standard elementary runoff parcels (plots) are 22 m in length and of 9% gradient; the surface of these parcels is kept without vegetation and is mechanically cultivated up or down the slope gradient after each storm. Tolerable soil loss is defined as the maximum soil loss by erosion that permits to maintain a sufficient and sustainable level of soil productivity at acceptable costs. Soil loss is calculated from the equation:

$$G = R \times K \times L \times S \times C \times P \text{ (t/area (acre or ha)/year).}$$

Equation variables are defined as:

G — Average annual soil loss. Units are international (t/area (acre or ha)/year)

R — Rainfall erosivity factor

K — Soil erodibility factor

L — Slope length factor

S — Slope steepness factor

C — Factor of the conservation effect of canopy cover

P — Support practice factor

The USA erosivity factor R was derived from a large quantity of precipitation data. Keeping the factors other than rainfall constant, the soil loss from a cultivated field during a rain event is directly proportional to the product of total kinetic energy of rainfall (E) and the rain events peak 30-minute intensity (I_{30}) represented by the following equation:

$$R = E \times I_{30}/100$$

The equations variables are defined as:

R — Rainfall erosivity factor (MJ/ha.cm/h)

I_{30} — Peak 30-minute intensity of rainfall (cm/h)

E — Total kinetic energy of rainfall (J/m²)

$$E = \sum_{i=1}^{n} E_i$$

E_i — Kinetic energy of the i-th segment of rainfall

n — Number of rainfall segments

$$E_i = (206 + 87 \log I_{si}) \times His$$

I_{si} — Intensity of the i-th segment of rainfall (cm/h)

H_{si} — Rainfall amount in the i-th segment (cm).

The increase in runoff is attributable to saturated soils, increased rainfall intensity or land use changes which decrease the absorbability of water into the soil. The Uniform Soil Loss Equation assists farmers in the consideration of the factors influencing erosion and controlling erosion within acceptable limits. The USLE equation also gives insight into the effect of changes in land use. Land use changes from swamp land to agriculture to drained agriculture often decrease the amount of time a given volume of water will enter a channel or a drainage area in a given time (Janecek, M. *et al.* 2006). Greater precipitation or decrease in the time water takes to drain also known as "peak discharge" from a watershed can cause the channel to

overflow (Randolph, J. 2004) as modeled in 31. The location of collection points for the Rowe model are shown in Figure 31 (Rowe, G. T. 2001).

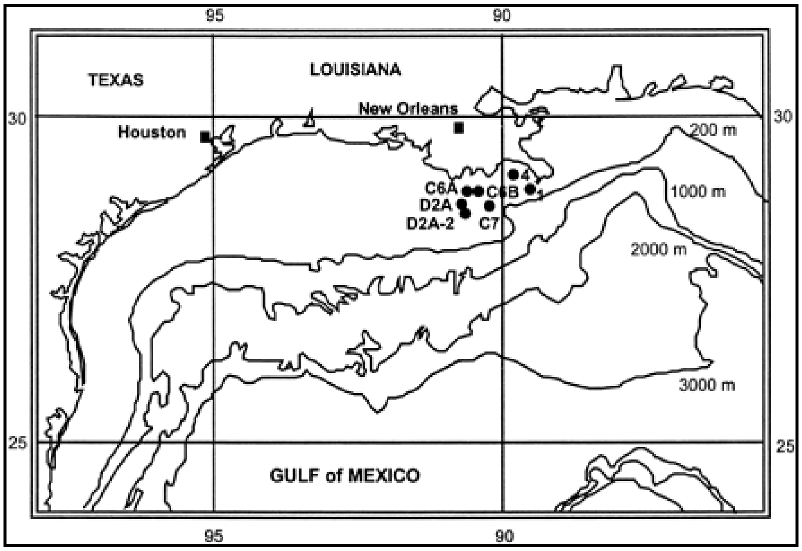


Figure 31. Data Stations in the Hypoxic Zone

Water column stratification (fresh water over denser more salty water) is essential for hypoxia to occur (Rabalais, N. N. 1999). The Rowe model does not consider complex mechanisms known as Ekman spirals which rely on the coriolis effect, which is due to the rotation of the Earth and the flow of water due to wind forces and friction (Hodne 2009) as shown in Figure 32.

The general circulation in all oceans is anticyclonic, i.e., clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere (Hodne 2009). The effect of wind and coriolis force produce an upwelling or a down welling of nutrients as shown by Figure 33.

The ecological forces acting on water include heat from solar insolation which creates temperature differentials and the winds which cause mixing and create Ekman spirals. Ekman spirals rely on the stratification of water created by friction as shown in Figure 34.

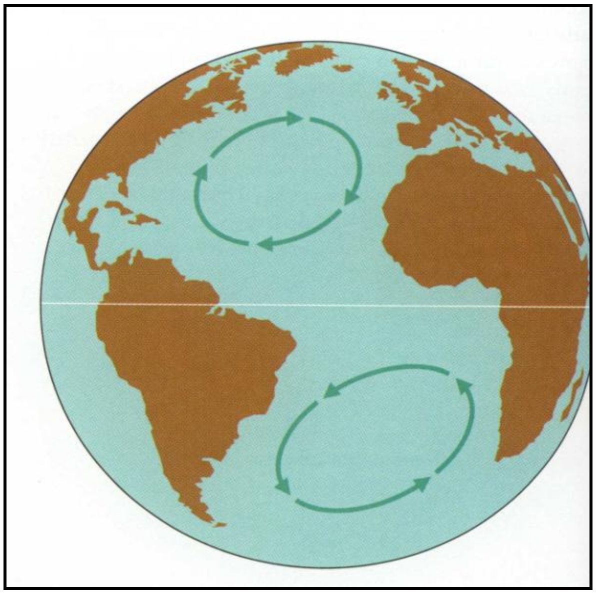


Figure 32. Coriolis Effect (Hodne 2009)

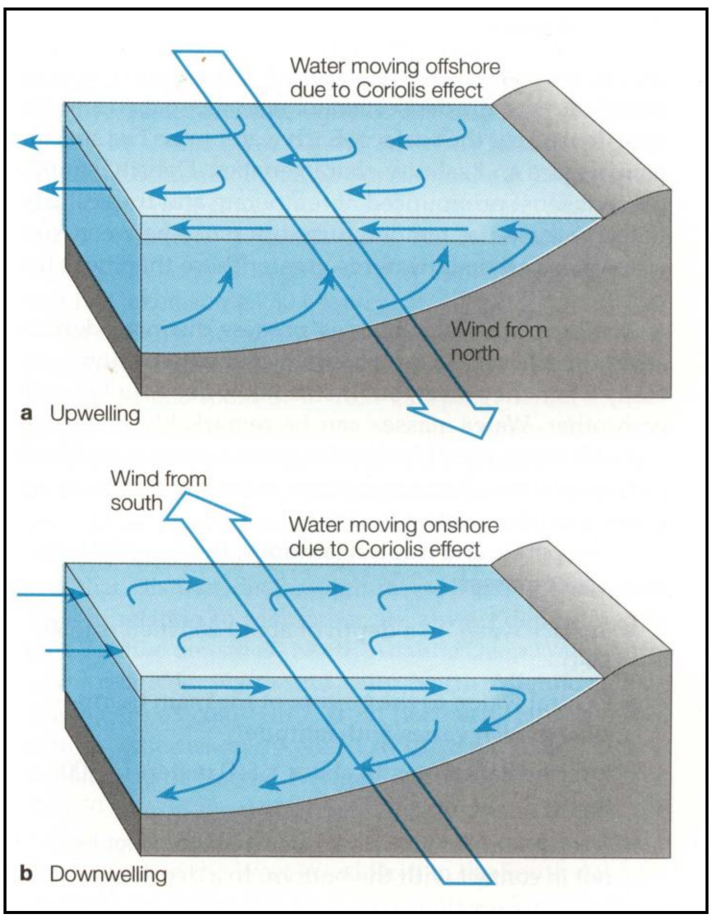


Figure 33. Up And Down Welling (Hodne 2009)

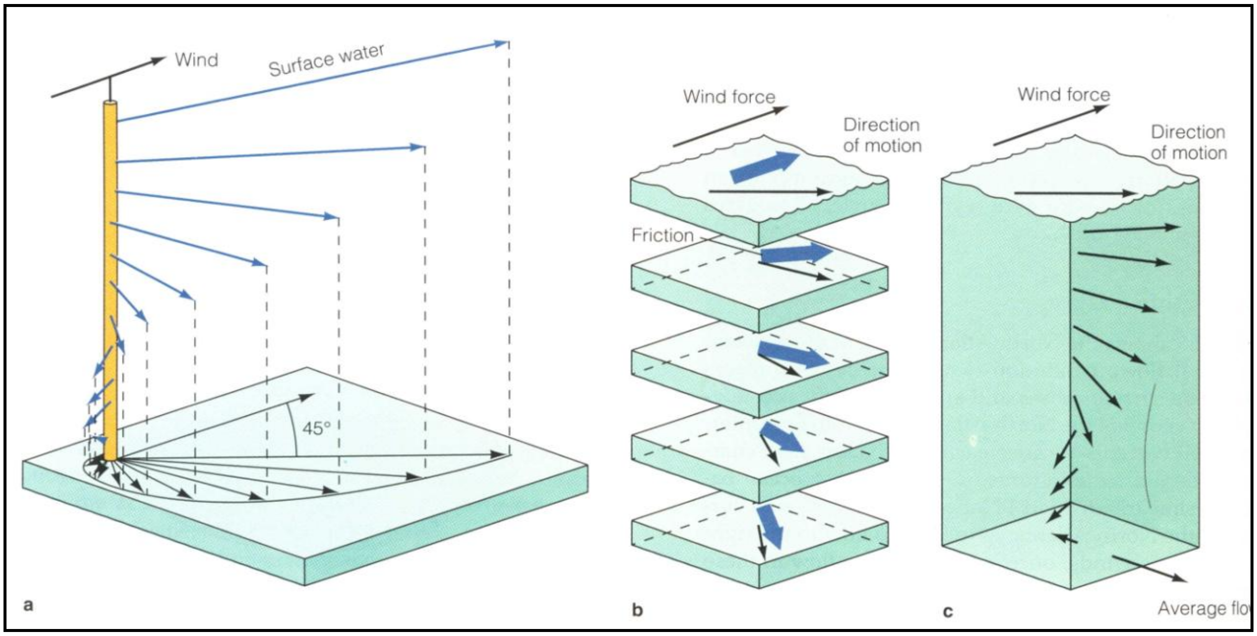


Figure **34**. Ekman Spirals **(Hodne 2009)**

The complexity of mixing, stratification of fresh water over more dense salt water, river plume from the Mississippi River (Wiseman, W. J. and R. W. Garvine 1995) (Figure 35), wind currents and Ekman spirals do not lend to simple modeling.

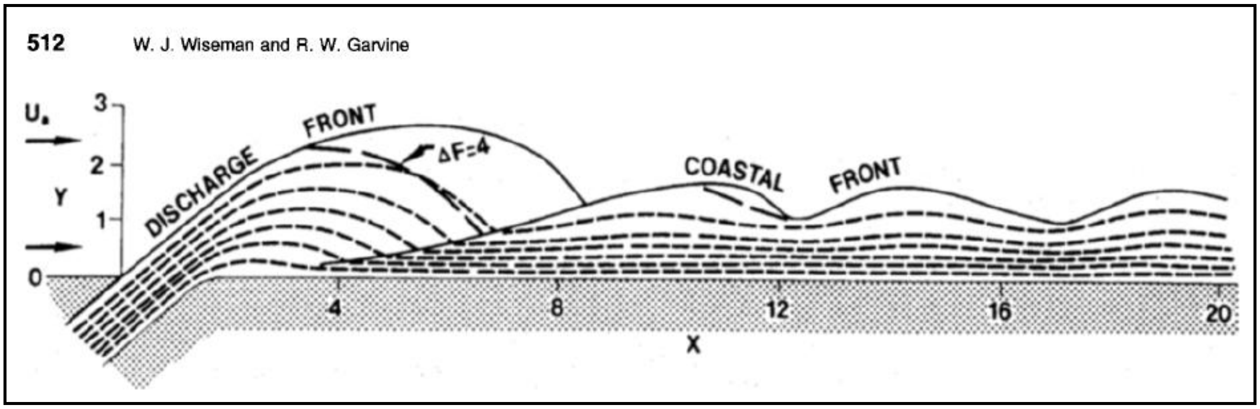


Figure 35. River Plume Discharge (Wiseman, W. J. and R. W. Garvine 1995)

The world ocean currents play a significant part in creating currents in the Gulf of Mexico as shown by Figure 36. Ocean currents, winds, tides, river plumes, the Coriolis effect and other factors create loop and eddy currents in the Gulf of Mexico as shown by Figure 37.

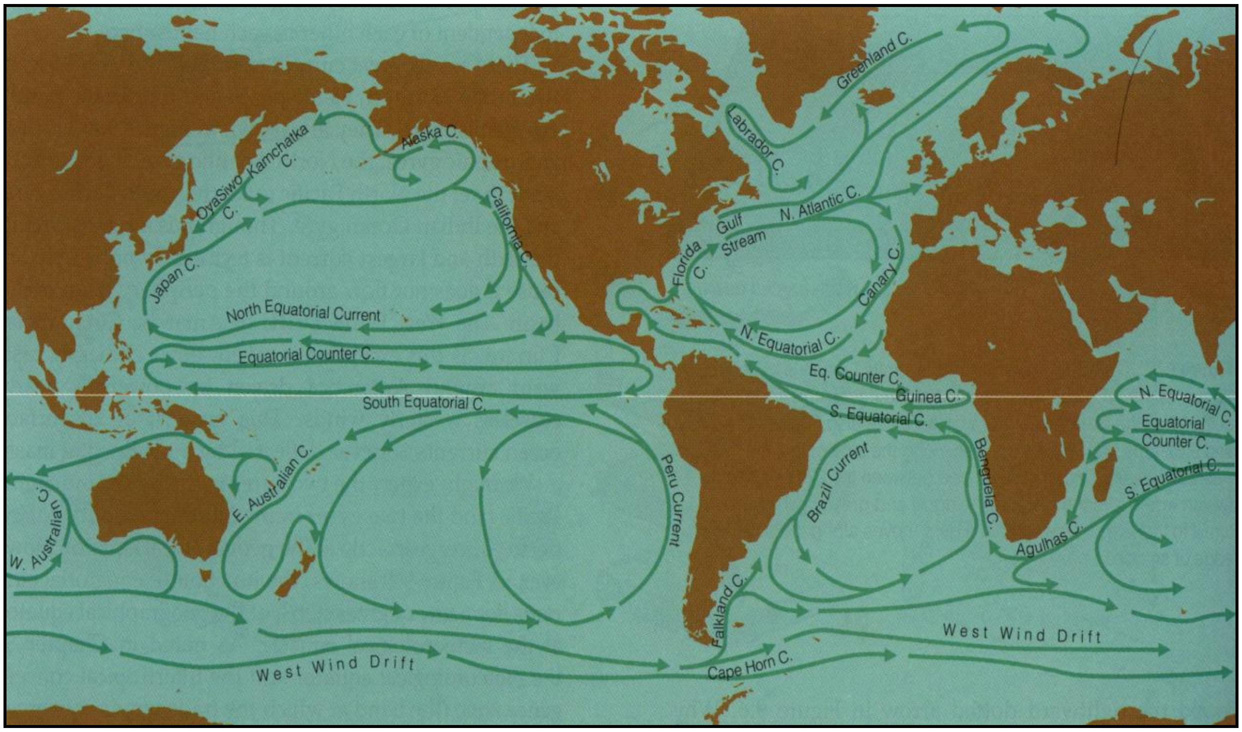


Figure 36. Ocean Currents (Hodne 2009)

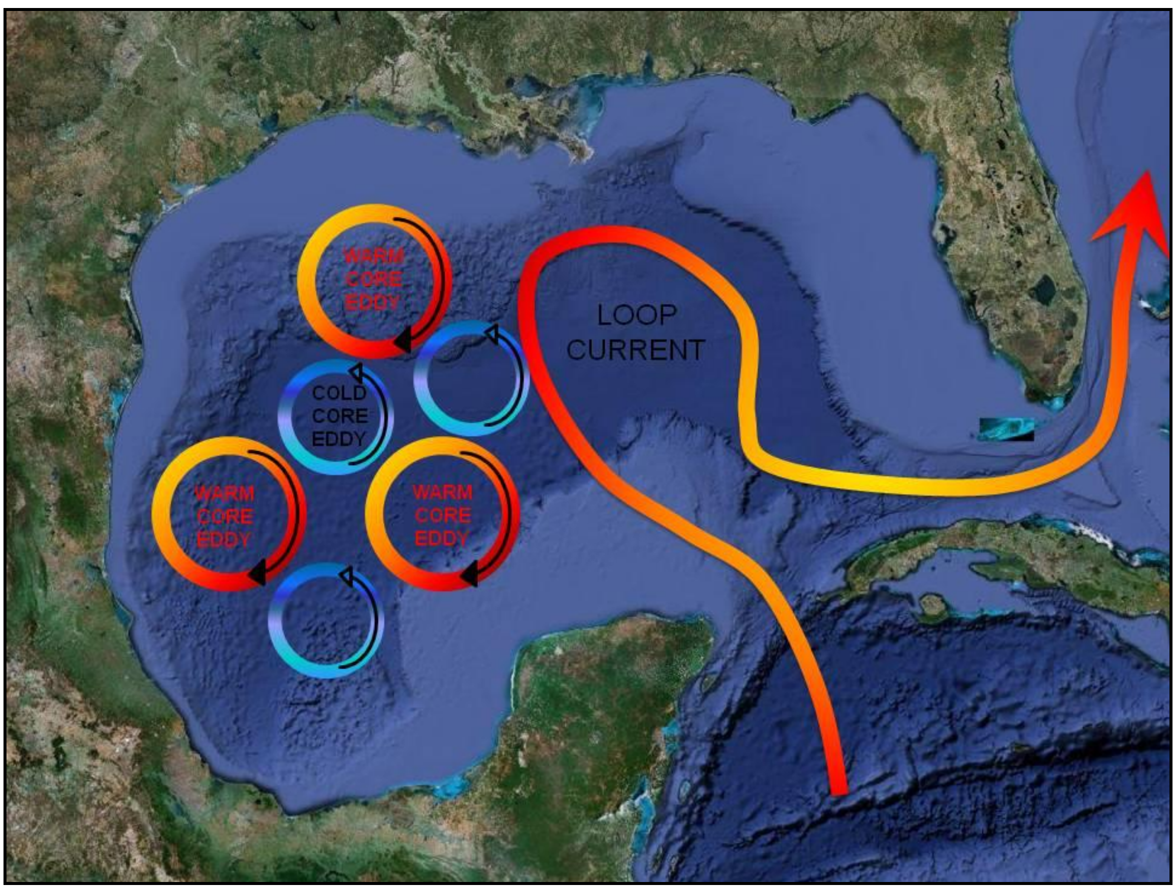


Figure 37. Loop Currents (Hodne 2009)

The coral reefs in the Gulf of Mexico are critical habitat for many species and are included for reference to the destructive fishing practices considered later in this discussion. The location of the reefs is interesting. The most interesting concept is to search for zones where trawling, fishing or other destructive activities to habitat are conducted which could be used as a control zone. The Flower Garden Banks is an example of an area which could be used as a control zone for comparison. These zones could be used as control zones to establish habitat and water quality comparisons (Hodne 2009) as shown by Figure 38.

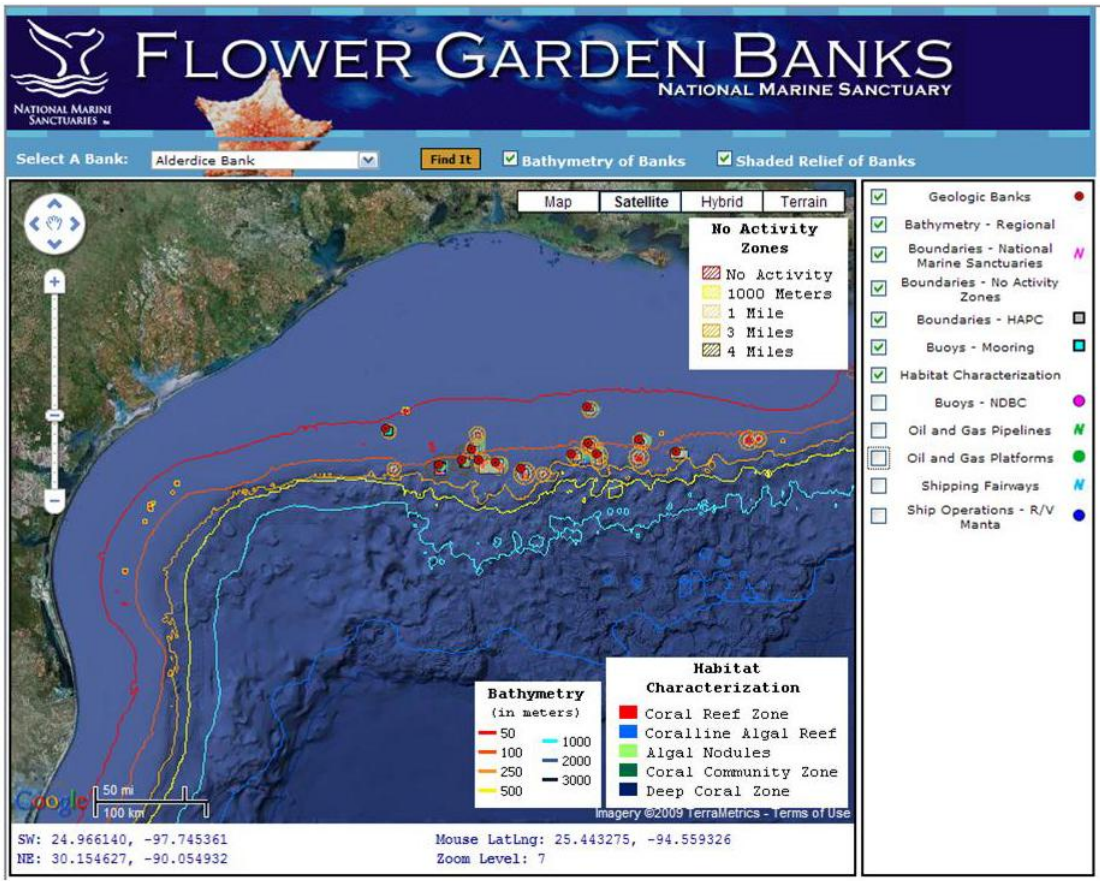


Figure 38. Coral Reef Maps Northwestern Gulf Of Mexico (Hodne 2009)

Turbidity affects the elements of the Rowe model and erosion is a major factor in sediment in the rivers and coastal waters of the Gulf of Mexico (Rowe, G. T. *et al.* 1995). Without erosion, the Mississippi River would not be known as “The Big Muddy”.

2.42 Erosion

Turbidity is caused by suspended particles of soil, detritus and plankton blooms. Turbidity is greatest near the mouth of the river and in the plume, and this diminishes potential photosynthesis (Zucker, L. A. and L. C. Brown 1998). Erosion of soil and the increase in turbidity was studied in experiments where forests were denuded from the landscape and controlled measurements made as described below.

2.43 Hubbard Brook Experimental Forest

The Hubbard Brook Experimental Forest in the White Mountains of New Hampshire has been studied since 1963. The results provide important insight into anthropogenic mechanisms affecting ecological processes. Hubbard is a nearly mature deciduous forest with several valleys, each drained by a small creek that is a tributary of Hubbard Brook. Hubbard is a long-term study of nutrient cycling in a forest ecosystem under both natural conditions and after vegetation is re moved. Bedrock impenetrable to water is close to the sun face of the soil, and each valley constitutes a watershed; that can drain only through its creek (Campbell, N. A. 1996).

Mineral budgets were determined for each of six valleys by measuring the inflow and out flow of several key nutrients. About 60% of the water added; to the ecosystem as rainfall and snow exits through the stream, and the remaining 40% is lost by transpiration; from plants and evaporation from the soil. Internal cycling within a mature terrestrial ecosystem conserves most of the mineral nutrients. Minerals were recycled within the forest ecosystem and inflow and outflow of minerals were statistically small compared to the amount of minerals recycled. The forest registered small net gains of a few mineral nutrients, including nitrogenous ones.

The effect of deforestation on nutrient cycling was determined experimentally in 1966. One 15.6 hectare valley was sprayed with herbicides for 3 years to prevent regeneration and all

original plant material was left to decompose. A control watershed was monitored for three years comparing inflow and outflow water and minerals in the experimentally altered water shed to the control for 3 years (Campbell, N. A. 1996).

Water runoff from the valley increased 30% to 40% after deforestation with huge losses of minerals from the deforested watershed. The concentration of Ca^{2+} in the creek increased fourfold, for example, and the concentration of K^{+} increased by a factor of 15. The concentration of nitrate in runoff from the deforested watershed was sixty times greater than in a control watershed. Nitrate was drained from the ecosystem and in the creek reached a level considered unsafe for drinking water. The amount of nutrients leaving an intact forest ecosystem is controlled by the plants in the ecosystem. These effects occur within a few months of de-forestation and continue in the absence of plants. The loss of nitrate from a deforested watershed in the Hubbard Brook Experimental Forest demonstrates sharp increases in losses of nitrogen after deforestation as shown by Figure 39 (Campbell, N. A. 1996).

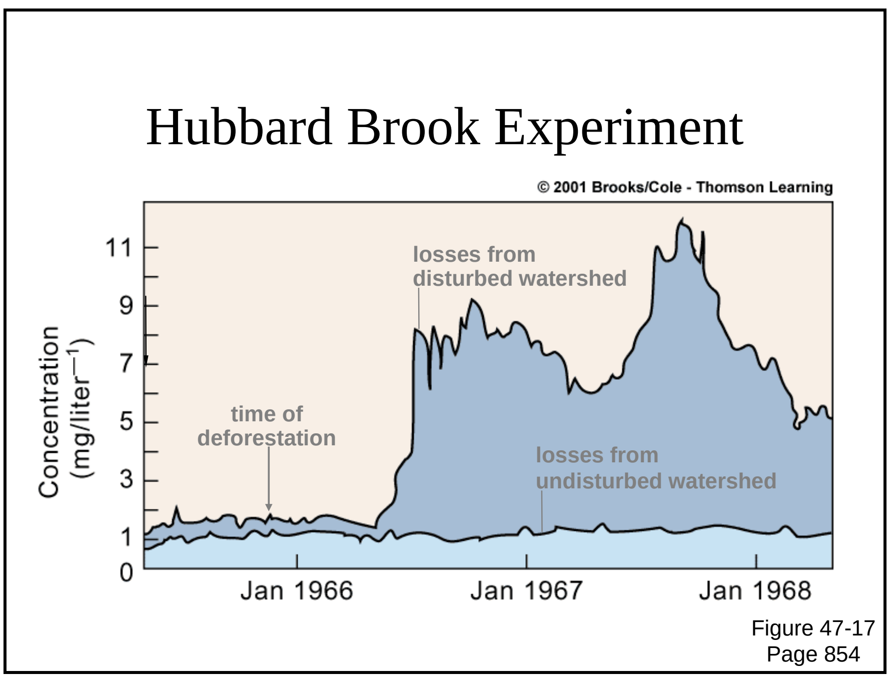


Figure 39. Hubbard Erosion Experiment (Campbell, N. A. 1996)

It is no longer possible to understand any cycle without taking human effects into account. Clear cutting forests to provide fertile land for agriculture was common practice. No fertilizer was need for a “free” period. The "free" period for crop production when there is no need to add nutrients to the soil vary greatly (Mississippi State University Extension Service 2010). When first tilled the North American prairie lands produced good crops for many years from the large store of organic materials in the soil which continued to decompose and provide nutrients. By contrast, some cleared land in the tropics can be farmed for only one or two years because so few of the ecosystems' nutrients are contained in the soil. Wetlands sequester nitrogen in their plant biomass and aquatic systems are usually low in nitrogen unless nitrogen is introduced from an outside source. Eventually, in any area under intensive agriculture the natural store of nutrients becomes exhausted, and industrially synthesized fertilizers must be added at considerable expense in terms of both money and energy (Campbell, N. A. 1996).

2.44 Carbon Dioxide

Since it is no longer possible to understand any cycle without taking human effects into account, what impact have humans had on atmospheric carbon dioxide concentration? Before 1850 the average carbon dioxide concentration in the atmosphere was about 274 parts per million (ppm). Scientist Charles Keeling measured carbon dioxide concentrations in the atmosphere at the South Pole and at Mauna Loa, Hawaii in 1958. The CO_2 concentration was 315 ppm in 1958. Today, the concentration of CO_2 in the atmosphere exceeds 357 ppm. If CO_2 emissions; continue to increase at the present rate, by the year 2075 the atmospheric concentration of this gas will double. Figure 40 displays historical temperature and carbon dioxide data. Concentration increase of carbon dioxide has been credited with the increasing temperatures associated with the phenomenon known as global warming.

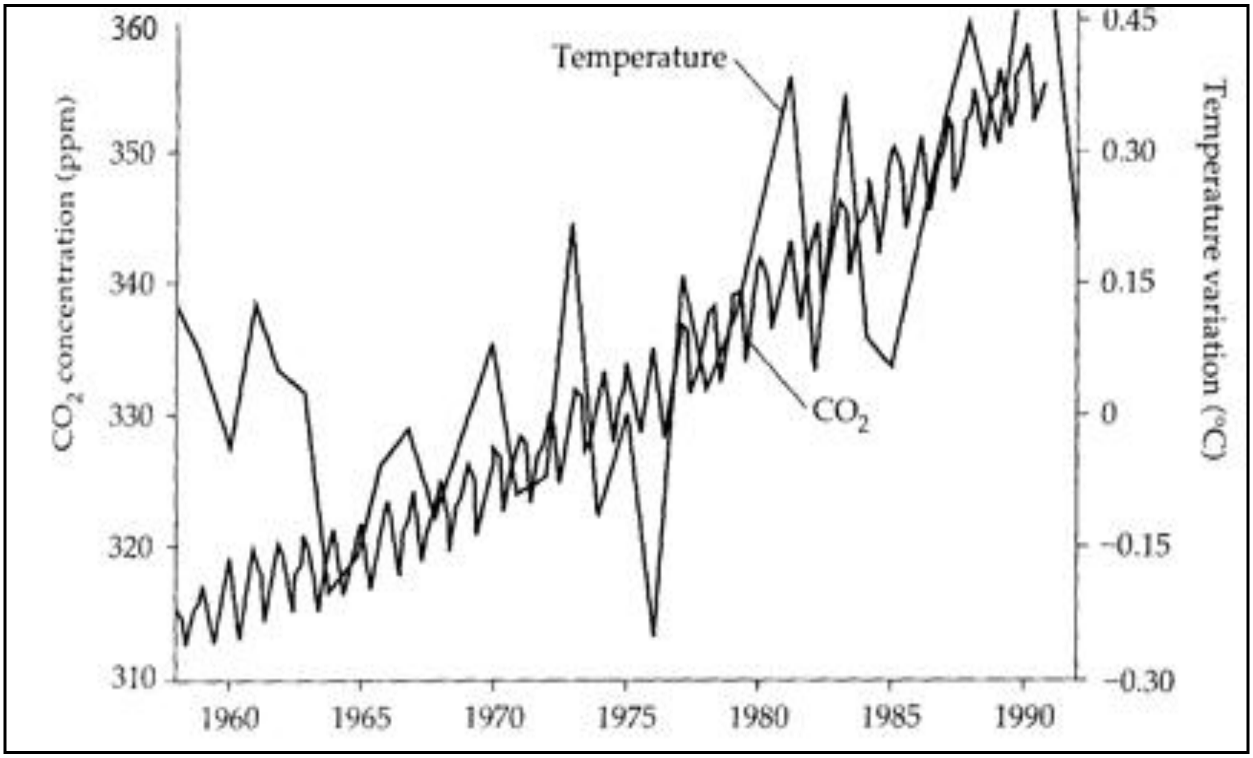


Figure 40. Atmospheric Carbon Dioxide Concentration (Campbell, N. A. 1996)

When CO_2 concentrations increase most plant growth increases. Plants utilize CO_2 with different efficiency and some (C_3) plants are more limited than other (C_4) plants by CO_2 availability, one effect of increasing CO_2 concentrations may be the spread of C_3 species into terrestrial habitats previously favoring C_4 plants. Corn, a C_4 plant and the most important grain crop in the United States, may be replaced on farms by wheat and soybeans, C_3 crops that out produce corn in a CO_2-enriched environment (Campbell, N. A. 1996). This could serve to limit the need for fertilizer and reduce CO_2 emissions. As the change from wetlands to farmland has radically changed the Mississippi River Basin, the ecology of the Gulf of Mexico has also been radically changed by destructive fishing practices. Both changes affect the utilization and sequestration of nitrogen and phosphorus as discussed in the following section.

2.45 Destructive Trawling

Figure 41 is a satellite image of trails caused by ships dragging trawls in the Gulf of Mexico. Trawling for any species is a non selective method of harvesting. Prawn trawling occurs throughout the world's oceans with a total catch of approximately 2.9 million tonnes per year for 3.5% of the total harvest from the marine ecology (82.5 million tonnes). In 1994 bycatch was estimated at 11.2 million tonnes worldwide (Broadhurst, M. K. 2000). Bycatch is discarded overboard; to be cycled as detritus (Diamond, S. L. 2004). "Bottom trawling is the most destructive of any actions that humans conduct in the ocean," said zoologist Les Watling of the University of Hawaii. "Ten years ago, Elliott Norse [of the Marine Conservation Biology Institute] and I calculated that, each year, worldwide, bottom trawlers drag an area equivalent to [an area of] twice the lower 48 states."

Figure 41. Destructive Deep Sea Bottom Trawling (Thompson, A. 2008)

As nets are dragged across the seafloor, they crush coral reefs, drag boulders across the bottom, and trap fish and animals not intended to be caught, called by catch. Stopping destructive trawling would curtail the sediments stirred from the seafloor, the crushing of coral reefs, the destruction of habitat by dragging boulders across the bottom. It is expected that the decrease in destructive trawling would increase deep water photosynthesis [and] bottom photosynthesis since there would be more plants on the bottom, increased predator activity of algae and possibly the increase of mixing due to a lack of stratification (Lsordo, T. M. and R. H. Piedrahita 1990). Stratification is caused by a temperature difference and temperatures and sunlight penetration are more uniform when the bottom surface is rich with plant and sea life (Thompson, A. 2008).

There is no consensus on which fish stocks may be heavily exploited, over-exploited or depleted, but there is consensus that habitat changes due to fishing and human activities have damaged the ecosystem and the structure and function of entire ecosystems has been affected (Castilla, O. D. J. C. 2005). Would stopping the habitat destruction or artificially enhancing habitat reverse the destruction? Many states have instituted artificial reef programs.

2.46 Artificial Reefs

Artificial reefs have been used for centuries to restore and expand marine and estuarine habitat. Florida, Mississippi, Louisiana and Texas have oil rigs to reefs programs which expand underwater habitat (Kaiser, M. J. and A. G. Pulsipher 2005). The state of Alabama is using artificial reefs to restore red snapper stocks (Shipp, R. L. and S. A. Bortone 2009). Natural oyster reefs impacted or destroyed by fishing and dredging activities have been repaired or replaced with natural shell material. Successful efforts to suppress wave energy and protect near shore environments with reef structures have reduced erosion and promoted beach growth. Coral

reef communities impacted by ship groundings have been restored with concrete modules or limestone boulders. Deep water restoration of coral habitat impacted by fishing activities off the central eastern Florida coast utilizing Reef Balls™ and small concrete discs has been attempted (Barnette, M. 2010). Restoration of habitat and estuaries reduce pressure on ecosystems. Many species of filter feeders have been exploited. Menhaden (algae predators) have been called the "liver of the sea" and the most important fish in the sea for their algae removal abilities by Bruce Franklin. The reduction of the numbers of menhaden are believed by Franklin to be one of the causes of the algae blooms and hypoxia in the Chesapeake Bay area and Franklin believes history is repeating itself in the Gulf of Mexico (Franklin, H. B. 2007).

2.47 Menhaden: "The Most Important Fish in the Sea"

In Franklin's (2007) book, he notes that dense schools of menhaden act like a submarine vacuum cleaner as wide as a city block and as deep as a train tunnel removing plankton, cellulose and detritus. Each adult fish filters about four gallons of water a minute. This action purges suspended particles, reduces turbidity and allows sunlight to penetrate. This increases bottom photosynthesis which then releases dissolved oxygen. The menhaden filtering prevents or limits devastating algal blooms and encourages the proliferation of other fish and shellfish, including oysters (which filter approximately 4 L of water an hour). These two filter feeders see the algae which "cause" the hypoxia zone (Rabalais, N. N. 2000) as a food source. Sara Gottlieb, author of a study on menhaden's filtering capability (which she compares to the human liver) states: "Over fishing menhaden," she says, "is just like removing your liver." (Franklin, H. B. 2007) What is not known is exact data on how much algae is in a set volume of water, the number of combined menhaden (and oysters) it would take to filter this water, the consumption requirements of menhaden fry and juvenile and the amount of time it would take to accomplish

the filtration. Without such data, modeling the phenomenon is difficult. The source of food for filter feeders is algae and phytoplankton. The rate of production for this food source depends on sunlight and available nutrients. Natural or anthropogenic nutrients must be transported from the Mississippi River Drainage Basin. Reduction of nutrients could be by filter feeders, preventing nutrients from entering the system (Rabalais, N. N. 2000), or by changing the delivery point. Mississippi River Diversion projects can certainly divert nutrients, but whether the diversion of sediment can restore the wetlands remains in question.

2.48 Mississippi River Diversion

One of the earlier works was by Mohamed Alawady who in 1974 described the beginning of the Mississippi River and the effect of early diversion projects (Alawady, M. 1974). The diversion of the Mississippi River would divert nitrogen laden water to potential farmlands which are now deserts. Since this is a potential transport problem, the reduction of stream flow could have the desired effect of algae bloom reduction and hypoxia reduction in the Gulf of Mexico. This hypothesis has no data. It is possible to divert water and nutrients. The feasibility diverting the Mississippi River will not be explored in depth in this work.

Sufficient sediment must be diverted to equal subsidence (approximately 0.25 centimeters to nearly 2 centimeters per year) plus sea level rise minus any natural wetland accretion for wetlands to maintain their present viability (Dean, R. G. 2006). Louisiana wetlands cover approximately 9,000 square miles, with an east-west dimension of 300 miles from the Mississippi state boundary on the east to the Sabine River at the Texas border on the west and a north-south dimension averaging 30 miles. The upstream construction of impoundments and agricultural practices to control erosion reduced the historic sediment delivery of the Mississippi River raising the question of whether the river now delivers enough sediment to stabilize or

increase the present wetland area. The Mississippi River has an annual mineral sediment delivery of approximately 100 million cubic meters. The proportions of mineral to organic sediment volume necessary to form wetlands vary from 1:10 to 1:4. To maintain elevation of the 9,000-square-mile area in the presence of an (assumed) average 0.25 centimeter per year relative sea level rise, the present rate of mineral sediment delivery is approximately 8 to 20 times the amount required if the sediment can be delivered to the needed areas (Dean, R. G. 2006). Energy costs increase as distance from the Mississippi River (primary source of sediment) increases making targeted delivery not economically feasible. The natural levees of the Mississippi River are the homes for many communities making it politically difficult and economically expensive to raise the general elevations of these areas leaving man-made levees as the only means of protection against flooding (Dean, R. G. 2006).

Diverting water and nutrients would be challenging, but diverting sediment would be even more challenging. Recovering or restoring isolated areas to sequester carbon and nutrients are projects worth considering. These efforts would serve to reduce the effect of codependent causes and should be considered important. The above water habitat contributes to the hypoxia in the Gulf of Mexico and the habitat in the Gulf of Mexico contributes as much if not more. Understanding the contributions of territorial and aquatic habitat would aid any management plan and are targeted for further study.

2.49 Multidisciplinary Program of Study

A multidisciplinary program supported by the U. S. National Oceanic and Atmospheric Administration's Nutrient Enhanced Coastal Ocean Productivity project (NECOP) along with regional university laboratories interested in eutrophication in the northern Gulf of Mexico (Turner, R. E. 1997). A concomitant investigation has been supported by the Minerals

Management Services of the U.S. Department of the Interior. Called LATEX, this study extended from 90°30' W longitude across the Texas shelf to the Mexican border. Both studies involved shipboard experiments and observations, long term moorings, remote sensing, and mathematical modeling (Rowe, G. T. 2001). This multidisciplinary approach attempted to incorporate as many ecological elements as possible paralleling the casual approach taken in this paper.

2.50 Summary of Literature Review

a. The foundation for any ecosystem is the producers which through the process of photosynthesis in the presence of sunlight build the base of trophic food pyramids and feed the consumers.
b. Natural systems achieve balance expressed with normal and inverted trophic pyramids.
c. Anthropogenic disturbances are a net output in an ecological system.
d. Nitrogen transport from the Mississippi River Drainage Basin, land use changes and increasing population are causes of point and non point pollution in ecology.
e. The legal system is adept at governing point source pollution and inept at governing non point pollution. This is unlikely to change.
f. There are two camps of thought on the causes of hypoxia in the Gulf of Mexico. The Western Camp (Texas) recognizes the arguments that the causes of hypoxia are stratification and river transport. The Western Camp believes hypoxia is disrupted by physical processes such as respiration and mixing. The Eastern Camp (Louisiana) postulates the cause of hypoxia is the transport of nitrogen which generates a biological algae bloom which on demise forms detritus which falls to the bottom and consumes oxygen until hypoxic conditions is generated.
g. Correlation is not causation.

h. Models have been created which show graphical outputs for dissolved oxygen based on elements of sediment oxygen content, respiration, mixing, solar energy and others. This information will be combined and reviewed.

CHAPTER 3: OBJECTIVES AND HYPOTHESIS

3.1 Objectives

a. Focus on the distinction between correlation of events and causation.

b. Review the postulate that hypoxia depends on the existence of stratification and the presence of detritus and is either driven by biological factors such as excess nutrients or physical conditions such as river plumes, mixing and wind currents by studying the various elements of the Mississippi River Basin, the transport system of the Mississippi River and the complex ecology of the Gulf of Mexico.

c. Prepare dynamic STELLA® models which graphically solve symbolic mathematical relationships to support or disprove the importance of biological or physical effects in the Gulf of Mexico.

d. Test the model fit to actual situations.

e. Make recommendations for future work.

3.2 Hypothesis

A dynamic STELLA® model or models could graphically simulate and harmonize the biological or physical real world causes and perturbations of the Gulf of Mexico hypoxia zone. The STELLA® models should be simple, standardized and repeatable showing that change in an ecological variable may correlate to; but not be the cause of hypoxia. Anthropogenic changes may cause or increase the effect of such ecological variables as erosion, nitrogen influx, decreasing wetlands and decreasing natural habit. An innovative modeling approach may suggest managerial solutions by modeling the biological and physical effects of ecological elements such as mixing, one time filter feeder harvest, reductions in destructive fishing

practices, restoring habitat and reductions in the available nitrogen. The objective is to use modeling as a tool to examine the effect of these ecological variables to guide potential managerial solutions to significantly diminish the size of the hypoxia zone.

CHAPTER 4. Materials and Methods

4.1 Stella® Tutorial Materials

STELLA® (Structural Thinking Experiential Learning Laboratory with Animation) is an icon-based mathematical model builder. The website for STELLA® is http://www.iseesystems.com. STELLA® graphically solves multiple partial differential equations and graphically displays the solutions over time. Permission listed in Appendix C was granted by iseesystems to use STELLA® tutorials and models.

STELLA® is based on symbols representing stocks and flows. A stock is an accumulation and a flow is a symbol representing transport from out to in or in to out of a reservoir. Stocks are represented by rectangles and flows by a symbol resembling a pipe with a cloud on one end, a value, and an arrow on the other as shown in Figure 42. Naming the flow in, stock, and flow out corresponds to an element of an equation and defines the relationship between these equation elements.

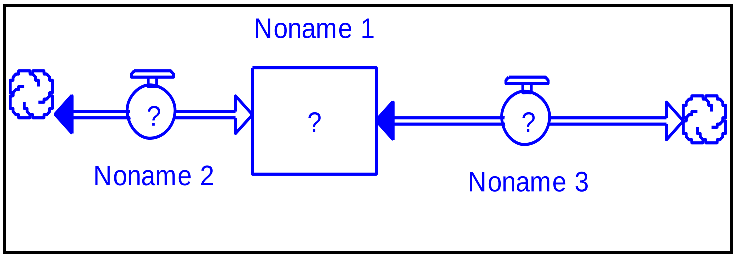


Figure 42. Stocks and Flows

In the next diagram the two elements will be named and a birth rate will be defined as well as a death rate. Since zero populations are incapable of breeding, some starting number will be given. For the purposes of this study modeling is a demonstration of change and the relationship of varying rates of change. Keeping stocks at low beginning points focuses on the rate of change. Births of 25, Deaths of 15 and a population of 25 will be used to illustrate STELLA® in Figure 43. STELLA® automatically produces a differential equation from defined

elements and provides graphs of results. The solution is a straight line as shown in Figure 44. Notice the equation is solved despite births and deaths being in the form of numbers rather than rates. STELLA® converts to the births/time and deaths/time for the solution (rates). STELLA® uses four types of stocks: reservoir, conveyor, queue and oven. Each type can be used to display a different relationship. The reservoir is an accumulation and the conveyor graphically represents a fixed delay. A stripped rectangle is the symbol for the conveyor. Not all elements of STELLA® will be utilized in this work.

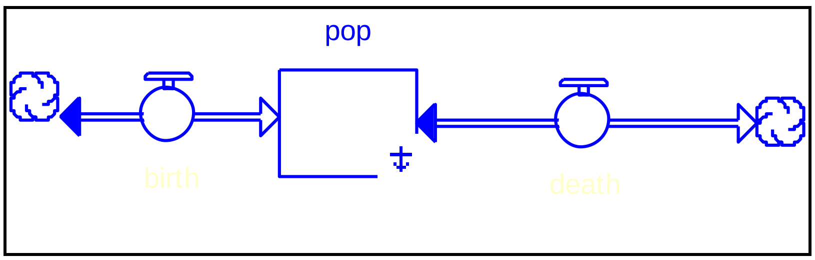


Figure 43. Population

The differential equations for the example presented in Figure 43 are listed:

pop (t) = pop (t - dt) + (birth - death) * dt

The elements are defined as:

p=pop=25

t=time

dt=change in time

b=births=25

d=deaths=15

The differential equation is presented here in a more recognized form.

$$p(t) = p(t - dt) + (b - d)dt$$

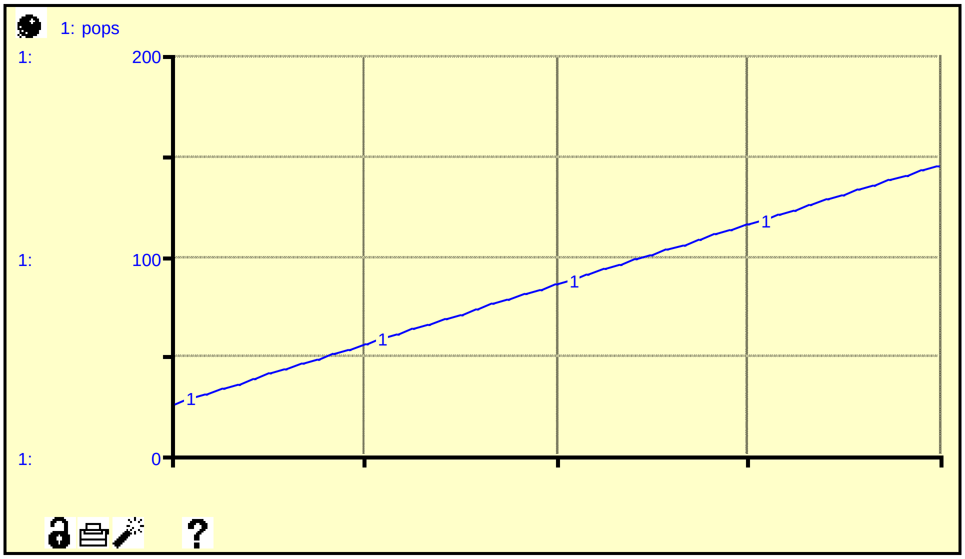


Figure 44. Simple Population Chart

To construct more complicated equations, more elements are needed and with STELLA® more stocks, flows and a new element called a connector is needed. A device which connects a population to a flow or a flow to another variable is called a connector. The use of a connector is demonstrated in Figure 45. The red lines with arrows are connectors.

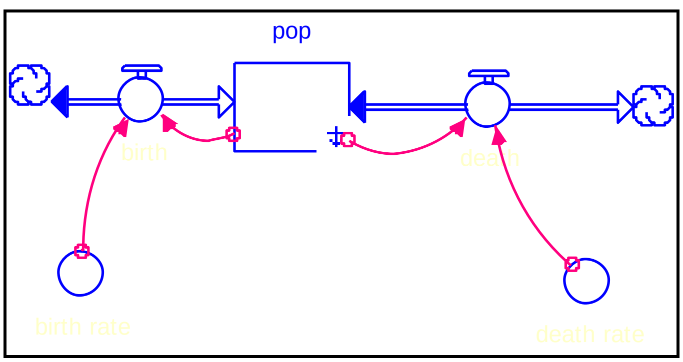


Figure 45. Modification of Flows

In STELLA® notation the following equations are generated. This presentation is reminiscent of early computer programming.

pop (t) = pop (t - dt) + (birth - death) * dt

INIT pop = 25

INFLOWS:

birth = pop* (1+birth_rate)

OUTFLOWS:

death = pop* (1-death_rate)

birth_rate = .25

death_rate = .15

Detailed definitions will not be used for the second example, but the differential equation in a more standard form would be:

$$p_s(t) = p_s(t-dt) + [(p_s(1+b_r)) - (p_s(1-d_r))]dt$$

and its results are shown in Figure 46.

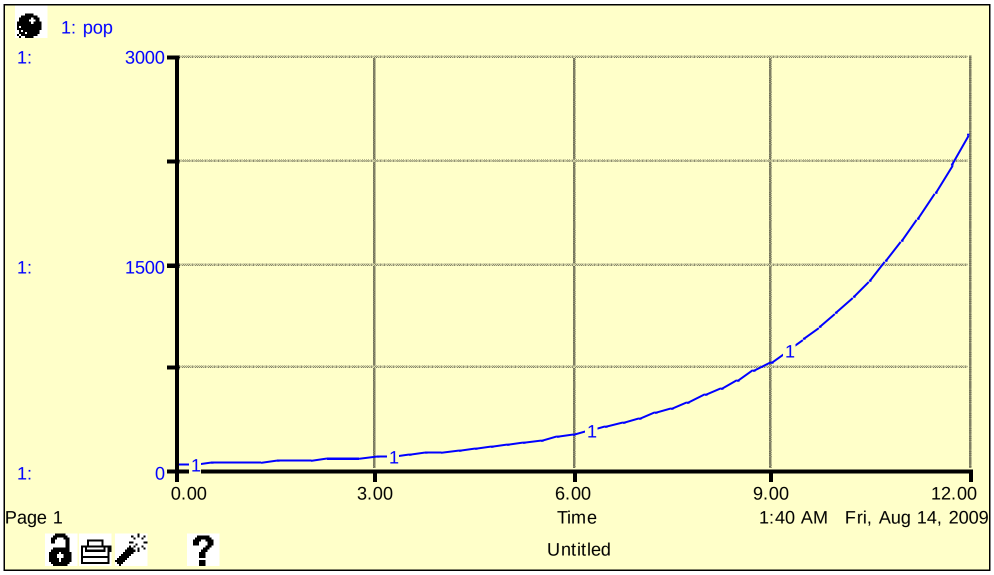


Figure 46. Modification Creates Curve

This graph demonstrates the solution of a single differential equation. Such solutions are useful in examining areas and population growth. Often solving more than one differential equation is necessary to define simple ecological relationships. Complexity is added by the addition of connectors to refine the relationships. Stocks can cumulate and flows can interact with each other. Comparison of the graphical solutions of two differential equations requires

linking the models of each with the applicable connectors. A more complicated result is realized as shown in Figure 47.

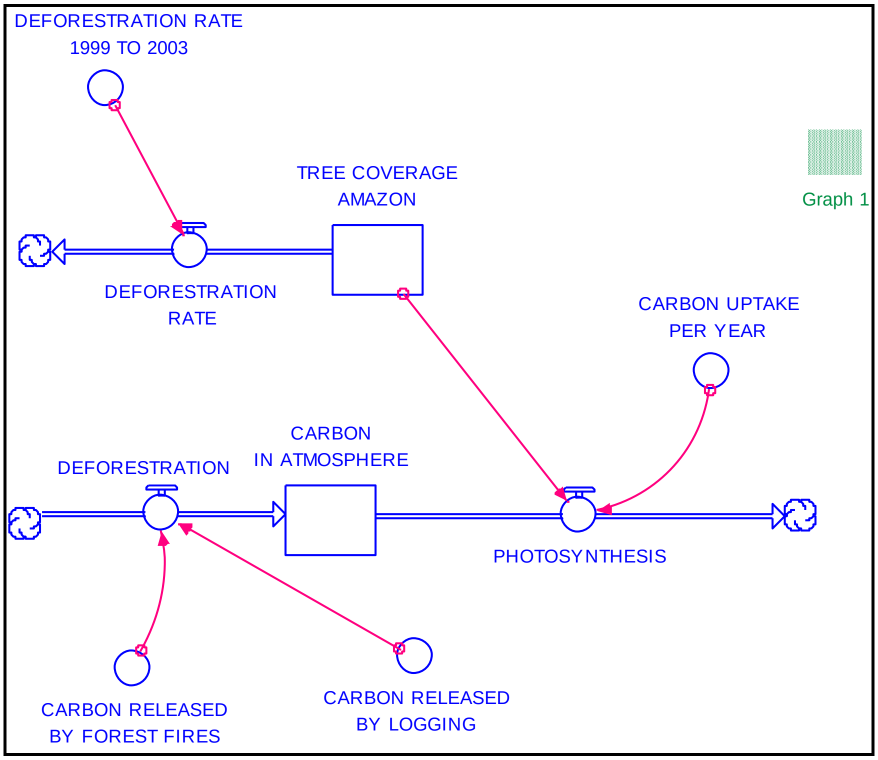


Figure 47. Deforestation

Again STELLA® automatically defines the differential equation system and solves it. In STELLA® language the following equations are generated.

CARBON_IN_ATMOSPHERE (t) = CARBON_IN_ATMOSPHERE (t - dt) + (DEFORESTATION - PHOTOSYNTHESIS) * dt

INIT CARBON_IN_ATMOSPHERE = 747

INFLOWS:

DEFORESTATION = CARBON_RELEASED_BY_FOREST_FIRES+CARBON_RELEASED_BY_LOGGING

OUTFLOWS:

PHOTOSYNTHESIS = CARBON_UPTAKE_PER_YEAR*TREE_COVERAGE_AMAZON

TREE_COVERAGE_AMAZON (t) = TREE_COVERAGE_AMAZON (t - dt) + (-DEFORESTATION_RATE) * dt

INIT TREE_COVERAGE_AMAZON = 4E8

OUTFLOWS:

DEFORESTATION_RATE = DEFORESTATION_RATE_1999_TO_2003

CARBON_RELEASED_BY_FOREST_FIRES = 6.885

CARBON_RELEASED_BY_LOGGING = .3

CARBON_UPTAKE_PER_YEAR = 4.125*10^-9

DEFORESTATION_RATE_1999_TO_2003 = 2013340

The STELLA® model of the carbon in the atmosphere is found in the STELLA® tutorials. This model is presented here for demonstration of the solution of multiple straight line differential equations. The solution for the two following equations is graphed in Figure 48.

$$C_A(t) = C_A(t-dt) + (D-F)dt$$

$$T_A(t) = T_A(t-dt) + (D-F)dt$$

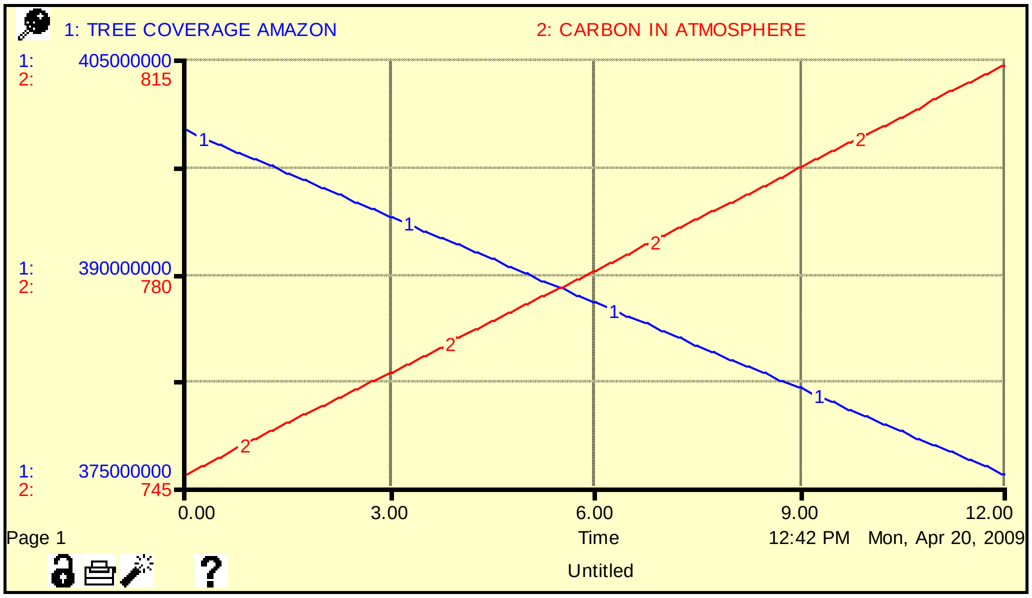


Figure 48. Relationship of Tree Cover to Carbon

This STELLA® model has not been verified or validated. A STELLA® model demonstrating predator-prey dynamics follows in Figure 47.

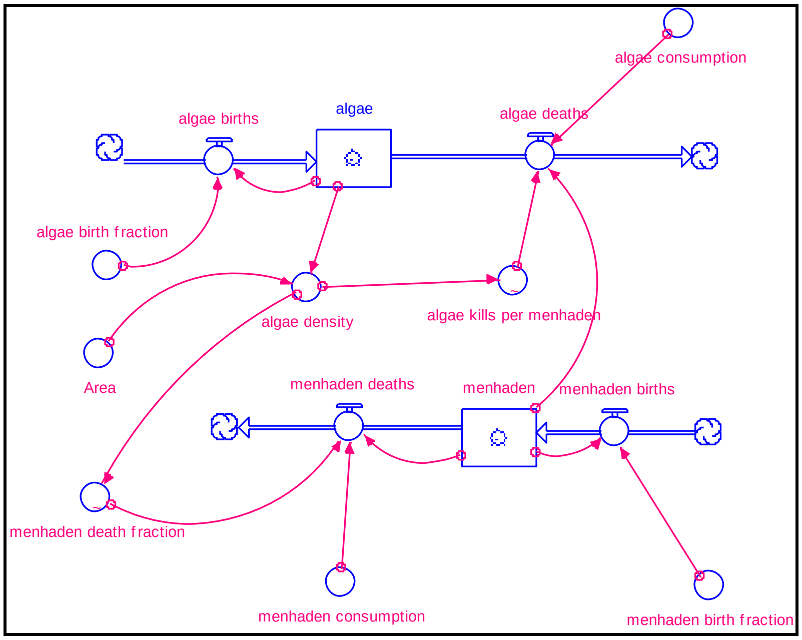


Figure 49. Predator Prey

The STELLA® modeling program automatically defines the differential equation system and solves it. In STELLA® language the following equations are generated.

algae (t) = algae (t - dt) + (algae_births - algae_deaths) * dt

INIT algae = 5E4

INFLOWS:

algae_births = algae*algae_birth_fraction

OUTFLOWS:

algae_deaths = (menhaden*algae_kills_per_menhaden)+pulse (algae_consumption, 5 ,1000000000)

menhaden (t) = menhaden (t - dt) + (menhaden_births - menhaden_deaths) * dt

INIT menhaden = 1250

INFLOWS:

menhaden_births = menhaden*menhaden_birth_fraction

OUTFLOWS:

menhaden_deaths = (menhaden*menhaden_death_fraction)+menhaden_consumption

algae_birth_fraction = 1.25

algae_consumption = 10000

algae_density = algae/Area

Area = 1000

menhaden_birth_fraction = .25

menhaden_consumption = 0

algae_kills_per_menhaden = GRAPH (algae_density)
(0.00, 0.00), (50.0, 50.0), (100, 100), (150, 150), (200, 200), (250, 250), (300, 300), (350, 350), (400, 400), (450, 450), (500, 500)

menhaden_death_fraction = GRAPH (algae_density)
(0.00, 0.5), (10.0, 0.45), (20.0, 0.4), (30.0, 0.35), (40.0, 0.3), (50.0, 0.25), (60.0, 0.2), (70.0, 0.15), (80.0, 0.1), (90.0, 0.05), (100, 0.005)

This model is presented for demonstration of the graphical solution of multiple differential equations with a more dynamic solution.

$$A(t) = A(t - \partial t) + (A_B - A_D)\partial t$$

$$M(t) = M(t - \partial t) + (M_B - M_D - M_H)\partial t$$

Graphical information can be introduced through a table or sketching a graph into the STELLA® program. Validation or certification should yield a model where predictions are closely tied to empirical observations. This model has not been verified or calibrated.

The algae and menhaden population functions are represented by the results shown in Figure 50. The rates of change of algae death and the menhaden death fraction are compared graphically in Figure 50. The graph shows the relationship between a predator and the prey upon

which it depends for food. With the combination of simple elements a dynamic graph has been created. Modifications in this relationship can be achieved by entering the equations layer of STELLA® and changing the algae consumed per menhaden to a larger number. This represents an increase in the efficiency of the predators. This increase in efficiency results are shown in Figure 51.

Predator-prey dynamics have been much discussed in the literature and it is essential that the dynamics of predator-prey are understood for ecological modeling. In the natural world, the food chain usually starts with plants which are eaten by herbivores which in turn are eaten by carnivores.

As plants prosper, herbivores prosper. As herbivores prosper, carnivores prosper. As carnivores prosper, herbivores decline. As herbivores decline, plants prosper. Verbally, this describes the cyclic relationship of the typical predator-prey system.

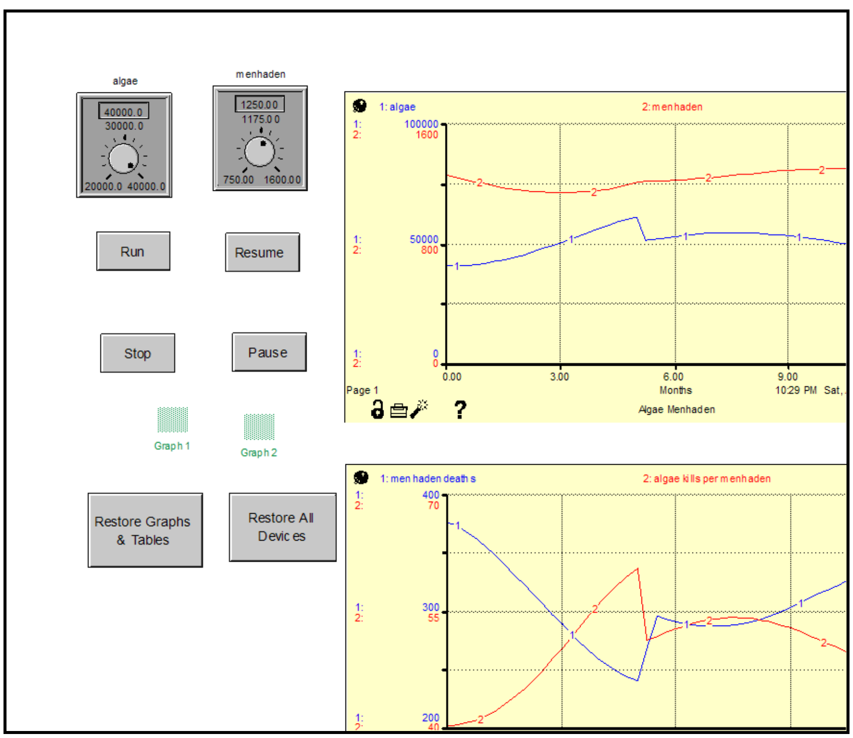


Figure 50. Predator prey dynamic graph

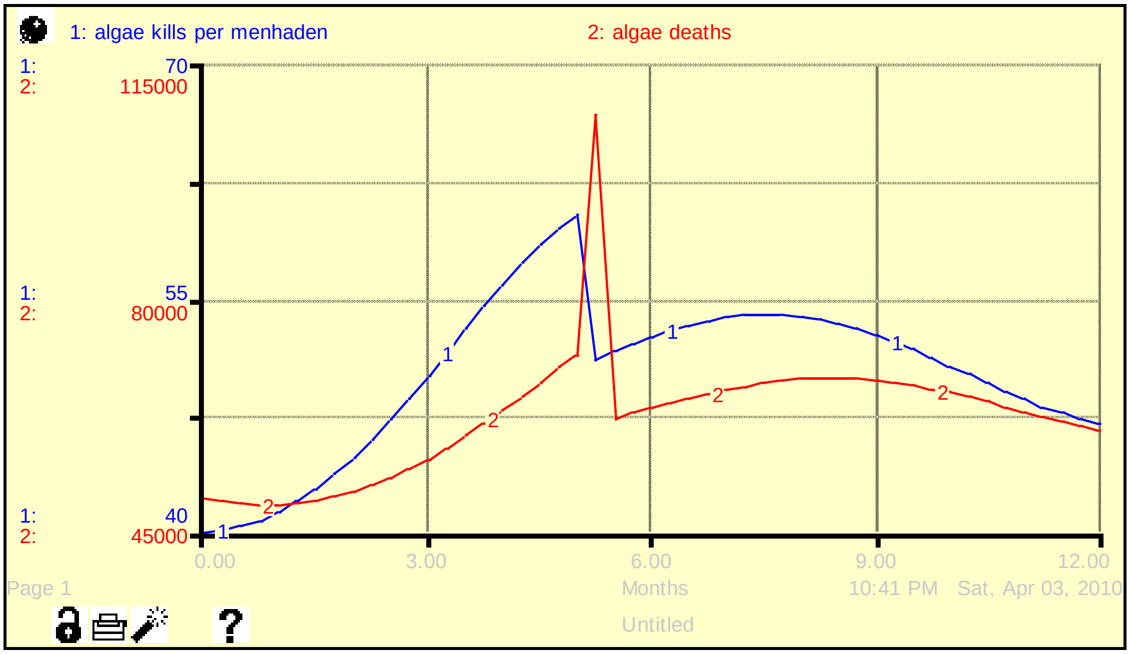


Figure 51. Efficient predator

There are many forms of the predator-prey equations contributed by many authors. The above predator-prey equations are descendants of the Lotka-Volterra equations (Bossel, H. 1994):

$$\frac{\partial x}{\partial t} = x(\alpha - \beta y) \qquad\qquad \frac{\partial y}{\partial t} = -y(\gamma - \delta x)$$

The study of ecosystems requires an understanding of energy harvest by producers (prey) and the transfer of energy by predation to the next tropic level.

4.1.1 Available Stella® Models

"A model is said to be verified if it behaves in the way the model builder wanted it to behave." (Jorgensen, S. E. and G. Bendoricchio 2001). The results of the first mathematical modeling efforts did not behave the way this model builder wanted them to behave. Being familiar with the Industrial Revolution the lack of standardization was readily apparent. The key idea of the American system of manufacturing or the use of standardized, interchangeable parts was developed by Eli Whitney in the United Stated in the late 1790s (Saleh, J. H. and K. Marais

2006). Modeling the complex ecological system from the Mississippi River Drainage Basin into the Mississippi River and into the Gulf of Mexico is a formidable a task. There should be some simpler method of modeling such a complex system. During the Literature Review many STELLA® models were examined. Each of these models was useful for examining one portion of the ecosystem and useless for examining the entire system. The mathematical model for the hypoxia system was begun and many of the parts for each of the smaller models were incorporated into the major model of the hypoxia system. The system model of the hypoxia zone in the Gulf of Mexico was complex. The thought came to mind that using models created by others in combination would be similar to the breakthrough that Eli Whitney achieved when he standardized parts of the musket making these parts interchangeable with any other musket. The inventor of the AK-47 rifle stated: "All that is complicated is worthless, all that is simple is useful" - Mikhail Kalashnikov. A simple and useful model became the objective.

4.1.2 Developing a Model

There are many methods of developing a model. A traditional method would be to develop differential equations around the system control volume (Tchobanoglous, G. and E. D. Schroeder 1987). However, unlike a continuous flow stirred tank reactor (CFSTR) the Gulf of Mexico is not a tank, nor is it continuously stirred, nor is the Gulf of Mexico subject to a continuous flow. The Gulf of Mexico is a semi enclosed basin open to the North Atlantic. Atlantic Ocean water enters the Gulf through the Yucatan Strait and exits through the Straits of Florida creating an influence known as a loop current. Upwelling and fresh water outflows from rivers feed into the Gulf of Mexico (Chao, Y. Y. and H. L. Tolman 2007).The size of the hypoxia zone in the Gulf of Mexico varies and the concentration of nitrogen and phosphorus vary (Rabalais, N. N. 2000). One can model living entities and ecosystems (Chameides, W. L. and E.

M. Perdue 1996). Since the (Carbon to Nitrogen to Phosphorus) C N P ratio is of critical importance, these materials can be incorporated into a model. The essential tenure of the discussion is the observation that discussions of the relationship between C N P are ongoing. The pictures of the ecological elements cycling in the Earth's system reveal that the picture of the cycle is related to the diagram of the model. By examining these essential elements, the observation that ecological cycles can be modeled and models can be combined was made.

4.1.3 The Carbon Cycle

Deforestation and the clear cut burning of forests places carbon into the atmosphere. The major culprit of carbon introduction is the burning of fossil fuels and this is reflected in the following model. The increasing carbon and the reduced ability of the ecosystems to sequester carbon is reflected in the atmospheric increase of carbon (Johnston, P. *et al.* 1999). Under these conditions carbon is not a limiting element. Carbon is critical in earth ecological systems and the cycle is presented in Figure 52.

From Figure 52, STELLA® was used to create a simple carbon cycle model possessing additive properties. From a measured atmospheric carbon of 730 gigatons, the model generates results of 740 gigatons as shown by Figure 53, the beginning of the certification process. The following is a combination of stocks and flows which depict in STELLA® symbols the pictorial representation of the carbon cycle. With this software, if you can depict the relationship with a photograph or envision the relationship mentally, the relationship can be modeled. This provided a tremendous advantage to the ecological modeler.

The graph of fossil fuels, atmospheric carbon, marine carbon, terrestrial carbon and organic carbon (expressed in gigatons) and their relationship over a twelve month period is displayed in Figure 54. As fossil fuels are burned, atmospheric carbon increases. As the marine

water system loads (line 3 of Figure 54) with carbon, the system saturates and carbon is then released into the atmosphere. These relationships in turn relate to other elements in ecology.

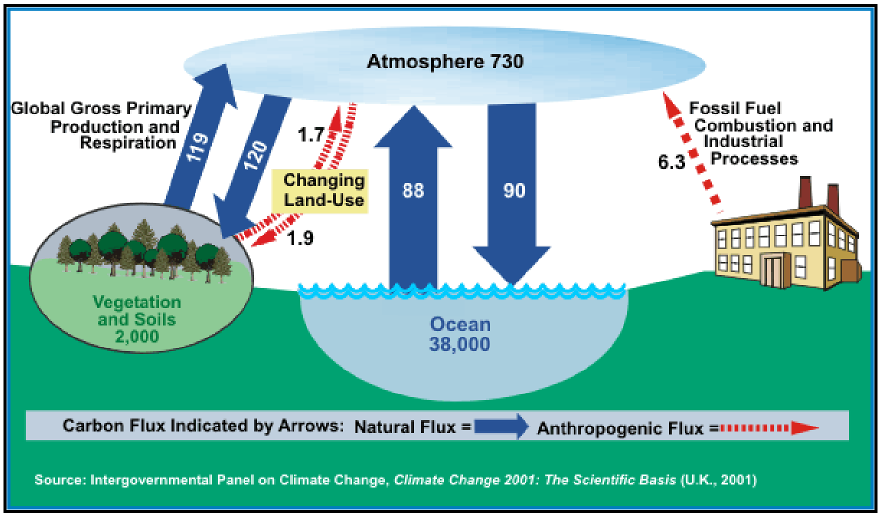


Figure 52. Carbon Cycle **(National Oceanic & Atmospheric Administration 2001)**

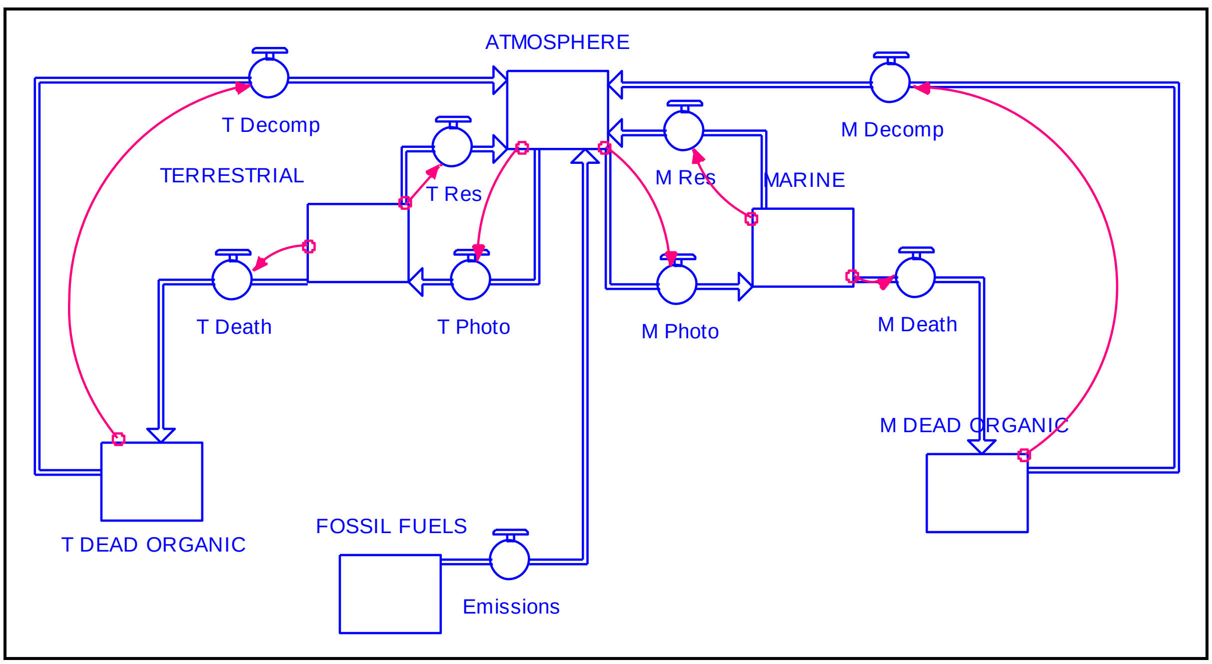


Figure 53. Carbon Cycle Model (iseesystems 2009)

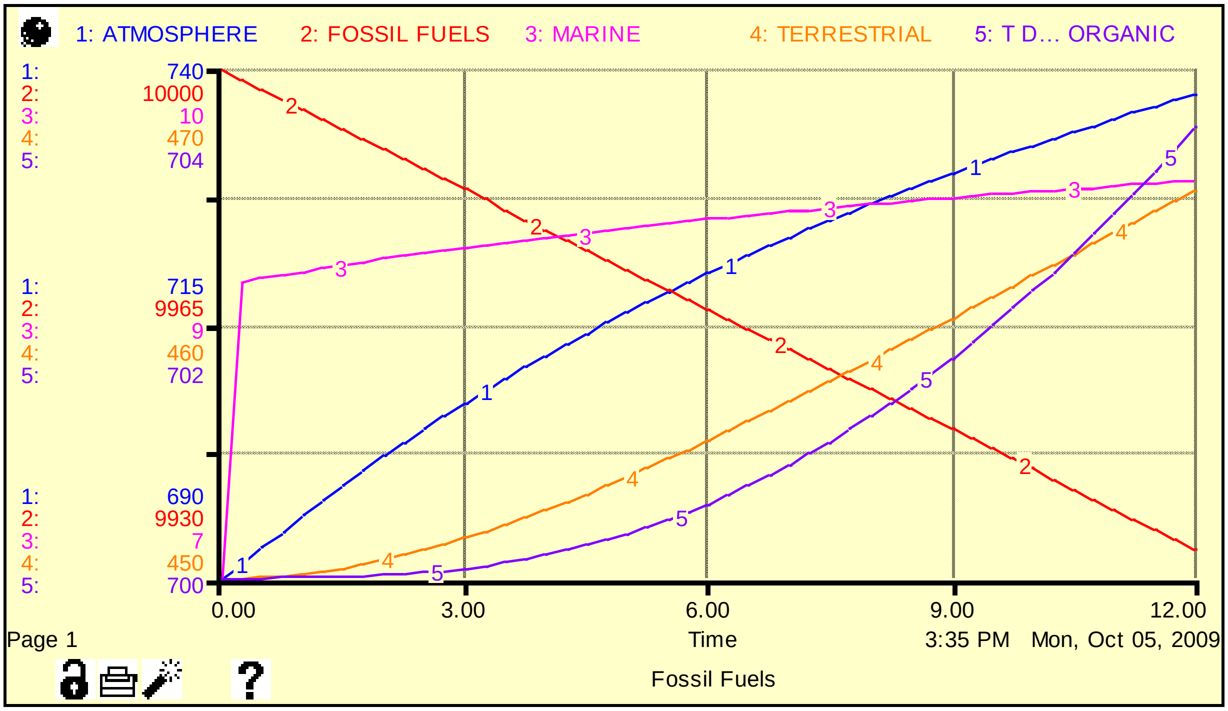


Figure 54. Graph Of Carbon (iseesystems 2009)

The atmospheric CO_2 values measured from Hawaii's Mauna Loa peak were displayed in Figure 40. The Mauna Loa data are being obtained at an altitude of 3400 m in the northern subtropics, and may not be the same as the globally averaged CO_2 concentration at the surface (National Oceanic & Atmospheric Administration 2010). If we examine the picture of the cycle and the model, it is observed that the atmospheric carbon is increasing. The Mauna Loa data reflects an increasing curve while the model displays a curve which is increasing but at a decreasing rate. This makes sense when you consider that the CO_2 is input into the atmosphere at a decreasing rate. Fossil fuels are limited and it would make sense that available supplies of fossil fuel would constantly decline. Marine sequestration of carbon would rise rapidly at first according to the graph and then increase at a lesser rate. These observations make sense and they can be modified as needed by changing equations and better data collection.

Tracing an imaginary drop of water which falls at the highest elevation of the Mississippi River Drainage Basin through an imaginary path through the basin into the Mississippi River and

on into the Gulf of Mexico gives some idea of the complex interrelationship of elements and energies in this ecological system. Adding the countless droplets which join this imaginary drop, the anthropogenic changes encountered on their path, the plants which depend on water for their growth, the minerals and nutrients absorbed on their way to the Gulf of Mexico and the countless species which exist in the Gulf of Mexico give full realization to the lack of homogeneity of the Gulf of Mexico. If we can show how essential elements are cycled, it will be easier to understand other ecological cycles. The second element in the C N P cycle is nitrogen; the accumulation of these imaginary drops and their path trace the cycle of nitrogen.

4.1.4 Nitrogen Cycle

Nitrogen is cycled through the ecosystem in organic and inorganic form. Not all forms of nitrogen are useful to plants. Man made fertilization is credited with the rise in the amount of nitrogen introduced into ecosystems. Nitrogen is usable as indicated in Figure 55 in the form of nitrate and ammonium. While absolutely essential for the production of crops to feed an ever-increasing population, the introduction of excess nitrogen is a cause for ecological concern. Nitrogen enhances the growth of crops and of algae. Ecological concern is created when algae growth reaches the point where detritus from algae blooms falls to the bottom to be consumed by bacteria consuming oxygen on the bottom below the level necessary to sustain marine life.

From the nitrogen cycle the STELLA® nitrogen model was generated. The nitrogen consumption in the Mississippi River Drainage Basin was shown in Figure 5 on page 25 as approximately 95 million tons (104,500,000 metric tons). An estimated 11.6 million metric tons of nitrogen added annually to the Mississippi and Atchafalaya basins is composed of approximately 51 percent commercial fertilizer, 30 percent livestock manure, 9 percent fixed by legumes, 5 percent from human domestic waste, and 4 percent deposited by rainfall. Municipal

(only 2 percent) and industrial point discharges (only 1 percent) contribute a small amount of nitrogen to the total annual nitrogen loading to rivers in the Mississippi basin because municipal and industrial point discharges of nitrogen are often directly to rivers, whereas the other potential nitrogen sources are applied or generated at the land surface.

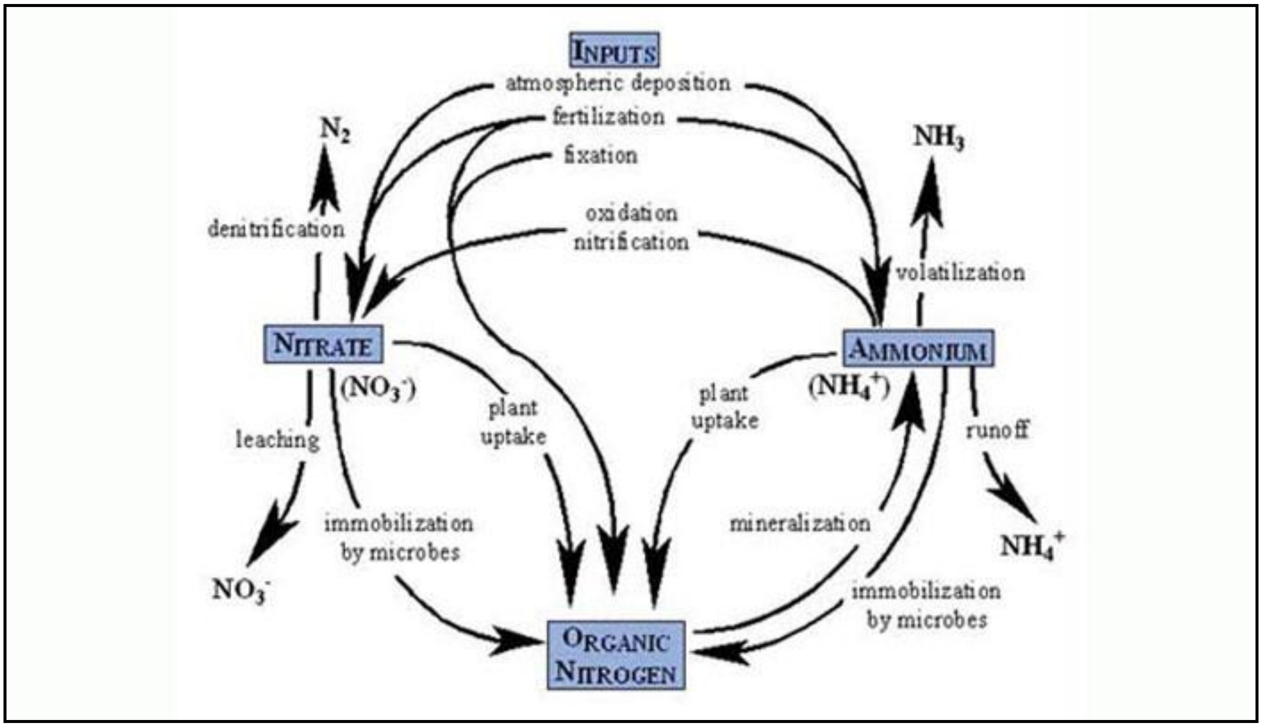


Figure 55. Nitrogen Cycle (National Park Service 2010)

Municipal and industrial point discharges of nitrogen to rivers could be the source of as much as 25 percent of the total nitrogen discharged to the Gulf of Mexico (Goolsby, D. A. *et al.* 1997). The introduction of nitrogen into the Gulf of Mexico through the Mississippi River is initially at a high concentration. As the spring begins the concentration drops as more water is added to stream flow the concentration increases as the amount of nitrogen increases. As the nitrogen rich river water “mixes” with the water in the Gulf of Mexico the concentration of nitrogen drops and when the fresh water stratifies over the denser saltier water of the Gulf of

Mexico, the concentration of nitrogen in the stratified water increases to the level where nitrogen is not a limiting factor to algae growth as shown in Figure 56. It is possible that nitrogen is in super saturated mode meaning nitrogen present in the system exceeds the ability of the system to use nitrogen (Castill, M. a. M. *et al.* 2003). Elements of living land biomass, land biomass growth rate, nitrogen in biomass mineralization fractions and others are modeled in the STELLA® model (Figure 57). Existing models have much to offer; increasing horsepower rather than buying new is a viable option. The nitrogen model is well done and offers insight into the graphical solutions available to show the interaction of available nitrogen and fertilizer introduced into a system with known data and a known model. The solution of the model showing metric tons versus time in months was graphed in Figure 58.

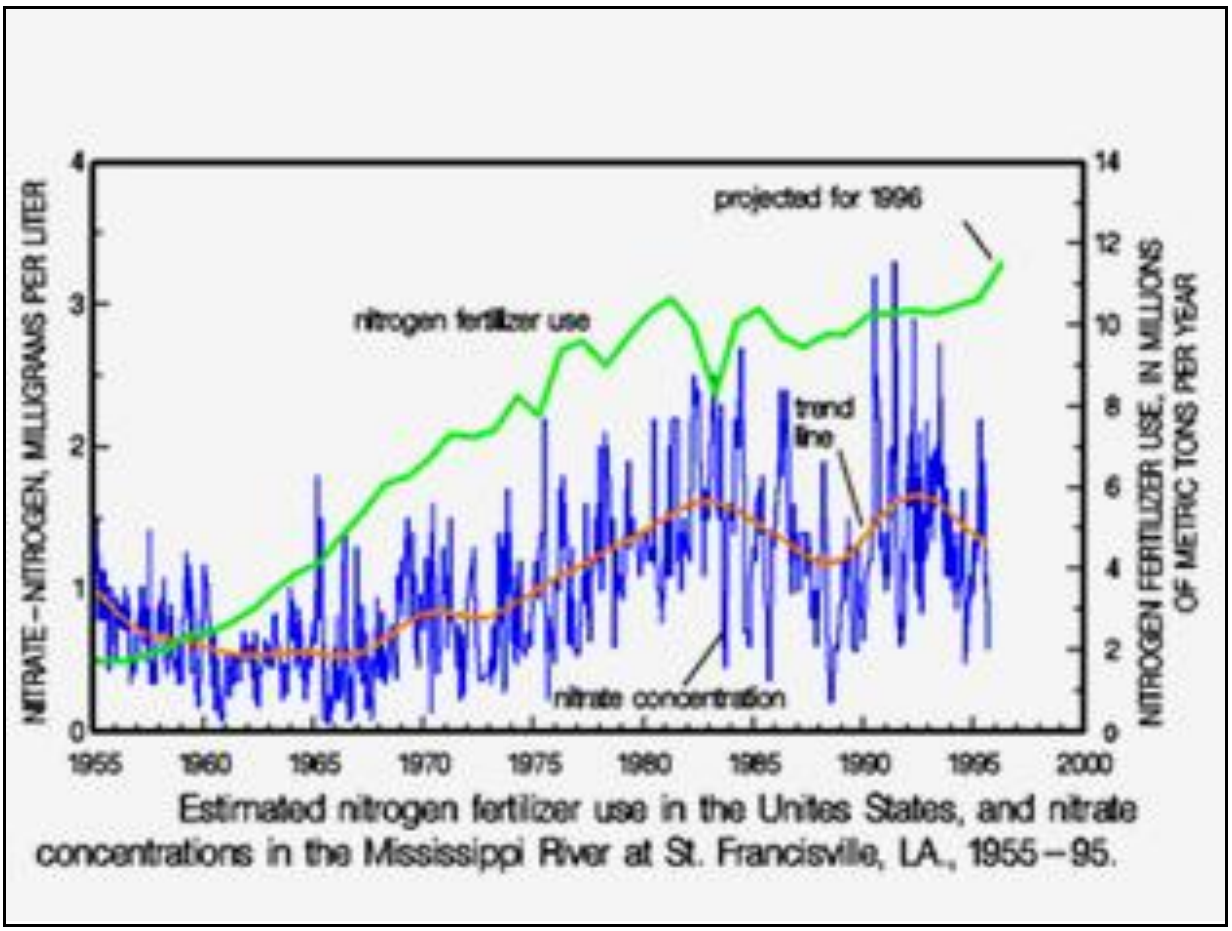


Figure 56. Nitrogen Concentrations (Goolsby, D. A. et al. 1997)

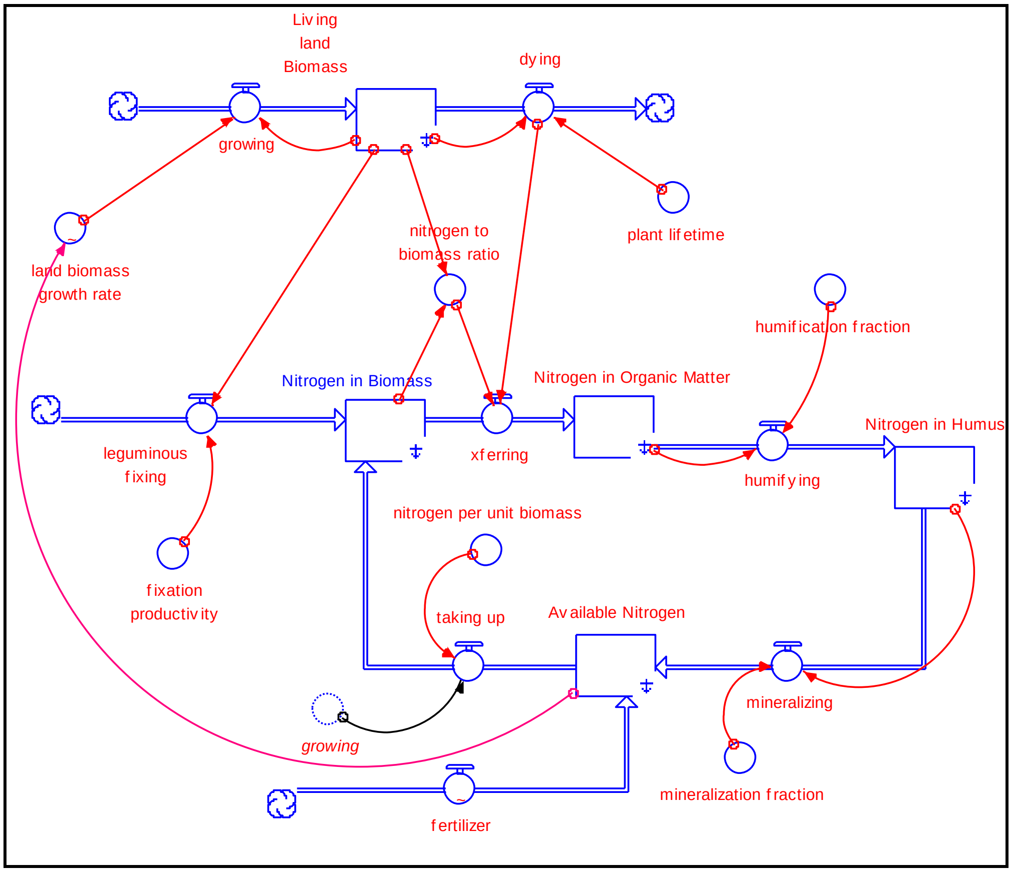


Figure 57. Available Nitrogen (iseesystems 2009)

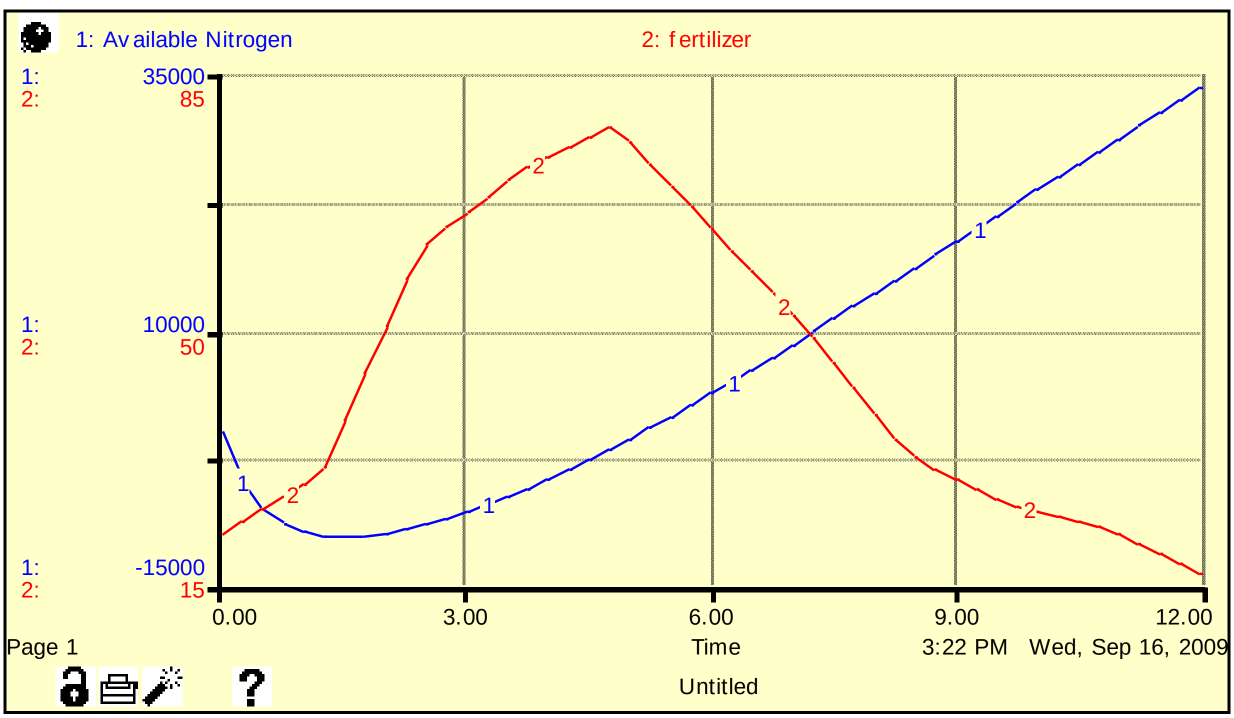


Figure 58. Graph Of Available Nitrogen (iseesystems 2009)

Are the cycle of nitrogen and the graphical solution of the nitrogen model useful? As fertilizer is introduced into the system, available nitrogen according to the graph diminishes. It is logically possible that nitrogen encourages biological growth and more nitrogen is tied up in plant and bacterial activity. Once primary needs for nitrogen are satisfied, available nitrogen will saturate the system. More fertilizer is added to increase available nitrogen with some success. A peak in fertilizer use occurs, but even after fertilizer use declines available nitrogen continues to climb. Is the available nitrogen leaching from the system? This is logical if the nitrogen is absorbed by plants and then as plant consumption is fulfilled available nitrogen rises even after fertilizer use declines (Chameides, W. L. and E. M. Perdue 1996). One can see the usefulness of the models at triggers for discussion. The third part of the trilogy of Carbon Nitrogen and Phosphorus is incorporated below.

4.1.5 The Phosphorus Cycle

The soil pH for optimum phosphorus availability is 6.5 (7 is considered neutral), which is considered as neutral pH. As pH rises or falls the growth of plants, bacteria and algae is affected (Chameides, W. L. and E. M. Perdue 1996) as shown in Figure 59. The STELLA® model diagram for the phosphorus cycle is shown in Figure 60. The graphical solution of the phosphorus cycle (in teragrams per year (Tg/yr)) is shown in Figure 61.

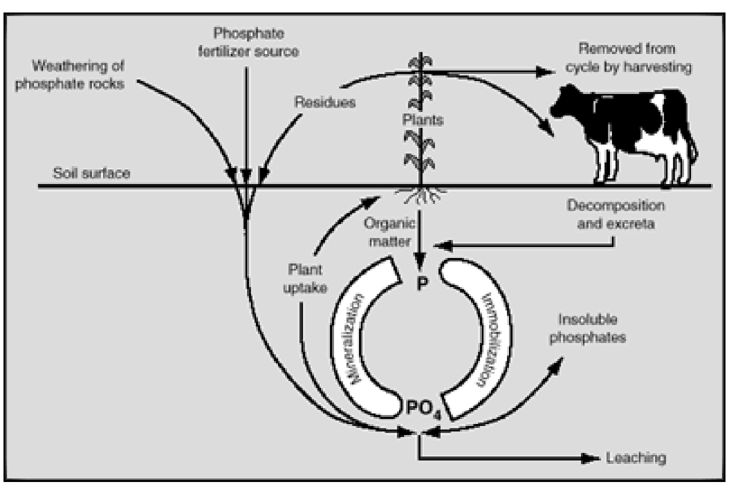


Figure 59. The Phosphorus Cycle (Manoa, U. o. H. 2010)

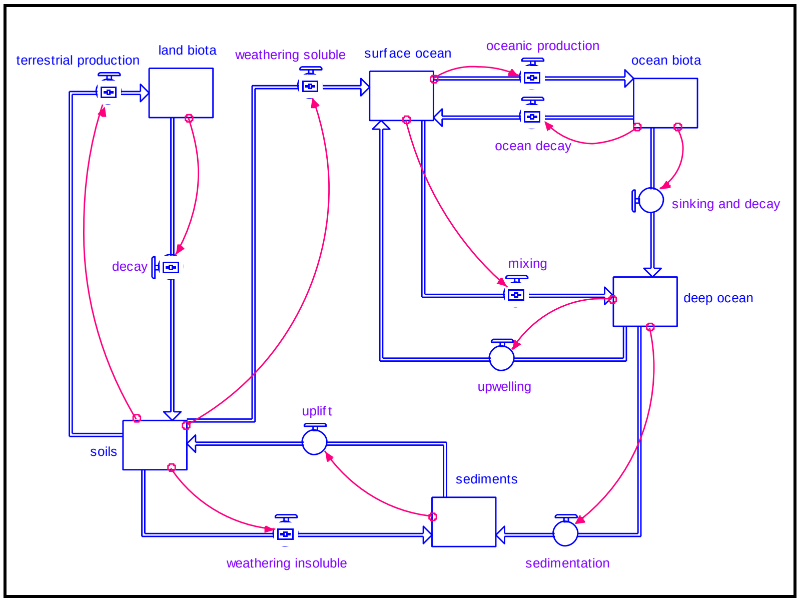


Figure 60. Model Of Phosphorus Cycle (iseesystems 2009)

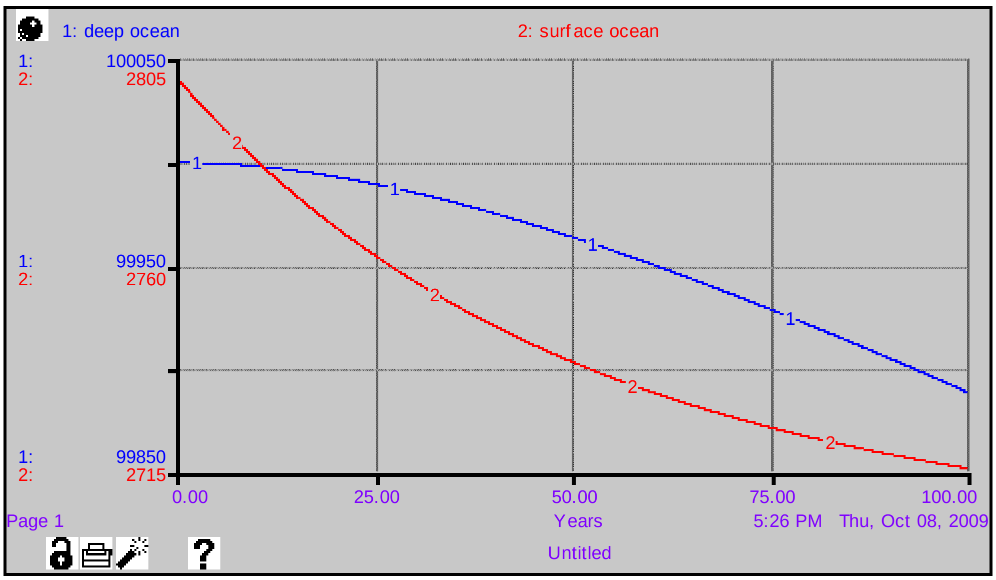


Figure 61. Graph Of Phosphorus Cycle (iseesystems 2009)

The solution of the phosphorus model is graphically represented in Figure 61 which shows that surface phosphorus is less than and declines faster than the deep water phosphorus. This is logical since phosphorus is soluble in water and concentrates in deeper denser water (Campbell, N. A. 1996). Phosphorus cycles through food webs not in the atmosphere. Leaching losses are balanced by rock weathering gain. Phosphorus is lost from the ecosystem through chemical precipitation or through settling of detritus. This phosphorus may become available to

ecosystems again through geological uplifting or stirring of sediment (Campbell, N. A. 1996). The models are standardized, use available data and are readily available from iseesystems. In the study of chemistry one of the greatest breakthroughs was the standardization of the periodic table and the chemical equations which describe the relationships of the elements in the formation of molecules. It is fascinating that all which was available before was a table of the components of a cycle, a cycle diagram, or a mathematical model of one element and its part in the ecological cycle. A model of the elements which are the foundation of life can now be dynamic instead of static. If a solution is wrong or makes no sense, the model and the underlying equations can be changed. If the solution is correct, then it can be improved. The consideration of C N P and the Redfield ratios indicate the ratios which compose life. This examination demonstrates that known cycles can be modeled and those dynamic models are useful triggers to discussion and analysis.

More importantly, an existing model usually works or can be made to work with skill and effort. The STELLA® software has the advantage of generating differential equations, and displaying graphical solutions. Modeling should not be a trauma, but an easy way to find tools to solve a problem. This writer finds all available models on the subject as the three above, studies those models, modifies if necessary and only after understanding what works combines or creates models which add to the solution of a particular problem.

Simple models allow models to be tested with simpler data sets and are more robust than complex models with complex data sets. The expense of developing, inputting data, calibrating and validating complex models along with the lack of robustness of complex models because of sensitivity of the model to changes in one or more variables indicates a different approach may be more productive (Hetland, R. D. and S. F. DiMarco 2007). Studying models and modeling

ability is a very desirable asset. It is just as desirable to be able to study models to gain insight into the production of the best model for the given ecosystem. Equally as important as the amount of a nutrient is the rate at which the nutrient cycles through the ecosystem.

Anthropogenic changes such as urbanization, agriculture drainage, loss of wetlands levees, and channelization create hydrological changes. The hydrological change can reduce runoff time for water, decrease absorption rates by changing surface types from natural forest to concrete. Any restriction of the natural flow of the stream or river such as a combination of channelization and levees can result in overtopping as modeled in Figure 62.

4.1.6 Wetlands Vs. Channelization (Mckelvey, S. 2010)

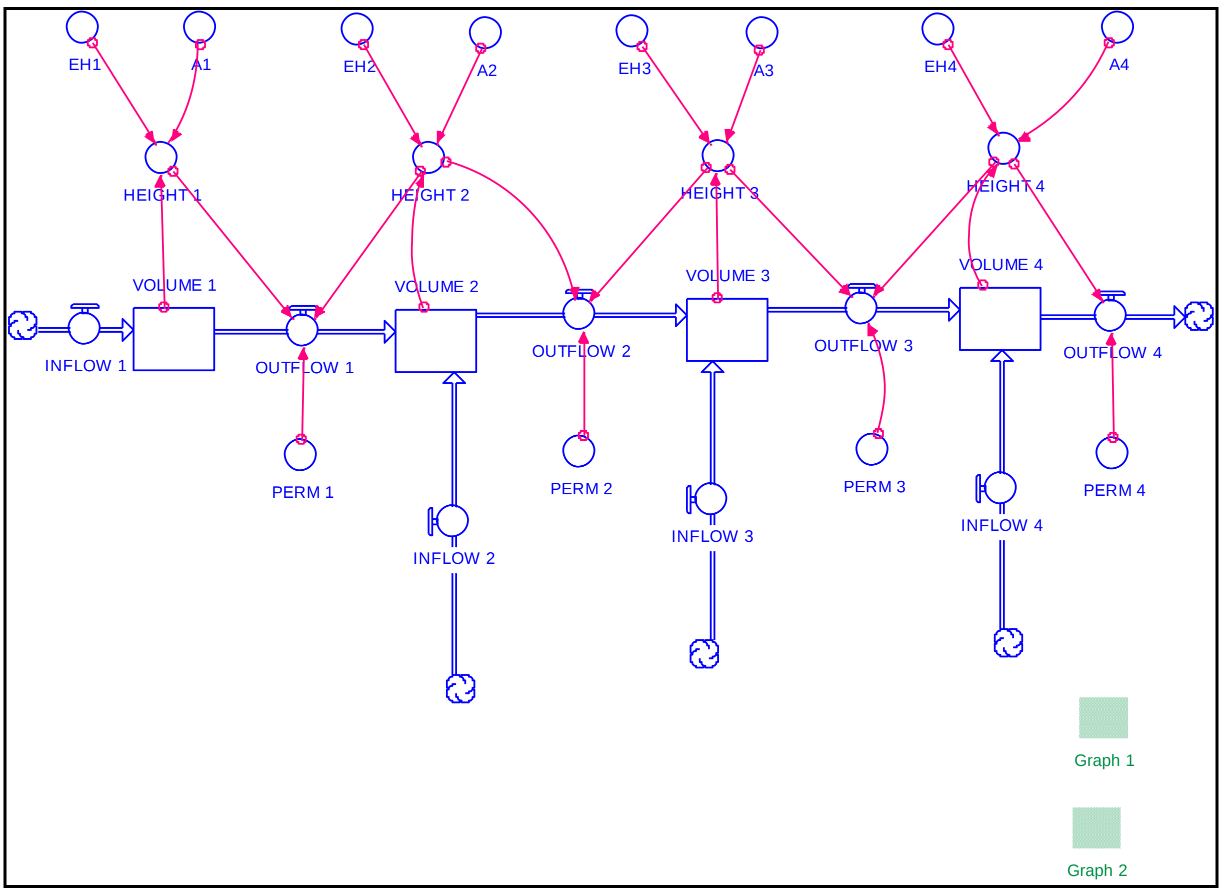


Figure 62. Stella Diagram For Wetland Channelization (McKelvey, S. 2010)

Inflow in the various structures causes the water level to move more rapidly through the straightened channels and rise on the sides of the levees until overtopping occurs. Where the channels and levees empty their contents into the wetlands or reach the mouth of the river, the water disperses and spreads over a wider area. The graph illustrates volume accumulation as shown in Figure 63. Outflows are labeled 1-4. Outflow 1 creates no problem. If the ground is dry and soaks up the moisture the curve mirrors reality. Outflow 2 shows a steady rise, indicating precipitation falling on saturated ground. The channel for 1 and 2 do not overflow until outflow two crosses outflow three. Outflow 3 is within the channel. Outflow 2 exceeds the capacity of the channel and overflows the banks. Outflow 4 spreads over the wide mouth of the Mississippi River, the wetlands and the Gulf of Mexico as is shown in Figure 64. The previous factors of nutrient transport, water clarity and stratification are "linked" and the consideration of an erosion model established the elements so troublesome to farmers in the Mississippi River Drainage Basin.

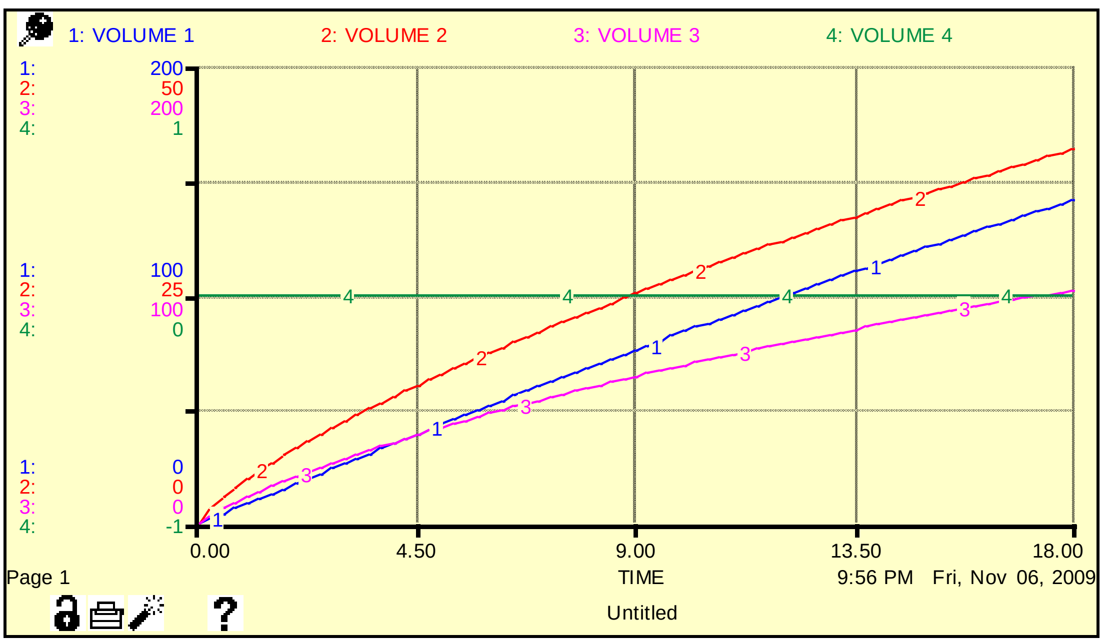


Figure 63. Graph Of Inflow Over Time (McKelvey, S. 2010)

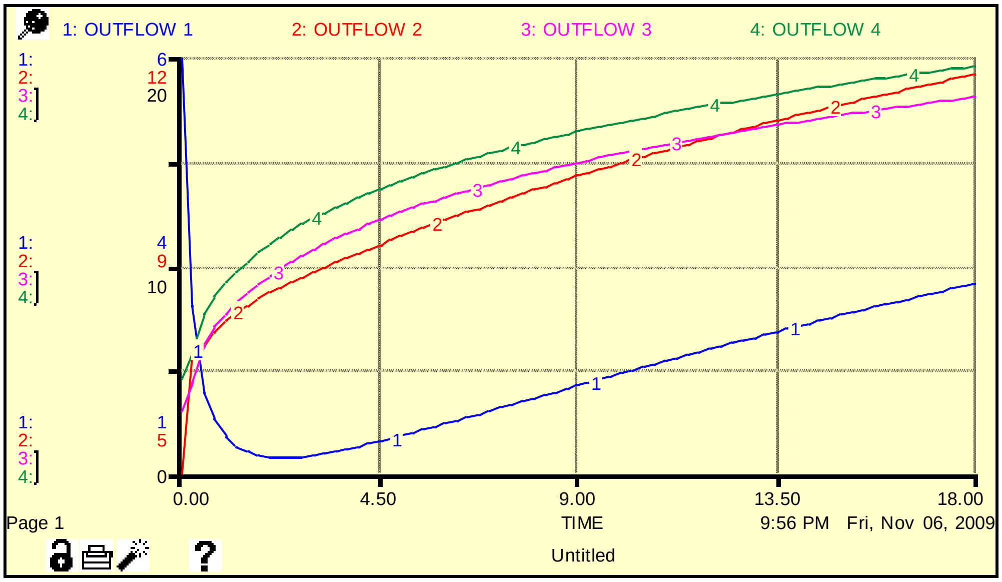


Figure 64. Graph Of Outflow Over Time (McKelvey, S. 2010)

4.1.7 Erosion Model

The STELLA® models including the Erosion Model was used with the permission of iseesystems listed in Appendix C. The Hubbard Brook Experimental Forest, a long term (from 1955 to 2010) clear cutting experiment, gave insight into the availability of nitrogen after clear cutting (Campbell, N. A. 1996). The diagram is shown in Figure 65. In the graphical solution of the Erosion Model high rainfall, after a slight delay for runoff time correlates to high soil erosion as shown in Figure 66. This is logical since the water would take time to saturate and then to run through the watershed. Any increase in rainfall would be followed by increased soil loss. This is logical and tracks reality. This is a fantastic model. Rainfall (4) is high in the first of the year, has a peak in the middle of the year and again rises in the end of the year. Soil loss (1) and vegetation growth (3) are correlated well with rainfall. Vegetation (5) is low in the beginning of the year stays flat during the middle of the year and rises at the end of the year. Vegetation degradation (2) rises at the first of the year, goes up in the dry part of the year, drops in the middle of the year rainy peak, and rises again in the second dry period.

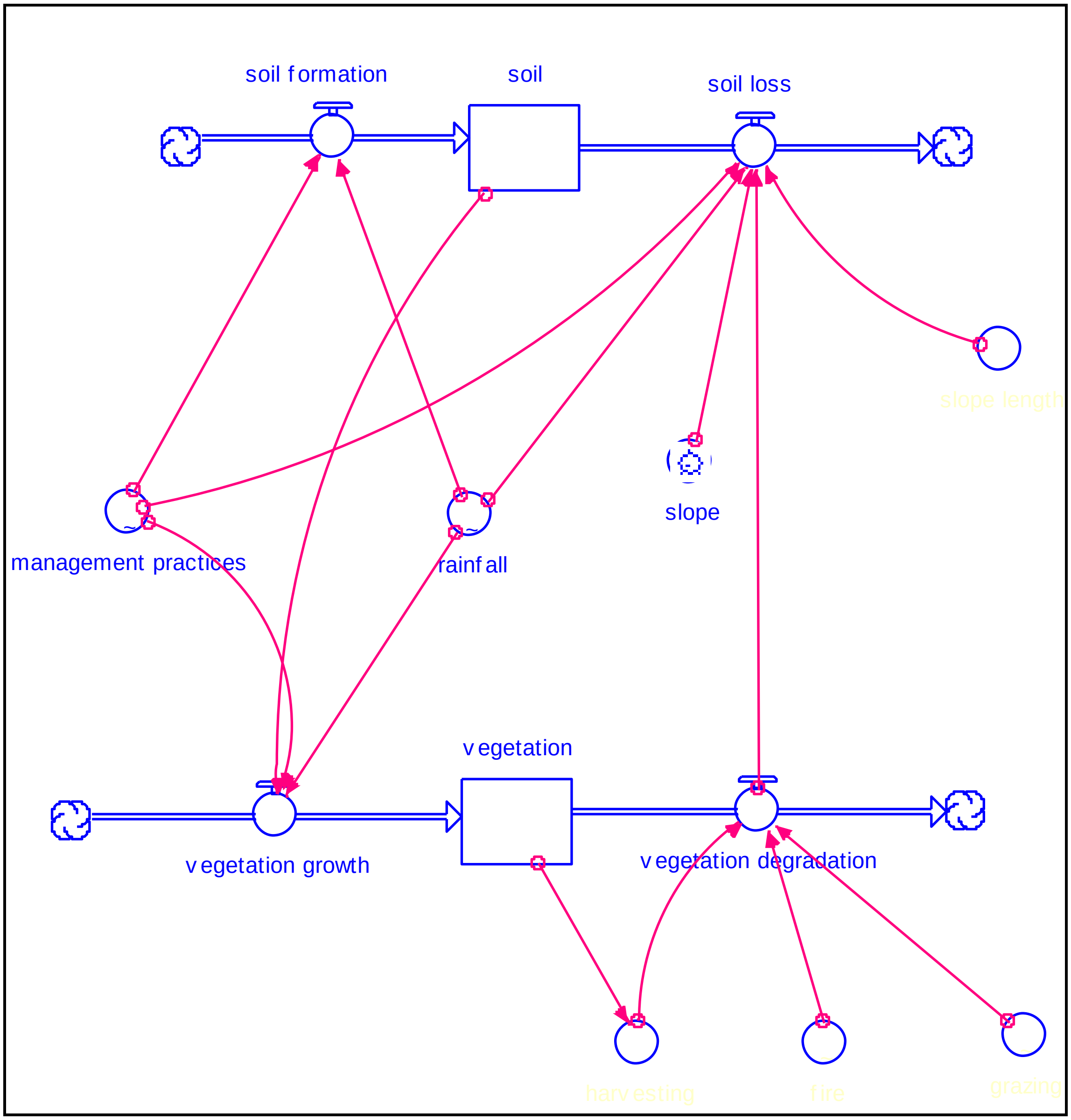


Figure 65. Erosion Model (iseesystems 2009; Totolo, O. *et al.* 1997)

The reason for desiring to examine this model is that the erosion from this model contributes to the detritus which is transported to the Mississippi River and travels down the Mississippi River and into the Gulf. There are anthropogenic phenomena which add to detritus. Destructive (trawling) fishing practices catch everything and discard the undesired. This "undesired" is bycatch and is thrown overboard as detritus.

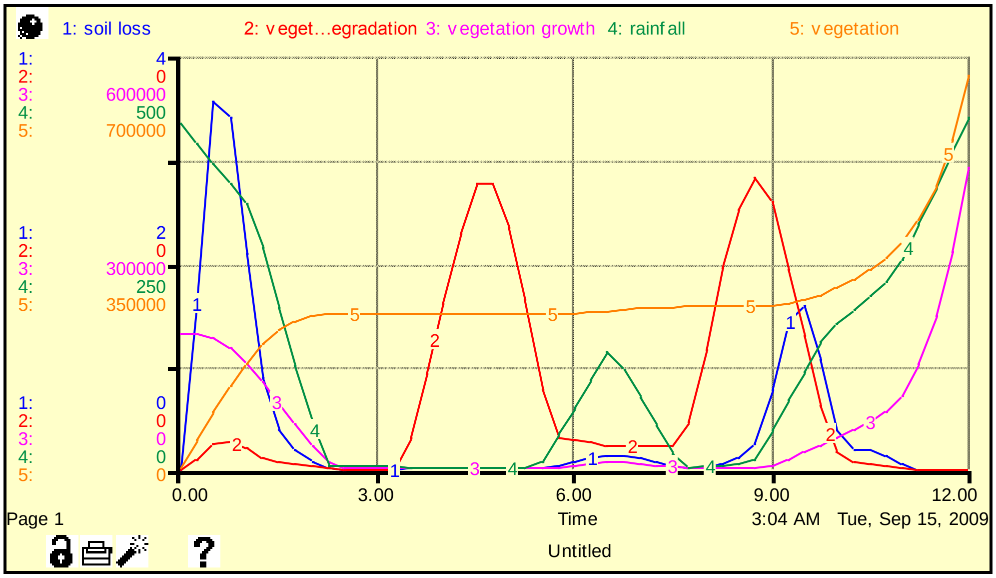


Figure 66. Graph Of Erosion (iseesystems 2009; Totolo, O. *et al.* 1997)

4.1.8 Bycatch

Detritus is explained as plant material from forest, field, farm and city. This detritus is rich in carbon, nitrogen and phosphorus. This is not the complete story of detritus as detritus also includes the bodies of all forms of plankton, plant and algae material which, once deceased, fall from the force of gravity to the bottom. The shrimp trawl fishery is an open access fishery with an estimated 20,000 vessels indiscriminately harvesting ocean species with trawling nets. The desired catch is sorted, processed and retained. The undesired catch (bycatch) is thrown overboard as detritus (Diamond, S. L. 2004) which falls to the bottom and depletes oxygen as logically the predators which consume the bycatch have been caught and killed or caught and processed. Bycatch is a problem in the menhaden fishing industry (Franklin, H. B. 2007). Bacteria consume (break down) detritus (bycatch) in the presence of oxygen (aerobic) or in the absence of oxygen (anaerobic). The classification of bacteria is based on the use of organic compounds (heterotrophic) as an energy source (detritus) and carbon for synthesis. An additional classification is facultatively anaerobic bacteria which use dissolved oxygen when available but can oxidize organic matter if oxygen is absent (Goyal, D. 2007). The amount of

bycatch is not known and thus is not modeled in this study. There are guidelines for studying ecosystems and for modeling ecosystems which shall be discussed below.

4.2 Methods

4.2.1 Methods to Studying Ecosystems

Currently there are several approaches (Likens, G. E. 1985) to the study of ecosystems which include:

1. Empirical studies where bits of information are collected and an attempt is made to integrate and assemble these into a complete picture.
2. Comparative studies where a few structural and a few functional components are compared for a range of ecosystem types.
3. Experimental studies where manipulation of a whole ecosystem is used to identify and elucidate mechanism.
4. Modeling or computer simulation studies.

Likens incorporated all of these approaches in a study of Mirror Lake located in Lake State Park at Lake Delton, Wisconsin. The Likens study demonstrates that all four approaches must be used to accomplish a good picture of many complex ecosystems. An ecosystem is so complex that you cannot capture all of the system properties with one approach (Jorgensen, S. E. and G.Bendoricchio 2001; Likens, G. E. 1985). Only after carefully studying many models and methods was any effort to model any portion of the Gulf of Mexico attempted. One of the most difficult concepts was consideration of a total mass balancing approach. Mass balancing in an open ecological system with over fishing and the heavy anthropogenic hand, the Gulf of Mexico has fish and products taken out and no corresponding input to maintain a balance.

4.2.2 Correlation Compared To Causation

When modeling the Gulf of Mexico, one must realize that the Gulf of Mexico is a large marine basin ecosystem (Global Ocean Associates 2004) and it is an open (to larger oceans) system and mass balancing can not be rigidly imposed. Simply, the Gulf of Mexico is a net output system. This is one of the reasons great emphasis was placed on the difference between correlation and causation. Available data on ecological systems measures symptoms rather than causes. These symptoms relate to sediment oxygen content, bottom oxygen content, nutrient content, river discharge, algae concentration and river plume. These are not causal events. The cause of algae growth is the combination of sunlight and nutrients in proper ratios. The nutrients can be natural or anthropogenic and their introduction into the system can be the result of causes or combinations of causes. Weather can exacerbate the transport of nutrients into the Gulf of Mexico with increases the size of the hypoxia zone or weather can cause mixing which would reduce or eliminate the hypoxia zone.

4.2.3 Basic Modeling Techniques

A list of steps for multidisciplinary spatially explicit simulation models is suggested below.

1. Identify objectives and constraints
2. Develop overall modeling constraint decision
3. Conceptualize full model
4. Develop submodels
5. Develop full model
6. Iteratively test and debug

The steps were followed and the Algae 0 to 4 Meters STELLA® Model was created as part of this work.

CHAPTER 5: RESULTS AND DISCUSSION

5.1 The ALGAE 0 TO 4 METERS STELLA® Model

The decision was made to divide a model into an upper realm and a lower realm. As stratification created fresh water over salt water reality, it was thought that the division of algae on top and detritus on the bottom would be realistic. Two broad realms describe the ocean environment: the benthic realm (consisting of the seafloor) and the pelagic realm (consisting of the ocean waters). Below 660 feet (200 meters) depth, not enough sunlight penetrates to allow photosynthesis. Photosynthesis diminishes as sunlight diminishes and sunlight penetration is less at greater water depth causing bottom photosynthesis to decrease (Campbell, N. A. 1996).

Hypoxia in the Gulf of Mexico ranges from shallow (4 to 5) meters to a depth of 60 meters and extends 55 kilometers from shore (Rabalais, N. N. *et al.* 2001). Louisiana's bar-built estuaries are broad and shallow with mean depths of only a meter or two (Inoue, M. *et al.* 2001).

Modeling the critical elements of carbon, nitrogen, phosphorus and oxygen is essential to model algae in the 0-4 meter depths of the Gulf of Mexico. While an alga grows at greater depths, this depth was made as an assumption. Water depth greater than 4 meters was thus eliminated from the model.

Modeling of the essential elements (carbon, hydrogen, oxygen, nitrogen, phosphorus, sulfur, magnesium, potassium, sodium, calcium and iron) is limited in this model to carbon, nitrogen, phosphorus and oxygen. Bacteria obtain these elements by utilizing atmospheric gases and by metabolizing carbohydrates and proteins. Temperature and pH play significant roles in bacteria growth. Bacteria may be classified into three general groups based on their temperature requirement thermophiles (55°–75° C, or 130°–170° F), mesophiles (20°–45° C, or 70°–115° F), or psychrotrophs (10°–20° C, or 50°–70° F) (Campbell, N. A. 1996). In addition, most but not

all, bacteria grow best in a neutral environment (pH equal to 7). These general statements are for the purpose of setting temperature and pH ranges for the growth of bacteria and algae. The range for temperature in the model is assumed to range from 40^0 F to about 80^0 F and to remain neutral (pH equal to 7).

The Algae 0-4 model is more complex than previous models with three stocks in three layers. The algae depend on nutrients, temperature, sunlight and streamflow. These elements are included in the model. The algae, available nitrogen and aerobic and aneorbic bacteria have been chosen as essential stocks for purposes of this model. The connectors define the relationships between the stocks in a manner predetermined by the STELLA® software. The availability of the essential elements of life determines the birth rate and the death rate of species. Algae grow and in some span of time dies. As the body of the algae dies it passes from the 0-4 zone through the intermediate zone to the bottom. The algae body is considered detritus and in its downward travel joins other organic and inorganic detritus.

The aerobic bacteria begin the decomposition process in the presence of oxygen and when the oxygen is consumed anaerobic bacteria continue the consumption process without the presence of oxygen. As oxygen is consumed, it is equally important that the oxygen not be replaced by any process. The presence of photosynthesis at the bottom of the ocean would add oxygen to the bottom layers increasing oxygen concentration. If the oxygen is added at a faster rate than is consumed the oxygen level will rise. Similarly, if the oxygen is depleted at a rate faster than oxygen is replenished then oxygen concentration will reduce.

The framework of the model was obtained by using models from the STELLA® tutorials and the diagram is shown in Figure 65-71.

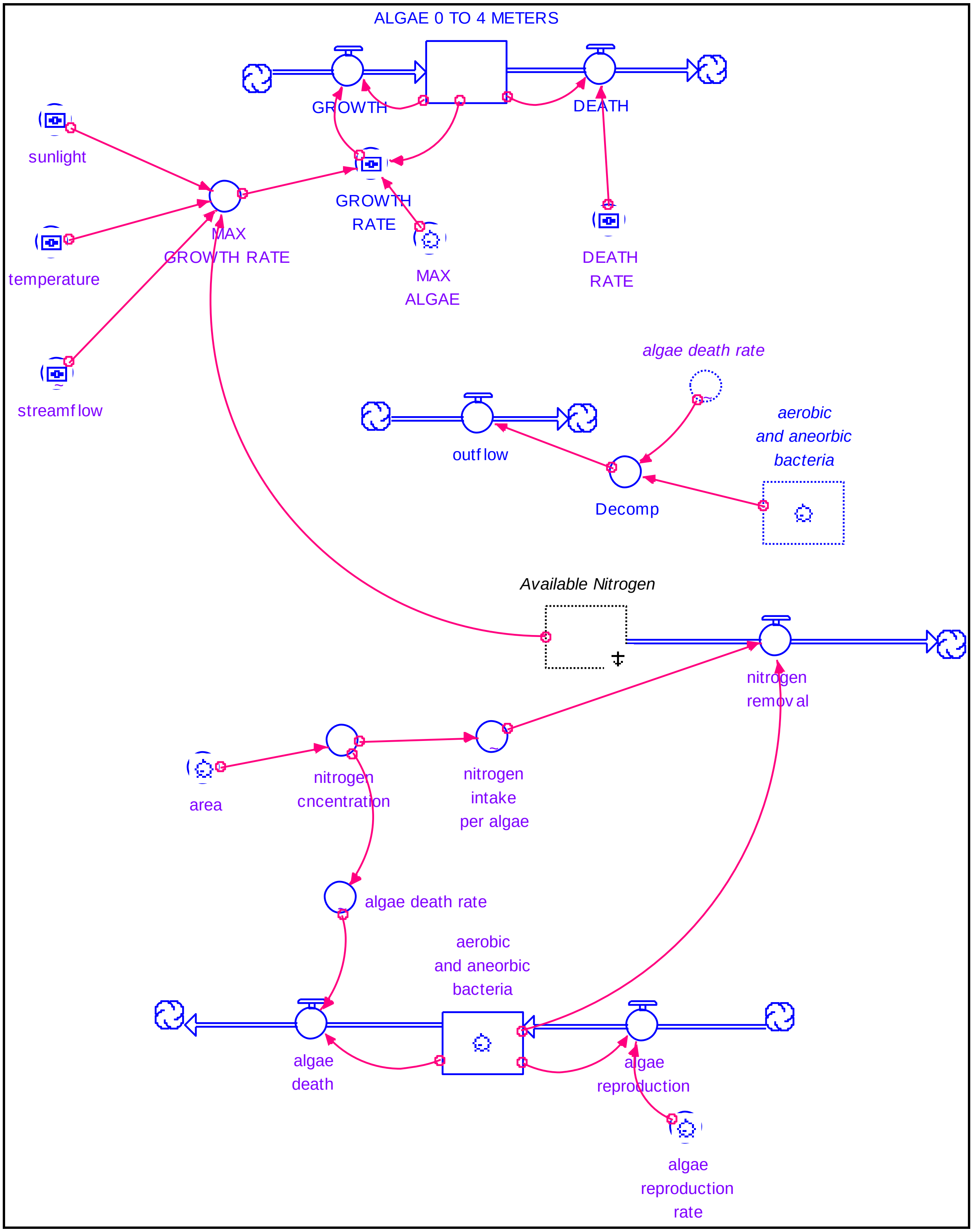


Figure 67. Algae 0-4 Meters Model

Initially the model had problems with the available nitrogen stock. Figures 5, 6 and 11 showed a flat consumption of nitrogen and phosphorus. Figure 12 showed the hypoxia zone increasing with the nitrogen introduced into the Gulf of Mexico decreasing. While it is permissible for a model to display trends, it is impermissible for a model to function adversely to trends shown by graphs based on gathered data. The following steps were retraced.

1. Identify objectives and constraints.
2. Develop overall modeling constraint decision.
3. Conceptualize full model.
4. Develop submodels.
5. Develop full model.
6. Iteratively test and debug.

The submodels were examined and found to display graphical solutions. The modeling stocks, flows, connectors, equations and parameters were checked and found reasonable. Models fail to function if a component is divided by zero or multiplied by a number too large to display. This did not occur in the model.

The components of a model often represent complicated components of an ecosystem. The interplay of these components in the completed model may play a key role in the modeling of an ecosystem under consideration (Westervelt, J. 2001). Modeling and the analytical equations whether generated by STELLA® or derived in some other analytical fashion are useful for modeling systems at or near some equilibrium point (Reice, S. R. 1994). However disturbance is a major contributor to diversity and diversity opens ecological niches for exploitation. Disturbance occurs at various scales (Pickett, S. 1989). Individuals and ecosystems can be disturbed as characterized by spatial distribution, frequency return interval,

rotation period, area, intensity, severity and synergism. “Equilibrium theories are restricted to behavior at or near an equilibrium point, while non-equilibrium theories explicitly consider the transient behavior of the system.” (Caswell, H. 1978) Predictability of ecological systems is dependent on the scale set to examine the ecosystem (Loucks, O. L. 1985). This and more was examined. The major problem was available nitrogen. Available nitrogen is not a fixed amount per period of time. Available nitrogen varies with stream flow and with the seasons of planting and harvest. The second problem is the difference with correlation and causation. Given an amount of available nitrogen, the algae bloom and the hypoxia zone could be affected by physical properties. Everything seemed to revolve around the positions taken by the Eastern and Western groups.

The idea of a modeling system which started at the top of the Mississippi River Drainage Basin and proceeded down the Mississippi River to the Gulf of Mexico began to take form. The models would have to be set to the same scale or to no scale. Data gathering and data input into a model should be uniform for the purposes of absolutely certain mathematical prediction. The problem with bringing data to the same scale when modeling the Gulf of Mexico is at least threefold.

First, the correlation and causation arguments are in a state of tremendous flux. It is not known whether the causes of the algae bloom and correlated hypoxia zone are biological (driven by excess nutrients) or physical (lack of mixing, river plumes and anthropogenic changes). Faced with the uncertainty of the difference between correlation and causation, little would be gained by the pursuit of none existent rigidity.

Second, the data gathered in often in different units from gigatons, nanagrams, acres, hectares, miles, kilometers, pounds and kilograms. Conversion equations can convert different

units to a uniform unit. The author does not recommend the use of more than one conversion equation since the model will often fail to function because of modeler error. It is not that bringing all data to the same scale should not be done. The time to convert is not when you are creating a new model or new methods of modeling. After the model is successful, as a final polish; data should be brought to the same units.

Third, if a business has declining income and increasing expenses, even the less astute businessman would realize that this situation must be reversed or the bottom line numbers would soon reflect the changing rates. Tell that same businessman that his shipping rates are going up by a certain percentage for domestic and foreign shipments and he understands that whether you measure in pounds or kilograms, whatever he ships will cost more. The process of linear correlation of data to a prediction uses a linear equation ($y = mx + b$). The variable is y dependent on m and x. The constant is b. The variable rate is m. The amount varied is x. In curvilinear form the equation can be in many forms (e^y is one). The variable could be defined in some form of mx+b. Differential equations (rate equations) which require integration for solution offer no greater insight into the graphical solution of the graphical STELLA® model. The STELLA® equations taken from the Deforestation model (pages 93 and 94) are CARBON_IN_ATMOSPHERE (t) = CARBON_IN_ATMOSPHERE (t - dt) + (DEFORESTRATION - PHOTOSYNTHESIS) * dt which translate to differential equations as $C_A(t) = C_A(t - dt) + (D - F)dt$, which is a rate equation. STELLA® graphically displays mathematical solutions of differential equations generated by the STELLA® modeling process. Understanding rates is essential to understanding STELLA® modeling.

The STELLA® software has a no scale setting, which was used exclusively for this work. The author reasoned, if the correlation and causation arguments are in a state of tremendous flux

and data is not in standard units the argument of which came first the model or data would best be resolved by creating the model first to demonstrate trends and relationships. In the future better data sets of causative events will result in better models. This is a trend analysis and due to the ease of adding data to the model the decision was made not to pretend greater scientific accuracy than was available awaiting resolution of causative and data issues.

With the no scale setting the models displayed in this paper were examined again. The practice of this modeler is to place model diagrams and the equations in one model. In this manner, combinations of the elements of various models can be achieved. The practice has served well to provide solutions which were not obvious. The decision was made to combine as many models and as many elements of models as possible. The ROWE STELLA® OXYGEN MODEL was combined with CARBON, NITROGEN, PHOSPHORUS, THE EROSION MODEL and THE ALGAE 0 TO 4 METERS STELLA® MODEL. The combined models produced graphic solutions providing an excellent worksheet for examining relationships between correlative and causal elements.

5.2 Combining Models

The diagrams of the combined models follow in Figure 68. The STELLA® Model is composed of stocks, flows, connectors and the underlying equations. Combination of models occurs if the stock in one is provided by the stock of another. The flows of one model can be disconnected from the parent model and graphed on to the new stock. As for connectors, the elements of two models can be connected to each other. Additionally, the equations can be examined and the values of the equations of one model can be used as the values of the equations of another model with the same equation. Combination of models is a sharing process. The sharing starts at the level of stocks, flows and connectors. Entire submodels can be shared with

other models creating extremely complex models. Efforts were made to maintain these models at the simplest and most repeatable level. Permission to use the models of John Snow, University of Oklahoma and Gilbert Rowe were given and gave insight into standardization of the models listed in Appendix C.

Please observe in combined models shown in Figures 68 to 73 that the flow for emissions connected to the atmospheric model and the respiration with its connector to fossil fuel as the connector joins the Simple Carbon Model. The input to one model is the output to another model.

The equations for the models shown in Figures 68 to 73 are included in the Appendix A.

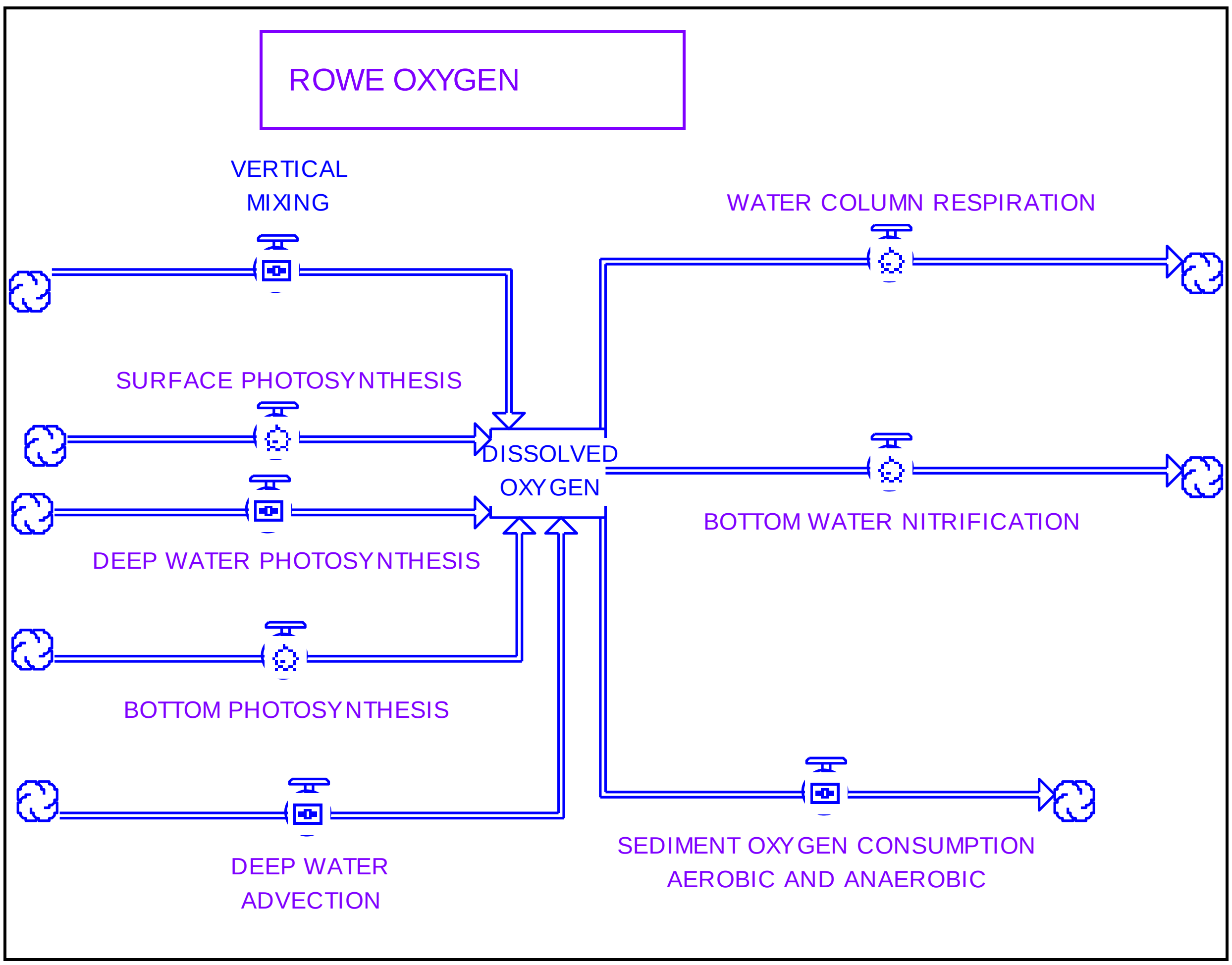


Figure 68. Oxygen submodel

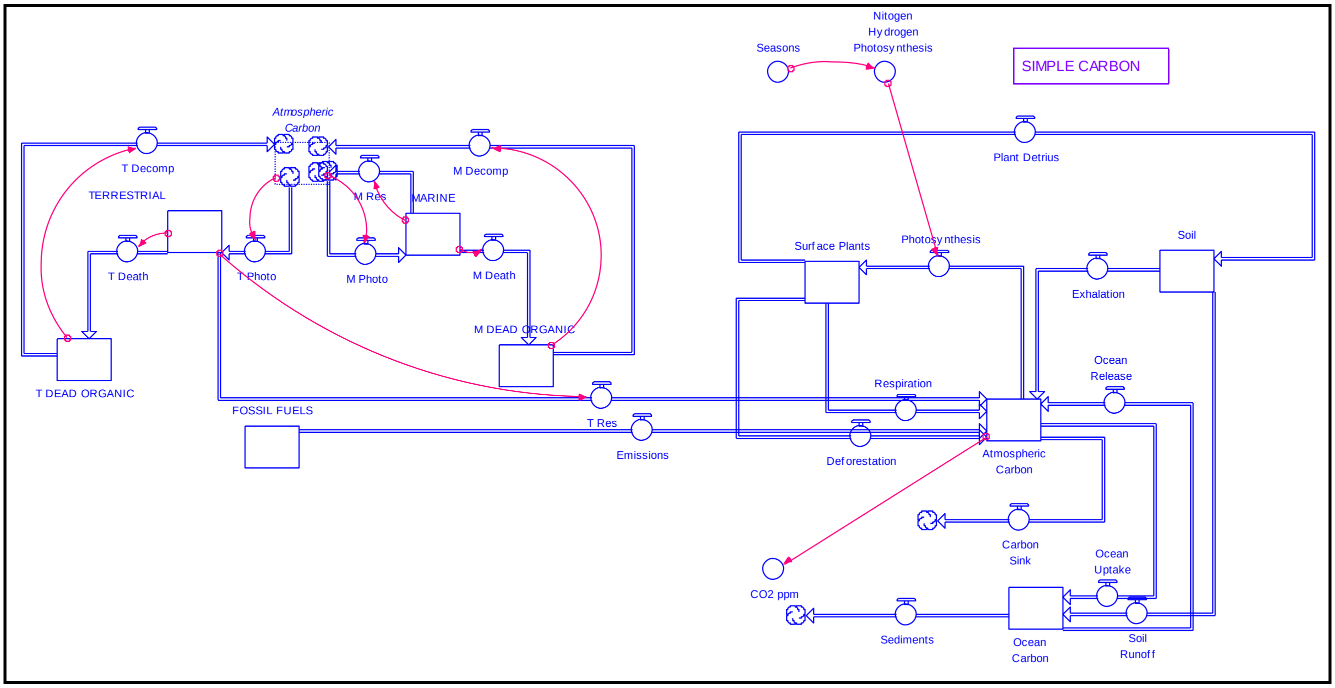


Figure 69. Decomposition submodel

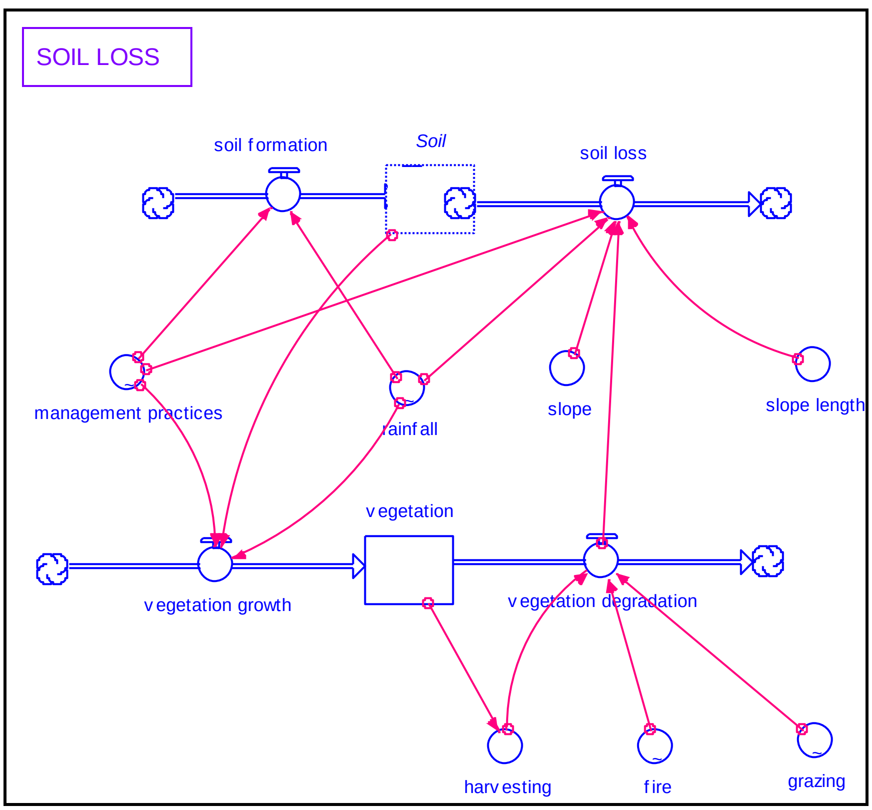


Figure 70. Soil loss submodel

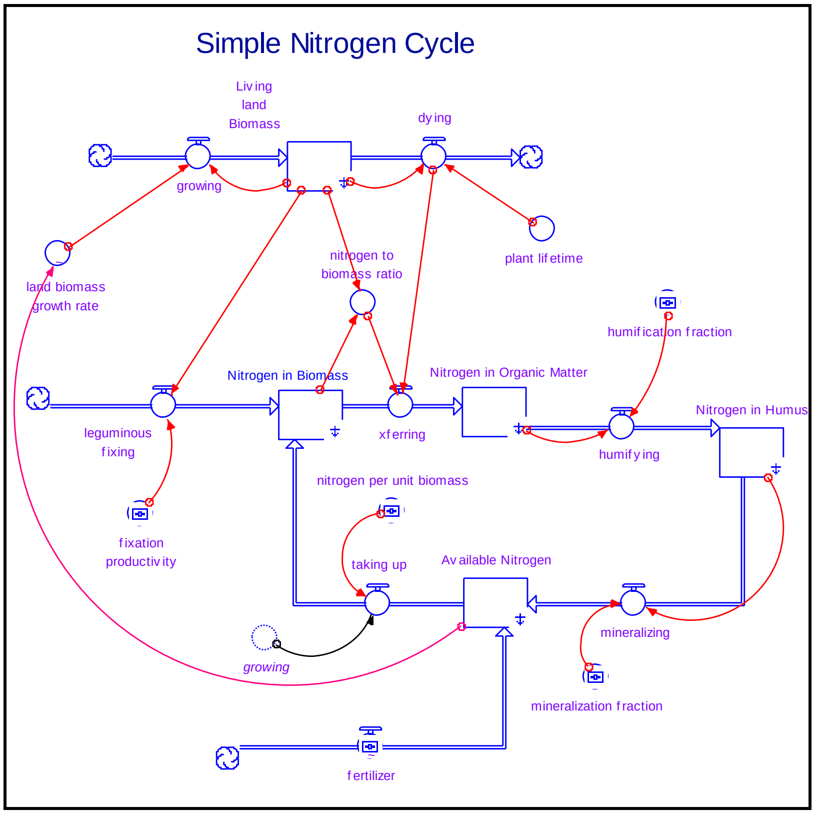


Figure 71. Nitrogen cycle submodel

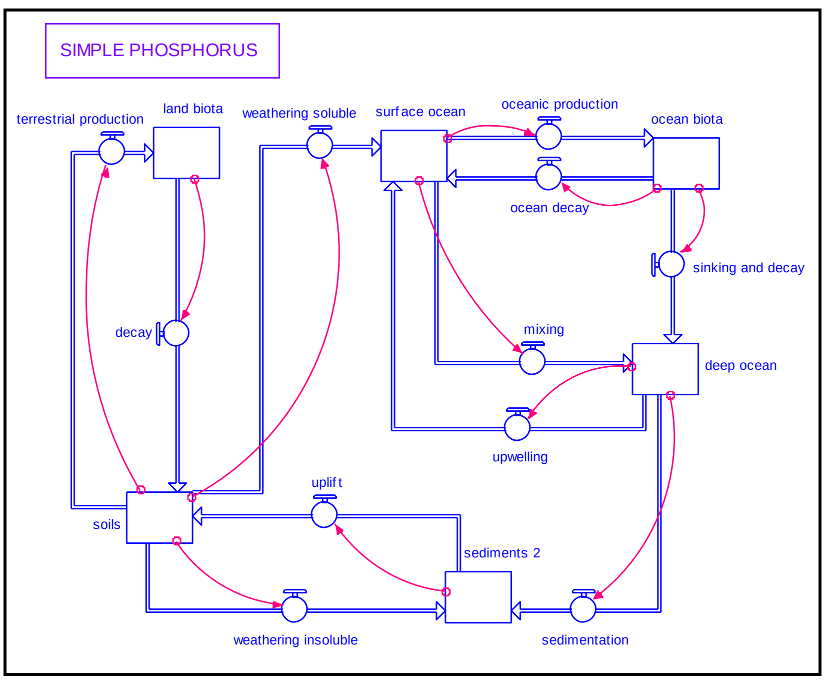


Figure 70. Phosphorus submodel

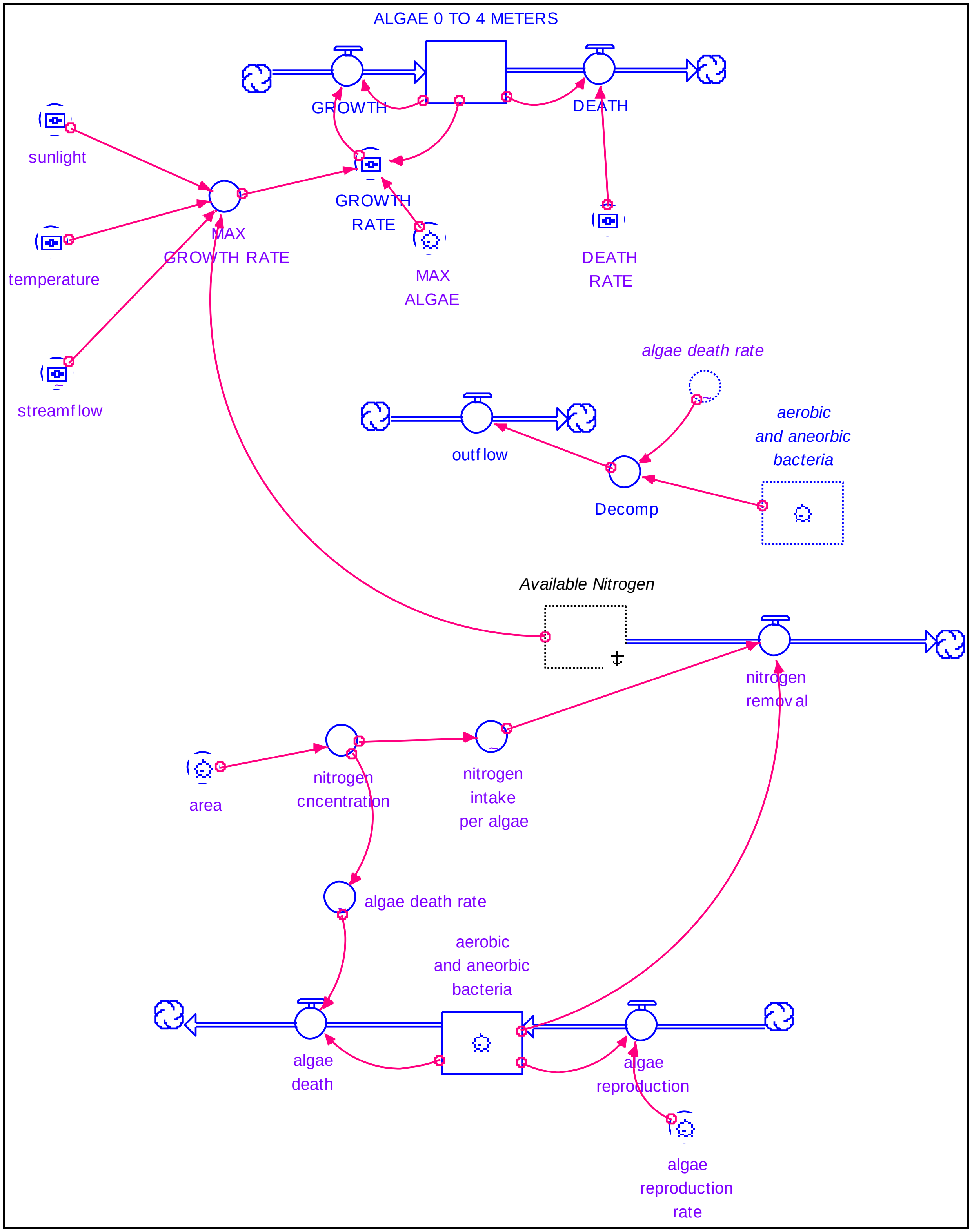


Figure 71. Algae 0 to 4 Meter submodel

5.3 Results and Discussion of Complex Model

The combined STELLA® model provided a system for examining the elements of various models and suggested methodologies where new models could be created. A system of 22 variables, adjustable by the use of sliders, a device which moves horizontally and a knob, a device which resembles a radio knob was created as shown in Figure 72. The following demonstrates that dynamic modeling is successful in demonstrating the relationship of various elements in the Gulf of Mexico. The hypoxia condition is started with a normal oxygen level of 7 ppm. A test of whether the model will show realistic trends will begin with a reduction in mixing and bottom photosynthesis.

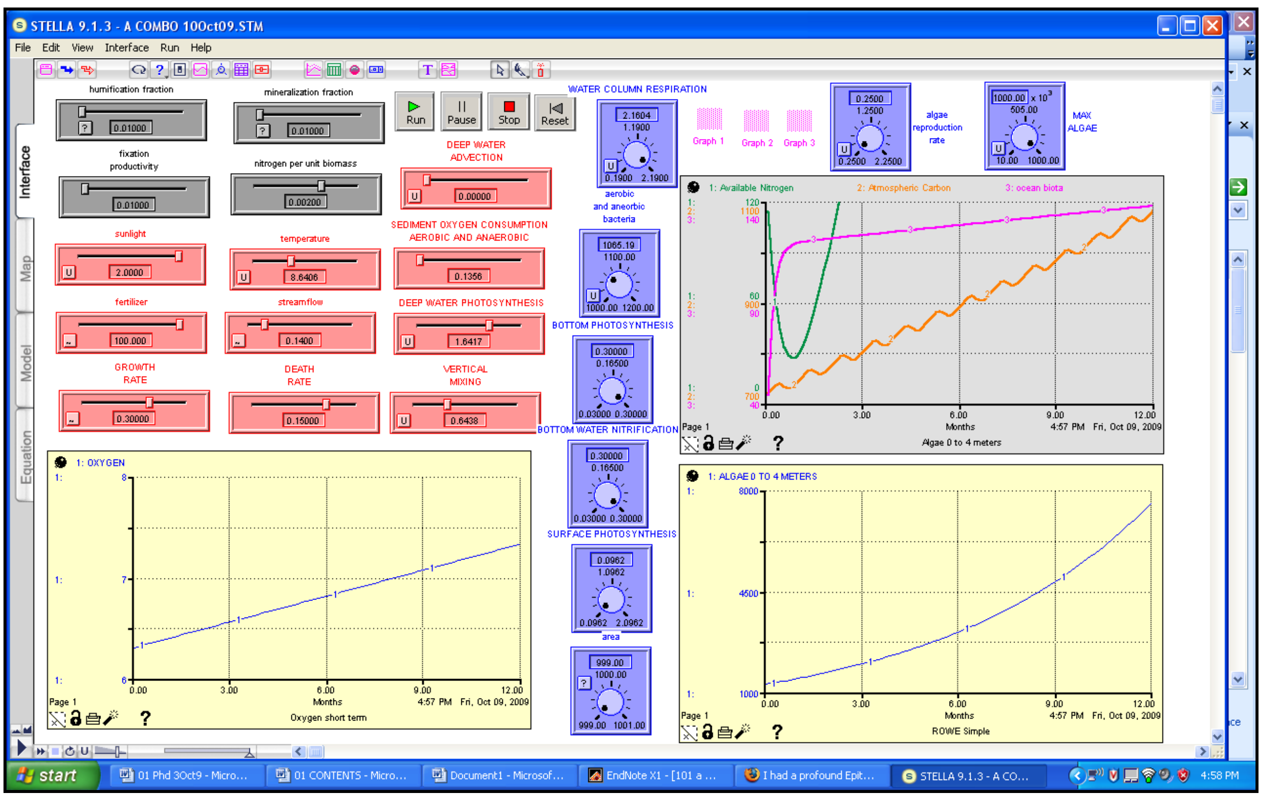


Figure 72. Graphical Solution of Combined Modified Model with Sliders and Knobs

A reduction in vertical mixing and deep water photosynthesis showed a trend for the oxygen level to drop to 0 over time as shown in Figure 77. At the same time inputting nitrogen reveals an increase in ocean biota and 0-4 algae. Figure 77 shows a return of normal conditions when WATER COLUMN RESPIRATION was increased and the oxygen level increased. The combined models support the hypothesis put forth by the Western camp (page 37-39 of this paper) which states that mixing and respiration were essential to decrease or eliminate the hypoxia zone.

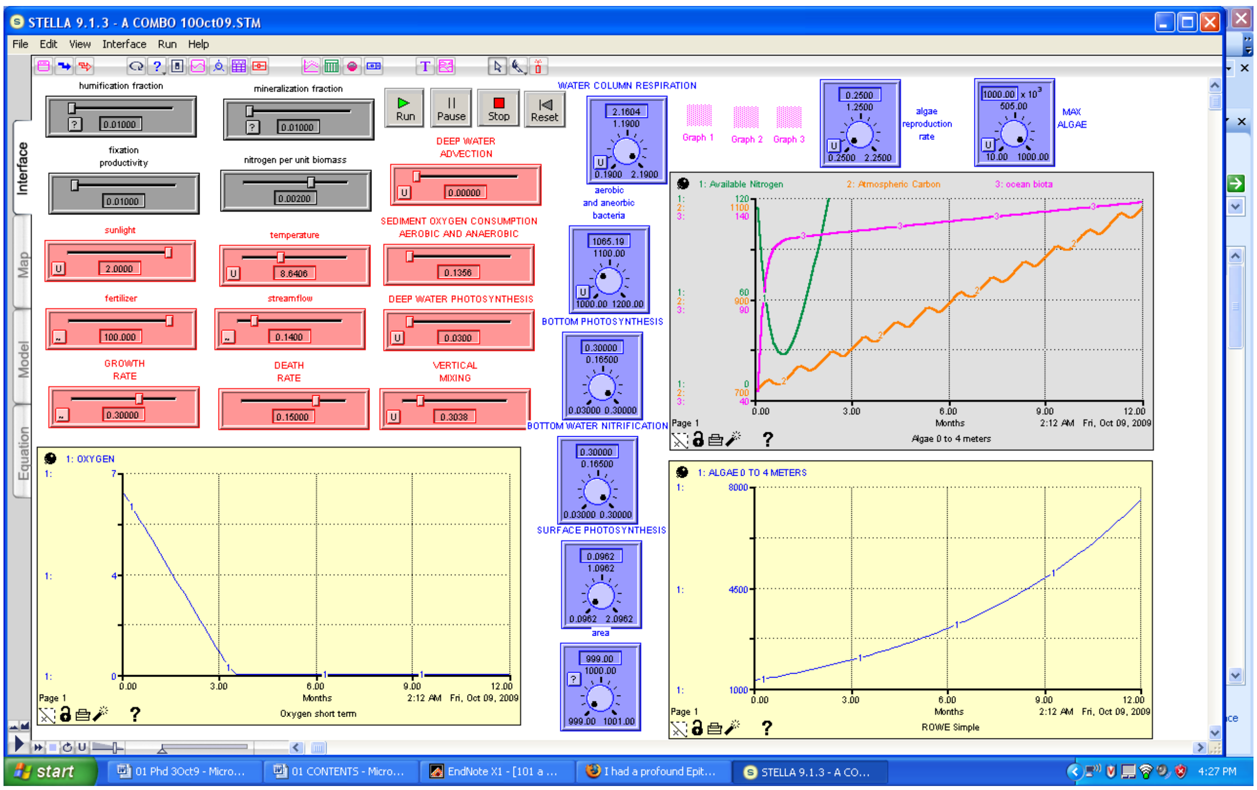


Figure 73. Second Graphical Solution of Combined Modified Model with Sliders and Knobs

The complexity of the figure and the inability to ascertain determinative values of the model require the parts to be enlarged for the ease of reading and understanding. Enlargements of parts are shown in Figure 76, 77, and 78.

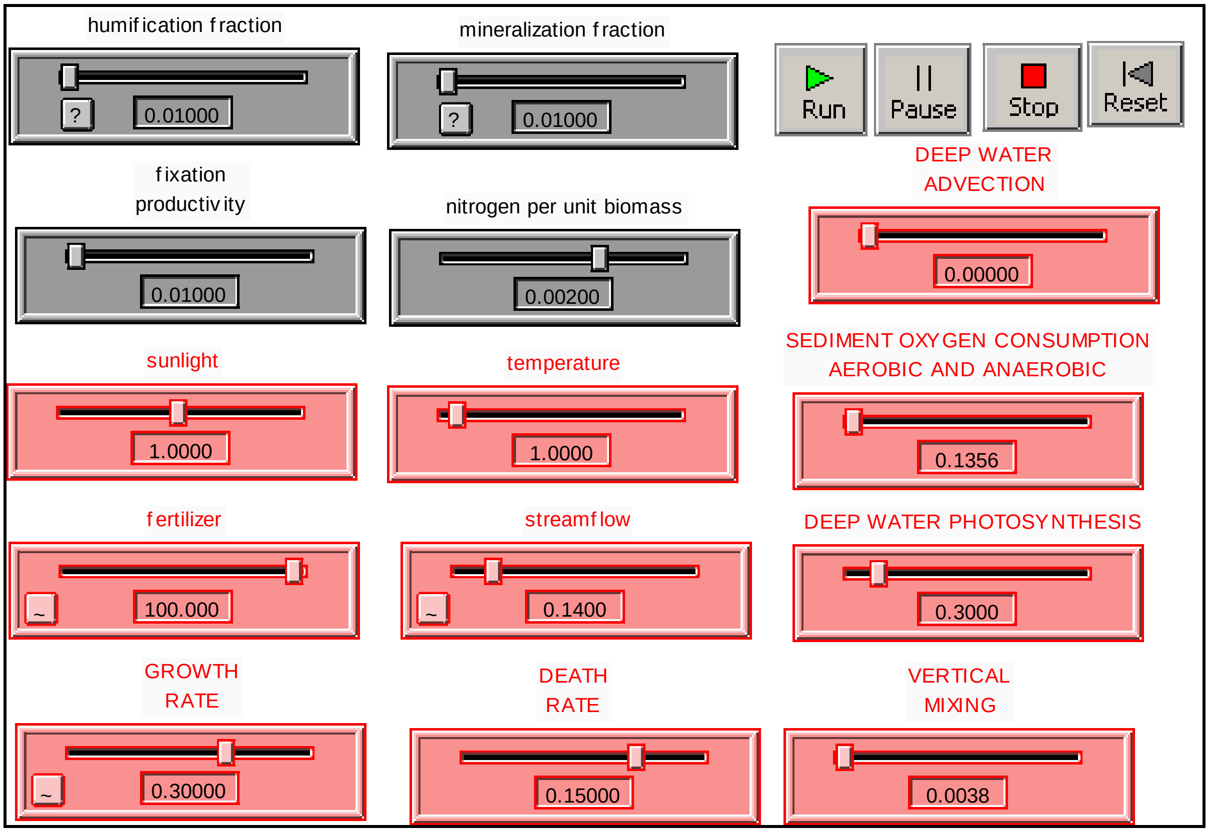


Figure 74. Enlarged Sliders

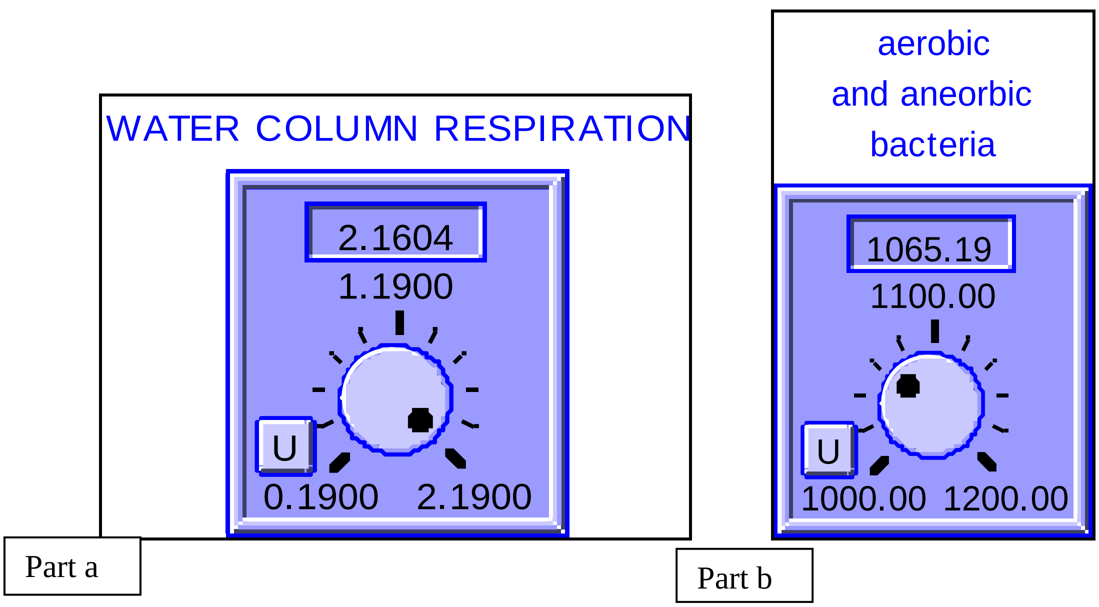


Figure 75. Water column respiration; Part b: aerobic and aneorbic bacteria

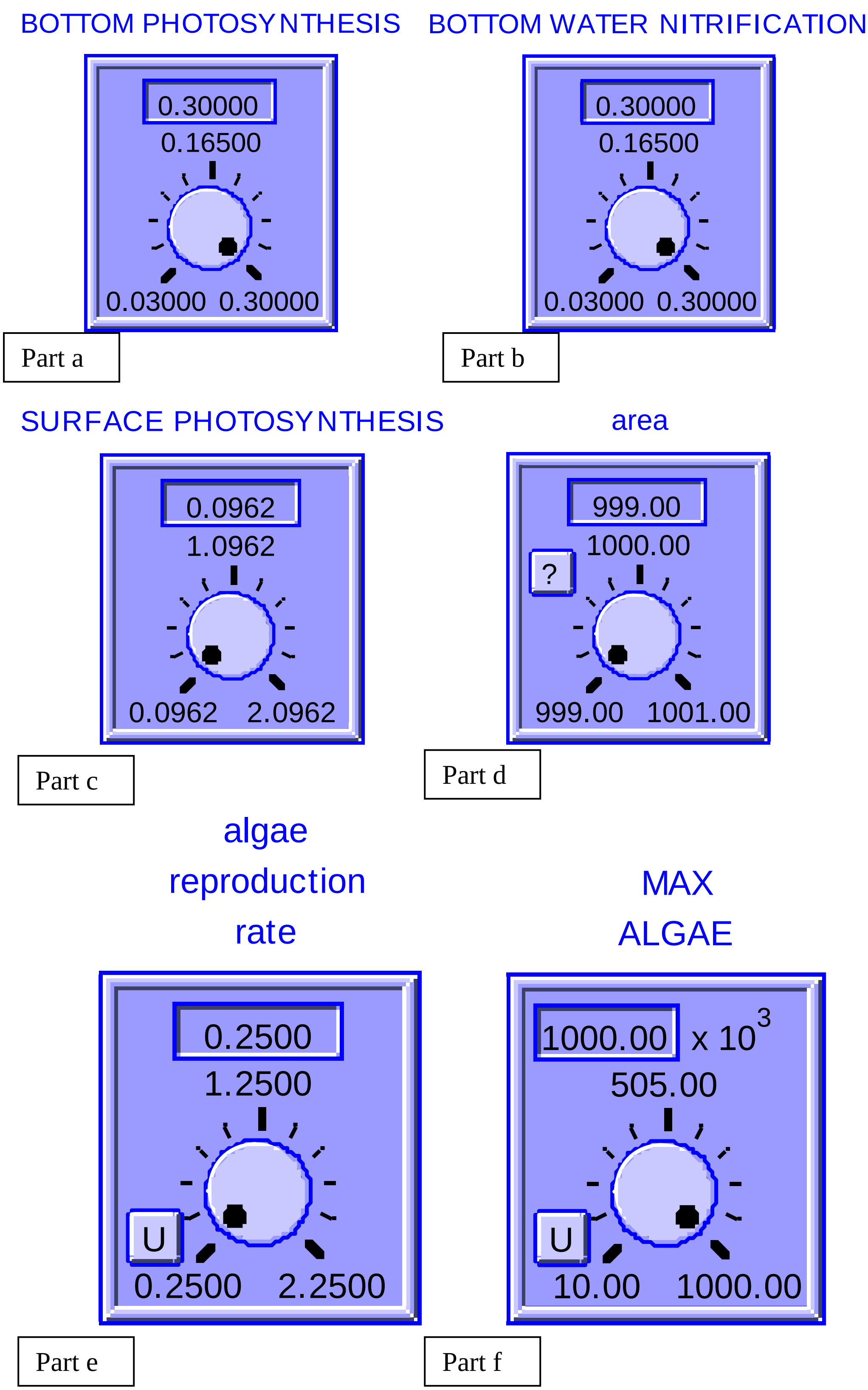


Figure 76. Parts a to f, Enlarged Knobs, pictures of specific controls

Changing all variables is not presented here, but two important variables shall be changed as an example to investigate the model and results. The deep water photosynthesis when set at 2.0 yields the following graphical solution as shown in Figure 78. This is a change from Figure 78 showing a declining dissolved oxygen level to zero. Models created with minimal data must have their performance tested in the mind by logical analysis. Deep water photosynthesis is set to one for normal. To increase photosynthesis the slider must be set at a value higher than one. In this instance the value is set to 2.0 for dissolved oxygen to increase. Dissolved oxygen is 0-8 in the normal range and 9 for super saturated (Campbell, N. A. 1996). Models will vary as shown below depending on the relationship to other variables.

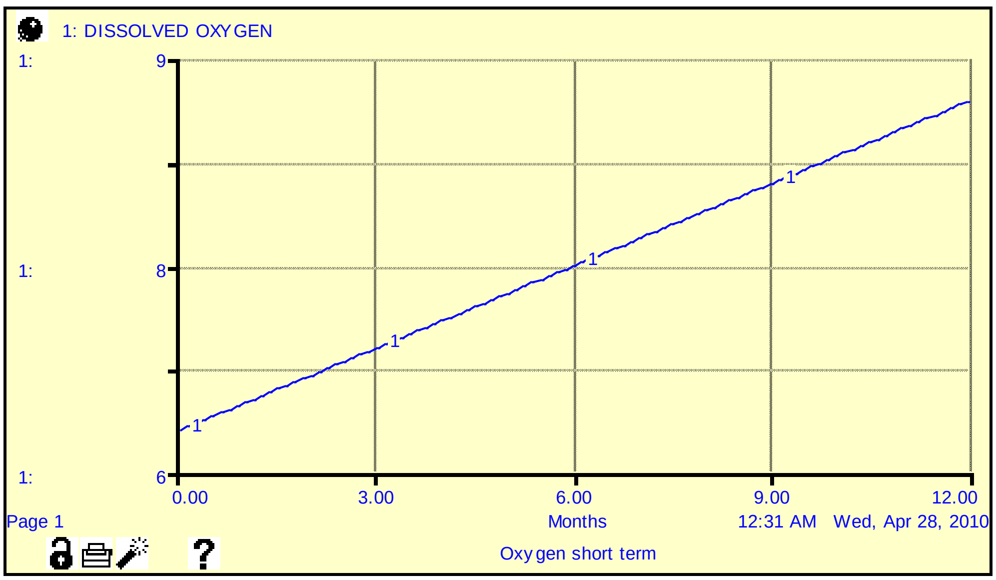


Figure 77. Increasing Oxygen Over 12 Months

Comparative graphs can be created to show the trends created when variables are changed. Keeping the photosynthesis setting for line 1 as 0.3, generate line 2 with 0.325, line 3 with 0.35, line 4 with 0.4, line 5 with 0.45 and line 6 with 0.5. The following comparative graph is shown in Figure 78. The x axis is set to equal divisions of four, a model feature.

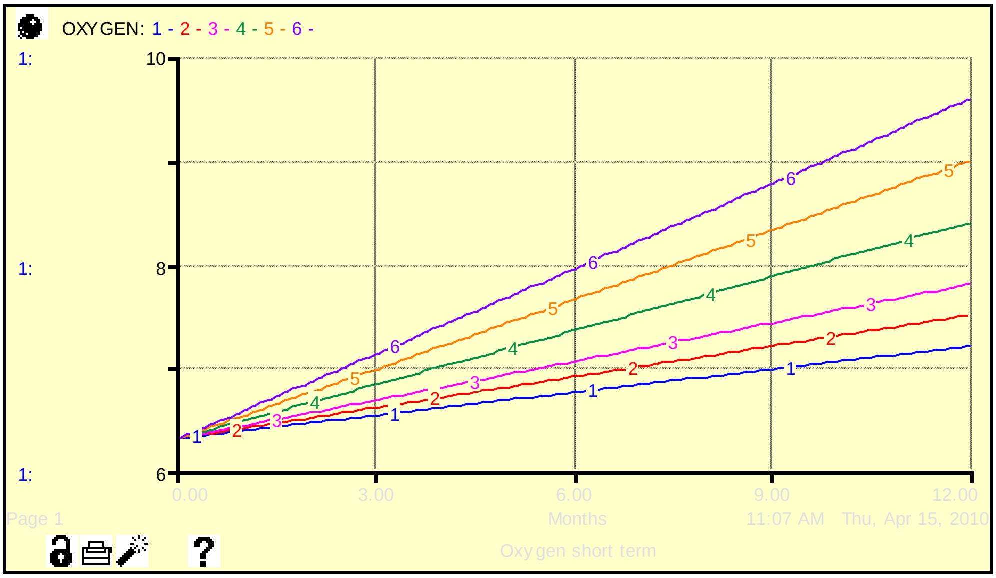


Figure 78. Increasing Deep Water Photosynthesis

If we keep the setting for photosynthesis for line 1 as 0.3 for the value of deep water photosynthesis, generate line 2 with 0.2, line 3 with 0.1, line 4 with 0.05, line 5 with 0.025 and line 6 with 0.0125. The following comparative graph is generated as shown in Figure 79.

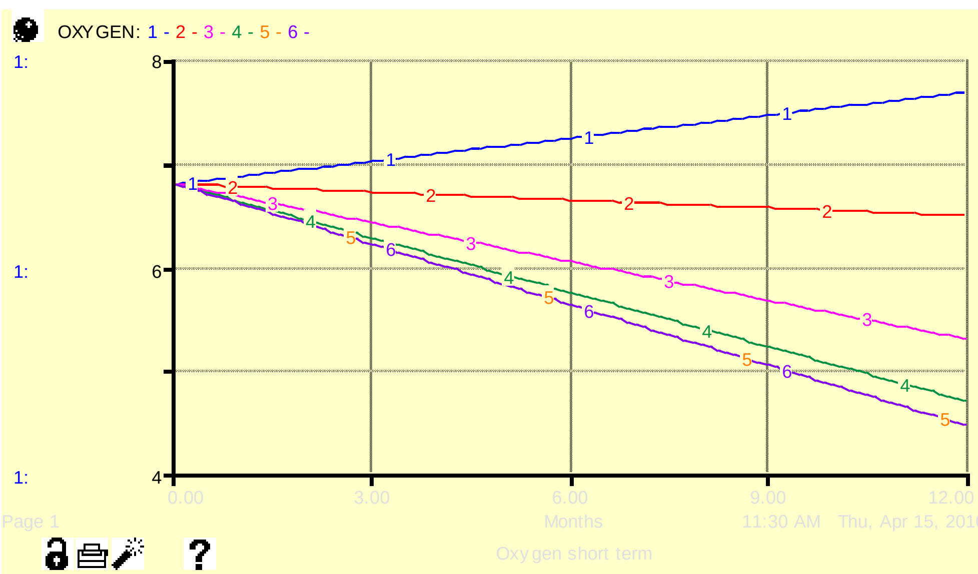


Figure 79. Reduction of Deep Water Photosynthesis

Deep water photosynthesis was shown in the Rowe model as a percentage and dissolved oxygen was shown in ppm. We need data to load into the model, but the model in this instance comes first. A second variable shall be bycatch.

Bycatch was discussed earlier in this work. It was stated that bycatch became detritus and detritus was broken down by aerobic and anaerobic bacteria and the common sense approach is that this would reduce the oxygen content in the water. Sediment oxygen consumption, aerobic and anaerobic, is a good description of this process. Returning the models to reset position and running the model gives the base line 1 the same procedure that used with deep water photosynthesis will be repeated.

If we keep line 1 as 0.1356 for the value of sediment oxygen consumption (aerobic and anaerobic), generate line 2 with 0.0, line 3 with 0.5, line 4 with 1.0, line 5 with 1.5 and line 6 with 2.0. The following comparative graph is generated as shown in Figure 80.

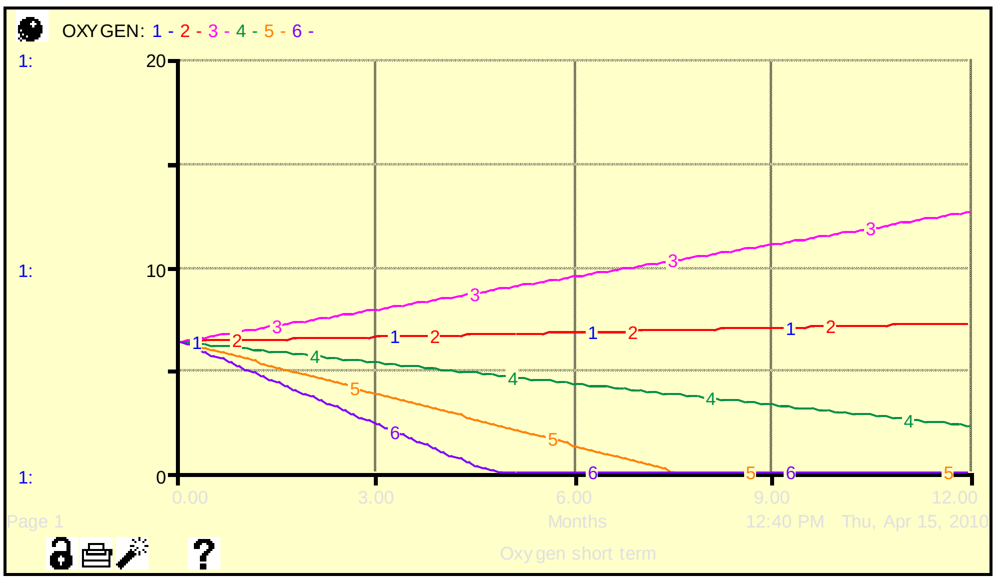


Figure 80. Bycatch or Detritus Added To Water

The results for varying sediment oxygen consumption aerobic and anaerobic line 1 (0.1356) and line 2 (0) show little or no change in the oxygen content. This reinforces the concept that low or no sediment oxygen consumption does not affect the oxygen content. The next observation is that line 3 (0.5) actually shows an increase in the oxygen content. This could be an unacceptable result, unsupported by logic or science. It could also be that bycatch or detritus is the same as adding nutrients to the water body which increases the growth of algae

which produces oxygen. Lines 4 (1.0), 5 (1.5) and 6 (2.0) show the increase of bycatch (detritus) reduce the amount of oxygen in the water. The oxygen content would increase because a little algae is good; but too much algae triggers eutrophication because the algae bloom triggers the runaway growth of algae which at demise turns into detritus which falls to the bottom of the water column making it necessary for aerobic and anaerobic bacteria to consume depleting oxygen and triggering the hypoxia zone (Rabalais, N. N. 2000).

If we keep the setting for sediment oxygen consumption for line 1 as 0.0 for the value of the growth rate, generate line 2 with 0.1, line 3 with 0.2, line 4 with 0.3, line 5 with 0.4 and line 6 with 0.5. The following comparative graph is generated as shown in Figure 81. Algae are in km^2 and the x-axis is in three month intervals.

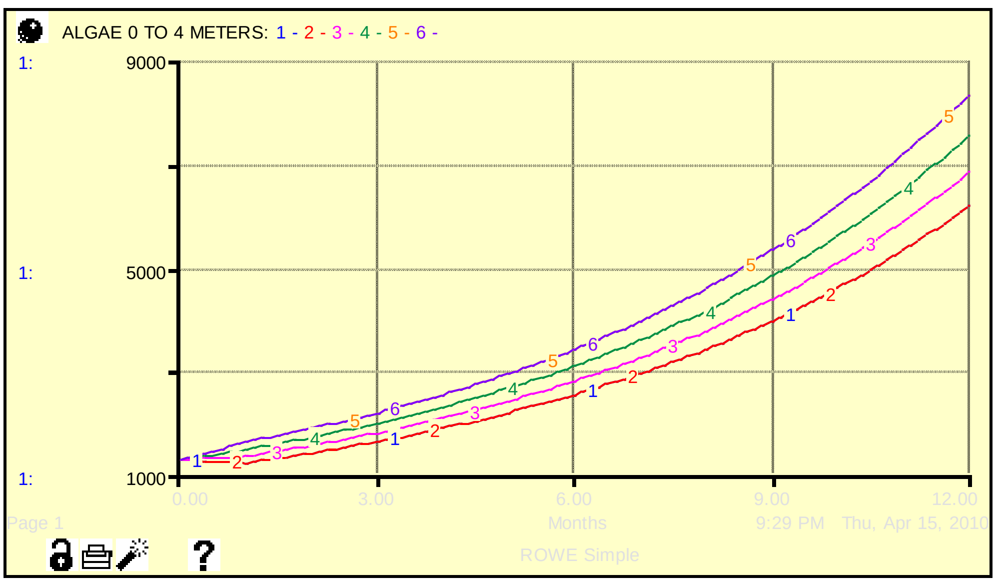


Figure 81. Growth Rate (0-0.5) and Algae

These are interesting results. The concurrence of lines 1 and lines 2 indicate a growth rate which is low results in algae curves which are overlay each other. This would indicate that low growth rates would not create rapid increases in algae growth. The concurrence of lines 5 and lines 6 indicate a high growth rate yields lines which overlay each other. This would indicate that algae blooms of very high growth rates reach a rate of maximum production.

Logically, this would be consistent with algae in an environment of saturated nutrients would be limited by growth rate. Algae which are at the maximum rate of growth are limited by the available nutrients or the ability to absorb them and are consistent with logical analysis. Lines 3 and 4 indicate growth rate latitude. The organisms are within the band of too little or too much and can display normal growth patterns. This graph shows algae in km^2 and the x-axis in three month intervals. This displays the change in algae growth and sediment oxygen consumption.

If we keep line 1 as 0.0 for the value of sediment oxygen consumption aerobic and anaerobic, generate line 2 with 0.1, line 3 with 0.3, line 4 with 1.0, line 5 with 1.5 and line 6 with 2.0. The following comparative graph is generated as shown in Figure 82.

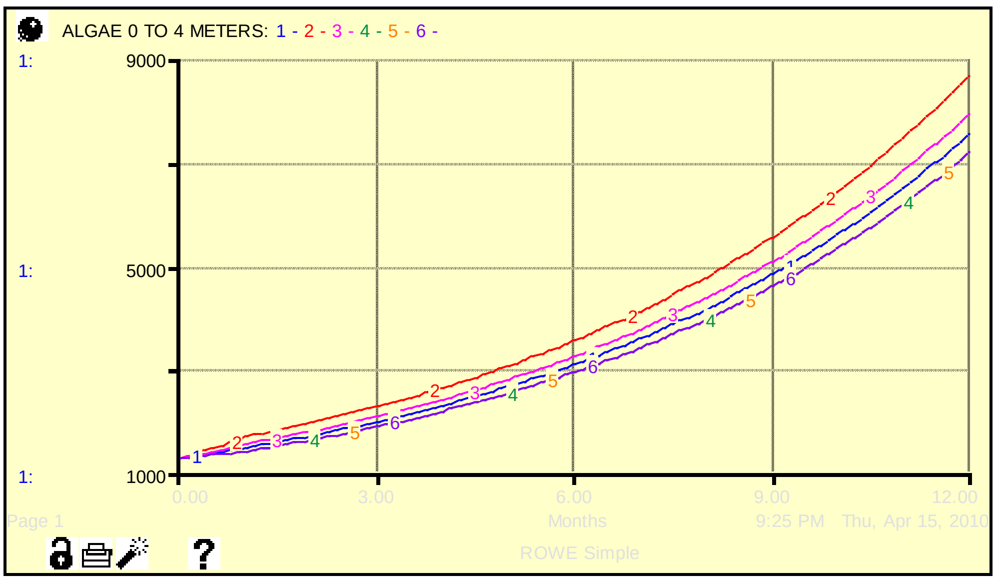


Figure 82. Death Rate and Algae

This solution would at first glance be an anomaly. Examination of the graphs reveal line 1ine 1 (0.0) as a middle of the solution system. As the rates of death increase, it seems incongruous that algae size would increase. This solutions set can not be logically explained and the examination of death rate versus size of algae would bear more scrutiny. As the death of algae occurs because of a normal maturation, it is possible that the algae would demise and the body would sink allowing the remaining algae to be in a more favorable competitive position.

The death rate could rise because the mass of the algae blocks the sunlight and exhausts available nutrients increasing the death rate. The model solution demonstrates incongruous results and points to a problem area. Algae are in km^2 and the x-axis is in three month intervals.

The other variable to illustrate here, for example, is mixing. Mixing may reduce or completely eliminate the growth of algae. The Rowe model starts mixing at 0.0038 which was assumed out of the initial Rowe model (Figure 24). Setting line 1 at (0.0038), line 2 at (1.0038) and line 3 at (2.0038) it is instantly observed that all lines overlap as shown as Figure 83.

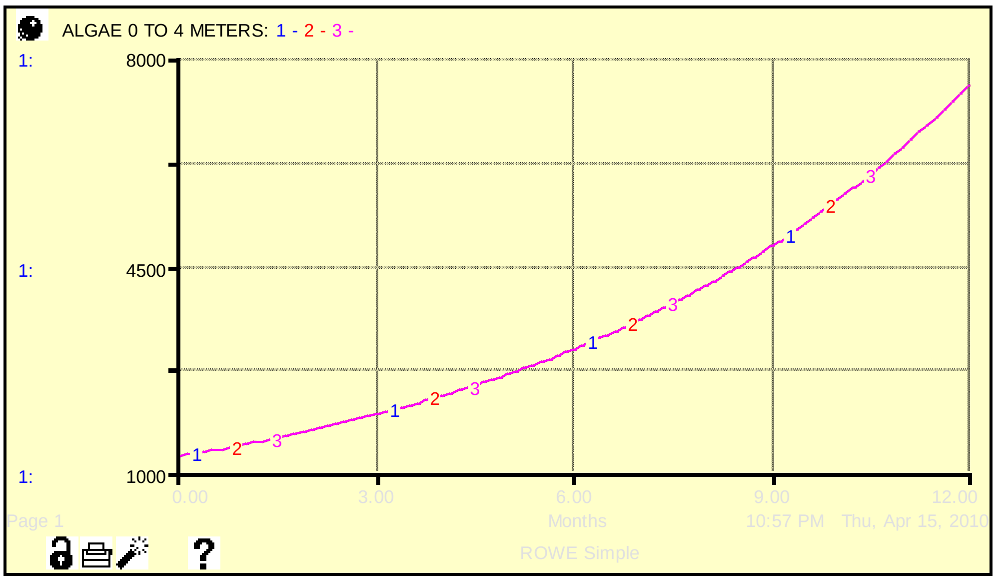


Figure 83. Mixing, the Overlay Paradox

This result is illogical and can not be accepted in lieu of the smaller than expected discussion on page 139 of this work where the “dead zone” was reduced because of mixing. Then it was remembered that “mixing” was assumed out of the initial Rowe model. Mixing in the combined model would have insignificant to no effect of the algae graph. The model was successful in pointing out a void in the analysis. If we are to consider mixing, a new model will have to be created. The essential elements of the model will have to be considered.

5.4 Elements

The desire herein was to create a theory based model. A model was created where growth rate of algae, death rate of algae, maximum growth rate, stream flow, sunlight, temperature and mixing could be varied in the model. The objective was to create a model where some event such as mixing would eliminate or multiply the effect of mixing. The following model (Figure 84) was created to simulate this physical property of the ecological system. Graph 1 and Graph 2 diagrams are devices which are used to hide and display graphs.

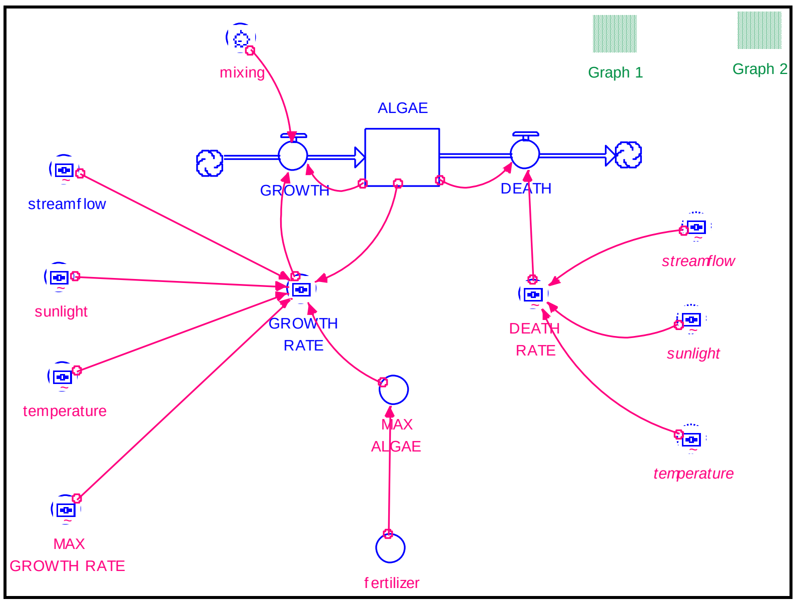


Figure 84. Algae Growth

What is desired is to determine an appropriate graph of algae growth for the time period selected. If we know the past range of algae growth in area then we can set several target numbers. Let us set the number of km^2 at 1,000 km^2. We have a second point of 3,000 km^2 that our graph would hopefully pass through in the year 2010. We can use a sensitivity test to determine the best fit. This term does not agree with the ordinary use of sensitivity, but it suits this purpose. Testing algae growth to determine sensitivity was accomplished in the model by going to the run menu and following the drop down instructions as shown in Figure 85and 86.

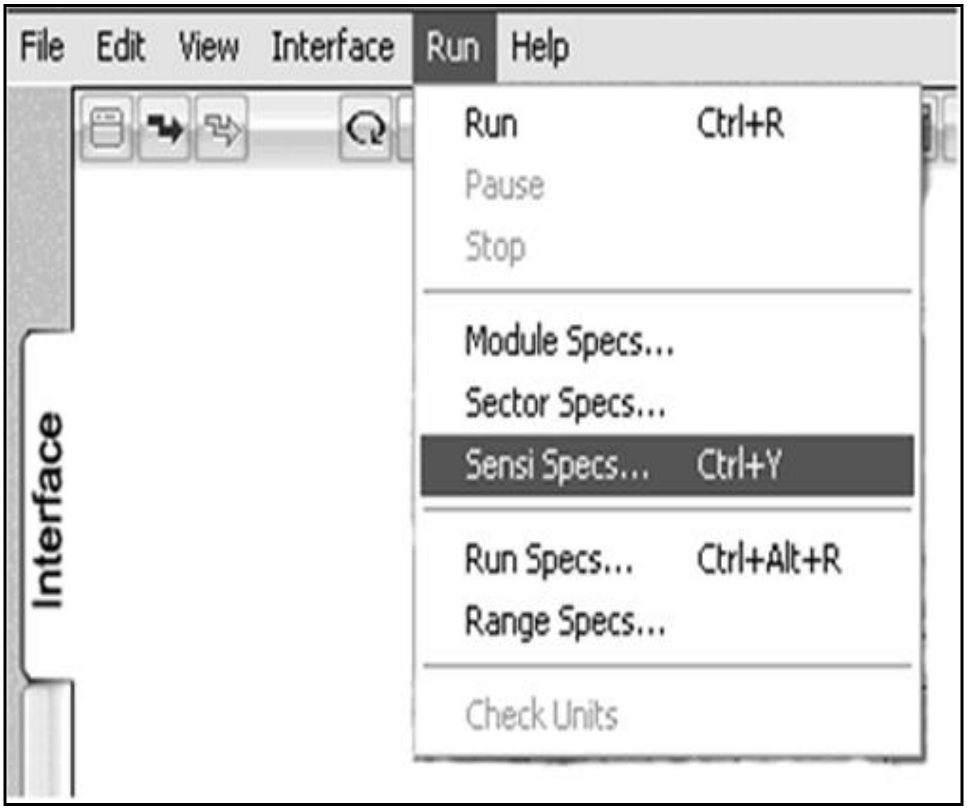


Figure 85. Sensi Specs Interface

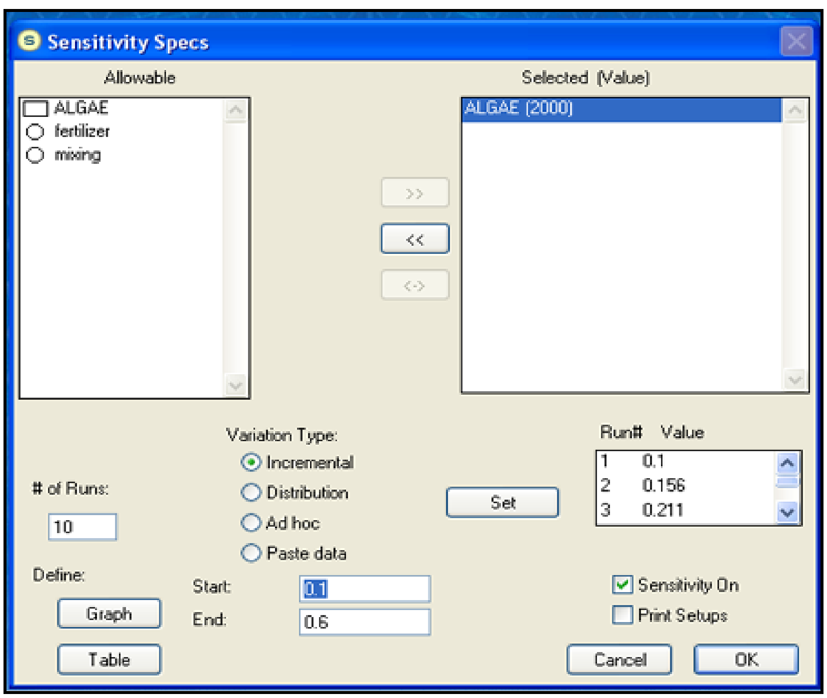


Figure 86. Sensi Specs

This is a method of curve fitting. By running the sensi specs aspect, you test variation from 0.1 to 0.6 and make 10 runs approximately 0.056 apart. This tests whether the graph is

uniform over the 0.1 to 0.6 range. Once the fit is established, we must determine the method of creating an equation which will affect mixing.

STELLA® generates a differential equation in word form. This equation can be a starting point for the purists who prefer pure mathematical solutions. The equations are available when you click on the equations tab.

MAX_GROWTH_RATE* (1- (ALGAE*streamflow*sunlight*temperature/MAX_ALGAE)).

The equation in standard form was created from the modeling process by the author.

$$A_{GR} = A_{MGR} * (1 - (\frac{A_{MASS} * SF * SL * T}{A_{\max}}))$$

where: A_{GR} = ALGAE GROWTH RATE calculated

A_{MGR} = ALGAE MAX GROWTH RATE maximum growth rate

A_{MASS} = ALGAE MASS AT A GIVEN TIME estimate of algae mass in hypoxia zone

SF = STREAMFLOW

SL = SUNLIGHT

T = TEMPERATURE

A_{MAX} = MAXIMUM ALGAE AT ANY GIVEN YEAR estimated

This is not the most complicated equation, nor is it intended to be. It is a version of the present value equation establishing the relationship of the area of the algae mat at a given time in relationship to a past or future time.

Data from Lee (2007) were used to set parameters for the model for sunlight, temperature and nutrients and made a part of the growth and death portion of the model. The model was set to a 12 month time frame and the algae graphic was for km^2. Mixing was set to 1. This model is for the purpose of demonstrating the feasibility of modeling the size of the algae mat in the Gulf of Mexico as shown in Figure 87.

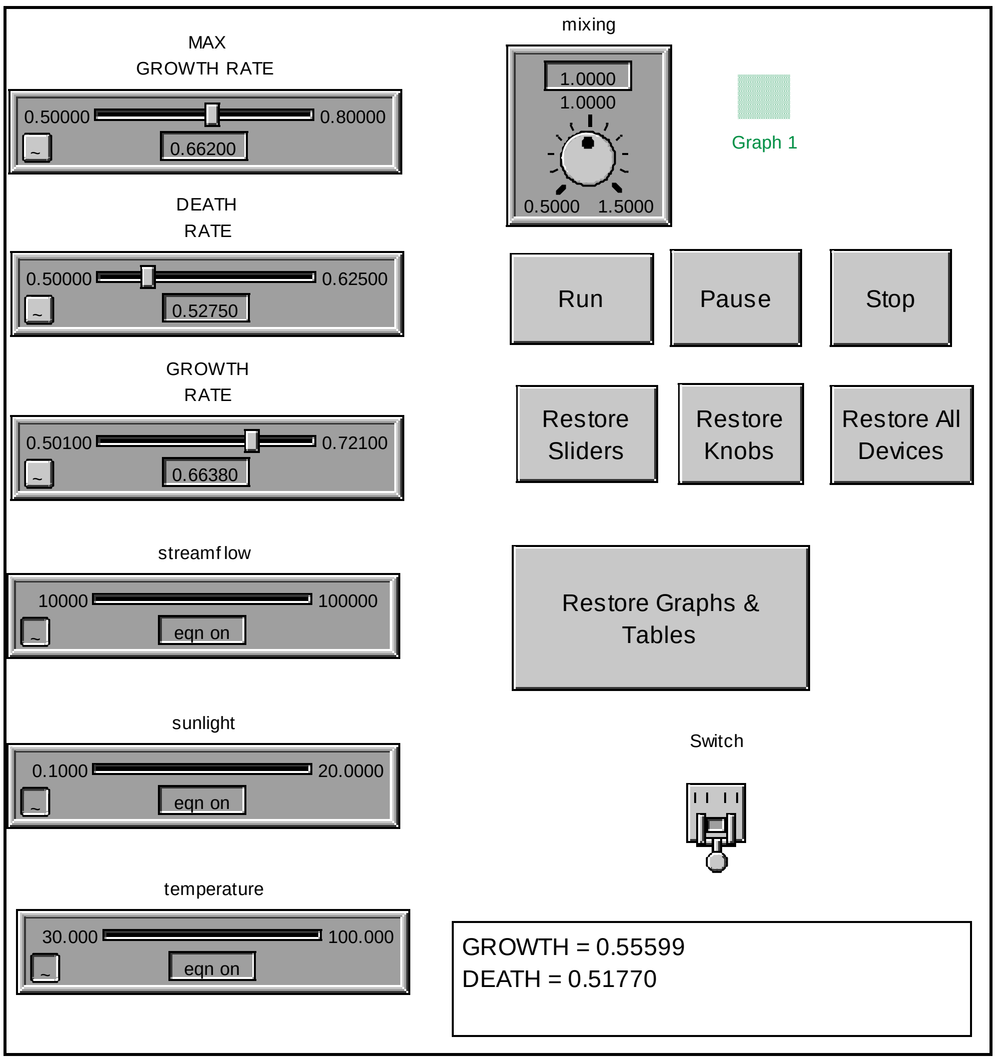


Figure 87. Interface for Algae Model

The control mechanisms are the devices which are used to control the relationships of the variables. A sensitivity analysis was run. The sensitivity analysis checks for the smoothness of the curve and displays the ability to perform a curve fitting process with the model. It is important to know that the model is capable of eliminating the hypoxia zone in the Gulf of

Mexico or accenting that zone as shown in Figure 88. Mixing is set to greater than one as shown in Figure 88.

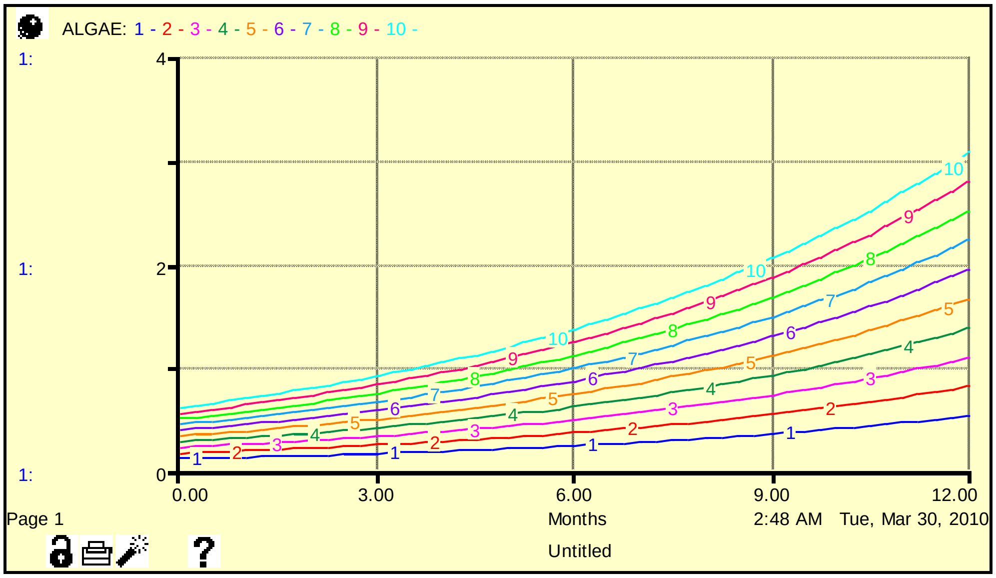


Figure 88. Curve Fitting Upward Trend

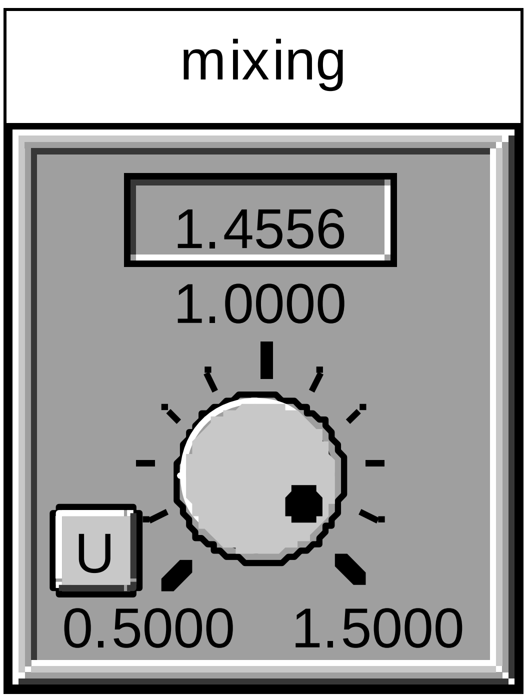


Figure 89. Mixing Set to Greater Than One

This results in the following and shows the feasibility of modeling the size of the hypoxia zone with mixing included as a parameter as shown in Figure 90.

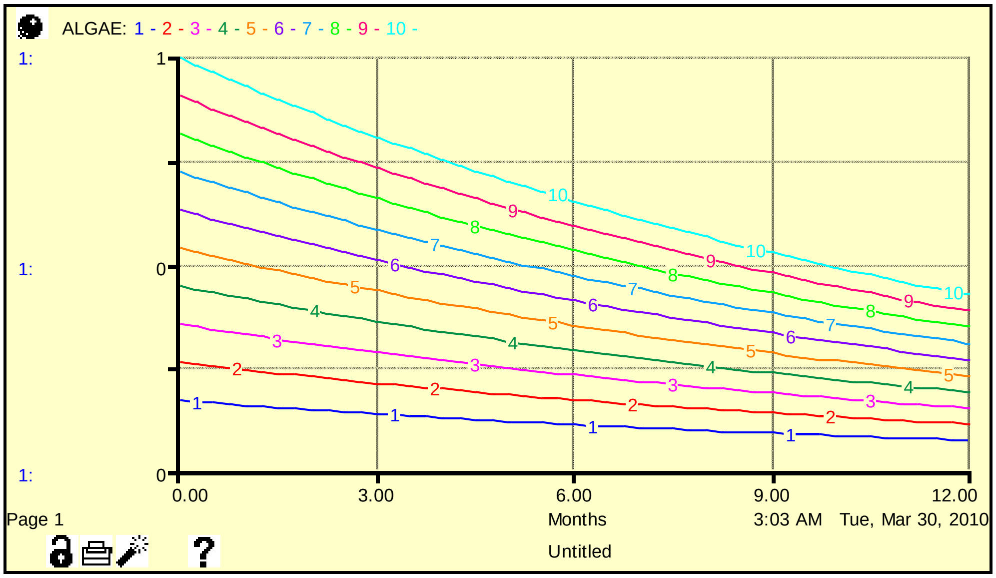


Figure 90. Mixing Decreases the Size of Hypoxia

Using the run and pause features the model will run, then when it is paused the model will be subjected to less mixing. Then, the model will run again to see the results. After the model has run, then it will be paused and mixing will be increased to greater than one as shown in Figure 91. Units for algae are in km^2. The graphical solution of a change in mixing is shown in Figure 92.

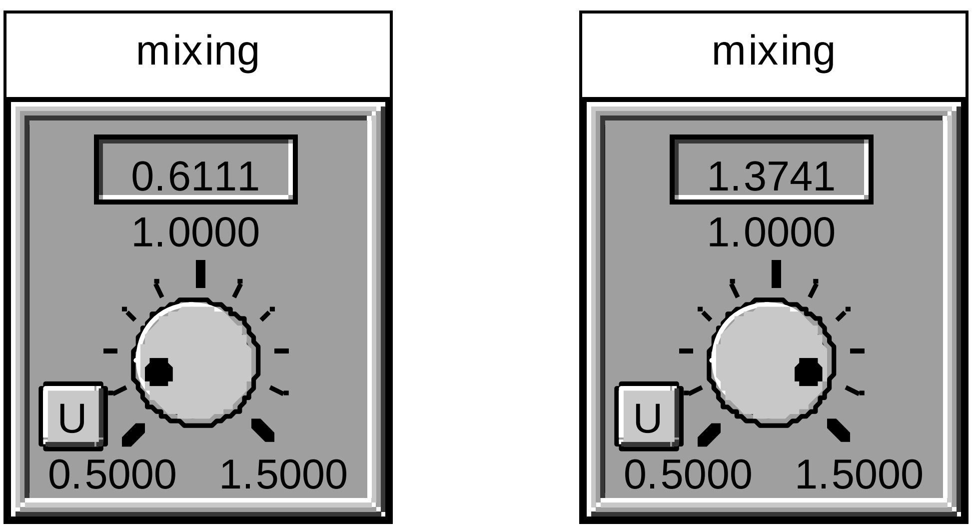


Figure 91. Enlarged Knobs Showing Changes

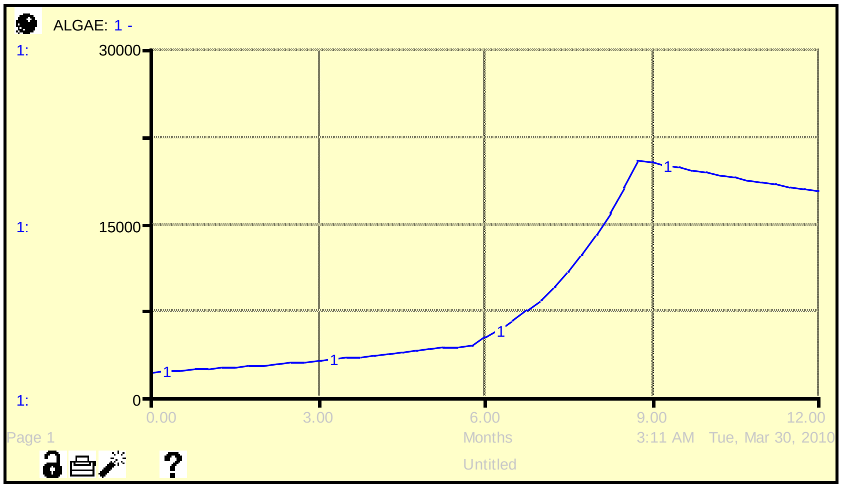
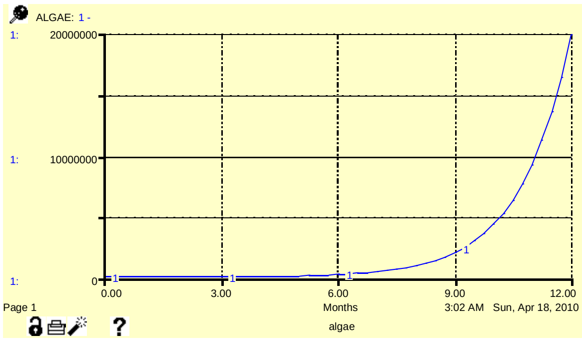


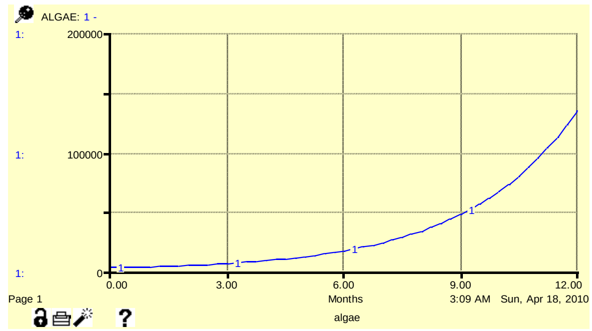
Figure 92. Effect of Mixing

It is possible then to model the effect of mixing on the size of an algae growth. As mixing decreases the size of the algae mat increases and as mixing increases the size of the algae mat decreases. All that is needed are data to calibrate the model to a specific system. The models are set to specific scale, but only demonstrate trends. Increased mixing decreases the size of the algae mat and decreased mixing increases the size of the algae mat.

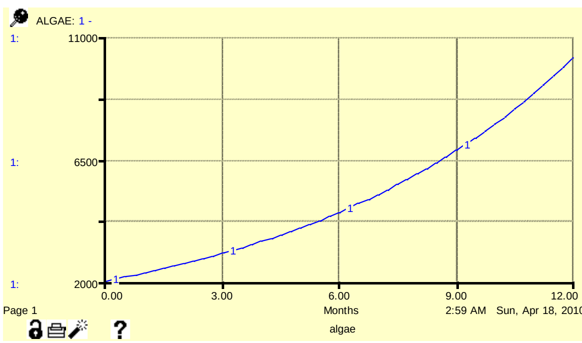
If you show mixing as constant throughout the year the curves will have a smooth appearance as shown in Figure 88. Mixing of 0.5 and 0.75 are not realistic as the model results in km^2 exceed any measured numbers and are not reflected in reality. When mixing is set to 1, the model projects an algae mat size of less than 11,000 km^2. Increasing mixing to 1.25 reduces the size of the algae mat to a little over 2,000 km^2 and an increase in mixing to 1.5 reduces the size of the algae mat to approximately 600 km^2. While more data are desired, the modeling technique reveals a trend of changing one variable to affect another in a logical manner. The setting of the graph was changed to comparative and mixing was changed during the year. The is shown in Figure 93



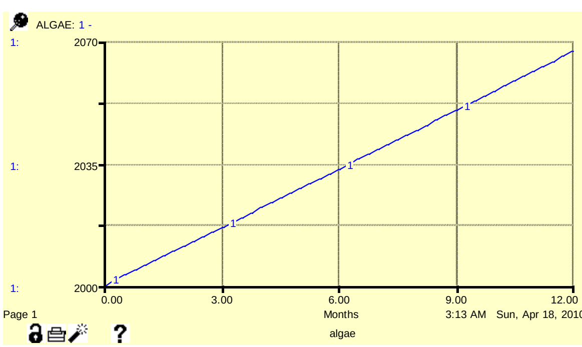
mixing set to 0.5



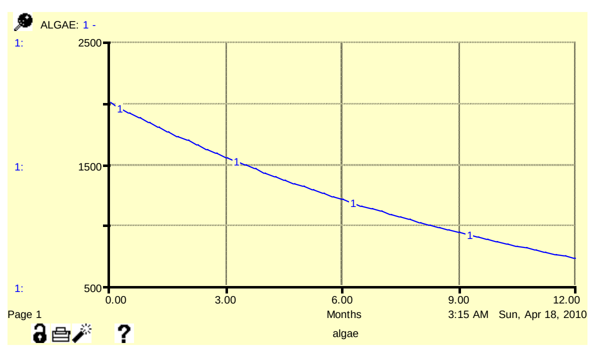
mixing set to 0.75



mixing set to 1



mixing set to 1.25



mixing set to 1.5

Figure 93. Smooth Curves with Mixing Is Constant

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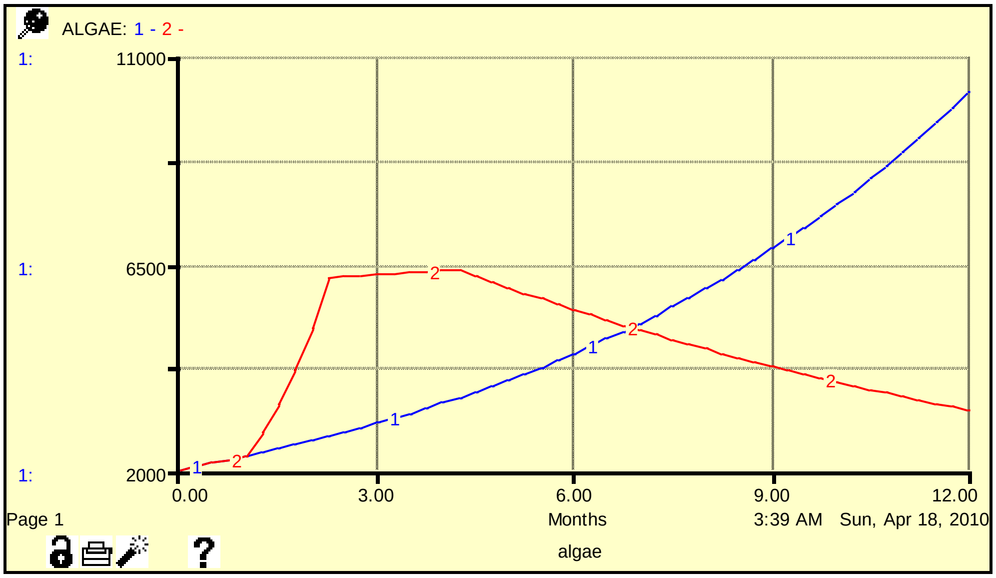

Figure 94. Mixing Changes during the Year.

For line 1, mixing was set to 1. For line 2, mixing was set to 1 until the first increase departure from line 1. Mixing was set to 1.3 when the algae mat graph was a mesa at approximately 6,500 km^2. The algae mat declined to approximately 3,000 km^2 in month 12 when mixing was set to 1.5. Setting mixing at higher numbers was not done as it was desired to keep the results conservative.

5.5 Discussion

The models demonstrate the hypoxia zone must have stratification, must have nutrients, must have algae, must have sunlight, and must have appropriate temperature. If hypoxia is triggered by detritus (including algae) falling to the bottom consuming oxygen it can be disrupted or eliminated by the effect of wind blowing across the surface of the Gulf of Mexico strongly enough to overcome the Mississippi River Plume and generate Ekman spirals strong enough to allow upwelling and mixing. Data on the various elements such as mixing which affect the size of the hypoxia zone are not gathered with sufficient accuracy to be useful (Cracknell 2001) in long term prediction efforts. A model diagram (Figure 71) was generated

which based algae growth on the variables of stream flow, sunlight, temperature and mixing. While it will be necessary to understand the Ekman currents, the stratification of the Gulf of Mexico water, the effect of wind and currents, it is possible to visualize the effect of mixing through modeling. The model demonstrates the area where data needs to be gathered. As more Gulf of Mexico data becomes available and models are reviewed and refined the model will be more valid and certification will be more certain. Modeling which mimics reality and is supported by the prediction of a hypoxia zone being reduced by mixing points will be more precise. To make the model useful, one must be aware of the limitations of the model. In this instance the graph can be set to any unit and while the model may generate a graphical solution this modeler must inform the reader that the model is useful to show trends and relationships, but lacks sufficient data to be accurate.

This model shows that the postulations of the Western Camp and the Eastern Camp are not dissimilar. Different viewpoints can be reconciled with the model. This reconciliation makes available more opportunities for management of the hypoxia zone in the Gulf of Mexico. Thus, changing the model variables can suggest more efficient management techniques.

5.6 Biological Model

The purpose of developing a biological model is to simulate changing the feeding pressure predators place on algae and observe if changes could cause the trophic food pyramid to invert. The compounded biomass of heterotrophs often exceeds the biomass of autotrophs (inverted pyramids) (Gasol, J. M. *et al.* 1997). Menhaden and oysters are two notable examples. Modeling the reduction of predators would test if free energy would be converted to algae mass. How much and how long is not known with the available data. What is available is the data that each higher level of a trophic pyramid consumes at the rate of 1 unit gained for each ten units

consumed of the lower level (Campbell, N. A. 1996). Normal trophic pyramids and inverted pyramids appear as shown in Figure 95.

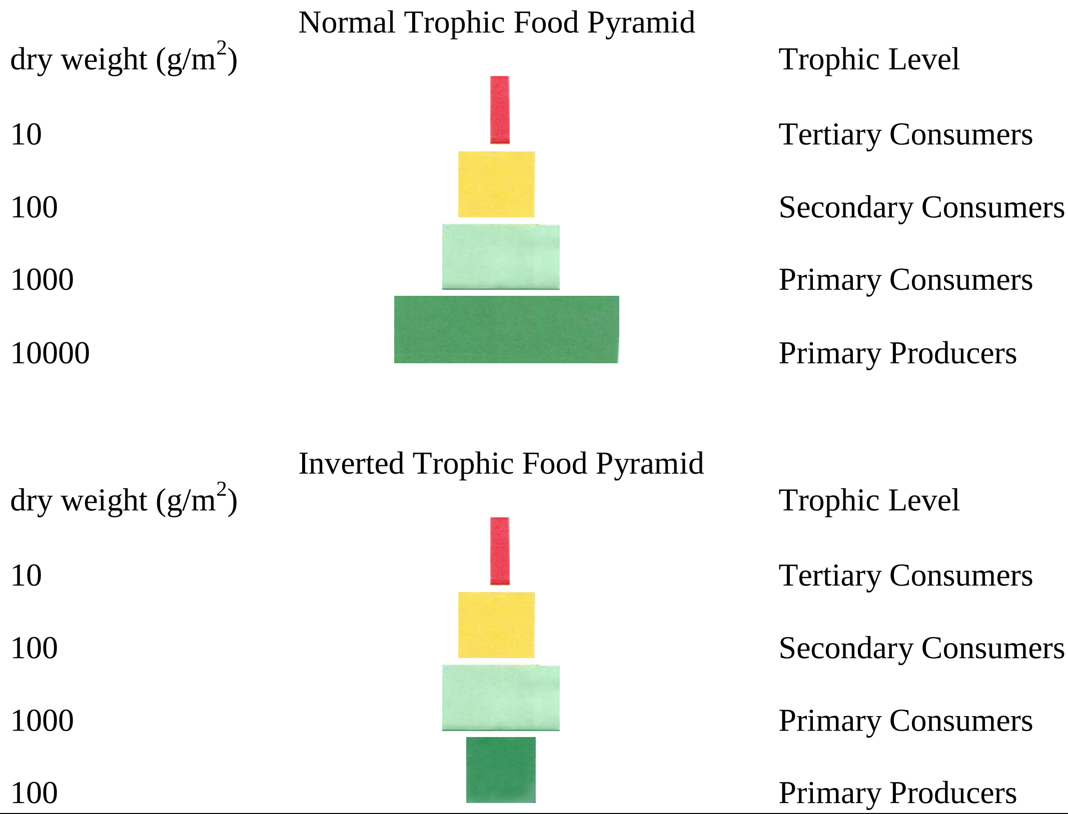

Figure 95. Normal and Inverted Pyramids

The normal pyramid only transfers 10% of the energy below to the next highest. In terms of biomass, the bottom level provides ten units of biomass to grow 1 unit of biomass for the level above. Energy pyramids can not be inverted, but biomass pyramids can. The normal biomass pyramid would look like the energy pyramid (Campbell, N. A. 1996). In an inverted biomass pyramid predators consume faster than the primary level of the biomass pyramid can reproduce.

Thus, if the inverted pyramid was the normal algae filter feeder trophic pyramid, reduction of the predators would reduce (if the harvest were large, the consumption rate could be close to zero) consumption of algae allowing the algae reproduction rate to generate algae blooms and trigger hypoxia zones (exactly the biological postulation of the Eastern camp).

Primary consumers (menhaden) could consume at greater than the 10 to 1 ratio. This could result in an inverted trophic food pyramid which resembles the following as is shown in Figure 96.

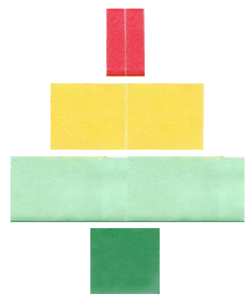

Figure 96. Inverted Trophic Pyramid

5.7 Inverted Trophic Pyramid

Menhaden relate to algae as predator to prey. The critical components of the predator prey models are the beginning population, birth rate, death rate, of both populations and the rate of competency of the predator. The harvest by man is a net output which acts to reduce the population or size of the menhaden level in this ecological system. The reduction in primary consumers would free energy which would not change the size of the energy pyramid, but would change the size of the base of the trophic biomass pyramid.

Choosing the size of the area for the model was based on the ability of menhaden to filter 4 (Franklin, H. B. 2007) to 7 (Luo, J. *et al.* 2001) gallons of water a minute per menhaden. The 7 gallons of water a minute filtering capacity of menhaden is conservative. The area of the water to be modeled was estimated at the amount of water one menhaden could filter (420 gallons an hour, 10,080 gallons per day, 3.68×10^6 gallons per year). The model is started with 1250 menhaden and after multiplying 1250 times 3.68×10^6 gallons per year and converting to km^2 an area of 1,000 km^2 was chosen. It was desired to show algae as rapidly reproducing and

menhaden with a slower reproduction rate. The reproduction rate of 1.25 was chosen for algae with an initial population of 5,000. The reproduction rate of .25 was chosen for menhaden with an initial population of 1250. A greater range of rates is possible, but nothing is gained and it becomes difficult to display graphically. The menhaden are efficient predators and consumption of large amounts of algae is necessary to gain one pound of menhaden mass (Campbell, N. A. 1996). A ten to one ratio is often used. This number is believed conservative. The STELLA model is shown in Figure 97.

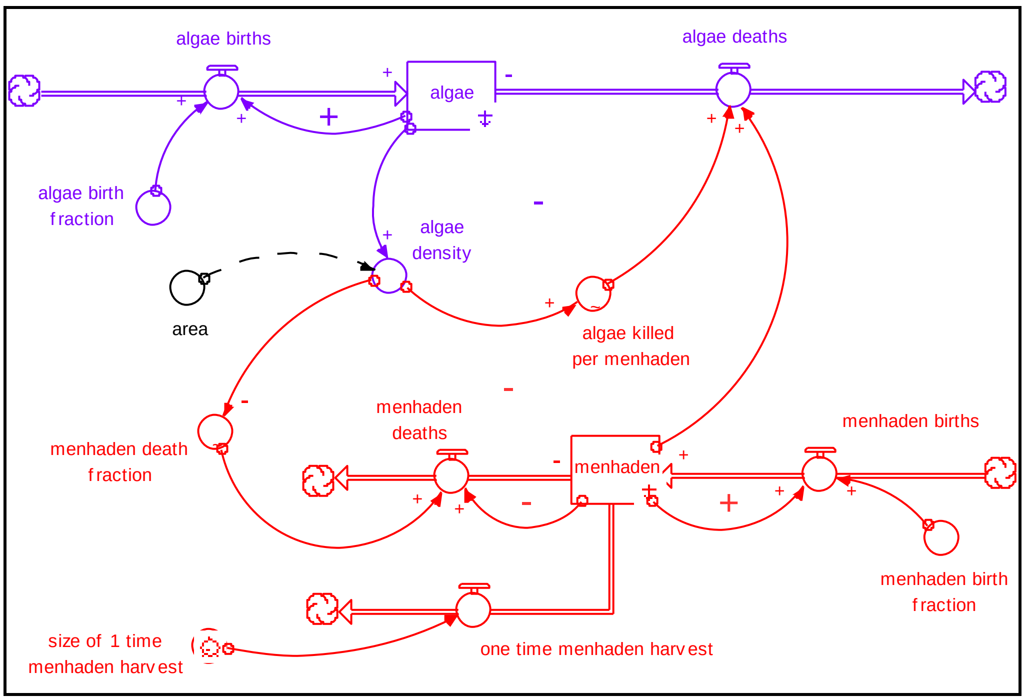

Figure 97. One Time Menhaden Harvest

Equations based on the numbers discussed were generated and are displayed below:

algae (t) = algae (t - dt) + (algae_births - algae_deaths) * dt

INIT algae = 5E4

INFLOWS:

algae_births = algae*algae_birth__fraction

OUTFLOWS:

algae_deaths = menhaden*algae_killed__per_menhaden

menhaden (t) = menhaden (t - dt) + (menhaden_births - menhaden__deaths - one_time_menhaden_harvest) * dt

INIT menhaden = 1250

INFLOWS:

menhaden_births = menhaden*menhaden_birth__fraction

OUTFLOWS:

menhaden__deaths = menhaden*menhaden_death__fraction

one_time_menhaden_harvest = PULSE (size_of_1_time__menhaden_harvest,4,1e3)

algae__density = algae/area

algae_birth__fraction = 1.25

algae_killed__per_menhaden = GRAPH (algae__density)

(0.00, 3.89e-305), (50.0, 50.0), (100, 100), (150, 150), (200, 200), (250, 250), (300, 300), (350, 350), (400, 400), (450, 450), (500, 500)

area = 1E3

menhaden_birth__fraction = .25

menhaden_death__fraction = GRAPH (algae__density)

(0.00, 0.94), (10.0, 0.66), (20.0, 0.4), (30.0, 0.35), (40.0, 0.3), (50.0, 0.25), (60.0, 0.2), (70.0, 0.15), (80.0, 0.1), (90.0, 0.07), (100, 0.05)

size_of_1_time__menhaden_harvest = 0

Personal conversation and permission to use the works of Bruce Franklin was given to give insight into the balance of Menhaden and the ecology of the Chesapeake Bay and the Gulf of Mexico listed in Appendix C.

5.8 Graphical Solution

For a zero harvest the equilibrium between algae and menhaden is a point as shown by Figure 98. Starting at the equilibrium position (initial menhaden position of 1,250 and initial algae position of 10,000) a onetime harvest of menhaden with the values of 190, 380, 610 and 750 will be graphically solved and compared for illustrative and informative purposes. This is an attempt to show how a small population of menhaden and algae would potentially react to an equilibrium disturbance.

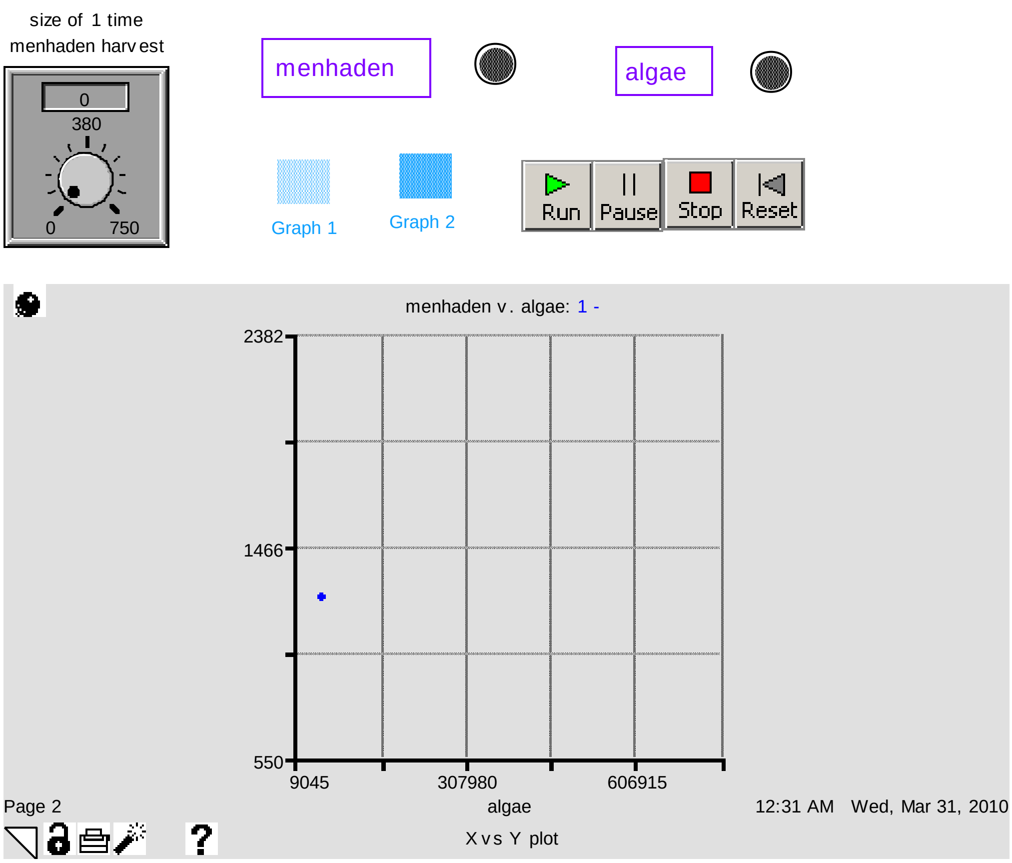

Figure 98. Equilibrium Point Solution

We would expect removal of 1 pound of menhaden to result in freeing energy to produce 10 pounds of algae. If our hypothesis of an inverted marine pyramid being a normal ecological

occurrence turning into a broad based trophic pyramid is correct, the model should reflect this trend. The reproductive cycles of menhaden is not known. There are thousands of species of algae, each with a reproductive rate which varies according to available nutrients, light, wind currents and a host of other factors and is not known. Bruce Franklin (2007) states menhaden clean 4-7 gallons of water per minute. It is unknown what weight of algae is contained in a gallon of water and it is unknown the harvest rate of algae by menhaden per minute. Thus precise modeling is difficult. However, results show model behavior is repeatable and provided suggestions for improvement of data collection, analysis and ecology management. Comparisons of one time relative menhaden harvests for 190, 380, 610 and 750 are displayed in Figure 99.

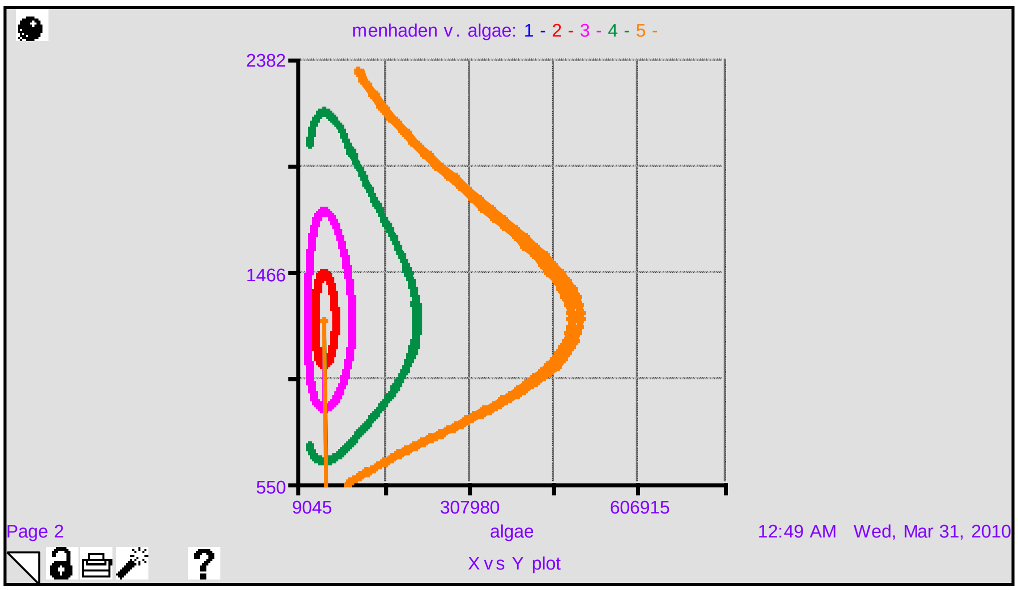

Figure 99. Comparative Graphical Solution

Considering the graphical solution of the 190 (shown in Figure 100) and 380 (shown in Figure 101) one time harvest over a twelve month cycle reveals an oscillation. These oscillations should not affect the ability of the population of menhaden to recover, but would reduce the ability of the menhaden to filter the waters of the Gulf of Mexico. The 380 one time harvest is shown in Figure 101. Moving the one time menhaden harvest to 610 reveals the drop in the

numbers of menhaden and the corresponding rise in algae. Since the menhaden consume faster than the algae reproduce the model reflects this by showing the numbers of menhaden exceeding the number of algae. This is an inverted pyramid as shown in Figure 102. The next graphical solution is a 750 one time menhaden harvest as shown in Figure 103.

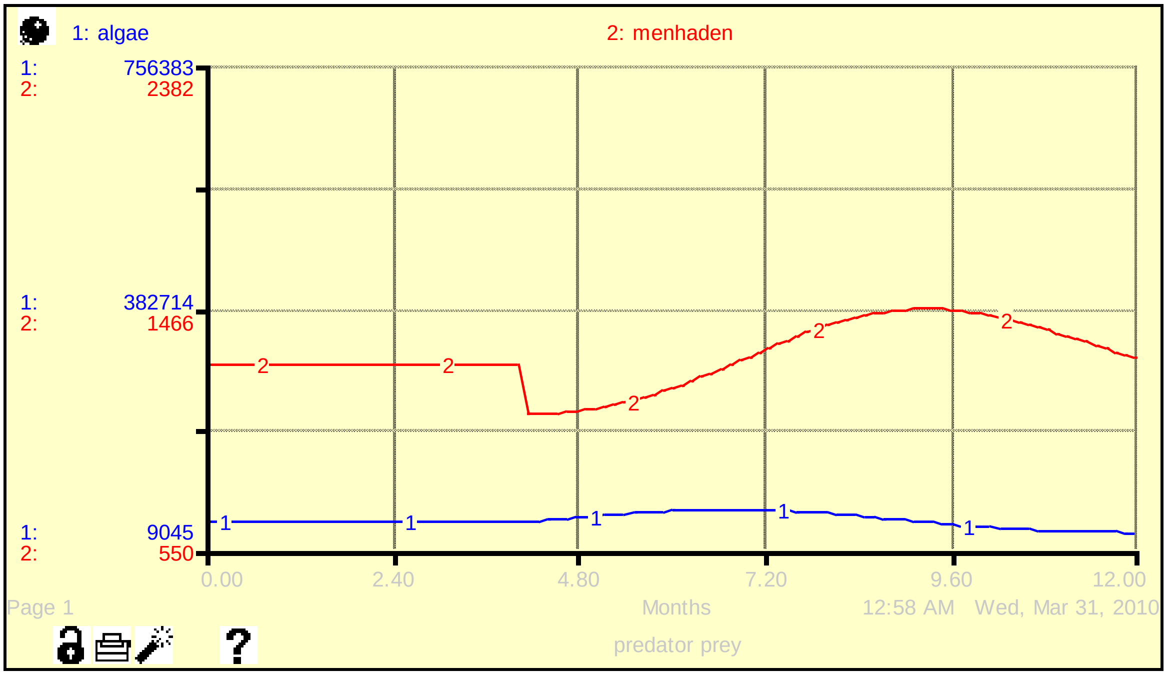

Figure 100. 190 One Time Menhaden Harvest

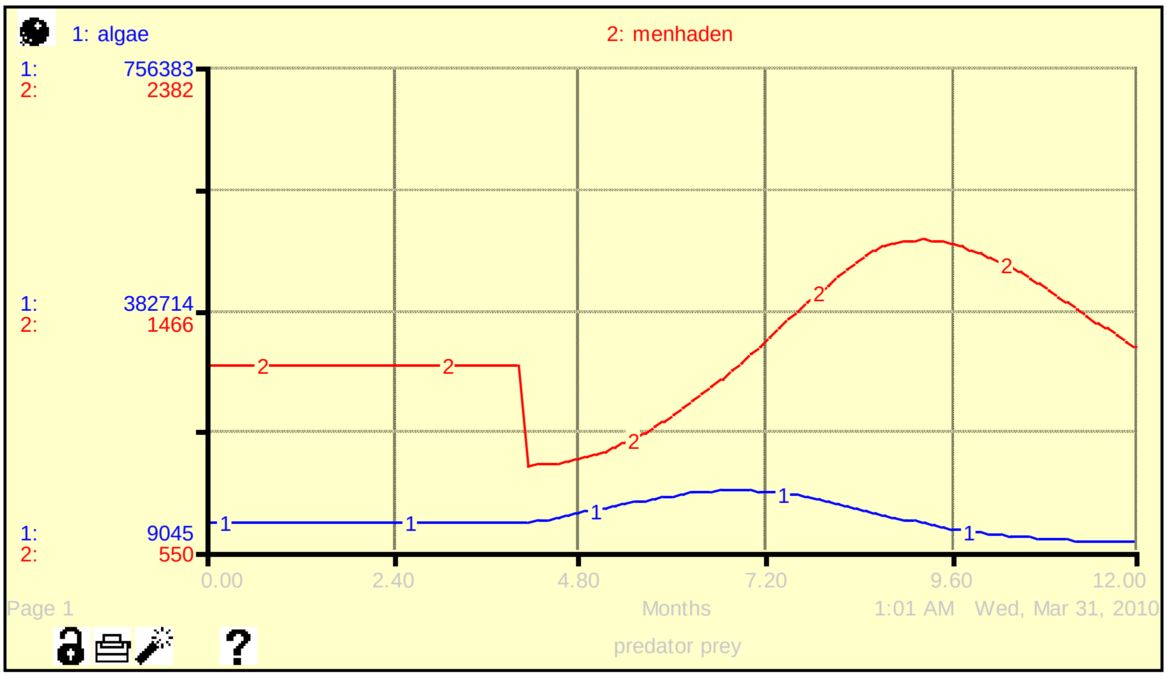

Figure 101. 380 One Time Menhaden Harvest

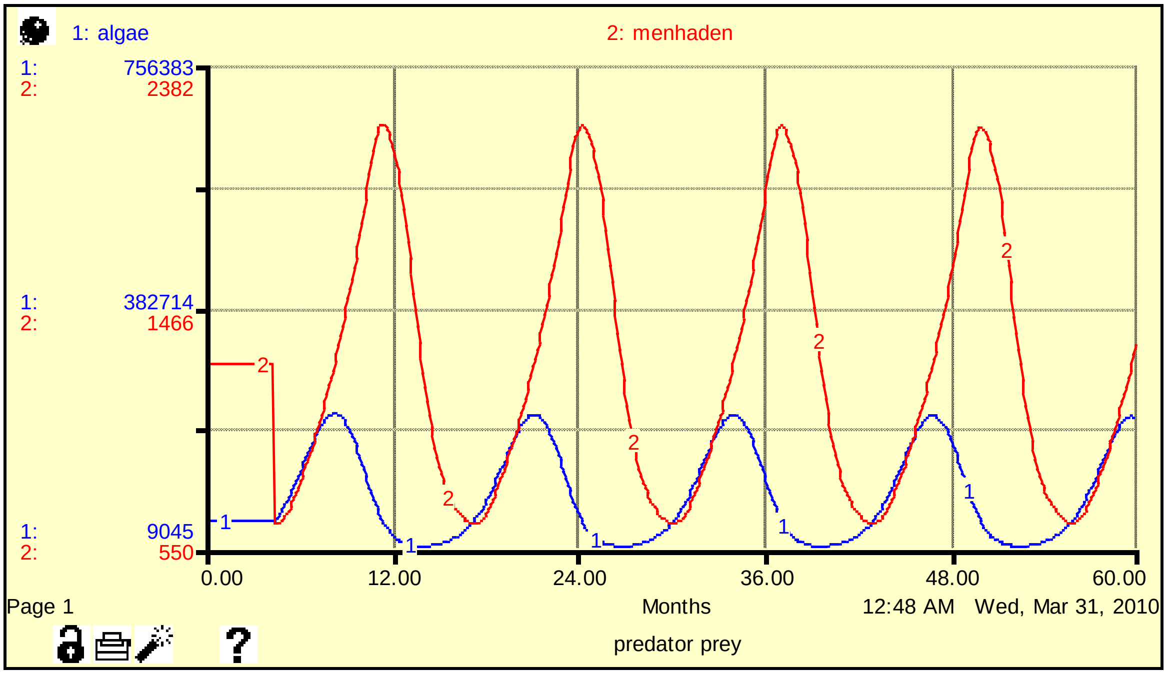

Figure 102. One Time 610 Harvest

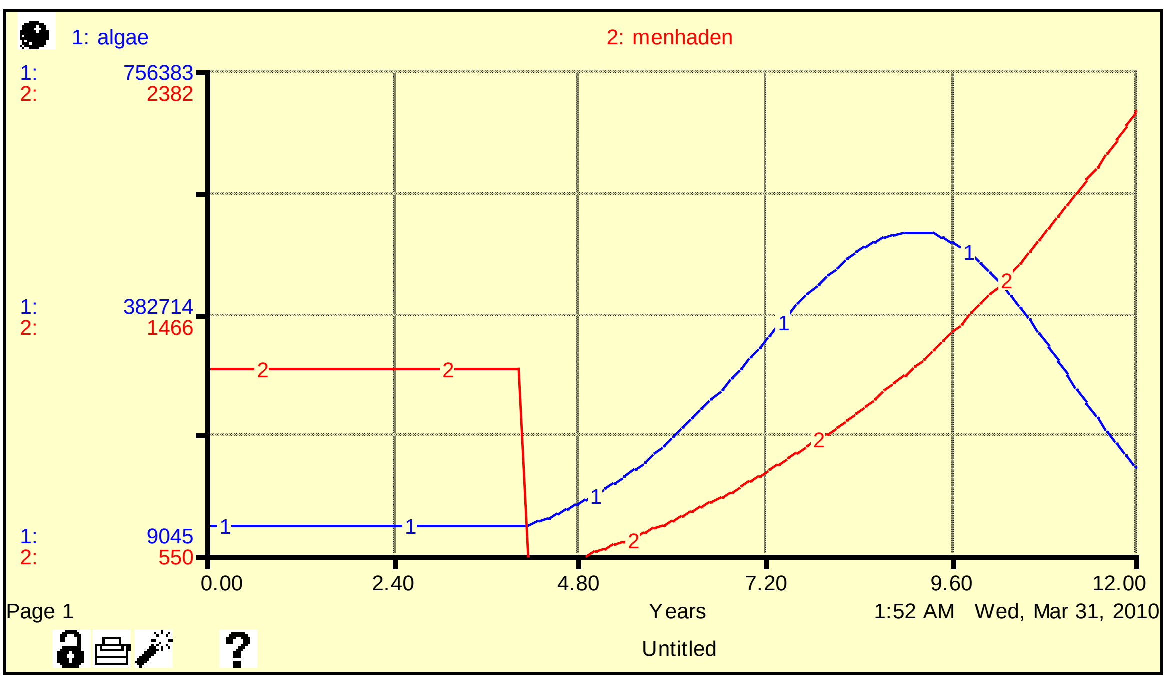

Figure 103. One Time 750 Harvest

The menhaden algae relationship begins as a typical marine inverted trophic pyramid. As the menhaden population drops the algae population rises above the menhaden population

forming a normal trophic pyramid. The broad based algae trophic food pyramid (Figure 95) shows what a onetime menhaden harvest could do to disrupt the typical inverted trophic biomass pyramid. Similar models are shown in other works (Campbell, N. A. 1996). This suggests the harvesting of a predator from the system could be a cause or a co-determinate cause of excess algae and algae blooms.

Fishing harvest data indicates a billion pounds of menhaden are harvested yearly from the Gulf of Mexico, which would consume ten times their weight to gain one pound with a million pounds of bycatch thrown overboard (Franklin, H. B. 2007; National Oceanic and Atmospheric Administration 2005). This frees previously consumed algae energy to produce ten billion pounds of algae and reduces the oxygen content on the bottom of the Gulf by the amount of oxygen necessary to consume algae detritus. The menhaden bycatch contribution to detritus is not analyzed as a potential reduction to bottom oxygen content but is a problem which deserves consideration. While no cause or contribution to cause should be overlooked the one time menhaden harvest model clearly suggests a link to the inversion of the marine inverted trophic pyramid to a broad based trophic food pyramid.

The model suggests that over harvesting of a keystone predator (species which is essential to the health of the ecosystem) could reduce the number of the predator below the number necessary to overcome the reproductive potential of the prey. There are historical accounts of menhaden in much greater numbers than present.

5.9 Historical Account

Menhaden schools (with their mouths open feeding on algae) were so thick it seemed you could walk on them and the menhaden were scooped up with a pan (Franklin, H. B. 2007). Comparison of the size of the hypoxia zone of the Gulf of Mexico (as shown in Figure 104) with

the menhaden landings for the Gulf of Mexico (as shown in Figure 105) suggests that the size of the hypoxia zone is increasing as the menhaden catch is declining. However, the size of the hypoxia zone in the Gulf of Mexico is claimed to be the result of over harvesting of menhaden (Franklin, H. B. 2007). This suggests that the number of menhaden harvested can be sustained, but the numbers are insufficient to maintain an inverted trophic food pyramid.

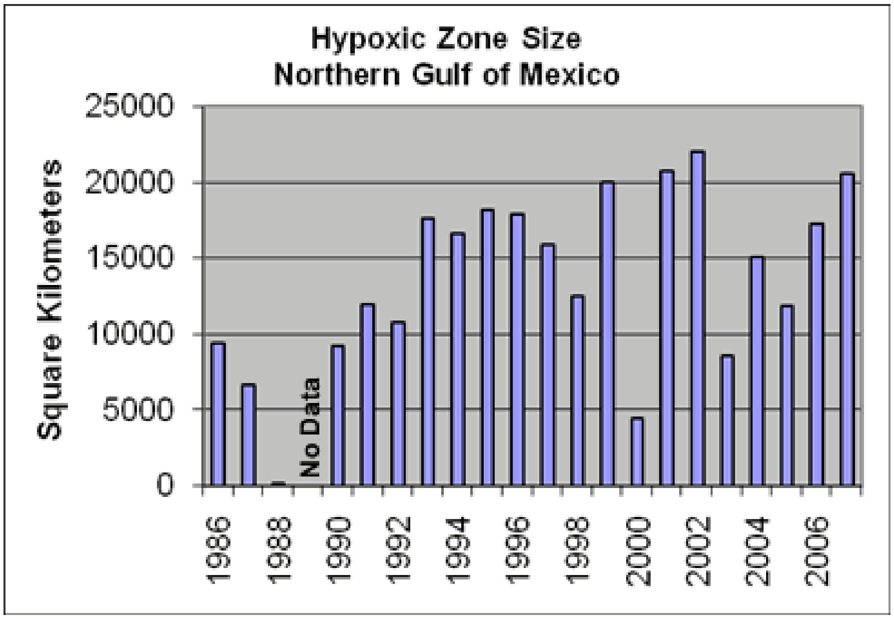

Figure 104. Hypoxia Zone Size Gulf Of Mexico (Rabalais, N. N. *et al.* 2007)

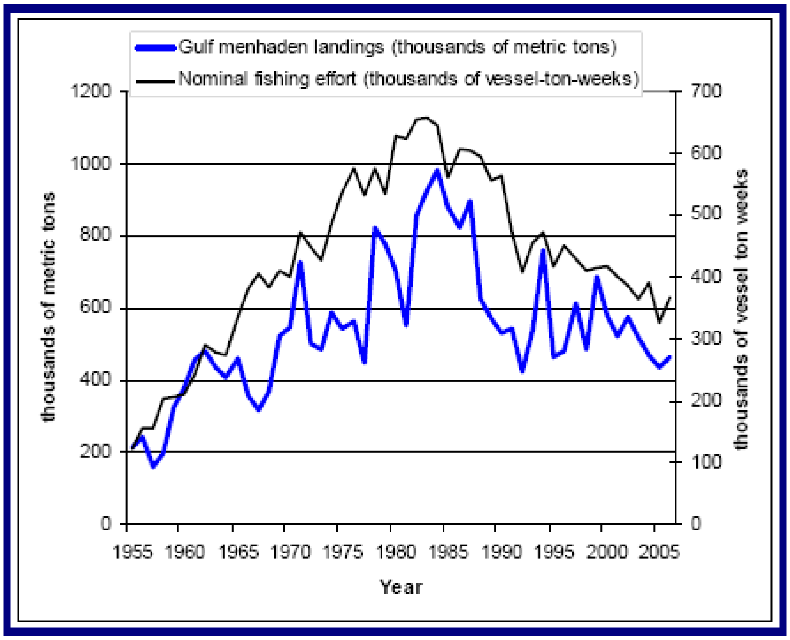

Figure 105. Menhaden Landings in Gulf of Mexico

With a little manipulation, the size of the hypoxia zone in the Gulf of Mexico and the menhaden landings are superimposed in Figure 101.   The harvest of menhaden prevents the filtering of algae and could be considered a contributing cause of the increasing size of the hypoxia zone.

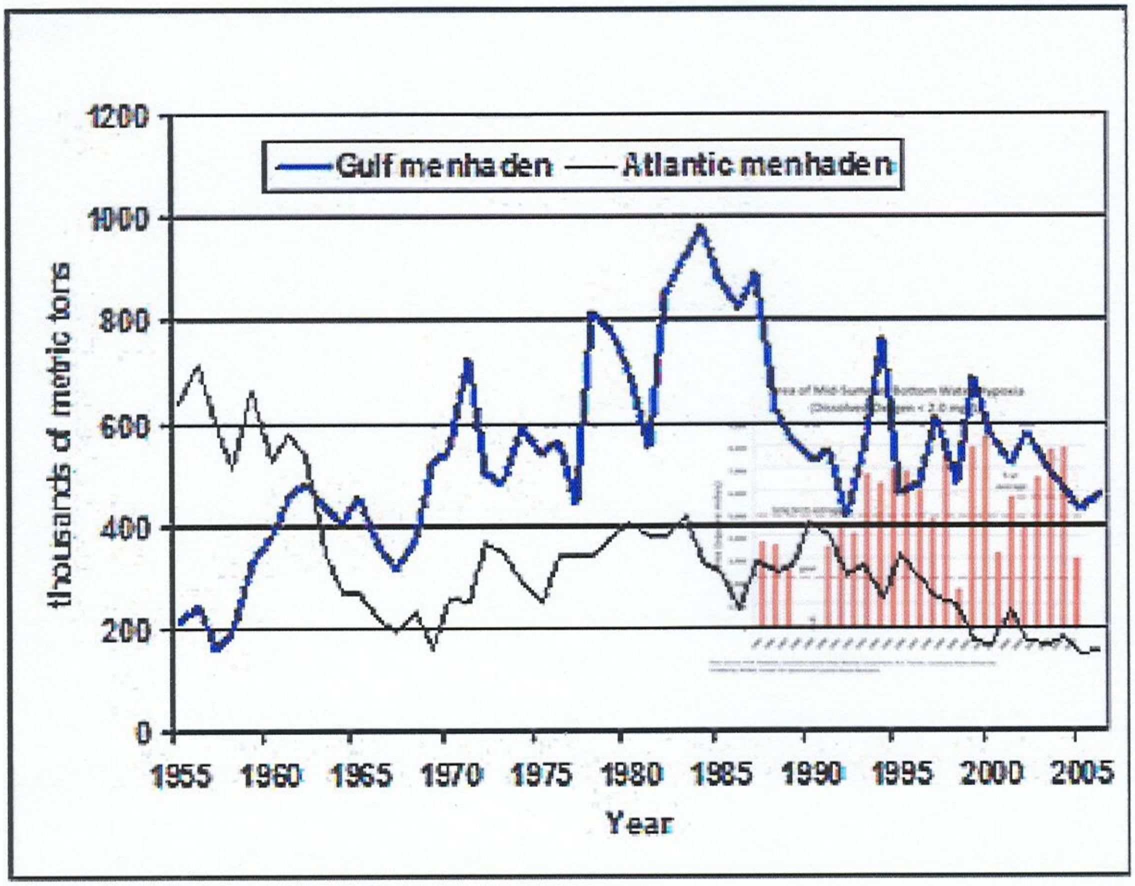

Figure 106. Menhaden Landings And Size Of Hypoxia Gulf Of Mexico (National Oceanic and Atmospheric Administration 2005; Rabalais, N. N. *et al.* 2007)

The relation between menhaden and hypoxia zone is either cause or correlation and the ONE TIME MENHADEN HARVEST model is a logical aid to discussion and analysis as it demonstrates the inversion of the trophic food pyramid. This is a new method of providing an analytical solution for the problem of hypoxia in the Gulf of Mexico. If you consider that the ecological system approaches the tipping point because of the combination of other factors such as levees, loss of wetlands, urbanization, increased stream flow, increased nutrients, then the

added burden of removing a predator on the algae would force the system past the tipping point and cause the normal marine pyramid to invert precipitating the algae bloom and the hypoxia zone.

CHAPTER 6: CONCLUSIONS

The following are restatements of the desired accomplishments of this work.

1. Focus on the distinction between correlation of events and causation.

   - CONCLUSION

     Annual Mississippi River flow to the Gulf of Mexico (Figure 13) may correlate to the variation in nitrate-N discharge. However, the transport of nitrate by stream flow of the Mississippi driving (causing) hypoxia is not supported by the paleo record (Osterman, L. E. *et al.* 2010) prior to sales of fertilizer. More than 28 million ha (70 million acre) in the Mississippi Basin had been drained by extensive systems of drain tiles and outlet ditches by 1980 moving surface and groundwater out of agricultural fields (Zucker, L. A. and L. C. Brown 1998) into the Mississippi River Basin and through the levee system. If you ask what caused the tiles to be laid, the only conclusion can be that the change was caused by the hand of man. Tracing each correlated event back to its origin results in the conclusion that the correlation was not causal.

2. Review the postulate that hypoxia depends on the existence of stratification and the presence of detritus and is either driven by biological factors such as excess nutrients or physical conditions such as river plumes, mixing, and wind currents by studying the elements of the Mississippi River Basin, the transport system of the Mississippi River, and the complex ecology of the Gulf of Mexico.

   - CONCLUSION

     The Eastern and Western groups postulate that stratification of fresh water over the saltier waters of the Gulf of Mexico and the presence of detritus to consume

oxygen was necessary for the occurrence of a hypoxia zone. From the PEB paleo-record hypoxia existed prior to the anthropogenic sales of fertilizer. The paleo-record offers no correlation or proof of the existence of stratification or detritus.

Anthropogenic changes have occurred in land use, agriculture and fertilizer use, drainage, wetlands, levees, river plumes, destructive trawling in the Gulf of Mexico, over fishing, loss of habitat and changes in the plant and sea life of the floor of the Gulf of Mexico. These changes were caused by the hand of man and correlate to the hypoxia zone in the Gulf of Mexico. The correlations do not amount to cause. The fact of the correlation offers man the opportunity to cause a change in one or more of the elements.

Mixing is a physical phenomenon. Only if mixing does not occur can the hypoxia zone occur. Having examined the trophic pyramids and the statements about removing algae grazers, the conclusion was that the removal of an algae grazer (the Chesapeake Bay oysters and the Gulf of Mexico menhaden) could create a change in pyramidal shape and create an algae bloom. The Eastern and Western groups are approaching the hypoxia problem from different sides. One group feels the elephant's tail and says the elephant is like a rope. The other group feels the elephant's leg and says it is like a tree. Both are right; both are wrong.

Much of the data does not define correlation or cause, only the boundary of a physical ecological occurrence. Temperature, sediment oxygen content, mixing, wind currents, Ekman currents, and loop currents define conditions in a semi enclosed marine system. The difference between correlation, causation and data which defines boundaries is not clearly understood.

3. Prepare dynamic STELLA® models which graphically solve symbolic mathematical relationships to support or disprove the importance of biological or physical effects in the Gulf of Mexico.

   - CONCLUSION

     The purpose of this work was to create something new or to add to the body of knowledge. This effort has accomplished both. The chemist does not create a new periodic table or new formulas to interpret chemical reactions. The physicist does not create new mathematics. From the study of the standardized and the understood come repeatable combinations and a new approach to the problem.

     The models of carbon, nitrogen, phosphorus, erosion, deforestation oxygen were combined with a 0-4 meter algae model. This model was used to examine variables. From the combined model two additional models were created. One was a model of algae growth and the other a model of one time menhaden or algae grazer harvest. The algae growth model strongly suggests that a physical phenomenon could increase/decrease or eliminate hypoxia. The one time menhaden harvest strongly suggests removal of the algae predator would free energy for algae to reproduce creating an algae bloom by a biological process.

     After examining the data and running the models, it is strongly suggested that stratification and detritus are required, but other phenomenon must not occur for hypoxia to be the present day problem. With stratification and detritus a given, there must be (one or a combination) no mixing, advection, one time menhaden harvest, oyster bed destruction, levees, wetland loss, lost coast and drought can not

occur. There must be things which occur combined with the things which do not occur. The list is not complete.

4. Test the model fit to actual situations.

- CONCLUSION

  This work raises the issue of which came first, data or the model. There is insufficient data to verify the model. The modeler can compare trends and can show that the model would behave in certain expected manners. The modeler can not state that a prediction of the size of the algae mat and corresponding hypoxia zone in any given year will be a certain size. It is strongly suggested that changing one or more variables will affect the algae mat relative size.

5. Make recommendations for future work.

CHAPTER 7: RECOMMENDATIONS

The recommendations for future work shall be limited to the following. More could be listed, but these shall suffice for this work.

- Until the economic and esoteric value of the Gulf of Mexico as a national asset (not the last "commons" (Hardin, G. 1974)) is realized, politics, economics and legal complexities will not present viable solutions.
- A standard definition of correlation and causation should be perfected.
- The methodology of gathering, calibrating storing and retrieving data should be standardized. While conversion factors and equations are available, these are sources for the introduction of error. It does not matter to science the measurement system, but it does matter the method of gathering, calibrating, storing and retrieving. Samples or measurements should be made in the same manner, at the same depth at the same time of day with recordation made of humidity, sunlight, temperature and other stated variables. While sunlight may not be a correlative or causative factor, it affects processes such as photosynthesis. Data gathering, storage and availability can in this manner be much improved.
- Standardized models should be created, stored and available for retrieval. If one needs a scalpel, a ½ inch wrench, a 10mm wrench, those tools are not created anew for use for the present task. The tool is available for use, stored, and is available for retrieval. The model can be used and not returned or the model can be returned in an improved form. These improved models can be stored in a data bank as sub models of a particular set.

- Above all else, the historical data gathered should be fed into the standardized and created models for verification of the models.

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APPENDIX A: EQUATIONS FOR COMBINED MODIFIED MODELS

EQUATIONS FOR **COMBINED MODIFIED MODELS** Figure 68

aerobic_and_aneorbic__bacteria (t) = aerobic_and_aneorbic__bacteria (t - dt) + (algae_reproduction - algae_death) * dt
INIT aerobic_and_aneorbic__bacteria = 1.25E3
INFLOWS:
algae_reproduction = aerobic_and_aneorbic__bacteria*algae_reproduction_rate
OUTFLOWS:
algae_death = aerobic_and_aneorbic__bacteria*algae_death_rate+PULSE (100,2,1E3)
ALGAE_0_TO_4_METERS (t) = ALGAE_0_TO_4_METERS (t - dt) + (GROWTH - DEATH) * dt
INIT ALGAE_0_TO_4_METERS = 1.25E3
INFLOWS:
GROWTH = ALGAE_0_TO_4_METERS*GROWTH_RATE
OUTFLOWS:
DEATH = ALGAE_0_TO_4_METERS*DEATH_RATE
Atmospheric_Carbon (t) = Atmospheric_Carbon (t - dt) + (Ocean_Release + Deforestation + Respiration + Exhalation + Emissions + T_Res - Photosynthesis - Ocean_Uptake - Carbon_Sink) * dt
INIT Atmospheric_Carbon = 720
INFLOWS:
Ocean_Release = 105
Deforestation = 2
Respiration = 60
Exhalation = 60
Emissions = 5.5
T_Res = 23* (TERRESTRIAL/450)
OUTFLOWS:
Photosynthesis = 80+Nitogen_Hydrogen_Photosynthesis
Ocean_Uptake = 107
Carbon_Sink = 2
Available_Nitrogen (t) = Available_Nitrogen (t - dt) + (mineralizing + fertilizer - taking_up) * dt
INIT Available_Nitrogen = 15+fertilizer
INFLOWS:
mineralizing = Nitrogen_in_Humus*mineralization_fraction
DOCUMENT: Each year, a certain fraction of the nitrogen bound in humus is converted to inorganic form.
fertilizer = GRAPH (TIME)
(0.00, 22.0), (1.20, 30.0), (2.40, 61.0), (3.60, 71.5), (4.80, 78.0), (6.00, 64.0), (7.20, 49.5), (8.40, 33.0), (9.60, 26.0), (10.8, 23.0), (12.0, 16.5)

OUTFLOWS:
taking_up = growing*nitrogen_per_unit_biomass
DOCUMENT: As plants grow, they incorporate nitrogen from the soil into their tissues.
deep_ocean (t) = deep_ocean (t - dt) + (sinking_and_decay + mixing - sedimentation - upwelling) * dt
INIT deep_ocean = 1.e5
DOCUMENT: All reservoirs are in units of Teragrams (Tg).
(1 Tg = 1*10^12 g)
INFLOWS:
sinking_and_decay = ocean_biota* (40./44.)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 40. is the steady state flow, and 44. the steady state reservoir content.
mixing = surface_ocean* (18./2800.)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 18. is the steady state flow, and 2800. the steady state reservoir content.
OUTFLOWS:
sedimentation = deep_ocean* (2./1.e5)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 2. is the steady state flow, and 1.e5 the steady state reservoir content.
upwelling = deep_ocean* (56./1.e5)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 56. is the steady state flow, and 1.e5 the steady state reservoir content.

FOSSIL_FUELS (t) = FOSSIL_FUELS (t - dt) + (- Emissions) * dt
INIT FOSSIL_FUELS = 10000
OUTFLOWS:
Emissions = 5.5
land_biota (t) = land_biota (t - dt) + (terrestrial_production - decay) * dt
INIT land_biota = 2600
DOCUMENT: All reservoirs are in units of Teragrams (Tg).
 (1 Tg = 1*10^12 g)
INFLOWS:
terrestrial_production = soils* (310./2.e5)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
 (1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 310. is the steady state flow, and 2.e5 the steady state reservoir content.
OUTFLOWS:
decay = land_biota* (310./2600.)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
 (1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 310. is the steady state flow, and 2600. the steady state reservoir content.
Living_land_Biomass (t) = Living_land_Biomass (t - dt) + (growing - dying) * dt
INIT Living_land_Biomass = 1E6
INFLOWS:
growing = Living_land_Biomass*land_biomass_growth_rate
DOCUMENT: Plant growth depends on how much biomass there is, as well as the biomass growth rate.
OUTFLOWS:
dying = Living_land_Biomass*plant_lifetime
MARINE (t) = MARINE (t - dt) + (M_Photo - M_Res - M_Death) * dt
INIT MARINE = 7
INFLOWS:
M_Photo = 35* (Atmospheric_Carbon/720)
OUTFLOWS:
M_Res = 5* (MARINE/7)
M_Death = 30* (MARINE/7)
M_DEAD_ORGANIC (t) = M_DEAD_ORGANIC (t - dt) + (M_Death - M_Decomp) * dt
INIT M_DEAD_ORGANIC = 3000
INFLOWS:

M_Death = 30* (MARINE/7)
OUTFLOWS:
M_Decomp = 30* (M_DEAD_ORGANIC/3000)
Nitrogen_in_Biomass (t) = Nitrogen_in_Biomass (t - dt) + (taking_up + leguminous_fixing - xferring) * dt
INIT Nitrogen_in_Biomass = 100
DOCUMENT: Nitrogen in Biomass represents the amount of nitrogen bound in organic form -- primarily in protein molecules -- within living plant tissue.
INFLOWS:
taking_up = growing*nitrogen_per_unit_biomass
DOCUMENT: As plants grow, they incorporate nitrogen from the soil into their tissues.
leguminous_fixing = Living_land_Biomass*fixation_productivity
DOCUMENT: legumes fix atmospheric nitrogen. The rate of fixation depends on how much of the plant mass is leguminous.
OUTFLOWS:
xferring = dying*nitrogen_to__biomass_ratio
DOCUMENT: nitrogen gets transferred as plants die.
Nitrogen_in_Humus (t) = Nitrogen_in_Humus (t - dt) + (humifying - mineralizing) * dt
INIT Nitrogen_in_Humus = 100
DOCUMENT: Humus is a nitrogen-rich, slowly decomposing substance in the soil. This stock represents the amount of nitrogen bound in soil humus.
INFLOWS:
humifying = Nitrogen_in_Organic_Matter*humification_fraction
DOCUMENT: Over time, biological processes transform partially decayed plant tissue into humus. As this happens, the associated nitrogen becomes bound into the humus. This flow provides an aggregate representation of the process. It states that a fraction of nitrogen in biomass is converted to humus, per unit time. humification frac tells how quickly the conversion occurs.
OUTFLOWS:
mineralizing = Nitrogen_in_Humus*mineralization_fraction
DOCUMENT: Each year, a certain fraction of the nitrogen bound in humus is converted to inorganic form.
Nitrogen_in_Organic_Matter (t) = Nitrogen_in_Organic_Matter (t - dt) + (xferring - humifying) * dt
INIT Nitrogen_in_Organic_Matter = 20
DOCUMENT: This stock represents the amount of nitrogen in dead plant tissue, which is in its initial stages of decay.
INFLOWS:
xferring = dying*nitrogen_to__biomass_ratio
DOCUMENT: nitrogen gets transferred as plants die.
OUTFLOWS:
humifying = Nitrogen_in_Organic_Matter*humification_fraction
DOCUMENT: Over time, biological processes transform partially decayed plant tissue into humus. As this happens, the associated nitrogen becomes bound into the humus. This flow provides an aggregate representation of the process. It states that a fraction of nitrogen in

biomass is converted to humus, per unit time. humification frac tells how quickly the conversion occurs.
Ocean_Carbon (t) = Ocean_Carbon (t - dt) + (Soil_Runoff + Ocean_Uptake - Ocean_Release - Sediments) * dt
INIT Ocean_Carbon = 38000
INFLOWS:
Soil_Runoff = .4
Ocean_Uptake = 107
OUTFLOWS:
Ocean_Release = 105
Sediments = .1
ocean_biota (t) = ocean_biota (t - dt) + (oceanic_production - sinking_and_decay - ocean_decay) * dt
INIT ocean_biota = 44
DOCUMENT: All reservoirs are in units of Teragrams (Tg).
(1 Tg = 1*10^12 g)
INFLOWS:
oceanic_production = surface_ocean* (980./2800.)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 980. is the steady state flow, and 2800. the steady state reservoir content.
OUTFLOWS:
sinking_and_decay = ocean_biota* (40./44.)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 40. is the steady state flow, and 44. the steady state reservoir content.
ocean_decay = ocean_biota* (940./44.)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 940. is the steady state flow, and 44. the steady state reservoir content.

OXYGEN (t) = OXYGEN (t - dt) + (VERTICAL_MIXING + DEEP_WATER_ADVECTION + BOTTOM_PHOTOSYNTHESIS + DEEP_WATER_PHOTOSYNTHESIS + SURFACE_PHOTOSYNTHESIS - WATER_COLUMN_RESPIRATION - BOTTOM_WATER_NITRIFICATION - SEDIMENT_OXYGEN_CONSUMPTION_AEROBIC_AND_ANAEROBIC) * dt
INIT OXYGEN = 6.3
INFLOWS:
VERTICAL_MIXING = .0038
DEEP_WATER_ADVECTION = 0
BOTTOM_PHOTOSYNTHESIS = .3
DEEP_WATER_PHOTOSYNTHESIS = .3
SURFACE_PHOTOSYNTHESIS = .0962
OUTFLOWS:
WATER_COLUMN_RESPIRATION = .19
BOTTOM_WATER_NITRIFICATION = .3
SEDIMENT_OXYGEN_CONSUMPTION_AEROBIC_AND_ANAEROBIC = .128+.0076
sediments_2 (t) = sediments_2 (t - dt) + (weathering_insoluble + sedimentation - uplift) * dt
INIT sediments_2 = 2.e9
DOCUMENT: All reservoirs are in units of Teragrams (Tg).
(1 Tg = 1*10^12 g)
INFLOWS:
weathering_insoluble = soils* (18./2.e5)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 18. is the steady state flow, and 2.e5 the steady state reservoir content.
sedimentation = deep_ocean* (2./1.e5)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 2. is the steady state flow, and 1.e5 the steady state reservoir content.
OUTFLOWS:
uplift = sediments_2* (20./2.e9)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady

state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 20. is the steady state flow, and 2.e9 the steady state reservoir content.
Soil (t) = Soil (t - dt) + (Plant_Detrius - Soil_Runoff - Exhalation) * dt
INIT Soil = 500
INFLOWS:
Plant_Detrius = 60.4
OUTFLOWS:
Soil_Runoff = .4
Exhalation = 60
soils (t) = soils (t - dt) + (decay + uplift - weathering_insoluble - weathering_soluble - terrestrial_production) * dt
INIT soils = 2.e5
DOCUMENT: All reservoirs are in units of Teragrams (Tg).
(1 Tg = 1*10^12 g)
INFLOWS:
decay = land_biota* (310./2600.)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 310. is the steady state flow, and 2600. the steady state reservoir content.
uplift = sediments_2* (20./2.e9)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 20. is the steady state flow, and 2.e9 the steady state reservoir content.
OUTFLOWS:
weathering_insoluble = soils* (18./2.e5)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 18. is the steady state flow, and 2.e5 the steady state reservoir content.
weathering_soluble = soils* (2./2.e5)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).

(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 2. is the steady state flow, and 2.e5 the steady state reservoir content.
terrestrial_production = soils* (310./2.e5)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 310. is the steady state flow, and 2.e5 the steady state reservoir content.
surface_ocean (t) = surface_ocean (t - dt) + (upwelling + weathering_soluble + ocean_decay - mixing - oceanic_production) * dt
INIT surface_ocean = 2800
DOCUMENT: All reservoirs are in units of Teragrams (Tg).
(1 Tg = 1*10^12 g)
INFLOWS:
upwelling = deep_ocean* (56./1.e5)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 56. is the steady state flow, and 1.e5 the steady state reservoir content.
weathering_soluble = soils* (2./2.e5)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 2. is the steady state flow, and 2.e5 the steady state reservoir content.
ocean_decay = ocean_biota* (940./44.)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady

state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 940. is the steady state flow, and 44. the steady state reservoir content.
OUTFLOWS:
mixing = surface_ocean* (18./2800.)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 18. is the steady state flow, and 2800. the steady state reservoir content.
oceanic_production = surface_ocean* (980./2800.)
DOCUMENT: All flows are in units of Teragrams per year (Tg/yr).
(1 Tg/yr = 1*10^12 g/yr)
The equation for each flow is: reservoir contents * a transfer coefficient. The transfer coefficient is equal to the flow out of the reservoir divided by the contents of the reservoir when the system is at steady state. At any timestep t, flow (t) = reservoir contents (t) * (flow at steady state/reservoir contents at steady state). Unless the reservoir content value is altered, the value of the flow will be equal to the flow out of the reservoir at steady state. Here, 980. is the steady state flow, and 2800. the steady state reservoir content.
Surface_Plants (t) = Surface_Plants (t - dt) + (Photosynthesis - Plant_Detrius - Deforestation - Respiration) * dt
INIT Surface_Plants = 560
INFLOWS:
Photosynthesis = 80+Nitogen_Hydrogen_Photosynthesis
OUTFLOWS:
Plant_Detrius = 60.4
Deforestation = 2
Respiration = 60
TERRESTRIAL (t) = TERRESTRIAL (t - dt) + (T_Photo - T_Res - T_Death) * dt
INIT TERRESTRIAL = 450
INFLOWS:
T_Photo = 48* (Atmospheric_Carbon/720)
OUTFLOWS:
T_Res = 23* (TERRESTRIAL/450)
T_Death = 25* (TERRESTRIAL/450)
T_DEAD_ORGANIC (t) = T_DEAD_ORGANIC (t - dt) + (T_Death - T_Decomp) * dt
INIT T_DEAD_ORGANIC = 700
INFLOWS:
T_Death = 25* (TERRESTRIAL/450)
OUTFLOWS:
T_Decomp = 25* (T_DEAD_ORGANIC/700)
vegetation (t) = vegetation (t - dt) + (vegetation_growth - vegetation_degradation) * dt
INIT vegetation = 500

INFLOWS:
vegetation_growth = Soil*management_practices*rainfall
OUTFLOWS:
vegetation_degradation = fire*grazing*harvesting
UNATTACHED:
nitrogen_removal = aerobic_and_aneorbic__bacteria*nitrogen_intake_per_algae
UNATTACHED:
outflow = Decomp
UNITS: g/time
UNATTACHED:
soil_formation = management_practices*rainfall
UNATTACHED:
soil_loss = vegetation_degradation*management_practices*rainfall*slope*slope_length
algae_reproduction_rate = .25
algae_death_rate = GRAPH (nitrogen_cncentration)
(0.00, 0.5), (9.09, 0.45), (18.2, 0.4), (27.3, 0.35), (36.4, 0.3), (45.5, 0.25), (54.5, 0.2), (63.6, 0.15), (72.7, 0.1), (81.8, 0.055), (90.9, 0.005), (100, 0.005)
area = 1E2
DOCUMENT: 1E3
CO2_ppm = 310* (Atmospheric_Carbon/720)
DEATH_RATE = .1
Decomp = aerobic_and_aneorbic__bacteria*algae_death_rate
fire = GRAPH (TIME)
(0.00, 0.05), (1.09, 0.05), (2.18, 0.00), (3.27, 0.00), (4.36, 2.80), (5.45, 0.15), (6.55, 0.1), (7.64, 0.1), (8.73, 2.45), (9.82, 0.05), (10.9, 0.00), (12.0, 0.00)
fixation_productivity = .25
grazing = GRAPH (TIME)
(0.00, 73350), (1.09, 6100), (2.18, 5450), (3.27, 2900), (4.36, 3000), (5.45, 5900), (6.55, 6050), (7.64, 5800), (8.73, 3300), (9.82, 3350), (10.9, 5950), (12.0, 6950)
GROWTH_RATE = MAX_GROWTH_RATE* (1-(ALGAE_0_TO_4_METERS/MAX_ALGAE))
harvesting = IF (vegetation>500)THEN (.000000000001*vegetation)ELSE (0)
humification_fraction = .25
DOCUMENT: Each year, 25% of the nitrogen in decaying organic matter is converted to humus.
land_biomass_growth_rate = GRAPH (Available_Nitrogen)
(0.00, 0.195), (1.09, 0.205), (2.18, 0.26), (3.27, 0.33), (4.36, 0.595), (5.45, 0.665), (6.55, 0.68), (7.64, 0.69), (8.73, 0.665), (9.82, 0.585), (10.9, 0.2), (12.0, 0.2)
management_practices = GRAPH (TIME)
(0.00, 0.935), (1.09, 0.525), (2.18, 0.4), (3.27, 0.14), (4.36, 0.095), (5.45, 0.09), (6.55, 0.085), (7.64, 0.1), (8.73, 0.205), (9.82, 0.29), (10.9, 0.43), (12.0, 0.95)
MAX_ALGAE = 1E6
MAX_GROWTH_RATE = Available_Nitrogen*sunlight*temperature*streamflow
mineralization_fraction = .05

DOCUMENT: Each year 5% of the nitrogen in humus is mineralized into an inorganic form. This value is roughly correct for temperate climates. In tropical climates, mineralization occurs at a much more rapid pace.
Nitogen_Hydrogen_Photosynthesis = PI*40*MAX (0,SIN (2*PI* (Seasons-.25)))
nitrogen_cncentration = area
nitrogen_intake_per_algae = GRAPH (nitrogen_cncentration)
(0.00, 3.89e-305), (45.5, 50.0), (90.9, 100), (136, 150), (182, 200), (227, 250), (273, 300), (318, 350), (364, 400), (409, 450), (455, 500), (500, 500)
nitrogen_per_unit_biomass = .1
nitrogen_to__biomass_ratio = Nitrogen_in_Biomass/Living_land_Biomass
plant_lifetime = 2
rainfall = GRAPH (TIME)
(0.00, 420), (1.09, 313), (2.18, 2.50), (3.27, 2.50), (4.36, 0.00), (5.45, 2.50), (6.55, 148), (7.64, 0.00), (8.73, 7.50), (9.82, 165), (10.9, 238), (12.0, 428)
Seasons = TIME-INT (TIME)
DOCUMENT: TIME-INT (TIME)
slope = 1/500
slope_length = 200
streamflow = GRAPH (TIME)
(0.00, 32.0), (1.82, 44.5), (3.64, 49.0), (5.45, 51.5), (7.27, 57.5), (9.09, 79.5), (10.9, 59.5), (12.7, 35.5), (14.5, 49.5), (16.4, 35.5), (18.2, 23.0), (20.0, 23.0)
sunlight = 1
temperature = 1

APPENDIX B: WHICH CAME FIRST?

Which came first?

Modeling is simply the reduction of the real world to imagination and then to model the imagination. The trick is to get imagination to be reflected in the model and the model to mimic reality. This is circular reasoning; effective for this purpose.

The problem with modeling is which came first? Did the model come first or did the data come first? Modeling a large marine ecosystem is not a task to be undertaken by the faint of heart. In this instance the available data was the measurement of an existing phenomenon. This phenomenon is the hypoxia zone of the Gulf of Mexico. Once you begin the modeling process, you identify stocks, flows, connectors and converters. These elements reflect change and are causative elements. Non causative elements may correlate to an increase in size or intensity, but would not necessarily be causative.

If it is real or unreal, it can be imagined. If it can be imagined, it can be modeled. It is clear that you can model without data and you can collect data and model with or without clarity.

The first thing which must be recognized is the issue of a lack of causative data when examining this phenomenon. It could be argued that the data is sufficient and the lack is in the modeler. It could be argued that the data is insufficient and the modeler has overcome.

Tutorial 1: Building Blocks

1. Deposit Stock
2. Document and Color
3. Draw and Inflow and a Outflow
4. Visit Equation Layer
5. Enter Initial Value for Stock
6. Define Flows as Constants

Tutorial 2: Running the Simulation

7. Run Specs
8. Create Graph Pad
9. Scale Variables

10. Create Table Pad
11. Format Table

Tutorial 3: Adding Feedback

11. Deposit Converters
12. Conectors
13. Define Converters
14. Graphical Function
15. Define a Ghost
16. Assign Polarity

Tutorial 4: Organizing and Testing

17. Set up Sensitivity Analysis
18. Run a Sensitivity Analysis
19. Create a Sector Frame
20. Run by Sector

Tutorial 5: Working with Modules

21. Create Modules
22. Import Model Structure
23. Define Inputs and Outputs
24. Copy Model Structure
25. Assign Inputs to Variables
26. Run Modules

Tutorial 6: Importing and Exporting Data

1. Import Data
2. Export Data
3. Manage Links

While there are 5 tutorials and 26 steps for creating a model, there are only 3 steps for importing, exporting and managing links. This program as with many others loads the difficulty in creating the model and getting the module to run. Loading data is by far the easier task. Data can be loaded from excel or linked to continuously uploading sources.

The ease of loading data into STELLA® drove the modeling first approach. Permission to use the tutorial list is from iseesystems.

APPENDIX C: PERMISSIONS

isee systems
"isee systems" (formerly High Performance Systems) is the creator of the STELLA® software. STELLA stands for Structural Thinking Experiential Learning Laboratory with Animation and represents a quantum improvement in the way Systems Thinking-based products enable people to increase their capacity to think, learn, communicate, and act more systemically. STELLA is an icon-based model building and simulation tool. STELLA graphically solves multiple partial differential equations and displays the solutions over time. The models created with STELLA are used with the permission of isee systems to demonstrate the intuitive power of STELLA to help solve problems and display the results. Complex models can be created after a short learning curve and models can be combined by the use of various tactics. The web site for STELLA is: http://www. iseesystems.com. Without the cooperation of the isee systems staff, my modeling efforts would not have been possible. I thank the staff and the support group at isee systems for permission to use models contained on their web site and to combine and modify those models. My model is a dynamic interactive model and a trial program can be downloaded so each variable can be changed and the effect of the change observed. With this potential, STELLA is a powerful tool for the study and management of ecological systems. We are only beginning to touch the surface of the potential of modeling. As powerful as STELLA is today, it is hoped that the dedicated staff of isee systems will continue to improve STELLA. The age old question of which comes first, the model or the data may never be fully answered, but with STELLA good models can be prepared and presented and data can be gathered to make those models better. Support [support@iseesystems.com] Joanne Egner

Gilbert T. Rowe
Gilbert T. Rowe, Department of Oceanography, Texas A&M University, College Station, Tx 77843 (growe@ocean.tamu.edu) graciously granted permission for me to use his model in his article Seasonal Hypoxia in the Bottom Water off the Mississippi River Delta published in the Journal of Environmental Quality 30:281-290 (2001)© 2001 American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America and to quote from his works.

H. Bruce Franklin
H. Bruce Franklin is the John Cotton Dana Professor of English and American Studies at Rutgers University-Newark and author of over eighteen books, one of which is, The Most important Fish in the Sea. Mr. Franklin discussed ecological problems and granted permission to use his works

John Snow
John Snow, University of Oklahoma, provided a source of inspirational STELLA models and granted permission to use his models and his works.

VITA

The author was born in Tylertown, Mississippi. His childhood was not memorable. A more rounded education was needed to better serve his clients in an ever more complex world. The author met Dr. David Constant who directed the author through a Master of Science in Engineering Science in 2006 and who is mentoring the degree of Doctor of Philosophy in the interdepartmental engineering science program.

The knowledge obtained supports my family, furthers my career, and allows me to become a more useful servant to my clients and friends. This dissertation analyzes the cause or causes of the hypoxia zone in the Gulf of Mexico emphasizing modeling as a dynamic tool to understand and recommend potential remediation.