The Effect of Increased Extreme Rainfall Events on the Iowa Nutrient Reduction Strategy: An Assessment

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Background:

The Mississippi River is the largest river in the United States, draining water and pollutants from 31 states in the country's heartland to the Gulf of Mexico. (U.S. Environmental Protection Agency, 2011) Its watershed is considered the most productive agricultural land in the country. Fertilizer use for industrial agriculture has increased in this watershed for the past several decades. (U.S. Environmental Protection Agency, 2011) A large portion of synthetic fertilizers made of nitrogen are not absorbed by crops. Instead, they are removed from harvested crops or lost through denitrification, volatilization, and soil mobilization. (Microbial Life Education Resource, 2019) Nutrients not absorbed by plants are often transported via rainfall runoff into the Mississippi River, which drains into the Gulf. Excess nutrients, including nitrogen and phosphorus, combined with regional circulation and water stratification has caused hypoxia (dissolved oxygen less than 2 milligrams) of the discharge area below the Mississippi River Basin. (Microbial Life Education Resource, 2019)

Two conditions are necessary for the formation of hypoxia: stratification of the water column in the Gulf and the presence of organic matter to consume oxygen. (USGS, 2000) The Mississippi River meets both conditions through large inputs of freshwater and nutrients. High streamflow in the spring and summer provides a large influx of freshwater, which promotes stratification in the Gulf with warmer, less dense water overlying colder, more dense salt water. (USGS, 2000) Nutrients from the Mississippi River fuel the production of algae in the surface water of the Gulf. Organic material from the algae and other organisms settles into the bottom water of the Gulf where it is decomposed by bacteria, which consume oxygen in the process. (USGS, 2000) Stratification blocks the replenishment of oxygen from the surface, and hypoxia develops. Hypoxia reaches a maximum in late summer, creating a "dead zone", and disappears each fall when reduced freshwater inputs, cooler temperatures, and mixing by storms breaks up stratification. (USGS, 2000)

A NOAA-supported scientist announced that the 2021 Gulf of Mexico "Dead Zone", was approximately 6,334 square miles from July 25 to August 1. (NOAA, 2021) This is equivalent to more than four million acres of habitat unavailable to fish and bottom species. In May 2021, discharge in the Mississippi and Atchafalaya rivers was about 2% below the long-term average between 1980 and 2020. (NOAA, 2021) The USGS estimates that this smaller-than-average river discharge carried 90,500 metric tons of nitrate into the Gulf of Mexico in May alone, and these nitrate loads were about 32% below the long-term average. (NOAA, 2021) Decreased levels of oxygen in water results in the decline of marine wildlife, which can also impact the US fishing industry. (Microbial Life Education Resource, 2019)

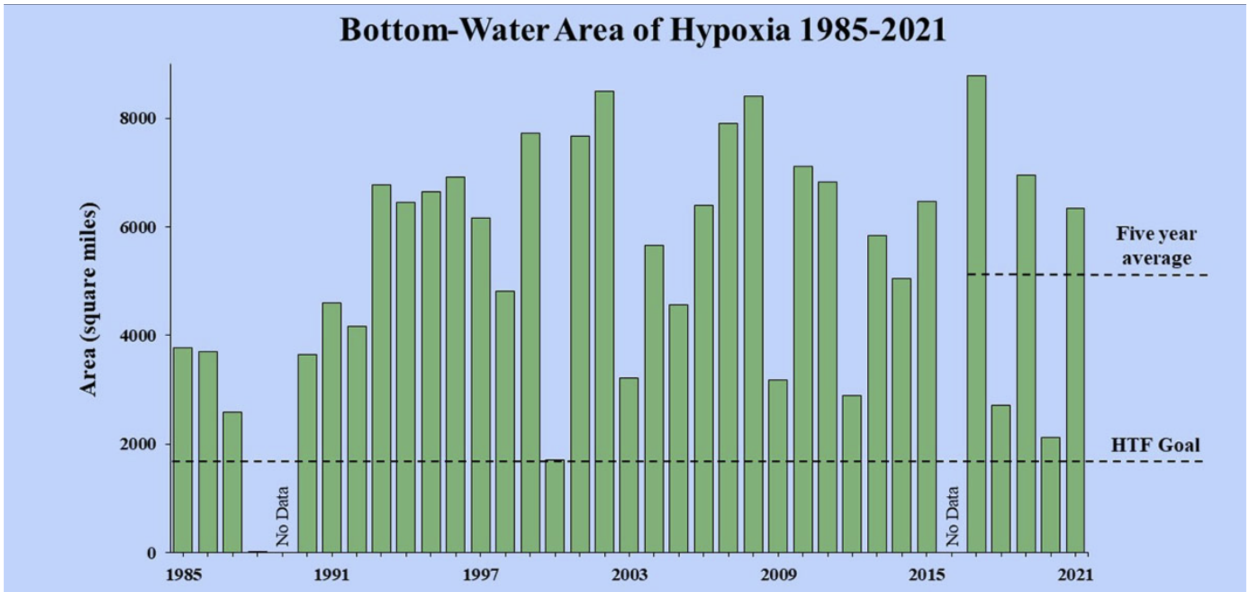


Figure 1. (Bottom bar) Long-term measured size of hypoxic zone measured during ship surveys since 1985, including target goal established by Mississippi River/Gulf of Mexico Watershed Nutrient Task Force and 5-year average measured size (black dashed lines). (NOAA, 2021)

One of the principal causes for the increasing size of the hypoxic zone is the increasing loading of nitrogen, particularly nitrate, delivered to the Gulf each year. Nitrogen occurs primarily in two forms in streams——nitrate and organic nitrogen (dissolved and particulate). (USGS, 2000) Nitrate is the most soluble and mobile form of nitrogen. From 1950 to 2000, there are six principal sources of nitrogen inputs to the Mississippi Basin: soil mineralization, fertilizer, legumes and pasture, animal manure, atmospheric deposition, and municipal and industrial point sources. (USGS, 2000) In our report, we will choose an area of Iowa as the background of our question and figure out the Effect of Increased Extreme Rainfall Events on the Iowa Nutrient Reduction Strategy

Precipitation is a key factor in the accumulation of nitrates in the Gulf of Mexico. Due to climate change, extreme rainfall events are becoming more common. (Lu, 2020) For example, over 60% of land area of the Mississippi Basin has experienced increasing extreme precipitation since 2000. (Lu, 2020) Despite occurring on average 9 days/year, extreme precipitation events (days with daily precipitation over 90th percentiles in each month) contribute about 1/3 of total nitrogen yields in the Gulf. (Lu, 2020) Over the years, states have taken measures to reduce the nutrient loading, but hydroclimate extremes (referring to drought and floods thereafter) that increase nutrient runoff make it more challenging to achieve the goals. (Lu, 2020)

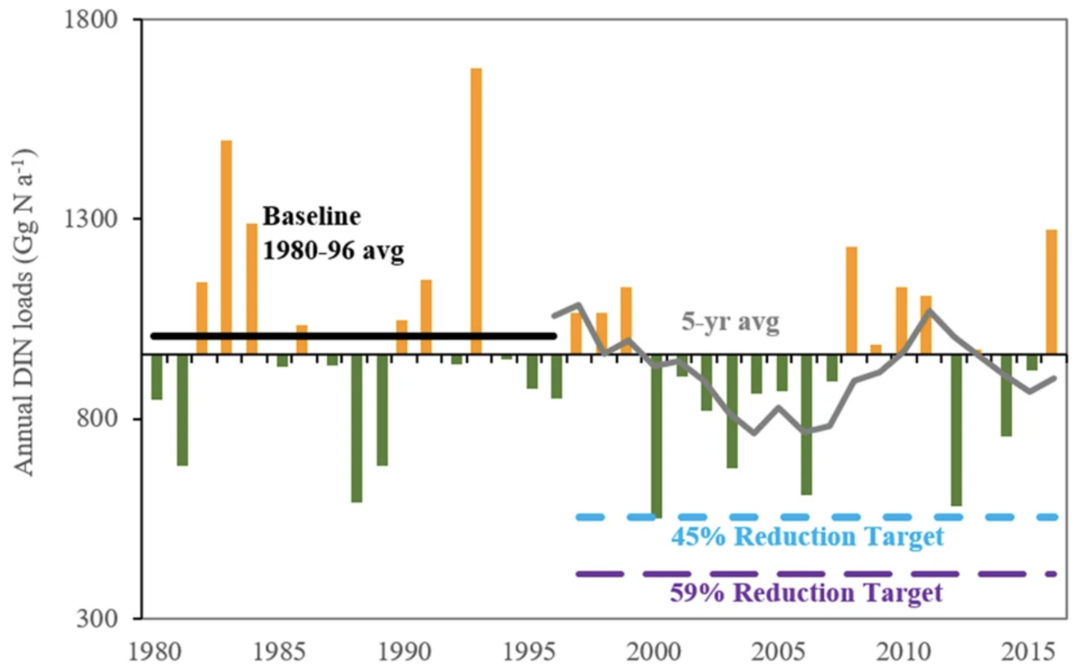


Figure 3. Large inter-annual variation can be found in the monitored dissolved inorganic nitrogen (DIN) loads from the Mississippi and Atchafalaya River basin (MARB) to the Gulf of Mexico during 1980-2017. (Lu, 2020)

Controlling the amount of nitrate flux into the Gulf is necessary to ensure the sustainability of our economies and ecosystems. Nutrient overloading and algal blooms lead to eutrophication, which has been shown to reduce benthic biomass and biodiversity. Many fish and shrimp are displaced by the low DO (dissolved oxygen) waters and move to more shallow inshore water, deeper offshore waters, or higher in the water column.(Rabalais, 2019) Organisms living in the sediments, such as polychaetas, burrowing shrimp, and echinoderms, cannot survive if the DO levels remain low enough for a long time.(Rabalais, 2019) After the hypoxic conditions abate, the abundance and biomass of the remaining infauna remains low, and food resources for returning demersal species are diminished, resulting in lowered secondary production. (Rabalais, 2019)

Eutrophied "dead zones" can also negatively impact the economy. The Gulf supplies 72% of U.S. harvested shrimp, 66% of harvested oysters, and 16% of commercial fish. (Microbial Life Education Resource, 2019) Few species that are common in fisheries can survive in hypoxic water, which leads to massive fish kills in the Gulf of Mexico. Hence, fisherman and coastal state economies are greatly impacted by the nitrogen influx from the Mississippi River.

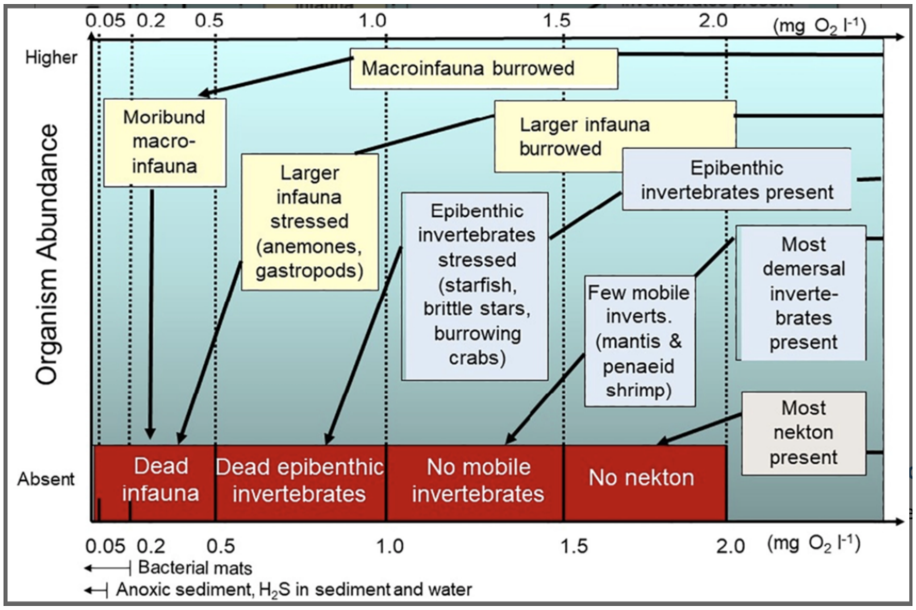


Figure 4. Progressive changes in fish and invertebrate fauna as the bottom-water oxygen concentration decrease from near 2 mg/l to anoxia (0 mg/l). (Rabalais, 2019)

Legislation has been created in Iowa to minimize the extent of the Gulf of Mexico's "dead zone" by reducing their nitrate discharges. This legislation is called the Iowa Nutrient Reduction Strategy and aims to decrease Iowa's nitrate runoff into the Mississippi by 45%. (Iowa Nutrient Reduction, 2020). In this paper, we will be calculating how nitrate levels will be affected upon achieving this goal and how these levels will be further affected by more frequent extreme precipitation events caused by climate change. These calculations will be able to provide support to legislators, farmers, and corporations as they develop strategies to reduce nitrate pollution from Iowa to the Gulf of Mexico.

The Question:

What comparative effect do climate change and Iowa's Nutrient Reduction Strategy (2013) have on the mass of nitrates that reach the Mississippi Atchafalaya River Basin (MARB)?

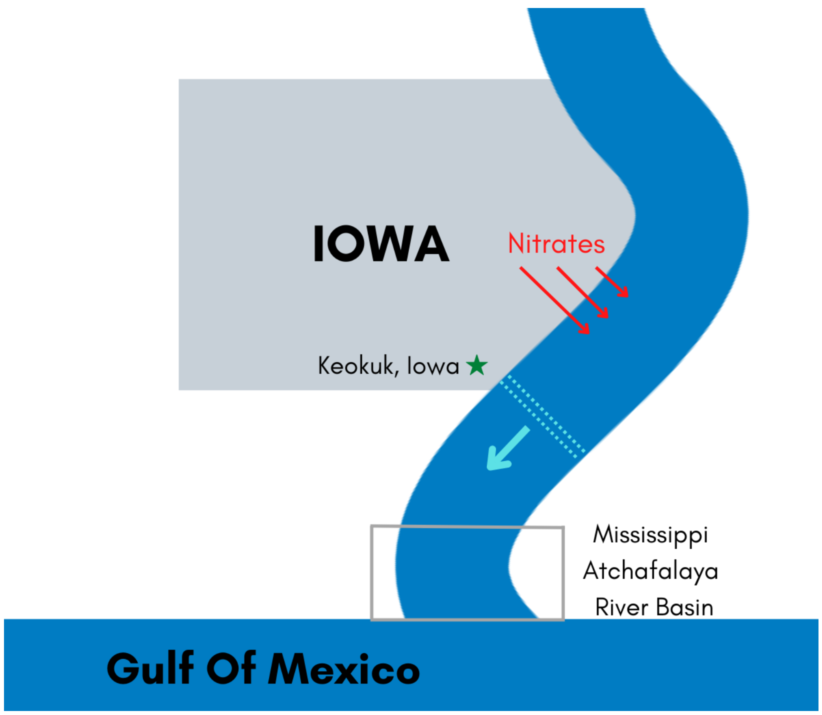
This question was broken down into nine parts:

1. Unit Conversions
2. Calculating Iowa's contribution to Nitrate Loading in the MARB based on the data informing the Iowa Nutrient Reduction Plan (INRP)
3. Calculating other contributions (discounting Iowa) to Nitrate Loading in the MARB based on the data informing the Iowa Nutrient Reduction Plan
4. Calculating Iowa's initial nitrate loading into the Mississippi River

5. Calculating Iowa's contribution to MARB nitrate load upon achieving the INRS goal of 45% discharge reduction
6. Calculating Total Nitrate Load in MARB upon achieving INRS goal
7. Calculating the estimated increase in nitrate runoff from Iowa due to climate change
8. Calculating Iowa's contribution to MARB nitrate load upon taking action to achieve the INRS goal, but now factoring in climate change effects
9. Calculating Total Nitrate Load in MARB upon taking action to achieve the INRS goal, but now factoring in climate change effects

Control Volume:

Our control volume (CV)for this project is the stretch of the Mississippi River (dashed light blue line). The water in the river in particular is the volume being considered. Using a Plug Flow Reactor (PFR) model, this CV will flow from Keokuk, Iowa (to encapsulate all the nitrate runoff from Iowa) to the Mississippi Atchafalaya River Basin (MARB) (which is representative of the discharge entering the Gulf of Mexico).



Assumptions:

Physical Science:

1. Assume that the deposition of fertilizer is constant, and that concentrations of fertilizer in the Mississippi are not near saturation. Assume concentration of fertilizer from upstream of Iowa does not affect the deposition rate of fertilizer in and downstream of Iowa.

2. Assume complete lateral mixing of fertilizer within the CV.
3. Assume no partitioning of fertilizer to the air, or other factors not considered in the loss rate.
4. Assume a constant volume of fertilizer is emitted year-round and that an increase in extreme weather events directly correlates with an increase in fertilizer runoff.
5. Assume that the only way climate change is affecting fertilizer runoff is increased runoff due to extreme weather, and that changes in temperature do not impact the rate deposition of the fertilizer.
6. Assume Q=13,500 m^3/s
7. Assume nitrate loadings in the Mississippi Atchafalaya River Basin (MARB) are equal to those in the Gulf of Mexico which cause hypoxic zones.
8. Assume Iowa contributes 31.5% of nitrate loading in the MARB
9. Assume Distance along Mississippi River from Keokuk, IA to Morgan City, LA (MARB) is 1650 km

Systemic:

1. Assume Climate change impacts extreme event increase one time
2. Assume contributions of all other non-Iowa sources are constant.
3. Assume other factors influencing runoff not considered by the Nutrient Reduction strategy, such as wetland cover, remain constant.

Data:

- Distance between Keokuk, IA (bottom of Iowa) -> Morgan City, LA (in MARB) (L) = 1650 km (Google Maps and ("UMESC - Data Library - River Miles"))
- Loss rate of Nitrate in Mississippi River (k) = 0.005 day^-1 (Alexander, Smith, and Schwarz)
- Average velocity of Mississippi River (v) = 1.2 mi/hr ("Mississippi River Facts - Mississippi National River and Recreation Area (U.S. National Park Service)")
- Annual average flow rate of Mississippi River (Q) = 7,000-20,000 m^3/s ("The Mississippi River – KYGRRO") (Assume 13,500 m^3/s)
- Nitrate Flux into MARB is 61% of total N flux into MARB (Goolsby et al.)
- Iowa contributes between 11 adn 52% of load (Jones et al.) (Assume 31.5%)
- Annual flux of N into MARB = 1,470,000 tons/year ("Total Nitrogen and Phosphorus Flux Delivered to the Gulf of Mexico | U.S. Geological Survey")
- 8.6 days of extreme rainfall account for ⅓ of Nitrates delivered to MARB ("Here's How Climate Change Is Affecting Iowa's Water Quality | Weareiowa.Com")
- Des Moines is averaging 4 more days/year with an inch or more rain than it did in 1950 ("Here's How Climate Change Is Affecting Iowa's Water Quality | Weareiowa.Com")

Mass Balance Equation:

$$\frac{dM}{dt} = M_{in} - M_{out} + M_{created} + M_{destroyed}$$

$$\frac{dM}{dt} = -M_{destroyed}$$

$$C_1 = \frac{C_2}{e^{-kt}}$$

Answer:

The contribution of Iowa to the amount of nitrates reaching the Gulf of Mexico under the Nutrient reduction strategy would be reduced from 1497.6 tons/day to 677.79 tons per day were the program to be effective. The effects of increased storms on the region would lead to a decrease in the effectiveness of this program, leading to a modified output if the goal were to be reached of 1049.49 tons/day of nitrates reaching the MARB. This is only a 29.9% reduction in emissions, which is significantly lower than Iowa's target reduction. Climate change is therefore an important factor to consider when planning how to reach that goal. (The math process is in the appendix section.)

Analysis of Assumptions:

Our model is a significantly simplified model of the real-world Mississippi river, intended primarily to demonstrate a rough magnitude of the magnitude of change produced by fluxes in fertilizer runoff. There are several major assumptions in our model that we know to be untrue. The model is intended more to calculate comparative magnitudes of different effects on fertilizer runoff than to produce an accurate model of nutrient concentrations in the river. The assumptions we made are strong enough to describe comparative magnitudes of these effects, which is useful information when considering whether current policy needs to be adjusted for the effects of climate change.

There are several forms of assumptions that had to be made to calculate the magnitude of these effects on the MARB. The first are a series of assumptions that make the math for this problem reasonable. These assumptions are, for the most part, fairly good assumptions. Assumptions such as no partitioning of fertilizer to air or complete lateral mixing are to some degree untrue, but likely do not significantly impact the value calculated, especially as our values are reported in such large masses. There are several assumptions made that are poorer, though. One of these is that the rate of deposition of nitrates is constant. We assume both that factors such as changing water temperatures or changing water viscosity do not affect deposition, and the concentration of fertilizer is nowhere near saturation. So upstream concentrations or other fluxes of nitrates don't affect the rate of deposition. While the magnitudes of these effects is likely small, if the magnitude were not any of these could significantly increase the deposition rate, affecting our calculations and making the final values reaching the MARB smaller.

The second form of assumption that had to be made concerned is the actual likelihood of external factors remaining constant. It is unlikely for instance, given positive environmental feedback loops, and given recent climate initiatives, that the rate of climate change will remain constant until the year 2035. Whether this value will be greater or less than the change since 1981 remains to be determined, but this value could either be an upper or lower limit on the change in the amount of severe weather Iowa experienced, depending on global climate trends. Given the current rate of climate change efforts and the processes already put into place, this is likely a lower bound on the changes in the likelihood of extreme weather events. Similarly, programs such as the ones in Iowa have been put in place throughout the Midwest——it's unlikely that Iowa would be the only state changing their fertilizer output. Changes in wetland management could also help to protect the Mississippi from nitrates. External reductions could further reduce the amount of nitrates reaching the MARB.

Citation

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Appendix:

Written solutions (Math Process):

Unit Conversions:

avg Velocity (V) = $\frac{1.2\,mi}{hr} \times \frac{1\,Km}{0.6214\,mi} \times \frac{24\,hr}{1\,day} = \underline{\underline{46.35\ Km/day}}$

annual avg flow rate (Q) = $\frac{13500\,m^3}{s} \times \frac{60\,s}{1\,min} \times \frac{60\,min}{1\,hr} \times \frac{24\,hr}{1\,day} = \underline{\underline{1.17 \times 10^9\ m^3/day}}$

Iowa's contribution to Nitrate Loading in MARB:

avg annual flux of Nitrogen into MARB = 1,470,000 tons N/year

↳ flux in ~61% nitrate = 896,700 tons nitrate/year

↳ IA contributes 11-52% load (assume 31.5%) = 282,460.5 tons nitrate/year

$M_2 = \frac{282460.5\ ton}{year} \times \frac{1\ year}{365\ days} = \boxed{773.86\ tons\ nitrate/day}$

from Iowa in MARB

Other contribution to Nitrate Loading in MARB:

$Flux_{total} = Flux_{Iowa} + Flux_{other}$

$Flux_{other} = Flux_{total} - Flux_{Iowa}$

$= 896700\ ton/yr - 282460.5\ ton/yr$

$= \frac{614{,}239.5\ ton}{yr} \times \frac{1\ yr}{365\ days}$

$= \boxed{1682.85\ ton\ nitrate/day}$

from other sources in MARB

Iowa's Initial Loading into Mississippi River

Keokuk

PFR

MARB

Distance traveled (L) = 1650 Km

loss rate (K) = $0.005\ \text{day}^{-1}$

avg velocity (V) = 46.35 Km/day

M_2 = 773.86 ton/day

$Q = 1.17 \times 10^9\ m^3/\text{day}$

Assume
- no nitrate in/out/formed in CV
- complete lateral mixing
- constant velocity & flow rate

Find: C_i to find M_1

boundary conditions:

$t_1 = 0$

$C_1 = ?$

$t_2 = \frac{L}{V} = \frac{1650\ Km}{46.35\ Km/day} = 35.6$ days

$C_2 = \frac{M}{Q} = \frac{773.86\ ton/day}{1.17 \times 10^9\ m^3/day}$

$= 6.614 \times 10^{-7}\ ton/m^3$

$$\frac{dM}{dt} = \cancel{\dot{M}_{in}}^{0} - \cancel{\dot{M}_{out}}^{0} + \cancel{\dot{M}_{formed}}^{0} - \dot{M}_{lost}$$

$$\cancel{V}\frac{dC}{dt} = -K\ C\ \cancel{V}$$

$$\left(\frac{1}{day}\right)\left(\frac{ton}{m3}\right)m^3$$

$$\int_{C_1}^{C_2} \frac{dC}{C} = -K \int_0^t dt$$

$$\ln C\Big|_{C_1}^{C_2} = -Kt\Big|_0^{t_2}$$

$$e^{\ln\frac{C_2}{C_1}} = e^{-Kt_2}$$

$$\frac{C_2}{C_1} = e^{-Kt_2}$$

$$C_1 = \frac{C_2}{e^{-Kt_2}} = \frac{(6.614\times10^{-7}\ ton/m^3)}{e^{-(0.005\ day^{-1})(35.6\ days)}}$$

$$C_1 = 7.90 \times 10^{-7}\ ton/m^3$$

$$M_1 = C_1 Q = \left(\frac{ton}{m^3}\right)\left(\frac{m^3}{day}\right) = \left(7.90\times10^{-7}\ \frac{ton}{m^3}\right)\left(1.17\times10^9\ \frac{m^3}{day}\right) = \boxed{924.3\ ton/day}$$

An average of 924.3 tons nitrate/day were released from Iowa runoff on average from 1981-2005. We will assume this data is representative of data that informed the 2008 Gulf Hypoxia Action Plan. This plan led to the formation of the Iowa Nutrient Reduction Strategy, whose goal was to reduce Nitrate discharge from Iowa by 45%.

Iowa's contribution to Nitrate Load in MARB upon achieving Iowa Nutrient Reduction Strategy Goal:

Keokuk — PFR — MARB

$K = 0.005\ day^{-1}$

$t_2 = 35.6\ days$

$C_1 = (7.90\times10^{-7}\ ton/m^3)(0.55) = \underline{4.34\times10^{-7}\ ton/m^3}$ [45% reduction goal]

$Q = 1.17\times10^{9}\ m^3/day$

Find: C_2 to find M_2

Assume: no nitrate in, out, formed in CV

$$\frac{dM}{dt} = \cancel{\dot{M}_{in}}^{0} - \cancel{\dot{M}_{out}}^{0} + \cancel{\dot{M}_{formed}}^{0} - \dot{M}_{lost}$$

$$\cancel{V}\frac{dC}{dt} = -KC\cancel{V}$$

$$\int_{C_1}^{C_2}\frac{dC}{C} = -K\int_{0}^{t_2}dt$$

$$e^{\ln\frac{C_2}{C_1}} = e^{-Kt_2}$$

$$C_2 = C_1e^{-Kt_2} = (4.34\times10^{-7}\ \tfrac{ton}{m^3})e^{(-0.005\ day^{-1})(35.6\ day)}$$

$$\underline{C_2 = 3.63\times10^{-7}\ ton/m^3}$$

boundary conditions:

$t_1 = 0$

$C_1 = 4.34\times10^{-7}\ ton/m^3$

$t_2 = 35.6\ days$

$C_2 = ?$

$$M_2 = C_2Q = (3.63\times10^{-7}\ \tfrac{ton}{m^3})(1.17\times10^{9}\ m^3/day) = \boxed{424.71\ ton\ nitrate/day}$$

Upon achieving the 45% runoff reduction goal outlined by the Iowa Nutrient Reduction Strategy, Iowa will be responsible for 424.71 tons nitrate/day in the MARB.

Total Nitrate Load in MARB after achieving Goal:

Assuming: $Flux_{other}$ remains constant

Given: $Flux_{other} = 1682.85\ ton/day$

$Flux_{Iowa} = 424.71\ ton/day$

$$Flux_{total} = Flux_{Iowa} + Flux_{other}$$

$$Flux_{total} = (424.71\ ton/day) + (1682.85\ ton/day)$$

$$Flux_{total} = \boxed{2107.56\ ton\ nitrate/day}$$

If Iowa achieves their 45% reduction goal and assuming all other sources of nitrate into the MARB remain the same, the total nitrate loading in the MARB will be 2107.56 ton nitrate/day.

$\boxed{\text{Estimated Increase in Nitrate Runoff from Iowa due to Climate Change:}}$

Given: 8.6 extreme precipitation days accaunt for 1/3 of nitrate yield
Des Moines, IA averaging 4 more days/yr of extreme precip due to climate change

Assume: Extreme precip will impact nitrate runoff equally across the state
No further growth of extreme precipitation days

$\frac{(1/3)^{\text{yearly nitrates}}}{8.6\text{days}} = 0.0388 = \underline{3.88\%}$ of yearly nitrate yield from 1 extrem precipitation event

$3.88\% \, (4) = \boxed{15.5\%}$ is the estimated increase in yearly nitrate runoff (C_I) due to climate change.

Iowa's contribution to MARB Nitrate Load upon achieving INRS goal, but now assuming for increased extreme precipitation events due to Climate Change:

Keokuk

$K = 0.005 \text{ day}^{-1}$

$t_2 = 35.6 \text{ days}$

$C_1 = (4.34 \times 10^{-7} \text{ ton/m}^3)(1.155) = 5.01 \times 10^{-7} \frac{\text{ton}}{\text{m}^3}$ [45% reduction goal x 15.5% increase]

MARB

$Q = 1.17 \times 10^9 \text{ m}^3/\text{day}$

Find: C_2 to find M_2

Assume: no nitrate in, out, or formed in CV

$$\frac{dM}{dt} = \cancel{\dot{M}_{in}} - \cancel{\dot{M}_{out}} + \cancel{\dot{M}_{formed}} - \dot{M}_{lost}$$

$$\cancel{V}\frac{dC}{dt} = -KC\cancel{V}$$

$$\int_{C_1}^{C_2} \frac{dC}{C} = -K\int_0^{t_2} dt$$

$$\ln\frac{C_2}{C_1} = -Kt_2$$

$$C_2 = C_1 e^{-Kt_2} = (5.01 \times 10^{-7} \tfrac{\text{ton}}{\text{m}^3}) e^{(-0.005 \text{ day}^{-1})(35.6 \text{ day})}$$

$$C_2 = 4.19 \times 10^{-7} \text{ ton nitrate/m}^3$$

boundary conditions:

$t_1 = 0$

$C_1 = 5.01 \times 10^{-7} \text{ ton/m}^3$

$t_2 = 35.6 \text{ days}$

$C_2 = ?$

$$M_2 = C_2 Q = (4.19 \times 10^{-7} \text{ ton/m}^3)(1.17 \times 10^9 \text{ m}^3/\text{day}) = \boxed{490.23 \text{ ton nitrate/day}}$$

Upon achieving the 45% reduction goal in discharge, but taking into account the effects of climate change, Iowa will be responsible for 490.23 ton nitrate/day in the MARB.

Total MARB Nitrate Load after achieving goal but considering climate change:

Assuming: $Flux_{other}$ remains constant

Given: $Flux_{Iowa} = 490.23$ ton/day

$Flux_{other} = 1682.85$ ton/day

$$Flux_{total} = Flux_{Iowa} + Flux_{other}$$

$$Flux_{total} = (490.23 \text{ ton/day}) + (1682.85 \text{ ton/day})$$

$$Flux_{total} = \boxed{2173.08 \text{ ton nitrate/day}}$$

If climate change induced extreme precipitation events effect Iowa while they contribute actions to meet the 45% reduction goal and assuming other sources of nitrate to the MARB remain constant, Nitrate loading of the MARB will be 2173.08 ton nitrate/day.