IE 550 Term Project

Dynamic Modelling of Harmful Algal Blooms and an Analysis on Potential Mitigation Strategies

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Dynamic Mitigation Strategies for Harmful Algal Blooms

1. Introduction

An algal bloom is an uncontrollable accumulation of algae in freshwater or marine life. Though the term algae is used both for species of seaweeds and cyanobacteria, the most common cause of algal bloom is the continuous reproduction of unicellular cyanobacteria which is essentially not algae but eukaryotic phototrophs. (Huisman, 2018) Common causes of algal blooms are chemical wastes (nitrogen and phosphorus), eutrophication, climate change, and ocean acidification. (Anderson, 2015) Algal blooms may pose a great danger to aquatic life via the accumulation of cyanotoxins and depletion of oxygen which interferes with the recreational function of the ecosystem leading to severe ecological phase shifts. (Wells, 2020) Also, usage of those freshwaters as drinking water and consumption of contaminated seafood leads to liver, digestive and neurological illnesses and death in humans, birds, and mammals. (Huisman, 2018) Such pestilent algal blooms are called "Harmful Algal Blooms" and their proper management is crucial for the sustainability of their ecosystem and surrounding environment including the human element.

Several mitigation methods are being implemented to manage HABs. Common mitigation strategies include; the usage of several biochemicals and biological processes in fight against uncontrollable algae reproduction, reduction of the chemical and anthropogenic waste which creates more nutrition, and introduction of biological agents such as parasites and grazers. (Rastogi, 2015) However, biochemicals used in the process usually are not host-specific, targeting other stakeholders of aquatic life, killing and contaminating them. Possible reduction of chemical waste is limited, since influential chemicals on algae reproduction, nitrogen and phosphorus, are substances used heavily in fertilizers, the most common and unavoidable type of waste (Glibert & Burford, 2017). Biological agents interfere with the fundamental structure of the freshwater food chain and knit additional feedback relations which may lead to undesirable results (Wiley, 2018; Anderson, 2015). Thus, each of these strategies come with a trade-off.

Considering these adverse effects, precaution against HABS, mitigation/control strategies are gaining importance as a field of research. In their work, Moore et al. (2008) also emphasize the necessity to build simulation models to integrate observations, test and validate a hypothesis and make projections concerning the potential impacts of HABs on public health. .

Building an effective mitigation strategy for HAB management by applying policy analysis requires an elaborative examination of this dynamic system while having consideration for various dynamic relations lying within, making System Dynamics Methodology an efficient tool for scenario analysis. Moreover, although data-driven prediction models are numerous in the field (Benayache *et al.*, 2019), causal modeling approaches are rather limited while conceptual models that provide a general overview is considered as one of the requirements for the progress of the field (Wells *et al.*, 2020). Motivated from this, in this study we aim to build a conceptual model of the population dynamics related to the formation of harmful blooms. Instead of providing a numeric accuracy, it is intended to focus on fundamental insights regarding the phenomena and introduce the subject to System Dynamics Modelling in order to promote the further investigation of the problem with a systemic approach.

2. Problem Definition

Most of the algae species are fundamental for the sustainability of water ecosystems considering their involvement in oxygen production, various nutrient cycles, and complex food webs. A small proportion of these algae, however, may cause problems for other species in the environment or even may pose a threat to the ecosystem itself (Glibert *et al*., 2018). Harmful Algal Bloom (HAB) is the disturbance of the water ecosystem, or consequently other relevant ecosystems, that is characterized by the "harm" it inflicts on the environment which can be attributed to either increased biomass of a particular type of algae or the observable effects of produced toxins along the food chain (Smayda, 1997). Due to increased biomass of algae or elevated toxin levels in the water, other species including humans often face lethal consequences such as the risk of intoxication, limited dissolved oxygen levels, disrupted food web interactions, or decreased level of sunlight in water (Burkholder *et. al.*, 2018). Moreover, it is estimated that HAB related annual expenses between the years 1987-1992 are on the order of $50 million annually for the USA nationwide with the main categories: public health, commercial fisheries, recreation and tourism, and monitoring and management (Hoagland *et al.*, 2002). Considering the increasing frequency and severity of HAB's (Glibert and Burford, 2017), up to date damage to the public health, economy, and the environment is even bigger which necessitates to come up with mitigation strategies to alleviate the negative consequences. However, formation of algal blooms is a dynamic process involves non-linear relationships among various factors, which will be elaborated on next section, and time delays which makes it impossible to come up with a static solution. Therefore, it is suitable to use simulation modelling to analyze different mitigation strategies to characterize each mitigation strategy with the corresponding consequences. To analyze the root structure, root causes and mitigation strategies of Harmful Algal Blooms will be discussed in the upcoming sections.

2.1. Drivers of Harmful Algal Blooms

For the emergence of HAB, the right environmental conditions and the right species must be present leading that causes can fall under two umbrella categories: they are caused by either a change in the current environment or introduction of new species to the new environment (Glibert and Burkholder, 2018). The latter is usually associated with the ballast water dispersal, shipping of aquaculture products, or climate-mediated ocean circulations (Smayda, 2007; Hallegraeff, 2010; Hégaret, 2008). However, change in the environment is a broad term including, eutrophication (nutrient increase in water such as increased N or P levels), temperature and acidification changes due to climate change, residence time, and turbulence (Glibert and Burkholder, 2018; Anderson et al., 2015).

Anderson et al. (2015) summarize the underlying causes of nutrient pollution as overpopulation, higher energy demand, extensive use of nitrogen (N) and phosphorus (P) fertilizers, increased meat demand and consequent animal waste and expanding aquaculture industries (e.g., Smil, 2001; Galloway and Cowling, 2002; Howarth et al., 2002; Glibert et al., 2006). Although nutrient loading (especially N and P) is considered as the main driver of the HABs, the relation between is far beyond simple (Anderson et al., 2015). The formation of HAB depends on complex dynamics between different types of algae species which have different adaptations to their environment (Glibert and Burkholder, 2018). Usually, ratios of the nutrients (Such as N:P, N:Si or P:Si ratios) are influencing the optimal growth rate of different algae species. Moreover, the form of the nutrients (different forms of nitrogen such as NH4+ or NO2-) also influential on the growth of a bloom. Once the bloom is formed, adaptive capabilities allow phytoplankton to sustain its life even though the optimal ratios are violated (Glibert and Burkholder, 2018).

Increased temperature and acidification in waters are proposed as a secondary effect of prevailing climate change. It is estimated that the temperature of 100m surface water of oceans will increase by 2°C by the end of the twenty-first century. It is also expected that temperature increase and lower pH levels due to climate change will extend the optimal growth periods for some species, which will increase the risk of HAB (Moore, 2008).

2.2 Consequences of HAB & Bloom Control Mechanisms

Possible consequences of HABs can be summarized as (1) intoxication along the food chain including plants, fisheries, mammals and human beings, even leakage of the produced toxins to the atmosphere (if aerosolized), and the potential contamination of water supplies from freshwater reservoirs or desalination plants; (2) decreased levels of dissolved oxygen and/or the irritation of biota as algal biomass decays; and (3) and physical damage to fish gill tissue (Anderson et al., 2015).

Control mechanisms are classified as direct and indirect control mechanisms depending on their application after or before the bloom occurs. Indirect control mechanisms include reducing nutrient pollution or modifying water circulation whereas direct control mechanisms involve physical, chemical, or biological interferences (Kim 2006). Summarizing table is provided below.

Controls	Mechanisms	Available agent
Biological	Grazing (top-down)	Copepods, ciliates, bivalves
	Algicidal agents	Bacteria, viruses
	Parasites	*Amoebophrya, Parvilucifera*
	Enzymes	Mannosidase
Physical	Destruction	Ultrasound
	Electrolysis	NaOCl
	Removal	Skimmer, screen filter
	Isolation	Shield curtain, perimeter skirt
Chemical	Flocculants	Clays and long-chain polymers
	Surfactants	Sophorolipid, aponin
	Mucolytic coagulants	Cysteine compounds
	Metals and liquids	Copper, $Mg(OH)_2$, H_2O_2

Table 1: Direct control mechanisms for HABs (Kim, 2006)

3. Model Description

After building a conceptual basis on the problem the generic structure of the model became more or less certain. Since the aim of this project is to test the performance of some short to medium term mitigation strategies, influence of global variables such as climate change or global warming is omitted. System is fundamentally a basic food chain with several external factors (such as nutrient loadings, climate...) all of which are responsible for the bloom problems via feeding the vicious feedback loops within the system structure.

Since we are building a generic model not for a specific water reservoir or basin, we have listed some of the model assumptions & simplifications:

- Scene is a small sized closed shallow freshwater ecosystem.
- Food chain has three steps, consisting of Cyanobacterias, Zooplankton and Fish. Fish feed on Zooplanktons and Zooplanktons feed on Cyanobacterias.
- Cyanobacteria's food source is accumulated total nutrients in the water. Phosphorus, Nitrogen and other nutrients are treated uniformly.
- Consumption of oxygen is constant for all members of a species independent of the current oxygen level in a state. Day and night differences among respiration rates are assumed to be aggregated in these constants.

- Biological agents to be covered in mitigation analysis is defined as a parasite which is a predator of cyanobacteria. Birth/death dynamics of this species is affected by the oxygen level but not by the cyanotoxins.
- Seasonal effects such as precipitation and temperature are omitted.
- Most of the initializations are made without data. However, standardilizations are used to observe the bloom dynamics.

3.1. Causal Loop Diagram

A causal loop diagram is constructed for the model as a formal representation of the system structure in terms of interrelations of the aforesaid entities in the model scope. There are three major causal loops governing the system structure.

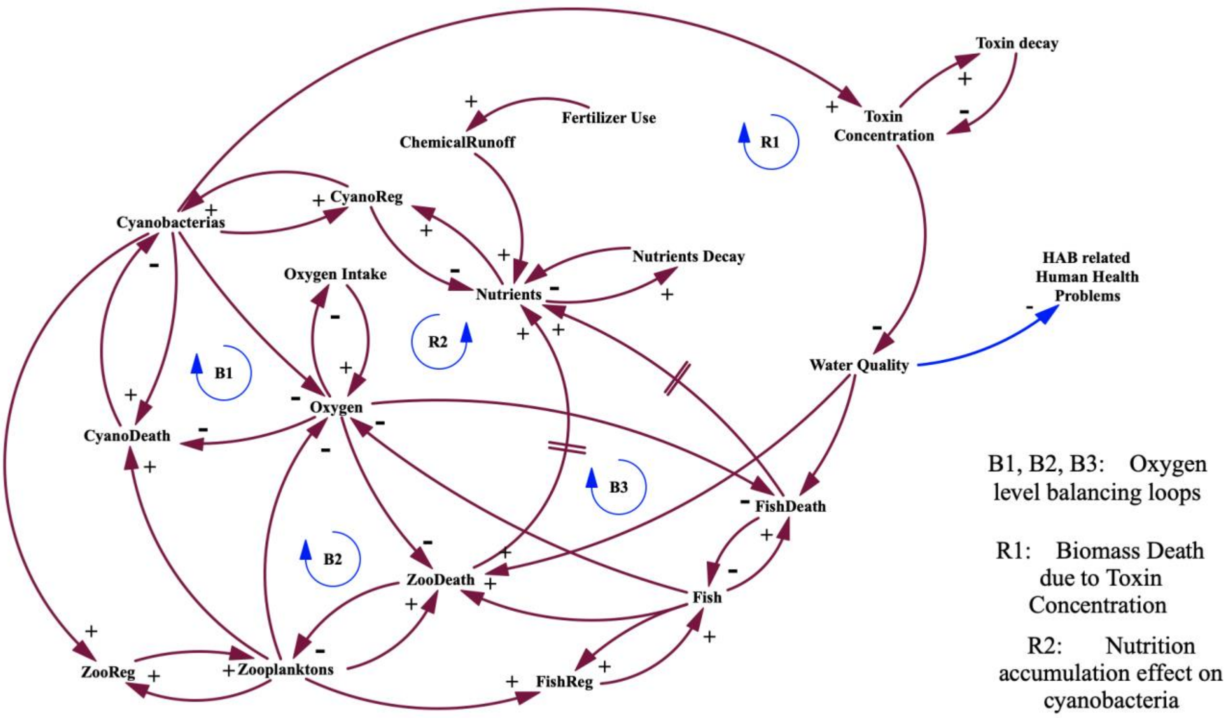


Figure 1: Causal Loop Diagram

First is the causal loop family of the oxygen level. Each entity of this three-step food chain consume oxygen for respiration and has shorter life spans for oxygen-poor waters. This is a natural balancing loop in a typical closed freshwater ecosystem. In the case of an abnormally quick and large regeneration level for cyanobacteria, B1 can not dominate thus creating an oxygen shortage; the same dynamic is also present for other species.

Second is a reinforcing loop of Biomass Death due to Accumulated Toxins, R1. As cyanobacteria pop increases due to high nutrition, so does cyanotoxin concentration, decreasing water quality as a result. This increases biomass death, adding to the nutrition of the water after a decomposition delay.

Last is the Nutrition Accumulation Effect on Cyanobacteria, R2. Decreasing oxygen levels and water quality increases the biomass death. Dead biomass, after a decomposition delay, becomes nutrients. Loop closes as more nutrition causes cyanobacteria to regenerate more and decrease water quality and oxygen.

Chemical runoff in above causal loop diagram is the external stimulator of R1 and R2 loops. As R1 and R2 are stimulated positively in their default directions, cyanobacteria population grow. B1 loop and consumption by zooplanktons activate in order to limit that growth but fail to dominate in certain scenarios with great amounts of nutrient inflow from chemical runoffs.

3.2 Causal Loop Diagram with Mitigation Strategies

Potential mitigation strategies are shown in the diagram below. We will analyze three policies as potential solutions to our problem: Use of chemical agents, cleaning efforts and introduction of biological predators.

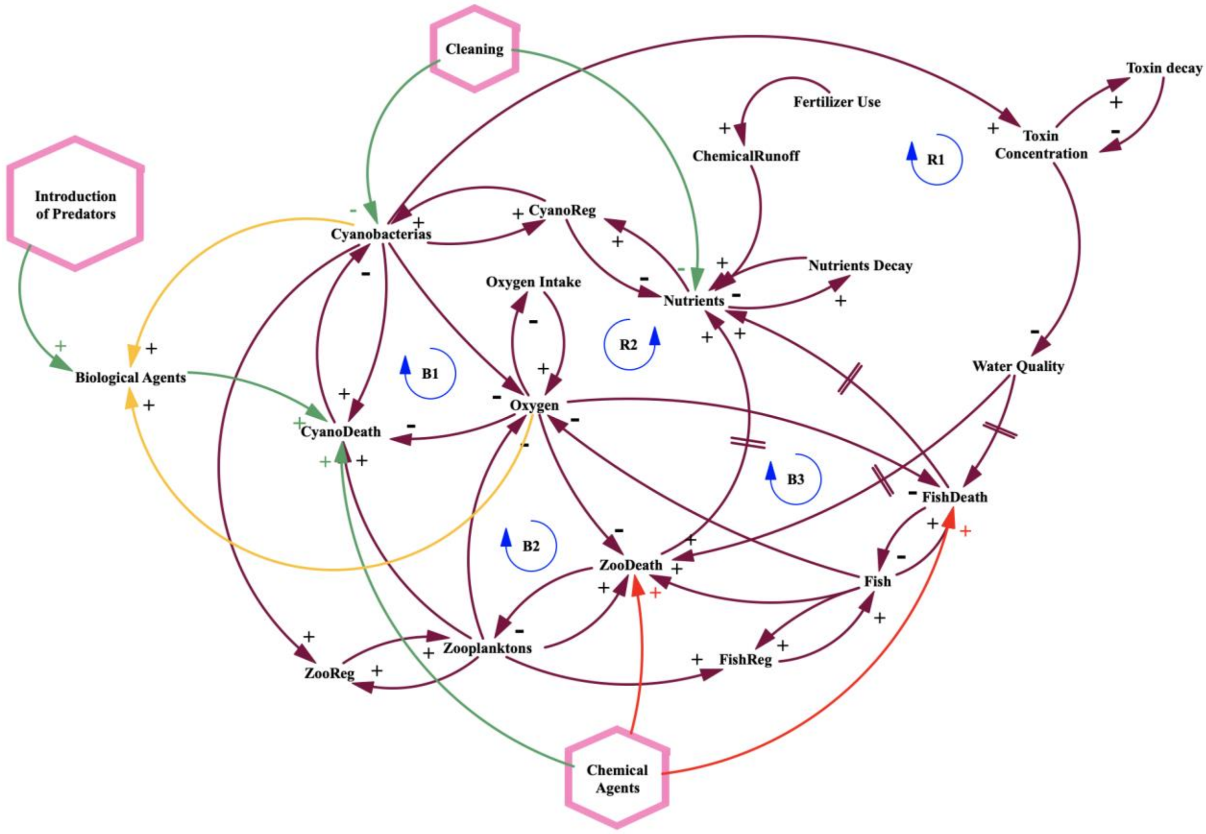


Figure 2: Causation of Potential Mitigation Strategies

Chemical algicide is a mix of biochemicals used in extermination of algae in small reservoirs. They are efficient in killing cyanobacterias via increasing their death rate. But, they also inflict damage on non-target aquatic life through an increase in biomass death. This trade-off is what makes algicide effects interesting since straightforward application may yield even worse outcomes.

Cleaning efforts are directed at two levels: Nutrients and cyanobacteria. Removal of portions of cyanobacteria and their food source from the system can balance the disproportional growth we wish to dominate. The question on this strategy is: should the cleaning be a one time exhaustive spring-clean or a series of regular small scaled processes in order to have a sustainable system free of HAB?

Last potential mitigation strategy is the introduction of biological predators of cyanobacterias, also known as freshwater grazing. Biological predators of cyanobacterias include other bacterias, microbes, parasites and fungi. Important is that once a new species is introduced, it becomes part of the ecosystem. This may lead to different behaviors in the long run towards new equilibria: new species may not adapt and go extinct, all species may reach a stable equilibrium, or some of the previous occupant species go extinct. The outcome is the result of the newly forging feedback relationship through oxygen consumption and cyanobacteria grazing and is highly affected by the state of the system at the time of the introduction as well as the incoming population amount of the new species. All this makes this strategy promising and worth an analysis.

3.3 Stock Flow Diagram

Stock flow diagram is drawn using STELLA. A complete list of stocks, flows and converters can be found in the Appendix. Graphical functions used in the model are given in section 3.4 with explanations.

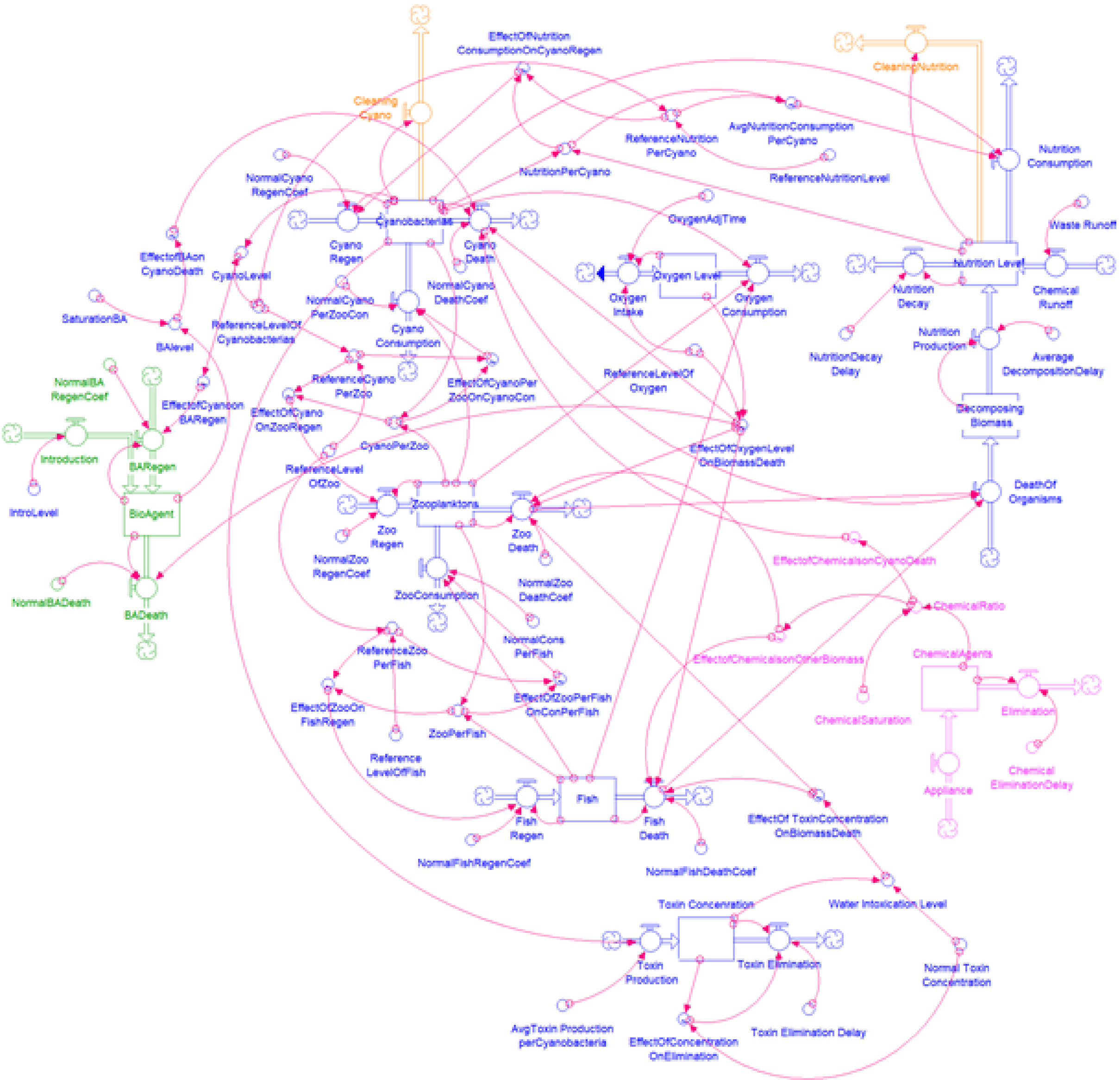


Figure 3: Stock Flow Diagram

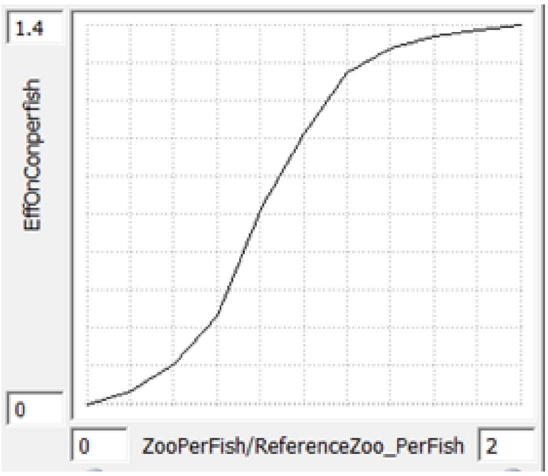
Food chain is modelled step by step using similar formulations across species. Population level of a prey affects the birth rate of a predator while population level of a prey affects the death rate of a predator. “Food availability” type formulation structure was used to give the nonlinear effects on births. In other words, effects between steps are graphical functions taking the prey/predator ratio as its input. A condition of multiplicative effects, all functions yield output of 1 (no effect on rate) to the input of 1(reference prey/predator ratio). Graphical functions saturate on both ends in order to avoid meaningless continuous increases in rates. Effects on regeneration saturate at zero, meaning that when there is no prey, we would not expect a regeneration of predator either. Other boundaries are also set to meaningful values.

Oxygen intake is formulated by a goal seeking behavior. As oxygen concentration falls below its reference level, oxygen intake (air-to-water solution) increases due to diffusion, evening out the oxygen discrepancy between air and water. A natural delay time is defined for this intake process. Oxygen consumption is given linear with the biomass levels with each species having its own oxygen consumption fraction per individual. Effect of oxygen shortage on deaths is drastic. it is expected that with no oxygen, everyone should die. Graphical function is drawn fulfilling this premise.

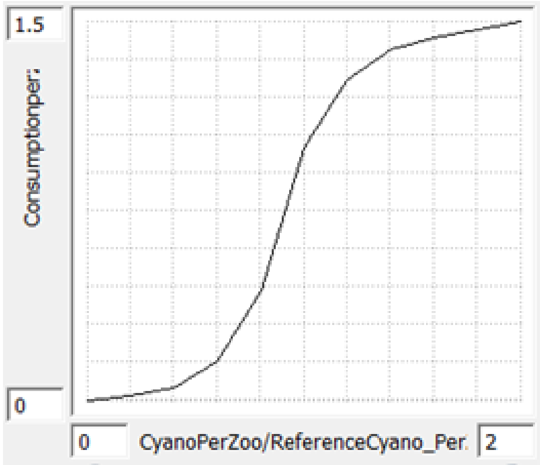
When organisms in the model die, the nutritious parts of their bodies proceed to Decomposing Biomass stock by a fraction for each species. After a decomposition delay, they join the accumulation of Nutrients in the lake. Chemical runoff directly adds to the Nutrients as they usually are in the form of non-complex anions. There are two outflows from the Nutrients stock: Nutrition Decay by other organisms and Nutrition Consumption by cyanobacterias. Average consumption per cyanobacteria, having a non-linear graphical function, is positively linked with nutrients per cyano ratio and saturates on both ends. Similar to the food chain, effect of nutrients on cyanobacteria regeneration is given using food availability formulation.

3.4 Graphical Functions

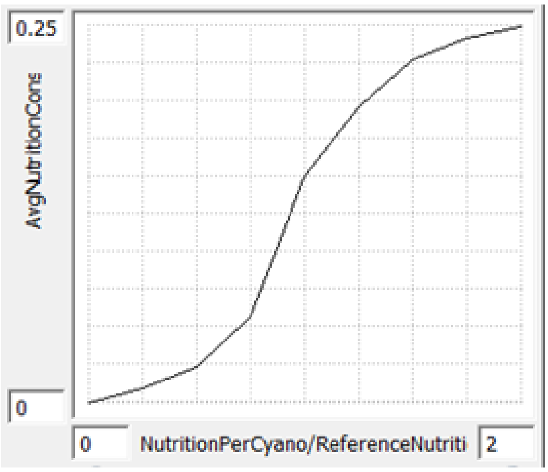
Effect of Food Availability on Consumption per Fish



Effect of Food Availability on Consumption per Zooplankton

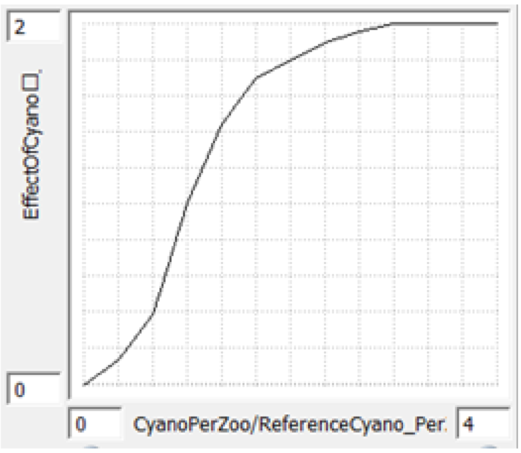


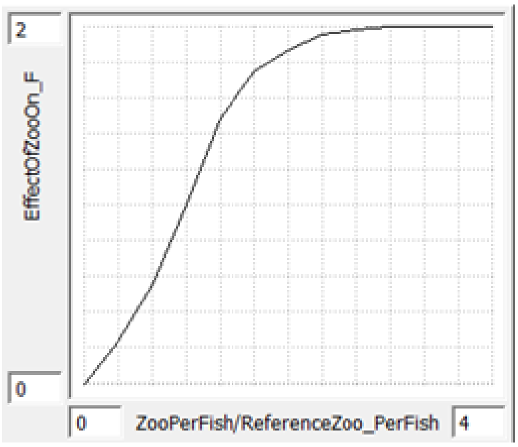
Effect of Nutrient Availability on Consumption per Cyanobacteria



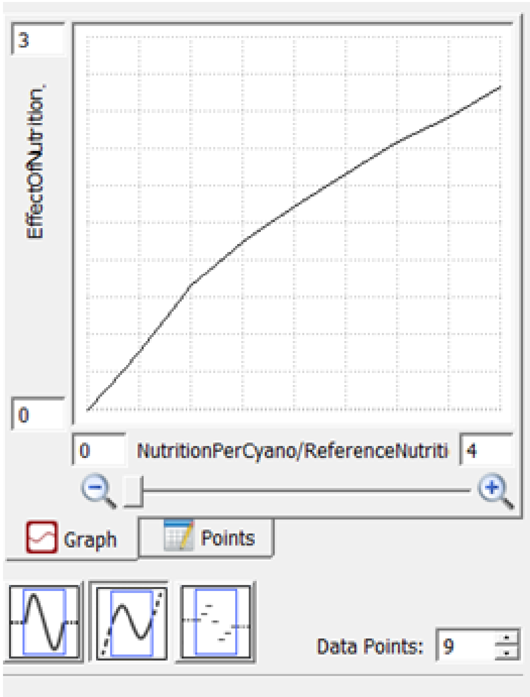
Food availability formulations assumes that as prey/predator ratio increases, consumption per predator also increases with a saturating effect. Conversely, as prey/predator ratio decreases finding new prey gets harder resulting in low consumption per predator on average. When the prey population is zero, average consumption per prey is naturally becomes zero. Since the prey/predator ratios are standardized, all graphs pass from the point (1,1).

Effect of Cyano on Zoo Regen



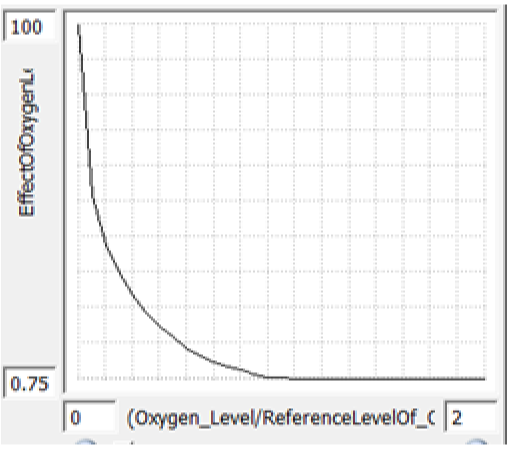


Effect of Nutrition on Cyano Regen



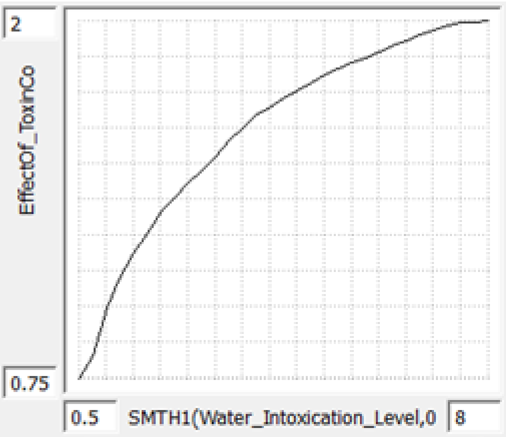
Since consumption per predator is a function of food availability, it makes sense for a predator to observe the benefits as the food is more available. Therefore, positive effects of preys on preadator regenerations are increasing graphical functions that are standardized by prey/predator ratio. The first two graphs are saturated S shaped graphs whereas the last one is a linear graph with extrapolation.

Effect of Oxygen Level on Biomass Death



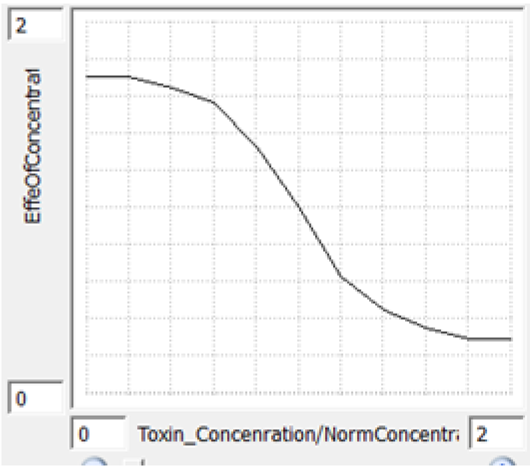
The effect of oxygen is similar to inverse x graph. As oxygen levels get close to 0 death rate of all living stocks hugely increase, ensuring death of all organisms.

Effect of Toxin Concentration on Biomass Death



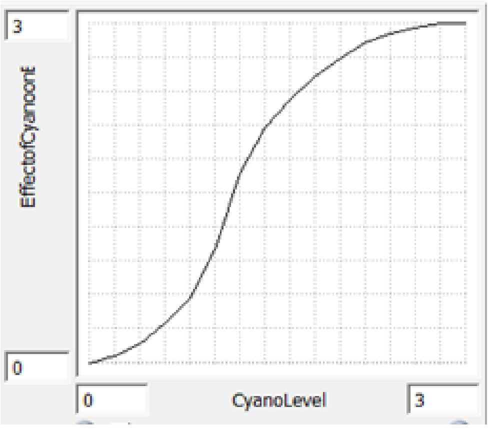
Since cyanobacterial toxins are presented in the water, the current toxin level is standardized with the reference value (Water Intoxication Level). As Water intoxication level increases death rate of all biomass other than cyanobacteria increases saturating at some point.

Effect of Toxin Concentration on Toxin Elimination Rate



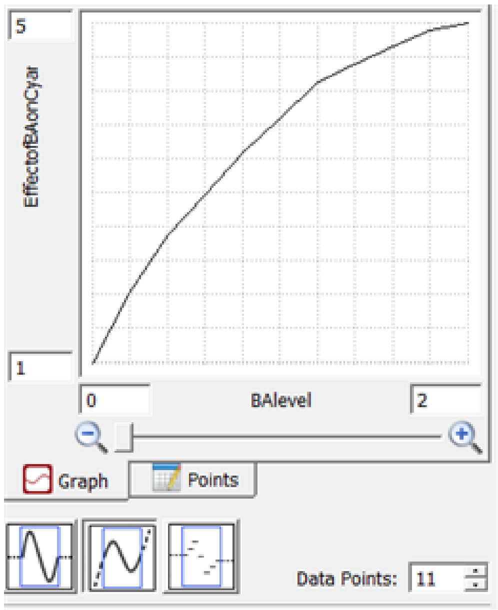
As toxin concentration increases, the biological agents that helps disolving are blocked therefore we observe a small decrease in case of elevated toxin levels.

Effect of Cyano on Biological Agent Regeneration



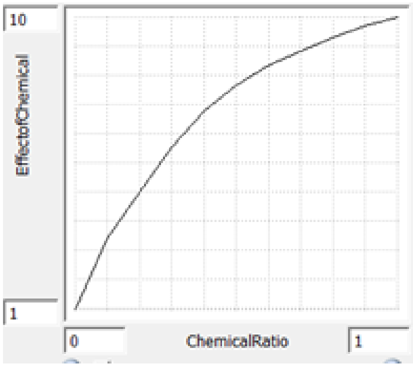
Biological agents feed on cyanobacterias as CyanoLevel i.e. Cyanobacteria/ReferenceCyanoLevel increases birth rate of biological agents increases and vice versa. These effects saturate as Cyano Level gets close to zero and 3 which is assumed to be the saturation level.

Effect of Biological Agent Level on Cyano Death

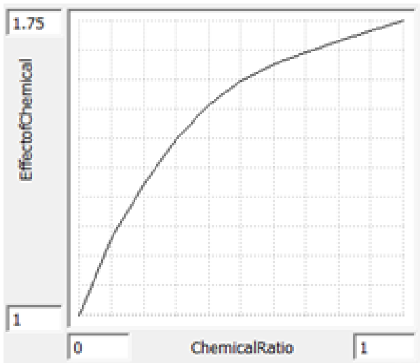


Biological agents feed on cyanobacterias therefore increased BA level indicates influence of Biologiccal agents on cyano death is more effective. Graph is chosen to extrapolate.

Effect of Chemicals on Cyano Death



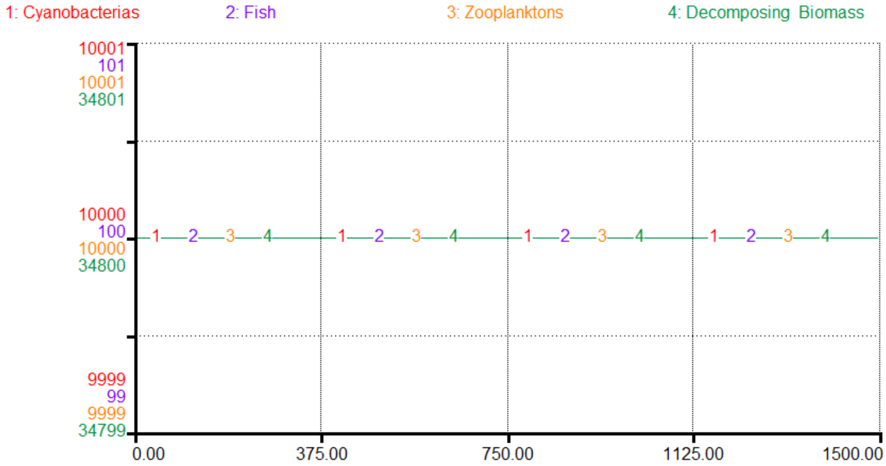
Effect of Chemicals on Other Biomass

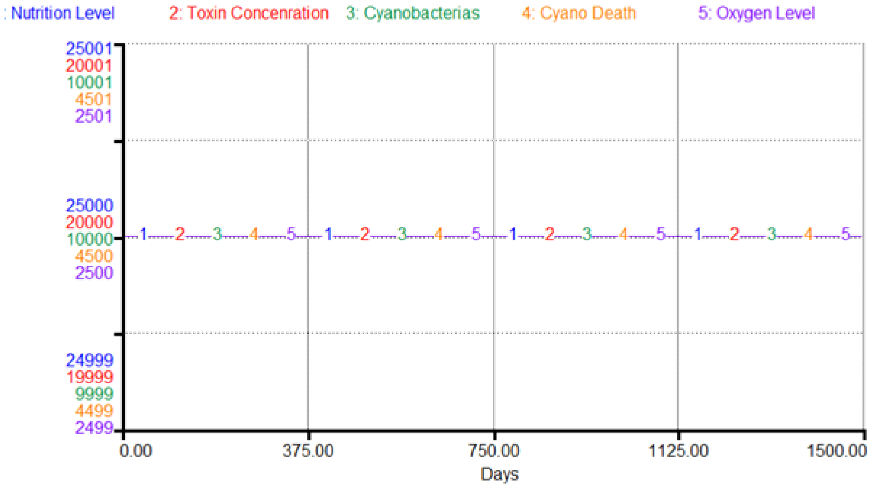


Chemical agents target cyanobacteria causes an increase in the death rate of cyanobacteria. However as a coleteral damage it increases the deathh of other livingbeings since most chemicals have secondary effects. However, effects are formulated such that overall impact on cyanobacteria is more present compared to the other livingbeings. Since chemicals are not presented in normal condition as chemicalratio get close to zero the effects take the value of 1.

4. Model Validation

Upon the completion of model construction and formulation of equations, stock values are initialized at equilibrium levels derived from traffic balance equations. Following figures show the variable responses in the base run of the model.

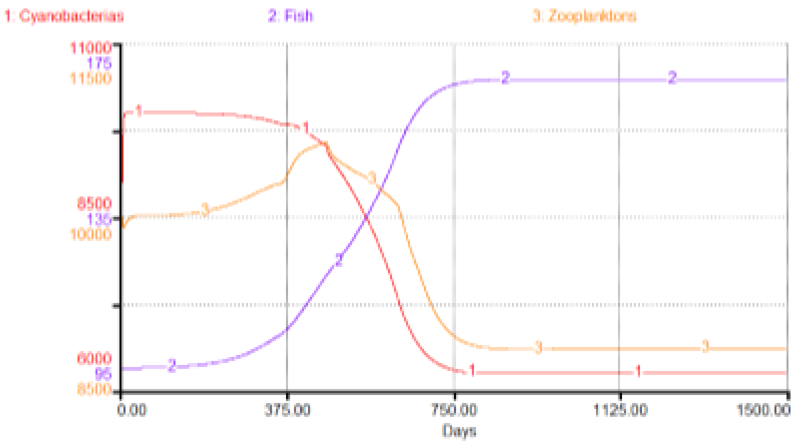


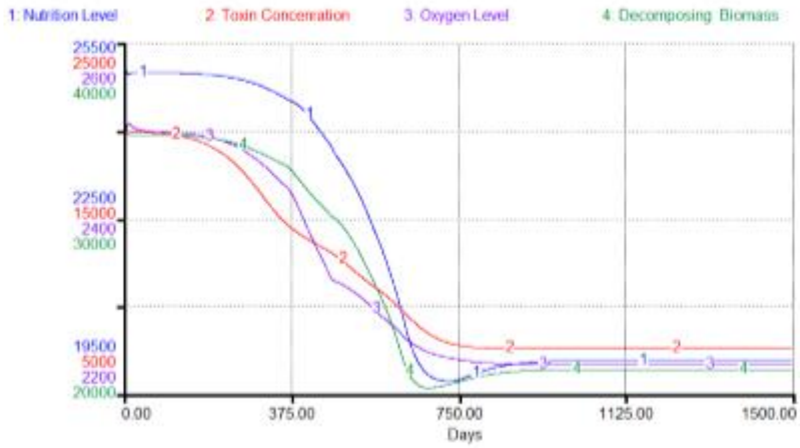


All stocks stays in their equilibrium levels with all graphical effect functions passing (1, 1). Here we present a perfectly stable ecosystem with no possible changes. It should be noted that this is not a representation of the dynamic problem but of a cakes and ale situation with tuned parameters. Parameter set (of species stocks) of the equilibrium level is as follows:

Equilibrium X: Fish, Zooplanktons, Cyanobacteria: (100, 10000, 10000)

Model behaviour should be observed under different conditions in order to test the structural validation of the model. Model is initialized with a slightly lower cyanobacteria population of 9000. (Previous default was 10000)



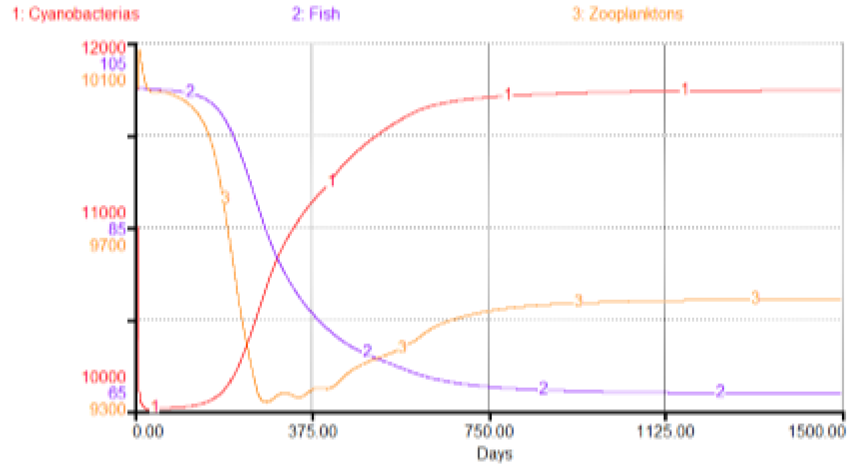


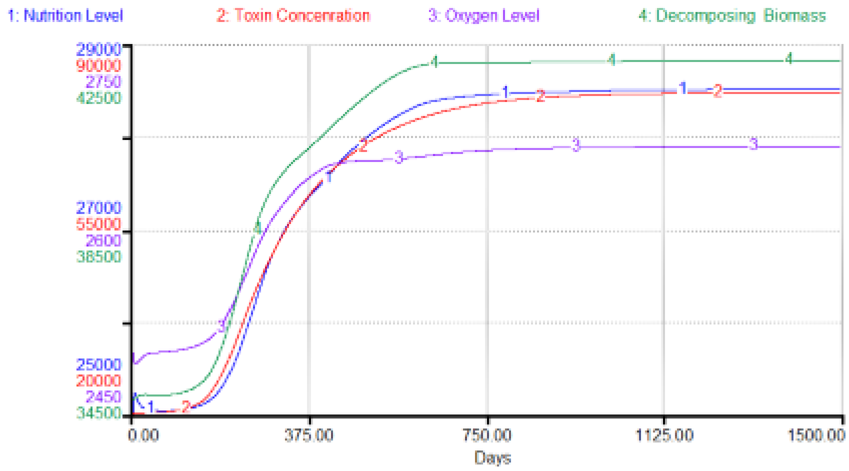
System experiences a phase shift to a new equilibrium level. In the new equilibrium, there is a greater fish population and lower cyanobacteria and zooplankton levels. Toxin concentration, oxygen and nutrition levels show a decrease. Model runs are also taken for lower initial values for other species stocks and nutrients. Results remained consistent, model reaches a new equilibrium at:

Equilibrium Y: Fish, Zooplanktons, Cyanobacteria: (166.67, 8856, 6238)

Also, observing a shift in such small changes may mean that the initial conditions taken above in base run section may represent an unstable equilibrium point; if we hit a domino, the rest collapses. (in this case, regenerates to other levels)

If we increase the initial cyanobacteria population by 1000, or zooplanktons by 1000, or fish by 10, or nutrients by 2500 (each being 10% increases), system reaches another equilibrium point.





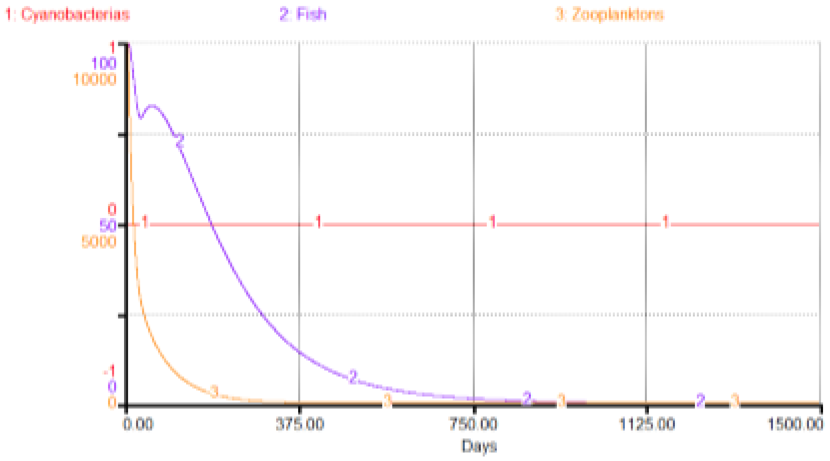
In the new equilibrium level, there is an increased stable population of cyanobacterias with lower zooplankton and fish populations; remaining stocks increase till saturation. Runs were then replicated with much lower differences from Equilibrium X levels but results remained consistent. A new equilibrium is achieved:

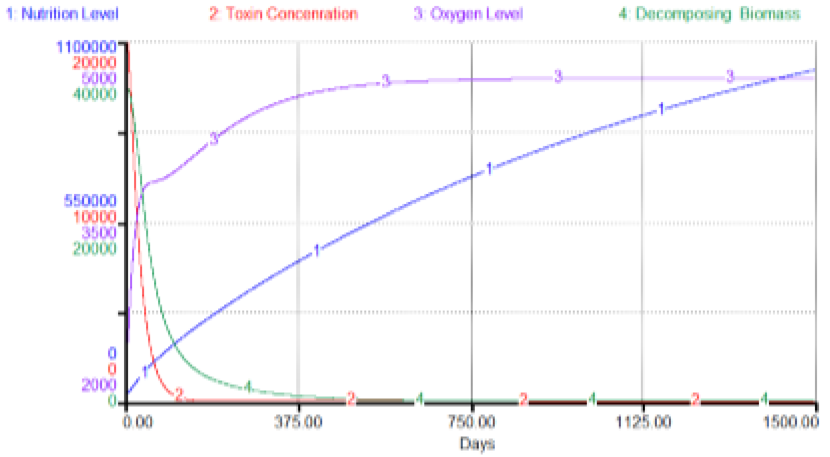
Equilibrium Z: Fish, Zooplanktons, Cyanobacteria: (67, 9541, 11740)

(Cyano 11740, Fish 67, Zoo 9541 , Nutrient 28516 ,Toxin 80880 ,Oxygen 2267 ,Dec. Biomass 42150)

Extreme input condition runs are conducted to test the justifiability of the model. If an abnormal behavior is observed there should be clearly something wrong. In this regard, species stocks are initialized at 0 and resulting graphical outputs are presented as follows:

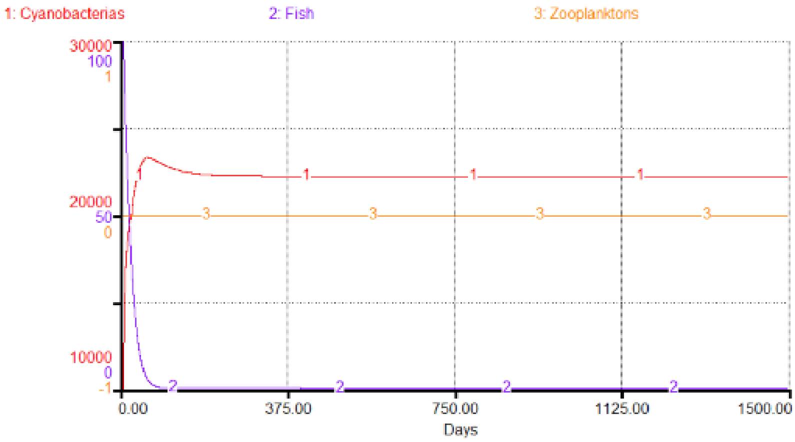
Initial cyanobacteria population = 0

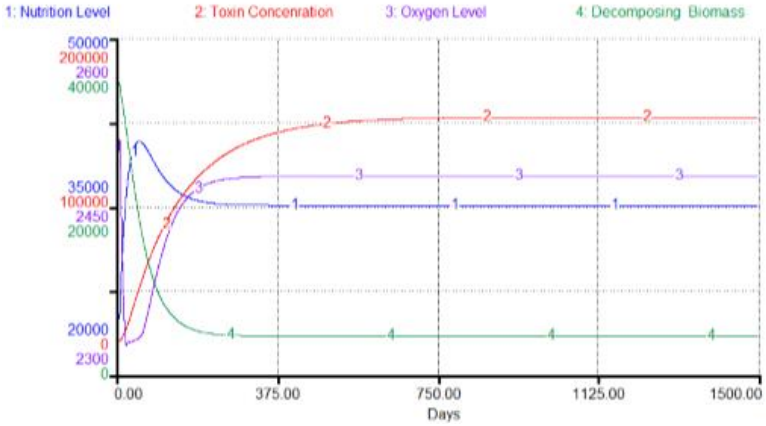




Fish and zooplankton levels starts decreasing immediately along with cyanotoxin concentration. It can be observed that fish levels experience a peak after a while. This behavior is due to the depletion of toxin concentration which decreases fish deaths. However, this climb is short lived as their -primary- food source zooplanktons collapse afterwards. Ultimately, all species go extinct.

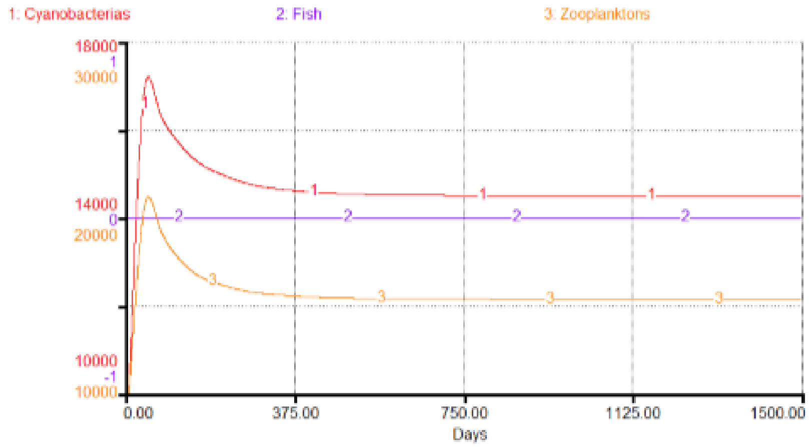
Initial zooplankton population = 0

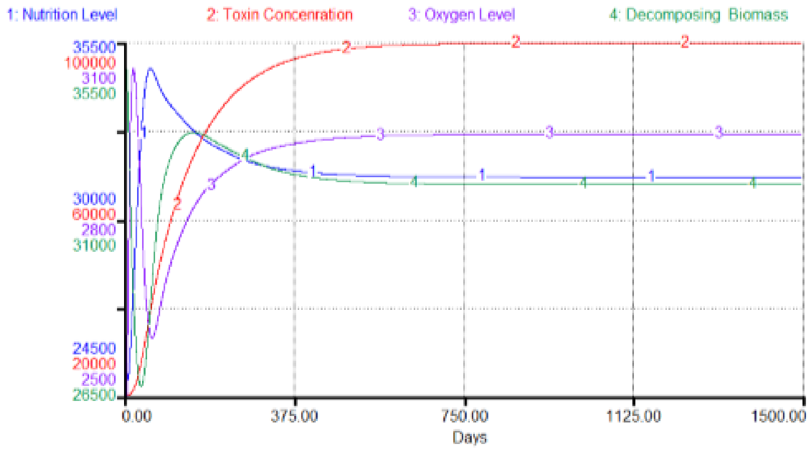




A simpler dynamic than before, this case shows the collapse of fish population to zero due to loss of food. The decrease is steeper than previous case as; their food source is swiftly removed, and occurring oxygen shortage by cyanobacterial growth imposes an increase in fish deaths. Cyanobacteria, freed from the chains of its natural predator, experience an increase and saturates in a higher value. Note that cyanobacteria do not collapse as they feed on constant nutrient inflow, becoming the sole inhabitant of the ecosystem.

Initial fish population = 0





Emptying the fish stocks results in an increase in remaining species. Two stocks (Cyano, Zoo) peaks, and then decays to a lower level after the oxygen shortage occurs. All stocks stabilizes to new values just as previous runs.

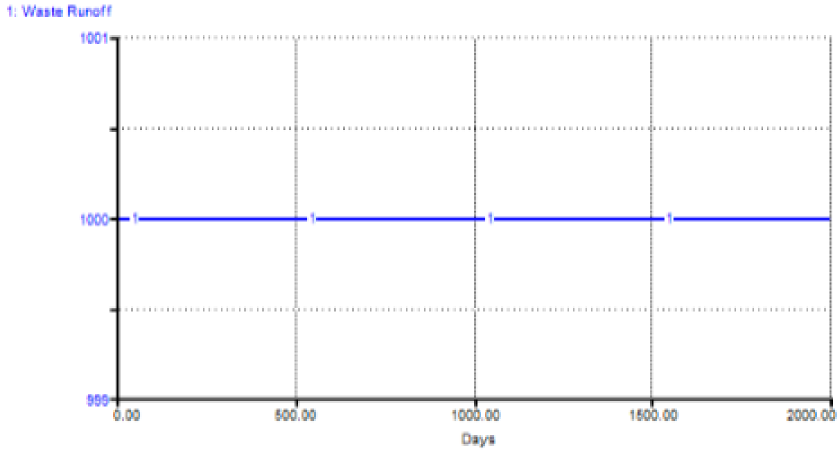
5. Simulation Experiments

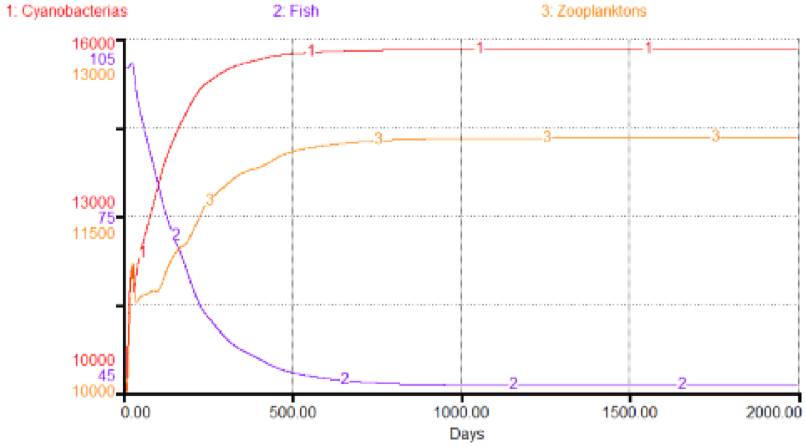
5.1 The Dynamic Problem

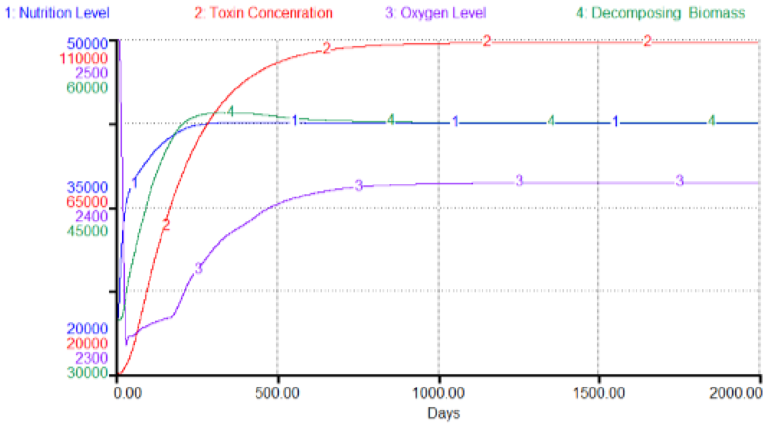
All simulation runs are taken for 2000 days to observe long-term dynamics. In some cases, results will be presented in a 365 days window. Aim of these experiments is to analyze the effect of different waste disposal regimens on the ecosystem inhabitants.

1) First run is taken for constant waste runoff at 1000. Resulting dynamics and waste disposal regime is shown in graph below. As nutrient level increases cyanobacterias who are fastly dividing in case of elevated nutrient levels start to increase.

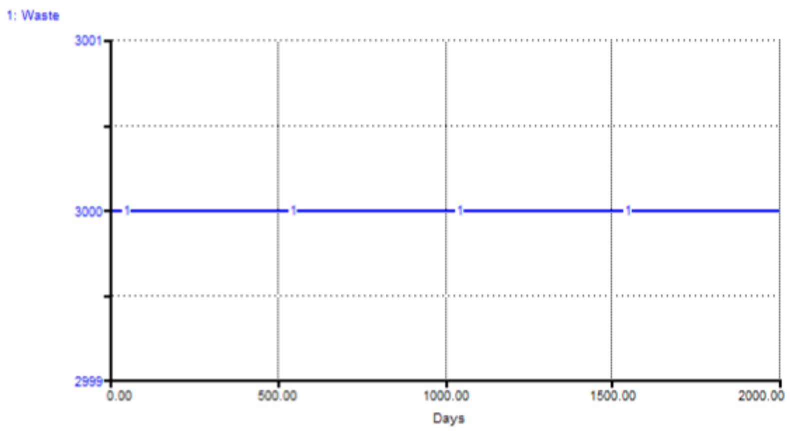
Zooplanktons follow this increase whereas limiting oxygen results in a decrease in number of fishes. As of around 3 years the system stabilizes at some equilibrium point which is rich in Cyanobacteria (~15000) and Zooplankton(~12000) and poor in Fish (46) compared to equilibriums reached in the base run. With high nutrient level, low oxygen ratio and low number of fishes, this case is a good representation of a eutrophic freshwater.

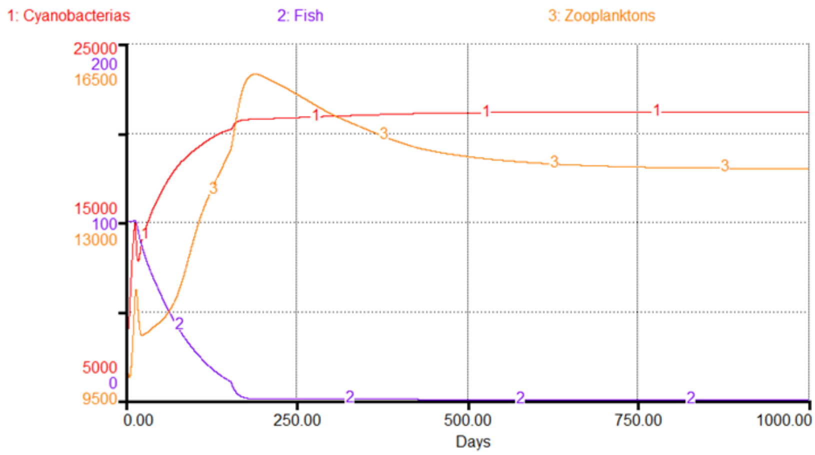


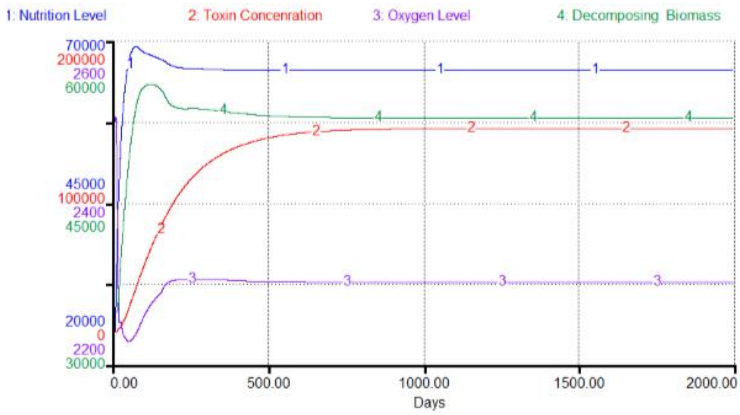




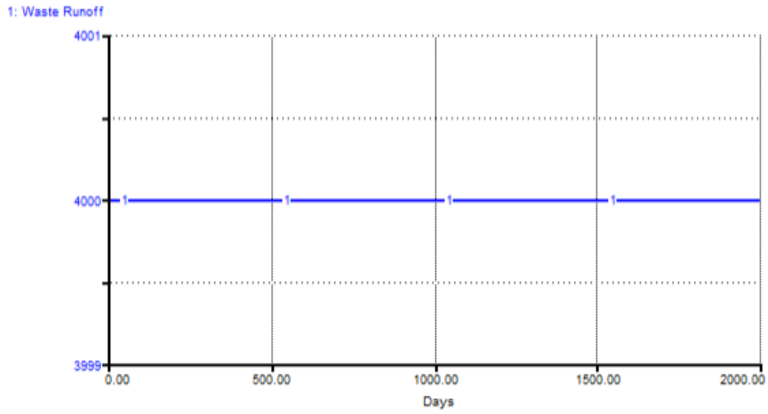
2) To observe the effect of increased density of waste runs are taken with constant waste 3000 and 4000 as well. When Waste is adjusted to 3000 we can see that fish population collapses whereas first decrease in zooplanktons due to increased toxin and low oxygen levels is compensated with the increased food availability. Thus we observe that animals that are higher on the food chain is lost whereas zooplanktons manage to survive with this increase.

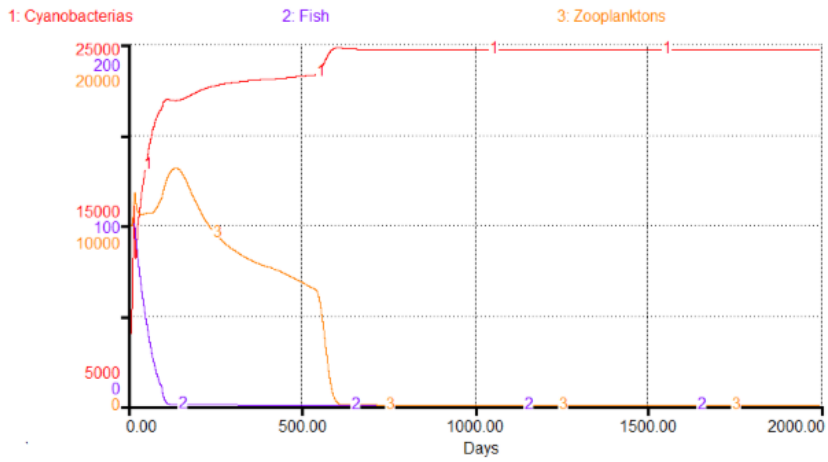


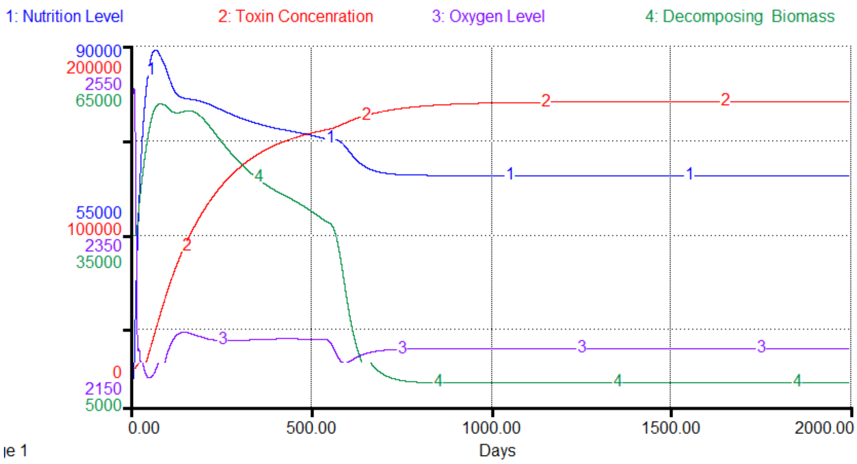




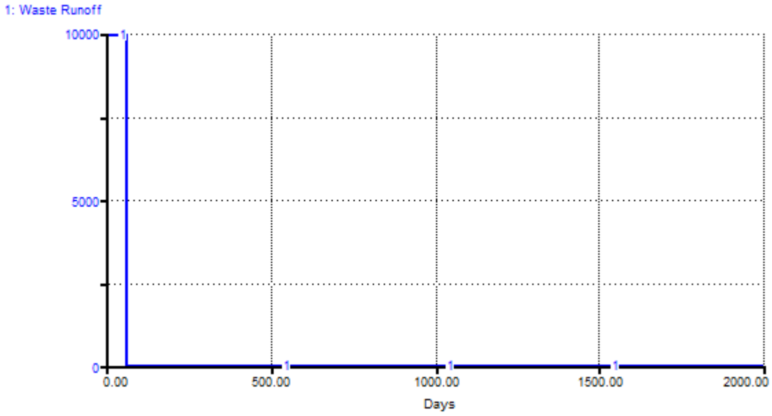
3) When we adjust waste run-off to 4000, we can observe that both zooplanktons and fishes extinct whereas cyanobacterias survive with a high population. Apart from Experiment 2, Zooplanktons also collapse since the oxygen levels are lower compared to the 3000 waste runoff case. Therefore, we observe lower biodiversity as amount of nutrient waste increases.

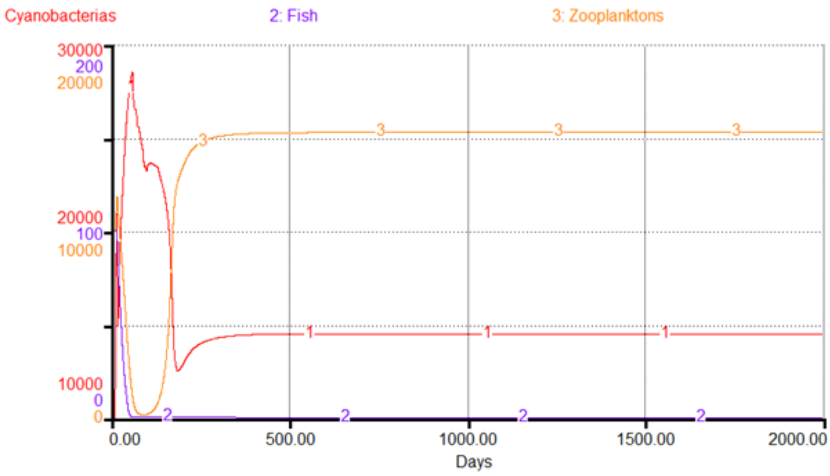


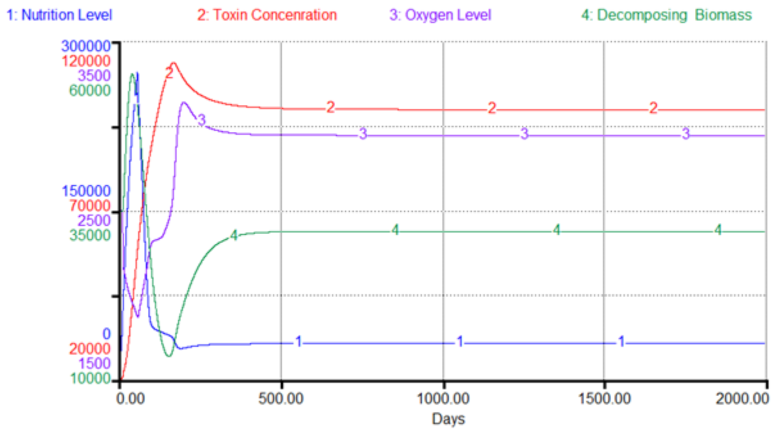




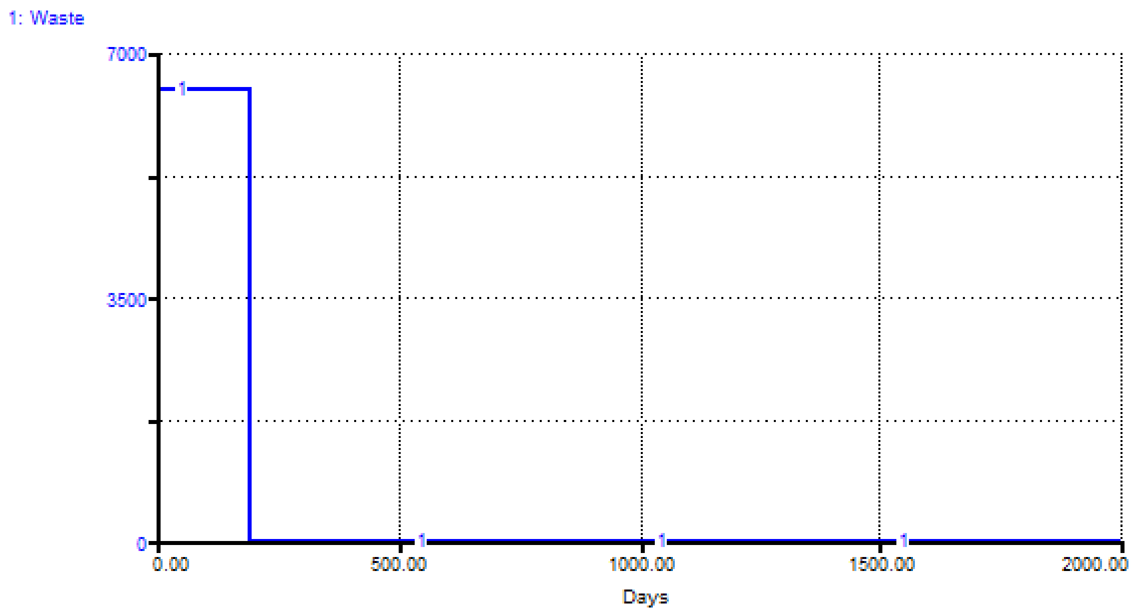
4) For experiment 4, instead of extending the waste disposal over time, we investigated the results of dense pollution within an interval. Therefore, Waste Runoff at 10000 is used for the first 50 days then no additional waste is added after 50th day. When we compare the results with Experiment 1, although the amount of cumulative waste is smaller for this run, it results in collapse of the fish population whereas the fish population is sustained with a lower level in Experiment 1.

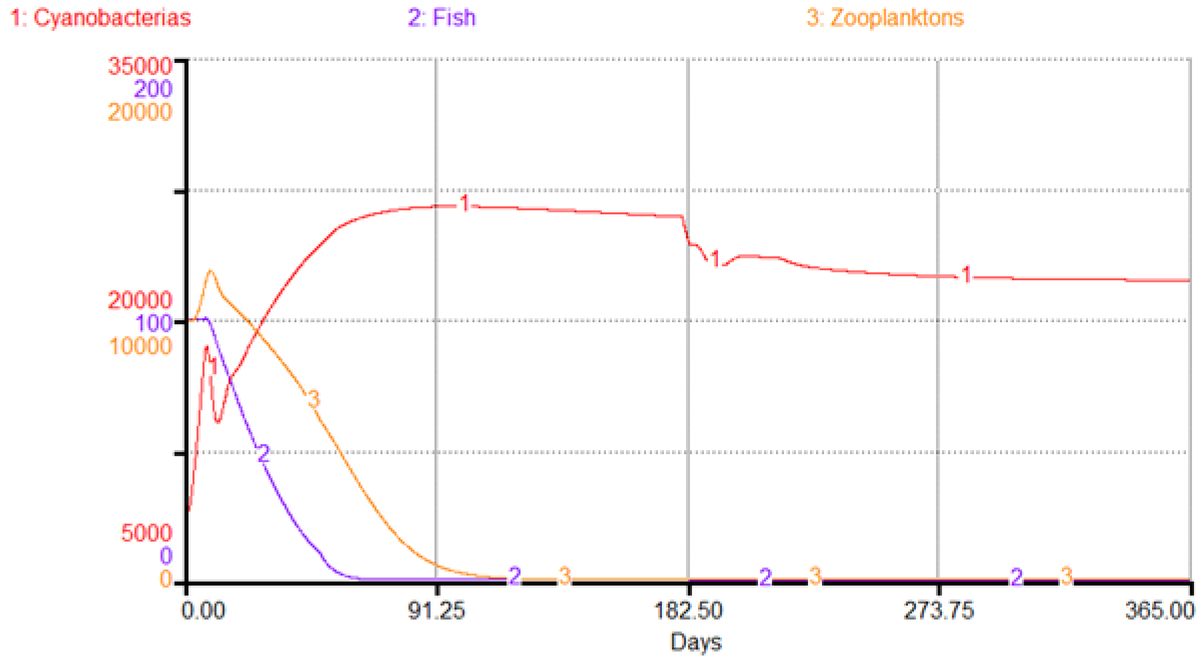


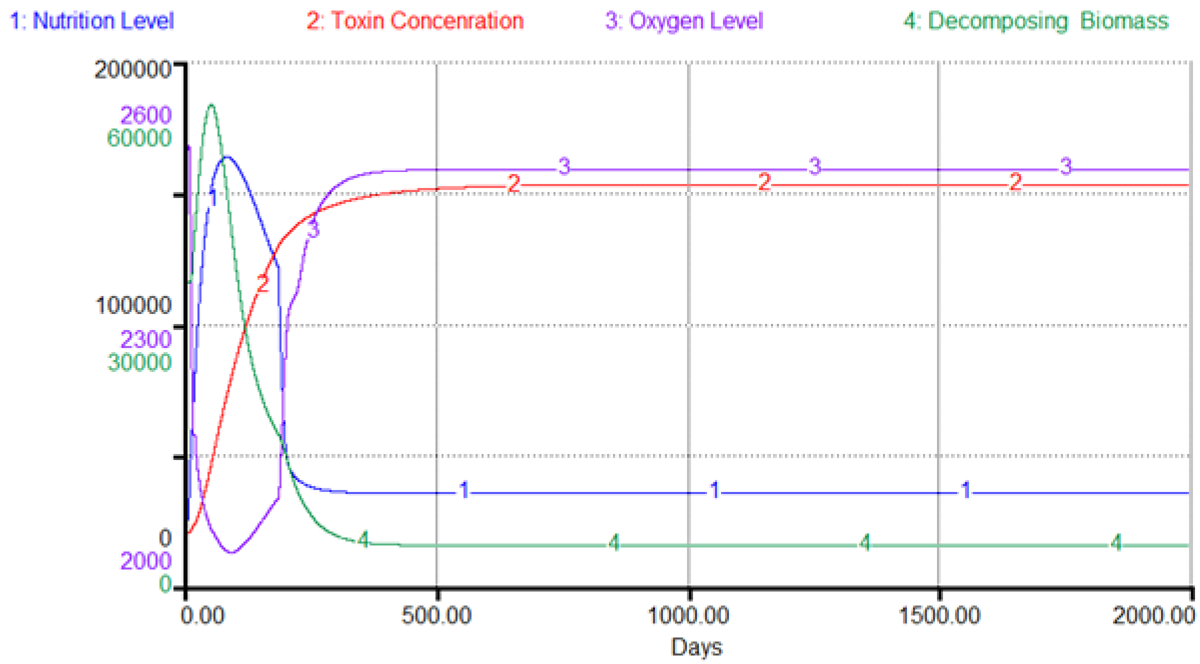




5) Lastly a base run is taken to implement and distinguish the effects of various mitigation strategies. For the mitigation to be needed we considered a high nutrient loading (6500) for the first 180 day. As seen on the graph below, high nutrient loading increases cyanobacteria consequently zooplanktons whereas fish population exponentially decays due to low oxygen and high toxin levels. After the initial peaks around the first week, zooplanktons also collapse where cyanobacteria dominate. For the next section, we will investigate the possible effects of mitigation strategies and whether they can save zooplankton and fish populations from extinction within the first 180 days.




1: Cyanobacterias
2: Fish
3: Zooplanktons
35000
200
20000
20000
100
10000
5000
0
0
0.00
91.25
182.50
273.75
365.00
Days


1: Nutrition Level
2: Toxin Concenration
3: Oxygen Level
4: Decomposing Biomass
200000
2600
60000
100000
2300
30000
0
2000
0
0.00
500.00
1000.00
1500.00
2000.00
Days

5.2. Scenario Analysis for Mitigation & Control Mechanisms

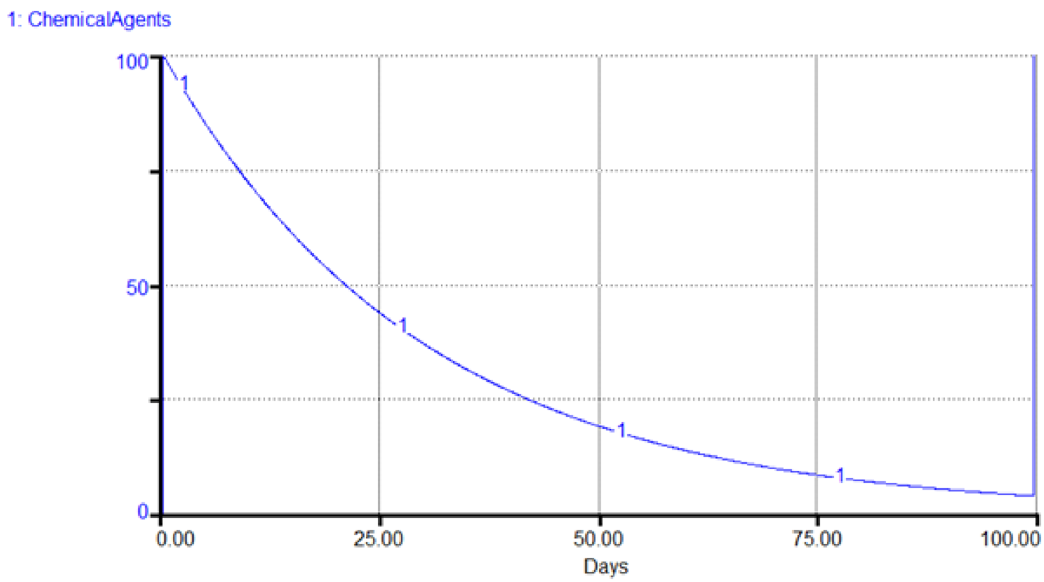
As the premise of our project, we will analyze different mitigation strategies in order to control the bloom of cyanobacteria of the base case in the previous section. In the base run, bloom dynamics drives fish population to extinction before three months and zooplanktons in around 4 months due to vicious R1 and R2 loops, highlighted in the causal loop diagram.

Analysis on mitigation methods not only works on providing a cure to this pestilent situation but also a learning tool for the effective dynamics lying within the structure. This section analysis three potential methods: release of chemical agents (algicides) into reservoir, brute force cleaning efforts and introduction of biological agents.

5.2.1. Chemical Agents

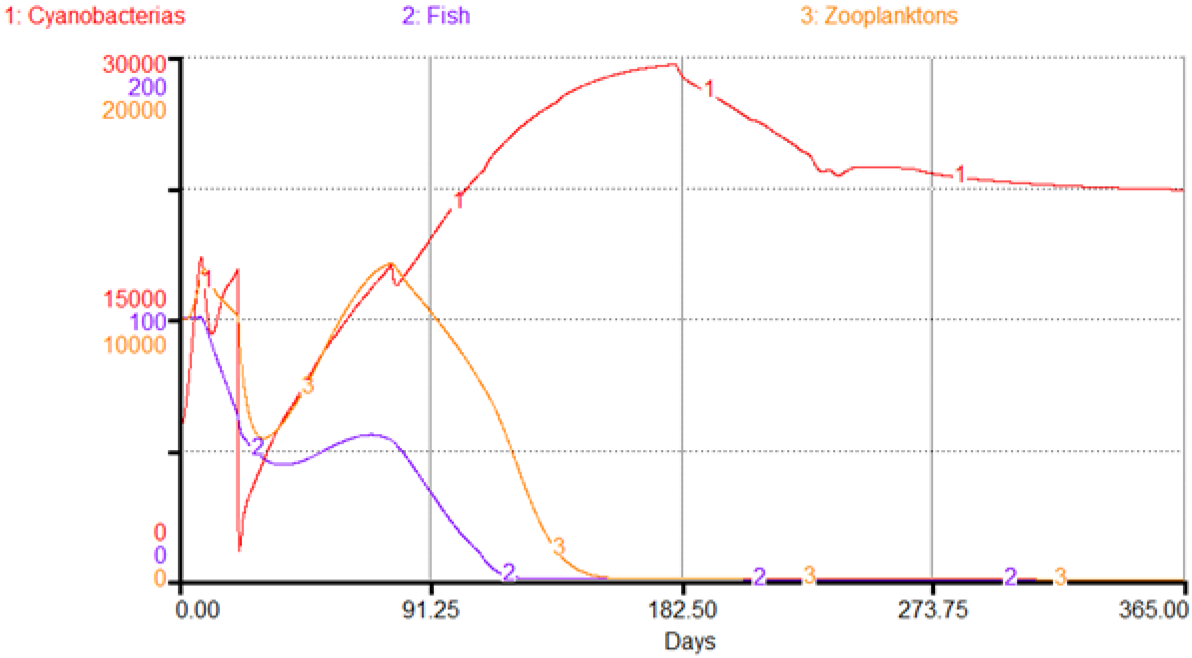
Biochemicals used in this process, as discussed before, inflicts damage not only to the cyanobacteria but also to the other inhabitants of the ecosystem. Even though that these agents are not host specific, their effect on algae is more powerful than on other biomass.

In our model, chemical accumulation is modelled as a stock variable with a constant decaying rate and a saturation level of 100. Effect of chemical agents on biomass death is a saturating function of the chemical agents and chemical saturation level ratio, passing through (0,1). Stock response to a one pulse appliance of saturation amount is shown below.



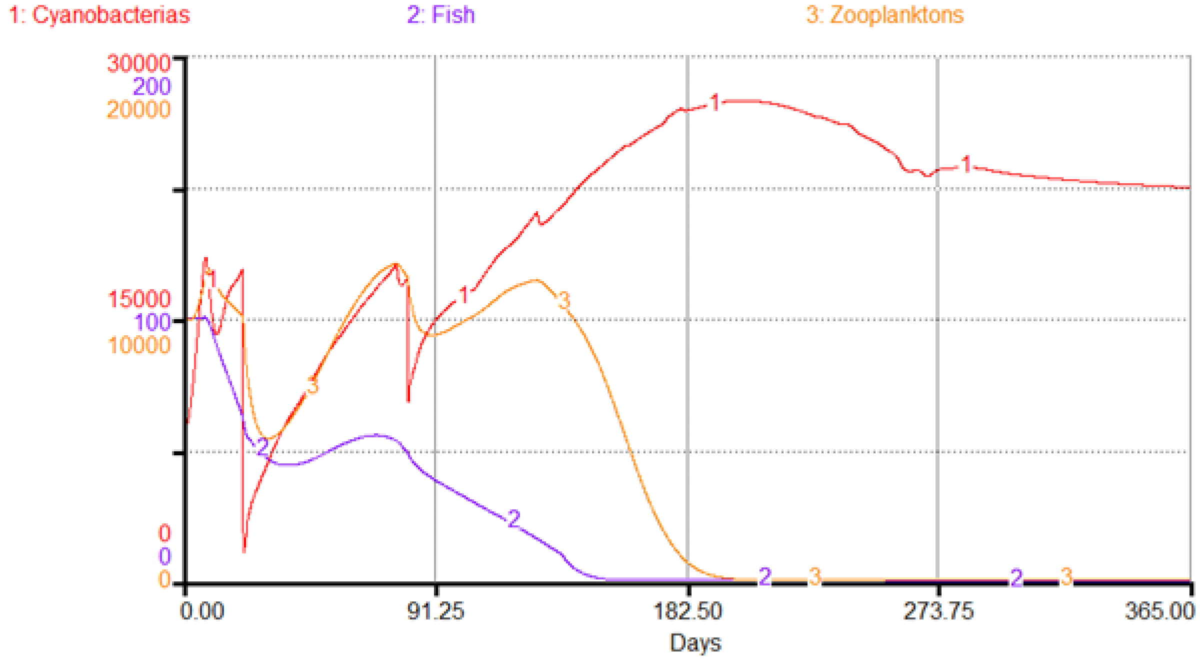
Chemical Agents variable shows an exponential decay towards zero and eliminated completely around 120 days. Several treatment protocols are tried in order to get a clear look at its effect on the system and see if an efficient control is achievable.

First protocol is a one shot appliance of twice the saturation amount at 20th day. A drastic drop at cyanobacterias is observed immediately. However, the cyanobacteria regenerate swiftly due to excess nutrient availability. Zooplankton and fish populations' decrease sharpens after t=20, when the chemical agents are saturated. After the drop of cyanobacteria regenerates the oxygen level significantly, they start an increase and reach a peak not present in the base case scenario above.



The increase in fish and zooplanktons quickly diminish to a decrease, with both species eventually going extinct. Their elimination is spread in a larger time than that of the base run, meaning an unfruitful improvement is made

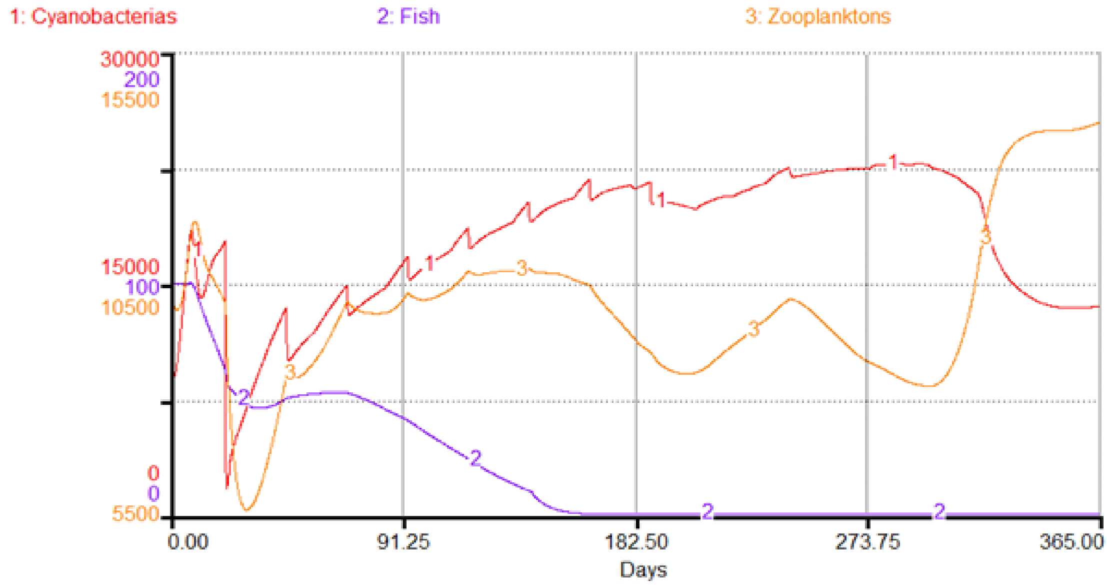
In the second protocol, another pulse of the same proportion is given 60 days after the first one, when the fish and zooplankton is at their local peaks.

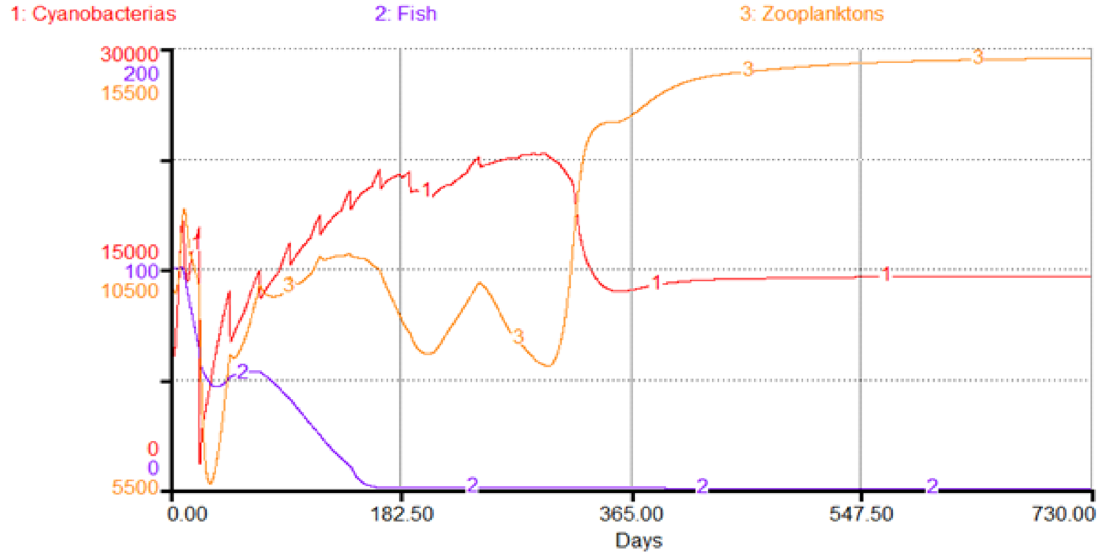


The second pulse inflicts a sudden decrease on cyanobacteria with a lower magnitude than the first one. This lowering of effect is due to the accumulation of nutrients from the dying biomass increasing the cyanobacteria regeneration (through R1 and R2), which dominates the cyanobacteria deaths caused by chemical agents.

Zooplankton sees a second peak as the result of second pulse and surpasses its equilibrium level. Fish population's condition is critical. Downward trend is trimmed and extinction takes longer, but a second peak is not present even though there is a surplus of food. Direct effects of toxins and agents run fish deaths to manageable levels. Here it can be inferred that effect of chemical agents are indeed not linear.

As the last protocol in this method, we will try 7 periodic appliances of chemical agents during the runoff season, starting from 20th day with a cycle of 24 days.



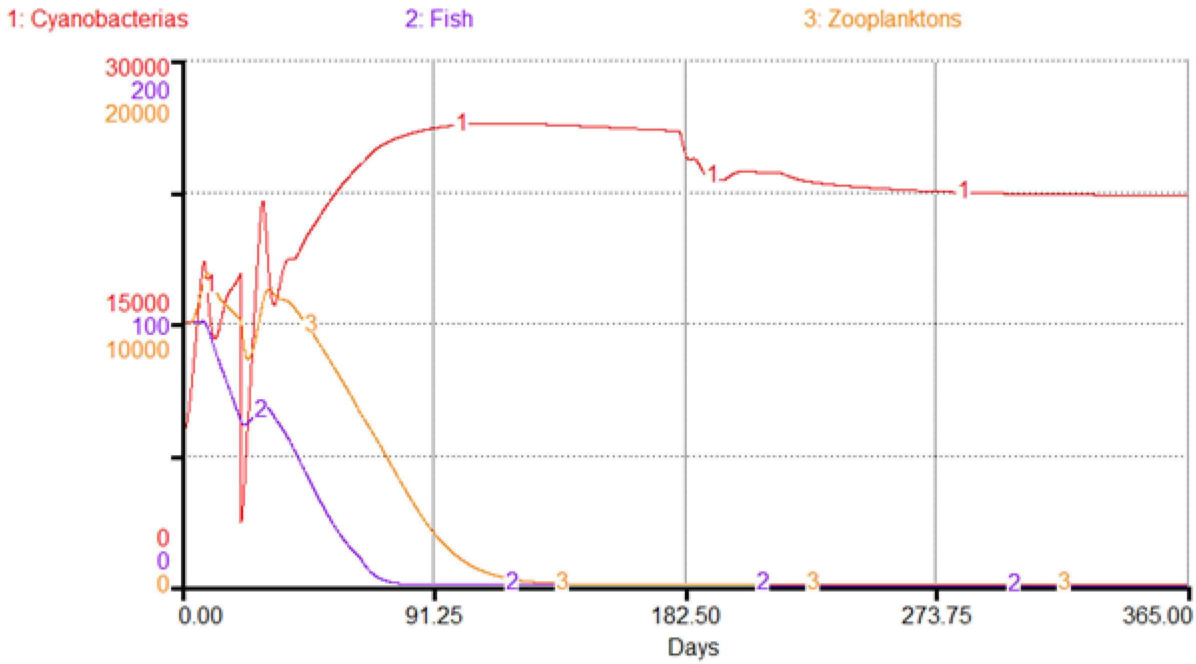


Resulting stock dynamics are given above. Periodic appliances overall saves the zooplankton but fails to save the fish. Depletion of oxygen and accumulation of toxins due to blooming cyanobacteria is not put under control. Reason behind the survival of zooplankton is the excess food supply in the lake as well as the elimination of natural predators Fish is not that lucky, bloom dynamics run the population dry.

5.2.2. Cleaning Efforts

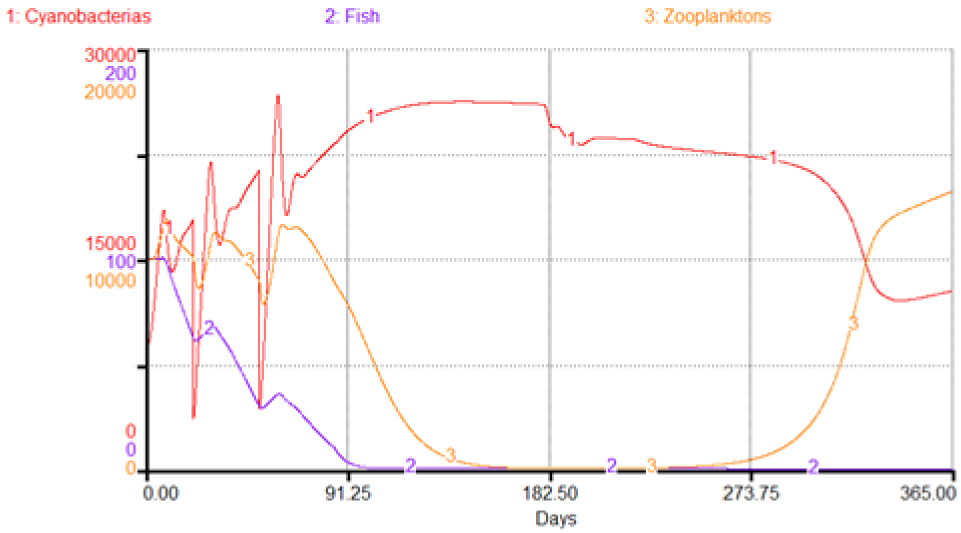
Another approach to be analyzed is the cleaning efforts directed at the nutrients and cyanobacteria population in the ecosystem. Here, cleaning is modelled as one time removal of some portion of stocks. Our analysis will be directed at comparing the performances of one time excessive cleaning with a continuous small scaled cleaning policy to be implemented

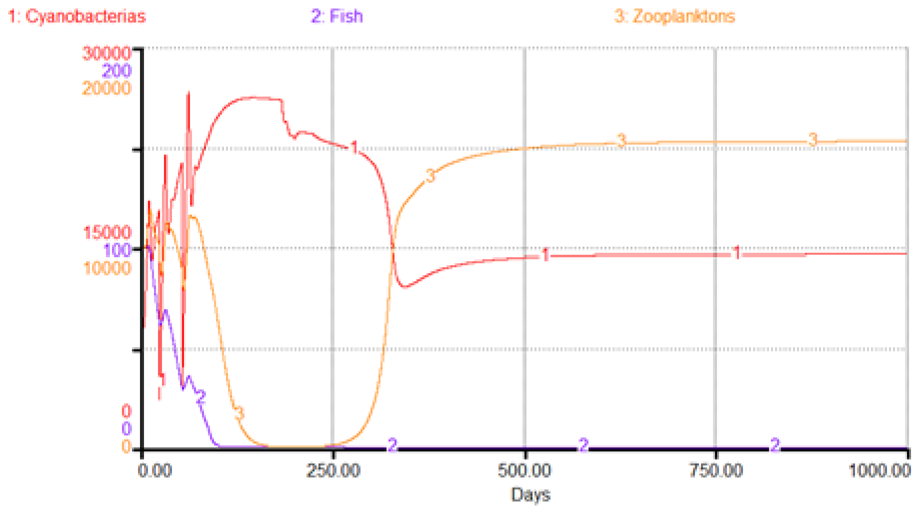
To test the resulting dynamics of a spring-clean, 80 percent portions of stocks are removed with a pulse at 20th day.



Cyanobacteria (expectedly) decreases sharply but recovers even swifter than one shot chemical agent application. It can be seen that zooplankton and fish experiences increases in their populations to a short term peak and collapse due to uncontrollable growth of cyanobacteria.

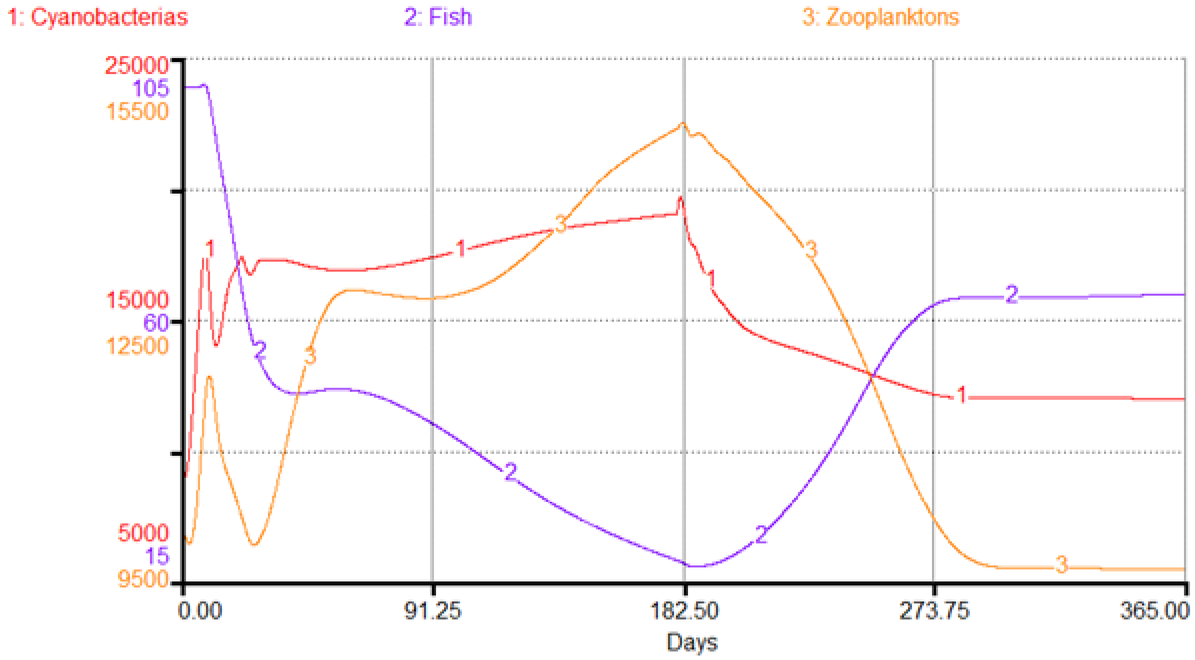
How about giving two shots of removal? A same magnitude cleaning is performed a month after the initial to see if an improvement is possible.





Again, cyanobacteria show a collapse and recover after the second cleaning. Fish population increases a little but goes extinct as before. Zooplankton comes to a second peak to decay towards zero. However, they still remain in very small values, enough to regenerate once the runoff ends to reach an equilibrium. Now the ecosystem is carried ton equilibrium of cyanobacteria and zooplankton with no fish present.

Second peak of the fish is about the same magnitude as the first one, meaning that it is promising to perform more cleaning to save the fish. A small scaled but steady cleaning is tried for the next run. Nutrients and cyanobacteria is removed by 6% of their amounts per unit time from day 20 to 180. (STEP(Stock*0.06,20)-STEP(Stock*0.06,180))

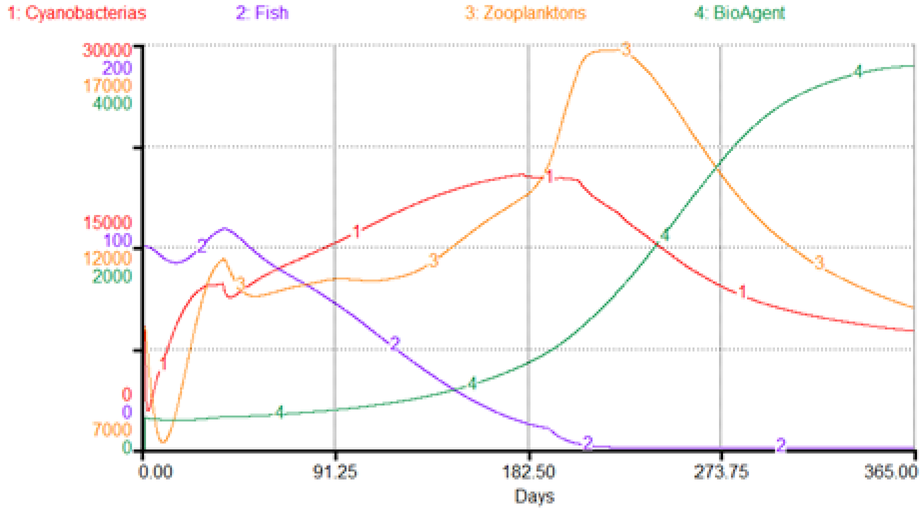


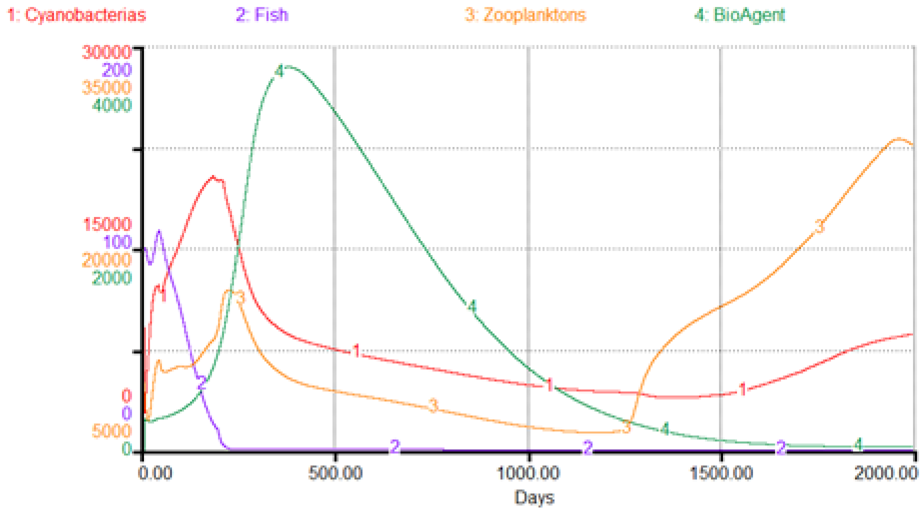
Behavior of species' stock variables are now more smoothed than the previous case due to STEP cleaning. This case shows an increase of zooplankton and cyanobacteria and a decrease of fish till the end of runoff season at 180th day. Since the runoff season is passed without an extinction of fish, ecosystem restores its balance, which happens to be Equilibrium Y.

5.2.3. Introduction of Biological Agents

Last mitigation strategy to be analyzed is introduction of biological agents such as parasites that are natural predators of cyanobacteria. They significantly increase the death of cyanobacteria and negatively affected by decreasing oxygen levels just like the other biomass. Once introduced, they become part of the ecosystem and its feedback structure. Thus, they are modelled as stocks; with a constant death rate and their regeneration is positively affected by increasing cyanobacteria.

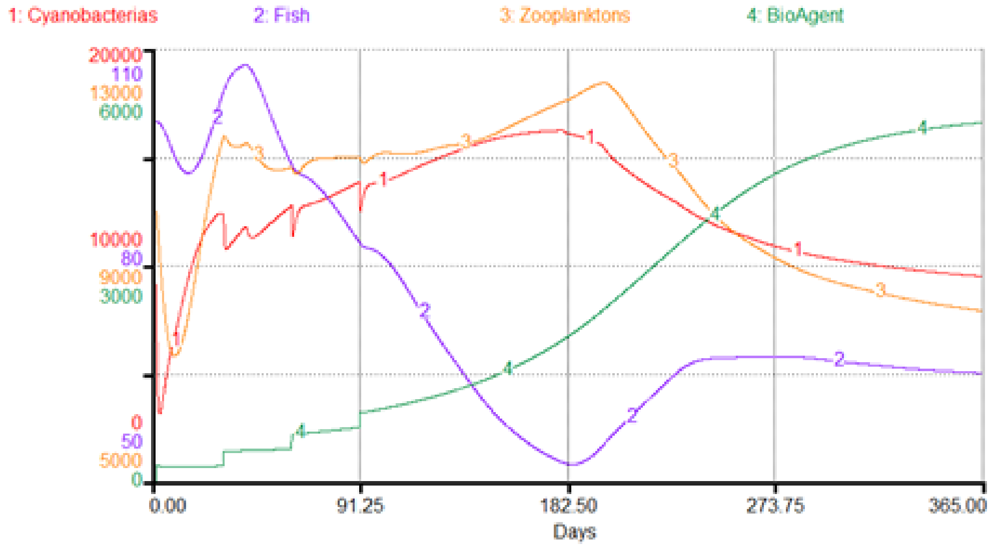
First case of this method introduces 300 member of species to the ecosystem at time 0. Their reference level is taken at 100, to be used in consumption formulation.

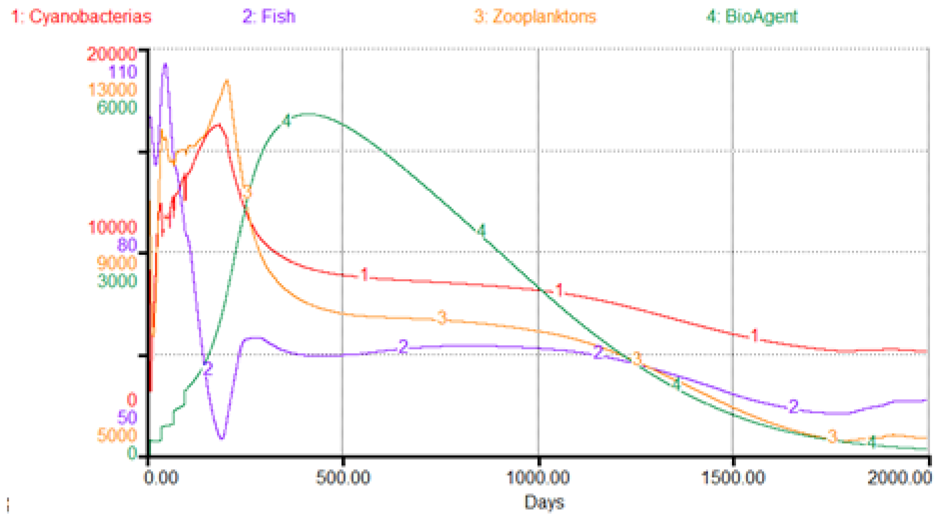




In this case, biological agents show an overshoot and collapse behavior in a window of 2000 days. Their introduction significantly affects other stakeholders of the system. Fish level initially increases to a peak higher than its equilibrium amount, zooplanktons show a boom, and cyanobacterias are flattened. Fish extinction is significantly delayed, nearly by 90 days. System reaches an equilibrium of cyanobacteria, zooplankton and new species coexistence. Method does not yield a prevention of fish deaths.

Second case introduces 200 bioagents monthly, twice the saturation amount this time, for 4 consecutive months. Resulting graphs are presented below.





Continuous feeding of biological agents to the ecosystem significantly reduces the mass of the bloom which prevents oxygen shortage and toxin accumulation and consequently saves the fish population.

Biological agents, again, shows an overshoot and collapse, due to lowering of cyanobacteria decreasing its regeneration rate. System slowly approaches to Equilibrium Y as biological agents fail to adapt and die off.

6. Conclusion

Several mitigation strategies were analyzed in terms of their performance to understand the dynamic behavior with the underlying internal system structure.

Use of biochemical algicide is found to be ineffective in treating the undesirable consequences of cyanobacterial blooms. Shots of chemical agents inflict an improvement in the short run but fails to provide a good performing outcome even for extreme applications (such as 7 repetitions) that would disrupt the environment beyond the boundary of our model.

Cleaning efforts, essentially, fail to address the main dynamics behind the problem as it only deals with apparent elements. Since the internal delays of biomass decomposition to nutrient and toxin concentration effect is not focal, extensive spring-cleans that only saves the day does not provide desirable results. A continuous policy on cleaning, modelled as small scale outflows during the runoff season, works well in protecting the existing balance of the ecosystem as it continuously treats the system.

Introduction of a biological predator species of cyanobacteria is proved to be an effective method in treating blooming cyanobacteria. Our analysis showed that one time introduction is not enough to dominate the bloom but several consecutive releases are necessary to get satisfactory results.

Our model works well in terms of providing a learning tool for the qualitative analysis of the focal system. Amateur applications to specific locations can be conducted using more tangible data that we lacked and with some modifications in the structure.

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APPENDIX

Stocks (with units)

Nutrition Level: Nutrition level in water (mg/ml)

BioAgent: Population of predator species that is introduced with purpose of decreasing Cyanobacterias (Number of Agents)

ChemicalAgents: Chemical Agents that are applied externally. (mg/ml)

Fish: Fish population in water (Fish)

Zooplanktons: Zooplankton population in water (Zooplankton)

Cyanobacterias: Cynobacteria population (Cyanobacteria)

Toxin Concentration: Concentration of toxin elements in water (mg/ml)

OxygenLevel: Oxygen level of water (mg/L)

DecomposingBiomass: Biomass that is composed of death organisms (mg/ml)

Flows (same units with stock per day)

DeathOfOrganisms: Death of organisms in water

CleaningNutrition: Cleaning the nutrition from water with external efforts

OxygenIntake: Oxygen intake

OxygenConsumption: Oxygen consumption

Toxin Elimination: Toxin that is eliminated from water

Toxin Production: Toxin produced by cyanıbacterias that increases toxin concentration

CyanoConsumption: Consumption of cyanobacterias by zooplanktons

CleaningCyano: Cyanobacteria elimination done by cleaning

CyanoRegen: Cyanobacteria regeneration

CyanoDeath: Cyanobacterai Death

Nutirition Decay: Decay of nutrition in water

Chemical Runoff: The addition of nutrition to water from chemicals used

Introduction : Addition of a substantial population of BioAgent to water body

BADeath : Bioagent death

BARegen: Bioagent regeneration

Appliance: Addition of chemical agents to water

Elimination: Elimination of chemical agents from water

FishRegen: Fish regeneration

ZooRegen: Zooplankton Regeneration

ZooDeath: Death of zooplanktons

Fish Death: Fish death

ZooConsumption: The amount of zooplanktons consumed by fish

NutritionProduction: Nutrition produced form decomposing biomass

NutritionConsumption: Nutrition consumed by cyanobacterias

Converters

IntroLevel : The amount (size of population) of bioagents that are released into water (Number of Bioagents)

NormalBARegenCoef : Regeneration fraction of bioagents under normal conditions (1/day)

NormalBADeath : Death fraction of bioagents when the system is in equilibrium (1/day)

BAlevel: Normalised value of bioagent populaiton by its saturation value (unitless)

SaturationBA: Reference level of bioagents (number of bioagents)

EffectofCyanoonBARegen: Effect of cyanobacteria population on bioagent regeneration (unitless)

EffectofBAonCyanoDeath: Effect of bioagent populaion on cyano death (unitless)

ChemicalEliminationDelay: Time it takes for chemical agents to be eliminated from water (day)

ChemicalRatio: Normalised value of Chemical agents by its saturated value (unitless)

ChemicalSaturation: Chemical agents amount under normal conditions (mg/ml)

EffectChemicalsonCyanoDeath: Effect of chemical agnets on cyanobacteria death (unitless)

EffectofChemicalsonOtherBiomass: effect of cheical agents on death of other biomass (unitless)

EffectOf ToxinConcentrationOnBiomassDeath: Effect of toxin concentration of water on death of species that live in the water (unitless)

Water Intoxication Level: Level of how toxic the water is (unitless)

Normal Toxin Concentration: Acceptable, sustainable concentration of toxin elements in water (mg/ml)

Toxin Elimination Delay: The time it takes for toxin elements to be eliminated from water (day)

EffectOfConcentrationOnElimination: The effect of toxin concentration on its elimination (unitless)

AvgToxin ProductionperCyanobactria: Average amount of toxin that is produced by a cyanobacteria (mg/ml)

NormalFishDeathCoef: Fish death fraction under normal conditions (1/day)

NormalFishRegenCoef: Fish regeneration fraction under normal conditions (1/day)

ReferenceLevelOfFish: Fish population level under normal conditions (Fish)

ReferenceZooPerFish: zooplankton per fish under normal conditions (Zoo/Fish)

ZooPerFish: Current zooplankton amount per fish (Zoo/Fish)

EffectOfZooOnFishRegen: Effect of zooplankton population on fish regeneration (unitless)

EffectOfZooPerFishOnConPerFish: Effect of zooplankton per fish on consumption of zooplanktons by fish (unitless)

CyanoLevel: The proportion of current cyanobacterias to normal level (unitless)

NormalConsPerFish: Zooplankton consumed by fish under normal conditions (Zoo/Fish)

NormalZooRegenCoef: Regeneration fraction of zooplanktons under normal conditions (1/day)

NormalZooDeathCoef: Death fraction of zooplanktons under normal conditions (1/day)

ReferenceLevelOfZoo: Population of zooplanktons under normal conditions (Zooplankton)

CyanoPerZoo: Current cyanobacteria per zooplankton (Cyanobacteria/Zooplankton)

EffectOfCyanoOnZooRegen: Effect of cynobacteria populaion on zooplankton regeneration (unitless)

ReferenceCyanoPerZoo: Cyanobacteria per zooplankton under normal conditions (Cyanobacteria/Zooplankton)

EffectOfCyanoPerZooOnCyanoCon: Effect of cyanobacteria per zooplankton on consumption of cyanobacteria by zooplankton (unitless)

ReferenceLevelOfCyanobacterias: Population of cyanobacterias under normal conditions (Cyanobacteria)

NormalCyanoPerZooCon: Cyanobacteria consumed per zooplanton under normal conditions (Cyanobacteria/Zooplankton)

NormalCyanoRegenCoef: Regeneration fraction of Cyanobacterias under normal conditions (1/day)

NomalCyanoDeathCoef: Death fraction of Cyanobacterias under normal conditions. (1/day)

EffectOfOxygenLevelOnBiomassDeath: Effect of oxygen level in water on death of biomass (unitless)

ReferenceLevelOfOxygen: Oxygen level under normal conditions (mg/L)

OxygenAdjTime: Time it takes for oxygen intake (day)

NutritionPerCyano: Current fraction of nutrition per cyanobacteria (mg/ml per Cyanobacteria)

EffectOfNutritionConsumptionOnCyanoRegen: Effect of nutrition consumption on cyanobacteria regeneration (unitless)

ReferenceNutritionPerCyano: Nutrition per cyanobacteria under normal conditions. (mg/ml per Cyanobacteria)

AvgNutritionConsumptionPerCyano: Average nutiriton consumed per cyanobacteria (mg/ml per Cyanobacteria)

ReferenceNutritionLevel: Nutrition level under normal conditions. (mg/ml)

WasteRunoff: Waste that reaches to water. (mg/ml)

NutritionDecayDelay: Time it takes for nutirions to decay. (day)

AverageDecompositionDelay: Average time it takes for biomass to decompose (day)

Appendix B. Stella Equations

BioAgent(t) = BioAgent(t - dt) + (Introduction + BARegen - BADeath) * dt

INIT BioAgent = 0

INFLOWS:

Introduction = (PULSE(IntroLevel,0,30)-PULSE(IntroLevel,120,30))

BARegen = BioAgent*NormalBA_RegenCOef*EffectofCyanoonBARegen

OUTFLOWS:

BADeath = BioAgent*NormalBADeath*EffectOfOxygenLevel_OnBiomassDeath

ChemicalAgents(t) = ChemicalAgents(t - dt) + (Appliance - Elimination) * dt

INIT ChemicalAgents = 0

INFLOWS:

Appliance = 0*PULSE(100,20,24)-PULSE(100,20+24*8,24)*0

OUTFLOWS:

Elimination = ChemicalAgents/ChemicalELiminationDelay

Cyanobacterias(t) = Cyanobacterias(t - dt) + (Cyano__Regen - Cyano_Death - ZooConsum - Clean) * dt

INIT Cyanobacterias = 9000

INFLOWS:

Cyano__Regen = Cyanobacterias*NormalCyano_RegenCoef*EffectOfNutrition_ConsumptionOnCyanoRegen

OUTFLOWS:

Cyano_Death = Cyanobacterias*NormalCyano_DeathCoef*EffectOfOxygenLevel_OnBiomassDeath*EffectofChemicalsonCyanoDeath*EffectofBAonCyanoDeath

ZooConsum = normalconscoef*Zooplanktons*Consumptionperzoo

Clean = PULSE(Cyanobacterias*0.8,20,1000)*0+STEP(Cyanobacterias*0.06,0)*0-STEP(Cyanobacterias*0.06,180)*0

Decomposing__Biomass(t) = Decomposing__Biomass(t - dt) + (DeathOf_Organisms - Nutrition_Production) * dt

INIT Decomposing__Biomass = 8700*4

INFLOWS:

DeathOf_Organisms = 0.05*Cyano_Death/4.5+Zoo__Death*6.4/9+Fish__Death*100

OUTFLOWS:

Nutrition_Production = Decomposing__Biomass/Average_DecompositionDelay

Fish(t) = Fish(t - dt) + (Fish__Regen - Fish__Death) * dt

INIT Fish = 100

INFLOWS:

Fish__Regen = Fish*NormalFishRegenCoef*EffectOfZooOn_FishRegen

OUTFLOWS:

Fish__Death = Fish*NormalFishDeathCoef*EffectOf_ToxinConcentration_OnBiomassDeath*EffectOfOxygenLevel_OnBiomassDeath*EffectofChemicalsonOtherBiomass

Nutrition_Level(t) = Nutrition_Level(t - dt) + (Chemical_Runoff + Nutrition_Production - Nutrition_Decay - Nutrition_Consumption - CleanN) * dt

INIT Nutrition_Level = 25000

INFLOWS:

Chemical_Runoff = Waste+Reference__Nutrient_Runoff

Nutrition_Production = Decomposing__Biomass/Average_DecompositionDelay

OUTFLOWS:

Nutrition_Decay = Nutrition_Level/NutritionDecay_Delay

Nutrition_Consumption = Cyanobacterias*AvgNutritionConsumption_PerCyano*1.98/1.5

CleanN = PULSE(Nutrition_Level*0.8,20,1000)*0+STEP(Nutrition_Level*0.06,20)*0-STEP(Nutrition_Level*0.06,180)*0

Oxygen_Level(t) = Oxygen_Level(t - dt) + (Oxygen__Intake - Oxygen_Consumption) * dt

INIT Oxygen_Level = 2500

INFLOWS:

Oxygen__Intake = 220+(ReferenceLevelOf_Oxygen-Oxygen_Level)/OxygenAdjTime

OUTFLOWS:

Oxygen_Consumption = 0.01*Cyanobacterias+Zooplanktons*0.002+Fish

Toxin_Concenration(t) = Toxin_Concenration(t - dt) + (Toxin__Production - Toxin__Elimination) * dt

INIT Toxin_Concenration = 20000

INFLOWS:

Toxin__Production = Cyanobacterias*AvgToxin_Production_perCyanobacteria

OUTFLOWS:

Toxin__Elimination = EffeOfConcentrationOnEliminaion*Toxin_Concenration/Toxin_Elimination_Delay

Zooplanktons(t) = Zooplanktons(t - dt) + (Zoo__Regen - Zoo__Death - ZooConsump) * dt
INIT Zooplanktons = 10000
INFLOWS:
Zoo__Regen = Zooplanktons*NormalZoo_RegenCoef*EffectOfCyano__OnZooRegen
OUTFLOWS:
Zoo__Death =
Zooplanktons*NormalZoo_DeathCoef*EffectOf_ToxinConcentration_OnBiomassDeath*EffectOfOxygenLevel_OnBiomassDeath*EffectofChemicalsonOtherBiomass
ZooConsump = NormalConsperfish*Fish*EffOnConperfish
Average_DecompositionDelay = 40
AvgNutritionConsumption_PerCyano =
GRAPH(NutritionPerCyano/ReferenceNutrition_PerCyano)
(0.00, 0.00), (0.25, 0.00993), (0.5, 0.024), (0.75, 0.0571), (1.00, 0.15), (1.25, 0.196), (1.50, 0.227), (1.75, 0.241), (2.00, 0.248)
AvgToxin_Production_perCyanobacteria = 0.05
BAlevel = BioAgent/(SaturationBA+1)
ChemicalEliminationDelay = 30
ChemicalRatio = ChemicalAgents/ChemicalSaturation
ChemicalSaturation = 100
Consumptionperzoo = GRAPH(CyanoPerZoo/ReferenceCyano_PerZoo)
(0.00, 0.00), (0.2, 0.0189), (0.4, 0.0505), (0.6, 0.158), (0.8, 0.435), (1.00, 1.00), (1.20, 1.27), (1.40, 1.39), (1.60, 1.43), (1.80, 1.47), (2.00, 1.50)
CyanoLevel = Cyanobacterias/ReferenceLevelOf_Cyanobacterias
CyanoPerZoo = If (Zooplanktons<1)Then(0) Else (Cyanobacterias/Zooplanktons)
EffectofBAonCyanoDeath = GRAPH(BAlevel)
(0.00, 1.00), (0.2, 1.83), (0.4, 2.51), (0.6, 2.98), (0.8, 3.47), (1.00, 3.88), (1.20, 4.31), (1.40, 4.52), (1.60, 4.72), (1.80, 4.91), (2.00, 5.00)
EffectofChemicalsonCyanoDeath = GRAPH(ChemicalRatio)
(0.00, 1.00), (0.1, 3.19), (0.2, 4.63), (0.3, 6.00), (0.4, 7.13), (0.5, 7.90), (0.6, 8.52), (0.7, 8.95), (0.8, 9.38), (0.9, 9.72), (1.00, 10.0)
EffectofChemicalsonOtherBiomass = GRAPH(ChemicalRatio)
(0.00, 1.00), (0.1, 1.19), (0.2, 1.33), (0.3, 1.45), (0.4, 1.54), (0.5, 1.60), (0.6, 1.64), (0.7, 1.67), (0.8, 1.70), (0.9, 1.72), (1.00, 1.75)
EffectofCyanoonBARegen = GRAPH(CyanoLevel)

(0.00, 0.00), (0.2, 0.0675), (0.4, 0.174), (0.6, 0.357), (0.8, 0.569), (1.00, 1.00), (1.20, 1.67), (1.40, 2.07), (1.60, 2.32), (1.80, 2.53), (2.00, 2.69), (2.20, 2.83), (2.40, 2.90), (2.60, 2.96), (2.80, 3.00), (3.00, 3.00)

EffectOfCyano__OnZooRegen = GRAPH(CyanoPerZoo/ReferenceCyano_PerZoo)

(0.00, 0.00), (0.333, 0.139), (0.667, 0.391), (1.00, 1.00), (1.33, 1.44), (1.67, 1.70), (2.00, 1.80), (2.33, 1.89), (2.67, 1.96), (3.00, 2.00), (3.33, 2.00), (3.67, 2.00), (4.00, 2.00)

EffectOfNutrition_ConsumptionOnCyanoRegen = GRAPH(NutritionPerCyano/ReferenceNutrition_PerCyano)

(0.00, 0.00), (0.5, 0.473), (1.00, 1.00), (1.50, 1.36), (2.00, 1.63), (2.50, 1.89), (3.00, 2.16), (3.50, 2.36), (4.00, 2.59)

EffectOfOxygenLevel_OnBiomassDeath = GRAPH((Oxygen_Level/ReferenceLevelOf_Oxygen))

(0.00, 99.4), (0.0667, 51.7), (0.133, 37.9), (0.2, 30.9), (0.267, 24.5), (0.333, 19.1), (0.4, 15.2), (0.467, 12.3), (0.533, 9.46), (0.6, 7.22), (0.667, 5.30), (0.733, 4.34), (0.8, 3.38), (0.867, 2.10), (0.933, 1.14), (1.00, 1.00), (1.07, 0.92), (1.13, 0.86), (1.20, 0.815), (1.27, 0.775), (1.33, 0.74), (1.40, 0.71), (1.47, 0.685), (1.53, 0.66), (1.60, 0.64), (1.67, 0.625), (1.73, 0.61), (1.80, 0.6), (1.87, 0.5), (1.93, 0.5), (2.00, 0.5)

EffectOfZooOn_FishRegen = GRAPH(ZooPerFish/ReferenceZoo_PerFish)

(0.00, 0.00), (0.333, 0.245), (0.667, 0.556), (1.00, 1.00), (1.33, 1.49), (1.67, 1.75), (2.00, 1.87), (2.33, 1.95), (2.67, 1.99), (3.00, 2.00), (3.33, 2.00), (3.67, 2.00), (4.00, 2.00)

EffectOf_ToxinConcentration_OnBiomassDeath = GRAPH(SMTH1(Water_Intoxication_Level,010))

(0.5, 0.25), (0.75, 0.834), (1.00, 1.00), (1.25, 1.10), (1.50, 1.19), (1.75, 1.26), (2.00, 1.33), (2.25, 1.39), (2.50, 1.43), (2.75, 1.48), (3.00, 1.53), (3.25, 1.58), (3.50, 1.63), (3.75, 1.67), (4.00, 1.69), (4.25, 1.73), (4.50, 1.76), (4.75, 1.78), (5.00, 1.81), (5.25, 1.83), (5.50, 1.86), (5.75, 1.87), (6.00, 1.89), (6.25, 1.91), (6.50, 1.93), (6.75, 1.95), (7.00, 1.97), (7.25, 1.98), (7.50, 2.00), (7.75, 2.00), (8.00, 4.00)

EffeOfConcentrationOnEliminaion = GRAPH(Toxin_Concenration/NormConcentration)

(0.00, 1.71), (0.2, 1.71), (0.4, 1.65), (0.6, 1.56), (0.8, 1.32), (1.00, 1.00), (1.20, 0.631), (1.40, 0.454), (1.60, 0.353), (1.80, 0.297), (2.00, 0.29)

EffOnConperfish = GRAPH(ZooPerFish/ReferenceZoo_PerFish)

(0.00, 0.00), (0.2, 0.0505), (0.4, 0.154), (0.6, 0.328), (0.8, 0.727), (1.00, 1.00), (1.20, 1.22), (1.40, 1.31), (1.60, 1.36), (1.80, 1.38), (2.00, 1.40)

IntroLevel = 0

NormalBADeath = 0.01

NormalBA_RegenCOef = 0.01

normalconscoef = 0.3

NormalConsperfish = 3

NormalCyano_DeathCoef = 0.45

NormalCyano_RegenCoef = 0.75

NormalFishDeathCoef = 0.05

NormalFishRegenCoef = 0.05

NormalZoo_DeathCoef = 0.045

NormalZoo_RegenCoef = 0.075

Normal_Toxin_Concentration = 20000

NormConcentration = 20000

NutritionDecay_Delay = 1250

NutritionPerCyano = If(Cyanobacterias=0)Then(5)Else(Nutrition_Level/Cyanobacterias)

OxygenAdjTime = 10

ReferenceCyano_PerZoo = ReferenceLevelOf_Cyanobacterias/ReferenceLevel_OfZoo

ReferenceLevelOf_Cyanobacterias = 10000

ReferenceLevelOf_Oxygen = 2500

ReferenceLevel_OfZoo = 10000

ReferenceNutritionLevel = 25000

ReferenceNutrition_PerCyano = ReferenceNutritionLevel/ReferenceLevelOf_Cyanobacterias

ReferenceZoo_PerFish = ReferenceLevel_OfZoo/Reference_LevelOfFish

Reference_LevelOfFish = 100

Reference__Nutrient_Runoff = 1130

SaturationBA = 100

Toxin_Elimination_Delay = 40

Waste = 0*(STEP(6500,0)-STEP(6500,180))+3000

Water_Intoxication_Level = Toxin_Concenration/Normal_Toxin_Concentration

ZooPerFish = If(Fish<10)Then(0)Else(Zooplanktons/Fish)