# What is the Impact of Introducing an Invasive Species Into an Ecosystem?

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May 8th, 2009



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## Introduction

Population stability of an ecosystem is a very important factor when understanding the dynamics of an environment. Nature seeks equilibrium, and when undisturbed, will find that equilibrium. Unfortunately, it is naïve to believe that an environment can be left "undisturbed" for any period of time. Slight disturbances in ecosystems occur every day: temperature changes, disease, erosion, climate, humidity, etc. These minor changes are part of the natural cycle of an ecosystem. If the ecosystem is stable and has existed for a long time, it finds ways to compensate and change in order to balance itself given the new circumstances.

While these minor changes are an important factor, it is not the subject of question that will be covered in this project. The question at hand is what happens when an ecosystem experiences a massive change, something that takes more than just a little adjustment to change. There are many changes that an ecosystem can experience, but the one that has been chosen to be tested is the effect of an invasive species on a previously stable ecosystem. This model will test both the effects of an invasive species, as well as give us a look at the stability of an ecosystem and see how resilient it is to change and disturbance.

Testing this type of scenario by any method would be extremely difficult. This is because species interact in very interesting and dynamic relation. Creating a mathematic equation to represent each species would be almost impossible. It would consist of several variable and even more unique constants. Trying to recreate this test in the real world with an actual ecosystem would also be extremely difficult. It would need to be very large scale and would require the experimenter to control many very uncontrollable variables. On top of that, this model is able to test a scenario over a period of 50 years in a very short amount of time, a luxury that is not available. Ultimately, math modeling is the best solution to answer this question.

Before we start our test however, we need either a hypothesis or a few possible outcomes for our model. As represented by this reference graph, we would hope that with the introduction of the new species, the original species would be left unaffected, allowing the ecosystem to continue without being disturbed. Of course, the fear of introducing a species is that it will grow unopposed and will hurt or kill the preexisting species.
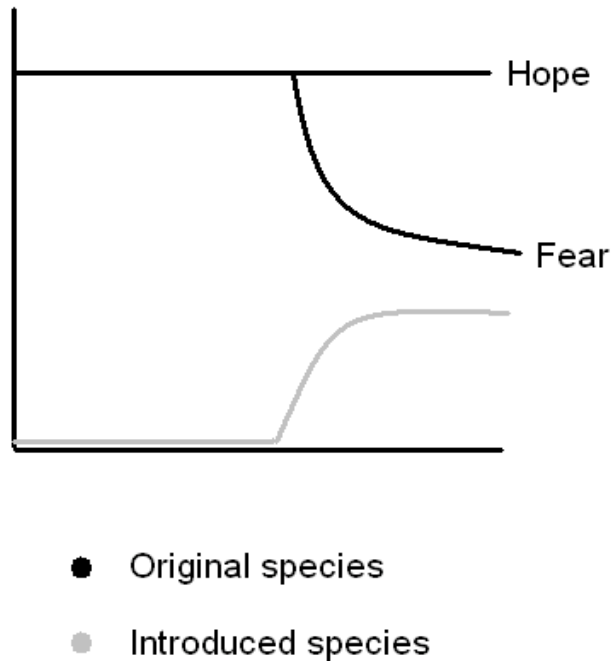
Figure 1: Hope and fear graph for preexisting and introduced species

As you can see, the desired outcome is that the original species will be unaffected by the introduced species, which will be able to easily coexist. Also, the fear, or result we want to avoid, is that with the introduction of the new species, the original species will die out, or be unable to compete with the new species. The purpose of this model is to give us an idea as to what the effect of the introduced species is. It can give us the insight to find out what the impact of an introduced species really is.

## Model Building Process

To begin a complicated model such as this one, it was important to start with several, small, individually working models. I figured it would be easier to find data about life spans and births in terms of years, so I set the model time in years. After a little research, I started building the first of the small models. I constructed a small, two-stock aging chain for the herons. It consisted of mature and adolescent herons, the distinction being adolescent herons do not contribute to the herons born (because they do not reproduce in the beginning of life).
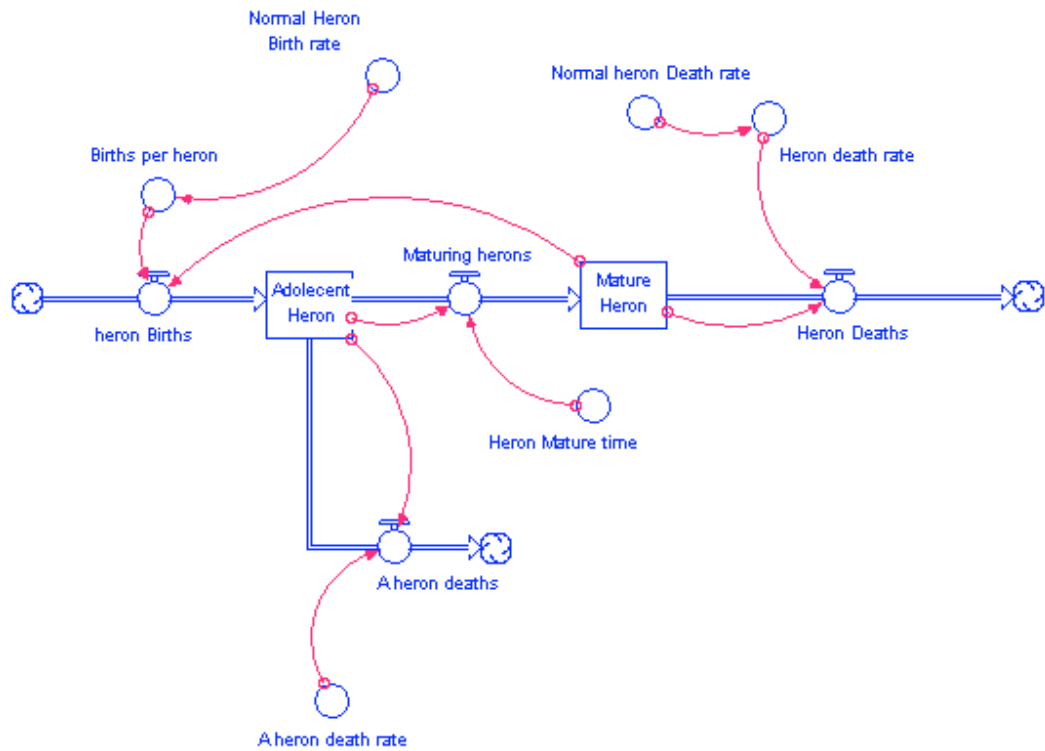
Figure 2: Simple Heron model

I then constructed a working model of trout, consisting of 3 stocks, eggs, adolescent trout, and mature trout. The rational for this construct was to differentiate between when the trout would be eaten and by what. For instance, a mature heron does not eat trout eggs, just as an adolescent heron couldn't consume a mature trout. In this way, we are better able to construct a more realistic and practical representation.
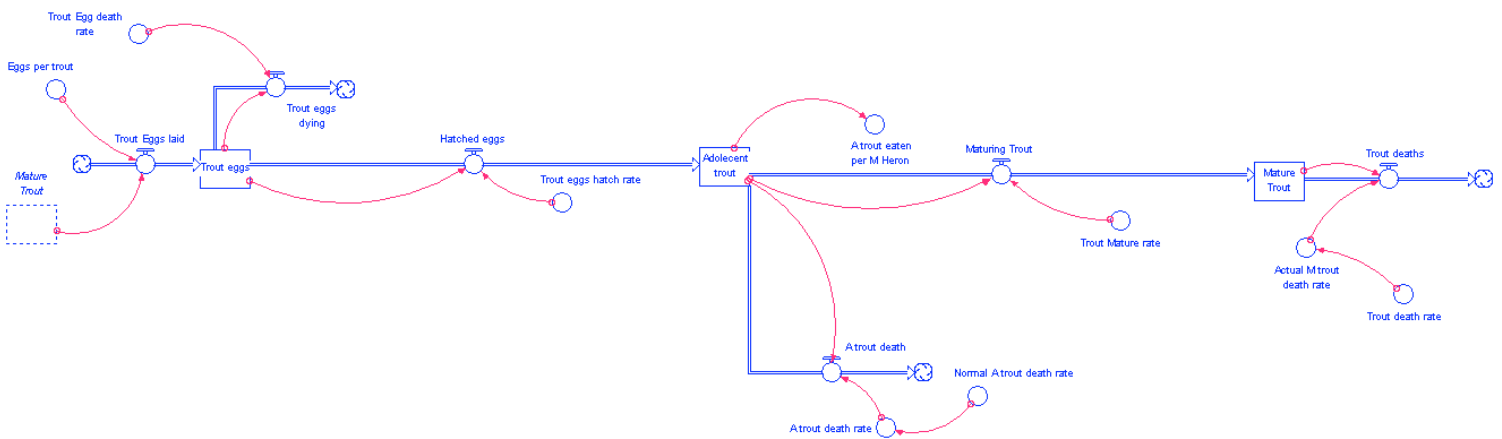


Figure 3: Simple Trout Model

I then constructed a working model for newts, again with the same three stocks (eggs, adolescent, mature). All of these aging chains were kept separate from each other to make sure they functioned correctly individually.
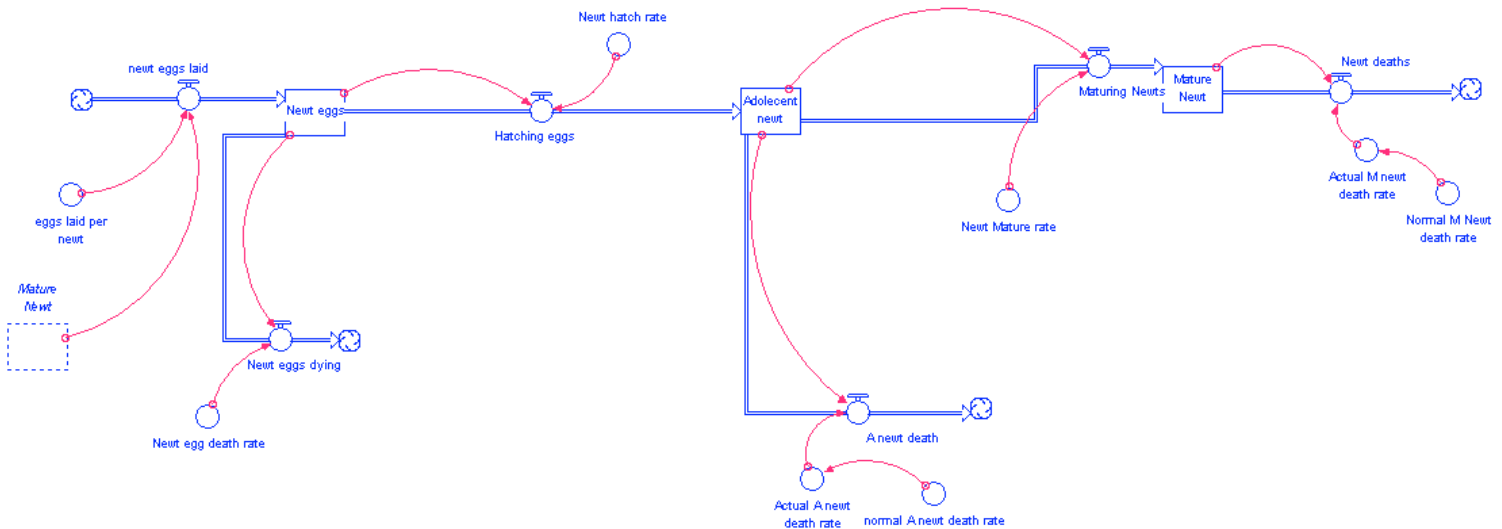


Figure 4: Simple newt Model

After these three models were up and running, I began connecting them to each other. I began with the top down, attaching a flow out of mature trout, representing trout eaten by herons. I then attached a similar flow out of adolescent trout representing trout eaten by adolescent herons. Eggs was left untouched at this point because research did not include eggs in the heron diet. I then moved on to newts. Similar out-flows were attached to newts representing the two levels of newts eaten by the two levels of herons. An outflow from newt eggs was added to represent the newt eggs eaten by adolescent trout. Research had shown that in early life, young trout often ate other amphibian's eggs, so I felt it was important to include this in the model.

I now had all 3 aging chains connected, yielding many unique feedback loops. I ran the model and adjusted the rate at which animals were eaten to provide a realistic effect on population. After they had reached equilibrium, I realized there was a problem with my model. At times, the population of a certain species, say newts, would be very low. During this time the heron and trout population would be effected in no way at all. I realized that in order to have a good model, the birth and death rates of the predators needed to depend on the amount of available food. To do this, I constructed a converter that added all the available food for the specific predator and then turned the ratio of needed food into an effect on birth/death rate converter. After re-running the model I found that this gave a much better outcome. When newt populations were down, the heron and trout population grew less and died more quickly. This is of course caused the number of newts being eaten to decrease, which forced the model to find a nice equilibrium where everything was in balance.

This is what I needed to achieve before I answered my ultimate question; what happens when you introduce an invasive species into a stable ecosystem. Of course, the ecosystem needed to be in equilibrium before they were introduced so that their effect would be

obvious. There was a little oscillation in the beginning as the ecosystem found equilibrium so I delayed the introduction till year 20. I constructed a whole new aging chain for bullfrogs, consisting of eggs, tadpoles, adolescent and mature. Also note that on the final stock (mature bullfrogs) there is a flow labeled "introduction of bullfrogs". This is where I will introduce the initial bullfrog population. It will put a few into the ecosystem and then will turn off.
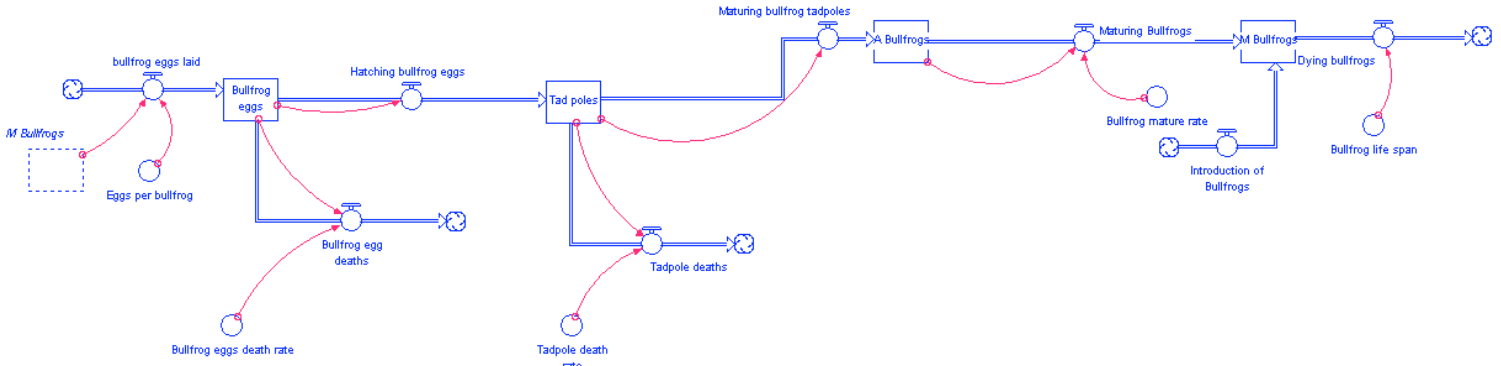


Figure 5: Simple Bullfrog Model

I also added additional flows out of the species that the bullfrogs would be a predator to, namely, newt eggs, adolescent newts and trout eggs.
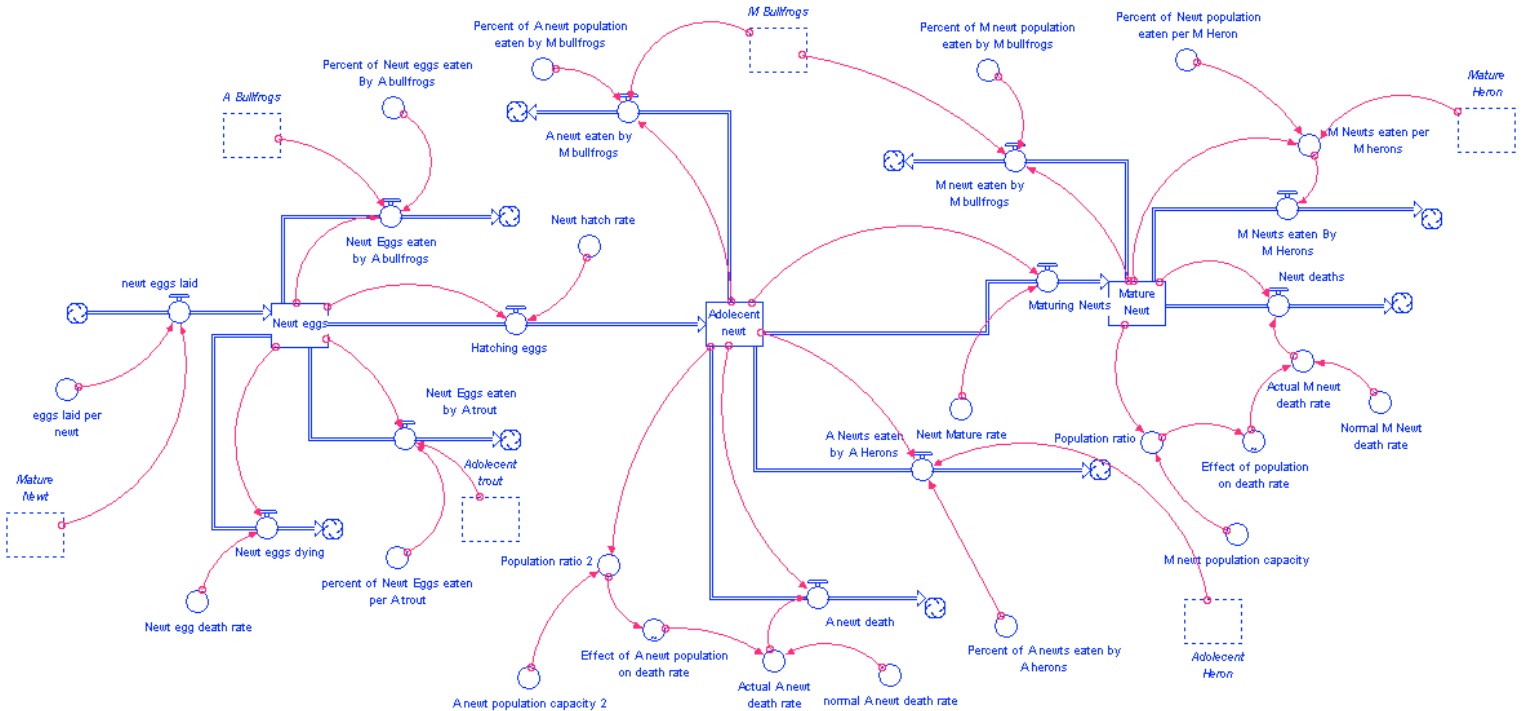


Figure 6: Advanced Model (with predator/prey flows)

I also included adolescent bullfrogs (research said a heron cannot kill a full grown bullfrog) into the heron's food, however I did not increase the amount of food they needed because the introduction would not naturally be part of their diet and therefore

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any bullfrogs would be a supplement to their diet, not a necessity. Originally I introduced 60 bullfrogs, but later found that because the mature ones have no natural predators in the northwest (the reason they are so invasive), the initial number didn't matter because they are able to reproduce for several years before the first ones start dying off and the system reaches equilibrium.

After running the model I found that I had made the bullfrogs too invasive. That is they ate too much of everything. After reassessing my data I settled on some more reasonable numbers. Finally I reached a very good value for all of them and found that my model had answered the question very well and given me some very important insight into the effect of invasive species.

## How the finished model works

The model I ultimately constructed is quite complex, but can be broken down into some very manageable parts. Basically, herons are at the top of the food chain and have no predators at any level, which is true based on research. We then have two secondary consumers, the bullfrogs and the trout. The adolescent bullfrogs eat some of the trout eggs and the adolescent trout eat some of bullfrog eggs, but ultimately, they are both eaten by the herons (save the mature bullfrogs). Then we have our tertiary consumer, the newt, which is eaten by everyone on almost every level. Also, the prey of every predator is tallied and put into a food converter to represent the availability of food and thus effects the death and birthrates. In the end, the model was very large, but as I stated before, had some small components that it consisted of. To make the model easier to understand, I have broken it into its 4 major parts, that is, the separate species, these 4 pieces and their interactions with each other make up the model as a whole.
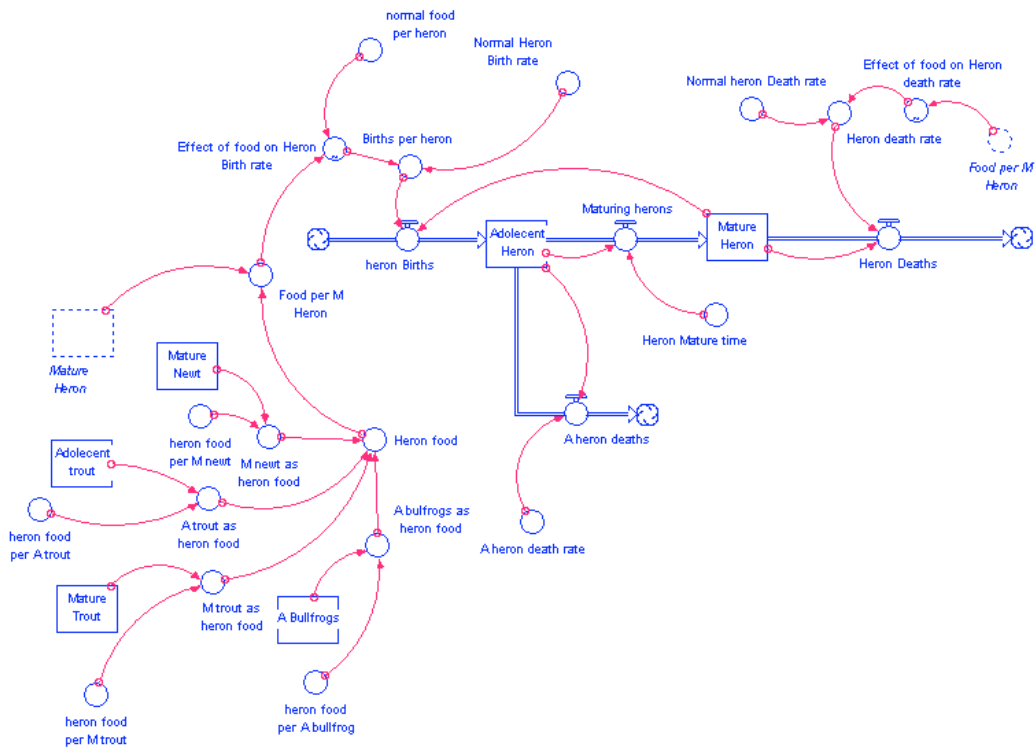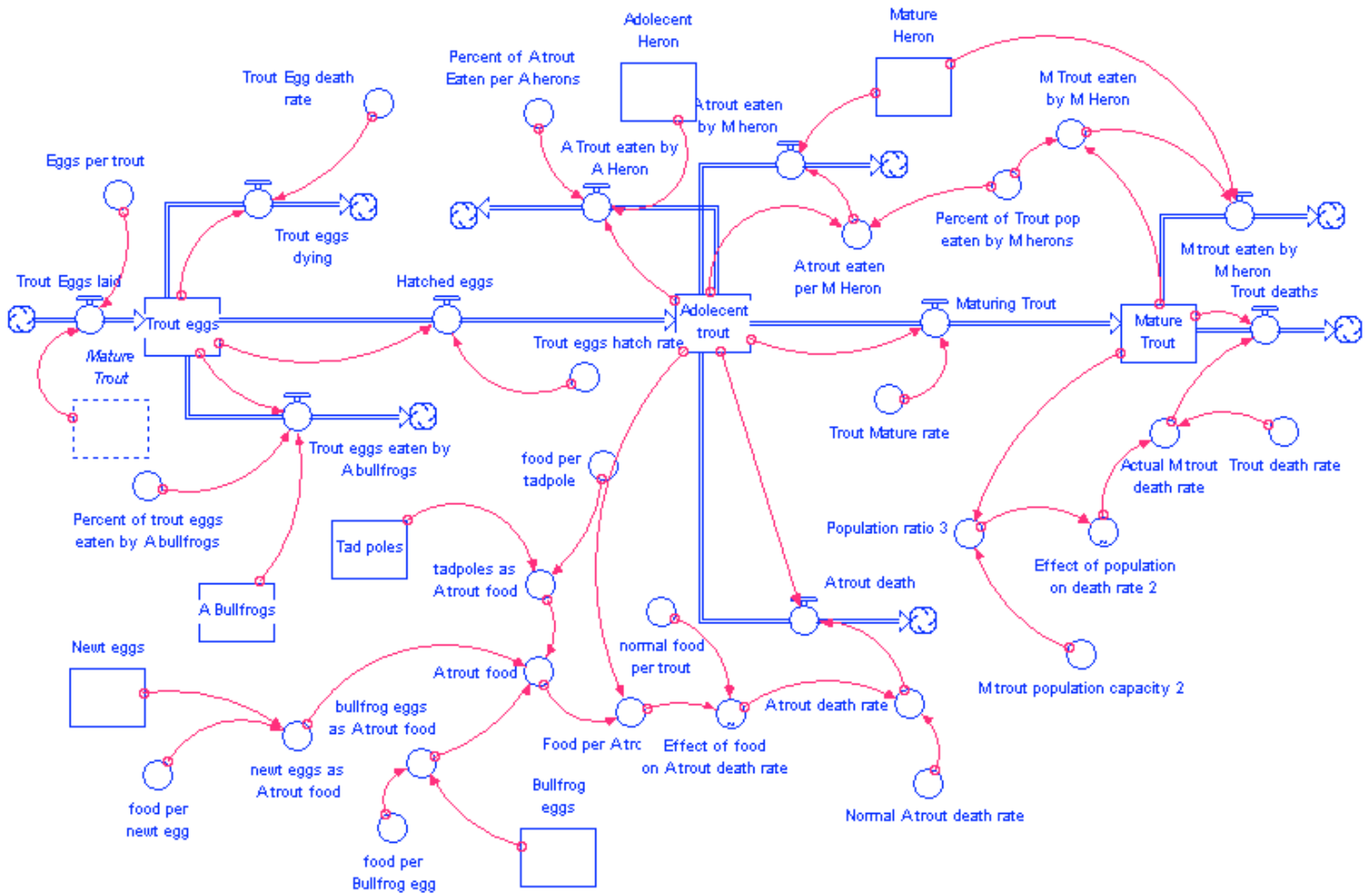
Figure 7: complete heron model
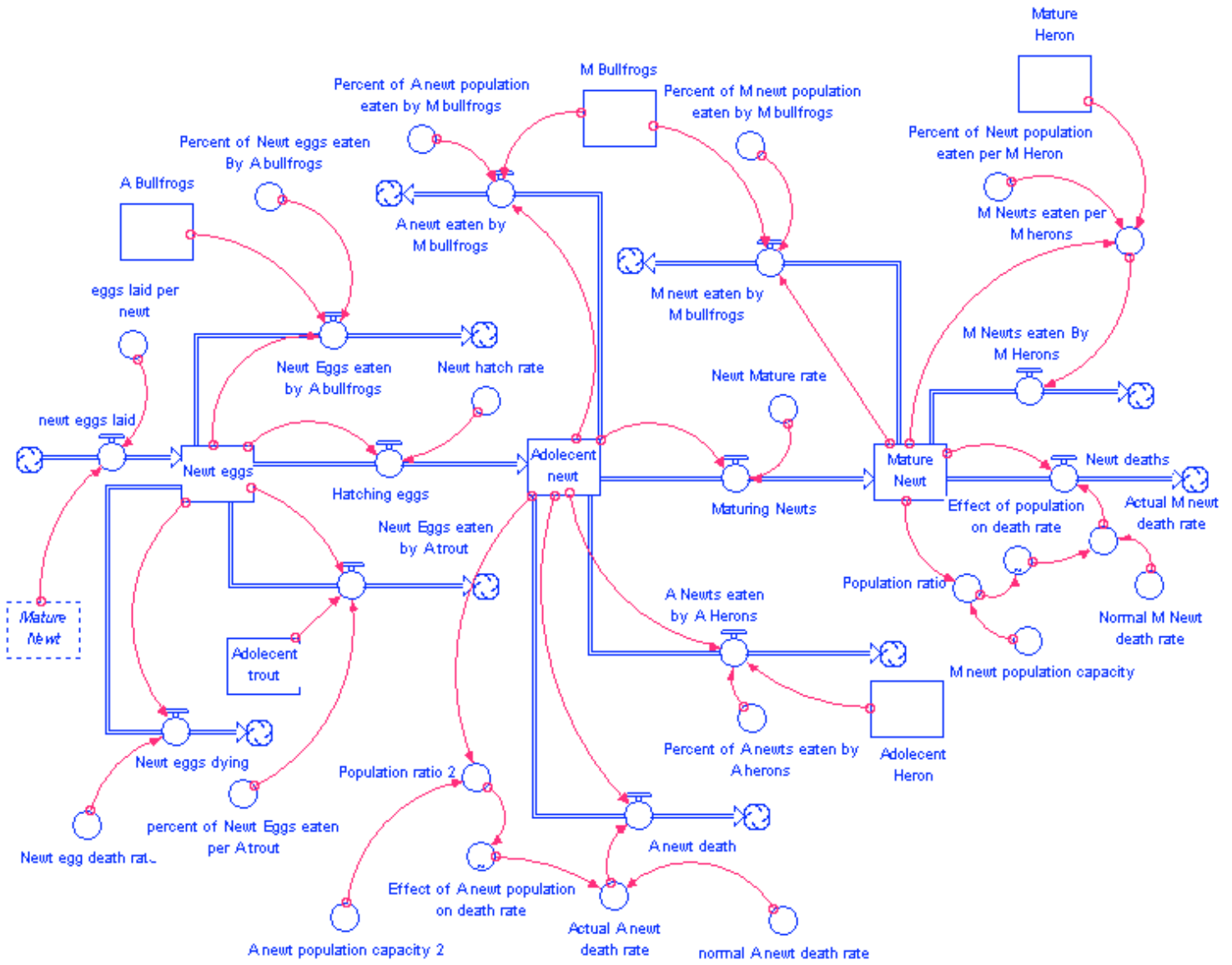
Figure 8: complete trout model



Figure 9: complete newt model

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percent of Bullfrog eggs eaten by A trout

Percent of Tadpoles eaten by A trout

Adolecent trout

Introduction of Bullfrogs

food per M newt

M Bullfrogs 2

bullfrog eggs eaten per A trout

tadpoles eaten per A trout

Percent of A Bullfrog population eaten per M Heron

Mature Heron

M newt as bullfrog food

M bullfrog food

food per M bullfrog

Bullfrog eggs eaten by A trout

Tadpoles eaten by A trout

A bullfrogs eaten by herons

normal M bullfrog food

effect of food on M bullfrog death rate

Mature Newt

bullfrog eggs laid

Hatching bullfrog eggs

Maturing bullfrog tadpoles

A Bullfrogs

Maturing Bullfrogs

M Bullfrogs 2

Bullfrog eggs

Tad poles

Dying bullfrogs

Eggs per bullfrog

Eggs hatching rate

Tadpole mature rate

A bullfrog deaths

Bullfrog mature rate

A newt as bullfrog food

food per A newt

M Bullfrogs

Bullfrog egg deaths

Tadpole deaths

Bullfrog life span

Adolecent newt

Bullfrog eggs death rate

Tadpole death rate

effect of food on A bullfrog death rate

A Bullfrogs 2

A bullfrog food

A bullfrog death rate

food per A bullfrog

normal A bullfrog food

newt eggs as bullfrog food

A bullfrog eaten by A heron

Trout eggs as bullfrog food

Adolecent Heron

Percent of A bullfrogs eaten by A heron

Trout eggs

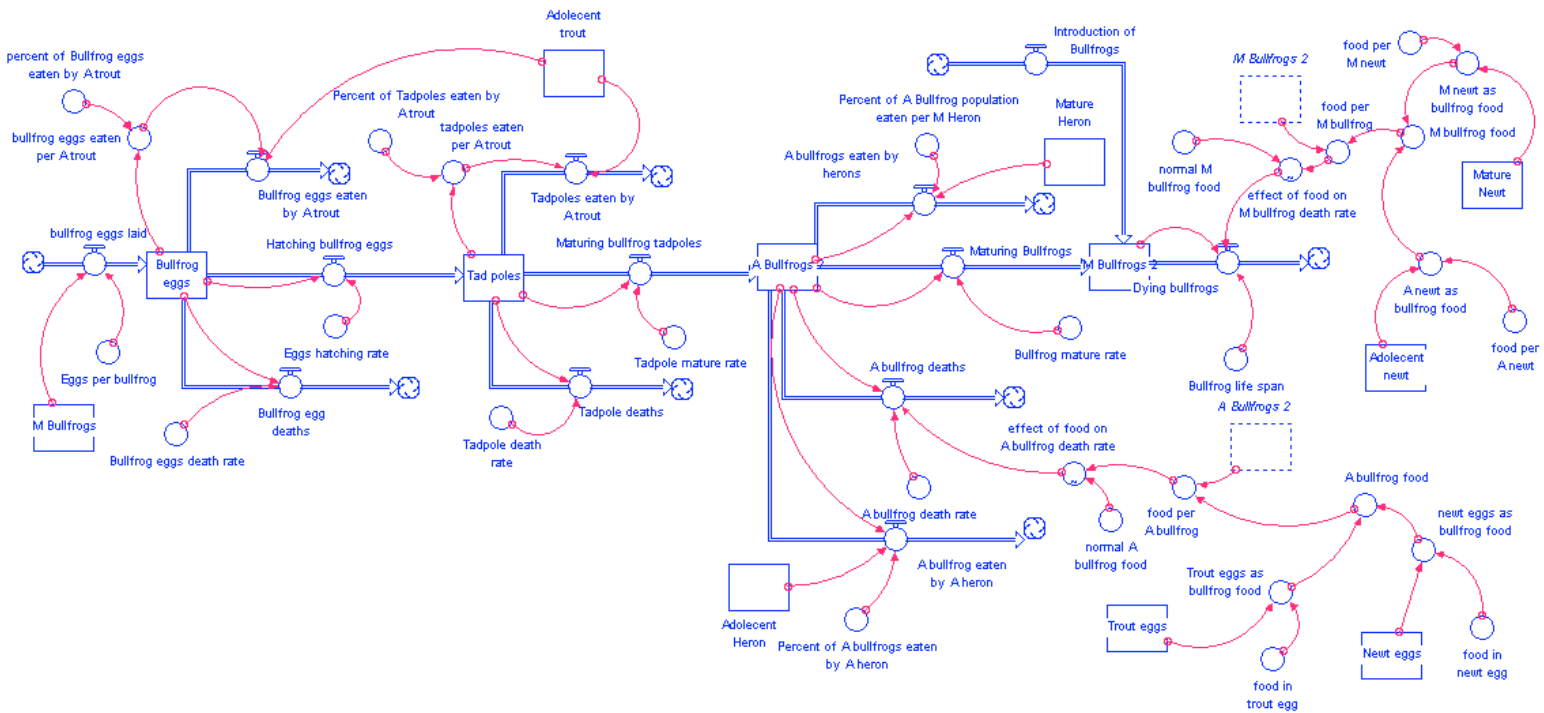Newt eggs

food in newt egg

food in trout egg

Figure 10: complete bullfrog model

The bullfrogs are introduced at year 20 and wreak massive havoc on the ecosystem. To begin with, we see a giant initial spike in their population at their birth because they have no natural predators in their new environment. Also, we see the newt population drop drastically because there is a new competitor and predator, so their population dies off and they go from being in the 4 thousands to down below a hundred. This momentarily brings everyone's population down because there is less food. As heron population decreases, the trout population, whose only real predator is the heron, begins to climb greatly. The ecosystem reaches equilibrium again, this time with herons lower than before, trout higher than before, newts almost extinct and bullfrogs finding a nice equilibrium.

The final model behaved very well. Each species reacted appropriately to a decrease in their food and showed some very interesting results. With the introduction of bullfrogs, a new food for the herons, we actually see a decrease in heron population because the bullfrogs hurt the new population more than they provide food for herons. With a reduction in herons, we see the trout population increase. Some very interesting behavior that shows just how dangerous an invasive species can be. This behavior can be shown by the next few graphs.
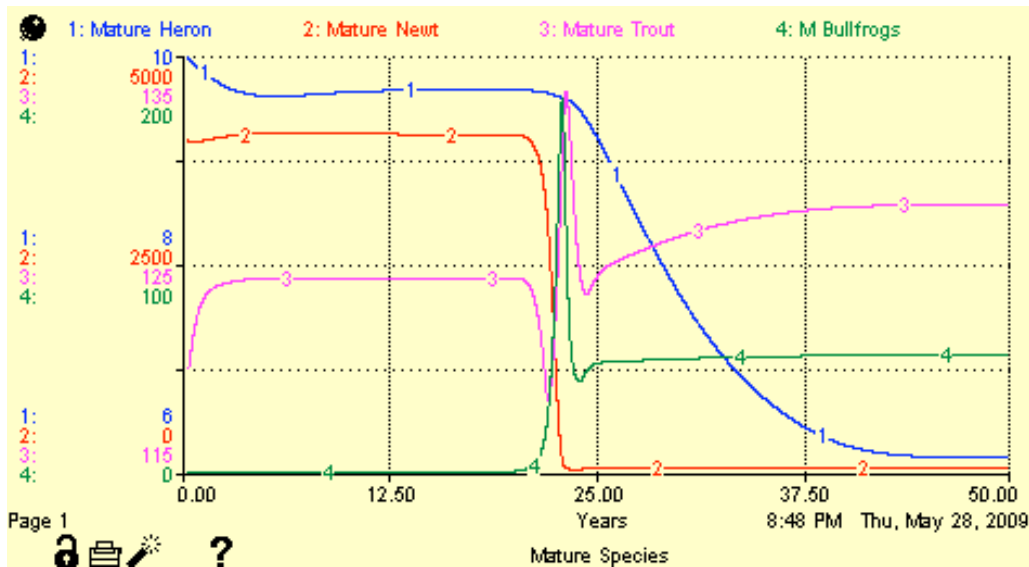
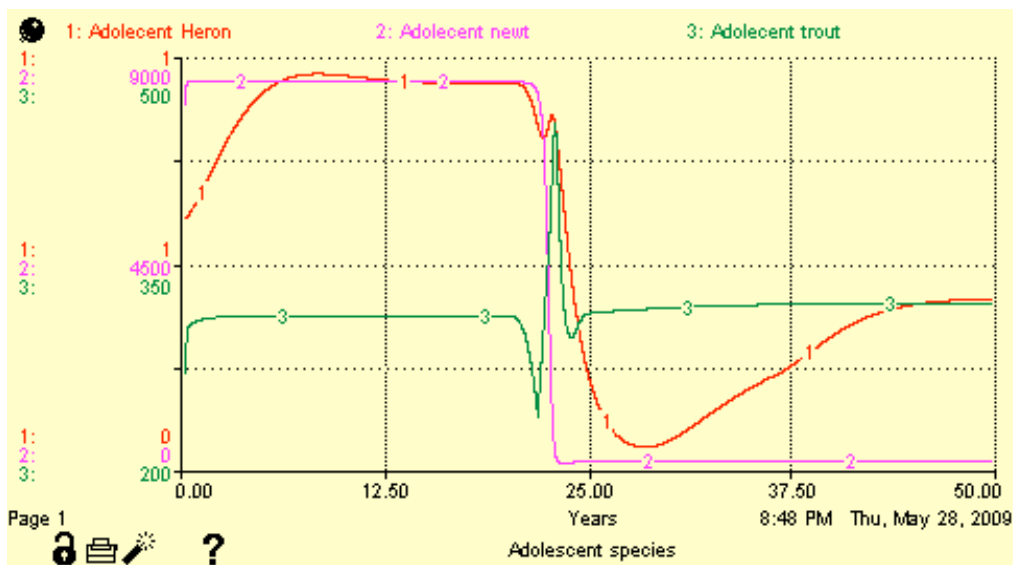Figure 11: Mature species graph with bullfrog introduction



Figure 12: Adolescent species graph with bullfrog introduction

## The Model Feedback and loop story

There are literally hundreds of feedback loops in this model and to analyze them all would be both difficult and unnecessary. In order to get a good understanding of the model, we can analyze a few key feedback loops. Before we do this, let's begin with a very small, very simple one so we have a good idea as to how they work.
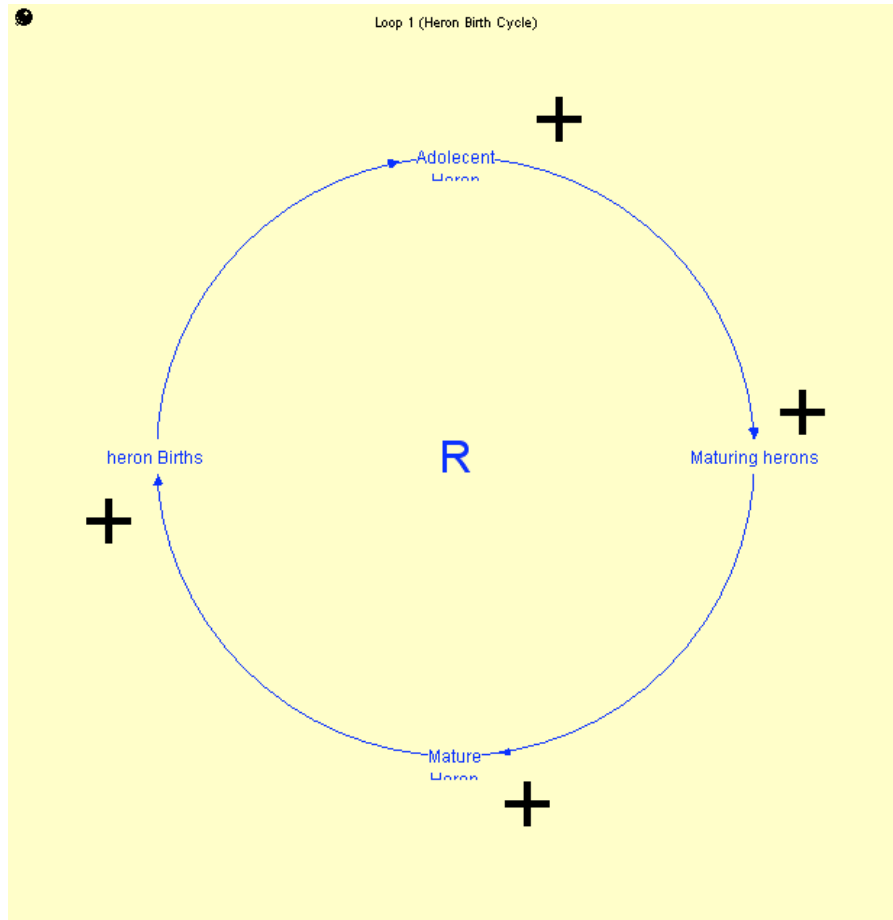
Figure 13: Simple heron loop

As you can see from this model, the heron population growth is dependant on the number of existing herons, meaning that if it is left alone, it will experience exponential growth. This is because an increase in one of them (say Adolescent Herons) will cause the number of maturing herons to increase, causing mature herons to increase, causing heron births to increase, all the way back to adolescent heron, beginning the cycle again. This is of course countered by a number of counteracting loops, which if left alone, would make them experience exponential decay. Because there are both counteracting and reinforcing loops, the model finds a nice equilibrium where everything is stable. Each aging chain consists of reinforcing loops to represent growth (or births) and counteracting loops for death. There are a few loops at the core of the model, which are effected by every stock in the model, such as this one.
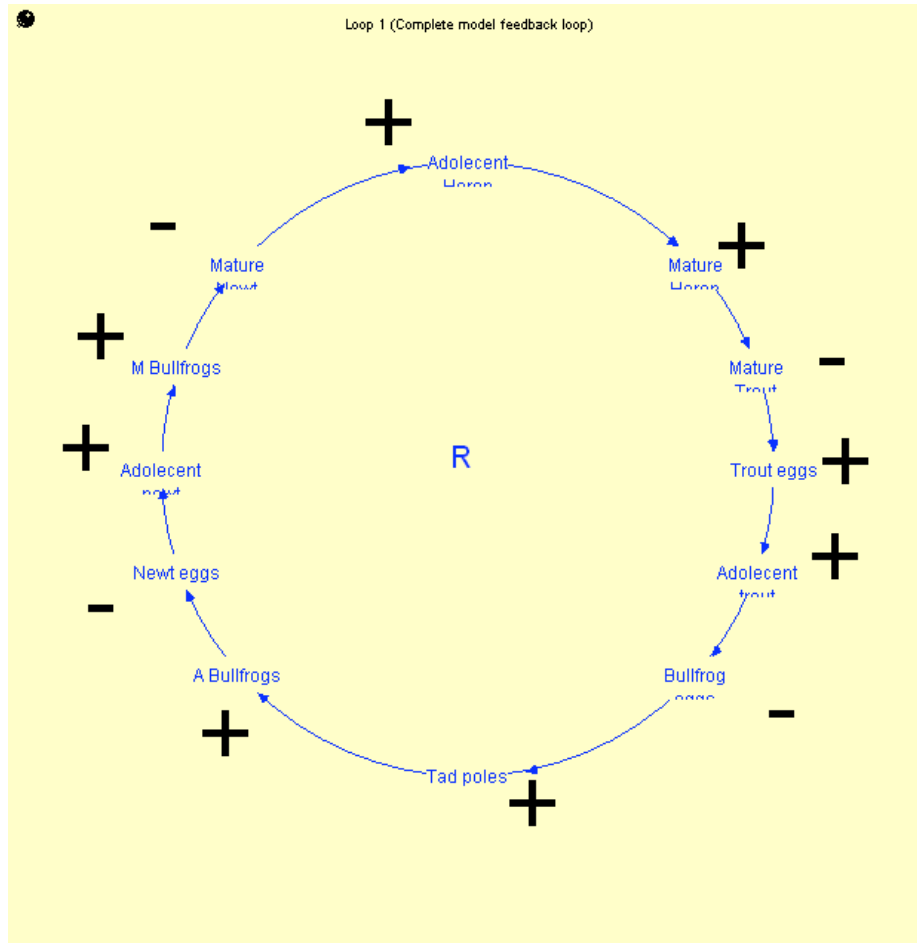
Figure 14: Complex model loop

An increase in adolescent herons leads to an increase in mature herons. An increase in mature herons leads to a decrease in mature trout. A decrease in mature trout leads to a decrease in trout eggs, which will decrease adolescent trout. A decrease in adolescent trout will lead to an increase in bullfrog eggs. An increase in bullfrog eggs will lead to an increase in tadpoles, which will lead to an increase of adolescent bullfrogs. An increase in adolescent bullfrogs leads to a decrease in newt eggs. A decrease in newt eggs would lead to a decrease in adolescent newts, which would lead to a decrease in mature bullfrogs, would lead to an increase in mature newts. An increase in mature newts would lead to an increase in herons. The fact that we go from increasing adolescent herons back to an increase in adolescent herons, then we know the loop is reinforcing. This loops lets us see some of the more complex aspects of this model, because we have a scenario where a predator is eating the prey of one of its competitors, making its competitor suffer, making the original predator grow more. It is these complex feedback loops that give this model its unique behavior.

This is the simple relationship between all the stocks in the model, and is perhaps the most important loop in the model. The relationship between every species in the model dictates the outcome. This helps explain some of the odd behavior we see. This model can show us that if you increase a species' (say trout) food source (say newts) you can end up giving more food to an overall predator (say herons) and end up killing off more of the first species (the trout). These feedback loops show us that an ecosystem is a very

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interconnected structure, and sometimes action to help a species might actually end up hurting it. Also, it can guide us in policy making to try and help a specific creature. Say for instance you want to increase the trout population. One strategy might be to grow trout in captivity and release them when they are full-grown. If you did that the heron population would increase, and because heron live longer, they would eat more trout in the long run than you put in. Now say for instance that we introduce more trout eggs raised in captivity. Because eggs are bullfrog food, we will see more bullfrogs. The more bullfrogs we have, the less newts we have, which are a main food source for heron. If the newts go down, so will the heron, meaning more trout will live. Of course it is important to look at all aspects of the model, and these feedback loops help us do that. Also, because of how the model is constructed, it will behave appropriately in each situation, not based on very specific starting values, making the model's behavior very endogenous.

## The Model Boundaries

Probably the biggest thing this model is missing is simply the next step in the food chain. The addition of insects or vegetation would greatly impact the scope of this model. Of course, this adds an entirely new element and is very difficult to include. Every additional step means basically resigning the model again.

Despite what it is lacking, I am confident that this model does behave appropriately. It does match my reference graph, which showed everything would decrease. I did not anticipate that trout might increase, but after working with this model, I can see that this is a purely logical occurrence, given the scenario. The model is also limited in that is spans a 50-year period. While it does reach equilibrium very quickly, there may be more helpful information down the line. While a longer time frame might not be helpful right now, if the model were to be more complex, subtle changes might have larger long term effects that we would need more time to look at.

Also, we have no indication of season or weather changes. Environmental factors can separate things dramatically, such as summer bringing an increase in food (and thus in birthrates) or winter making food sparse (meaning a decrease in birth rates and lifespan).

## Model Testing

The model appears to be working correctly because it is quite difficult to change the end behavior, even when you change some of the numbers. Change in eating rates has some effect, but ultimately, the general trend is exactly the same. With the bullfrogs, it didn't matter if I introduced 60 or 100 or 20 or 10, the end value was always within 1 bullfrog. I was able to boost newts only by about 30 or 40 by decreasing how much they were eaten across the board. The mature rates did effect the population pretty dramatically, although it makes sense that this number would be very sensitive.

We also used the model to do some testing of solutions to the problems presented by this model. The first thing we did was completely eliminating the bullfrog eggs. The effect of

this was that the ecosystem began to recover, and approached that initial equilibrium. This shows us that the model is working properly because we see that there is a specific range of number that a system with these rates experiences. Of course, as stated above, if we change those rates, it can affect those numbers.
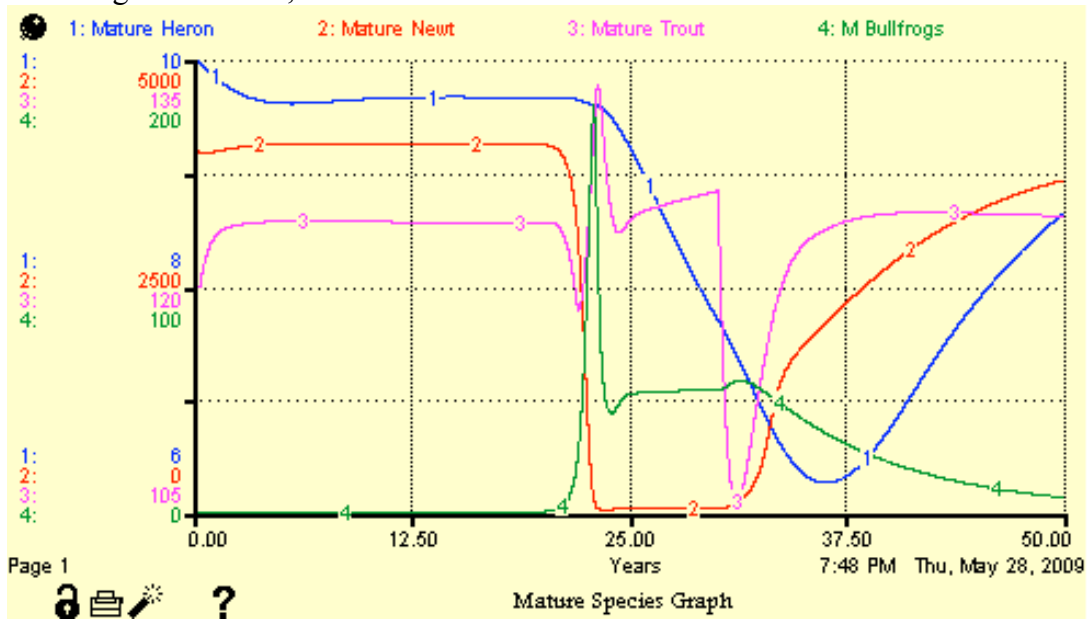


Figure 15: Bullfrog egg collection policy beginning at year 30

We also tested what happens when you try removing few of the mature bullfrogs. In this scenario we see very little change because of the fact that as long as there are a few, the population will always recover (because initially we only introduce a few). This can help us realize that if you want to stop the problem, the best way to do it is to capture and sequester the eggs, not the mature bullfrogs (although that can be a part of the solution).
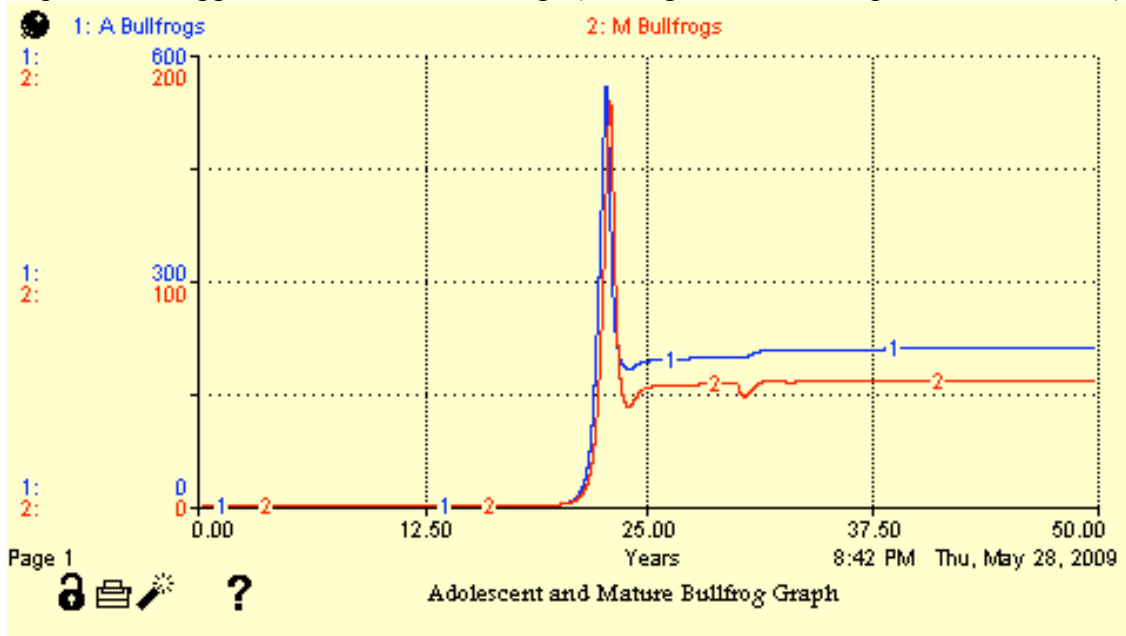


Figure 16: Bullfrog graph with bullfrog capture policy at year 30

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When we combine both policies, we see that it is more effective than before. This is because we have fewer bullfrogs laying eggs, and less eggs hatching into bullfrogs. Because the model responds this way, we can be sure that it is working correctly, and can use to help us figure out what we need to do in order to combat the bullfrog problem
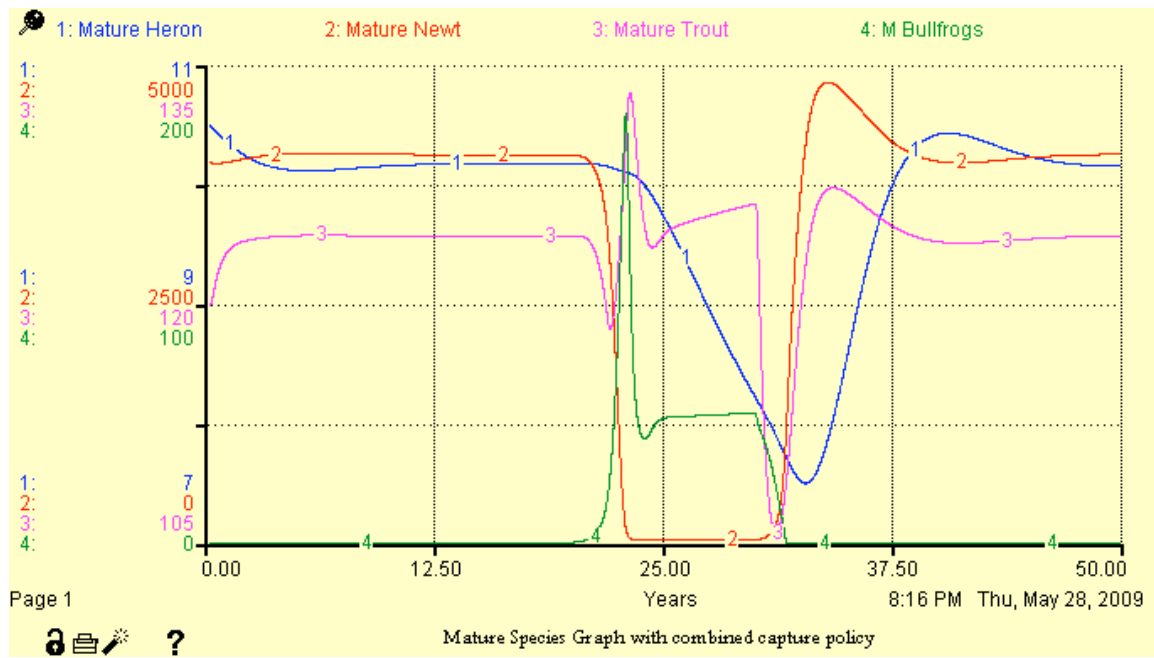


Figure 17: Combined bullfrog capture and egg capture policy at year 30

As you can see by comparing the three graphs, combining the two policies works the quickest and it best for the ecosystem. Had we not had this model, we may have only gone after the mature bullfrogs, which would have resulted in a less than favorable result.

## The Result of Modeling and Thinking

This model helps us understand the danger of introducing an invasive species. It has shown us that by adding another predator and competitor, we almost completely eliminated a species. We also see that there are unintended "benefits" such as the trout population increase. This of course would change the rates of whatever else (not included in this model) that trout are a part of, such as the ecosystem in the ocean.

The final graph demonstrates that after the bullfrogs are introduced, the population of newts and herons drops, while trout drops momentarily, then increases to a higher number. Newts of course have a new predator and begin to drop off right away. Herons start to lose their main food source and begin to die and the trout population loses it main predator, and thus begins to grow. Also, bullfrogs spike in the beginning, then the adults begin to die off and we see that they find their own equilibrium.
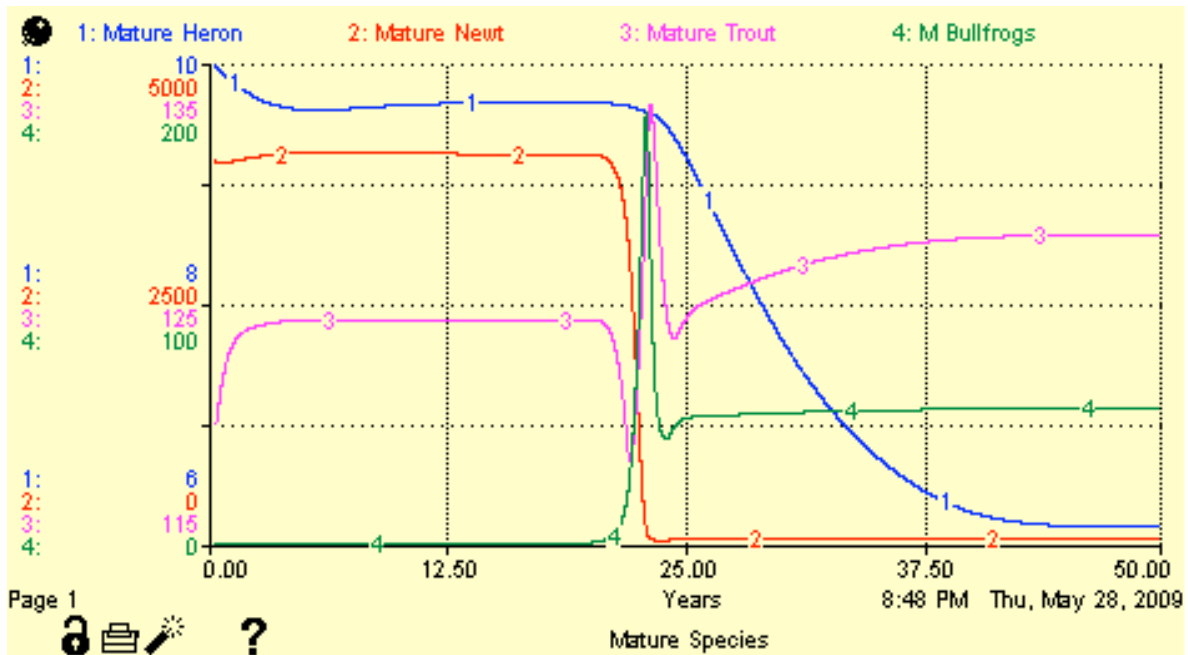
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Figure 18: Mature species graph, showing equilibrium before and after

The table supports this story, giving different ending equilibrium values for the 3 original species. It shows us the newts drop from around 4000 to below 100, the heron's dip and the trout's increase.

| 7:16 PM  5/25/2009 | | | | Table 1 (number of animals per species) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Years | 19.500 | 20.000 | 20.500 | 21.000 | 21.500 | 22.000 | 22.500 | 23.000 | 23.500 | 24.000 | 24 |
| Mature Heron | 9.68 | 9.68 | 9.68 | 9.67 | 9.67 | 9.65 | 9.62 | 9.60 | 9.56 | 9.47 | ! |
| Adolecent Heron | 1.30 | 1.30 | 1.30 | 1.29 | 1.25 | 1.19 | 1.20 | 1.19 | 1.02 | 0.86 | |
| Mature Trout | 124.25 | 124.26 | 124.23 | 123.68 | 121.78 | 118.41 | 123.49 | 132.87 | 128.77 | 124.21 | 12: |
| Adolecent trout | 311.55 | 311.55 | 310.29 | 300.13 | 272.83 | 262.92 | 353.81 | 444.40 | 317.01 | 295.66 | 30 |
| Trout eggs | 516.45 | 516.45 | 509.79 | 477.08 | 387.11 | 205.99 | 101.15 | 159.73 | 207.25 | 206.24 | 20 |
| Mature Newt | 4,067.75 | 4,067.83 | 4,046.21 | 3,962.37 | 3,708.91 | 2,901.28 | 1,056.88 | 55.75 | 21.18 | 24.86 | 2 |
| Adolecent newt | 8,488.06 | 8,488.07 | 8,482.99 | 8,468.98 | 8,413.32 | 7,951.65 | 4,364.18 | 261.69 | 111.10 | 135.14 | 15 |
| Newt eggs | 17,884.82 | 17,885.10 | 17,779.96 | 17,501.87 | 16,432.98 | 10,723.61 | 2,342.63 | 142.83 | 64.89 | 79.05 | 9 |
| M Bullfrogs | 0.00 | 0.00 | 0.62 | 2.36 | 7.66 | 29.48 | 106.51 | 147.24 | 51.27 | 43.90 | 4 |
| A Bullfrogs | 0.00 | 0.00 | 1.88 | 10.47 | 40.50 | 175.60 | 495.37 | 288.40 | 189.93 | 181.13 | 18 |
| Tad poles | 0.00 | 0.00 | 12.25 | 50.75 | 189.97 | 822.59 | 1,854.10 | 2,001.66 | 1,248.73 | 1,159.17 | 1,22 |
| Bullfrog  eggs | 0.00 | 0.00 | 80.69 | 318.55 | 1,110.81 | 4,450.77 | 12,774.94 | 15,609.37 | 7,227.58 | 6,419.34 | 7,03 |

Figure 19: Table of species and their respective values

## Key Learning from the Modeling Process

- It is important to model a problem because there are often effects that cannot easily be predicted
- Many ecosystems have so much interconnection that they are able to find a new equilibrium even when they are disturbed

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- While these ecosystems are resilient, the effects of an invasive species can be devastating to every creature in the ecosystem
- It is imperative that when you try to make a very large model, you start with several smaller models and connect them
- A model that only works for one specific set of data is poorly constructed and not very useful

Ultimately, we reach the conclusion that any disruption to an ecosystem can be devastating. Introducing an invasive species can disrupt every creature and in this case, even leads to the close extinction of a tertiary consumer.

This model can be easily adapted to represent any ecosystem like this, and could be expanded to contain many other species. The generic structure really only applies to ecosystems, but it can be applied and changed to fit almost any relation between species.

## Bibliography

Heron information: Birth rate, Life span, Diet, and Habitat
http://www.hww.ca/hww2.asp?id=43


Trout information: Eggs lay per couple, Life span, Diet, Habitat, Predators
http://www.naparcd.org/steelheadtrout.htm


Bullfrog information: Eggs lay per couple, Life span, Diet, Habitat, Predators
http://yosemite.epa.gov/r10/ECOCOMM.NSF/B724CA698F60547988257057006
93650/52CF90301EF287AA88257416005F8108?OpenDocument


Newt information: Eggs lay per couple, Life span, Diet, Habitat, Predators
http://www.californiaherps.com/salamanders/pages/p.stormi.html

# Model Equations and Documentation

Adolecent_Heron(t) = Adolecent_Heron(t - dt) + (heron_Births - Maturing_herons - A_heron_deaths) * dt
INIT Adolecent_Heron = 1
UNITS: heron
INFLOWS:
heron_Births = Mature_Heron*Births_per_heron
UNITS: heron/yr
OUTFLOWS:
Maturing_herons = Adolecent_Heron/Heron_Mature_time
UNITS: heron/yr
A_heron_deaths = Adolecent_Heron*A_heron_death_rate
UNITS: heron/yr
Adolecent_newt(t) = Adolecent_newt(t - dt) + (Hatching_eggs - Maturing_Newts - A_Newts_eaten__by_A_Herons - A_newt_death - A_newt_eaten_by__M_bullfrogs) * dt
INIT Adolecent_newt = 8000
UNITS: newts
INFLOWS:
Hatching_eggs = Newt_eggs/Newt_hatch_rate
UNITS: newts/yr
OUTFLOWS:
Maturing_Newts = Adolecent_newt/Newt_Mature_rate
UNITS: newts/yr
A_Newts_eaten__by_A_Herons = Adolecent_Heron*Adolecent_newt*Percent_of_A_newts_eaten_by_A_herons
UNITS: newts/yr
A_newt_death = Adolecent_newt/Actual_A_newt__death_rate
UNITS: newts/yr
A_newt_eaten_by__M_bullfrogs = Adolecent_newt*M_Bullfrogs*Percent_of_A_newt_population_eaten_by_M_bullfrogs
UNITS: newts/yr
Adolecent_trout(t) = Adolecent_trout(t - dt) + (Hatched_eggs - Maturing_Trout - A_Trout_eaten_by_A_Heron - A_trout_eaten__by_M_heron - A_trout_death) * dt
INIT Adolecent_trout = 270
UNITS: trout
INFLOWS:
Hatched_eggs = Trout_eggs/Trout_eggs_hatch_rate
UNITS: trout/yr
OUTFLOWS:
Maturing_Trout = Adolecent_trout/Trout_Mature_rate
UNITS: trout/yr
A_Trout_eaten_by_A_Heron = Adolecent_Heron*Adolecent_trout*Percent_of_A_trout_Eaten_per_A_herons
UNITS: trout/yr
A_trout_eaten__by_M_heron = Mature_Heron*A_trout_eaten_per_M_Heron
UNITS: trout/yr
A_trout_death = Adolecent_trout*A_trout_death_rate
UNITS: trout/yr
A_Bullfrogs(t) = A_Bullfrogs(t - dt) + (Maturing_bullfrog_tadpoles - Maturing_Bullfrogs - A_bullfrog_deaths - A_bullfrogs_eaten_by__herons - A_bullfrog_eaten_by_A_heron) * dt
INIT A_Bullfrogs = 0
UNITS: frogs
INFLOWS:
Maturing_bullfrog_tadpoles = Tad_poles/Tadpole_mature_rate
UNITS: frogs/yr
OUTFLOWS:
Maturing_Bullfrogs = A_Bullfrogs/Bullfrog_mature_rate
UNITS: frogs/yr
A_bullfrog_deaths = A_Bullfrogs*A_bullfrog_death_rate/effect_of_food_on_A_bullfrog_death_rate
UNITS: frogs/yr
A_bullfrogs_eaten_by__herons = A_Bullfrogs*Mature_Heron*Percent_of_A_Bullfrog_population_eaten_per_M_Heron
UNITS: frogs/yr
A_bullfrog_eaten_by_A_heron = Adolecent_Heron*A_Bullfrogs*Percent_of_A_bullfrogs_eaten_by_A_heron
UNITS: frogs/yr
Bullfrog__eggs(t) = Bullfrog__eggs(t - dt) + (bullfrog_eggs_laid - Hatching_bullfrog_eggs - Bullfrog_egg_deaths - Bullfrog_eggs_eaten_by_A_trout) * dt
INIT Bullfrog__eggs = 0
UNITS: frogs
INFLOWS:
bullfrog_eggs_laid = M_Bullfrogs*Eggs_per_bullfrog
UNITS: frogs/yr

OUTFLOWS:
Hatching_bullfrog_eggs = Bullfrog__eggs/Eggs_hatching_rate
UNITS: frogs/yr
Bullfrog_egg_deaths = Bullfrog__eggs*Bullfrog_eggs_death_rate
UNITS: frogs/yr
Bullfrog_eggs_eaten_by_A_trout = Adolecent_trout*bullfrog_eggs_eaten_per_A_trout
UNITS: frogs/yr
Mature_Heron(t) = Mature_Heron(t - dt) + (Maturing_herons - Heron_Deaths) * dt
INIT Mature_Heron = 10
UNITS: heron
INFLOWS:
Maturing_herons = Adolecent_Heron/Heron_Mature_time
UNITS: heron/yr
OUTFLOWS:
Heron_Deaths = Mature_Heron/Heron_death_rate
UNITS: heron/yr
Mature_Newt(t) = Mature_Newt(t - dt) + (Maturing_Newts - Newt_deaths - M_Newts_eaten_By__M_Herons -
M_newt_eaten_by_M_bullfrogs) * dt
INIT Mature_Newt = 4000
UNITS: newts
INFLOWS:
Maturing_Newts = Adolecent_newt/Newt_Mature_rate
UNITS: newts/yr
OUTFLOWS:
Newt_deaths = Mature_Newt/Actual_M_newt__death_rate
UNITS: newts/yr
M_Newts_eaten_By__M_Herons = M_Newts_eaten_per__M_herons
UNITS: newts/yr
M_newt_eaten_by_M_bullfrogs = Mature_Newt*M_Bullfrogs*Percent_of_M_newt_population_eaten_by_M_bullfrogs
UNITS: newts/yr
Mature_Trout(t) = Mature_Trout(t - dt) + (Maturing_Trout - Trout_deaths - M_trout_eaten_by__M_heron) * dt
INIT Mature_Trout = 120
UNITS: trout
INFLOWS:
Maturing_Trout = Adolecent_trout/Trout_Mature_rate
UNITS: trout/yr
OUTFLOWS:
Trout_deaths = Mature_Trout/Actual_M_trout__death_rate
UNITS: trout/yr
M_trout_eaten_by__M_heron = Mature_Heron*M_Trout_eaten_by_M_Heron
UNITS: trout/yr
M_Bullfrogs(t) = M_Bullfrogs(t - dt) + (Maturing_Bullfrogs + Introduction_of_Bullfrogs - Dying_bullfrogs) * dt
INIT M_Bullfrogs = 0
UNITS: frogs
INFLOWS:
Maturing_Bullfrogs = A_Bullfrogs/Bullfrog_mature_rate
UNITS: frogs/yr
Introduction_of_Bullfrogs = (Step(1,20)-Step(1,21))
UNITS: frogs/yr
OUTFLOWS:
Dying_bullfrogs = M_Bullfrogs/(Bullfrog_life_span*effect_of_food_on_M_bullfrog_death_rate)
UNITS: frogs/yr
Newt_eggs(t) = Newt_eggs(t - dt) + (newt_eggs_laid - Hatching_eggs - Newt_eggs_dying - Newt_Eggs_eaten_by_A_trout -
Newt_Eggs_eaten__by_A_bullfrogs) * dt
INIT Newt_eggs = 8000
UNITS: newts
INFLOWS:
newt_eggs_laid = Mature_Newt*eggs_laid_per_newt
UNITS: newts/yr
OUTFLOWS:
Hatching_eggs = Newt_eggs/Newt_hatch_rate
UNITS: newts/yr
Newt_eggs_dying = Newt_eggs*Newt_egg_death_rate
UNITS: newts/yr
Newt_Eggs_eaten_by_A_trout = Adolecent_trout*Newt_eggs*percent_of_Newt_Eggs_eaten_per_A_trout
UNITS: newts/yr
Newt_Eggs_eaten__by_A_bullfrogs = A_Bullfrogs*Newt_eggs*Percent_of_Newt_eggs_eaten_By_A_bullfrogs
UNITS: newts/yr
Tad_poles(t) = Tad_poles(t - dt) + (Hatching_bullfrog_eggs - Tadpole_deaths - Tadpoles_eaten_by_A_trout -
Maturing_bullfrog_tadpoles) * dt
INIT Tad_poles = 0
UNITS: frogs

INFLOWS:
Hatching_bullfrog_eggs = Bullfrog__eggs/Eggs_hatching_rate
UNITS: frogs/yr
OUTFLOWS:
Tadpole_deaths = Tad_poles*Tadpole_death__rate
UNITS: frogs/yr
Tadpoles_eaten_by_A_trout = Adolecent_trout*tadpoles_eaten_per_A_trout
UNITS: frogs/yr
Maturing_bullfrog_tadpoles = Tad_poles/Tadpole_mature_rate
UNITS: frogs/yr
Trout_eggs(t) = Trout_eggs(t - dt) + (Trout_Eggs_laid - Hatched_eggs - Trout_eggs__dying - Trout_eggs_eaten_by_A_bullfrogs) * dt
INIT Trout_eggs = 500
UNITS: trout
INFLOWS:
Trout_Eggs_laid = Mature_Trout*Eggs_per_trout
UNITS: trout/yr
OUTFLOWS:
Hatched_eggs = Trout_eggs/Trout_eggs_hatch_rate
UNITS: trout/yr
Trout_eggs__dying = Trout_eggs*Trout_Egg_death__rate
UNITS: trout/yr
Trout_eggs_eaten_by_A_bullfrogs = A_Bullfrogs*Trout_eggs*Percent_of_trout_eggs_eaten_by_A_bullfrogs
UNITS: trout/yr
Actual_A_newt__death_rate = normal_A_newt_death_rate*Effect_of_A_newt_population__on_death_rate
UNITS: yr
Actual_M_newt__death_rate = Normal_M_Newt__death_rate*Effect_of_population__on_death_rate
UNITS: yr
Actual_M_trout__death_rate = Trout_death_rate*Effect_of_population__on_death_rate_2
UNITS: yr
A_bulfrogs_as_heron_food = A_Bullfrogs*heron_food_per_A_bullfrog
UNITS: food
A_bullfrog_death_rate = .3
UNITS: 1/year
A_bullfrog_food = newt_eggs_as_bullfrog_food+Trout_eggs_as_bullfrog_food
UNITS: food
A_heron_death_rate = .1
UNITS: 1/year
DOCUMENT: was ommited for a ling time, when added this rate was made up, doesn't actually do much.

A_newt_as_bullfrog_food = Adolecent_newt*food_per_A_newt
UNITS: food
A_newt_population_capacity_2 = 10000
UNITS: newts
DOCUMENT: Reasonable extrapolation given the circumstances.

A_trout_as_heron_food = Adolecent_trout*heron_food_per_A_trout
UNITS: food
A_trout_death_rate = Normal_A_trout_death_rate/Effect_of_food_on_A_trout_death_rate
UNITS: 1/year
A_trout_eaten_per_M_Heron = Adolecent_trout*Percent_of_Trout_pop_eaten_by_M_herons
UNITS: trout/heron/year
A_trout_food = newt_eggs_as_A_trout_food+bullfrog_eggs_as_A_trout_food+tadpoles_as_A_trout_food
UNITS: food
Births_per_heron = Normal_Heron__Birth_rate*Effect_of_food_on_Heron_Birth_rate
UNITS: 1/year
bullfrog_eggs_as_A_trout_food = Bullfrog__eggs*food_per_Bullfrog_egg
UNITS: food
Bullfrog_eggs_death_rate = .5
UNITS: 1/year
DOCUMENT:
http://yosemite.epa.gov/r10/ECOCOMM.NSF/B724CA698F6054798825705700693650/52CF90301EF287AA88257416005F8108?O
penDocument

bullfrog_eggs_eaten_per_A_trout = Bullfrog__eggs*percent_of_Bullfrog_eggs_eaten_by_A_trout
UNITS: frogs/trout/year
Bullfrog_life_span = 8
UNITS: yr
DOCUMENT:
http://yosemite.epa.gov/r10/ECOCOMM.NSF/B724CA698F6054798825705700693650/52CF90301EF287AA88257416005F8108?O
penDocument

Bullfrog_mature_rate = 2

UNITS: yr
DOCUMENT:
http://yosemite.epa.gov/r10/ECOCOMM.NSF/B724CA698F6054798825705700693650/52CF90301EF287AA88257416005F8108?O
penDocument

Eggs_hatching_rate = .25
UNITS: yr
DOCUMENT:
http://yosemite.epa.gov/r10/ECOCOMM.NSF/B724CA698F6054798825705700693650/52CF90301EF287AA88257416005F8108?O
penDocument

eggs_laid_per_newt = 100
UNITS: 1/year
DOCUMENT:  http://www.californiaherps.com/salamanders/pages/p.stormi.html

Eggs_per_bullfrog = 5000
UNITS: 1/year
DOCUMENT:
http://yosemite.epa.gov/r10/ECOCOMM.NSF/B724CA698F6054798825705700693650/52CF90301EF287AA88257416005F8108?O
penDocument

Eggs_per_trout = 100
UNITS: 1/year
DOCUMENT:  http://www.naparcd.org/steelheadtrout.htm

food_in_newt_egg = 1
UNITS: food/newts
food_in_trout_egg = 1
UNITS: food/trout
food_per_A_bullfrog = A_bullfrog_food/(1+A_Bullfrogs)
UNITS: food/frogs
food_per_A_newt = .5
UNITS: food/newts
Food_per_A_trout = A_trout_food/(Adolecent_trout+1)
UNITS: food/trout
food_per_Bullfrog_egg = .01
UNITS: food/frogs
DOCUMENT:  same as the food per newt egg

food_per_M_bullfrog = M_bullfrog_food/(M_Bullfrogs+1)
UNITS: food/frogs
Food_per_M__Heron = Heron_food/Mature_Heron
UNITS: food/heron
food_per_newt_egg = .01
UNITS: food/newts
DOCUMENT:  was originally 1, but was reduced when the bullfrog segment was added

food_per_tadpole = .5
UNITS: food/frogs
DOCUMENT:  has been varied to make it realistic

food_per__M_newt = 1
UNITS: food/newts
Heron_death_rate = Normal_heron_Death_rate*Effect_of_food_on_Heron_death_rate
UNITS: yr
Heron_food = A_bulfrogs_as_heron_food+A_trout_as_heron_food+M_newt_as_heron_food+M_trout_as_heron_food
UNITS: food
heron_food_per_A_bullfrog = .5
UNITS: food/frogs
DOCUMENT:  has risen slightly from 1/3

heron_food_per_A_trout = .5
UNITS: food/trout
DOCUMENT:  made up, has been varied from .75 to .25 but is now back to its original value

heron_food_per_M_newt = 1/12
UNITS: food/newts
DOCUMENT:  Has varied from 1/3 down in order to control the newt population

heron_food_per_M_trout = 1
UNITS: food/trout
DOCUMENT:  made up, has always been 1 baseline "meal" for the herons

Heron_Mature_time = 2
UNITS: yr
DOCUMENT:  http://www.hww.ca/hww2.asp?id=43


M_bullfrog_food = A_newt_as_bullfrog_food+M_newt_as_bullfrog_food
UNITS: food
M_Newts_eaten_per__M_herons = Mature_Newt*Percent_of_Newt_population_eaten_per_M_Heron*Mature_Heron
UNITS: newts/yr
M_newt_as_bullfrog_food = Mature_Newt*food_per__M_newt
UNITS: food
M_newt_as_heron_food = Mature_Newt*heron_food_per_M_newt
UNITS: food
M_newt_population_capacity = 8000
UNITS: newts
DOCUMENT:  Reasonable extrapolation given the circumstances.


M_trout_as_heron_food = Mature_Trout*heron_food_per_M_trout
UNITS: food
M_Trout_eaten_by_M_Heron = Mature_Trout*Percent_of_Trout_pop_eaten_by_M_herons
UNITS: trout/heron/year
M_trout_population_capacity_2 = 200
UNITS: trout
DOCUMENT:  Reasonable extrapolation given the circumstances.


newt_eggs_as_A_trout_food = Newt_eggs*food_per_newt_egg
UNITS: food
newt_eggs_as_bullfrog_food = Newt_eggs*food_in_newt_egg
UNITS: food
Newt_egg_death_rate = .5
UNITS: 1/year
DOCUMENT:  http://www.californiaherps.com/salamanders/pages/p.stormi.html


Newt_hatch_rate = .15
UNITS: yr
DOCUMENT:  http://www.californiaherps.com/salamanders/pages/p.stormi.html


Newt_Mature_rate = 1.3
UNITS: yr
DOCUMENT:  http://www.californiaherps.com/salamanders/pages/p.stormi.html


normal_A_bullfrog_food = 20
UNITS: food/frogs
normal_A_newt_death_rate = 3
UNITS: yr
Normal_A_trout_death_rate = .5
UNITS: 1/year
DOCUMENT:  http://www.naparcd.org/steelheadtrout.htm


normal_food_per_heron = 120
UNITS: food/heron
DOCUMENT:  This has been varied, in order to reduce the heron population


normal_food_per_trout = 20
UNITS: food/trout
DOCUMENT:  hasnt changed much since it was first implemented


Normal_heron_Death_rate = 15
UNITS: yr
DOCUMENT:  http://www.hww.ca/hww2.asp?id=43


Normal_Heron__Birth_rate = .3
UNITS: 1/year
DOCUMENT:  http://www.hww.ca/hww2.asp?id=43


normal_M_bullfrog_food = 20
UNITS: food/frogs
Normal_M_Newt__death_rate = 9
UNITS: yr
DOCUMENT:  http://www.californiaherps.com/salamanders/pages/p.stormi.html


Percent_of_A_bullfrogs_eaten_by_A_heron = .15

UNITS: 1/heron/year
Percent_of_A_Bullfrog_population_eaten_per_M_Heron = .1
UNITS: 1/heron/year
Percent_of_A_newts_eaten_by_A_herons = .15
UNITS: 1/heron/year
DOCUMENT:  Reasonable extrapolation given the circumstances.

Percent_of_A_newt_population_eaten_by_M_bullfrogs = .05
UNITS: 1/frogs/year
DOCUMENT:  Reasonable extrapolation given the circumstances.

Percent_of_A_trout_Eaten_per_A_herons = .05
UNITS: 1/heron/year
DOCUMENT:  considering there is only ever 1 adolescent heron in the final stage of this model, this doesnt really affect much.

percent_of_Bullfrog_eggs_eaten_by_A_trout = .1
UNITS: 1/trout/year
DOCUMENT:  Reasonable extrapolation given the circumstances.

Percent_of_M_newt_population_eaten_by_M_bullfrogs = .05
UNITS: 1/frogs/year
DOCUMENT:  Reasonable extrapolation given the circumstances.

Percent_of_Newt_eggs_eaten_By_A_bullfrogs = .05
UNITS: 1/frogs/year
DOCUMENT:  Reasonable extrapolation given the circumstances.

percent_of_Newt_Eggs_eaten_per_A_trout = .05
UNITS: 1/trout/year
DOCUMENT:  Reasonable extrapolation given the circumstances.

Percent_of_Newt_population_eaten_per_M_Heron = .15
UNITS: 1/heron/year
DOCUMENT:  Reasonable extrapolation given the circumstances.

Percent_of_Tadpoles_eaten_by__A_trout = .07
UNITS: 1/trout/year
Percent_of_trout_eggs_eaten_by_A_bullfrogs = .2
UNITS: 1/frogs/year
DOCUMENT:  made up, has been fairly constant.

Percent_of_Trout_pop_eaten_by_M_herons = .02
UNITS: 1/heron/year
DOCUMENT:  Reasonable extrapolation given the circumstances.

Population_ratio = Mature_Newt/M_newt_population_capacity
UNITS: Unitless
Population_ratio_2 = Adolecent_newt/A_newt_population_capacity_2
UNITS: Unitless
Population_ratio_3 = Mature_Trout/M_trout_population_capacity_2
tadpoles_as_A_trout_food = Tad_poles*food_per_tadpole
UNITS: food
tadpoles_eaten_per_A_trout = Tad_poles*Percent_of_Tadpoles_eaten_by__A_trout
UNITS: frogs/trout/year
Tadpole_death__rate = .4
UNITS: 1/year
DOCUMENT:
http://yosemite.epa.gov/r10/ECOCOMM.NSF/B724CA698F6054798825705700693650/52CF90301EF287AA88257416005F8108?O
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Tadpole_mature_rate = 1
UNITS: yr
DOCUMENT:
http://yosemite.epa.gov/r10/ECOCOMM.NSF/B724CA698F6054798825705700693650/52CF90301EF287AA88257416005F8108?O
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Trout_death_rate = 4
UNITS: yr
DOCUMENT:  http://www.naparcd.org/steelheadtrout.htm

Trout_eggs_as_bullfrog_food = Trout_eggs*food_in_trout_egg
UNITS: food

Trout_eggs_hatch_rate = .042
UNITS: yr
DOCUMENT:  http://www.naparcd.org/steelheadtrout.htm

but has been slightly modified

Trout_Egg_death__rate = .25
UNITS: 1/year
DOCUMENT:  Made up, should probably be closer to .5 or even .75 to be more realistic.

Trout_Mature_rate = 3
UNITS: yr
DOCUMENT:  http://www.naparcd.org/steelheadtrout.htm

Effect_of_A_newt_population__on_death_rate = GRAPH(Population_ratio_2)
(0.00, 0.99), (0.1, 0.99), (0.2, 0.975), (0.3, 0.94), (0.4, 0.84), (0.5, 0.485), (0.6, 0.235), (0.7, 0.13), (0.8, 0.045), (0.9, 0.005), (1, 0.005)
UNITS: Unitless
effect_of_food_on_A_bullfrog_death_rate = GRAPH(food_per_A_bullfrog/normal_A_bullfrog_food)
(0.00, 0.00), (0.1, 0.08), (0.2, 0.365), (0.3, 0.54), (0.4, 0.69), (0.5, 0.805), (0.6, 0.895), (0.7, 0.94), (0.8, 0.98), (0.9, 0.995), (1, 1.00)
UNITS: Unitless
Effect_of_food_on_A_trout_death_rate = GRAPH(Food_per_A_trout/normal_food_per_trout)
(0.00, 0.01), (0.1, 0.02), (0.2, 0.15), (0.3, 0.355), (0.4, 0.6), (0.5, 0.76), (0.6, 0.875), (0.7, 0.945), (0.8, 0.97), (0.9, 0.985), (1, 1.00)
UNITS: Unitless
Effect_of_food_on_Heron_Birth_rate = GRAPH(Food_per_M__Heron/normal_food_per_heron)
(0.00, 0.00), (0.1, 0.02), (0.2, 0.035), (0.3, 0.07), (0.4, 0.125), (0.5, 0.21), (0.6, 0.385), (0.7, 0.69), (0.8, 0.9), (0.9, 1.00), (1, 1.00)
UNITS: Unitless
Effect_of_food_on_Heron_death_rate = GRAPH(Food_per_M__Heron)
(0.00, 0.003), (2.00, 0.015), (4.00, 0.05), (6.00, 0.095), (8.00, 0.14), (10.0, 0.225), (12.0, 0.375), (14.0, 0.565), (16.0, 0.855), (18.0, 0.96), (20.0, 0.995)
UNITS: Unitless
effect_of_food_on_M_bullfrog_death_rate = GRAPH(food_per_M_bullfrog/normal_M_bullfrog_food)
(0.00, 0.00), (0.1, 0.06), (0.2, 0.295), (0.3, 0.495), (0.4, 0.645), (0.5, 0.755), (0.6, 0.845), (0.7, 0.92), (0.8, 0.965), (0.9, 0.99), (1, 1.00)
UNITS: Unitless
Effect_of_population__on_death_rate = GRAPH(Population_ratio)
(0.00, 1.00), (0.1, 0.995), (0.2, 0.985), (0.3, 0.93), (0.4, 0.865), (0.5, 0.75), (0.6, 0.435), (0.7, 0.22), (0.8, 0.1), (0.9, 0.015), (1, 0.001)
UNITS: Unitless
Effect_of_population__on_death_rate_2 = GRAPH(Population_ratio_3)
(0.00, 1.00), (0.1, 0.995), (0.2, 0.985), (0.3, 0.93), (0.4, 0.865), (0.5, 0.75), (0.6, 0.435), (0.7, 0.22), (0.8, 0.1), (0.9, 0.015), (1, 0.001)
UNITS: Unitless