COMPUTER METHODS AND MODELING IN GEOLOGY
LAKE LEVEL CHANGES IN THE ARID WEST

The parts of this exercise for students are in normal text, whereas answers and explanations for faculty are italicized.

Closed-basin lakes in the western United States have been termed "nature's rain gauges" because they respond to changes in precipitation by changing their levels. Many basins in the arid West today contain small lakes, but also contain shoreline deposits that indicate these lakes were once much larger. Basin center deposits combined with shoreline materials indicate that lakes oscillated in size during the late Pleistocene. The causes of these oscillations are not yet entirely understood, though many believe that lakes expanded because the jet stream was forced southward by the large Laurentide ice sheet. The jet stream (today found at the latitude of Washington and Oregon) is the locus of storm activity, and computer models of late Pleistocene climate suggest that it split around the ice sheet, with its southern track ending up in Nevada and eastern California.

In today's lab we'll explore the impact of changes in climate on the level of lakes in the Owens River system. These lakes, which were separated by bedrock sills and which were fed by runoff from the eastern flank of the Sierra Nevada mountains in California, were headed by Owens Lake. When Owens Lake filled to its maximum level, it overflowed into the China Lake Basin, which in turn overflowed into Searles Lake. During particularly wet periods in the geologic past Searles overflowed into Panamint Lake, which ultimately overflowed into Manly Lake in Death Valley. In our modeling effort today we'll see what combinations of runoff and evaporation might have led to Pleistocene lake level oscillations.

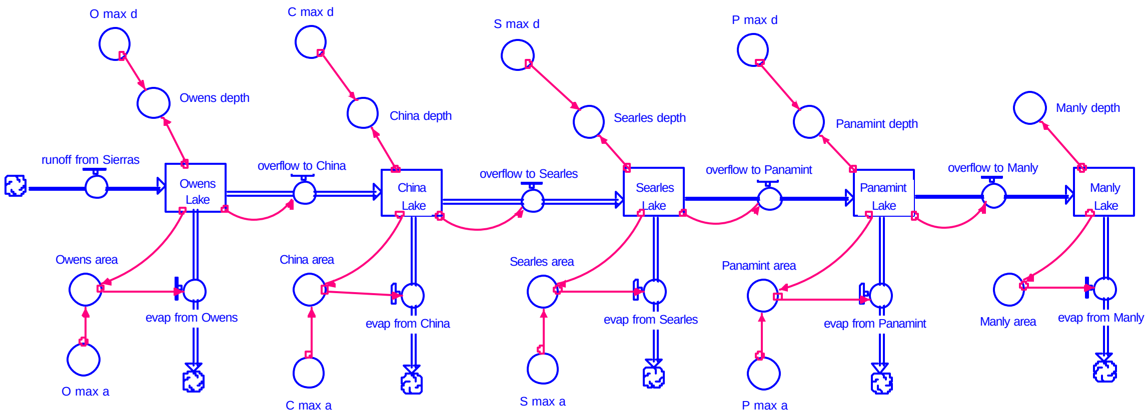
Readings

Menking, K.M., and Anderson, R.S., unpublished, A Model of Runoff, Evaporation, and Overspill in the Owens River System of Lakes, Eastern California.

Exercises

1) Create a model of the entire chain of lakes. Note that the evaporative outflow from each lake depends on the surface area of the lake. This requires that we incorporate into our model a relationship between lake volume and area for each lake in the chain.

Owens River chain of lakes STELLA model



STELLA code - provided in the event that you are using an older version of STELLA than that we're using or if you have problems downloading and opening the model

*China_volume(t) = China_volume(t - dt) + (overflow_to_China - evap_from_China - overflow_to_Searles) * dt*
INIT China_volume = 0

INFLOWS:
overflow_to_China = if(Owens_volume>25.e9)then(Owens_volume-25.e9)else(0.0)
OUTFLOWS:
*evap_from_China = 1.41*China_area*
overflow_to_Searles = if(China_volume>1.2e9)then(China_volume-1.2e9)else(0.0)
*Manly_volume(t) = Manly_volume(t - dt) + (overflow_to_Manly - evap_from_Manly) * dt*
INIT Manly_volume = 0

INFLOWS:
overflow_to_Manly = if(Panamint_volume>117.e9)then(Panamint_volume-117.e9)else(0.0)
OUTFLOWS:
*evap_from_Manly = 1.97*Manly_area*
*Owens_volume(t) = Owens_volume(t - dt) + (runoff_from_Sierras - evap_from_Owens - overflow_to_China) * dt*
INIT Owens_volume = 0

INFLOWS:
*runoff_from_Sierras = 1*3.98e8*
OUTFLOWS:
*evap_from_Owens = 1.34*Owens_area*
overflow_to_China = if(Owens_volume>25.e9)then(Owens_volume-25.e9)else(0.0)
*Panamint_volume(t) = Panamint_volume(t - dt) + (overflow_to_Panamint - evap_from_Panamint - overflow_to_Manly) * dt*
INIT Panamint_volume = 0

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INFLOWS:
overflow_to_Panamint = if(Searles_volume>76.0e9)then(Searles_volume -76.0e9)else(0.0)
OUTFLOWS:
evap_from_Panamint = 1.65*Panamint_area
overflow_to_Manly = if(Panamint_volume>117.e9)then(Panamint_volume -117.e9)else(0.0)
Searles_volume(t) = Searles_volume(t - dt) + (overflow_to_Searles - evap_from_Searles - overflow_to_Panamint) * dt
INIT Searles_volume = 0.

INFLOWS:
overflow_to_Searles = if(China_volume>1.2e9)then(China_volume-1.2e9)else(0.0)
OUTFLOWS:
evap_from_Searles = 1.65*Searles_area
overflow_to_Panamint = if(Searles_volume>76.0e9)then(Searles_volume -76.0e9)else(0.0)
China_area = if(China_volume<=0.)then(0.)else if(China_volume>=1.2e9)then(C_max_a)else(1.238e8+(0.047279*China_volume) -(1.4788e-12*(China_volume^2)))
China_depth = if(China_volume<=0.)then(0.)else if(China_volume>=1.2e9)then(C_max_d)else(0.98637+(5.9886e-9*China_volume)-(3.7316e-19*(China_volume^2))+(1.2192e-29*(China_volume^3)))
C_max_a = 1.886548e8
C_max_d = 7.7
Manly_area = if(Manly_volume<0.)or(Manly_volume=0.)then(0.)else(2.1382e8+(0.023849*Manly_volume) -(1.9685e-13*(Manly_volume^2))+(6.5806e-25*(Manly_volume^3)))
Manly_depth = if(Manly_volume=0.)then(0.)else(14.782+(2.1584e-9*Manly_volume) -(1.3675e-20*(Manly_volume^2))+(4.2019e-32*(Manly_volume^3)))
Owens_area = if(Owens_volume<=0.)then(0.)else if(Owens_volume>=25.e9)then(O_max_a)else(75991.*(Owens_volume^0.37636))
Owens_depth = if(Owens_volume<=0.)then(0.)else if(Owens_volume>=25.e9)then(O_max_d)else(3.5837+(4.009e-9*Owens_volume) -(9.5021e-20*(Owens_volume^2))+(1.2319e-30*(Owens_volume^3)))
O_max_a = 5.665292e8
O_max_d = 63.7
Panamint_area = if(Panamint_volume<=0.)then(0.)else if(Panamint_volume>=117.e9)then(P_max_a)else(1.1632e8+(0.0085949*Panamint_volume) -(2.4725e-14*(Panamint_volume^2)))
Panamint_depth = if(Panamint_volume<=0.)then(0.)else if(Panamint_volume>=117.0e9)then(P_max_d)else(11.93+(5.4291e-9*Panamint_volume) -(4.6059e-20*(Panamint_volume^2))+(1.7191e-31*(Panamint_volume^3)))
P_max_a = 7.839459E+08
P_max_d = 292.0
Searles_area = if(Searles_volume<=0.)then(0.)else if(Searles_volume>=7.6e10)then(S_max_a)else(1.691e8+(0.008888*Searles_volume)-(3.4502e-14*(Searles_volume^2)))
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Searles_depth = if(Searles_volume<=0.)then(0.)else if(Searles_volume>=76.0e9)then(S_max_d)else(6.3665+(4.5202e-9*Searles_volume)-(4.2614e-20*(Searles_volume^2))+(2.1146e-31*(Searles_volume^3)))
S_max_a = 6.460949E+08
S_max_d = 196.6

In the Classes>Geo365 folder on your computer you'll find a file called "hypsometry_data.txt" that contains area/volume/depth relationships for each lake in the chain. Create a scatter graph of area as a function of volume for Owens Lake and then apply a curve fit to this graph to determine the function that relates these two variables. Use this relationship in your model. Note that your relationship will not be linear, but instead a polynomial or power of some sort. Try to get the best possible curve fit between the two variables.

2) Repeat step 1 for the other 5 lakes in the chain.

The data are available here on the Vassar blackboard site in the file called "hypsometry_data.txt." Each student will likely use a different hypsometry equation, so you need to have some tolerance for variability in model outputs from student to student.

Many students will go crazy and try to use polynomials of degree 5 or higher. In general, most of the area/volume/depth relationships work fine with polynomials of order 2-3.

Since each lake, except Manly, has a spillway, the maximum surface area that each lake can attain is limited. This limitation must be expressed in the area converter that is fed by the lake volume reservoir. For example, for Owens lake, the following expression is used:

Owens_area=
if(Owens_volume<=0.)then(0.)else
if(Owens_volume>=25.e9)then(O_max_a)else(75991.*(Owens_volume^0.37636))

This expression sets the area to be zero when the lake contains no water, sets the area to the maximum possible when the lake has reached its maximum volume (O_max_a) at overspill, and otherwise calculates the area based on the volume.

Each lake area converter needs a similar expression.

3) Next, what do you need to do to allow the lakes to overflow when they fill up with water? Write the equation for overflow that you're using for Owens Lake and apply the same logic to the other lakes in the chain.

You need to put in an if-then statement that compares the volume in each lake to the maximum volume the lake is capable of holding, and that will overflow the excess to the next lake in the chain if the volume exceeds the maximum volume. For example:

overflow_to_china=
if(Owens_volume>25.e9)then(Owens_volume-25.e9)else(0.0)

If Owens Lake's volume exceeds 25.10^9 m^3, the excess (Owens_volume-25.e9) is allowed to flow to the China lake. Otherwise, there is no outflow.*

4) Use the data in the "hypsometry" kaleidagraph file to determine the relationship between depth and volume for each lake.

Just as with the lake area converter, the lake depth converter requires a statement to limit the depth of the lake to its maximum depth at spillover. For example, for Owens lake, the following statement is used:

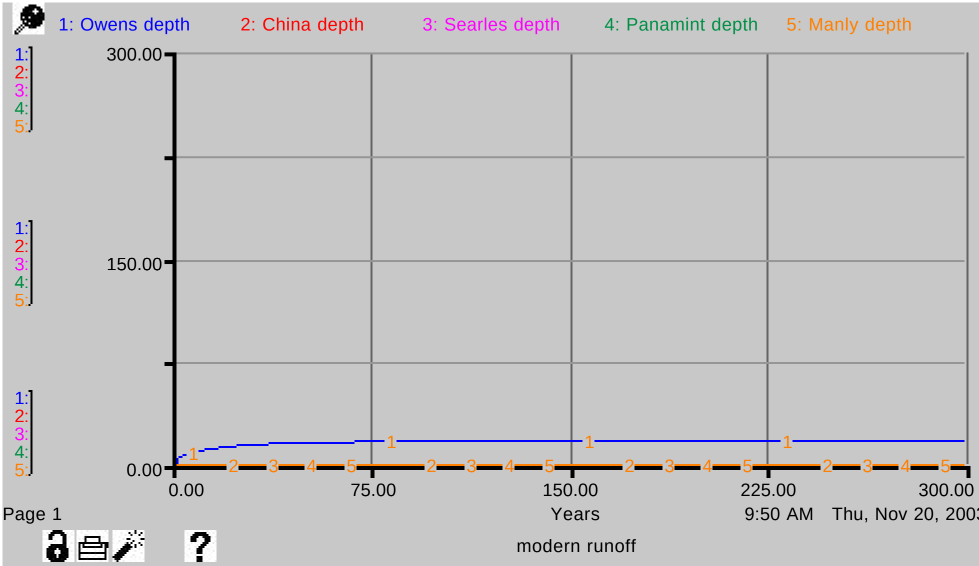
Owens_depth=
if(Owens_volume<=0.)then(0.)else
*if(Owens_volume>=25.e9)then(O_max_d)else(3.5837+(4.009e-9*Owens_volume)-(9.5021e-20*(Owens_volume^2))+(1.2319e-30*(Owens_volume^3)))*

This statement sets the depth to zero when the lake contains no water, constrains the depth to the depth at spillover when the lake is at its maximum volume, and calculates intermediate depths from the polynomial function of the volume.

5) Fill in your remaining initial conditions – initial lake volumes = 0, and evaporation and runoff rates as specified in your reading for the modern climate.

6) Run your model for about 200 years and **describe and explain** the resulting behavior of the lake level curves (depth). What size lakes do you get? Why does the depth of Owens Lake eventually reach steady state?

DT = 1/16 year



Under modern climatic conditions, the only lake to contain water is Owens Lake. It reaches a steady state depth of ~16-17 m.

Owens Lake reaches steady state once the water coming in is balanced by the water going out via evaporation. This balance is achieved as soon as the lake has grown to a sufficiently large surface area that the area multiplied by the evaporation rate equals the amount of runoff entering the lake.

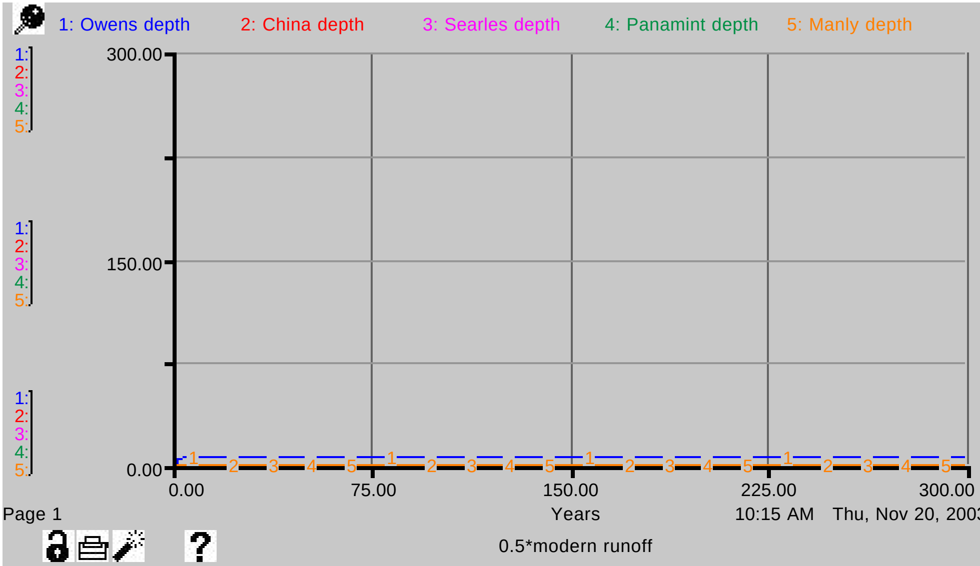
7) How long does it take for Owens Lake to reach 95% of its steady state depth? Note: I'm asking for 95% of steady state because the lake approaches steady state asymptotically, so it is difficult to determine when it has reached complete steady state. For all future questions regarding time required to reach steady state you may also look at the 95% value.

About 53 years.

8) Experiment with changing the amount of runoff into the lake. Double, triple, and halve the runoff. What impact does runoff amount have on the time required for Owens lake to reach steady state?

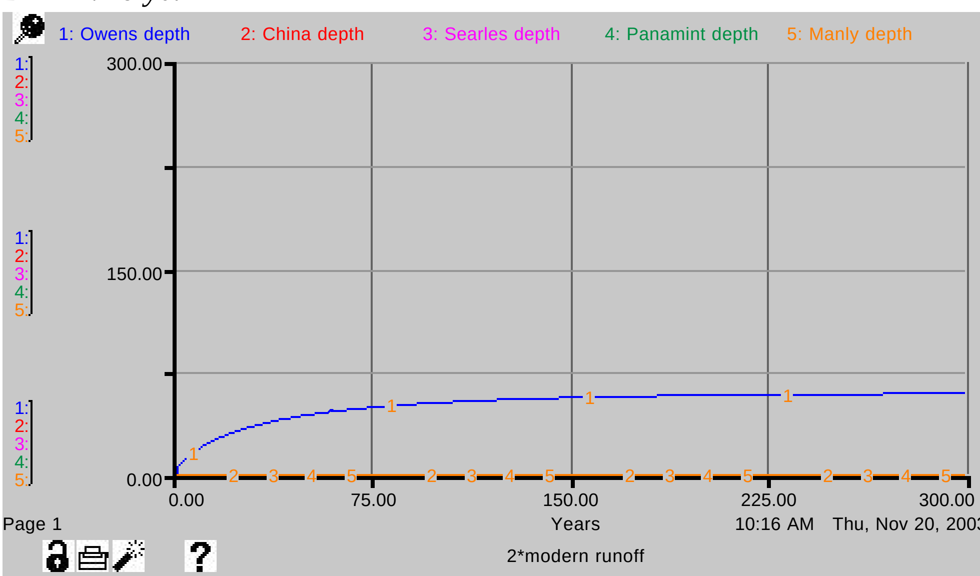
With a halving of runoff, it takes ~12 years to reach a steady state depth of 5.8 m.

DT = 1/16 year



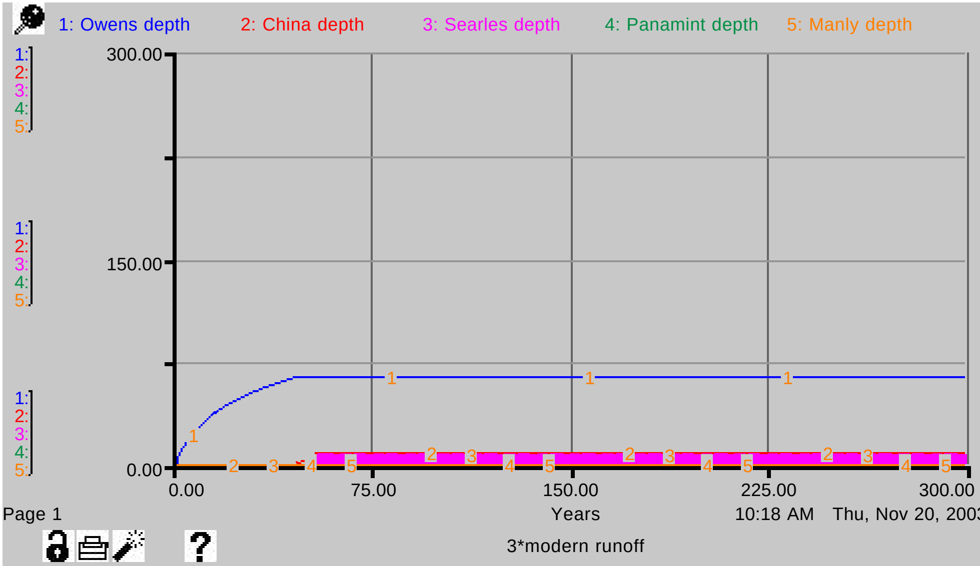
With a doubling of runoff, it takes the lake ~150 years to reach steady state depth of 58 m.

DT = 1/16 year



With a tripling of runoff, it takes ~44 years to reach steady state, but this number is misleading. In fact, the lake is now overflowing to China lake, which in turn is overflowing into Searles lake. For this reason, it would be more appropriate to look at the response of all 3 lakes.

DT = 1/16 year

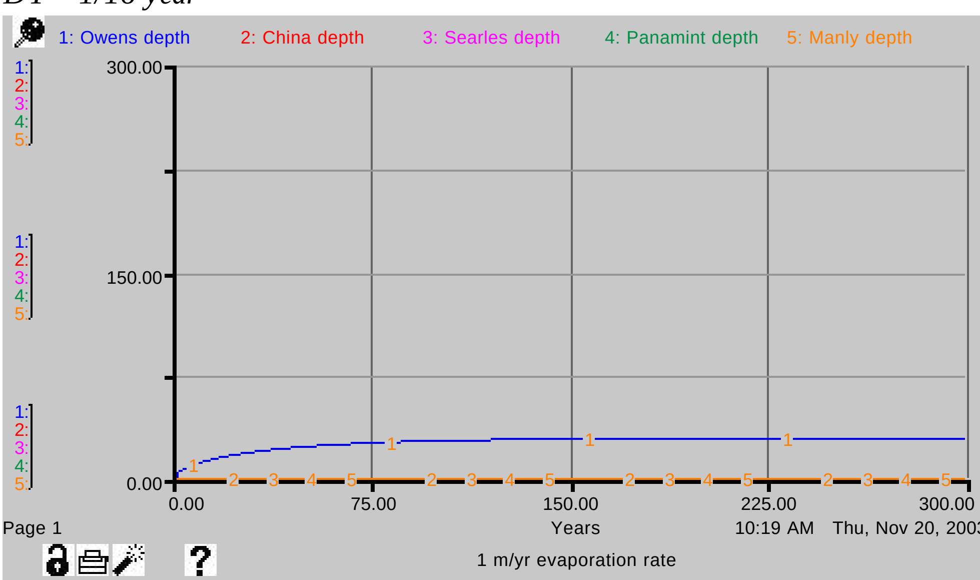


In general, however, as long as the lake is not overflowing, an increase in runoff leads to an increase in the amount of time required to reach steady state.

9) Change your runoff back to the modern value and then experiment with changing evaporation rates. What impact does evaporation rate have on the time required to reach steady state?

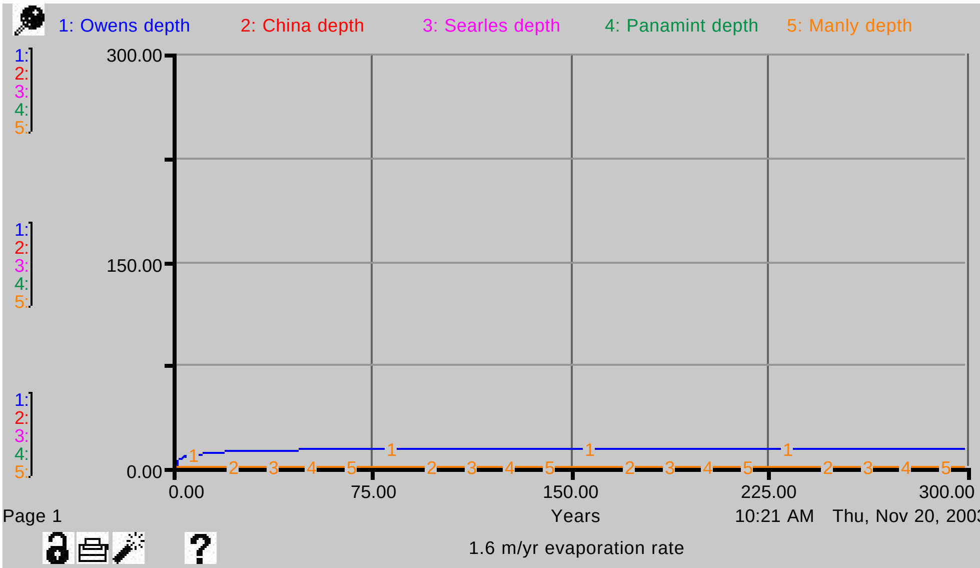
Dropping Owens Lake's evaporation rate to 1.0 m/yr from 1.34 m/yr results in a time to reach steady state of ~115 years and a depth of 29 m.

DT = 1/16 year



Increasing the evaporation rate to 1.6 m/yr, drops the time to reach steady state to ~25 years and the depth to ~12 m.

DT = 1/16 year



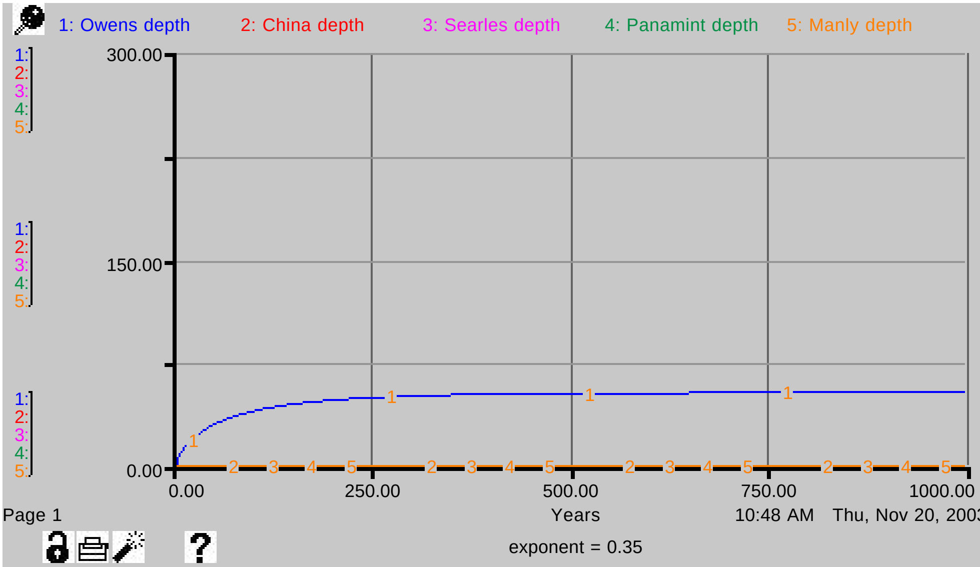
In general, an increase in evaporation rate decreases the time required to get to steady state. Another way to think about this is that increasing the evaporation rate allows the evaporative outflow to balance the inflow more quickly.

10) Change your evaporation rate back to the modern value. Let's mess around with changing the area/volume relationship for Owens Lake to see what impact lake hypsometry (basin shape) has on the response time for the lake (response time = time required to reach steady state).

Change your exponent in the area/volume equation to values higher and lower than the value you got for Owens Lake. What happens to the response time as you change the exponent? Why?

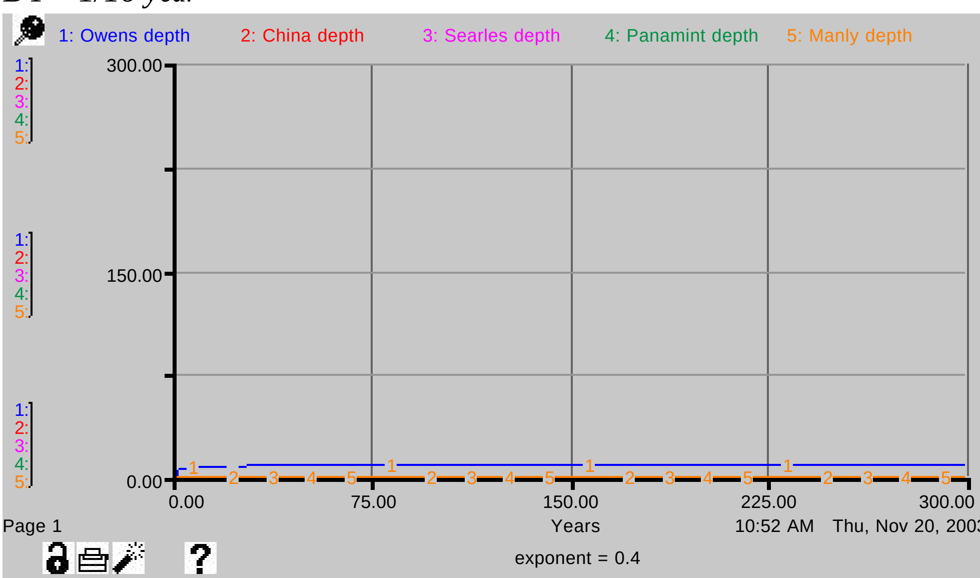
The response time is extremely sensitive to changes in the area/volume relationship. Dropping the exponent on the area/volume equation to 0.35 from 0.37636 results in a 52 m deep lake (as opposed to 16-17 m) that reaches 95% of its steady state volume after ~280 years.

DT = 1/16 year



Raising the value of the exponent to 0.4, results in a lake only 7.3 m deep that reaches 95% of its steady state volume in 11.5 years.

DT = 1/16 year



The explanation for this behavior lies in an understanding of what the exponent means in the overall lake geometry. A lake with a high value for the exponent has a flat, pan shape. As volume increases, surface area increases markedly. On the other hand, a lake with a *low value for the exponent has a narrow, cone shape. As volume increases, surface area changes little.*

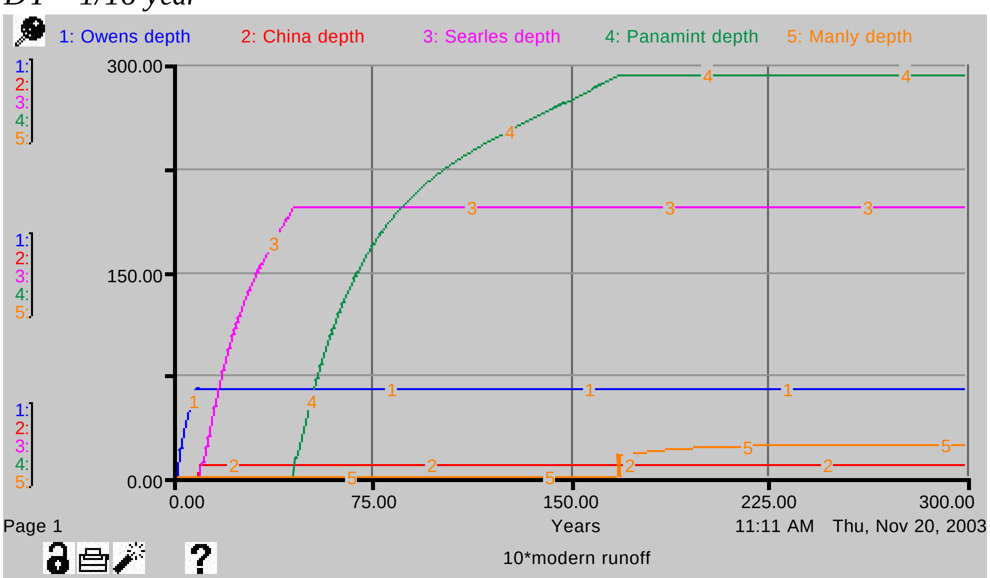
Because of the high surface area to volume ratio, evaporation from the flat pan-shaped lake quickly balances inflow, allowing the lake to reach a steady state rapidly. In contrast, evaporation from the narrow, cone-shaped lake doesn't change much as runoff fills the lake, and a long time is required before the evaporative outflow balances the inflow.

Students who use exponents lower than 0.35 will find that they get a turn around in the response time. In other words, the lower the exponent, the faster the lake appears to reach steady state. You should point out to them, however, that this apparent steady state results solely from the fact that the lake is overflowing, and that to really gauge how long it takes for the lake system to come to steady state, they must include the lakes downstream.

11) Set your exponent back to its original value. Now determine how much you need to increase runoff by in order to get water to flow all the way to Lake Manly given modern evaporation rates.

A minimum of 9 modern runoff is required to get water to Manly given the model I've included in this website. At this level of runoff, the water that flows into Manly is completely evaporated in every timestep, leading to oscillatory behavior. A value of 10* modern runoff leads to an ~23 m deep lake at the end of the run.*

DT = 1/16 year



12) We know that glacial period evaporation rates were significantly depressed relative to modern because of the colder average surface temperature of Earth. Incorporate a 30% reduction in evaporation rate to all of the lakes and again determine how much water is required to get water to spill into Lake Manly.

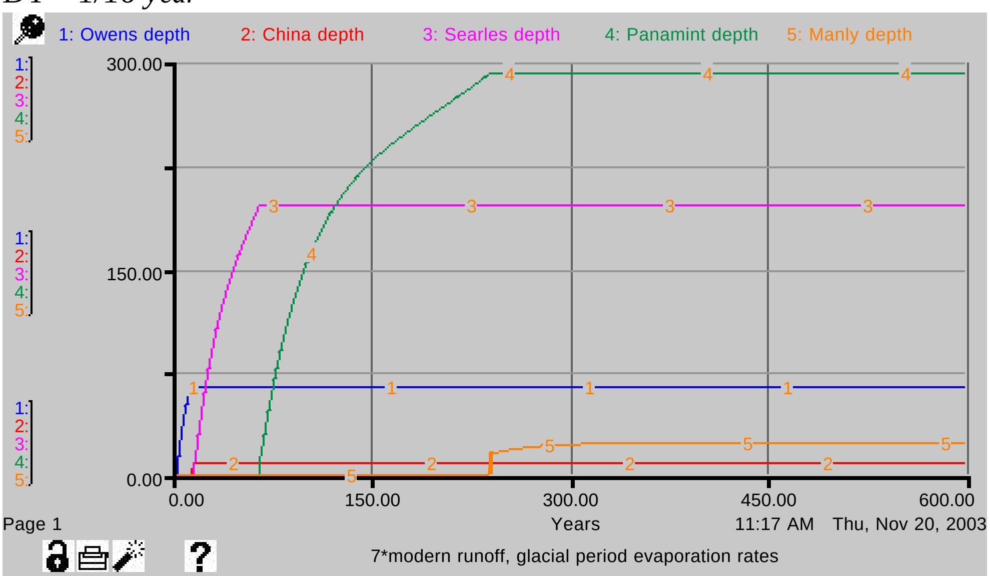
To carry out this experiment, multiply the evaporation outflow for each lake by 0.7. For example, for Owens Lake:

evap_from_Owens=
*1.34*0.7*Owens_area*

where 1.34 is the modern evaporation rate.

Doing this for all of the lakes in the chain reduces the amount of runoff necessary to get overflow to Manly to about 7 times modern:

DT = 1/16 year



13) How long does it take the lake chain to reach a steady state under this glacial scenario?

Manly stabilizes at a depth of ~23 m in ~300 years. At this point, the whole chain is in steady state.

14) Given the response times you have determined in 12 and 13, comment on the ability of the lake chain to record climatic changes (such as long droughts or exceptionally wet periods) that occur on the timescale of decades.

Since it takes the lake chain on the order of hundreds of years to respond to a change in climate, it is unlikely that it would be able to record changes that occur on the timescale of decades. The lake chain would still be responding to the last change when it was forced to respond to the new change. These short climatic events would therefore either not be recorded or only partially recorded.

15) Would the lakes be able to record climatic changes that occur on the timescale of thousands of years?

Since the response time is on the order of hundreds of years, the lake chain should be able to faithfully record climatic changes occurring on longer timescales.

16) Using your modern evaporation rates, let's put your answers to 14 and 15 to the test. Create an equation that will allow the runoff to vary between modern and 10x modern values with a period of 100 years. What is your equation?

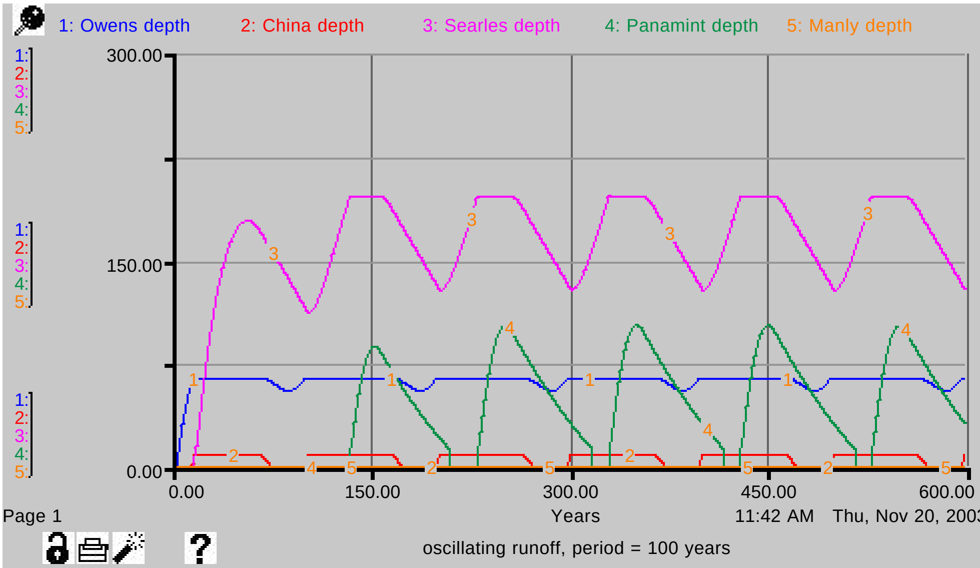
runoff_from_sierras =
*5.5*3.98e8+4.5*(3.98e8*sin(2*pi*time/100))*

*When the sin has a value of -1, the runoff will be 1*modern where modern = 3.98e8. When the sin has a value of +1, the runoff will be 10*modern.*

17) Run the model for several hundred years and show the behavior of the lakes. Is the chain in steady state? How do you know?

With a period of 100 years, the lake chain is never in steady state. This can be determined by examining the behavior of Owens Lake carefully. The climate passes through modern conditions every 100 years, yet Owens Lake never achieves its modern depth of 16.5 m at these times. The lake level drops, but doesn't fall below about 55 m. The climate is changing so rapidly that the lake chain doesn't have a chance to fall to its modern levels before it has to respond to a wetter climate:

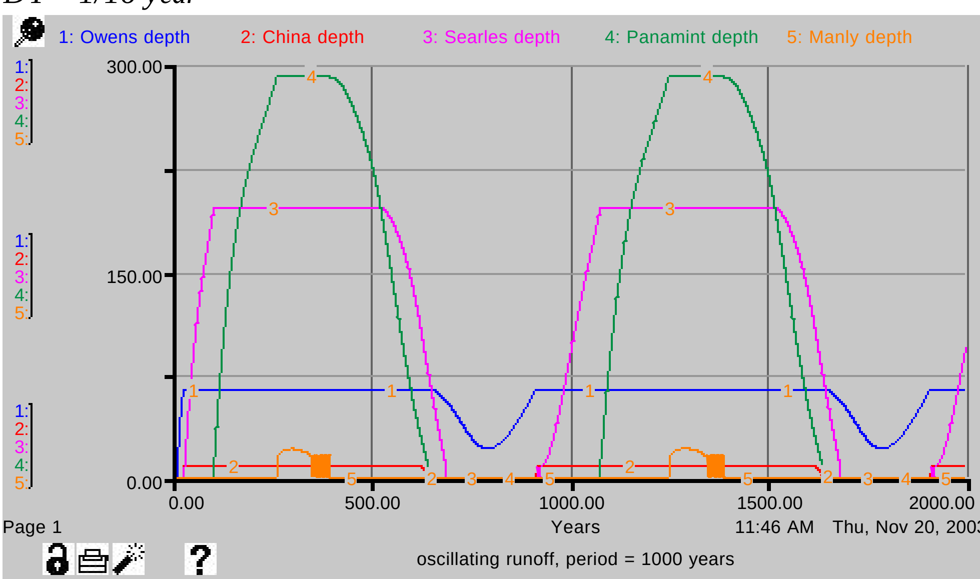
DT = 1/16 year



18) Now change the period to 1000 years and run the model for a few thousand years. Is the chain in steady state now?

The chain is much closer to being in steady state. This time, Owens Lake drops to ~20 m during episodes of modern climate (as compared to ~16.5 m in the steady state case for modern climate), suggesting the chain is responding at close to steady state.

DT = 1/16 year



The following plot was created using a period of 2500 years and a timestep of 1/4 year. In this scenario, Owens Lake comes down to its modern steady state value of ~16.5 m during modern climate.

DT = 1/4 year