COMPUTER METHODS AND MODELING IN GEOLOGY
THE GLOBAL PHOSPHORUS CYCLE

Phosphorous (P) is an essential nutrient for life. It is found in the RNA and DNA of all organisms, as well as in the adenosine triphosphate molecule (ATP) that allows cells to carry out metabolic processes. In vertebrates, P is an important component of bones and teeth. P is found in every part of the Earth system, but in vastly different amounts. Most P on Earth is found in the +5 valence state (able to accept 5 electrons) as PO_4^{3-}, commonly known as phosphate. Phosphate is found dissolved in water, found as the mineral apatite (nearly 95% of P in minerals is found in apatite) in soils, rocks, teeth, and bones, and found as mineral dust in the atmosphere.

P is unusual among many of the elements necessary for life in that it does not have a naturally occurring gaseous form of any significance. For this reason, the cycling of P throughout the Earth system is dependent on slow-acting geologic processes such as weathering of rocks, transport of sediments in streams, decay of terrestrial plants, and upwelling of ocean water. Because these processes occur slowly, P is considered a limiting nutrient. To understand what this means, consider the following: Organisms have a tendency toward exponential growth given infinite resources. However, since P is only made available to organisms a little at a time, it acts as a brake on this exponential growth. You might be interested to know that the tremendous increase in the human population that has occurred in the last century is a by-product primarily of the use of phosphate fertilizers on crops. More phosphate for crops means bigger harvests, and bigger harvests allow the human population to grow. The fertilizer phosphate has been mined from natural accumulations of phosphorous rich sediments deposited in the oceans and on land (bat guano and bird guano are the terrestrial sources). At present rates of consumption, we have enough minable phosphate to last us about another 400 years. What do you think might happen to the future population of the Earth when all of the minable phosphate has been exhausted?

Today we will create a STELLA model of the global phosphorous cycle and use it to test a number of scenarios. As we use the model, consider how you might be able to extend it to examine the influence of the P cycle on various ecologic systems. I want you to answer all of the questions below. Open up Microsoft Word at the same time that you have STELLA running. You can write the answers to your questions as you go along. You can also paste directly into your Word document any graphs you would like to use to answer your questions.

Readings

Chameides, W.L., and Perdue, E.M., 1997, Biogeochemical Cycles: A Computer-Interactive Study of Earth System Science and Global Change, New York: Oxford University Press, p. 97-107 (Chp. 5, The Global Phosphorous Cycle).

Jahnke, R.A., 1992, The Phosphorus Cycle, in Butcher, S.S., Charlson, R.J., Orians, G.H., and Wolfe, G.V. (eds.), Global Biogeochemical Cycles, New York: Academic Press, p. 301-315.

Lerman, A., Mackenzie, F.T., and Garrels, R.M., 1975, Modeling of Geochemical Cycles: Phosphorus as an Example, Geological Society of America Memoir 142, p. 205-218.

Exercises

1) Using the Chameides and Perdue (1997) figure 5.5 on pg. 103, create a STELLA model of the global phosphorus cycle. For the moment, ignore the minable P part of the sediments reservoir.

As you set up your model think about the fluxes between the reservoirs. Is this a closed system or open system model? How should the fluxes be specified?

2) Once your model is created, run it and keep track of the sizes of all of the reservoirs over time. Use a simulation period of 10 years and a timestep of 0.25. Describe what you see.

The model is supposed to show steady state behavior. Does it? Explain how you know.

If it doesn't, try to explain why it's not in steady state and modify your model until you get it to reach steady state.

3) Now we'll explore an anthropogenic change to the system. Let's see what happens if we take all of the minable phosphorous in the world and apply it as fertilizer to the land surface.

a) Which reservoir do we change, and by how much?

b) Run the model again and both **describe and explain** what you see. You may want to use a longer simulation time (try 100 years).

4) In the 1950s to 1970s people began to realize that over-application of fertilizer and use of phosphate-containing detergents was leading to serious declines in the health of aquatic ecosystems. The influx of P caused algal blooms in lakes

and along coasts. As the algae died, they fell through the water column and decayed, a process that consumed dissolved oxygen in the water as carbon compounds were oxidized to CO_2. The loss of dissolved oxygen prompted fish kills and the death of other aquatic animals that use gills to breathe.

Sketch out a STELLA model that you could add to your existing model that would simulate this process (called eutrophication). I don't expect you to come up with numbers. Just show me the fluxes and reservoirs you would have to consider to model this problem. One of you may want to use this as your independent research project later in the semester!

5) Set the reservoirs back to their initial values in problem 1. We will now explore a possible impact of a climatic change on the P cycle. Today, ocean circulation is considered akin to a huge conveyor belt. Warm water near the equator in the Atlantic flows northward toward Scandinavia. As it flows, evaporation causes it to become more saline, and heat exchange with the atmosphere causes it to cool off. Both of these processes cause the water to increase in density, and once it reaches the North Atlantic, the water sinks, flowing back across the bottom of the ocean as North Atlantic Deep Water. During the Last Glacial Maximum, about 20,000 years ago, this thermohaline circulation, as it is called, is thought to have either stopped or slowed down significantly. The probable cause: melting of ice from the large continental ice sheets around the North Atlantic decreased the salinity of the water, making it less dense and causing the sinking rate to decline or go to zero. Since water no longer was sinking in the N. Atlantic, the entire conveyor belt circulation shut down, depriving northern Europe of an important source of heat (see Bradley, R.S., 1999, Paleoclimatology: Reconstructing Climates of the Quaternary, 2nd edition, New York, Academic Press, p. 260-275 for a nice summary of this problem). This hypothesis has not been fully proven yet, but ocean circulation models suggest that this mechanism could have worked.

Let's see what kind of impact we might expect on the P cycle, were the ocean to no longer circulate.

a) What do we need to change about the model?

b) Once you've made your change, run the model for a 1000-year period. What happens to the different reservoirs over time? **Describe and explain** what you see.

c) Which reservoirs adjust most dramatically and why? To answer this, pay attention to the scale of each variable on your graph.

d) Which reservoirs adjust most gradually and why?

e) Why does the deep ocean reservoir first increase in size and then very gradually begin to decrease? Would you have predicted this behavior?

6) Next we'll study what would happen if the Earth underwent an increase in plate tectonic rates, such as is thought to have occurred during the late Cretaceous. Set your model back to the way it was in problem 1.

a) Suppose plate tectonic rates increased so that continents collided at faster rates, resulting in an increase in the uplift transfer coefficient of 25%. What do you predict would happen to the amount of P in all of the reservoirs?

b) Change your model and run it for 1000 years. Were you correct in your predictions? Why or why not?

c) Keep track of the uplift and insoluble weathering fluxes as a function of time. **Describe and explain** their behavior.

7) Another by-product of glaciation is that the rate of insoluble weathering probably went up. Glaciers produce vast quantities of finely ground up rock flour that is transported by streams to the oceans. Set your model back to the way it was in problem 1. Now, modify it to exhibit a 25% increase in the transfer coefficient for insoluble weathering.

Describe and explain what you see as you run the model.

8) Land plants first arose during the Silurian (439-409 Ma). Let's do an experiment in which we look at the phosphorous cycle in the absence of land plants. Set your model back to the steady state scenario in problem 1.

a) What do we have to change about the model to simulate no land plants?

b) Run your model and keep track of the different reservoirs as a function of time. **Describe and explain** what you see. Were you surprised, or did you predict the result?

9) The following questions come from the reading by Jahnke (1992): In recent years, many of the world's forests have been cut down and replaced with short-lived crops. What effect, if any, might this have on: (1) the P stored in the land biota reservoir, (2) the exchange rate of P

between the land biota and the land reservoirs, and (3) the exchange rate between the land reservoir and the surface ocean?

Modify your STELLA model to explore these questions and then explain your findings.