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Environmental Mathematical Modeling: Grand Canyon

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How do you spend your summer? Would you like to go a little deeper into mathematics? How about a mile deeper; say, to the bottom of the Grand Canyon? For several years, my students and I have been involved in a research project that has taken us down the Colorado River in Grand Canyon National Park—both literally (we've been on several white-water rafting trips) and mathematically, with a computer model that we developed for the National Park Service.

Background

In this day and age of extreme sports and extreme vacations, the allure of white-water rafting through the spectacular cliffs of the Grand Canyon continues to grow. Over 20,000 people take rafting trips down the Colorado River, and the demand increases each year.

It's the job of the National Park Service to figure out how to manage this recreational demand. How many people should be allowed to go? The National Park Service has to balance protecting the natural resource while still allowing access to this public park. If too many people go, their visits could negatively impact the delicate desert environment. More hikers on the trails could increase erosion. Additional people visiting Native American archeological sites could be problematic. Campsite degradation and negative impacts to the populations of fish, plants, and wildlife can also result from excessive human visitation. On top of all of this is the fact that anyone who chooses such an extreme vacation is seeking a wilderness experience. Consequently, there's a strong interest in avoiding huge crowds in the Grand Canyon!

In 1996, the National Park Service decided to take advantage of mathematical modeling to help them develop a new plan for managing the white-water rafting on the Colorado River. They sponsored the development of a computer simulation model, called the Grand Canyon River Trip Simulator (GCRTSim). As you can imagine, this was a huge team effort—a partnership that included academia, the federal government, business leaders, activists and other stakeholders. The

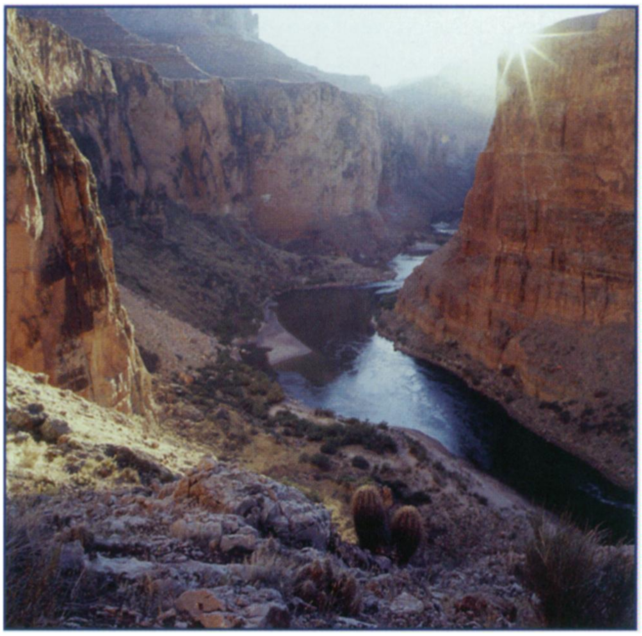

Photo by Larry Loruso (2001) courtesy of Grand Canyon Private Boaters.

computer model was developed by professors and students from Northern Arizona University (my former institution) and the University of Arizona. My research group included four undergraduate students—three computer science/math majors and one physics/math major—in addition to other faculty and a graduate student in geology.

Rafting in the Grand Canyon

Because the high cliffs in the Grand Canyon limit access to the river, once a trip launches, there are only a few opportunities to exit. The trip is over 200 miles long and it takes about one week on a motorized raft or two weeks on an oar-powered raft. The rapids are extreme and the camping is primitive; this is a vacation for adventurous people who want to leave technology and the world behind.

There are two ways to take a Grand Canyon river trip—commercially or privately. A commercial trip is for the general public. It comes with professional guides who provide the boats, gear, food, and on-site guidance and interpretation. A private trip consists of a group of experienced river runners who don't need the services of a commercial guide. The Park Service controls the number of people who can go on the river each year by managing access for these two groups. Commercial companies are given an annual allotment of passes that

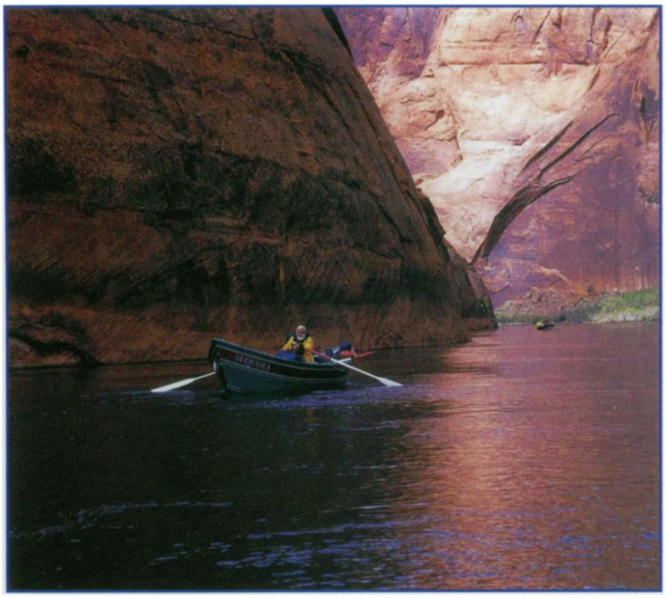

Photo courtesy of Catherine Roberts.

they can use to bring paying customers on trips. The private boaters have, until recently, put their name on a waiting list, where the folks at the top are given passes each year.

With demand so high, there's inevitably going to be some backlog in scheduling a Grand Canyon river trip. So, how far in advance does a person have to plan a trip? Most people are interested in commercially guided trips. These typically sell out a year or so in advance. On the other hand, if you have the skills to lead your own trip, the waiting list for private trip permits is very long—over 7,000 names! With only 262 private launches per year, this translated to a wait time of approximately twelve years. Yes, you read that right...private boaters were waiting for over a decade for a chance to raft the rapids in the Grand Canyon! Recently, the park has instituted a new system for noncommercial boaters. It's a weighted lottery system that, it is hoped, will help improve this dire situation.

A Good Idea

It's a special day when it occurs to someone that the problem solving skills of a mathematician might help them address a challenging situation. One day, a private boater called my department's office to ask if there might be someone on the faculty who could help him out. He believed that a mathematician might be able to figure out a better way to manage the rafting schedule. Couldn't he and his friends get on the river sooner, in a way that would be fair to everyone and still protect the environment? Even though my training wasn't specifically in natural resource modeling, I knew that with my degree in applied mathematics and my overall problem-solving skills, I could lend a hand. I was thrilled to get involved in this project, which opened up a totally new research area for me.

The managers at the Park wanted to improve their operations by reducing the waiting time for private boaters, but they didn't want to end up with a river that was too crowded. This suggested a need to determine the carrying capacity of the Colorado River. Moreover, there was an interest to learn how the ratio between the faster-moving motor boats and the slower-moving oar boats played out downstream. Perhaps a new schedule could be developed, with a different ratio of private/commercial and motor/oar trips, that could help alleviate some of the pressures on the Park managers. And these pressures were quite real...in addition to pressure from lobbyists and activists, there were lawsuits pending in the court system that called for an increase in the private boater's allocation of annual passes, as well as for the elimination of the motor boats altogether.

The park managers decided to partner with scientists to develop a computer model for white-water rafting in the Grand Canyon. This computer model could help describe the traffic patterns that would develop downstream over time (the steady-state). It could help the managers understand how these traffic patterns might impact congestion, competition for campsites, and visitation levels at key attraction sites. With the computer model, the park managers could try out different launch schedules. A schedule with more private launches could be test-run down the simulated river. Another one with a different mix of motor- and oar-powered boats could be test-run down the simulated river. If the computer program could provide enough reliable information, then perhaps new policies could be developed with greater confidence. The park managers realized that it would be more efficient to use a computer simulation model, because the costs associated with making on-the-river changes are large. By testing out their ideas first on the computer, the managers hoped to avoid making a bad policy decision.

Mathematical Modeling

The steps to developing a computer simulation model for white-water rafting traffic in the Grand Canyon are very similar to the problem-solving steps that are taken in the development of any mathematical model. First, our team had to learn all we could about river rafting practices. We needed to collect information (data) and analyze it. This analysis provided insight into how to build our model. Once we could identify relationships between different factors (variables and parameters) and come up with equations to model those relationships, we were on our way to having a model. We also used our data to help refine and calibrate our model so that it would reflect, as best as we were able, the real-life situation. Finally, we could run computer simulations and explore new ideas for the managements of river trips in the Grand Canyon. We needed a way to assess the quality of the results that our model generated, too, so that we could tell if our results were reasonable and trustworthy.

So, how did we learn about river rafting? When developing a brand new model, it's critically important to understand the problem as fully as possible. We spent two years learning about river rafting before we felt comfortable with our efforts to design the mathematical model. Even though our project was substantially mathematical, the park managers had many additional considerations. For example, there are political and economic ramifications to any management decision that is made. Historical precedent also plays a big role. To understand as much as possible, everyone on the team had to be open to learning about these nonmath aspects, as well. I attended a number of meetings with stakeholders, who are people and groups who care about the Grand Canyon. These stakeholders include, for example, the owners of the commercial rafting companies, the leadership of the Grand Canyon Private Boaters Association, and the training seminars for the Grand Canyon river guides. I spent many a night over a few beers asking experienced river runners questions about how they made decisions on their trips—how did they select campsites? How did they choose where to pull over for a hike? Everyone on the team went down the Colorado River at least once—I went three times; each of my trips lasted two weeks. Most importantly, we collected over 300 trip diaries over the course of two summers. These trip diaries documented the decisions that real trips made every day by recording the time spent at camping and hiking locations throughout the Grand Canyon.

We spent two years analyzing the trip diaries and the other information that we collected. This helped the team develop the rules that would drive our simulation model. For example, we needed to understand how everyday decisions were made, such as how the trip leaders determined when and where to stop to camp for the night. Such decisions depend upon many factors, and we needed to understand how these factors are weighed in the minds of trip leaders. We learned, for example, that private trips have waited so long to get on the river, that their interest in camping at the premier sites and in visiting the key attraction sites is very high. On the other hand, we learned from a social scientist that the private boaters were more sensitive to crowding issues and would factor crowding into their decision-making a little more heavily than the commercial trips. We learned that if two trips share an interest in the same campsite, that a commercial trip is likely to defer to a private trip, and that a motorboat is more likely to defer to an oar boat.

The Grand Canyon River Trip Simulator

The model is called the Grand Canyon River Trip Simulator (GCRTSim). It is a computer program that simulates rafting traffic on the Colorado River within the Grand Canyon National Park. GCRTSim models the complex and dynamic interactions of human recreators within a natural environment.

Photo courtesy of Canyon Explorations and Expeditions.

My team was responsible for developing the kernel of the model, which means we developed the algorithms to send the trips down the virtual river in a fashion that mimicked the way real trips behave. We wanted these virtual trips to make decisions on their own that were consistent with the kind of behavior that we learned about during the data analysis stage of the model's development. We did not take advantage of any existing "packages" for computer simulation modeling, in part because our team wanted the experience of developing the program from first principles. We developed this model from scratch using the VisualBasic programming language. We modeled the river as a one-dimensional string, where the boat traffic can only travel in one direction (downstream). Along this string, our teammates from the University of Arizona (who also developed the user-interface) used Geographical Information Systems (GIS) mapping software to identify the precise locations of every site. Each site had specific attributes associated with it—for example, could a trip camp there and, if so, how many people could it accommodate; moreover, during which hours would the site be in the full sun or in shadow (since this might affect the desirability)? The computer model can be described as a spatio-temporal model because it tracks each trip in both space (its location on the river) and in time.

In the computer model, each trip behaves in a way consistent with the data that we collected and analyzed. We wanted to incorporate realistic decision-making into the model, so we used a method called intelligent-agent modeling. We created four different trip personalities, because our analysis revealed that different trips can behave differently, even under similar scenarios. For example, a motorized trip with only six nights on the river wouldn't have sufficient time to opt for a long, six-hour hike. On the other hand, an oar trip with two weeks to complete the trip may have time to spend two nights at the same campsite in order to participate in a lengthy hike. Essentially, each of these four trip types has its own set of associated preferences. With intelligent-agent modeling, each trip acts as its own agent, much like the agent for a movie or sports star. Each trip tries to make decisions that it believes will result in the best, optimal experience. Using ideas from decision theory, each trip makes action choices based on a fixed set of alternatives and we measure the utility gained from any particular choice. We aim to maximize the utility for each trip (best camps, visits to key attraction sites, low crowds). In the model, as time marches forward, trips come to decision points where they assess their current situation and compare it to their goals for the day, and select an action plan that makes sense for that particular trip's personality type.

We also needed to use ideas from game theory, because we learned that strategic behavior and bargaining play a role. For example, when trips pass each other on the river, they often exchange information about their future plans. How this information is communicated and used by the trips depends on several factors. When I was on my trips, I saw one really interesting gaming behavior play out, time and time again. As one trip passes another, there's only a small window of time when the two trips are within shouting distance. Each trip wants to know where the other one is planning to camp, in the hopes that there won't be any competition for the same site. In general, the person who asks first will be the loser. Why? Let's think about it: say you are with some friends at a restaurant and you are selecting desserts out of a display case. There's only one slice of your favorite Boston cream pie left. If you ask your friend which desserts she wants and if she chooses that last slice of Boston cream pie, the polite thing to do is to select something else. You aren't likely to fight for it, especially if you're on a date! This means that if you are the first one to ask, then you are also more likely to concede if you don't like the answer. On a river trip, the person who asks the other trip where it plans to camp will concede that campsite if the other trip lays claim to it. Consequently, nobody wants to be the first person to ask and run the risk of losing out on a primo campsite! Many times, I listened while two trips shouted back and forth about all sorts of matters...and, similar to a game of chicken, it would only be in the last possible second that one trip would break down and ask the other where they planned to camp.

In general, these individual agents, which each represent one trip, comprise a complex system. Each raft trip has its own sphere of influence that can propagate downstream. Each raft trip seeks to maximize its utility and a raft trip can't control the other trip's moves. Each trip makes action choices based on a fixed set of alternatives, and the particular personality of that trip determines the likelihood (the statistical odds) of selecting one alternative over another. The computer program is calibrated to the data set and, we believe, fairly represents the dynamic interplay of recreational users on rafting trips in the Grand Canyon National Park.

The computer program was used by the managers at the Park to help them investigate several potential new management scenarios. They hired a student from my team to run simulations with all sorts of different launch calendars. They compared the downstream impacts of the current launch schedule with these new ideas, to see if any of their new ideas might satisfy their management objectives more effectively. For example, one management objective is that a trip ought to have only a 10% chance of camping within sight or sound of another trip. With GCRTSim, they could see how well they're meeting this objective now and they could experiment with other launch calendars to see if they could improve on this objective. The new management plan, which was adopted on March 23, 2006, has made several adjustments to the way that people take rafting trips on the Colorado River. For example, the private user day allocation has been doubled and the peak commercial season has been extended. The changes should result in a less crowded river at any one time, even though more than 200 additional people will be allowed to go on river trips each year.

How You Can Get Involved

If you think you might be interested in mathematical modeling, it's important to get as broad an education as possible. You need to develop excellent problem-solving and communication skills, as well as the ability to think flexibly. Try a few classes in a field that would welcome your mathematical approach to problem-solving, such as biology, environmental studies, or computer science. Courses in applied math, such as mathematical modeling, differential equations, and numerical analysis are essential. You can develop your communication skills with a proofs course, a writing-intensive English course, or public speaking and debate classes.

Seek out professors who are interdisciplinary researchers. Ask if you could participate in a summer research opportunity. Each spring semester, there's a Mathematical Contest in Modeling where teams of undergraduates spend a weekend solving an open-ended problem. If your school doesn't already participate, ask a professor to register a team with you on it! (`www.comap.com/undergraduate/contests/mcm/`).

The Mathematical Association of America runs a special interest group on Environmental Mathematics (`sigmaaem.intellihawk.org/`). There are a number of undergraduate mathematics texts that address environmental modeling, such as ones by Charles Hadlock, Ben Fusaro, Patricia Kenschaft, and Greg Langkam/Joseph Hull. The *Resource Modeling Association* `www.resourcemodeling.org` holds conferences and publishes an interdisciplinary journal *Natural Resource Modeling*. Contact the author for additional references to her work for the Grand Canyon `croberts@holycross.edu`. ■