Judges' Commentary: The Outstanding National Water Strategy Papers

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Problem Statement

Fresh water is the limiting constraint for development in much of the world. Build a mathematical model for determining an effective, feasible, and cost-efficient water strategy for 2013 to meet the projected water needs of [pick one country from the list below] in 2025, and identify the best water strategy. In particular, your mathematical model must address storage and movement, de-salinization, and conservation. If possible, use your model to discuss the economic, physical, and environmental implications of your strategy. Provide a nontechnical position paper to governmental leadership outlining your approach, its feasibility and costs, and why it is the "best water strategy choice."

Countries: United States, China, Russia, Egypt, or Saudi Arabia

Introduction and Overview

This problem is similar to one used for the 2009 High School Mathematical Contest in Modeling (HiMCM)®. The problem was expanded for the 2013 Mathematical Contest in Modeling (MCM)® contest. The judges expected more sophisticated modeling, higher resolution, better analysis, and fuller interpretation by the MCM teams. The judges were not disappointed.

The problem was deliberately written to have a potentially overwhelming amount of detail, and to force the student teams to decide what simpli-

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fying assumptions could be made so the problem would be tractable in the time allowed yet provide useful insights. It was also written so that students with a background in only lower-division mathematics could attempt it.

To recognize the increasing international diversity of the student teams in the MCM, teams were allowed to choose among five possible countries. Reflecting the high participation rate from the People's Republic of China, by far the greatest number of teams chose to model China. Many fewer teams chose the United States, Egypt, or Saudi Arabia. This judge did not see a single paper that addressed Russia.

As has been the norm recently, there were required elements in the problem statement. Almost every paper included the required nontechnical position paper this year.

This commentary will discuss the various elements of the problem, with observations from the judging. It will then conclude with a summary.

Readers interested in a discussion of the mechanics of the judging process will find a very good report on the process in the accompanying commentary on the Brownie Pan Problem by Dr. Kelly Black [2013], on pp. 141–149 of this issue.

What is the "Best Water Strategy"?

Models are constructed to answer questions. Here, we are asked to identify the best water strategy. But what did a team mean by "best"? Was it to provide a certain level of water at least cost? Was it to have the most reliable supply? Was it to have the highest water quality? Was it to provide the greatest net economic benefit to the country? Many teams never stopped to define clearly the purpose of their models, but plunged immediately into modeling aspects of the problem.

The better teams considered carefully what they meant by "best" and included a discussion in their restatement of the problem.

Projected Water Needs

Predicting the water demand by 2025 was a required element of the problem. Student teams used a variety of methods. These included predicting the population at 2025 and then assuming a per-capita water use, and directly modeling the water usage for a prediction at 2025. Teams divided the countries in different ways, some by river basins and some by political entities.

Most teams that modeled the population and then multiplied by a per capita usage rate did not explore the possibility that the usage rate might change based on shifts to the underlying economy. On the other hand, some teams explicitly modeled industrial demand, agricultural demand, and domestic demand: These papers were stronger.

Prediction methods used included statistical methods (typically regression) and differential equation models (typically Gray's model). Almost every team reported a point estimate instead of an interval estimate (either a confidence interval for the mean demand or, better, a prediction interval for the actual demand). The judges ranked interval estimates much higher.

Teams varied in the sophistication of the predictors that they used to model demand. Some strictly analyzed the problem as a time series. Others included industrial development, climate change, loss of wetlands, and externally imposed changes to agricultural practices, such as prohibiting certain irrigation practices or the cultivation of water-intensive crops.

In addition to modeling uncertainty, the best teams included an assessment of the sensitivity of their demand models to changes in their assumptions.

Finally, many teams over-reported the precision of their results. It was not unusual to see 10 or 12 "significant" digits in the estimated demand, where the source data had only two or three significant digits. Many teams did not include the units for their answers, or used them inconsistently. These are poor practices.

Storage and Movement

Most teams modeled the movement of water as a network problem. Modeling choices included the selection of nodes, the representation of arcs, and the costs associated with the arcs.

Many teams divided the country into regions, and represented each region by a point, usually the regional capital. Arcs were constructed between these points to represent flow between regions. Most teams modeled the cost of construction and transport along these arcs as proportional to the geographic linear distance between the nodes. Almost every team neglected elevation differences, but the better teams at least acknowledged that they were ignoring those differences. Since the cost to lift water is very high compared to the cost to move it laterally, treating elevation was an important discriminator.

A few of the better papers modeled water distribution inside the regions as well.

The teams that modeled China usually acknowledged the South-to-North Water project and incorporated it directly or indirectly into their model. This included drawing cost data from the project.

Many teams incorporated environmental issues into the movement and storage options by acknowledging that some options resulted in human displacement, wetlands loss, and aquifer depletion. The better papers moved beyond subjective descriptions to quantitative models that were incorporated as elements when weighing the best national strategy.

The criteria for the problem that I as problem author developed before the contest included the comment that "teams that model wear-out or degradation of existing infrastructure and system reliability, and include consideration of those issues in their overall model, distinguish themselves if all other modeling parts are done very well." Few if any papers addressed this.

Desalination

Desalination was the second of the required topics. Many papers assumed it away, to their disadvantage. Modeling desalination involved infrastructure, power, cost of unit production, and then subsequent transportation, including lift, since by definition desalination starts at sea level. Most teams that addressed desalination considered cost, but few thoroughly treated transportation. Of note, one month after the contest date, Lockheed Martin filed a patent for a nanometer-thick desalination filter that claims to reduce the power needed for desalination by two orders of magnitude [Alexander 2013].

Conservation

Most teams modeled conservation. There were several approaches, primarily involving reduced use and recycling.

Reduced use models focused extensively on irrigation. Inefficient practices such as flooding of fields were chosen for elimination, and the resulting water savings calculated and subtracted from the overall demand.

A second class of reduced use focused on prohibiting crops that required significant amounts of water, choosing to import those, and focusing on crops that needed less water. The concept of "virtual water" was used to describe this, and the practice was noted as already in use in Saudi Arabia.

Water recycling by treatment was also discussed in many papers, affecting the cost, supply, and environmental aspects of the trade space.

Other topics addressed under conservation were the management of limited aquifers, reduced industrial use, and reduced domestic use.

Model Integration

Once teams had developed submodels for demand, storage and transport, desalination, and conservation, they had to integrate them in some manner to determine the "best" water strategy. There were several approaches used most frequently.

- One approach was to minimize cost, given a required supply. Students attempted to do this by linear programming, and in some cases by using the greedy algorithm or simulated annealing models.
- Many papers used the Analytic Hierarchy Process (AHP) to incorporate the different elements of the solution into one decision model. Teams used their own judgment to estimate the priorities among the elements. Since different teams provided different weights and inputs, solutions varied widely.
- Weaker papers did not have an explicit method to integrate their problem elements or to determine a "best" strategy. They found a feasible solution, and stopped.

Sensitivity Analysis and Model Testing

As in previous years, the judging criteria for this problem considered sensitivity analysis and model checking. Many papers neglected to consider these issues and were scored lower as a result.

Sensitivity analysis was appropriate for all elements of the models, and especially for the predicted demand, supply, and cost models. For AHP, sensitivity analysis would have involved varying the weights (or pairwise rankings) to explore what conditions would cause the alternative ranking to change.

Model testing took several forms. For prediction models, graphical methods for examining residuals of historical data were often used. Statistical tests of significance were used for regressions. Consistency checks were used for the AHP. The better papers used these methods and others to convince the reader that the models selected were appropriate.

Country Issues

In some countries (China, the United States, Russia), water scarcity is a problem only in parts of the country. Teams that elected to only deal with regions where there was scarcity were not penalized if that approach met their definition of "best."

Data were fully available for China and the United States, and to a lesser degree for Egypt, Russia, and Saudi Arabia. The judges recognized this when evaluating papers.

The overwhelming majority of papers chose to model China. Some papers initially advanced in the competition partly because they addressed countries that were almost completely neglected by most teams, so there would be some balance in the later judging rounds.

Communication

Papers were judged on the quality of the writing. Special attention was paid to the abstract and to the nontechnical letter.

The quality of writing, in general, is improving from year to year. This is notable in the papers that come from countries where English is not the primary language spoken. About half of the Outstanding papers this year were from teams where English was a second language, and that was a record.

The strongest abstracts included a definition of what the team meant by "best," the results of the model analysis, and an explicit, quantified description of the best strategy and its cost. The judges continue to be surprised by the number of papers where the abstract only describes what the team will attempt without describing what they found.

Similarly, many of the required nontechnical position papers omitted key details that a decision maker would need, such as particulars on the solution and the economic and noneconomic costs and benefits. A nontechnical letter does not mean that numbers are not included. Rather, it means that someone can read it meaningfully without having an education in advanced mathematics. Too many of the position papers omitted all details of the solution.

Papers that labeled figures and tables with informative captions were scored higher than those that did not.

The quality of citations was also a discriminator. Papers that cited their sources and provided complete references formatted according to a recognized standard were scored higher than those that did not.

Several of the very best papers were a joy to read. The explanations were clear and complete, and the phrasing was almost lyrical. The judges will continue to value outstanding writing.

Summary

The Outstanding teams modeled all the aspects of the problem described in the problem statement, included the standard contest discussions (assumptions, sensitivity analysis, strengths and weaknesses, etc.), had defensible cost models, explained the modeling choices made, and were well-written.

The judges were pleased by the student submissions. The topic allowed for a wide range of solutions, and the allowed choice of countries provided a diversity of solutions. The growth in the quality and number of submissions is very encouraging to those who work to promote the practice of good mathematical modeling.

References

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