Judges' Commentary: Water Scarcity

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Introduction

The ICM continued to challenge students to address real-world problems concerning environmental science in Problem E. This year, teams sought to identify and understand the drivers of water scarcity in order to create a model to predict the ability of a region to provide clean water to meet the needs of its population. Teams were asked to research and then create intervention strategies for a water-vulnerable region to mitigate its water crisis. The teams had to consider both environmental constraints on water supply and how social factors influence availability and distribution of clean water. Due to the interdisciplinary nature of the Problem E, the teams choosing this problem had to leverage the strengths and skills of their individual members as they navigated this challenge

The problem statement is given in the contest report earlier in this issue.

Judges' Criteria

The general framework used to evaluate submissions for the environmental science problem is described here. The judges that utilized this

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framework included representatives from a diverse set of fields including sustainability, biology, geography, applied mathematics, statistics, and engineering. Their main objective in the ICM problem judging was to find and evaluate modeling that includes good science and leads to measurable and viable solutions. The judges were looking for papers that clearly communicated each of the following elements:

- An understanding of the complexity of the problem, including the social and environmental drivers taking into account both physical and economic scarcity.
- The development of a meaningful model incorporating the dynamic nature of the problem affected by both supply and demand; and then the utilization of this model to determine the chosen region's ability to provide clean water to meet its needs, both before and after implementation of intervention strategies.
- A relevant and feasible set of intervention strategies tailored specifically to the region chosen.

Each paper was evaluated using a common assessment guide. In the sections below, we offer commentary of the critical components of the environmental science problem and highlight the innovation seen in this year's submissions.

Executive Summary

As in past years, it remained important that the executive summary succinctly and clearly explain the highlights of the submissions. The executive summary should contain brief descriptions of both the problem and the bottom-line results. The description of the problem must be written in the team's own voice and not taken directly from the problem statement. Better papers had a well-connected and concise description of the methodology, results, and recommendations.

Researching the Problem

Judges were looking for insight into a team's knowledge concerning the critical aspects of water scarcity that were incorporated into the model, as well as the specific drivers of water scarcity within a team's region of focus. The judges sought to understand the resources that teams used to obtain what they considered to be the relevant factors.

In the analysis of the primary causes of water scarcity, the judges expected a discussion of factors associated the growing rates of consumption in addition to physical and economic scarcity as indicated in the problem statement. This discussion should lead teams to differentiation between supply and demand constraints which include not only environmental factors but also social influences on availability and distribution of this resource. Most importantly, the judges were looking for the interpretation that drove the selection of a team's input factors. The explanations of why a factor was included weighed more heavily with the judges than the actual factor itself or even the number of factors chosen for inclusion. We wanted to gain insight into the team's motivation for selecting and utilizing the particular factors in order to gauge a team's true understanding of the complexity of the environmental crisis concerning water throughout the world.

The background presented on the region of focus was critical in the judges' assessment of a team's completion of the second requirement. Better teams introduced the water scarcity of the country or region of choice in general and then addressed the details according to the factors included in their model. Teams that chose a smaller, more homogeneous region or nation were more successful in this analysis.

Developing the Model

The judges determined that a well-researched and developed model should include an explanation of the reasoning behind the chosen approach as well as the assumptions used in developing the model. Outstanding teams motivated their model with background research.

The inclusion of assumptions used in developing a model was importation in evaluating the submissions. The better solutions explained why key assumptions were made, as well as how they affected the model development. Since this problem is so extensive and there were so many factors to consider associated with water scarcity and the ability of a nation to provide for its population's needs, a common assumption in many strong submissions was that the inputs used were correctly chosen to represent the complex nature of the real world situation. Strong teams realized that their initial model included assumptions that could be changed to add some complexity or address some of the weaknesses in the model based on initial results.

The critical aspect of this challenge was to create a model that defined the ability of a nation to deliver water to meet the needs of the population. Judges were impressed by the variety of ways that teams chose to create this metric. Some teams combined their factors without weights, treating all equally, while others chose mathematically rigorous weighting methods or even a hierarchical approach. We saw such a range of approaches and applaud teams for their innovation. The judges read papers from teams that developed completely original models, while other teams leveraged and improved upon models available in the literature. The best teams created a unique model and then conducted verification by testing it against a known metric identified through their research. Regardless, the expectation remained that the teams cite work that is not their own.

We want to caution some teams from over-modeling. A verified, simpler model may be better than going one step further in order to demonstrate increased mathematical knowledge or incorporation of an advanced method. Teams that developed a strongly researched, well explained model with details of its strengths and weaknesses were judged highly.

Testing and Using the Model

After working hard to develop their models, the majority of teams validated their models and then developed intervention strategies to assist a region or nation in mitigating their water scarcity problem. The application of the intervention strategies needed to be incorporated in order to determine a projection of the effectiveness of the strategies long-term.

Even a well-developed model will not produce useful results unless the inputs are reasonable. Judges were impressed with teams that discriminated between objective and subjective input parameters, especially when teams proposed and implemented methods to address the subjective nature of certain parameters. As an added challenge, teams encountered the problem of missing data. Judges looked for the usage of effective methods for handling missing data.

Validation and sensitivity analysis often set a great paper apart from just a good report. Validation is an important part of the modeling process, as it can instill confidence in results or help identify weaknesses in the model. Several papers presented a range of models from simple to complex and used a validation approach to justify the selection of one of those choices, considering the trade-offs. Many of the strong papers, at a minimum, conducted a validation based on another commonly-accepted published measure in order to compare. Additionally, sensitivity analyses can be done in a variety of ways; so judges were looking closely at the rationale behind each team's approach. Some teams revisited early simplifying assumptions, while others assessed the relative impacts of different types of improvements. There is no one way; but teams that attempted a sensitivity analysis in order to determine the robustness, flexibility, or accuracy of their model demonstrated to the judges a higher level of knowledge concerning the impact and usefulness of their model.

Judges appreciated the discussions that teams presented on the variety of intervention strategies they considered. An explanation of possible strategies and then justification or analysis of strengths and weaknesses for those implemented was preferred. Teams that truly extended themselves and did not confine themselves to standard or already-implemented strategies were praised by the judges. We saw innovative intervention plans that were truly tailored to the specific region in crisis.

Once the intervention plans were determined, implemented, and analyzed for effectiveness or cost, the intent of the problem was to utilize the model of Task 1 to determine long-term impacts. Judges understood the need to implement forecasting methodologies but were discouraged when they saw teams adopt completely new models in order to determine the effect of their intervention strategies.

The problem statement required teams to detail the strengths and weaknesses of their model. Outstanding teams not only analyzed the strengths and weaknesses of their model but also of their data, intervention strategies, and assumptions as well. Judges encourage providing such analysis throughout the submission vs. putting it at the end of their report as a seeming afterthought. Strengths and weaknesses are relevant to the entire modeling process.

Presenting the Results

Every year, the judges seek to highlight submissions that offer a balance of sound mathematics with well written justifications. The strongest submissions have a clear organizational structure with equations coupled with explanations and, when appropriate, graphics to help convey complicated ideas, with appropriate citations completed to give appropriate credit to past problem solvers.

Outstanding papers include clearly presented ideas which are introduced in a logical sequence with transitions between topics to link the document together. The subtasks within the problem statement provide the start of a logical sequence to answer the questions. Of course, the spelling and grammar must be correct so as not to inhibit the judges understanding of the approach. Additionally, when Outstanding teams presented equations or steps within their model or analysis, they also included justifications for their approach. Judges continued to look for explanations within the document vs. just including a variable list as an appendix.

The judges understood both the time- and the page-limit constraints. It can be challenging to convey the results of a weekend of intense modeling in a 20-page report. However, with effective use of diagrams, graphs and tables, many strong teams overcame this part of the challenge. These Outstanding papers included graphical visualizations with accompanied interpretations.

Earlier, we emphasized the need for teams to conduct the appropriate research of the topic and possible mathematical approaches to solving complex problems. When conducting the research and using the ideas gained through research, it is imperative that a team's submission include a list of references used. Additionally, in-text citations allow a team to credit specific portions of their paper, such as a quotation or the support for a certain assertion. Plagiarism goes against the contest rules and the spirit of the competition.

Problem Challenges

Due to the nature of the problem, the competing teams used varying modeling techniques focusing on different aspects of water scarcity and selected diverse target regions for analysis. As a result, the submissions provided great innovations and excitement for the judging panel.

Most papers offered sound models but there were several common reasons that teams did not reach the final judging. These papers generally suffered from shortcomings in one of three categories:

- answering the problem as specified,
- making true connections to the real world, and
- effective communication.

Some teams did not answer all the questions as specified in the problem by either leaving out relevant factors that affect both supply and demand or failing to provide any explanation or discussion for a specified task.

Additionally, some teams offered models that were not sufficiently structured to address the question of water scarcity for a region. Other papers did not draw meaningful connections between the mathematical modeling inputs or outputs and their significance in the context of intervention plans for a target nation.

More often, effective communication was the most significant discriminator in determining which papers reached the final judging stage. Some teams did not clearly communicate the models or the rationale behind them or failed to provide descriptions and explanations of techniques and instead provided lists of equations, tables, values, results.

Discussion of Outstanding Papers

Each of the five Outstanding papers used a different methodology in addressing the problem of providing clean water to meet the needs of a population in a comprehensive way. These Outstanding papers were generally well written and provided clear explanations of their modeling procedures. Some demonstrated unique and innovative approaches, distinguishing themselves from other papers. Others were noteworthy for either their thoroughness of their modeling or for the significance of their results. Some provided well-thought-out, implementable intervention plans, perfectly tailored to the chosen region. The summaries for the Outstanding papers for the environmental problem follow.

Brown University, Providence, RI: "A Model for Projected Water Needs and Intervention Strategies in India"

While many teams were content to use the established Water Scarcity Index (WSI) as a metric, this team proposed a new metric to measure a region's water scarcity, the Excess Water Ratio (EWR). The EWR incorporates a different view of water scarcity by considering how much unused water is available per person, enabling the population of a country or region to be taken into account when considering the water situation. In addition, by dividing water use into separate categories for industrial use, agricultural use, personal use, and ecological demands, the EWR metric more thoroughly captures the various factors that affect a region's water supply.

The most impressive feature of this paper is the development of innovative ideas for interventions to improve water supply in the future. The two most thoughtful interventions are the proposals to affect societal changes in food consumption, and by changing food production to emphasize more water efficient crops, as shown in **Figure 1**.

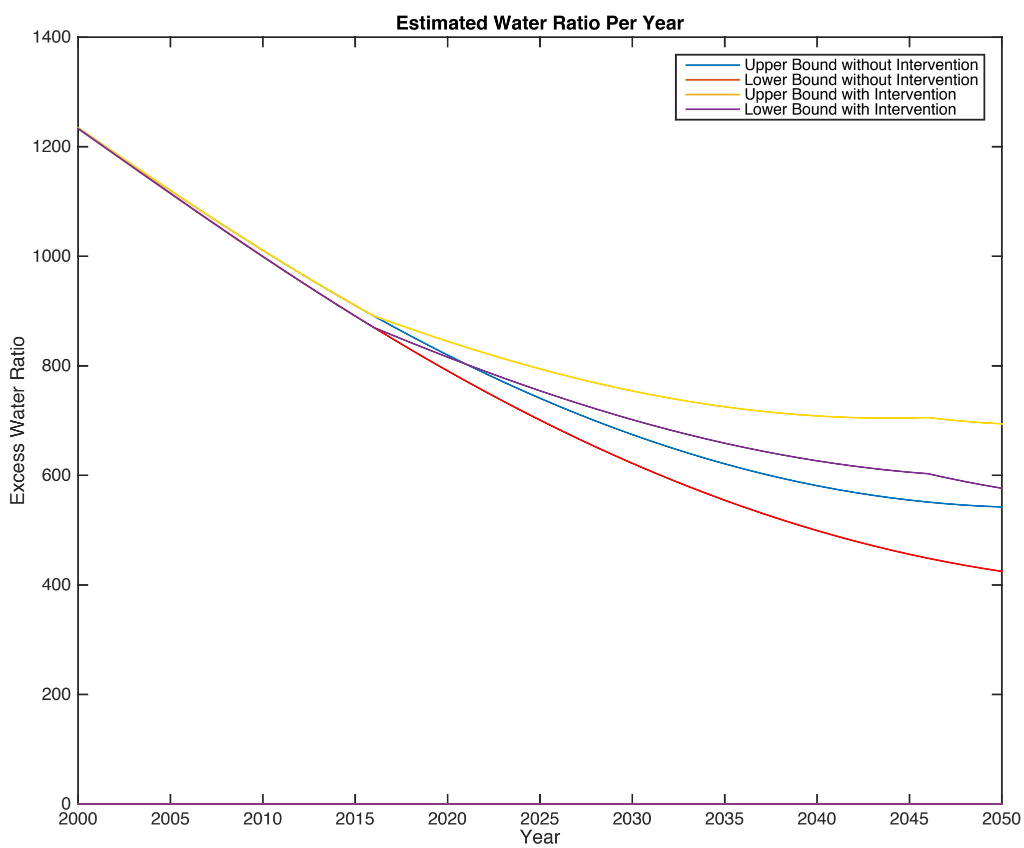

Figure 1. India's projected excess water ratio with and without millet interventions, 2000 to 2050.

The team incorporated the fact that 92% of India's water use goes to agricultural purposes, and recognized that they could gain the most by improvements in that area. They thoroughly discuss the strengths and challenges in incorporating these interventions. While the team proposes some more-standard interventions, such as watershed development and wastewater treatment, these also were well-researched and used data from current implementations of these techniques in India to predict cost, effects of the intervention, and time frame for implementation.

The paper is exceptionally well-researched, demonstrating a strong depth of understanding of current issues and practices involving water in India. For each course of action proposed, the team thoroughly analyzes the impact and discusses the strengths and weaknesses of the course of action based on their research and grounded their recommendations in that analysis. The paper is extremely well written, makes excellent use of references, and presents results with clear graphics, all of which combined to make this paper stand out.

NC School of Science and Mathematics, Durham, NC: "Where's My Water? Global Water Scarcity and Haiti's Water Crisis"

The Outstanding submission by the North Carolina School of Mathematics and Sciences was unlike any other seen by the judges this year. Instead of treating each task as a separate requirement, this team treats the overall problem of water scarcity as a project. The judges appreciated their interesting and very well written submission as well as the effort they demonstrated in tackling the problem of water scarcity by developing three different models which could be applied globally and then demonstrating the model's output, specifically using Haiti.

The team begins their submission with a history of Haiti entitled "Rags to Riches," as they explain how Haiti went from having it all to having the lowest access rates to improved water and sanitation. This upfront analysis is accompanied by common interventions currently seen in Haiti, analyzed according to the team's developed metric for a country's success in delivering needed water to their population. Their metric incorporates economic and environmental costs, as well as the ability to be self-sustainable and socially viable.

In each step of their modeling process for all three models, the team motivates the analysis, demonstrates them mathematically, explains them for the general case, then apply them specifically to Haiti, including detailed reasonable assumptions and justifications. This is followed by a sensitivity analysis. This approach is tremendous and was appreciated by the judges.

or the first model, they develop a systems network model, demonstrated in **Figure 2**, which creates differential equations for each of the six main factors of their model. This characterizes water flow by taking into account different sources of water and all varied uses of water. From there, it is applied to Haiti to understand that both the physical and social infrastructure for transportation and dissemination of potable water need to be highlighted.

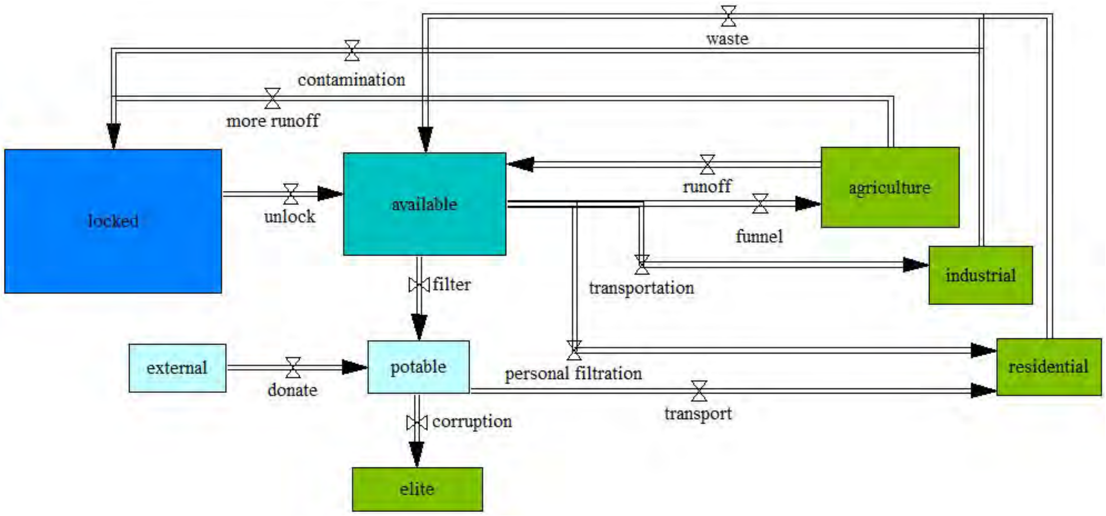

Figure 2. Systems network model of the team from North Carolina School of Science and Mathematics.

The team then examines uniquely-tailored intervention strategies for Haiti. Their first effort was to determine an optimal solution to their initial general success metric through particle swarm optimization. Then, they utilized agent-based network modeling to determine the best method for implementing a clean-water distribution system, the most critical of their intervention strategies for Haiti. Finally, the team compared current invention strategies to their proposed innovative solution using both a short- and a long-term planning horizon.

Specifically, in the discussion of water scarcity, the judges appreciated the understanding of the problem as a whole. The team looked into the cultural aspects and fairness of wealth and poverty when examining water scarcity and how solutions would be accepted within a society. When applied to Haiti, the team really understood the challenges of a water distribution network in such a nation. The judges appreciated the considerations of control of distribution nodes, presence of NGOs, infectious disease spread, the effectiveness of the government, and the operation of gangs. Overall, this was the most unique modeling the judges had seen, and the incorporation of such tailored innovative solutions was superior. The team from the North Carolina School of Mathematics and Sciences worked hard to convince us that they had good models that worked well for Haiti and could be applied globally.

United States Military Academy, West Point, NY: "Are We Heading Towards a Thirsty Planet?"

The team from the United States Military Academy provides an exceptional report focusing on water scarcity in Egypt which not only contains an extraordinarily well-written summary but also provides excellent discussion on the issue of water scarcity as well as an innovative policy recommendation for intervention. The USMA team began by analyzing the dynamics of water supply and demand through a simple flow model as shown in **Figure 3**. Each component of the model was then further developed and broken down into several individual models. Water deficit was calculated by dividing demand (or outflow) by supply (or inflow).

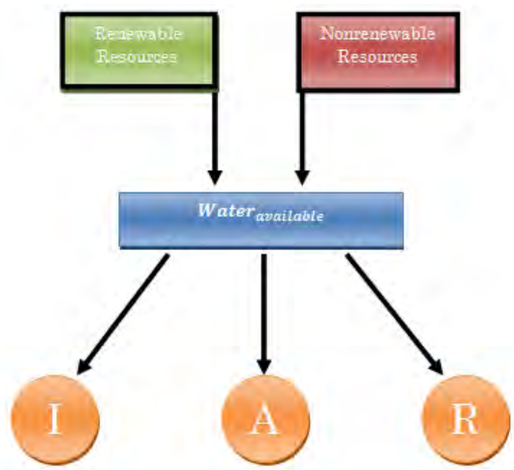

Figure 3. USMA supply and demand flow model.

Thoughtful assumptions were made concerning water recycling and artificial replenishment which added to the complexity of the model. Components such as population, industrial consumption and agricultural consumption were modeled in order to make predictions. The team goes on to provide excellent discussion of the drivers of water scarcity in Egypt, later incorporated into their intervention plan. Judges were impressed by the team's conversation about population and the fact that water consumption was not just tied directly to population but instead was broken into three separate models. Unlike many teams, the USMA team adjusted for climate change in their predictive models. They created two models, one which accounted for climate change and one which did not.

The report incorporates a well-thought-out intervention plan appropriate for the geographic region and takes specific drivers of water scarcity into account. Their intervention plan includes replacing part of the domestic crop production with international imports. This idea intrigued the judges because it was a unique idea that also makes sense for the region. The team not only addresses the impact that the intervention would have on future water scarcity but also provides nice justification and explanations for each aspect of the intervention plan.

The USMA team's ability to clearly communicate their ideas and results in a concise and thorough way pleased the judges. This, along with their inventive intervention plan, earned them an Outstanding ranking.

University of Colorado Denver, Denver, CO: "Tackling Water Scarcity: Modeling Water Access in India Using MultipleRegression Analysis"

This paper stood out because it did an exceptional job of assessing water access in India. The team uses a particularly well-thought-out structure for their intervention plan, taking account of all the critical variables that do, in fact, shape India's water crisis. They put their finger squarely on the fact, that, despite all the debates about population change, populations will certainly increase in this part of the world. One direct implication of this population growth rate is that demand for clean drinking water will increase as well. And, for all that GDP is a grossly flawed indicator of development, investment in water infrastructure is certainly tightly tied to increases in national wealth.

The team submitted a very well-written data modeling paper with excellent descriptions of their modeling process and well-chosen visualization. The statistical approach is all encompassing, with a series of detailed multiple linear regressions in which the team chose the best subset of attributes based on an adjusted R^2 value. Those included in the model are shown in **Figure 4**.

What was clearest to the judges when reading this submission was that the team did an excellent job in analyzing the nature, scale, and scope of India's water crisis. They showed a strong grasp of the realities that undergird the story of modern-day development in India. Overall, their model and recommendations were all inclusive and very innovative.

While there was some discussion amongst the judges about the extent to which the team's proposed interventions were, in fact realistic, the complete package that was their intervention plan was clearly well-thought-out and—within the limits of their assumptions—entirely defensible. The team went so far as to include a future work section in which they identified not only the weaknesses in their model but exactly how they could tackle those weaknesses.

Xiamen University, China: "Are We Heading Towards a Thirsty Planet?"

This paper was chosen largely based on its model development, including discussion of existing models in the literature, and strong data-based validation of the proposed model. The team develops two metrics, the

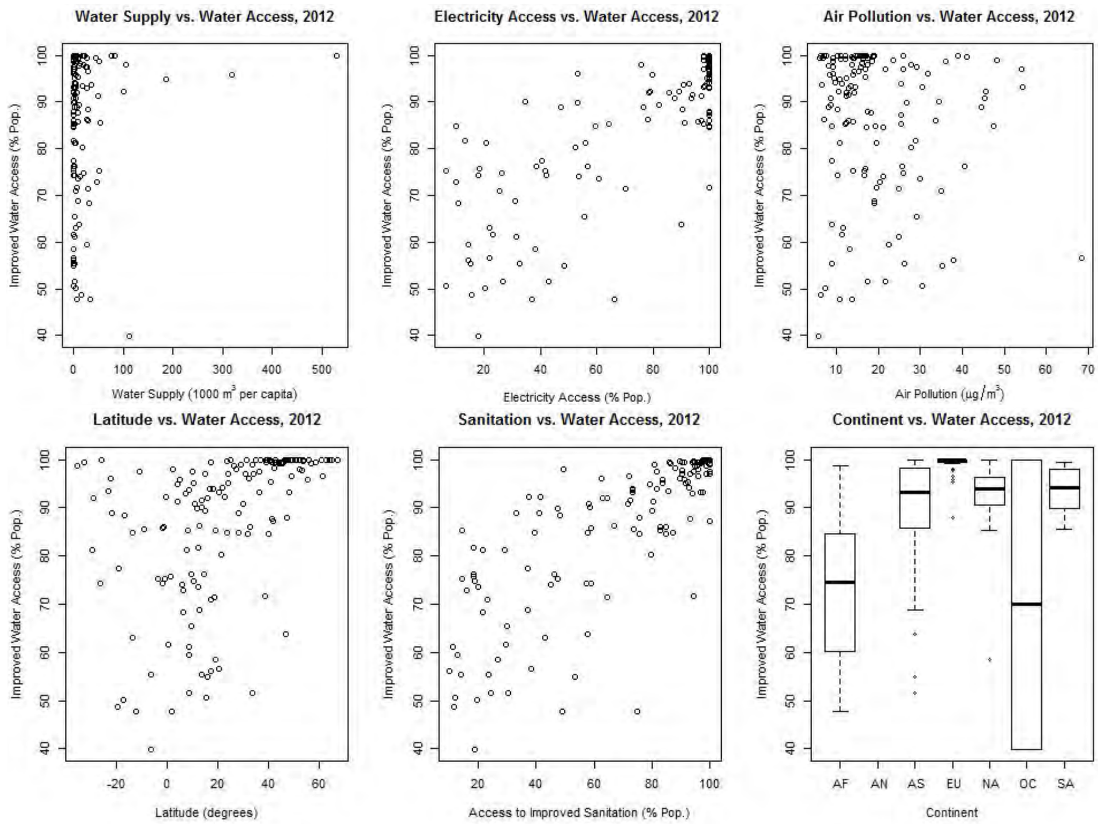

Figure 4. Data analysis for chosen attributes of the model.

Physical Scarcity Metric (PSM) and Economic Scarcity Metric (ESM), which are combined into a Total Scarcity Metric (TSM)—the ability of a country to provide clean water to its people. The main factors considered in this model are divided into technology, infrastructure, and human factors, with emphasis on the social—which was appreciated by the judges.

The team conducted extensive research that was highlighted in their literature review, where four known indices are explained and evaluated. After assessing the strengths and weaknesses of each of these measures, the team's TSM is developed using the mathematical technique of Grey Relational Analysis. To combine the PSM and ESM, the team develops an innovative solution with relative weights depending on the different country being assessed.

This paper distinguished itself in its thorough use of data in the verification of the model. Four different online data sources were used, ultimately resulting in the use of 83 countries' data. Using this data and Grey Relational Analysis, weights were found for the factors included. The following figure shows the resulting values of PSM and ESM for the 83 countries (**Figure 5**). Higher PSM and ESM correspond to more severe water scarcity. The team then compares their calculation to the UN Water Scarcity Map, with the resulting conclusion that the developed model matches the UN results well, noting possible reasons for some of the deviations. Following this analysis, the paper includes an extensive sensitivity analysis for the relative weight of PSM and ESM, choosing eight countries of varying values, as labeled in **Figure 5**. This team consistently assesses their work throughout the paper, a quality not seen among many other teams' papers.

Though the judges thought this paper was excellent overall, they had some reservations about the interventions proposed by the team which were fairly standard among those proposed by other teams. Overall, the judges recognize this team's outstanding efforts including comparisons of countries, nice explanations of mathematical techniques, extensive literature review which was used to inform the development of the metric and thorough validation of the model based on available data.

Recommendations for Future Participants

For those attempting the environmental problem in next year's competition, the judges recommend focusing on three areas. The first involves making a plan for the weekend and conducting the critical initial research. Next, solve the problem and all the subtasks that were outlined in the problem statement. Last, ensure you present your solutions and recommendations thoughtfully with explanations and interpretations.

Make a Plan

Have a plan for your 96 hours and then adjust as needed in order to ensure a completed solution and submission. Every year, there are submissions that do a tremendous job on one aspect of the problem but then are unable to complete their solution, obviously due to a lack of time or lack of coordination of the plan. To coordinate your plan, leverage the strengths of individual team members. The more your team can synchronize the efforts of its members and integrate the writing into a seamless paper, the stronger your final submission will be. Incorporate time into the plan for the best writer to edit and ensure smooth transitions throughout the document. Lastly, ensure that research is the first aspect of your plan. It is important to do the research up front and understand the context of the complex interdisciplinary problem. The judges do not expect the teams to be experts in all the aspects of a particular problem, but we do expect you to read about the environmental situation so that you ensure that you know what you are actually modeling.

Solve the Problem

Since time is short, all initial efforts must be dedicated to answering all the questions that are asked in the problem statement. Outstanding teams always address all aspects as required and then often go beyond for a particular aspect. Additionally, remember that a simple model can be just as effective as a complex one! As noted in the discussion of this year's Outstanding papers, a simple model that is nicely researched, explained, and implemented impresses the judges when coupled with excellent contextual real-world interpretation of the environmental crisis we are trying to solve.

Interpret and Present

Remember that the motivation for this competition is the real-world environmental problem. Therefore, the model itself is not the solution. Outstanding teams always use their models to produce interpretable applicable results as well as a recommendation for a solution. Throughout your process, explain what you are doing and why. The judges desire to read the explanations behind what a team is doing and the descriptions of why vs. a list of equations and numbers without words. If you are using information from other sources in your model or analysis, ensure that you use references for that information and then cite them accordingly. Please ensure that you give appropriate credit to the sources used throughout your research.

About the Authors

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