Design and Evaluation of Aquatic Ecosystems via Discrete Event Simulation

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Problem Statement

Environmental issues will continue to be of great importance in the XXI Century. For they affect health, drive production costs up (short and long term) and are felt across borders, making them a global problem. In addition, ecological problems are fairly complex, involving many physical, human and socioeconomic factors that often interact with each other. Therefore, building tractable mathematical models for ecological problems is difficult and often leads to oversimplification of model assumptions. As a result, these mathematical models bear little resemblance with the real problem entities being modeled.

In this paper we present an alternative analysis tool for environmental modeling. We propose the use of discrete event simulation, via specialized languages such as GPSS (General Purpose Simulation System). This approach presents several important advantages over purely mathematical ones, for environmental studies. For example, the modeler can now use broader distribution assumptions, in addition to Exponential or Normal. The modeler can now also consider all problem factors and their interactions. There is no longer need to keep the model formulation simple, in order to obtain a closed form solution. These two gains, by themselves, more than justify pursuing a simulation modeling approach.

In the rest of this paper, we review the literature on this topic and present an illustrative prototype simulation model of an aquatic ecosystem. Our simulator has been successfully presented to audiences in the Environmental Protection Agency (EPA), the Great Lakes Research Consortium (GLRC) and the Mexican Institute of Water Technology (IMTA), among others.

Literature Review

From the above comments, it is apparent how simulation is an appropriate and useful tool in environmental studies and, therefore, should have been frequently used. However, as we will show in this section, it has seldom been applied in this area of research, and the question is “why not”? To try to answer this, we reviewed, among other sources, the last decade of the Winter Simulation Conference (WSC) an important forum for discrete event simulation. We found that (i) not many simulationists and operations research (O.R.) engineers have worked in modeling environmental problems and (ii) few environmentalists use simulation to model ecological problems. This is intriguing, since other quantitative researchers such as statisticians, are already actively applying their models and tools in ecological studies.

Since 1990 we found few WSC papers dealing with environmental topics. In 1992, one WSC session was dedicated to natural resource models. Three papers were presented, dealing with ecological issues. Knisel et al. (1992) describe the development of a mathematical model with three basic components (hydrology, erosion and chemistry) to evaluate pollution from agricultural and forestry sources. The model simulates impact of management on response of field-size areas to climatic input. Wiles et al. (1992) conducted simulation experiments to evaluate scouting plans for use with weed control decision model for soybeans. As in the present paper, the authors were concerned with demonstrating the simulation methodology as a valid tool for evaluation of alternatives. Chang and Odeh (1992) presented a simulation model to generate monthly data for water quality using a first order Markovian process.

Clymer (1993) in a limited review of the simulation literature discusses the merits "of discrete event model applications in the field of global simulation". Clymer discovers that "very little use has been made of discrete event models in world simulation." He suggests a list of eight global problems for discrete event simulation (including land, fresh water, atmosphere and ocean physics and chemistry, including pollutants and thermal effects). And he presents a short bibliography of papers about modeling ecological problems or related subjects.

In 1994, the WSC dedicated another session to waste management and environmental modeling problems and there were six papers presented. Boomer et al. (1994) develop a dynamic model that simulates expected activities occurring between underground waste storage tanks and define activities and functions for planned systems. Hand and Barr (1994) present two flexible simulation models for trans ceramic waste and perform trade-offs between different system design alternatives. Shaver (1994) describes a simulation model for the development of a proposed solid waste management system and evaluates alternative system configurations, throughput and capacity of proposed solutions.

Hoefer et al. (1994) simulate a safety subsystem at an operating nuclear plant and compare different models on the basis of cost. Ross et al. (1994) simulate environmental restoration activities and remedial strategies for contaminated water and storage facilities, predicts system behavior, and compares alternative solutions. Lehr et al (1994) discuss the sensitivity analysis for a simulation model that investigates the oil weathering process. Ioannou (1999) uses simulation in dam construction, but only to optimize the use of construction equipment. Finally, only Romeu (1995 and 1997) briefly outlines a GPSS simulation model of an aquatic ecosystem, within several educational applications of simulation, and then proposes its use for applied environmental work.

Modeling work done by ecologists, using simulation, is not much broader. For example, Hall et al. (1989) and Jourdonnais et al. (1990), among selected few, implement simulation models. Hall simulated (in FORTRAN) the Flathead River Basin, Montana, an ecological system including a lake and stream fish reserve. Jourdonnais showed how simulation provides a neutral context in which to negotiate the necessary trade-offs between economic and ecological advantages of a given resource management strategy, and arrive to a satisfactory solution. This was an extremely interesting characteristic of his model.

Ecologists using simulation in their research, usually employ HOL languages (e.g. FORTRAN). The development of HOL programs can take several months and hundreds of lines of code (Hall, personal communication). This is another advantage of modeling ecosystems using simulation with a specialized language such as GPSS, where the development of these same programs take significantly less.

Finally, some statisticians are already actively working in ecological problems. The American Statistical Association (ASA) has an Environmental Section that publishes a newsletter and offers yearly modeling and paper awards and several statistical institutes (e.g. at Penn State U.) specialize in this area and regularly publish their work in refereed journals (e.g. SPRUCE, 1995; Gilbert, 1987; Baltzer, 1996; CIMAT, 1993).

The Simulation Modeling Approach

Simulation modeling has been characterized, and rightly so, as a method of last resort. The first choice is always a theoretical model, when it exists. Unfortunately, it often doesn't, or the required assumptions are so stringent that one is forced to oversimplify them in order to obtain a closed form solution. Secondly, we can turn to an empirical model, most often of the regression type. However, due to the many problem factors and their (first, second and higher order) interactions, the amount of data required to develop the model is beyond availability. In addition, the functional form selected for the regression model is usually arbitrary. Hence, we are left with the simulation approach as our "last resort tool", since all other available modeling techniques are no longer applicable or are very difficult to implement.

For implementing the simulation model we need (i) knowledge of, and relationships between, system components and (ii) data to estimate the distributions and parameters that describe their functions. Subject matter experts can provide the first. And the data for modeling and validation (the second requirement) can be obtained from the census as well as hydrological, industrial, business and agricultural databases of the local, state and federal governments. From the different system components we obtain the simulation model factors. From their inter-relationships, we obtain the factor interactions. In the simulation model, these elements can be defined in minute detail, something more difficult (or even impossible) to do in the theoretical or regression models.

The use of special purpose simulation languages, such as GPSS, make the actual programming and debugging efforts less onerous than if HOL languages (e.g. FORTRAN, C) were to be used. Finally, the simulation model can yield a host of responses and performance measures of interest. Moreover, these model responses can then be recombined, via the use of adequate weights, into broader meta-responses that allow a more objective comparison of the conflicting and competing interests of the various aquatic ecosystem constituents (e.g. ecologists vs. business developers).

Once the simulation program is written and verified (programming part is correct) it needs to be validated. That is, we need to show that the simulation actually mimics the real system it purports to model. When modeling existing aquatic ecosystems, the real data also exists. Hence, we can use it for validation (to compare it with the simulation model output). Once the validity of the model is established, we can start experimenting with it, which is the final objective of the entire simulation exercise.

Simulation is a numerical procedure. Hence, running it once and obtaining a point estimator is not very useful. We want to run a series of similar cases (a sample of pseudo-independent and identically distributed observations) and use them to derive confidence intervals (CI) for the system responses or performance measures of interest. We can also implement what-if analyses and hypotheses tests for specific system conjectures of interest. In addition, we can investigate whether some specific mode factor, or a combination of them, effect the model response and, if so, to estimate the magnitude and direction of these effects. Such results are obtained via the implementation of statistical experiments, usually factorial or (if many effects are under scrutiny) fractional factorial designs. To illustrate this approach we present, in the next section, a simulation model for an aquatic ecosystem.

An Applications Example

We describe below the prototype simulation model of an aquatic ecosystem that is common along the coast of the Gulf of Mexico. It is composed of estuaries, wetlands, lagoons and river-lake systems. Two specific examples of these ecosystems are the river ports of Tampico and the Papaluapan-Alvarado estuary, both in Mexico. Such ecosystems are very important for the preservation of species and their habitats (wetlands, lagoons) as well as for their socioeconomic development (river commerce, industry, agriculture, urban uses, energy and recreation). But these two activities define two constituencies (environmentalists and business developers) that often compete for, and disagree about, the ecosystem resources and how to better use them. And there is a need for an analysis tool (the simulation model) to help them better resolve their differences and work together.

We built a GPSS simulation model of a system of two inter-connected water environments: the Panuco river and its lagoon (the river port of Tampico, Tamaulipas, in northeastern Mexico). These water environments (ecosites) constitute our real ecosystem. In our simulation model, each ecosite has its own parameters: maximum and minimum water capacity levels, physical configuration and water distribution policies (Figure 1). These ecosite parameters reflect the socioeconomic and political requirements, constraints and characteristics of the two above-mentioned constituencies. The simulation model assesses the overall effects that constituent-driven changes in the ecosystem factors, produce in the operation levels and the services rendered by the ecosystem (e.g. port activities, agricultural yields, urban quality of life). The simulation model also assesses the corresponding environmental effects (e.g. deterioration of wildlife habitats).

Figure 1 shows a schematic of the above-described aquatic ecosystems, which has several deterministic and stochastic water delivery obligations. The lagoon provides water for drinking and other personal uses to the population, as well as for agriculture, animal husbandry, etc. It also provides humid environments (wetlands) for wildlife reproduction as well as recreational facilities for the population. The river port provides the means of transportation to bring in raw materials and food, and to export regional products. Its derived economic activity supports agriculture, local industry, commerce and general transportation needs of the population, therefore generating badly needed jobs. In our model we do not consider the effects of evaporation or possible water theft which, if need arises, can also be incorporated into the simulation. All the above-described activities and services constitute outputs of our aquatic ecosystem model.

On the other hand, water for all system obligations come from only three ecosystem sources: rain, the water table and “borrowing” from the other water mass, either lagoon or the river port itself. Let’s explain.

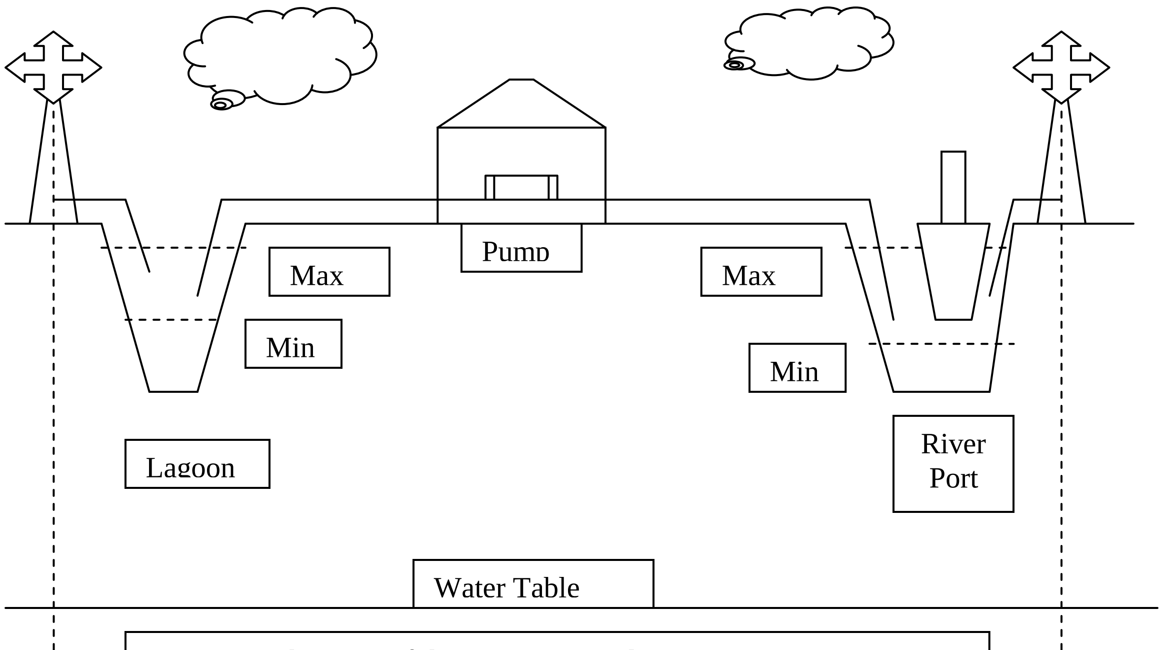
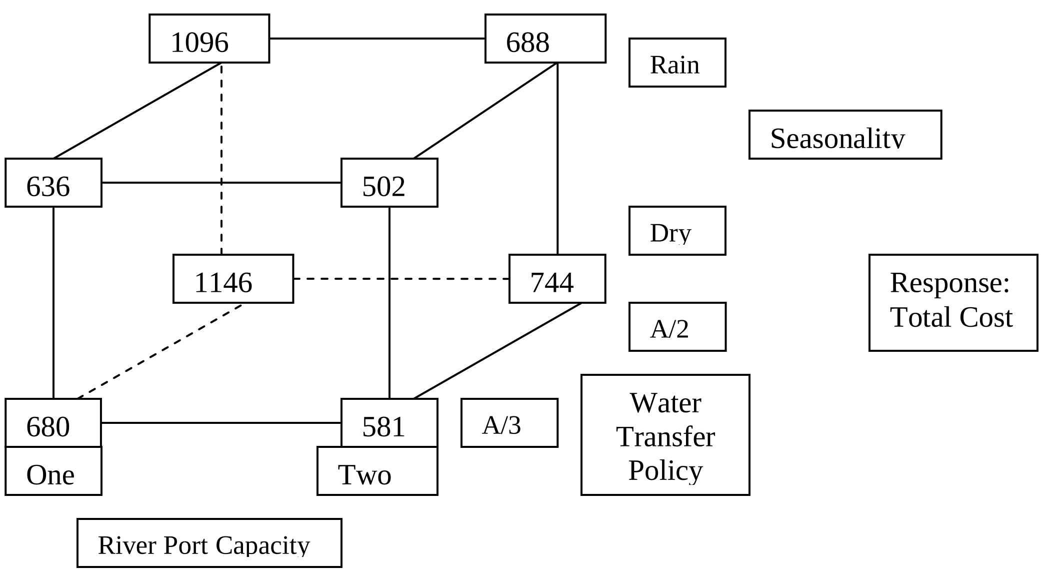


Figure 1: Schematic of the River Port and Lagoon aquatic ecosystem.

Figure 2: Complete Factorial Experiment for the Simulation



When the rainfall (which is a stochastic input, whose statistical distribution is specified in the simulation model) is insufficient, the lagoon or the river levels drop below acceptable levels (Min, in Figure 1). Then, the other ecosite (river or lagoon) can "lend" some of its water via a water transfer. Alternatively, and as a last resource, ecosites can also obtain water from the water table. However, there is a high economic and environmental cost associated with water pumped from the water table. All the aquatic ecosystem ecological and economic variables or factors defined in Figure 1, and their trade-offs, are summarized in Table 1.

The river port capacity and configuration design (Max, in Figure 1) depends on the available water and the commerce needs. If there were enough water, the river canal could be widened to accommodate more ships, enhancing its commercial capacity. But as water falters during the dry season, the river level drops below acceptable levels (Min) and ships cannot operate unless additional water is transferred from the lagoon or the water table to fill the gap. On the other hand, a narrower river canal would ensure the uninterrupted port operation at lower water levels, without need for drawing excessive water from the lagoon, or draining the water table. But this would also let fewer ships access the river port, inducing a slower economic activity.

The total system operation cost, as well as the costs of distributing water among competing user constituents (agriculture, industry, commerce, general population) constitute the economic objective, or response function of interest. We include the corresponding linear, non-linear, deterministic and stochastic problem constraints (Max, Min, rainfall distribution, etc). The simulation model can also consider other performance measures such as the number of water transfers between ecosites, the number of (and time to first) water stock-outs, changes in agricultural, industrial and commercial outputs, in levels of employment, etc. all of which are a direct consequence of the levels of water available in the two ecosites (or water masses). Other problem constraints include operating budgets, available land, ecological mandates, water distribution priorities, etc.

The response variable used in our example was the total cost of water transfers. This included, in addition to the cost of physically transferring water from one ecosite to the other, also the indirect costs induced by the ensuing lack of water (affecting the economy, ecology, population lifestyle, etc). Other ecological responses (e.g. size of the wetland areas, changes in flora and fauna reproduction levels) may also be used. The possibility of trading off real life conflicting (economic vs. ecological) management policies (e.g. rationing versus selling water) adds another important feature to the simulation modeling capabilities.

Implementation

Our GPSS simulation model was used to assess and compare the economic and ecological effects of diverse water management strategies and river and canal designs, on the entire ecosystem. The simulation was also used to assess the joint impact of these strategies and ecosite designs on the ecological, social and economic resources of the entire ecosystem.

In particular, we wanted to assess the joint effect of three factors. One, was the use of the water from the water table versus the use of several inter-ecosite water transfer policies, to balance water deficits within the ecosystem. This factor is important because the water table depletion produces serious and long-term adverse effects on the flora and fauna, as well as on agriculture and animal husbandry. In addition, the amount and speed of the ensuing water transfers affect water temperature and salinity, which, in turn, impacts fish and foul reproduction.

Another factor of interest was the ecosite configuration and design. Port and canal design configurations (e.g. their sizes and capacities) impact the available water in an ecosystem. The size of the river port (capacity for servicing one or two ships) determines the level of commerce, thus impacting the number of jobs in industry, agriculture, etc. Therefore, for economic reasons, we want the larger port. On the other hand, maintaining such larger capacity during the dry season requires draining water from the lagoon and perhaps even from the water table. This, in turn, affects agriculture and the environment. Lagoon water draining reduces crop yields and levels of species reproduction (smaller wetlands). In addition, tampering with the water table may produce irreversible damage to the ecosystem. Therefore, for ecological reasons, we want a small port. This is a classical example of two different constituencies that conflict, due to requiring the use of the same, constrained (water) resources, while espousing very different value systems.

Table 1 : Aquatic Ecosystem Trade-Off Design/Decision Variables and Costs

Controlled Variables

Economic	Ecologic
* EcoSite Replenishing Levels (MIN)	* Wetland size
* EcoSite Capacities (MAX)	* Water Temp
* EcoSite Ordering Schedule	* Transfer Speed
* Water Transfer Policy	* Water Salinity
* Water Usage Policy	* Pollution
* Water Shortage Policy	* Area/Depth
* Water Table Level	* Fish/Foul Population
* EcoSite Initial Conditions	* Fish/Foul Reproduction

Associated Costs:

* of pumping water from Water Table	* of foul/fish extinction
* of pumping water from EcoSite to EcoSite	* of biodegradation
* of sale of water to users	* of habitat Damage
* of water shortages	* of habitat clean up
* of lack of water	* of habitat reconditioning
* indirect costs	* of species relocalization
* total costs	* total costs

Uncontrolled Variables:

* Water Table capacity	* Salinity
* Weather conditions	* Oxygen
* Rain schedules	* Temperature
* Water Theft	* Evaporation

Types of Problems:

* New system design	* Regulation trade-off
* Existing system optimization	* Impact evaluation
* Comparison of strategies	* Conflict mediation
* Education of the population	* Risk Analysis

The third factor of interest, seasonality, depends entirely on nature and mainly serves to complicate the above-described situation by its interaction with the first two factors. When rain is scarce and the port design is too large, there is a water shortage. Maintaining the port open during the dry season then requires draining the water table or the lagoon, thus endangering the health of the ecosystem as well as the agriculture and animal husbandry activities. And there is also less water to serve the general needs of the population (drink, hygiene, etc.).

Thus, the three factors included in our statistical model (and their levels) were the following. First, River Port capacity (denoted α), which had two levels: high (two ships) or low (only one). The second factor was Seasonality (denoted β) with two levels, defined by the rain schedules for the rainy and dry seasons. The third factor (denoted γ) was the (inter-site) Water Transfer Policy. The first priority was always pumping from the water remaining above the alternative ecosite respective minimum level (transfers were 1/3 or ½ of such availability). Only when the alternative ecosite did not have enough water, was it allowed to pump water from the water table. The factor interactions were denoted with double letters (e.g. $\alpha\beta$). Each factor had two levels, denoted with letters i=j=k=2. Finally, we used l=9 replications for each run setting or factor combination.

The mathematical expression of the (2^3 complete) factorial model implemented is:

$$Y_{ijkl} = \mu+\alpha_i+\beta_j+\gamma_k+(\alpha\beta)_{ij}+(\alpha\gamma)_{ik}+(\beta\gamma)_{jk}+(\alpha\beta\gamma)_{ijk}+\varepsilon_{ijkl} \qquad (1)$$

The response variable (denoted Y) was Total Operation Cost, considered in the following manner. The port capacity (one or two ships) influenced, through the amounts of goods moved in and out of the region, the levels of employment in agriculture, industry and commerce. On the other hand, capacity also determined the water shortage levels. Water transfer policies defined the amounts (and sources) of water "loaned" from one ecosite to the other, during a water shortage. Smaller amounts implied more frequent transfers -but allowed more water for use in its original ecosite, e.g. transportation, wetlands or agriculture. On the other hand, larger but less frequent transfers decreased the levels of the lagoon and river port, also effecting the transportation and agriculture as well as the wetland sizes. These, in turn, affected employment and species reproduction levels. Finally, seasonality (rainy and dry seasons) aggravated the above-mentioned situations, directly as well as via its interaction with the two other factors.

Therefore, the response function Y included the cost of the actual water transfers as well as the social, economic and ecologic “costs” that such transfers induced. Individual costs were defined by placing a dollar value on their impact on each of the aforementioned elements, by unit of water level lost, in each of the two ecosites. In our simulation, costs were defined by the “business developer”. Similarly, experiments using our model but with costs defined by “ecologists” or other interested parties can also be run and their results can be compared. This is one more advantage of simulation in these types of studies.

Analysis results

The GPSS simulation model was run for a 2^3 complete factorial experiment. A batch means output analysis method was used. Each batch consisted of one month of daily operation, starting at “average level”. The first ten batches were discarded to account for the transient or warm up period. After this, we took every fifth batch, to avoid inter-batch correlation, for a total of nine replications. The analysis of variance results (Table 2) show how every main effect (as well as the interaction between ecosite capacity and water transfer policy) were all statistically significant. The other interactions were not statistically significant.

Source	D. F.	Mean Square	F Value	P-Value
River Port Capacity	1	1219401	588.71	0.000
Water Transfer Policy	1	1828892	882.96	0.000
Seasonality (Rain/Dry)	1	58186	28.09	0.000
Enviro-Site x Policy	1	373104	180.33	0.000

Table 2: Analysis of Variance Table for the Simulation Experiment

The ecosite capacity factor (design of the river port) was highly significant. The amount of water (and hence of transfers) required to maintain the river port open (as well as adequate wetlands for reproduction needs) depend on the river port size. But river port capacity also affects the need for water transfers, whose costs include the (environmental and economic) effects produced by such transfers. The statistical analysis showed that the single most significant factor was Water Transfer Policy. Assessing water transfer sizes and their induced costs was an important analysis objective. Assessing the effects of establishing different water prices versus establishing water distribution policies (i.e. rationing) is now possible with the simulation model.

Another important problem element, that can now be analyzed, is water user profile (e.g. different agricultural, industrial, commercial and household water requirements). Water usage impacts directly and indirectly the quality of the life of both, the population and the ecosystem. It produces low level, short-term, effects (e.g. lack of water for lawns, for swimming pools). It can also reduce the size of wetlands for wildlife reproduction, for habitats, etc. inducing long-term effects. Stochastic user profiles can be included in the simulation model, something much more difficult to implement either in the theoretical or empirical models. Simulation can also consider the joint effect of several of these factors (Table 1), via complete and fractional factorial experimental designs, obtaining through them, valuable quantitative information.

We can see in Table 3 how the two largest changes in the Cost response function (in respectively inverse direction) correspond to factors Size of River Port and Water Transfer Policy. These factors modify the total cost (response) in Equation (1) by the amount and the direction indicated Table 3, (adding or subtracting from average cost).

Factor	Change Effected	95% CI Factor Effect on Response
Size of the river port	One to two ships capacity	Cost decrease in $232 to $287
Water Transfer Policy	Transfer 1/3 to 1/2 of availability	Cost increase in $293 to $344
Seasonality	Dry into Rainy Season	Cost decrease in $33 to $80
Size x Transfer Policy	Dry/one ship to Rain/Two ships	Cost decreases in $122 to $165

Table 3: Examples of model-derived quantitative information (CI of changes in the Total Cost function)

Table 3 is based on Figure 2, a schematic of the 2^3 complete factorial design implemented. For example, the most expensive (total cost) factor combination ($1146) corresponds to operating a port designed for one ship, during dry season and with 1/2 availability water transfer policy. And the least expensive combination ($502) corresponds to operating a port designed for two ships, during rainy season and with a transfer policy of 1/3 of ecosite available water. The better of the two water transfer policies analyzed is moving only one-third of the available water in the ecosite. Under such policy, there is not a very large difference between one or two ships port design –but two ships is less expensive.

Again, the simulation results presented are based upon cost "values" defined by the "business developers". The simulation can also be run with different cost values (of agricultural production losses, wetland deterioration, species reproduction reduction, etc.) defined by other constituencies (ecologists, farmers, etc.). Such other cost definition may yield totally different results. We can also run alternative "what if" scenarios. These can then be traded-off, compared, etc. The simulation now becomes a decision-support and an arbitration tool.

For example, multi-criteria (ecological, social, economic, etc.) system responses (from the elements in Table 1) can now be obtained, by combining (say k) contrasting and competing individual responses (say $Y_1, \ldots, Y_k$) into a single, complex one. This is done by defining a set of weights (say $\alpha_i; 1 \le i \le k; \sum \alpha_i = 1$) that respond to the different priorities or costs defined by the different constituencies interested in the ecosystem problem. The linear combinations formed using such weights ($\sum \alpha_i Y_i$)quantify the contrasting policies and philosophies of these different constituencies. This way, a more objective comparison of such competing and contrasting policies, produced by the (unbiased) simulation model results, can now provide a more rational environment where these diverse constituencies can discuss their differences and better reach a consensus.

Summary and Conclusions

This paper discussed how discrete event simulation can be effectively used to model environmental problems and shows the many advantages that simulation brings to the environmental modeling area. These two key advantages are (1) the possibility of the consideration and inclusion, in the simulation model, of all the problem characteristics, and (2) the possibility of doing so without having to resort to an oversimplification of the problem or its assumptions in the model.

Finally, we implemented a prototype simulation model and analyzed an aquatic ecosystem with it. We discussed the modeling requirements and constraints, we developed a full factorial experiment as an illustrative application, where the entire approach was implemented, we presented different uses of objective functions that can be built and contrasted, and we provided examples of how the simulation model can now be used as an arbitration tool, in addition to an analysis and design tool, to help the different constituencies arrive to a consensus.

With this illustrative example, we hope to provide an answer to the question in our initial literature search, regarding why simulation is not more widely used in this area. And we also hope to encourage the practical uses of discrete event simulation in the area of ecological modeling and analysis.

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