Proceedings of the 2010 Winter Simulation Conference
B. Johansson, S. Jain, J. Montoya-Torres, J. Hugan, and E. Yücesan, eds.

SUPPLY CHAIN AND HYBRID MODELING: THE PANAMA CANAL OPERATIONS AND ITS SALINITY DIFFUSION

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ABSTRACT

This paper deals with the simulation modeling of the service supply chain and the salinity and its diffusion in the Panama Canal. An operational supply chain model was created using discrete-event simulation. Once complete, a component based on differential equations was added to the model to investigate the intrusion of salt and the resulting salinity diffusion into the lakes of the canal. This component was implemented in the AnyLogic simulation modeling environment by taking advantage of the concept of hybrid modeling that is embedded in AnyLogic.

1 INTRODUCTION

The evolution of supply chain management has not been linear over time. Various concepts and theories have been formulated to optimize supply chains to higher and higher degrees. The reasons for optimizing supply chain systems are multidimensional and include cost minimization, increased levels of service, improved communication among partner companies, and increased flexibility in terms of delivery and response (Lancioni, Smith, and Oliva 2000; Bowersox, Closs, and Drayer 2005). In addition to the above areas, a supply chain simulation model can contribute to the understanding of other important features which are part of the complexities of a supply chain system.

In order to understand a supply chain and its complexities, we have to capture and model its structure. Simulation modeling is a very effective tool for improving our understanding of the complexities behind supply chains. Therefore, we first created a simulation model of the Panama Canal supply chain operations that includes the increased operations due to the expansion of the canal and the addition of a third set of locks.. The Panama Canal expansion through a third set of locks presents new challenges to the Panamanians. One challenge is the potential increase in salinity of the canal lakes (Lakes Gatun and Miraflores), above permissible levels, that threaten the quality of these freshwater lakes, and impact various plant and animal species, which could be negatively significant.

While studies have been conducted to verify the fresh water quality of the Panama Canal and its watershed, these investigations were made several years ago before the expansion of the canal and the impact of increased ship traffic. This fact raises the question of whether the expansion of the canal and the addition of a third set of locks is one of the conditions leading to the change in salinity of the canal lakes (Gatun Lake and Miraflores Lake). To address this question, we proposed to model the changes in ship traffic and design and implement a system that allows us to estimate accurately, reliably and efficiently, increases and /or decreases in salinity in the freshwater bodies along the Panama Canal so that we can alternatively design and implement plans to reduce or mitigate adverse effects of the increased traffic. The supply chain system we modeled must be able to see the largest possible number of variables which significantly affect the problem. Therefore, we added a component based on differential equations to the supply chain model to study the future salinity of the lakes.

2 THE CANAL'S SUPPLY CHAIN

Figure 1. depicts the Panama Canal, a shortcut between the Atlantic and Pacific Oceans that allows ships to travel in both directions across the Isthmus of Panama, saving both time and money.

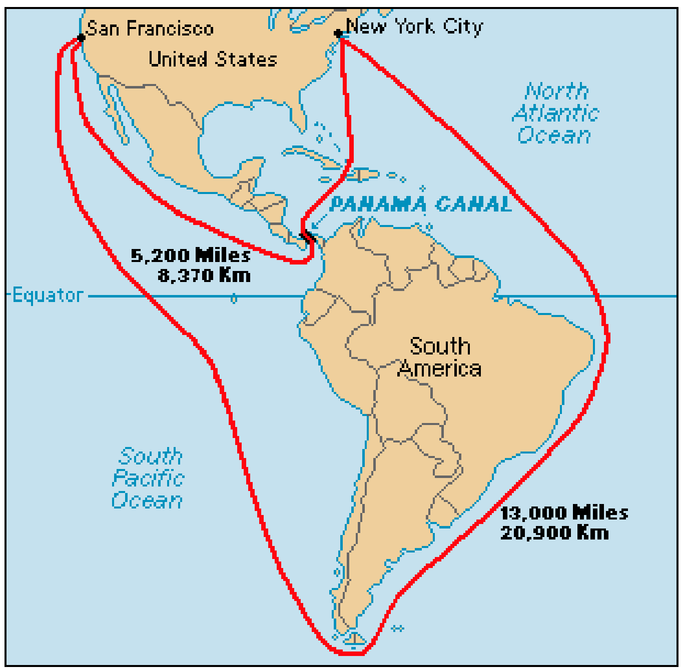

Figure 1: Shortest trade route provided by the Panama Canal (Adapted from: Council for Economic Education **(**2010)**)**

As trade continues between various countries, the need exists for mass transportation of goods. The route used before the construction of the Panama canal was to travel round the "Cape Horn" (located in southernmost tip of South America), covering a distance of approximately 24,000 Kms. (San Francisco to New York). This travel takes approximately a month. But since the construction of the Panama canal, a ship has to travel only 10,000 Kms., which is less than half the distance via Cape Horn. The use of the canal substantially saves time and cost incurred for fuel. Thus the Panama Canal has made a great impact on shipping and world trade (Global Security, 2009).

The Panama Canal supply chain participants'(Figure 2) objective is to identify operational improvements and to increase integration and communication between the supply chain members now that more and larger ships transit the canal. A major concern of this activity is the increased salinity of the canal's lakes as a result of increased ship size and traffic.

Our proposed simulation models the variation in salinity levels in the Gatun lake and the Miraflores lake. The salinity depends on different variables within the supply chain: number of vessels passing through the canal every day, temperature, size of ships, along with additional environmental factors (rain) that contribute to the variability of the phenomenon. The knowledge gained will allow us to design and construct the necessary tools for making decisions and implementing systems to mitigate or offset the increases in salinity in lakes Gatun and Miraflores and at the same time, optimize the supply chain. *This information may be used by the responsible managers to make decisions that may not only reduce damage to the lakes, but also reduce the costs of implementation, operation and maintenance of any control systems needed to be developed.*

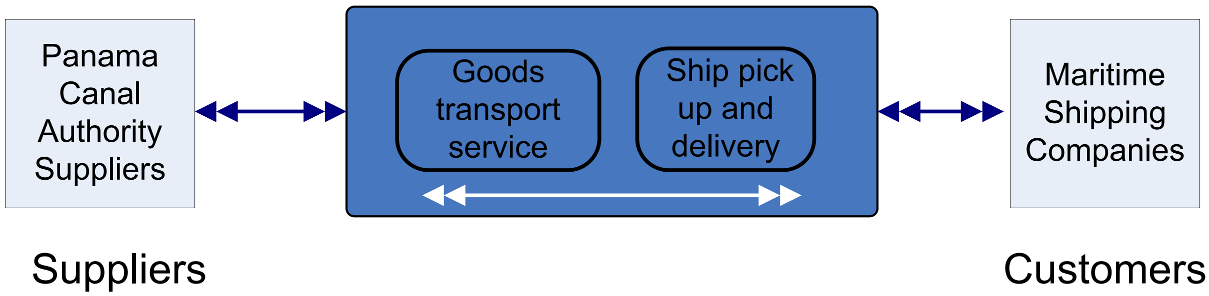

Figure 2: Panama Canal Service Supply Chain

3 SIMULATION MODEL OF PANAMA CANAL TRAFFIC FLOW

The model was built using AnyLogic, it is based on discrete event systems. This is a traditional approach to simulation. In this type of simulation system we state changes through the execution of events, which are stored in a list of events. One or more processes devoted to the implementation of the event advances the simulation time as they execute and eliminate pending events for the current time value. Thus, one can model the passage of a ship and the operations of the locks. Basically, the execution of an event can trigger the generation of new upcoming events. Each event is marked by its time, so that the order of generation of upcoming events matches the order of execution. For example, a ship crossing from the Pacific to the Atlantic passing Miraflores Locks triggers other events such as the passage through the Pedro Miguel Locks. The language constructs given AnyLogic simulation consist of the following elements for the simulation of the Panama Canal:

- State and sequence diagrams are used in discrete event models
- Action Diagrams are used to define algorithms
- Process Flow Diagrams of the basic construction are used to define the modeling process over the ships through the Panama Canal.

Figure 3 shows the flow diagrams that model the rules for the passage of a ship through the Panama Canal using the concept of "queues." Moreover, there are also stochastic and probability distributions that provide the statistical variations that can occur. This is intrinsic to a discrete-event model!

4 DATA COLLECTION

The Panama Canal is 80.5 km long and connects the Atlantic and Pacific Oceans and extends northwest to southeast. There are three locks in the Panama Canal: 1) Gatun, 2) Pedro Miguel, and 3) Miraflores that are used to raise and lower vessels to match the different sea levels. The locks are 110 feet wide, 1,000 feet long, and seven stories high (Global Security 2009). A ship entering the Canal from the Atlantic Ocean and going to the Pacific Ocean enters at the Gatun Locks. After going through Gatun Lake and Gaillard Cut, the ship enters Pedro Miguel Locks and is lowered 31 feet. After Pedro Miguel Locks, one mile later it enters Miraflores Locks to be lowered 54 feet to the Pacific Ocean. While going through the Panama Canal, a ship will be raised and lowered eighty-five feet.

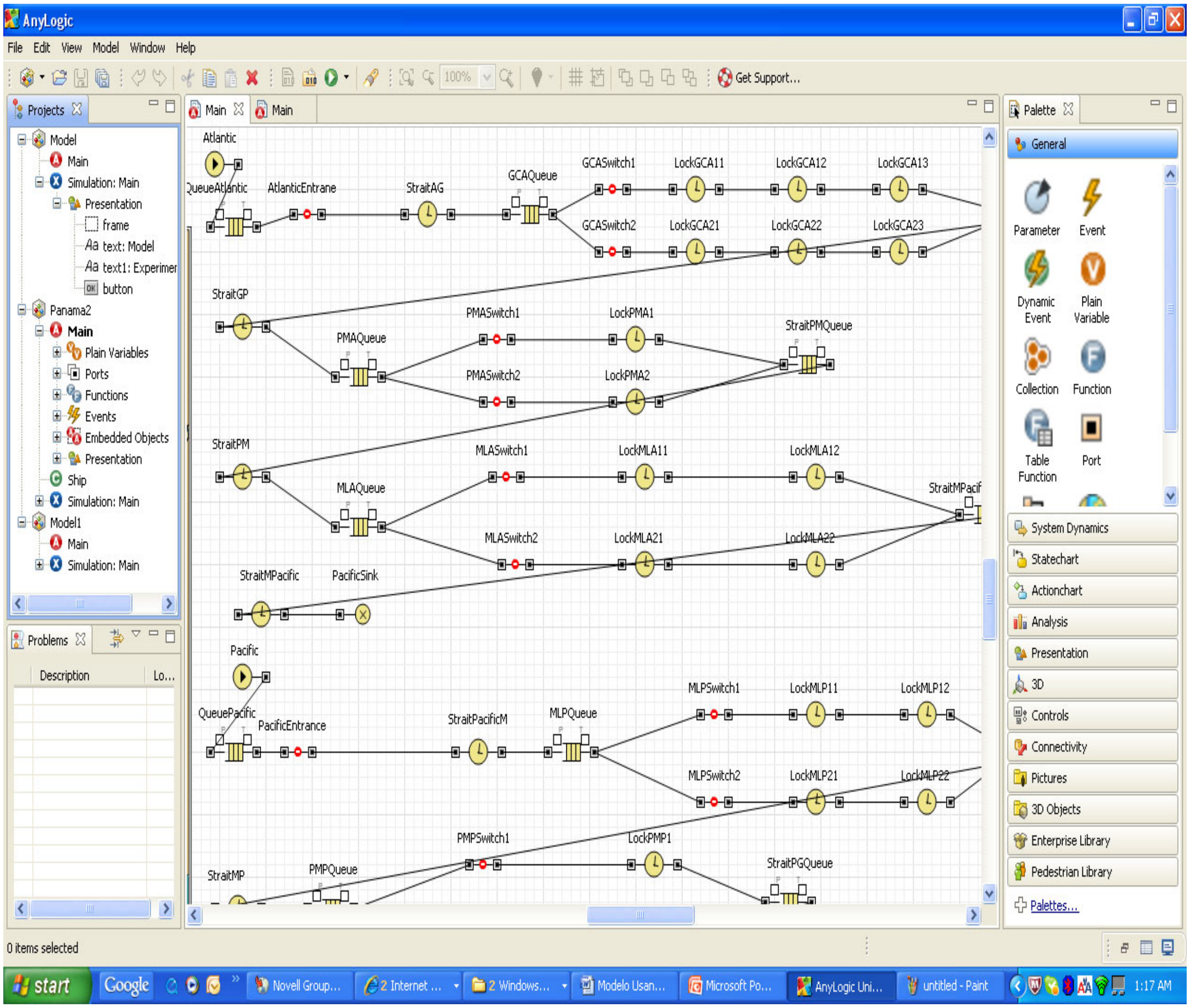

Figure 3**:** Flow Diagrams build in AnyLogic

A ship from the Atlantic Ocean enters the Panama Canal waters at the Port of Cristobal. Upon arrival in Panama Canal waters, if a ship is not scheduled to transit that day, it will drop anchor and wait for its scheduled transit time. Otherwise, the vessel will sail toward Gatun Locks. The Panama pilots take control of the vessel during its transit through Panama Canal waters. The chief pilot will instruct the ship's captain as to the speed and direction of the vessel. The chief pilot also will tell the tug operators, line-handlers, and locomotive engineers what assistance they need to provide, while the pilot remains in contact with the Panama Canal Traffic Control Center (TCC) and each lock tower. The captain relays the pilot's instructions to his/her crew members, who perform the proper maneuver (Global Security, 2009).

5 ANIMATION

The animation of the model was created using JAVA and geographical directions. The user can watch the ships pass through the locks as well as visualize the salinity changes in the lakes. The animation is scalable and hierarchical and it gives us an overview of the Panama Canal process and some aggregate indicators such as salinity. This animation background is depicted in the following figure 4.

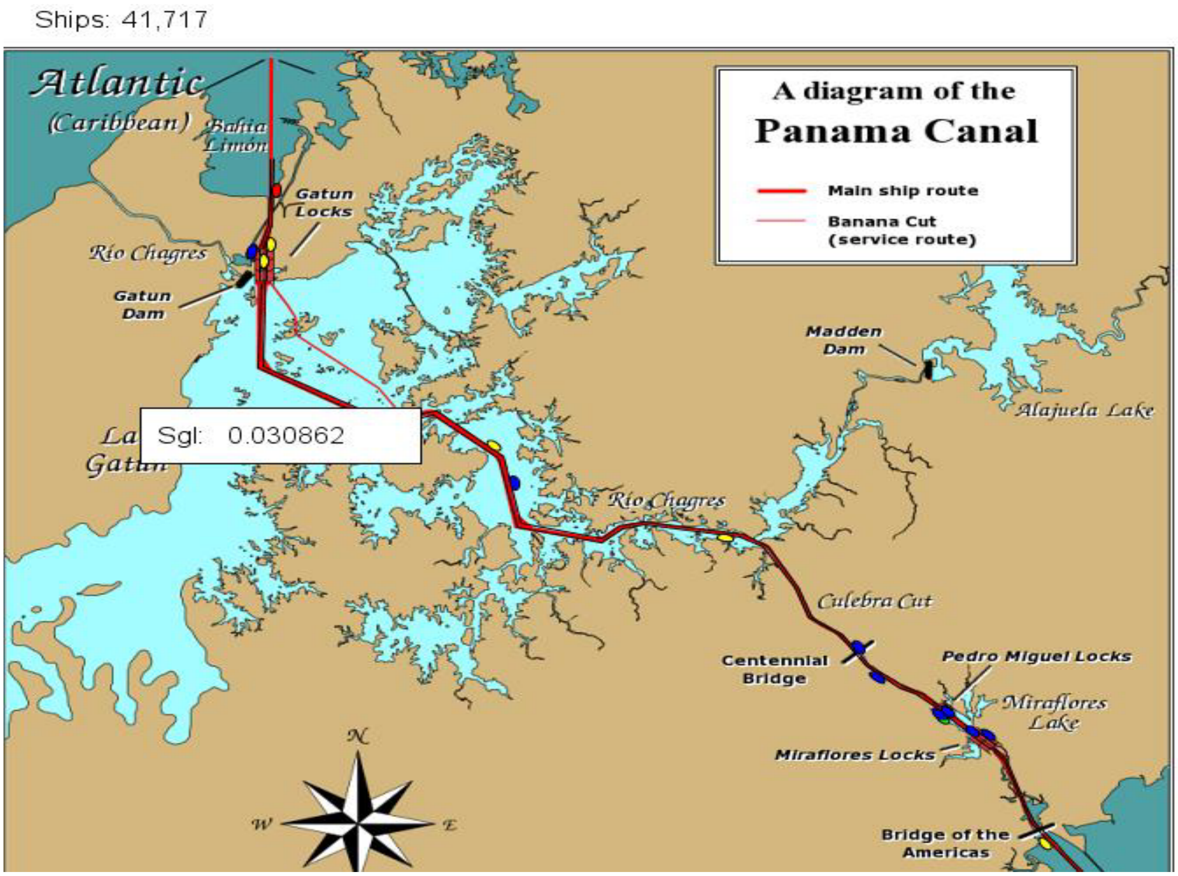

Figure 4: Animation background (adapted and modified from Tripharbour.ca (2010))

6 MODELS USED FOR SALINITY ESTIMATION

AnyLogic (XJ Technologies 2010) is a commercial simulation modeling environment that is promoted as the only hybrid discrete/continuous simulation tool. This hybrid mechanism that goes beyond discrete-event simulation allows us to model not only the discrete-event supply chain but also the salinity diffusion (that is a consequence of the supply chain interactions with the environment). AnyLogic uses concepts from the Unified Modeling Language (UML)-based simulation modeling framework and utilizes Java as the development environment to build simulation models. Specifically AnyLogic extends UML for Real Time (UML-RT) collaboration and state chart diagrams to capture sophisticated interdependencies of discrete and continuous behaviors in hybrid systems (Borshchev and Filippov 2004). The AnyLogic simulation environment offers a set of useful object libraries to be used as model building blocks. In addition, users can write Java code for any modeling purposes and add arbitrary Java modules as well to the existing libraries.

The hybrid engine is conceptually a mathematical equation solver. Figure 5 depicts the hybrid *simulation engine* architecture of AnyLogic. The discrete simulation engine generates a set of global algebraic differential equations and sends it to the mathematical solver. Based on predefined state chart and model settings, the results of the solution would indicate a threshold value has been met or a condition satisfied, then a change event occurs and the model makes the appropriate state transition. The check for the condition is performed for each time step. If the condition is true then a triggering event is generated and a transition is enabled. Otherwise the calculations continue to update the continuous variables until the next discrete event.

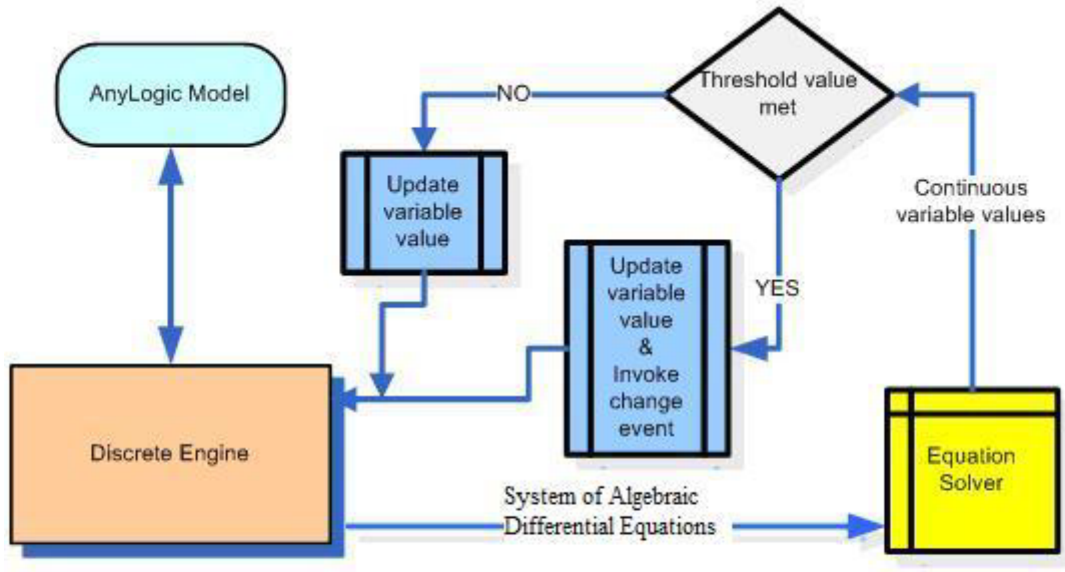

Figure 5: AnyLogic's hybrid architecture (XJ Technologies 2010)

The system state changes only by events and these events can be generated because of some continuous variables in the system. All events are timeless. Thus AnyLogic updates the state of the system in a discrete way only. Events do not change the simulation time of the system. Between the occurrences of events the time can advance and it advances in a continuous way if continuous variables are present. Otherwise the model (in a pure discrete model) would just jump between the events' time stamps. AnyLogic thus advances time during the continuous phase but it does not change the system state until the end of this phase or the occurrence of a change event due to the continuous calculations results. In either case an event would trigger a transition that changes the system state. Afterward, the continuous calculations restart using the updated system state as new initial conditions.

In the continuous phase (between discrete events) AnyLogic advances time to the nearest event (or events) in the events list while solving the algebraic-differential equations. During this phase a change event may occur. The discrete part of AnyLogic engine does not know when a change event associated with a transition occurs (It depends on the equation set being solved numerically by a continuous part of the engine to read the time for the change event). Once this happens, the clock is advanced to the time reported by the continuous-time equation solver, and the event is executed by the discrete part. The AnyLogic User Manual (XJ Technologies, 2010) considers continuous behavior affecting the discrete behavior in this way. On the other hand, each time an event is executed, the system state changes and the updated state is used in the continuous part as new initial conditions for the calculations. In fact, AnyLogic regenerates the set of algebraic-differential equations after each state update.

6.1 Gatun Lake

Using the equations for the exchange of salinity in the locks, you can develop a set a numerical and differential equations models to define the salinity in Lake Gatun, taking into account the exchange of water (and salinity) in the upper locks of Pedro Miguel and Gatun, and the water contribution by lakes Gatun and Madden tributaries that flow into these lakes. This relationship is expressed by the following equation (Parchure et al., 2004):

$$S_{GL}^{t+1} = \frac{V_{GL} \cdot S_{GL} + (V_{Madden} + V_{trib}) \cdot S_{Madden} + (V_{L3} - V_s) \cdot S_{L3} \cdot EX_{L3} + (V_{L4} - V_s) \cdot S_{L4} \cdot EX_{L4}}{V_{GL} + V_{Madden} + V_{trib} + (V_{L3} - V_s) \cdot EX_{L3} \cdot N + (V_{L4} - V_s) \cdot EX_{L4} \cdot N}$$

Where S_{GL}^{t+1} is the salinity in Gatun Lake at the end of "time step", SGL is the initial salinity in Lake Gatun (before doing the calculation), V_{GL} is the volume of Lake Gatun (annual), V_{Madden} is the volume of fresh water in Madden Lake Alajuela (annual) S_{Madden} is the salinity in Lake Madden (historically nil), V_{trib} is the volume of fresh water from rivers that flow into Lake Gatun and Madden, V_s is the average volume of water displaced by a ship, V_{L3} is the volume of water in the lock at Pedro Miguel, V_{L4} is the volume of water in the lock "greatest" of Gatun, EX_{L4}... EX_{L3} and exchange coefficients are calculated in salinity locks above Pedro Miguel and Gatun, while S_{L3} and S_{L4} are the respective salinities measured in these locks, and finally, N is the number of lockages per unit time (38 lockages per day).

To determine the salinity in L3 when the ship enters the Gatun Lake, we use the relation:

$$S10_{L3} = \frac{103.33 \times 10^3 \cdot SLG + 142.51 \times 10^3 \cdot S9 - V_s \cdot S9}{245.84 \times 10^3 - V_s}$$

and assume an average volume of travel generated by a ship of 32.29x10^3 m$^{3:}$

$$SL3 = \frac{(V_{14})(SLG) + (V_{13})(S_9)}{V_{13} + V_{14}}$$

$$SL3 = \frac{35.63 \times 10^3 - 0.25(32.29 \times 10^3)}{245.84 \times 10^3 - (32.29 \times 10^3)}$$

$$SL3 = 0.129\, ppt$$

$$SL3 \approx 0.1\, ppt$$

To determine the salinity in L4 when the ship enters the Gatun Lake, we use the relation:

$$V_{22} = 33.53m \times 326.44m \times 8.53m$$

$$V_{22} = 93.37 \times 10^3\, m^3$$

and assume an average volume of travel generated by a ship of 32.29x10^3 m$^{3:}$

$$SL4 = \frac{(V_{22})(SGL) + (V_{21})(SL4)}{V_{21} + V_{22}}$$

$$SL4 = \frac{22.02 \times 10^3 - 0.15(32.29 \times 10^3)}{240.16 \times 10^3 - (32.29 \times 10^3)}$$

$$SL4 = 0.083\, ppt$$

$$SL4 \approx 0.1\, ppt$$

$$SL3 = \frac{(V_{14})(SLG) + (V_{13})(S_9)}{V_{13} + V_{14}}$$

$$SL3 = \frac{35.63\times10^3 - 0.25(32.29\times10^3)}{245.84\times10^3 - (32.29\times10^3)}$$

$$SL3 = 0.129\,ppt$$

$$SL3 \approx 0.1\,ppt$$

To verify the behavior of the numerical model for the salinity estimation at lake Gatun, we will use data from the following table 1 in equation :

$$S_{GL}^{t+1} = \frac{V_{GL}\cdot S_{GL} + (V_{Madden} + V_{trib})\cdot S_{Madden} + (V_{L3} - V_s)\cdot S_{L3}\cdot EX_{L3} + (V_{L4} - V_s)\cdot S_{L4}\cdot EX_{L4}}{V_{GL} + V_{Madden} + V_{trib} + (V_{L3} - V_s)\cdot EX_{L3}\cdot N + (V_{L4} - V_s)\cdot EX_{L4}\cdot N}$$

Table 1. Data used for zero-order model of Gatun Lake.

Location	***Variable***	***Value***
Lake Gatún	Time interval	1 year
	Initial Salinity	0
	Volume (m^3)	5.15×10^9
Lake Madden y Tributaries	Average Volume of Madden (m^3)	1.89×10^9
	Tributary Volume (m^3)	1.28×10^9
	Salinity (ppt)	0
Pedro Miguel Locks	Annual Volume L3 (m^3)	1.45×10^9
	Interchange Coefficient	0.5
	Salinity L3 (ppt)	0.1
	Number of Lockages	38 per day
Gatún Locks	Annual Volume de L4 (m^3)	1.54×10^9
	Interchange Coefficient	0.5
	Salinity L3 (ppt)	0.1
	Number of Lockages	38 per day

The salinity level predicted at Gatun Lake is shown by the graph in figure 6.

2.2 Miraflores Lake

Using the equations for exchange of salinity in the locks, you can set a numerical model to define the salinity in Miraflores Lake, taking into account the exchange of water (and salinity) in the upper locks of Pedro Miguel and Miraflores, and the water contribution by lakes Miraflores and Madden tributaries that flow into these lakes. This relationship is expressed by the following equation:

$$S_{MF}^{t+1} = \frac{V_{MF}\cdot S_{MF} + (V_{L3} - V_s)\cdot S_{L3}\cdot EX_{L3} + (V_{L2} - V_s)\cdot S_{L2}\cdot EX_{L2}}{V_{MF} + (V_{L3} - V_s)\cdot EX_{L3}\cdot N + (V_{L2} - V_s)\cdot EX_{L2}\cdot N}$$

Where S_{MF}^{t+1} is the salinity in Miraflores Lake at the end of "time step", S_{mf} is the initial salinity in Lake Mirflores (before doing the calculation), V_{fL} is the volume of Lake Miraflores (annual), V_{Madden} is the volume of fresh water in Madden Lake Alajuela (annual), S_{Madden} is the salinity in Lake Madden (historically nil), V_{trib} is the volume of fresh water from rivers that flow into Lake Gatun and Madden, V_s is the average volume of water displaced by a ship, V_{L3} is the volume of water in the lock at Pedro Miguel, V_{L2} is the volume of water in the lock "greatest" of Miraflores, $EX_{L3...}$ EX_{L2} and exchange coefficients are calculated in salinity locks above Pedro Miguel and Miraflores, while S_{L3} and S_{L2} are the respective salinities measured in these locks, and finally, N is the number of lockages per unit time (e.g., 38 lockages per day). The salinity level predicted at Miraflores Lake is shown by the graph in figure 7.

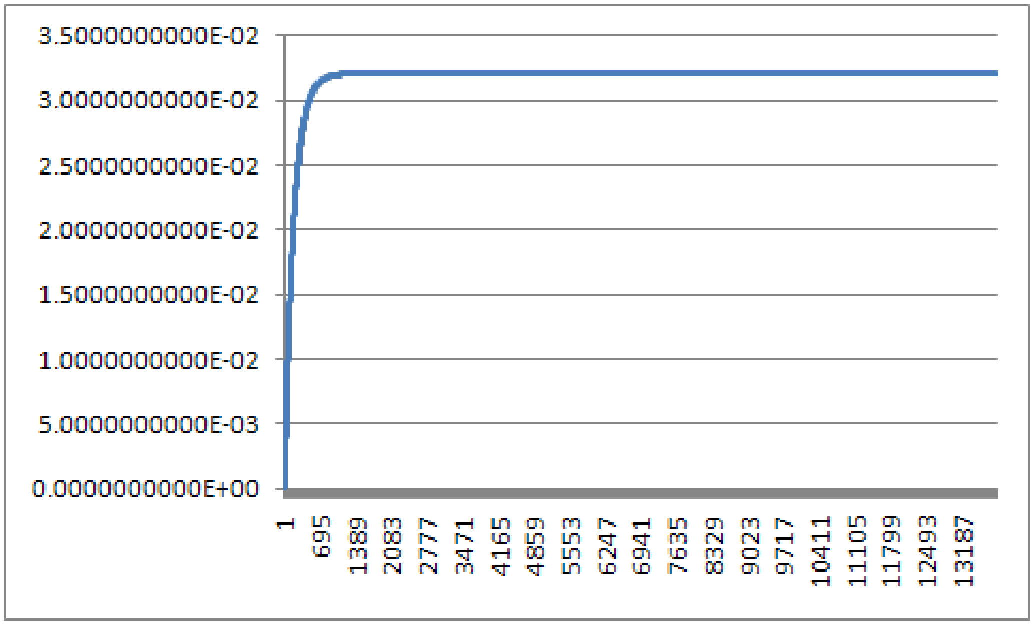

Figure 6: Prediction of Salinity Level at Gatun Lake (Predicted Level = 0.032, Actual Level Measured by Salinity Sensors = 0.032)

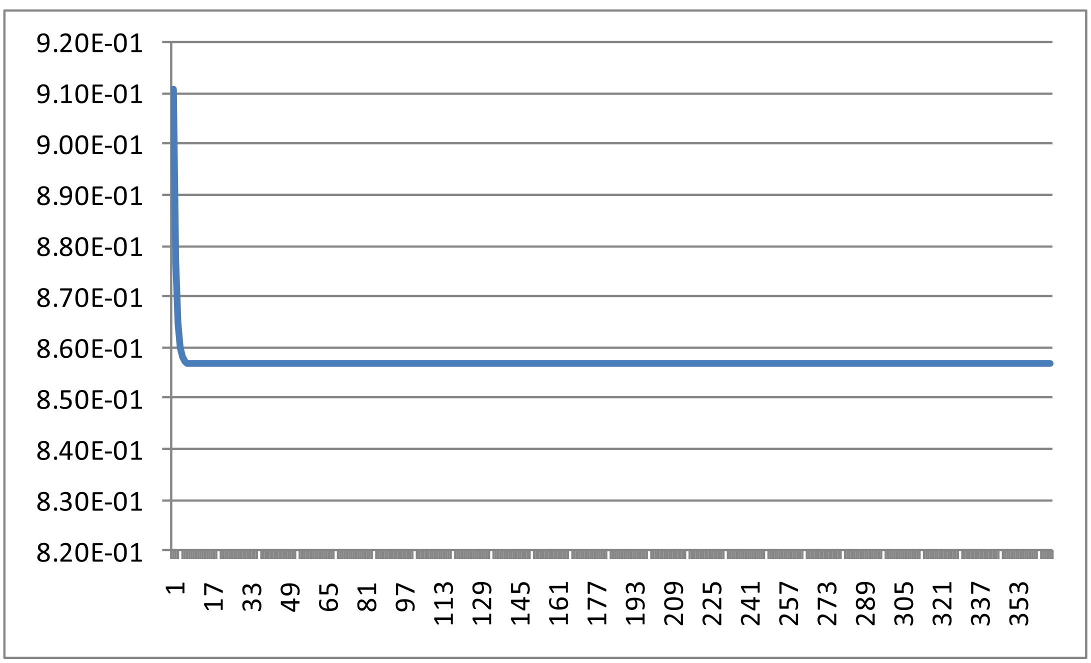

Figure 7: Prediction of Salinity Level at Miraflores Lake (Predicted Level = 0.858, Actual Level Measured by Salinity Senors = 0.85)

7 CONCLUSIONS

This research provides a unique example of applying hybrid modeling to service supply chain organizations. Hybrid modeling can benefit these organizations by providing a mechanism to view the different contributors to complex supply chains and by providing them with a highly accurate prediction capability, which takes into account the internal and external changes taking place. This work can be used in other types of supply chains.

ACKNOWLEDGMENTS

This work was sponsored by the Secretaría Nacional de Ciencia, Tecnología e Innovación (SENACYT) of the Republic of Panama under contract/project number **FID09-079.**

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