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AN ENVIRONMENTALLY SOUND FLOOD PREDICTION SYSTEM

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Abstract

The primary objective of this project was to develop an effective flood prediction system (FPS) to save the environment, properties, and lives. This system is capable of predicting downstream flood using upstream data collection. This FPS primarily uses sonar along with advanced mathematical algorithms to accurately predict downstream flood. This system monitors the development of floodwaters in various river locations. The system helps the emergency units by providing advanced warning to downstream cities that are in danger, evacuating people if necessary, and initiating flood preparation activities in critical areas. To be effective, this system must be initiated early to allow cities to evacuate people in a timely manner and to warn the emergency units ahead of the flood. To test the system, it was necessary to select a river and use it as a model to show how adjacent basins can affect the flow rate of water along its different points. The Mississippi River valley was chosen as the model to simulate and test the FPS, and to illustrate how its six basins feeding the river affects flow rate and flooding downstream.

1. Introduction

The overall objective of this project was to develop an FPS for flood prediction downstream using upstream data collection for the general benefit of the public (our customer). Using sonar along with advanced mathematical algorithms, these FPS units would be able to monitor the development of floodwaters and give advanced warning to downstream cities in danger. To be of use, the warnings would have to arrive early enough to allow cities to evacuate people and initiate emergency preparation for the flood. As a result, one has to collect data from entire river basins and understand how the intersection of rivers affects their flows. In nature, a lag time exists between the occurrence of a major rainstorm and its effects on cities located downstream from the original area affected by the storm. Thus, the initial objective of this project was to model a river and illustrate how adjacent basins affected the flow rate of water along different points of the river.

The Mississippi River valley was chosen as a model to test the FPS and to illustrate how six basins feeding one river affected flow rate and flooding downstream. The designed and developed FPS is shown in Figure 1. As Figure 1 indicates, the FPS consists of an antenna, buoyant floating ring, electronic package, which houses the sensors and an anchor that keeps the system in one location. It is also important to note that for the FPS system to effectively operate (e.g., transmit and receive information), its antenna must stay above the water more than 90% of the designate time. The designated time includes the actual data gathering time or cycle time after the FPS is successfully placed in the river.

Pertaining to this design and all its features, a patent application was filed by Dr. Bahador Ghahramani in the United States Patent and Trademark Office:

> "Emergency Marker System, Marker Device, Components Therefore and Methods of Making the Same," Patent Pending, United States Patent.

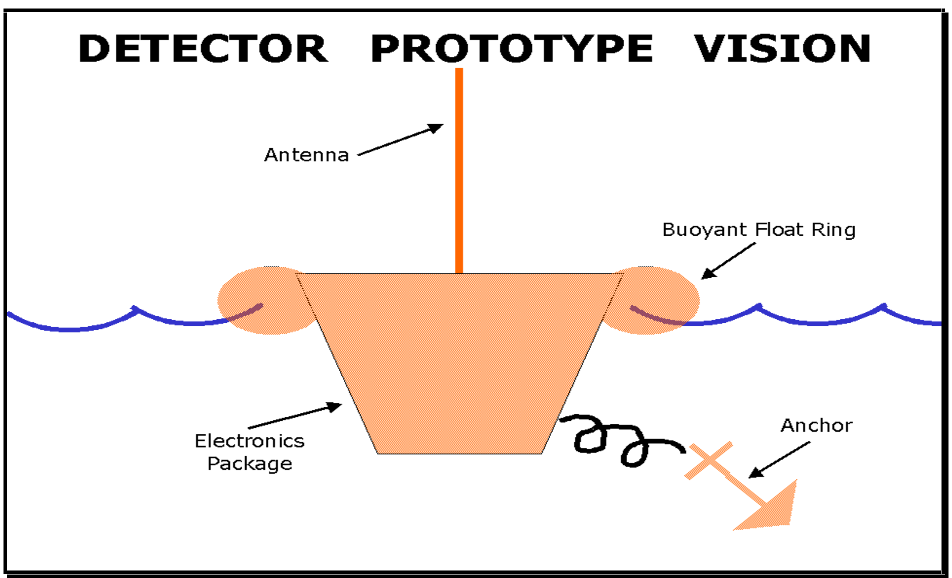

FIGURE 1, THE FLOOD PREDICTION SYSTEM.

2. Assumptions

- Sensor design, central to the FPS concept is the characteristics of its sensors that provide input to the system. The simulation was designed based on an FPS with the following characteristics:

  a. FPS units were buoyant, and attached to a fixed anchor.
  b. FPS design included sonar transponders to measure channel dimensions, water velocity, and any other pertinent hydrology metrics necessary to calculate flow rates.

c. FPS sonar sensors were capable of measuring channel dimensions within a 150-foot radius of an FPS's location. As a result, more than one FPS would need to be deployed, with an overlapping search radius, to cover most river sections.
d. Individual FPS units were capable of transmitting observed data to a central processing location.
e. FPS design was robust enough to withstand the shock of air delivery.
f. FPS's internal power supply was adequate for five days of continuous transmission.
g. System units were water proof, storm proof, and impervious to tampering.

- FPS units were deployed at an exactly known location.
- FPS units remained horizontal and buoyant throughout the simulation.
- FPS units were not affected by tidal surge.
- Each basin was emptied by a single river, joining the Mississippi River at a single junction point.
- FPS sensors were dropped at all junctions where tributaries emptied into the Mississippi River.
- FPS sensor positions accounted for all inputs to the Mississippi River.
- At each individual junction, FPS units were deployed in a pattern that provided complete coverage of the river cross-section.
- The FPS monitoring unit was capable of filtering redundant inputs.
- All FPS sensors were fully operational at the beginning of the simulation.
- All junction points in the model began with a flow rate approximately twice their steady-state volumes.
- All rainstorms affecting the Mississippi watershed began simultaneously, but varied in intensity.
- Increased flow did not alter the cross-sectional dimensions of the river channel during the simulation -- existing banks and levies remained intact.
- Flow rates within each segment of the model remained constant from initialization of the model through the time when the segment passed all storm flow from upstream locations. At that time, it returned to its steady-state flow rate for the remainder of the simulation.
- River segments that became filled to capacity continued to pass a constant volume of water, backing up preceding segments.
- All segments of the flow path began and ended at the same steady-state flow rate.

3. Analysis

To simulation run of the model, a Coast Guard boat was selected as a mean to place these FPS units at various basins adjoining the Mississippi River. Figure 2 is a simulation view of the Coast Guard boat and various FPS units, which were placed in the river. ProModel 4.0 was chosen to model the FPS, based on its superior availability, cost efficiency, and client guidance. The modeling process began with analysis of basins adjoining the Mississippi River, where excess water would flow during a strong rainstorm.

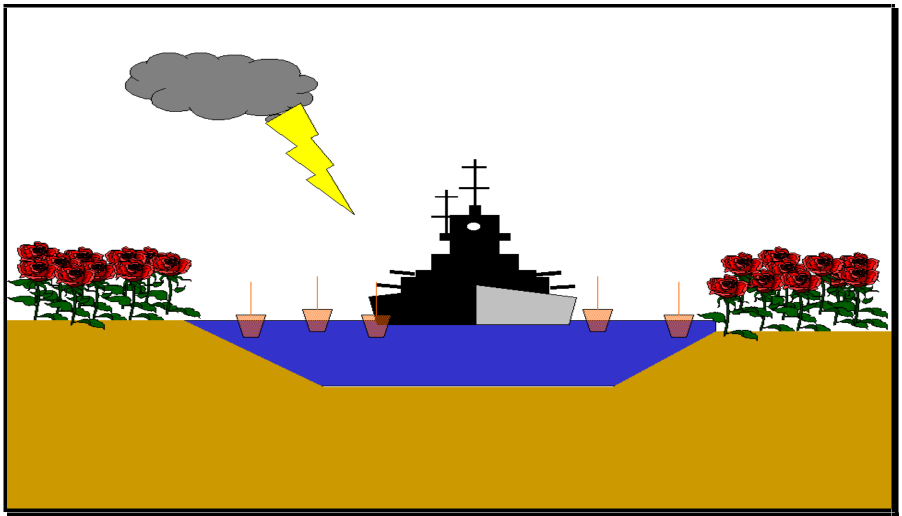

FIGURE 2, SIMULATION OF A COAST GUARD BOAT PLACING FPS UNITS IN THE RIVER.

The following adjoining basins were selected from a map of the mid-western United States: Shreveport Basin/Red River, Little Rock Basin/Arkansas River, Kansas City Basin/Missouri River, Des Moines Basin / Des Moines River, Minneapolis Basin/Upper Mississippi River, and Louisville Basin/Ohio River. River-tributary junctions along the Mississippi River were selected as gage reading points, so all interactive inputs to the river delta in the vicinity of New Orleans could be recorded throughout the model run. The following ten cities were selected as gage locations: Rock Island, Illinois; Hannibal, Missouri; Saint Louis, Missouri; Cairo, Illinois; Memphis, Tennessee; Greenville, Mississippi; Vicksburg, Mississippi; Natchez, Mississippi; Baton Rouge, Louisiana; and New Orleans, Louisiana. Another reason for selecting gage points at junctions was that those locations are most likely to experience flooding during a storm.

Elementary hydrology was used to determine the effects that each individual basin had on the Mississippi's flow rate at New Orleans. The parameters duration time of storm, time of concentration, storm intensity, size of basin, and runoff coefficients are needed to model such a problem. The model's parameters were taken from the Civil Engineering Reference Manual, which is edited by Michael Michael R. Lindeburg. Each basin in the model carried different parameters, thus they each affected the Mississippi River in different ways. For example, each different basin would have a different acreage size and runoff coefficient. The runoff coefficient is based on the type of surface, which exists throughout the basin (i.e., forested area, asphalt area, well drained lawn areas, etc). The high runoff coefficients occur in areas where water can flow easily. Thus, an area that is predominately asphalt will have a high runoff coefficient in contrast to a forested area. The forested area can absorb water into the ground and significantly decrease the amount of flow on the surface of the land. In contrast, the asphalt area cannot absorb water, and thus, all rainwater becomes surface water. The bottom line is that basins with high runoff coefficients and large areas result in high flow rates.

The modeling program chosen for this project left few options for modeling the continuous flow of liquids. In ProModel, tanks are used to keep track of the amount of flow at the different basins and gage reading locations. Since ProModel can keep track of basic tank concepts such as tank levels, rate of flow in and out of tanks, tank transfer from one tank to another, and tank capacity, it was assumed that this capability would best allow us to model basins feeding water into the Mississippi River. Figure 3 shows position of these tanks at various locations in the simulated model. As Figure 3 indicates, the simulated water level at each six basins feeding into the river at a particular time of the simulation run. Figure 3 also shows the water accumulation level in the designated ten downstream cities for a period of time.

Originally we looked at establishing processes, routing identifiers, and entities, but it was determined that these steps are too complex for the purposes of moving water from one point of the river to another. Instead, the User's Manual for Pro Model 4.0 recommended modeling all flows in the initialization logic. The main limitation to using only the initialization logic is that all flows must start immediately as the model time begins and rainstorms cannot be introduced at a later point in time. This is not a problem, though, because we could run the model for each storm and then total the output data along the time line as necessary. The important pre-defined tank subroutines that we utilized were the following: Tank_Empty, Tank_Fill, Tank_SetLevel, and Tank_TransferDownTo.

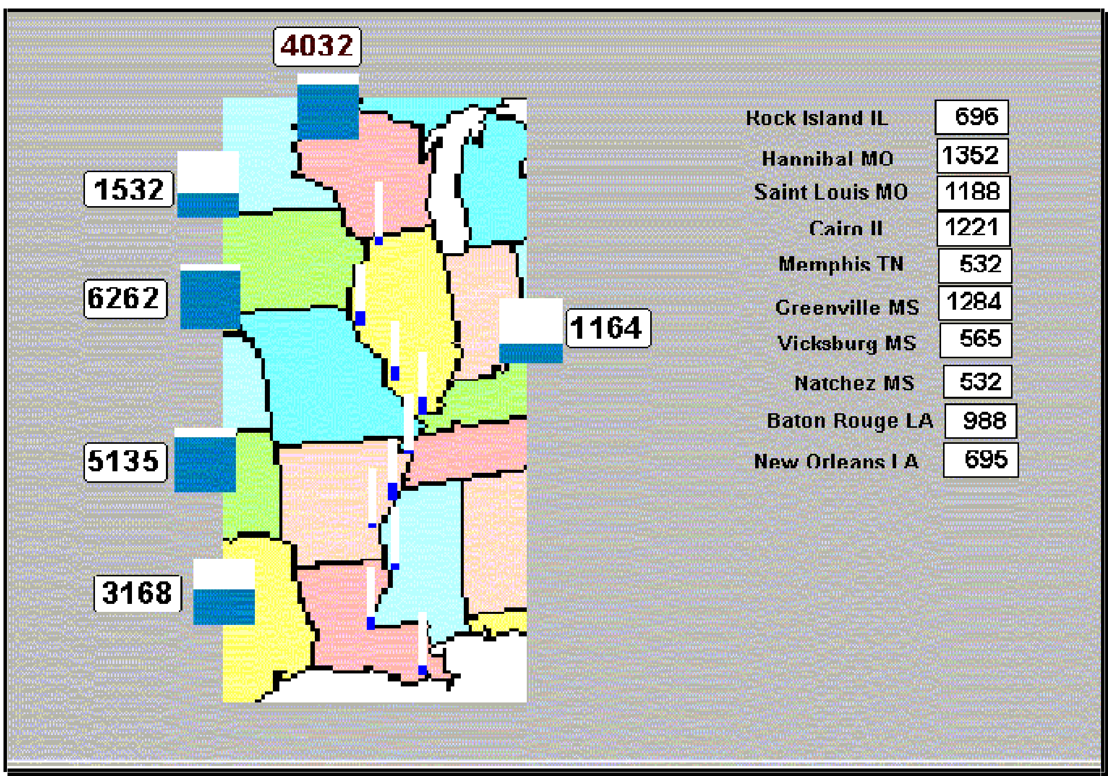

FIGURE 3, SIMULATION MODEL OF THE WATER LEVEL AT THE SIX BASINS AND TEN CITIES SELECTED AS GAGE LOCATIONS.

Tank_Empty required us to enter such parameter values as tank identification, empty quantity, empty rate, and resume level. In our model, the Tank_Empty was used only at the city of New Orleans because the destination for the incoming water was not to another tank, but rather out of the system (the Gulf of Mexico). Tank_Fill parameters included tank identification, fill quantity, fill rate, and resume level. The Tank_Fill option was used to model rainstorm events at all the different basins. Since no rainstorm around a big region drops the same amount of precipitation along adjacent basins, the fill quantity and rates differ from basin to basin to show different storm intensities and storm durations. Tank_SetLevel identifies the following parameters as important: tank identification and quantity. This option was used to model the initial water contained within each basin and corresponding river. This initial water corresponds to the warm-up period usually needed in modeling problems. Finally, the Tank_ TransferDownTo option allowed us to transfer water from basin to gage reading points and from gage reading points to other gage points along the flow direction of the Mississippi River. Tank_TransferDownTo logic also keeps water flowing regardless of the water fed through the FPS station. Parameters needed are: FROM Tank ID, TO Tank ID, TO level, FROM rate, and TO rate. Note that Pro Model 4.0 allows the individual tanks transferring water to fill at the same time that they empty.

The final model demonstrates the effects of an initial rainstorm. Unlike natural conditions, Pro Model 4.0 limited this simulation to an initial event. The program does not allow additional fluid flow to be introduced into the model at any time other than time zero. As a result, our output illustrates how an initial rainstorm affects fluid flow along the Mississippi River. To obtain rainstorm event effects starting at different times, the model was run for each event and then the data points for the later rain events were added at the appropriate delay time. For instance, if storm event A starts at time zero in the Kansas City basin and storm event B starts twelve hours later in the Louisville basin (i.e., a storm moving west to east across the Mississippi river valley) the model was run once for storm event A and it was also run once for storm event B. Then, the data output for storm event B was added to the output for storm event A starting at storm event A's twelve hour point (which is the zero hour point for storm event B).

4. Analysis of the Results

As expected, locations along the southern part of the river experienced a significant amount of flooding as compared to very little flooding along the northern portion of the river. With the introduction of lag time due to difference in time between the occurrence of a storm and its effects on cities downstream, the cities in the south will start taking on an increase in flow as the simulation moves in time. Let's begin by first looking at the characteristics of the river basins.

The following three graphs illustrate the effects of a single rainfall occurring simultaneously in all regions at time zero. As expected, rainfall increases the amount of water present in each basin. Also, representative of nature, each region accumulates and disperses water at different rates. This water is then run-off into the river, initializing the flooding process. Figures 4, 5 and show the effect of the single rainfall level occurring simultaneously in: Des Moines basin and Minneapolis basin; Kansas City and St. Louis Basins; and Little Rock and Red River Basins.

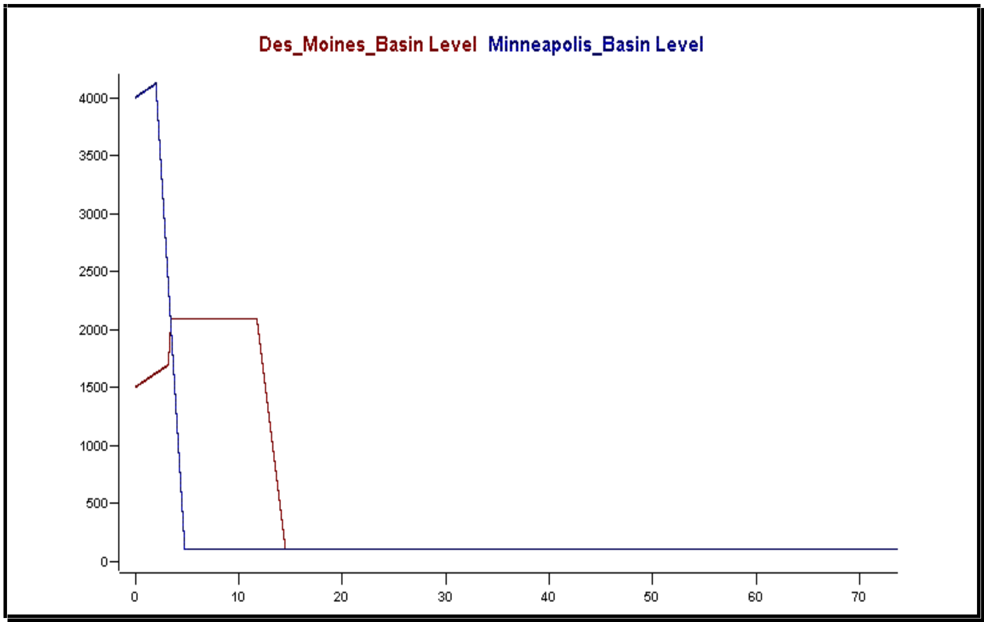

FIGURE 4, THE EFFECTS OF A SINGLE RAINFALL OCURRING SIMULTANEOUSLY IN DES MONIES AND MINNEAPOLIS BASINS.

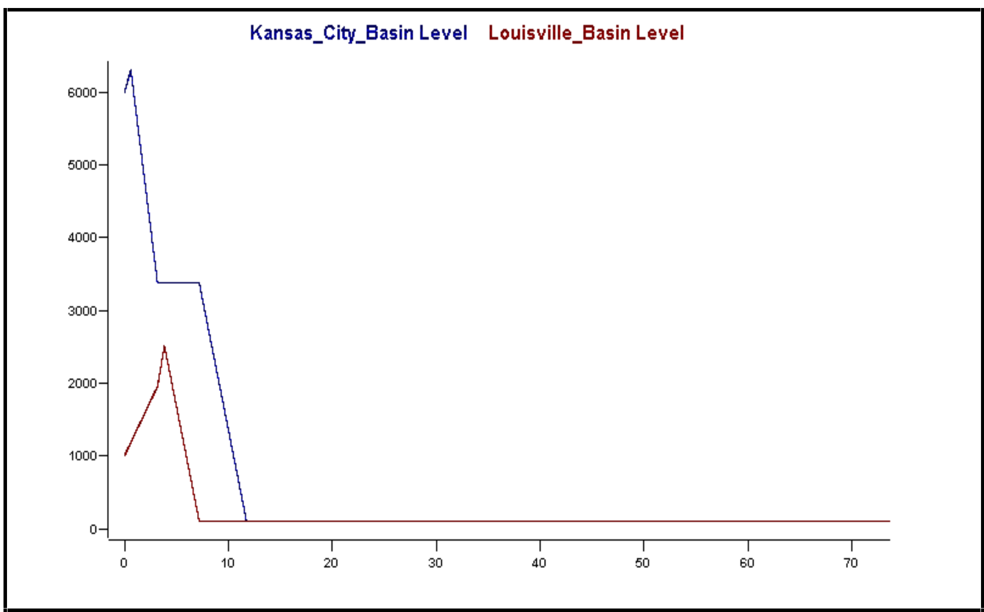

FIGURE 5, THE EFFECTS OF A SINGLE RAINFALL OCCURING SIMULTANEOUSLY IN Kansas City AND ST. LOUIS BASINS

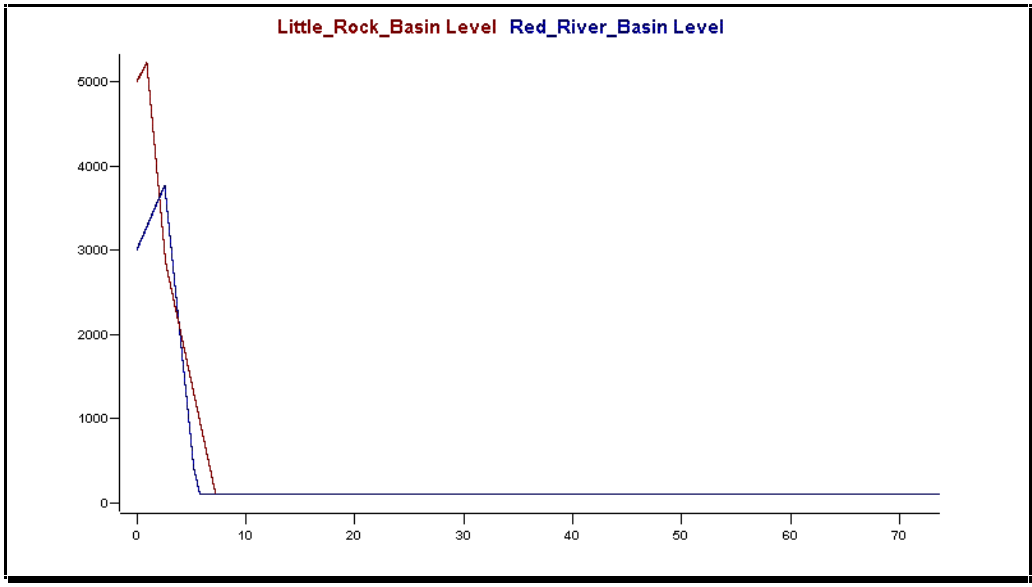

FIGURE 6, THE EFFECTS OF A SINGLE RAINFALL OCCURING SIMULTANEOUSLY IN LITTLE ROCK AND RED RIVER BASINS.

After it became evident of how the flooding process begins, it was important to look at the effects at certain points along the Mississippi River. As the river flow quickly increased early in the simulation, water levels quickly rose to the flood stage near the Midwest cities of Hannibal and Rock Island. Note that flooding will occur at different stages along the river. This phenomenon is easily explained by different bank heights, river depth, etc. These locations, however, stay flooded for only a relatively short period of time. The flow of water received from the basins has decreased allowing the outgoing flow at these locations to catch up and deliver the water further down river, which is illustrated in Figure 6.

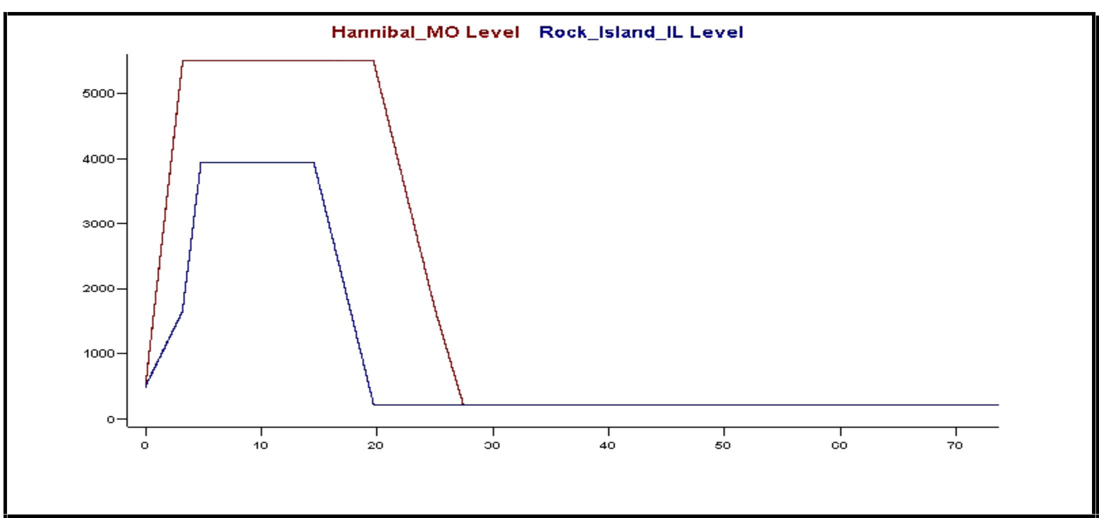

FIGURE 7, THE EFFECTS OF A SINGLE RAINFALL OCCURING SIMULTANEOUSLY IN HANIBAL AND ROCK ISLAND BASINS.

Cairo and Saint Louis are located slightly further down-river. As a result, they experience a greater volume of water flow and stay flooded for a longer period of time. In essence, water continues to flow into the system at an increased rate while it exits the system at a fairly constant rate. The volume exiting in the system, however, is not large enough to compensate for the volume entering the system, which is shown in Figure 7.

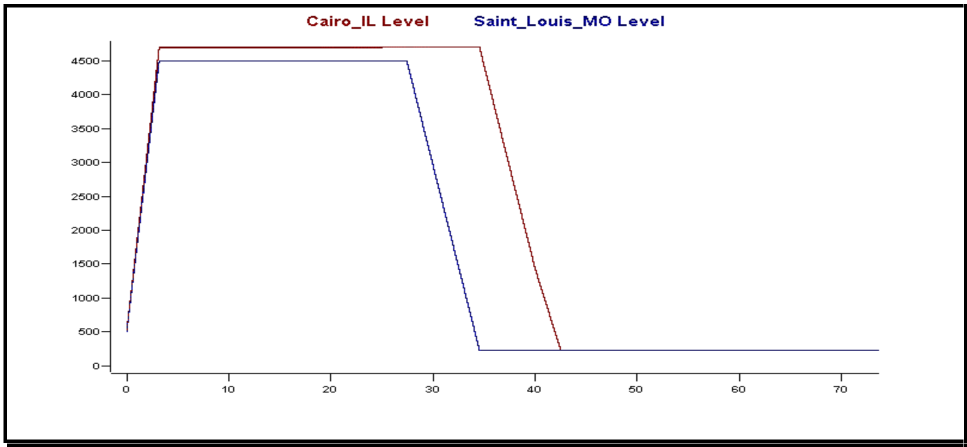

FIGURE 8, THE EFFECTS OF A SINGLE RAINFALL OCCURING SIMULTANEOUSLY IN CAIRO AND ST. LOUIS BASINS.

It was also noticed that a new phenomenon occurs in the river flow near Memphis. There are two flex points in the graph before the river reaches flood stage. The first flex point results from a delay in the initial increase in flow. Then waters from the basins arrive and flow is significantly increased. At approximately hour nine, however, the additional water received from the basins begins to dissipate. Yet inflow remains in excess of outflow and the level continues to rise at a steady rate. Greenville has a lower flood stage, which is quickly reached, which is shown in Figure 8.

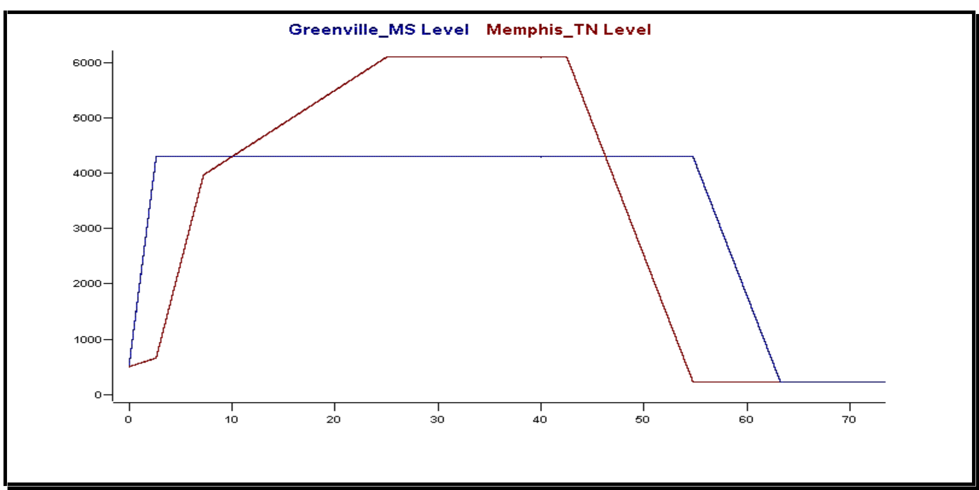

FIGURE 9, THE EFFECTS OF A SINGLE RAINFALL OCCURING SIMULTANEOUSLY IN GREENVILLE AND MEMPHIS BASINS.

Natchez and Vicksburg are located further south along the Mississippi. All the water from the basins has entered the river prior to this point and filtered through the locations further north. Thus, there was no sudden increase in flow. However, water flow had increased further up-stream. The result was an increase in outflow to an elevated constant rate. Consequently, these locations further down-stream received water at an elevated constant rate. The more gradual rate of inflow allowed these systems more time for their outflows to catch up, which is shown in Figure 10.

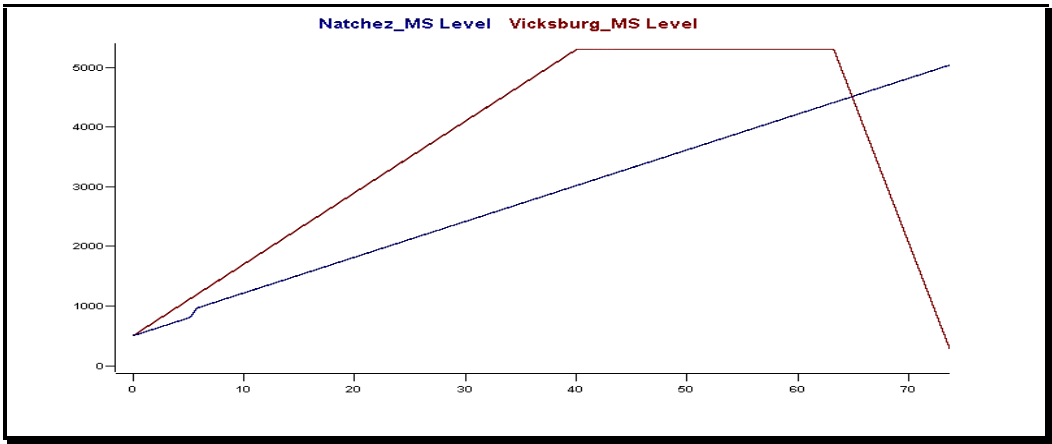

FIGURE 10, THE EFFECTS OF A SINGLE RAINFALL OCCURING SIMULTANEOUSLY IN NATCHEZ AND VICKSBURG BASINS.

The water levels at Baton Rouge exhibit a new characteristic. After reaching flood stage for a short period of time, outflows dominate and the water level decreases. Inflow then increases once again as water from up-river makes its way south, however, water flows in at the same rate at which it flows out of the system, which is shown in Figure 11.

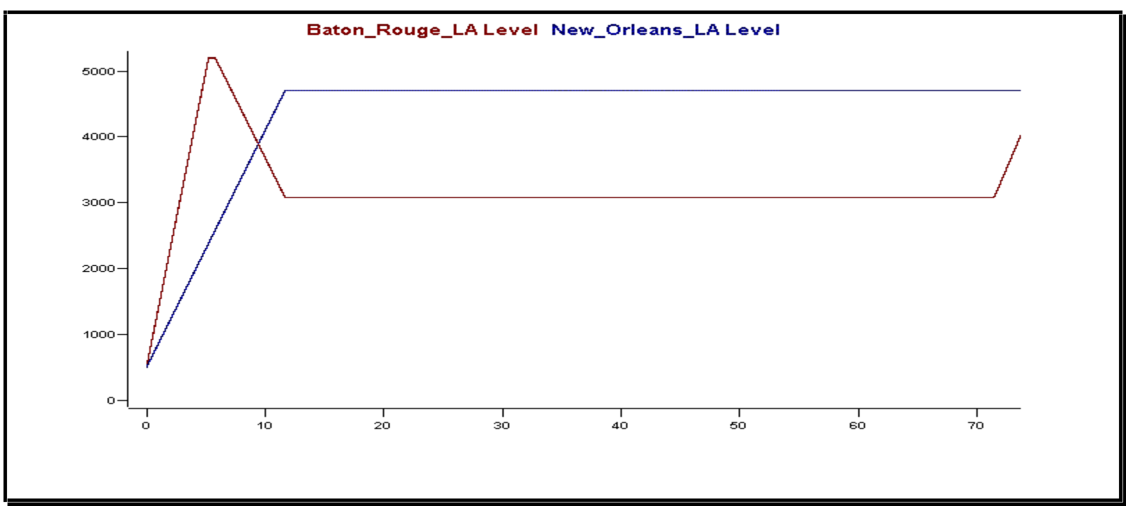

FIGURE 11, THE EFFECTS OF A SINGLE RAINFALL OCCURING SIMULTANEOUSLY IN BATON ROUGE AND NEW ORLEANS BASINS.

5. Recommendations

Locations along the river exhibit unique characteristics with regards to flood stages and water levels. Accurate data must be collected at significant points, i.e. near big cities, to establish a benchmark for when a location is in danger of flooding. If the FPS senses the river height at which flooding is immanent, it could then send a signal to the monitoring agency once that level is reached.

A flood FPS prototype will develop as soon as possible in order to do further analysis and testing of the flood monitor system. The prototype will be Global Positioning System (GPS) capable to increase its ability to accurately report its position in the river rather than determining its position via the aircraft that dropped the FPS into the river or stream. Further studies will be done for various stream and river basins to validate the model and further enhance development of the FPS and its supporting software system. This software will be developed simultaneously as the prototype so that it can be tested and validated in its beta form. The supporting software package will take all measurements and data in real time from weather agencies to help take with inputs as well as satellite data to determine runoff coefficients and basin dimensions.

According to our model, flooding can occur in a short amount of time, especially in the northern cities. Thus flooding conditions must be predicted as early as possible without giving a false alarm.

6. Conclusions

This model only scratches the surface of this problem. A detailed analysis of river and basin hydrology is necessary to develop a more accurate and realistic model. In addition, simulation software specifically designed to model fluid flow would prove a much more useful tool. With that said, the model developed for this project does provide a basic look at the effects a rainstorm has on a river, allowing us to draw some initial assumptions and recommendations regarding the flood FPS.

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Biography of the Author

Dr. Bahador Ghahramani is an Associate Professor of Engineering Management in the School of Engineering at the University of Missouri-Rolla (UMR). Prior to joining UMR he was a Distinguished Member of Technical Staff (DMTS) in AT&T-Bell Laboratories. His work experience covers several years of academics, industry, and consulting. Dr. Ghahramani has presented and published numerous papers and is an active participant and officer of various national and international organizations and honor societies. He holds three patents the "*Eye Depth Testing Apparatus*", "*A Method for Measuring the Usability of a System and for Task Analysis and Re-engineering*", and " *A Method for Measuring the Usability of a System*". He has another patent pending "*Emergency Marker System, Marker Device, Components Therefore and Methods of Making the Same*". Dr. Ghahramani also maintains copyrights on five other AT&T designs. Dr. Ghahramani received a Ph.D. in industrial engineering from Louisiana Tech University; an MBA from Louisiana State University; an MS in industrial engineering from Texas Tech University; M.S. in applied mathematics from Southern University; and a B.S. in industrial engineering from Oklahoma State University.