Physical Sciences

U.S. Army Corps of Engineers - Simulated Water Management Model (SWMM) Lesson Plan

TABLE OF CONTENTS

KEY WORDS

Endogenous Variables
Exogenous Variables
Empirical
Flood Risk
Flood Risk Management Reservoir
Hydrograph
Hyetograph
Impervious Ground Cover
Infiltration
Inflows
Interflow
Levees
Levee Failure
Runoff
Saturated Ground
Stock and Flow Relationship
System Dynamics Model

1.0. Introduction

Human civilization, for thousands of years, has been centered on sources of water, an integral aspect of survival. Rivers and lakes provide drinking water needed by people (and plants and animals). Fresh water allows for improved sanitation, preventing disease that stymied human development for millennia. It directly supports commerce and jobs that leads to the formation of cities (for example, waterways used for navigation between markets and towns). More recently, through the advent of technologies to harness and direct it, water has generated hydropower electricity that powers our homes and drives our current economy. However, water also exposes us to the destructive force of floods; the same water that gives rise to communities and civilizations also threatens people and property.

The Physical Sciences lesson is a primer on the management of water, through the use of dams that "reserve", or hold back, precipitation (inflow) and release it in a calculated fashion (outflow). Students can build intuition regarding the relationship between weather, rivers and streams, reservoirs and mitigation of flood risks through human infrastructure such as levees.

Concepts in physical science, earth science, engineering and math, and particularly concepts in hydrology and hydraulics, are covered in the discussion and use of this model and game.

1.1. Link to Curriculum

The topics covered in this lesson are closely aligned with the following standards explained in the National Research Council (NRC) document, "A Framework for K-12 Science Education": *Developing and Using Models (MS-PS1-1, MS-PS1-4), Analyzing and Interpreting Data (MS-PS1-2), Constructing Explanations and Designing Solutions (MS-PS1-6), Cause and Effect (MS-PS1-4), Scale Proportion and Quantity (MS-PS1-1) and Obtaining Evaluating and Communicating Information (MS-PS1-3).*

1.2. Summary of Model and Game

In the "model" version, students explore the relationships between rainfall, stream runoff, infiltration of ground water and inflows into a reservoir. The model also builds intuition regarding the functions of a reservoir and how it serves to mitigate flood risks.

An analytical game is also provided, which tests students' understanding of inflow relationships and flood risk management function of a reservoir. In the "game" version, students make predictions about inflows based on precipitation data, convert river flows to stocks of water held behind the reservoir, and set releases from the reservoir that will reduce the risks of flooding in a fictional downstream community. In the process, students will graph cause and effect relationships, examine the proper scale and proportion of the variables in question and make decisions under uncertainty. Students may verbalize their understanding of the concepts, data and reasoning behind their decision making. Within groups, students work collaboratively to form and revise their hypotheses and predictions, based on their developing understanding of these relationships.

The model and game are based on the operations of a reservoir during a storm event. Rain falls on an hourly time step, over the course of three days (72 hours) within the model. This rainfall is converted, through runoff and *interflow* (the horizontal flow of water through the ground) to stream flows that enter the reservoir. Some of the inflows in the reservoir must be held back (i.e. stored) and some must be released in order to prevent flooding in a fictitious downstream community. Students examine the relationship between variables (e.g. precipitation and inflow or flooding and outflow) in the model, and begin to build intuition for the proper management of the reservoir. In the game, students test their intuition by setting hourly releases from the reservoir and attempting to prevent downstream flooding or dam failure by overtopping.

2.0. The Model

Flood risk management reservoirs are designed to store peak river flows that may otherwise flood areas downstream. By storing (reserving) river flows, downstream flood risk is temporarily reduced and the stored water can be released at a later time more slowly and safely. The fundamental question facing the water manager at a reservoir during a storm (or snowmelt) event is: how much water should be stored? Conversely, how much water should be released? In order to answer this question, water managers must make predictions about the inflows (river flows into the reservoir) based on the precipitation they expect. Models assist the water manager in predicting what may happen through scenarios and simulations.

2.1. System Dynamics Models

The type of model used in this lesson is an example of a *system dynamics model* built using software called Vensim. These models are growing in popularity and use in the fields of economics, business management, life sciences, physical sciences and engineering to explain complex and interconnected operations, organizations and/or processes; also known as *systems*. The system dynamics approach to understanding complex operations, organizations and processes (e.g. systems) involves modeling the system as an array of interrelated, *endogenous* variables. System dynamics models use feedback loops and *stock and flow relationship*s to predict complex (and often confusing) behaviors and outcomes.

In the system dynamics model shown in Figure 1 (the physical sciences model view), the watershed during a storm is the modeled system. Each term (e.g. "rain") represents a model variable. The arrows between the variables represent relationships between their values. Specifically, the values of variables with arrows pointing toward them are dependent on the values of the variables to which they are connected (in other words, the variable values are determined within the system model).

Any variable with an internally determined value is known as an *endogenous* variable*.* These are the variables with values determined by the model. *Exogenous* variables have values that are entered into, rather than determined by, the model. The goal of any model is to predict the value of *dependent* or *endogenous* variables.

One of the strengths of the system dynamics approach is the ability of such models to replicate *stock and flow* relationships. In systems models, *stocks* are equivalent to accumulations of flows, for example, the water in a reservoir. Water flows into the reservoir from the rivers and out of the reservoir through the dam. The difference between this inflow and outflow is accumulated, or stored, in the reservoir, which is a stock variable. In the game, students will be asked to record and graph this stock and flow relationship.

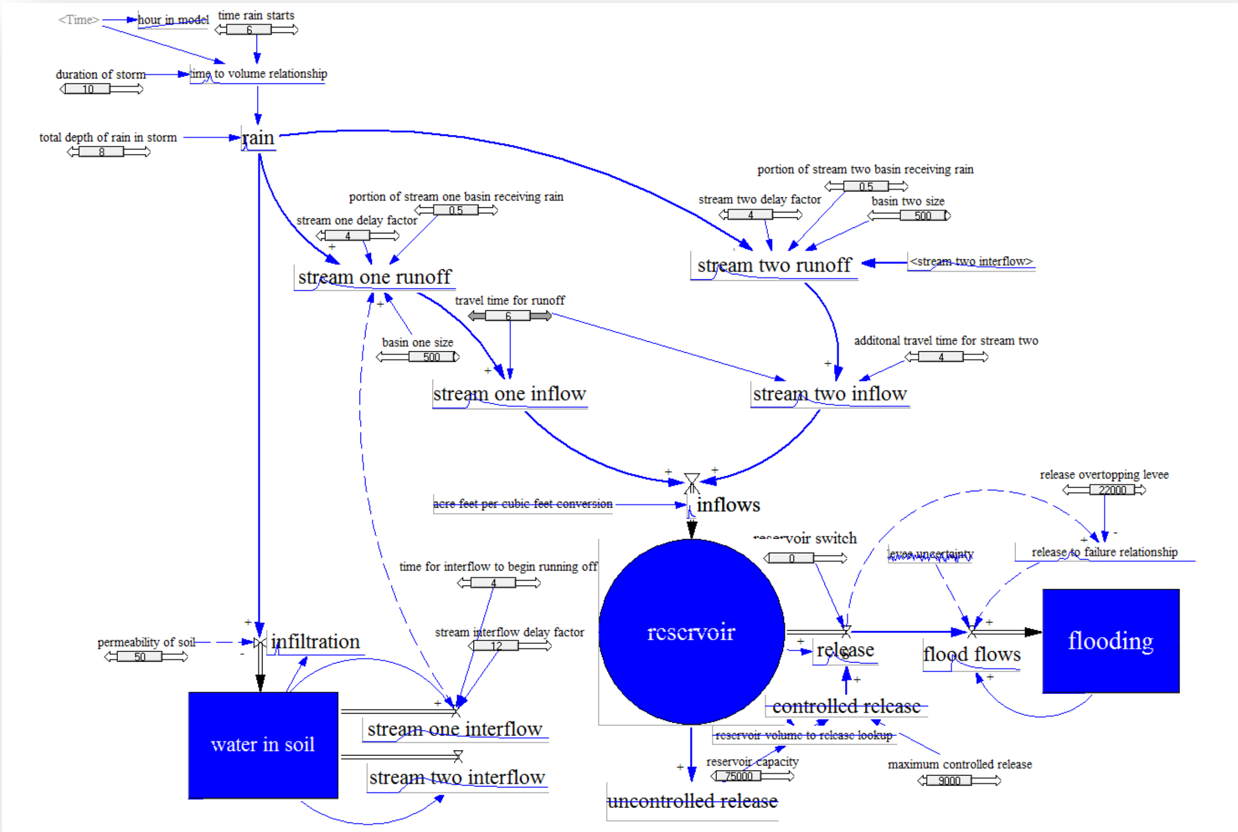

Figure 1 - System Dynamics Model (Physical Science Example)

System modeling is now its own field of study at a growing set of universities such as the Massachusetts Institute of Technology (MIT), California State University Chico (CSUC) and others.[1] The goal of this model and game is not an introduction into *system dynamics modeling*. However, students and instructors may be interested in learning more about the field and careers in system dynamics. A few useful links are provided in the footnote below.[2]

2.2. Model View

In the physical sciences "model view", each box or word corresponds with a variable in the model (other variables are hidden from view, but can be revealed in the Vensim Model Reader using the process described in the User's Guide). The variables linking with each other are mathematically defined through a system of equations (also viewable, using the process described in the User's Guide) and are symbolized by the arrows displayed on the model screen. The positive or negative

[1] MIT program in system design and management: http://sdm.mit.edu/; CSU-Chico program in Business Information Systems: http://www.csuchico.edu/cob/prospective/explore/majors.shtml

[2] System Dynamics Society: http://www.systemdynamics.org/what-is-s/, Wikipedia page on system dynamics: http://en.wikipedia.org/wiki/System_dynamics.

impact of one variable on another is illustrated by a plus (+) or minus (-) symbol displayed next to the arrow. Variables without a clearly (i.e. *monotonically*) positive or negative impact on the outcome variable lack these symbols.

2.2. Dashboard View

The physical science "dashboard view" illustrates a different perspective on variables, and it dynamically presents important behaviors produced by the model. In this view, variables of interest are grouped together by topic. They can be adjusted within a simulation of the model using the procedures described in the User's Guide, and their dynamic impact on outcome variables can be viewed in the graphs.

If a player is in model view, change the view to dashboard view to see the variables and *hyetographs* described in this section.

2.2.1. Storm Control Box

The model simulates the operation of a flood risk management reservoir based on three days (72 hours) of inflow. During this period a storm occurs. By adjusting the slider variables, values in the "storm control box", the start of storm, depth of rain and duration can all be dynamically adjusted. These variables will affect the outcomes displayed in the graphs in the dashboard view.

2.2.2. Inflows Box

The inflows box displays rainfall, runoff and infiltration relationships. The first graph in the model shows precipitation (rainfall). A graph that displays precipitation as a function of time is called a *hyetograph*.

The hyetograph shows the portion of rainwater that is infiltrated into the ground and the portion that runs off over land. The vast majority of the rainfall in any large storm is destined to either flow over land and enter the river *or* infiltrate into the ground where it may run (more slowly) through the soil, eventually entering the river.

> <u>*Example Question*</u>*: If precipitation does not equal inflow, where does the rest of the rainfall go?*
>
> <u>*Example Answer*</u>*: Some of the runoff is trapped in puddles or vegetation (and never reaches the river); some of the infiltrated water percolates into the groundwater table (and never flows into the river); some water is absorbed by plants; some water will evaporate after the storm is over.*

During a storm, most rainfall sinks into the soil until the soil has become *saturated* (e.g. full of water). Once the soil has absorbed as much water as it can, the rest of the rainfall becomes *runoff*, or water that flows over land and into the river. This model uses a common *empirically based* equation to determine the portion of the rainfall that is absorbed into the ground and the portion that flows into the steam. *Empirical* equations are those based on scientific observation and experience rather than pure theory or logic. This equation is called the *Soil Conservation Rainfall to*

Runoff Curve Number Equation.[3] An important determinant of the amount of water infiltrated into the ground in this equation is the absorbency of the ground (called the curve number). Not all soil types absorb the same amount of water.

In highly developed areas, concrete (which absorbs no water) causes it all to run off into the river (concrete has a curve number of 100). Land covered in concrete and other impenetrable surfaces (like rocks) are called *impervious ground cover.* In other areas with sandier soil, more water is absorbed before runoff begins (curve numbers closer to 30). **Students can adjust the curve number to visualize the impact of soil absorbency on infiltration and runoff by adjusting the "permeability of soil" slider.**

> <u>Example Question:</u> *How does increased development of an upstream town (building more roads, homes, buildings, parking lots, etc…) impact a downstream community's flood risks?*
>
> <u>Example Answer</u>: *Increased development can lead to more ground being covered in concrete, which absorbs/infiltrates no rainwater. As a result, the amount of rainwater that enters the stream adjacent to the upstream town as runoff increases. This results in higher downstream storm flows. These higher storm flows increase the risk of flooding in downstream communities.*

Students may notice that the amount of water infiltrated into the ground (versus running off into the river) is also influenced by the duration of the storm. Some of the water initially infiltrated into the ground will enter the river as *interflow*, which is water traveling underground parallel to the surface. Some may be percolated in the groundwater table, freeing up space in the soil to hold more water. When the duration of the storm is long enough, the ground will be saturated and subsequently partially drained (by interflow and groundwater percolation) several times during the storm.

Water travels more slowly underground where soil, plants, rock and other material present impediments to its speed. As a result, inflow begins more slowly than runoff and continues for a longer period of time. **The role that runoff and interflow play in inflows into the reservoir is displayed in graph 2 of the inflow box**.

The model includes two streams located in two separate *drainage basins*, within the same watershed. A stream's drainage basin is the area of land over which the stream's water runs off. As such, some of the rain runs off into stream #1, while some runs off into stream #2. **Students can control the amount of rainfall entering streams #1 and #2 by adjusting the size of the two basins and the portion each receives in rainfall.**

Graph 2 in the inflows box displays a *hydrograph.* All hydrographs show the flow of water (describe as a volume of water flowing through a fixed location) on the vertical axis (e.g. y-axis) and time on the horizontal axis (e.g. x-axis). Often, the flow of water (y-axis) is labeled "Q", while the time axis

[3] The SCS runoff curve number equation was developed by the Soil Conservation Service (which is now known as the US Department of Agriculture Natural Resources Conservation Service) through observation of several small plots of land used for experiments and empirical investigations. A Wikipedia page describing the equation can be found here: http://en.wikipedia.org/wiki/Runoff_curve_number.

(x-axis) is labeled "t". The shape of any river's hydrograph is influenced by the shape of the watershed. Figure 2, displayed below, shows three commonly shaped watersheds and the hydrographs associated with a point in the stream at the bottom of the watershed (displayed as a red dot). Radial watersheds tend to have relatively uniform topography (e.g. terrain). As a result, water tends to flow downstream at a relatively similar rate. The hydrograph at the end of the watershed will likely mimic the hyetograph.

The hydrograph shown in graph 2 most closely resembles the divided sub-basin type. In this example, the watershed is split into two distinct sub-basins; the dotted line in Figure 2 (below) marks the dividing line. If rain falls to the left of this line, it enters the top river. If rain falls below the dotted line, it enters the second (lower) river. The length and velocity (i.e. speed) of the flows along the two rivers will determine when flows begin to pass (and then finish passing) the hygrograph's location. If the time it takes for the flows from rivers one and two to pass the location of the hydrograph differs, the hydrograph will have two relatively distinct peaks. In the model, it is useful to imagine the red dot in the Figure 2 as the point at which flows enter the reservoir. **Students can adjust the time it takes for the flows from stream #1 and #2 to begin entering the reservoir using the "travel time for runoff" and "additional travel time for stream two" sliders.**

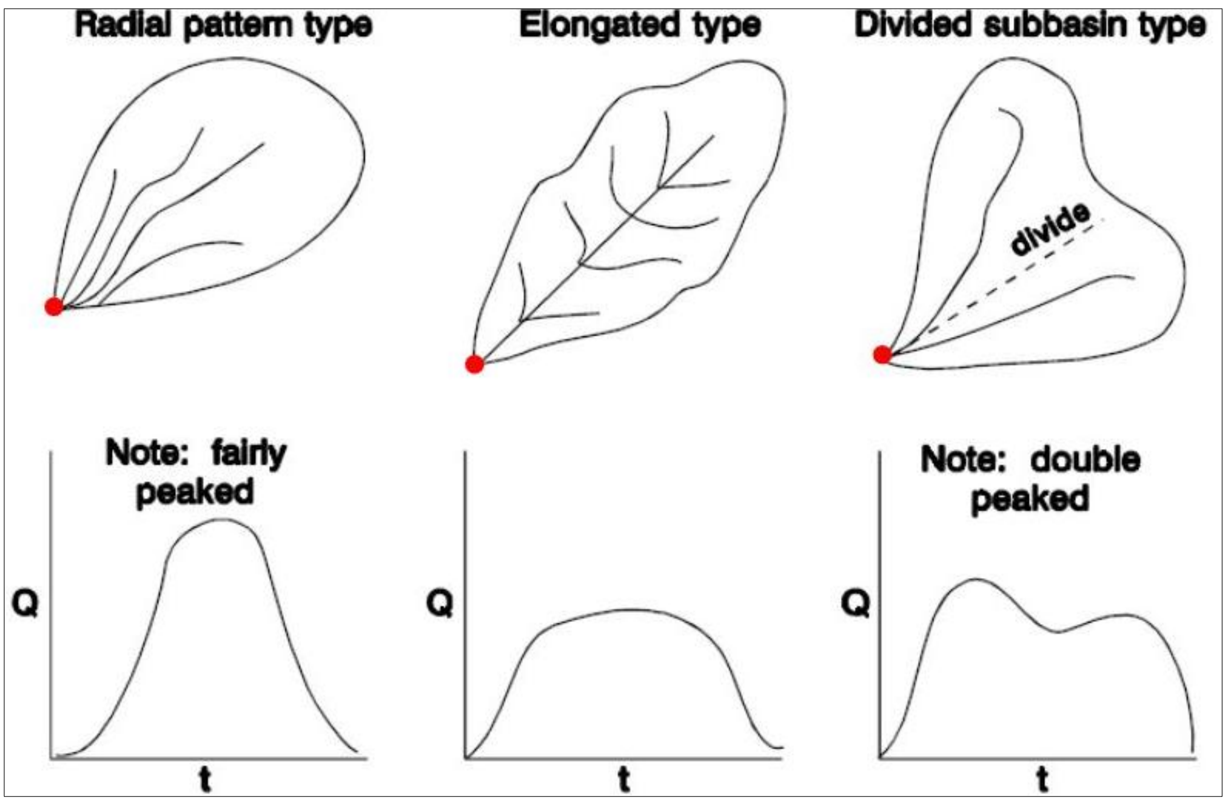

Figure 2 - Example Hydrographs

> *<u>Example Question:</u> Can you explain why the "elongated type" watershed shape produces the hydrograph shape shown in this figure?*

<u>Example Answer:</u> The "elongated type" watershed shown has a "mainstem" river fed by eight upstream tributary rivers. Flows from the most downstream tributary are likely to begin and finish passing by the location of the hydrograph (middle red dot) first. These flows, from the first tributary will be followed by the next (downstream) tributary's flows. This trend will continue until the flows from the most upstream tributary have passed the point of the hydrograph. Since the flows pass through the hydrograph's location sequentially, rather than all at once, the hydrograph is likely to rise and then fall more slowly than the other hydrographs.

<u>Example Question:</u> What sort of factors may influence the time it takes for runoff to enter the stream and flow past a downstream hydrograph location?

<u>Example Answer:</u> The steepness of the terrain: water will flow more quickly though steep terrain; The length of the river: water will take longer to flow down a longer river; the roughness of the channel and ground over which the water flows: water will be slowed down by vegetation, rocks, etc… that it "bumps into" on its way to and down the stream; etc…

2.2.3. Outflows Box

Outflows in this lesson are explained to articulate *flood risk*. A location's (e.g. home, city, farmland, etc…) *flood risks* are defined by: (1) the area's <u>probability</u> of flooding and (2) <u>consequences</u> associated with the range of possible flood events. While this model includes measurements of the probability of flooding, it does not include measurements of consequences associated with flooding. As a result, it does not model flood risk entirely (the earth sciences model includes measurements of flood consequences).

In the outflows box, the function of the reservoir and operational decisions during the storm are explored. **Students can start by moving the "reservoir switch".** When the switch is set to "0" no water is stored; inflows equal outflows. In short, water moves through the reservoir as if it did not exist. By switching the reservoir "on" (e.g. slider set to "1") and "off" (e.g. slider set to "0"), the reservoir's basic functions can be evaluated.

In the outflows box, the maximum controlled release, shown as a **slider** and **the gray line in graph 1** represent the greatest flow that will not <u>overtop</u> the levee. **The green line in graph 1** represents the greatest flow that poses no risk of levee <u>breach</u>. Above the green line, the risk of flooding is higher than 0 percent. Below the grey line, it is less than one hundred percent. Since levee breaches are unpredictable between these two lines, the risk of flooding is between zero and 100 percent. **Graph 2** shows the risk of flooding, as a result of levee failure, associated with the reservoir releases (e.g. outflows).

Reservoirs work by storing storm flows that would otherwise cause flooding and releasing water when stream flows are lower, between storms. The flooding that reservoirs are designed to reduce occurs when a stream overtops its banks or levees. *Levees* (also called dikes, embankments, flood banks or stop banks) are elongated natural or man-made ridges (e.g. mounds) or walls of fill (e.g. sediment, soil, concrete, etc…) that run parallel to the flow of water, increasing the capacity of the river to convey (e.g. move) storm flows. Figure 3 shows a simple diagram of a levee within a floodplain.

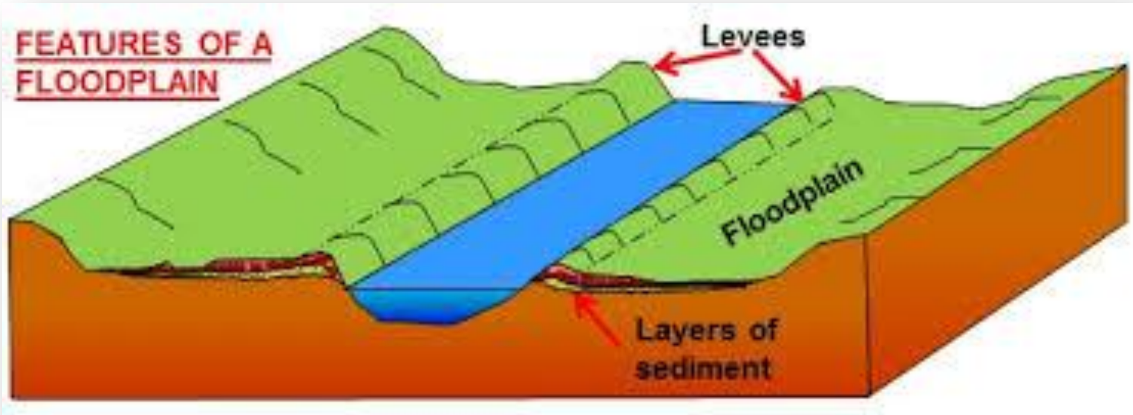

Figure 3 - Features of a Floodplain

Levees are said to "fail" when flooding occurs, because they are either: (1) *overtopped*, when water in the river rises high enough for water to flow over the top of the levee; or (2) *breach* or collapse. Figure 4 shows a photo of a levee failure (due to breach) along the Sutter Bypass in California.

Figure 4 - Levee Breach (Photo by U.S. Army Corps of Engineers)

Increasing the size of a reservoir or conveyance capacity of a levee decreases the probability of flooding under most scenarios. However, no reservoir or levee can eliminate the chance of flooding under all scenarios (e.g. storm events), and often a location's flood risk is transformed or transferred to another location, rather than reduced. In other words, actions that reduce the chance of flooding under one set of circumstances may <u>increase</u> the consequences of flooding under other circumstances. For example, when a levee is built, flood risks behind that levee are reduced for all events that do not result in levee failure. However, in the event that the levee <u>does</u> fail, the river's flood waters will enter the town as a fast moving (and more dangerous) wave, rather than rising slowly, as may have occurred before the levee's construction. Additionally, flood risks once threatening a town are transferred downstream, threatening other communities as a result of the levee's construction.

> *Example Question: What are some variables that will increase the chance of a levee failure due to breach?*
>
> *Example Answer: Higher flows in the river will increase a levee's chance of failure by putting more stress on the levee. Higher velocity flows may cause erosion that could cause a levee to breach without overtopping. Tree roots, boat docks and other natural or man-made structures placed on levees may interfere with their design and performance, increasing stress on the levee. During a storm event, this extra stress on the levee could lead to failure as a result of a levee breach.*

Students can adjust the "maximum controlled release (e.g. largest release not overtopping the levee)" and "reservoir capacity" sliders and dynamically view how these impact the probability of levee failure (graph 2) and flooding (graph 3). Note that the releases shown in **graph 1** include controlled and uncontrolled releases. Once the reservoir exceeds its capacity, uncontrolled spilled releases must be made, to bring the stock of the reservoir back down to a safe level, increasing flood risks. Therefore, increasing "reservoir capacity" lowers flood risks by making uncontrolled releases less likely. Increasing the maximum controlled release reduces flood risks by making levee overtopping less likely, and by reducing the risk of having to make an uncontrolled release.

When a levee is overtopped, it is generally severely damaged in the process. Often a section will collapse or breach, during the overtopping event. For this reason once a levee is overtopped it is assumed a breach. Therefore, all subsequent flows (after the overtopping or breach event) cause flooding until the levee can be repaired, after the storm. **Graph 3** displays the stock of flood waters escaping the river and entering the floodplain.

3.0. The Game

This section provides some basic instructions on how to play the physical sciences game (general instructions on how to play all SWMM games in Vensim are included in the User's Guide), as well as some information necessary to make decisions while playing the game. It is recommended that students construct tables and graphs similar to the example displayed below, in order to help them keep track of their reservoir's volume throughout the game, and to aid them in their decision making process.

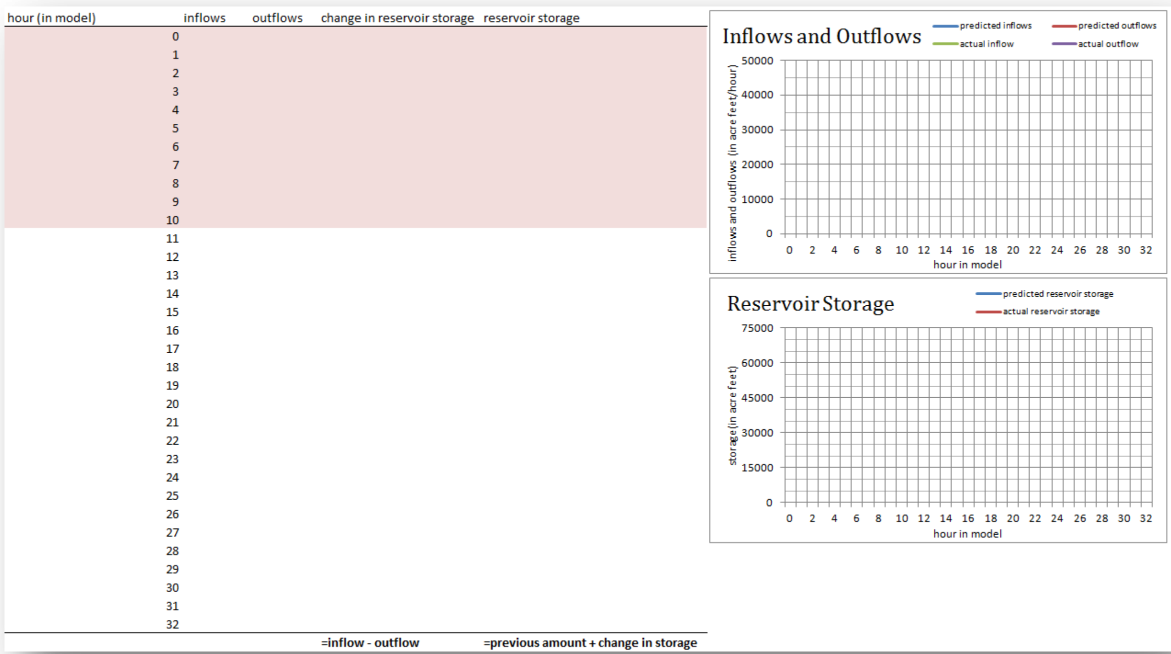

Figure 5 - Example Tables and Graphs for Game

In order to make sound decisions, students will need to use the quantitative information from the table and graphs in the "physical science game" view in Vensim.

The students will need to read the instructions provided below carefully in order to play the game. In the game, students are asked to operate the reservoir by setting controlled releases for 32 hours following a 10 hour storm. They will set these controlled releases using the "controlled release" game variable, based on conditions shown in the graphs and tables found in the "physical science game" view. Their objective is to minimize or avoid flooding.

3.1. Necessary Information

The sub-sections below detail the information players will need to successfully play the game.

3.1.1. Storm Duration

The storm starts as soon as the game begins (e.g. at time equals 0) as evidenced by the hyetograph provided in the “physical science game” view. The storm ends when the rainfall in the hyetograph returns to zero inches per hour (e.g. it does not start raining again after the initial storm has passed).

3.1.2. Reservoir Volume

The volume of water in the reservoir at the beginning of the model is zero acre feet (AF) – in other words, the reservoir is empty. The model records the volume of water in the reservoir as the sum of the previous time period’s inflows minus the previous time period’s outflows. The table below provides an example, starting with a reservoir volume of 6000 AF:

Time (hour)	1	2	3	4
Reservoir Volume (acre feet)	6000	5000	6000	?
Inflows (acre feet per hour)	1000	3000	7000	
Outflows (acre feet per hour)	2000	2000	5000	

Figure 6 - Computation of Reservoir Volumes

<u>Example Question</u>: What is the correct value for the reservoir in the time equals 4 column?

<u>Example Answer</u>: 8,000

The maximum amount of water that can be released in any given time period (e.g. the maximum outflow) is equal to the volume of water held in the reservoir during that period plus the incoming inflow. If a larger release is set (e.g. the student attempts to release more water than is currently in and entering the reservoir) the release will be reduced to the total volume of water in the reservoir (including the incoming inflows). Following such an event, the total volume of water in the next time period will be zero AF.

3.1.3. Reservoir Capacity

The full capacity of the reservoir in this game is 75,000 AF of water. If the volume of water in the reservoir, plus the current time period’s inflows, minus the controlled release, exceeds the reservoir capacity, an uncontrolled release will automatically be made (which the students cannot control) to ensure the volume in the reservoir never exceeds 75,000 AF.

3.1.4. Release Overtopping Levee

A release of 22,000 AF per hour or greater will overtop the levee and cause flooding. Once flooding occurs, all subsequent releases will result in more flooding.

3.1.5. Maximum Non-Damaging Release

Up to 11,000 AF per hour can be released with no probability of levee failure (e.g. breach or overtopping). Any release between 11,000 and 22,000 AF per hour may induce flooding (through a levee breach). The probability of breach increases as the release approaches 22,000 AF per hour. Any release greater than 22,000 AF per hour will induce flooding by overtopping the levee.

The best course of action in the game may include making a release with some probability of flooding (e.g. a controlled release of between 11,000 and 22,000 AF per hour). Students will want to consider whether many releases with a low probability of flooding (e.g. release just above 11,000 AF per hour) are preferable to making one or two releases with a high probability of flooding (e.g. releases near 22,000 AF per hour).

3.1.6. Levee Failure to Outflow Relationship

Players will minimize flooding in the game by setting prudent controlled releases. Flood risks in any given time period will be driven by the probability of levee failure, which is a function of the total outflow (e.g. controlled plus uncontrolled releases from the reservoir). The graph and table below display the risk of levee failure as a function of total outflow. As is mentioned above, releases of less than 11,000 AF per hour are associated with a zero percent chance of levee failure; releases of greater than 22,000 AF per hour are associated with a 100 percent chance of levee failure.

release	probability of failure
0	0.00
10,999	0.00
11,000	0.10
13,200	0.15
15,400	0.20
16,500	0.25
17,600	0.35
19,800	0.50
20,900	0.60
22,000	1.00
25,000	1.00

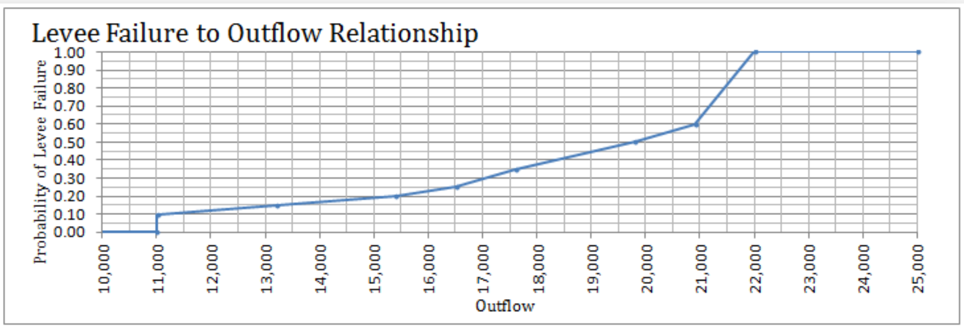

Figure 7 - Levee Failure to Outflow Relationship

3.1.7. Travel Time for Rainfall to Streams #1 and #2

Runoff from rainfall in the hyetograph will begin entering streams #1 and #2 starting at four hours after the rainfall. Interflow will also begin entering both streams within four hours. However, interflow will enter runoff into the streams much more slowly (e.g. over a longer period of time).

3.1.8. Travel Time for Stream #1 Flows

Flows entering stream #1 (upstream of the reservoir) take six hours to make their way downstream into the reservoir. Thus, rainfall that occurs in time period zero will begin to enter the reservoir in time period ten.

3.1.9. Travel Time for Flows in Stream #2

Flows entering stream #2 (upstream of the reservoir) enter the reservoir ten hours after entering the stream. Thus, rainfall in stream #2's basin that falls in time period zero will begin to enter the reservoir in time period 14.

3.1.10. Conversion from Cubic Feet to Acre Feet
There are 43,560 cubic feet in one AF of water. Flows into the river at the upstream gauges are measured and displayed (e.g. in graph 2 and the "physical sciences game" view table) in cubic feet per second (cfs). Inflows, outflows and reservoir volume are measured in AF per hour (e.g. inflows and outflows) or AF (e.g. reservoir).

3.1.11. Conversion from Seconds to Hours
There are 3,600 seconds per hour. Stream flows upstream of the reservoir are measured in cfs. Inflow and outflow from the reservoir are measured in AF per hour.

3.2. Game Instructions
The game begins with the onset of a storm. Flows are delayed in the game, as they are in real life; therefore, the reservoir is empty before the first inflows arrive (time period ten). Players will want to use the information provided in the first ten time periods to make predictions about future inflows and determine the volume of their first controlled release. However, since no release can be made in the first ten time periods, players can advance through these time periods quickly (instructions on how to advance in the game are provided in the User's Guide). Players may make releases between time period ten and time period 32 (the end of the game). The goal of these releases should be to prevent flooding. The winning player(s) will have the smallest amount of flooding in the game view table in the final time period (time period 32).

Players will want to use the downloadable excel file to enter and graph their predictions about inflows, outflows and reservoir volumes, using the data in the game view graphs and tables. When using information from the hyetograph for stream (rather than reservoir inflow) hydrographs to make predictions about future inflows, outflows and reservoir volumes, players will need to be careful to make proper unit conversions.

3.3. Example Game Solution and Message

As in the real world, many "good solutions" to the game fail and some "sub-optimal solutions" succeed, primarily as a result of the uncertain (e.g. random) levee failure in the model. While an optimal *apriori* decision exists (based on the probability of levee failure associated with various releases), the solution requires a combinatorics answer that is far beyond the skill set of most middle and high school students. Furthermore, even this "theoretically optimal solution" may induce flooding, due to the random chance of levee failure for a given outflow; while a less theoretically optimal solution may induce no levee failure or flooding.

hour (in model)	inflows	outflows	change in reservoir storage	reservoir storage
0	-	-	-	-
1	-	-	-	-
2	-	-	-	-
3	-	-	-	-
4	-	-	-	-
5	-	-	-	-
6	-	-	-	-
7	-	-	-	-
8	-	-	-	-
9	-	-	-	-
10	1,814	-	-	-
11	6,480	1,814	1,814	1,814
12	16,353	6,480	4,666	6,480
13	15,577	10,999	9,873	16,353
14	14,590	10,999	4,578	20,931
15	17,114	10,999	3,591	24,522
16	25,462	10,999	6,115	30,637
17	23,480	10,999	14,463	45,100
18	19,866	10,999	12,481	57,581
19	17,184	15,400	8,867	66,448
20	15,254	15,400	1,784	68,232
21	13,675	10,999	(146)	68,086
22	12,435	10,999	2,676	70,762
23	11,352	10,999	1,436	72,198
24	10,502	10,999	353	72,551
25	9,758	10,999	(497)	72,054
26	9,022	10,999	(1,241)	70,813
27	8,217	10,999	(1,977)	68,836
28	7,547	10,999	(2,782)	66,054
29	6,984	10,999	(3,452)	62,602
30	6,507	10,999	(4,015)	58,587
31	6,098	10,999	(4,492)	54,095
32	5,745	10,999	(4,901)	49,194
			=inflow - outflow	=previous amount + change in storage

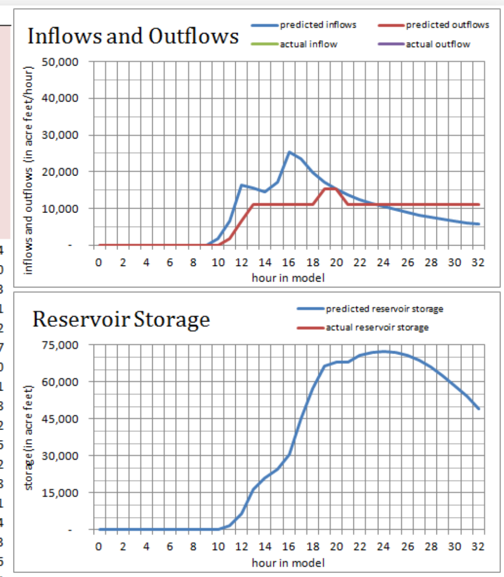

Figure 8 - Example Solution

Water resources decisions are complex and often the set of "right" and "wrong" answers is unknown or only available after the fact. Many times, well reasoned decisions fail. However, as players come to appreciate, poor results do not negate the importance of rigor and well reasoned decision making.