Earth Sciences

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

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KEY WORDS

Acre Foot of Water
Empirical
Endogenous Variables
Exogenous Variables
Flood Risk
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Saturating Rainfall
Stock and Flow Relationship
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Thornthawaite Equation

1.0. Introduction

Water is essential to our survival and prosperity. However, living so close to water also has its risks (namely flooding). As a result, many of the largest and most important pieces of human infrastructure are built to maximize the benefits of water (e.g. water supply for crops, drinking and commerce; navigation along rivers; hydropower; etc…) and minimize the risks (e.g. flooding and drought, etc.).

In the Earth Sciences lesson, students study the size and function of a dam and reservoir using a real-world water resources model, and they examine earth sciences concepts such as precipitation, infiltration of rainwater, percolation of groundwater, snowpack, runoff and evaporation, as well as the impacts of these factors in the construction of a reservoir. The model illustrates the dynamic impact of natural and human factors impacting the processes (e.g. the impact of temperature on evaporation or the impact of human development on runoff and flood risks). Finally, students are asked to play a game in which they, as water resource managers, attempt to select the optimal size of a new dam and reservoir. The game tests the students' abilities to work collaboratively within a team to apply the concepts introduced in the model, and to compete against other teams to build the best reservoir (i.e. the least cost/smallest reservoir that will prevent flood damages over a four year period).

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, percolation of ground water and inflows into a reservoir. The model also builds the students' intuition regarding the function of a reservoir and how it mitigates flood risks.

An analytical game is provided, which tests students' understanding of inflow and outflow relationships, and the flood risk management function of a reservoir. In this game, students are asked to select the proper size for a new reservoir based on predictions on inflows, conversion of river flows to stocks of water held behind the reservoir and the set releases and natural outflows from the reservoir. In the process, students will learn about the function of a dam and reservoir and its relation to precipitation, runoff, infiltration, interflow and percolation; students will also examine the proper scale and proportionality 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 their groups, students will work collaboratively to form and revise their hypotheses and predictions, based on their understanding of these relationships.

The model and game are based on the operations of a reservoir over a four year period of time. Rain falls on a monthly time step over a four year period within the model. This rainfall is converted, through runoff and *interflow* (the horizontal flow of water through the ground) to stream flows, which 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 downstream flooding and associated flood damages in a fictitious downstream community.

Students are able to dynamically examine the relationship between variables of interest (e.g. precipitation and inflow or outflow and flooding) in the model; by doing so, they build an intuition for the proper sizing of the reservoir (i.e. how large does the reservoir need to be in order to maximize flood risk reduction while minimizing cost). In the game, the students will use inflow and outflow relationships to correctly choose the size of a new dam and reservoir in order to safely pass flood waters in an attempt to prevent flooding under four different scenarios.

2.0. The Model

Flood risk management reservoirs are designed to store (in a lake) peak river flows that may otherwise result in flooding. By doing so, river flow is temporary reduced and the stored water can be released more slowly and safely when the river flow is naturally lower. The fundamental question facing the students is: what should the reservoir size (capacity) be in order to prevent flood damages downstream while minimizing cost? In order to answer this question, the students must make predictions about the inflows (river flows into the reservoir) based on the precipitation (or snowmelt) that they expect will occur.

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 where they are used 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 otherwise confusing behaviors and outcomes.

In the system dynamics model shown in Figure 1 (the earth sciences model view) the watershed is the modeled system. Each term (e.g. "precipitation") 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 which 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.

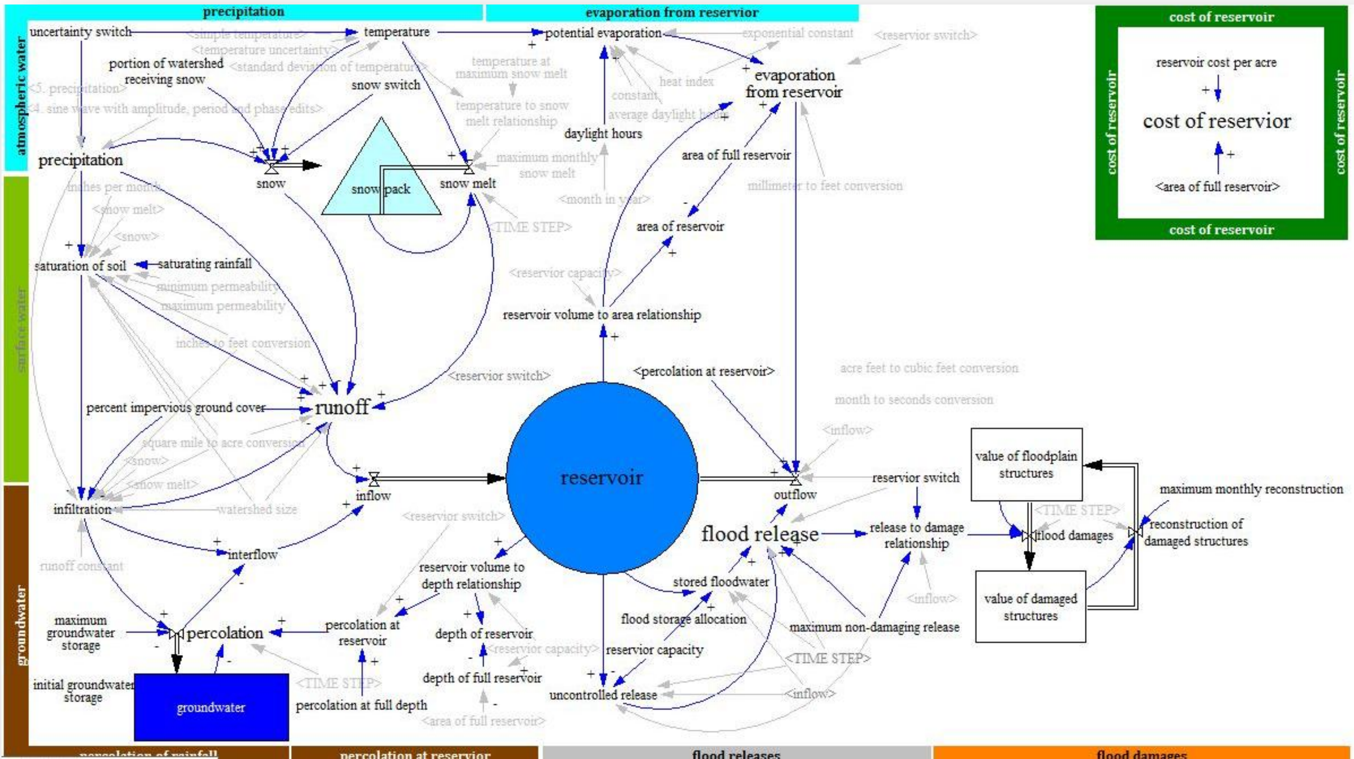

Figure 1 - System Dynamics Model (Earth Science Example)

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 at Chico (CSUC) and others.[1] The goal of this model and game is not to serve as an introduction into *system dynamics modeling*. However, should students and or instructors be interested in learning more about the study, field or careers in system dynamics a few useful links are provided in the footnote below.[2]

2.2. Model View

In the "earth science model view", each box or word corresponds with a variable in the model (more variables are hidden from view but can be revealed in the *model reader* using the process described in the user's manual). These variables' linkages with each other are mathematically defined through a system of equations (that can be viewed using the process described in the user's manual) and symbolized by the arrows displayed on the model screen. The positive or negative impact of one variable on another is symbolized by the "+" or "-" sign displayed next to the arrow. Variables without a clearly (e.g. monotonically) positive or negative impact on the outcome variable lack a "+" or "-" symbol.

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[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.

2.2. Dashboard View

The earth science “dashboard view” in Figure 2 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.

Figure 2 - Earth Sciences Dashboard View

The earth sciences model exposes students to key components of the cycle of water – particularly the portions of this cycle manipulated by people. These include the relationships between precipitation and runoff, infiltration, ground water percolation and interflow; temperature and snow fall, snow melt evaporation and flood flows. The function of a reservoir and its role in interrupting flooding is also displayed dynamically in conjunction with the other model variables. The model displays four years in the life of a reservoir, measured on a monthly basis.

2.2.1. Function of a Reservoir

In the “function of a reservoir” box, the function of the reservoir and operational decisions during a storm are to be 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.

The earth sciences model is based on four years in the life of a flood risk management reservoir; during this period storms occur. By adjusting the slider variables values’ in the “earth sciences dashboard”, the “flood storage allocation”, “maximum non-damaging release”, “uncertainty”, “percent change in precipitation range”, “saturating rainfall”, “water table depth”, “percent change in temperature range”, “area of full reservoir”, “initial groundwater storage”, “hydraulic conductivity”, “snow” and “percent of watershed receiving snow" can all be dynamically adjusted. These variables will affect the outcomes displayed in the graphs discussed below.

Graph 1 labeled "1. Inflows into Reservoir" (shown in Figure 3) displays the inflows entering the reservoir over a four year period. Months 1, 13, 25 and 37 represent January of years 1, 2, 3 and 4 respectively. As is the case in most of California, inflows are highest in the winter (rainy) months and lowest in the summer (dry) months. Inflows are measured in acre feet (AF) per month. An *acre foot of water* is the volume of water that would cover an acre with a foot of water. It is the common unit of measurement for the volume of storage at U.S. reservoirs.

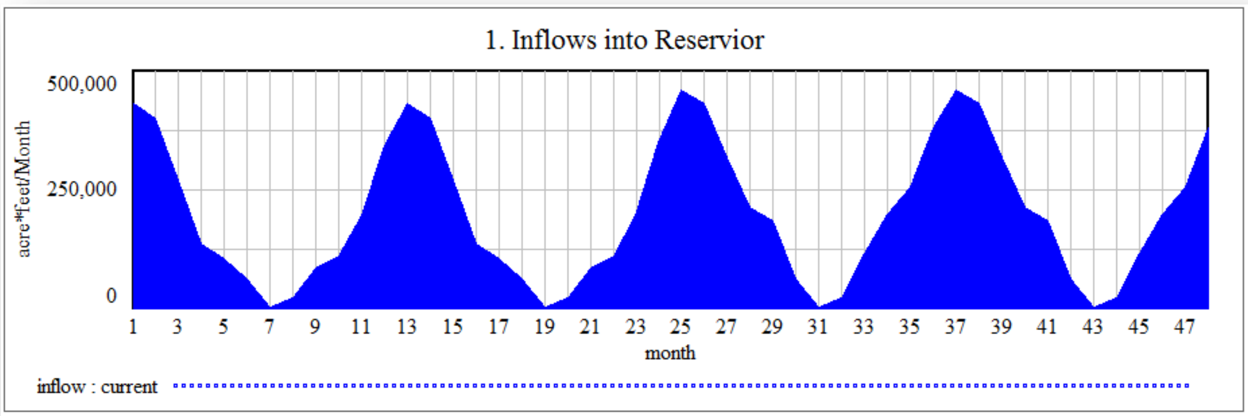

Figure 3 - Inflows into Reservoir

Graph 2 labeled "2. Water Stored at Reservoir" (shown in Figure 4) displays how the reservoir alters the rivers' flows over time. In this graph, the red line shows the inflows, which are equivalent to outflows in the event that no reservoir is built. As the inflows on the river increase, the flood releases from the reservoir (blue line) also increase, but only to a point. The points at which the outflows stop increasing (the flat parts of the blue line) represent the highest safe (e.g. non-damaging) outflow from the reservoir.

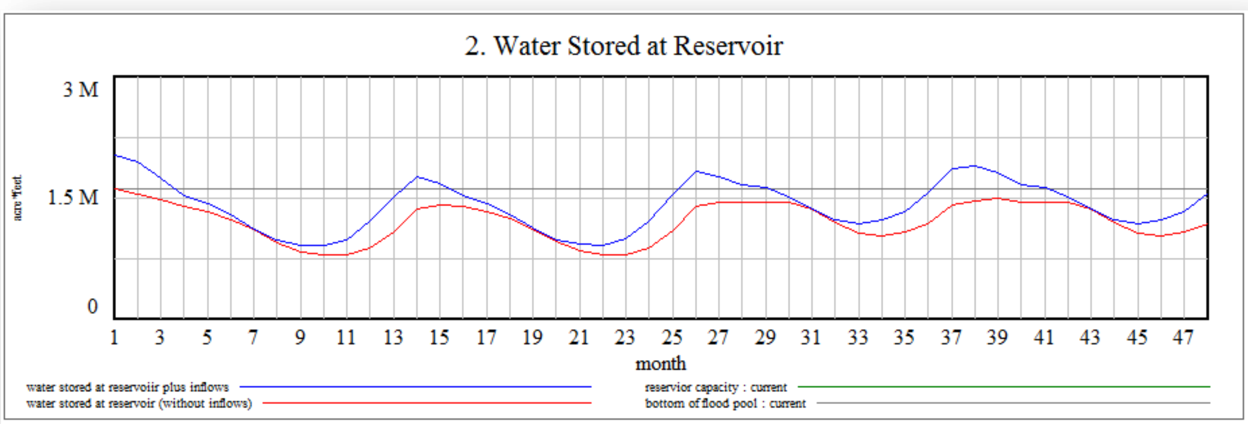

Figure 4 - Water Stored at Reservoir

Any inflow above this line is stored in the reservoir. Notice that in less rainy months the flood release (blue outflow) exceeds the red inflow line. This is the period in which the stored flood flows are being released back into the river.

Graph 3 labeled "3. Flood Releases" (shown in Figure 5) displays the impact that reservoir has on flood damages.

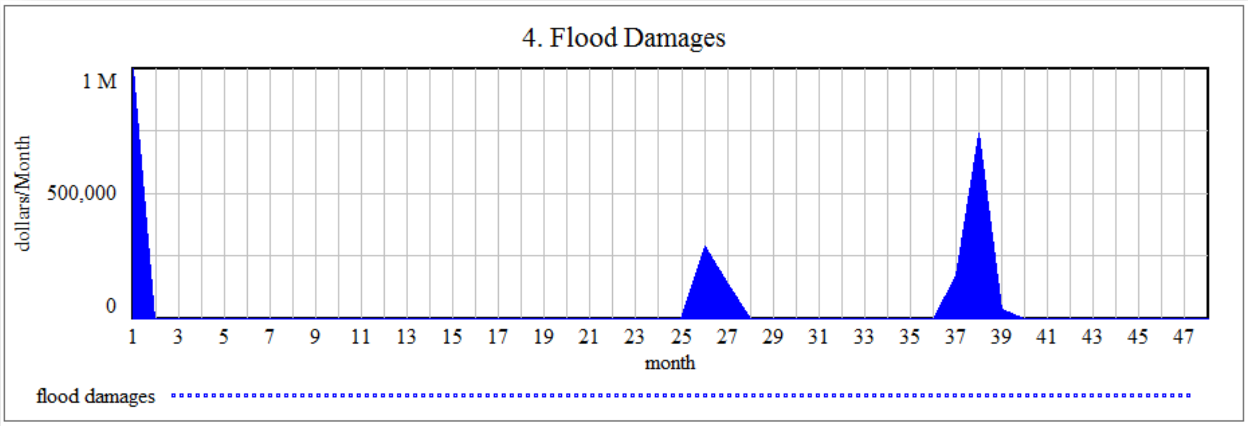

Figure 5 - Flood Damages

Students can slide the "reservoir switch" at the top of the screen back and forth to analyze with- and without-reservoir scenarios. They can also adjust the volume of water allocated (i.e. designated) to storage of flood waters using the "flood storage allocation" slider and the maximum non-damaging release (i.e. the maximum water release that will not cause downstream economic damages due to flooding) using the "maximum non-damaging release" slider.

2.2.2. Predicting Inflow

During a storm most rainfall first sinks into the soil, until it 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 determinate of the amount of water that is infiltrated into the ground in this equation is the absorbency of the ground (called the curve number). As is shown in Figure 6, not all soil types absorb the same amount of water. In highly developed areas (like southern California) much of the watershed is covered in concrete which absorbs no water, causing it all to run off into the river (concrete has a curve number of 100). Engineers, who make predictions about river's storm flows call land covered in concrete and other

[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.

impenetrable surfaces (like rocks) *impervious ground cover.* In other areas with sandier soil, more water is absorbed before runoff begins (curve numbers closer to 30).

Figure 6 - Permeability of Soil

Some of the water initially infiltrated into the ground will enter the river as *interflow* (i.e. water flow that travels parallel to the surface underground); or will be percolated into the abyss of groundwater – thus freeing up space in the soil to hold more water. During a single month within the model the ground may be saturated and subsequently partially drained (by interflow and groundwater percolation) several times. Figure 7 below shows the processes of runoff and interflow.

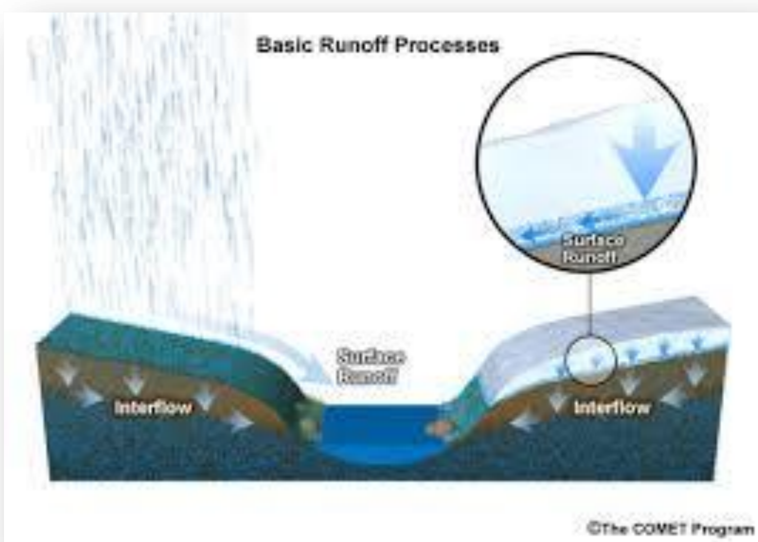

Figure 7 - Runoff and Interflow

The figure below shows the process of groundwater storage.

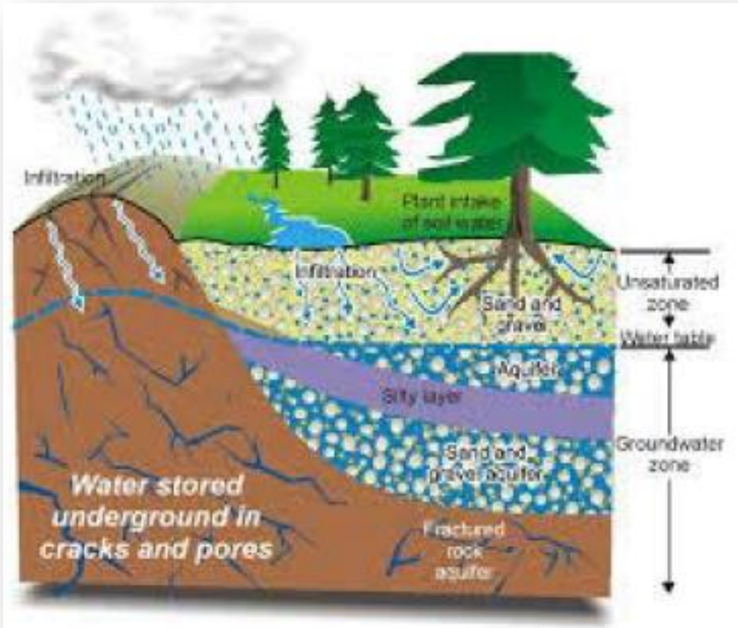

Figure 8 - Groundwater Storage

The role that runoff, interflow and groundwater recharge play in inflows into the reservoir is displayed in **graph 3**, labeled “3. Infiltration, Interflow and Groundwater Recharge” (shown in Figure 9). Water travels more slowly underground where soil, plants, rock and other material represent an impediment to its speed. As a result, the interflow begins more slowly than runoff and continues for a longer period of time.

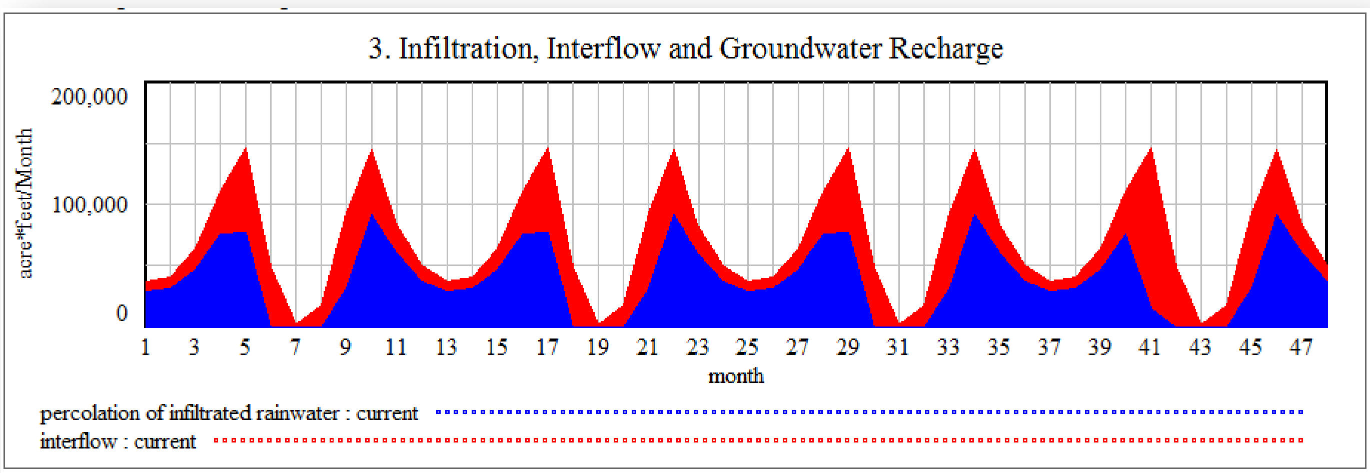

Figure 9 - Infiltration, Interflow and Groundwater Recharge

Perhaps the most important step in sizing a reservoir is predicting the amount of water that will flow into it. In topic one "function of a reservoir", inflows were discussed *exogenously* (taken as a given, without questioning how they were determined). In this topic, the relationship between precipitation and inflows into the reservoir is explored.

Graph 1, labeled "1. Historic Precipitation Min, Mean and Max" (shown in Figure 10) in the "predicting inflows" box displays the precipitation predicted in the model. The actual historic average, minimum and maximum monthly precipitations in the Upper American River (California) watershed are displayed by the red, blue and green lines, respectively. The modeled precipitation (i.e. the precipitation produced and used within the model) is shown in gray.

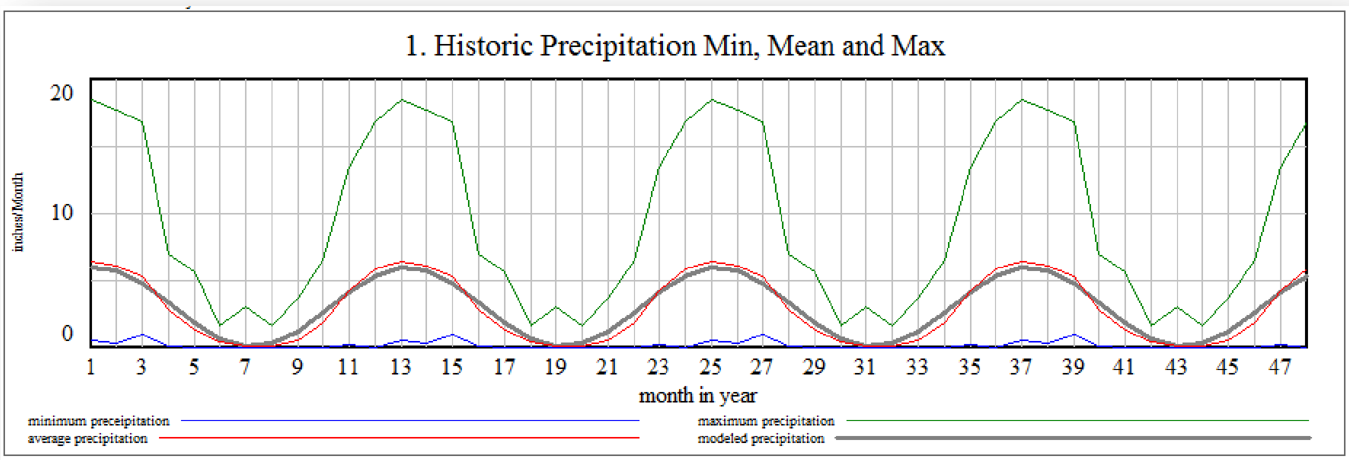

Figure 10 - Modeled and Historic Precipitation

The method used to model precipitation within the Vensim model is covered as a topic in the Trigonometry Lesson Plan.

As a default, the model shows an average amount of precipitation for each month in the year. However, in real life, the amount of precipitation (rain or snow) that falls each month is highly uncertain. An <u>uncertainty switch</u> is included in the model to more accurately reflect the uncertainty that water managers face when deciding how to size (or operate) a reservoir. **Students can use the "percent change in precipitation range" and "uncertainty switch" sliders to observe how increases/decreases in the range of potential precipitation amounts and uncertainty in precipitation amounts affect other modeled outputs (e.g. inflow, runoff, flood releases and damages graphs).**

> *<u>Example Question</u>: What is the likely disadvantage of sizing a reservoir based on the average inflows in the reservoir?*
>
> *<u>Example Answer</u>: Average precipitation and the inflows produced by average amounts of precipitation will exclude the inflows associated with above average storm activity. Since reservoirs are typically designed to mitigate against flooding associated with large storms and inflows (rather than average*

ones) a reservoir size based on average precipitation is unlikely to provide much flood risk mitigation and is likely to lead to more dangerous flooding when larger than average inflows and storms occur.

Example Question: What is the likely disadvantage of sizing a reservoir based on the maximum inflows in the reservoir?

Example Answer: The maximum inflows represent a monthly "worst observed case" scenario. In some cases, they may understate the "worst possible" case in any given month or be based on the occurrence of a single, incredibly rare or unlikely event. Furthermore, the chances of receiving the "worst observed" inflows every month for an entire year may represent an entirely implausible scenario.

Graph 2, labeled "2. Infiltration and Runoff" (shown in Figure 11 on the following page) displays the relationship between runoff and infiltration in the model. As a default, all precipitation in the model falls as rain (although precipitation can also fall as snow if the "snow switch" slider is turned on).

During a rain event, rain becomes (a) runoff (i.e. rainfall flowing into the river), (b) infiltrated rainwater (rainwater that is absorbed into the ground) or rainwater that is "lost" to evaporation, puddles, absorption by plants and animals, etc. Since both infiltrated rainwater transformed to interflow and runoff may enter the reservoir, the focus is on those within the model. The amount of rain apportioned to infiltration versus runoff is dependent on a number of natural and human factors.

Two factors are highlighted in the model: the ability of the watershed to infiltrate water, and the human development in the watershed.

Ability of the watershed to infiltrate water. The ability of the watershed to infiltrate water is dependent upon a number of factors such as the composition of the soil, steepness of the terrain, the amount and type of vegetation in the watershed, etc… Thus, different watersheds have different saturation points. The higher the saturation point the greater the amount of rainwater that is infiltrated into the soil (as opposed to becoming runoff). In the model, a "saturating rainfall" variable exists that describes the amount of rain in inches that fully saturates dry ground at a given point in time causing any additional rain to runoff.
Students can adjust the watershed's saturation point by moving the "saturating rainfall" slider.

Human development in the watershed. As people build homes, highways, parking lots, shopping malls, businesses etc… in the watershed they cover more and more of it with surfaces that water cannot infiltrate (i.e. penetrate). As a result, less water soaks into the ground and more runs off into rivers.
Students can explore the relationship between human development in the watershed and flood risks by moving the "percent impervious ground cover" slider.

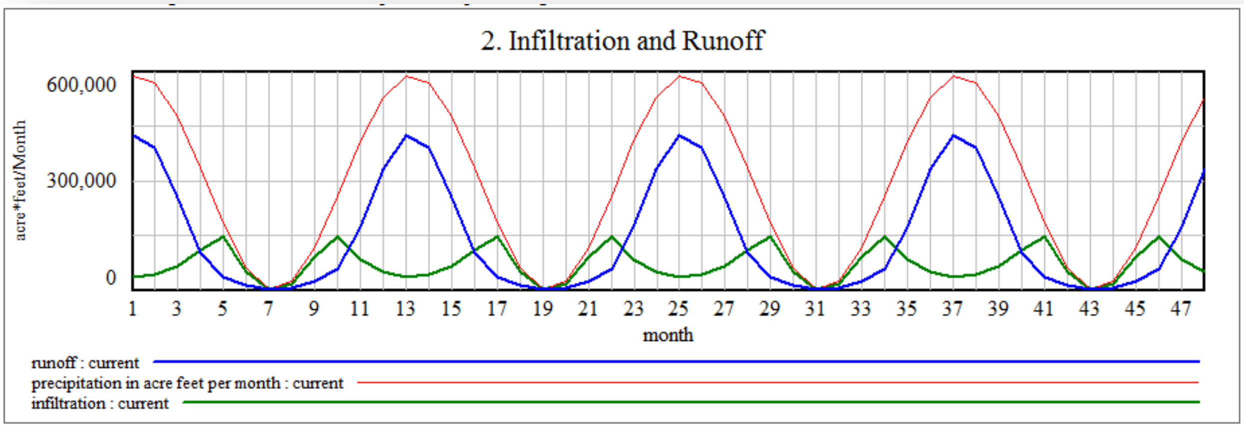

Figure 11 - Infiltration and Runoff

Note that when precipitation is low, the ground successfully infiltrates all or nearly all of the rainwater. As the amount of precipitation increases, runoff also increases. As the ground reaches its saturation point, more rainwater is converted to runoff than infiltrated rainwater.

The model uses the "Soil Conservation Service Runoff Curve Number Equation" to generate runoff and infiltration from precipitation. This equation is widely used in the real world and empirically based on U.S. Department of Agriculture experiments and historical observations.

Graph 3, labeled "3. Infiltration, Interflow and Groundwater Recharge" (Figure 9 on page 10) displays the amount of infiltrated water in the model as the sum of interflow and groundwater. Infiltrated water (e.g. water held in the soil) ultimately either sinks into the groundwater table through a process called *percolation* or flows through the soil as interflow until it drains into the river. Graph 3 breaks down total infiltration (shown by the green line in graph 2) into interflow (infiltrated water that will become runoff) and percolation of water infiltrated into the groundwater table.

The amount of water that is percolated into the groundwater abyss is dependent upon: the permeability of the soil through which water must travel in order to percolate, also called *hydraulic connectivity*; the distance the water must travel (e.g. the depth of groundwater table); and the volume of water the groundwater table can hold. **Students can adjust these variable my moving the "hydraulic connectivity", "water table depth" and "initial groundwater storage" sliders.**

(The percolation function used in this model is based on experiments and observations recorded by Wu, et al. (1996) in the Journal of Hydrology, a prominent academic journal on the subject.)

Graph 4, labeled "4. Inflows into Reservoir", (shown in Figure 12 on the next page) displays total inflows into the reservoir (same as in "1. Inflows into Reservoir" graph) broken down by runoff and interflow. As one would expect, inflow accounts for a greater portion of the inflows during drier months when more precipitation infiltrates into to the ground.

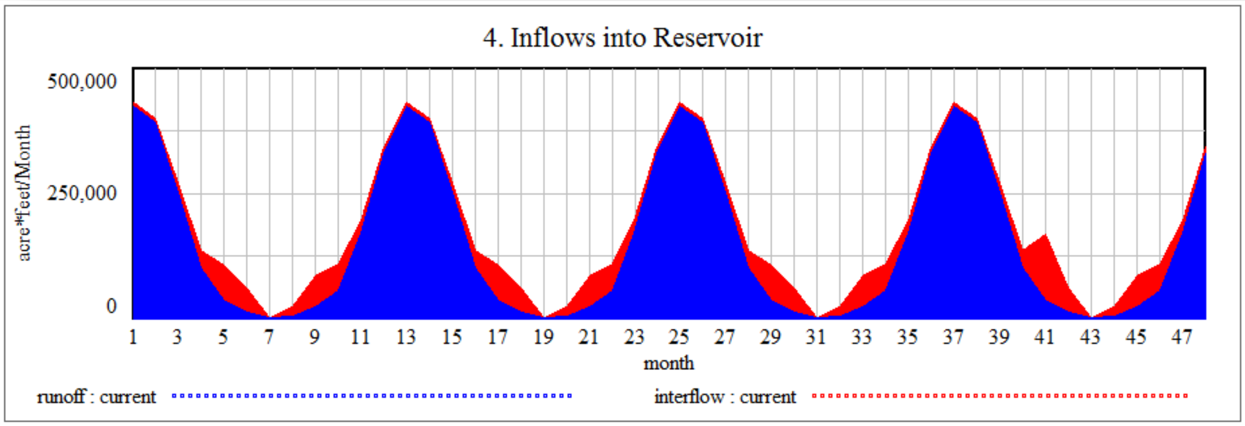

Figure 12 – Inflows into Reservoir, broken down by Runoff and Interflow

2.2.3. Predicting Outflow

The largest outflows from a reservoir are planned releases of water, these include: releases of flood waters, releases to generate hydropower or supply water for agriculture, homes and business. However, these are not the only releases of water from a reservoir. Each day some water may be evaporated or percolated into the groundwater table. Often a water manager must incorporate these losses into decision making (to size or operate a reservoir). The earth sciences version of the model does not include hydropower or water supply releases, as these are included in other lessons. Instead, students focus on three outflows from the reservoir: flood releases, evaporation and percolation at the reservoir.

Graph 1, labeled “1. Summary of Outflows” (shown in Figure 13 on the following page) summarizes total outflows from the reservoir by stacking controlled flood releases, uncontrolled flood releases, percolation and evaporation at the reservoir on top each other. Students will notice that while evaporation is as large at 3,000 acre feet per month (enough water to fill an acre of land with 3,000 feet of water!) it is completely dwarfed by flood releases to the point on almost not being visible in the graph (more on this below). Percolation, while less insubstantial is also dwarfed by flood releases, when flood releases are occurring (**NOTE** in the game students play the “hydraulic connectivity” in the model is reduced and percolation during all time periods is substantially reduced). Uncontrolled releases at the reservoir occur when the volume of the water in the reservoir plus new inflows into the reservoir exceed both the reservoir’s capacity (e.g. the reservoir is overtopped) and the maximum controlled release (e.g. out a flood gate, e.g. giant pipe releasing flood water out of reservoir). **Note** that since uncontrolled releases are flood releases in *excess* of the maximum non-damaging releases, uncontrolled releases always result in flood damages.

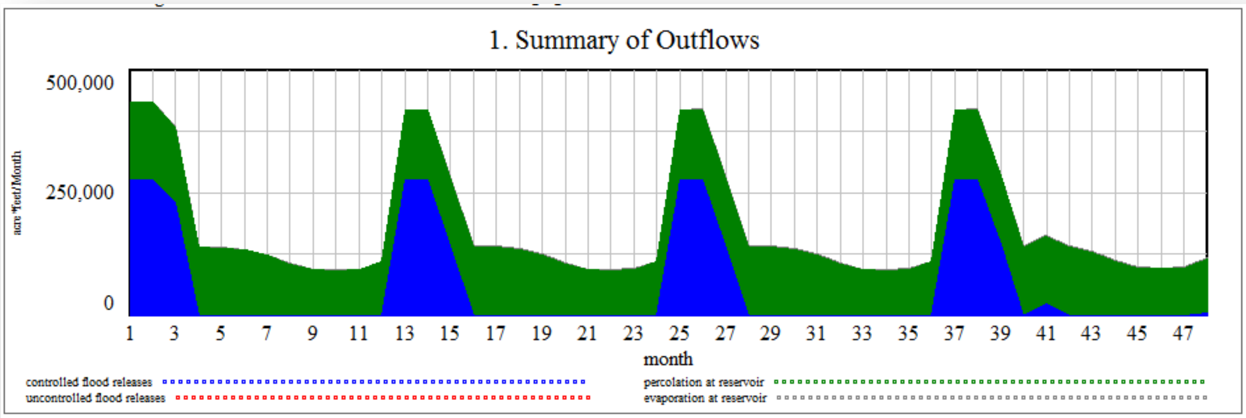

Figure 13 - Summary of Outflows

Students can adjust the “flood storage allocation” and “maximum non-damaging release” sliders to adjust the reservoirs flood releases.

Graph 2, labeled “2. Temperature” (shown in Figure 14) displays the modeled temperatures along with the actual historic average maximum and minimum temperatures by month.

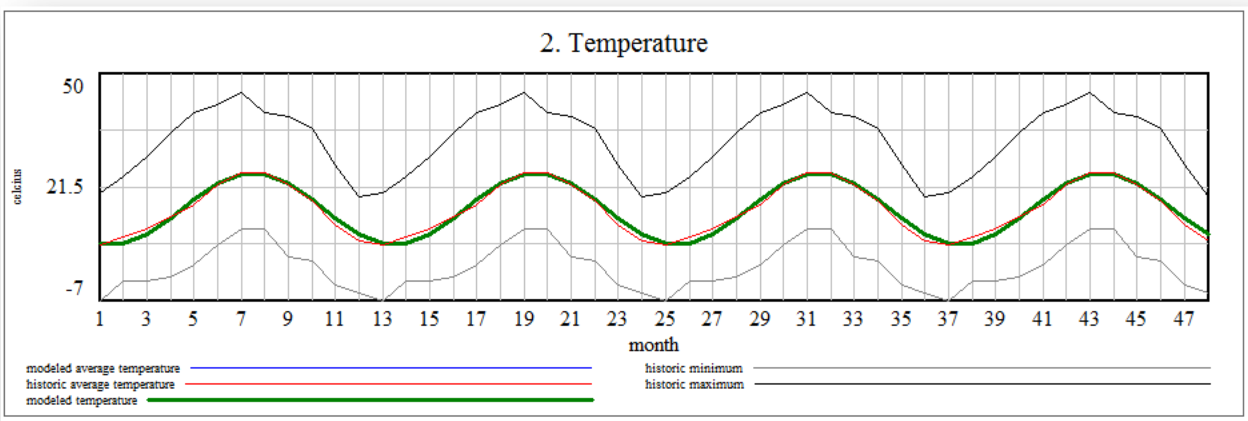

Figure 14 - Temperature

Students can create a more realistic temperature by using the “uncertainty switch” (which will allow the modeled temperature to deviate from its historical average. They can also adjust the temperature range by using the “percent change in temperature rage” slider.

Graph 3, labeled “Evaporation from Reservoir” (Figure 15 on the next page) displays evaporation for the reservoir. Temperature plays a major role in evaporation (and as discussed below snow fall, snow pack and snow melt). Graph 3 shows monthly evaporation from the reservoir.

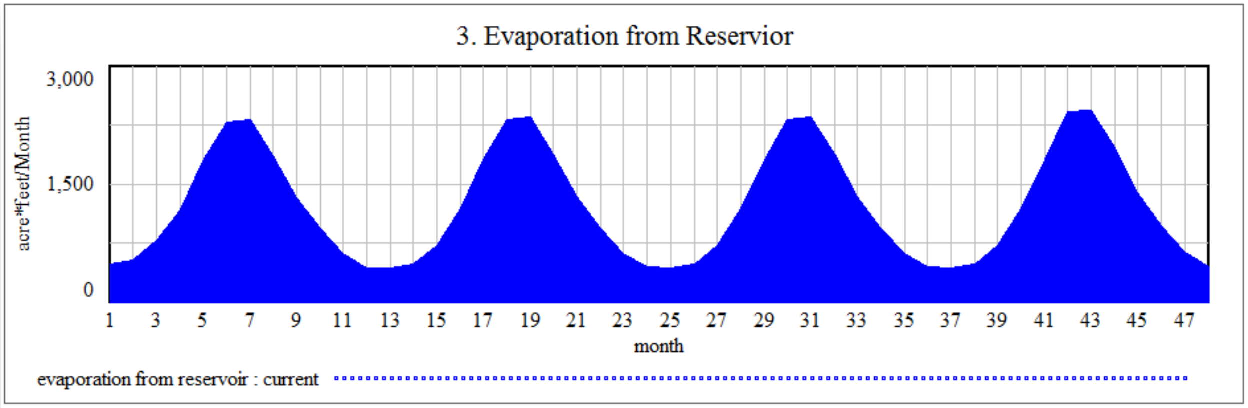

Figure 15 - Evaporation from Reservoir

Evaporation, in the model, is modeled based on the now famous Thornthawaite Equation. This equation models the amount of evaporation that will occur *if there is a sufficient supply* of water to evaporate. Thus it does *not* account for the availability of the water to evaporate. Fortunately the model is based on evaporation at a reservoir, where standing water continuously exists. Climatologists define arid areas as those areas where annual potential evaporation (from the Thornthawaite Equation) exceeds annual rainfall. Wet areas are defined as those areas where precipitation exceeds potential evaporation.

It is also worth noting that while this equation is good at estimating the potential evaporation over a large area and period of time (such as watershed and month) it excludes variables that are important to making precise predictions of evaporation such as wind speeds, the surface temperature of the water being evaporated, etc… This underscores the importance of having multiple tools when making scientific predictions and inquires! While without Thornthawaite's equation we would have a difficult time assessing the "dryness or aridness" of various geographic areas across the globe, it is not a good tool to apply to try to answer a precise problem like estimating the amount of standing water that will evaporate from your driveway a day after a storm.

Graph 4, labeled "4. Percolation at Reservoir" (shown in Figure 16 on the following page) displays groundwater percolation at the reservoir, based on work done by Wu et. al. (1996). Percolation refers to infiltration of water through soil and permeable rocks. Deep percolation or groundwater penetration is the hydrologic process by which water moves down from surface water to groundwater.

The recharge of stormwater flows into the groundwater table (where they can be access later via a well) is a growing source of water supply for agricultural, industrial and human uses. In arid parts of California, many reservoirs are being investigated and/or re-operated to increase the amount of groundwater recharge they provide, in order to provide a sustainable and readily available source of water for growing cities and job centers.

> *Example Question: What is one possible disadvantages of re-operating a reservoir to increase storm water storage, for the purpose of groundwater recharge?*

Example Answer: The flood risk management function of a reservoir requires that "empty" space be set aside to collect and store river's storm flows during a storm event, so that they may be released afterward when the river level is low. Therefore, if stored flood water is kept at the reservoir for the purpose of groundwater recharge the amount of "empty" space at the reservoir will be periodically reduced (e.g. in the days, weeks and months following storm events). Thus one disadvantage of reservoir re-operation is that the flood risk mitigation benefits the reservoir provides may be reduced. This disadvantage may be reduced if flood water is only stored during periods when a follow-up storm is not expected to occur (e.g. when no follow-up storm is "in the forecast" or at the end of the "rainy" season).

Example Question: What are some factors water managers should consider in proposing reoperation of a reservoir to increase groundwater percolation?

Example Answer: They hydraulic connectivity of the soil at the bottom of the reservoir, the depth of the water table and perhaps most importantly the potential impact on flood risk management benefits provided by the reservoir. The amount of potential ground water storage (e.g. empty space in the groundwater table) and accessibility of this water (e.g. location of water table and wells) to farmers, businesses and homes are also all important considerations.

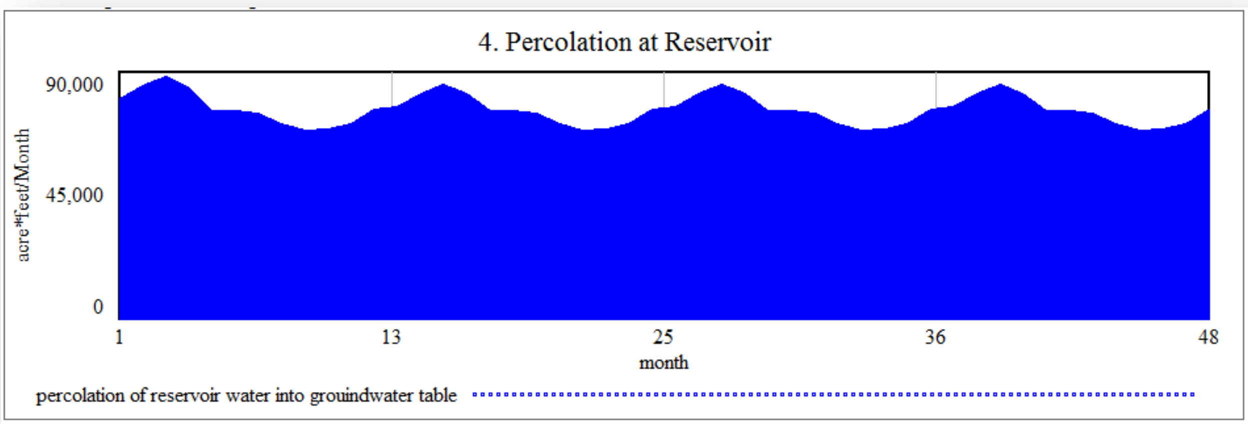

Figure 16 - Percolation of Groundwater at Reservoir

Students can use the "initial groundwater storage" and "water table depth" sliders to adjust how full or empty the groundwater table is and how deep the water must penetrate to reach the groundwater table. When there is more available space in the groundwater table for water to be recharged, there is less interflow. When the groundwater table is saturated or full, there is more interflow. When the groundwater table is deeper, there is less infiltration and more interflow. When the groundwater table is shallower, there is more infiltration and less interflow.

2.2.4. Additional Topics

The Sierra Nevada snowpack is incredibly important to California. It is the source of much of California's water supply, and it increases the efficiency of central valley reservoirs. Snowfall occurs during mid-winter when precipitation is at its highest. However, it runs off into streams and reservoirs months later when storm events are smaller and less frequent. In effect, the snowpack acts like a reservoir, storing would-be floodwaters at their peak (mid-winter) and releasing them later (as snowmelt) when flood flows are smaller and less frequent (generally in Spring and Summer).

In order to show this, turn snow "on" in the model by sliding the "snow switch" to 1. Students can explore how increasing the portion of the watershed receiving snow, precipitation uncertainty and temperature affect snow fall, snow pack and snow melt as well as other variables in the model such as inflows into the reservoir and flood damages.

Graph 1, labeled "1. Snowfall and Melt" (shown below) displays how snow falls (blue line) when precipitation (red line) is at or near its peak. This water gets "locked up" in snowpack reducing the flood flows associated with mid-winter storms. Snow melts (green line) and runs off in the spring and summer when precipitation is much lower and easier to "control" at the reservoir.

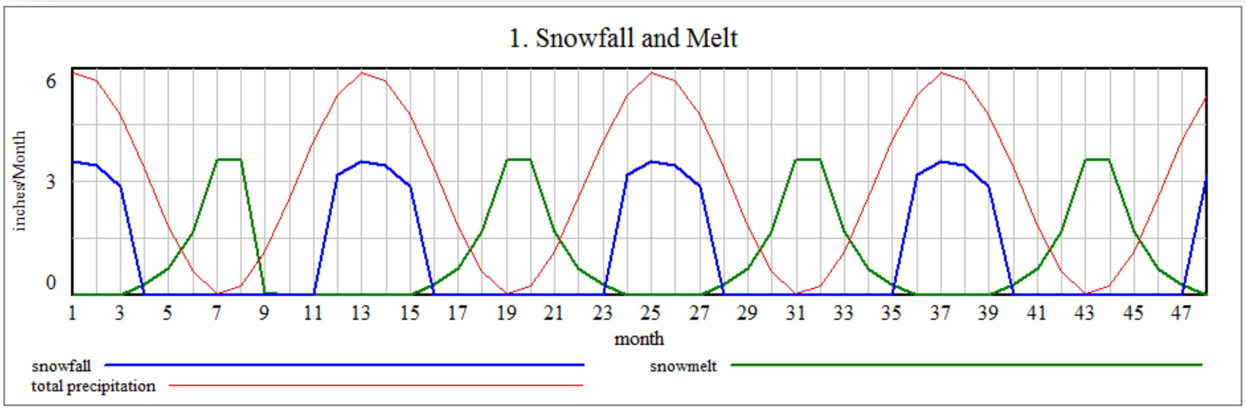

Figure 17 - Total Precipitation, Snowfall and Snowmelt

Graph 2, labeled "2. Snowmelt and Rain" (Figure 18) provides another view. The red line represents total precipitation, or the amount of rain that would fall if none fell as snow. The blue line shows rainfall with the area between the blue and red lines representing the snow fall. The green area represents snow melt.

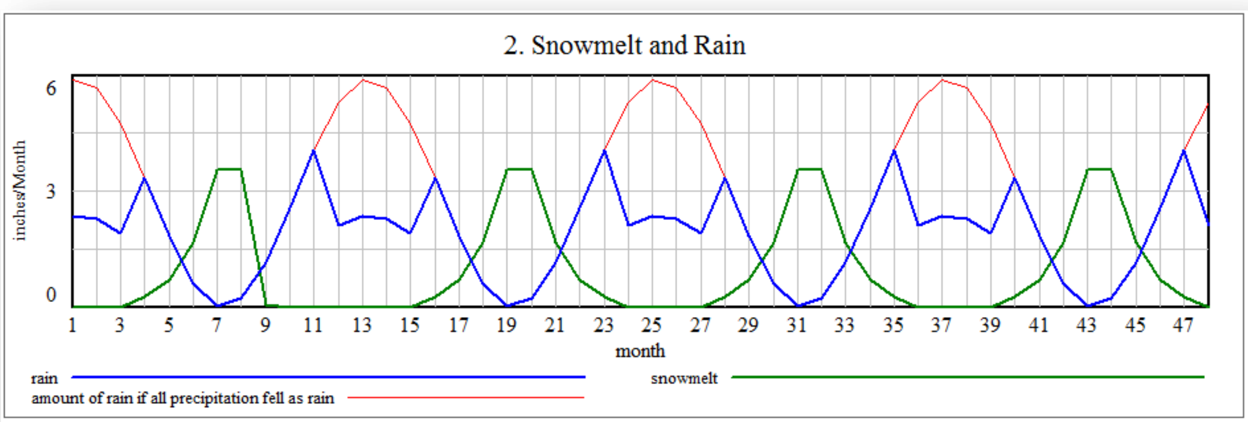

Figure 18 - Total Precipitation, Rain and Snowmelt

The period in which snow melts has an impact on flood risks. The earlier snow melt occurs (in the year) the more likely it is to be combined with late-winter or early-spring storm flows. Thus, in warm years the snow pack can actually *increase* flood risks. Not surprisingly, this is one concern that water managers associate with climate change.

> *Example Question: How might climate change impact snow pack and flood risks?*
>
> *Example Answer: A warming climate may lead to early snow melt. As a result, snow melt may occur more often during late-winter and early spring storms, increasing storm flows. Climate change may also make mid-winter snows smaller, increasing the rainfall and runoff associated with these storms.*

3.0. The Game

The students will need to read the necessary information and instructions carefully in order to play the earth science game (general instructions on how to play all SWMM games in Vensim are included in the User's Guide). Students will play the game four times, under four different scenarios. In each case the goal is to (in the first time period) enter a volume of flood storage allocation (e.g. size of dam) at the reservoir that will prevent flooding, at the lowest possible cost. Players will need to make predictions regarding the flood storage volume needed at the reservoir to prevent flood damages, given the scenario variables (provided in section 3.1). In order to make these predictions players should use the "earth sciences model" to inform their estimates of the inflows, outflows and flood storage volume necessary to prevent damages. Students may want to use tables and graphs to record their estimates of key inflow and outflow variables used to make predictions regarding the maximum necessary volume of flood storage. An example set of tables and graphs is shown on the next page in Figure 19.

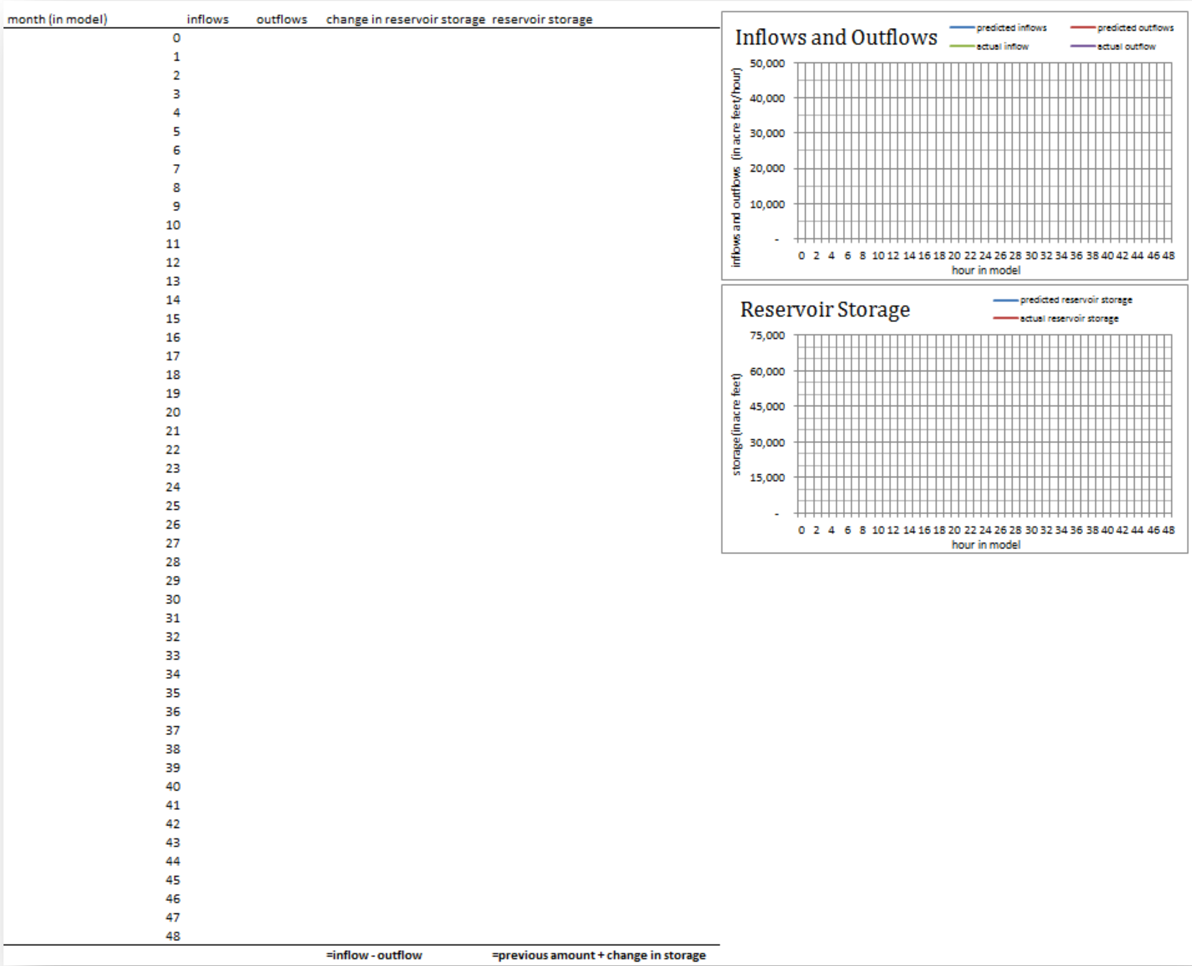

Figure 19 - Example Tables and Graphs for Game

3.1. Necessary Information

The following is a list of information players will need to successfully play the game:

3.1.1. Volume of Non-Flood Storage

The reservoir in the model and game includes a 1,000,000 AF pool of water that is *not* allocated to flood storage (meaning that flood release can*not* be made from this pool of water). While it is not discussed in the model or game, it is helpful for students to think of this water as space devoted to recreation or groundwater recharge, since no releases are made from this pool of water. Outflows from this pool may occur as ground water percolation or evaporation, but <u>no flood releases</u> can be made from this pool.

The total capacity of the reservoir is equal to this space (e.g. 1 million AF), plus the space allocated to flood storage. Flood release can only be made when the total volume of water at the reservoir (including inflows) is greater than 1 million AF.

3.1.2. Flood Storage Allocation (Volume)

The volume of water in the reservoir at the beginning of the model is 1 million AF. This corresponds with the volume of water allocated to other (e.g. non-flood risk management) purposes. 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 20 - 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 is equal to the volume of water held in the reservoir during that period plus the incoming inflow minus the non-flood storage volume (e.g. 1 million acre feet). If a larger release is set (e.g. the student attempts to release more water than is current in and entering the flood storage pool) the release will reduce the total volume of water in the flood storage pool (including the incoming inflows). Following such an event, the total volume of flood storage in the next time period will be 0 AF.

The player sets the volume of flood storage allocation in the earth sciences game as the game variable. The full capacity of the reservoir in the game is the sum of the non-flood and flood storage capacity volumes. 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 does never exceeds its capacity.

3.1.3. Maximum Non-Damaging Release

Up to 100,000 acre feet per month can be released with no probability of levee failure (e.g. breach or overtopping). Any release greater than 100,000 AF per month will induce flooding by overtopping the levee.

3.1.4. Rainfall

The following table provides average, maximum and minimum rainfall values. In the game rainfall amounts without uncertainty will be near the average. Rainfall amounts with uncertainty will range between the maximum and minimum amounts. The rainfall values are in inches per month, while inflows and outflows are measured in acre feet per month. Therefore if the player elects to uses this data in their predictions they should be careful to convert the values. In the game rainfall is assumed to fall uniformly across the watershed (e.g. if rainfall is set at 6 inches per month, it is assumed 6 inches of rain falls across the entire watershed). The watershed in the game is 1.2 million acres in area (e.g. 1875 square miles). There are 12 inches per foot.

	Rainfall in Inches		
Month	Average	Max	Min
January	6.4	18.42	0.52
February	6.01	17.61	0.26
March	5.25	16.77	0.93
April	2.79	6.93	0.07
May	1.21	5.58	0.00
June	0.37	1.57	0.00
July	0.05	2.97	0.00
August	0.08	1.59	0.00
September	0.46	3.68	0.00
October	1.83	6.42	0.00
November	4.16	13.45	0.12
December	5.86	16.78	0.00
total	*34.47*		

Figure 21 - Historic Monthly Rainfall Totals

Note that the rainfall amounts under uncertainty in the model differ from those used in the game! Students should not assume the rainfall totals in the model will perfectly match those used in the game.

3.1.5. Temperature

The following table provides average, maximum and minimum temperature values. In the game temperature values without uncertainty will be near the average. Temperature values with uncertainty will range between the maximum and minimum amounts. As is discussed above, temperatures in the model impact snow fall, melt and evaporation.

	Temperature in Celsius		
Month	Average	Maximum	Minimum
January	7	20	-7
February	9	24	-2
March	11	29	-2
April	14	35	-1
May	17	40	2
June	22	42	7
July	25	45	11
August	25	40	11
September	22	39	4
October	18	36	3
November	12	27	-3
December	8	19	-5

Figure 22 - Historic Monthly Temperature Totals

Note that the temperature values under uncertainty in the model differ from those used in the game! Students should not assume the rainfall totals in the model will perfectly match those used in the game.

3.1.6. Reservoir Cost per Acre Foot or Storage Volume

In the game each additional acre foot of reservoir storage costs $1,000. Since the reservoir has a minimum storage volume of 1 million acre feet (e.g. the non-flood storage volume) the minimum reservoir cost is $1 billion.

3.1.7. Other Important Variables

The following provides a table of other variables in the prediction of inflows and outflows and flood storage in the game.

Variable	Value
Hydraulic Connectivity	5 feet per month
Initial Groundwater Storage	0 acre feet
Water Table Depth	4.92 feet

Figure 23 - Other Important Variables Values

3.2. Instructions

The earth sciences game is played four times, under four different scenarios. Prior to playing each game the player should name the simulation: "game one", "game two"… according to the game the player intends to play. In each game, the player sets the game variable, "flood storage allocation" to the desired value once - in the first time period zero. However, prior to setting the game variable to the desired value each player should set the sliders in the "game setup" box to the values given in the earth sciences game view. Once the player has set the game setup variables to the correct values and entered their desired flood storage allocation value, the player should advance the game to the final time period (time period 47).

The team's score for each game is the sum of the cost of their reservoir and the cumulative flood damages in time period 47. The overall winner is the team with the lowest score across all four games.

General instructions on how the play a Vensim game, including naming game simulations, entering values for game variables and advancing in the game can be found in the User's Guide.

3.3. Solution and Message

The following are solution values for flood storage allocation in the four games (e.g. values that prevent flood damages and minimize costs): 1 million acre feet, 6.1 million acre feet, 200,000 acre feet and 350,000 acre feet, respectively.

The purpose of the game is to encourage students to think critically about the dynamic role of the system of variables that influence decision to construct and size a new reservoir. In game one, students are asked to size a reservoir under the simpliest of all possible scenarios, one in which the rainfall and inflows are predictable. In the second game students are asked to size the reservoir under a more realistic scenario, one in which rainfall and thus inflows are uncertain. Under this scenario a solution is much more difficult to obtain. A third model named "earth science_model of game two" allows students and educators to explore the long run equalibrium of the reservoir under uncertain precipitaiton and temperature (e.g. the model is identical to the "earth sciences_model" but runs over a period of 120 months), since the reservoir barely reaches equilibrium values over the first 48 months. Finally the last two games provide students with a dynamic example of California's natural reseroir the Sierra Nevada snow pack, under current and climate change conditions.

This lesson is intended to develop students' dynamic intuition on the management of flood risks and emphasize the contextual importance of earth science topics in water resources.