Physics

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

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Endogenous Variables
Exogenous Variables
Empirical
Flood Risk
Flood Risk Management Reservoir
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1.0. Introduction

Reservoir management is perhaps the most crucial aspect of water management because it most directly impacts the well-being of the general public. Not only do reservoirs serve as a source of drinking water, but they also serve to meet the energy demands of the public through hydroelectric power. Through the advent of technologies to harness and direct it, water has generated hydropower electricity that powers our homes and drives our current economy. The energy that a reservoir provides directly impacts the quality of life for those that depend on that power source, which underscores the importance of conserving enough water to meet future electricity demands during periods where a sufficient water supply may be constrained. However, water also exposes us to the destructive force of floods; the same water that supports and sustains communities also threatens people and property. Thus, the challenge in managing a reservoir is striking a balance between protecting the public from potential flooding while also responsibly allocating sufficient water supply hydropower releases to meet future electricity demands (where the reservoir fulfills all of these purposes).

The Physics lesson is the fourth lesson in the series on water management that focuses on the use of reservoirs to produce hydroelectric power to meet electricity demands. The bulk of the models within the series focuses primarily on flood risk and describes the flood risk mitigation function of a reservoir. To provide a more comprehensive look at all of the possible functions of a reservoir, this lesson rounds out the series by focusing on an alternative use of water held at a reservoir. Students can build intuition regarding the relationship between reservoir depth, hydropower release, and hydroelectric supply and demand.

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.

1.0.1. Relationship Between Hydropower and Physics

Hydropower underscores one of the most fundamental concepts in physics: conservation of energy. The conservation of energy states that the amount of energy in the universe is a constant, in other words energy can neither be created nor destroyed, but only transformed. So, the amount of energy in the universe 100,000 years ago is the same as the energy in the universe today, and is the same amount that will exist 100,000 years in the future.

A hydropower dam provides evidence of the conservation of energy in action. Water flowing down a stream moves with kinetic energy. As that river water enters a reservoir, it slows down and stops, transforming the kinetic energy into potential energy. Using the equations that students learn in physics, the amount of kinetic energy in the stream flow can be easily calculated. The amount of potential energy added to the reservoir can also be calculated, and will match the amount of kinetic energy from the stream flow.

The reservoir is useful in the creation of hydropower because stored water (i.e. energy) behind the reservoir can be released at a later time when it is needed. At the time of release the energy state of the water again transforms from potential to kinetic energy. As that kinetic energy hits a *turbine* in a hydropower plant, the turbine turns, creating mechanical energy, which is then transformed through electromagnetism to electrical energy. This process is displayed in the diagram below in Figure 1.

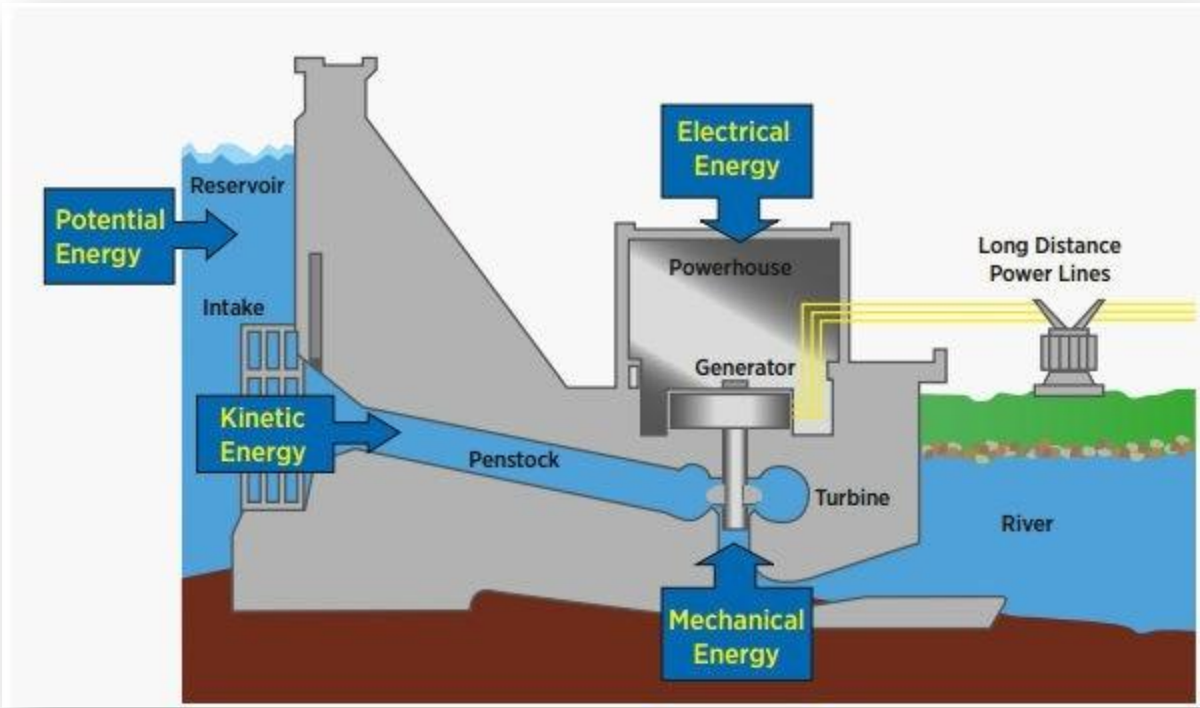

Figure 1 - Diagram of Hydropower Energy Transformation (source: sites.uoit.ca)

> *<u>Example Question</u>: Is hydropower a renewable source of energy? If so, why?*
>
> *<u>Example Answer</u>: Yes. Water stored behind a reservoir is released downstream through the hydropower plant, creating electricity. Those drops of water are destined to be added to the atmosphere through evaporation, to the groundwater table via groundwater percolation or to flow down the rivers and streams into the ocean. Future rains that occur over the watershed will again create water flows that will enter the reservoir in the future. Theoretically, via the water cycle the same drops of water can be used many times to create electricity at many reservoirs.*

Within the model and game, students will compute the amount of energy being produced from releases from the reservoir. The students will measure energy in *Watts*, the unit of measurement for electricity. A Watt is a measurement of energy over time. In other words, it is a measurement of the flow of energy. A Watt represents the number of Joules per second. How do we measure energy in physics? As students learn in Physics Class, it is measured in *Joules*.

1.0.2. Measurement of Energy

Energy (or *Joules)* is defined by the capability of a system to perform work. The terms energy and Joules can be used interchangeably in Physics. In order to define the capability of a system to perform work, a measurement for work must be defined. So, how is work measured in Physics? Work is defined as force times displacement. Force is measured in *Newtons.* Newton $= \text{kg} * \frac{\text{m}}{\text{s}^2}$, where kg is kilograms, m is meters and s is seconds.

Why is a Newton a good measurement of force? Let's consider some examples common in Physics text books. Throwing a ball is an energetic activity. How is the energy put in to throwing the ball measures in Joules? Concentrate on the force applied to the ball. As an individual winds up to throw the ball, the heavier the ball is, the more energy the thrower will have to use to throw it; or more precisely more force will have to be applied to throw it.

One of the terms used in force is *kilograms*, which measures weight. The heavier an object, the more force is necessary to move it. In the case of the measurement of energy, if the ball is heavier, the amount of energy needed to toss the heavy ball is greater than the amount needed to toss a lighter ball. Would a pitcher be able to throw a 90 mile-per-hour fastball with a bowling ball? Maybe, but it would require much more energy to throw a bowling ball instead of a baseball.

The second term in a Newton,$\frac{\text{m}}{\text{s}^2}$, is the acceleration of mass (units for acceleration). Why should this be part of the measurement of force? As the ball it thrown, it has to be accelerated up to the velocity that it will travel at as it leaves the thrower's hand. The faster that the thrower gets the ball up to that velocity, the more energy is required.

> <u>Example Question</u>: *Why is it that acceleration is used in the equation for force rather than velocity or speed?*
>
> <u>Example Answer</u>: *As the ball is thrown, just after it leaves the hand it is travelling at the same speed it as it was at the moment it left the hand. So if speed is included in the equation, it would be incorrectly assumed that the thrower is still applying force or energy to the ball the moment after it leaves the hand. Thus, what is important in the calculation of force or energy is not the speed at which the ball is moving but rather the force and energy that was required to get it to that speed. The way the changing speed of an object is measured is acceleration (Note that after the ball leaves the thrower's hand, forces are being applied to the ball such as gravity and friction, but the force of the thrower is no longer applied.*

There is one more term in the equation for work or energy that measures displacement or distance over which force is applied. Returning to the baseball example, the thrower can either wind up slowly or quickly. The thrower with a slow wind up will apply the same amount of energy to the ball, but will do it over a longer distance with slower acceleration than the thrower with the fast wind up who will apply the same amount of energy to the ball, but will do it faster over a shorter distance. Thus, in order to measure energy, the acceleration and the distance over which the object is accelerated must be taken into account.

Putting this together, the measurement of work, which is also the measurement of energy or Joules is measured in $\text{kg} * \frac{\text{m}^2}{\text{s}^2}$.

Energy = Joules = Ability of a system to perform work = Force * Displacement = kg $* \frac{\mathrm{m}^2}{\mathrm{s}^2} *$ m

The question remains: Why do these units do a good job measuring force, displacement and in turn, energy? The energy required to throw the ball is variable of interest. Applying some of these concepts to hydropower production will use the same terms in energy but the variables will be different; for instance, the properties of water will remain constant throughout the duration of the calculations (density, viscosity, vapor pressure, etc.). Returning to the physics example, both the mass of the ball the mass of the object that water is retained in is consistent, however the volume of water is what varies.

Meters per second squared or acceleration in the physics example is a variable; in the case of water, acceleration is a constant at 9.81 $\frac{m}{s^2}$. The variables of interest in hydropower are different than the typical physics example, such as the variable that describes the volume of water behind the reservoir will change. Additionally, hydraulic head measures the falling distance of water from the top of the pool to the turbine. Thus a given quantity of water will produce different amounts of power based on the height of the pool, in which elevation serves as in important variable.

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 inflows into a reservoir, hydropower production and electricity supply and demand. The model also builds intuition regarding the functions of a reservoir and how it serves to meet electricity demands.

An analytical game is also provided, which tests students' understanding of outflow relationships and hydropower management function of a reservoir. In the "game" version, students make predictions about electricity demand based on temperature data, convert reservoir volumes and depths, and set target releases from the reservoir that will meet the energy demands of 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 seven day period. The reservoir must maintain a sufficient supply while also meeting the electricity demands of the downstream community. Students must determine an appropriate target release for each day that to meet electricity demands. Students examine the relationship between variables (e.g. change in depth of reservoirs and electricity supply and demand) in the model, and begin to build intuition for the proper management of the reservoir. In the game, students test their intuition by setting target releases from the reservoir and attempting to meet electricity demands without compromising reservoir depth.

2.0. The Model

Flood risk management reservoirs are designed to store peak river flows that may otherwise flood areas downstream and may also serve as a power source for providing hydroelectricity. By storing (reserving) river flows, downstream flood risk is temporarily reduced and the stored water can be released more slowly and safely. In terms of electricity supply, hydropower release must be managed responsibly to meet the short term electricity demands while also conserving enough supply to address future electricity demand. The fundamental question facing the water manager at a reservoir addressing hydropower electricity demand is: how much water should be released? Conversely, how much water should be conserved for long term usage? In order to answer this question, water managers must make predictions about the electricity demand based on the hydropower supply they expect to have available. Models assist the water manager in predicting what may happen in different 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 relationships* to predict complex (and often confusing) behaviors and outcomes.

In the system dynamics model shown in Figure 2 (the physics model view), the reservoir providing hydropower electricity is the modeled system. Each term (e.g. "hydropower supply") represents a model *variable.* The arrows between the variables represent relationships between their values. Specifically, the values of variables with arrows pointing <u>toward</u> them are dependent on the values of the variables to which they are connected (in other words, the variable values are determined <u>within</u> 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 manage this stock and flow relationship in a hydropower electricity supply and demand exercise.

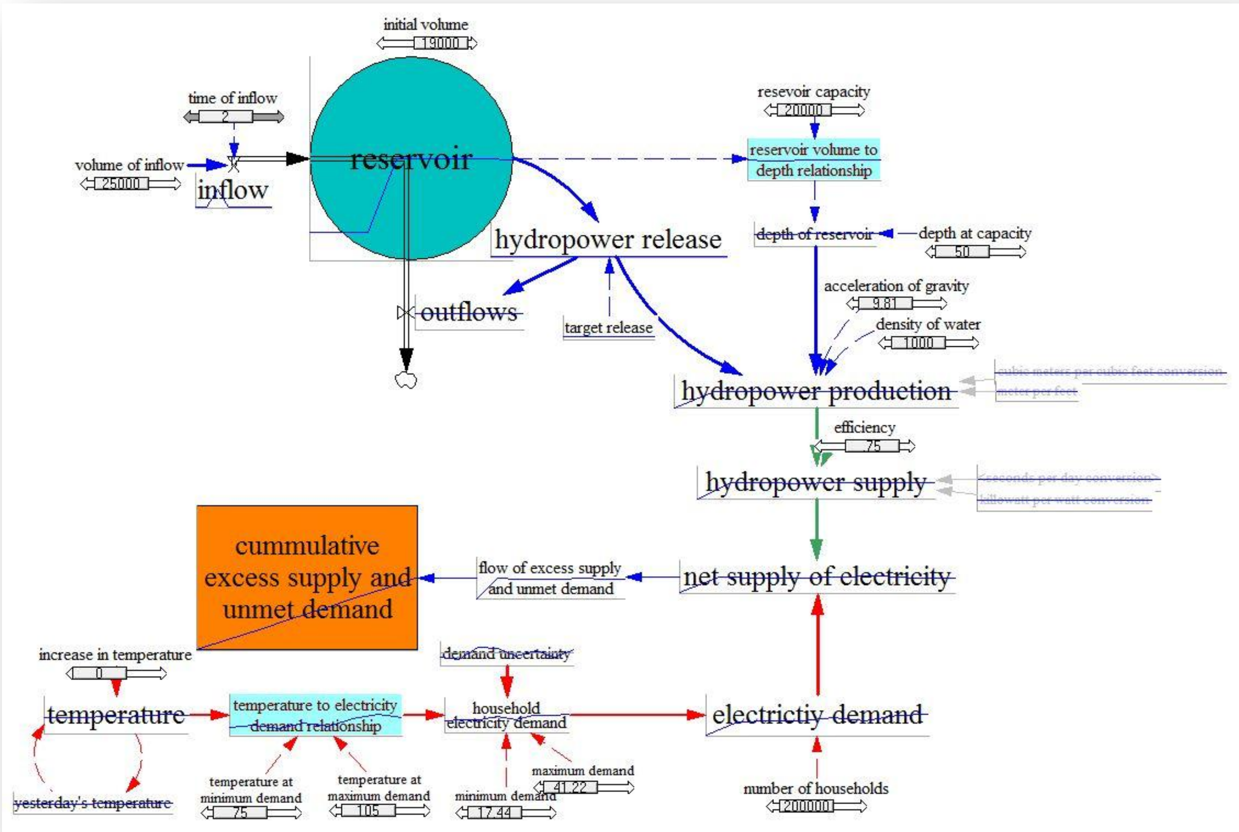

Figure 2 - System Dynamics Model (Physics Example)

System modeling is now its own field of study at 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 physics 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). These variables linking with each other are mathematically

[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.

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 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 physics "dashboard view" in Figure 3 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.

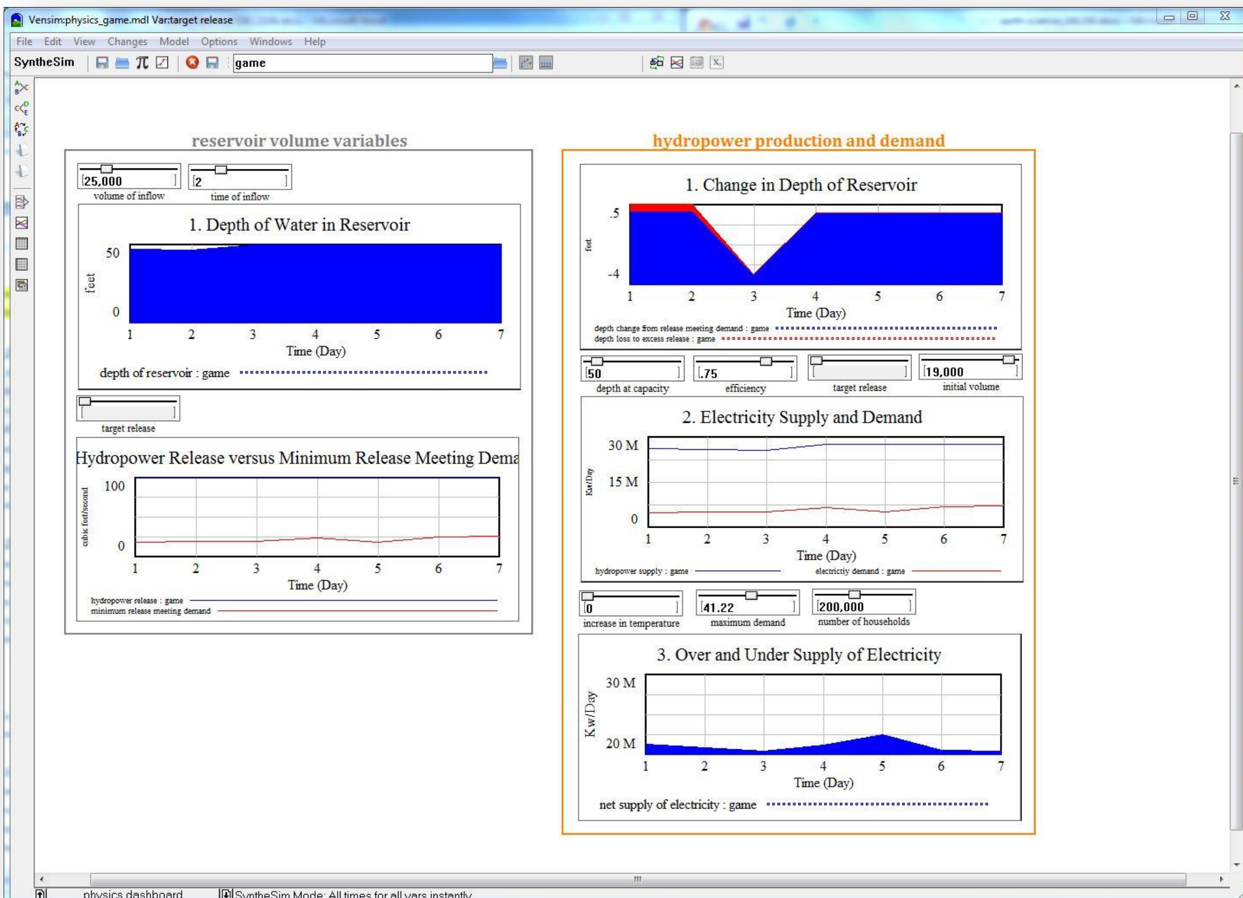

Figure 3 - Physics Dashboard View

In the dashboard view, the player should be able to see the reservoir volume variables and hydropower production and demand variables described in this section. In particular, these reservoir volumes variables are reflected by reservoir depth, while the hydropower production variables are translated to electricity supply and demand.

2.2.1. Reservoir Volume Variables Box

In the "reservoir volumes variables" box, the management of a reservoir to meet hydropower electric demand is examined. Students can begin by toggling the values for the slider variables "volume of inflow" and "time of inflow". The variables can be dynamically adjusted to represent a storm event and what day that the storm event occurs.

Graph 1 labeled "1. Depth of Water in Reservoir" (shown in Figure 4) displays the depth of the reservoir over a seven day period in the life of the reservoir. The depth of the reservoir is measured in feet, while time is represented in days. As the volume of inflow increases for any given day 1-7, the depth of the reservoir will increase for that specific day.

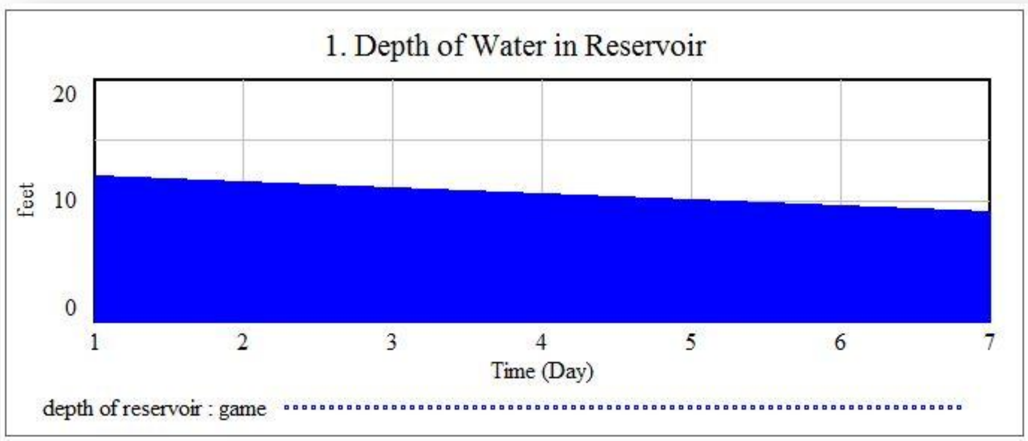

Figure 4 - Depth of Water in Reservior

The stored volume of water influences the depth of the reservoir; as volume increases, so does the depth of water in the reservoir. Conversely, as volume decreases, the depth will also decrease. Another factor that impacts reservoir depth is the shape of the reservoir. A wider, shallower pool would have a smaller depth compared to a narrower, deeper pool; Figure 5 illustrates a basic example of the two.

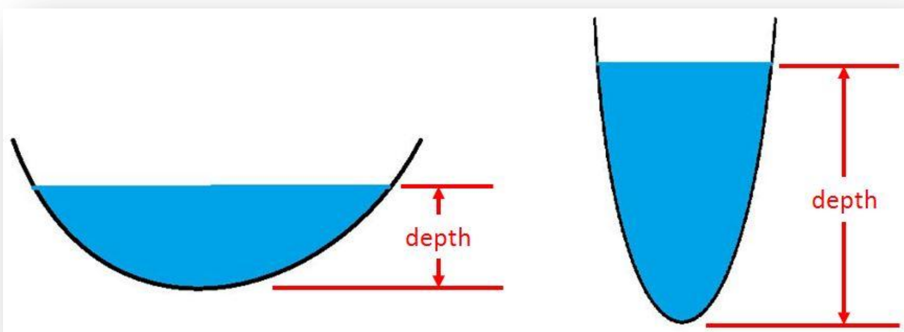

Figure 5 - Wider, Shallow Reservoir Pool vs. Narrower, Deeper Reservoir Pool

Graph 2 labeled "Hydropower Release versus Minimum Release Meeting Demand" (shown in Figure 6) plots the hydropower release (blue line) in cubic feet per second across the seven day period. The red line plots the minimum release required to meet hydropower demand; as demand increases, the minimum release will increase over time period.

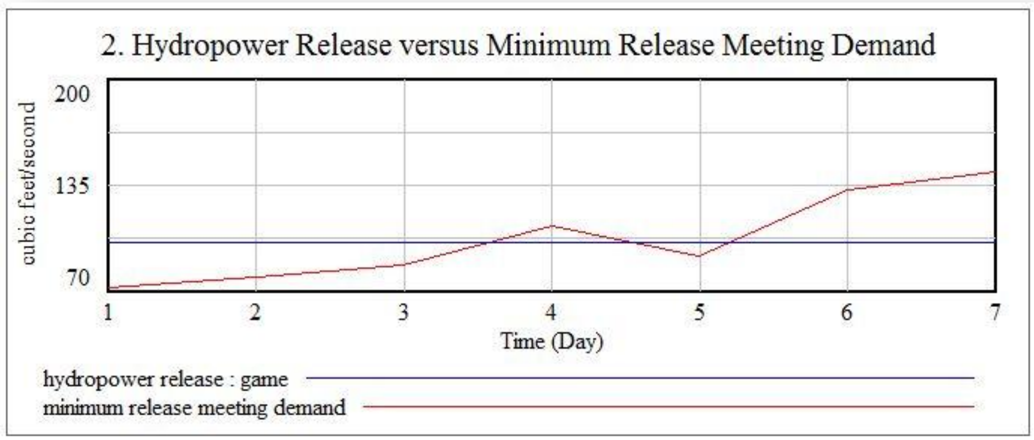

Figure 6 - Hydropower Release versus Minimum Release Meeting Demand

Students can adjust the "targeted release" variable, which represents the hydropower release variable that is dependent on the supply of water available in the reservoir. The hydropower release cannot exceed the amount of water that is stored in the reservoir.

These variables dictate the depth of water in the reservoir which will affect the outcomes displayed in the graphs in the dashboard view.

> *Example Question: How might the chance of rain during a "hot" forecast impact the water manager's decision to release water?*
>
> *Example Answer: The water manager can be more liberal with water releases with less chance of long term impact associated with excess release.*

2.2.2. Hydropower Production and Demand Box

The depth of a reservoir is also an important consideration for potential energy and hydropower. The volume of water, which determines the depth of available water that is stored in the reservoir, influences the hydraulic head. The hydraulic head is measured by the falling distance of water from the top of the pool to the turbine as shown in Figure 7. A given quantity and depth of water will produce different amounts of power based on the height of the pool.

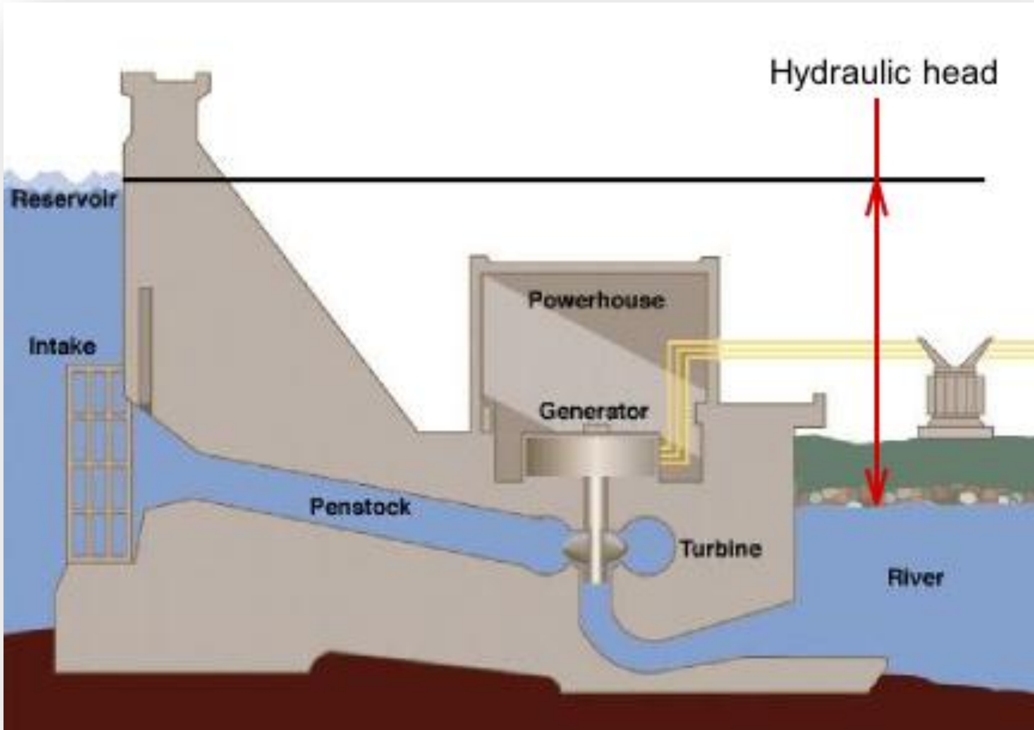

Figure 7 - Reservoir Hydraulic Head (source: commons.wikimedia.org)

Graph 1 labeled "1. Change in Depth of Reservoir" (shown in Figure 8) compares the depth change of the reservoir from meeting electricity demand (blue) with the depth change due to excess release (red). If the water manager were to accurately predict and meet electricity demand, the change in depth of the reservoir graph would entirely be blue across the seven day period.

The supply of hydropower is a function of reservoir volume and depth as well as efficiency and transmission. As water turns the turbine, some energy is wasted due to inefficiencies. These energy losses can be reduced by improving technology and equipment used to transform the energy. Students can adjust the sliders for "depth at capacity", "efficiency", "target release", and "initial volume" to alter the outcome displayed in the graph.

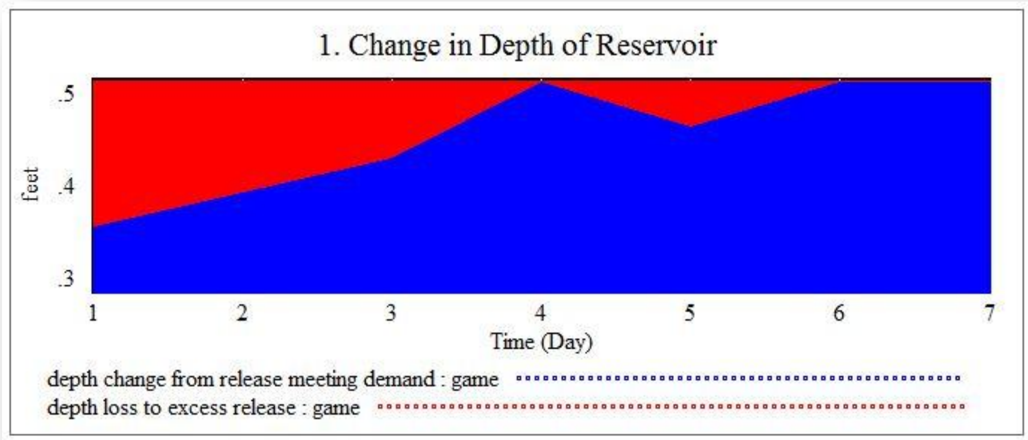

Figure 8 - Change in Depth of Reservior

> *Example Question: Describe the advantages and disadvantages of different shaped reservoirs if the volume of water was the same? (compare shallow versus deep pool)*
>
> *Example Answer: A wider reservoir is advantageous in providing more constant depth, but the disadvantage of a wider reservoir includes limited elevation, which means the falling water is less productive because there is less hydraulic depth. Conversely, an advantage of a deeper reservoir is the greater falling distance that the water will travel which results in a more productive hydraulic head. The disadvantage to a deeper and narrower pool is that any excess release will be more costly because it will have a greater impact on reservoir depth.*

The water manager must release enough water to meet hydroelectric power demands without jeopardizing future water supply to meet current needs. For instance, the hydroelectric power demands during the summer months would be greater than the winter months, thus the reservoir manager must be cognizant of maintaining an adequate water supply during the winter in preparation for the dry months where storm events occur less frequently. Demand for electricity is complicated and is often associated with other external variables.

> *Example Question: What factors can influence the demand for energy?*
>
> *Example Answer: types of houses, appliances, plug-in devices, and **temperature**!*

Graph 2 labeled "Electricity Supply and Demand" (displayed in Figure 9) plots the hydropower supply in blue with the electricity demand in red, across the seven day period. If the blue line were to fall below the red line that would indicate a deficit in hydropower supply in which the electricity demands were not met. The electricity supply and demand is measured in kilowatts per day. Students can adjust the values for "increase in temperature", "maximum demand", and "number of households" to examine different energy supply and demand scenarios.

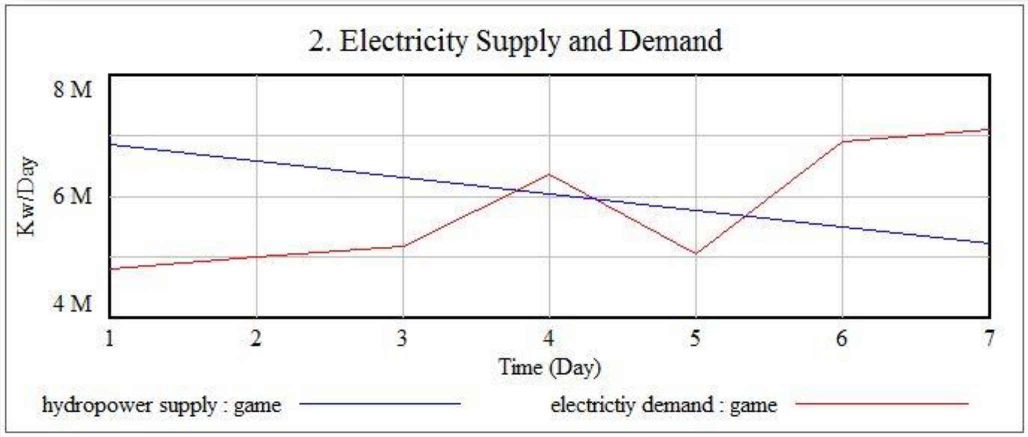

Figure 9 - Electricity Supply and Demand

Graph 3 labeled "Over and Under Supply of Electricity" (shown in Figure 10) plots the net supply of electricity in kilowatts per day across the seven day period. It is important to be aware of the zero axis line that runs through the middle of the plot in the y-axis. The graph plots the supply of electricity along a zero axis line to reflect if the supply was sufficient or not. A negative supply that falls below the zero line indicates a deficit in which the electricity supply was not sufficient to meet demand.

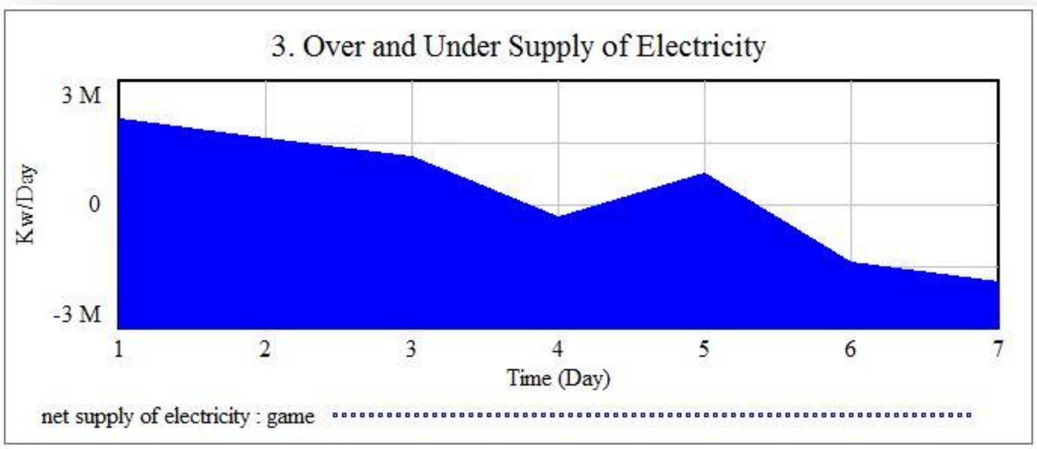

Figure 10 - Over and Under Supply of Electricity

In this model and game, the focus is on the short term variable of temperature; as the temperature outside decreases or increases, the demand for energy to control interior household temperatures is likely to increase. Energy demand is more greatly influenced by warmer days as opposed to cooler days since most heating in California is provided by natural gas.

<u>Example Question</u>: How does temperature affect demand through heating and cooling?

<u>Example Answer</u>: Air conditioners operate on electricity while heating (i.e. wall units) are powered through natural gas.

3.0. The Game

This section provides some basic instructions on how to play the physics 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 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.

The physics model allows students to explore important relationships in the generation of hydropower over 7 days in the life of the reservoir. The game associated with the model allows the students to play water resource manager over that 7 day period setting releases during a time in which the reservoir is nearly empty. In order to make sound decisions, students will need to use the quantitative information from the table and graphs in the "physics game" view in Vensim.

Predicted Values

Day (in model)	Reservoir Volume (acre feet)	Reservoir Depth (meters)	Release (cubic meters/day)	Production (kW/day)	Temperature (farhenheit)	Demand (kW/day)	Net Supply (kW/day)
1	5,000						
2							
3							
4							
5							
6							
7							

Actual Values

Day (in model)	Reservoir Volume (acre feet)	Reservoir Depth (meters)	Release (cubic meters/day)	Production (kW/day)	Temperature (farhenheit)	Demand (kW/day)	Net Supply (kW/day)
1	5,000						
2							
3							
4							
5							
6							
7							

Figure 11 - Example Table for Game

The students will need to read the following instructions carefully in order to play the game. In the game, students are asked to operate the reservoir by setting controlled releases for 7 days to meet electricity demands. They will set these controlled releases using the "target release" game variable, based on conditions shown in the tables found in the "physics game" view. Their objective is to meet electricity demand without releasing excess water.

3.1. Necessary Information

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

3.1.1. Reservoir Volume

The volume of water in the reservoir at the beginning of the model is 5,000 acre feet (AF). 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 12 - 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 (there are no forecast inflows during the period of the game). If a larger release is set (e.g. the student attempts to release more water than is current 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 0 AF.

3.1.2. Temperature

The expected temperature for any time period is the previous day's average temperature ±10 degrees Fahrenheit. Additionally, 68% of temperature changes are within 5 degrees of the previous day's average temperature. The value of the temperature is determined randomly by the computer within the game.

3.1.3. Temperature to Demand Relationship

The table below shows the relationship between temperature (in degrees Fahrenheit) and the daily consumption of energy (in kilowatts per day) per household.

Temperature to Demand Relationship

temperature (in fahrenheit)	daily consumption (in kW per day)
75	17
80	21
85	25
90	29
95	33
100	37
105	41

Figure 13 - Temperature to Demand Relationship

In the game, the temperature values will influence the demand for energy. However, demand is uncertain and can increase/decrease by as much as 10% from the expected values given in the table.

3.1.4. Reservoir Volume to Depth Relationship

Students will need to estimate reservoir depth based on the depth of water; the following figure represents the relationship between reservoir volume in acre feet to reservoir depth in feet.

Reservoir Volume to Depth Relationship

Volume (in acre feet)	Depth (in Feet)
-	0
2,000	5
4,000	10
6,000	15
8,000	20
10,000	25
12,000	30
14,000	35
16,000	40
18,000	45
20,000	50

Figure 14 - Reservior Volume to Depth Relationship

3.1.5. Conversion from Cubic Feet to Acre Feet

There are 43,560 cubic feet in one AF of water. Inflows and hydro releases are measured and displayed in cubic feet per second (cfs) while reservoir volumes are measured in AF.

3.1.6. Conversion from Seconds to Days

There are 86,400 seconds per day. Inflow and outflow from the reservoir are measured in cfs.

3.1.7. Conversion from Feet to Meters

There are 0.3048 meters per foot. The conversion from feet to meters is required for calculating production and energy demand in kW/day.

3.1.8. Conversion from Acre Feet to Cubic Meters

There are 1,233 cubic meters in one AF of water. The conversion from feet to meters is required for calculating production and energy demand in kW/day.

3.1.9 Other Considerations

There are no forecast inflows during the period of the game. The efficiency of energy conservation and transmission is 75% of the energy released from the reservoir is converted to electricity.

3.2. Game Instructions

The game begins on an 88 degree day. Players will want to use the information to make predictions about future electricity demand and determine the volume of their first target release. Players will make releases between time period 1 and time period 7 (the end of the game). The goal of these releases should be to meet electricity demand without releasing too much excess. The winning player(s) will have the smallest amount of excess in the game view table in the final time period (time period 7).

Players will want to use the downloadable excel file to enter their predictions about reservoir volumes, depths, release, and production using the data in the game view graphs and tables. 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) temperature and electricity demands in the model. While an optimal *apriori* decision exists (based on the probability of temperature demand associated with various target releases), the solution requires a combinatorics answer that is far beyond the skill set of most middle and high school students. Furthermore, even this "example solution" may not meet demand, due to the random temperature changes; while a less theoretically optimal solution may meet demand without compromising reservoir volume and depth.

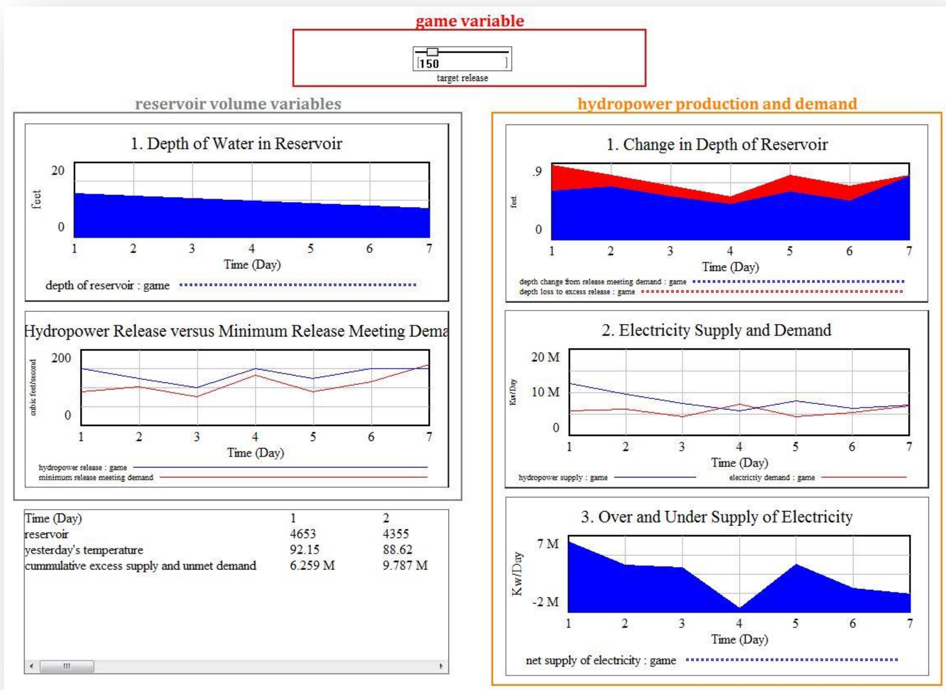

Figure 15 - Example Solution

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.