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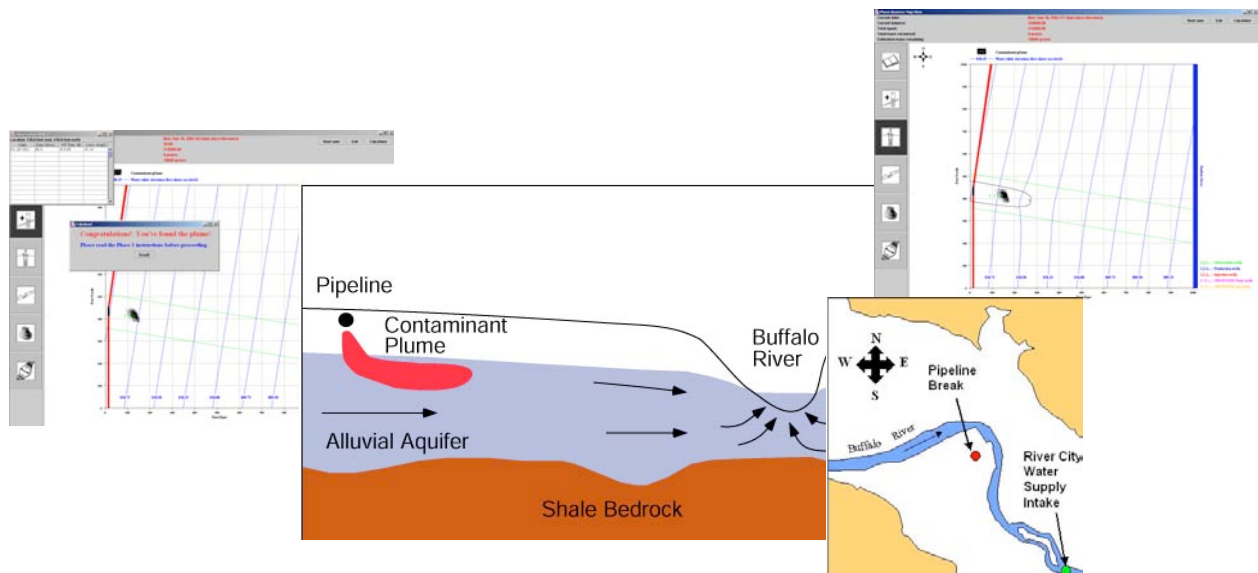
# Kansas Geological Survey

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## A TEACHER'S GUIDE TO PLUME BUSTERS

By

P. Allen Macfarlane, M.A. Townsend, G.C. Bohling and Steve Case



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## **Preface**

The Teacher's Guide to Plume Busters is designed for use with the interactive Plume Busters software. Users are advised to read the Computer System Requirements section of the manual prior to loading or downloading the software. This section provides operating system requirements, suggested browsers for viewing the HTML pages, and screen resolution control settings. The software and installer are contained on the CD that accompanies this manual from the Kansas Geological Survey (KGS). The software is also downloadable from the KGS website. Prior to downloading and installing from the CD, the installer checks your operating system to determine if the JAVA run-time environment (JRE) is present. If not, the installer comes with JAVA and will install it as part of the process. If you are downloading from the KGS website, you will have to download the JRE from the Sun website.

The ground-water tutor is in two parts: a set of HTML pages that have been grouped into sections, some of which have been linked in sequence to guide the student through introductory material; and a JAVA-based numerical ground-water model that simulates the flow of water and the movement of contaminants through the Buffalo River valley alluvial aquifer. The software is also divided into Locating the Plume and Remediate the Plume parts. These are sequential and with the completion of the first part the student moves on to the second part.

The software is designed in such a way that it is not necessary to read through the teacher's guide prior working through the Plume Busters. Adequate directions are provided in the HTML pages that this step is not necessary. Starting the Plume Busters software involves double-clicking on the desktop short-cut.

Grade 11-12, undergraduate non-hydrogeology major, and undergraduate hydrogeology major appropriate versions are currently available. The grade 11-12 and undergraduate non-hydrogeology major versions are appropriate for earth science, environmental geology, environmental science, and other introductory water resources and earth science classes at the high school and college undergraduate levels.

For teachers, the manual (1) identifies the national and Kansas science, environmental science, mathematics, and geography standards addresses by the tutor, (2) describes the student role-play, (3) outlines the sequence of operations followed as the student progresses through the tutor, (4) provides useful information on how best to integrate the software in earth and environmental science classes and (5) gives teachers tips to help guide students through the tutor. Terms that might be unfamiliar to users are underlined and defined in the Glossary at the back of this guide.

Questions, comments, or problems with the software should be directed to Dr. P. Allen Macfarlane at the Kansas Geological Survey by phone at (785) 864-2068 or by e-mail at [dowser@kgs.ku.edu](mailto:dowser@kgs.ku.edu)



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## Overview

Using the interactive Plume Busters software, students take on the role of an environmental consultant and apply the principles of ground-water flow and well hydraulics to solve a simulated contamination problem. Introduction of the software should follow basic instruction covering the hydrologic (water) cycle, the principles of ground-water flow, and concepts related to the effect of wells withdrawing or adding water on an aquifer. Follow-up activities can range from discussion of environmental policy and ethics to the role of technology in solving societal and environmental problems. Grade 11-12, and undergraduate non-hydrogeology and undergraduate hydrogeology major appropriate versions are currently available.

In the role as an environmental consultant, students use ground water and other science, mathematics, and geography concepts to simulate the cleanup of a chemical spill from a ruptured pipeline. The chemical spill has contaminated an aquifer and if unchecked, the contaminants will travel through the aquifer from the spill site, seep into a nearby river, and pollute a downstream public water supply. In this exercise, the pipeline owner hires an environmental consultant. The consultant's objective is to eliminate the contamination from the aquifer in the shortest amount of time for the least cost to the pipeline owner. Well installation, chemical analyses of water samples from wells, and operation of the wells used for remediation have associated with them time and money costs and in some cases, regulatory requirements also have an associated time cost. In the first part of the simulation (Locate the Plume), the student uses the concepts of hydraulic gradient, the porosity and permeability properties of aquifer materials, Darcy's law, and average ground-water velocity to estimate the location of the contaminants in the aquifer at any given time. Locating the contamination requires the student to install monitoring wells in the aquifer. In the second part of the simulation (Remediate the Plume), the student uses the concepts of cone of impression, cone of depression, zone of influence, and capture zone to design a wellfield to remove the contaminants from the aquifer. The wellfield consists of production wells or a production well/injection well couplet and as it is operated, students observe the simulated removal of the contaminants from the aquifer. The software gives students the opportunity to apply their knowledge of ground-water systems in the context of a simulated real-world situation.

## Science and Environmental Policy Context

Water is temporarily stored in a number of different reservoirs and moves from one reservoir to another in a hydrologic cycle that encompasses the atmosphere, biosphere, and lithosphere (Figure 1). Water cycles within the hydrosphere by solar-driven evaporation from the oceans and other water bodies, evaporates from near the atmosphere/lithosphere boundary, and through transpiration and respiration from the biosphere, replenishes the atmospheric reservoir. Precipitation transports water back to the earth's surface where it either infiltrates into the subsurface or runs off to streams, lakes, and eventually the oceans. That portion of water that

infiltrates into the subsurface below the root zone of plants may eventually reach the water table and recharge the ground-water system.

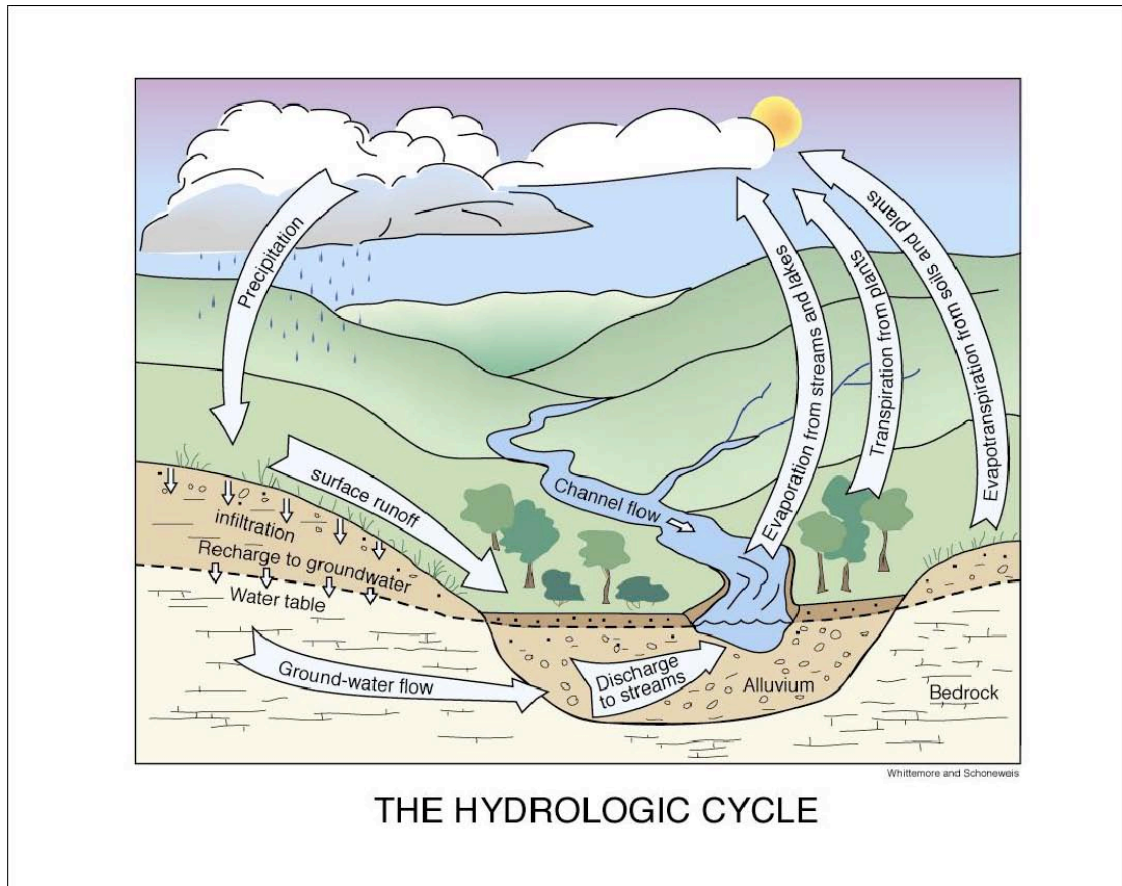


Figure 1. The drainage basin hydrologic cycle.

Water is the elixir of life on the Earth. Issues related to water supply, water quality, and the degradation of aquatic environments are central to modern daily life in many ways. Water is needed for everything from daily consumption to food and energy production. Ground water plays a significant role since it accounts for approximately 25% of all the freshwater near the Earth's surface with much of the rest stored as ice in polar ice caps and glaciers. Of the freshwater available to the majority of human society, ground water represents 94% of the total. In the United States ground water accounts for 25% of all water resources utilized by industrial society. Aquifers also supply approximately 51% of the drinking water consumed in the United States (US EPA, 1998). These sources of water are under increasing pressure because of contamination as a result of human activity.

Public perception of the issues surrounding ground-water use and protection from contamination is lacking because, unlike water bodies at the Earth's surface, ground water cannot be observed directly in most cases. Contrary to the public perception of water flowing in underground rivers, ground-water typically moves at rates that are orders of magnitude slower than rates for water in streams and is generally not confined to discrete channels. This inability to visualize how water flows through aquifer systems from areas of recharge to areas of discharge directly affects the public perception of human impacts on this part of the hydrologic cycle. Public education on the impact of human activities on water and environmental quality is crucial to society's ability to make informed decisions on natural-resource management and environmental quality. Figure 2 is a concept map of the Buffalo River drainage and the human impacts simulated in the Plume Busters software.

### **Secondary Education Standards**

The Plume Busters software addresses both federal and state, secondary, science education standards and the Kansas mathematics, environmental science, and geography education standards. The National Science Education Standards (NAS, 1996) for grades 9-12 state that students should develop an understanding of the geochemical cycles and the role of water as a carrier of material (Earth and Space Science Content Standard D, p. 187). Under the Science in Personal and Social Perspectives Content Standard F (p. 193) students are to develop an understanding of the impact of human activity on natural resources and environmental quality through control of the hydrologic cycle and disposal of wastes. Under this standard, understanding of basic concepts and principles of science and technology should precede active debate of science- and technology-related issues.

Tables 1-4 identify the Kansas science, mathematics, environmental, and geography education standards, benchmarks, and indicators relevant to Plume Busters.

### **What Students Gain from Working through the Plume Busters Software**

The benefits to the student from working with the ground-water tutor are fivefold.

First, the student must draw on concepts from geology, geography, ground-water science, mathematics, and economics to remedy this environmental problem. By drawing on the concepts from these diverse sources, the student can begin to see how these disciplines fit together as an integrated body of knowledge and tools.

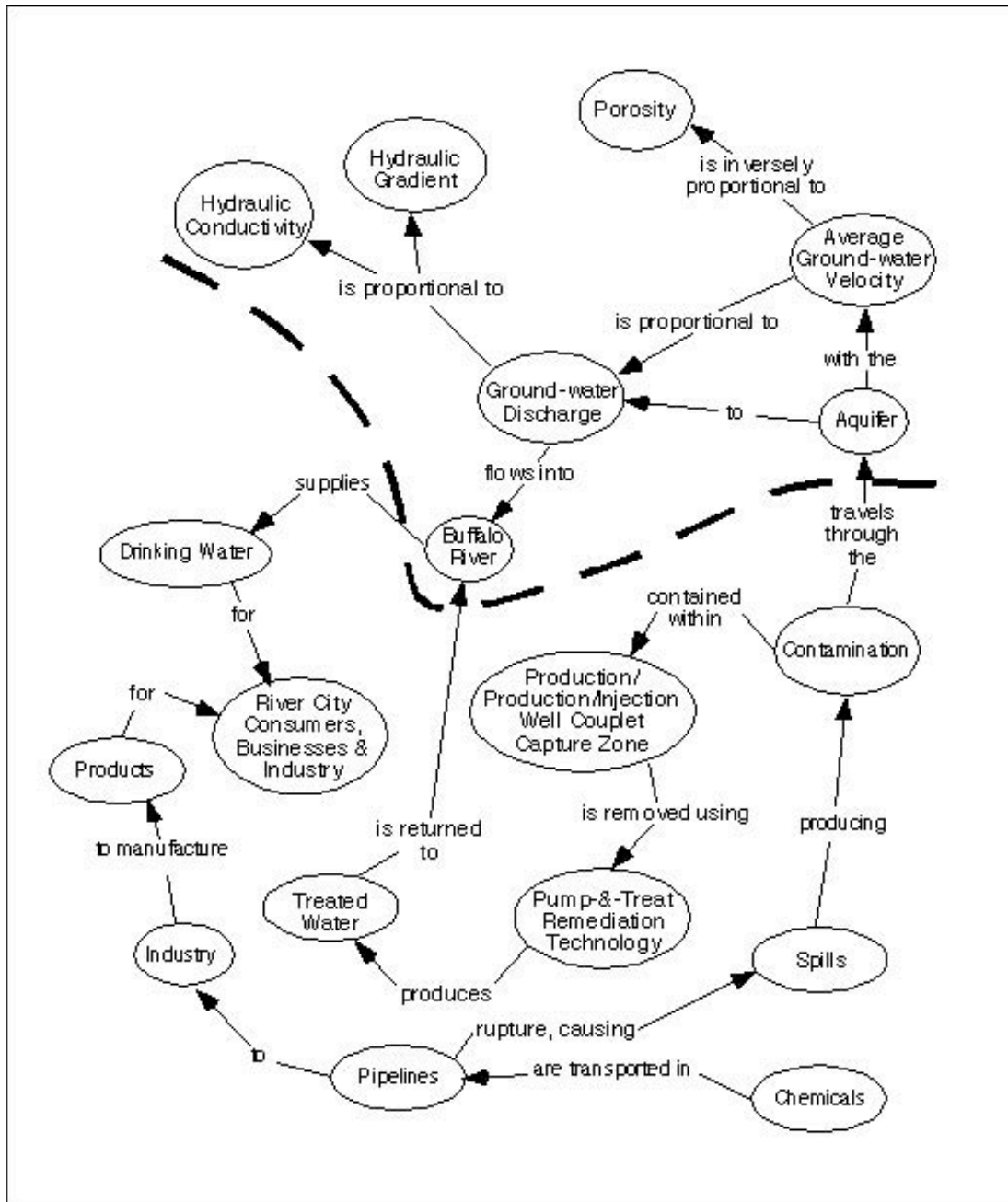


Figure 2. Concept map of the water cycle in the human-impacted Buffalo River drainage basin as it is portrayed in the ground-water tutor. The linked concepts above the dashed line represent the surface and ground-water parts of the basin hydrologic cycle that are pertinent to the tutor. The linked concepts below the dashed line represent human impacts portrayed in Plume Busters.

Table 1. Kansas science education standards, benchmarks, and indicators relevant to Plume Busters. (Excerpted and adapted from Kansas State Board of Education, 2001)

	Standard	Benchmark	Indicator
By the end of 8 <sup>th</sup> grade	Science As Inquiry	Benchmark 1: Demonstrate abilities necessary to do the processes of scientific inquiry  Benchmark 2: Apply different kinds of investigations to different kinds of questions	Design and conduct a scientific investigation  Use appropriate tools, mathematics, technology, and techniques to gather, analyze, and interpret data  Apply mathematical reasoning to scientific inquiry  Differentiate between a qualitative and a quantitative investigation  Develop questions and adapt the inquiry process to guide an investigation
	Earth and Space Science	Benchmark 1: Develop an understanding that the structure of the earth system is constantly changing due to the earth's physical and chemical processes	Model earth's cycles
	Science in Personal and Environmental Perspectives	Benchmark 2: Develop an understanding of the impact of human activity on resources and environment	Investigate the effects of human activities on the environment
	History and Nature of Science	Benchmark 1: Develop scientific habits of mind	Base decisions on evidence
By the end of 12 <sup>th</sup> grade	Science As Inquiry	Benchmark 1: Demonstrate the fundamental abilities necessary to do scientific inquiry	Use technology and mathematics to improve investigations and communications  Formulate and revise scientific explanations and models using logic and evidence
	Earth and Space Science	Benchmark 2: Develop an understanding of the actions and interactions of the earth's subsystems: the geosphere, hydrosphere, atmosphere, and biosphere	The students will understand the processes of the carbon, rock, and water cycles.
	Science in Personal and Environmental Perspectives	Benchmark 1: Develop an understanding of the overall functioning of human systems and their interaction with the environment in relation to specific mechanisms and processes related to health issues  Benchmark 3: Develop an understanding that human populations use natural resources and influence environmental quality  Benchmark 4: Develop an understanding of the effect of natural and human-influenced hazards  Benchmark 5: Develop an understanding of the relationship between science technology, and society	The students will understand that hazards and the potential for accidents exist for all human beings.  The students will understand that materials from human activities affect both physical and chemical cycles of the earth.  The students will understand that there is a need to assess potential risk and danger from natural and human-induced hazards.  The students will understand that understanding basic concepts and principles of science and technology should precede active debate about the economics, policies, and ethics of various challenges related to science and technology.

Table 2. Kansas environmental education standards, benchmarks, and indicators relevant to the Plume Busters software. (Excerpted and adapted from Kansas Association for Conservation and Environmental Education, 1999).

Standard	Benchmark	Indicator
Standard 1: Earth as a Physical System	Benchmark 2: Explain how the process of photosynthesis transforms the sun's energy in plants and releases oxygen into the air	Illustrate how different elements and compounds cycle through ecosystems at different rates
Standard 3: The Varied Roles and Interactions between Humans and the Environment	Benchmark 1: Analyze the relationship between individuals, groups, cultures, and the environment  Benchmark 2: Analyze the relationships among laws, politics, economics, and environment  Benchmark 3: Investigate and analyze the relationships among resources, technology, and environment  Benchmark 4: Identify and evaluate environmental issues from multiple points of view	Describe how the actions of businesses, community groups, and other societal organizations may bring about unintended impacts on the environment  Explain human rights, economic development, public health, resource allocation, and environmental quality from the perspectives of the individual, the community, the nation, and the world  Describe the short-term and long-term costs and benefits of addressing local, national, and worldwide environmental problems  Describe the governmental and non-governmental roles in addressing local, national, and worldwide environmental problems  Describe how technology has influenced the quality of life  Describe how technology has altered the natural environment  Describe how agriculture, mining, manufacturing, energy production, highway construction, and other economic development activities have altered the natural environment in Kansas  Identify the various uses of <u>soil</u> and water in Kansas  Identify the risks and benefits that agriculture, petroleum production, manufacturing, energy production, human communities, and other economic development activities can have on soil and water in Kansas  Describe the problems Kansans face in regard to solid and hazardous waste disposal
Standard 4: Development of the Abilities Necessary to Conduct Scientific Inquiry	Benchmark 1: Develop the abilities necessary to conduct scientific inquiries  Benchmark 2: Demonstrate scientific inquiry skills	Identify an environmental topic to be studied using primary and secondary sources of information, and pose a research question or hypothesis, identifying key variables  Apply observation and measurement skills in field situations  Gather information from a variety of sources  Integrate and summarize information from a variety of media
Standard 5: Development of the Abilities Necessary to Participate and Make Informed Decisions Regarding Environmental Issues	Benchmark 1: Demonstrate the skills necessary to understand and communicate ideas about environmental issues	Identify and clearly articulate environmental issues and their connections to other issues  Identify different perspectives on environmental issues and approaches to resolving them  Discuss social, political, and economic implications of environmental issues  Project the likely consequences of failure to resolve a specific environmental issue

Table 3. Kansas mathematics education standards, benchmarks, and indicators relevant to Plume Busters. (Excerpted and adapted from Kansas State Board of Education, 2003)

Standard	Benchmark	Indicator
<p>Standard 1: Number and Computation – Use of Numerical and Computational Concepts and Procedures in a Variety of Situations</p>	<p>Benchmark 3: Estimation – Computational estimation with real numbers in a variety of situations</p> <p>Benchmark 4: Computation – Models, performs, and explains computation with real numbers and polynomials in a variety of situations</p>	<p>The student:</p> <p>Adjusts original rational number estimate of a real-world problem based on additional information (a frame of reference)</p> <p>Determines if a real-world problem calls for an exact or approximate answer and performs the appropriate computation using various computational strategies including mental math paper and pencil, concrete objects, and/or appropriate technology</p> <p>Explains the impact of estimation on the result of a real-world problem (underestimate, overestimate, range of estimates)</p> <p>Generates and/or solves multi-step, real-world problems with real numbers and algebraic expressions using computational procedures (addition, subtraction, multiplication, division, roots, and powers excluding logarithms) and mathematical concepts</p>
<p>Standard 2: Algebra – Use of algebraic concepts and procedures in a variety of situations</p>	<p>Benchmark 3: Functions – Analysis of functions in a variety of situations</p> <p>Benchmark 4: Models – Development and use of mathematical models to represent and justify mathematical relationships found in a variety of situations involving tenth grade knowledge and skills</p>	<p>The student:</p> <p>Translates between the numerical, graphical, and symbolic representations of functions</p> <p>Interprets the meaning of the x- and y-intercepts, slope, and/or points on and off the line on a graph in the context of real-world situations</p> <p>Uses the mathematical modeling process to analyze and make inferences about real-world situations</p>
<p>Standard 3: Geometry – Use of geometric concepts and procedures in a variety of situations</p>	<p>Benchmark 2: Measurement and Estimation – Estimation, measurement, and use of geometric formulas in a variety of situations</p>	<p>The student:</p> <p>Solves real-world problems by using rates of change</p> <p>Estimates to check whether or not measurements or calculations for length, weight, volume, temperature, time distance, perimeter, area, surface area, and angle measurement in real-world problems are reasonable and adjusts the original measurement or estimation based on additional information (a frame of reference)</p> <p>Uses indirect measurements to measure inaccessible objects</p>
<p>Standard 4: Data – Use of concepts and procedures of data analysis in a variety of situations</p>	<p>Benchmark 2: Statistics – Collection, organization, display, explanation, and interpretation of numerical (rational) and non-numerical data sets in a variety of situations</p>	<p>The student:</p> <p>Uses data analysis (mean, median, mode, range, quartile, interquartile range) in real-world problems with rational number data sets to compare and contrast two sets of data, to make accurate inferences and predictions, to analyze decisions, and to develop convincing arguments from data displays</p> <p>Determines and explains the advantages and disadvantages of using each measure of central tendency and the range to describe a data set</p>

Table 4. Kansas geography education standards, benchmarks, and indicators relevant to Plume Busters. (Excerpted and adapted from Kansas State Board of Education, 1999)

	Geography Standard	Benchmark	Indicator
By the end of 8 <sup>th</sup> grade	Spatial organization of Earth's surface	Benchmark 1: Maps and Locations: Use maps and graphic representations to locate, use, and present information about people, places, environments	Locate major physical features of Earth from memory and compares the relative locations of these features.  Develop and use different kinds of maps, globes, graphs, charts, databases, and models.  Evaluate relative merits of maps, graphic representations, tools and technologies in terms of value in solving geographic problems: satellite photos, Geographic information systems, aerial photographs, topographic maps.  Use geographic tools and technologies to pose and answer questions about past and present spatial distributions.
		Benchmark 2: Regions: Analyze spatial organization of people, places and environments that form regions on Earth's surface	Identify and compare physical characteristics of world regions in terms of climate, topography, location and resources.  Identify and explain changing criteria that can be used to define a region such as physical characteristics.  Identify how technology has influenced a region (e.g. <u>perceptions of resource availability, economic development</u> ).
		Benchmark 3: Physical Systems: Understanding of Earth's physical systems and how physical processes shape Earth's surface	Explains patterns in the physical environment in terms of physical processes (i.e. erosion and deposition, <u>hydrologic cycle</u> )  Explains the challenges faced by ecosystems ( <u>contamination of alluvial aquifer systems; overuse of aquifers; natural disasters</u> )
		Benchmark 5: Human-Environment Interactions: Understand the effects of interactions between humans and physical systems	Explain and analyze the role of technology in past, present, future of human modifications of environment (movement of water; water-quality alterations, contamination of aquifers)  Describe local, national, international impacts of use or misuse of resources (over-consumption of water, contamination of aquifers)  Evaluates viewpoints regarding use of water  Identifies and develops plans for management and use of resources



Table 4. Continued

	Geography Standard	Benchmark	Indicator
By the end of 11 <sup>th</sup> grade	Spatial organization of Earth's surface	Benchmark 1: Maps and Locations: Use maps and graphic representations to locate, use, and present information about people, places, environments	Locate major physical features of Earth from memory and compares the relative locations of these features.  Interprets maps and other graphical representations to analyze and suggest solutions to problem (such as <u>contamination</u> of municipal <u>water supply</u> )  Use geographic tools and technology to interpret and justify spatial organization.
		Benchmark 2: Regions: Analyze spatial organization of people, places and environments that form regions on Earth's surface	Student demonstrates how regional frameworks are used to interpret the complexity of the Earth (vegetation, climate, resources).  Explains factors that contribute to physical changes in regions (overuse of water, contamination of water supplies)
		Benchmark 3: Physical Systems: Understanding of Earth's physical systems and how physical processes shape Earth's surface	Explain Earth's physical processes, patterns, and cycles using concepts of physical geography ( <u>hydrologic cycle</u> , erosion, deposition)  Describe ways in which Earth's physical processes are dynamic and interactive (wind and water deposition, stream and <u>aquifer</u> interactions)  Analyze and ecosystem to understand and solve problems regarding environmental issues (groundwater-contamination, impacts of <u>contaminants</u> on plants and animals, <u>water supply</u> issues)
		Benchmark 5: Human-Environment Interactions: Understand the effects of interactions between humans and physical systems	Evaluate local-to-global impacts of technology on human modifications of the physical environment (toxic waste, farming practices, overuse of water)  Evaluate alternative strategies to respond to constraints placed on human systems by physical environment (irrigation, sustainable agriculture, water diversion)  Evaluates policies and programs for resource management (e.g., EPA, water-rights in western states, use of recycled water)

Secondly, students use quantitative information in the grade 11-12 version and both qualitative and quantitative information in the college undergraduate versions of the software to locate the contamination in the alluvial aquifer. Undergraduates must also deal with uncertainty because of the necessity to make estimates based on somewhat vague qualitative information.

Thirdly, the student gains confidence from being able to solve a real-world problem. In working with Plume Busters, the student must make decisions and deal with their consequences. Students also confront the practical side of environmental consulting as they solve this real-world environmental problem. Decisions made by the student are constrained not only by the time it will take for the contamination to reach the river, but also by economic and regulatory realities.

Fourthly, the software also introduces the student to the application of technology to the solution of environmental problems. Using the available information, the student designs and operates a remediation wellfield to remove contamination from the aquifer. Well hydraulics is not typically

included in secondary- and minimally introductory undergraduate-level earth science classes. Thus, the software provides the student with an opportunity to develop a qualitative understanding of this topic without rigorous quantitative instruction.

Finally, the software also provides a lead-in to discussions focusing on environmental policy, including the means to achieving environmental protection, topics related to the economic cost of human activities on environmental quality, how clean are our water resources, and setting limits on acceptable levels of contamination in water resources.

### **Science Concepts**

The emphasis of Plume Busters is on the practical application of ground-water concepts to “real-world” problem solution. Using monitoring wells, students attempt to locate ground-water contaminants in an aquifer in the first part of the simulation and in the second part, they remove the contaminants from the aquifer by designing and operating a remediation system.

To accomplish the task of locating the contaminants, the student uses Darcy’s law and the data provided to determine the average ground-water flow velocity and in the college undergraduate hydrogeology major version, the likely path taken by the contaminants from the spill site to the nearby river. The ground-water flow “corridor” from the spill site to the river is provided to the student in the grade 11-12 and undergraduate non-hydrogeology major versions. To locate the contaminated ground water in the aquifer, the student must estimate how long the contamination has been moving with the ground-water flow from the spill site. This task is similar to that faced by those who play the board game Battleship, except that the target is moving in a predictable manner instead of being stationary.

The main science concepts stressed in this part of the software include:

- Monitoring wells are the primary means by which an environmental consultant determines the extent and location of a contaminant plume or slug in an aquifer.
- The average ground-water flow velocity is calculated as the quotient of the specific discharge divided by the aquifer porosity.
- The bulk porosity of an aquifer can be calculated as the average of the representative porosities of the sediments that constitute the aquifer weighted according to their relative thickness (college undergraduate versions).
- The distance traveled and the direction of movement of contaminants moving with the ground-water flow can be estimated approximately from the average ground-water flow velocity and the time since the contaminants were released into the aquifer.

Fundamental science concepts stressed in this part of the software include:

- An alluvial aquifer consists of porous and permeable materials deposited by physical processes in river channels and on floodplains that can store and transmit water at rates fast enough to supply reasonable amounts to wells (Figure 3).
- The water table is the upper boundary of an unconfined aquifer (Figure 4).
- The hydraulic head is the elevation of the water level in wells penetrating an aquifer (Figure 5). In unconfined aquifers, it is equivalent to the elevation of the water table and the elevation of the water surface in surface water bodies, such as lakes and streams (Figure 4).

- Ground water flows from regions of high hydraulic head to areas of low hydraulic head (Figure 5).
- The hydraulic gradient is the slope of the water table and is calculated as the change in hydraulic head per unit distance in the direction of ground-water flow (Figure 5).
- A monitoring well is a well designed for measuring water levels and for obtaining water samples to test for testing ground-water quality.
- Hydraulic conductivity is a measure of the capacity of earth materials to transmit fresh water.
- Porosity is a measure of the relative amount of void space in earth materials (Figure 6).
- Darcy's law states that the flow rate of water through porous materials is proportional to the hydraulic gradient. The constant of proportionality is the hydraulic conductivity (Figure 7).
- The average ground-water velocity is the speed and direction of travel of ground water through an aquifer.
- Contaminants often move laterally through aquifers at the same speed and in the same direction as the ground-water flow.
- The distance traveled and the direction of movement of contaminants moving with the ground-water flow can be calculated from the average ground-water flow velocity.

The hydraulic gradient is calculated from measurements of water-table elevation in at least two wells (Figure 5). Over a small geographic area, the water table is considered a planar surface that is defined by the water level elevations in three wells. In the college undergraduate hydrogeology major version, a map of the water table does not appear until the student sites three monitoring wells. This parameter is important because ideally the direction of ground-water flow is perpendicular to the slope of the water table and in the direction of decreasing water table elevation.

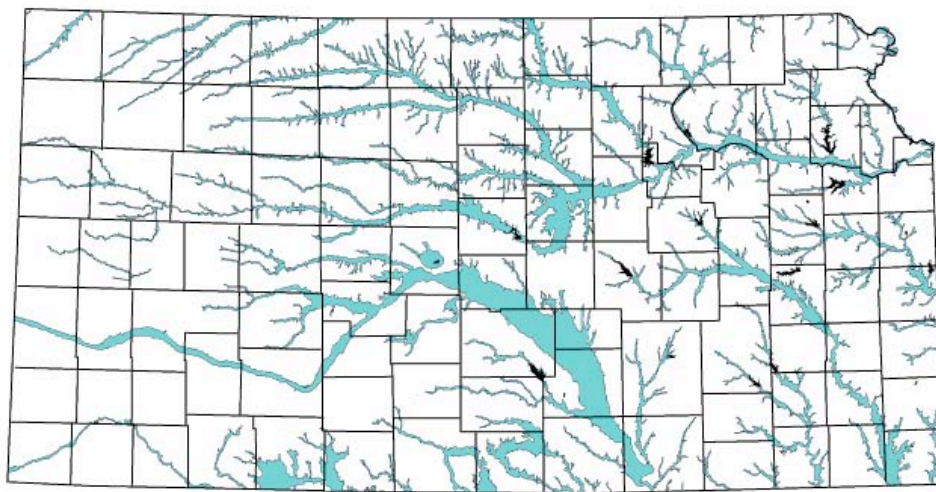


Figure 3. The alluvial aquifers of Kansas.

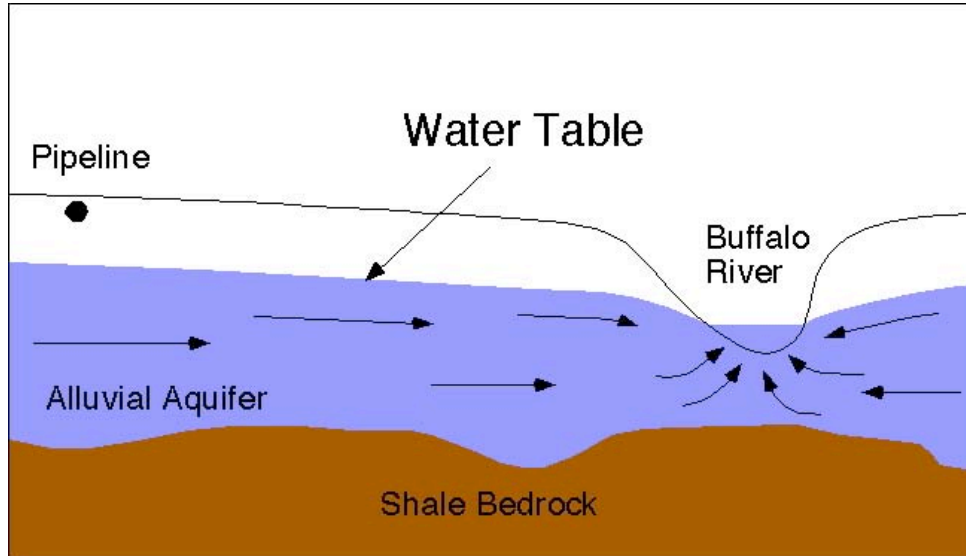


Figure 4. The water table defined the upper saturated part of an unconfined alluvial aquifer. In the figure, the flow of water is from the alluvial aquifer to the stream and the stream is considered to be gaining.

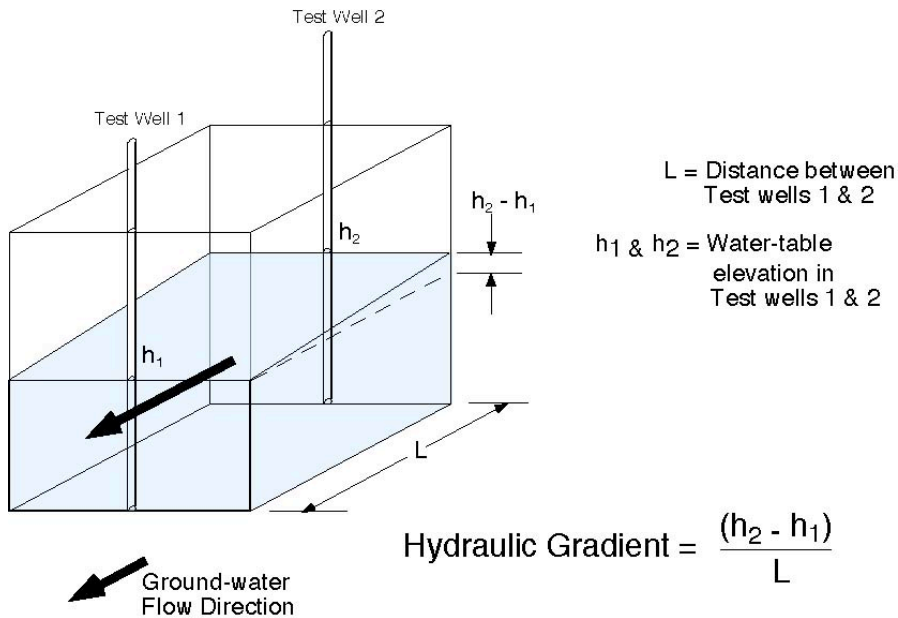


Figure 5. Hydraulic head is equivalent to the elevation of the water table above sea level. The hydraulic gradient is the change in hydraulic head ( $h_1 - h_2$ ) over a horizontal distance  $L$  in the direction of ground-water flow.

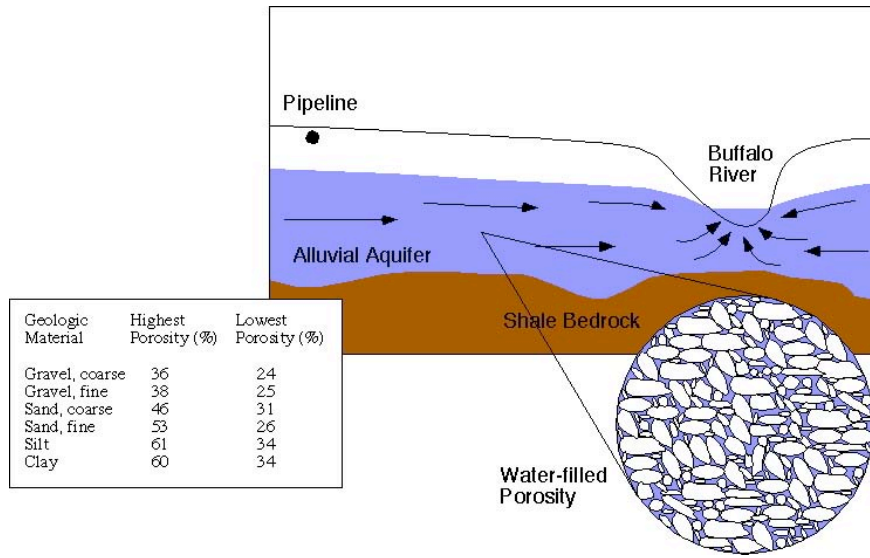
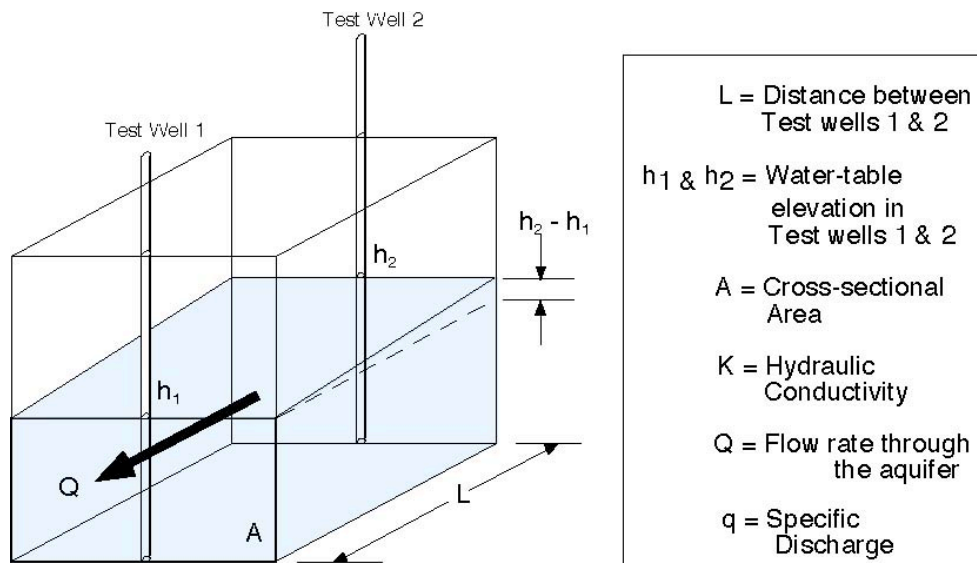


Figure 6. Porosity is the relative amount of void space or the space between the sediment grains in the alluvial aquifer and is usually expressed as a percentage of the bulk volume (the space occupied by the grains and the voids).



$$\text{Darcy's Law: } \frac{Q}{A} = q = K \frac{(h_2 - h_1)}{L}$$

Figure 7. Darcy's law is a fundamental equation of ground-water flow. It states that the flow,  $Q$ , is proportional to the hydraulic gradient and the cross-sectional area through which it passes. The constant of proportionality is the hydraulic conductivity. In shallow aquifers containing fresh water the hydraulic conductivity depends on the earth materials that constitute the aquifer.

Darcy's law is the fundamental ground-water flow equation, developed experimentally by Henri Darcy in 1856. The equation relates the hydraulic gradient (the slope of the water table), the cross sectional area of the aquifer and the hydraulic conductivity (permeability) of the aquifer to the ground-water flow rate (Figure 7):

$$Q = K(\Delta h/\Delta L)A,$$

where Q is the ground-water flow rate (seepage), K is the hydraulic conductivity, h is hydraulic head, L is the distance between two hydraulic-head measurement points, and A is the cross-sectional area of the aquifer through which flow is occurring. The quantity  $(\Delta h/\Delta L)$  is the hydraulic gradient. In many applications the Darcy's Law is used to calculate the specific discharge:

$$\text{Specific Discharge} = Q/A = K(\Delta h/\Delta L),$$

which is the rate of flow per unit cross-sectional area (in terms of units:  $L^3/T/L^2$  or  $L/T$ ). The average ground-water velocity is calculated taking into account the aquifer cross-sectional area that is occupied mostly by aquifer material and the flow of ground water is restricted only to the interconnected pore space (porosity). The average ground-water flow velocity is calculated using the porosity and Darcy's Law:

$$\text{Ave. Ground-water Velocity} = K(\Delta h/\Delta L)/n,$$

where n is the porosity of the aquifer materials.

Using the distance = rate x time relation, the distance traveled by the contamination in the aquifer can be estimated if the elapsed time since the contaminants entered the aquifer can be estimated. These concepts and their relationships are shown in the diagram below in Figure 8.

In the second part of the simulation, the goal is to apply ideas from well hydraulics to design the remediation wellfield that will be used to remove the contaminants from the aquifer. The student is limited to one of two possible wellfield designs: one or more production wells or one production well and one injection well. The student is also allowed to select rates of withdrawal less than or equal to 40 gallons per minute from the production and injection wells. The primary science concept stressed in this part of simulation include:

- Pump and treat is a common technology used to remove contaminants from aquifers using production wells to withdraw water from an aquifer or using a well couplet consisting of production well and an injection well (a well used put water into an aquifer) (Figures 9-10).
- The capture zone is the region of the aquifer contributing to ground-water flow to a well. The shape of the capture zone is parabolic and its size depends on the average linear ground-water velocity, the rate at which the well is being pumped, and the hydraulic conductivity of the aquifer (Figure 11). In the case of a production well-injection well couplet, the capture zone is elliptical in shape its size depends on the average linear ground-water velocity, the rate at which the production and injection well are withdrawing from and adding water to the aquifer, and the aquifer hydraulic conductivity (Figure 12).

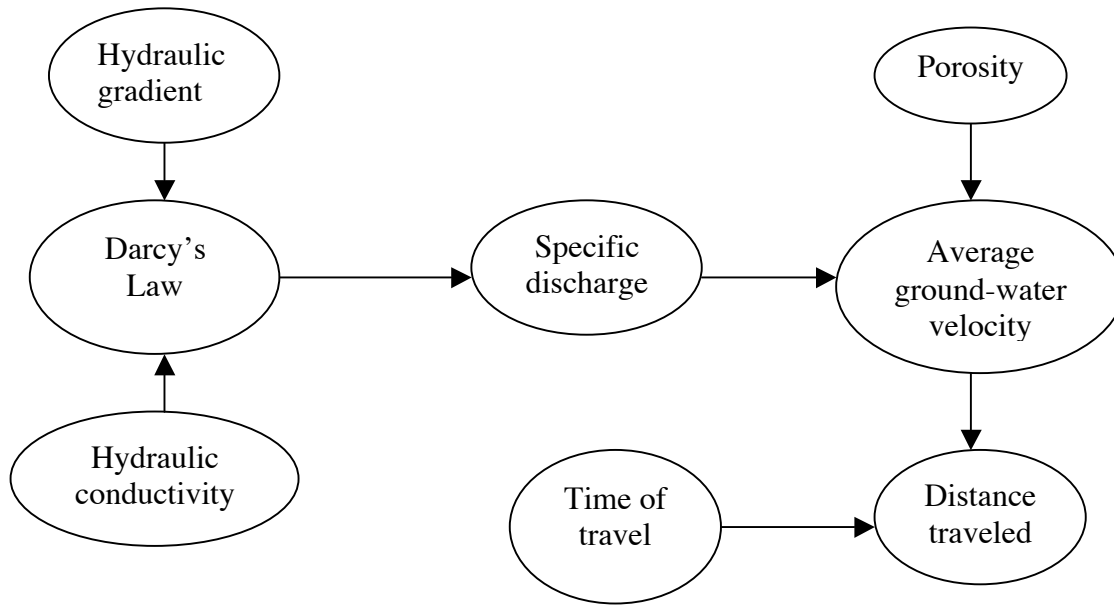


Figure 8. Subsidiary science concepts and their relationship in the contaminant discovery phase of Plume Busters.

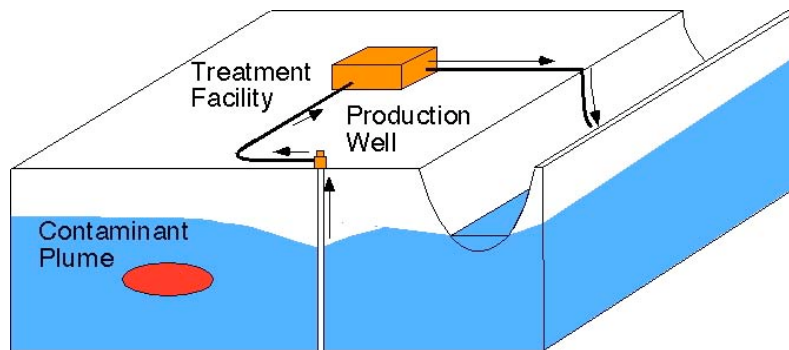


Figure 9. The pump-and-treat method of remediation using production wells only to remove contamination from an aquifer.

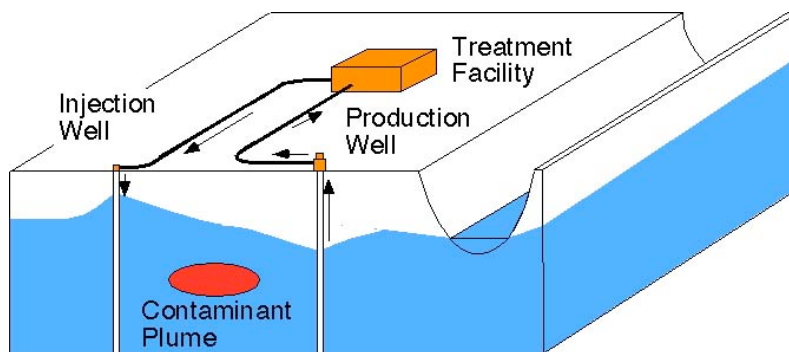


Figure 10. The pump-and-treat method of remediation using a production-injection well couplet to remove contamination from an aquifer.

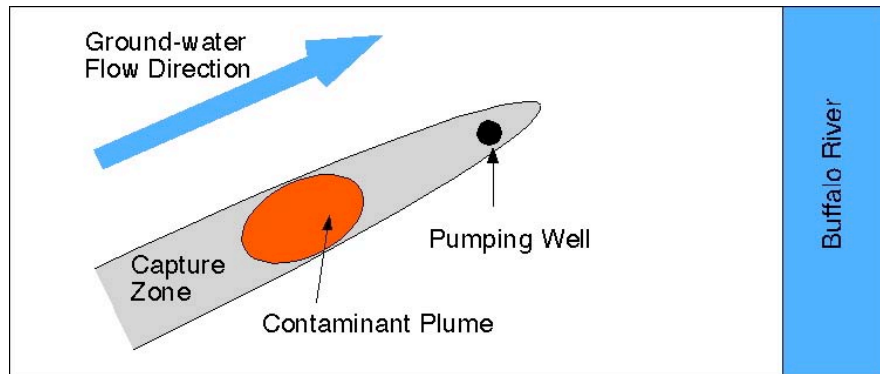


Figure 11. Capture zone created by pumping a production well. The capture zone outline is parabolic in shape and production well is located at the focus of the parabola. If the student elects to use a production well to remediate the aquifer, the limits of the contamination must be contained entirely by the capture zone created by the production well.

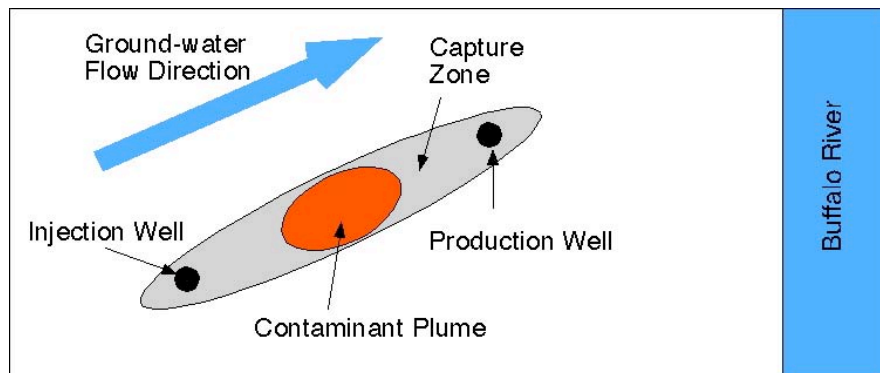


Figure 12. Capture zone created by pumping a production and injection well couplet. The capture zone outline is elliptical in shape. As in Figure 11, if the student elects to use production-injection well couplet to remediate the aquifer, the limits of the contamination must be contained entirely by the capture zone created by the couplet.

Fundamental science concepts stressed in this part of the software include:

- Ground-water withdrawal using a production well causes a local lowering of the water table in the well vicinity to create a cone of depression. The lowering of the water table results because water is removed from the aquifer at a faster rate than it can be replenished by ground-water flow moving toward the well (Figure 13). For a given aquifer, the size of the cone of depression is determined by the rate at which ground water is being withdrawn from the aquifer.



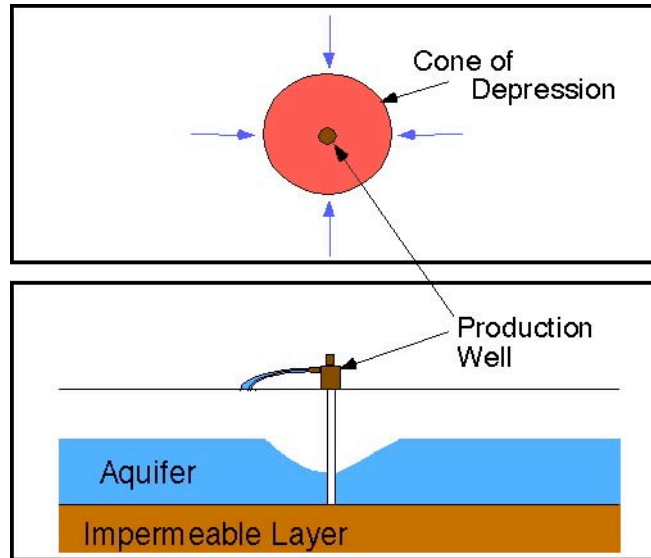


Figure 13. A cone of depression (shown in red in plan view) forms when a production well is pumped because water is being withdrawn from the aquifer than it is being replenished by ground-water flow (shown by the blue arrows). As a result the ground-water withdrawals cause a lowering of the water table (shown in the vertical cross section).

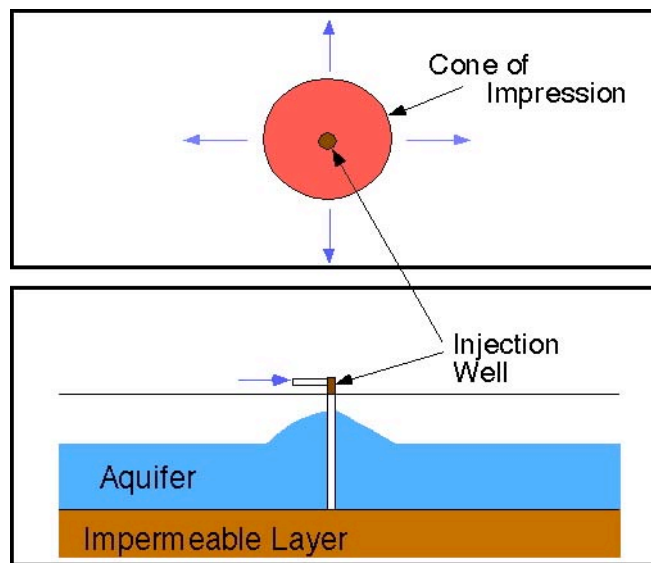


Figure 14. A cone of impression (shown in red in plan view) forms when an injection well is pumped because water is being added to the aquifer at a rate faster than it can move away from the well (shown by the blue arrows in plan view). As a result the addition of water causes a water-table rise near the well (shown in the vertical cross section).

- The zone of influence is the region of the aquifer affected by the addition of water to the aquifer from an injection well (Figure 15). In plan view, its shape is parabolic and its size depends on the average linear ground-water velocity, the rate at which the well is added to the aquifer, and the aquifer hydraulic conductivity.
- The addition of water to an aquifer through an injection well causes a local rise in the water table to create a cone of impression. The water table rise results when water is added to the aquifer at a faster rate than it can move away from the injection well into the surrounding aquifer by ground-water flow (Figure 14). For a given aquifer, the size of the cone of impression is determined by the rate at which water is added to the aquifer.

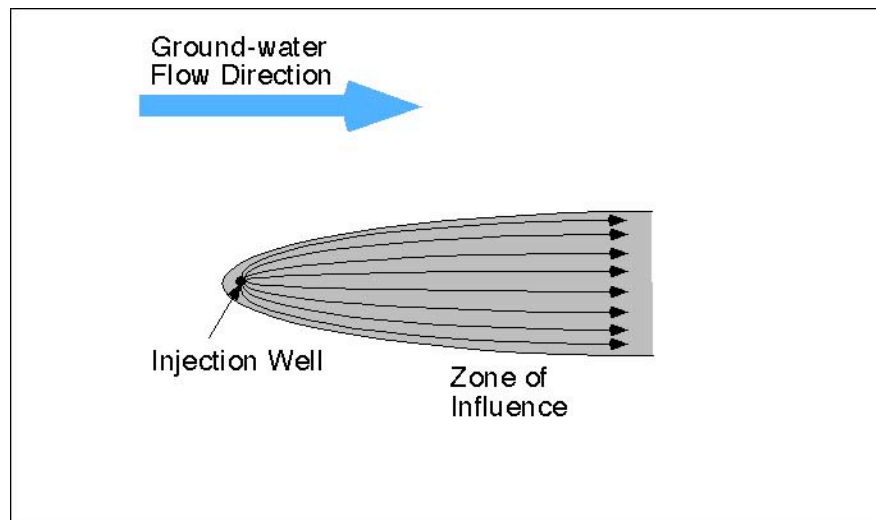


Figure 15. A zone of influence created by the addition of water to the aquifer from an injection well.

From a vantage point above the aquifer, capture zones are parabolic in shape with the production well located at the focus of the parabola (Figure 11). For a production well, the capture zone is oriented parallel to the flow direction with the open end of the parabola pointing up gradient. The zone of influence created by water inflow to the aquifer through an injection is similarly shaped but is oriented but with the open end of the parabola pointing down gradient from the well (Figure 13).

With a production well/injection well couplet, the injection well is placed upgradient and the production well is placed downgradient of the contaminated zone in the aquifer (Figure 12). As a result, the capture zone and the zone of influence overlap to create a new capture zone that is elliptical in shape. Within the capture zone, ground-water movement is directed to the production well from the injection at higher rates of flow than would be possible with only a production well withdrawing water at the same rate. This can significantly reduce the time required for remediation. The well couplet has the effect of hydraulically isolating the zone of contamination from the rest of the ground-water flow system.

Ideally, the maximum width of the capture zone or the zone of influence depends on the specific discharge (the product of the hydraulic conductivity and the hydraulic gradient, U), the aquifer thickness (B), and the rate of ground-water withdrawal by the production well or the rate of water inflow to the aquifer from the injection well (Q):

$$\text{Maximum Capture Zone or Zone of Influence Width} = Q/BU.$$

This relation assumes constant withdrawal or addition of water over long time periods approximating steady state conditions. In the ground-water flow model, the aquifer specific discharge and thickness are constant. The aquifer hydraulic conductivity varies slightly and is essentially a constant. Hence the relative maximum width of the capture zone or the zone of influence depends only on the rates of withdrawal or inflow from the production or the injection wells. The fundamental concepts and their relationships stressed in the second task are shown in the diagrams below (Figure 16).

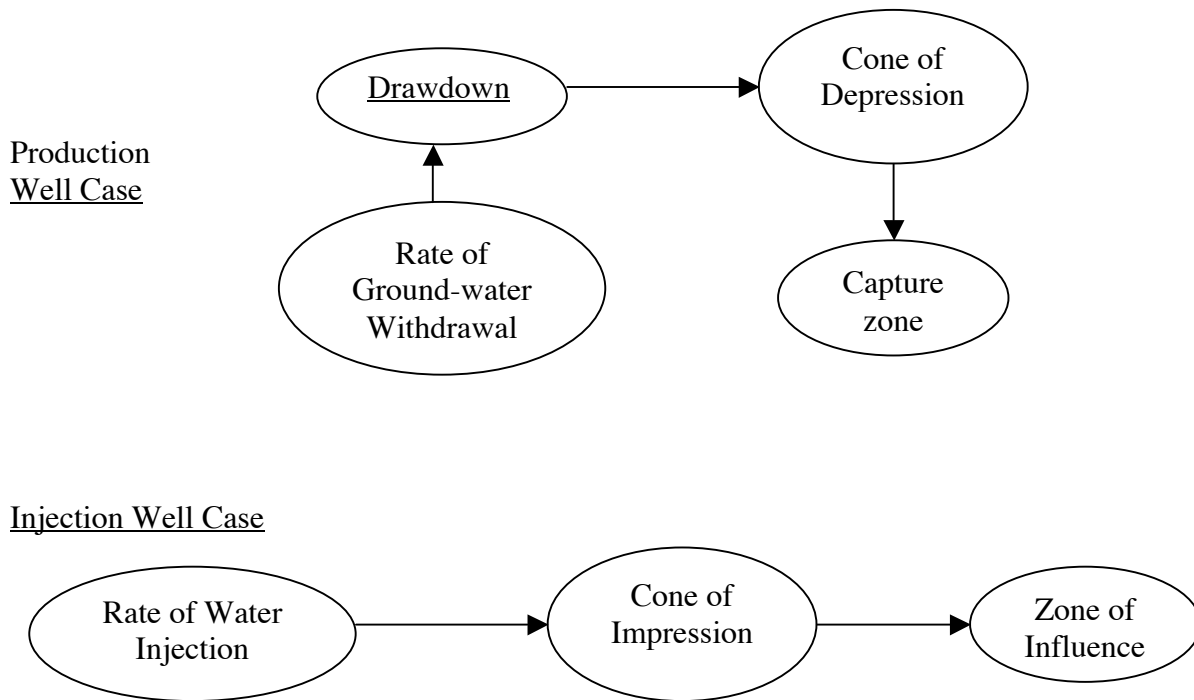


Figure 16. Subsidiary science concepts and their relationship in the aquifer remediation phase of the interactive ground-water tutor.

## Structure of Plume Busters

Plume Busters consists of a (1) JAVA-based, numerical model to simulate ground-water flow and the movement of contaminants through the aquifer and (2) a set of linked HTML pages. The user interacts with the numerical model through an interface called Map View that contains a gridded map of the spill site vicinity (Figure 17). Map View shows the location of the pipeline, the spill site and the river. The dimensions of the map are 1,000 feet by 1,000 feet. At the top of the Map View screen, the current calendar date and the time in days since the contamination was found are posted. Map View also provides information on the money remaining in the consultant's bank account that has been provided by the pipeline owner and the total amount of money spent on the project to date. Along the left side of Map View, there is a series of buttons. Using these buttons, the student adds/samples and resamples monitoring wells in Locating the Plume, adds/removes production and injection wells, modifies pumping rates, adds/samples and resamples monitoring wells, negotiates with the pipeline owner for more money, and advances the simulation in Remediating the Plume.

The linked HTML pages are grouped into sections and structured to help guide and provide resources and references to the student using Java Script (Figures 18-20). Most of this information is available to the student through the navigation bar. In the Grade 11-12 version, the problem description, directions on how to proceed, and the rules are combined into one section that starts just after the opening page. In the college undergraduate versions, these subsections are broken out and placed as separate items on the navigation bar as The PROBLEM, WHAT TO DO, and RULES. The WHAT TO DO and RULES categories provide information pertinent to both parts of the simulation. The Reference Library contains information on Darcy's law and capture zones, the calculation of average ground-water velocity and distance traveled by the plume. There is also a Glossary of terms that can be accessed by clicking on highlighted terms in the text or by clicking on the navigation bar.

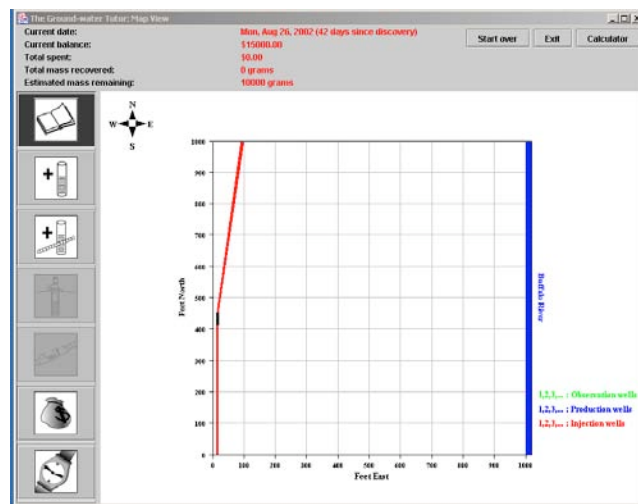


Figure 17. The Map View screen is the interface between the user and the ground-water model of the spill site vicinity. Note the array of tool buttons along the left side of the screen.

# Plume Busters

RESOURCES

REFERENCES

GLOSSARY

- 
- Site Tour
  - Data Repository
  - Darcy's Law
  - Ground-water Velocity
  - Travel Distance
  - Capture Zones
  - Trichloroethylene

Figure 18. Navigation bar layout for the Grade 11-12 version of Plume Busters.

# Plume Busters

THE PROBLEM

WHAT TO DO

RULE

RESOURCES

REFERENCES

GLOSSARY

- 
- Locating the plume
  - Remediating the plume
  - Locating the plume
  - Remediating the plume
  - Site Tour
  - Data Repository
  - Darcy's Law
  - Ground-water Velocity
  - Capture Zones
  - Trichloroethylene

Figure 19. Navigation bar layout for the college undergraduate non-hydrogeology major version of Plume Busters.

# Plume Busters

THE PROBLEM

WHAT TO DO

RULE

RESOURCES

REFERENCES

GLOSSARY

- 
- Locating the plume
  - Remediating the plume
  - Site Tour
  - Data Repository
  - Darcy's Law
  - Ground-water Velocity
  - Capture Zones
  - Trichloroethylene

Figure 20. Navigation bar layout for the college undergraduate hydrogeology major version of Plume Busters.

### **Student Interaction with Plume Busters**

The overall objective of the simulation is to remove the contamination from the aquifer with minimal cost in terms of time and money. To accomplish this objective, it is important for the student to:

- Use the provided information to best estimate where the contamination is located in the aquifer at a specified time after the pipeline leak started and not to randomly install monitoring wells in the hope of finding the contamination, and
- Take advantage of the preview function in the Wellfield Remediation phase to determine if the proposed wellfield design will remove all of the contamination from the aquifer prior to operating the remediation design.

Following these guidelines will allow the student to move efficiently through the simulation.

It is assumed that the student has received prior instruction on the principles of ground-water flow. It is also assumed that the level of detail provided to the student during instruction increases from Grade 11-12 students to college undergraduate non-hydrogeology majors to undergraduate hydrogeology majors. Thus, it is assumed that student understanding of the basic principles progressively increases from the Grade 11-12 through the undergraduate hydrogeology major versions. Likewise, it is also assumed that students have acquired increasing levels of competence and facility with respect to basic computer skills from Grade 11-12 through undergraduate hydrogeology major levels.

#### Starting Plume Busters

To start Plume Busters open the PlumeBusters directory and scroll down to the HTML file, PlumeBusters (Figure 21). The JAVA application (PlumeBusters[HS, NonMaj, or Maj]) can be opened at this stage but it is not necessary. As an alternative, short-cuts can be created and placed on the Windows desktop to allow easy access to both parts of the software.

#### Locating the Plume (Grade 11-12 Version)

The opening narrative informs the student that a pipeline transporting industrial chemicals, including trichloroethylene (TCE) has ruptured in a corn field in the Buffalo River valley and just upstream of River City (Figure 22). The source for the River City water supply is the Buffalo River and the water supply intake is located less than 3 miles downstream of the pipeline break (Figure 23). The emergency response team notes that the pipeline was leaking for some time prior to discovery of the break and that the contaminants from the pipeline have reached the water table of the alluvial aquifer. It is unclear if the contamination is moving toward the river but if it is moving in that direction, River City's water supply will be jeopardized.

At this point, the student is charged with taking on the role of an environmental consultant whose initial task it is to find where the contamination from the spill is located in the aquifer. Once located the student must remove the contamination from the aquifer before it gets to the river and endangers the city water supply.

*The navigation bar:* The student is provided with a menu of resources that are available to help solve this environmental problem (Figure 24). Sections included under the Resources tab include the Site Tour, Well Log, and Soils Information.

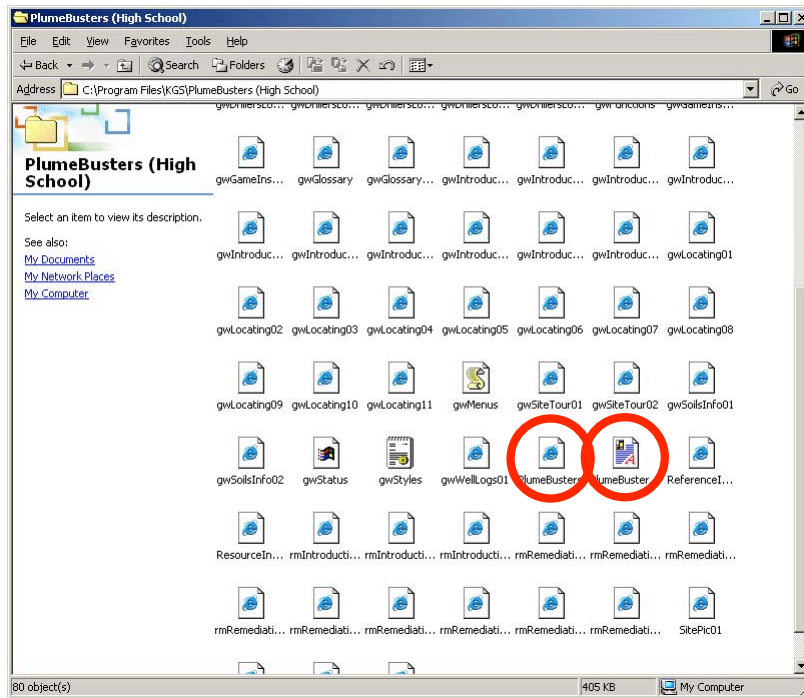


Figure 21. To start the ground-water tutor open the file PlumeBusters to access the HTML pages and PlumeBusters(HS, NonMaj, or Maj) to open the JAVA application ground-water model.

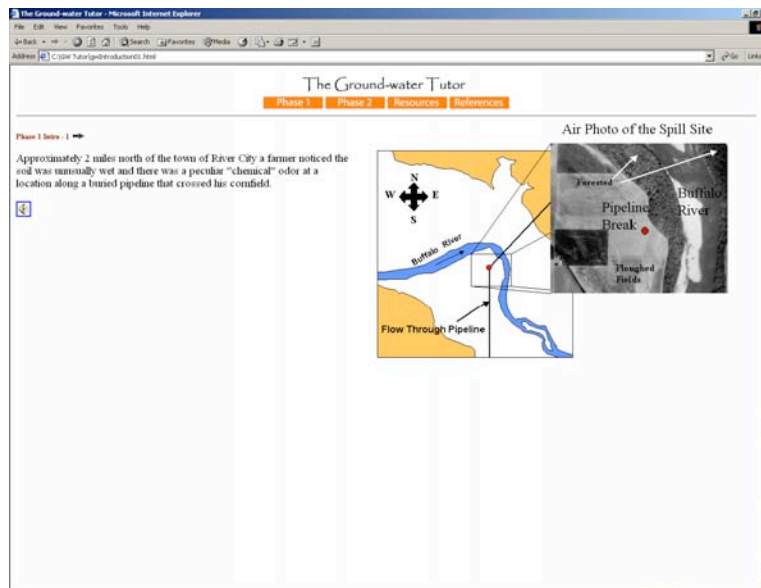


Figure 22. Introduction to the pipeline-spill problem to be solved by the student

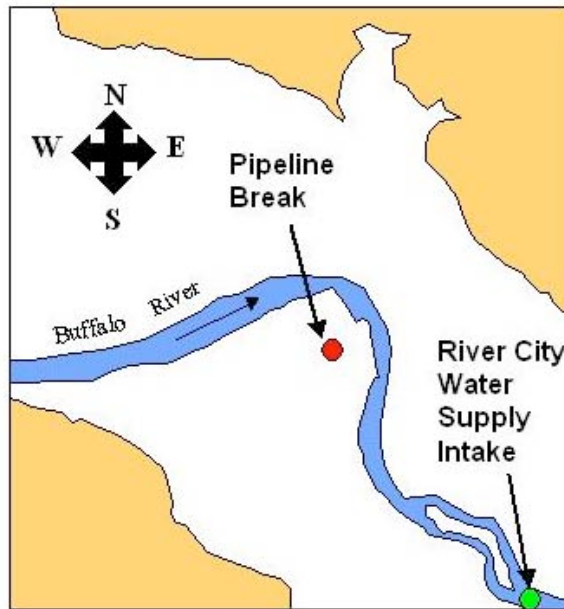


Figure 23. Location of the pipeline break in the Buffalo River valley with respect to the intake for the River City water supply.

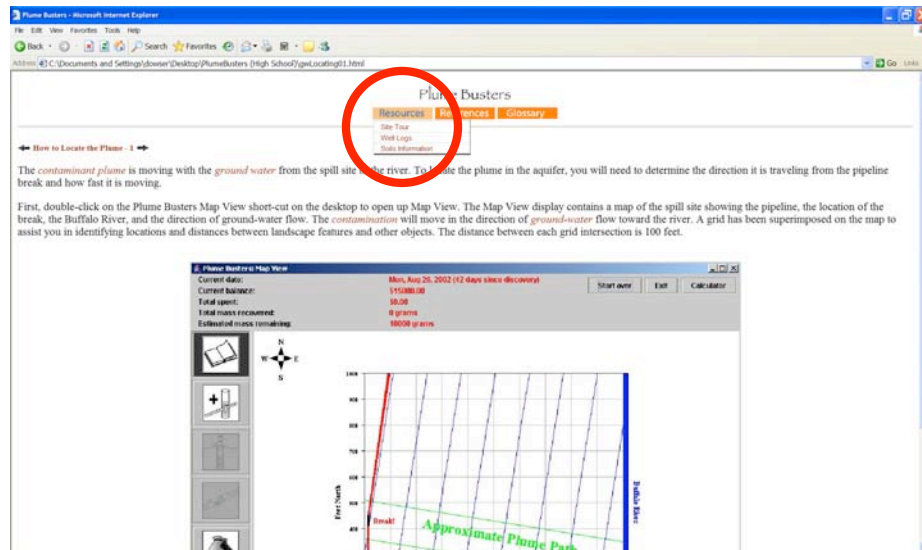


Figure 24. The drop-down menu of resources is available to the student for both parts of Plume Busters by clicking on the Resources tab on the navigation bar.



The Site Tour contains photos of the spill site and introduces to the student some of the protective clothing and other gear needed by those working at the site.

The Well Logs section contains the drillers' logs of water wells located near the site (Figure 25). This information is presented graphically and in tabular form (Figure 26). A table listing the porosity range of earth materials is also provided (Figure 25).

Information on the variation of soil texture with depth at a nearby site is provided in the Soils Information section.

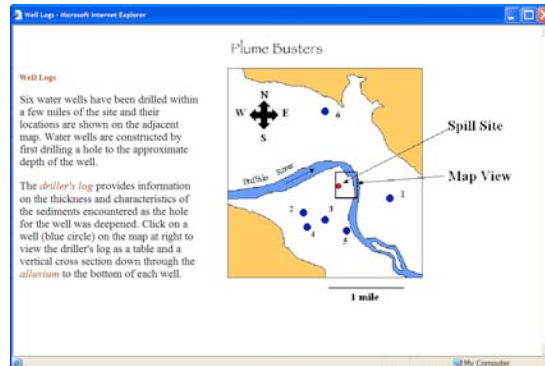


Figure 25. Locations of water wells where there is an available driller's log.

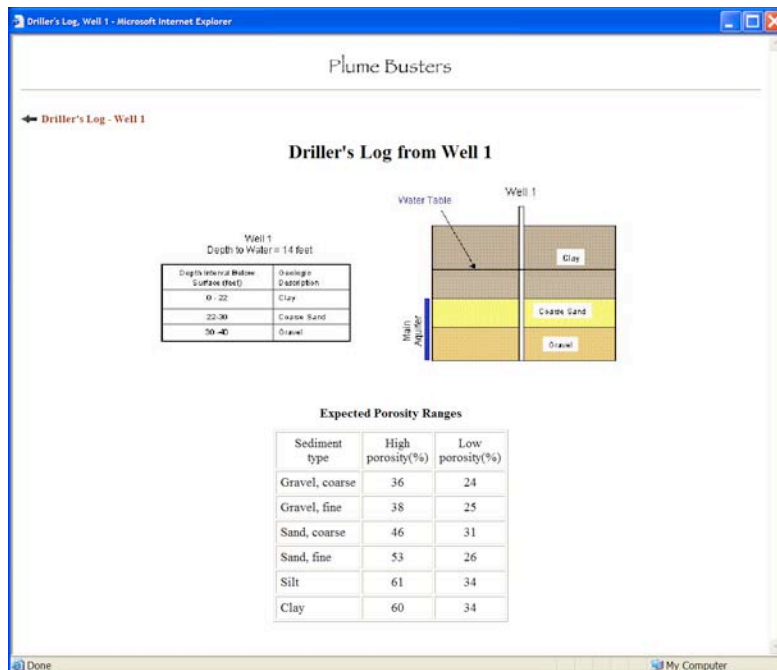


Figure 26. The driller's log of water well 1 is presented in tabular and in graphical formats. A table showing the expected range of porosity values for typical sediment types is also presented.

Under the References tab, summary information is provided on Darcy's law, Calculation of Ground-water Velocity, Calculation of Distance Traveled, Capture Zones, and Trichloroethylene. The student from the navigation bar can access a Glossary of terms used in the software.

*The rules of the simulation:* The rules govern actions taken by the student and are designed to provide some real-world constraints on the exploration for and remediation of the contaminants in the aquifer. The consultant is provided with funds to conduct the exploration phase in small \$15,000 allotments. Well installation and the chemical analysis of water samples cost money and time (\$4,000 per well, \$1,000 per chemical analysis, and one week of time to do both). The allotment provided by the pipeline owner is small enough that the consultant must negotiate for more money every time three wells are installed and water samples are analyzed for TCE under most conditions. Each negotiation takes two weeks to complete, during which the contaminants are slowly migrating through the aquifer and toward the river. Thus, from the student's point of view, minimizing the number of negotiation sessions is the best strategy to follow in this part of the simulation. The rules are provided as part of the narrative contained in the HTML-linked pages.

*Description of the features in Map View:* Summary descriptions of the various features of the Map View interface with the numerical ground-water model are provided as part of the narrative under the section How to Locate the Plume, including descriptions of the tools that allow the student to interact with the ground-water model. These tools are activated by clicking with the mouse the buttons arranged along the left side of the Map View screen. In the upper right corner of the Map View screen, there is a Start Over button that allows the student to restart the simulation.

*The consultant's accountant:* Map View also acts as an accountant and keeps track of the amount of money in the consultant's account and the total amount spent on the project. This information is displayed at the top of the Map View screen. Each negotiation with the pipeline owner yields \$15,000 to the consultant's account.

*Other information displayed in the Map View screen:* Also displayed at the top of the Map View screen are the current calendar date, the number of days since the contaminant was discovered, and the total amount of contamination remaining in the aquifer in kilograms.

*The tools used in the Locate the Plume part of the simulation:* In the first part of the simulation, the student places monitoring wells on the grid in Map View and collects and chemically analyzes water samples to find the contamination using the monitoring well siting/sampling tool. To assist in well placement, the program provides a ruler to more accurately place the well on the grid at distances away from the spill site to the nearest foot (Figure 27). Clicking once on the spill site and moving the cursor toward the desired location of the well to be sited on the Map View grid activates this feature of the siting tool. The ruler is displayed as a red line with the distance in red type. With the siting of each well, the student is provided with data on the water-table elevation and the contaminant concentration (Figure 28).

The notebook tool allows the student to review the water level and contaminant concentration data from any well selected. To retrieve the data the student clicks on the monitoring well location and the data will appear in a pop-up window.

The money bag button is clicked to signify a negotiation period during which the simulation is advanced by two weeks and another \$15,000 allotment is added to the consultants account.

*Game play in the Locate the Plume simulation:* Using the information provided, the student uses the Calculator (Figure 30) to estimate where the contamination is in the aquifer with respect to the spill site along the ground-water flow corridor that extends from the spill site to the Buffalo River that is outlined in green. The student uses the monitoring-well siting/sampling tool and the

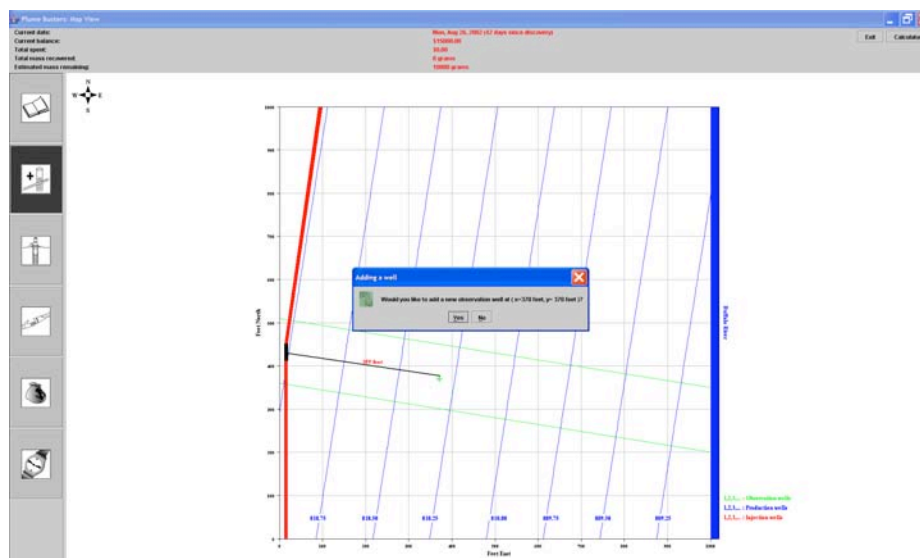


Figure 27. Siting a monitoring well in Locate the Plume. The monitoring siting/sampling tool is activated by clicking on the darkened button on the left side of Map View. A mouse click on the spill site enables the ruler that measures horizontal distance and can be used to more accurately locate a monitoring well with respect to the spill site. The student clicks the mouse over the desired site for the monitoring well. A pop-up screen appears and asks the student if a well is meant to be sited at the chosen location.

ruler to locate the first and succeeding monitoring wells. After siting each well, the student should update the estimate of the location of the contamination in the aquifer using the Calculator. If after the third well has been sited the student obtains another \$15,000 allotment from the pipeline owner and the simulation advances two weeks. This sequence of plays continues until the student finds contamination in three wells, with two of the wells having been sited in the same \$15,000 budget round (Figure 29).

*The Calculator:* The Calculator (Figure 30) is used to estimate average ground-water flow velocity, but the student does not explicitly interact with the Darcy's law equation. However, to set up the calculation, the student uses the hydraulic conductivity and hydraulic gradient data

provided in the Data Repository and the value of aquifer porosity. These data are provided in the narrative along with instructions on how to use the Calculator.

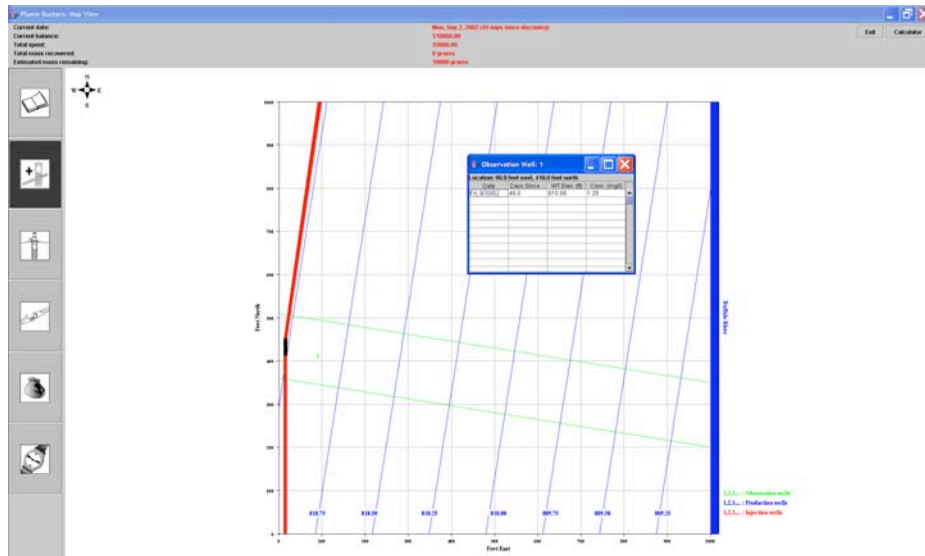


Figure 28. If the student responds positively with a yes to the question posed in the dialog box then a monitoring well is placed at the desired location and a pop-up screen appears and displays information on the current calendar date, the number of days since discovery of the spill, the water-table elevation, and the concentration of TCE.

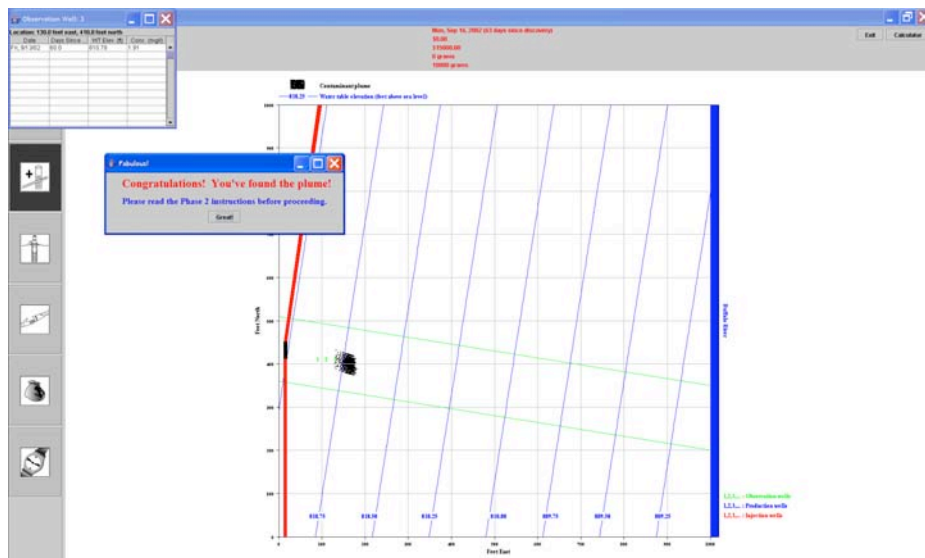


Figure 29. At the conclusion of Locate the Plume, a banner of congratulations is displayed along with instructions to proceed to the Remediate the Plume part of the simulation. Also, the contaminant plume appears on the map grid.

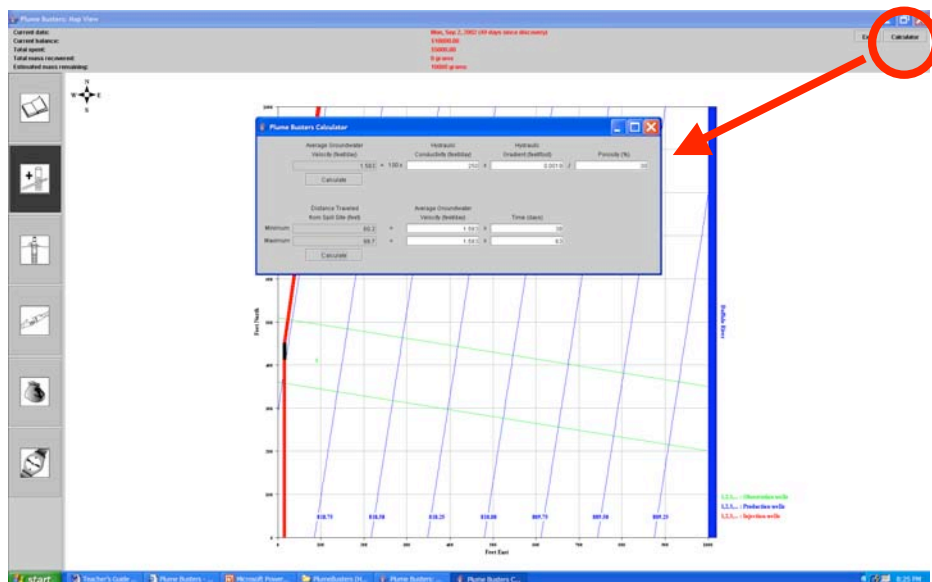


Figure 30. The student accesses the Calculator by clicking on the button in the upper right hand corner of Map View. Once displayed, the student can use the Calculator to determine average ground-water velocity and the distance traveled by the contamination from the spill site.

### Remediating the Plume (Grade 11-12 version)

The narrative in the linked HTML-linked pages is divided into an Introduction and How to Remediate the Plume. In the Introduction the text provides information on the concept of maximum contaminant level (MCL) concentration as an environmental benchmark. The maximum contaminant level is the highest allowable concentration of a contaminant in water as set by either the US Environmental Protection Agency or the state environmental regulatory agency. The MCL is set based on toxicology studies on laboratory animals. Most often, the results of these studies must be extrapolated to estimate the health risks to humans. Typically, aquifer remediation efforts cease once the level of contamination in ground water is below the MCL.

In How to Remediate the Plume, the student is introduced to the pump-and-treat remediation technology that is commonly used to remove and treat contaminated ground water, a process referred to as remediation (Figures 9-10). Two alternative pump and treat designs are described. The simpler design involves only production wells used to pump water and contaminants from the aquifer. One or more production wells are sited downgradient of the contaminants in such a way that the contaminated part of the aquifer is completely contained in the capture zone created by pumping the production well(s) (Figure 11). An alternative design uses a production well to remove contaminants from the aquifer and an injection well to return the produced water back to the aquifer after it has passed through the treatment plant (Figure 12). As in the previous design,

the production well is sited downgradient of the contamination. The injection well is sited close to the production well and upgradient of the plume. With both wells close together and operating and the plume in between them, the injection well drives the contamination to the production well at a faster rate than would be possible if only a production well were used. Thus, it is possible to reduce the time needed to remediate the aquifer.

*The navigation bar:* Under the References tab, the student can find further information on capture zones and TCE.

*The rules of the simulation:* The consultant is provided with funds to install and operate the remediate wellfield in \$30,000 allotments. Installation of production or injection wells costs \$5,000 to install and the weekly operation cost of the wellfield and the treatment facility is \$2,000. As in the previous part of the simulation, negotiation with the pipeline owner for more money takes two weeks to complete, during which the contaminants continue to migrate through the aquifer and toward the river.

*Description of the features in Map View:* Summary descriptions of the various features of the Map View interface with the numerical ground-water model are provided as part of the narrative under the section How to Remediate the Aquifer, including descriptions of the tools that allow the student to interact with the ground-water model. These tools are activated by clicking with the mouse the buttons arranged along the left side of the Map View screen.

*The consultant's accountant:* Map View also acts as an accountant and keeps track of the amount of money in the consultant's account and the total amount spent on the project. This information is displayed at the top of the Map View screen. Each negotiation with the pipeline owner yields \$30,000 to the consultant's account.

*Other information displayed in the Map View screen:* Also displayed at the top of the Map View screen are the current calendar date, the number of days since the contaminant was discovered, and the total amount of contamination remaining in the aquifer in kilograms.

*The tools used in the Remediate the Plume part of the simulation:* Production or injection wells are sited on the Map View grid by first clicking once on the well siting tool (Figure 31). Once the student is satisfied with the design, it is submitted to the model by clicking on the Submit Wellfield Design button with the mouse. The model is advanced one week in time by clicking with the mouse on the Advance the Simulation button.

*Game play in the Remediate the Plume simulation:* At the beginning of this part of the simulation, the student should click on the money bag to receive from the pipeline owner the first allotment of \$30,000. This will insure that there is enough money in his account to install and operate the remediation wellfield for at least one week after installation. If there are insufficient funds to cover these initial costs, the proposed wellfield design cannot be installed and operated. Next the student should decide which of the two possible wellfield designs to use. Information is contained in the narrative to help the student make that decision. To site a well the student clicks with the mouse on the production/injection well siting tool to the left of the Map View grid (Figure 31). The student selects the location of well using the information contained in the

narrative and a pop-up window appears and requests the student to select a pumping rate of 20 gallons per minute or less. If the well is to be a production well then the pumping rate is a positive number, but if the well is for injection, the pumping rate should be a negative number.

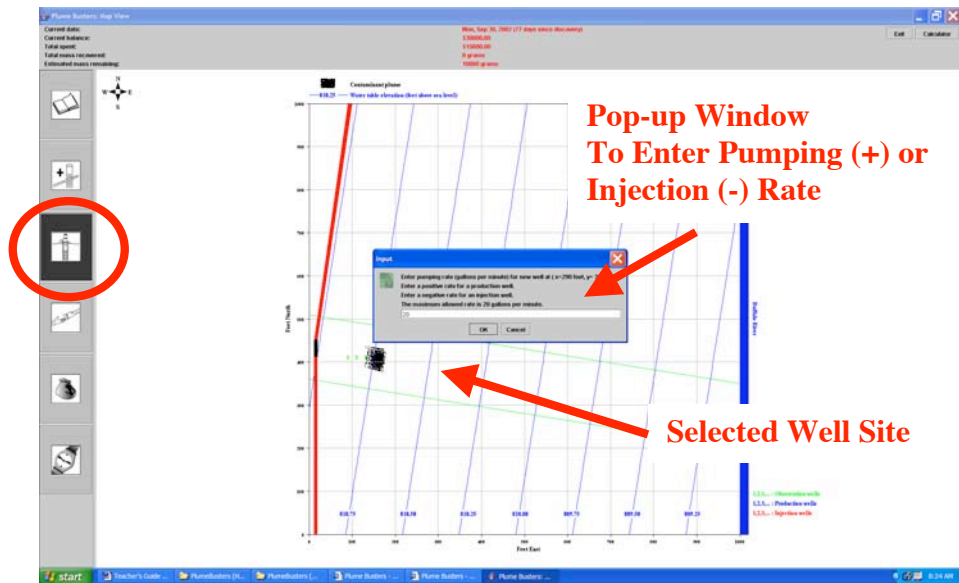


Figure 31. The button circled in red activates the production or injection well siting tool. Once the student selects a location with a single click of the mouse on the Map View grid, a pop-up window appears and asks the student to enter a pumping or an injection rate in gallons per minute (less than or equal to  $\pm 20$  gallons per minute).

A key feature of Map View in this part of the simulation is the ability of the student to preview the likely success in remediating the aquifer once a wellfield design has been selected and the production or the production and injection well pumping rates have been selected. Once the pumping rate has been entered in the appropriate box and the OK button has been clicked with the mouse, the pop-up window disappears and the outline of the capture zone is displayed on the Map View grid (Figure 32). The student submits the design to the model for implementation if he is satisfied that all the contamination is contained within the capture zone boundaries by clicking on the Submit Wellfield Design button (Figure 33). If there are sufficient funds in the account the design is approved and operated for one week.

Clicking on the Advance the Simulation button in the Map View advances the model one week at a time and operates the wellfield (Figure 34). With each click the time button the student can observe the movement of the contaminants toward the production well and their removal from the aquifer and the outflow of funds from his account. Once all of the contamination has been removed from the aquifer, a congratulations banner is displayed and signifies the conclusion of the simulation (Figure 35). With a mouse click on the notebook tool, a graph of time vs. the cumulative mass of the contaminant removed from the aquifer is displayed to the student (Figure 36).

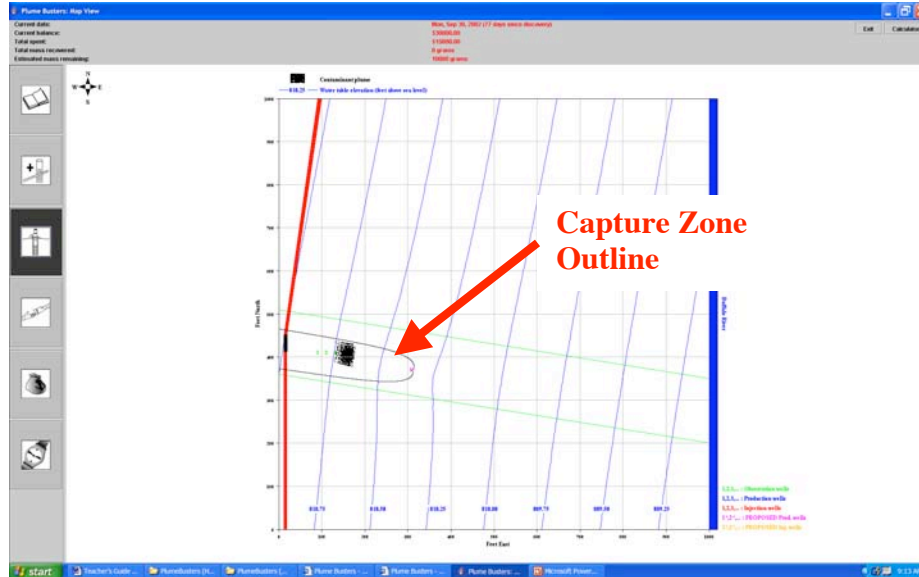


Figure 32. Outline of the capture zone created by pumping a production well. Note that all of the contamination is contained within the boundaries of the capture zone.

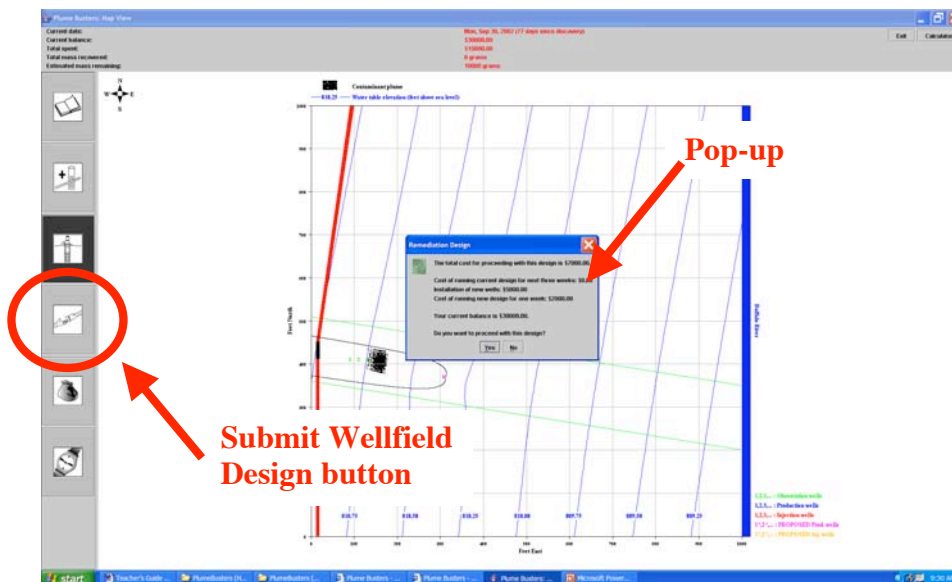


Figure 33. To submit the wellfield design to the model to initiate remediation, the student clicks with the mouse the button circled in red on the left side of Map View. A dialog box appears to inform the student of the cost of operating the remediation wellfield. If there is not enough money in the bank to operate, the model informs the student to negotiate for more money from the pipeline owner. If there is enough money, the student activates the design and model advances one week in time.



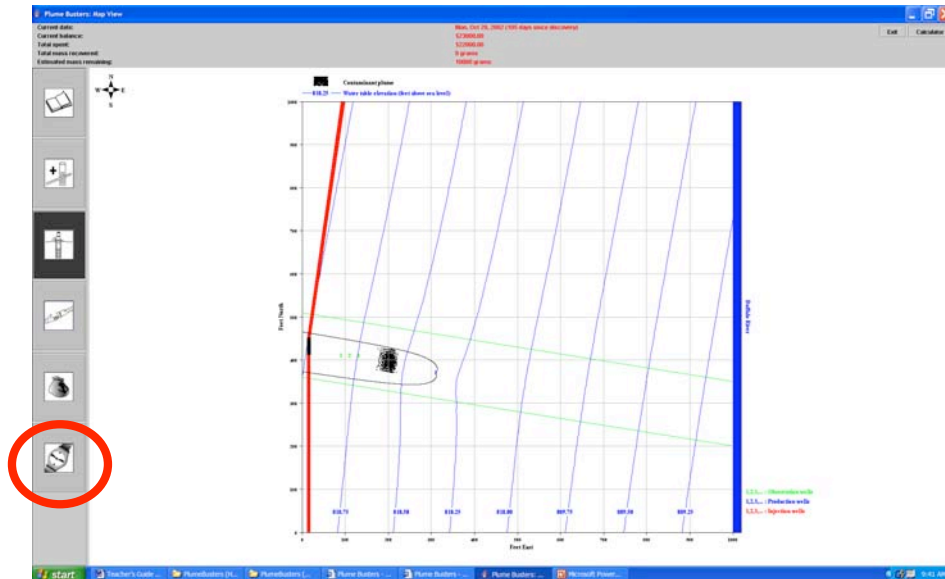


Figure 34. To advance the model through time by one week, the student clicks on this button in the lower left hand corner of Map View.

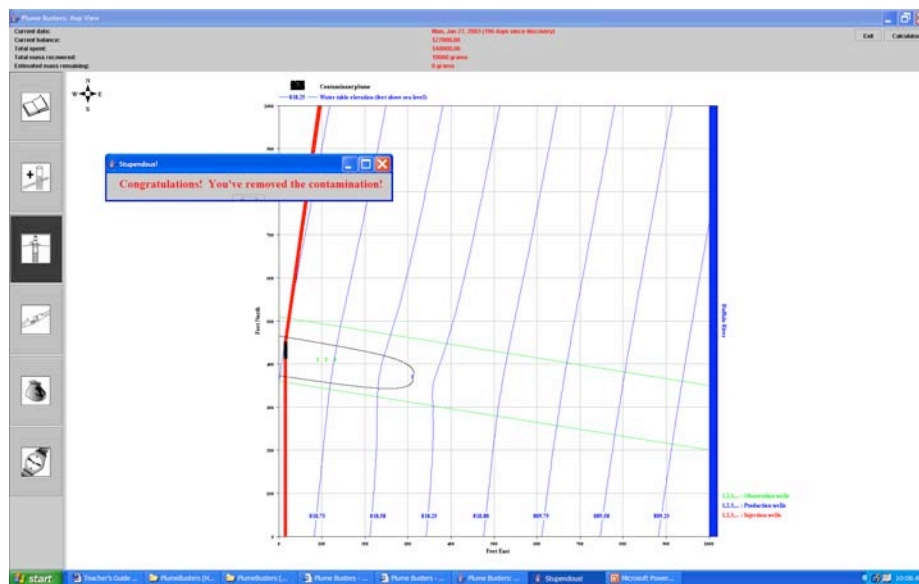


Figure 35. The Congratulations banner is displayed once all of the contamination has been removed from the aquifer. This display signifies the end of this part of the simulation.

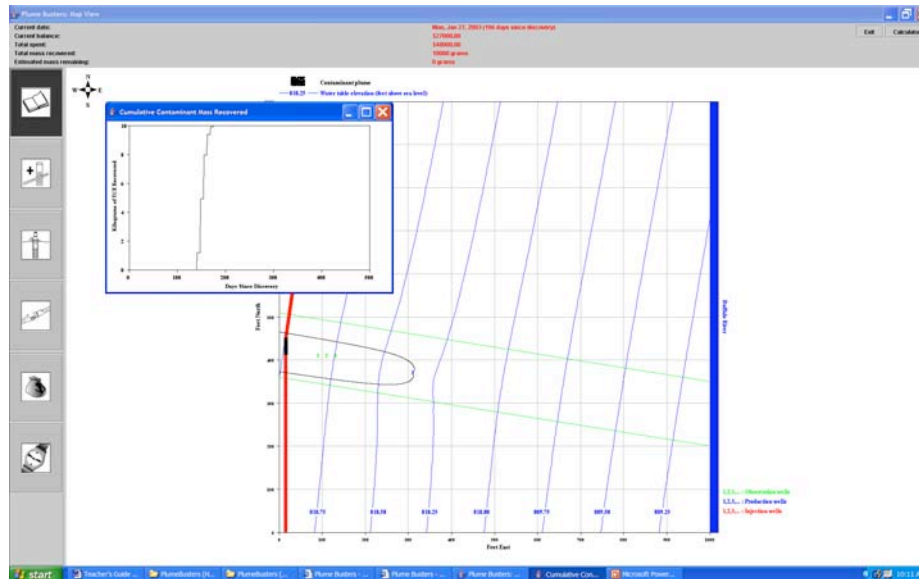


Figure 36. With a mouse click on the data notebook button and one on the production well, the simulation produces a pop-up window with a graph of time vs. the cumulative mass of the contaminant removed from the aquifer.

### Locating the Plume (College Undergraduate Non-Hydrogeology Major Version)

The opening screen is the beginning of The Problem section of the HTML-linked pages (Figure 19). The student is informed that a pipeline transporting industrial chemicals, including trichloroethylene (TCE) has ruptured in a corn field in the Buffalo River valley and just upstream of River City (Figure 22). The source for the River City water supply is the Buffalo River and the water supply intake is located less than 3 miles downstream of the pipeline break (Figure 23). The emergency response team notes that the pipeline was leaking for some time prior to discovery of the break and that the contaminants from the pipeline have reached the water table of the alluvial aquifer. It is unclear if the contamination is moving toward the river but if it is moving in that direction, River City's water supply will be jeopardized.

At this point, the student is charged with taking on the role of an environmental consultant whose initial task it is to find where the contamination from the spill is located in the aquifer. Once located the student must remove the contamination from the aquifer before it gets to the river and endangers the city water supply.

*The navigation bar:* The student is provided with a menu of resources that are available to help solve this environmental problem (Figures 18, 37). Sections included under the Resources tab include the Site Tour, Well Log, and Soils Information.

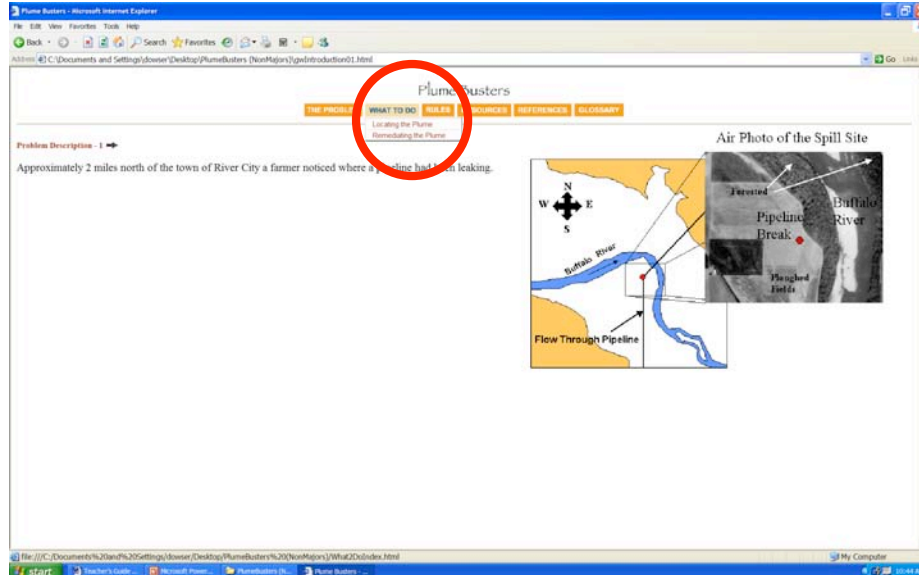


Figure 37. The drop-down menu of resources is available to the student for both parts of Plume Busters by clicking on the Resources tab on the navigation bar.

The What to Do tab (Figures 18, 37) provides step-by-step instructions with regard to game play for both Locating the Plume and Remediating the Plume. The text in these sections is in red and black. Text is red or in bold black provides critical instructions or information to the student. Text in plain black provides supporting information to the student.

Under the Resources tab the student will find a tour of the site and the Data Repository (Figure 18). The Site Tour contains photos of the spill site, shows the student some of the protective clothing and other gear needed by those working at the site and presents information on the variation of soil texture with depth in a dug pit described in the literature about the site vicinity.

The Data Repository contains a table of critical information about the site and a section on estimating porosity from driller's logs. The table of critical information contains information gleaned from the literature on the hydrogeology of the site as well as some information on the timing of the spill and the estimated amount of TCE leaked into the aquifer from the spill. Following this section, the student is provided with a map showing the location of water wells near the site that have driller's logs (Figure 25). The logs are presented graphically and in tabular form (Figure 38). A table listing the porosity of the sediments is also provided (Figure 25).

Also included is a way of using the information provided to estimate aquifer porosity in the spill site vicinity. Main Aquifer porosity is calculated as the average of the porosity of the materials forming this part of the aquifer weighted according to their relative thickness. These calculations should be done manually using a calculator. Aquifer porosity in the spill site vicinity is simply the arithmetic average of the porosities of the calculated for the Main Aquifer at each of the water-well sites.

Under the References tab, there is summary information provided on Darcy's law, Calculation of Average Ground-water Velocity, Capture Zones, and Trichloroethylene. The student from the navigation bar can access a Glossary of terms used in the software.

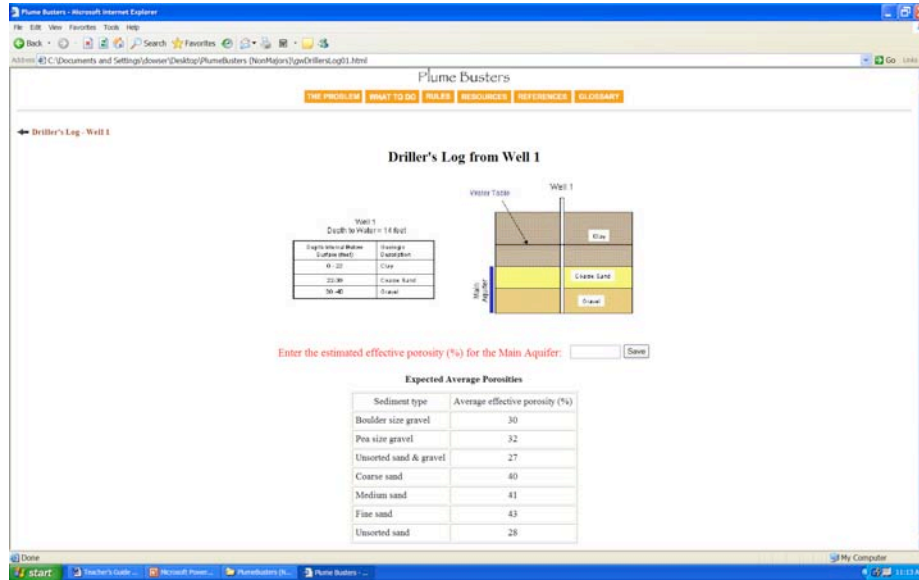


Figure 38. The driller's log of water well 1 is presented in tabular and in graphical formats. A table showing the expected porosity for typical sediment types is also presented.

*The rules of the simulation:* The rules govern actions taken by the student and are designed to provide some real-world constraints on the exploration for and remediation of the contaminants in the aquifer. The consultant is provided with funds to conduct the exploration phase in small \$15,000 allotments. Well installation and the chemical analysis of water samples cost money and time (\$4,000 per well, \$1,000 per chemical analysis, and one week of time to do both). The allotment provided by the pipeline owner is small enough that the consultant must negotiate for more money every time three wells are installed and water samples are analyzed for TCE under most conditions. Each negotiation takes two weeks to complete, during which the contaminants are slowly migrating through the aquifer and toward the river. Thus, from the student's point of view, minimizing the number of negotiation sessions is the best strategy to follow in this part of the simulation. The rules for this part of the simulation can be found under the Rules tab on the navigation bar.

*Description of the features in Map View:* Summary descriptions of the various features of the Map View interface with the numerical ground-water model are provided as part of the narrative under the section How to Locate the Plume, accessed from the What to Do tab on the navigation bar. The buttons on the left of the Map View interface tools activate tools that allow the student to interact with the simulation (Figure 17). The student has access to these tools by clicking once on them with the mouse.

*The consultant's accountant:* Map View also acts as an accountant and keeps track of the amount of money in the consultant's account and the total amount spent on the project. This information is displayed at the top of the Map View screen. Each negotiation with the pipeline owner yields \$15,000 to the consultant's account.

*Other information displayed in the Map View screen:* Also displayed at the top of the Map View screen are the current calendar date, the number of days since the contaminant was discovered, and the total amount of contamination remaining in the aquifer in kilograms.

*The tools used in the Locate the Plume part of the simulation:* In this part of the simulation, the student places monitoring wells on the grid in Map View and collects and chemically analyzes water samples to find the contamination using the monitoring well siting/sampling tool. To assist in well placement, the program provides a measurer to more accurately place the well on the grid at distances away from the spill site to the nearest foot (Figure 27). This feature of the siting tool is activated by clicking once on the spill site and moving the cursor toward the desired location of the well to be sited on the Map View grid. With the siting of each well, the student is provided with data on the water-table elevation and the contaminant concentration (Figure 28).

The notebook tool allows the student to review the water level and contaminant concentration data from any selected well. To retrieve the data the student clicks on the monitoring well location and the data will appear in a pop-up window.

The money bag button is clicked to signify a negotiation period during which the simulation is advanced by two weeks and another \$15,000 allotment is added to the consultants account.

*Game play in the Locate the Plume simulation:* One of the first tasks to complete is the estimation of aquifer porosity in the vicinity of the spill site. Information on how to do this can be found in the Data Repository. Calculations should be done with a hand calculator or using the Windows calculator accessory. With the data provided, the student uses the Plume Busters' Calculator (Figure 30) to estimate where the contamination is in the aquifer with respect to the spill site along the ground-water flow corridor. The flow corridor extends from the spill site to the Buffalo River and is outlined in green (Figure 17). The student uses the monitoring-well siting/sampling tool and the ruler to locate the first and succeeding monitoring wells. After siting each well, the student should update the estimate of the location of the contamination in the aquifer using the Calculator. If after the third well has been sited the student obtains another \$15,000 allotment from the pipeline owner and the simulation advances two weeks. This sequence of plays continues until the student finds contamination in three wells, with two of the wells having been sited in the same \$15,000 budget round. Completion of this part of the simulation is indicated by the display of a Congratulations banner in a pop-up window (Figure 29).

*The Calculator:* The Calculator (Figure 30) is used to estimate average ground-water flow velocity, but the student does not explicitly interact with the Darcy's Law equation. However, to set up the calculation, the student uses the hydraulic conductivity and hydraulic gradient data provided in the Locating the Plume section under the What to Do tab and the value of porosity calculated using the method outlined in the Data Repository. Instructions on how to use the

Calculator can also be found in the Locating the Plume section under the What to Do tab on the navigation bar.

Remediating the Plume (College Undergraduate Non-Hydrogeology Major Version)  
Step-by-step instructions for remediating the plume can be found under the What to Do tab in the Remediating the Plume section. The text provides introduces the student to the concept of maximum contaminant level (MCL) concentration as an environmental benchmark. The maximum contaminant level is the highest allowable concentration of a contaminant in water as set by either the US Environmental Protection Agency or the state environmental regulatory agency. The MCL is set based on toxicology studies on laboratory animals. Most often, the results of these studies must be extrapolated to estimate the health risks to humans. Typically, aquifer remediation efforts cease once the level of contamination in ground water is below the MCL.

The student is also introduced to the pump-and-treat remediation technology that is commonly used to remove and treat contaminated ground water, a process referred to as remediation (Figures 9-10). Two alternative pump and treat designs are described. The simpler design involves only production wells used to pump water and contaminants from the aquifer. One or more production wells are sited downgradient of the contaminants in such a way that the contaminated part of the aquifer is completely contained in the capture zone created by pumping the production well(s) (Figure 11). An alternative design uses a production well to remove contaminants from the aquifer and an injection well to return the produced water back to the aquifer after it has passed through the treatment plant (Figure 12). As in the previous design, the production well is sited downgradient of the contamination. The injection well is sited close to the production well and upgradient of the plume. With both wells close together and operating, the injection well drives the contamination to the production well at a faster rate than would be possible if only a production well were used. Thus, it is possible to reduce the time needed to remediate the aquifer.

*The navigation bar:* Under the Rules tab the student find the rules that pertain to this section of the simulation and under the References tab, the student can find further information on capture zones and TCE.

*The rules of the simulation:* The consultant is provided with funds to install and operate the remediation wellfield in \$30,000 allotments. Installation of production or injection wells costs \$5,000 to install and the weekly operation cost of the wellfield and the treatment facility is \$2,000. As in the previous part of the simulation, negotiation with the pipeline owner for more money takes two weeks to complete, during which the contaminants continue to migrate through the aquifer and toward the river.

*Description of the features in Map View:* Summary descriptions of the various features of the Map View interface with the numerical ground-water model are provided as part of the narrative under the section How to Remediate the Aquifer, including descriptions of the tools that allow the student to interact with the ground-water model. These tools are activated by clicking with the mouse the buttons arranged along the left side of the Map View screen.

*The consultant's accountant:* Map View also acts as an accountant and keeps track of the amount of money in the consultant's account and the total amount spent on the project. This information is displayed at the top of the Map View screen. Each negotiation with the pipeline owner yields \$30,000 to the consultant's account.

*Other information displayed in the Map View screen:* Also displayed at the top of the Map View screen are the current calendar date, the number of days since the contaminant was discovered, and the total amount of contamination remaining in the aquifer in kilograms.

*The tools used in the Remediating the Plume part of the simulation:* Production or injection wells are sited on the Map View grid by first clicking once on the well siting tool (Figure 31). Once the student is satisfied with the design, it is submitted to the model by clicking on the Submit Wellfield Design button with the mouse. The model is advanced one week in time by clicking with the mouse on the Advance the Simulation button.

*Game play in the Remediate the Plume simulation:* At the beginning of this part of the simulation, the student should click on the money bag to receive from the pipeline owner the first allotment of \$30,000. This will insure that there is enough money in his account to install and operate the remediation wellfield for at least one week after installation. If there are insufficient funds to cover these initial costs, the proposed wellfield design cannot be installed and operated. Next the student should decide which of the two possible wellfield designs to use. Information is contained in the narrative to help the student make that decision. To site a well the student clicks with the mouse on the production/injection well siting tool to the left of the Map View grid (Figure 31). The student selects the location of well using the information contained in the narrative and a pop-up window appears and requests the student to select a pumping rate of 20 gallons per minute or less. If the well is to be a production well then the pumping rate is a positive number, but if the well is for injection, the pumping rate should be a negative number.

A key feature of Map View in this part of the simulation is the ability of the student to preview the likely success in remediating the aquifer once a wellfield design has been selected and the production or the production and injection well pumping rates have been selected. Once the pumping rate has been entered in the appropriate box and the OK button has been clicked with the mouse, the pop-up window disappears and the outline of the capture zone is displayed on the Map View grid (Figure 32). The student submits the design to the model for implementation if he is satisfied that all the contamination is contained within the capture zone boundaries by clicking on the Submit Wellfield Design button (Figure 33). If there are sufficient funds in the account the design is approved and operated for one week.

Clicking on the Advance the Model button in Map View advances the model one week at a time and operates the wellfield (Figure 34). With each click the time button the student can observe the movement of the contaminants toward the production well and their removal from the aquifer and the outflow of funds from his account. Once all of the contamination has been removed from the aquifer, a congratulations banner is displayed and signifies the conclusion of the simulation (Figure 35). With a mouse click on the notebook tool, a graph of time vs. the cumulative mass of the contaminant removed from the aquifer is displayed to the student (Figure 36).

### Locating the Plume (College Undergraduate Hydrogeology Major Version)

The opening screen is the beginning of The Problem section of the HTML-linked pages (Figure 19). The student is informed that a pipeline transporting industrial chemicals, including trichloroethylene (TCE) has ruptured in a corn field in the Buffalo River valley and just upstream of River City (Figure 22). The source for the River City water supply is the Buffalo River and the water supply intake is located less than 3 miles downstream of the pipeline break (Figure 23). The emergency response team notes that the pipeline was leaking for some time prior to discovery of the break and that the contaminants from the pipeline have reached the water table of the alluvial aquifer. It is unclear if the contamination is moving toward the river but if it is moving in that direction, River City's water supply will be jeopardized.

At this point, the student is charged with taking on the role of an environmental consultant whose initial task it is to find where the contamination from the spill is located in the aquifer. Once located the student must remove the contamination from the aquifer before it gets to the river and endangers the city water supply.

*The navigation bar:* The student is provided with a menu of resources that are available to help solve this environmental problem (Figures 19, 37). Sections included under the Resources tab include the Site Tour, Well Log, and Soils Information.

Under the Problem tab, environmental problem is described and the features of the Map View screen interface are briefly described.

Information under the What to Do tab (Figure 19) tells the student in general terms how he will locate the plume, describes how the model advances through time in response to actions taken, where to find data with which to site monitoring wells, and the game play for the Locating the Plume simulation. Because there is adequate information contained under the What to Do section, there is not a separate section describing how the student will remediate the plume under this tab because there is adequate information on the tools available to accomplish this objective without explicit discussion. A description of the tools available to the student is provided on the second page of this section. These tools are available by using the mouse to click on the buttons on the left side of the Map View screen.

Under the Resources tab the student will find a tour of the site and the Data Repository (Figure 19). The Site Tour contains photos of the spill site, shows the student some of the protective clothing and other gear needed by those working at the site and presents information on the variation of soil texture with depth in a soil pit described in the literature about the site vicinity.

The Data Repository contains a table of critical information about the site and a section on estimating porosity from driller's logs. The table of critical information contains information gleaned from the literature on the hydrogeology of the site as well as some information on the timing of the spill and the estimated amount of TCE leaked into the aquifer from the spill. Following this section, the student is provided with a map showing the location of water wells near the site that have driller's logs (Figure 25). The logs are presented graphically and in



tabular form (Figure 37). A table listing the porosity of the sediments is also provided (Figure 25).

Also included is a way of using the information provided to estimate aquifer porosity in the spill site vicinity. Main Aquifer porosity is calculated as the average of the porosity of the materials forming this part of the aquifer weighted according to their relative thickness. These calculations should be done manually using a calculator. Aquifer porosity at the site is simply the arithmetic average of the porosities of the calculated for the Main Aquifer at each of the water-well sites.

Under the References tab, there is summary information provided on Darcy's Law and Calculation of Ground-water Velocity. The student from the navigation bar can access a Glossary of terms used in the software.

*The rules of the simulation:* The rules govern actions taken by the student and are designed to provide some real-world constraints on the exploration for and remediation of the contaminants in the aquifer. The consultant is provided with funds to conduct the exploration phase in small \$15,000 allotments. Well installation and the chemical analysis of water samples cost money and time (\$4,000 per well, \$1,000 per chemical analysis, and one week of time to do both). The allotment provided by the pipeline owner is small enough that the consultant must negotiate for more money every time three wells are installed and water samples are analyzed for TCE under most conditions. Each negotiation takes two weeks to complete, during which the contaminants are slowly migrating through the aquifer and toward the river. Thus, from the student's point of view, minimizing the number of negotiation sessions is the best strategy to follow in this part of the simulation.

The rules for this part of the simulation can be found under the Rules tab on the navigation bar. The text in these sections is in red and black. Text is red or in bold black provides critical instructions or information to the student. Text in plain black provides supporting information to the student.

*Description of the features in Map View:* Summary descriptions of the various features of the Map View interface with the numerical ground-water model are provided in the What to Do tab on the navigation bar. The buttons on the left of the Map View interface tools activate tools that allow the student to interact with the simulation (Figure 17). The student has access to these tools by clicking once on them with the mouse.

*The consultant's accountant:* Map View also acts as an accountant and keeps track of the amount of money in the consultant's account and the total amount spent on the project. This information is displayed at the top of the Map View screen. Each negotiation with the pipeline owner yields \$15,000 to the consultant's account.

*Other information displayed in the Map View screen:* Also displayed at the top of the Map View screen are the current calendar date, the number of days since the contaminant was discovered, and the total amount of contamination remaining in the aquifer in kilograms.

*The tools used in the Locate the Plume part of the simulation:* In the first part of the simulation, the student places monitoring wells on the grid in Map View and collects and chemically analyzes water samples to find the contamination using the monitoring well siting/sampling tool. To assist in well placement, the program provides a measurer to more accurately place the well on the grid at distances away from the spill site to the nearest foot (Figure 27). This feature of the siting tool is activated by clicking once on the spill site and moving the cursor toward the desired location of the well to be sited on the Map View grid. With the siting of each well, the student is provided with data on the water-table elevation and the contaminant concentration (Figure 28).

The notebook tool allows the student to review the water level and contaminant concentration data from any well selected. To retrieve the data the student clicks on the monitoring well location and the data will appear in a pop-up window.

The money bag button is clicked to signify a negotiation period during which the simulation is advanced by two weeks and another \$15,000 allotment is added to the consultants account.

*Game play in the Locate the Plume simulation:* One of the first tasks to complete is the estimation of aquifer porosity in the vicinity of the spill site. Information on how to do this can be found in the Data Repository. Calculations should be done with a hand calculator or using the Windows calculator accessory. With the data provided, the student uses the estimated porosity at the spill site and Darcy's law to calculate the average ground-water flow velocity and based on the time since the contaminants have been in the aquifer, the maximum and minimum distances traveled from the spill site. To do the calculation, the student must use either the Windows calculator accessory or a hand calculator. Ground-water flow direction from the spill site to the river must be inferred and only a range of hydraulic gradient values is provided from the literature on the alluvial aquifer along with a single value of hydraulic conductivity from the critical information in the Data Repository. After the first three monitoring wells are sited, simulation displays the water table map and the hydraulic gradient information to the student on the Map View grid.

The student uses the monitoring-well siting/sampling tool and the ruler to locate the first and succeeding monitoring wells. After siting each well, the student should update the estimate of the location of the contamination in the aquifer. If after the third well has been sited the student obtains another \$15,000 allotment from the pipeline owner and the simulation advances two weeks. This sequence of plays continues until the student finds contamination in three wells, with two of the wells having been sited in the same \$15,000 budget round. Completion of this part of the simulation is indicated by the display of a Congratulations banner in a pop-up window (Figure 29).

Remediating the Plume (College Undergraduate Non-Hydrogeology Major Version)  
Step-by-step instructions for remediating the plume are not provided under the What to Do tab in the Remediating the Plume section, but there is a description of the tools needed to complete this part of the simulation. Information is also provided in Remediating the Plume section of The Rules and under The Problem.

In this part of the simulation the student is introduced to the pump-and-treat remediation technology that is commonly used to remove and treat contaminated ground water, a process referred to as remediation (Figures 9-10). Two alternative pump and treat designs are available. The simpler design involves only production wells used to pump water and contaminants from the aquifer. One or more production wells are sited downgradient of the contaminants in such a way that the contaminated part of the aquifer is completely contained in the capture zone created by pumping the production well(s) (Figure 11). An alternative design uses a production well to remove contaminants from the aquifer and an injection well to return the produced water back to the aquifer after it has passed through the treatment plant (Figure 12). As in the previous design, the production well is sited downgradient of the contamination. The injection well is sited close to the production well and upgradient of the plume. With both wells close together and operating, the injection well drives the contamination to the production well at a faster rate than would be possible if only a production well were used. Thus, it is possible to reduce the time needed to remediate the aquifer.

*The navigation bar:* Under the Rules tab the student find the rules that pertain to this section of the simulation and under the References tab, the student can find further information on capture zones and TCE.

*The rules of the simulation:* The consultant is provided with funds to install and operate the remediate wellfield in \$30,000 allotments. Installation of production or injection wells costs \$5,000 to install and the weekly operation cost of the wellfield and the treatment facility is \$2,000. As in the previous part of the simulation, negotiation with the pipeline owner for more money takes two weeks to complete, during which the contaminants continue to migrate through the aquifer and toward the river.

*Description of the features in Map View:* Summary descriptions of the various features of the Map View interface with the numerical ground-water model are under The Problem tab and under the What to Do tab where there are descriptions of the tools that allow the student to interact with the ground-water model. These tools are activated by clicking with the mouse the buttons arranged along the left side of the Map View screen.

*The consultant's accountant:* Map View also acts as an accountant and keeps track of the amount of money in the consultant's account and the total amount spent on the project. This information is displayed at the top of the Map View screen. Each negotiation with the pipeline owner yields \$30,000 to the consultant's account.

*Other information displayed in the Map View screen:* Also displayed at the top of the Map View screen are the current calendar date, the number of days since the contaminant was discovered, and the total amount of contamination remaining in the aquifer in kilograms.

*The tools used in the Remediate the Plume part of the simulation:* Production or injection wells are sited on the Map View grid by first clicking once on the well siting tool (Figure 31). Once the student is satisfied with the design, it is submitted to the model by clicking on the Submit Wellfield Design button with the mouse. The model is advanced one week in time by clicking with the mouse on the Advance the Simulation button.

*Game play in the Remediate the Plume simulation:* At the beginning of this part of the simulation, the student should click on the money bag to receive from the pipeline owner the first allotment of \$30,000. This will insure that there is enough money in his account to install and operate the remediation wellfield for at least one week after installation. If there are insufficient funds to cover these initial costs, the proposed wellfield design cannot be installed and operated. Next the student should decide which of the two possible wellfield designs to use. Information is contained in the narrative to help the student make that decision. To site a well the student clicks with the mouse on the production/injection well siting tool to the left of the Map View grid (Figure 31). The student selects the location of well using the information contained in the narrative and a pop-up window appears and requests the student to select a pumping rate of 20 gallons per minute or less. If the well is to be a production well then the pumping rate is a positive number, but if the well is for injection, the pumping rate should be a negative number.

A key feature of Map View in this part of the simulation is the ability of the student to preview the likely success in remediating the aquifer once a wellfield design has been selected and the production or the production and injection well pumping rates have been selected. Once the pumping rate has been entered in the appropriate box and the OK button has been clicked with the mouse, the dialog box disappears and the outline of the capture zone is displayed on the Map View grid (Figure 32). The student submits the design to the model for implementation if he is satisfied that all the contamination is contained within the capture zone boundaries by clicking on the Submit Wellfield Design button (Figure 33). If there are sufficient funds in the account the design is approved and operated for one week.

Clicking on the time button in the Map View advances the model one week at a time and operates the wellfield (Figure 34). With each click the time button the student can observe the movement of the contaminants toward the production well and their removal from the aquifer and the outflow of funds from his account. Once all of the contamination has been removed from the aquifer, a congratulations banner is displayed and signifies the conclusion of the simulation (Figure 35). With a mouse click on the notebook tool, a graph of time vs. the cumulative mass of the contaminant removed from the aquifer is displayed to the student (Figure 36).

### **What Students Need to Have Been Exposed to Before Using the Plume Busters Software?**

The following is a list of the topics that students should be exposed to prior to working with the interactive ground-water tutor:

- Hydrologic cycle
- Rocks and minerals
- Porosity of earth materials
- Permeability of earth materials
- Hydraulic head
- Hydraulic gradient
- Confined and unconfined aquifers
- Darcy's law
- Distance, time, and velocity relationships

- Interpretation of simple water-table elevation maps to determine ground-water flow direction
- Ground-water flow systems
- Ground-water quality
- Cone of depression
- Cone of impression
- Capture zone
- Zone of influence
- Remediation

Cone of depression, cone of impression, capture zone, and zone of influence are sufficiently well explained in the Grade 11-12 and college undergraduate non-hydrogeology major version of Plume Busters to fulfill student needs if there is not enough time to cover these topics in the classroom. These topics are not covered in the college undergraduate hydrogeology major version of the software.

### **What Basic Skills Do Students Need to Have before Using the Plume Busters Software?**

The following is a list of the skills that should be helpful to students to working with the interactive ground-water tutor:

- Map reading
- Map scales
- Interpretation of x,y-graphs
- Interpretation of time limes
- Estimation based on reference points or standards
- Operation of personal computers with Windows-based operating systems
- Measurement units, English and metric

### **What to Pay Attention to During the Simulation**

The student's overall objective is to use his/her understanding of ground-water systems and the information provided by the tutor to find and remediate the plume in the shortest amount of time with the least cost to the pipeline owner.

To find the plume, the student must make some initial decisions of where to site monitoring wells based on the limited and somewhat sketchy information provided by the software. In the Grade 11-12 and undergraduate non-hydrogeology major versions, a ground-water flow corridor is provided that extends from the spill site to the river. Students should limit their search for the plume to this corridor. The Data Repository contains a range of hydraulic gradient values, an aquifer hydraulic conductivity value and information about when the spill occurred. In the college undergraduate versions, the student must estimate porosity from the well logs in order to calculate average ground-water flow velocity.

Students need to remember that ground-water velocities are very low in comparison to the flow water in a stream or river. Ground-water flow velocities in sandy aquifers are typically on the order 1-2 feet per day. Use of the calculator to estimate ground-water flow velocities and travel distances should reinforce this generalization. Hence the initial monitoring wells should be located less than 150 ft from the spill site.

In the college undergraduate hydrogeology major version, the student is informed that the ground-water flow direction is toward the river in an easterly direction in the site vicinity. After the third monitoring well has been sited, the water-table map is presented to the student and the true hydraulic gradient is provided at the top of the gridded map. The hydraulic gradient information should be used to update ground-water-flow velocities.

When estimating the distance traveled by the contamination, the student needs to remember that a week transpires between monitoring well sitings. When money is requested from the pipeline owner to site more wells or continue remediation, the simulation advances in time by two weeks. During that time the contamination continues to move with the ground-water flow to the river. Thus, it is important for the student to continually update his/her estimates of where the contamination is located in the aquifer before siting the next monitoring well. Using the current date information at the top of Map View will help the student make these estimates.

To remediate the contaminated aquifer the most important consideration is that the production well(s) or the production/injection well couplet must be able capture all of the contamination at the pumping rate selected by the student. Wellfield design consists of setting the locations of the production and injection wells and selecting pumping and injection rates. The production well should be sited downgradient of the contamination (between the contamination and the river) and if an injection well is used, it should be located upgradient of the contamination. Wells should be sited near the contamination but not directly within it. Siting the production well within the contaminated portion of the aquifer will allow some of the contamination to move past the well to the river. Siting the remediation wells too far away from the contamination will only increase the time needed for remediation of the aquifer.

The student will be prompted to enter a pumping rate once a well has been sited in Map View. Pumping rates for production wells are positive numbers and injection well rates are negative numbers. Thus the student would enter -10 gallons per minute for an injection well where water is being added to the aquifer or in the case of a production well where water is withdrawn from the aquifer, 10 gallons per minute. Once the design has been submitted, the boundaries of the capture zone will be displayed. To insure success the contamination must be completely contained within the capture zone boundaries.

Finally, it is also possible for the student to completely start over in Map View at any time only in the Grade 11-12 version of the software. This option was added to allow these students to learn from earlier trials of trying to locate the plume.

### **Keeping Score**

Students will naturally want a measure of how well they performed with the ground-water tutor. Assuming the contamination is found after three monitoring wells have been installed and sampled and the remediation wellfield is sited appropriately, it is possible for the consultant to spend \$40,000 to completely remove the contamination from the aquifer in 18 weeks (126 days). In this round, \$15,000 was spent to locate the plume in 3 weeks (21 days) and \$25,000 was spent to remediate the plume over a 15-week (105 day) period.

## **Linkages to Environmental Policy Issues**

The ground-water tutor provides teachers with a means to initiate student exploration of a wide range of environmental issues. Listed below are some suggested topics:

- Source-water assessment, ground-water and wellhead protection zones, and environmental protection using land-use planning and zoning regulations;
- The impact of human activities and technology on the hydrosphere and the biosphere;
- The role of technology in the resolution of environmental issues;
- The social, political, and economic implications of environmental issues;
- The impacts of environmental laws and regulations on the social, political, and economic systems;
- Assessment of risk to environmental quality from human activities; and
- Assessment of human health risks from pollutants.

More information can be found by exploring the Internet links listed in the Resources section of this teacher's guide.

## **Assessment**

### Grade 11-12

The National Science Education Standards (NAS, 1996), the Benchmarks for Science Literacy (AAAS, 1994) and most local science education standards call for placing an emphasis on classroom environments that engage students in worthwhile scientific tasks and that facilitate discourse about science process. The interactive ground-water tutor is intended to increase student understanding of both environmental knowledge and problem solving process. Plume Busters provides fertile ground where students can transfer learning to multiple contexts by engaging them in complex, real-world issues and then asking them to acquire and apply skills and knowledge in a variety of contexts.

As the students work through the software they will be exposed to work in all levels of Bloom's taxonomy of intellectual behaviors.

- Knowledge - seeking facts, testing recall and recognition
- Comprehension - translating, interpreting, and describing
- Application - demonstrating situations that are new or unfamiliar
- Analysis - creating categories or distinguishing events or behaviors
- Synthesis - combining or organizing components into a new pattern
- Evaluation - judging according to some criteria and providing a rationale

This sequence represents a general guide to assessment. Students should be asked to keep a "field log" of their work with the software. The field log should contain a record of their activity, decisions, and outcomes. They should also reflect on their outcomes and their decisions and explain their successes (or failures).

Suggested content for the field log;

- State the problem or issue
- Specify the assets and or needs that can be applied to this problem.
- Clearly articulate the approaches that have worked best in the past? (what do you know!)

- What is the student intending to do and what are the expected outcomes? Make sure to state any assumptions behind how and why your proposed program will work.
- Clearly lay out your planned work and your intended results.
- What was the outcome of your program?
- Is this the best possible outcome in terms of results, cost and time?
- What will you do differently next time?

It might be worthwhile to have the students divide the log pages in half (top to bottom) and record information in the left column and their thoughts and reflections in the right column. This helps the students do both as they go along.

#### Grade 11-12 Assessment Scoring Rubric

Tables 5 and 6 present a scoring rubric that is appropriate for Grade 11-12 students working with the Plume Busters software for evaluating student performance in the Locate the Plume and Remediate the Plume simulations.

#### College Undergraduate Scoring Rubric

Tables 7-8 and Tables 9-10 present scoring rubrics that are appropriate for college undergraduate non-hydrogeology and hydrogeology majors, respectively, to evaluate student performance in the Locate the Plume and Remediate the Plume simulations.



Metric	Excellent	Good	Fair	Poor
Locate the Plume				
Number of Restarts	1 or less	2	3	More than 3
Monitoring well placement during the first budget round	Within the ground-water flow corridor indicated & within 125 feet of the spill site	Within the ground-water flow corridor indicated & within 250 feet of the spill site	Within the ground-water flow corridor indicated & more than 250 feet away from the spill site	Outside of the ground-water flow corridor boundary
Number of days since discovery required to find the plume with three monitoring wells	Up to 98	99 – 175	176 – 301	More than 301
Money spent on completing this part of the simulation	Up to \$30,000	\$30,001 – \$60,000	\$60,000 – \$215,000	More than \$215,000
Total number of monitoring wells constructed during this part of the simulation	Up to 6	7 – 12	13 – 18	More than 18
Calculation of average ground-water flow velocity	Uses the data provided to calculate ave. ground-water flow velocity using the Calculator provided			Cannot calculate average ground-water flow velocity
Calculation of maximum travel distance	Correctly estimates the maximum length of time the contaminants have been in the aquifer; uses Darcy’s Law to estimate the location of the plume leading edge of the plume from the spill site; and updates the location before siting each monitoring well.	Correctly estimates the maximum length of time the contaminants have been in the aquifer and uses Darcy’s Law to estimate the location of the leading edge of the plume from the spill site. Does not update the location of the plume leading edge before siting each monitoring well.	Does not correctly estimate the maximum length of time the contaminants have been in the aquifer	
Calculation of minimum travel distance	Correctly estimates the minimum length of time the contaminants have been in the aquifer; uses Darcy’s Law to estimate the location of the plume trailing edge of the plume from the spill site; and updates the location before siting each monitoring well.	Correctly estimates the minimum length of time the contaminants have been in the aquifer and uses Darcy’s Law to estimate the location of the trailing edge of the plume from the spill site. Does not update the location of the plume trailing edge before siting each monitoring well.	Does not correctly estimate the minimum length of time the contaminants have been in the aquifer.	

Table 5. Scoring rubric for the Grade 11-12 version of Locate the Plume.

Metric/Task	Excellent	Good	Fair	Poor
Remediate the Plume				
Number of days since discovery required to completely remove the contamination from the aquifer	Up to 217	218 – 294	295 – 553	More than 553 days
Production well placement relative to the spill  Or  Orientation of the production/injection well couplet with respect to the plume and the flow system	Production well placed downgradient of the plume  Or  Injection well located upgradient and production well located downgradient of the plume			Production well placed upgradient of the plume  Or Injection well located downgradient and production well located upgradient of the plume
Containment of the plume within the capture zone in the initial submitted design	Entirely			Partially
Money spent on completing only this part of the simulation	Up to \$21,000	\$21,001 – \$37,000	\$37,001 – \$77,000	More than \$77,000
Wellfield design selected	Production/injection well couplet	1 or 2 Production wells		
Number of subsequent modifications to the wellfield design needed to capture all of the contamination	None	Modification of production/ injection rate only	Added 1 additional production well	Added more than 1 additional production well

Table 6. Scoring rubric for the Grade 11-12 version of Remediate the Plume.

Metric/Task	Excellent	Good	Fair	Poor
Locate the Plume				
Number of days since discovery required to find the plume with three monitoring wells	Up to 98	99 – 175	176 – 301	More than 301
Money spent on completing this part of the simulation	Up to \$30,000	\$30,001 – \$60,000	\$60,000 – \$215,000	More than \$215,000
Monitoring well placement during the first budget round	Within the ground-water flow corridor indicated & within 125 feet of the spill site	Within the ground-water flow corridor indicated & within 250 feet of the spill site	Within the ground-water flow corridor indicated & more than 250 feet away from the spill site	Outside of the ground-water flow corridor boundary
Total number of monitoring wells constructed during this part of the simulation	Up to 6	7 – 12	13 – 18	More than 18
Calculation of average ground-water flow velocity	Uses the data provided to calculate ave. ground-water flow velocity using the Calculator provided			Cannot calculate average ground-water flow velocity
Calculation of maximum travel distance	Correctly estimates the maximum length of time the contaminants have been in the aquifer; uses Darcy's Law to estimate the location of the plume leading edge of the plume from the spill site; and updates the location before siting each monitoring well.		Correctly estimates the maximum length of time the contaminants have been in the aquifer and uses Darcy's Law to estimate the location of the leading edge of the plume from the spill site. Does not update the location of the plume leading edge before siting each monitoring well.	Does not correctly estimate the maximum length of time the contaminants have been in the aquifer
Calculation of minimum travel distance	Correctly estimates the minimum length of time the contaminants have been in the aquifer; uses Darcy's Law to estimate the location of the plume trailing edge of the plume from the spill site; and updates the location before siting each monitoring well.		Correctly estimates the minimum length of time the contaminants have been in the aquifer and uses Darcy's Law to estimate the location of the trailing edge of the plume from the spill site. Does not update the location of the plume trailing edge before siting each monitoring well.	Does not correctly estimate the minimum length of time the contaminants have been in the aquifer.

Table 7. Scoring rubric for the college undergraduate non-hydrogeology major version of Locate the Plume.

Metric/Task	Excellent	Good	Fair	Poor
Remediate the Plume				
Number of days since discovery required to completely remove the contamination from the aquifer	Up to 217	218 – 294	295 – 553	More than 553 days
Production well placement relative to the spill  Or  Orientation of the production/injection well couplet with respect to the plume and the flow system	Production well placed downgradient of the plume  Or  Injection well located upgradient and production well located downgradient of the plume			Production well placed upgradient of the plume  Or  Injection well located downgradient and production well located upgradient of the plume
Money spent on completing only this part of the simulation	Up to \$21,000	\$21,001 – \$37,000	\$37,001 – \$77,000	More than \$77,000
Wellfield design selected	Production/injection well couplet	1 Production well	2 Production wells	
Number of subsequent modifications to the wellfield design needed to capture all of the contamination	None	Modification of production/injection rate only	Added 1 additional production well	Added more than 1 additional production well

Table 8. Scoring rubric for the college undergraduate non-hydrogeology major version of Remediate the Plume.

Metric	Excellent	Good	Fair	Poor
Locate the Plume				
Number of days since discovery required to find the plume with three monitoring wells	Up to 98	99 – 175	176 – 301	More than 301
Money spent on completing this part of the simulation	Up to \$30,000	\$30,001 – \$60,000	\$60,000 – \$215,000	More than \$215,000
Number of monitoring wells constructed during this part of the simulation	Up to 6	7 – 12	13 – 18	More than 18
Calculation of average ground-water flow velocity	Uses the data provided and Darcy's Law to estimate specific discharge and uses the specific discharge and the porosity to calculate average ground-water flow velocity using the Windows or a hand calculator.		Uses the data provided and Darcy's Law to estimate specific discharge and uses the specific discharge using the Windows or a hand calculator. Cannot calculate average ground-water flow velocity.	Cannot calculate specific discharge from the data provided or the average ground-water flow velocity.
Calculation of maximum travel distance	Correctly estimates the maximum length of time the contaminants have been in the aquifer; uses Darcy's Law to estimate the location of the plume leading edge of the plume from the spill site; and updates the location before siting each monitoring well.		Correctly estimates the maximum length of time the contaminants have been in the aquifer and uses Darcy's Law to estimate the location of the leading edge of the plume from the spill site. Does not update the location of the plume leading edge before siting each monitoring well.	Does not correctly estimate the maximum length of time the contaminants have been in the aquifer.
Calculation of minimum travel distance	Correctly estimates the minimum length of time the contaminants have been in the aquifer; uses Darcy's Law to estimate the location of the plume trailing edge of the plume from the spill site; and updates the location before siting each monitoring well.		Correctly estimates the minimum length of time the contaminants have been in the aquifer and uses Darcy's Law to estimate the location of the trailing edge of the plume from the spill site. Does not update the location of the plume trailing edge before siting each monitoring well.	Does not correctly estimate the minimum length of time the contaminants have been in the aquifer.

Table 9. Scoring rubric for the college undergraduate hydrogeology major version of Locate the Plume.

Remediate the Plume				
Number of days since discovery required to completely remove the contamination from the aquifer	Up to 217	218 – 294	295 – 553	More than 553 days
Money spent on completing only this part of the simulation	Up to \$21,000	\$21,001 – \$37,000	\$37,001 – \$77,000	More than \$77,000
Wellfield design selected	Production/injection well couplet	1 or 2 Production wells		
Number of subsequent modifications to the wellfield design needed to capture all of the contamination	None	Modification of production/ injection rate only	Added 1 additional production well	Added more than 1 additional production well

Table 10. Scoring rubric for the college undergraduate hydrogeology major version of Remediate the Plume.

## Resources

The ground-water part of the hydrologic cycle is difficult for students and adults to visualize and understand. Fortunately, there are many resources available in print and on the Internet to help teachers develop lesson plans and “hands-on” experiments. In this section, we present an annotated list of these resources.

### Ground Water Basics

Lesson Plans and Resources for Teaching Environmental Sciences (TX Natural Resource Conservation Commission, TNRCC); good overview of surface and ground water issues K-8 lesson plans included <http://www.tnrcc.state.tx.us/admin/topdoc/gi/268/chap02.pdf>

University of Illinois – Meteorologic and hydrologic information – good graphics and explanations. World Weather 2010 program – online guides to a variety of topics [http://ww2010.atmos.uiuc.edu/\(Gh\)/guides/mtr/hyd/home.rxml](http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/hyd/home.rxml)

Ground Water Primer – Online discussion with good graphics about the hydrologic cycle, water use and demand, water quality issues, what you can do section. Developed by: Agricultural and Biological Engineering, Purdue University: <http://www.epa.gov/seahome/groundwater/src/ground.htm>

USEPA Fact Flash 5 Groundwater (superfund lesson plan site) – good basic information about ground water and hydrologic cycle [http://www.epa.gov/superfund/students/clas\\_act/haz-ed/ff\\_05.htm](http://www.epa.gov/superfund/students/clas_act/haz-ed/ff_05.htm)

USEPA region 1 (New England) groundwater resources – basic ground water information with examples from New England area <http://www.epa.gov/region01/students/pdfs/gwb1.pdf>

### Underground water

<http://earthsci.org/geopro/ugwater/ugwater.html> Excellent site from Australia presents graphics on ground-water occurrence, well drilling, groundwater monitoring, ground-water modeling, water quality issues, ground-water remediation, and geophysical exploration for ground water.

What is an Aquifer? Physical model to be built by students. Similar to Aquifer in a cup (see below) but has more questions suited to 9-12 students.

[http://www.epa.gov/superfund/students/clas\\_act/haz-ed/aquifer.htm](http://www.epa.gov/superfund/students/clas_act/haz-ed/aquifer.htm)

### About NIH Image

<http://www.isat.jmu.edu/users/klevicca/Image/#Laboratories> Groundwater sand tank flow model demonstration of movement of a plume through an aquifer. Background on ground-water basics, equations for Darcy’s Law, velocity, hydraulic conductivity, and hydraulic gradient. Excellent source of information.

### Water Science for Schools: Earth's water

<http://www.ga.usgs.gov/edu/mearth.html> USGS water web site for schools. Good compilation of information, ideas, and graphics to explain the water cycle and different aspects of hydrology.

Plumeflow project, Columbia University Environmental Molecular Sciences Institute, Excellent information source on use of sand tanks to teach hydrogeology concepts. Junior high lesson plan for inclusive study program on use of sand tanks for study of hydrogeology in conjunction with reading various non-fiction and fiction works (such as a Civil Action or Silent Spring)  
<http://www.cise.columbia.edu/emsi/edout/sandtanks/curricula/>

USEPA groundwater model – groundwater model in a cup - more suited for 7-12 if students building model  
[http://www.epa.gov/region07/education\\_resources/teachers/activities/wateractivity1.htm](http://www.epa.gov/region07/education_resources/teachers/activities/wateractivity1.htm)

Aquifer in a Cup: Curricula for 4-6 grade but it is a useful exercise for getting students to think how an aquifer is put together and works in the hydrologic cycle. PDF download format  
<http://wildlifestewards.4h.oregonstate.edu/education%20tools/lesson.htm>

USEPA Classroom experiments lesson plans all levels  
<http://www.epa.gov/OGWDW/kids/exper.html>

USEPA Water Sourcebooks lesson plans for all ages including grades 9-12. Good selection of lesson plans on groundwater basics, hydraulic properties, flow nets for determining ground water flow direction, cleaning up groundwater etc. <http://www.epa.gov/safewater/kids/wsb/>

#### Darcy's Law

Teaching Quantitative Skills in a Geoscience Context, “Darcy’s Law for multiple levels in Math and Geoscience Courses” Developed by Steve Leonhardi (Math/Stats) and Cathy Summa (Geoscience) Winona State University  
<http://dlesecommunity.carleton.edu/quantskills/events/NAGT02/projects/darcyslaw.pdf>  
Good reference with ideas and examples for teaching Darcy’s Law

#### Porosity and Permeability experiments

Soil Permeability and Texture by Kimberly Flessner (intermediate – 8<sup>th</sup> grade lesson plan)  
Also

POROSITY AND PERMEABILITY by Mark Skiles (High School level) – experiment to look at porosity and permeability of different materials  
[http://www.woodrow.org/teachers/esi/1999/princeton/projects/modeling/lab2app\\_c.html](http://www.woodrow.org/teachers/esi/1999/princeton/projects/modeling/lab2app_c.html)

#### Ground-Water Contamination

Groundwater Contamination by Christine McLelland – Discussion articles and questions dealing with groundwater contamination issues  
[http://www.geosociety.org/educate/LessonPlans/Groundwater\\_Contamination.pdf](http://www.geosociety.org/educate/LessonPlans/Groundwater_Contamination.pdf)

Subsurface contamination of ground water by Jane Maczuzak: Example of how buried source can contaminate an aquifer. Could add a grid on surface of ground overlying buried source to work on location/mapping skills for identifying geographic location of contaminants  
<http://www.accessexcellence.org/AE/AEPC/WWC/1991/groundwater.html>



Paper chromatography experiment – uses coffee filters and washable black markers (and other colors if desired) to illustrate the several colors that compose black ink. Experiment illustrates the idea of breakdown products of contaminants, and the presence of breakdown products plus parent product in an aquifer <http://www.kyantec.com/Tips/paperchromatography.htm>

USEPA region 1 (New England) Groundwater contamination pdf – good explanation of contamination issues <http://www.epa.gov/region01/students/pdfs/gwc1.pdf>

US EPA enviromapper – Enter zip code or look at sites provided under map section to see location of waste discharge and disposal sites in your area <http://www.epa.gov/enviro/html/>

USEPA Superfund for teachers and students Fact Flash 8- Information about cleanup methods for remediating aquifers [http://www.epa.gov/superfund/students/clas\\_act/haz-ed/ff\\_08.htm](http://www.epa.gov/superfund/students/clas_act/haz-ed/ff_08.htm)  
Simpler format than the Ground-water remediation technologies analysis center (next)

Ground-Water Remediation Technologies Analysis Center <http://www.gwrtac.org/>  
Information on ground-water remediation technologies – good definitions and technical reports on the topics available for downloading.

USEPA Superfund for Students and Teachers – good background information on hazardous waste sites, contaminants, and cleanup; lots of information and lesson plans  
[http://www.epa.gov/superfund/students/clas\\_act/haz-ed/hazindex.htm](http://www.epa.gov/superfund/students/clas_act/haz-ed/hazindex.htm)

USEPA reading list on hazardous waste topics  
[http://www.epa.gov/superfund/students/clas\\_act/haz-ed/rdlist.htm](http://www.epa.gov/superfund/students/clas_act/haz-ed/rdlist.htm)

The Numbers Game (USEPA superfund for students and teachers site)– gives students insight into the meaning of parts per billion and parts per trillion  
[http://www.epa.gov/superfund/students/clas\\_act/haz-ed/numbers.htm](http://www.epa.gov/superfund/students/clas_act/haz-ed/numbers.htm)

Hazardous waste issues in the news – good information for beginning discussion of contamination issues [http://www.epa.gov/superfund/students/clas\\_act/haz-ed/news.htm](http://www.epa.gov/superfund/students/clas_act/haz-ed/news.htm)

USEPA superfund site Fact Flash 9 – Common Contaminants – Simplified explanation of TCE (trichloroethylene) [http://www.epa.gov/superfund/students/clas\\_act/haz-ed/ff\\_09.htm](http://www.epa.gov/superfund/students/clas_act/haz-ed/ff_09.htm)

Agency for Toxic Substances and Disease Registry Case Studies in Environmental Medicine Trichloroethylene Toxicity- exposure information about TCE  
<http://www.atsdr.cdc.gov/HEC/CSEM/tce/tce.pdf>

National Park Service Environmental Contaminants Encyclopedia – look for TCE. It is a pdf downloadable file <http://www.nature.nps.gov/toxic/list.html>

USEPA Sources of common contaminants and their health effects  
<http://www.epa.gov/superfund/programs/er/hazsubs/sources.htm>

### Mapping Expertise

New England USEPA Region 1 – Predicting ground water flow using contour maps

<http://www.epa.gov/region01/students/pdfs/gwb10.pdf>

USGS online Exploring maps module lesson plans for 7-12. Use of maps, making maps, navigation, information, exploration

<http://interactive2.usgs.gov/learningweb/teachers/exploremaps.htm>

USGS Earthshots: Satellite images of environmental change: photos show a variety of changes over time <http://edcwww.cr.usgs.gov/earthshots/slow/tableofcontents>

Orienteering – making a map of the school grounds in order to understand topography and maps

<http://www.en.eun.org/eun.org2/eun/en/vs-physicaleducation/content.cfm?lang=en&ov=4906>

Mapping lesson 2 – representation of elevation in 2 dimensions

<http://www.en.eun.org/eun.org2/eun/en/vs-physicaleducation/content.cfm?lang=en&ov=4907>

### Discussion Topics on Environmental Issues

USEPA Suggested readings about hazardous waste disposal and cleanup

[http://www.epa.gov/superfund/students/class\\_act/haz-ed/rdlist.htm](http://www.epa.gov/superfund/students/class_act/haz-ed/rdlist.htm)

Current national or Global “Problem & Solution” worksheet to help students evaluate and critique environmental articles

[http://www.pbs.org/newshour/extra/teachers/lessonplans/general/global\\_problem\\_and\\_solution.html](http://www.pbs.org/newshour/extra/teachers/lessonplans/general/global_problem_and_solution.html)

Geological Society of America (GSA) Reaction Paper – help direct students to read critically and evaluate issues [http://www.geosociety.org/educate/LessonPlans/s\\_gen.htm](http://www.geosociety.org/educate/LessonPlans/s_gen.htm)

### Articles

Don't Use It All Up – global use and distribution of water resources

<http://www.sd5.k12.mt.us/glacieref/aquak12.htm>

Decision process for drinking water – how water moves, how to keep it clean, costs involved good discussion questions (USEPA) <http://www.epa.gov/OGWDW/kids/decision.pdf>

USEPA Office of Ground Water and Drinking water – Myths and Realities of Ground Water

<http://www.epa.gov/OGWDW/kids/myths.pdf>

Groundwater and contamination articles written for the Portage County area in Wisconsin. Good discussion of issues and public view points.

<http://www.uwsp.edu/water/portage/teach/pieart.htm#Portage%20County%20Groundwater%20Goals%20Ready%20for%20Public%20Review>

Scientific American: Search on groundwater contamination or ground water to find articles

<http://www.sciam.com/>

Scientific American: Bad Actors rendered harmless, article about bacteria being used to break down TCE.

<http://www.sciam.com/article.cfm?articleID=000E12E6-8481-1C76-9B81809EC588EF21>

Scientific American: A Case of the Vapors – Denver, CO, dry cleaning solvents in groundwater

<http://www.sciam.com/article.cfm?articleID=00096AA4-7891-1D06-8E49809EC588EEDF>

Scientific American: Drinking Without Harm: Arsenic in Bangladesh ground water

[http://www.sciam.com/print\\_version.cfm?articleID=0003DF8E-DABF-1C73-9B81809EC588EF21](http://www.sciam.com/print_version.cfm?articleID=0003DF8E-DABF-1C73-9B81809EC588EF21)

Scientific American: In a Dry Land – Southwest US faces a dry future

<http://www.sciam.com/article.cfm?articleID=00045D04-BEA6-1C6F-84A9809EC588EF21&catID=2>

Scientific American: Out of Sight, Out of Mind - an oncoming crisis over misuse of a hidden resource – America’s aquifer

<http://www.sciam.com/article.cfm?articleID=000E0D9E-B4FE-1DF7-9733809EC588EEDF&catID=2>

Scientific American: Protecting the Nation’s Water Supply

<http://www.sciam.com/article.cfm?articleID=000C7709-A9E6-1C75-9B81809EC588EF21&catID=4>

Scientific American: Toxins on the Firing Range – EPA orders cleanup of unexploded ordinance

<http://www.sciam.com/article.cfm?articleID=0002772B-6643-1C74-9B81809EC588EF21&catID=2>

Smithsonian Magazine: California Scheming, Water wars in Los Angeles area

[http://www.smithsonianmag.si.edu/smithsonian/issues02/oct02/water\\_wars.html](http://www.smithsonianmag.si.edu/smithsonian/issues02/oct02/water_wars.html)

Smithsonian Magazine: Wastewater problem? Just plant a marsh

[http://www.smithsonianmag.com/smithsonian/issues97/jul97/phenom\\_july97.html](http://www.smithsonianmag.com/smithsonian/issues97/jul97/phenom_july97.html)

### **Computer System Requirements**

Currently the ground-water tutor runs in a Windows operating system environment. The most recent version of the tutor runs on systems with Windows NT with Microsoft Office 2000 and Windows XP with Microsoft Office 2003. File sizes are generally small in kilobyte size range and the ground-water tutor occupies less than 4 Megabytes on the computer.

The HTML pages can be displayed with either Netscape, Explorer, or Mozilla browsers, but seem to have the best appearance in Explorer and Mozilla. The main issue with part of the tutor is computer screen resolution, which needs to be set as high as possible. The graphics included on the HTML pages use a fixed number of pixels on the computer screen irrespective of screen resolution. Higher resolution allows both the graphics and the text to be displayed such that the

text is not wrapped around the graphic due to the smaller total number of pixels available on the screen.

The ground-water model uses the Java 2 SDK version of the JAVA programming language. This software is intended for use on Microsoft Windows 95, 98 (1<sup>st</sup> or 2<sup>nd</sup> 2000 Professional, 2000 Server, 2000 Advanced Server) or XP operating systems. A Pentium 166MHz or faster processor with at least 32 megabytes of physical RAM is required to run graphically based applications. You should have 70 megabytes of free disk space before attempting to install the Java 2 SDK software.

Most of the newer Windows operating systems already have JAVA installed as part of the Windows operating system software. As part of the ground-water tutor installation package, the installer checks to determine if a Java run-time environment is present. If not, the installer will establish one as part of the software download for installation.

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## **Glossary**

Alluvial -- An adjective referring to alluvium.

Alluvial aquifer -- An aquifer formed by materials deposited by physical processes in river channels and on floodplains.

Alluvium -- Deposits of clay, silt, sand, gravel, or other particulate materials that have been deposited by a stream in a streambed or on a flood plain.

Aquifer -- A geologic formation, which contains sufficient, saturated permeable material to yield significant quantities of water to wells and springs.

Average ground-water velocity -- The speed and direction of travel of ground water through an aquifer. The average ground-water velocity is calculated from the specific discharge and the aquifer porosity.

Biosphere -- The realm of living things on Earth.

Capture zone -- The area contributing to flow to a well. The shape of the capture zone depends on the average linear ground-water velocity, the rate at which the well is being pumped, and the hydraulic conductivity of the aquifer. The upgradient extent of the capture zone depends on how long the well is being pumped.

Concentration -- The amount of contaminant (or other constituent) in a given volume of water, often as milligrams per liter (mg/L).

Contaminants -- Anything found in water (including microorganisms, minerals, chemicals, radionuclides, etc.), which may be harmful to human health.

Contamination -- The degradation of natural water quality beyond permissible limits as a result of man's activities. Such limits depend on the potential uses of the water in question.

Contaminant plume -- An elongate zone of moving contaminated water in surface or ground water moving away from the contaminant source.

Cone of depression -- The depression, roughly conical in shape, produced in a water table by the extraction of water from a well at a given rate. The size of the cone of depression depends on the duration of pumping, the pumping rate, and the hydraulic conductivity, specific yield, and thickness of the aquifer.

Cone of impression -- A rise, roughly conical in shape, produced in the water table from the addition of water from an injection well at a rate that is faster than the ability of the aquifer to transmit the water away from the well. The size of the cone of impression depends on the

duration of pumping, the pumping rate, and the hydraulic conductivity, specific yield, and thickness of the aquifer.

Darcy's law -- A mathematical equation stating that the flow rate of water through porous materials is proportional to the hydraulic gradient. The constant of proportionality is the hydraulic conductivity.

Discharge -- The volume of water that passes a given location within a given period of time. Usually expressed in cubic feet per second or gallons per minute.

Downgradient -- Toward areas of lower hydraulic head or toward the discharge area or in the direction of ground-water flow.

Drawdown -- The lowering of the water table caused by pumping, measured as the difference between the original water table elevation and the current elevation after a period of pumping.

Driller -- a person who uses a drilling rig

Driller's log -- A log kept at the time of drilling showing the depth, thickness, character of the different rock strata penetrated, and location of water-bearing strata.

Environmental consultant -- A professional who directs the clean-up of environmental contamination or pollution for hire.

Flowpath -- An underground route for ground-water movement, extending from a recharge (intake) zone to a discharge (output) zone such as a shallow stream.

Ground water -- (1) water that flows or seeps downward and saturates soil or rock, supplying springs and wells. The upper surface of the saturate zone is called the water table. (2) Water stored underground in the pores of geologic materials that make up the Earth's crust..

Ground-water flow system -- The underground pathways by which ground water moves through several aquifers that are linked together from areas of recharge to areas of discharge.

Hydraulic conductivity -- The capacity of a rock to transmit fresh water, expressed usually as feet per day or meters per second.

Hydraulic gradient -- The slope of the water table which determined as the change in hydraulic head per unit distance in a given direction.

Hydraulic head -- The elevation of the water level in wells penetrating an aquifer and in this case, it is equivalent to the elevation of the water table. Also, the elevation of the water surface in surface water bodies, such as lakes and streams.

Hydrologic cycle -- The continuous movement of water between the atmosphere, lithosphere, and biosphere.

Hydrosphere -- That part of the earth that contains all of the water reservoirs and the hydrologic cycle on Earth.

Injection well -- A well used to pump or drain fluids, such as treated water, into an aquifer.

Liter (L) -- A volume slightly larger than a quart and equal to approximately 0.26 gallons.

Lithosphere -- The solid outer part of the planet Earth. Composed of rock usually considered considered to be the outer 50 mi (80 km) in thickness.

Maximum Contaminant Level (MCL) -- (1) The greatest amount of a contaminant that can be present in drinking water without causing a risk to human health. (2) Maximum permissible level of a contaminant in water that is delivered to any user of a public water system. MCLs are enforceable standards established by the U.S. Environmental Protection Agency. EPA sets MCLs at levels that are economically and technologically feasible. Some states set MCLs which are more strict than EPA's.

Monitoring -- (1) Repeated observation, measurement, or sampling at a site, on a scheduled or event basis, for a particular purpose. (2) Testing that water systems must perform to detect and measure contaminants. A water system that does not follow EPA's monitoring methodology or schedule is in violation, and may be subject to legal action.

Monitoring well -- A well designed for measuring water levels and testing ground-water quality.

Permeability -- The ability of a material to allow the passage of a liquid, such as water through rocks. Permeable materials, such as gravel and sand, allow water to move quickly through them, whereas slightly permeable material, such as clay, does not allow water to pass through it freely.

Permeable -- Capable of transmitting water (porous rock, sediment, or soil).

Plume -- See contaminant plume.

Pollutant -- Any substance that, when present in a hydrologic system at sufficient concentration, degrades water quality in ways that are or could become harmful to human and/or ecological health or that impair the use of water for recreation, agriculture, industry, commerce, or domestic purposes.

Porosity -- The ratio of the pore or void space to the total volume occupied by a material. With respect to water movement, it is not just the total magnitude of porosity that is important, but the size of the voids and the extent to which they are interconnected, as the pores in a formation may be open, or interconnected, or closed and isolated. For example, clay may have a very high porosity with respect to potential water content, but it constitutes a poor medium as an aquifer because the pores are usually so small.

Production well -- A well used to withdraw water or fluids from an aquifer.



Pump-and-treat method -- This is the most common method of aquifer remediation. Contaminants are removed from the aquifer by means of a production well. The produced water is treated to remove the contaminants and the treated water is returned to either a surface water body or the aquifer.

Pumping rate -- The rate at which water is being withdrawn from an aquifer by a well.

Recharge -- (1) Water added to an aquifer. (2) Process by which water is added to the zone of saturation to replenish an aquifer.

Remediation -- Removal of the source of contamination and treatment of the ground water, the aquifer materials, or both to remove the contaminants in the water.

Soil -- The uppermost layer of the Earth's surface, containing unconsolidated rock and mineral particles mixed with organic material.

Specific discharge -- The volume of water transmitted through a permeable material per unit cross-sectional area calculated from Darcy's law.

Trichloroethylene (TCE) -- This organic compound is a chlorinated hydrocarbon, a colorless liquid, and a cancer-causing agent and is in the top 15 priority pollutant list compiled by the US Environmental Protection Agency.

Unconfined aquifer -- An aquifer in which the upper boundary is the water table.

Upgradient -- Toward areas of higher hydraulic head or the recharge area or moving in the direction opposite to that of ground-water flow.

Water sample -- A small volume of water collected from a surface- or ground-water source that is chemically and physically representative of the larger water body.

Water supply -- All of the processes that are involved in obtaining water for the user before use. Includes withdrawal, water treatment, and distribution.

Water table -- (1) The level below the earth's surface at which the ground becomes saturated with water. (2) The top of an unconfined aquifer; indicates the level below which soil and rock are saturated with water.

Water-table Elevation -- The height of the water table above sea level.

Well hydraulics -- A body of knowledge that pertains to the flow of ground water toward a production well or away from an injection well.

Wellfield -- The layout of production or production and injection wells.

Wellfield design -- The act of planning the layout of production or production and injection wells based on the effects of pumping or injection on the aquifer and the contaminant plume. Pumping/injection rates are usually considered as part of the wellfield design. Placement of the wells is usually governed by the desired effect, such as controlling the movement of a contaminant plume.

Zone of influence -- The area surrounding an injection well within which the water table has been changed due to recharge caused by the addition of fluids.