Developing and Validating a Learning Progression for Computational Thinking in Earth and Environmental Systems Sciences

Beth A. Covitt[1], Alan Berkowitz[2], Randall Boone[3], Bess Caplan[2], Judith Cooper[4], Kristin Gunckel[4], Michael Jahnke[1], Garrett Love[5], Dan Marino[4], John Moore[3]
[1]University of Montana, [2]Cary Institute of Ecosystem Studies, [3]Colorado State University, [4]University of Arizona, [5]North Carolina School of Science and Mathematics

Abstract
In order to be prepared to participate in addressing socioenvironmental problems, an informed public needs to be able to access and understand evidence-based arguments that draw on computational models of Earth and environmental systems sciences. In an effort to expand understanding of how students make sense of and learn to engage in computational thinking practices, this paper synthesizes work over the past four years from a project aimed at integrating computational thinking into high school level Earth and environmental systems (EES) sciences hydrology instruction. The paper presents project products including (1) a validated learning progression identifying levels of knowledge and practice associated with EES-related computational thinking in hydrologic contexts, and (2) evidence of student learning as a result of engaging in instruction designed with reference to the learning progression upper anchor and responsiveness to students' ways of thinking. Findings show that high school students make sense of computational modeling in hydrologic contexts in increasingly more sophisticated ways spanning from "literal model use," to "nascent principle-based model use," to "proficient principle-based model use." Analyses of data from 1,279 students who participated in instructional units informed by our learning progression research demonstrated significant pre/post learning gains related to making sense of computational models of hydrologic systems.

Subject/Problem
Earth and environmental systems (EES) scientists construct computational models that account for the scale and complexity of systems in order to understand the processes that operate within them. They then use developed and validated models to explain and predict processes, events, and trends within systems. While many types of models are used in EES sciences, our focus is on computational models because of their expediency in utilizing large data sets to produce outputs such as maps, graphs, and other visualizations that communicate complex relationships in parsimonious forms (Wainwright & Mulligan, 2005). The power of computational models rests in their ability to handle numerous data streams across multiple scales (Wing, 2014). Their usefulness depends on their capacity to test the validity of assumptions, develop knowledge of systems and how they operate, and make predictions that extend into the future.

Creating, using, and interpreting computational models requires understanding of computational thinking concepts and practices such as abstraction and generalization, decomposition, discretization, parameterization, and validation (Wing, 2011; Grover & Pea, 2013). Systems thinking concepts are necessary too, in order to define problem spaces, identify components and boundaries of the system being modeled, and understand the relationships that emerge from the model (Hmelo-Silver, Marathe, & Liu, 2007). These computational and systems concepts and practices provide both scientists and the public with the ability to explore and evaluate possible outcomes to scenarios, deal with uncertainty, and develop a sense of the extent to which arguments about systems may be viewed as valid and trustworthy (e.g., regarding climate change or a groundwater contamination case).

Unfortunately, while EES scientists have made great strides in developing and using computational models to understand and address environmental systems, typical school science approaches to teaching EES sciences tend to fall short of scaffolding the knowledge and practice needed to make sense of and judge outputs of computational models of environmental systems and problems. For example, traditional school science often emphasizes naming processes and describing events rather than explaining events using mechanistic models (Gunckel, Covitt, Salinas, & Anderson, 2012; Braaten & Windschitl, 2011; Hmelo-Silver, Marathe, & Liu, 2007). This situation can lead to a public that is locked out of conversations where EES sciences play a role and has the potential to breed indifference to scientific perspectives and rejection of evidence-based arguments about potential courses of action (Gauchat, 2008).

To support the development of a public that is prepared to understand and participate in addressing socioscientific issues that draw on Earth and environmental systems (EES) computational models and computational thinking (CT), and consistent with the Next Generation Science Standards' focus on computational thinking (NGSS Lead States, 2013), we argue that computational thinking necessary for accessing and participating in public discussions and decisions that draw on EES computational models should be better integrated into K-12 science. While a growing body of work has defined frameworks for computational thinking for K-12 education (e.g., Weintrop et al., 2016), this task has not been undertaken in the context of EES and, additionally, relatively little research in any domain has examined how students initially make sense of and can develop increasingly sophisticated ways to make sense of computational models (e.g., Wilensky & Reisman, 2006).

Aims and Research Questions

Responding to these needs, we have embarked on a project titled *Comp Hydro* that involves design-based research (Cobb et al., 2003) in the EES sciences context of high school hydrology instruction. The Comp Hydro project aims to:

1. integrate ideas from CT (e.g., Barr & Stephenson, 2011; Grover & Pea, 2013; Weintrop et al., 2016), systems thinking (e.g., Ben-Zvi Assaraf & Orion, 2005; Hmelo-Silver, Holton, & Kolodner, 2000), and EES sciences (e.g., Anderson, Woessner, & Hunt, 2015; Oreskes, Shrader-Frechette, & Belitz, 1994), to articulate a learning progression (LP) framework for CT in K-12 EES sciences;
2. develop and test approaches for instructional integration; and
3. examine learning as a result of instruction designed with reference to the LP.

The following research questions are addressed in this paper:

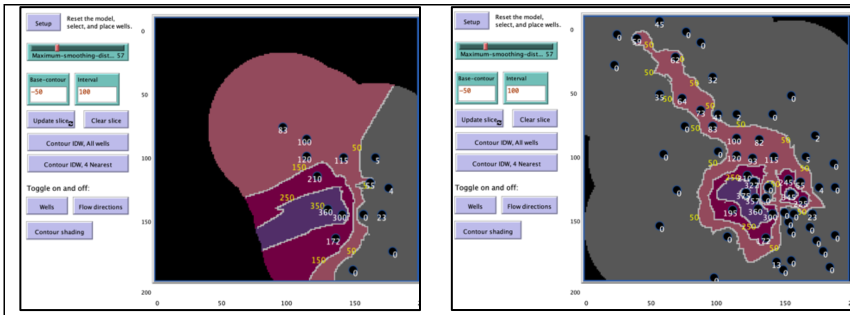
1. What patterns in students' written performances are evident as students reason about three EES CT progress variables: (1) defining the system, (2) sense making with data and representations, and (3) explaining and predicting events with imperfect models and data?
2. How do student performances change as a result of participating in LP-informed units of instruction that integrate computational thinking and modeling into EES science instruction?

Methods

Context: Our project studies integration of CT into high school hydrology instruction. In this paper, we report on data and results from two Comp Hydro project groups, both in Mountain West states (one southern and one northern)[1]. In both cases, the unit context is groundwater contamination at a state Superfund site. In the 2 to 3-week units, students engaged in multiple connected experiences with different types of groundwater system models (e.g., physical, conceptual, computational), moving from more concrete to more abstract experiences over time. Figure 1 describes an example lesson that engages students in modeling a selenium contamination plume and developing understanding of how inputting additional data is one approach to reducing uncertainty in computational modeling.

> Students use selenium concentration data collected from 15 wells at a Superfund site to create contamination plume contour maps by hand. Students practice linear interpolation and extrapolation as they estimate where contour lines should be drawn and explore data limitations. Then, they use a NetLogo Contour Map Model to generate plume contour maps with data from 15, 30, and 60 wells.

[1] The Comp Hydro project involves groups from four states. This paper focuses on results from two of those four states.



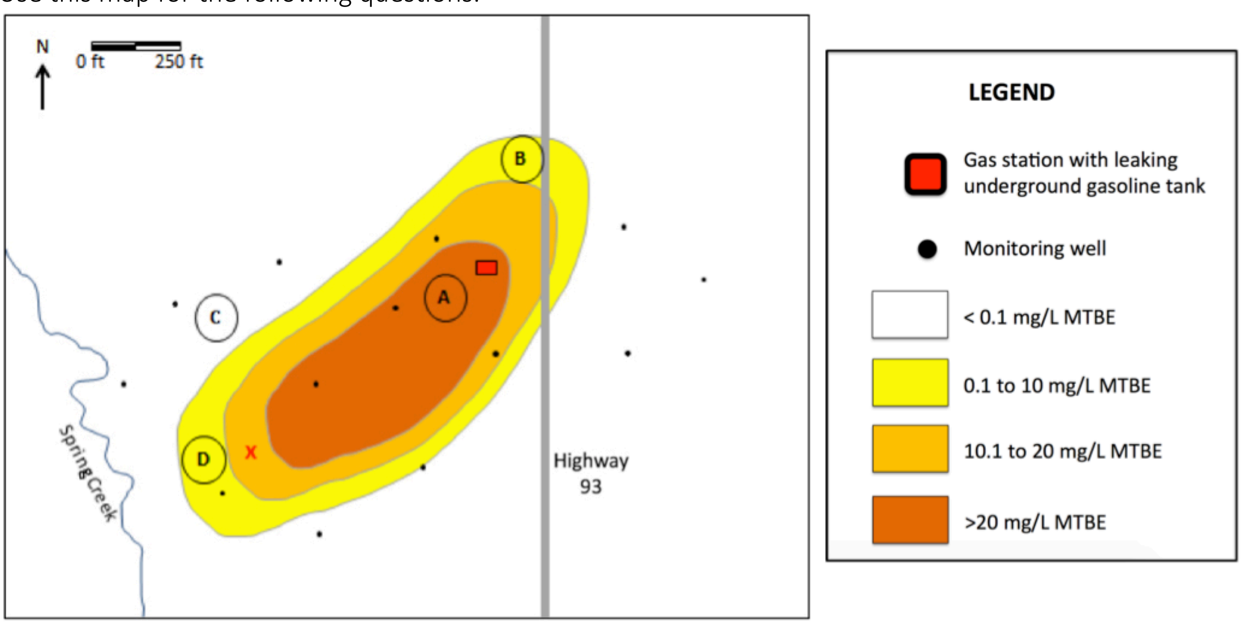
Students develop understanding that with too little data, it is not possible to constrain contaminant plume boundaries or to have sufficient resolution to identify distinct contamination sources.

Figure 1. Lesson Example: Using Data to Model Contamination Plumes

Data: Matched pre/post assessments come from 1,279 students. 602 students (7 teachers) were from the southern state and 677 students (12 teachers) were from the northern state. One site included rural school districts. The other participating site was an urban school district with a student population that is over 90% persons of color.

We report on data from 15 assessment items (an example item is shown in Figure 2 and the full set of assessment items is provided in Appendix I). Each assessment item is designed to elicit a constructed response or a combination of a forced choice and constructed response. Items are designed to elicit student responses related to each of the three progress variables as shown in Table 1. Table 1 is also a representation of the upper anchor (target knowledge and practice) for the LP progress variables. An example item (Judging uncertainty) is provided in Figure 2.

The map below shows a computer-generated picture of the contamination (pollution) plume from the leaking storage tank. The plume map was created using MTBE concentration data from the monitoring wells on the map. Use this map for the following questions.



At which location would you be most uncertain about the concentration of MTBE modeled by the computer?

A. A
B. B
C. C
D. D

Please explain why you are most uncertain about the concentration at that location.

Figure 2. Assessment Item EPM3: Judging Uncertainty

Research Development and Analysis: Our LP research involves iterative assessment cycles aimed at developing, refining, and validating a model of cognition over multiple years (National Research Council, 2006). Literature from relevant fields was used to define an initial upper anchor model for integrated computational and hydrologic thinking and data sensemaking. Associated assessment items were both adapted from previous work and newly developed, as were the accompanying units of instruction. Each year, assessment responses were collected, and the model of cognition and items were refined through analyses.

We analyzed responses using an iterative development and validation process for creating a LP (Gunckel et al., 2012; National Research Council, 2006). Exemplars with coding indicators representing reasoning at different LP levels are provided in Appendix II. Weighted Cohen's Kappas for interrater reliability among pairs of coders for responses by item ranged from 0.78 to 1.0.

We use an Item Response Theory (IRT) analysis approach to LP validation to account for item difficulties when examining student performances (Wilson, 2005). Using data collected in 2017-18 and 2018-19, we include a Wright Map displaying assessment item difficulties and person estimates based on matched pre-post assessments from 1,279 students from two states. The IRT analysis informs findings for research question 1, providing evidence of patterns in students' performances as they reason about EES CT progress variables. Table 1 shows the upper anchor LP framework with associated assessment items. To answer research question 2 (concerning evidence of student learning as a result of instruction) we examined the average of all students' pre to post change in performances for each progress variable.

Table 1. Upper Anchor Framework with Associated Assessment Items

Progress Variables and Attributes	Items
Defining the system (DTS): Students understand and reason about the following computational operations…	
-Employ abstraction to reduce a system into fundamental parameters	DTS1
-Designate a model domain and boundaries	DTS2, DTS3
-Decompose or discretize model to make it tractable to quantitative approaches	DTS4, DTS5
Sense making with system data and representations (DSM): Students understand and reason about…	
-How data are abstracted, represented in outputs including graphs and maps	DSM1, DSM2
-How system events/phenomena are represented in multiple connected spatial/ temporal scales and dimensions	DSM3
-How interpolation and extrapolation may be used	DSM4, DSM5
-Affordances/constraints of different scales of resolution and discretization	DSM6
Explaining and predicting events with imperfect data and models (EPM): Students understand that developing, refining, and using a computational model to address an environmental problem involves the following operations…	
-Define/employ rules (algorithms) using scientific principles to quantify system processes and computationally reproduce system activities	No items
-Calibrate model using real data (observations) to demonstrate that model outputs can reproduce events in real systems with some level of confidence	EPM1
-Judge validity and limitations of computational model and its outputs	EPM2, EPM3
-Use a validated model to predict/evaluate system responses to possible actions that could be taken to address an environmental problem	EPM4

Findings RQ1: What patterns in students' written performances are evident as students reason about CT in EES contexts?

Table 2 summarizes levels of increasingly more sophisticated knowledge and practice observed in performances. Given our focus on CT necessary for public participation, we identified "principle-based model users" as an upper anchor. In contrast, an upper anchor reflecting model development (e.g., including coding) will likely be appropriate for other CT projects' contexts.

Table 2. LP Levels for CT in Earth and Environmental Sciences Contexts

Levels	**Defining the system**	**Sensemaking with data & representations**	**Explaining & predicting w/models**
Upper: Proficient Principle-based model users	Understands how computational operations of abstraction, parameterization, boundary designation, & discretization are used to define system models.	Makes sense of system model outputs such as graphs & maps that use abstractions across scales & dimensions w/appropriate use of interpolation & extrapolation.	Understands how computational operations including calibration, & validation are used to develop, refine, & judge models that can be used to explain & predict.
Middle: Nascent principle-based model users	Views model as connected to real world physical system but is novice at connecting computational operations & scientific principles to define system models.	Applies simplifications in sensemaking that result in incomplete &/or inaccurate data inferences.	Understands models are used to explain/predict but w/black box approach/generalizations (e.g., says models aren't accurate w/out reference to how/why).
Lower: Literal model users	View models primarily through lens of "player" interacting w/graphical user interface (GUI). Model itself is the only "it," not a representation of a real-world system.	Makes informal literal and proximity-focused interpretations of data representations (e.g., "steep" map contour line is a hill).	May indicate models can't be used to represent real world or that it is possible to change real world by changing model.

The hypothesized LP framework was supported by item response theory analyses. Figure 3 shows a Wright Map with the 15 assessment items (using combined pre and post data for all students). The histogram on the left shows the distribution of the students' proficiency scores by progress variable. Diamonds show the difficulty thresholds for each item. Items showed good fit within the acceptable range of 0.75 to 1.33 (weighted MNSQ). The blue lines show the median thresholds between levels 1 and 2, levels 2 and 3, and levels 3 and 4.

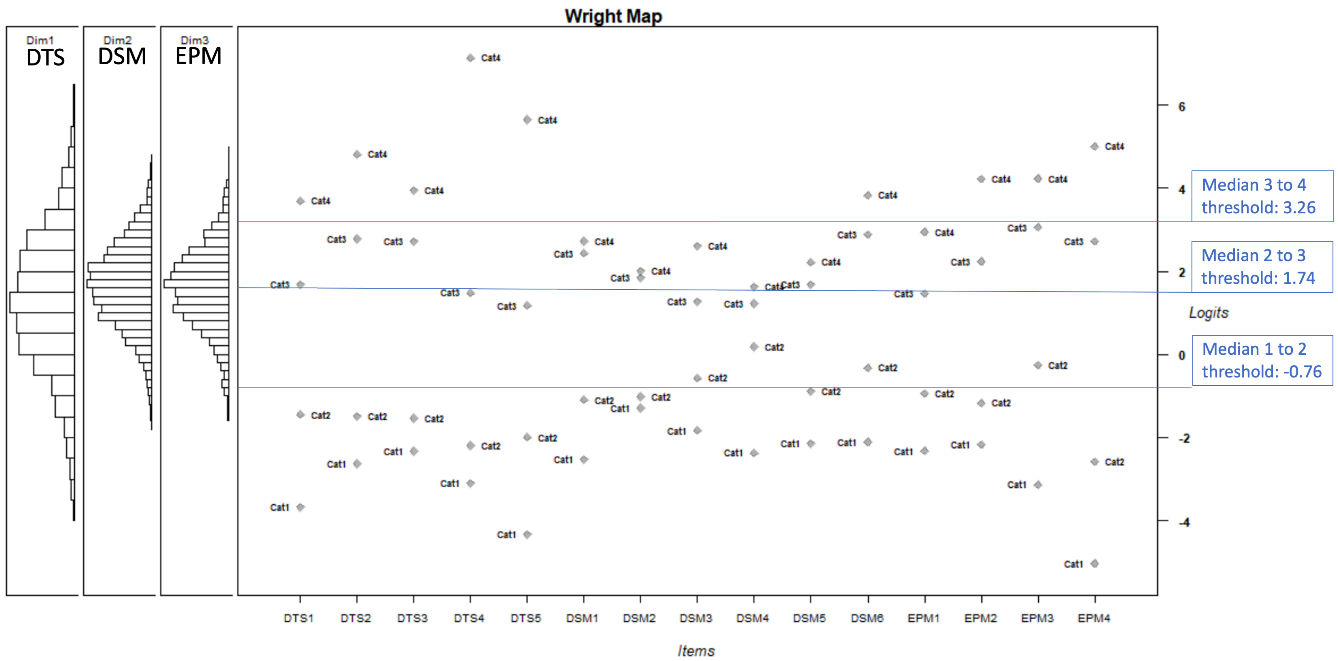


Figure 3. Wright Map with 15 assessment items

Findings RQ2: How do student performances change as a result of participating in LP-informed units of instruction?
Change from pre to post for Weighted Likelihood mean Estimates (WLEs) for each progress variable (for all students combined) are shown in Table 3. For all three progress variables, the effect size, d, for pre to post change is medium. On average, students moved from lower to higher level 2 range for the defining the system progress variable and from the level 2 range to the level three range for the data sense making and explaining and predicting with models progress variables.

Table 3. Pre to post change in students' average performances for each progress variable

Progress Variable	WLE Mean Pre	WLE Mean Post	SD	Effect Size (d)	P-value
Defining the system (DTS)	0.20	1.62	1.62	0.78	<0.001
Data sense making (DSM)	1.34	1.92	1.01	0.63	<0.001
Explaining and predicting w/ models (EPM)	1.30	1.84	0.96	0.56	<0.001

Implications

Several important insights with implications for designing effective instruction that integrates computational thinking and environmental sciences have emerged. First, we see that it is possible to develop a learning progression that defines and measures growing sophistication in EES model-based CT in terms of shifting how one views what a system and/or computational system model is and what it is useful for. Students' performances in response to the assessment items suggest that becoming more sophisticated in CT is not just a matter of becoming incrementally better at interpreting system models, including computational system models. Rather, it appears that students may first undergo a shift from engaging in literal reasoning about systems and system model representations toward reasoning that acknowledges the representational function of computational models (i.e., shift from literal model users to nascent principle-based model users).

The second shift – from nascent to proficient principle-based model users – appears to be a somewhat less extreme shift. While students moving from literal to nascent principle-based levels seem to be changing their essential views of what models are and what models are for, students shifting from nascent principle-based model users to proficient principle-based model users instead maintain the perspective that models are useful representations of the real world, while gaining knowledge and practice with respect to important principles related to defining system models, making sense of system model data and representations, and recognizing affordances and limitations of using models to explain and predict events and phenomena in Earth and environmental systems. As students move from engaging in literal reasoning about systems and system model representations toward reasoning that invokes scientific principles to explain and predict events and processes in systems, they become better positioned to think computationally (e.g., concerning boundaries, discretization, and parameterization) about those systems.

A second insight from this work concerns how learning experiences may support students in developing more sophisticated EES-related computational thinking knowledge and practice. We have found that an instructional approach that engages students in multiple connected experiences with different types of models of the same system (e.g., physical, conceptual, computational), and that move from more concrete to more abstract experiences over time, can support students in developing increased sophistication and capacity for integrated systems and computational reasoning. Comp Hydro units that integrate this approach to teaching are available on our project website at: http://ibis.colostate.edu/comphydro/

Conclusion

Computational thinking has been recognized as an essential competency for twenty-first century problem-solving (Grover & Pea 2018). As the field of science education grapples with what computational thinking is and how to integrate it into the science curriculum, our framework for computational thinking in the discipline of the ESS sciences builds on and brings together several efforts in science education research. Importantly, our framework aligns with the direction established by the *Framework for K-12 Science Education* (National Research Council 2012) and the Next Generation Science Standards (NGSS Lead States 2013) by integrating computational thinking practices into disciplinary core concepts in the EES sciences. It also integrates and aligns components of both systems thinking (e.g., Ben-Zvi Assarf & Orion 2005; 2010; Hmelo-Silver, Holton, & Kolodner 2000; Krasny 2009; Mehren et al. 2018) and computational thinking (e.g., Angeli et al. 2016; Barr & Stephenson 2011; Grover & Pea 2013; Weintrop et al. 2016; Wing 2006), especially with respect to defining systems, identifying boundaries, decomposing problems, and utilizing scientific principles when designing and interpreting models and model representations. By engaging in EES sciences curricula based on this framework, students can learn not only disciplinary core ideas, but also computational thinking concepts and practices necessary to make sense of environmental problems and analyze potential solutions.

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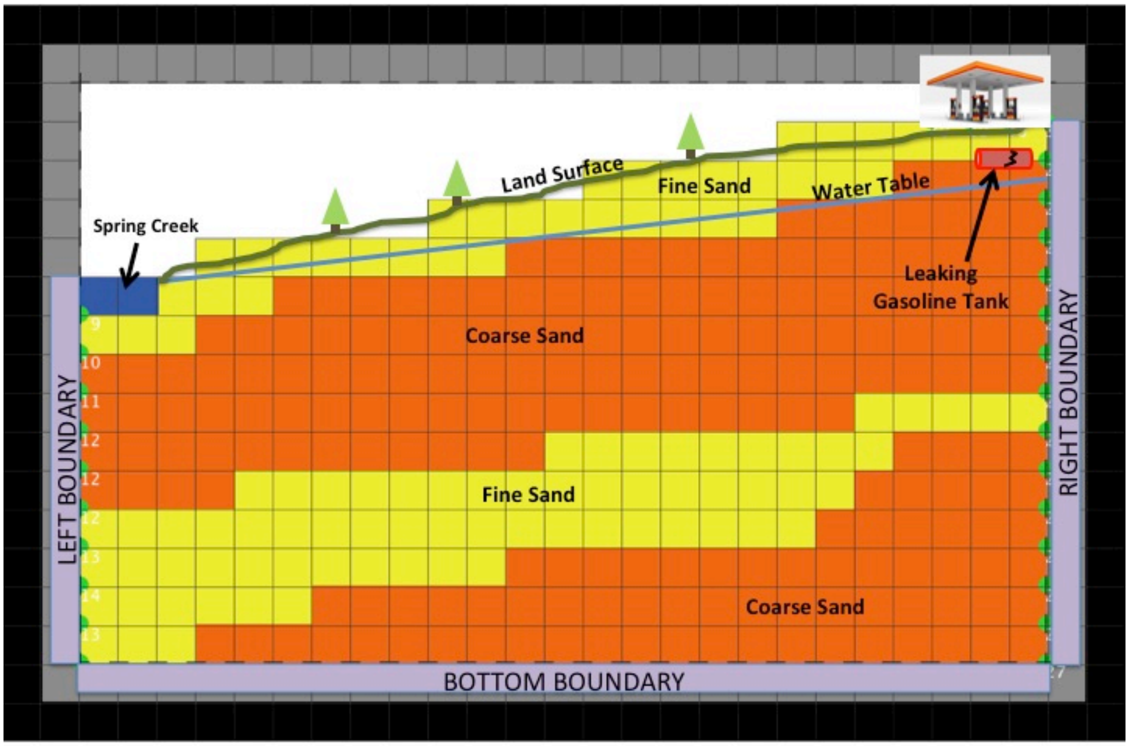
Appendix I. Assessment Items

DTS1. Parameter ID

The image below shows a cross-section of the area where the underground gasoline tank is leaking. A grid has been applied over the cross-section to begin making a computer model of the gasoline spill.



What information about each cell in the grid would be needed to compute and predict the flow of water and MTBE through the system?

Please explain why each type of information (parameter) you listed is important.

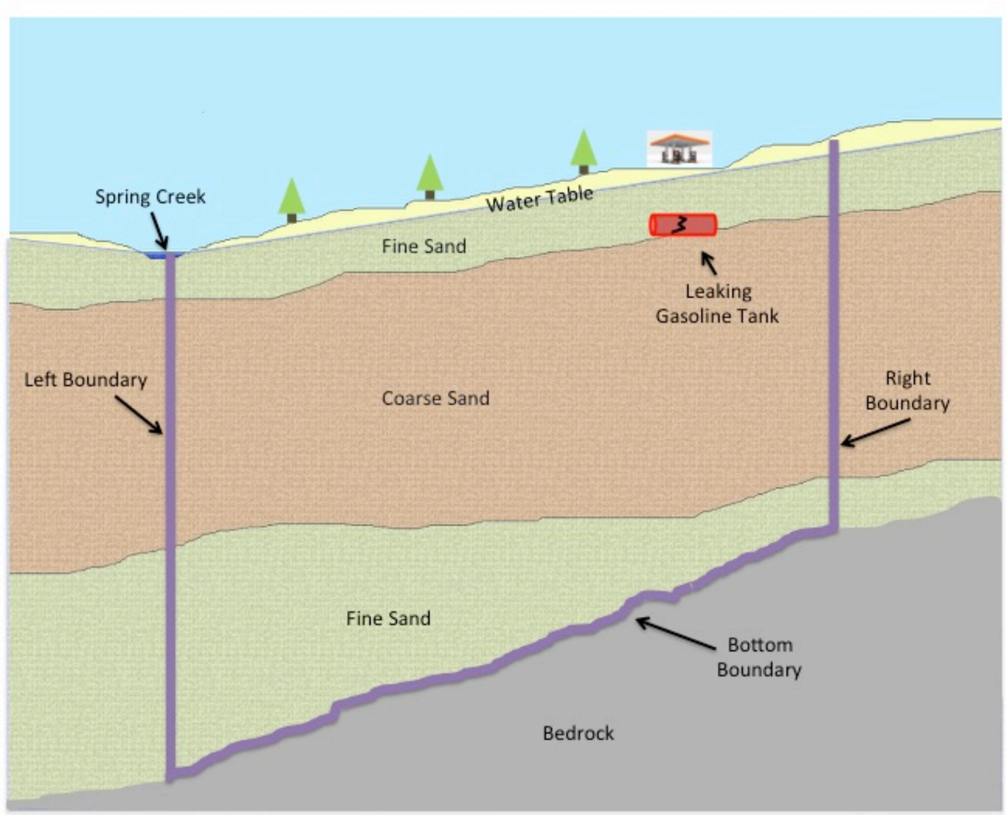
DTS2. Boundaries 1

If you were creating a computer model of the system shown in the image below and were using the model boundaries shown by the purple lines, how would you set the right boundary in the model? (CHOOSE ONE)

A. Open - Allow water to flow across the RIGHT boundary

B. Closed - Stop water from flowing across the RIGHT boundary

Why would you set the RIGHT boundary the way you chose (as either open or closed)?



DTS3. Boundaries 2

How would you set the BOTTOM boundary in the [same] model? (CHOOSE ONE)

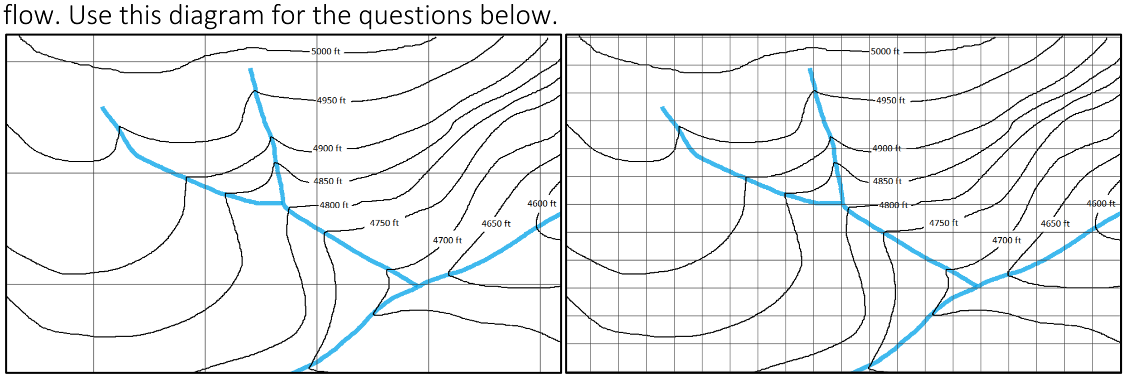
A. Open - Allow water to flow across the BOTTOM boundary

B. Closed - Stop water from flowing across the BOTTOM boundary

Why would you set the BOTTOM boundary the way you chose (as either open or closed)?

DTS4. Discretization 1

The diagram below shows two different grids to divide the map into cells to develop a computer model of water flow. Use this diagram for the questions below.



Grid A Grid B

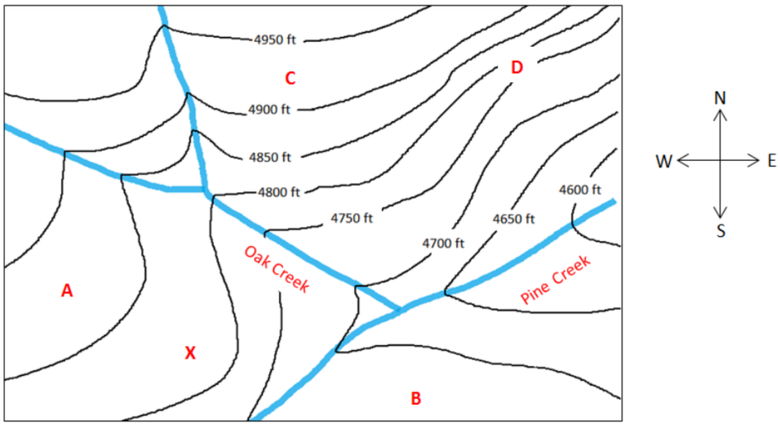
What is the purpose of dividing the area into cells?

DTS5. Discretization 2

[Using diagram from previous item] Give at least one advantage and one disadvantage of using Grid B (smaller cells) for your computer model.

a. Advantage:
b. Disadvantage:

DSM1. Topo Gradient



Where is the slope of the land the steepest?

A. A
B. B
C. C
D. D

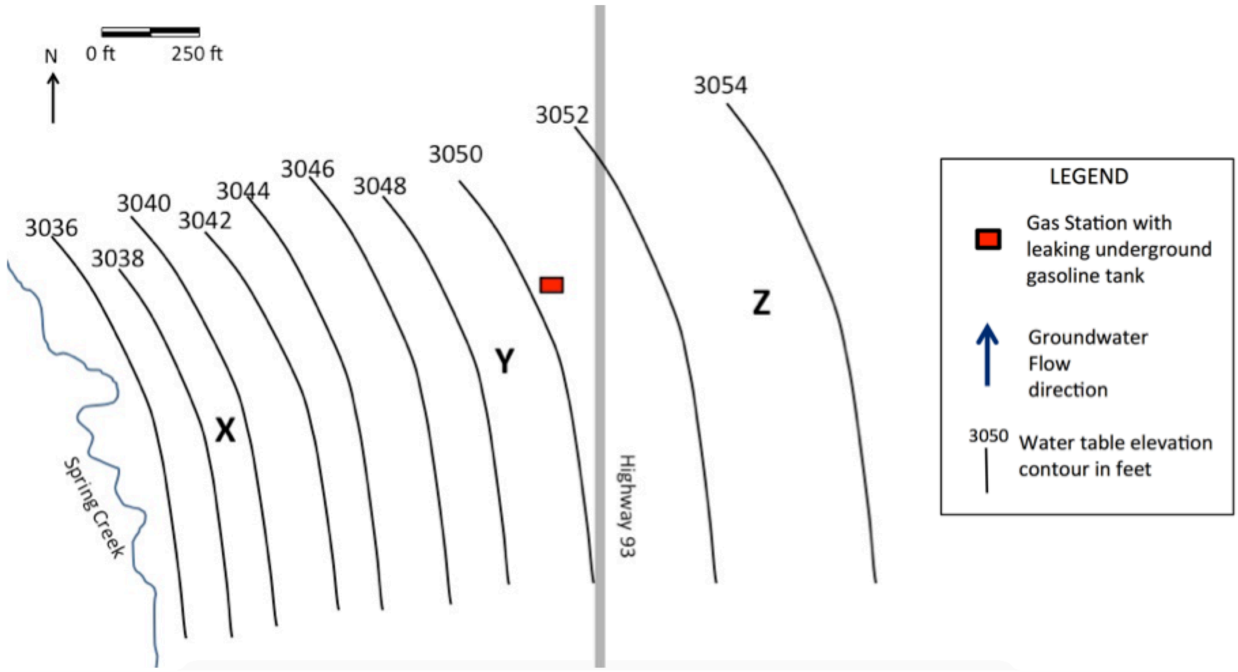
Please explain why you chose that answer.

DSM2. Ronan Gradient

On the map below, at which of the locations (X, Y, or Z) is the slope of the water table the steepest?

A. X
B. Y
C. Z

Please explain why the slope of the water table is the steepest at the location you chose.

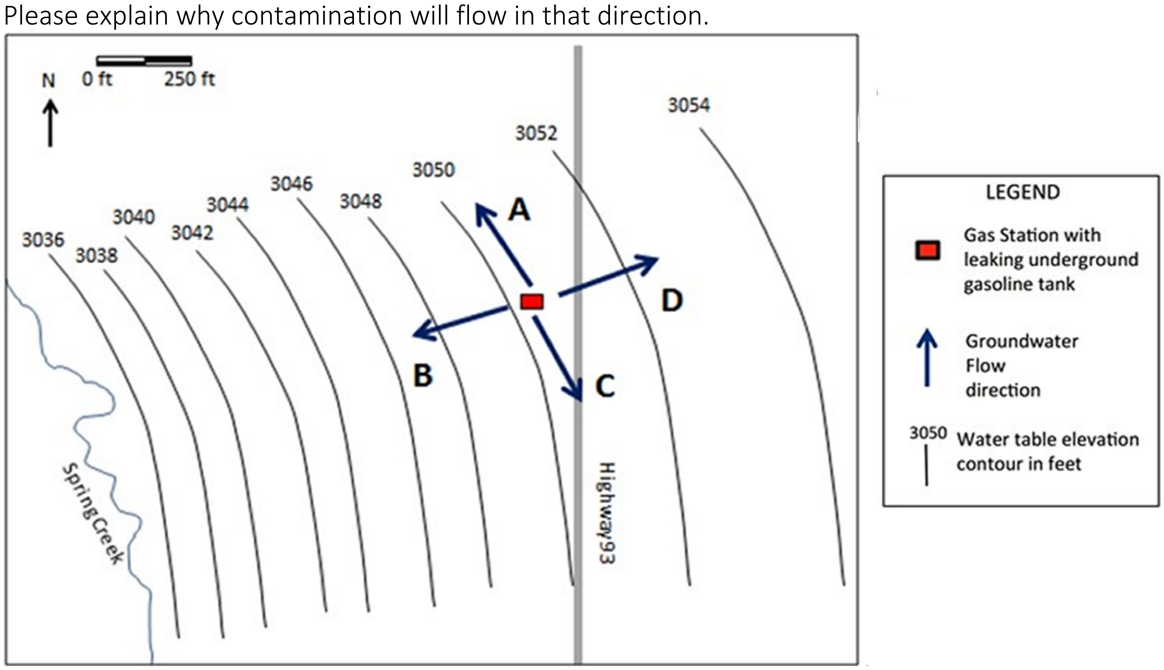


DSM3. Ronan Waterflow Arrows

The map below shows the site of the gas station and the water table elevation contours. Which of the four arrows on the map best shows the direction contamination will flow from the leaking storage tank?

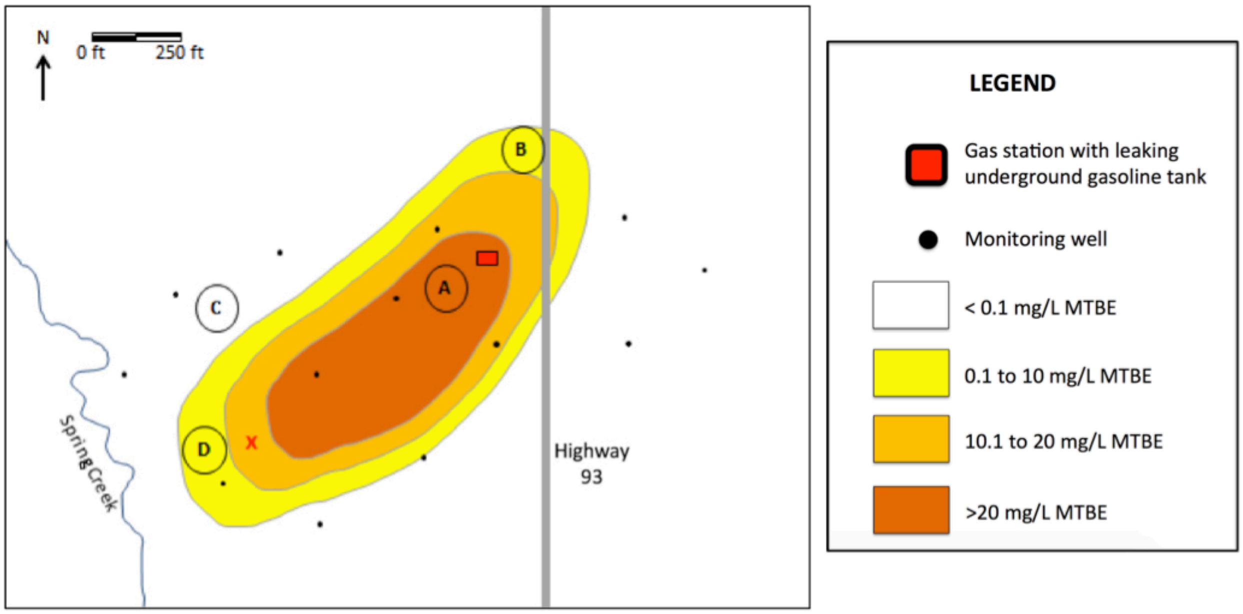
A. Arrow A
B. Arrow B
C. Arrow C
D. Arrow D

Please explain why contamination will flow in that direction.



DSM4. Ronan Interpolation

The map below shows a computer-generated picture of the contamination (pollution) plume from the leaking storage tank. The plume map was created using MTBE concentration data from the monitoring wells on the map. Use this map for the following questions.



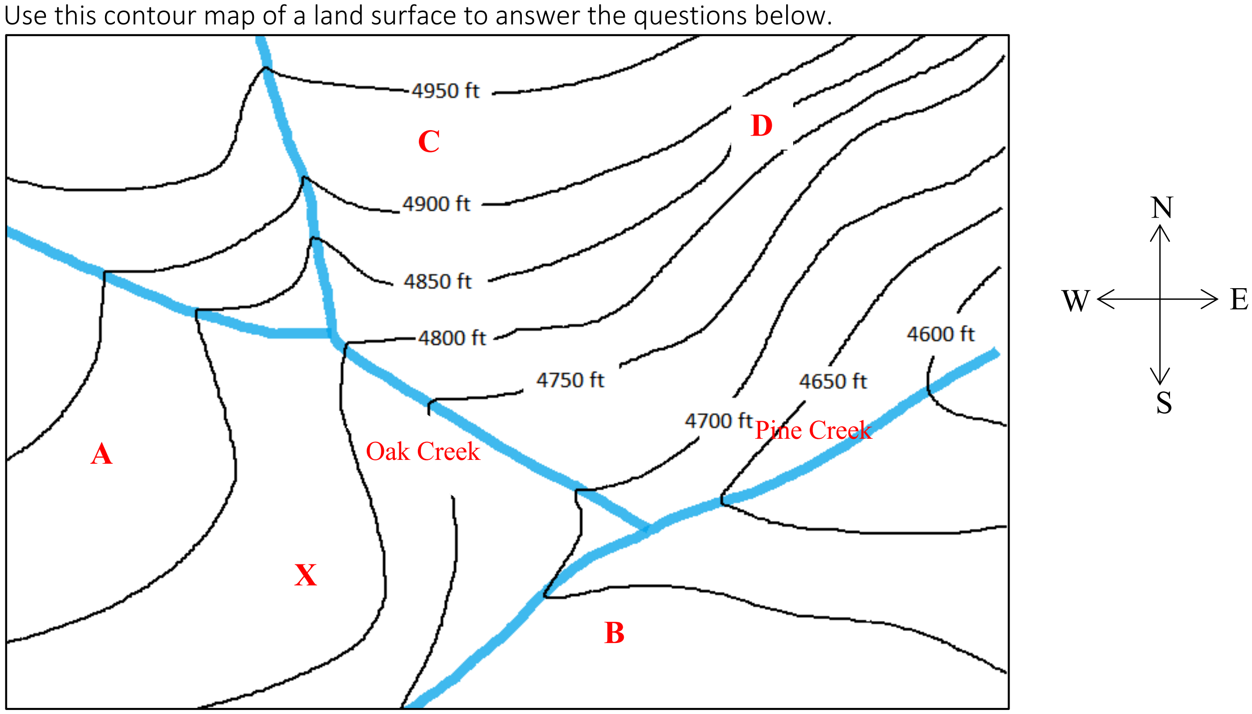
What would be a reasonable estimate of the concentration of MTBE from a groundwater sample taken from a well at the X?

A. 0.2 mg/L
B. 3.0 mg/L
C. 14 mg/L
D. 31 mg/L

Please explain why your choice is the best estimate of concentration.

DSM5. Topo Interpolation

Use this contour map of a land surface to answer the questions below.



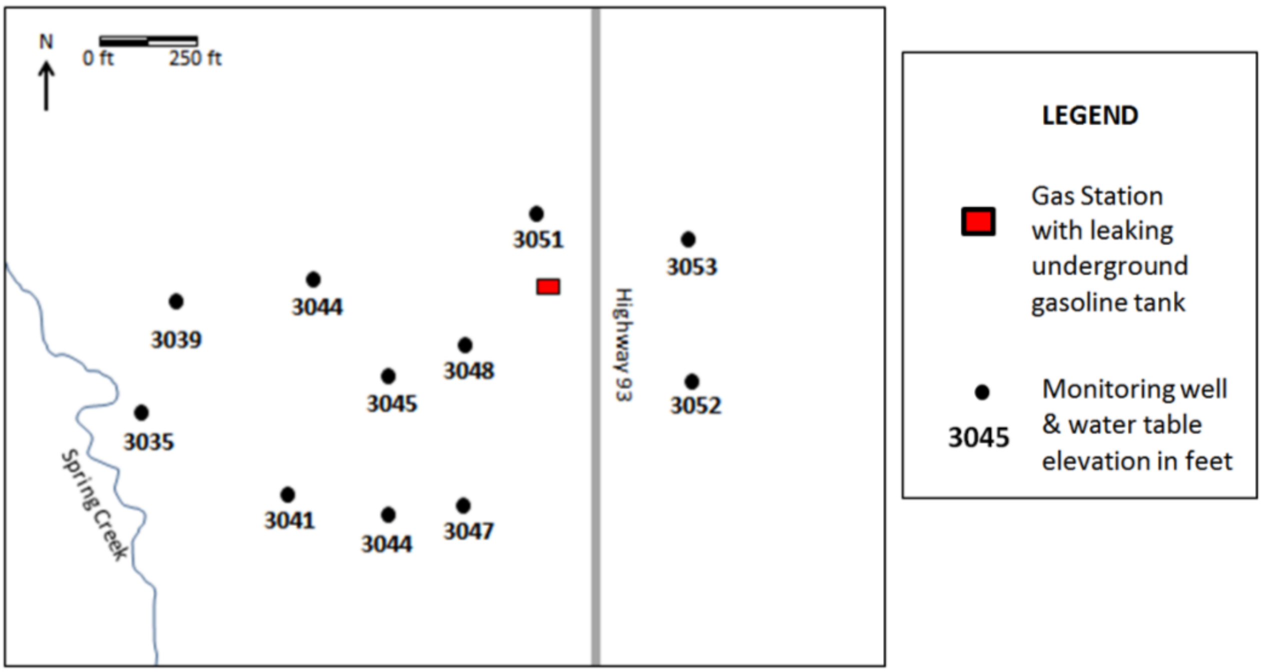
What would be a reasonable estimate for the elevation of the land surface at the X on the map?

A. 4800 ft
B. 4850 ft
C. 4815 ft
D. 4765 ft

Please explain why you chose that answer.

DSM6. Ronan Interval

A gas station has been leaking gasoline from an underground storage tank. A chemical called MTBE that occurs in gasoline has been found to be contaminating the groundwater.



The map above shows the location of the gas station and some monitoring wells. The numbers next to the wells show the elevation of the water table. What groundwater elevation contour interval would be the best choice for making a contour map of the water table?

A. 0.2 foot
B. 2 feet
C. 20 feet
D. 200 feet

Please explain why your choice is best for showing groundwater elevation on this map.

EPM1. Judging Model Accuracy

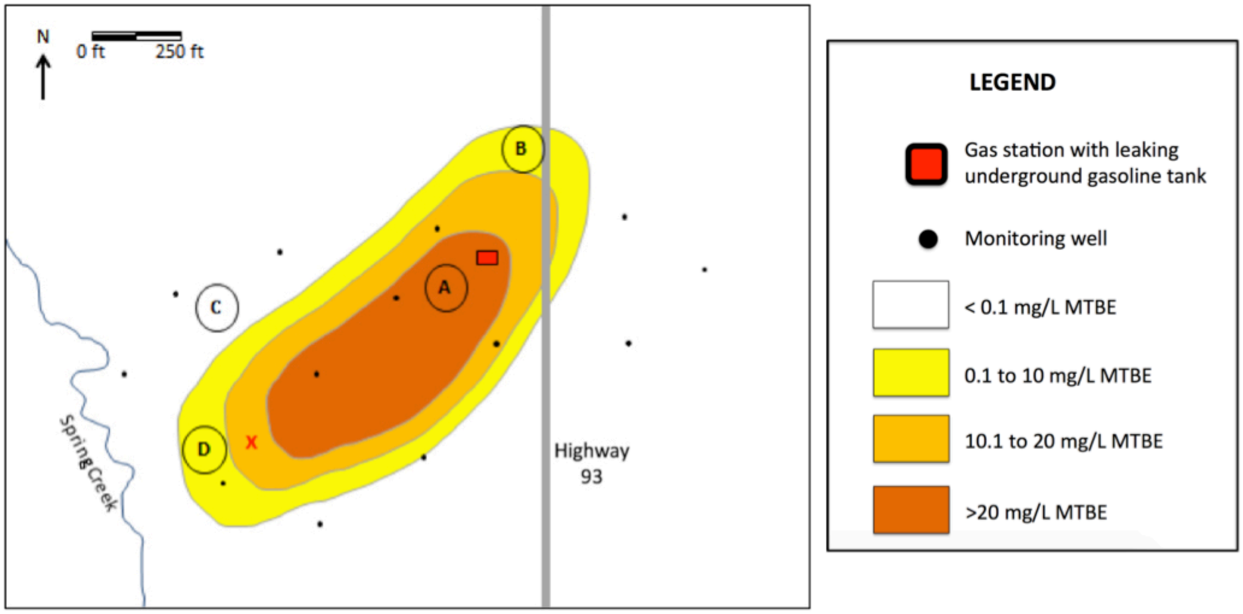
How can a scientist judge if a computer model is accurate?

EPM2. Model Problems

What are some problems with using a computer model to understand a real world water problem?

EPM3. Judging Uncertainty

The map below shows a computer-generated picture of the contamination (pollution) plume from the leaking storage tank. The plume map was created using MTBE concentration data from the monitoring wells on the map. Use this map for the following questions.



At which location would you be most uncertain about the concentration of MTBE modeled by the computer?

E. A
F. B
G. C
H. D

Please explain why you are most uncertain about the concentration at that location.

EPM4. Model Uses

What do you think scientists use computer models for?

Appendix II. Coding Rubrics

DTS1. Parameter ID

Level	Indicators
4	Understands that computer uses certain information and can explain what that information is and how it is used in model. 4.A. Identifies at least one **RELEVANT** parameter (e.g. potential energy, hydraulic head, elevation, pressure, permeability, composition, type of soil/"sand"/sediment) **AND** States or implies its effects such as direction and/or rate (doesn't necessarily need to use the ideal terminology) **AND** Connects/**Explains** the parameter and its effects using an accurate principle. 4.B. PE/elevation affect the rate and/or direction because water flows from higher to lower PE/elevation. 4.C. Permeability/hydraulic conductivity and/or sediment composition affects the rate and/or direction of flow because more permeable sediments allow fluids to flow more quickly through them. FOR ALL RESPONSES: Evidence used to support responses is mostly correct. Ok if mentions porosity if with other relevant parameters (e.g., potential energy, permeability, etc.).
3	States what model can do or be used for; doesn't indicate how model works. 3.A. States or defines (even if implicit) at least one relevant parameter that affects the movement of water and/or contamination in the model **BUT** does <u>not explain</u> how the model uses the parameter **OR** how it affects the flow of water (i.e., does not connect parameters to effects using accurate principles **OR** incorrect principle (e.g., relates flow rate with porosity or density or texture). 3.B. <u>Uses the model</u> (NOT JUST THE PICTURES, either before or after) to discover specific information, solve a problem, or <u>do</u> something (more than "compute and predict the flow of water and MTBE through system," which is the question stem) 3.C. States or implies that <u>the model</u> is used to discover or predict (e.g., where, how much, etc.) 3.D. Might refer to ideas of accuracy, precision, or "rightness;" use the right parameters to make the model more accurate. Evidence used to support answers may be inaccurate.
2	Describe what is seen in the provided picture or the picture in their heads, but do not indicate that the model uses the items described to solve a problem. May describe what people need to know rather than the computer. "I don't know what you're asking so I will tell you what I see!" 2.A. Only describes what the model shows/"tells you" 2.B. Describes locations (where the leak is, where the brook is, where the water is or goes, cell boundaries) 2.C. Describes pathway of water through the diagram in the question (i.e., the picture on the test or the computer), the groundwater tank, or the game. 2.D. Describes the output of the model (output is the picture after "running" the model: where and how fast the water and contamination flow) AND does not use the output to do something. 2.E. Only describes what people need to know, rather than the model, to solve a problem. 2.F. Only uses phrases directly from the stem of the question 2.G. Have not separated model from phenomenon 2.H. Focused on the reality of a gasoline spill
1	1.A. Unclear reasoning (is not talking about the question as far as you can tell) 1.B. IDK / No reason / Students wrote that "they guessed" or "just by looking at it" or "because" with nothing else

DTS2 and DTS3. Boundaries 1 and 2

Level	Description	Indicators
4	* Demonstrates an understanding of what is involved in using a computer model to model the hydrologic system. * Understand that the computer uses certain information and can explain what that information is and how it is used in the model. * Connects computational principles to hydrologic principles.	4.A. Open and correctly links to a hydrologic principle (e.g., water would be flowing in from the right) 4.B. CT principle is that you use properties of the system to determine the setting of the boundaries. 4.C. Indicates purpose of model 4.D. May state that they are setting the model to reflect conditions in the physical world
3	* Recognizes that computer models are useable to solve a problem, answer a question, or find something out related to a hydrologic system. * States what the model can do or be used for; doesn't indicate how the model works. * Response must include some evidence of use of a computational principle, even if not correctly applied or ambiguous.	3.A. Indicates the model is useful for learning something or seeing what happens but does not explain how the model works. 3.B. What proposes using the model for might not be realistic, but does include or describe an incorrect or ambiguous principle or ideas about hydrology and/or boundaries or how they work. 3.C. If talks about seeing something, must be something that wouldn't be visible unless the model was "run" 3.D. May talk about testing something or running an experiment, but doesn't connect to hydrologic principle or computational principle. 3.E. Response is about how the water moves or how the water moves contamination, not just how the contamination would move.
2	* Describe what is seen in a model * May see the model as a way to manipulate the system. Doesn't separate the model from reality * "I don't know what you are asking so I will tell you what I see" * have a hydrologic principle but no grasp of how would set a model boundary. * May talk about only about how the contamination would move and not how the water would move. * Uses proximity reasoning. *Repeats or restates the stem of the question as the only answer.	2.A. Suggests that the model controls or influences the physical system (engineering answer) 2.B. Suggests that some action about the boundary could contain the contamination. 2.C. Answer is about the picture; describes the picture or uses the picture as the model rather than seeing the picture as a representation of a computer model. 2.D. Have a force dynamic idea (e.g., natural tendency of water) with no grasp of how would set a model boundary. 2.E. May talk about only about how the contamination would move and not how the water would move. 2.F. Proximity reasoning 2.G. Repeats or restates the stem of the question as the only answer.
1	*Unclear reasoning (is not talking about the question as far as you can tell) *IDK/ No reason / Student wrote that "they guessed" or "just by looking at it" or "because" with nothing else	

DTS4 and DTS5. Discretization 1 and 2

Level	Indicators
4	**Response connects to reasonable ideas about needing DISCRETIZATION for computer modeling and/or modeling data.** 4.A. The grids are part of the process of making computer models (W/OUT RESTATING THE PROMPT!) 4.B. Compares the ease/difficulty of model-making using smaller and larger cells (more cells produced more information that computer could use, explicitly that COMPUTER has more to process) 4.C. The grids introduce or affect an element of error in the data 4.D. The purpose of cells is to average, estimate, or generalize information over an area. 4.E. Cells are useful for translating continuous data/information into discrete parts (i.e., breaking up or dividing). 4.F. Information in cells is needed to model the system (hydrological processes in system)
3	**Response is about doing something that requires having the space broken up (e.g., finding a location, comparing/contrasting information in cells, etc.) or for advantage/disadvantage items, may discuss degree of effort of using model as described below. Focus may be on individual cells rather than modeling whole.** 3.A. Cells are (or dividing into cells is) useful for purposes that fall short of 4D or 4F or 4G. E.g., for • comparing/contrasting information/areas • compare degree of effort in using the model (how much work they had to do) or associated with the model (other than 4B “making model” or 2 things like “a lot to look at”) • to solve problems, • make measurements • show or find/pinpoint the location of features or information • organizing or showing more precise or accurate information (just seeing/showing more detail or for item 1 just “more accurate” is level 2) • accomplishing something more than just constructing grid • creating/making graphs, graphing
2	**Response focuses on map or picture as a whole rather than need for discretization, OR focus on seeing or showing as in 2B – that does not require discretization, or repeats question, or purpose of dividing into cells is to divide into cells or grid. See also 2E, 2F, and 2G.** 2.A. Only describes or compares what the maps look like with the grids laid over them (state what is in the picture). 2.B. Cells “show” or “focus on” or help “to see,” “read,” or “understand” something **WITHOUT** indicating what (examples of significance: direction, location, etc.). Describes how information will be seen (e.g., closer, zoomed in, more depth, farther out, etc.) 2.C. Restate all or part of the introductions to or stems of the assessment items. To develop a computer model of water flow. 2.D. To show different grids, divide the map into cells, describe the act of constructing the grid 2.E. cells are physical divisions in the natural landscape. Or believe “cells” refers to the biological structures. 2.F. Cells are part of doing the activity or playing a game. 2.G. Other reasoning where seem to be answering the question. Ambiguous reference to effort; not clear what effort/work is directed at. (or comparing grid A and B for first item)
1	1.A. Unclear reasoning (is not talking about the question as far as you can tell) 1.B. IDK / No reason / Students wrote that “they guessed” or “just by looking at it” or “because” with nothing else

DSM1 and DSM2. Topo Gradient and Ronan Gradient

Level/Ind	Reasoning Indicator
4.1	(D) Change of elevation is fast or over a small distance reasoning (use this if ALSO 4.2 or 4.3)
4.2	(D) Closer/more lines = steeper reasoning
4.3	(D) Closer/more lines reasoning
3.1	(A,B, or C) Change of elevation is fast or over a small distance reasoning
3.2	(A,B, or C) Closer/more lines = steeper reasoning
3.3	(A,B, or C) Closer/more lines reasoning
3.4	(D) Steep line or steepest by look reasoning
3.5	(D) Lines far apart reasoning
2.1	(A,B, or C) Steep line reasoning or steepest by look or steepest w/no reason or (A,B,C, or D) High or big number or elevation reasoning
2.2	(A,B, or C) Lines far apart reasoning
2.3	(Any letter) Low elevation or number reasoning
2.4	(Any letter) Proximity reasoning (to something other than things in other indicators like high elevation)
2.5	(Any letter) Other reasoning (is talking about the question as far as you can tell)
1.1	Unclear reasoning (not talking about the question as far as you can tell)
1.2	IDK/ No reason / Student wrote that "they guessed" or "just by looking at it" or "because" with nothing else

DSM3. Ronan Waterflow Arrows

Level/Ind	Reasoning Indicator
4.1	(B) High to low potential energy (may also mention additional explanations)
4.2	(B) High to low elevation, to decreasing elevation (may ALSO mention additional explanations - e.g., perpendicular to or through contours, gravity)
4.3	(B) Gravity or gravity plus down or downhill or slope
3.1	(A,C, or D) High to low potential energy (may also mention other explanations)
3.2	(A,C, or D) High to low elevation, to decreasing elevation (may ALSO mention additional explanations - e.g., perpendicular to or through contours)
3.3	(B) Down, down slope, downhill, downwards, down to river, lower (without mentioning elevation), slope (w/out gravity) (may ALSO mention additional explanations - e.g., perpendicular to or through contours)
3.4	(B) Elevation w/out "decreasing" sort of explanation
3.5	(A,C, or D) Gravity or gravity plus down or downhill or elevation or slope
3.6	(B) Perpendicular to or through contours only
3.7	(B) To the water or to the creek or river
2.1	(A,C, or D) Down, down slope, downhill, downwards, down to river, slope (w/out gravity)
2.2	(A,C, or D) Elevation w/out other explanation or to different or higher or steeper elevation
2.3	By or to the highway or location of gas leak, or by proximity
2.4	Because the map shows or mentions lines, or parallel to line reasoning
2.5	(A,C, or D) To the water or to the creek or river
2.6	(Any letter) Other reasoning (is talking about the question as far as you can tell)
1.1	Unclear reasoning (not talking about the question as far as you can tell)
1.2	IDK/ No reason / Student wrote that "they guessed" or "just by looking at it" or "because" with nothing else

DSM4. Ronan Interpolation

Level/Ind	Indicator
4.1	(14mg/L) Estimated or in between or middle of reasoning.
3.1	(0.2, 3.0, or 31mg/L) In between or estimated or middle of reasoning or 3 is in 3 to 30 (or other appropriate range)
3.2	(14mg/L) Used map, key, or color reasoning or used map to find area of contamination without mention of the range
3.3	(14mg/L) Because of movement/flow reasoning
2.1	(0.2, 3.0, or 31mg/L) Used map, key, or color reasoning (without mention of range and other than proximity to color) or area of contamination reasoning (other than high contamination reasoning)
2.2	(0.2, 3.0, or 31mg/L) Because of movement/flow reasoning
2.3	Proximity reasoning (including proximity to color)
2.4	High, highest, high or other amount of contamination reasoning
2.5	(Any letter) Other reasoning (is talking about the question as far as you can tell)
1.1	Unclear reasoning (not talking about the question as far as you can tell)
1.2	IDK/ No reason / Student wrote that "they guessed" or "just by looking at it" or "because" with nothing else

DSM5. Topo Interpolation

Level/Ind	Reasoning Indicator
4.1	(4815) Above or slightly above reasoning or higher (than 4800)
4.2	(4815) Described reason as in-between, estimated, interpolated.
3.1	(Not 4815) Above or slightly above/below or higher/lower than reasoning
3.2	(Not 4815) In-between, estimated, interpolated reasoning
3.3	(4815) Elevation (no explanation) reasoning
3.4	(4815) Proximity (close to, near to) to 4800 reasoning or far from reasoning
2.1	(Any elevation) Number reasoning
2.2	(Any elevation) Water flow direction or creek (flow) reasoning
2.3	(Any elevation) Line reasoning (other than proximity to line reasoning)
2.4	(Not 4815) Elevation (no explanation) reasoning
2.5	(Not 4815) Proximity (near or close or next to or connected to something or far from something)
2.6	(Any elevation) Low (area of map) reasoning
2.7	(Any letter) Other reasoning (is talking about the question as far as you can tell). Could be counting reasoning.
1.1	Unclear reasoning (not talking about the question as far as you can tell)
1.2	IDK/ No reason / Student wrote that "they guessed" or "just by looking at it" or "because" with nothing else

DSM6. Ronan Interval

Level/Ind	Indicators
4.1	indicates 2 feet and provides reason that refers (even if implicitly) to an appropriate scale to show and make sense of water table and/or direction of flow of water table. May say things like .2 would be too small to see what's happening with water table or 20 or 200 would b e too big to see what's happening with water table.
4.2	Indicates 2 feet and response shows student is making sense of the data in a way that is productive for interpreting the map (e.g., elevations) (e.g., MT17-18 line 5)
3.1	Indicates 2 feet but reason is just because that's the best to choose or similar.
3.2	Indicates 2, but reason does not describe how that interval helps map reader make sense of the data and/or the water table, direction of flow. May just mention numbers but nothing about the water table or understanding the map.
3.3	May mention things like right level of accuracy in a way that conflates accuracy with detail

3.4	Indicates a response other than 2 feet and provides a reason similar to that for level 4.
2.0	Indicates a response other than 2 feet and provides other reasons (need to see what they are)
2.1	Number reasoning and or feet reasoning
2.2	In between reasoning
2.3	distance between wells or other types of well reasoning
2.4	conflates water table elevation and surface distances
2.5	deepness reasoning
2.6	Proximity reasoning
2.7	Other reasoning
1.1	Writes a response, but unclear reasoning (is not talking about the question as far as you can tell)
1.2	IDK/ No reason / Student wrote that "they guessed" or "just by looking at it" or "because" with nothing else

EPM1. Judging Model Accuracy

Level/Ind	Indicator
4.1	Use calibration, and/or iteration
4.2	Compare model to the real world, or vice versa. Go check it or test in real world and compare. Compare to real world measurements.
3.1	Test it with a physical model that you make or compare the computer model to another model.
3.2	Run model multiple times.
3.3	Use/input accurate data. Get more data.
3.4	If model is scientifically logical, matches known information, past research, or expected results.
2.1	If model makes sense. Double check, check calculations, or get a second opinion.
2.2	If model fixes the problem
2.3	They can't
2.4	Run tests (no specifics) - not saying that they're running the model more than once.
2.5	Other reasoning - (is talking about the question as far as you can tell)
1.1	Writes a response, but unclear reasoning (is not talking about the question as far as you can tell)
1.2	IDK/ No reason / Student wrote that "they guessed" or "just by looking at it" or "because" with nothing else

EPM2. Model Problems

Level/Ind	Indicator
4.1	The model may not account for uncontrolled or all of the important independent variables.
4.2	Models may be difficult to calibrate (to achieve match between modeled and observed).
4.3	Models are only as good as the data that is entered, require a lot of data, or are constrained by how much data modeler is able to enter.
3.1	Models aren't perfect; aren't or may not be accurate.
3.2	Model code or specification (don't need to use actual words) could be wrong.
2.1	Model could crash, break, lose something (like data or output), or stop working. Model could be completely wrong.
2.2	Computer models can't simulate or predict the real world.
2.3	Models have boundaries.
2.4	Models are expensive.
2.5	Other reasoning - (is talking about the question as far as you can tell)
1.1	Unclear reasoning (is not talking about the question as far as you can tell)
1.2	IDK/ No reason / Student wrote that "they guessed" or "just by looking at it" or "because" with nothing else

Level is highest indicator.

EPM3. Judging Uncertainty

Level/Ind	Indicator
4.1	(B) Not near wells, or references insufficient data
3.1	(A) Large range of concentration values and/or no maximum
3.2	(B) Elevation related or appropriate direction of flow reasoning
3.3	(A,C) No or few close wells
2.1	Out of range, no data for C
2.2	Color related (only w/out supporting explanation such as concentration)
2.3	Proximity
2.4	Concentration of contamination (e.g., high or low) (ok to infer student is talking about concentration)
2.5	(A,C,D) Direction of flow
2.6	Other reasoning - (is talking about the question as far as you can tell)
1.1	Unclear reasoning (is not talking about the question as far as you can tell)
1.2	IDK/ No reason / Student wrote that "they guessed" or "just by looking at it" or "because" with nothing else

EPM4. Model Uses

Level/Ind	Indicator
3.1	Virtually model/simulate; virtually show something happening/test (don't need to use word virtually)
3.2	Test/experiment (something you would use a computer model to test or experiment). If 3.1 and 3.2 then only indicate 3.1
3.3	Predict (needs to be pretty clear)
3.4	Find or develop solutions (solve problems)
3.5	Figure out or understand how something works
3.6	Analyze or calculate
3.7	Replication; faster, run multiple tests
2.1	To be accurate or more accurate (without specifics about how or about what)
2.2	Collect, share, or record data
2.3	Less expensive or safer (for humans or environment)
2.4	See, find, show, or visualize something; map something (in a literal sense).
2.5	Use models because it's EASIER
2.6	Other reasoning - (is talking about the question as far as you can tell)
1.1	Unclear reasoning (is not talking about the question as far as you can tell)
1.2	IDK/ No reason / Student wrote that "they guessed" or "just by looking at it" or "because" with nothing else

Level 4 is two or more Level 3 indicators. One Level 3 indicators is Level 3. One or more Level 2 indicators is Level 2. If only Level 1 indicator(s), Level 1.