Interactive Educational Tool Summer Field Session 2025: Depletion of Fully Penetrating Stream by a Pumping Well

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Organization Background

The Groundwater Project was initiated in 2017 to enhance prospects for expansion of human capacity in groundwater problem solving and public understanding of groundwater. The Project is a volunteer-based, nonprofit, nongovernmental organization (NGO) registered in Canada and global in scope. It advances groundwater understanding and awareness by creating high-quality learning materials in many languages and making them available for download free-of-charge from its website. The GW-Project is led by Dr. John Cherry (recipient of the 2020 Stockholm Water Prize) and functions with a two-person staff, a volunteer board of directors, and over 1000 volunteer authors, reviewers, editors, and translators.

Description of Project

Complete a project started by your previous classmates in the Fall of 2024. The project description they had is included the support materials in a zip file that you can download at this **DropBox Link**. The folder in the zip file has all the files I mention in this proposal with filenames starting with a number in the order that I mention them here. The project description changed a bit during the semester and I provide that file as named below.

01_InteractiveEducationalTool_DepletionOfFullyPenetratingStream_FallSession2024Proposal.pdf

Their mission was to create an online, interactive, educational tool to demonstrate depletion of flow from a fully penetrating stream in response to a pumping well. Their final report is included in the folder in the file as named below.

02_Groundwater Report.docx (1).pdf

You can rebuild the tool from scratch or by modifying the files they created in the file as named below. It is written in Javascript and you can continue that way or if you prefer you can redo it in Python and serve it through Streamlit. It is possible that using Python might make the calculations more efficient.

03_Groundwater-main (2).zip - please note that when I try to execute it now, the graphs do not appear but one of their earlier versions had graphs with errors.

I provided feedback to the Fall 2024 team for an earlier working version and in the push at the end of the semester it was unclear how and whether these items were addressed. The notes I sent were a bit rushed because they were under a time crunch but they will help you get started with revisions. My notes are in the file as named below.

04_CalculationProblems.pdf

In case what I mean by interactive educational tools is not clear, I provide links and downloadable files at the end of this proposal, that provide examples.

In case the science underlying the educational tool is not familiar to you, I provide a description at the end of this proposal.

Any time the team meets an obstacle, please contact me soon so we can brainstorm a solution or an alternative approach.

The final product will be included on the Groundwater Project web site gw-project.org under the educational tools https://gw-project.org/interactive-education/.

Tasks

The Crux

The crux of your work is to complete a project started in the Fall of 2024 and provide a working tool with nice graphical output for posting on the site https://interactive-education.gw-project.org/. The letters DFPS are an acronym for "Depletion Fully Penetrating Stream". This is used in some file names and as shorthand in the following discussion. To get a feel for the underlying files of an interactive learning tool, review the HTML, JavaScript, Python, and Streamlit files for the existing tools (WTR, TDPF, and Well-Capture). Links to working tools are provided in a later section of this proposal titled: Examples of Interactive Tools.

Debug the Files from Fall 2024

It is not clear at this time how big a challenge this is. The team had finally reached the stage where I could review a working set of files and I gave some feedback but they were not able to accomplish it and we were not able to do the final stage of back-and-forth review and revision. It was a big project and they accomplished a lot and I think this additional field session should be enough to wrap it up. It should help that you do not have other classes to juggle at the same time, so it will be easier to focus, which is useful when coding.

- As you work, consider your tool from the perspective of an uninformed user and enhance it in ways to help them intuit how to use it.
- As you work, check the results against the sample results that I provide in files titled as follows for time increments, drawdown, and stream depletion, respectively.

  05_TestTimeIncrementCalculations.xlsx
  06_TestDrawdownCalcDFPS-parametersFromFirstMeeting_withCurrentDefaultInputs.xlsx
  07_TestQcalcDFPS-parametersFromFirstMeeting_withCurrentDefaultInputs.xlsx

- As you work, try to find inputs that "break" the tool and include code to catch those problems and write error or warning messages to the user and deal with the problem gracefully in the output. I can help with issues related to results that may look reasonable in numbers and graphs but that do not make physical sense.
- As you near completion, send the tool to me for review and iterate a few times until we clean up any problems.
- After building the tool, please review the surrounding HTML files and offer your suggested edits/revisions. We will need to add information about the Spring 2025 team members for the about.html file.

If you feel I can provide any more information to help you decide if you want to work on this project, do not hesitate to contact me: epoeter@mines.edu (970-509-0336).

Optional Changes/Enhancements

- Optionally, convert to Python if you are convertible with it. This might make the calculations more efficient. If you use Python then it has to be served using Streamlit in order to be used on the Groundwater Project web site.
- Optionally, convert to Bokeh or used Bokeh graphing. Here is a link to a brief write up on how to make a Bokeh application as written by Gaelen Merrit who also volunteers for the Groundwater Project and would be willing to answer questions and provide advice. If you visit this page, scroll down to the section titled "**Bokeh Applications for the Groundwater Project."**

Details of the Tool as Delineated in Fall 2024

Input Parameters for the user input form

Spatial dimensions

- Perpendicular distance from the well to the stream, d, in meters
- Factor for size of domain (Fd) to be displayed, F is dimensionless (the mathematical domain is infinite but the tool will provide a square of specified size in meters)

Aquifer parameters

- Hydraulic conductivity K_a in centimeters/second then converted to meters per day
- Aquifer thickness b in meters
- Specific Yield S_y (dimensionless)

Note T is used in the calculations and is calculated as: T=Kb

Stream parameters

- Hydraulic conductivity of stream bed K_{sb} in centimeters/second then converted to meters per day
- Stream flowrate Q_s in cubic meters per second

Well information the well location will be defined as x,y = 0,0

- pumping rate, Q_w in liters per minute then converted to cubic meters per day and sometimes per second for calculations (positive for withdrawal of water and negative for injection)
- locations of observation wells for graphing drawdown as a function of time
    - ox1,oy1 in meters relative to the pumping well (can be + or -)
    - ox2,oy2 in meters relative to the pumping well (can be + or -)

Time information

- Duration of pumping, t in days, always positive
    - Number of increments of time to be calculated (minimum 1 up to some allowed maximum, perhaps 10?)

Prepare Map of Drawdown, s

- The lower left corner of the contour map will be y = -(Fd/2) and x = -(Fd-d).
- Draw a dot for the well at x,y=0,0 and a vertical line for the stream at x=d and from y=-Fd/2 to +Fd/2.
- Calculate the time increments logarithmically Δtime1 = TotalTime ((2.5-1)/(2.5$^{\#increments}$–1)), each time step there after will be 2.5 times longer and added to the previous cumulative time. You could let the user specify the multiplier. Here is an example.

PERLEN	NSTP	TSMULT
100	5	2.5
	$\Delta t_1 = \text{PERLEN}\left(\frac{\text{TSMULT} - 1}{\text{TSMULT}^{\text{NSTP}} - 1}\right)$	
delta t	**time for drawdown calculation**	**step #**
1.551891368	1.551891368	1
3.879728419	5.431619787	2
9.699321048	15.13094083	3
24.24830262	39.37924345	4
60.62075655	100	5

- Calculate the fraction of pumped water that is coming from the stream (i.e., stream depletion) at time t as follows (note: use consistent units):

$$Q_{fraction} = \text{erfc}\left(\sqrt{\frac{Sd^2}{4Tt}}\right)$$

where:

$Q_{fraction}$ = fraction of pumping rate leaking from stream into groundwater system at time t (dimensionless)

S_y = specific yield (dimensionless)

d = perpendicular distance from well to stream in meters

T = transmissivity ($K_a b$) in meters^2 per day

K_a = aquifer hydraulic conductivity (centimeters per second – convert to meters per day)

b = aquifer thickness (meters)

t = time in days

erfc = complimentary error function = 1-erf, approximation of erf given below

erf(β) = a fairly good approximation is $\text{erf}(\beta) \approx \frac{2}{\pi}\arctan\left(2\beta(1+\beta^4)\right)$

- Calculate the rate of leakage from the stream in meters^3 per day at time t then convert to meters^3 per second for the output graphs:

$$Q_{streamleakage@t} = Q_{fraction}\, Q_w$$

Q_w = pumping rate converted to meters^3 per second

- Calculate the stream discharge in meters^3 per second at time t:

$$Q_{s@t} = Q_s - Q_{streamleakage@t}$$

Q_s = initial volumetric discharge of the stream (meters^3 per second)

$Q_{s@t}$ = volumetric flow rate in the stream at time t (meters^3 per second)

- Choose a grid spacing for the map view within the square where values of drawdown will be calculated so they can be shown as contours on a map and as a line on a cross-sectional graph – make sure one set of grid points is along the centerline of the square from left to right – perhaps you will always use a grid that divides the square into 21 x 21 points with one at 0 and one at the size the user specifies for the dimensions of the square (Fd), then the 11th row of grid points will always be long the center line with 10 grid squares between it and zero and 10 squares between it and the length of the square.

- For each time increment, at each grid point determine the straight-line distance, r, to the well (i.e., r = the square root of the sum of the difference in the x's squared and the difference in the y's squared) and calculate the drawdown at that grid point using the formula below (note: use consistent units).

$$s(x, y, t) = \frac{Q_w}{4\pi T}\left(W(u) - W(u')\right)$$

where:

s(x,y,t)	=	drawdown at a location x,y and time t
Q_w	=	constant well discharge rate
T	=	transmissivity (Kb)
S	=	storativity (S_sb)
t	=	time
r	=	straight-line distance from the well to x,y
W(u)	=	$-\ln(u) + a0 + a1\,u + a2\,u^2 + a3\,u^3 + a4\,u^4 + a5\,u^5$
u	=	$\frac{\sqrt{x^2+y^2}}{\frac{4Tt}{S}}$ (dimensionless)
u'	=	$\frac{\sqrt{(2d-x)^2+y^2}}{\frac{4Tt}{S}}$ (dimensionless)
a0	=	-0.57721566
a1	=	0.99999193
a2	=	-0.24991055
a3	=	0.05519968
a4	=	-0.00976004
a5	=	0.00107857

Calculate Velocity Vectors

Given a set of heads on the four corners of a square with side length equal to L, find the maximum and minimum head on a circle with radius 0.01 around the center point of a unit square. Then calculate the magnitude of the Darcy velocity in the full-size cell as the difference between the max and min head values on the circle divided by (0.02*L) and multiplied by the K_a (aquifer hydraulic conductivity). The direction of the Darcy velocity is the angle associated with the minimum head. Specific steps are given below.

To find the value of head at each point on a 0.01 radius circle, starting with north as zero radians, calculate 73 unit-cell x,y locations as (0.5+0.01*sin(radians),0.5+0.01*cos(radians)) to reach 2π radians (the complete circle) at 5-degree intervals (i.e., $2\pi/72$ radian intervals), and calculate the head at those locations as follows.

$$h_{x,y} = a00 + a10\ x + a01\ y + a11\ x\ y$$

where the "a"-values are based on the heads at the 4 corners of the grid cell:

$a00 = h_{LowerLeft}$

$a10 = h_{LowerRight} - h_{LowerLeft}$

$a01 = h_{UpperLeft} - h_{LowerLeft}$

$a11 = h_{UpperRight} - h_{UpperLeft} - h_{LowerRight} + h_{LowerLeft}$

Next, find the maximum and minimum of heads (check that these are 180 degrees -- that is, π radians -- apart and if they are not, then print a warning along with their values – a small offset is not a concern for this graphic display). Then, calculate the velocity vector with magnitude $((h_{max} - h_{min})\ K_a)/(0.02\ L)$ and direction equal to the angle at which the minimum head occurred. I will provide an illustrative spreadsheet.

Output to Display below Submit and Reset Buttons

- I include an image of the data input form and output at the end of this document with an example result sketched below it. There are slight, desirable, modifications from this in the files built by the Fall 2024 team.
- At each time when the user clicks forward or back, for that time t, draw the **Contour map** of the values of drawdown within the square with a symbol for the location of the pumping well and each observation location o1 o2. If a location falls outside of the square print a message stating that, but continue with calculations to create the contour map within the square.
- Also, at each time when the user clicks forward or back, for that time t, draw the **Vector** on each cell, or if that is too crowded, draw vectors on every other, or every third or fourth cell. Adjust the size so the largest vector is scaled to the length of the side of a cell and all other vectors lengths are scaled logarithmically (that is, draw vectors that are the log(calculated value). We use a logarithmic scale because a linear scale may make the smallest vectors too small to see.
- At each time when the user clicks forward or back, for that time t, draw the **Cross-Sections** of drawdown along the mid-line of the square on the W-E and beneath the stream in the S-N direction, that is, for W-E from 0,L/2 to L,L/2 and for S-N at x=d from y=+Fd/2 to -Fd/2. If I recall correctly, you can give javascript the function and say how many points you want and it will adjust everything as needed – I think I did that for the water table in the example WTR tool that I provided.

- For the range of time specified, draw a line on the four **Graphs** (Fraction of Pumping, Streamflow Rate, and drawdown versus time for both observation locations. These can be calculated once when the submit button is pressed. There will need to be enough values of time to make a fairly smooth curve that ranges in time from 0 to the pumping duration time.
- It would be beneficial if you could have a red vertical line on each graph that changes to show the TIME at which the MAP and CROSS SECTIONS are drawn. It should be stated somewhere: The red vertical line indicates the time of the map and cross sections.

Reasonable Numbers to Use for Testing the Code

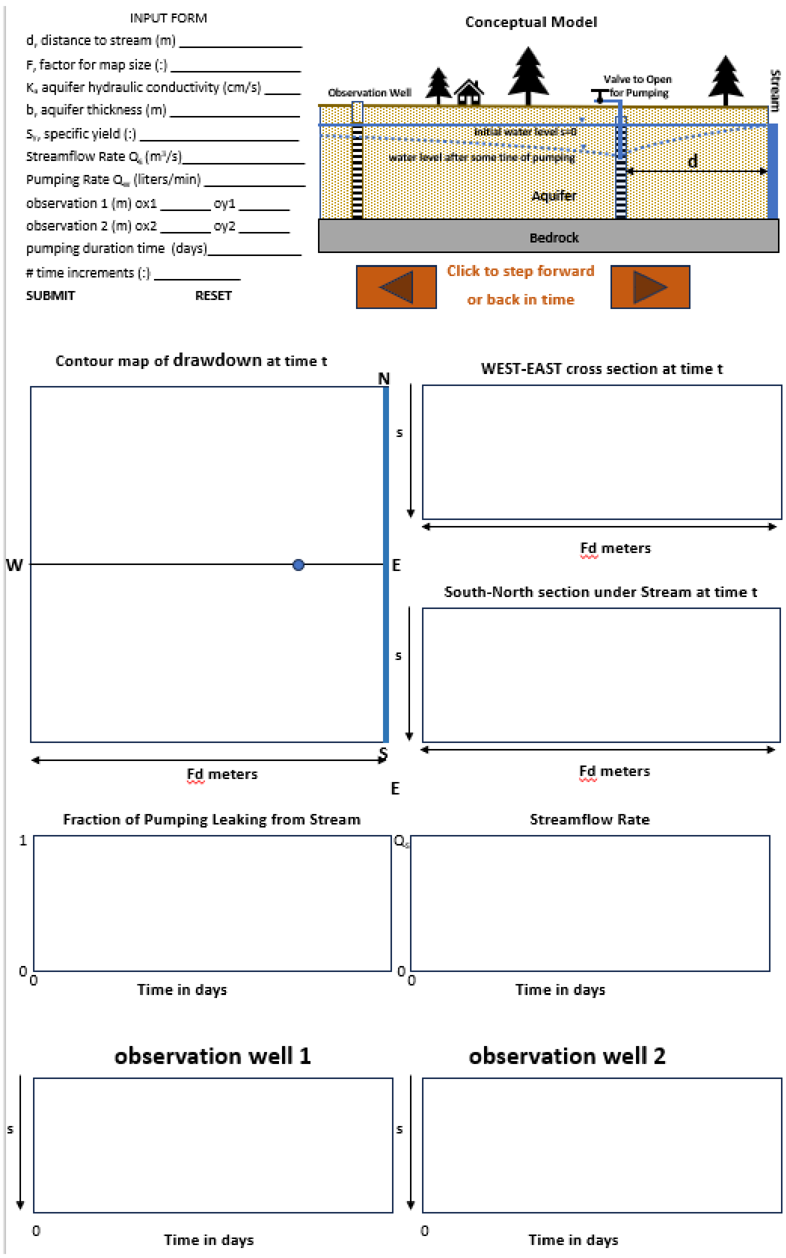
- Perpendicular distance from the well to the stream, d, 50 meters
- Factor for size of domain (Fd) to be displayed, F, 4
- Hydraulic conductivity K_a enter 0.001 cm/sec then convert to meters per day
- Aquifer thickness b 10 meters
- Specific Yield S_y 0.15
- Hydraulic conductivity of stream bed K_{sb} enter 0.01 cm/sec then it is internally converted to meters per day
- Stream flowrate Q_s 3 cubic meters per second (like clear creek in Golden in early August 2024
- pumping rate, Q_w 2000 liters per minute then it is internally converted to cubic meters per day and sometimes per second for calculations
- ox1,oy1 in meters -100,45
- ox2,oy2 in meters 30,-50
- Duration of pumping, t 365.25 days
- Number of increments of time to be calculated 3

Student Team Requirements

- Team size: estimated to be 4 students
- Work will be done remotely
- One meeting per week by zoom to review progress, discuss issues (questions are welcome at any time by text, email, or phone)
- Some skill in web site development utilizing HTML and JavaScript, optionally Bokeh or Python and Streamlit can be used
- Interest in learning more HTML, JavaScript, and optionally Bokeh or Python and Streamlit while undertaking the project

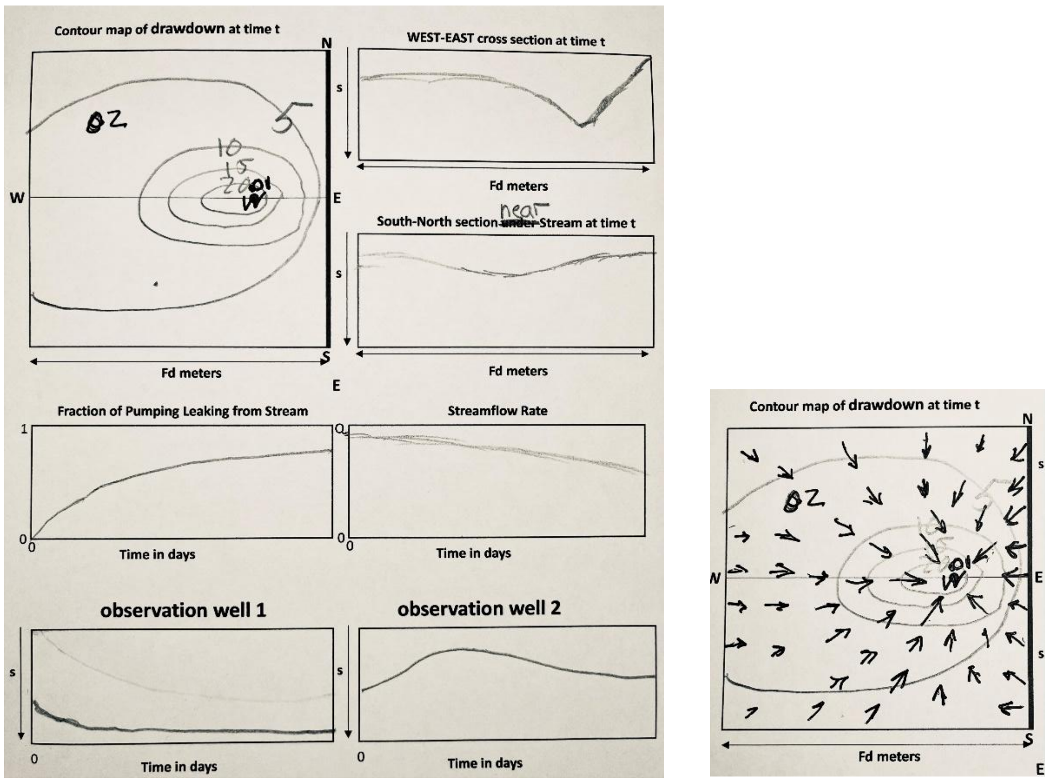
- My expectation is that we will work together throughout the semester so I can offer what I know to help you and I can learn along with you as you develop the tool
- If at any time, you have any suggestions for doing things differently that what I outline in this proposal, please bring it up and we will discuss it and change the plan if we decide the new way would be better
- The Groundwater Project is interested in contracting for development of additional tools

Example Input Image



Example Output Image

This is a rough hand sketch of how the output could look - Everything is approximate – inset on right illustrates vectors on contour map



You may want to use a color scale instead of contour lines. That would require a legend to indicate the value of the colors. I provide a rough idea of that using an MSExcel image here.

4.5	4.7	5.0	5.2	5.4	5.5	5.4	4.9	4.0	2.6	0.9	100
4.8	5.2	5.5	6.0	6.3	6.7	6.7	6.4	5.4	3.6	1.3	80
5.1	5.6	6.1	6.7	7.3	8.0	8.6	8.6	7.6	5.2	1.9	60
5.3	5.9	6.5	7.3	8.3	9.5	10.8	11.9	11.3	7.9	2.8	40
5.5	6.1	6.8	7.8	9.0	10.7	13.2	16.7	18.7	12.3	4.0	20
5.6	6.2	6.9	7.9	9.3	11.2	14.3	20.5		15.9	4.6	0
5.5	6.1	6.8	7.8	9.0	10.7	13.2	16.7	18.7	12.3	4.0	-20
5.3	5.9	6.5	7.3	8.3	9.5	10.8	11.9	11.3	7.9	2.8	-40
5.1	5.6	6.1	6.7	7.3	8.0	8.6	8.6	7.6	5.2	1.9	-60
4.8	5.2	5.5	6.0	6.3	6.7	6.7	6.4	5.4	3.6	1.3	-80
4.5	4.7	5.0	5.2	5.4	5.5	5.4	4.9	4.0	2.6	0.9	-100
-160	-140	-120	-100	-80	-60	-40	-20	0	20	40	

Examples of Interactive Tools

To help you understand what I mean by an interactive tool, you can visit this example of a high-level tool at tdpfonline.net. The TopoDrive tool is more complex than the tool I am requesting from the field session. There are written directions for how to use it in the header menu but you may prefer to view this video that explains what to do after clicking on Launch TopoDrive. On the other end of the spectrum is a much simpler tool called Water Table Recharge (WTR) https://interactive-education.gw-project.org/wtr/. A video showing how WTR is used is provided at that link. We also have an interactive tool about well capture https://gw-project.org/interactive-education/well-capture/ that is coded in Python and served by Streamlit and if you prefer to convert the previous team's tool from JavaScript to Python and Streamlit, that is fine with me. If you want to view them, the files for these existing tools are available in the zip file in a folder called "*InteractiveToolExamples*". You do not have to look at these but you are welcome to use them in any way that will help you complete the project.

You can view and try them out by retrieving the zip files from the folder in the zip file I provided, unzipping them on your computer, and double clicking on index.html.

- WTR.zip contains the Water Table Recharge (WTR) tool. It is a simple JavaScript code that I wrote recently while teaching myself to code in JavaScript. I welcome your advice on improving the code.
- TDPF.zip contains the Topodrive/ParticleFlow (TDPF) tool. It is a more complex code relying on the object-oriented programming features of JavaScript. This was created by a past Groundwater Project board member, Paul Hsieh, who moved on to other endeavors. It is public domain, housed on one of his websites and is referenced from the gw-project website as well as form a few Groundwater Project books.
- Well-Capture.zip contains the landing page that is on the gw-project.org site in the folder *well-capture* as well as the Python/Streamlit files from GitHub. The landing page points to the Streamlit app. The Python/Streamlit code I housed on GitHub.

Science Underlying the DFPS Tool

An aquifer is a layer of sediment or rock in the subsurface that transmits water in sufficient quantities to be of use to people as a water supply.

We drill holes in the ground and line them with plastic or steel pipe that has slots along the depth zone where the aquifer occurs so that when we lower a pump into the hole and begin to draw water via the pump, groundwater moves into the well through the slots, which lowers the water level in the aquifer causing water to move through the aquifer toward the well, which causes water further from the well to move toward the well, which in turn lowers the water level more. This creates what we call a cone of depression in the water levels around the well.

Groundwater moves toward the lower the water level in the well because, in a porous material, water flows at a rate directly proportional to the water level difference over distance (hydraulic gradient) and the area perpendicular to flow. It is described by Darcy's Law with the constant of proportionality being hydraulic conductivity. It is equivalent to the flow of electrical current that is described by Ohm's Law where the current flow is directly proportional to the voltage gradient and the area of the conductor. The constant of proportionality for current flow is electrical conductivity (the inverse of resistivity). There are many places to read about Darcy's Law – here is one: 4.1 Darcy's Law – Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow (gw-project.org).

The Theis equation describes the water level decline, s, at any distance, r, from a well that pumps at a constant rate, Q, at any time after pumping begins, t. It is assumed the pumping rate, Q, is constant and the aquifer is homogeneous and isotropic (i.e., has the same properties at all locations and the properties are the same regardless of the direction of flow. The properties are Transmissivity, T, and storativity, S. T is the product of hydraulic conductivity, K, and the thickness of the aquifer, b. Hydraulic conductivity describes the ease with which water moves through the aquifer and is analogous to the electrical conductivity of an object for the flow of current. Storativity describes the amount of water the aquifer can store for a given change in water level. It is equivalent to capacitance in an electrical circuit that describes the amount of charge that can be stored for a given voltage change. There are many places to read about the Theis equation, here is one: we do not have a webbook version for this book yet so I point you to Section 8.1 of the PDF that can be downloaded here: An Introduction to Hydraulic Testing in Hydrogeology | The Groundwater Project (gw-project.org).

The Theis equation is intended for use in confined aquifers but can be applied to unconfined aquifers as long as the drawdown is not too large relative to the aquifer thickness. You can view an animation of it in the first 1 minute and 7 seconds of this video: https://gw-project.org/videos/concept-testing-confined-and-leaky-confined-aquifers/.

A conceptual presentation of stream flow depletion due to pumping well is presented online in Section 5.1 "Streamflow Depletion" of the Groundwater Project book titled Groundwater Resource Development. A PDF of the book can be downloaded at this link: Groundwater Resource Development.

A stream that fully penetrates an aquifer will maintain the water level in the aquifer at the stream stage along its length provided there is sufficient water flowing in the stream that the pumpage does not lower its water level. To mathematically represent a fully penetrating stream we can superpose the Theis solution of a well injecting the same rate as the pumping well but at a perpendicular distance on the other side of the stream equal to the distance of the pumping well to the stream. Mathematically, this results in no change in water level at the stream because the lowering of the water level by withdrawing water is exactly equal to the raising of the water level by injecting water. However, the superposed values at every other location are different and their sum indicates the cone of depression around the well near to the stream. The gradient created by the difference in head between the stream and the aquifer determines the amount of water that leaks from the stream into the aquifer. Calculating stream depletion is discussed in: Jenkins, C.T., 1968, Techniques for computing rate and volume of stream depletion by wells. Ground Water, volume 6, number 2, pages 37–46. A pdf of that paper is in the zip folder with the following file name.

08_Groundwater-Journal-March1968-Jenkins-Techniques-for-Computing-Rate-and-Volume-of-Stream-Depletion-by-Wells.pdf.