



An Interactive Physical Three-Dimensional Water Table Model Teaching Tool

William W. Woessner, Beth A. Covitt,
and W. Payton Gardner

*An Interactive Physical
Three-Dimensional
Water Table Model
Teaching Tool*

The Groundwater Project

i

William W. Woessner

*Emeritus Regents' Professor of Hydrogeology
Department of Geosciences
University of Montana
Missoula, Montana USA*

Beth A. Covitt

*Head of Science Education Research & Evaluation
Broader Impacts Group
University of Montana
Missoula, Montana USA*

W. Payton Gardner

*Associate Professor of Hydrogeology
Department of Geosciences
University of Montana
Missoula, Montana USA*

An Interactive Physical Three-Dimensional Water Table Model Teaching Tool

*The Groundwater Project
Guelph, Ontario, Canada*

SUSTAINABLE INNOVATIVE RESOURCES MANAGEMENT



Smart solutions for using resources efficiently, protecting our planet, and securing a prosperous future.

SECTORS



WATER



ENVIRONMENT



MINING
INTEGRATED WATER SERVICES
LIFECYCLE



GREEN ENERGY



DIGITIZATION
AND AUTOMATION



COMPREHENSIVE
MONITORING SOLUTIONS



DISASTER MANAGEMENT
SYSTEMS CATEGORY

SERVICES



The Groundwater Project relies on private funding for book production and management of the Project.

Please consider sponsoring the Groundwater Project so that our books will continue to be freely available. <https://gw-project.org/donate/>[↗]

Thank you.

All rights reserved. This publication is protected by copyright. No part of this book may be reproduced in any form or by any means without permission in writing from the authors (to request permission contact: permissions@gw-project.org). Commercial distribution and reproduction are strictly prohibited.

GW-Project works can be downloaded for free from gw-project.org. Anyone may use and share gw-project.org links to download GW-Project's work. It is not permissible to make GW-Project documents available on other websites nor to send copies of the documents directly to others. Kindly honor this source of free knowledge that is benefiting you and all those who want to learn about groundwater.

Copyright © 2026 William W. Woessner, Beth A. Covitt, and W. Payton Gardner
(The Authors)

Published by the Groundwater Project, Guelph, Ontario, Canada, 2026.

An Interactive Physical Three-Dimensional Water Table Model Teaching Tool /
William W. Woessner, Beth A. Covitt, and W. Payton Gardner.

73 p.

DOI: <https://doi.org/10.62592/IAAQ9558>.

ISBN: 978-1-77470-145-4

Please consider signing up for the GW-Project mailing list to stay informed about new book releases, events, and ways to participate in the GW-Project. When you sign up for our email list, it helps us build a global groundwater community. [Sign up](#).

APA (7th ed.) Citation

Woessner, W. W., Covitt, B. A. & Gardner, W. P. (2026). *An Interactive Physical Three-Dimensional Water Table Model Teaching Tool*. The Groundwater Project. <https://doi.org/10.62592/IAAQ9558>.



Domain Editors: Eileen Poeter and John Cherry.

Board: Eileen Poeter, Shafick Adams, John Cherry, Gabriel Eckstein, Kenneth Goldstein, Richard Jackson, Ineke Kalwij, Renée Martin-Nagle, Abhijit Mukherjee, Everton de Oliveira, Marco Petitta, and Chunmiao Zheng.

Cover Image: The interactive physical three-dimensional water table model teaching tool set up in a parking lot with a blue line added to make the position of the yarn used to mark the water table more visible. William W. Woessner, 2024.

Table of Contents

TABLE OF CONTENTS.....	VI
THE GROUNDWATER PROJECT FOREWORD	VIII
FOREWORD	IX
PREFACE	X
ACKNOWLEDGMENTS.....	XI
1 INTRODUCTION	1
1.1 GOALS AND OBJECTIVES	2
1.2 ORGANIZATION OF MATERIALS	3
2 BASICS: GROUNDWATER, WATER TABLE, UNCONFINED AND CONFINED AQUIFERS, MONITORING WELLS, WATER LEVEL MEASUREMENTS, AND GROUNDWATER FLOW.....	5
2.1 GROUNDWATER.....	5
2.2 WATER TABLE AND UNCONFINED GROUNDWATER SYSTEMS	7
2.3 CONFINED GROUNDWATER SYSTEMS	8
2.4 TRANSMISSION PROPERTIES OF GEOLOGIC MATERIALS	9
2.5 MONITORING WELLS, WATER LEVEL MEASUREMENT, AND DEFINING HYDRAULIC HEAD	12
2.6 CONTOURING WATER TABLE ELEVATION (HEAD)	15
2.7 PLOTTING GROUNDWATER FLOW LINES	18
3 AN INTERACTIVE PHYSICAL THREE-DIMENSIONAL WATER TABLE MODEL TEACHING TOOL.....	20
3.1 SETTING UP THE MONITORING WELL NETWORK.....	20
3.2 MEASURING THE WATER LEVELS.....	21
3.3 ILLUSTRATING THE WATER TABLE	24
3.4 COMPUTING HYDRAULIC HEAD AND PLOTTING GROUNDWATER FLOW	25
3.5 COMPUTING GROUNDWATER DISCHARGE THROUGH A CROSS-SECTIONAL AREA AND AVERAGE GROUNDWATER VELOCITY WITHIN THE MODEL	27
3.6 SUMMARY	28
4 EXPANDING THE BASIC EXERCISE	29
4.1 EXPLORE A TWO-DIMENSIONAL REPRESENTATION OF GROUNDWATER FLOW.....	29
4.2 EXPLORE DEFINING THE SLOPE OF THE WATER TABLE USING A RIGID THREE-DIMENSIONAL SURFACE	30
4.3 EXPAND THE WELL NETWORK	32
4.4 ASSIGN A MEAN SEA LEVEL ELEVATION TO THE HORIZONTAL DATUM	33
4.5 VARY THE LENGTH OF MODEL WELL CASINGS.....	33
4.6 MEASURE WATER LEVELS WHEN CASING TOPS ARE NOT HORIZONTAL.....	34
4.7 DISPLAY A LAND SURFACE AND THE WATER TABLE CONFIGURATION	34
4.8 DEFINE MEASUREMENT ERRORS	35
4.9 DETERMINE UNCERTAINTY IN WATER LEVEL MEASUREMENTS	37
5 MODEL COMPONENTS	39
5.1 CONSTRUCTING THE CLEAR DEMONSTRATION WELL	39
5.2 CONSTRUCTING THE MONITORING WELL NETWORK	40
5.3 ARRANGING AND SUPPORTING THE MODEL MONITORING WELL NETWORK	41
5.4 MEASURING THE WATER VOLUME	43
5.5 MEASURING WATER LEVELS.....	44
5.6 MAPPING THE WATER TABLE	46
6 SUMMARY.....	48

7	EXERCISES	49
	EXERCISE 1 - COMPUTING AND INTERPRETING HEAD VALUES	49
	EXERCISE 2 - PLOTTING FLOWLINES AND COMPUTING DISCHARGE AND VELOCITY.....	49
	EXERCISE 3 - QUANTIFYING MEASUREMENT ERROR AND INSTRUMENT BIAS.....	50
8	REFERENCES	52
9	BOXES	54
	BOX 1 - INTERPOLATION OF WATER TABLE ELEVATION DATA	54
	<i>Basic Manual Linear Interpolation</i>	54
	<i>Automated Contouring Methods</i>	57
	BOX 2 - RECOGNIZING INSTRUMENT BIAS, DISPLACEMENT ERRORS IN MODEL WELLS, AND OPERATOR ERROR WHEN REPORTING WATER LEVELS	59
10	EXERCISE SOLUTIONS	63
	SOLUTION EXERCISE 1.....	63
	SOLUTION EXERCISE 2.....	64
	SOLUTION EXERCISE 3.....	66
11	NOTATIONS	69
	FUNDING ACKNOWLEDGMENT	70
12	ABOUT THE AUTHORS	71

The Groundwater Project Foreword

The 2022 United Nations (UN) World Water Day theme “*Groundwater – Making the Invisible Visible*” was pivotal in raising global awareness about groundwater as an invaluable resource, and the year concluded with the UN Water Summit on Groundwater at the UNESCO headquarters. One of the key outcomes of the Summit was a call for governments and other stakeholders to scale up their efforts to better manage groundwater.

Groundwater makes up 99% of all liquid fresh water on Earth, underpinning its importance in providing drinking water to the world, sustaining food production, and maintaining healthy ecosystems. Many important global organizations have concluded that there is a freshwater crisis and given that nearly all freshwater is groundwater, the freshwater crisis is a groundwater crisis. During droughts, in many locales groundwater is the only freshwater available, putting even more pressure on groundwater resources.

According to the World Health Organization and UNICEF ([WHO/UNICEF, 2025](#)), 2.1 billion people (1 in 4) live without safely managed drinking water and 3.4 billion people (4 in 10) live without safely managed sanitation. With groundwater directly supporting 8 of the 17 UN Sustainable Development Goals, groundwater is an invaluable resource. Safe and reliable access to groundwater directly supports the 2026 UN World Water Day (March 22) Theme “*Water and Gender Equality*” focusing on ensuring that women and girls have equal rights and leadership in water management.

The Groundwater Project (GW-Project), a registered Canadian charity founded in 2018, pioneers in advancing the understanding of groundwater by providing groundwater education to everyone. Recognizing that the world needs more highly skilled groundwater scientists to solve the water crisis, the GW-Project plays a pivotal role in creating the knowledge base for building the much-needed human capacity for the development and management of groundwater.

The GW-Project gained global recognition with publication of 64 original books, 94 translated books (in 59 languages), 7 interactive groundwater educational tools/modules, and over 50 high-quality educational videos, all made possible by a dedicated international group of over 1000 volunteer professionals from a broad range of disciplines throughout 70 countries on six continents. Academics, practitioners, and retirees contribute by writing and/or reviewing books aimed at diverse levels of readers including children, youth, undergraduate and graduate students, groundwater professionals, and the general public.

The GW-Project operates with the philosophy that high-quality groundwater education should be freely accessible for everyone, and to that end our publications are available free-of-charge on our [website](#). We thank our corporate sponsors and private donors for making this possible. Please consider sponsoring the GW-Project so we can continue to provide groundwater education free of charge.

The Groundwater Project Board of Directors, January 2026

Foreword

Experience in educating students to understand groundwater shows that most students have difficulty picturing groundwater systems in three-dimensional space. Many students have difficulty converting data collected below the land surface into mental pictures of the groundwater system. This spatial-thinking skill is the essence of understanding nearly all aspects of groundwater. Once acquired, it becomes second nature, and many of us who teach about groundwater, do not realize that the students are not understanding what we are trying to teach because the students do not have this essential spatial-thinking skill. Many of the students are not familiar with reading maps, making it even more difficult to extend their vision into the subsurface.

This book describes how to conduct an exercise that introduces students to the simplest form of three-dimensional thinking in groundwater science. This exercise is based on students seeing an array of monitoring wells and using the wells for water level measurements to understand water level maps. For the purposes of the exercise, the wells are not in the ground, they are above the ground. The wells are pieces of PVC pipe filled with water to various levels above the datum, which is a relatively flat surface of land such as a parking lot or the floor in a classroom.

At first glance this exercise can appear to be too simple to be useful, but experience shows that it is superbly effective as a starting point for developing the spatial-thinking skill that is the most essential skill needed for understanding groundwater. In fact, some students who graduate in hydrogeology have not mastered the full capability to think in three dimensions. This exercise goes beyond learning three-dimensional thinking to introduce concepts in measurement error, interpolation, and the use of student-measured data to interpolate flow directions and make basic groundwater flow calculations.

This book describes every detail needed for setting up the exercise and using the data. The three authors of this book are University of Montana faculty and personnel who teamed up to create this innovation in groundwater teaching. Dr. William Woessner is a distinguished professor emeritus in the Department of Geosciences where he conducted research and taught hydrogeology over three decades; Dr. Beth Covitt is Head of Science Education Research & Evaluation with University of Montana's Broader Impacts Group and prompted this effective simplification of groundwater education; and Dr. Payton Gardner is an associate professor in the Department of Geosciences where he does research and teaches hydrogeology courses. There are several other GW-Project books that introduce concepts of the most basic parameter in groundwater science, hydraulic head. A particularly useful companion to this book "*Conceptual and Visual Understanding of Hydraulic Head and Groundwater Flow*" by Cohen and Cherry (2020) advances visualization of hydraulic head in one and two dimensions.

John Cherry, The Groundwater Project Leader
Guelph, Ontario, Canada, January 2026

Preface

Groundwater science students are required to visualize and quantify processes hidden underground. Collecting data needed to decipher how groundwater occurs, moves, and transmits contaminants usually requires boring into the groundwater system, installing wells, and measuring conditions at multiple locations. Hydrogeologists regularly collect and interpret well-water-level data to determine the rate and direction of groundwater flow.

In a classroom setting, the process of measuring water levels and the science used to interpret groundwater flow directions are described and illustrated in two-dimensional drawings and pictures. It is the intention of this book to provide instructors with a physical, three-dimensional interactive model of a monitoring-well network that can be used to reinforce lecture material by having the students practice making physical well water level measurements, plotting the water table surface, and visualizing three-dimensional groundwater flow directions.

The PVC (polyvinyl chloride) tube-based instructional tool presented in this book is easy to assemble and install in a classroom setting. The application of the model is discussed in addition to relative costs of components. The model has been used as a standard component of a university groundwater curriculum, a high-school-level groundwater learning module, and is well-suited for use in continuing education and community outreach settings promoting groundwater education.

Acknowledgments

We deeply appreciate the thorough and useful reviews of and contributions to this book by the following individuals:

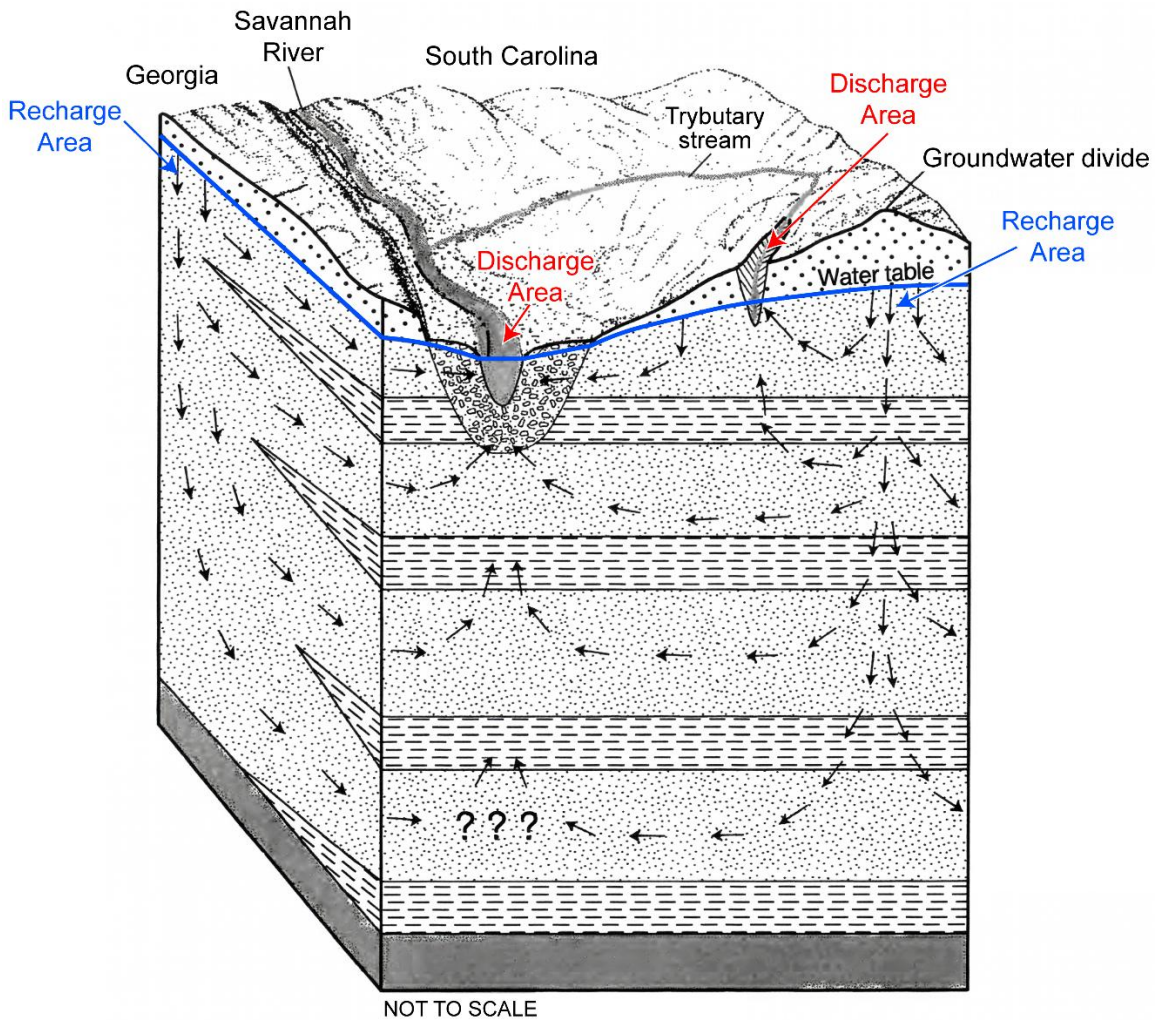
- ❖ Laura Toran, Professor, Temple University, Department of Earth and Environmental Science, Philadelphia, Pennsylvania, USA;
- ❖ John Sharp, Jr., Dave P. Carlton Centennial Professor Emeritus in Geology, Department of Earth and Planetary Sciences, Jackson School of Geosciences, University of Texas, Austin Texas, USA;
- ❖ Dr. Mathew Uliana, INTERA Geosciences Pty Ltd, Australia;
- ❖ Marty Frisbee, Associate Professor, Purdue University, Department of Earth, Atmospheric and Planetary Sciences, West Lafayette, Indiana, USA.

We appreciate the contributions of all the reviewers and would like to extend special thanks to Professor Laura Toran, as her review was particularly extensive and insightful. We are grateful to Amanda Sills and the Formatting Team of the Groundwater Project for their oversight and copyediting of this book. We thank Claire Tiedeman (Scientist Emeritus, US Geological Survey, USA) and Eileen Poeter (Colorado School of Mines, Golden, Colorado, USA) for reviewing, editing, and producing this book.






The sources of figures and/or tables are cited in their captions. Where a citation does not appear, the figures and/or tables are original to this book.

1 Introduction

Groundwater scientists (hydrogeologists) are tasked with exploring groundwater systems, often using sparse one- or two-dimensional data sets to construct three-dimensional conceptual models of the geological framework, distribution of groundwater, directions and rates of groundwater flow, and pathways of contaminants (Figure 1).



EXPLANATION

AQUIFER			ALLUVIUM
	Unsaturated zone		CONFINING UNIT
	Saturated zone		BASEMENT ROCK

→ DIRECTION OF GROUNDWATER FLOW—Queried where unknown

Figure 1 - Conceptual model of the water table (blue line) and groundwater flow systems in the vicinity of Savannah River Site, Georgia and South Carolina, USA. Recharge areas (blue lettering) are where water enters the groundwater system and generally flows vertically downward. Discharge areas (red lettering) are where groundwater flow is mostly vertically upward (modified from Clarke & West, 1998).

Wells provide windows into the underlying groundwater system. Hydrogeologists use networks of wells to measure groundwater-level elevations and interpret groundwater flow directions, determine geologic boundaries and properties, sample the spatial distribution of groundwater constituents, and calculate rates of groundwater movement. Groundwater flow is often shown in map or cross-section views (Figure 2).

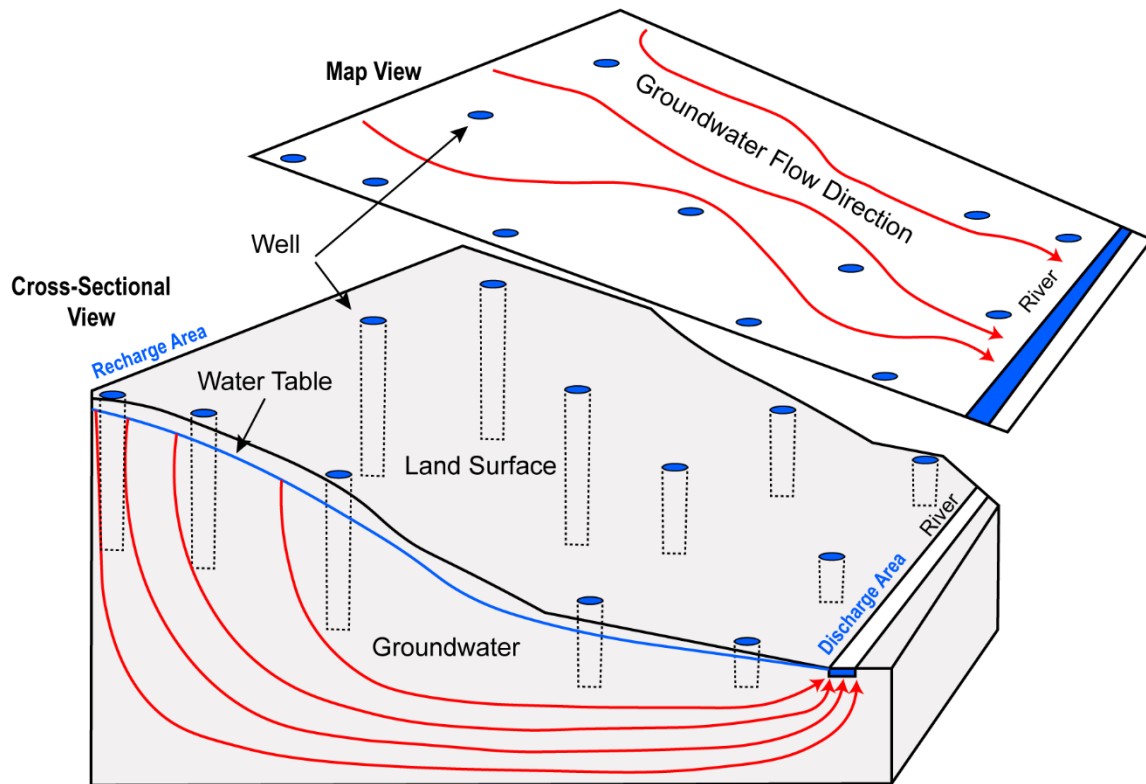


Figure 2 - Schematic of a monitoring well network used to determine the water-table elevation within a shallow groundwater system. Two-dimensional map and cross-sectional views of the interpreted groundwater flow path (red arrows) are indicated. The cross section shows water flowing from the recharge area into the system (downward) and then upward in the discharge area. Flow in a portion of the system is mostly horizontal.

The water level elevations measured in wells underpin interpretation of groundwater flow rates and directions.

1.1 Goals and Objectives

This book provides groundwater educators with a simple, low-cost, three-dimensional, physical model of a water table that is used to teach students how to make measurements of the water table position in a zone of horizontal flow, compute associated hydraulic heads, and map groundwater flow directions. The exercises associated with the model reinforce key groundwater principles.

The instructional, physical model of a water table can be easily incorporated into a groundwater curriculum. It provides a physical representation of the water table surface and resulting groundwater flow direction. In a groundwater course, it is best to present these concepts before students are introduced to the model. Two of the authors regularly

use this tool in a college hydrogeology class to reinforce lecture material (Figure 3). It also fits well in hydrogeology laboratory exercises and field camps.



Figure 3 - Setup of a model monitoring well network (white numbered PVC pipes) in a classroom. Groups of students are determining water levels in wells and mapping the water table surface relative to ground surface elevation provided for each pipe. After examining the shape of the water table, the groundwater flow direction is visualized.

The model has also been used as part of a groundwater learning experience with high school students (Covitt et al., 2018). Most recently, it was included as a modeling tool in an NSF-funded science education research project that examined how incorporating computational models supports STEM learning (Covitt et al., 2023). In addition to college and high school classroom use, the model is also appropriate for public workshops on groundwater basics, science-center demonstrations and exhibits, and community continuing education experiences.

This book provides details on the model application as well as the construction of the physical model and the estimated cost of constructing the model.

1.2 Organization of Materials

Section 2 provides a review of basic groundwater terms and principles governing groundwater flow. If readers are familiar with, regularly teach, or practice groundwater science, Section 2 can be skipped. Those not as familiar with groundwater are introduced to the basic concepts and principles governing groundwater occurrence and methods to determine flow directions. Links to videos that augment the text are referenced. For

additional context and detail, the reader is directed to a number of Groundwater Project books, which are free and downloadable, including: *Groundwater in Our Water Cycle: Getting to Know Earth's Most Important Freshwater Source* (Poeter et al., 2020); *Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow* (Woessner & Poeter, 2020); *Using Groundwater Head Maps* (Toran, 2025); *Basic Hydrogeology: An Introduction to the Fundamentals of Groundwater Science* (Uliana, 2025); *A Glossary of Hydrogeology* (Sharp, 2024); *Conceptual and Visual Understanding of Hydraulic Head and Groundwater Flow* (Cohen & Cherry, 2023); and *Groundwater Velocity* (Devlin, 2020). Additional books on a wide variety of groundwater subjects are available at gw-project.org.

Section 3 describes use of the model to support teaching of basic groundwater concepts. Section 4 presents options for expanding the basic exercise in Section 3. Section 5 provides information needed to construct and operate the model, including the estimated cost of materials. Section 6 summarizes the book. Section 7 contains exercises, Section 8 provides cited references, Section 9 contains Boxes referred to in the text, and Section 10 provides solutions to the exercises of Section 7.

2 Basics: Groundwater, Water Table, Unconfined and Confined Aquifers, Monitoring Wells, Water Level Measurements, and Groundwater Flow

Teaching with the three-dimensional, physical, groundwater model requires familiarity with basic groundwater principles. To help readers of this book acquire basic knowledge about groundwater prior to learning about the physical model, this chapter begins by defining groundwater. Next, the water table is described and the relationship of the water table to unconfined groundwater systems and aquifers is presented. Then, confined groundwater systems are introduced. The application of monitoring well networks to define the water table, including methods to measure water levels in wells, follows. Principles governing how the direction of groundwater flow is determined are described, and controls on the rate of flow are presented to finish the section. The teaching tool described in Section 3 represents a simple water table groundwater system; thus, this chapter emphasizes the water table and unconfined groundwater flow.

2.1 Groundwater

Groundwater is water that occurs below the ground surface in zones of porous or fractured materials where all the pore spaces or cracks (fractures) are filled with water, and that water has a higher pressure than the atmosphere (Figure 4).

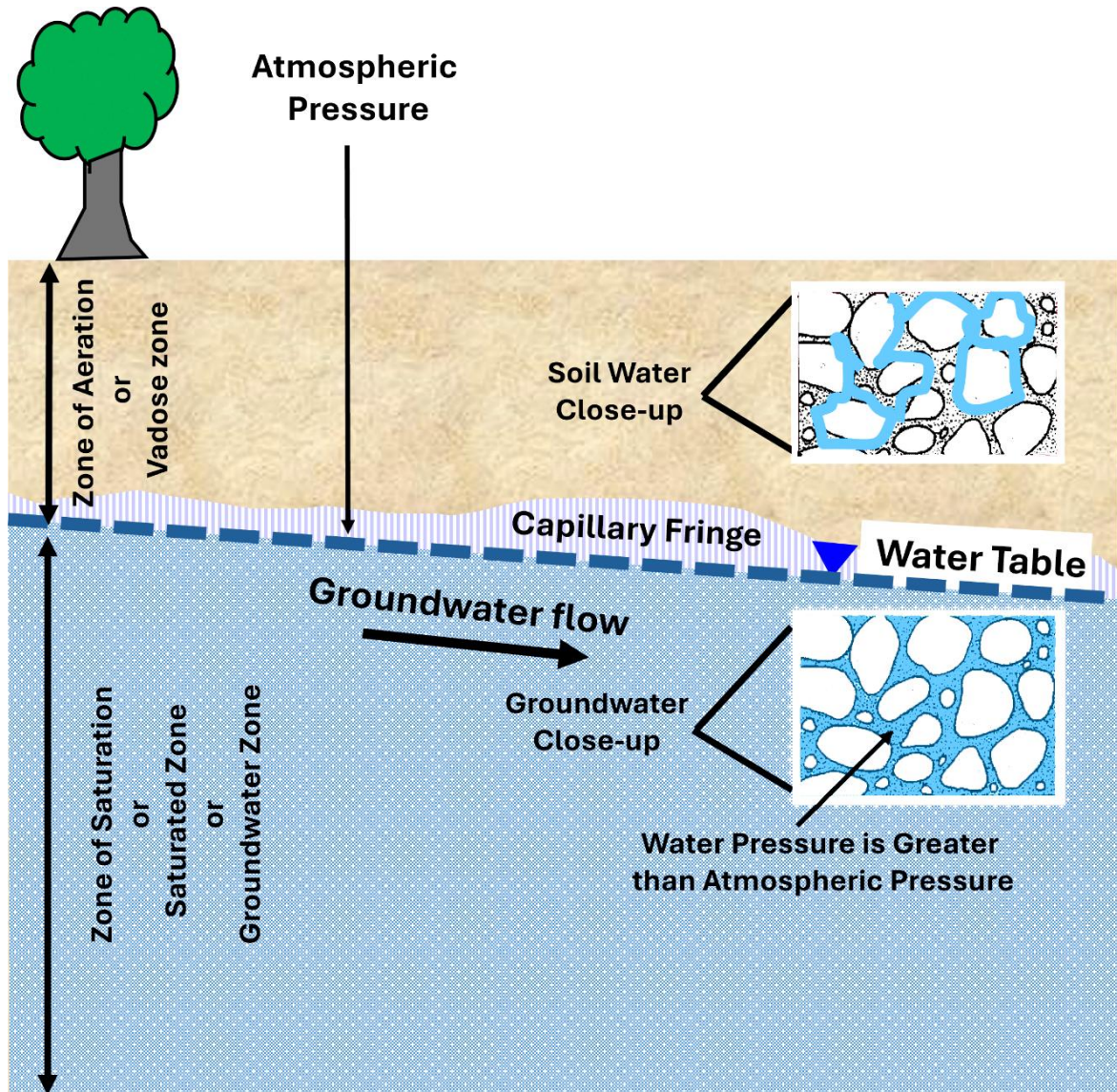




Figure 4 - Schematic of shallow water zones in the subsurface, including the Saturated Zone (blue stippled area) below the water table (heavy dashed blue line with inverted blue triangle), and the Vadose Zone (light tan) including the capillary fringe above the water table. In the close-up of soil water, the blue color represents water. Groundwater is defined as the water that occurs in the Zone of Saturation, with a pressure greater than atmospheric pressure. Groundwater moves from areas of high-water table elevation to lower water table elevation (adapted from Woessner & Poeter, 2020).

The region or zone where groundwater is found is referred to by a number of terms including the zone of saturation, saturated zone, zone of phreatic water, or groundwater zone. The upper surface of the groundwater system, occurring closest to the land surface, is defined by the water table. Above the water table is the zone of aeration, also called vadose zone or unsaturated zone. This includes the capillary fringe and water in partially filled soil pore spaces. In the vadose zone, including the zone where water above the water table is held by capillary forces (capillary fringe), water pressure is less than atmospheric pressure. Here, water is held against the force of gravity by surface tension to fractures and pore surfaces.

Below the water table, the water pressure is greater than atmospheric pressure, and groundwater can flow from areas of high–water-table elevation to areas of low–water-table elevation. Some literature refers to all water below the land surface as groundwater. However, in scientific literature, groundwater is defined as only the water occurring in the saturated zone. A video titled, [What is groundwater?](#)  posted by Northern California Public Media (2018) provides additional details.

2.2 Water Table and Unconfined Groundwater Systems

The first groundwater encountered below the surface is defined as an unconfined groundwater system. The upper surface is a water table (Figure 5). The system is overlain by rock or sediment that allows water originating from the surface to freely infiltrate to the water table. Unconfined groundwater systems receive recharge from rainfall and/or melting snow; they are not overlain by a lower permeability unit that restricts the movement of water to the system. Unconfined systems are also referred to as water table systems. When saturated materials are extensive, easily conduct water (i.e., are permeable), and yield that water economically to wells, the system is referred to as an *aquifer* (Woessner & Poeter, 2020) (Figure 5). A video [What is an Aquifer?](#)  provides additional detail on aquifer types and systems (McConnell & Dixon, 2016).

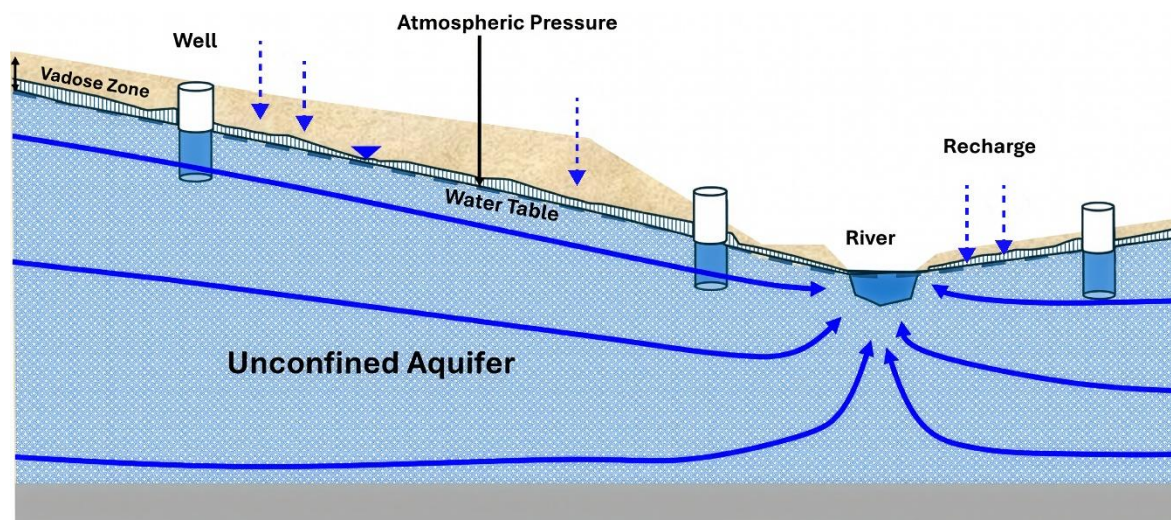


Figure 5 - Schematic of an unconfined aquifer. The upper surface is the water table (dashed blue line) and the bottom boundary is typically a less permeable unit (gray bar). Water levels in wells penetrating to depths just below the water table are shown. Recharge occurs to the water table from infiltration at the land surface (blue dashed arrows). The long solid blue arrows show general groundwater flow directions. In this example, groundwater is discharging to the river (adapted from Woessner & Poeter, 2020).

When the water table is penetrated by a shallow well, groundwater will fill the well to the height of the water table (Figure 5). Unconfined groundwater systems that meet the definition of being an aquifer are referred to as unconfined aquifers. In settings where groundwater movement is slow and only small amounts of water are derived from wells

such that the aquifer definition does not fit; groundwater conditions are commonly described as unconfined systems, not unconfined aquifers.

2.3 Confined Groundwater Systems

As illustrated in Figure 6, unconfined groundwater systems and aquifers are the first occurrence of groundwater encountered below the land surface. Groundwater in deeper systems is often confined by geologic material of lower permeability (generally referred to as confining units) that limits the movement of groundwater into or out of a confined groundwater system.

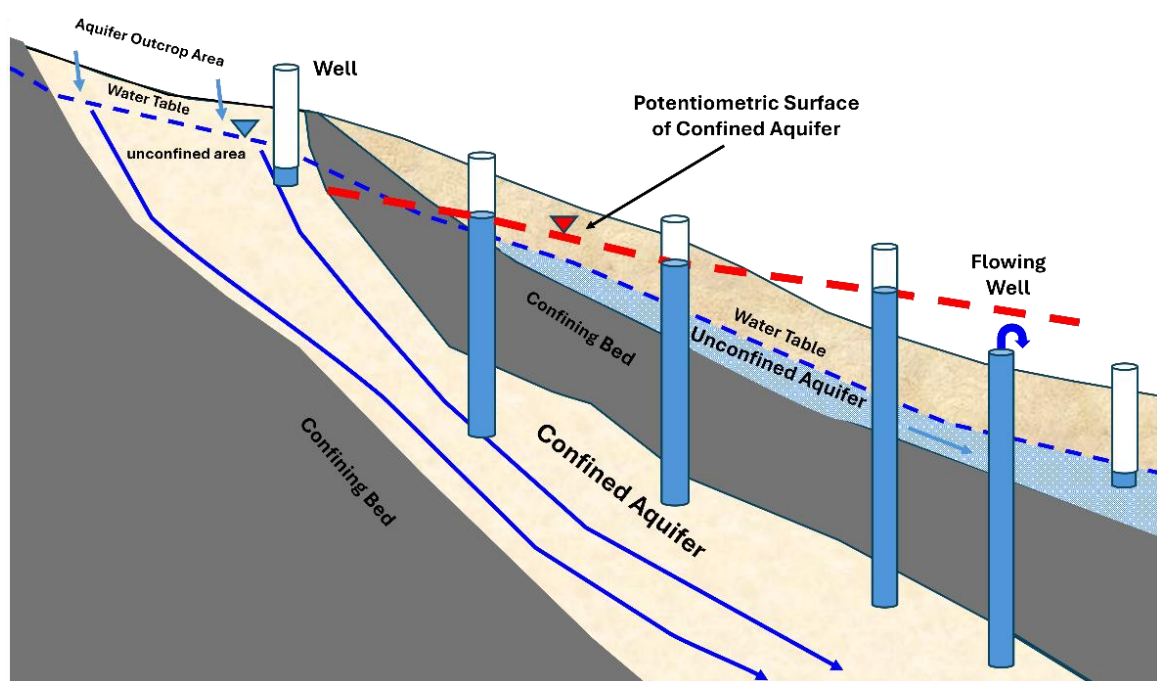



Figure 6 - Schematic of multiple aquifer systems composed of an unconfined and confined groundwater system. The unconfined aquifers are indicated by the presence of a water table at their upper surface. In this illustration, recharge (light blue arrows) enters an unconfined area where the confined system outcrops. As water moves deeper into the geologic setting, flow becomes constrained by the presence of less permeable materials labeled here as confining beds. The presence of these constraints forces flow mostly parallel to the overlying and underlying confining units. Blue arrows in the confined and unconfined aquifers indicate the general direction of groundwater flow. The water levels in tightly cased wells penetrating the confined aquifer can rise above the top of the confined aquifer (base of the overlying confining unit). The surface representing the elevation of water in these wells is referred to as the potentiometric surface of the confined system or aquifer (dashed red line) (adapted from Woessner & Poeter, 2020).

Water in wells penetrating confined systems rises above the base of the overlying confining unit. These confining layers often allow some groundwater flow between aquifers depending on their capacity to transmit water. When a confining unit allows some leakage, it is referred to as an aquitard (retards movement of water). A unit with a much smaller amount of leakage is referred to as an aquiclude (generally precludes movement of water).

The elevation to which water rises in wells penetrating a confined aquifer is referred to as the potentiometric surface (Figure 6). Confined aquifers do not have water tables.

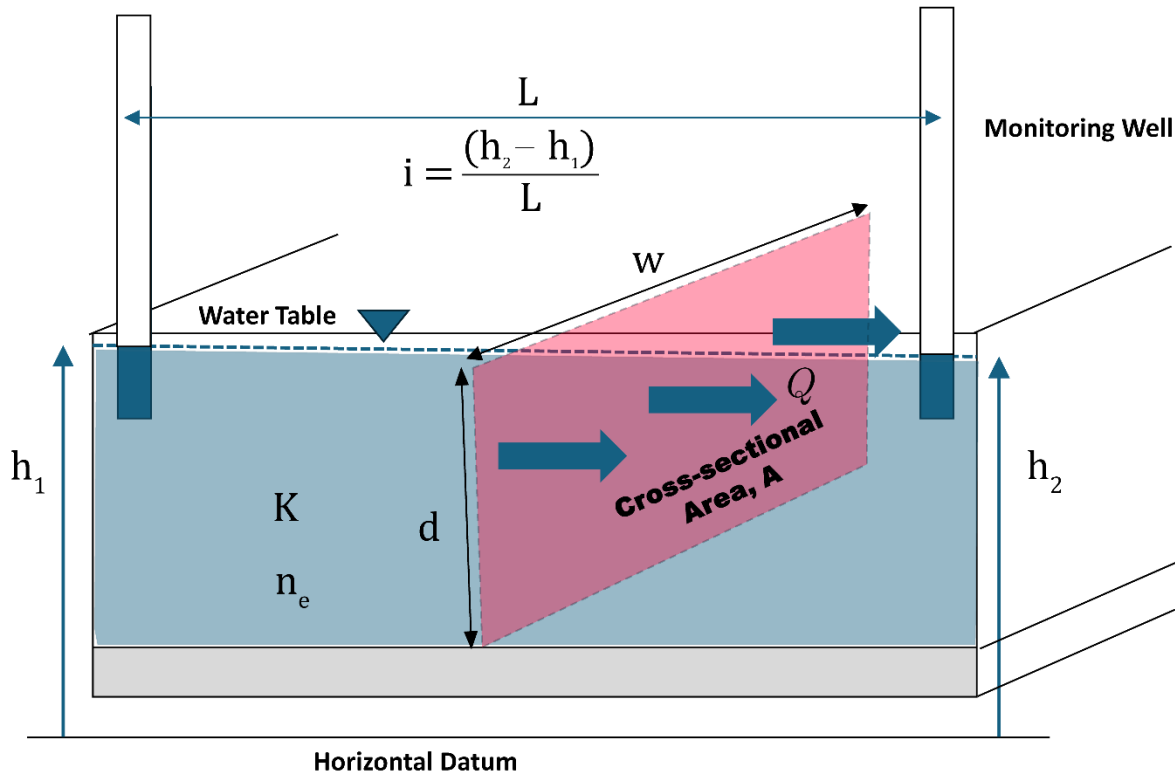
Confined aquifer wells will flow at the land surface without pumping if the potentiometric surface is higher than the top of the well casing. This is illustrated with the “flowing well” shown toward the right side of Figure 6. Confined aquifers can be overlain and underlain by other confined aquifers depending on the geologic setting. These systems can be recharged at outcrop areas and/or via leakage from overlying and underlying aquifers through aquitards. Discharge occurs as water flows to regional water bodies, overlying aquifers, or pumping wells.

Additional information on confined aquifers is available in the video, *What is an aquifer?*  (McConnell & Dixon, 2016), and in the free Groundwater Project books mentioned in the beginning of this section.

2.4 Transmission Properties of Geologic Materials

The transmission capacity of a geologic material is described by a material’s hydraulic conductivity, K . In general terms, hydraulic conductivity can be defined as the relative ease of water passage through a porous material. The term includes influences of the structural setting, type of geologic materials, and properties of the fluid (water) being transported. Standard characterization methods (Woessner & Poeter, 2020; Woessner et al., 2023) can be used to determine the magnitude of transmission capacity for geologic materials. Generally, materials with small pore spaces that are poorly interconnected have low values of hydraulic conductivity (e.g., a silty clay). In contrast, a clean sand and gravel deposit with large pore spaces that are well connected have a large hydraulic conductivity. Large values of hydraulic conductivity represent a high capacity to transmit groundwater. When field- or laboratory-derived values are not available, it is possible to refer to tables of typical values for geologic materials (e.g., Woessner & Poeter, 2020). Hydraulic conductivity for a material such as sand can vary by orders of magnitude depending on sand size and the portion of finer-than-sand-sized material mixed with the sand. Determination of characteristics using a sample of the groundwater system material in a laboratory or testing in the field is preferred over selecting values from a table (e.g., Woessner & Poeter, 2020; Woessner et al., 2023).

Values of hydraulic conductivity along with the slope of the water table are required to compute groundwater discharge (Q) in an unconfined system. Discharge is the volume of groundwater per unit of time that passes through a cross-sectional area (A) located at a right angle to the direction of the water table slope, or hydraulic gradient (i) (Figure 7). The hydraulic gradient for a water table is calculated from water elevations in wells located along a groundwater flow line as the difference in a pair of water elevations divided by the distance between them (Figure 7).



$$A = dw$$

$$Q = -KiA$$

$$v = \frac{Q}{An_e} = -\frac{Ki}{n_e}$$

Figure 7 - Schematic of an unconfined system (shaded blue) showing the water table (dashed blue line and inverted blue triangle) between two monitoring wells located along the direction of groundwater flow. The elevations of the water levels in the wells (h_1 and h_2 , blue vertical arrows) are measured from a horizontal datum, often sea level. The hydraulic gradient or water table slope is computed as i . A less permeable material (e.g., aquitard) underlies the unconfined system (gray shading). In this setting, the representative hydraulic conductivity is K and the effective porosity is n_e . The shaded red plane represents a cross-sectional area ($A = dw$) of the groundwater system located at a right angle to the flow. Monitoring wells are open to the groundwater and water has moved into the wells (dark blue section). The slope of the water table (i) is negative (i.e., it is higher on the left than the right). Equations for estimating the discharge (Q) passing through a cross section of the unconfined system and computing average velocity (v) are shown below the diagram.

The equations shown in Figure 7 are expressed below followed by definitions of all terms. The discharge relationship shown in (1) is referred to as Darcy's Law. The negative sign is specified because positive groundwater flow is always in the direction of the negative water table gradient or slope, from high groundwater elevation to low groundwater elevation. Calculating the hydraulic gradient (2) by subtracting the water level at high elevation from that at low elevation produces a negative value, yielding a positive value of Q in (1). The cross-sectional area term of Darcy's Law is calculated using (3). To estimate groundwater velocity (4), the effective porosity (n_e) is required. Effective porosity is a measure of the total volume of interconnected pore space in a sample of geologic material divided by the total sample volume of aquifer material. The effective

porosity is determined using laboratory methods or estimated from tables of values for varying types of geologic materials (e.g., Woessner & Poeter, 2020).

$$Q = -KiA \quad (1)$$

$$i = \frac{(h_2 - h_1)}{L} \quad (2)$$

$$A = dw \quad (3)$$

$$v = -\frac{Ki}{n_e} \text{ or } v = \frac{Q}{An_e} \quad (4)$$

where:

- Q = discharge (L^3T^{-1})
- K = hydraulic conductivity (LT^{-1})
- i = hydraulic gradient (dimensionless)
- h_1 = head at a higher elevation (L)
- h_2 = head at a lower elevation (L)
- L = distance between h_1 and h_2 (L)
- A = vertical cross-sectional area (L^2)
- d = cross-sectional depth (L)
- w = cross-sectional total width (L)
- v = average groundwater velocity (LT^{-1})
- n_e = effective porosity (dimensionless)

For example, using Figure 7 above, if $h_1 = 125$ m, $h_2 = 123$ m and $L = 1000$ m, the hydraulic gradient would be: $i = (123 \text{ m} - 125 \text{ m}) / 1000 \text{ m} = -0.002$. If $K = 50$ m/d, the discharge through a cross section that is 90 m (d) by 200 m (w) would be as follows.

$$Q = -50 \frac{\text{m}}{\text{d}} (-0.002) ((90 \text{ m})(200 \text{ m})) = 1,800 \frac{\text{m}^3}{\text{d}}$$

A groundwater velocity could also be computed assuming an effective porosity of 0.19.

$$v = \frac{1,800 \frac{\text{m}^3}{\text{d}}}{(90 \text{ m})(200 \text{ m})(0.19)} = 0.53 \frac{\text{m}}{\text{d}}$$

In this book, it will be assumed that groundwater discharge and velocity are estimated using conditions illustrated in Figure 7. Additional methods used to quantify discharge in an unconfined aquifer are presented in several groundwater project books (e.g., Woessner & Poeter, 2020).

In some settings, hydraulic conductivity may vary depending on which direction groundwater is flowing in porous media (preferential interconnectedness), or because

different geologic materials are present at different locations within a study site. Without delving too deeply into how the directional and spatial properties of the hydraulic conductivity affect groundwater flow directions, it will be assumed for the figures and physical model presented in this book that the values of hydraulic conductivity within the model area are uniform and constant. This condition is described as the hydraulic conductivity being *homogeneous* and *isotropic*. When this is the case, a single hydraulic conductivity value is used to represent groundwater transmission properties at the site or within the model. Additional information on how variations in hydraulic conductivity influence groundwater flow directions is discussed in Woessner and Poeter (2020). Further information on calculating and observing groundwater velocities is available in The Groundwater Project book [Groundwater Velocity](#) by Devlin (2020).

2.5 Monitoring Wells, Water Level Measurement, and Defining Hydraulic Head

Groundwater scientists access the groundwater system by drilling boreholes and constructing wells to measure water levels. When groundwater is unconfined and connected to surface streams, the stream elevation is also monitored and recorded at designated locations. The type of geologic material returned to the surface during drilling, the depths at which groundwater is encountered, and the final water level in a completed well are important observations used to characterize the physical and hydrological system. In addition, if a sample of water is collected, the local groundwater quality can be established.

Groundwater scientists establish a multi-well monitoring network for a study area (Figure 8a). Drillers' well logs and databases containing well records are useful when incorporating existing wells into a monitoring well network. Further information on using well databases is provided by Kennedy (2022). Toran (2025) discusses how differences in well construction, such as the length of well screen or open zones, impact water level data. When existing wells are sparse, specially constructed monitoring wells are often installed to better define site conditions (Figure 8b).

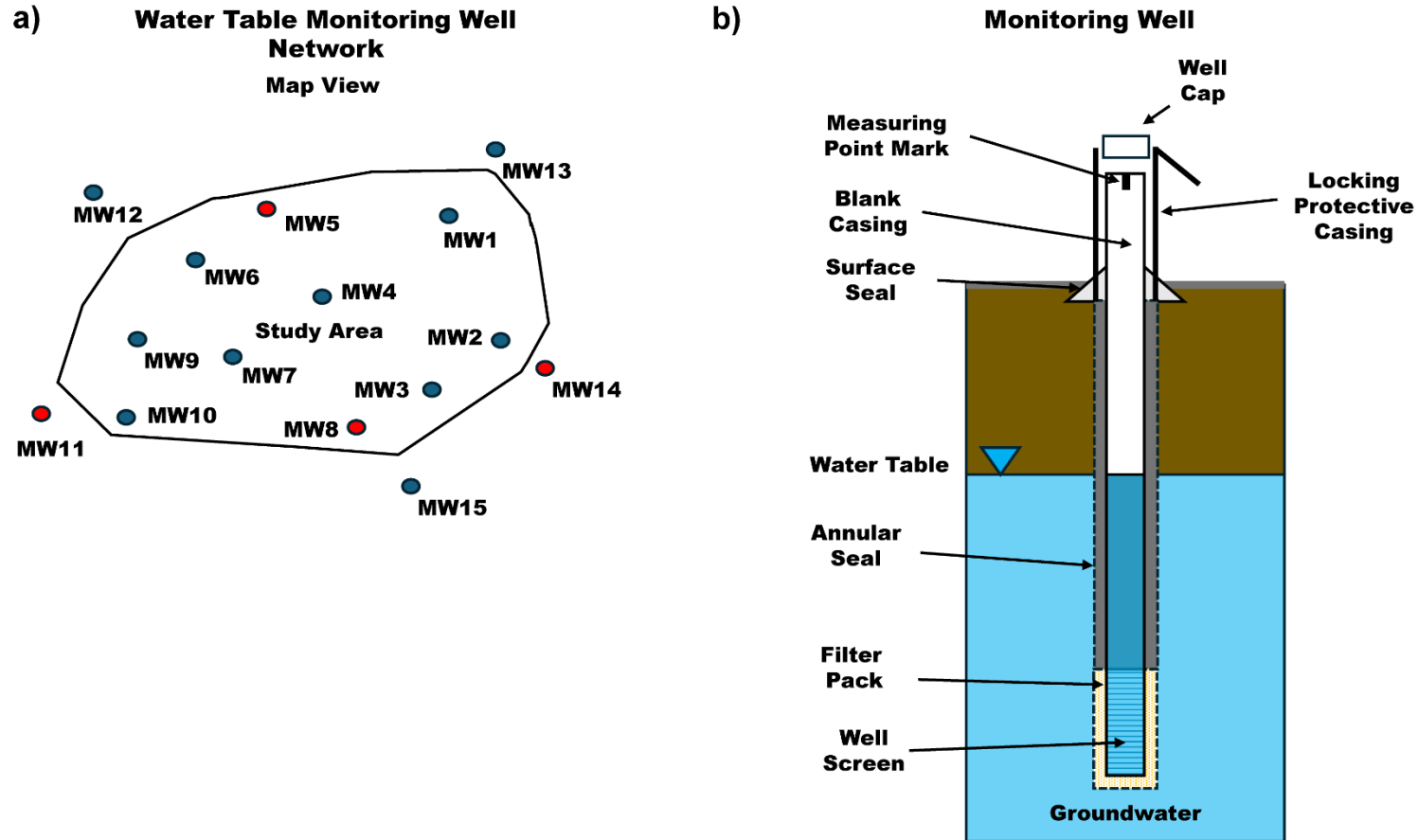


Figure 8 - Map view of a monitoring well network and cross-sectional view of the components of a monitoring well. a) A study area (black outline) in which new monitoring wells (blue dots, e.g., MW1) have been installed to expand the network defined by existing wells (red dots, e.g., MW8). Well locations were chosen to provide information within the site and slightly beyond the site boundaries. b) Cross section of a typical groundwater monitoring well design. Well diameters vary, many use 5.1 cm (2 in) diameter casing with a perforated interval (well screen) at the bottom. The well casing and screen are placed in a drilled borehole (dashed outline). A permeable filter pack, often sand (yellow), is placed around the screen and the remainder of the borehole is sealed with a low permeability material such as bentonite clay or concrete. Where the casing passes through the surface additional material is used as a seal to prevent surface water from entering the well. The well is finished by installing a protective casing and a locking cap. The top of the monitoring well casing is marked indicating a measuring point for collecting water level data. That point is then surveyed to a common horizontal elevation datum, most often sea level.

Water level measurements are collected at each monitoring well to define groundwater conditions at the site. Measurements are reported as the elevation of the water level above a horizontal datum such as sea level. To determine the water level, the distance from the established surveyed measuring point at the top of the monitoring well to the groundwater level is measured (Figure 9a). This designated measuring point is assigned an elevation by surveying its elevation relative to a horizontal datum. The calculation of the water level elevation is described in Figure 9.

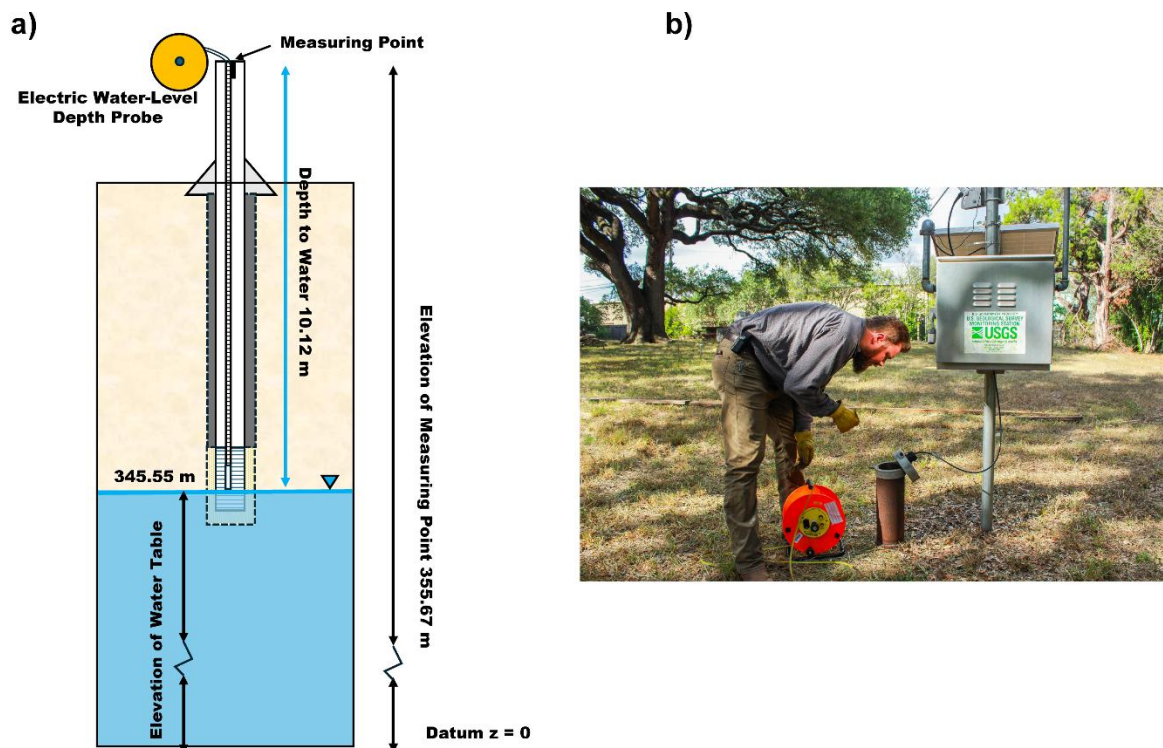


Figure 9 - Measuring the water level in a monitoring well and determining the water table elevation (referred to as the hydraulic head, total head, or head in a groundwater system). a) The water level depth below the measuring point (black mark on the top of the casing) is determined. The total head, in this example 345.55 m, is derived by subtracting the depth to water (10.12 m) from the measuring point elevation (355.67 m). b) Using an electronic water-level-depth probe to locate the depth to water (Hlavaty, 2023). Once the probe sensor indicates contact with water, the meter tape is kept taut with one hand and then using the thumb and forefinger of the other hand, the tape is grabbed at the measuring point and a depth to water reading is taken.

Several different tools can be used to measure the water level in a monitoring well. These include a chalked steel tape, a transducer, an electric water level tape, and an acoustic sounder. Woessner & Poeter (2020) and Toran (2025) describe measuring tools. Two informative videos, one titled [Where is the Water Table?](#) (McConnell et al., 2016) and a second titled [Measuring Groundwater with Electric Tape](#) (USGS, 2015) show how water levels are measured using an electric water level meter, also called a sounder, as shown in Figure 9b. Once a measurement of the depth to water in the well is made in an unconfined system, the water table position is reported as an elevation by subtracting the depth to water in the well from the surveyed elevation of the measuring point (Figure 9a).

Hydrogeologists refer to the water level elevation in a monitoring well as the hydraulic head, total head, or head.

The elevation of the water level in the well (head) represents the energy of the groundwater at the location sampled. Groundwater flows from areas of high head to low head. As shown in Section 2.4, when measured along a flow line, the difference in head divided by the measured linear distance between the head measuring points is the groundwater gradient, also called the hydraulic gradient (Figure 7). Toran (2025) and Woessner & Poeter (2020) provide discussions of head measurements and how they are used to make maps of groundwater systems, interpret flow directions, and compute flows and velocities.

2.6 Contouring Water Table Elevation (Head)

When producing maps or cross sections showing groundwater flow directions, the first step is to carefully assess if each well in the well network represents conditions in the aquifer being evaluated. A review of the well depths, construction data, and geologic setting is needed. If some wells are found to penetrate multiple groundwater systems (e.g., both unconfined and confined), head values in these wells will not reflect conditions of the unconfined aquifer. If defining flow in an unconfined system is a goal, only wells penetrating that system are selected for inclusion in the network (Toran, 2025) (Figure 10). An additional complicating factor in unconfined systems is that monitoring wells completed to different depths in a recharge area (vertical flow downward) or discharge area (vertical flow upward) may not represent the elevation of the water table, instead reflecting head values deeper in the water table system. Ideally, for defining the position of the water table, wells that are completed below but close to the water table position provide the most representative data for mapping the water table. When water flow in an unconfined system is mostly horizontal, wells finished at deeper depths in the unconfined system are also representative of the water table elevation (Figure 10). Head data are collected from a representative set of wells during a short time period (e.g., 1 day) and used to construct groundwater flow maps.

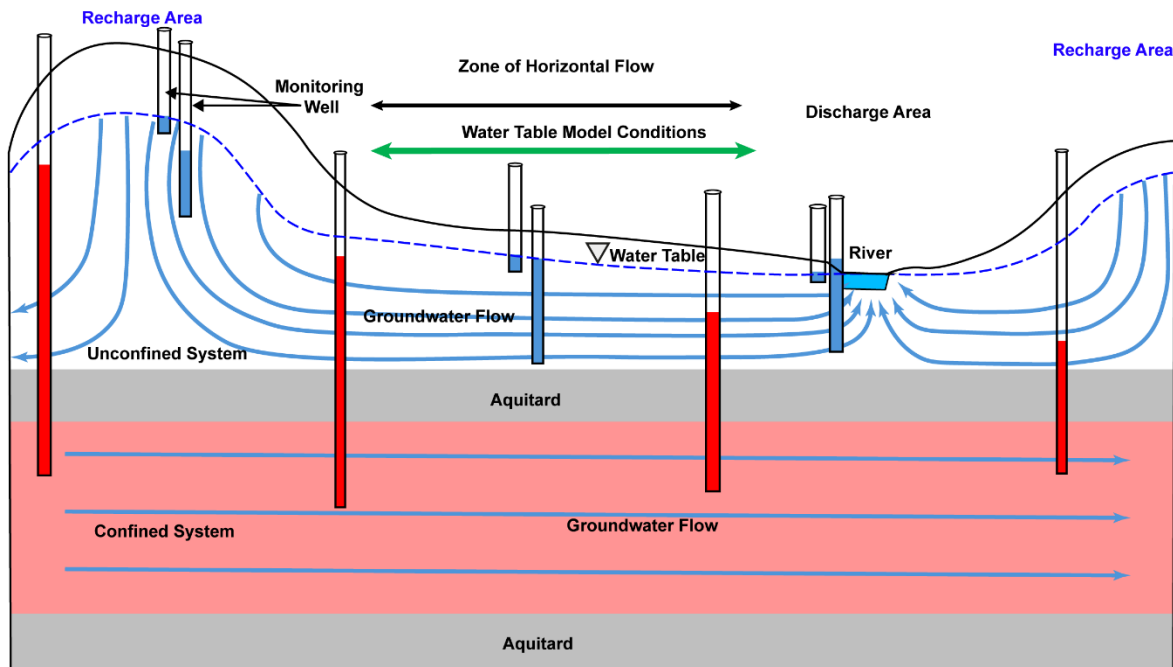


Figure 10 - Schematic cross-section of an unconfined and confined system showing water levels in monitoring wells. Monitoring wells are open at the bottom and the height to which water rises at a well location is indicated by the blue (unconfined system) and red (confined system) cylinders. Groundwater flow paths are shown as blue arrows. In the unconfined system, groundwater flows from recharge areas to a river in a discharge area. Wells completed slightly below the water table reflect the position of the water table. If monitoring wells are drilled deeper into the unconfined groundwater system at the same location of wells finished at the water table, water levels are affected by flow conditions. Water levels in deeper wells in a recharge area are lower than the water table. Water levels in deeper wells in a discharge area are higher than the water table. The green double arrow indicates conditions assumed when monitoring water levels in the physical three-dimensional water table model described in this book. The water levels in wells penetrating the underlying confined system do not represent the water table. If these wells are included in a monitoring well network used to represent the water table system, the interpreted flow directions would not be correct. These data must be eliminated from the water table system evaluation.

When evaluating the direction of groundwater flow, the first step is to plot the head data from monitoring wells penetrating the same groundwater system on a map or cross section. A two-dimensional map view of the configuration of the water table is created by interpolating contours of equal head (water level elevation) as shown in Figure 11a (Toran, 2025; Woessner & Poeter, 2020). Contours of equal head are referred to as equipotential lines and are usually drawn using a constant contour interval (e.g., an interval of 5 m in Figure 11a and 10 m in Figure 11b).

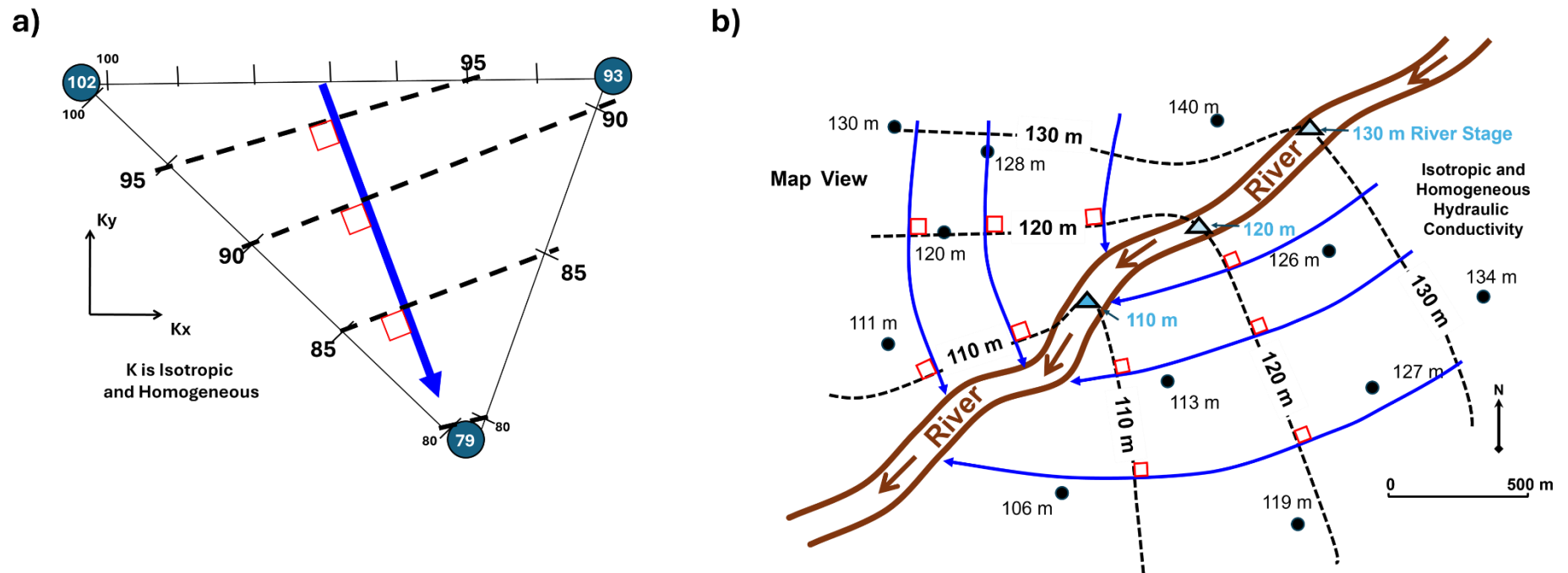


Figure 11 - Examples of constructing equipotential lines in map view using linear interpolation. a) Groundwater elevation measurements from three wells (blue circles labeled 102 m, 93 m, and 79 m) penetrating the water table. The line between wells is divided into segments to linearly interpolate the values of head between the wells. Then dashed black equipotential lines are drawn to connect equal values of interpolated head at a regular interval (e.g., every 5 m). The equipotential lines represent the locations of equal head values. If the aquifer material has uniform groundwater transmission properties (isotropic and homogeneous hydraulic conductivity) then groundwater flow (large blue arrow) will occur in the direction of the maximum decrease in gradient, which is calculated as the difference between two equipotential lines (high values to low values) divided by the shortest distance between the lines. The flow is at right angles (shown by red squares) to the equipotential lines. b) Water table map of an isotropic and homogeneous unconfined aquifer. Head measurements are plotted at well locations (black dots with black labels). The surveyed river stages (light blue triangles) also represent head values because groundwater discharges to the river in this setting and the water table is connected to the river stage. Heads are contoured using a 10 m interval creating the equipotential lines shown as dashed black lines. Blue arrows represent flow lines constructed at right angles (indicated by red squares) to the equipotential lines and in the direction of decreasing head (adapted from Woessner & Poeter, 2020).

Methods to interpolate the distribution of groundwater elevations include linear interpolation (Figure 11), often performed by hand-fitting data (Marshall et al., 2025) or automated methods that use algorithms available in specialized software. [Box 1](#) includes details on performing simple linear interpolation and contouring as illustrated in Figure 11, and the basics of how automated programs handle interpolating and contouring data. A link to a Google Colab automated contouring program is also provided in Box 1. The reader is cautioned that automated programs can distort head estimates near the outside edge of the monitoring well network when no data are available to define the values of head beyond the well network. It is often desirable to have monitoring data that extend beyond the immediate study area boundary to better constrain conditions at the boundaries (Figure 8 and Figure 11). The distribution of head interpolated from field measurements is dependent on the number and distribution of wells forming the network and the procedure used to interpolate between the values.

2.7 Plotting Groundwater Flow Lines

Groundwater flow in saturated material with a uniform groundwater transmission capacity (i.e., hydraulic conductivity is the same everywhere) occurs in the direction of the maximum decrease in head. This is the direction of the shortest distance between two equipotential lines, and is the maximum negative gradient, defined as the change in head divided by the distance along the flow path (Figure 11). This slope is referred to as a negative gradient because groundwater movement is downslope, from high to low head.

Measured heads associated with a shallow aquifer in a river valley are plotted at the well locations shown in Figure 11b. Flow directions are shown as flow lines crossing equipotential lines (water table contours) at right angles with water moving from high to low head values. This method of determining groundwater flow directions will be used to determine flow directions in the modeling tool described in Section 3. A second example of interpolating flowlines is shown in Figure 12. Toran (2025) has an expanded discussion on constructing and interpreting maps of head data that provides numerous examples and includes tips for avoiding common errors.

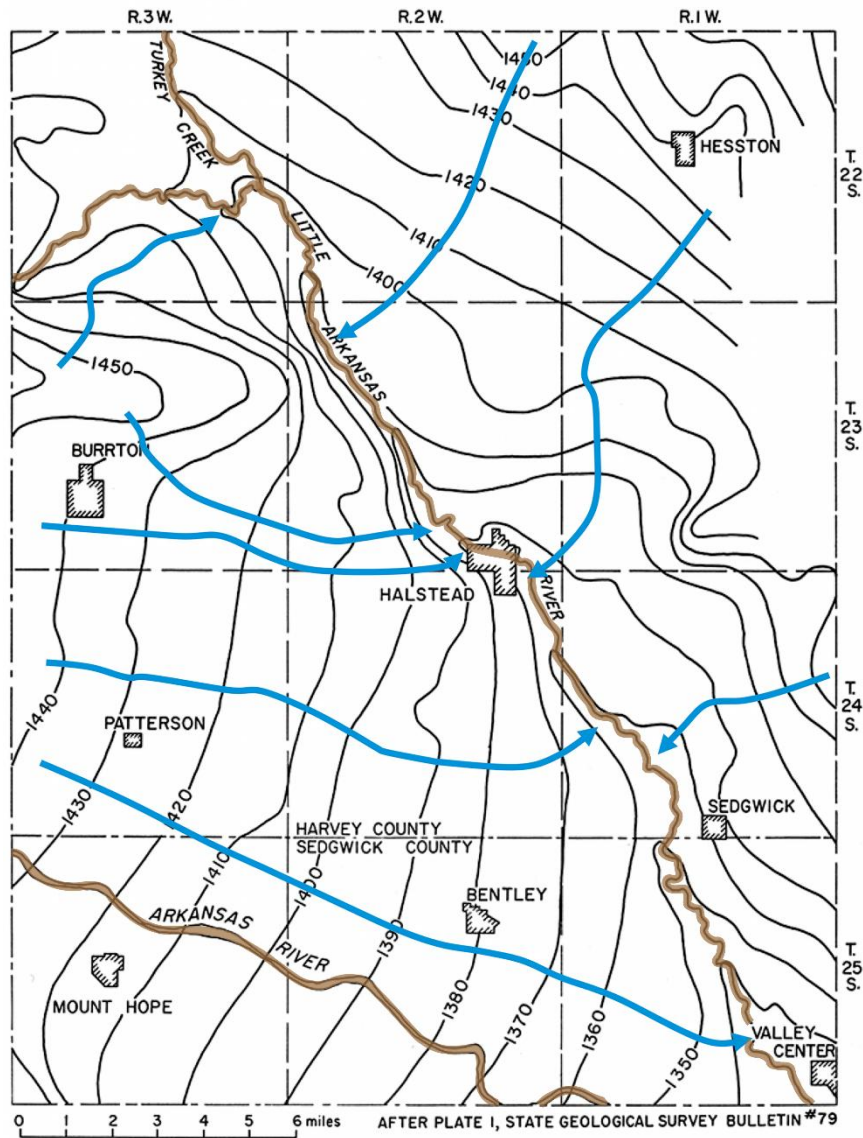


Figure 12 - Contours of the water table elevation (black equipotential lines with labels) generated in 1940 for an unconfined groundwater system referred to as the Equus beds groundwater system in a portion of the state of Kansas, USA. Equipotential lines are in feet above sea level with a contour interval of 10 ft (3 m). Blue arrows are interpreted as groundwater flow lines assuming aquifer transmission properties are isotropic and homogeneous (modified from Stramel, 1956).

3 An Interactive Physical Three-Dimensional Water Table Model Teaching Tool

The three-dimensional, instructional, water-table model engages students in practicing methods and making interpretations that hydrogeologists perform on a regular basis. Students are tasked to measure water levels, calculate heads, and visualize the groundwater flow direction (Figure 2 and Figure 13). Students then plot heads, construct an equipotential map, generate flowlines on a map view of the model, and visualize the flowlines within the physical model.

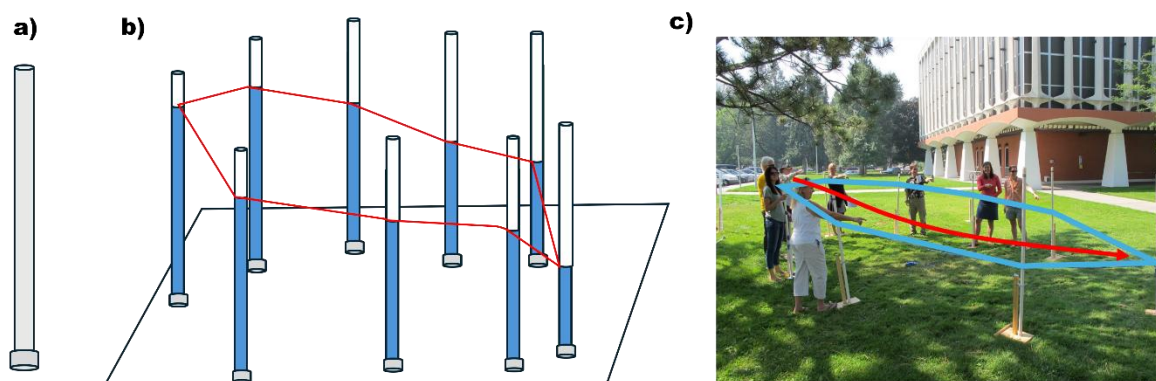


Figure 13 - Basic components and set up of the physical model. a) Hollow, bottom-capped, small-diameter, PVC pipes are used to represent monitoring wells tapping a water table system. b) A model network of monitoring wells partially filled with water (indicated by the blue shading) to represent the water table position (hydraulic head) at the well location. The red line represents the shape of the water table surface. c) Example of setting up the model well network outside on a flat lawn space for a workshop on groundwater. Measurements are made and the water table position is determined (blue outline). The group then inspects the water table surface and visualizes the three-dimensional groundwater flow path (red arrow).

3.1 Setting up the Monitoring Well Network

The model monitoring well network described here is composed of eight hollow 2.3 cm inner diameter PVC (polyvinyl chloride) pipes capped on the bottom then partially filled with water. The model wells represent eight screened monitoring wells penetrating an unconfined aquifer in a horizontal flow zone (Figure 10). The water level in each tube represents the water table position at the well location (Figure 13). The partially water-filled tubes are distributed in the classroom or another space to represent water level depths for a portion of the groundwater flow system (Figure 14). Paper maps of the well positions are handed out to the students.

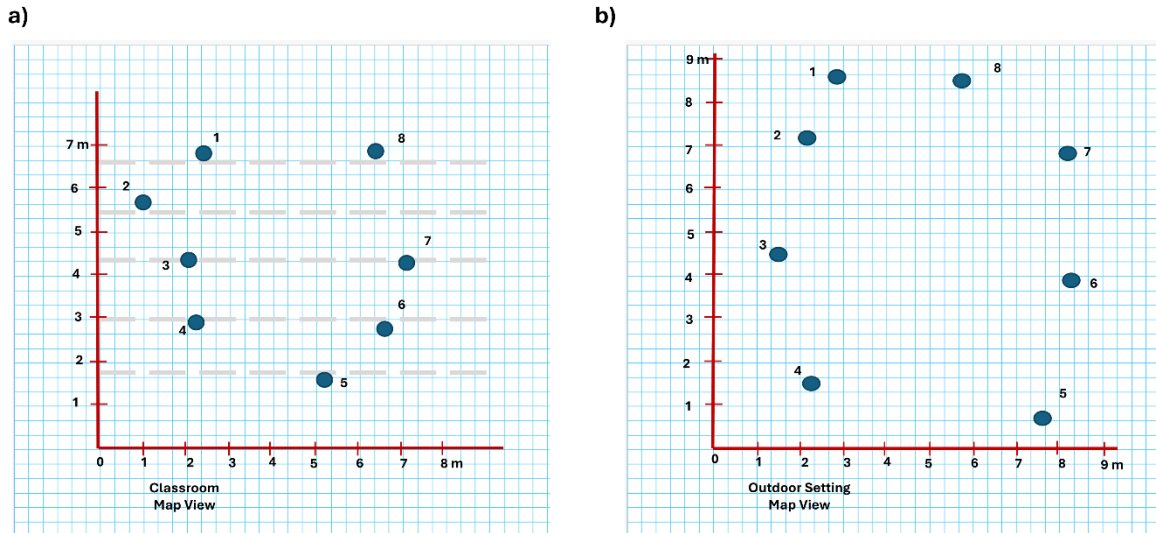


Figure 14 - Examples of network maps used to set up the monitoring well network. These maps are also used to plot and interpret head data from the acquired measurements. Numbered blue circles represent tube locations. a) Schematic of a classroom setting. Dashed gray lines represent individual seats or classroom bench locations. b) An example of an outdoor or other open space network map.

For the well networks illustrated in Figure 14, each well is 152 cm (5 ft) long. The pipe has an outer diameter of 2.7 cm and an inner diameter of 2.3 cm (classified as 3/4 inch diameter PVC pipe). This type of pipe is SDR 21 and is considered a thin-walled pipe. Schedule 40 pipe is another type that has the same outer diameter and also works well. It has an inner diameter of about 2.0 cm.

Wells in the network are filled with water using volumes listed in Table 1. Of course, the instructor can choose another PVC pipe diameter, or schedule, and a different number of wells, and to fill them with other volumes of water.

Table 1 - Volumes of water, water level position from the measuring point, and head values measured from a local datum such as the floor of the classroom. For 2.3 cm inner diameter PVC pipe (classified as 3/4 inch diameter SDR 21 pipe, commonly referred to as thin walled), about 415 ml of water fills 100 cm pipe length.

Well #	Water Volume (ml)	Depth to Water from the Top of the Casing (cm)	Elevation of Water Above Horizontal Plane* (cm)
1	561	17	135
2	540	22	130
3	519	27	125
4	486	35	117
5	515	28	124
6	536	23	129
7	552	19	133
8	581	12	140

*All PVC monitoring wells in this example are 152 cm long

3.2 Measuring the Water Levels

Typically, students are separated into groups and tasked with measuring water levels in two or three model wells. If time permits, each group can measure levels in all wells. Measurements are completed with measuring tapes (carpenter’s tape) marked with

water soluble pens, chalked wooden dowels and a measuring tape or meter stick, or other devices (Figure 15).

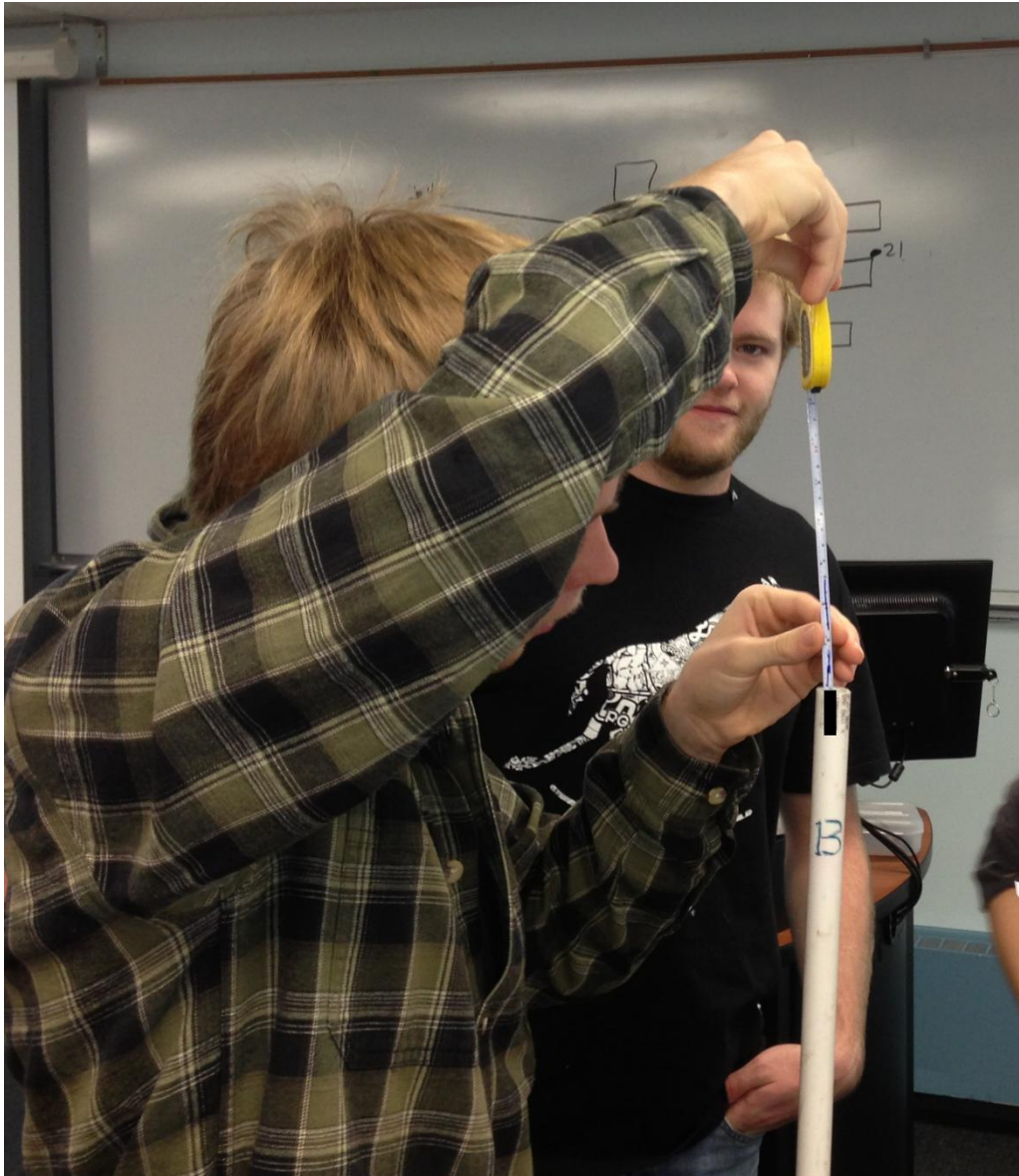


Figure 15 - Example of measuring the depth to water in each well from the top of the casing measuring point (marked on each well as a black vertical stripe). A small width measuring tape with the end marked with a water-soluble marker (blue) is lowered into the well and held at the measuring point at the top of the casing. The depth to water is computed by extracting the tape and noting the length of tape between the measuring point and the point where the well water washed away the blue ink. If all the blue ink is unaffected, the tape is lowered deeper into the well until the water level is encountered.

If standard electric water level measurement probes commonly used by hydrogeologists are available, they can also be used. However, the size and diameter of the probes will need to be checked to ensure they fit in the tube diameters used in the model.

It is useful to provide a visual aid so students can see how various water level measuring devices interact with the water level in a model well. The authors of this book and our reviewer colleague, Professor Laura Toran, have constructed and used a clear

monitoring well to demonstrate the water level measuring process and behavior of instruments as they contact the water surface. Ideally, a clear PVC pipe (with a white PVC cap at the bottom) that is supported vertically and partially filled with water can be used as a demonstration well (Figure 16a).

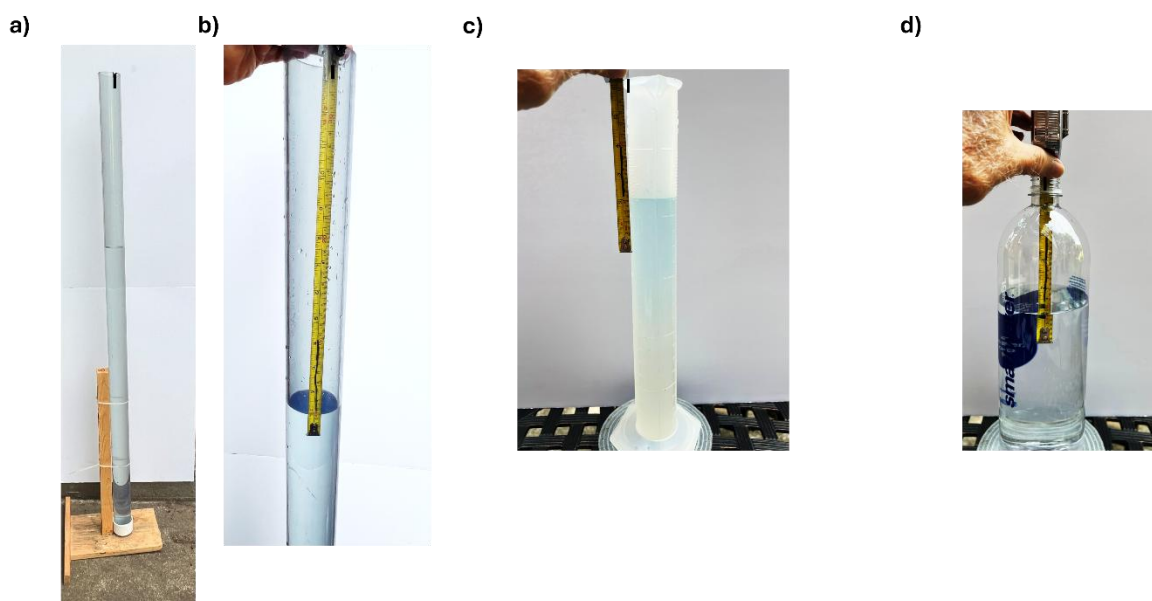


Figure 16 - Demonstration wells. a) A clear PVC pipe capped at the base with a schedule 40 white PVC cap. This well has a 5.08 cm inner diameter and is 152 cm long. A wooden base and zip ties hold the well. A demonstration well can be constructed of various diameters of clear PVC pipe with a water-soluble marker applied to a steel measuring tape used to measure the water level. b) Water level measurement in the well shown in a). c) Graduated cylinder used as a demonstration well. d) A clear large water bottle used as a demonstration well.

Selected water level measuring tools are inserted into the demonstration well and the water level measurement is observed (Figure 16). This demonstration well model can be made of any clear material and does not have to be the same length or diameter as the model white PVC tubes. If clear PVC is not available, a partially filled translucent graduated cylinder, a clear groundwater sampling bailer sealed at the base, a clear water bottle with the top cut off, or a large glass of water could also be used. The advantage of using a longer tube is that water level measurements can easily be made from a marked reference point as described in Section 2.5.

Typically, when water levels are measured in a model well network, three measurements should be taken. Then a representative measurement is computed as a mean. When a tape or a chalked wooden dowel is used, hold measurement device at the measuring point (e.g., tape held at 25 cm) and the length of wetted tape (e.g., submerged tape section 2.38 cm) should be recorded. With these data, the depth to the water level from the measuring point is computed. Water level measurement using an electric sound is directly read at the measuring point (e.g., depth to water is 7.89 cm) (Figure 9).

Once the depth to water in a tube is determined, the resulting water level is marked on the outside of the tube with blue masking tape (Figure 17). This provides a visual

representation of the water table position. The results collected by each group of students are combined into a single data set. If more than one group measures the same wells, the measurements are compared and a representative value is derived usually by taking an average of the reported values.



Figure 17 - Outdoor model with water levels representing the water table marked with blue tape. The three-dimensional water table surface has been outlined with blue yarn. The darker green-gray tape near the top of the casings was used to indicate the land surface position in this example.

3.3 Illustrating the Water Table

A piece of string or yarn is tied to each well at the water table elevation (blue tape) and then extended around the network linking each water table elevation (Figure 17). Once completed by returning to the starting point, the three-dimensional shape of the water table is observable. The students are asked to walk around the model and visualize the three-dimensional flow direction—applying the principle that groundwater flows from areas of high to low total head (Figure 18).

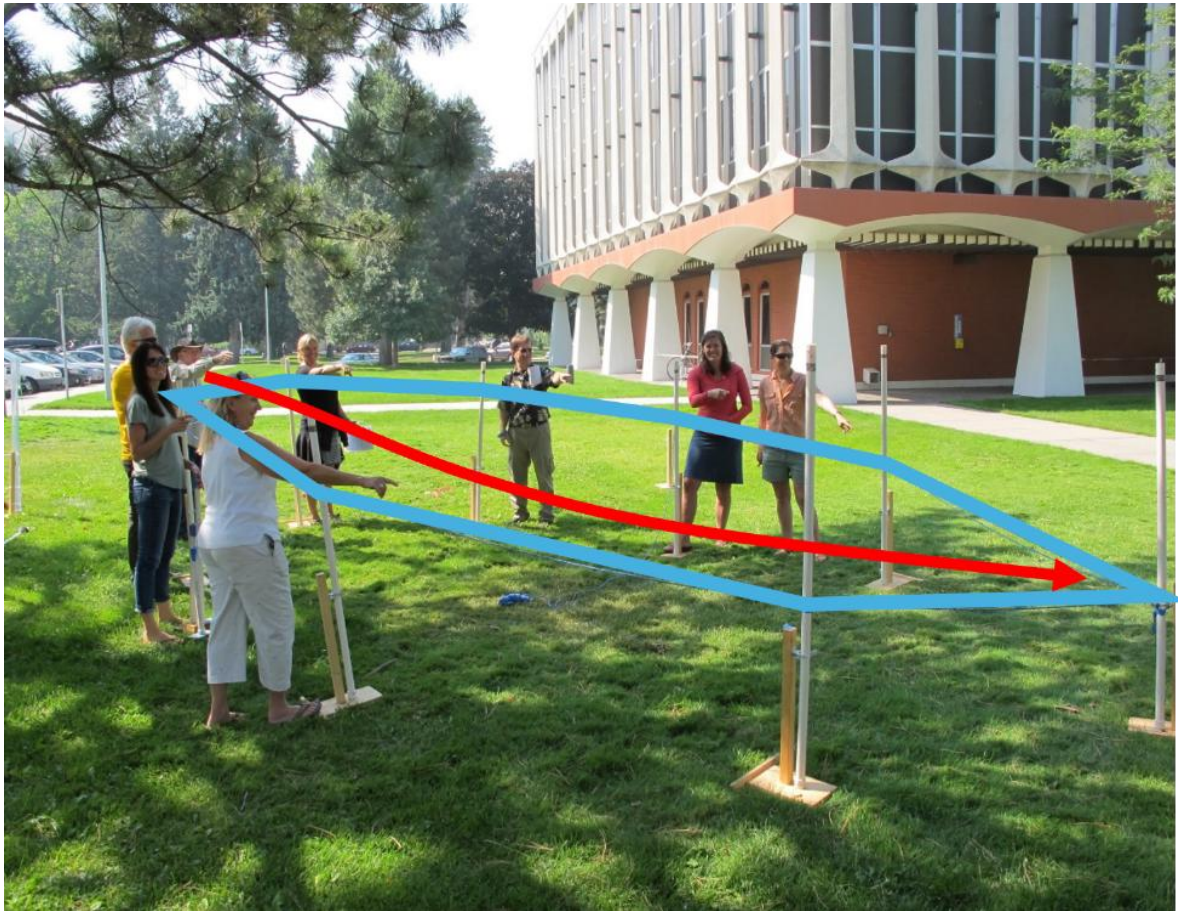


Figure 18 - Three-dimensional model set up on a lawn for a groundwater workshop. The blue outline indicates the shape of the water table as delineated by the position of the blue yarn. The yarn was stretched between the blue tape water table marks on each well. The group was asked to walk around the model and then point to the perceived direction of groundwater flow (red arrow).

3.4 Computing Hydraulic Head and Plotting Groundwater Flow

Using the horizontal classroom floor or a level grass surface or parking-lot surface as a reference horizontal plane (elevation = 0 cm), hydraulic heads are measured for each well as the elevation of the marked water level (distance in cm) above the plane (e.g., as illustrated in Table 1). The calculated heads are plotted on a map of the well network and equipotential lines are interpreted by contouring the heads as shown in Figure 19.

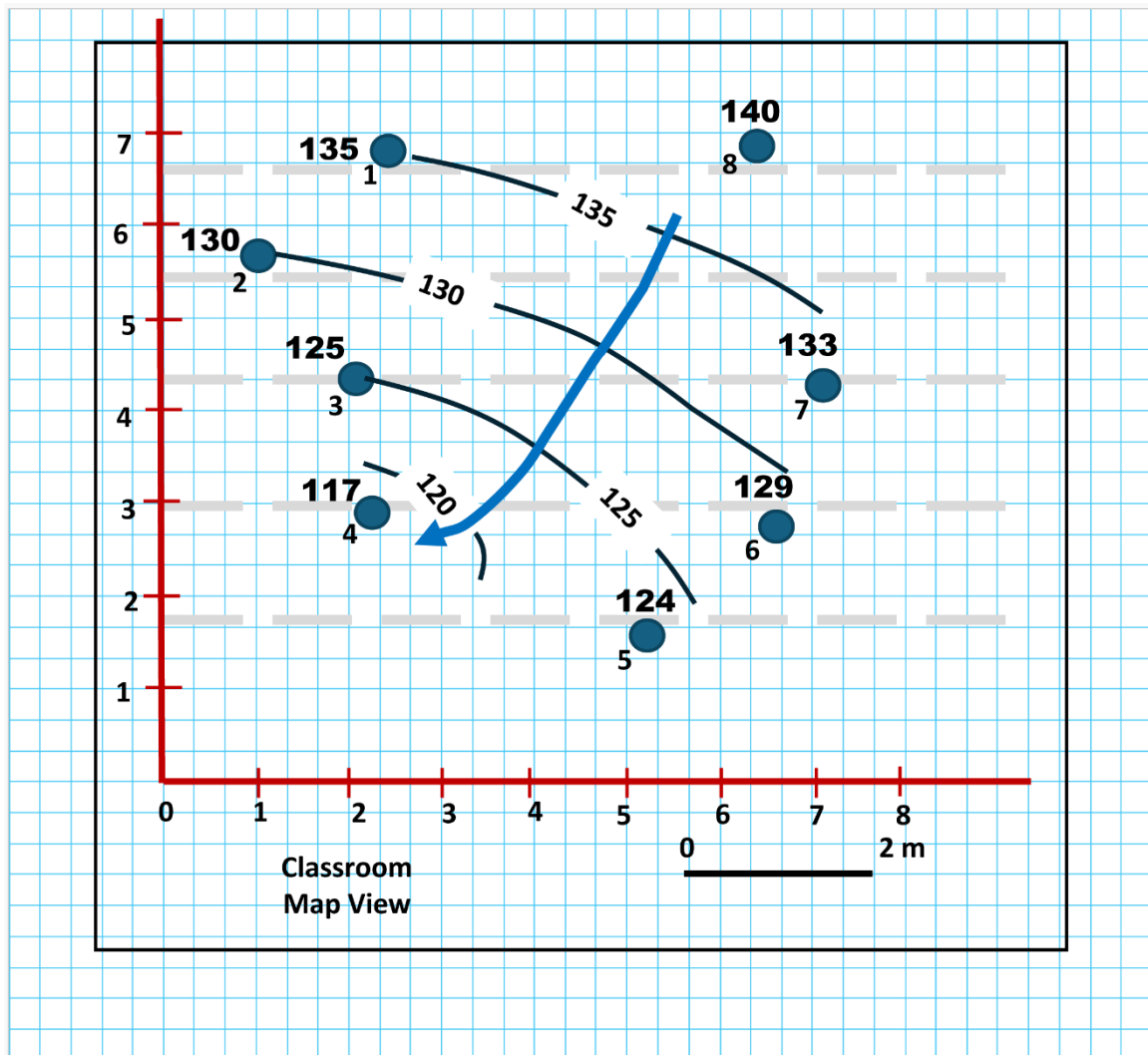


Figure 19 - Map view of the classroom model well network (numbers 1–8), and computed head values that are the water table elevations (bold numbers). Head in this case is given in centimeters (Table 1). Equipotential lines are contoured using linear interpolation and lines drawn by hand as described in Box 1. The contour interval is 5 cm. Assuming the hydraulic conductivity for the area is represented by a single value, a flow line is shown with the blue arrow.

Equipotential lines can also be shown on the physical model by stretching a different colored yarn (yellow in this case) between points of equal heads measured as the distance from the blue yarn water table surface to the horizontal plane below (Figure 20). To accomplish this, a measuring tape could be extended to 125 cm and then locations on the perimeter where the distance to the water table is 125 cm are marked on the blue yarn. Lines are then constructed between these points (Figure 20). In some cases, these equipotential lines may only be a rough interpretation of the lines as the sloped surface may further affect the interpolated position. Box 1 discusses interpolation and contouring. [Exercise 1](#) is an opportunity for students to calculate hydraulic heads for their physical water table model and to create equipotential lines both by hand contouring and by automated methods.

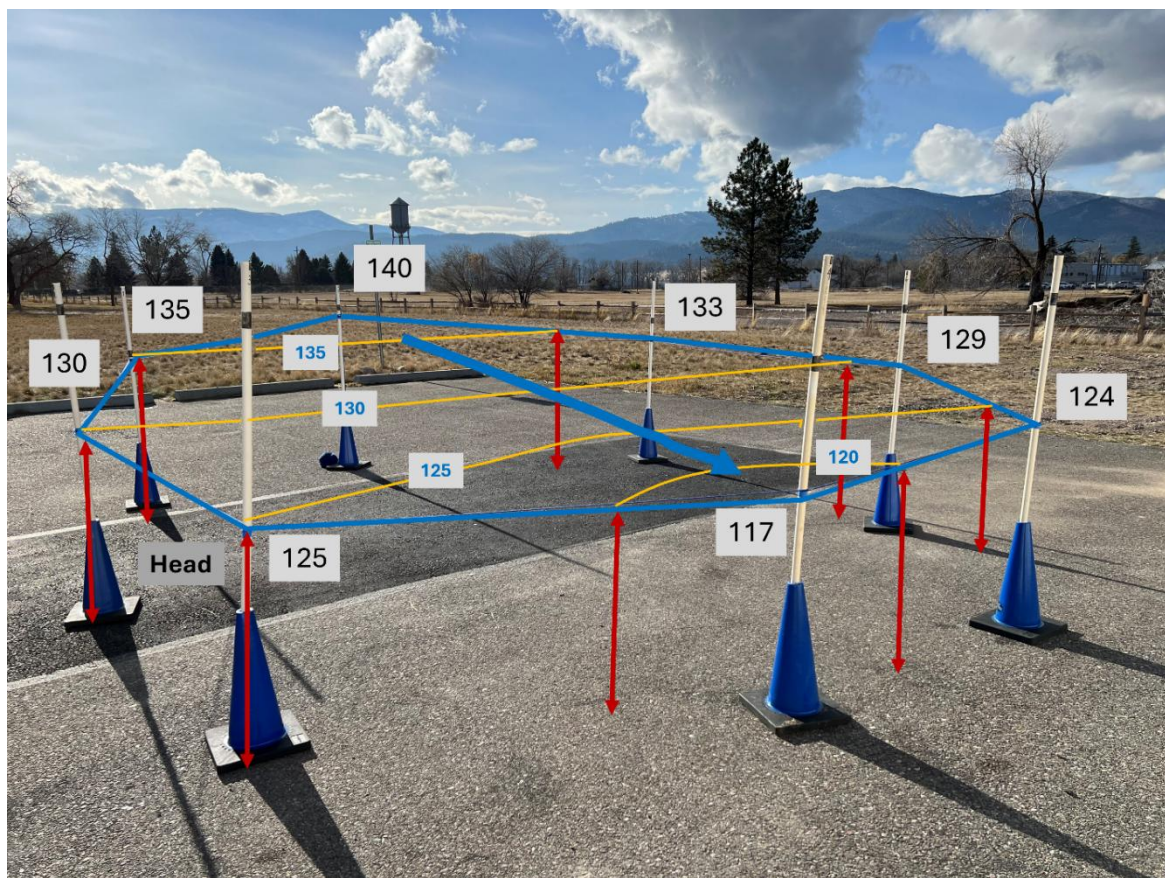


Figure 20 - Three-dimensional model set up in a parking lot. This example is based on the pipe fill volumes in Table 1. The blue line connecting each well represents the elevation of the water table—large numbers represent head in cm at the pipes. The red arrows indicate the position of the water table above the parking lot surface at points along the blue yarn where the head is 120, 125, 130, or 135 cm (5 cm contour interval). Yellow lines are equipotential lines drawn on the photograph of the model and labeled with blue numbers. These lines connect points of equal value at the red arrows. The thick blue arrow is drawn at right angles to the equipotential lines to show the interpreted direction of groundwater flow.

Assuming hydraulic conductivity is uniform and isotropic throughout the physical model, groundwater flow directions are interpreted. They are plotted on the map of head and the physical model using the principle that flow occurs along the maximum change in water table slope—at right angles to the equipotential lines—and in the direction of decreasing head (Figure 19 and Figure 20).

3.5 Computing Groundwater Discharge Through a Cross-Sectional Area and Average Groundwater Velocity Within the Model

Once the equipotential lines are designated for the model area (Figure 20), take a rectangular piece of cardboard that is 2.0 m long and 1.3 m high and place it along a section of the 130 cm equipotential line (Figure 21). This forms a cross-sectional area of 2.6 m², $A = (2.0 \text{ m})(1.3 \text{ m})$, perpendicular to the groundwater flow direction.

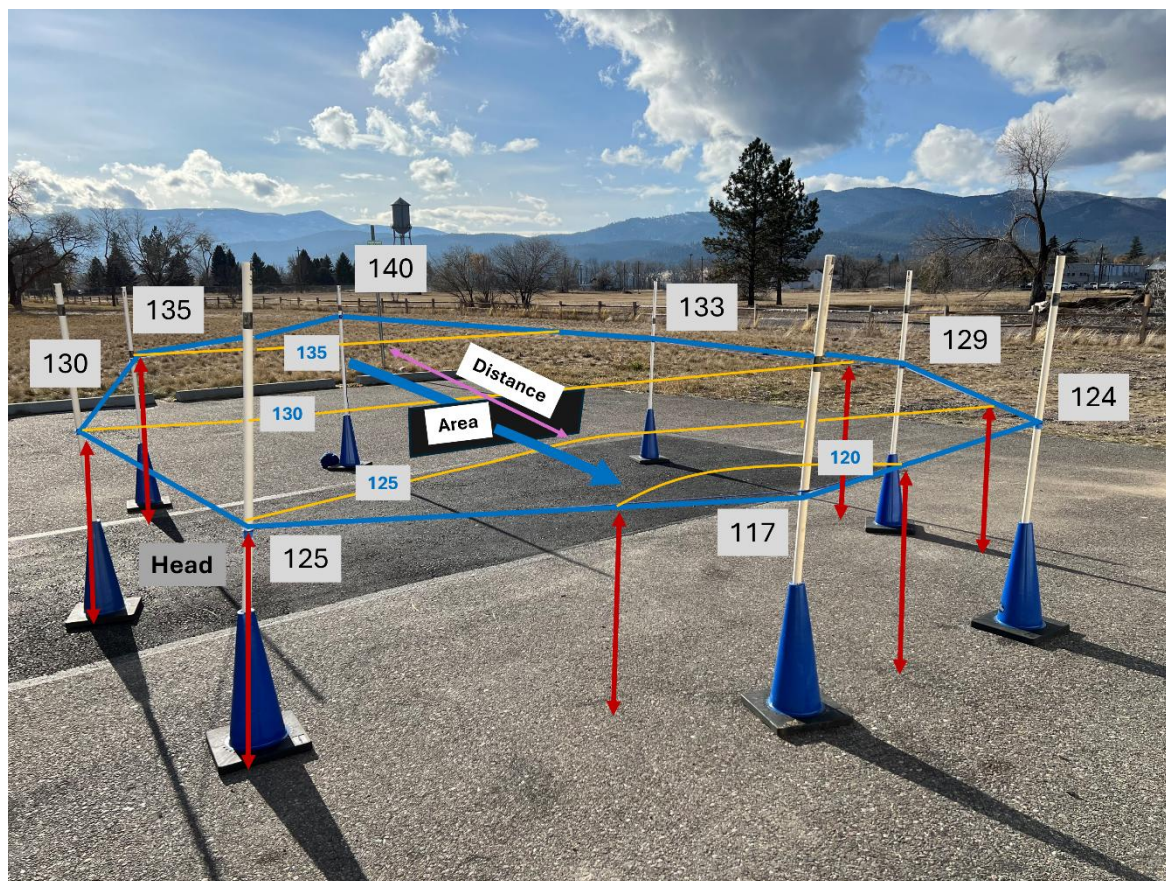


Figure 21 - Illustration of placing a 1.3 m by 2 m rectangular piece of dark brown cardboard along the 130 cm (1.30 m) equipotential line. Values in the figure represent heads in centimeters in this portion of the unconfined system. The slope of the water table is computed over the distance between the 135 cm and 125 cm equipotential lines along the pink arrow that passes at a right angle through the cross section. This is a groundwater water flow line. The hydraulic gradient or slope is the head difference (1.35 m–1.25 m) divided by the distance which is the length of the pink line (2.5 m).

[Exercise 2](#) shows how data necessary to compute groundwater discharge and velocity can be derived from interpolated equipotential maps. This exercise applies (1) and (2) to the unconfined, physical, three-dimensional, aquifer model. Assume a composition of the aquifer material, a corresponding value of hydraulic conductivity (K), and an effective porosity (n_e), for example sand and gravel with $K = 90$ m/d and $n_e = 0.15$. (1) can be used to compute the groundwater discharge and (2) can be used to compute the velocity.

3.6 Summary

Skills and concepts taught in Section 3 include:

1. methods to measure the water levels in a well;
2. the three-dimensional nature of the surface of a water table;
3. how to determine the distribution of hydraulic head;
4. how to interpret the head distribution in the physical model and in map view; and
5. how to determine the direction of groundwater flow.

4 Expanding the Basic Exercise

The physical model presented in Section 3 is intended to reinforce important basic groundwater concepts and give students hands-on opportunities to measure heads, visualize and interpret head data, and to determine the direction and velocity of groundwater flow. As instructors use this tool, we encourage them to expand and modify the model to meet their teaching goals. As the main model exercise is often completed in a single class period the following demonstrations and calculations are suggestions and left to the instructor's discretion.

This section begins by demonstrating how having data from only a two-dimensional plane is not sufficient for interpretation of flow direction. Then, three wells are set up in a triangle (not on a line) to examine the direction of the groundwater gradient. In additional sections it is proposed to increase the number of wells in the network, have the well casing lengths vary, examine how a non-horizontal well casing top affects water level measurements, assign an elevation to the horizontal plane used to calculate heads, and display a ground-surface configuration. The last two sections introduce students to the concept that water level measurements have both error and uncertainty associated with them. Expanding the lesson to include material presented in Section 4 is optional. Parts and pieces of Section 4 could be extracted to enhance the learning environment as deemed appropriate by the instructor.

4.1 Explore A Two-Dimensional Representation of Groundwater Flow

Once the water levels in each well have been measured and marked with blue tape, choose two wells in the network, and using a piece of blue yarn, connect the water level in only these wells. These wells should not be on a groundwater flow line, for example wells 2 and 8 in Figure 22 would be a good choice.



Figure 22 - An interpreted water table slope and direction of groundwater flow when only two wells are available, wells 2 and 8. Blue tape shows the water levels in the wells. The red arrows represent the water level elevations above the parking lot datum (head in red letters). Interpreted groundwater flow is from high head to low head (blue arrow). However, as the wells are not located along a groundwater flow line (dashed blue arrow), which can only be known by using at least three wells positioned in a triangle, the illustrated slope does not represent conditions in the three-dimensional system. When all head data are interpreted the shape of the water table shows groundwater flow goes from left to the right (dashed blue arrow).

Direct the class to view the water table slope and predict the direction of groundwater flow based only on these two data points. Emphasize that groundwater flows from high head to low head and in the direction of the decreasing slope of the water table. In this two-dimensional representation, the groundwater flow direction interpretation using only the two points will misrepresent the groundwater flow direction in this portion of the three-dimensional water table system. This is because these wells are not on a groundwater flow line, so interpreted slope and flow directions are incorrect. Thus, additional wells are needed to define the three-dimensional water table surface and slope (Figure 22).

4.2 Explore Defining the Slope of the Water Table Using a Rigid Three-Dimensional Surface

Next, construct a small-scale physical groundwater model using three of the network wells. The wells are separated from the larger group of wells and arranged about 0.5 m apart in a triangle (Figure 23). Fill these three wells with water using volumes shown in Table 2. Direct the students to measure the water levels, and to mark with tape the level on the outside of each well casing.

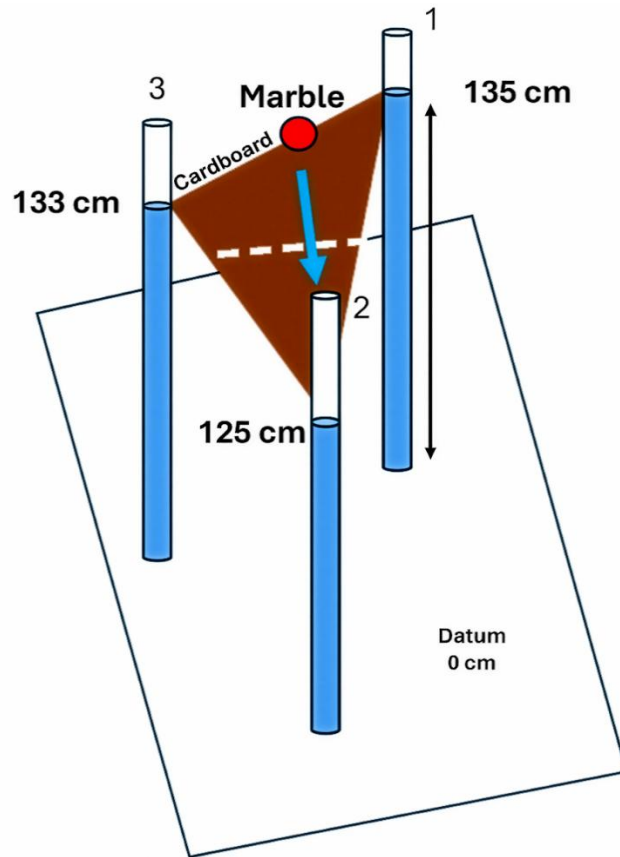


Figure 23 - A three-well network representing heads (water elevations above the datum plane) as given in Table 2. The wells are arranged in a triangular pattern about 0.5 m apart. A triangular piece of smooth cardboard is cut so that each corner is touching the water level in a tube. The cardboard is secured to each well with duct tape. A marble is held at a location on the higher edge and allowed to roll down and off the cardboard. The pathway of the marble represents the maximum slope of the water table as defined by the three wells. The white dashed line is the 130 cm equipotential line, and the bright blue arrow shows the direction of groundwater movement in this setting.

Table 2 - Volumes of water, water level position from the measuring point, and head values measured from a local datum such as the floor of the classroom. For the 2.3 cm inner diameter PVC pipe, 415 ml of water fills about 100 cm pipe length.

Well #	Water Volume (ml)	Depth to Water from the Top of the Casing (cm)	Elevation of Water Above Horizontal Plane* (cm)
1	561	17	135
2	519	27	125
3	552	19	133

*PVC monitoring wells in this example are 152 cm long

Instruct the students to fit a triangular piece of smooth cardboard so its corners touch each well at the water table (blue tape). Fix the cardboard surface to the wells with duct tape. This surface represents the water table as defined by the three wells. A marble is placed anywhere on the upper edge of the cardboard and released. The marble will follow the steepest slope. The marble's path from a chosen location follows a groundwater flow line. Repeat the process by changing the location of the marble. In this example you can

plot the 130 cm equipotential line on the cardboard (Figure 23) and see the flow path is at right angles to the equipotential line.

MacCarthy and others (2021) provide a similar approach using three PVC wells with marked water levels in a classroom setting. They use string or yarn to mark the water level surface and then map the position of an equipotential line.

4.3 Expand the Well Network

Additional wells beyond the eight used in the original model can be added to make a larger network (Figure 24). In general, it works well to have the outer portion of the network form a perimeter of a section of the water table. This makes contouring and flow directions easier to formulate. However, actual well networks in aquifers have wells within the model perimeter. Such a distribution better defines the shape of the water table and the groundwater pathways.

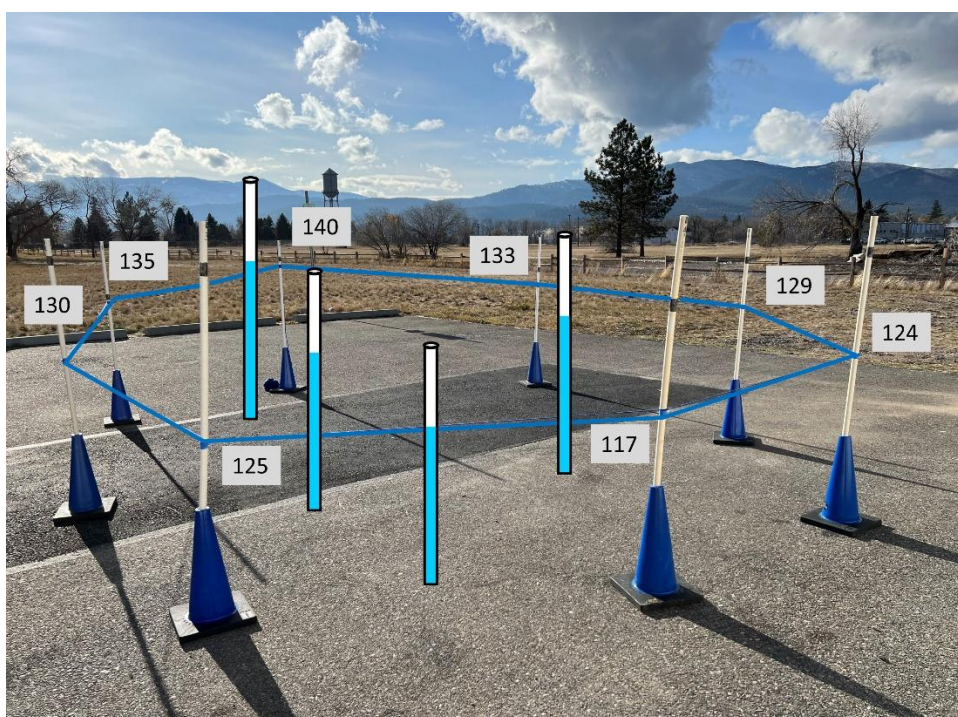


Figure 24 - Well network with four additional monitoring wells added to the central model area by drawing on the photograph pipes that are partially filled with water. The perimeter blue yarn is placed around the outside wells but not attached to the internal wells. Then equipotential lines (as shown in Figure 20 for the network with 8 wells) would be configured on the basis of head values around the perimeter and those in the wells within the perimeter.

With this new network design, assigned water levels will need to be carefully planned so desired locations of equipotential lines and flow directions are achieved. With wells located internally, stretching a blue yarn to all the marked water levels gives a rough idea of the water table distribution. It may be most useful to only use the blue yarn to mark the water table position in the perimeter wells (Figure 24). A second color of yarn representing equipotential lines can be used to incorporate the head information from the

wells located within the perimeter. If the internal wells are located so that they correspond with the planned location of a desired equipotential line (e.g., 135 cm), then internal wells can be used to help support the yarn representing equipotential lines. Based on the mapped equipotential lines a general groundwater flow direction can be indicated. The additional wells will allow for a more detailed water table map and better representation of a three-dimensional flow line. The surface does not have to be a smooth plane. It could be irregular and at advanced stages of instruction could include mound or depressions that would be explained as localized recharge or pumping wells.

4.4 Assign a Mean Sea Level Elevation to the Horizontal Datum

The horizontal datum used to measure head is the level classroom floor, outdoor parking lot surface, or a level grassy area. Using a topographic map, GPS, or Google map, the instructor can assign an elevation above sea level to the reference horizontal plane. Then students can determine the well measuring point elevations from this reference elevation and calculate heads for all model wells.

It would also be instructive to place the model on an uneven (sloping) surface and then discuss how the horizontal datum would be defined and head values determined.

4.5 Vary the Length of Model Well Casings

Instead of the wells all being the same length (e.g., 152 cm), the network can be made up of shorter and longer tubes (Figure 25). This represents field situations where networks cover a varied landscape and contain wells that are finished at different elevations above land surface, producing different measuring point elevations across the network. This has no impact on the head values assigned by filling the tube with known volumes of water because the water table elevations are reported as heads measured from the horizontal datum (e.g., the level floor).

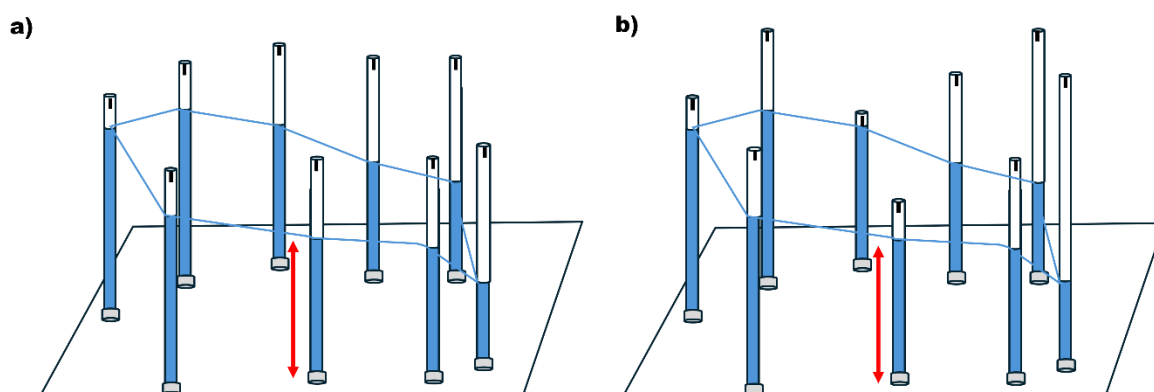


Figure 25 - Casing height variation. Two model well networks with tubes (white) and water levels (blue) are shown. The black vertical bar represents a water level measuring point on the top of the tube. The red arrow represents the head measured from the horizontal plane datum. a) A network with all the casing heights and measuring points at the same height. b) A network with varying casing heights and measuring point elevations.

4.6 Measure Water Levels When Casing Tops Are Not Horizontal

The purpose of creating a measuring point on the top of the well casing is to avoid making measurements from different positions on an uneven top that will yield slightly different values if the same point is not used. This is demonstrated by cutting the top of a well at an angle and initially not having a monitoring point marked on the well (Figure 26). Three or more students are asked to come up and measure the water level in the well. Most likely they would not choose the same location on the tube top from which to read the water level and consequently depth to water values will be different. Then designate a measuring point on the tube top and have the students repeat the measurement. Measurement values should be more similar. A discussion of measuring errors could also be included here to explain why each measurement is not exactly the same.

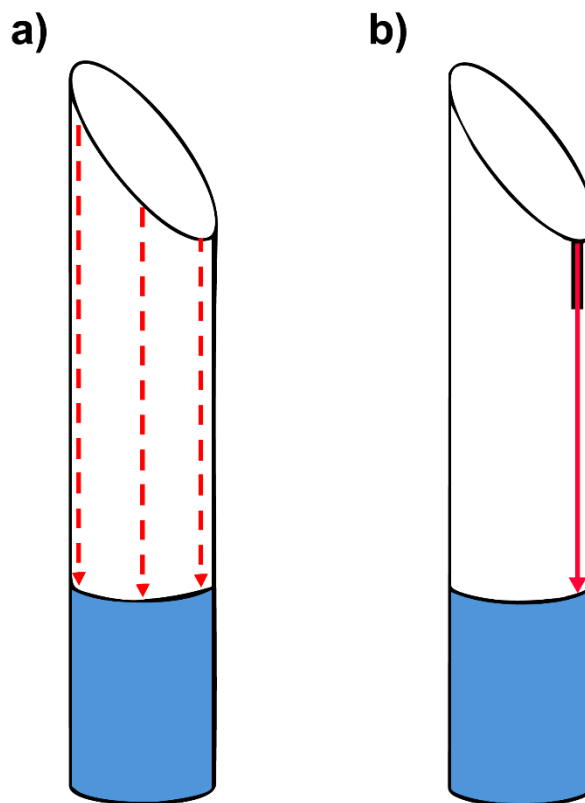


Figure 26 - Measuring water levels from an uneven top of a well. The blue section of the well represents the water level. a) An angled casing top showing the possible multiple different measurement locations and depths to water (dashed red lines) that could be acquired. b) The solid red arrow is the measured value from the surveyed measuring point location (black bar).

4.7 Display a Land Surface and the Water Table Configuration

A second color of tape is attached to each well near its top but below the measuring point that, in the previous discussions of the model, represented the land surface. This tape color now represents the land surface. A brown yarn is stretched connecting the land

surface marks to illustrate the shape of the surface (Figure 27). Depending on what is being illustrated by the land surface configuration, discussions of how the surface shape may or may not reflect the shape of the water table can be addressed. The land surface tape could be left on the casings once they are dismantled or changed each time the model is used.

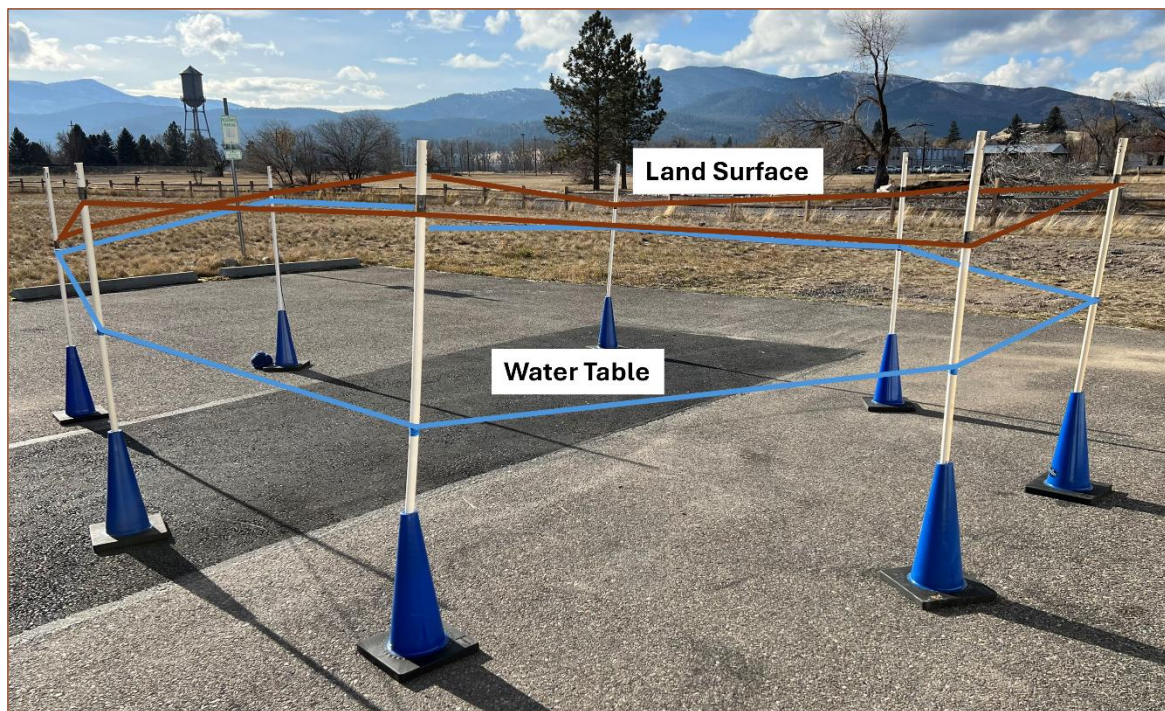


Figure 27 - Physical model showing the water table and land surface. The water table position is marked on the outside of the casing with blue tape, and these points are connected with a blue line representing the water table. The land surface is marked on the tubes using a green-brown tape and these elevations are connected with a brown line.

4.8 Define Measurement Errors

In the original model operation information in Section 3, it is recommended that three measurements be taken at each well with the final value reported as the computed average water level. This is the level used to compute head and is marked on the outside of the well with a piece of blue tape. From these values, the rest of the interpretations in Section 3 are formulated. However, the position of the water level each well could be improved upon by including measurement uncertainty.

When hydrogeologists measure water levels in wells, they standardize their measuring tools. In this exercise, select a carpenter's tape or other steel tape and designate it as the standard tape. Stretch out each of the tapes, sounders, or caulked wood dowels used to measure water level in the model well network next to the tape and see whether over a meter or so of distance your instrument readings line up with the standard tape. Most likely they will be slightly off. Record the difference in readings. This is called instrument bias. Use this +/- difference and correct your original water level measurements

as this is a constant for each measuring instrument. This is the first step in improving your measurement data. [Box 2](#) provides information on instrument bias.

A second water level error occurs because the model network uses capped water filled pipes to represent standard screened monitoring wells. Depending on how much the water level measuring instrument is submerged at the time of the measurement, a higher-than-normal water level occurs because of the displacement of water by the instrument. This is referred to as the displacement error. It is unique to measuring a water level in a sealed water-filled tube. The water displaced by a measuring device in a well that is open to the groundwater will flow out of the opening into the groundwater rather than raising the water level in the well. Box 2 provides details for correcting water level measurements affected by displacement error.

To address displacement error, first determine the volume of water displaced (displacement volume) for the measurement instruments. That is the volume of water displaced by, (1) a sounder lowered to its sensing level, or (2) for each submerged centimeter of a steel tape or wooden dowel.

The shape of sounder tips vary depending on the manufacturer, so to determine displacement volume for (1) the electric sounder, use your demonstration well to determine the water level rise when the probe is submerged to the point that the water level is indicated and divide that length by the area of the monitoring water level surface in the demonstration well. The area of the surface is determined by squaring the inside radius of the well and multiplying by π . This volume is constant for all measurements made by the sounder because the submergence depth does not vary from one measurement to another.

$$\text{displacement volume sounder cm}^3 = (\text{water level rise at indicator cm}) (r \text{ cm})^2 \pi$$

To determine displacement volume for (2) a tape or dowel, we first need to determine the volume displaced per centimeter of length because the instrument does not always extend the same distance below water. To do this, measure the width and thickness of the tape, or the diameter of the dowel, then compute the volume of the instrument per centimeter of length. For a tape the volume is width multiplied by thickness and then multiplied by 1 unit of length and here we use a centimeter for the unit length. To determine the volume per unit length of the dowel, divide the diameter by two, then square that value, multiply by π and multiply by 1 centimeter. This volume per centimeter of length needs to be multiplied by the submerged length in order to determine the volume used to calculate the displacement error.

$$\text{displacement volume for a centimeter of tape cm}^3 = (\text{width cm}) (\text{thickness cm})(1 \text{ cm})$$

$$\text{displacement volume for a centimeter of dowel cm}^3 = (r \text{ cm})^2 \pi (1 \text{ cm})$$

Next, calculate the displacement error for each measurement in your records, determine if a sounder or a tape/dowel was used, then follow the appropriate procedure.

The displacement error for a sounder is calculated as its displacement volume divided by the water surface area in the tube, with r_T being the inner radius of the well tube.

$$\text{sounder displacement error (cm)} = \frac{\text{displacement volume (cm}^3\text{)}}{(r_T \text{ cm})^2 \pi}$$

The displacement error for a tape or dowel is determined by first calculating the total displacement volume as the wetted probe length for each measurement multiplied by the displacement volume per centimeter. Then to determine the displacement error, divide the displacement volume by the water surface area in the tube.

$$\begin{aligned} &\text{tape displacement error (cm)} \\ &= \frac{(\text{wetted length (cm)}) (\text{displacement volume per centimeter of tape cm}^3)}{(r_T \text{ cm})^2 \pi (1 \text{ cm})} \end{aligned}$$

$$\begin{aligned} &\text{dowel displacement error (cm)} \\ &= \frac{(\text{wetted length (cm)}) (\text{displacement volume per centimeter of dowel cm}^3)}{(r_T \text{ cm})^2 \pi (1 \text{ cm})} \end{aligned}$$

Now correct each of the original three measurements at the well using the computed values of instrument bias and displacement error. Then recalculate the average water level. How much did it change? Will your interpretation of flow be altered?

It is important to note that monitoring wells that penetrate a water table system are open at the end or have openings in a section of the pipe (screened). In these settings, when a measuring device is submerged and displaces water, the water level temporarily rises in the well casing. In response to this slight increase in water level water flows from the well through the openings in the casing into the groundwater system and the water level returns to its equilibrium level (original static level). Consequently, displacement error correction is not needed.

4.9 Determine Uncertainty In Water Level Measurements

Using either the uncorrected average data or the data set that has been corrected for measurement bias and displacement error, determine the uncertainty in the reported average water level. Fortunately, you have already taken three measurements at each well and have computed an average water level. Based on the slight differences between the average values and the original measured values, uncertainty can be described by a statistical value referred to as the standard error which is the standard deviation of the average (mean) of the measured values .

To compute the standard deviation, use the equation presented in Box 2. This value is then reported as a +/- term. For example, 13.45 cm +/- 0.2 cm. This means that the measurement of 13.45 cm could vary between 13.47 cm and 13.43 cm. The smaller the range, the smaller the uncertainty.

Once uncertainty is computed for each mean well measurement, discuss if the uncertainty range will change your conclusions about the interpreted direction of flow. If there is high uncertainty in a mean measurement, could it be lowered by carefully remeasuring the water level in that well?

5 Model Components

The materials needed to construct and operate the physical model are presented in Section 5. As of 2026, the eight-monitoring-well model discussed costs between \$180 and \$310 USD. The range in cost mainly reflects the method chosen to support the model monitoring well network—traffic cones versus a roll of duct tape, the diameter of the clear PVC pipe used for the demonstration well, and the choice of water level monitoring tools (Table 3).

Table 3 - Summary of the Equipment Costs for the Three-Dimensional Model (USD).

Component	Low Cost*	High Cost*
Clear PVC Demonstration Well	\$40	\$91
PVC Monitoring Wells	\$51	\$51
Monitoring Well Support	\$7	\$64
Water Volume Measurement	\$12	\$18
Water Level Measurement	\$56	\$58
Mapping Yarn and Tape	\$16	\$25
Total	\$182	\$307

*Values rounded to nearest dollar

Each component of Table 3 is discussed in detail in this section. Overall cost can be reduced by being creative and using leftover pieces of pipe, recycled materials, or salvaged parts. In some settings more model wells may be appropriate and the cost will increase. Generally, the materials required to construct the model can be ordered from suppliers on the internet, found in a local hardware store, or salvaged from used plumbing supplies. Constructing the model is basically a one-time cost.

5.1 Constructing the Clear Demonstration Well

The clear demonstration well can be constructed out of nominal 1.95 cm (3/4 in) to nominal 5.08 cm (2 in) diameter Schedule 40 clear PVC pipe capped at the base with a standard white PVC cap (Figure 16). PVC pipe is classified by its nominal diameter, which is smaller than the actual outer diameter (OD) of the pipe. The inner diameter (ID) varies depending on the type of PVC pipe (e.g., SDR-21, Schedule 40). A section of clear PVC 152 cm long by nominal 1.95 cm diameter costs about \$23. A traffic cone base can be used to support the tube (e.g., Figure 17) or a wooden support can be used (e.g., Figure 16 and Figure 18). Larger diameter clear PVC pipe is more expensive (e.g., 5.08 cm diameter by 152 cm is about \$74). Other options such as using a partially filled graduated cylinder, a

clear water bottle, or a water glass could also be used (Figure 16). A trip to the hardware store may yield other possibilities. Costs are listed in Table 4.

Table 4 - Approximate cost of building a clear PVC demonstration well.

Model Monitoring Wells	Unit Cost	Quantity	Total
1.5 m (5 ft) by 2.7 cm OD ¹ (nominal 3/4 in diam.) Clear PVC Pipe	\$23	1	\$23
PVC Cap for 3/4 in Pipe	\$2	1	\$2
Traffic Cone Support	\$8	1	\$8
PVC Glue (4 oz)	\$7	1	\$7
Total Construction Cost			\$40

¹Outer Diameter

5.2 Constructing the Monitoring Well Network

The model is composed of PVC tubes 152 cm long and 2.3 cm inner diameter (5 ft length of nominal 3/4 inch, thin-walled, PVC SDR 21). A nominal PVC pipe size of 3/4 inches has an outer diameter of 2.7 cm (1.05 inches) and, for SDR 21 pipe, has an inner diameter of approximately 2.3 cm. The thicker-walled Schedule 40 pipe (nominal size 3/4 inches, with an inner diameter of approximately 2.0 cm) can also be used. Other diameters of pipe also work well. The only constraint in choosing a diameter is to be sure measuring devices will fit into the tubes.

The number of tubes used to represent the model will depend on the size of the space available and the number of student groups that will collect data. The use of eight tubes is described here. The tubes are then sealed on one end with the appropriate-sized caps (glued on) making them leak proof (Figure 28).

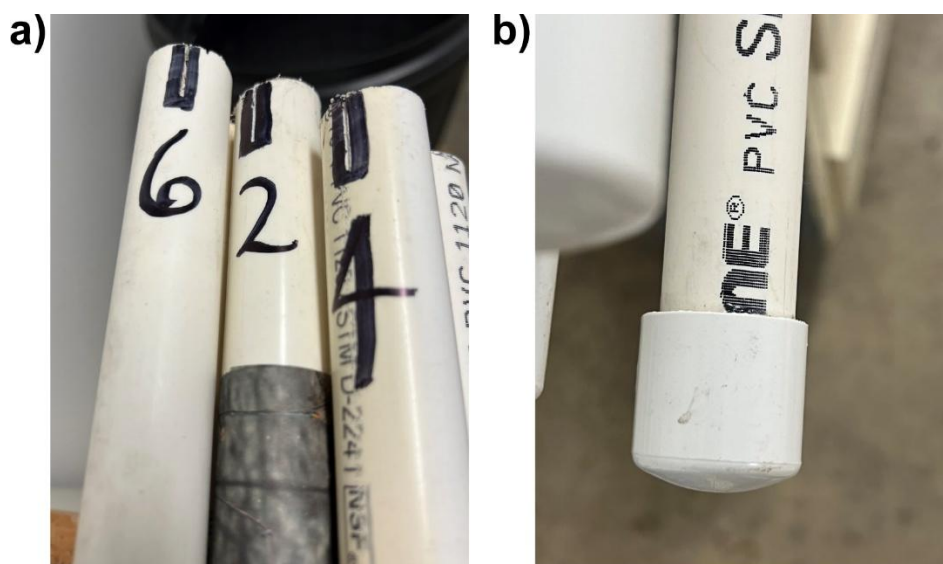


Figure 28 - Model monitoring wells are PVC tubes 152 cm and 2.3 cm inner diameter (5 ft by 3/4 inch). a) Each well is numbered, and a measuring point is marked on the open end of the pipe (black stripe). b) The tube bottom is sealed with a glued cap.

Each well is given an individual number that is marked on the casing. A mark is made on the top of the casing (and down the side) to designate the location of the reference point for collecting the water level measurement (Figure 28). This is important because if the top of the casing is not level, taking measurements at different places will yield different water levels. The cost of the eight wells is shown in Table 5.

Table 5 - Approximate cost of building an eight-well network in USD.

Model Monitoring Wells	Unit Cost	Quantity	Total
1.5 m (5 ft) by 2.7 cm OD ¹ (nominal 3/4 inch) PVC Pipe	\$4	8	\$32
PVC Cap for 3/4-inch Pipe	\$2	8	\$12
PVC Glue (4 oz)	\$7	1	\$7
Total Construction Cost (eight wells)			\$51

¹Outer Diameter

5.3 Arranging and Supporting the Model Monitoring Well Network

The shape of the water table perimeter, number of wells, volume of water added to each well, and the location of the wells are controlled by the instructor. It is best to assess the space where the wells will be placed and conceptualize where the highest and lowest water levels will occur. When the network is installed, the well numbers and locations are plotted on a scaled map or placed using the scaled map provided in this book (Figure 19). Future networks can easily be based on the initial map. Copies of the well location map are given to students and used to record water level and head data and to interpret groundwater flow directions.

The network needs to remain stable (staying vertically upright) as water levels are measured, and yarn is strung between wells. This requires each well to be secured independently. In a classroom setting it is often possible to install the network by securing wells to a classroom chair or desk with a few pieces of duct tape or similar tape (Figure 29). It is recommended to place a circle of tape under the bottom cap so that the pipe adheres to the floor.

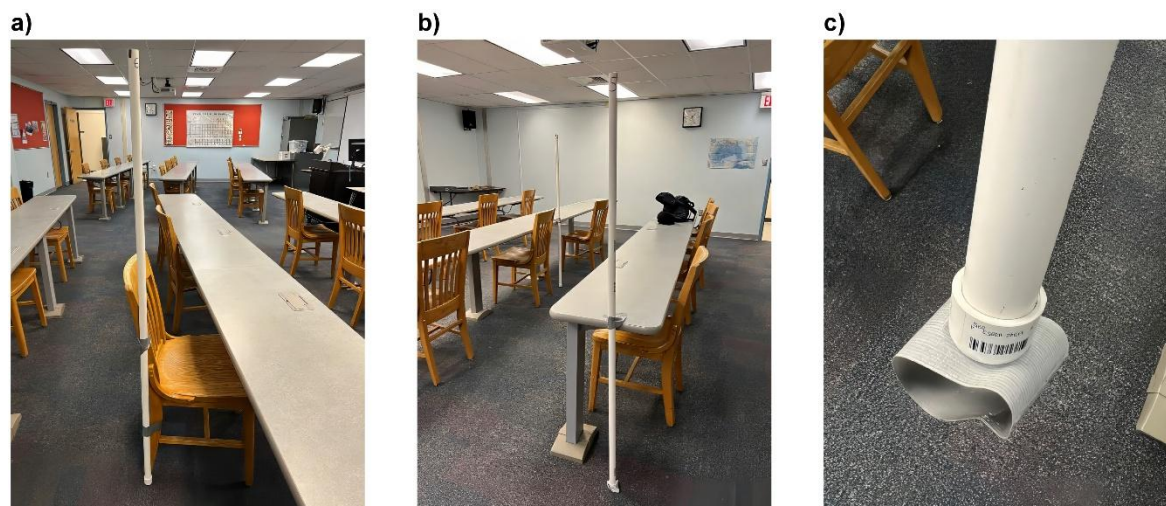


Figure 29 - Model wells are secured to existing classroom items. a) Tubes are secured to a classroom chair with duct tape. b) PVC tubes are secured with duct tape to a classroom table. c) A tape loop is placed on the bottom of the cap in b) to secure the tube to the floor. Care needs to be taken to avoid disturbing the position of the wells during the measurement activities.

In open areas where there are no classroom supports, a base will need to be built for each tube. A base constructed of pieces of wood (Figure 13) or a support like a small traffic cone can be used (Figure 30). Cone bases should be sufficiently weighted, so tubes do not tip over easily. Cost estimates of well supports are presented in Table 6.



Figure 30 - Wells supported using small traffic cones. Well numbers are shown in black next to each well.

Table 6 - Cost of Supporting the Model Monitoring Wells in USD.

Monitoring Well Support	Unit Cost	Quantity	Total
Traffic Cone Base	\$8	8	\$64
Duct Tape on Existing Support	\$7	1	\$7

5.4 Measuring the Water Volume

Model tubes are filled with water to represent the position of the water table (e.g., Table 1). A large, graduated cylinder or a kitchen measuring cup can be used to fill the tubes with the desired water volume (Figure 31). Once tubes are filled, the water level should be measured to assure the water level pattern meets the model goal set by the instructor. The cost of water measuring devices is shown in Table 7.



Figure 31 - Graduated cylinder and measuring cup used to fill model wells with water.

Table 7 - Water Measuring Equipment in USD.

Water Volume Measurement	Unit Price
500 ml Polypropylene Graduated Cylinder	\$12
or	
1000 ml Polypropylene Measuring Pitcher	\$18

5.5 Measuring Water Levels

Students, either individually or in groups, determine the water level in the wells and mark the depth to water on the outside of the tube. When taking measurements, three pieces of information are recorded. The first is the measured depth of the water level in each well from the top of the casing. Second is the height of the top-of-casing measuring point from the floor or the horizontal surface supporting the well network. Third is a calculation of head, which is the water table elevation (i.e., height of the top-of-casing measuring point minus the measured water level depth) relative to the datum. It is recommended that students have meter sticks and/or measuring tapes available to make measurements of head.

There are many tools that are used to measure groundwater levels. As noted previously, the same set of tools should be used to measure all water levels (e.g., marked steel tapes, electric water level measuring devices, or chalked solid tubes like dowels). At universities with groundwater programs, electric water level measuring probes may be available (Figure 9). The electric tape is lowered into the tube until the water is encountered by the probe. Either a light will illuminate or a buzzer will sound when water is located. Then a reading from the measuring point on the top of the tube is taken and recorded. While electric water level measuring tapes often cost \$500 to \$800 USD, less expensive alternatives are available. These include using metal measuring tapes and wooden dowels (Figure 32).

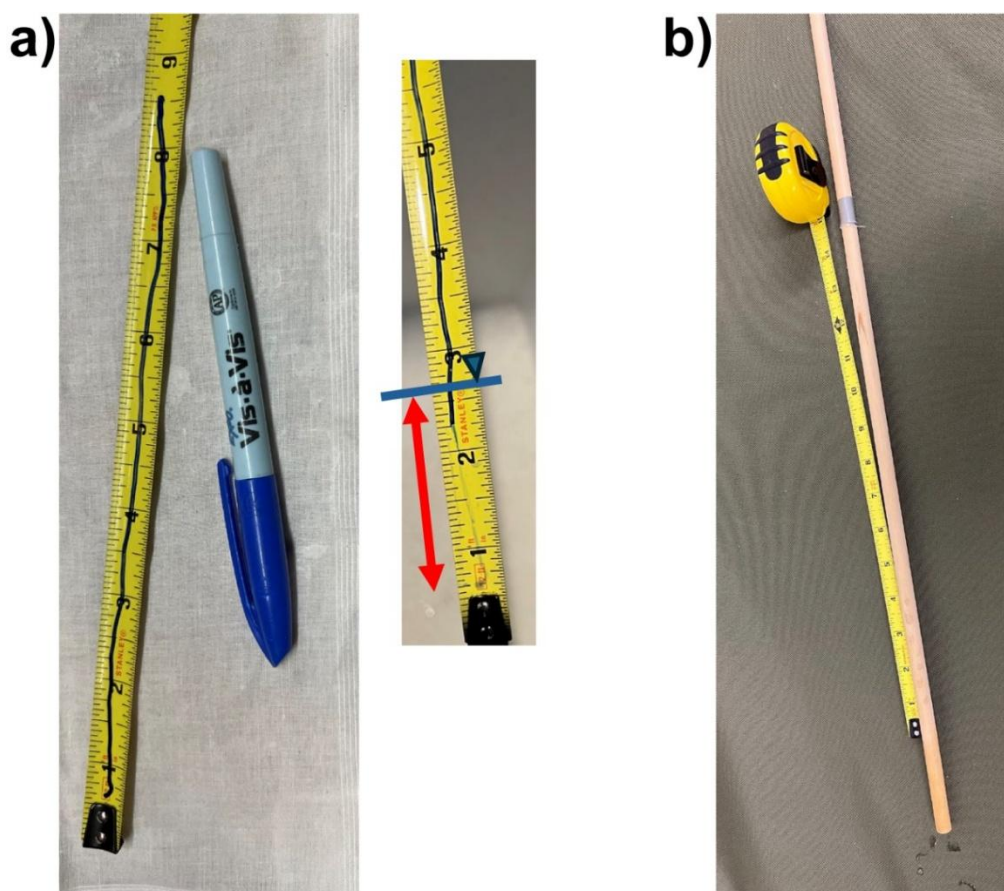


Figure 32 - Methods to measure water level (head) in the model monitoring wells. a) A narrow measuring tape (yellow carpenter's tape) with the lower 28 cm marked with a water-soluble marker. The tape is extended into the well to a length where part of the lower marked tape is below the water level. The tape measurement value at the measuring point is noted. When the tape is extracted, the portion of the tape below the water surface will wash away (red arrow) (Figure 16). The depth to water is determined as the tape measurement value at the top of the casing measuring point minus the length of tape below the water table (2.25 inches (5.71 cm)). b) A wooden dowel. The lower portion is dry and rubbed with chalk (minimally visible in the photograph). The dowel is suspended into the well to a depth where a portion of the rod is below the water surface. The chalk will wash off indicating the location of the water level. The dowel at the measuring point is marked with a pencil or wrapped with a rubber band. The depth to water is measured as the distance between the mark at the measuring point and the top of the wet portion of the rod using a meter stick or carpenter's tape.

A steel tape, such as a carpenter’s tape, can be used with a water-soluble marker (Figure 16). The end of the tape is dried and a line with a water-soluble marker is made on the bottom 10 cm or so of the tape (Figure 32a). The tape is then extended into the well bore (tube) to a predetermined depth (say 60 cm) with the 60 cm mark being held at the measuring point. After a few seconds the tape is extracted and if it has contacted the water the water-soluble pen marking will be dissolved up to the level of the water table. The reading at this point minus the reading at the hold point at the top of the casing (60 cm) is the depth to the water level in the tube.

A second method uses a wooden rod or stick along with a meter stick or tape measure. The dry wooden rod is covered in blackboard or carpenter’s chalk and lowered into the tube so that the end is below the water level. A mark is made on the rod at the measuring point (rubber band or pencil mark) (Figure 32b). Once withdrawn, a ruler is used to measure the distance between the top of the wetted zone and the point at which the rod was held at the measuring point mark. The depth to water is recorded.

As discussed previously, when multiple measuring devices of the same type are used to determine water levels, both instrument bias and operator measurement errors may be included in the reported measurement. These issues are discussed in Box 2.

Cost estimates of these measuring devices are listed in Table 8. It is assumed four sets of tools would be needed for each class set.

Table 8 - Costs of water level measuring devices in USD.

Option	Components	Unit Cost	Quantity	Total
Option 1	Carpenter’s Tape 3.5 m	\$11	4	\$44
	EvoriVus a Bus Water-Soluble Marker	\$3	4	\$12
	Total for 4 sets			\$56
Option 2	1.2 m (4 ft) Long 0.93 cm (3/8 inches) Wooden Dowels	\$1	4	\$4
	Carpenter’s Tapes 3.5 m	\$11	4	\$44
	Chalk (24 sticks)	\$10	1	\$10
	Total for 4 sets			\$58

5.6 Mapping the Water Table

At each well, when the water level is determined, a piece of blue masking tape is applied to the outside of the PVC tube at the water surface level so the water level can be visualized (Figure 33). A three-dimensional model of the water table is created by tying a piece of string or yarn onto one of the tubes at the marked water table position and then proceeding to extend the string to the levels on the other tubes (Figure 17 and Figure 20).

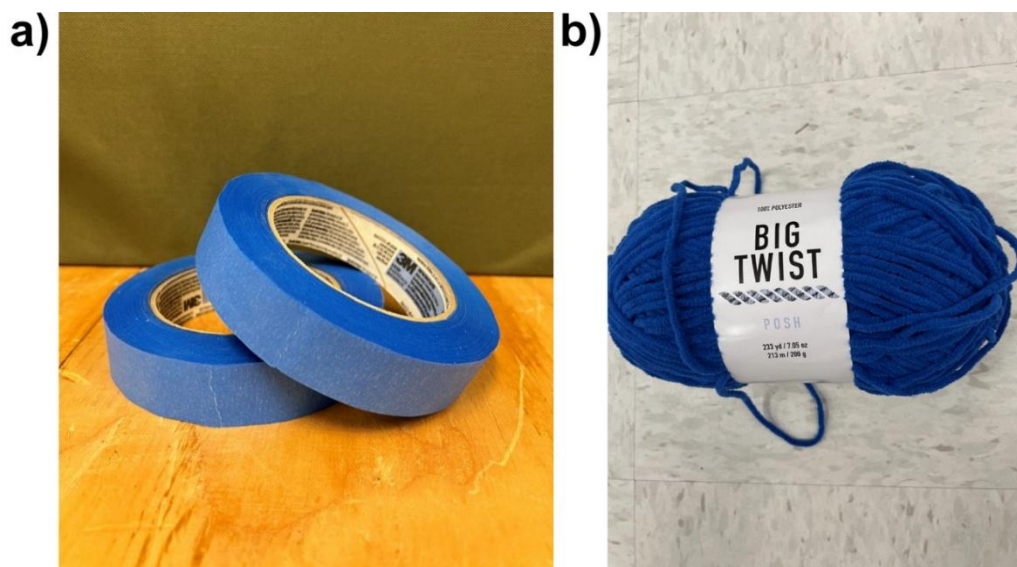


Figure 33 - Tape and yarn. a) Rolls of blue masking tape. b) Yarn used to form the water table perimeter.

Costs of yarn and tape are listed in Table 9. If additional yarn is needed to mark equipotential lines on the physical model as described in Section 3.3, two skeins of yarn would be required.

Table 9 - Cost of Yarn and Water Level Marking Tape in USD.

Water Table Indicator				
Item	Description	Unit Price	Quantity	Total
1	Blue Yarn Big Twist 223 yd (213 m) 7.5 oz (200 g)	\$9	1	\$9
2	Yellow Yarn Big Twist 223 yd (213 m) 7.5 oz (200 g)*	\$9	1	\$9
3	Roll of Blue Masking Tape (0.94 inches 2.4 cm by 100 yd/91 m)	\$7	1	\$7
Total Cost				\$25

*Yarn for Equipotential Lines

6 Summary

The construction and application of a simple, low-cost, three-dimensional physical water table model is the focus of this book. The model principally consists of a set of small-diameter PVC tubes that are partially filled with water. This model well network is used to represent a water table groundwater system. Students make measurements of the water table position, compute associated hydraulic heads, and map groundwater flow directions. The model provides a three-dimensional visualization of the water table. It reinforces key hydrogeologic principles and fits well into a standard hydrogeology class curriculum, as well as science demonstrations, and high school Earth Science classes.

An example setup and operation of the model is provided. Details on the materials required to build the model and estimates of costs are included.

Use of the model in a classroom or outdoor setting engages students as they work in groups and teaches standard, hands-on methods used regularly by practicing groundwater scientists.

7 Exercises

Exercise 1 - Computing and Interpreting Head Values

- a) Using the measurements from your physical water table model, convert the depth-to-water readings to values of hydraulic head.
- b) Plot the well locations and their associated head on your classroom or outdoor map with scaled axes and create equipotential lines using linear interpolation as described in Box 1.
- c) Use the x and y coordinates and the head value (z) for each well location together with an automated interpolation method to contour the model head data. A link to a Google Colab contouring program is provided in Box 1.

[Solution to Exercise 1](#) ↴

[Return to where text linked to Exercise 1](#) ↲

Exercise 2 - Plotting Flowlines and Computing Discharge and Velocity

Use the model map of interpreted equipotential lines and plot a few groundwater flow lines. Assume the water table groundwater system is composed of sand and gravel with an isotropic and homogeneous hydraulic conductivity of 90 m/d.

- a) Along a flow line that crosses two equipotential lines, compute the groundwater gradient. Then compute the groundwater discharge, Q , through a cross section that extends 2 m along one of the equipotential lines and is 1.3 m deep.
- b) At the same site compute the average linear groundwater velocity assuming the porosity for the sand is 0.15.

[Solution to Exercise 2](#) ↴

[Return to where text linked to Exercise 2](#) ↲

Exercise 3 - Quantifying Measurement Error and Instrument Bias

Measuring water levels in monitoring wells accurately is important because in some settings the difference in water table position between wells may be only a few centimeters. Hydrogeologists need to assess both operator error and instrument bias when taking and reporting water levels. Box 2 discusses how to compute measurement errors.

- a) Determining operator error. At one of the wells in the network take three consecutive measurements of the water level with the same water level measuring device. Record the values. Report the water level as an average and the error as a standard deviation. Box 2 explains how to make these calculations.
- b) Determining instrument bias. Instrument bias is defined as the difference of the measuring device length with a designated standard tape. If different types of measuring tools are being used for the session (e.g., electric water level tape; carpenter's tape and marker; and wooden dowel, chalk and meter stick), each tool will need to be calibrated to a selected standard measuring device.

Assign a number to each instrument used to measure water levels. On a level surface, like a tabletop, stretch out the measuring tools and compare them to a separate steel tape that is designated as the standard tape. For measuring devices with electric probes, you will first need to place them in a clear glass or the demonstration well to obtain the position of the sensor that detects the water level. Make a table of the results. The difference between the standard and the measuring device is reported as instrument bias and must be subtracted or added to the readings obtained by students using that device.

- c) Operator error and instrument bias are the standard concerns when measuring water levels in a field setting. Our representation of a monitoring well network with small diameter closed tubes (no outlet for the water displaced when measuring instruments are placed in the wells) introduces an additional measurement error. This is a displacement error caused by the submerged portion of the measuring device creating an artificial rise in the water level. To investigate the magnitude of this effect on model well measurements, a few example calculations are performed. Box 2 provides a discussion of displacement errors.

- 1) An electric sounding probe is used to measure water levels in the model tube. It has a radius of 1.75 cm and is submerged 0.7 cm into a 2.3 cm diameter model well. Compute the size of the displacement water level that would occur from using this water level measuring device.
- 2) A thin carpenter's tape is used to measure the water level in a 2.3 cm diameter model well. The tape has a width of 1 cm and a thickness of 0.2 cm. To obtain the water level 4.32 cm of tape was below the water level. Compute the size of

- the displacement water level that would occur from using this water level measuring device.
- 3) A thin chalked dowel is used to measure the water level in a 2.3 cm diameter model well. The dowel has a diameter of 0.63 cm. To obtain the water level 4.32 cm of the dowel was below the water level. Compute the size of the displacement water level that would occur from using this water level measuring device.
 - 4) Comment on whether not accounting for the displacement of water levels would have impacted your interpretation of the head distribution and direction of flow in the model conditions represented by your model.

[Solution to Exercise 3](#) ↓

[Return to where text linked to Exercise 3](#) ↑

8 References

- Clarke, J. S. & West, C. T. (1998). *Simulation of ground-water flow and stream-aquifer relations in the vicinity of the Savannah River Site, Georgia and South Carolina, predevelopment through 1992* (Water-Resources Investigations Report 98-4062) (pp. 135). US Geological Survey. <http://pubs.usgs.gov/wri/wri98-4062/>.
- Cohen, A. J. B., & Cherry, J. A. (2020) *Conceptual and visual understanding of hydraulic head and groundwater*. The Groundwater Project. <https://doi.org/10.21083/978-1-7770541-6-8>.
- Covitt, B. A., Gunckel, K. L., Berkowitz, A. R., Woessner, W. W., & Moore, J. (2023). Employing a groundwater contamination learning experience to build proficiency in computational modeling for socioscientific literacy. *Journal of Science Education and Technology*, 33(2), 228–50. <https://doi.org/10.1007/s10956-023-10062-z>.
- Covitt, B. A., Podrasky A., Fassnacht, D., Paquette, R., & Woessner, W. W. (2018). Delving below the surface with the Montana Groundwater Academy. *Connected Science Learning*, 1(5). <https://doi.org/10.1080/24758779.2018.12420491>.
- Devlin, J. F. (2020). *Groundwater velocity*. The Groundwater Project. <https://doi.org/10.21083/978-1-77470-000-6>.
- Hlavaty, Shay. (2023, November 28). *Lovelady monitoring well: Past and present*. Barton Springs Edwards Aquifer Conservation District. <https://bseacd.org/2023/11/lovelady-monitor-well-past-and-present/>.
- Kennedy, G. (2022) *Water well record databases and their uses*. The Groundwater Project. <https://gw-project.org/books/water-well-record-databases-and-their-uses/>.
- MacCarthy, M. F., Binet, S. E., Perry, H. J., St. Clair, I. E., & Resto-Fernandez, C. (2021). *Groundwater principles: A hands-on 3-dimensional classroom activity to determine groundwater flow direction & gradient*. 2021 ASEE Southeastern Section Conference, American Society for Engineering Education. <https://sites.asee.org/se/wp-content/uploads/sites/56/2021/04/2021ASEESE75.pdf>.
- Marshall, S. K, Peeters, L. J. M., Batelann, O., Noorduijn, S., & Velterop, T. (2025). Using expert participation to evaluate the accuracy of hand-drawn water-table maps. *Groundwater*, 63(1), 52–67. <https://doi.org/10.1111/gwat.13431>.
- McConnell, D., & Dixon, J. (2016). *What is an aquifer?* [Video]. Department of Marine, Earth and Atmospheric Sciences, North Carolina State University. <https://www.youtube.com/watch?v=g7R0yLX0V9E>.
- McConnell, D., Dixon, J., & Jones, J. (2016). *Where is the water table?* [Video]. Department of Marine, Earth and Atmospheric Sciences, North Carolina State University. <https://www.youtube.com/watch?v=UfgyJkmZgK8>.
- Northern California Public Media. (2018). *What is groundwater?* [Video]. <https://www.norcalpublicmedia.org/video/what-is-groundwater-handbrake>.

- Poeter, E., Fan, Y., Cherry, J., Wood W., & Mackay, D. (2020). *Groundwater in our water cycle: Getting to know the earth's most important freshwater source*. The Groundwater Project. <https://doi.org/10.21083/978-1-7770541-1-3>.
- Sharp, J. M., Jr. (2025). *A glossary of hydrogeology*. The Groundwater Project. <https://doi.org/10.21083/978-1-77470-079-2>.
- Stramel, G. J. (1956). Progress report on the ground-water hydrology of the Equus Beds Area, Kansas. *Bulletin (Kansas Geological Survey)*, 119, 1–59. <https://doi.org/10.17161/kgbulletin.no.119.22108>.
- Toran, L. (2025). *Using groundwater head maps*. The Groundwater Project. <https://gw-project.org/books/using-groundwater-head-maps/>.
- Uliana, M. M. (2025) *Basic Hydrology: An introduction to the fundamentals of groundwater science*. The Groundwater Project. <https://doi.org/10.62592/CBIQ7579>.
- USGS. (2015). *Measuring Groundwater with Electric Tape Video*. United States Geological Survey. <https://youtu.be/jknI9anIwF4?si=vrHdAfzXMFgI3dFo>.
- Woessner, W. W., & Poeter, E. P. (2020). *Hydrogeologic properties of earth materials and principles of groundwater flow*. The Groundwater Project. <https://doi.org/10.21083/978-1-7770541-2-0>.
- Woessner, W. W., Stringer, A. C., & Poeter, E. P. (2023). *An introduction to hydraulic testing in hydrogeology: Basic pumping, slug, and packer methods*. The Groundwater Project. <https://doi.org/10.21083/978-1-77470-090-7>.

9 Boxes

Box 1 - Interpolation of Water Table Elevation Data

When a student is instructed to interpolate a set of land-surface elevation data and construct contour lines of equal elevation, a topographical map results. In the groundwater world, when water table elevations are contoured, lines of equal head are created. These are referred to as equipotential lines. When the number of head values to be contoured is small, simple linear interpolation (most often hand drawn) is implemented. In settings with tens to hundreds of monitoring well head data points, automated contouring methods are applied.

A recent article by Marshall and others (2025) addresses the strengths and weaknesses of producing hand-drawn water table maps versus producing maps using automated interpolation methods. Automated methods have the advantage of generating a good fit to observations, a measure of uncertainty, and are repeatable. In contrast, manual interpolation is weaker in these areas, yet stronger in fitting maps to a conceptualization based on professional experience. This box addresses basic manual linear interpolation and automated interpolation methods.

Basic Manual Linear Interpolation

As described in Section 2.6, for sparse data sets with limited point data, linear interpolation can be accomplished by hand as shown in Figure 11. To contour a data set by hand, the map creator constructs curved lines connecting locations with equal groundwater elevations. Marshall and others (2025) found that when they instructed 63 professional groundwater scientists to contour the same data set, the results differed but were "...consistent in their representation of the dominant regional groundwater flow directions." The work of Marshall and others is an interesting read and recommended if students wish to delve deeper into methods for interpolating groundwater head data.

Using the linear interpolation method, the elevation is assumed to vary linearly—i.e., having a constant slope—between two data points. This dictates that the change in elevation between the two points divided by the plotted map distance between them generates a uniform distribution of water level elevation—hydraulic head. For example, as shown in Figure Box 1-1a, the water table elevation of point A is 100 m and the elevation of point B is 94 m and the wells are separated by 510 m, so the change in head with distance is $6\text{ m}/510\text{ m} = 0.012$. Suppose that in map view the well locations are plotted using a scale of $1\text{ cm} = 50\text{ m}$, so that points A and B are spaced 10.2 cm apart.

$$\frac{510\text{ m}}{\frac{50\text{ m}}{1\text{ cm}}} = 10.2\text{ cm}$$

Applying linear interpolation assumes the head change of 6 m occurs uniformly over the 10.2 cm of map distance. So, for every centimeter of map distance along a line from point A to point B, the head changes 0.59 m.

$$\frac{6 \text{ m}}{10.2 \text{ cm}} = 0.59 \text{ m/cm}$$

Further calculation shows that a 1 m head change occurs for every 1.69 cm of distance between point A and point B.

$$1 \text{ m} \frac{1 \text{ cm}}{0.59 \text{ m}} = 1.69 \text{ cm}$$

This relation is used to mark the interpreted locations of 1 m head changes between A and B in Figure Box 1-1a.

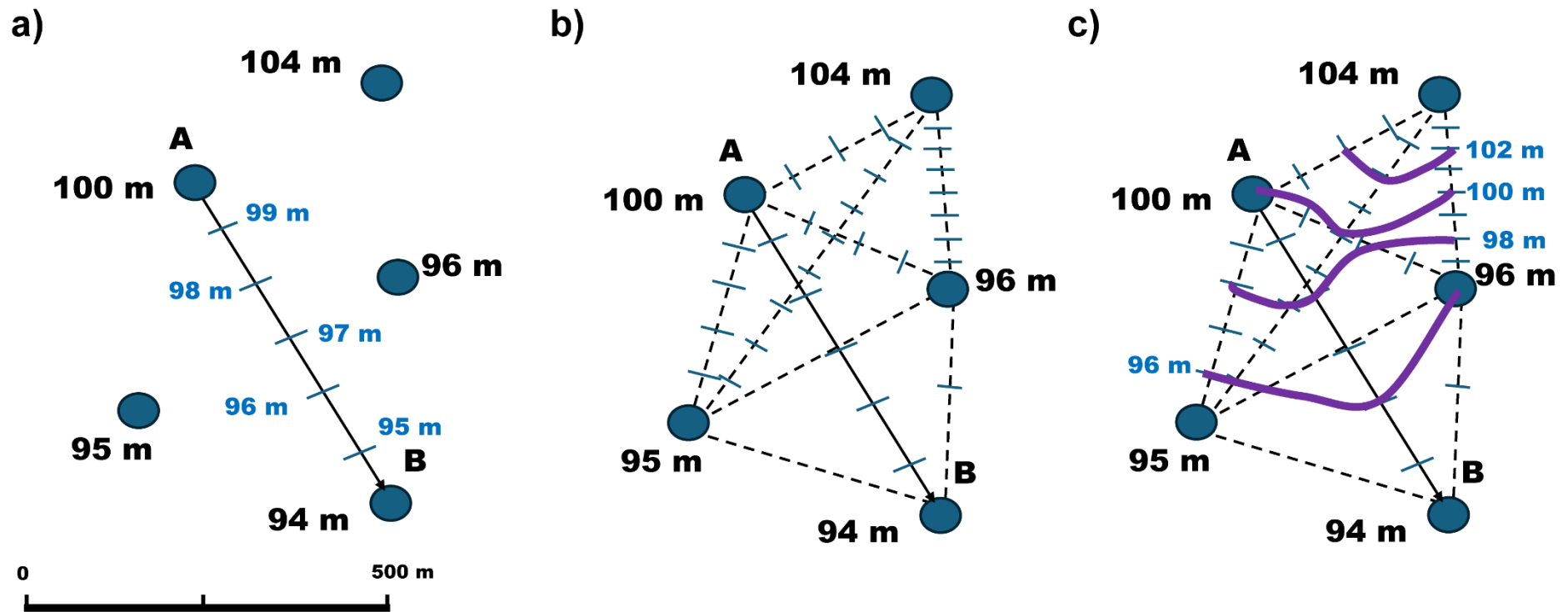


Figure Box 1-1 - Example of interpreting equipotential lines using linear interpolation. When using this approach, interpolations, shown by the bars on the solid black and black dashed lines, would yield the same values when lines intersect. However, in some cases, values at intersections may be different because hand interpolation was used and/or because the change in groundwater surface elevation is not linear between data point locations. a) Estimated distribution of head between wells A and B. b) Expanded interpretation of the head distribution between each well in the network. c) Interpolated equipotential lines (purple lines and blue numbers).

Next, additional nearby well locations are interpolated between adjacent wells, and a network of interpolated heads is generated (Figure Box 1-1b). These heads are then contoured with an interval of 2 m by connecting locations of equal value (Figure Box 1-1c). Typically, a constant contour interval is used when mapping the head distribution (e.g., 0.5 m, 1 m, 5 m, 10 m). The contour interval is selected to generate the desired detail in the plot. Often this is done by “hand contouring” where equal elevations are connected by hand drawn curved lines. Standard rules for constructing contours (in this case equipotential lines) are as follows.

1. Every point on an equipotential line is the same elevation.
2. Equipotential lines must either form a closed loop or start and end at a boundary.
3. Equipotential lines must never cross, split, or intersect.
4. The area between equipotential lines must contain values that are lower than the value of the highest line and higher than the value of the lowest line.

The equipotential lines in Figure Box 1-1c show how the water table gradient varies across the well network. It tends to be steeper near the wells with heads ≥ 100 m and flatter near the wells with heads less than 100 m.

Automated Contouring Methods

Contour and equipotential maps can also be generated using automated interpolation and contouring methods available in software programs that are available for free on the internet or are purchased from commercial vendors. Data sets must be keyed to a scaled map coordinate location system (x, y) and the data to be contoured (here, water table elevation) are the z coordinate. Marshall and colleagues (2025) generally observe that automated methods provide strong fits to observations, allow characterization of uncertainty, and are repeatable. If interventions by modelers operating the interpolation software are not well reported (use of default settings or changes to settings), reproducibility of results suffers. Automated methods may also only weakly fit hydrogeological conceptualization of the setting.

As an example of automated interpolation software, the modeling program SURFER™ (Golden Software) provides 13 interpolation algorithms that can be applied to location and elevation data sets. These include kriging, inverse distance to a power, minimum curvature, nearest neighbor, triangulation with linear interpolation, moving average, and others. Each method defines the relationship between data points differently. A user needs to read all documentation, assess advantages and disadvantages, and set internal parameters when applying a chosen method to a data set.

Typically, automated programs divide space into a new uniform grid (x, y). The numerical interpolation method uses the observed data to generate an elevation value at each new grid point. Next, a contouring program is executed, and contour lines—or

equipotential lines—are generated. More representative maps of the elevation distribution are achieved when the surveyed data points are numerous, regularly spaced, and include conditions both at and outside of the defined site boundaries. When data sets are sparse and not evenly distributed, the resulting maps will have more uncertainty and conditions at the boundaries may be poorly represented and unrealistic in some instances.


An example of an automatic contouring program created in Python is available as a Google Colab Jupyter Notebook. To use this program, you will need to have a free Google Drive account. If you don't have one you can set it up here (drive.google.com) and click on Create Account. A gmail.com email is required. The Colab Jupyter Notebook linear interpolation program can be accessed via this link,

<https://colab.research.google.com/drive/1hFuQfQACqLH0CtHmCMCxacNMBOcwSmFR?usp=sharing>.

You can use this Colab program with your own data set by modifying the example data input in the Data section of the program. Edit the values used in the example by clicking on them. The data format is {xx}, {yy}, and {zz} set out in three rows, (e.g., all xx values are in one row). The point location is designated by xx and yy, and the head value is placed in row zz. Data in each row are separated by commas and enclosed by brackets. Once your data are entered and the rest of the example data are deleted you can run the program either using the '▶ Run all' command located above the top figure on the command bar or by clicking the 'Run' button (circle arrow) at each program heading. Make sure you click on each circle-arrow symbol to progressively activate each section of the program: Start load libraries, Data, Make a basic location plot, Interpolation, Contour. You can save a copy of your results by going to the Copy to Drive command on the command bar or to File, then Save a Copy in Drive. Results will be in your Google Drive account.

[Back to where text linked to Box 1↑](#)

Box 2 - Recognizing Instrument Bias, Displacement Errors in Model Wells, and Operator Error When Reporting Water Levels

The procedures to correct for instrument bias, model well displacement errors, and operator errors are presented using the following example. Assume the measured water level is 25.87 cm below the top of the casing measuring point. This measurement is recorded using a steel carpenter's tape, the second of four tapes used by the water level measuring team. Instrument bias—sometimes referred to as the instrument error—is defined as the degree to which different tapes yield slightly different length values because of variations in the manufacturing process. To determine instrument bias for each tape used to collect water levels, the four tapes should be compared to a fifth tape designated as a standard. If a tape used to measure a water level does not perfectly match the standard tape values, then an instrument bias is determined for that tape. For example, if the tape used to make the water level measurement was slightly longer than the standard control tape, say 0.01 cm, a uniform value of instrument bias (0.01 cm) would need to be subtracted from the field-determined water level when it is reported. The collected water level reported would be $25.87 \text{ cm} - 0.01 \text{ cm} = 25.86 \text{ cm}$. The instrument bias is a constant for each tape used by the monitoring team. Each tape should be assigned a number or letter, and field monitoring notes should record the specific tape used to make the measurements. The specific instrument bias value is used to correct all water levels before reporting the final value. Tapes used for water level measurement also can stretch when long sections of the tape are used to measure deep water levels. Though not a factor in our model exercise, this bias is mentioned here to be more complete in our discussion. A video titled [*Measuring Groundwater with Electric Tape*](#)  (USGS, 2015) discusses the use of a standard reference tape when electric water level monitoring tools are used.

Unique to the physical model configuration described in this book, static water levels in tubes sealed at the bottoms are artificially displaced during a water level measurement by the volume of the submerged measuring device (displacement error) (Figure Box 2-1).

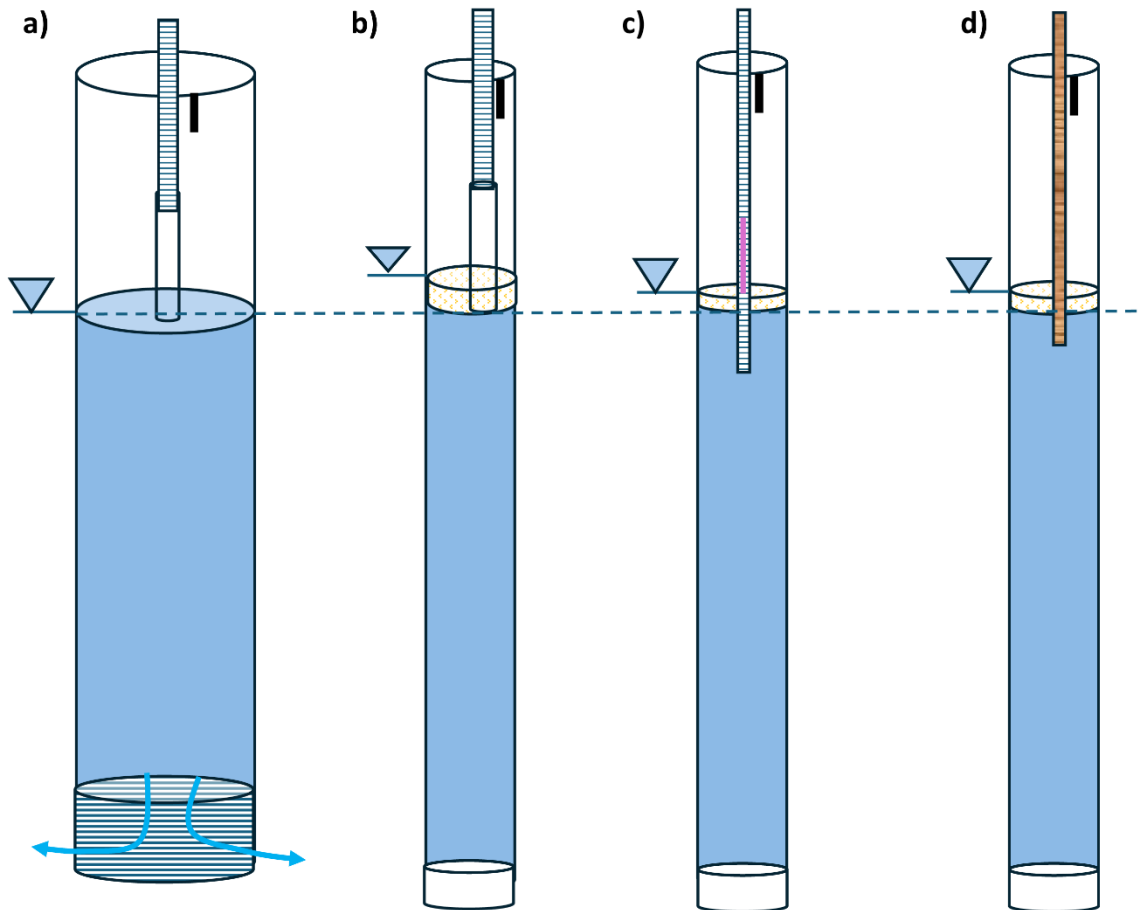


Figure Box 2-1 - Schematic of the effect of placing water level instruments in a monitoring well and the capped (white cylinders) tubes used in the physical water table model. The black vertical line is the surveyed measuring point. Blue shading and the dashed line represent the initial water level (static water level) in the well and tubes. The solid line with the inverted triangle represents the water level after various instruments are inserted. The orange stippled cylinder in the model tubes (b, c, and d) shows a rise in water level caused by the measuring devices displacing water. a) A water level sounder is used to measure the water level (top of blue cylinder) in a monitoring well screened at the base (open to the groundwater system). As the sounder enters the water, it displaces a volume of water equal to the volume of the submerged portion of the probe (water level rises slightly). With this slight increase in head, the displaced volume flows (blue arrows) out into the aquifer through the well's screen (striped cylinder at the base). As a result, the water level in the well (blue line and inverted triangle) re-equilibrates to the original water level (dashed line). No displacement error occurs. The capped tubes filled with water used in the physical model do not let water escape when measurement instruments are inserted. As a result, water levels rise based on the volume of water displaced as illustrated by the white cylinder above the blue cylinder. b) A water level sounder. c) A thin steel tape with a purple water-soluble ink mark. d) A small diameter chalked dowel.

The magnitude of a displacement error is computed by first determining the volume of the instrument submerged ($V_{displaced}$). This is calculated as the submerged length multiplied by the width and multiplied by the thickness. For a dowel the volume displaced is computed as the length of the submerged dowel multiplied by π and multiplied by the radius squared. In general, the resulting rise in the water level inside the tube (WL_{rise}) is computed using Equation Box 2-1.

$$\frac{V_{displaced}}{\pi r_t^2} = WL_{rise} \quad (\text{Box 2-1})$$

where:

$$\begin{aligned}
 V_{displaced} &= \text{volume of submerged instruments (L}^3\text{)} \\
 \pi &= 3.14 \text{ (dimensionless)} \\
 r_t &= \text{inside radius of model well (L)} \\
 WL_{rise} &= \text{displacement of water level in the model tube (L)}
 \end{aligned}$$

For example, if a thin carpenter's tape is submerged 1 cm below the water level in a model well it will displace a volume of equal to 0.05 cm³ (1.0 cm long by 0.5 cm wide by 0.1 cm thick). With the surface area of the water in the model monitoring well computed as 3.14(2.3 cm/2)² = 4.15 cm², an increase in volume of 0.05 cm³ would cause a rise of 0.012 cm (Equation Box 2-1). Thus, knowing how much of the tape was submerged (portion where the water-soluble marker is washed off) the original static water level can be computed by subtracting this value of water level rise from the final reported water level. As an example, a measurement of 28.57 cm would be first corrected for instrument bias, 28.57 cm - 0.01 cm = 28.56 cm. Then it would be corrected for displacement error, 28.56 cm - 0.012 cm = 28.55 cm. Displacement error can be minimized by minimizing the length of instrument submergence. [Exercise 3](#) illustrates the magnitude of this effect on measurements.

The third source of error relates to how the person taking the measurement affects the reported value, which is called operator error. To quantify operator error, more than one measurement of the water level is taken at a single well. Typically, three measurements are recorded, and the average value and its standard deviation (uncertainty) are reported.

For example, an operator attempting to quantify how precisely the water level was measured takes three measurements and then corrects them for instrument bias and, in the case of model wells, displacement error. After corrections the three water level measurements are reported as 28.58 cm, 28.55 cm, and 28.54 cm. This results in an average water level of 28.56 cm. The operator error is expressed as a standard deviation as shown by Equation Box 2-2.

$$s = \left[\frac{\text{SUM}(X - x_{average})^2}{n - 1} \right]^{0.5} \quad (\text{Box 2-2})$$

where:

$$\begin{aligned}
 s &= \text{standard deviation (cm)} \\
 X &= \text{water level measurement (cm)} \\
 x_{average} &= \text{mean water level measurement (cm)} \\
 n &= \text{number of measurements}
 \end{aligned}$$

For this example, the standard deviation is as follows.

$$\left[\frac{(28.58 \text{ cm} - 28.56 \text{ cm})^2 + (28.55 \text{ cm} - 28.56 \text{ cm})^2 + (28.54 \text{ cm} - 28.56 \text{ cm})^2}{3 - 1} \right]^{0.5} = 0.02 \text{ cm}$$

Operator error is usually determined during initial visits made to a well network. Usually only a few wells are measured three consecutive times to provide data for a

calculation of operator error. This error is then assigned to all measurements made by that individual.

Other errors can influence head value computations as typically they are reported as an elevation above sea level. This requires the measuring point on each well to be surveyed to determine the elevation. Errors associated with defining the surveyed elevation are also included in reported measurements. These survey errors include instrument and operator errors that are beyond the scope of this book. In the physical well model described in this book, the survey error is assumed to be zero, though it could be calculated by making multiple measurements of the height of the well measuring point above the horizontal surface datum (floor or ground). Using the methods described above—taking three individual measurements and computing the average and the standard deviation of the error—the water level reported for the well measured from the measuring point would be computed as the average depth to water minus the average surveyed elevation of the measuring point.

For example, assuming the individual measurements have been corrected for instrument bias and displacement errors (model wells), if the operator error is 28.56 cm \pm 0.02cm, and the survey error associated with the measuring point results in an average measuring point elevation and standard deviation of 152.10 cm \pm 0.3 cm, then the average water level is computed by subtracting the average values, and the total error is calculated by combining reported errors. The head is 152.10 cm–28.56 cm = 123.54 \pm the combined errors as described in the next paragraph.

When mean values are added or subtracted, the combined standard deviation error is computed using Equation Box 2-3.

$$Total_error = ((error1)^2 + (error2)^2)^{0.5} \quad (\text{Box 2-3})$$

where:

error1 = Standard deviation of the water level measurement

error2 = Standard deviation of the survey error

In this example, the computed combined error is $((0.02 \text{ cm})^2 + (0.3 \text{ cm})^2)^{0.5} = 0.3 \text{ cm}$ So, the reported water level is 123.54 cm \pm 0.3 cm.

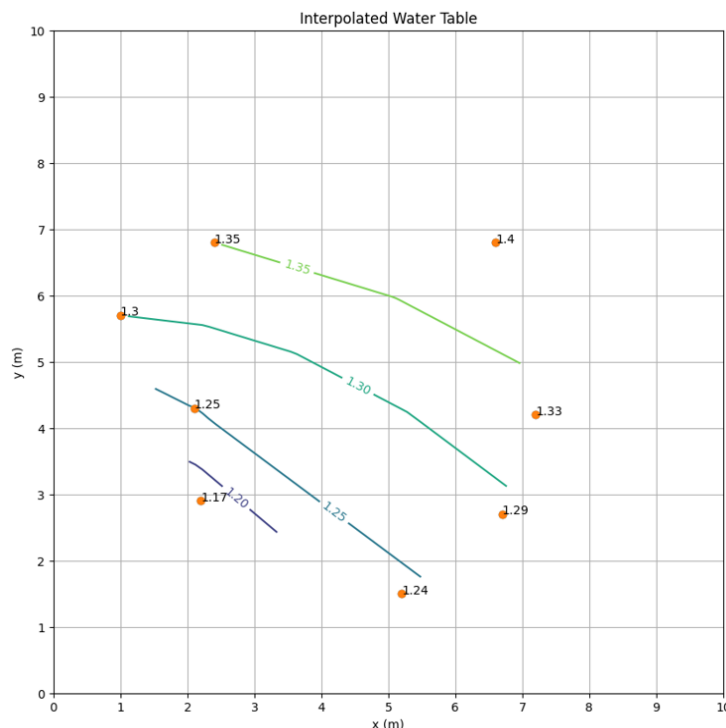
[Back to where text linked to Box 2](#) ↑

10 Exercise Solutions

Solution Exercise 1

Your solution for Exercise 1 will be derived from the unique classroom or outdoor water table model that your instructor has set up. Example solutions for the three parts of this exercise are provided below.

- To obtain the hydraulic head in a pipe (well), subtract the depth to water measurement from the top elevation of the pipe. Table 1 shows an example of this conversion.
- Figure 14 shows examples of network maps created by plotting well locations to scale. Figure 19 shows an example of plotting hydraulic heads and drawing equipotential lines by hand.
- The image shown below is an example of using the Google Colab contouring program, accessed using the link (provided both in Box 1 where the program is described and in the caption below), for automatic linear interpolation of the head data in Figure 19 to create an equipotential map.



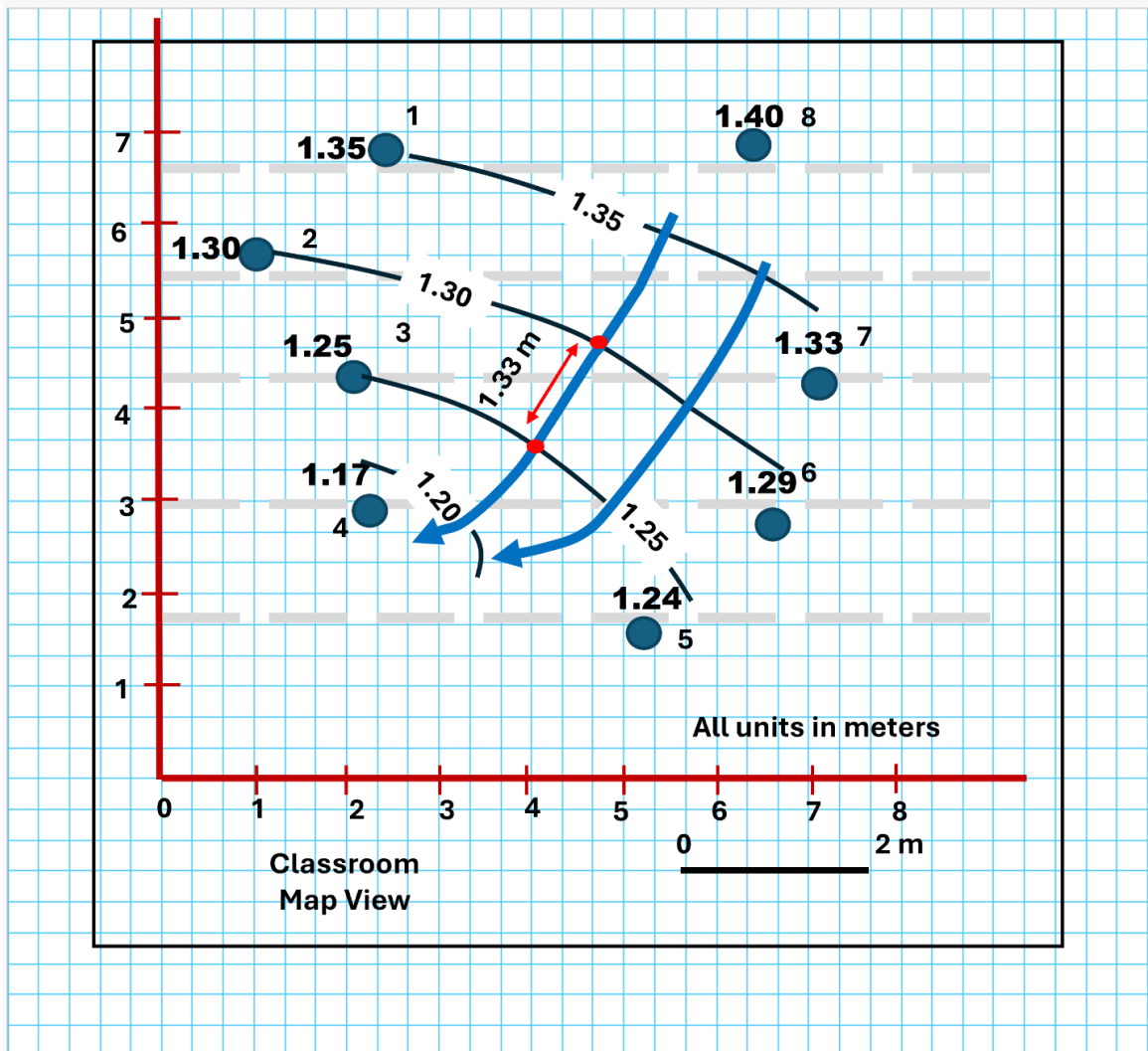
Equipotential map created using automated linear interpolation. The program used was generated in Python and is accessible using the following link.
(<https://colab.research.google.com/drive/1hFuQfQACqLHOcTmCMCxacNMBOcwSmFR?usp=sharing>)

[Return to Exercise 1](#) ↑

[Return to where text linked to Exercise 1](#) ↑

Solution Exercise 2

Discharge is computed using Darcy's Law (Equation (1)). First, field data are used to compute the hydraulic gradient, i . Then the gradient, cross-sectional area parallel to an equipotential line and the hydraulic conductivity are used to compute groundwater discharge, $Q = -KiA$. The image shows how a gradient is calculated using the example physical model described in this book. The gradient is computed along a groundwater flow line plotted at right angles to the interpolated equipotential lines. The distance along a flow line between two equipotential lines is the shortest distance between the lines when conditions are isotropic and homogeneous (i.e., a single hydraulic conductivity value represents the material, as is the case here). The groundwater gradient, i (Equation (3)), is the head difference from one equipotential line to the next divided by the perpendicular distance between the lines, $i = -0.05 \text{ m}/1.33 \text{ m} = -0.04$ in this example. Often water table gradients in the field are 0.01 to 0.001.



Map of an interpolated flow field. All units are in meters. Blue arrows are groundwater flow lines. The change in head over a distance of 1.33 m is 0.05 m (between red dots).

Discharge through a 2 m long by 1.3 m deep vertical cross section of the sand and gravel water table system at right angles to a groundwater flow line is computed as:

$$Q = -\frac{90 \text{ m}}{d}(-0.04)(2 \text{ m})(1.33 \text{ m}) = 9.4 \frac{\text{m}^3}{d}$$

- a) The average linear velocity, v , is computed assuming the porosity for the sand and gravel is 0.15. Using Equation (4) the average linear velocity is computed as:

$$v = -\frac{Ki}{n_e} = -\frac{\frac{90 \text{ m}}{d}(-0.04)}{0.15} = 24 \frac{\text{m}}{d}$$

[Return to Exercise 2](#) ↑

[Return to where text linked to Exercise 2](#) ↑

Solution Exercise 3

a) As an example, well 3 shown in Table 1 was measured three times and readings of the water levels were 26.70 cm, 27.10 cm and 26.98 cm. The average water level is their sum divided by the number of measurements, i.e., 3.

$$\frac{26.70 \text{ cm} + 27.10 \text{ cm} + 26.98 \text{ cm}}{3} = 26.93 \text{ cm}$$

As shown in Equation (Box 2-1), the error as a standard deviation is as follows.

$$s = \left[\frac{\text{SUM}(X - x_{\text{average}})^2}{n - 1} \right]^{0.5}$$

For this example, the standard deviation s is as follows.

$$\left[\frac{(26.70 \text{ cm} - 26.93 \text{ cm})^2 + (26.71 \text{ cm} - 26.93 \text{ cm})^2 + (26.98 \text{ cm} - 26.93 \text{ cm})^2}{3 - 1} \right]^{0.5} = 0.21 \text{ cm}$$

The operator error uncertainty is most frequently designated as one standard deviation. For example, using the above calculation the reported water level that accounts for operator uncertainty is 26.93 cm \pm 0.21 cm. To correct for instrument bias, adjust each original measurement value by the constant instrument bias value before computing the average water level.

b) The table below shows an example of determining the instrument bias for three steel carpenter's tapes by comparing them to a measuring tape designated as a standard.

Tape Number	Difference from Standard Tape (cm)
1	+ 0.01
2	-0.02
3	-0.01

These differences would be subtracted from each measurement made with the individual tape.

c) These examples quantify the magnitude of the displaced water in the model wells from an electric sounding probe, a carpenter's tape, and a chalked wooden dowel.

1. An electric sounding probe is used to measure water levels in the model tube. It has a diameter of 1.75 cm and is submerged 0.7 cm into a 2.3 cm diameter model well. The displacement water level change would be computed as

$$\frac{3.14 \left(\frac{1.75 \text{ cm}}{2}\right)^2 0.7 \text{ cm}}{3.14 \left(\frac{2.3 \text{ cm}}{2}\right)^2} = 0.41 \text{ cm}$$

2. A thin carpenter's tape is used to measure the water level in a 2.3 cm diameter model well. The tape has a width of 1 cm and a thickness of 0.2 cm. To obtain the water level 4.32 cm of tape was below the water level. Compute the magnitude of the displacement water level that would occur from using this water level measuring device.

$$\frac{1 \text{ cm} (0.2 \text{ cm}) (4.32 \text{ cm})}{3.14 \left(\frac{2.3 \text{ cm}}{2}\right)^2} = 0.21 \text{ cm}$$

3. A thin chalked dowel is used to measure the water level in a 2.3 cm diameter model well. The dowel has a diameter of 0.63 cm. To obtain the water level 4.32 cm of the dowel was below the water level. Compute the magnitude of the displacement water level that would occur from using this water level measuring device.

$$\frac{3.14 \left(\frac{0.63 \text{ cm}}{2}\right)^2 4.32 \text{ cm}}{3.14 \left(\frac{2.3 \text{ cm}}{2}\right)^2} = 0.32 \text{ cm}$$

4. Comment on whether accounting for the displacement of water levels would have impacted your interpretation of the head distribution and direction of flow in the model conditions represented by your model.

For the examples presented, the three measurement methods caused an additional 0.2 to 0.5 cm of water level rise in the model well. This condition is likely more than instrument error or operator errors computed as part of this exercise. If the wells were all of the same diameter and the measurements at all wells were made with the same instrument, with the same amount of the submerged tool at each well, then the displacement would be the same for every measurement. Although this would create a constant bias with all levels slightly higher than the static level, these relative water levels would yield acceptable flow direction and discharge values with water level correction. If the instrument was a sounder then the amount of submersion is always the same, so if all the wells had the same diameter, then displacement error would not need to be considered. For the purpose of the classroom model this would not affect over all flow interpretations. However, if different instruments were used or the same instrument was used and submerged to different levels in each of the wells, displacement water level would affect final reported values and may influence

interpretations. Displacement values would then need to be computed for all the water level measurements, and the water levels would need to be corrected. For the classroom example, since water levels were rounded to the nearest centimeter to complete interpolation and contouring, the displacement effects are likely to have little impact on final flow and gradient interpretations. However, it is recommended to determine displacement errors and make the corrections.

[Return to Exercise 3](#)↑

[Return to where text linked to Exercise 3](#)↑

11 Notations

- A = vertical cross-sectional area (L^2)
 d = cross-sectional depth (L)
error 1 = standard deviation of the water level measurement
error 2 = standard deviation of the survey error
 h_1 = head at a higher elevation (L)
 h_2 = head at a lower elevation (L)
 i = hydraulic gradient (dimensionless)
 K = hydraulic conductivity (LT^{-1})
 L = distance between h_1 and h_2 (L)
N or n = number of measurements
 n_e = effective porosity (dimensionless)
 π = 3.14 (dimensionless)
 Q = discharge (L^3T^{-1})
 r_t = inside radius of model well (L)
 s = standard deviation (dimensions of parameter evaluated)
 v = average groundwater velocity (LT^{-1})
 $V_{displaced}$ = volume of submerged instrument (L^3)
 w = cross-sectional total width (L)
 WL_{rise} = displacement of water level in the model tube (L)
 X = water level measurement (L)
xaverage = mean water level measurement (L)

Funding Acknowledgment

Refinement of material presented in this book was supported in part by funding received by the University of Montana. Grants include award number NE-96830301 funded by the US Environmental Protection Agency (EPA) and award number 1543228 funded by the National Science Foundation (NSF). This work has not been reviewed by the EPA or the NSF. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the EPA or the NSF. Neither the EPA nor the NSF endorses any products or commercial services mentioned in this publication.

12 About the Authors



William W. Woessner is a Montana University System Emeritus Regents' Professor of Hydrogeology. For over 30 years, he taught introductory and graduate courses in the hydrogeological sciences at the University of Montana, Missoula, USA. As a teacher he is always looking for innovative approaches to reinforcing basic groundwater principles. Dr. Woessner is the Past Acting Director of the Center for Riverine Science and Stream Re-naturalization, and President of Woessner Hydrologic, LLC. He has mentored over 60 graduate students, many of whom have founded environmental consulting firms; worked for environmental non-profits; local, state, and federal agencies, and corporations. Professor Woessner is well versed in field methods and application of modeling tools. He is the coauthor of two editions of *Applied Groundwater Modeling: Simulation of Flow and Advective Transport*. He served as a 2011 Fulbright Scholar-NAWI Austria. Professor Woessner is a Fellow of the Geological Society of America, served as the Geological Society of America Hydrogeology Division Birdsall-Dreiss Lecturer in 2005, and received the society's 2020 O. E. Meinzer Award. In addition, he is a Fellow and Life Member of the National Groundwater Association and was awarded the John Hem Excellence in Science and Engineering Award in 2008.



Beth A. Covitt, Head of Science Education Research & Evaluation with the University of Montana's Broader Impacts Group, has been working in the fields of environmental and science education for over 30 years. She has a keen interest in environmental science literacy and supporting students in becoming well prepared to use science to inform decision-making. Dr. Covitt has served as PI, Co-PI, or evaluator on numerous projects (funded, for example, by EPA, NASA, NOAA, NSF, and USDA) spanning many topics but has particular interest in water and climate education. Her efforts encompass science education research and evaluation, program and curriculum development, and teacher professional learning. She has an MS in environmental resource policy and behavior and a PhD in environmental education and conservation psychology, both from the University of Michigan. She currently serves as editor of *The Journal of Environmental Education*.



W. Payton Gardner is an Associate Professor of Geosciences at the University of Montana. Dr. Gardner has an active research program in Hydrogeology and has taught classes in Hydrogeology and Hydrology from the introductory to graduate level. Dr. Gardner's research focuses on regional hydrogeology, mountain hydrogeology, hydrogeodesy, and isotope hydrology. He is an active member of the American Geophysical Union, European Geophysical Union, and Geological Society of America.

Please consider signing up for the GW-Project mailing list to stay informed about new book releases, events and ways to participate in the GW-Project. When you sign up for our email list it helps us build a global groundwater community. [Sign up](#)[↗].

