Modeling Your Water Balance

Purpose
To model a soil's water storage over a year

Overview
Students create a physical model illustrating the soil water balance using glasses to represent the soil column. They use data from the GLOBE Database to calculate the potential evapotranspiration (the amount of water needed to meet the demand for the month), average monthly temperatures and precipitation for their model. They then construct a model representing the soil water balance for their site.

Student Outcomes
Students will be able to create a model of the physical environment and explain how the model can be used to interpret data and form predictions.

Science Concepts

Earth and Space Science
- Soils have properties of color, texture and composition; they support the growth of many kinds of plants.
- Soils consist of weathered rocks and decomposed organic matter.
- Water circulates through the biosphere, lithosphere, atmosphere and hydrosphere (water cycle).

Scientific Inquiry Abilities
- Identify questions.
- Design and conduct a scientific investigation.
- Use appropriate tools and techniques.
- Use data to construct a reasonable explanation.
- Recognize and analyze alternative explanations.
- Use appropriate mathematics.
- Communicate procedures and explanations.

Time
One class period to calculate values

One class period to construct model

One class period for hypothesis testing

Level
Intermediate and advanced

Materials and Tools
Part I: Physical model
- 14 beakers, glasses, or graduated cylinders (approximately 20-25 cm tall, or tall enough to hold the total precipitation for the wettest month at your model site)
- Water
- Red and black permanent markers
- Ruler
- Data from the GLOBE server or from the example below

Part II: Mathematical model
- One year of precipitation, temperature, and soil moisture data
- Tables and charts from this activity

Preparation
For Part II, find schools which have appropriate data in the GLOBE database.

Prerequisites
Simple math calculations, reading graphs, and using the GLOBE visualizations tools.

Background

The amount of water stored in the soil at your site can be estimated by creating a water balance model for your area. The water content of your soil depends on the balance between water gained due to precipitation and water lost through evaporation and transpiration. The combined amounts of water lost through evaporation and transpiration is *evapotranspiration*. The maximum amount of evapotranspiration, *potential evapotranspiration*, would occur if water were always available. Since at times, for instance during a dry summer, the amount of water evaporated may exceed precipitation, water is not always available to meet demand.

The water content of your soil is a key factor in determining which plants can grow in your area. Several factors control the water content of your soil including temperature, the duration of sunshine, the amount of groundcover and the amount of precipitation. One might think the months of highest precipitation would also be the months with the greatest soil water content. This may not be true, but not always! If the temperatures are so great that most of the water evaporates, a cooler month may actually have higher soil water content. Scientists study the water balance in an area to predict when plants will grow and when they will be under stress due to lack of water.

Teacher Support

Advance Preparation

Discuss with students the importance of water held in the soil. You may want to do the *Just Passing Through* learning activity to illustrate the holding capacity of different soils.

What to Do and How to Do It

Examine the data from 1999 for Reynolds Jr Sr High School. Potential Evapotranspiration (PE) is the amount of water that would be lost through evaporation and transpiration if water was always available. When PE is less than precipitation, water is available to plants. When PE is greater than precipitation, plants must depend on water stored in the soil. PE is calculated for this model using a mathematical formula that includes two variables, temperature and duration of sunlight.

Have the students answer the following questions to interpret the data.

- Which month has the most precipitation? Which has the least?
- Which month is the warmest? Which is the coldest?
- During which months might you expect to have runoff (too much water to store in the soil)?
- During which months would you expect to have a water shortage (not enough water stored in the soil to meet the needs of plants)?

Reynolds Jr Sr High School, Greenville, PA, US, 1999 data

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total Monthly Precipitation (mm)	120	70	55	121	63	50	77	84	62	35	109	56
PE Potential Evapotransportation (mm)	0.0	0.0	0.0	42	85	118	141	109	83	36	20	0.0
Average Monthly Temperature (˚C)	-4.6	-0.7	-1.1	9.0	14.8	19.5	22.4	19.2	17.0	8.9	6.2	-1.6

Part I – A Physical Model

Setting Up Your Model

1. Have students set out 12 containers representing months of the year. Label them from January through December. See Figure HY-BA-1.
2. Using the Reynolds data (or other data provided), have the students find the PE for each month. They can use a ruler and a black marker to draw a line on each container indicating the PE in mm for each month.
3. Mark the 13th container as storage. Make a line at 100 mm on the container to indicate when storage is full. The 14th container is for Precipitation.

Using Your Model

Provide the following instructions to your students.

1. Find the amount of precipitation for January in the table. Measure out this amount of water into the precipitation beaker. Then pour the 'precipitation' into the January beaker, using the following rules:

Rule 1: If you have more precipitation than you need for the month, fill the January container to the PE line, then pour the rest of the water into Storage.

Rule 2: The Storage container can only be filled to 100 mm. If January is full to the PE line and the Storage is full, throw away the rest of the water.

Rule 3: If you do not have enough precipitation to fill the January container to the PE line, pour in all the precipitation then take water out of storage to fill up January to the PE line.

Rule 4: If you have used all the precipitation for the month and the Storage is empty, make a red line on the January cup indicating the water line. The difference between the black and red lines is a water shortage.

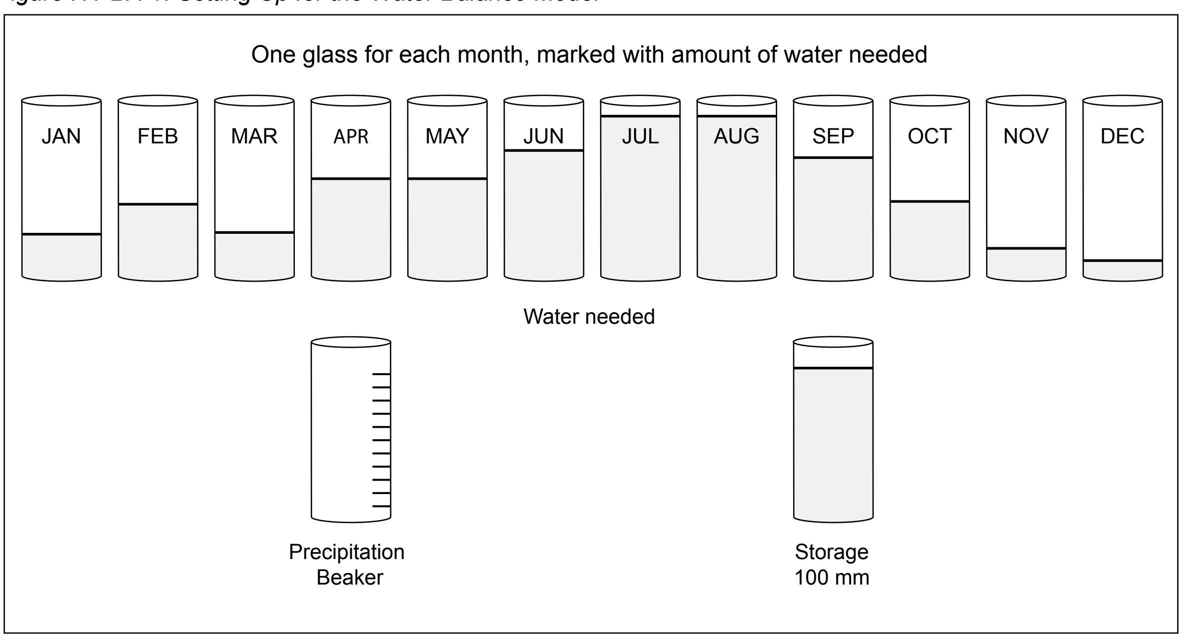
2. Repeat the steps for each month, progressing through the year.

Discuss Your Results

Ask students the following questions,

1. Which months show a water shortage? Did this agree with your hypothesis? Are there any variables you might now take into consideration in forming a hypothesis on water shortages at a site?
2. Are water shortages always in months with the least precipitation?
3. Are water shortages always in months with the highest temperatures?
4. During which months might you expect floods?

Figure HY-BA-1: Setting Up for the Water Balance Model



Testing Hypotheses With Your Model

Have your students form hypotheses that predict how the water balance will change with changes in variables.

Have them consider the following possibilities.

1. What happens if you have a particularly wet winter? (increase the winter precipitation for one winter month)
2. What happens if you have an unusually dry summer? (decrease the summer precipitation for one summer month)
3. What happens if you have an unusually hot summer (increase the water needed (PE) for the summer months)
4. What happens if you increase your storage through building an artificial reservoir? (increase Storage to 150 mm)

Have students test their hypotheses by changing variables in the table and running the model again.

Notes: Have students start the experiment with October as the starting month. Hydrologists sometimes define a “water year” as starting in October (in the northern hemisphere), before the winter snow accumulation season. Is there a different result?

Further Investigations

Using the Calculating Potential Evapotranspiration Using Graphs Work Sheet or the formulas at the end of the activity, students can find the PE figures for any GLOBE school with a year of temperature data.

Have students:

1. Use their own school data, or find other GLOBE schools in different parts of the world, to explore differences in the water balance in different ecosystems or biomes.
2. Examine the water balance of one site for several years. Does the water balance change from year to year?

Part II – A Mathematical Model

Have students complete the *Water Balance Table Work Sheet* for their own site or another site using GLOBE data.

Have students do the following steps to fill in the *Work Sheet*:

1. Find the total monthly precipitation for each month and fill in the precipitation row in the table.
2. Find the Potential Evapotranspiration (PE) for each month and fill in the PE row in the table. (PE may be calculated using the *Calculating the Potential Evapotranspiration (PE) Using Graphs Work Sheet* or by using the formulas at the end of the end of this activity.
3. Find the difference between the precipitation and the water needed (PE) for the first month.
   - *If there is more water than needed,* enter the difference in the Extra Water Row.
   - Enter this difference into the Storage row, adding it to any water already in Storage from the previous month.

   Note: In the first month there is no number to add from the previous month.
   Note: Storage cannot be greater than 100. Put the amount over 100 mm into Runoff.
4. *If there is less water than needed,* enter the difference into the Extra Water Needed row.
   - To find the Storage, subtract

   (Storage from the previous month) – (Extra Water Needed from the current month).

   If the difference is greater than 0, enter this number into the Storage box. If the number is less than 0, enter 0 into Storage and the result into Shortage.
   Note: Shortages are not cumulative. Do not add them together from previous months.
5. Follow Step 3 across the table for each month.
   Note: The months must be done in order.
6. Calculate the actual amount of water loss through evapotranspiration (AE):
   If Precipitation > PE:

   AE = PE

   If precipitation < PE:

   AE = PE - Shortage
7. Graph the precipitation, actual evapotranspiration, and PE (3 lines) for the site on one graph using the months on the X-axis, and mm of water on the Y-axis. Examine the graph and shade in areas where you have water surplus, water shortage, recharge, and runoff.

Water Balance Table Work Sheet

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation (mm)												
(PE) Potential Evapotranspiration												
Extra Water												
Water Needed												
Storage												
Shortage												
Runoff												
(AE) Actual Evapotranspiration												

Key to Table

Precipitation: Total precipitation for the month

Potential Evapotranspiration (PE): Total amount of water that would be lost through evaporation and transpiration if water were always available. Find the PE using the *Calculating Potential Evapotranspiration Using Graphs Work Sheet* or by using the formulas at the end of the activity.

Extra Water: Precipitation in excess of what is needed to meet monthly demand

Extra Water = (Precipitation – PE) when the difference is positive

Extra Water Needed: Water needed from storage to meet demand

Extra Water Needed = (Precipitation – PE) when the difference is negative

Water in Storage: Water stored in soil. Storage is never less than 0 or greater than field capacity (field capacity is assumed to be 100 mm for this model)

Storage = Storage (previous month) + Extra Water or

Storage = Storage (previous month) – Extra Water Needed

Water Shortage: Water needed in excess of precipitation and storage to meet demand

Shortage = Water Needed (current month) – Storage (previous month)
when the difference is negative

Runoff: Water lost when precipitation is greater than PE and Storage is at capacity

Runoff = Extra Water (current month) + Storage (previous month)
when sum >100

Actual Evapotranspiration (AE): the amount of water that is actually lost through evaporation and transpiration

AE = PE - Shortage

Further Investigations

Have students:

1. Examine the GLOBE soil moisture data from the site where they modeled the water balance. What correlation can they find between your model and the soil moisture data?
2. Graph their measurements of water chemistry. Are there any indications of changes in the water balance that may correlate with water quality?
3. Use their model to examine possible effects of a hotter summer or wetter rainy season than normal.
4. Think about other factors that may affect their soil moisture such as vegetative cover, soil type, etc. How could they incorporate these variables into their model?

Have students think about assumptions that are made in this simple model such as 'soil holds 100 mm of water' or 'all water not held in storage runs off'. How might these assumptions affect their results? How could they make the model better?

Example Answers: School: Reynolds Jr Sr High School, Greenville, PA, US, 1999 data)

Water Balance Table Work Sheet

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation (mm)	120	70	55	121	63	50	77	84	62	35	109	56
(PE) Potential Evapotranspiration	0	0	0	42	85	118	14	109	83	36	20	0
Extra Water	120	70	55	79							88	56
Water Needed					22	68	64	25	21	1		
Storage	100	100	100	100	78	10					88	100
Shortage							53	25	21			
Runoff	20	70	55	79								44
(AE) Actual Evapotranspiration	0.0	0.0	0.0	42	85	118	87	84	62	35	20	0
Temperature (˚C)	-4.6	-0.7	-1.1	9.0	14.8	19.5	22.4	19.2	17.0	8.9	6.2	-1.6

Completed Potential Evaporation Table

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avg. Monthly Temperature (˚C)	-4.6	-0.7	-1.1	9	14.8	19.5	22.4	19.2	17	8.9	6.2	-1.6
Heat Index (from equation)	0	0	0	2.4	5.2	7.9	9.7	7.7	6.4	2.4	1.4	0
UPE (from equation)	0	0	0	38.1	68.2	94.2	110.9	92.5	80.2	37.6	24.6	0
Correction Factor (CF) (from table)	0.84	0.83	1.03	1.11	1.24	1.25	1.27	1.18	1.04	0.96	0.83	0.81
PE (UPE x CF)	0	0	0	42	85	118	141	109	83	36	20	0

Using the equation method (step 2) – I is the sum of the monthly Heat Indexes. I = 43

And m is an exponent calculated in step 3a. m = 1.17

Method 1: Calculating Potential Evapotranspiration Using Graphs

Calculating Potential Evapotranspiration (PE) Using Graphs Work Sheet

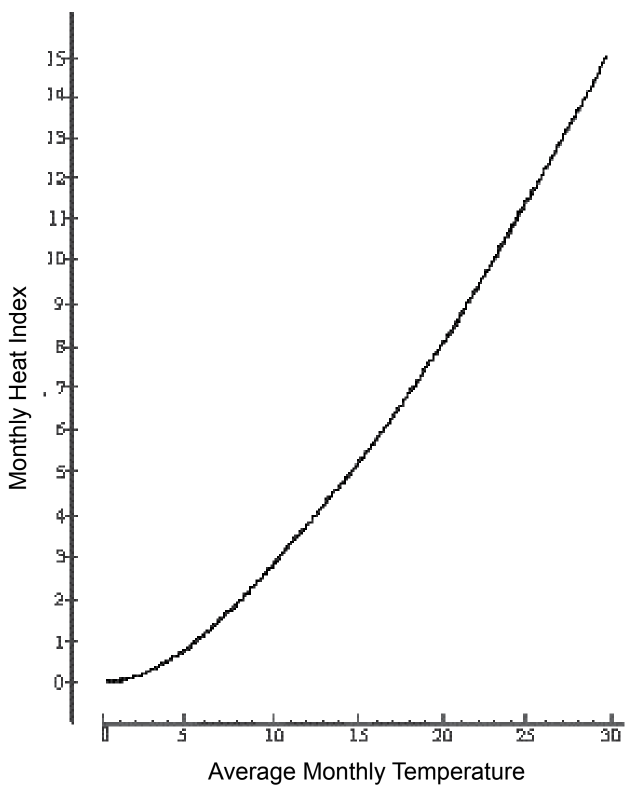
Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avg. Monthly Temperature (˚C)												
Heat Index (from graph)												
UPE (from graph)												
Correction Factor (CF) (from table)												
PE (UPE x CF)												

Step 1

Determine the Average Monthly Temperature for your site by exporting the data from the GLOBE visualization tool (e.g., into a spreadsheet and calculating monthly averages).

Step 2

Find the **Heat Index** for each month from the graph below.



Month	Average Monthly Temperature (˚C)	UPE (Unadjusted Potential ET) (mm)
Jan		
Feb		
Mar		
Apr		
May		
Jun		
Jul		
Aug		
Sep		
Oct		
Nov		
Dec		
Annual Heat Index ________________		

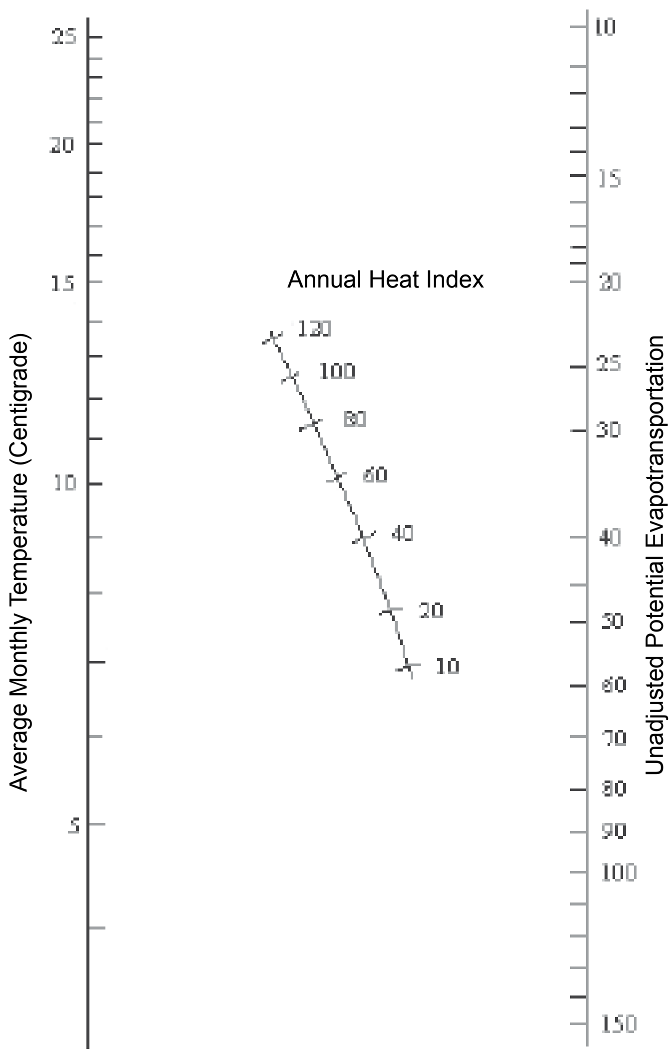
Step 3

Add the Monthly Heat Indexes together to get the Annual Heat Index: ____________

Step 4

Use the **Annual Heat Index** and the **Average Monthly Temperature** for each month to find the **Unadjusted Potential Evapotranspiration** (UPE) from the graph below. **Note:** If the average temperature for the month <0, the UPE for that month is 0. If the average temperature for the month >25.0, use the **UPE for High Temperatures** graph.

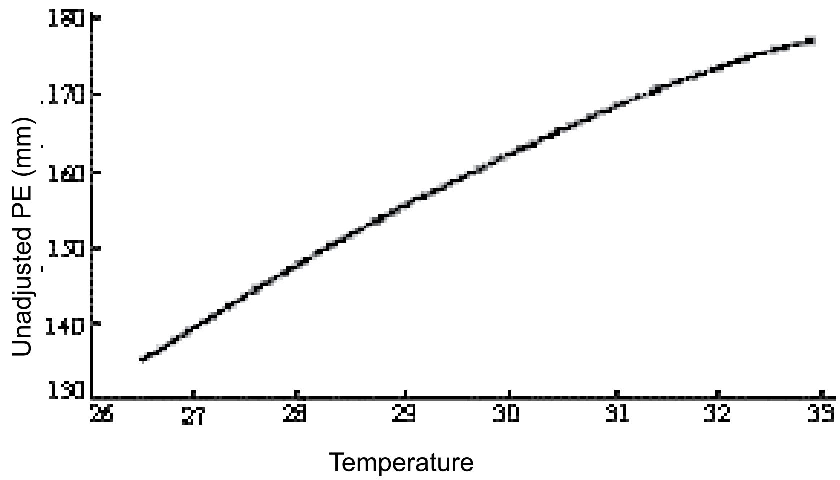
Unadjusted Potential Evapotransportation



Annual Heat Index ___________		
Month	**Average Monthly Temperature (˚C)**	**UPE (Unadjusted Potential ET) (mm)**
Jan		
Feb		
Mar		
Apr		
May		
Jun		
Jul		
Aug		
Sep		
Oct		
Nov		
Dec		

Note: To use the graph above, find your Average Monthly Temperature on the left and your Annual Heat Index in the center. Make a straight line joining the 2 points across the graph and read the UPE on the right.

Unadjusted PE for High Temperature



Note: Draw a vertical line up from temperature to the curve, then a horizontal line left from the curve to the UPE line. For example, a temperature of 27˚ C would have a UPE of ~ 140 mm

Step 5

Find the latitude of the school. Record the **Correction Factor** for each month from the table below.

Daylight Correction Factors for Potential Evapotranspiration

Latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	1.04	0.94	1.04	1.01	1.04	1.01	1.04	1.04	1.01	1.04	1.01	1.04
10 N	1.00	0.91	1.03	1.03	1.08	1.06	1.08	1.07	1.02	1.02	0.98	0.99
20 N	0.95	0.90	1.03	1.05	1.13	1.11	1.14	1.11	1.02	1.00	0.93	0.94
30 N	0.90	0.87	1.03	1.08	1.18	1.17	1.20	1.14	1.03	0.98	0.89	0.88
40 N	0.84	0.83	1.03	1.11	1.24	1.25	1.27	1.18	1.04	0.96	0.83	0.81
>50 N	0.74	0.78	1.02	1.15	1.33	1.36	1.37	1.25	1.06	0.92	0.76	0.70
10 S	1.08	0.97	1.05	0.99	1.01	0.96	1.00	1.01	1.00	1.06	1.05	1.10
20 S	1.14	1.00	1.05	0.97	0.96	0.91	0.95	0.99	1.00	1.08	1.09	1.15
30 S	1.20	1.03	1.06	0.95	0.92	0.85	0.90	0.96	1.00	1.12	1.14	1.21
40 S	1.27	1.06	1.07	0.93	0.86	0.78	0.84	0.92	1.00	1.15	1.20	1.29
>50 S	1.37	1.12	1.08	0.89	0.77	0.67	0.74	0.88	0.99	1.19	1.29	1.41

Step 6

Multiply the Correction Factor by the UPE to find the Potential Evapotranspiration (PE). Record the PE on the *Water Balance Work Sheet*.

Method 2: Calculating Potential Evapotranspiration Using Formulas

Older students, or schools which have monthly average temperatures outside the range of the graphs, may use the following formulas to find the PE.

Step 1

First calculate a monthly heat index (i) for each month using the following formula

$$i = \left(\frac{T}{5}\right)^{1.514} \quad \text{for } T > 0$$

$$i = 0 \quad \text{for } T \leq 0$$

where T is the average temperature of the month in degrees C.

Step 2

Find the sum of the twelve monthly heat indexes to get the annual heat index (*I*)

$$I = i_{JAN} + i_{FEB} + i_{MAR} \ldots + i_{DEC}$$

Step 3

a. First calculate the exponent *m*, to be used below. *m* is a number that depends on *I*. The value of m is given by the formula

$$m = (6.75 \times 10^{-7})\, I^3 - (7.71 \times 10^{-5})\, I^2 + (1.79 \times 10^{-2})\, I + 0.492$$

b. To get the unadjusted PE use the formula

$$\text{Unadjusted PE (millimeters)} = \begin{cases} 0 & T < 0^\circ C \\ 16\left(\frac{10T}{I}\right)^m & T \leq 0 \leq 26.5^\circ C \\ -415.85 + 32.24T - 0.43T^2 & T > 26.5^\circ C \end{cases}$$

Where T is the average temperature in degrees C for the specific month being considered.

c. Once the unadjusted PE has been calculated, use the Daylength Correction Table to find the adjusted PE.

*adapted from *Physical Geography Today: A Portrait of a Planet* (1978) Robert A. Muller and Theodore M. Oberlander, Random House: using the Thornthwaite Formula for Potential Evapotransporation

Method 1: Calculating Potential Evapotranspiration Using Graphs

Calculating Potential Evapotranspiration (PE) Using Graphs Work Sheet

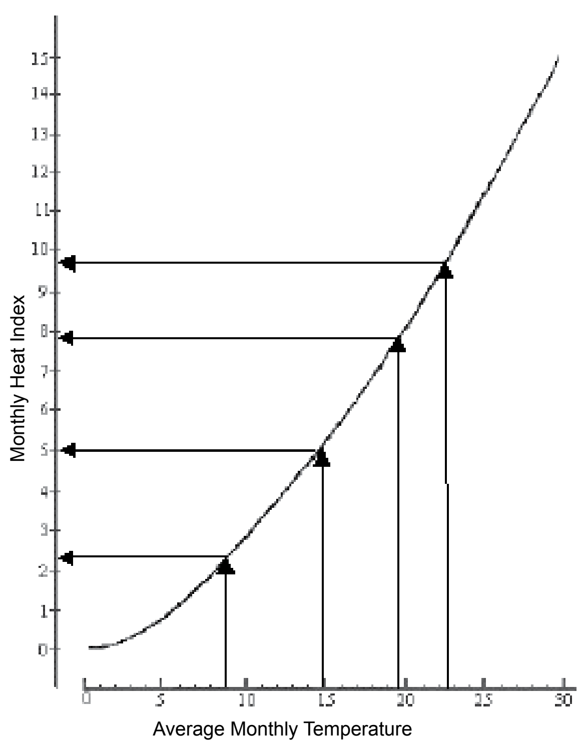
Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avg. Monthly Temperature (˚C)	-4.6	-0.7	-1.1	9.0	14.8	19.5	22.4	19.2	17.0	8.9	6.2	-1.6
Heat Index (from graph)	0	0	0	38	66	91	108	89	78	37	25	0
UPE (from graph)	1.04	0.94	1.04	1.01	1.04	1.01	1.04	1.04	1.01	1.04	1.01	1.04
Correction Factor (CF) (from table)	0.84	0.83	1.03	1.11	1.24	1.25	1.27	1.18	1.04	0.96	0.83	0.81
PE (UPE x CF)	0	0	0	42	82	114	137	105	81	36	21	0

Step 1

Determine the Average Monthly Temperature for your site by exporting the data from the GLOBE visualization tool (e.g., into a spreadsheet and calculating monthly averages).

Step 2

Find the **Heat Index** for each month from the graph below.



Month	Average Monthly Temperature (˚C)	UPE (Unadjusted Potential ET) (mm)
Jan	-4.6	0
Feb	-0.7	0
Mar	-1.1	0
Apr	9.0	2.3
May	14.8	5.0
Jun	19.5	7.8
Jul	22.4	9.8
Aug	19.2	7.6
Sep	17.0	6.5
Oct	8.9	2.4
Nov	6.2	1.2
Dec	-1.6	0
Annual Heat Index 42.6 (rounds to 43)		

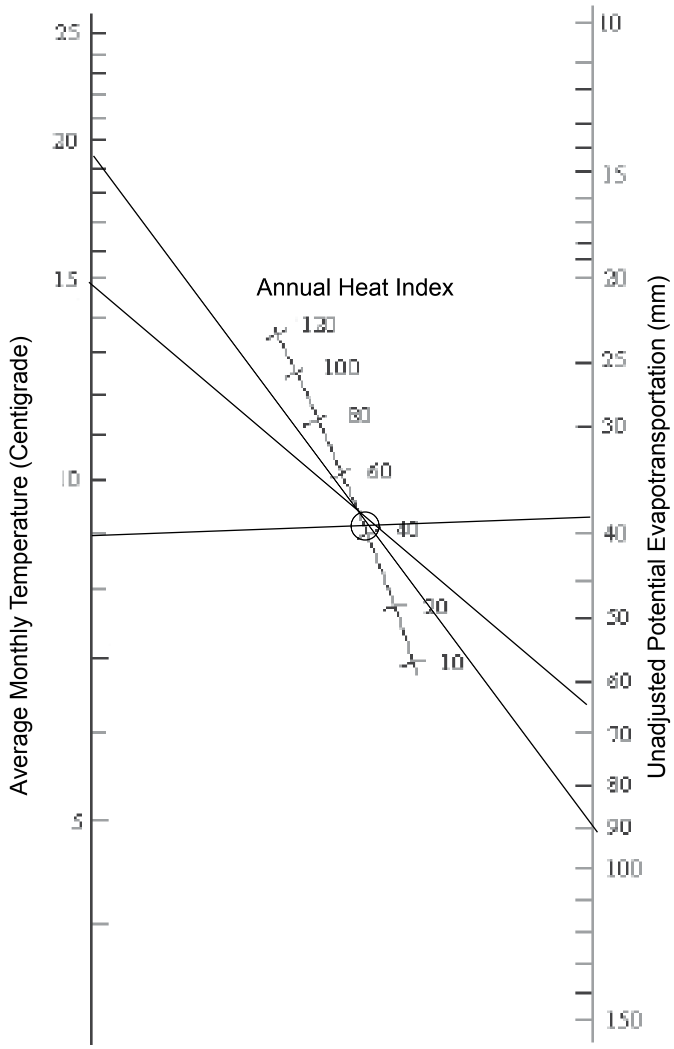
Step 3

Add the Monthly Heat Indexes together to get the Annual Heat Index: 43

Step 4

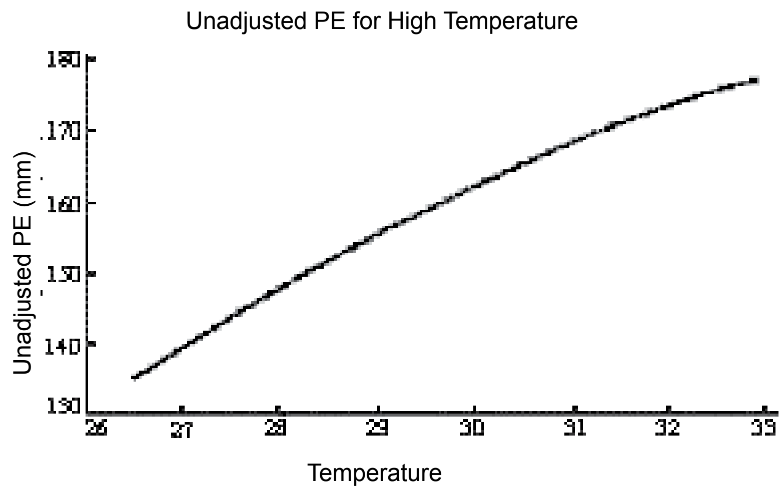
Use the **Annual Heat Index** and the **Average Monthly Temperature** for each month to find the **Unadjusted Potential Evapotranspiration** (UPE) from the graph below. **Note:** If the average temperature for the month <0, the UPE for that month is 0. If the average temperature for the month >25.0, use the **UPE for High Temperatures** graph.

Unadjusted Potential Evapotransportation



Annual Heat Index 43		
Month	**Average Monthly Temperature (˚C)**	**UPE (Unadjusted Potential ET) (mm)**
Jan	-4.6	0
Feb	-0.7	0
Mar	-1.1	0
Apr	9.0	38
May	14.8	66
Jun	19.5	91
Jul	22.4	108
Aug	19.2	89
Sep	17	78
Oct	8.9	37
Nov	6.2	25
Dec	-1.6	0

Note: To use the graph above, find your Average Monthly Temperature on the left and your Annual Heat Index in the center. Make a straight line joining the 2 points across the graph and read the UPE on the right.



Note: Draw a vertical line up from temperature to the curve, then a horizontal line left from the curve to the UPE line. For example, a temperature of 27º C would have a UPE of ~ 140 mm

Step 5

Find the latitude of the school. Record the **Correction Factor** for each month from the table below.

Latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	1.04	0.94	1.04	1.01	1.04	1.01	1.04	1.04	1.01	1.04	1.01	1.04
10 N	1.00	0.91	1.03	1.03	1.08	1.06	1.08	1.07	1.02	1.02	0.98	0.99
20 N	0.95	0.90	1.03	1.05	1.13	1.11	1.14	1.11	1.02	1.00	0.93	0.94
30 N	0.90	0.87	1.03	1.08	1.18	1.17	1.20	1.14	1.03	0.98	0.89	0.88
40 N	0.84	0.83	1.03	1.11	1.24	1.25	1.27	1.18	1.04	0.96	0.83	0.81
>50 N	0.74	0.78	1.02	1.15	1.33	1.36	1.37	1.25	1.06	0.92	0.76	0.70
10 S	1.08	0.97	1.05	0.99	1.01	0.96	1.00	1.01	1.00	1.06	1.05	1.10
20 S	1.14	1.00	1.05	0.97	0.96	0.91	0.95	0.99	1.00	1.08	1.09	1.15
30 S	1.20	1.03	1.06	0.95	0.92	0.85	0.90	0.96	1.00	1.12	1.14	1.21
40 S	1.27	1.06	1.07	0.93	0.86	0.78	0.84	0.92	1.00	1.15	1.20	1.29
>50 S	1.37	1.12	1.08	0.89	0.77	0.67	0.74	0.88	0.99	1.19	1.29	1.41

Step 6

Multiply the Correction Factor by the UPE to find the Potential Evapotranspiration (PE). Record the PE on the *Water Balance Work Sheet*.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UPE	0	0	0	38	66	91	108	89	78	37	25	0
Correction Factor	0.84	0.83	1.03	1.11	1.24	1.25	1.27	1.18	1.04	0.96	0.83	0.81
PE	0	0	0	42	82	114	137	105	81	36	21	0