Introduction to Hydrological Models

University of Oklahoma/HyDROS

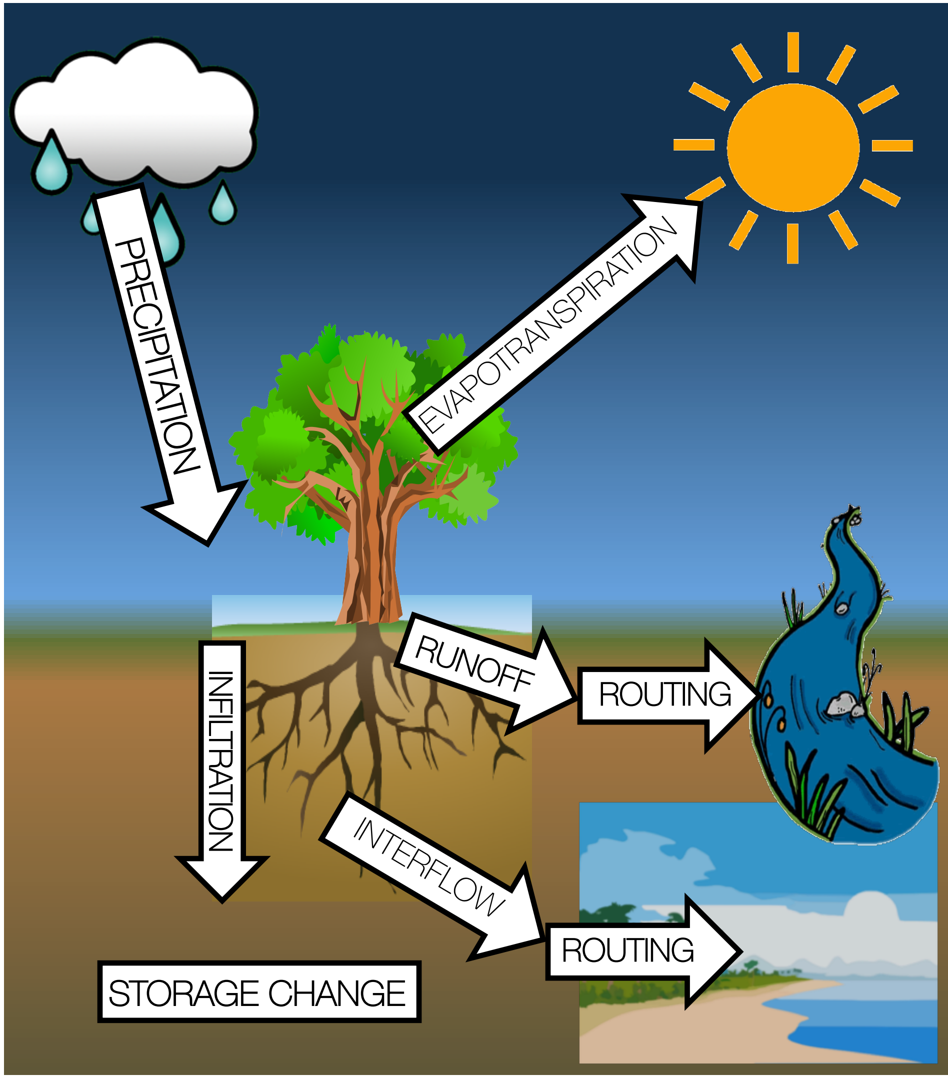
Module 1.2

Outline – Day 1

WELCOME

INTRODUCTION TO HYDROLOGICAL MODELS

- The water cycle
- Defining hydrological processes
- Modeling hydrological processes
- Run the model
- Create a hydrograph



The Water Cycle

The water cycle is the movement of water between ice, the oceans, the atmosphere and fresh water

It consists of several <u>processes:</u>

Precipitation – condensed atmospheric water falling to earth

Evaporation – phase transition of a liquid to a gas occurring from the liquid's surface

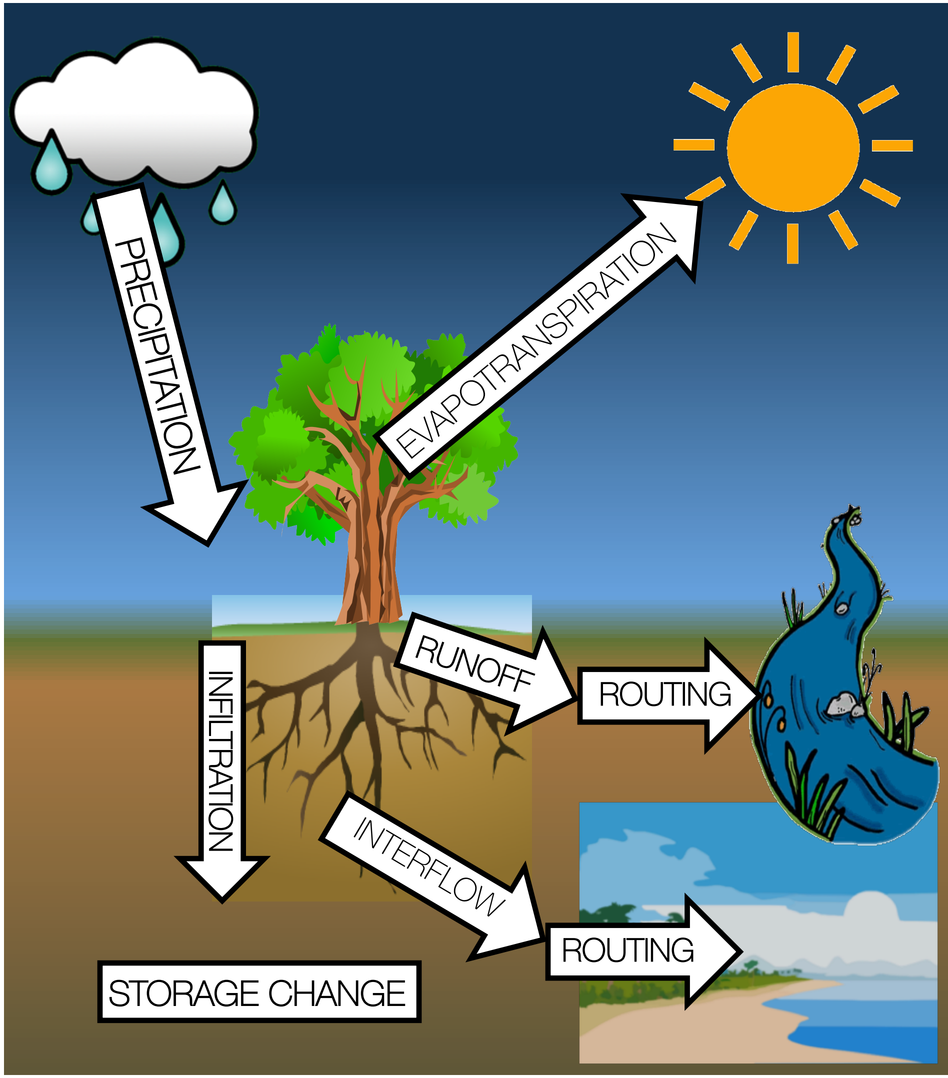
Transpiration – movement of water within and out of plants into the atmosphere

Infiltration – water entering soil from the ground surface

Runoff – flow of water over the earth's surface

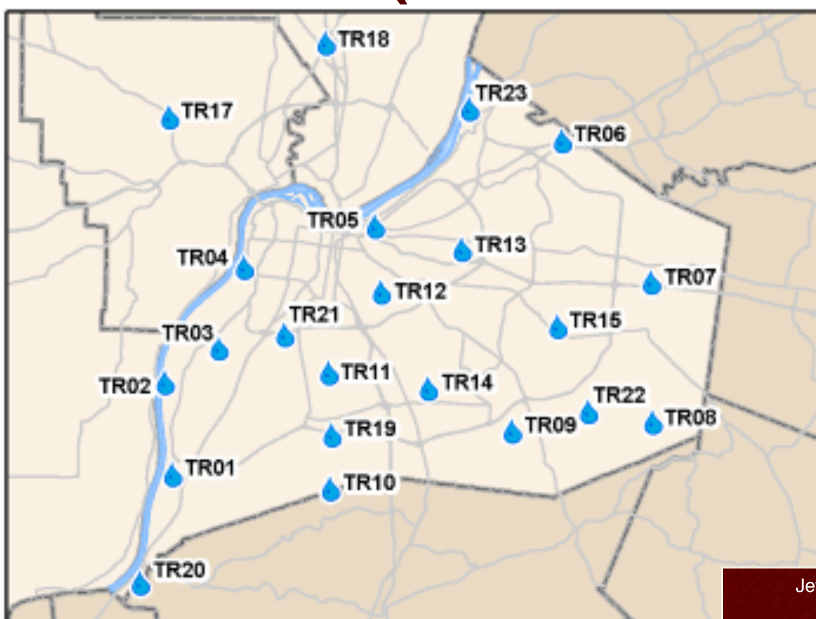
Interflow – flow of water within the soil layer(s)

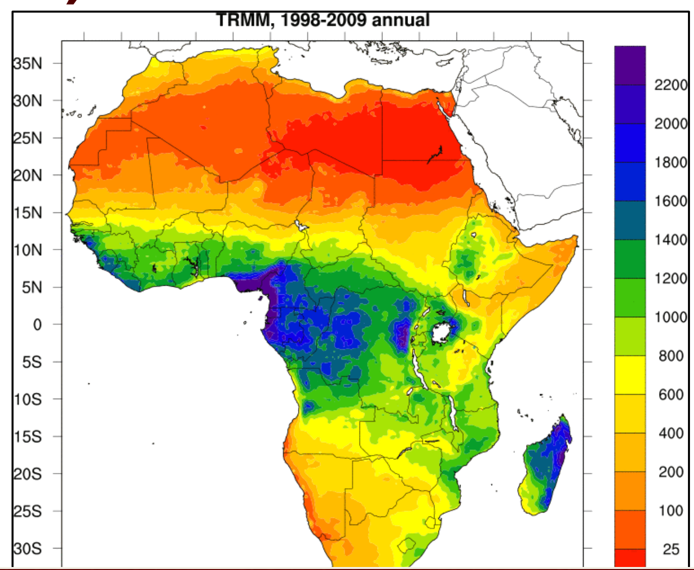
Routing – the movement of water "downstream"



Precipitation

- **Precipitation can take many forms**
  - Ice (snow, hail, graupel, sleet)
  - Water (rain, drizzle)
- **It can be measured at a point (gages) or estimated over an area (satellite or radar)**





Jefferson County, Kentucky rain gauge network (figure: Louisville/Jefferson County Metropolitan Sewer District)
Annual average estimated TRMM precipitation over Africa (image: NOAA/ESRL/PSD/Brant Liebmann)

Precipitation

We want gridded precipitation

- We could use a series of rain gauges (point data) and then analyze them to a grid
- More commonly, this comes from weather radar or satellite sensors from which precipitation amounts have been derived

A hydrological model is fed with precipitation grids at regular intervals throughout the length of the simulation

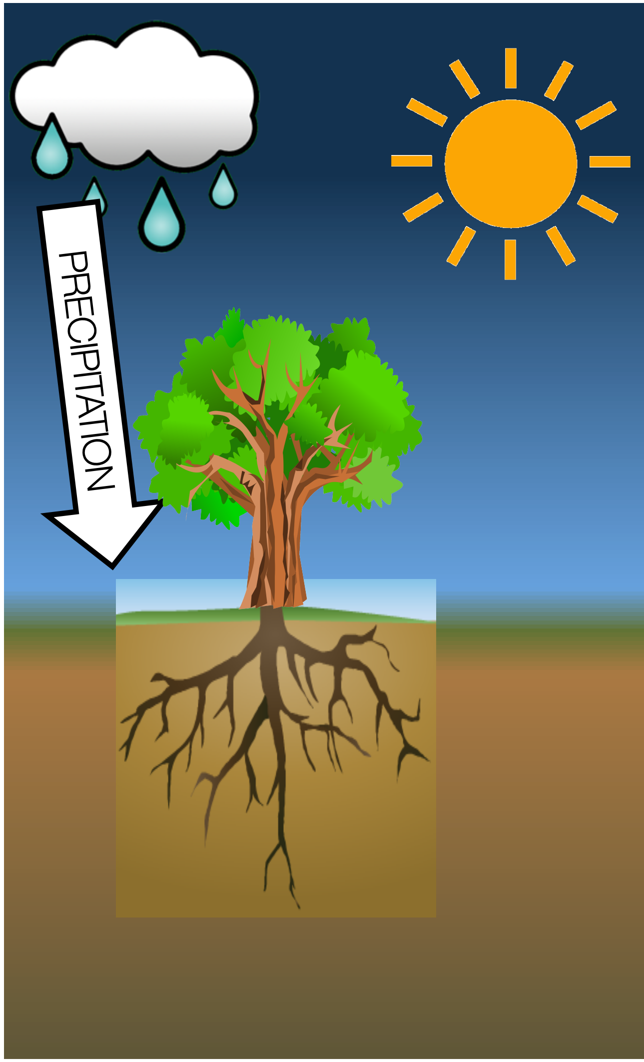
- Satellite precipitation may be available every 3 hours or once a day
- Weather radar data may be available every 5 minutes
- Rain gauge reports can be at either end of this range or anywhere in the middle

Precipitation

Not all precipitation reaches the ground

Some amount evaporates or sublimes back into the atmosphere

Some is intercepted by the "canopy" (which includes plants and rain barrels)



Hydrological models deal with this in different ways

One solution is to make this intercepted rain part of the modeled evapotranspiration process

Evapotranspiration

Evapotranspiration = evaporation + transpiration

Evaporation is the general term for conversion of a liquid from its surface into a gas

- Here, the liquid is water
- The "liquid" surface is the land surface, which includes soil, concrete, etc

Transpiration is more specific and refers to the transfer of liquid water from plants into the atmosphere as a vapor

Evapotranspiration

ET is hard to measure so we calculate it indirectly

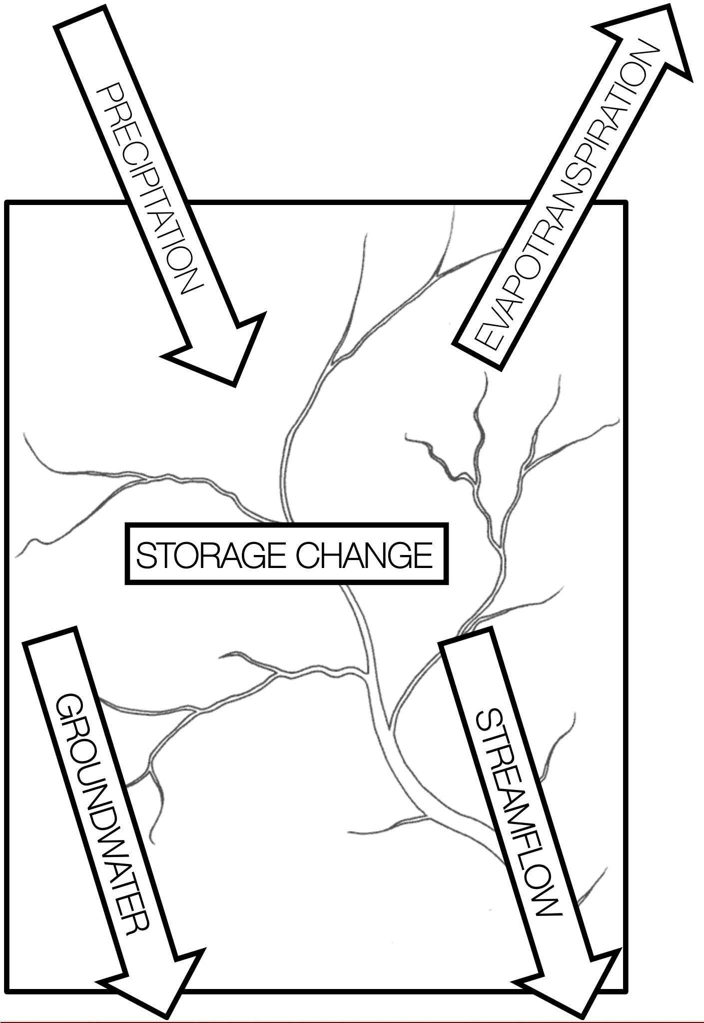
Let's start with the basic water cycle principle:

Water in = Water out

Now let's draw a box around a river basin and look at what goes in and what goes out

The change *S* in the amount of water in our box must equal precipitation *P* minus *ET*, groundwater *G*, and streamflow *Q*

$$S = P - ET - G - Q$$



River basin diagram/IB Geography course (geobecks.net)

We can measure, or at least more easily estimate, Q, G, P, and S

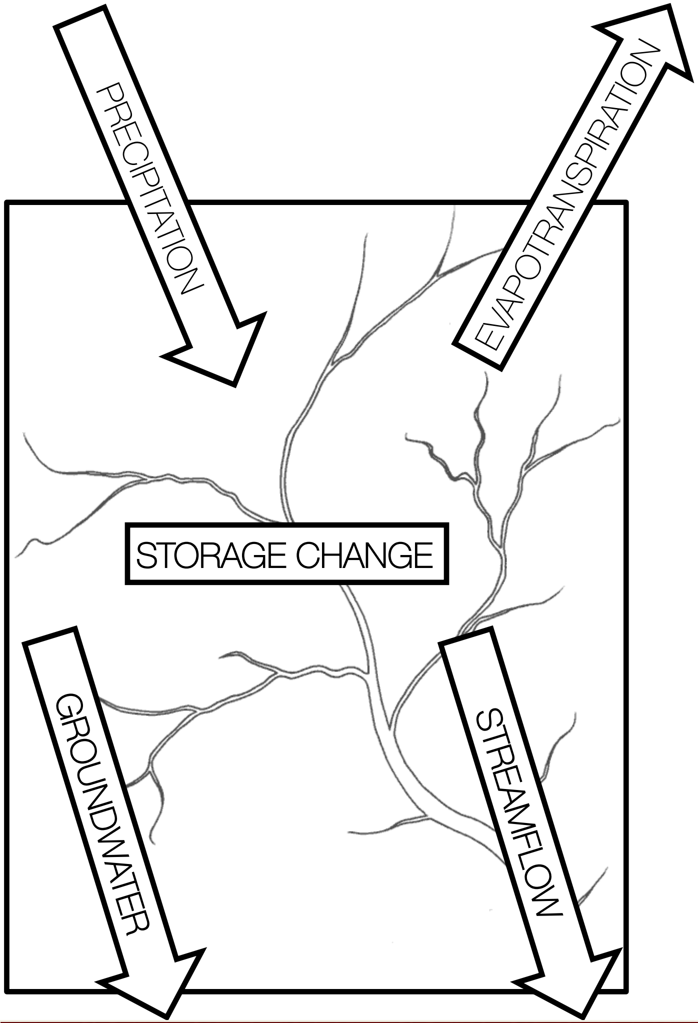
And then we can solve for ET

$$ET = P - S - Q - G$$

The reason ET is hard (or impossible) to measure is because it varies drastically across small scales

The species of plant, the age and health of the plant, the sun angle, sky cover, the temperature, the wind, the humidity, the land cover, and more

It can be measured experimentally but this is expensive, difficult, and subject to error



River basin diagram/IB Geography course (geobecks.net)

Potential Evapotranspiration

Now our cartoon more accurately reflects what can happen in a model

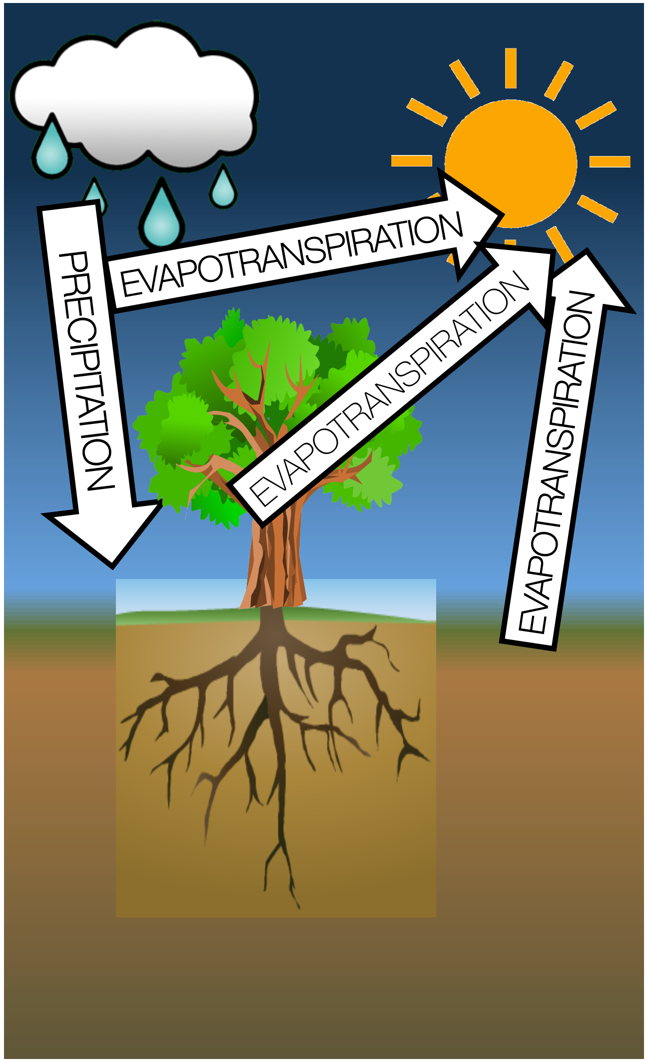
PET can act upon plants, soil, or any other land covering, but it can also act on precipitation before it reaches the ground

PET is expressed as a water depth

This amount of water must <u>always</u> be removed from the model

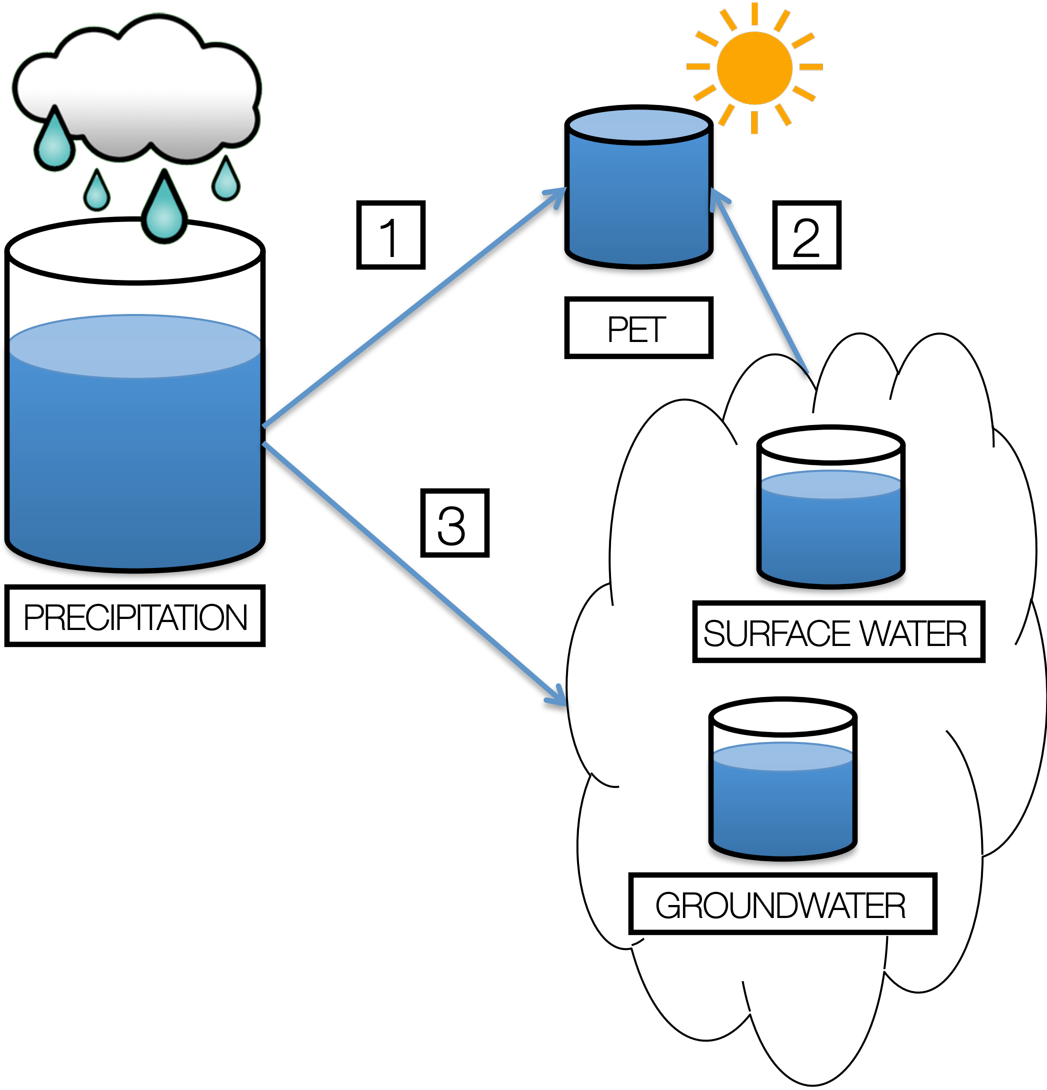
If there is enough precipitation available, we use that

If there is not, we use other sources



Here are the steps:

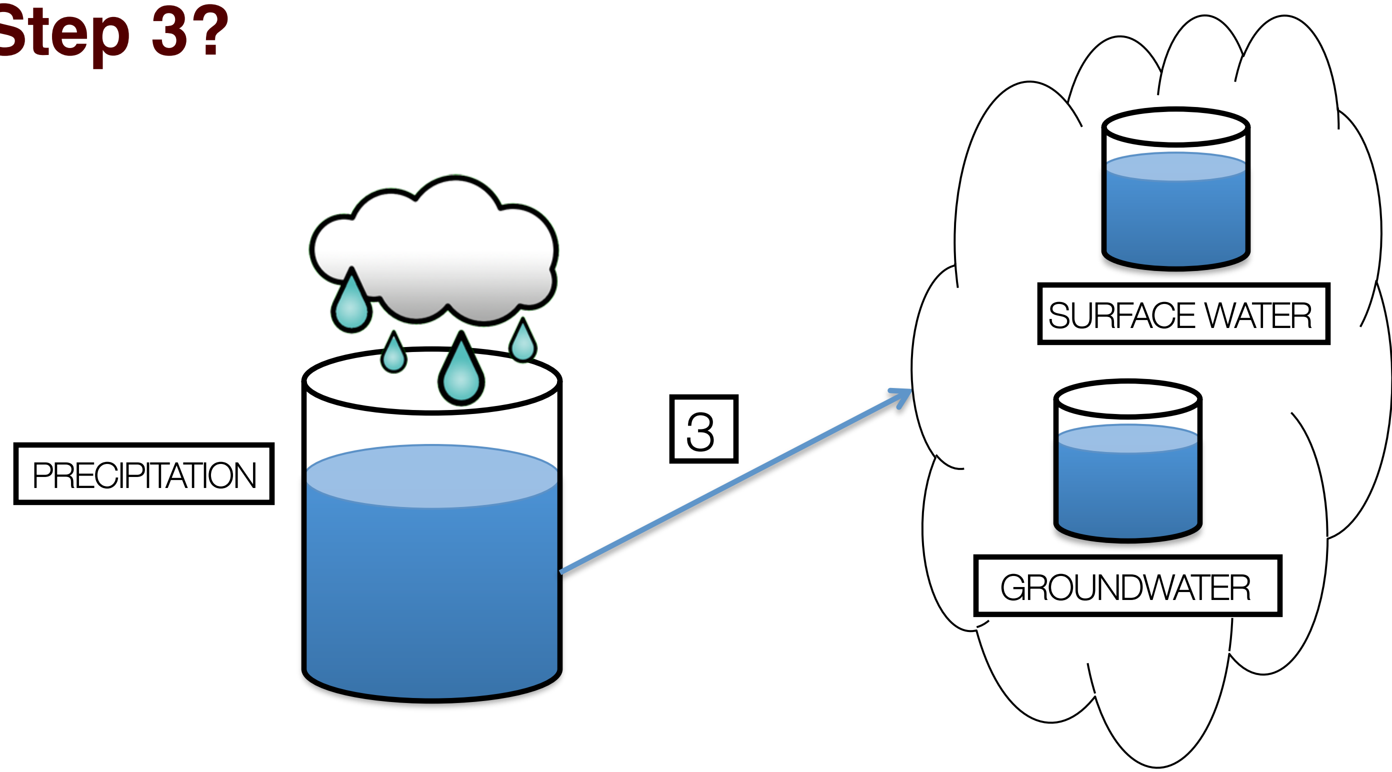
1. PET takes water from the precipitation bucket until the PET bucket is full
2. If PET is still not full, it takes water from the rest of the model (surface and groundwater)
3. Once PET is full, the remaining precipitation can flow to the rest of the model



Potential Evapotranspiration

We will return to PET in Module 2.3

Next we need to answer what, exactly, happens after Step 3?



Runoff and Infiltration

At this point, our PET requirement has been satisfied and our precipitation is free to reach the land surface

We know some portion of this water will drain into the soil

We know some other portion will run off

- This happens for a couple of reasons
- One is easy – imagine a slab of concrete. Here, the water cannot be absorbed by the concrete. It must become runoff. This is governed by the "percent impervious" area of the region being modeled
- The other is trickier. Soil can absorb some water, but after a certain point, even that water runs off

These two processes are called <u>runoff</u> and <u>infiltration</u>

Runoff is simply water that, when it reaches the land surface, does not infiltrate into the soil but instead flows over the land surface

Infiltration is the opposite: it's water that flows into the land surface

- How do we decide how much water becomes run off and how much is infiltrated?

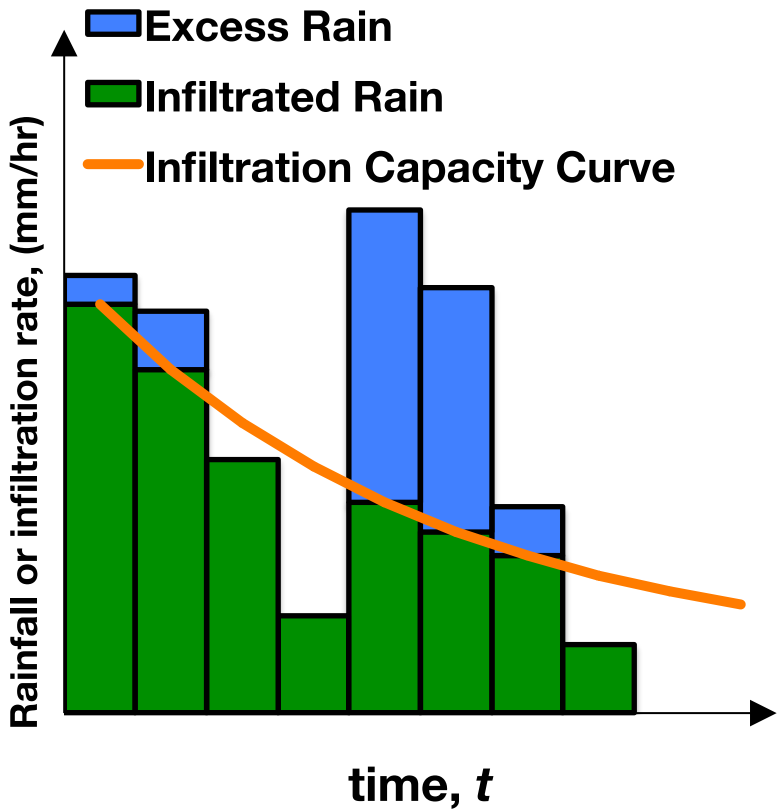
Infiltration

Look at the orange curve

- This is the maximum amount of water that can be absorbed into the soil
- More rain than this (blue) cannot be absorbed by the soil = runoff
- Less rain than this (green) is absorbed by the soil = infiltration

The infiltration capacity of the soil drops as water enters the soil but never quite reaches zero

- This is governed by the properties of the soil
- And by the amount of rain and how fast it falls



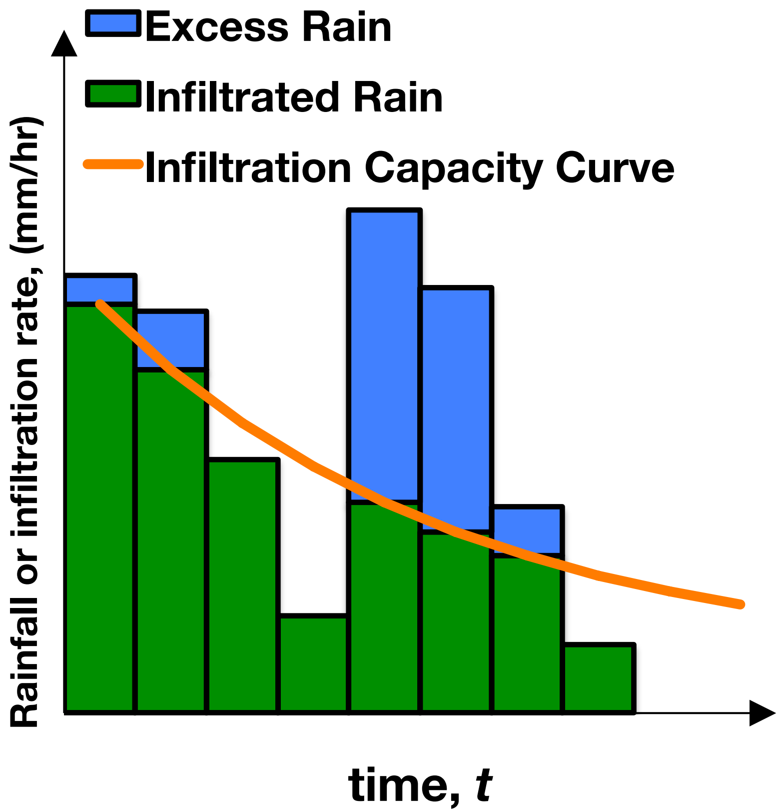
After a figure in Hydrology, Chapter 11 (Louy Alhamy)

Infiltration

This method is easy to understand, but…

This doesn't account for spatial differences in soil properties

Instead of the infiltration capacity curve, we need a storage capacity curve that accounts for the spatial differences



After a figure in Hydrology, Chapter 11 (Louy Alhamy)

Variable Infiltration Curve

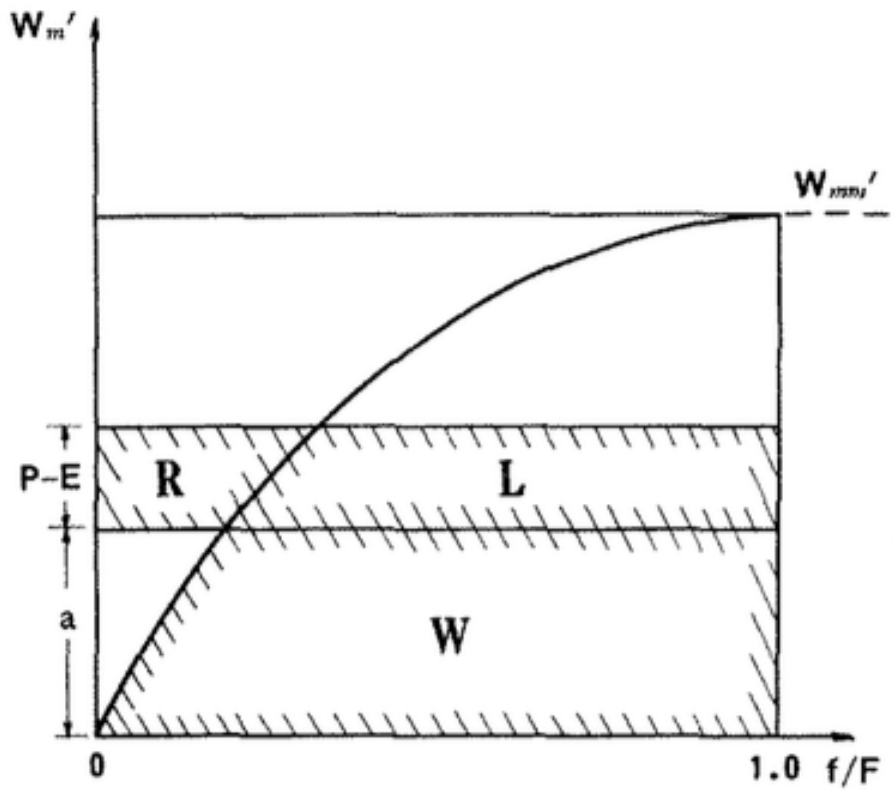
F is the total area of the basin and *f* is the partial area

The curve is the area with storage capacity equal to or less than a value of W_m'

Read the vertical axis as the capacity at a point

W_{max}' is the maximum storage capacity

When f/F is less than 1.0, $W_m' < W_{max}'$, as you would expect (the point storage capacity has to be less than the maximum storage capacity)



Zhao,R., et al. The Xinanjiang Model (1980) (Figure 2A)

Variable Infiltration Curve

W_m' is the point storage capacity

***W* is the actual storage in the basin**

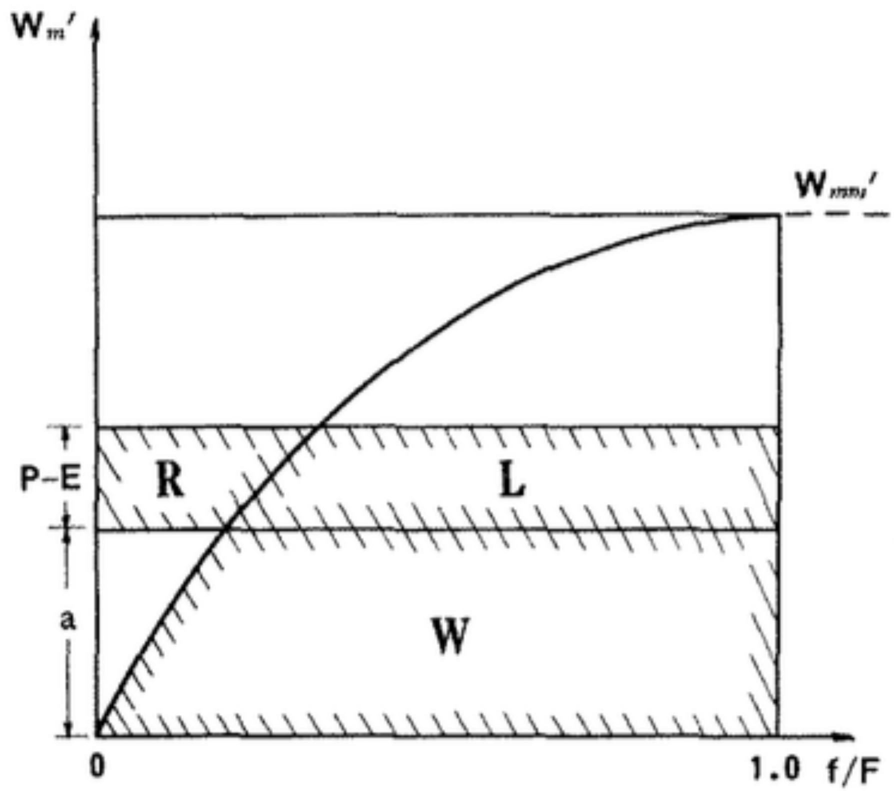
(we assume groundwater can move horizontally through the basin to equilibrium, so the value of *W* is the same regardless of the value of *f*/*F*)

To that storage *W*, we add *P – E*

If this is distributed evenly, due to interflow, then…

Only part of this fits under the storage capacity curve – this is *L*, the loss

The part that can't be held by the soil is *R*, the runoff



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Variable Infiltration Curve

If W_{max}' = 25 mm

And W = 10 mm (when expressed as a depth)

P is 10 mm and E is 5 mm

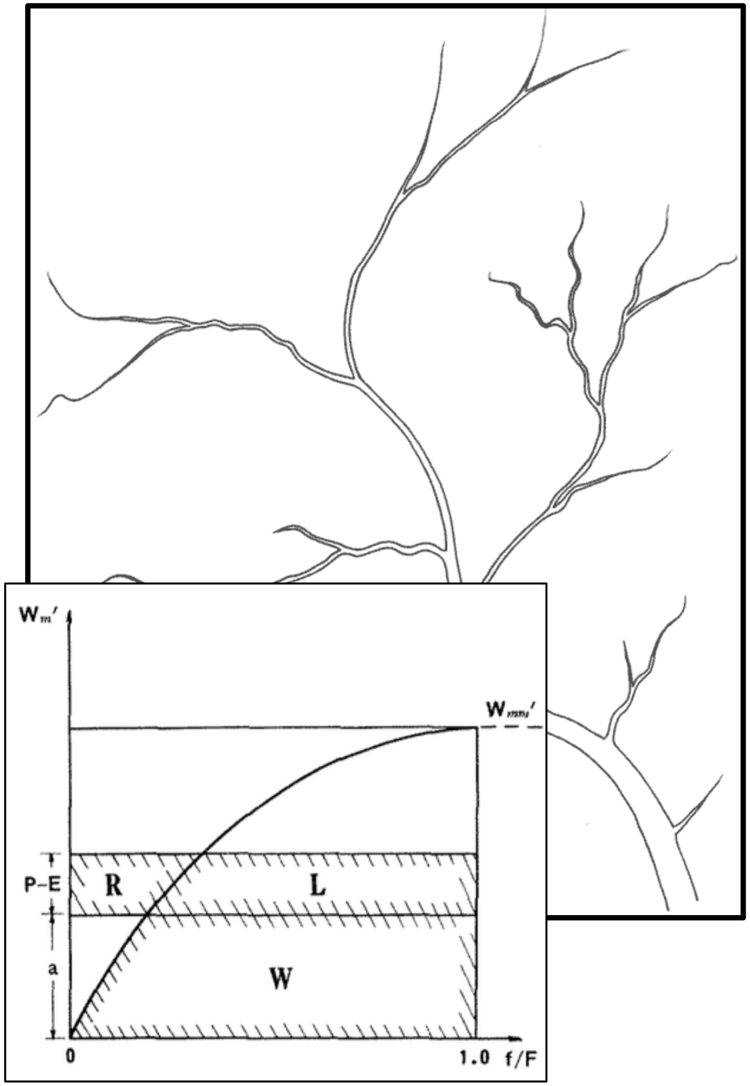
So $P - E$ = 5 mm

If F is 100 km^2, then the volume of R + L is 500,000 m^3

Which portion is R? (~25% or 125,000 m^3)

Governed by the shape of the curve

- This depends on the properties of the soil
- And on the settings in the hydrological model



Variable Infiltration Curve

Let's say we measure W_m' at a point in the basin as 20 mm

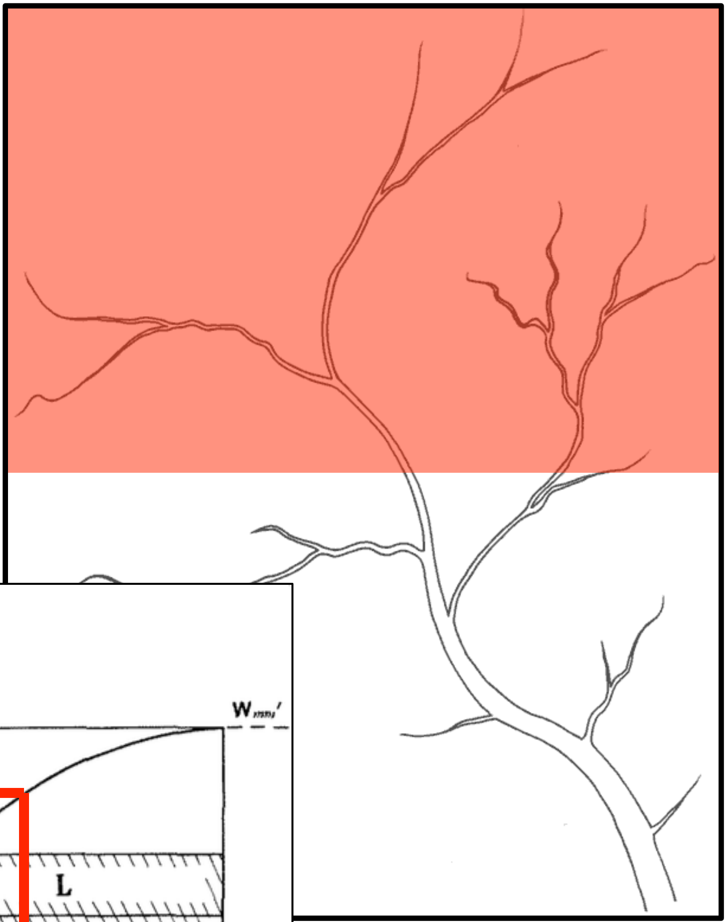
What portion of the basin has W_m' greater than this value?

Use the curve and get ~ 50%

If I measure W_m' = 10 mm, I get ~85%

So in this example…

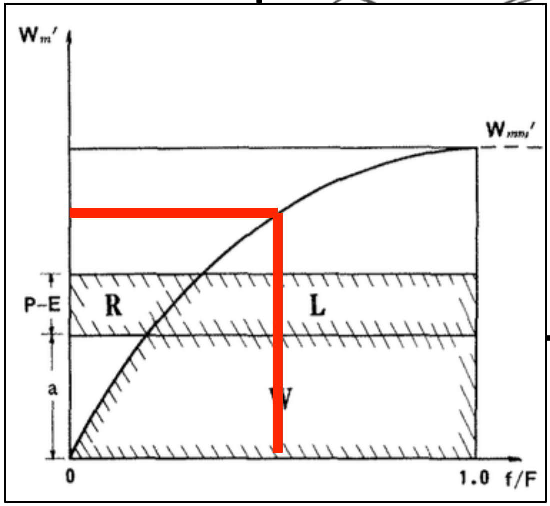
- 25% of the basin: > 23 mm
- 50% of the basin: > 20 mm
- 75% of the basin: > 13 mm
- 90% of the basin: > 4 mm



F = Area = 100 km^2

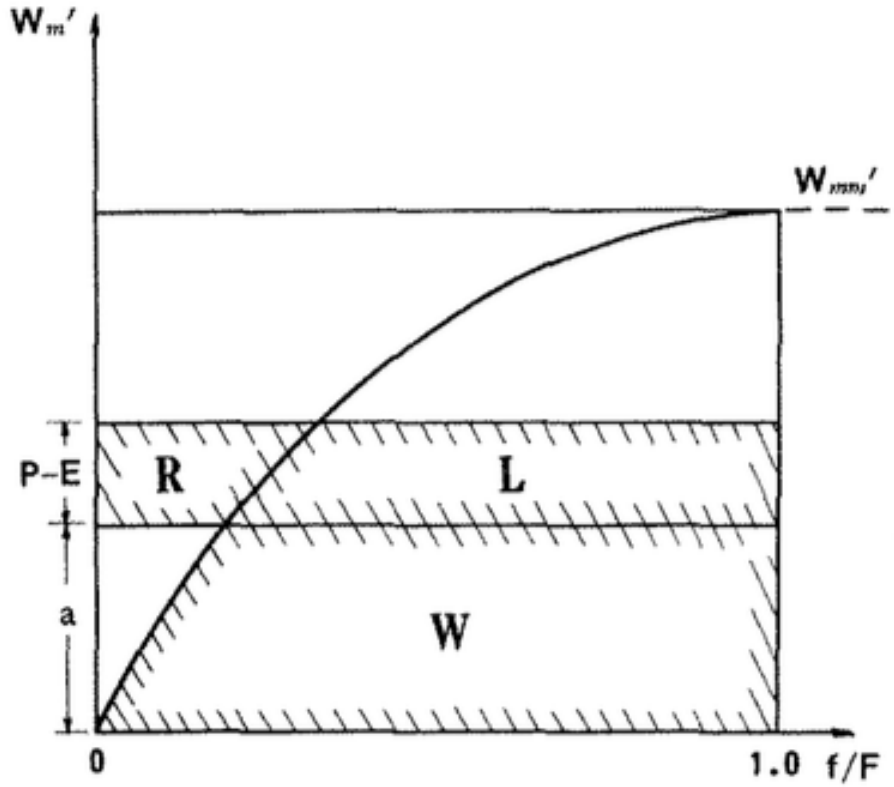
f (in red) = 50 km^2

f/F = 0.5



Let's look at the general characteristics of the VIC

- As *P* increases, so does *R*
- As *E* increases, *R* decreases
- When *W* is low, *R* is smaller
- As *W* increases, the fraction of *P – E* that becomes *R* increases



Zhao,R., et al. The Xinanjiang Model (1980) (Figure 2A)

These should be intuitive results

Variable Infiltration Curve

As *P* increases, so does *R*

More rain = more runoff

As *E* increases, *R* decreases

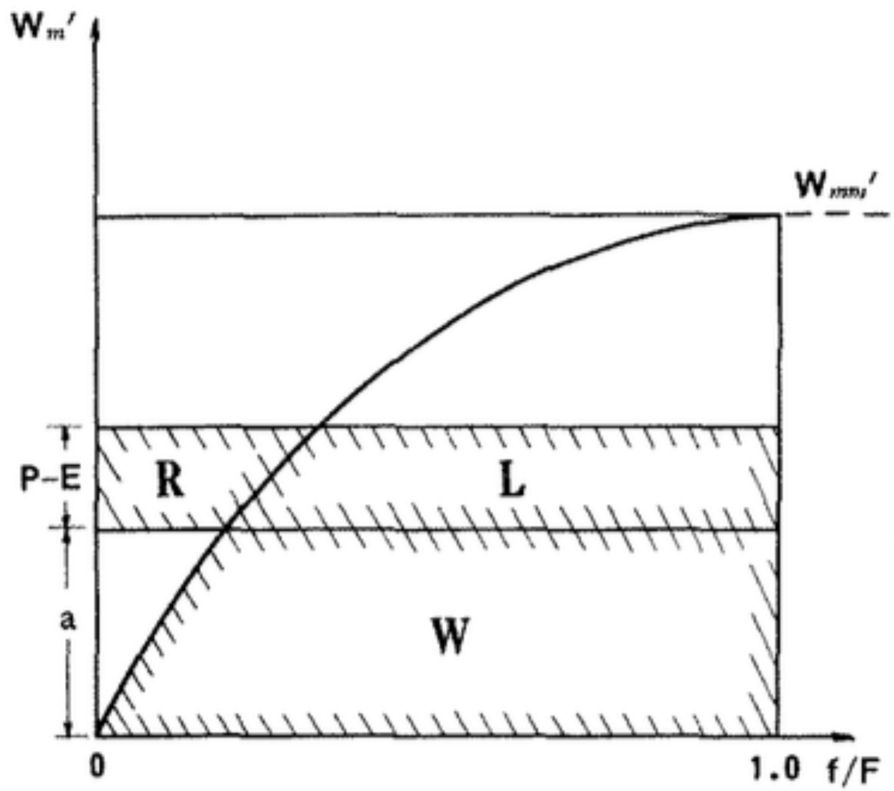
More evapotranspiration = less precipitation = less runoff

When *W* is low, *R* is smaller

Less water stored in the soil = more space for additional water in soil = less runoff

As *W* increases, the fraction of *P* – *E* that becomes *R* increases

More water stored in soil = less space for additional water = more runoff



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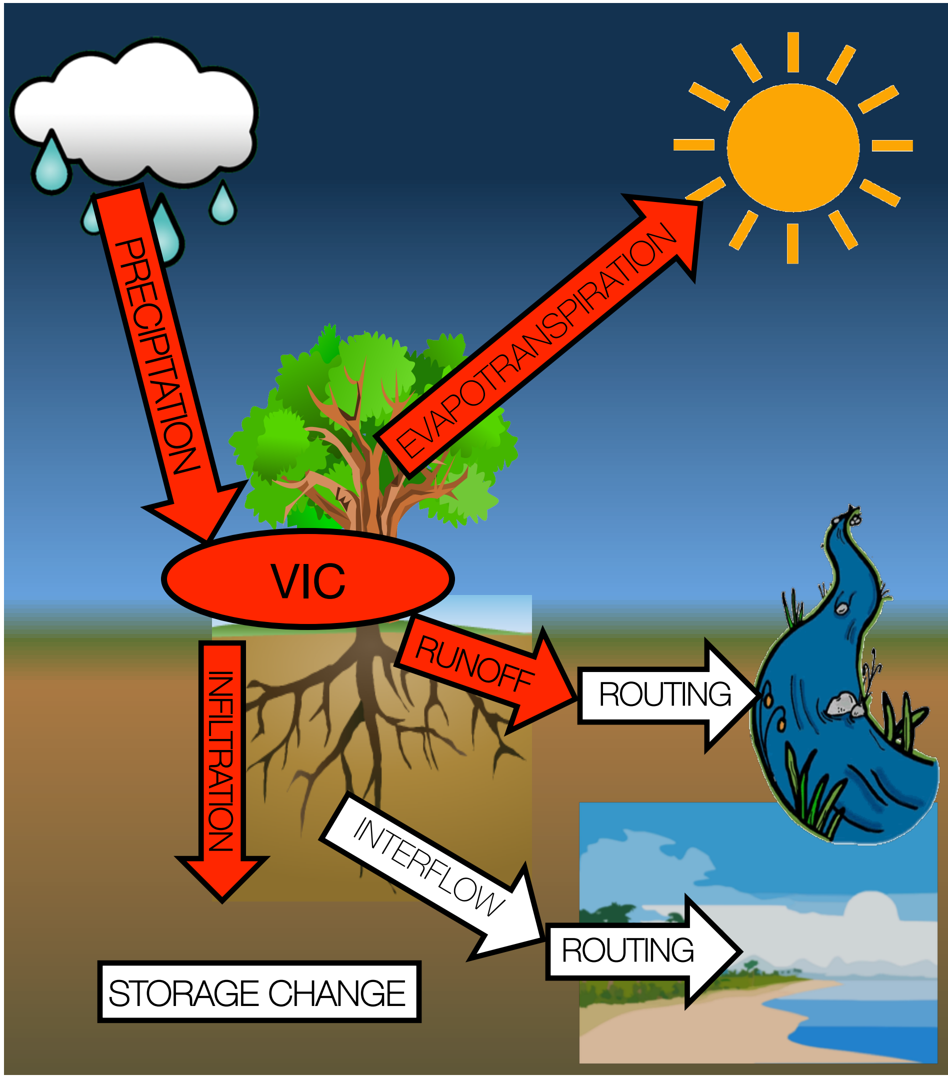


Interflow

From the portion of precipitation reaching the soil, P_{soil}, VIC tells us which part infiltrates and which part is excess rain

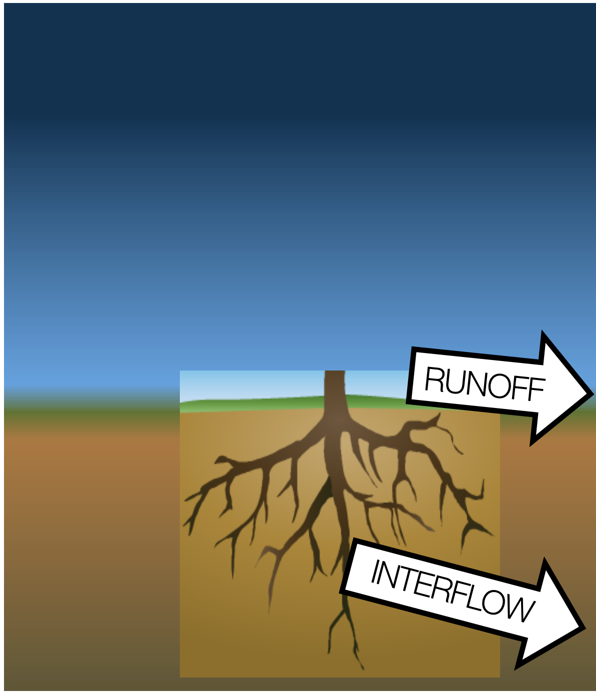
Excess rain exists in two forms: interflow and overland runoff

When P_{soil} < infiltration rate of the soil, all P_{soil} becomes interflow and no overland runoff is produced

Otherwise, P_{soil} is partitioned based on the hydraulic conductivity

This is how “easy” it is for water to enter the soil

The higher the hydraulic conductivity, the more P_{soil} becomes interflow and the less is available for overland runoff

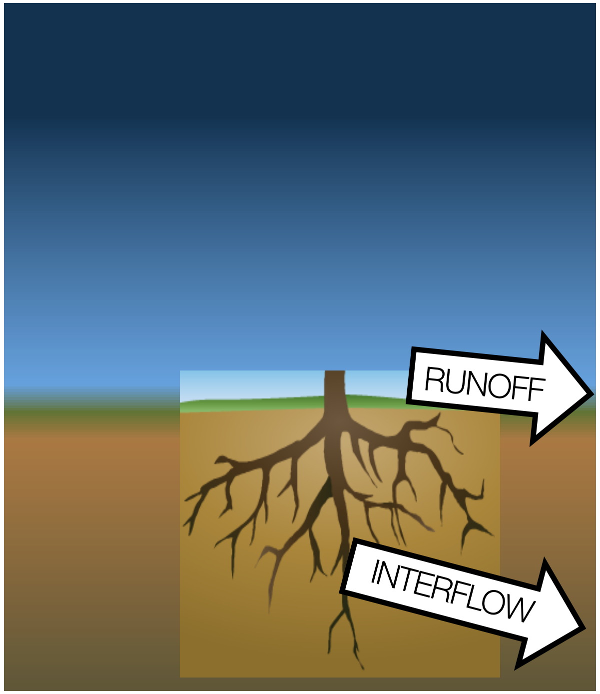


Interflow

Interflow and overland runoff can be routed, or moved downstream, via separate model processes

Interflow allows for hydrographs that represent a slow response to precipitation

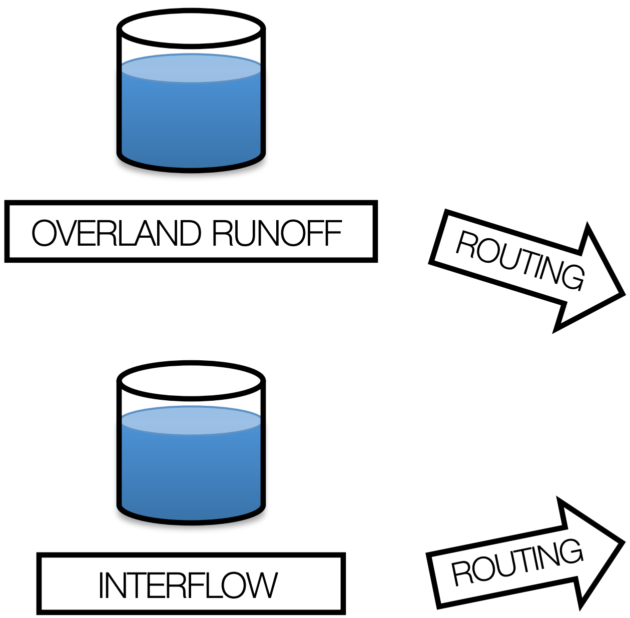
And runoff allows for faster response to precipitation



Routing

Now we have accounted for and divided up all the water entering the model

- Some is evapotranspired
- The rest is precipitation reaching the soil
  - Infiltration
  - Excess rainfall
    - Overland runoff
    - Interflow



The question now is what happens to the interflow and the overland runoff?

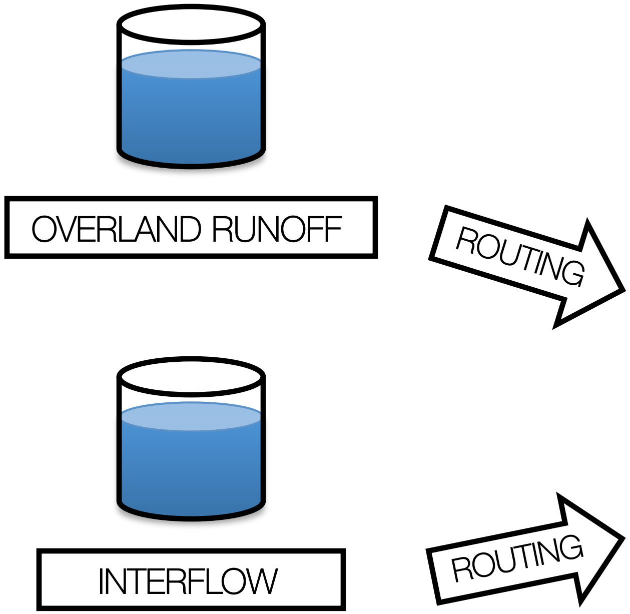
Routing

Each type of flow is routed until it reaches a river channel

- It then becomes open-channel flow

The time required for routing is a function of

- The distance between the where the precipitation occurred and the channel
- The slope between these points
- And empirical factors



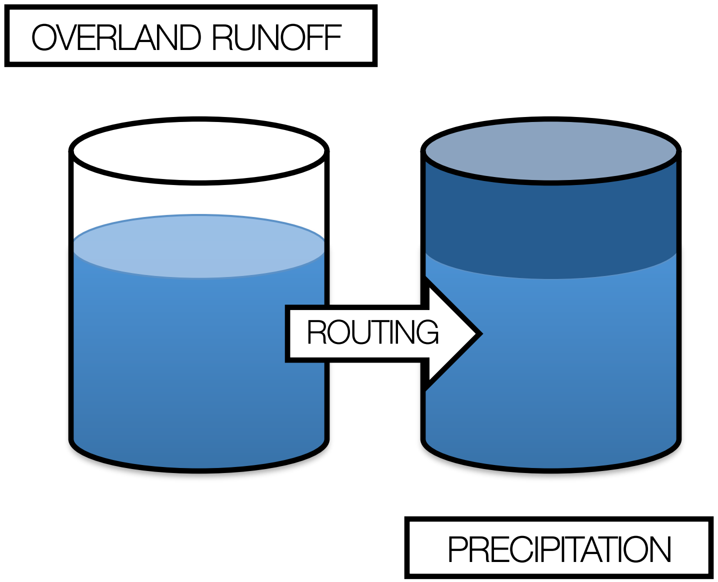
For flows in the soil, this factor is the soil saturated hydraulic conductivity for interflow

Overland runoff: The factor is the roughness of land

Coupling

If I'm standing at a point where overland water from upstream is flowing toward me, I need to account for it

- I can add it to my P_{soil} bucket
- In this case it acts just like additional precipitation falling from the sky, so it can be
  - Evapotranspired
  - Infiltrated into the soil
  - Converted to overland runoff
  - Converted to interflow



Dark blue – new precipitation from forcing at downstream point

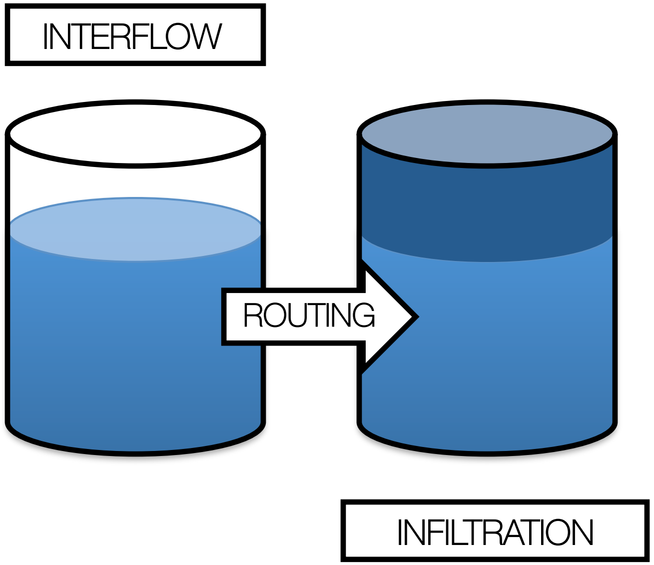
Light blue – "precipitation" from upstream overland runoff

Coupling

If overland water is flowing toward me, it is accounted for as new precipitation if we are NOT in a river channel

If it IS in a river channel

We account for this by adding the upstream water directly to the overland runoff bucket



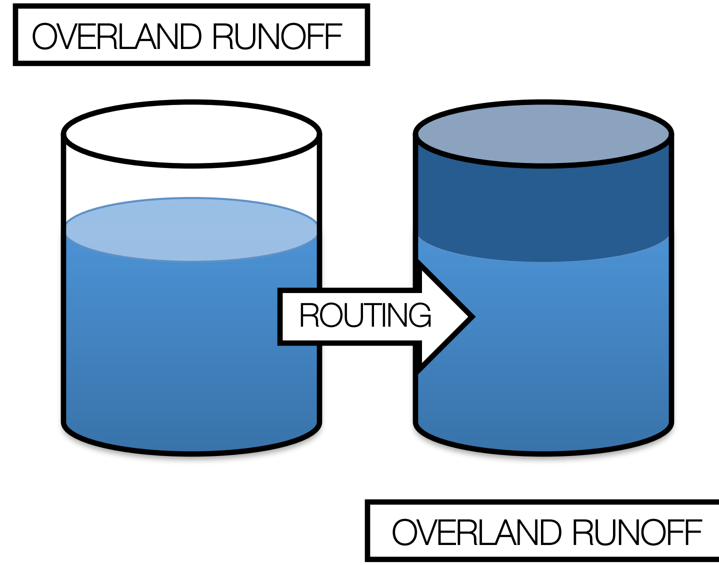
Dark blue – new infiltration from VIC process at downstream point

Light blue – old infiltration water from upstream interflow

Coupling

If overland water is flowing toward me, there's also water under the surface – interflow – flowing toward me

We account for this by adding to the infiltration water at the new downstream point



Dark blue – overland runoff newly generated at downstream point

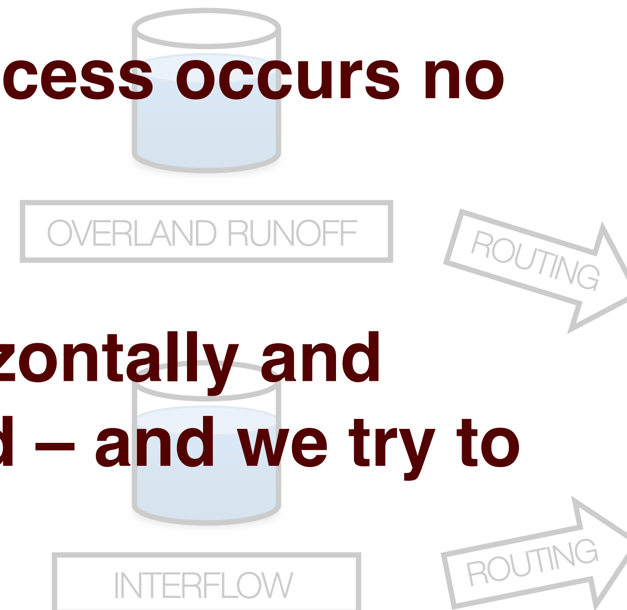
Light blue – overland runoff from upstream

Coupling

Upstream overland runoff can be treated only one or the other way – not both

But the infiltration modification process occurs no matter what, river channel or not

In the real world, water moves horizontally and vertically over and through the land – and we try to model that as best we can



Model Cells

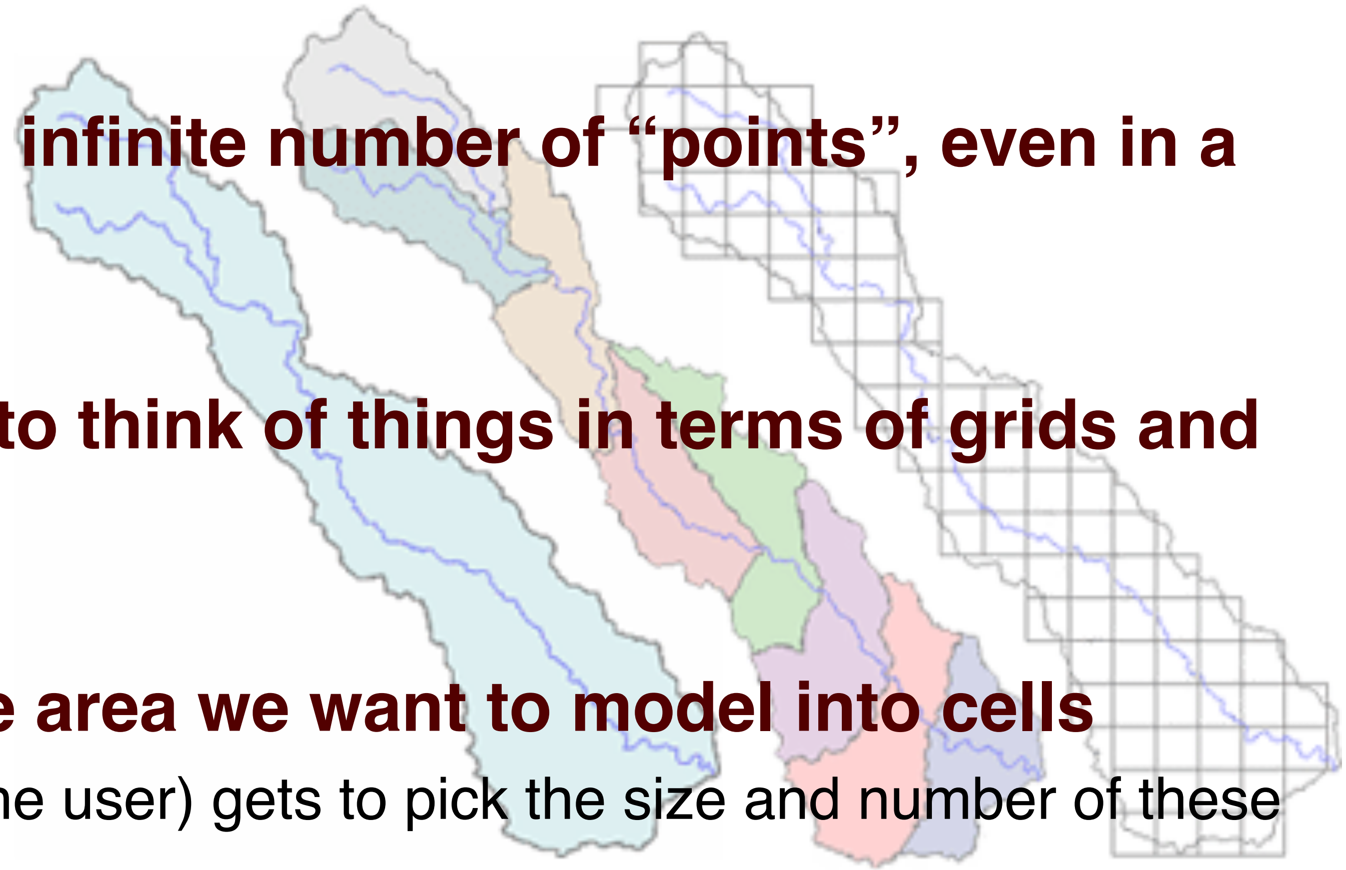
So far we've discussed this in terms of "points"

But there are an infinite number of "points", even in a small basin

Computers like to think of things in terms of grids and cells

So we divide the area we want to model into cells

- And you (the user) gets to pick the size and number of these cells!

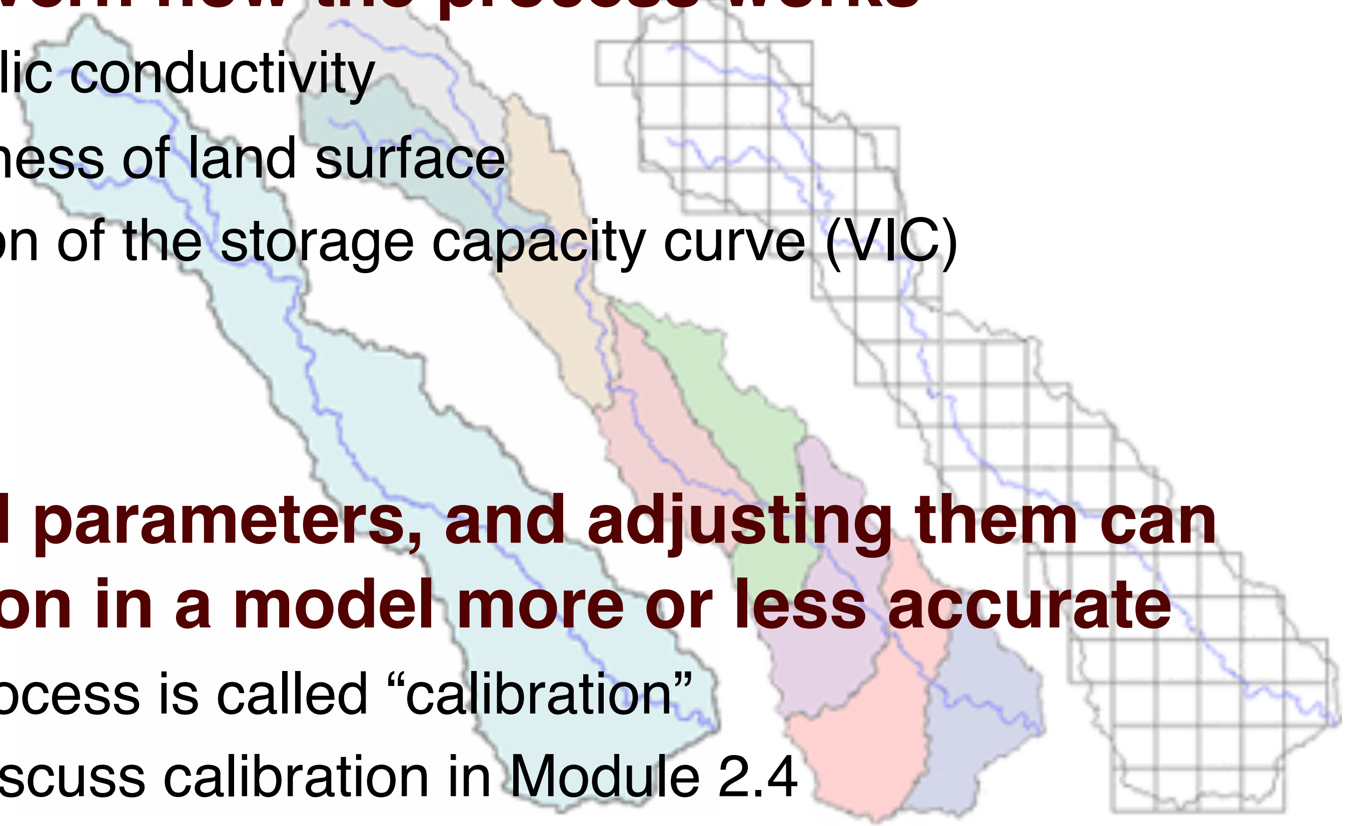


NOAA/NWS/The Comet Program (Runoff Processes: International Edition)

Types of Hydrological Models

In each process we've discussed, there are factors or settings that govern how the process works

- Hydraulic conductivity
- Roughness of land surface
- Equation of the storage capacity curve (VIC)
- etc….



These are called parameters, and adjusting them can make a simulation in a model more or less accurate

- This process is called "calibration"
- We'll discuss calibration in Module 2.4

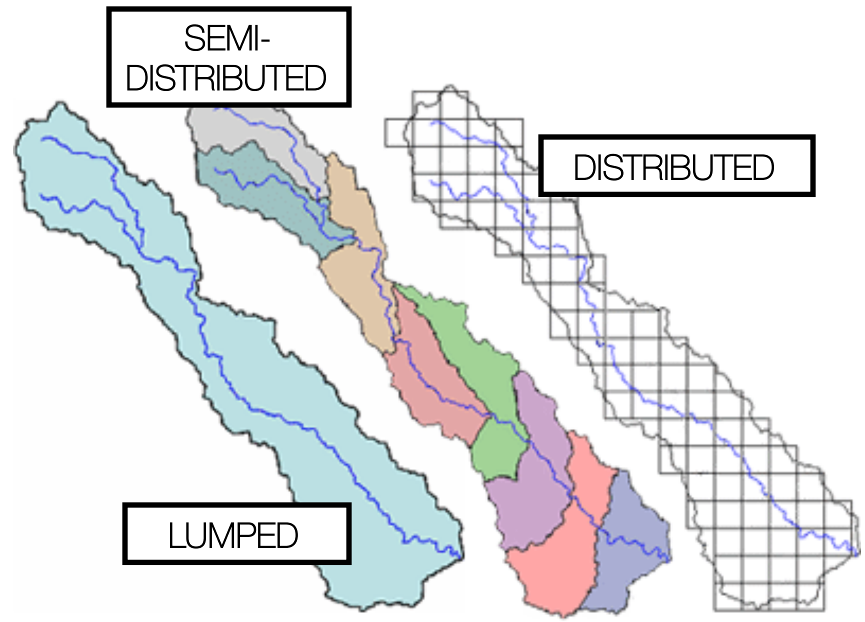
NOAA/NWS/The Comet Program (Runoff Processes: International Edition)

Types of Hydrological Models

If I can adjust these parameters for each model cell independently, I have a <u>distributed model</u>

If I can adjust these parameters in a few spots over a river basin, I have a <u>semi-distributed model</u>

And if I have only one constant set of parameters for my whole area, I have a <u>lumped model</u>

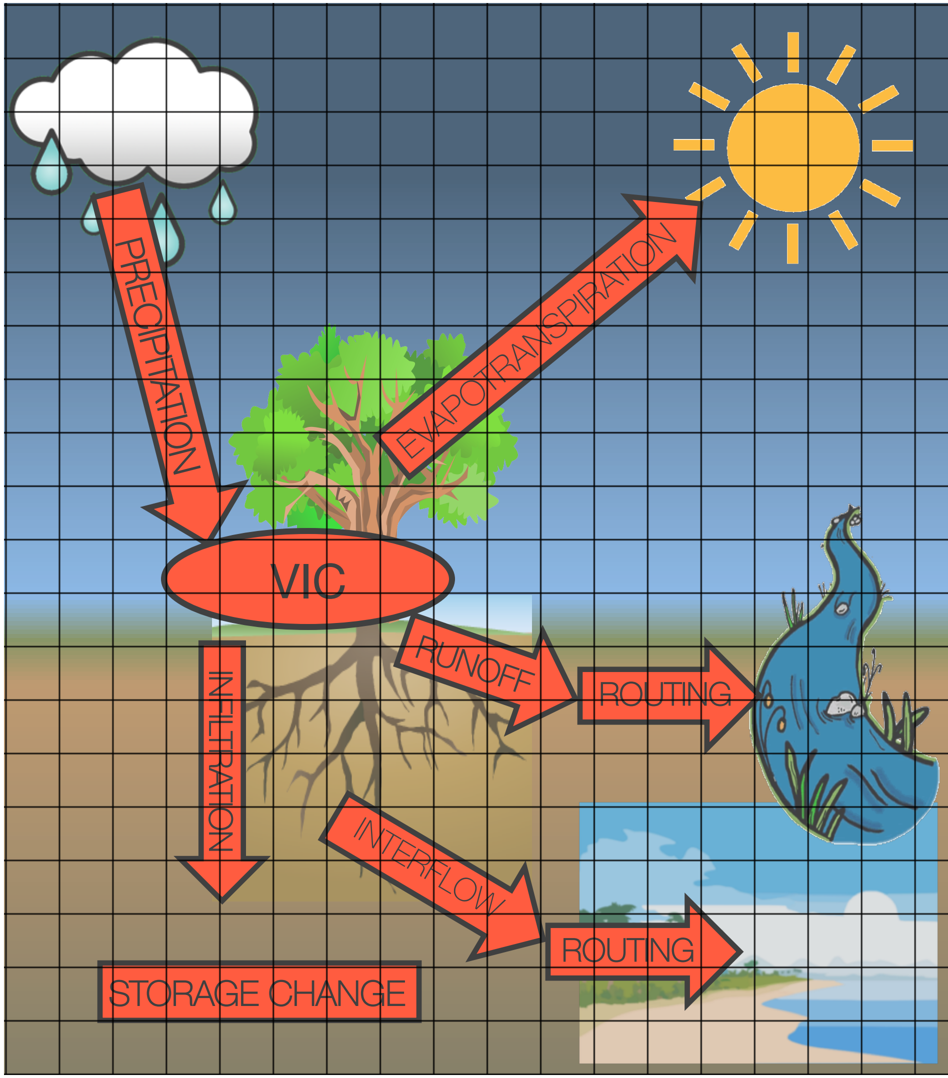


NOAA/NWS/The Comet Program (Runoff Processes: International Edition)

The Water Cycle

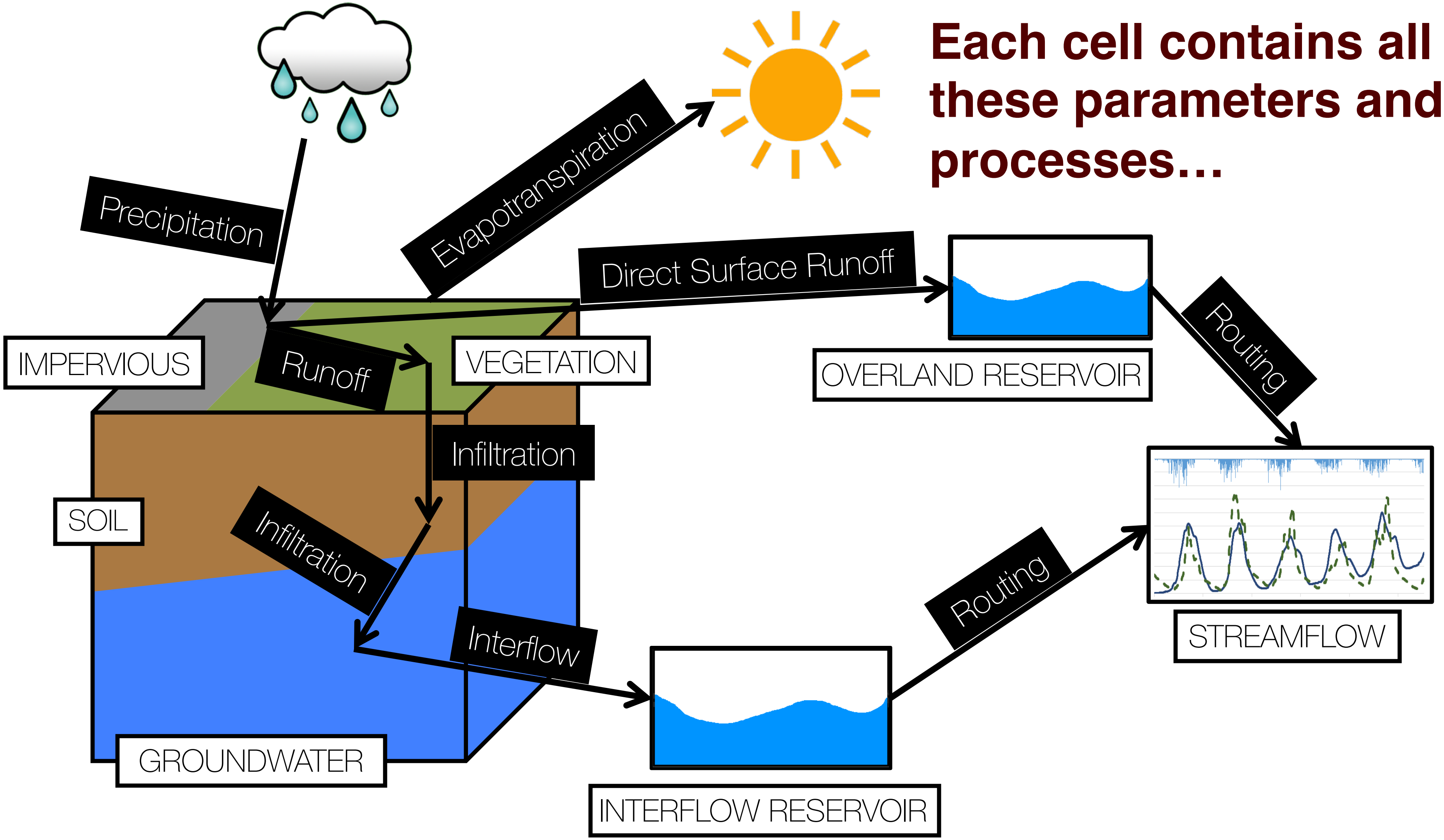
The water cycle is the movement of water between ice, the oceans, the atmosphere and fresh water

We turn the water cycle into a series of model cells, each one of which contains a set of the processes we've discussed



A Sample Model Cell

Each cell contains all these parameters and processes…

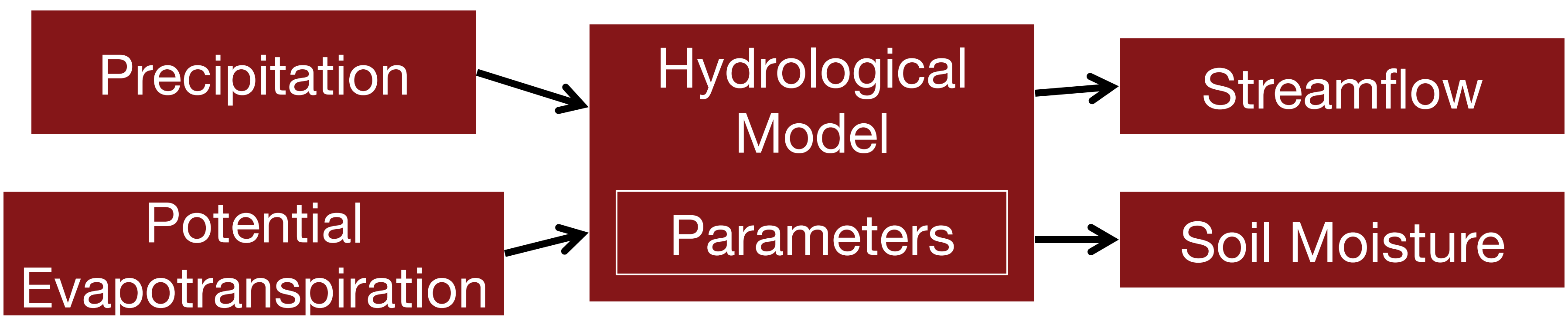


A Simplified Workflow

And all these cells are connected together and govern how the others behave

This process is complex but computing power makes it possible

In day-to-day use, we think of this as just our inputs, outputs, and the model parameters



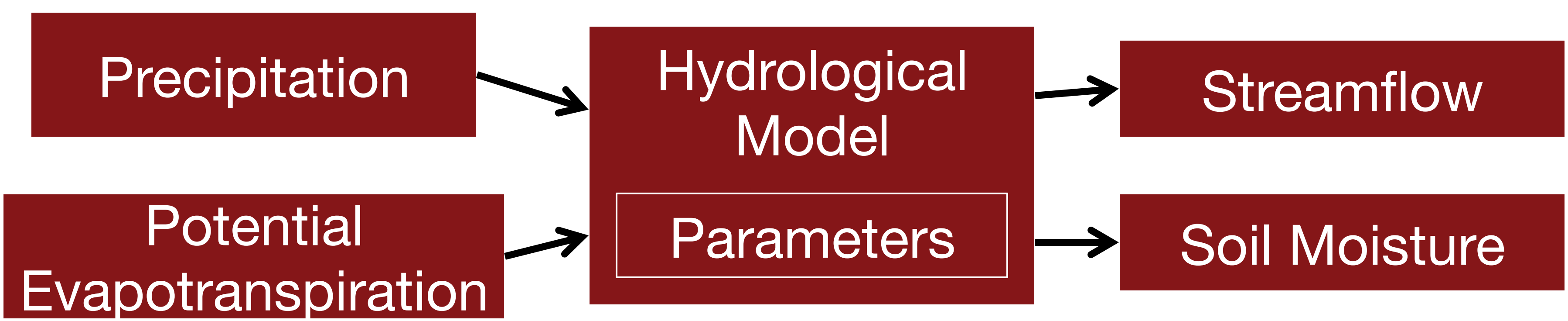
Example 1

So let's start with the simplest possible use of the model

- If our inputs and our model parameters are already provided to us, all we need to do is run the model, right?

Navigate to the following folder:

`\EF5_training\examples\wangchu\`

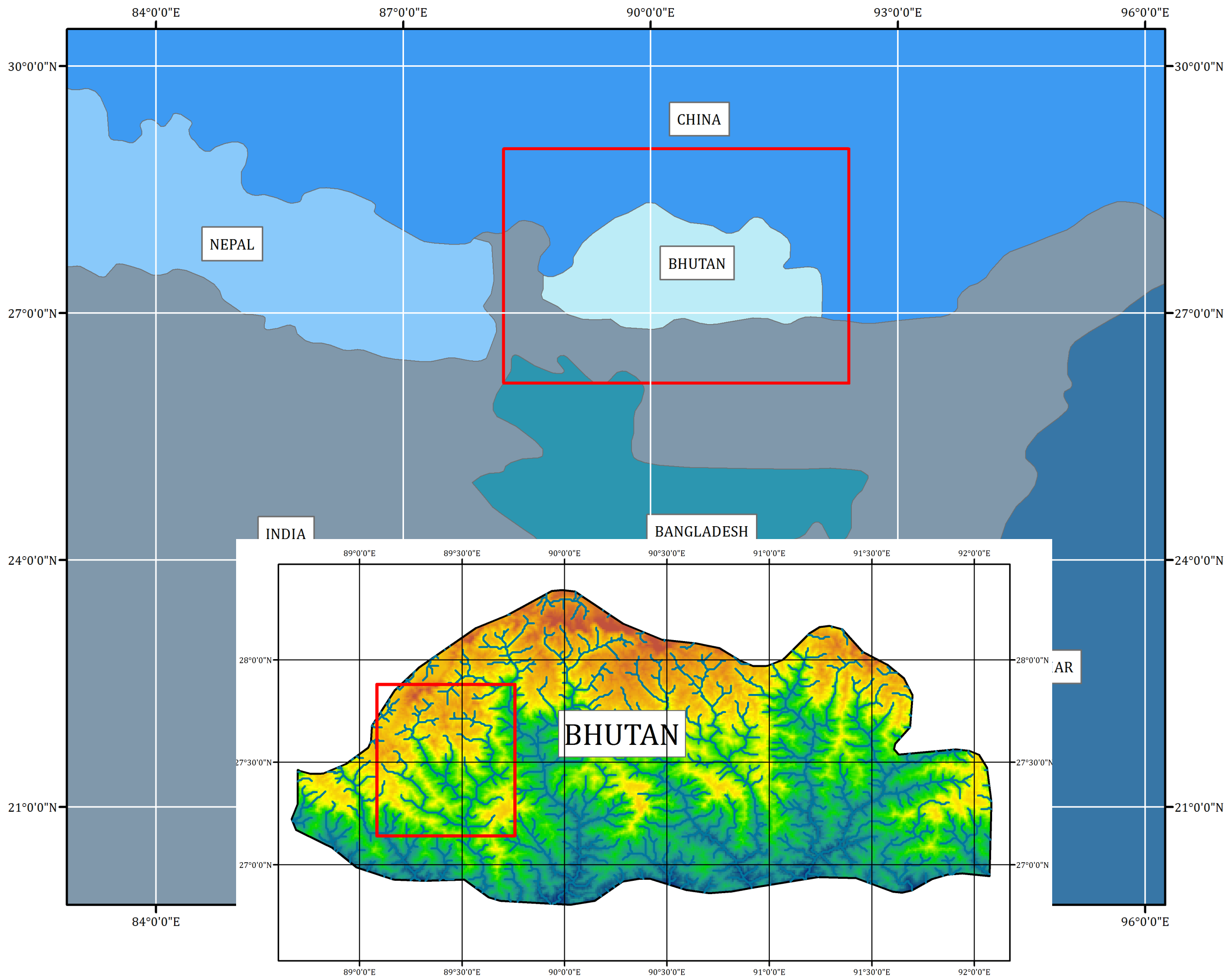


Wang Chu Basin

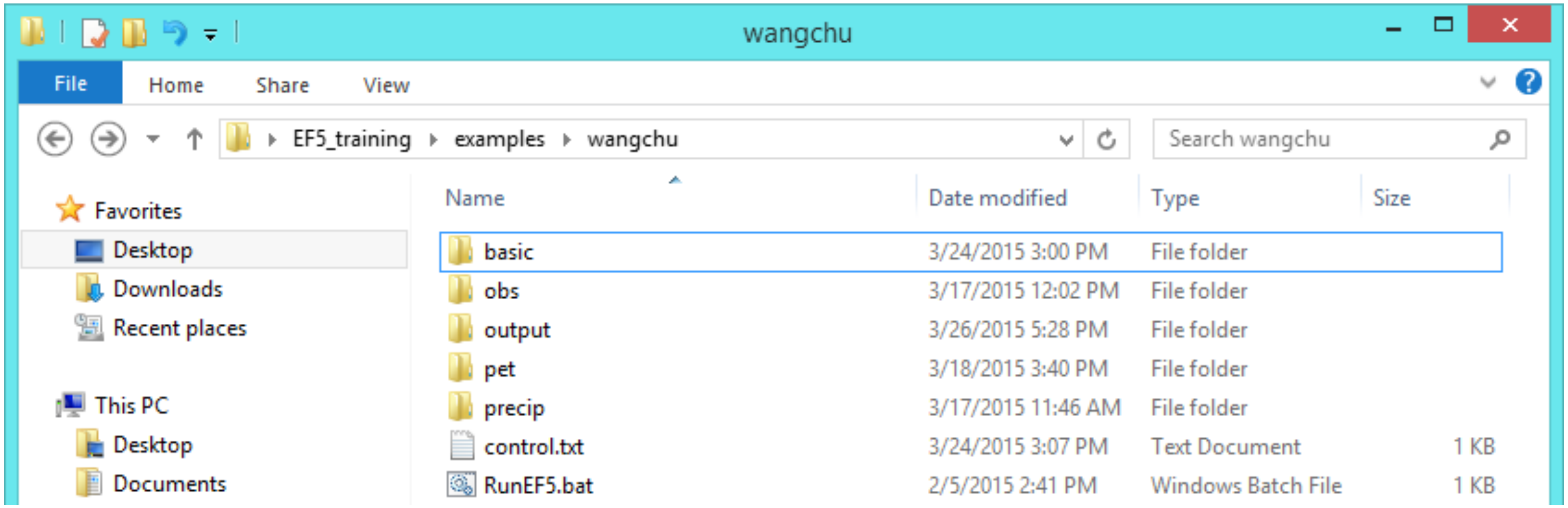
Our first example is the Wang Chu River Basin in eastern Bhutan

Located in Himalaya Mountains

A tributary of the Brahmaputra River



Wang Chu Basin



In your `wangchu` folder, you should have five sub-folders

The `basic` folder contains topographical data for the model

The `obs` folder contains observed streamflow for the example

The `output` folder will contain the model output once the example has run

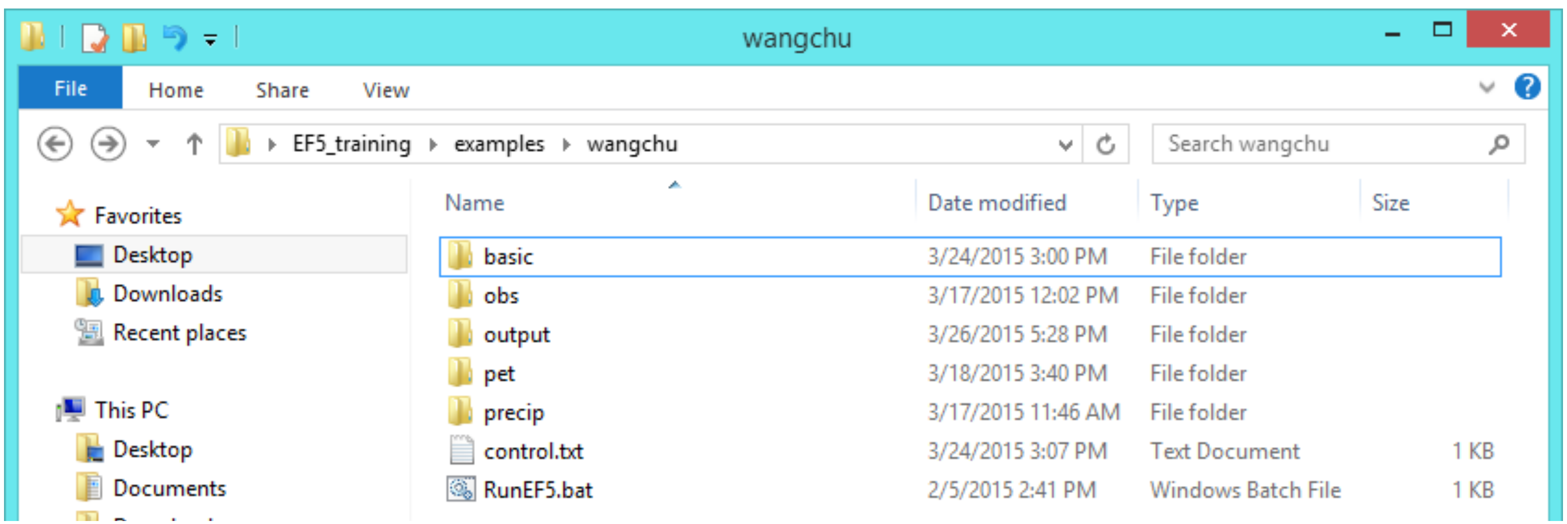
The `pet` folder contains the potential evapotranspiration data

Wang Chu Basin

The `precip` folder contains the precipitation data

The `control.txt` file tells the model what to do and the `RunEF5.bat` file runs the model

This folder organization is just the way we've set it up – you can organize your folders however you want as long as you tell EF5 what you're doing in the `control.txt` file

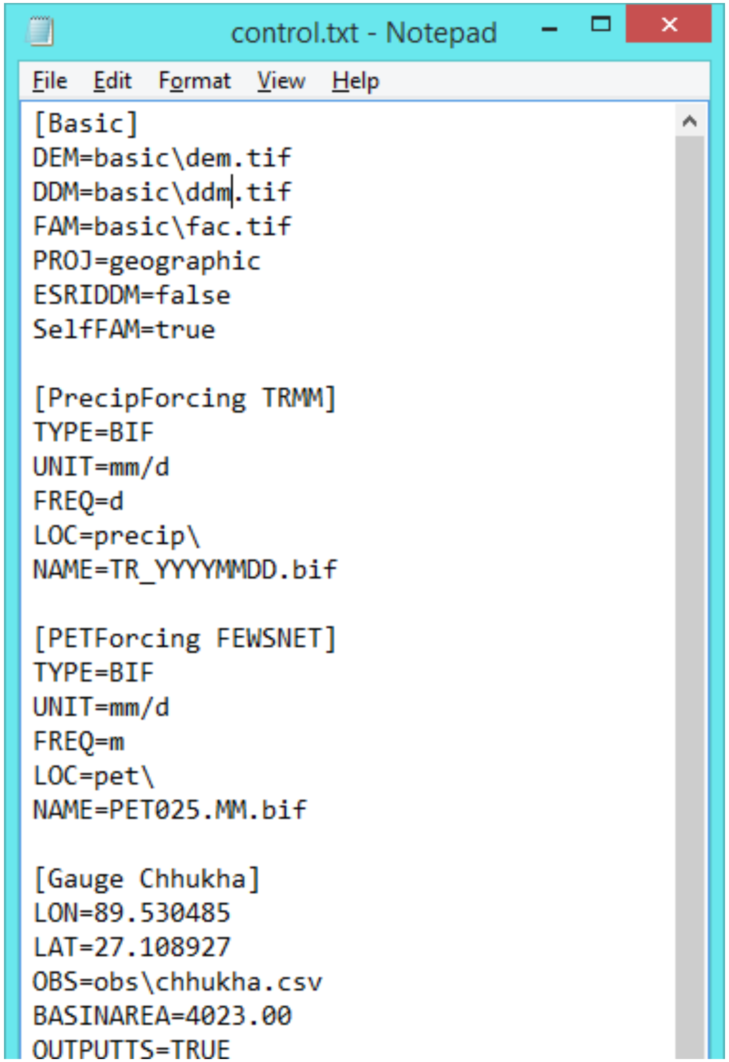


Wang Chu Basin

Open the `control.txt` file

EF5 control files are organized into blocks

- Basic
- PrecipForcing
- PETForcing
- Gauge
- Basin
- CrestParamSet
- kwparamset
- Task
- Execute



control.txt - Notepad

File Edit Format View Help

```
[Basic]
DEM=basic\dem.tif
DDM=basic\ddm.tif
FAM=basic\fac.tif
PROJ=geographic
ESRIDDM=false
SelfFAM=true

[PrecipForcing TRMM]
TYPE=BIF
UNIT=mm/d
FREQ=d
LOC=precip\
NAME=TR_YYYYMMDD.bif

[PETForcing FEWSNET]
TYPE=BIF
UNIT=mm/d
FREQ=m
LOC=pet\
NAME=PET025.MM.bif

[Gauge Chhukha]
LON=89.530485
LAT=27.108927
OBS=obs\chhukha.csv
BASINAREA=4023.00
OUTPUTTS=TRUE
```

We'll thoroughly discuss the control file later in the training

Wang Chu Basin

```
Ensemble Framework For Fl
Current Timestep: 12/31/2002 00:00
**********************************************************
**   Ensemble Framework For Flash Flood Forecasting   **
**                Version 0.2                 **
**********************************************************
INFO: Loading DEM: basic\dem.tif
INFO: Loading DDM: basic\ddm.tif
INFO: Loading FAM: basic\fac.tif
INFO: Executing task runwangchu
INFO: Gauge chhukha (27.080000, 89.529999; 92, 53): FAM 3296
INFO: Walked 3296 (out of 3296) nodes for chhukha!
Done!
```

Now double-click `RunEF5.bat` to run the model

EF5 reads in the necessary topographical information

The model's current time is shown at the top of the window and the simulation is complete when "Done!" is printed on screen

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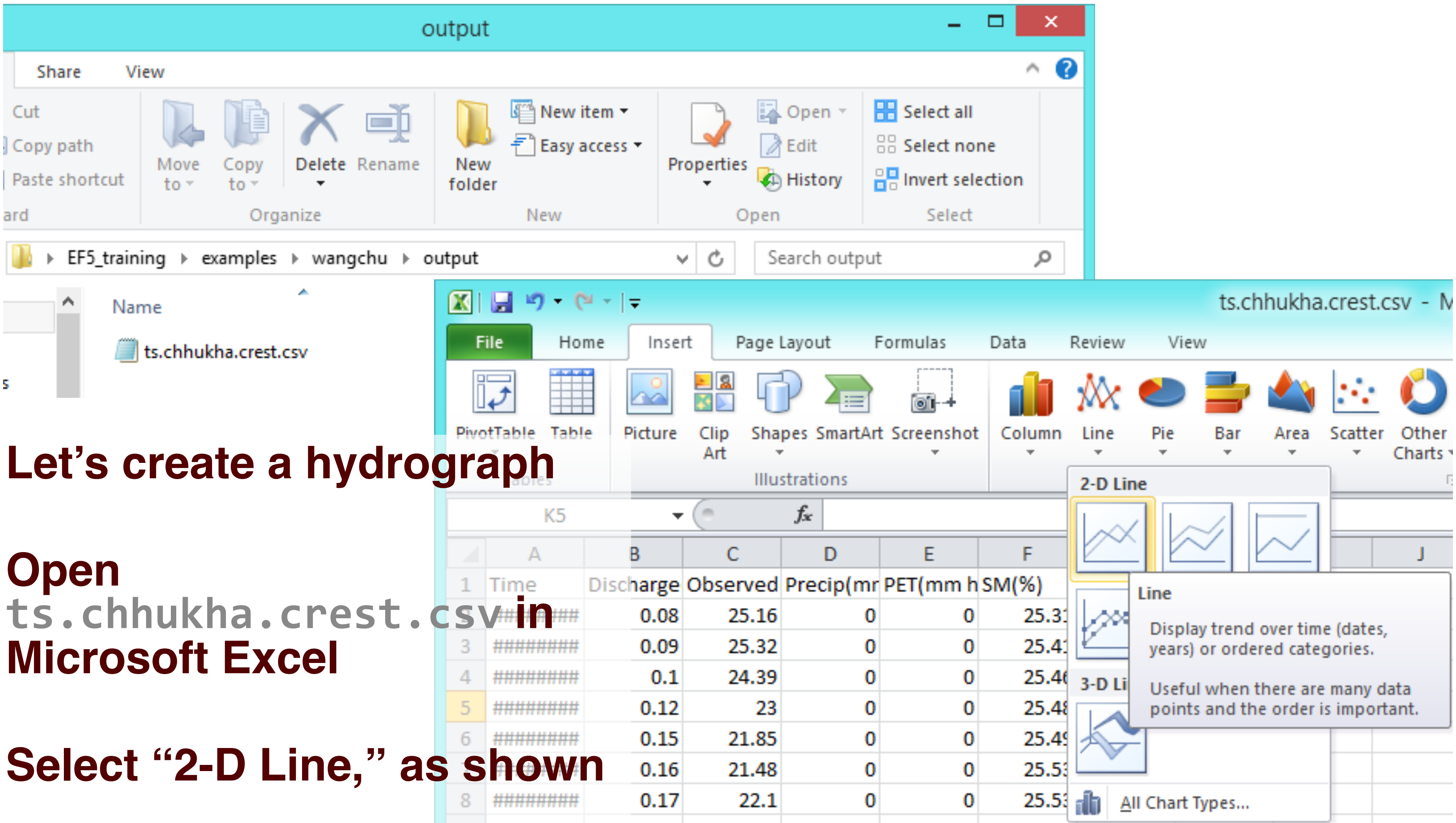

Let's create a hydrograph

Open `ts.chhukha.crest.csv` in Microsoft Excel

Select "2-D Line," as shown

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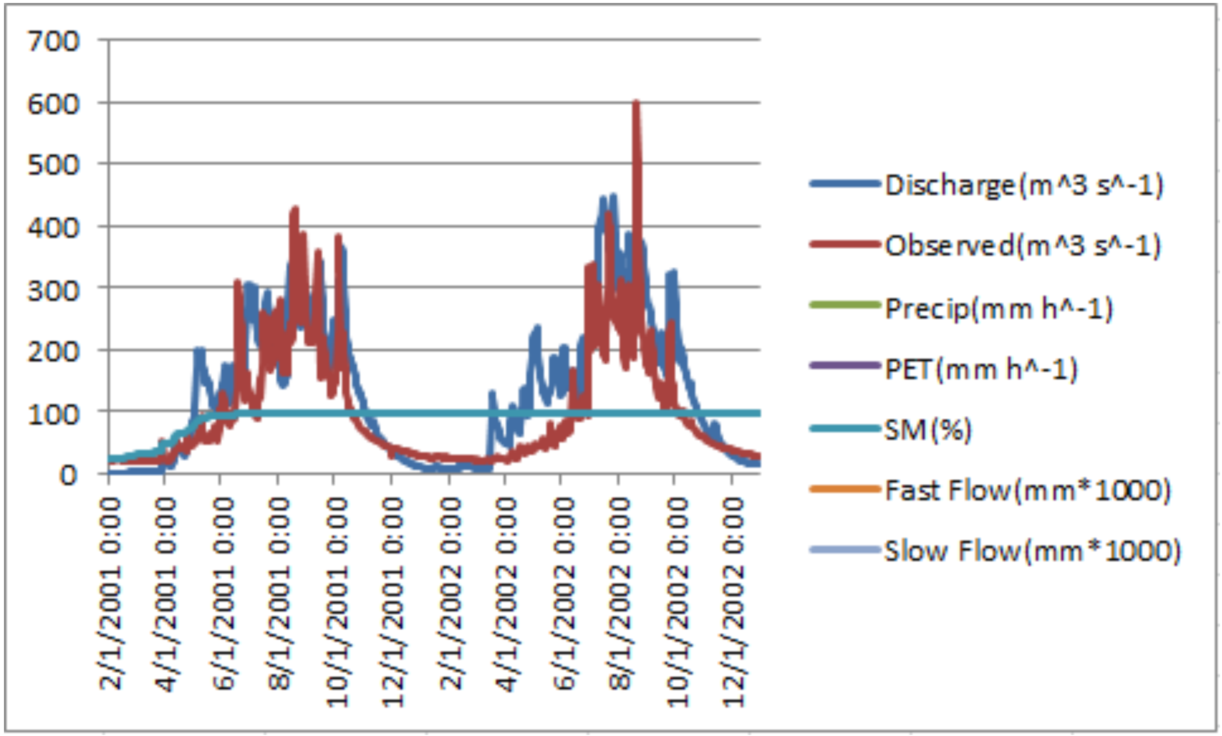

The raw figure is a little hard to interpret, and includes a bunch of information not needed for our purposes

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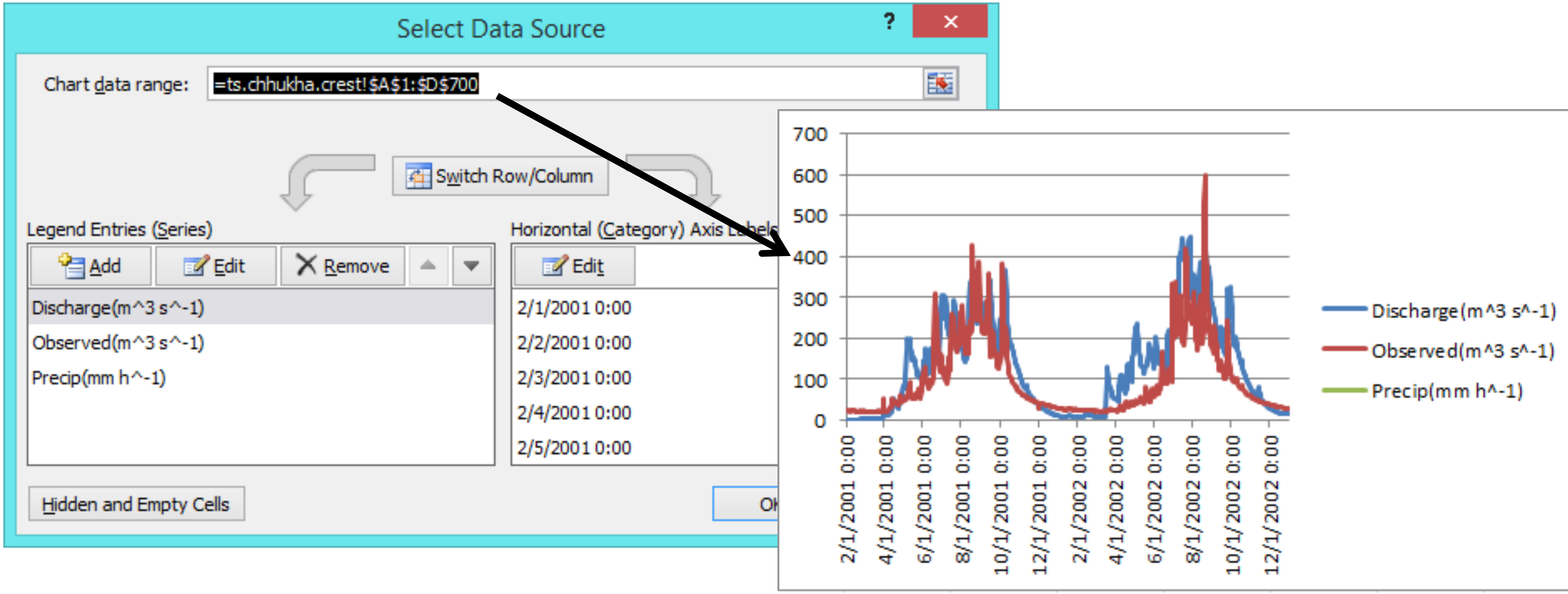
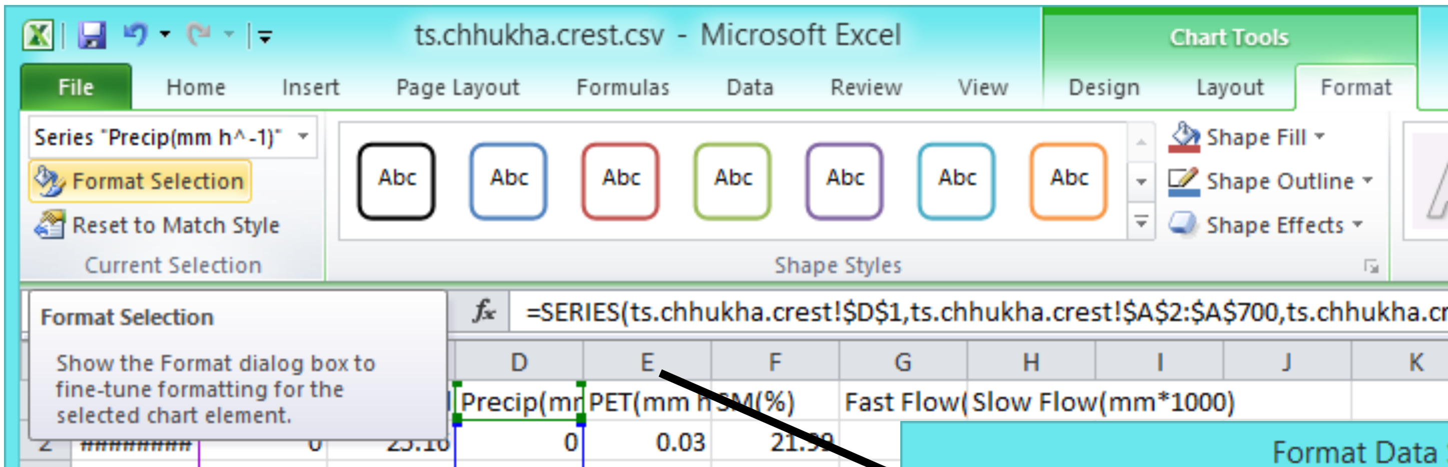
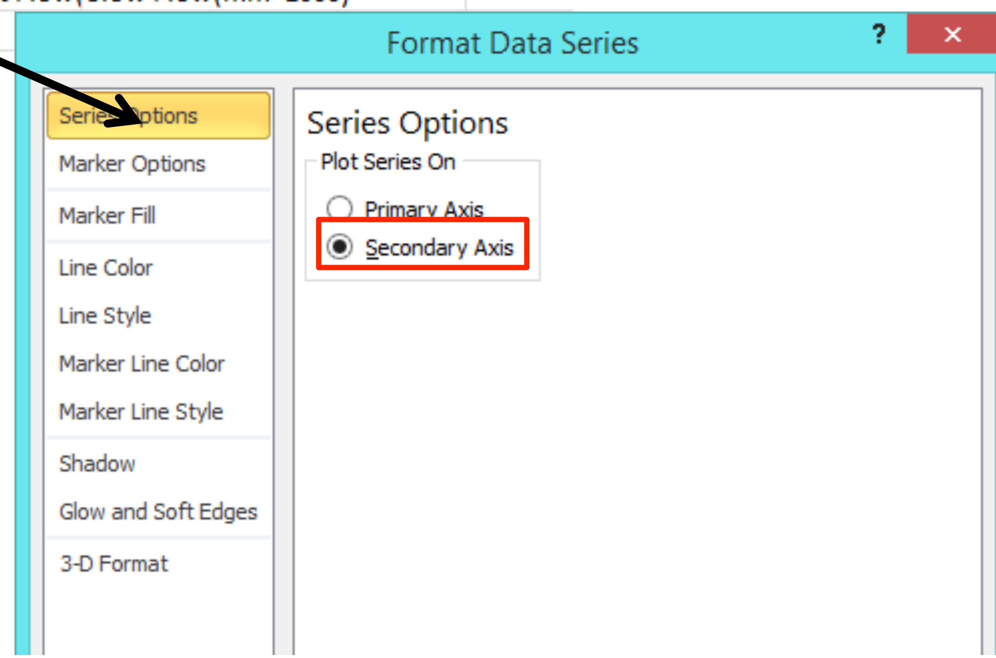


Select the chart, then the "Design" tab on the ribbon, and then the "Select Data" button

Change the chart data range to include the first 4 columns, as shown (Time, Discharge, Observed, and Precip)





Select the "Precip" data series and then "Format Selection"

Select "Secondary Axis"

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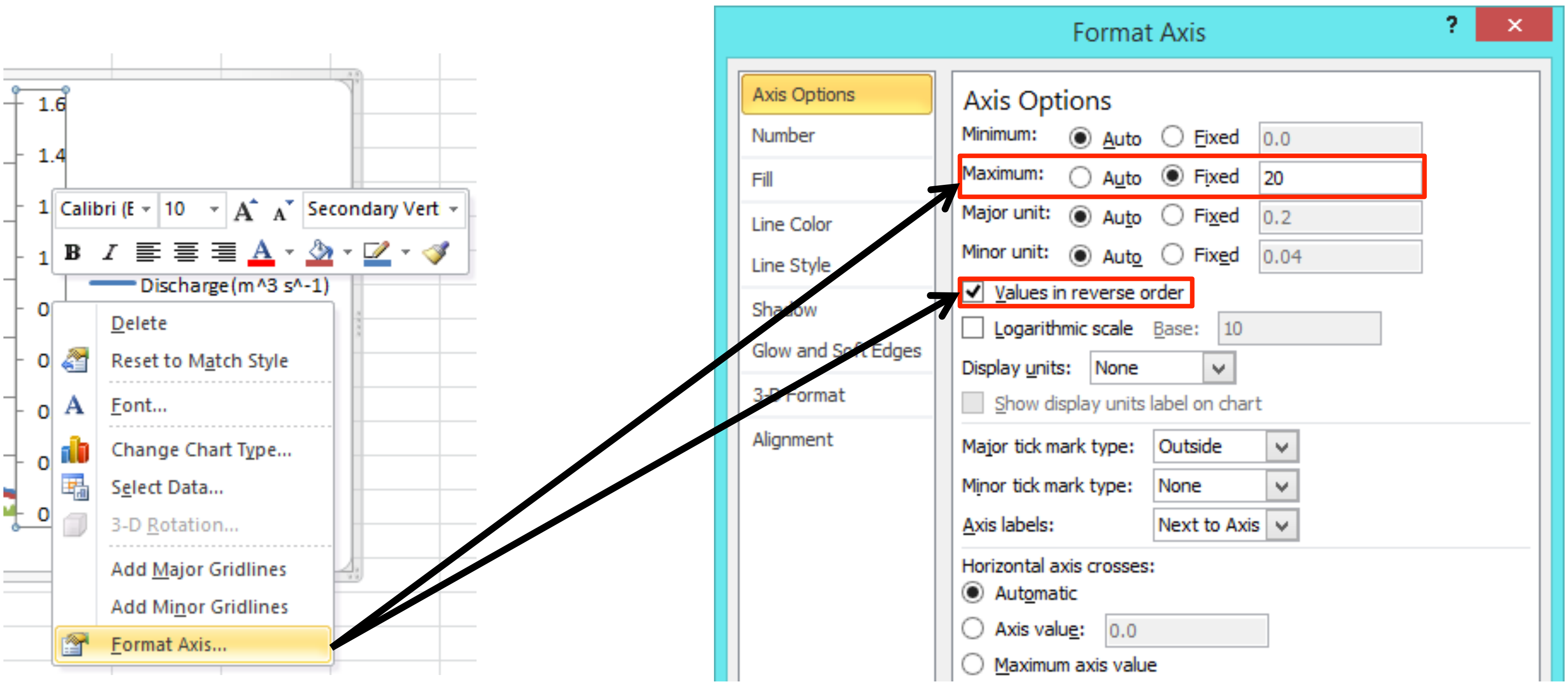
Now right-click the new Precip axis (on the right side) and select "Format Axis…"

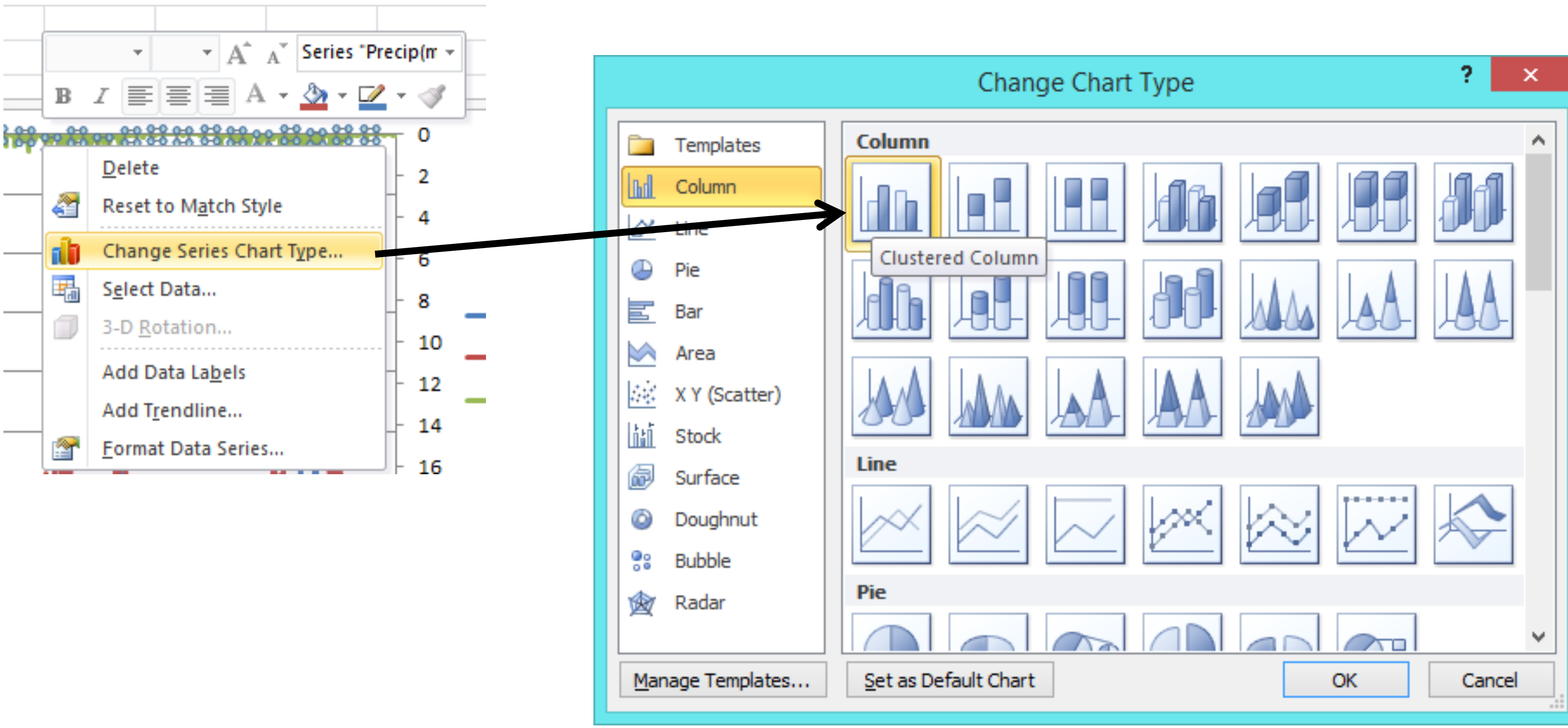
Check "Values in reverse order"

Then set the maximum axis value to "Fixed" and select some larger value than the default

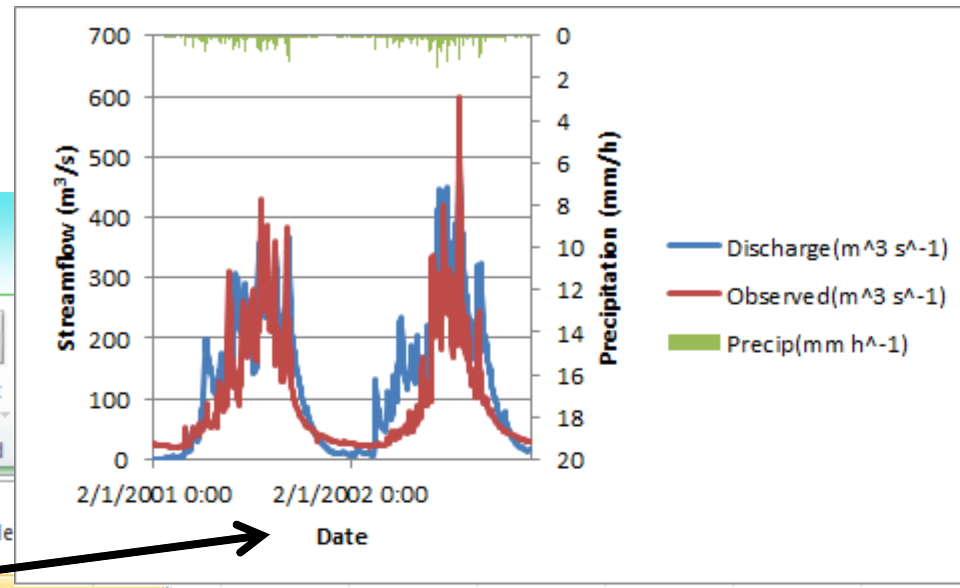


Right-click the "Precip" data set and select "Change Series Chart Type…"

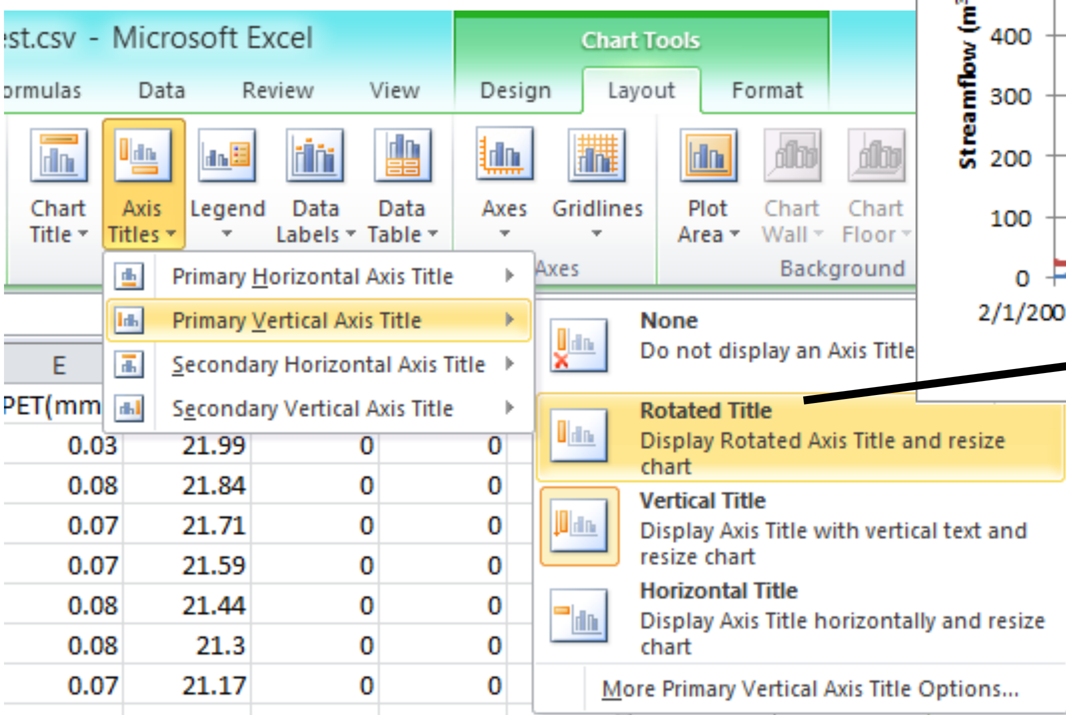
Change to the "Clustered Column" option



Click “Axis Titles” and turn on “Primary Vertical Axis Title”, “Primary Horizontal Axis Title”, and “Secondary Vertical Axis Title”



Edit axis titles as appropriate



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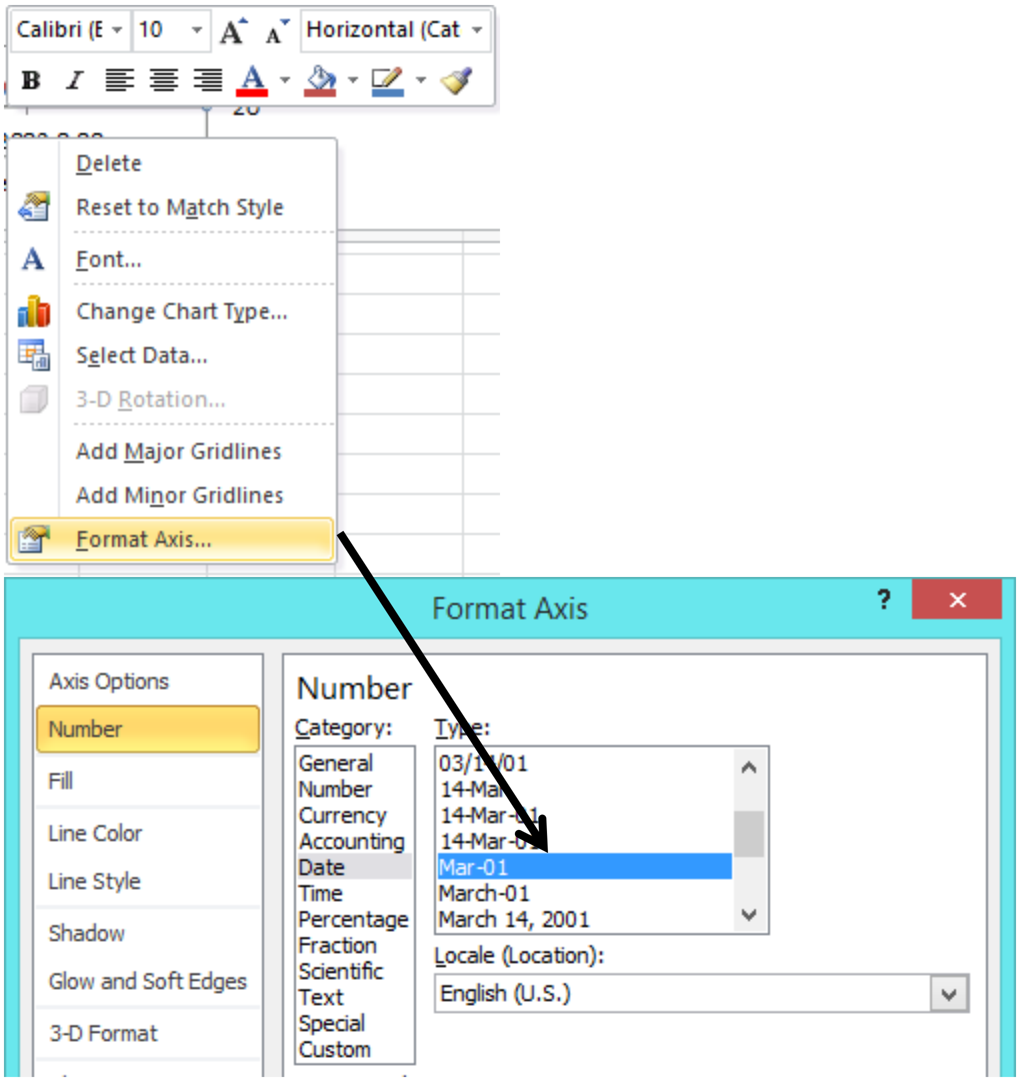


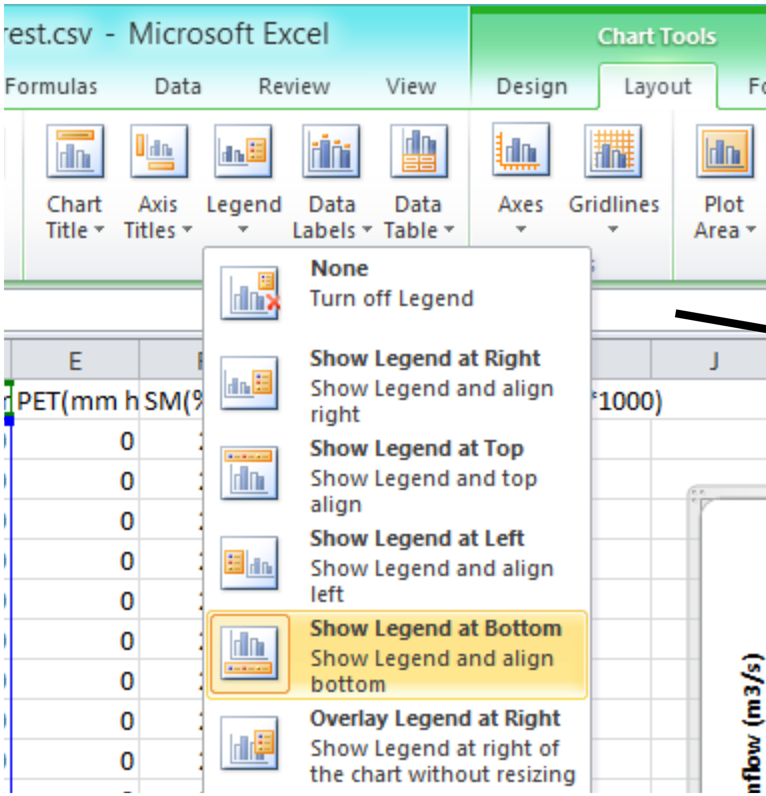
Edit the labels of the time axis

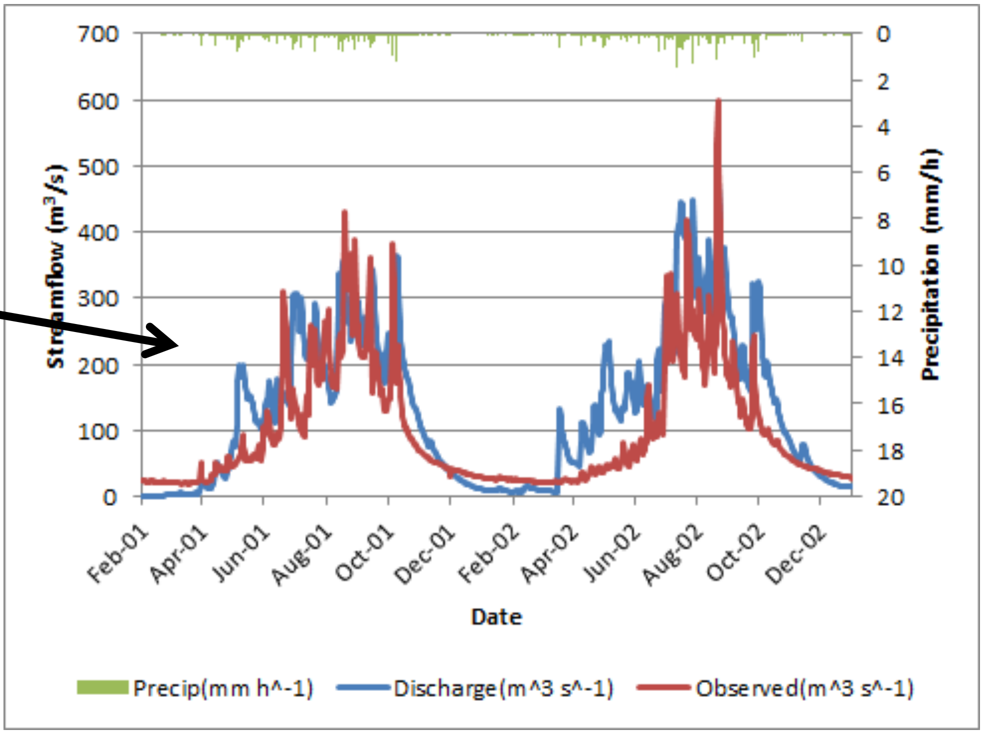
Right-click the horizontal axis and select "Format Axis…"

Go to "Number", then select "Date" in the "Category:" field

Choose whatever you like – in this example, we have 2 years (24 months), so showing the abbreviated month and the year together is nice

I moved my legend to the bottom

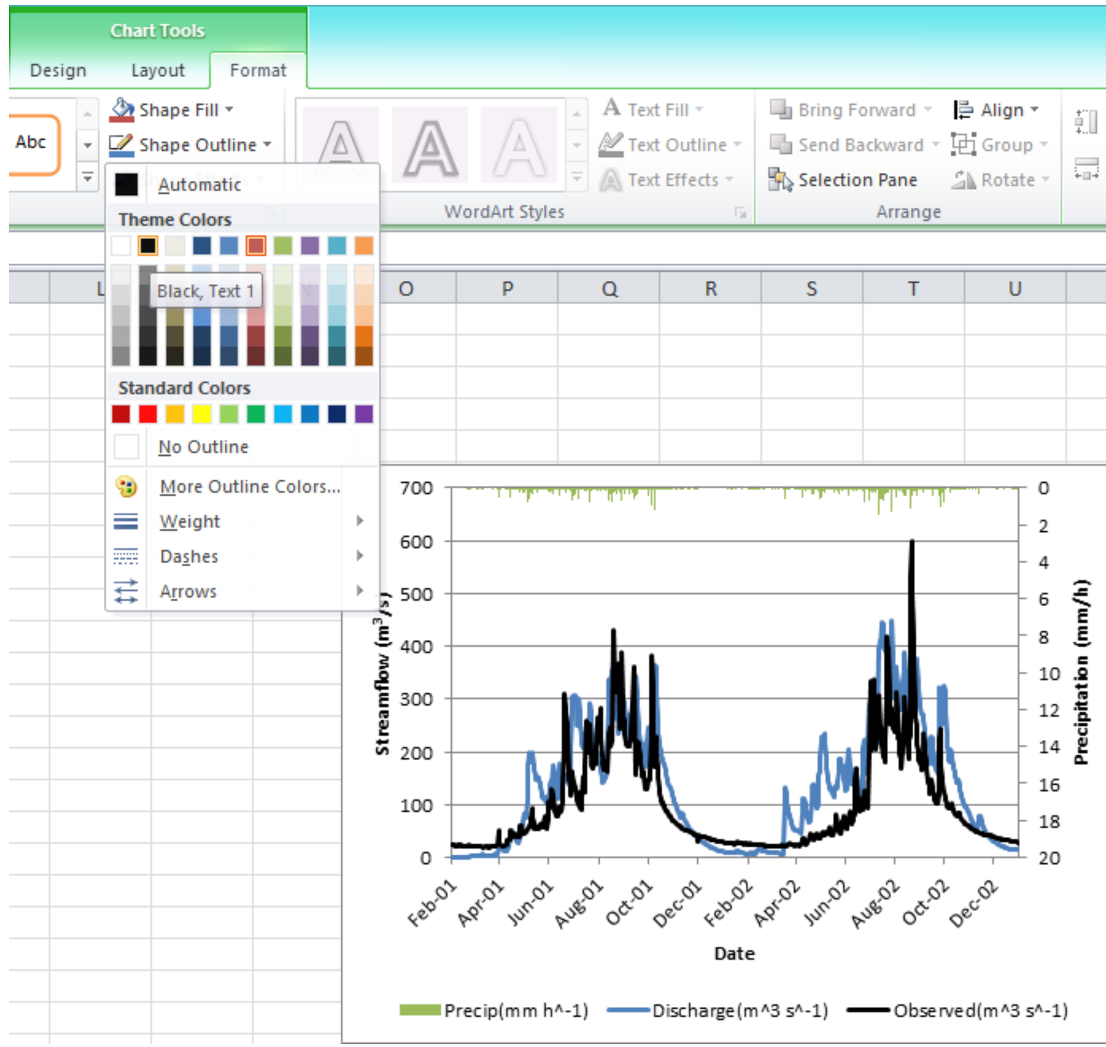




Select the observations data series

Go to "Chart Tools", then the "Format" tab, then "Shape Outline"

Change the observed time series to black



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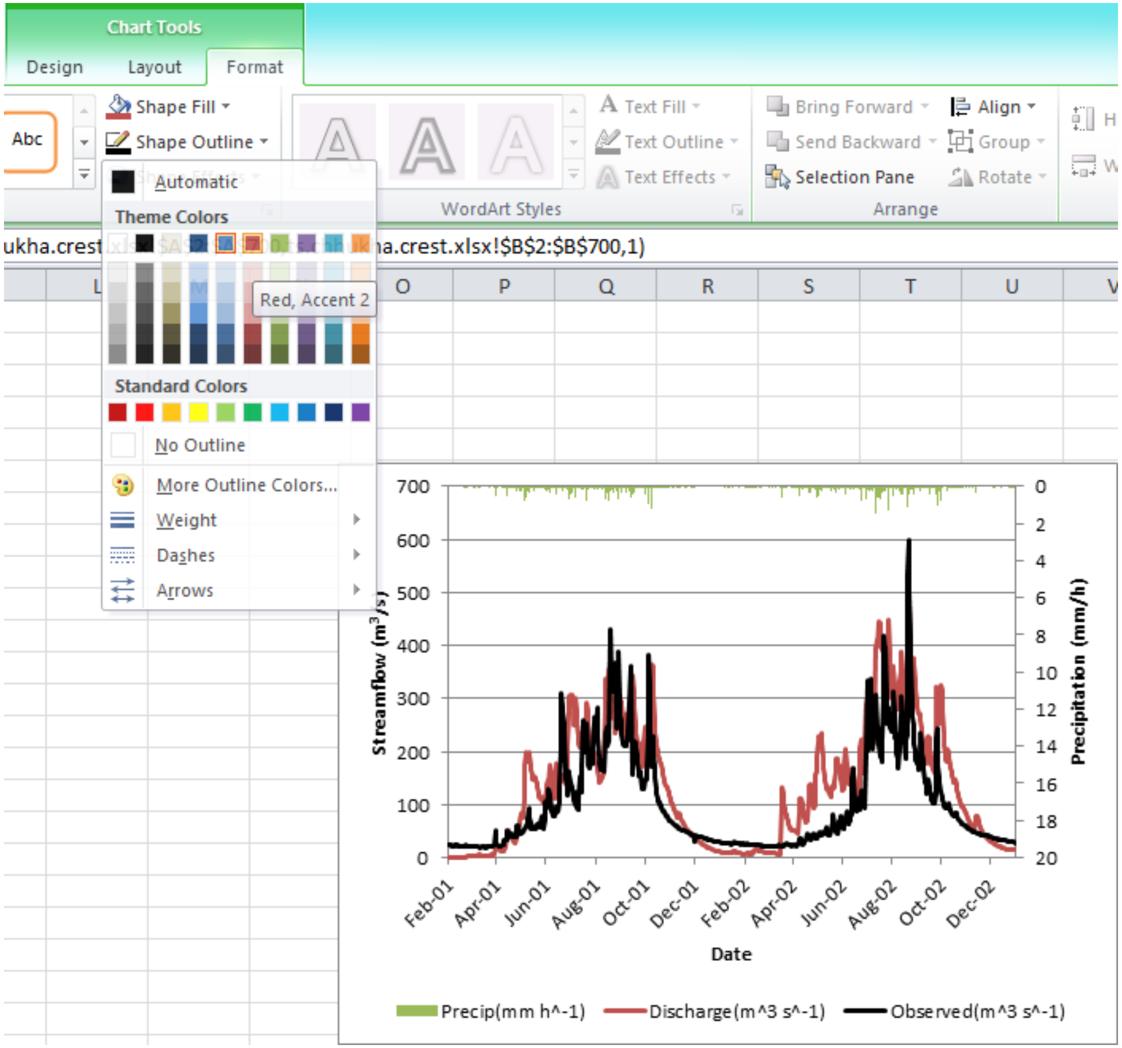
Change the simulated or discharge time series to red, repeating the process from the previous slide



And that completes the hydrograph!

Coming Up….

The next module is

EF5 OVERVIEW

You can find it in your `\EF5_training\presentations` **directory**

Module 1.2 References

EF5 Training Doc 4 – EF5 Control File, (March 2015).

Wang, J., Y. Hong, L. Li, J. J. Gourley, S. I. Khan, K. K. Yilmaz, R. F. Adler, F. S. Policelli, S. Habib, D. Irwn, A. S. Limaye, T. Korme, L. Okello, (2011). The coupled routing and excess storage (CREST) distributed hydrological model. *Hydrological Sciences Journal* 56: 1, 84-98. (Paper 1 – CREST.pdf)

Zhao, R., Z. Yilin, F. Leren, L. Xinren, Z. Quansheng, (1980). The Xinanjiang Model. In: *Hydrological Forecasting* (Proc. Oxford Symp., April 1980), 351-356. Wallingford: IAHS Press, IAHS Publ. 129. (Paper 7- The Xinanjiang Model.pdf)