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# WEAP

Water Evaluation And Planning System

# Tutorial

A collection of stand-alone modules to aid in learning  
the WEAP software

October 2023

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# WEAP

## Water Evaluation And Planning System

# Tutorial Modules

Tutorial Overview.....	3
WEAP in One Hour.....	15
Basic Tools.....	41
Scenarios .....	51
Refining the Demand Analysis.....	73
Refining the Supply .....	93
Data, Results and Formatting.....	115
Reservoirs and Power Production .....	135
Water Quality .....	147
Linking WEAP to QUAL2K .....	169
Hydrology .....	177
Catchment Calibration .....	201
Snow Hydrology .....	255
Glaciers.....	271
Financial Analysis.....	287
Linking WEAP to MODFLOW.....	299
Linking WEAP to LEAP.....	353

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# WEAP

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# Tutorial Overview

<i>Introduction</i> .....	4
<i>Background</i> .....	4
<i>WEAP Development</i> .....	5
<i>The WEAP Approach</i> .....	5
<i>Program Structure</i> .....	6
<i>The Tutorial Structure</i> .....	9

October 2023

## Introduction

WEAP<sup>®</sup> is a microcomputer tool for integrated water resources planning. It provides a *comprehensive, flexible* and *user-friendly* framework for policy analysis. A growing number of water professionals are finding WEAP to be a useful addition to their toolbox of models, databases, spreadsheets and other software.

This overview summarizes WEAP's purpose, approach and structure. The contents of the WEAP tutorial are also introduced; the tutorial is constructed as a series of modules that takes you through all aspects of WEAP modeling capabilities. Although the tutorial itself is built on very simple examples, it covers most aspects of WEAP. A more complex model presenting those aspects in the context of a real situation is included with WEAP under the name "Weeping River Basin." A detailed technical description is also available in a separate publication, the *WEAP User Guide*.

## Background

Many regions are facing formidable freshwater management challenges. Allocation of limited water resources, environmental quality, and policies for sustainable water use are issues of increasing concern. Conventional supply-oriented simulation models are not always adequate. Over the last decade, an integrated approach to water development has emerged that places water supply projects in the context of demand-side issues, water quality and ecosystem preservation.

WEAP aims to incorporate these values into a practical tool for water resources planning. WEAP is distinguished by its integrated approach to simulating water systems and by its policy orientation. WEAP places the demand side of the equation—water use patterns, equipment efficiencies, re-use, prices and allocation—on an equal footing with the supply side—streamflow, groundwater, reservoirs and water transfers. WEAP is a laboratory for examining alternative water development and management strategies.

WEAP is comprehensive, straightforward, and easy-to-use, and attempts to assist rather than substitute for the skilled planner. As a database, WEAP provides a system for maintaining water demand and supply information. As a forecasting tool, WEAP simulates water demand, supply, flows, and storage, and pollution generation, treatment and discharge. As a policy analysis tool, WEAP evaluates a full range of water development and management options and takes account of multiple and competing uses of water systems.

## WEAP Development

The Stockholm Environment Institute provided primary support for the development of WEAP. The Hydrologic Engineering Center of the US Army Corps of Engineers funded significant enhancements. A number of agencies, including the World Bank, USAID and the Global Infrastructure Fund of Japan have provided project support. WEAP has been applied in water assessments in over one hundred countries.

## The WEAP Approach

Operating on the basic principle of a water balance, WEAP is applicable to municipal and agricultural systems, single catchments or complex transboundary river systems. Moreover, WEAP can address a wide range of issues, *e.g.*, sectoral demand analyses, water conservation, water rights and allocation priorities, groundwater and streamflow simulations, reservoir operations, hydropower generation, pollution tracking, ecosystem requirements, vulnerability assessments, and project benefit-cost analyses.

The analyst represents the system in terms of its various supply sources (*e.g.*, rivers, creeks, groundwater, reservoirs, and desalination plants); withdrawal, transmission, and wastewater treatment facilities; water demands and ecosystem requirements; and pollution generation. The data structure and level of detail may be easily customized to meet the requirements of a particular analysis, and to reflect the limits imposed by restricted data.

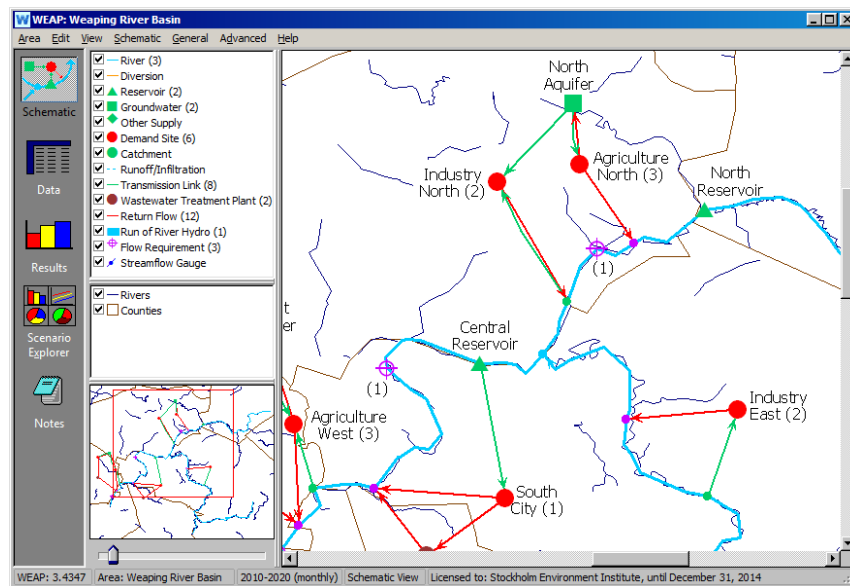
WEAP applications generally include several steps. The *study definition* sets up the time frame, spatial boundary, system components and configuration of the problem. The *Current Accounts*, which can be viewed as a calibration step in the development of an application, provide a snapshot of actual water demand, pollution loads, resources and supplies for the system. Key assumptions may be built into the Current Accounts to represent policies, costs and factors that affect demand, pollution, supply and hydrology. *Scenarios* build on the Current Accounts and allow one to explore the impact of alternative assumptions or policies on future water availability and use. Finally, the scenarios are *evaluated* with regard to water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables.

# Program Structure

WEAP consists of five main views: Schematic, Data, Results, Scenario Explorer and Notes. These five views are presented below.

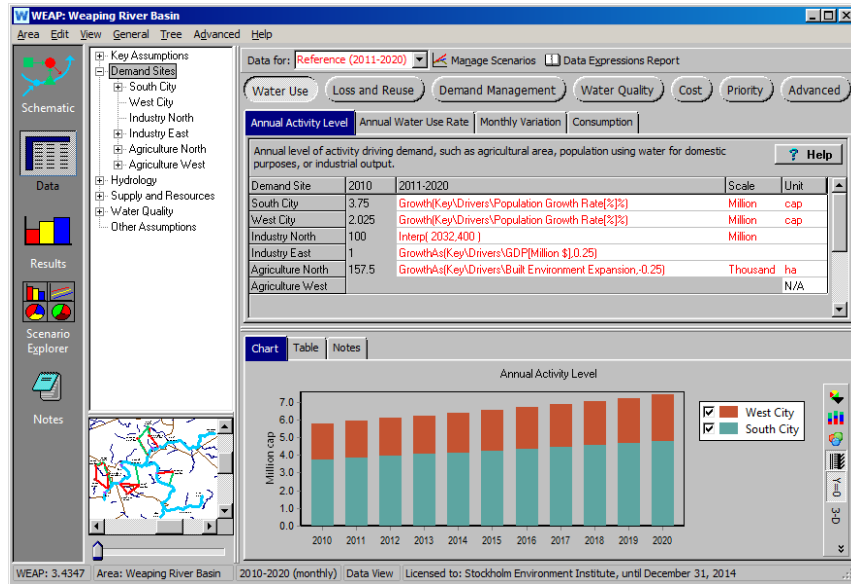
## Schematic:

This view contains GIS-based tools for easy configuration of your system. Objects (e.g., demand nodes, reservoirs) can be created and positioned within the system by dragging and dropping items from a menu. ArcView or other standard GIS vector or raster files can be added as background layers. You can quickly access data and results for any node by clicking on the object of interest.



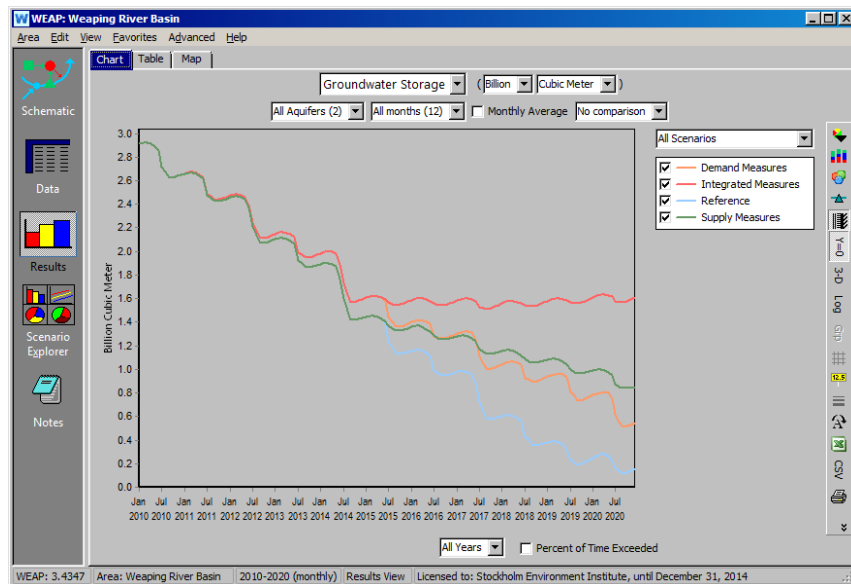
## Data:

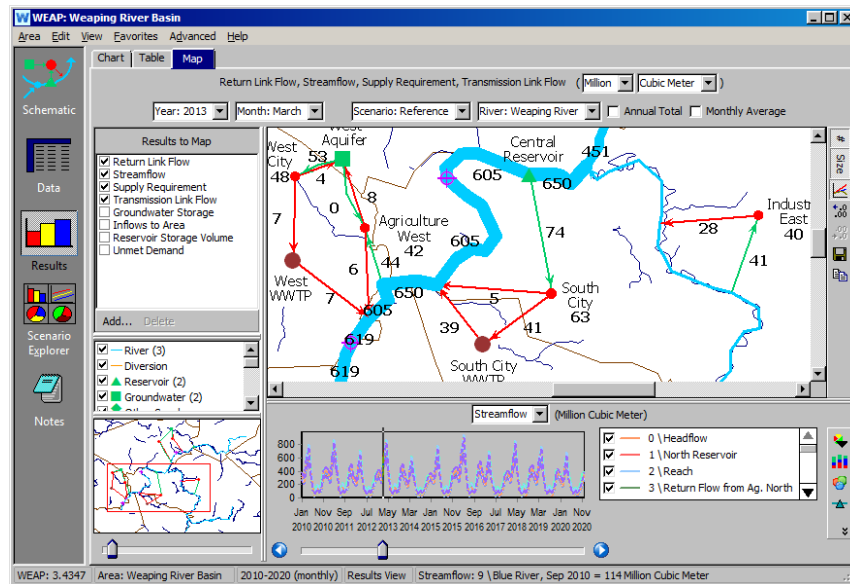
The Data view allows you to create variables and relationships, enter assumptions and projections using mathematical expressions, and dynamically link to Excel.



## Results:

The Results view allows detailed and flexible display of all model outputs, in charts and tables, and on the Schematic.





## Scenario Explorer:

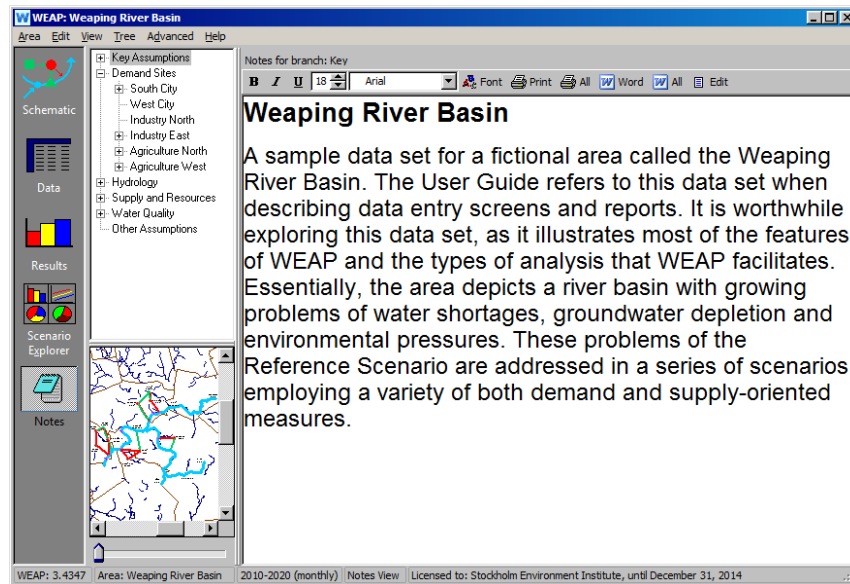
You can highlight key data and results in your system for quick viewing.



## Notes:

The Notes view provides a place to document your data and assumptions.





## The Tutorial Structure

This complete tutorial guides you through the wide range of applications that can be covered with WEAP. The first three modules (WEAP in One Hour, Basic Tools, and Scenarios) present the essential elements needed for any WEAP modeling effort. The other modules present refinements that may or may not apply to your situation.

Aside from the three basic modules, the tutorial modules can be completed in any order and independently, as you see fit. They all start with the same model that you will create after completing the first three modules.

Below is a list of all modules, starting with the three basic modules; the bulleted points indicate the aspects covered in each module.

### *WEAP in One Hour*

- Creating a New, Blank Study Area
- Setting General Parameters
- Entering Elements into the Schematic
- Getting First Results

### *Basic Tools*

- Creating and Using Key Assumptions

- Using the Expression Builder

### ***Scenarios***

- Preparing the Ground for Scenarios
- Creating the Reference Scenario
- Creating and Running Scenarios
- Using the Water Year Method

### ***Refining the Demand Analysis***

- Disaggregating Demand
- Modeling Demand Side Management, Losses and Reuse
- Setting Demand Allocation Priorities

### ***Refining the Supply***

- Changing Supply Priorities
- Modeling Reservoir Supply
- Adding Flow Requirements
- Modeling Groundwater Resources

### ***Data, Results and Formatting***

- Exchanging Data
- Importing Time Series
- Working with Results
- Formatting

### ***Reservoirs and Power Production***

- Modeling Reservoir Operation
- Adding Hydropower Computation

- Modeling Run-of-River Power Plants

### ***Water Quality***

- Setting up Quality Modeling
- Entering Water Quality Data
- Using Water Quality Inflow Constraints for a Demand Site
- Entering Pollution Generating Activity for Demand Sites
- Modeling a Wastewater Treatment Plant

### ***Linking WEAP to QUAL2K***

- Linking to QUAL2K
- Running Scenarios

### ***Hydrology***

- Modeling Catchments: The Simplified Coefficient Method
- Understanding the Soil Moisture Method
- Modeling Catchments: The Soil Moisture Method
- Simulating Surface Water-Groundwater Interaction

### ***Catchment Calibration***

- Gather Observed Data and Select the Model Calibration Locations
- Complete Observed Data and Select the Model Calibration Period
- Visually Assess Model Calibration
- Adjust key parameters and conduct model sensitivity analysis
- Optimize calibration based on visual and statistical assessment
- Model Calibration Tips

### *Snow Hydrology*

- Explore the Pre-Existing Model
- Enter Catchment Climate and Calibration Data
- Explore the Model Sensitivity
- Calibrate with PEST
- Appendix

### *Glaciers*

- Modeling a Glacier
- Enter Catchment Climate
- Effect of Cooling Temperatures
- Effect of Warming Temperatures
- Parameter Sensitivity (Radiation Coefficient)

### *Financial Analysis*

- Setting up the Cost and Benefit Model
- Modeling Cost
- Modeling Benefits

### *Linking WEAP to MODFLOW*

- Linking to MODFLOW
- Running MODFLOW and Viewing Results
- Scenario: Increased Population
- Scenario: Irrigation
- Scenario: Artificial Recharge

*Linking WEAP to LEAP*

- Linking WEAP and LEAP
- Scenario: Hydropower Generation from WEAP
- Scenario: Demand for Cooling Water from LEAP
- Scenario: Electricity Demand from WEAP



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# WEAP

Water Evaluation And Planning System

# WEAP in One Hour

## ***A TUTORIAL ON***

*Creating a New, Blank Study Area.....16*

*Setting General Parameters .....20*

*Entering Elements into the Schematic.....23*

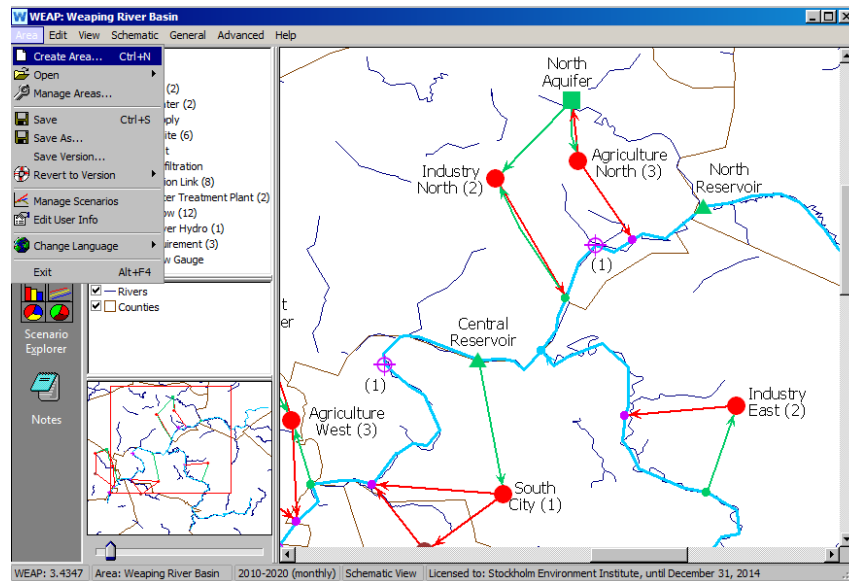
*Getting First Results.....37*

**October 2023**

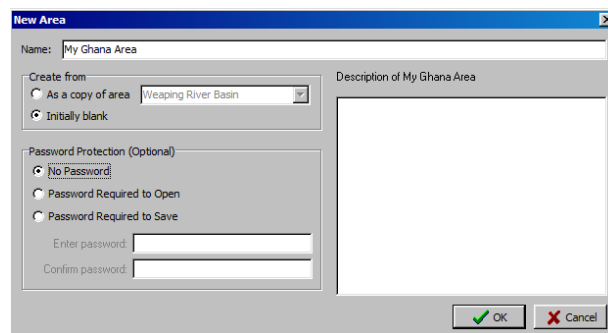
# Creating a New, Blank Study Area

## 1. Establish a New, Blank Area

You are now going to practice creating a new, blank area. When you open WEAP for the first time, a project area called “Weaping River Basin” will appear. Use the Area, Create Area menu option to make a new, blank area.

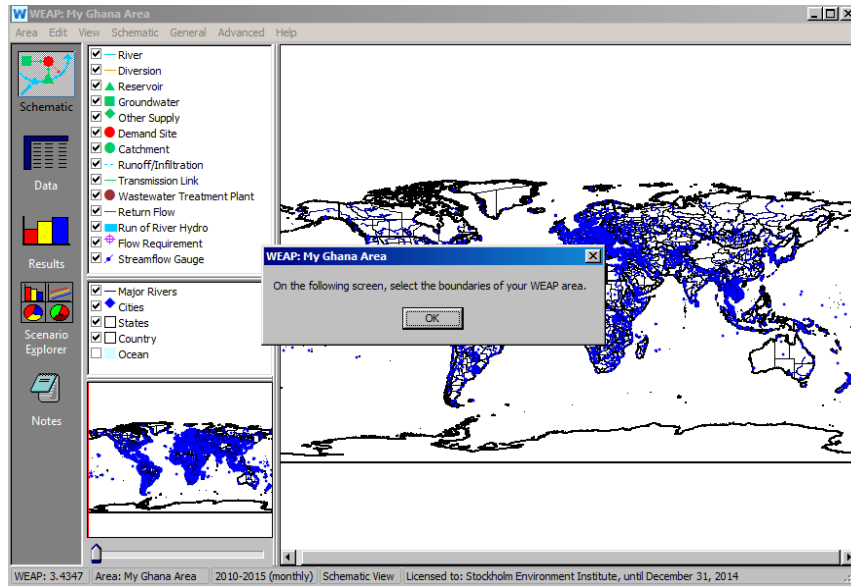


A window, as shown below, will appear in which you should click on the “Initially Blank” option. In the next steps, you will be defining this area for a specific geographic area of the world - so you can name the area based on this selection if you like (e.g., My Ghana Area). You can also save it as another version of model under construction, in the event you wanted multiple versions. Note that you can choose whether to have it password protected.

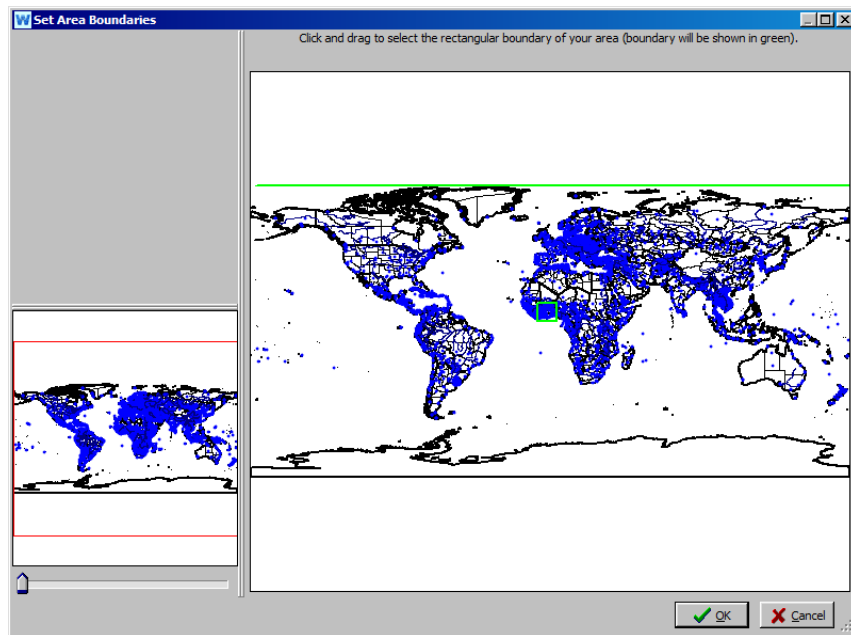


After clicking “OK” you may be prompted to save changes to the Weaping River Basin. After clicking yes or no, you will get the following screen:

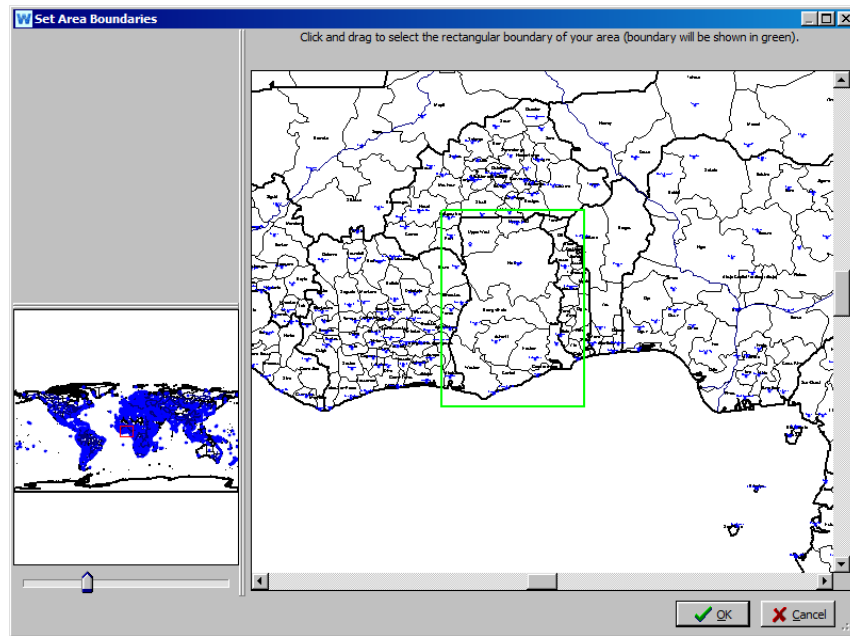




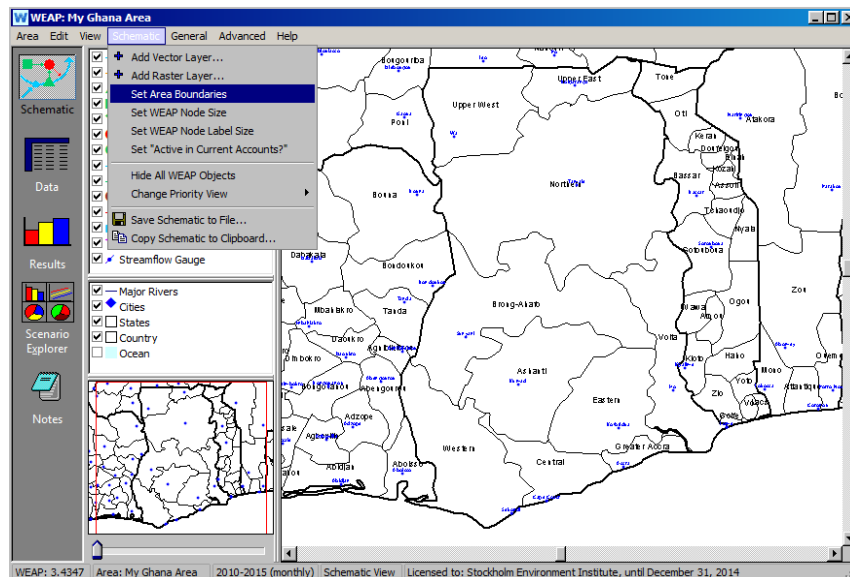
Click “OK” again. In the next screen, you will select the geographic area for your project from the world map that appears. Use your cursor to draw a rectangle around the area that your project will represent. The boundaries will appear as a green rectangle.



You can then use the slider bar on the lower left of the window to zoom into this selected area.



You can redraw your green rectangle to best capture the area you want in this view. Click on “OK” when you are satisfied with your area boundaries. Note that you can modify these boundaries later by choosing “Set Area Boundaries” on the pull-down menu under Schematic on the top menu bar.



In WEAP, models are called “areas.”

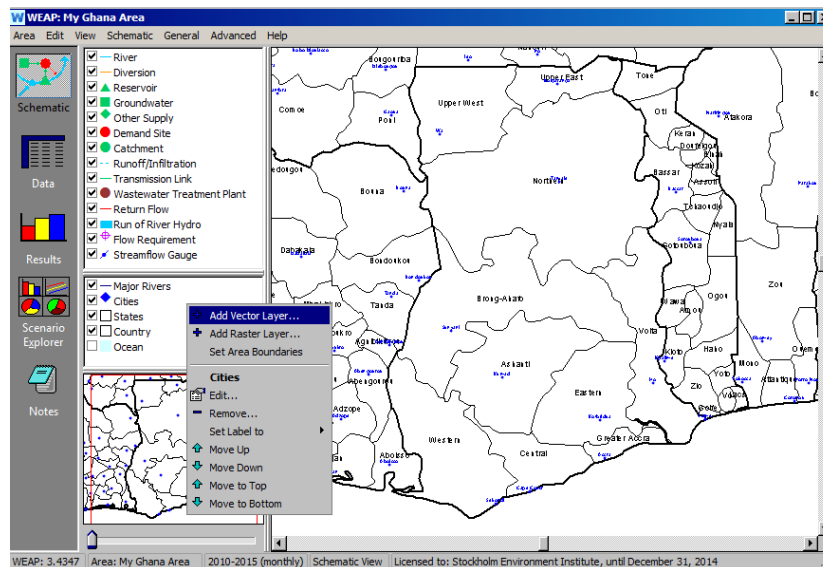


Areas are limited by boundaries, which define the extent of the project area. If you create a new area by copying an existing one, the boundary is kept identical to that of the existing area. To modify boundaries once you have established a New Area, go to Schematic on the menu, and choose “Set Area Boundaries.”

Note that if you want to start with a “blank” area, you can use the steps above to select a geographic area over one of the oceans instead of a land mass.

## 2. Add a GIS layer to the Area

You can add GIS-based Raster and Vector maps to your project area - these maps can help you to orient and construct your system and refine area boundaries. To add a Raster or Vector layer, right click in the middle window to the left of the Schematic and select “Add a Raster Layer” or “Add a Vector Layer.”



A window will appear in which you can input the name of this file and where WEAP can find it on your computer or on the internet. For now, close the window by pressing the “Cancel” button.

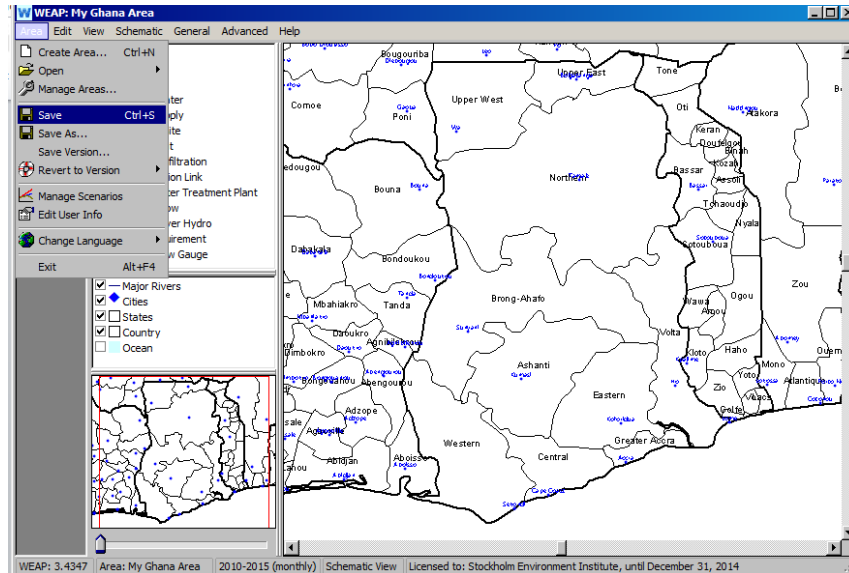


Background vector data can be added by clicking “Add Vector Layer.” WEAP reads vector information in the SHAPEFILE format. This format can be created by most GIS software.

A large amount of georeferenced data (both in vector and raster format) is available on the Internet, sometimes for free. Beware that some of the downloadable data might need GIS processing before being usable in WEAP, especially to adapt the projection and/or coordinate system.

### 3. Saving an Area

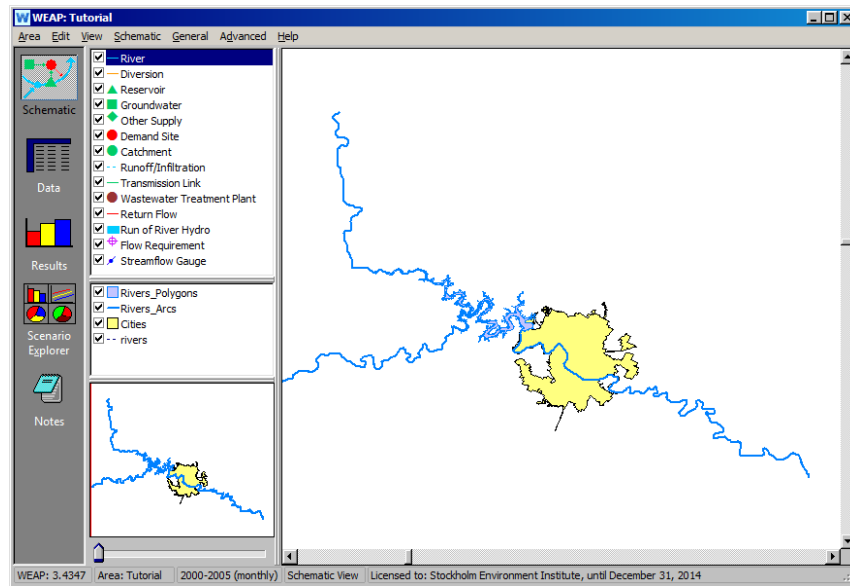
If you want to save this Area for your own use later, Use the “Area”, “Save...” menu or press Ctrl+S.



## Setting General Parameters

We are now going to proceed with learning how to navigate through WEAP and its functionalities. For the remaining exercises in this tutorial, we will be using a pre-defined Area called “Tutorial.”

To open this Area, on the Main Menu, go to Area and select “Open.” You should see a list of Areas that includes “Tutorial”. Select this Area. You should now see the Schematic as shown below—with blue lines for rivers and a yellow polygon for the city.



If you do not see this, go to the Area Menu, select “Revert to Version” and choose the version named “Starting Point for ‘WEAP in One Hour’ module” (it will have a date and time before the title).

#### 4. Set the General Parameters

Once the Area opens, use the “General” menu to set Years and Time Steps.

*Set the Current Accounts Year to 2000 and the Last Year of Scenarios to 2005. Set the Time Steps per year to 12. Set the Time Step Boundary to “Based on calendar month” and starting in January (see below) Keep the default (SI units) for now.*

**Years and Time Steps**

Time Horizon  
 Current Accounts Year: 2000  
 Last Year of Scenarios: 2005

Time Steps per Year  
 12  
 Add Leap Days?

Time Step Boundary  
 Based on calendar month  
 All time steps are equal length  
 Set time step length manually

Water Year Start  
 January

#	Title	Abbrev.	Length	Begins	Ends
1	January	Jan	31	Jan 1	Jan 31
2	February	Feb	28	Feb 1	Feb 28
3	March	Mar	31	Mar 1	Mar 31
4	April	Apr	30	Apr 1	Apr 30
5	May	May	31	May 1	May 31
6	June	Jun	30	Jun 1	Jun 30
7	July	Jul	31	Jul 1	Jul 31
8	August	Aug	31	Aug 1	Aug 31
9	September	Sep	30	Sep 1	Sep 30
10	October	Oct	31	Oct 1	Oct 31
11	November	Nov	30	Nov 1	Nov 30

Time Step Name Format: October / Oct

The study period will run from January, 2000 to December, 2005.

? Help      ✓ Close

Under “General”, the units also be set. We will leave them in the default (SI units) for now.



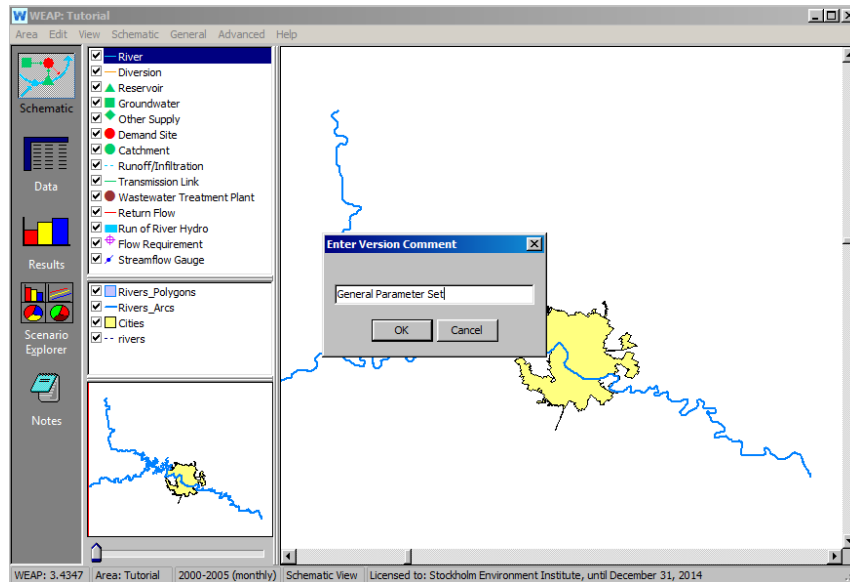
The year 2000 will serve as the “Current Accounts” year for this project. The Current Accounts year is chosen to serve as the base year for the model, and all system information (e.g., demand, supply data) is input into the Current Accounts. The Current Accounts is the dataset from which scenarios are built. Scenarios explore possible changes to the system in future years after the Current Accounts year. A default scenario, the “Reference Scenario” carries forward the Current Accounts data into the entire project period specified (here, 2000 to 2005) and serves as a point of comparison for other scenarios in which changes may be made to the system data. There will be a more detailed discussion of scenarios in an upcoming module.



The time steps should be chosen to reflect the level of precision of the data available. A shorter time step will increase the calculation time, especially when several scenarios have to be calculated.

## 5. Save a version of your Area

Select “Save Version” under the “Area” menu. A window will appear asking for a comment to describe this version. Type “general parameters set.”




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As with any other program, it is usually a good idea to regularly save your work in WEAP. WEAP manages all the files pertaining to an area for you. Saving a new area will automatically save the related files. The files are saved in the WEAP program installation folder. You can manage the areas, export and import them, back them up and send them per email using the Area..., Manage Areas menu.



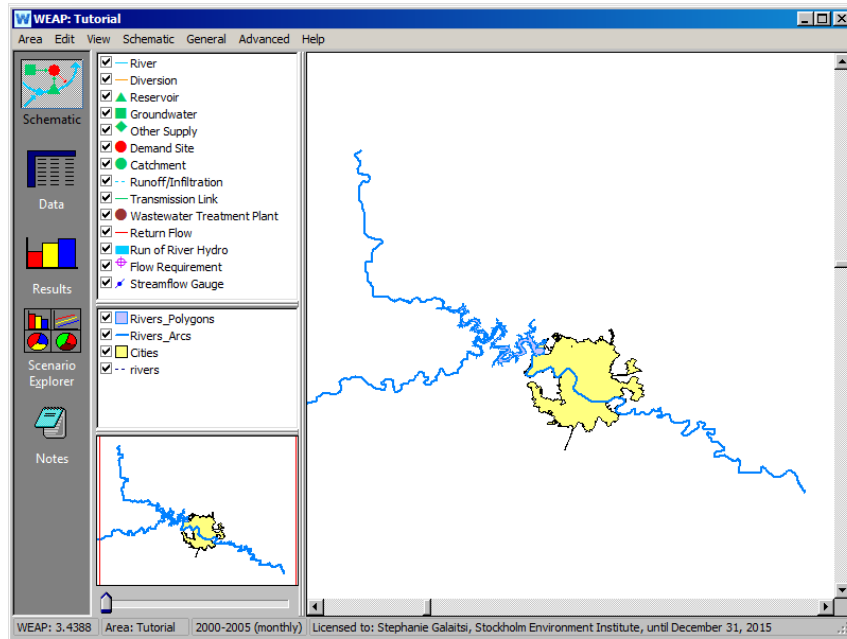
WEAP also has a very convenient versioning feature that allow saving versions of a model within the same area. Use the “Area”, “Save Version...:” menu to save a version, and the “Area”, “Revert to Version” to switch to another version. You can switch between recent and older versions without losing data. WEAP will automatically create versions of your model every time you save. It is however better to manually create a version of a status you really want to keep since WEAP will eventually delete old automatic versions to save disk space, keeping only a few.

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## Entering Elements into the Schematic

### 6. Draw a River

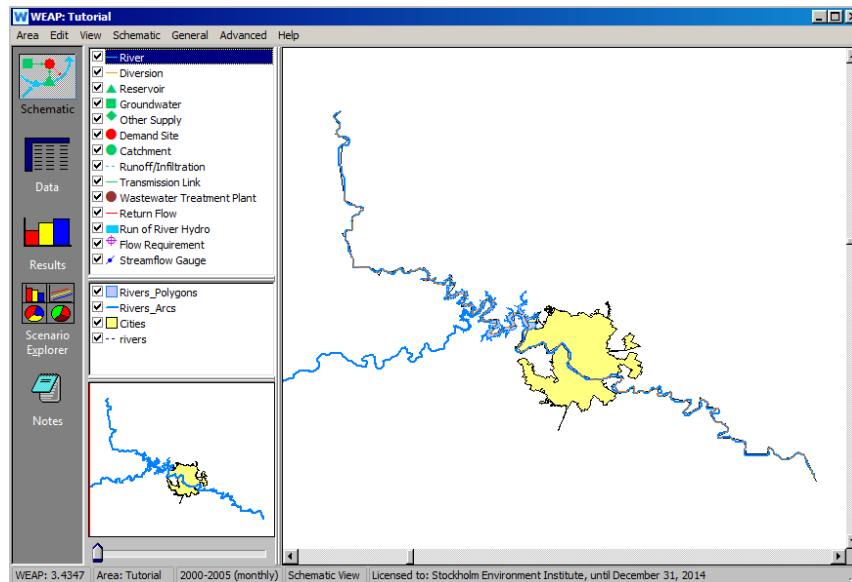
Click on the “River” symbol in the Element window and hold the click as you drag the symbol over to the map. Release the click when you have positioned the cursor over the upper left starting point of the main section of the river. Move the cursor, and you will notice a line being generated from that starting point.



The direction of drawing matters: the first point you draw will be the head of the river from where water will flow. You can edit the river course later on by simply clicking-moving any part of the river to create a new point, or right-clicking any point to delete it.

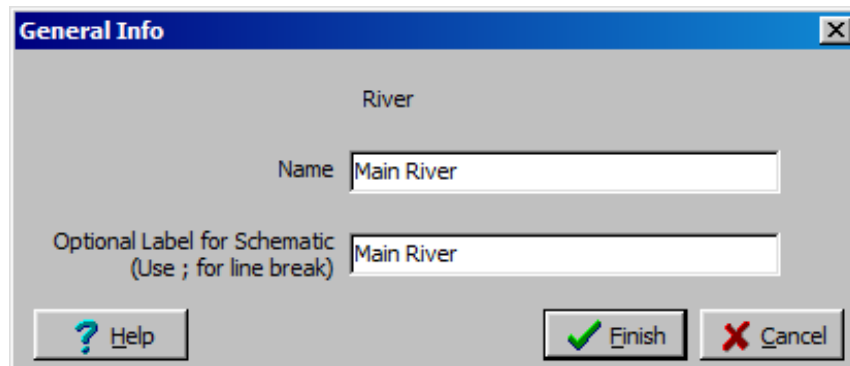
*Follow the main river, drawing from the upstream (upper left) to the downstream (lower right), clicking once to end each segment that you draw. You can follow the line of the river as closely as you like, or you can draw a less detailed representation (below). Note though, that how closely you follow the actual course of the river will have implications for the performance of certain functionalities in WEAP. For example, if you plan to model water quality parameters along the river, it would be advantageous to construct the river element as closely as possible to the actual river course, because WEAP will need to calculate residence times in the river (a function of reach lengths) to perform water quality simulations. Zooming in on the river (using the zooming bar in the lower schematic window) can help if you want to follow the rivers path more closely. You do not need to draw a river on the branch coming horizontally from the left. You can also adjust the river later if you want to add more detail.*





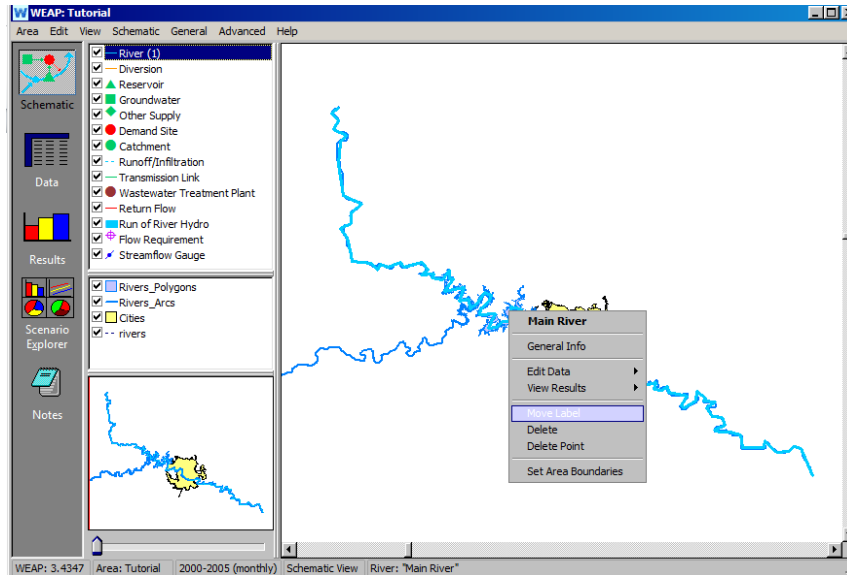
When you double click to finish drawing the river, a dialog box appears for naming the river (see below).

*Name the river “Main River.”*



You may also enter an optional label for the schematic presentation (a shorter label can help to keep the schematic from becoming cluttered).

You can move the river label to another location by right clicking anywhere on the river and selecting “Move Label.” The label will follow the cursor - single click when the label is in the desired location.

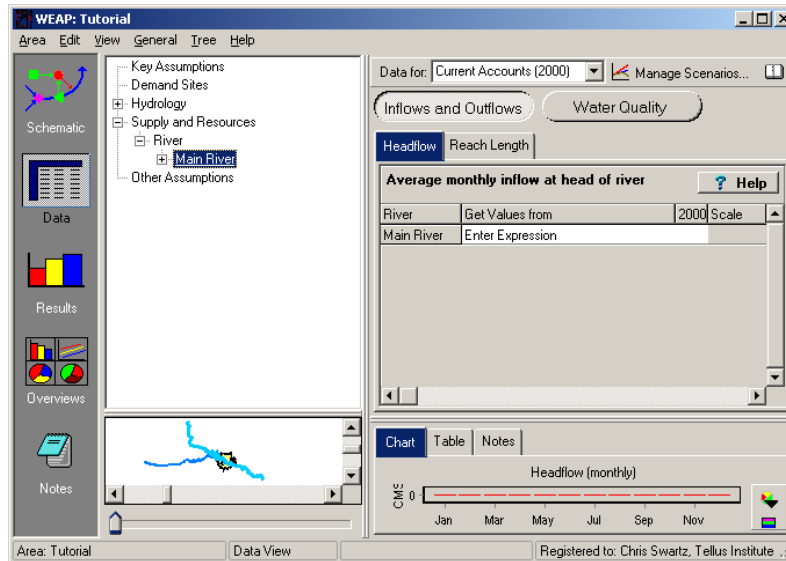


## 7. Enter Data for the Main River

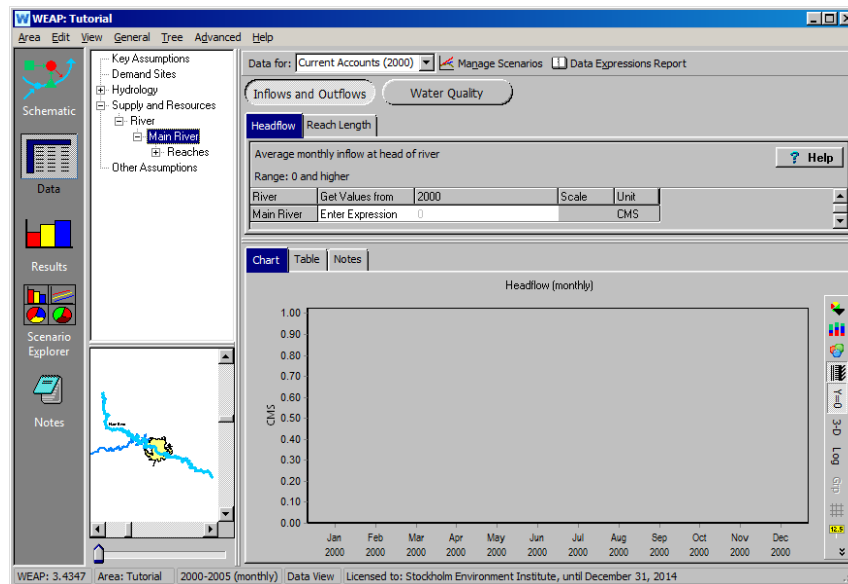
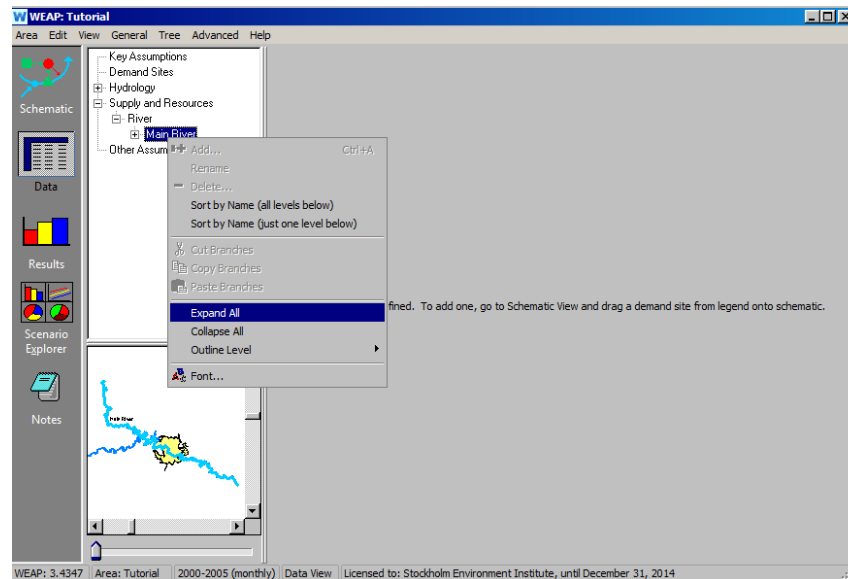
There are two ways to navigate to the data entry section of WEAP to enter data for the Main River.

Right-click on the Main River and select Edit data and any item in the list.

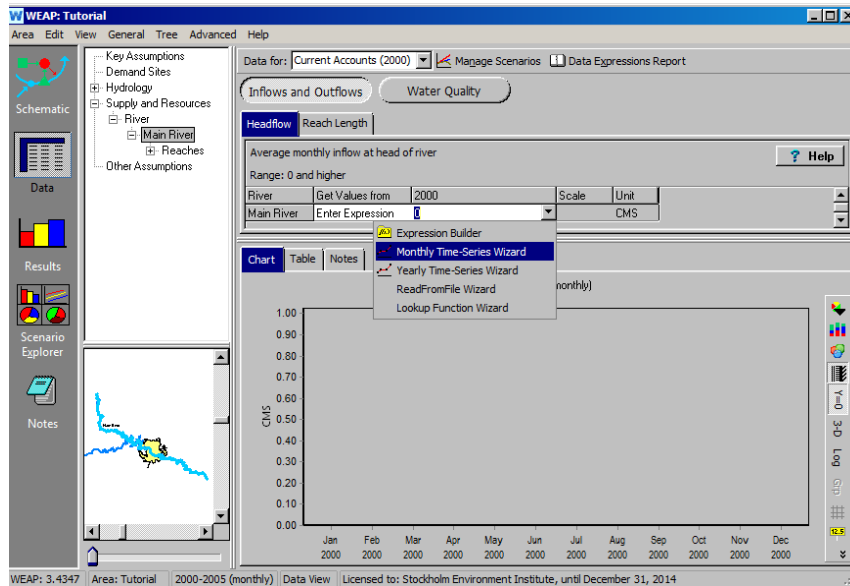
Switch to the Data view by clicking on the Data symbol on the left of the main screen. Select: *Supply and Resources/ River /Main River* in the Data tree. You may have to click on the “plus sign” icon beside the Supply and Resources branch in order to view all of the additional branches below it in the tree.



Alternatively, you can use the Tree pull-down menu and select “Expand All” to view all branches.



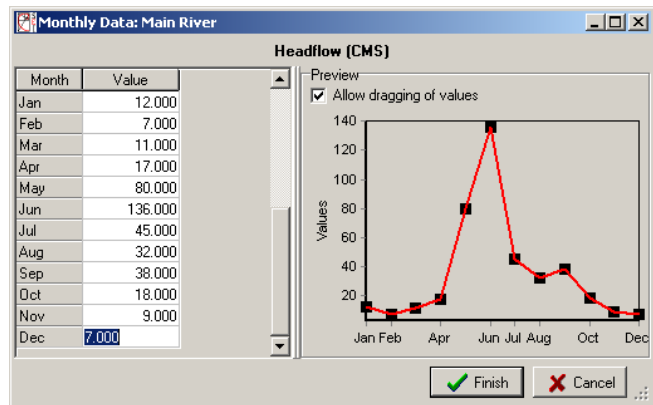
The “Inflows and Outflows” window should be open - if it isn't, click on the appropriate button. Click on the “Headflow” tab. Click on the area just beneath the bar labeled “2000” in the data input window to view a pull-down menu icon. Select the “Monthly Time-Series Wizard” from the drop--down menu.



Use the *Monthly Time Series Wizard* to enter the following data series:

MonthFlow (CMS)

Jan	12
Feb	7
Mar	11
Apr	17
May	80
Jun	136
Jul	45
Aug	32
Sep	38
Oct	18
Nov	9
Dec	7



Note that as you enter each data point, the data is shown graphically also. Do not input or change any other data yet. Push Finish to close the wizard.

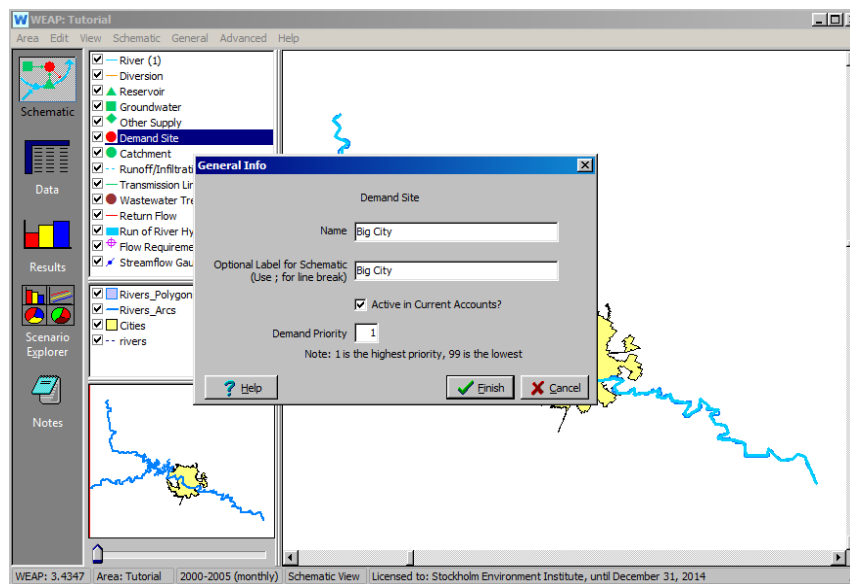


WEAP divides up rivers into reaches (segments). Originally your river has only one reach; as you add withdrawal and return points, WEAP will automatically create new reaches.

## 8. Create an Urban Demand Site and Enter the Related Data

Creating a demand node is similar to the process you used to create a river. Return to the Schematic view and pull a demand node symbol onto the schematic from the Element window, releasing the click when you have positioned the node on the left bank of the river (facing downstream) in the yellow area that marks the city's extent.

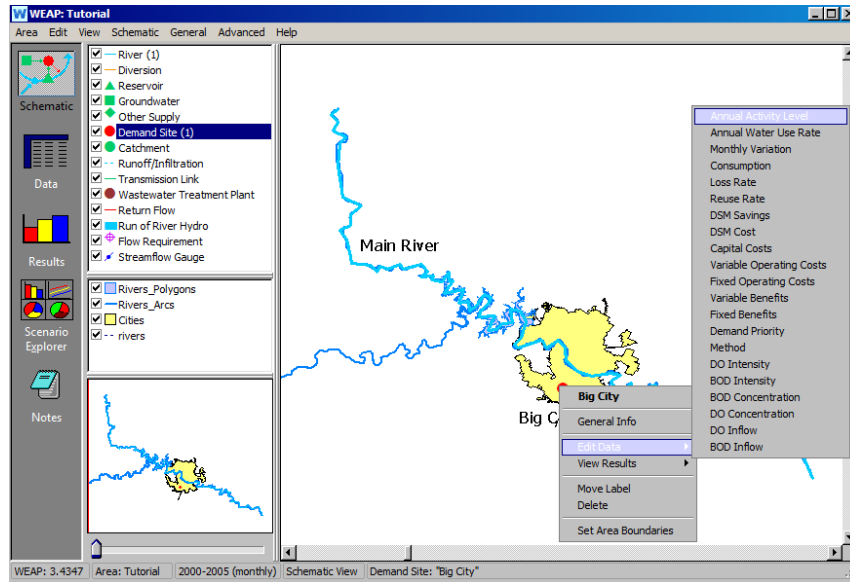
*Enter the name of this demand node as “Big City” in the dialog box, and set the demand priority to 1.*



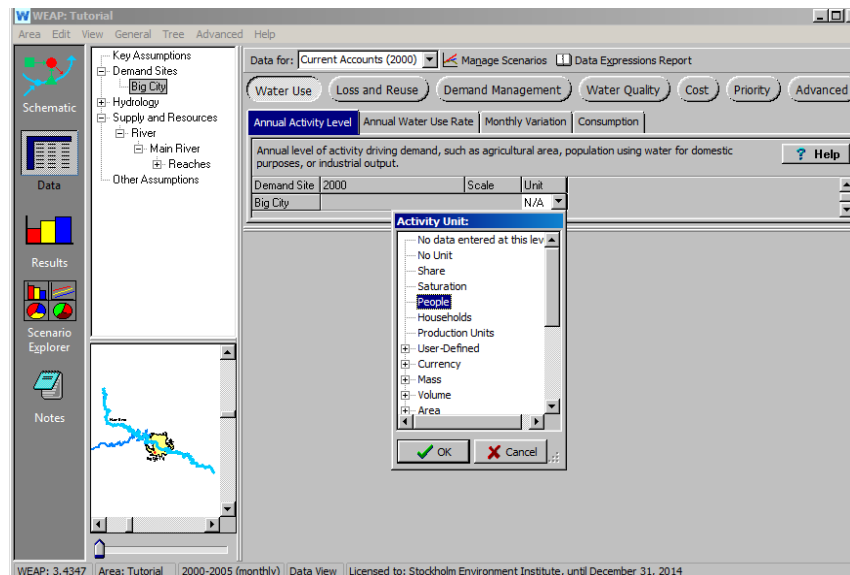
Right click on the Big City demand site and select “Edit data” and “Annual Activity Level.” This is the alternative way to edit data, rather than clicking on the “Data” view icon on the side bar menu and searching through the data tree.



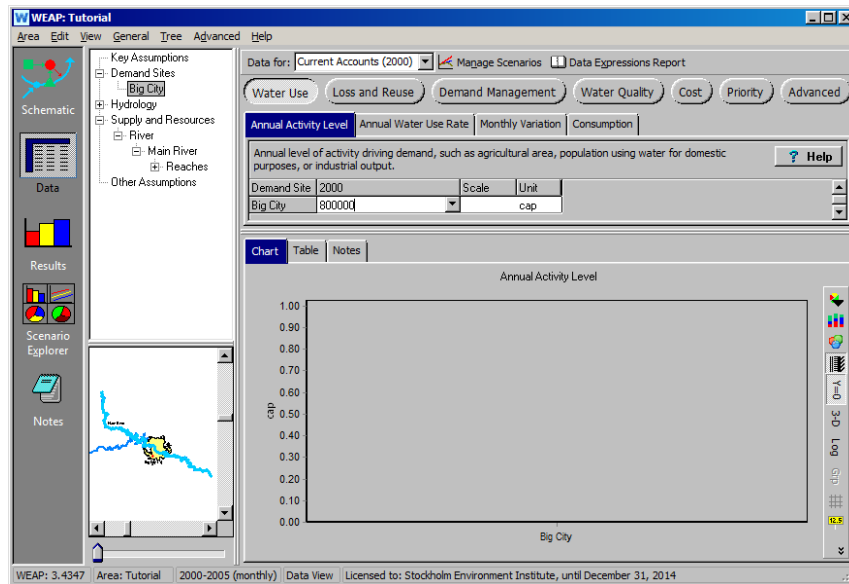
The Demand Priority represents the level of priority for allocation of constrained resources among multiple demand sites. WEAP will attempt to supply all demand sites with highest Demand Priority (1), moving to progressively lower priority sites until all of the demand is met or all of the resources are used—whichever happens first.



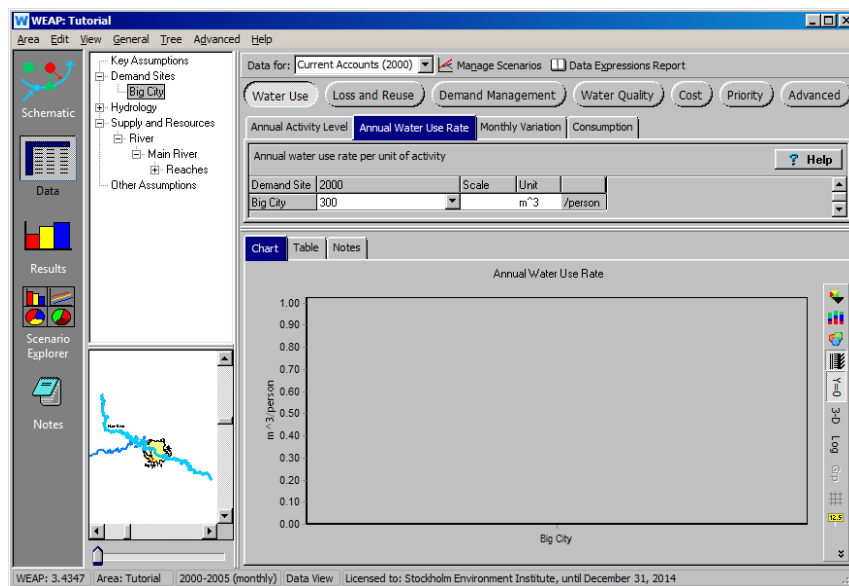
You must first select the units before entering data. Click on the “N/A” under Unit in the Annual Activity level tab. Pull down the arrow that appears, select “People”, and click “OK.”



*In the space under the field labeled “2000”, enter the Annual Activity Level as 800,000.*



*Next, click on the “Annual Water Use Rate” tab and enter 300 under the year 2000.*



The monthly variation is expressed as a percentage of the yearly value. The values for all of the months have to sum to 100% over the full year. If you don't specify monthly variation, WEAP will prescribe a monthly variation based on the number of days in each month.

We will not edit these values for the city demand, but we will edit them later for the agricultural demand.

*Finally, click on the “Consumption” tab and enter 15. Note that the units are pre-set to “percent.”*

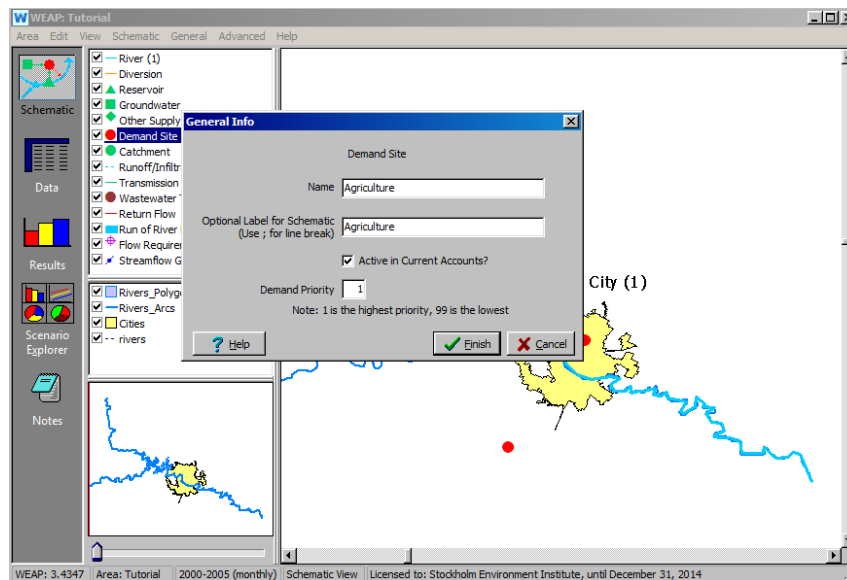
## 9. Create an Agriculture Demand Site

Pull another demand node symbol into the project area and position it on the other side of the Main River opposite and downstream of Big City.

*Name this demand node “Agriculture” and set the demand priority to 1.*



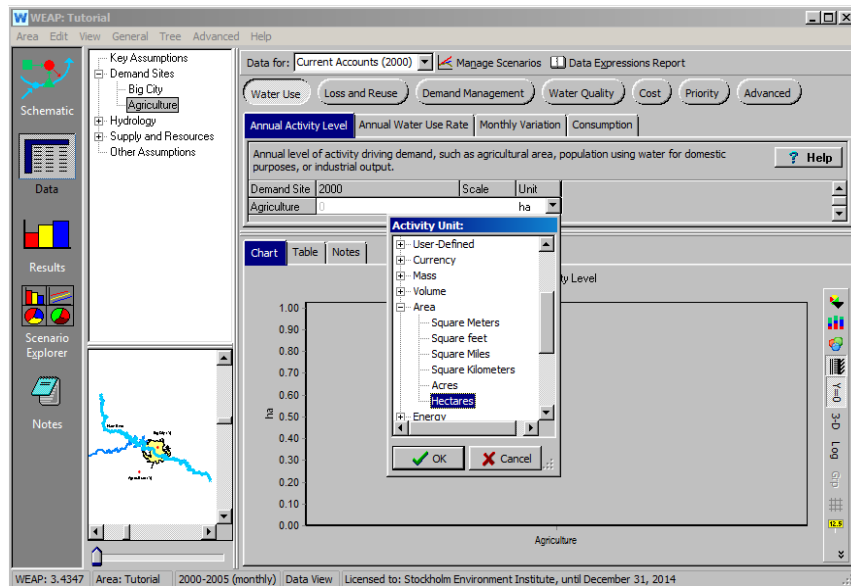
Consumption represents the amount of water that is actually consumed (i.e. is not returned in the form of wastewater).



In the same manner as for Big City, enter the Annual Activity Level and Annual Water Use Rate in the Data View for the Agriculture demand site after first selecting “hectares” as the units (you may have to click on the “plus” sign to the left in the tree in order to see all of the options for area units).

*Annual Activity Level      100,000 hectares*  
*Annual Water Use rate    3,500 m<sup>3</sup> / hectare*

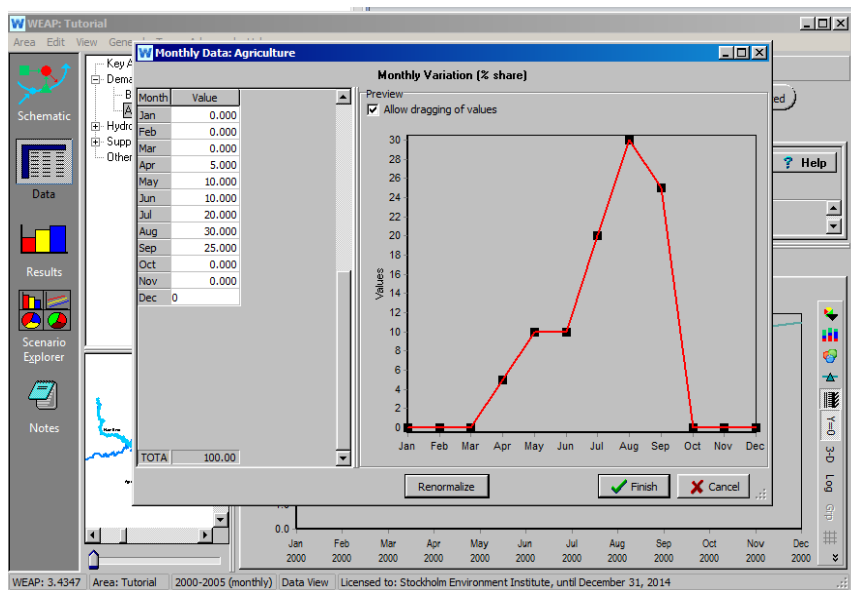




Select the Monthly Variation tab and the Monthly Time Series Wizard to enter the data below for the monthly variation in the water use rate.

*Monthly Variation:*

- 5% in April
- 10% in May and June
- 20% in July
- 30% in August
- 25% in September
- 0% for the rest of the year



Finally, click on the Consumption tab and enter 90.

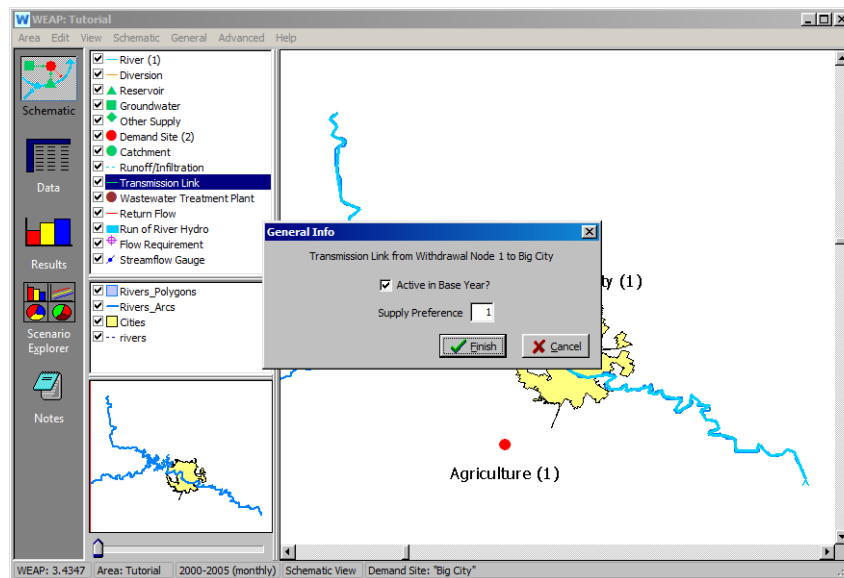


You could have created one single demand site integrating both urban and agriculture demand. However, we will see later that this removes some of the flexibility in the water supply priorities allocation.

## 10. Connect the Demand with a Supply

You now need to tell WEAP how demand is satisfied; this is accomplished by connecting a supply resource to each demand site. Return to the Schematic view and create a Transmission Link from the Main River to Big City and to Agriculture. Do this by dragging the Transmission Link first to a position on the river, releasing the click, then pulling the link to Big City and double clicking on this demand node. Do the same for Agriculture, but start the Transmission Link downstream of the one created for Big City.

*Select a Supply Preference of 1 for each Transmission Link.*



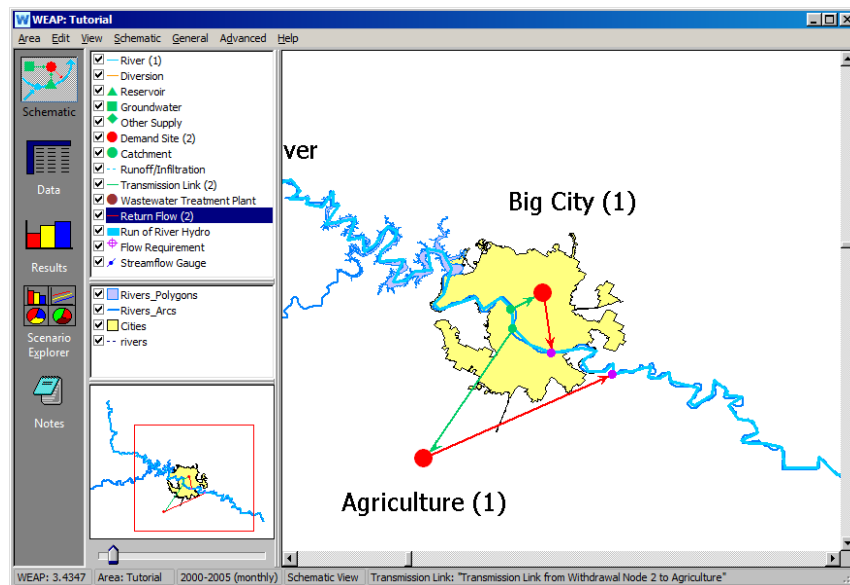
## 11. Create Return Flow Links



The Supply Preference parameter allows you to define which source should be used in priority to supply water to this Demand Site. WEAP will attempt to supply all of the demand with sources having the highest preference level (1), only using lower-level sources if the high-level sources do not have sufficient supply.

Now create a Return Flow from Big City to the Main River. Do the same for Agriculture to the Main River. Follow the same “drag and release” procedure as for the Transmission Links.

*The return flow for the urban demand site should be positioned downstream of the agriculture withdrawal point. In the flow direction, the sequence should be: withdrawal for Big City, withdrawal for Agriculture, return from Big City, return from Agriculture.*



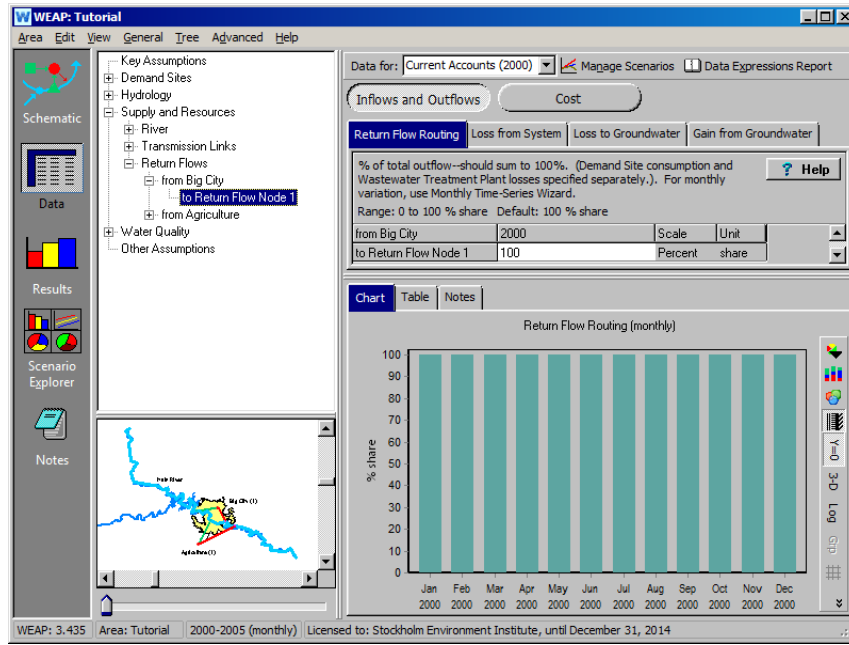
Next, set the Return Flow Routing for the Big City Return Flow. Do this by right-clicking on each Return Flow and selecting “edit data” and “Return Flow Routing” or by going to the Data view\Supply and Resources\Return Flows\from Big City.

*Set the Return Flow Routing to 100%.*

*Do the same for the Agriculture Return Flow.*

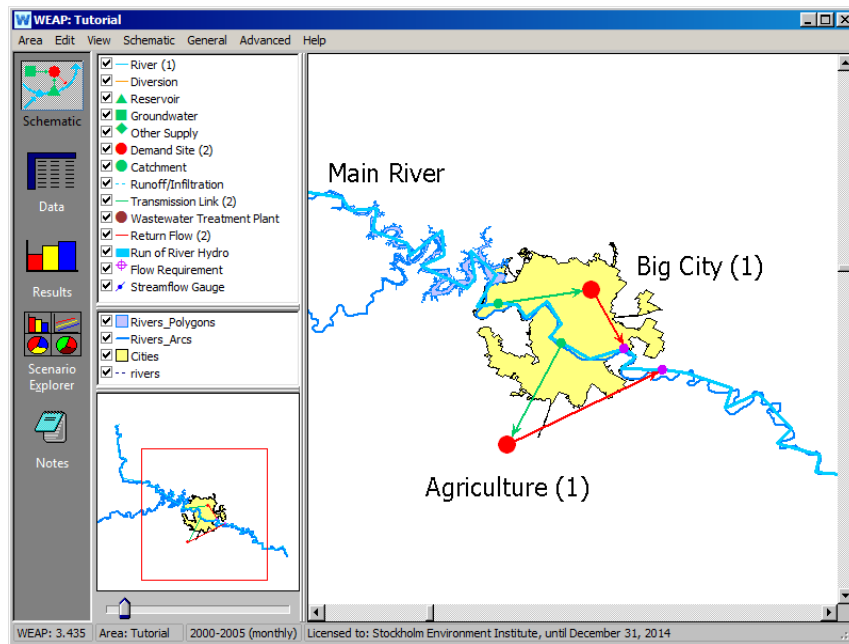


Return Flow Routing is the percent of total outflow from a demand site that is directed through a Return Flow Link. If only one Return Flow Link is created for a demand node, then the Return Flow Routing for that link must be 100%. Likewise, if multiple Return Flow links are created for a demand node, then Routing factors for all of the links must sum to 100%. Losses within the Return Flow Links are specified separately.



## 12. Check your Model

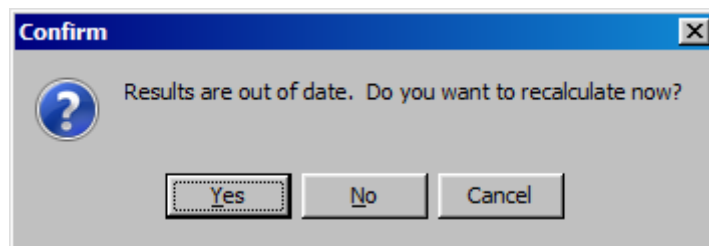
At this point, your model should look similar to the figure below.



# Getting First Results

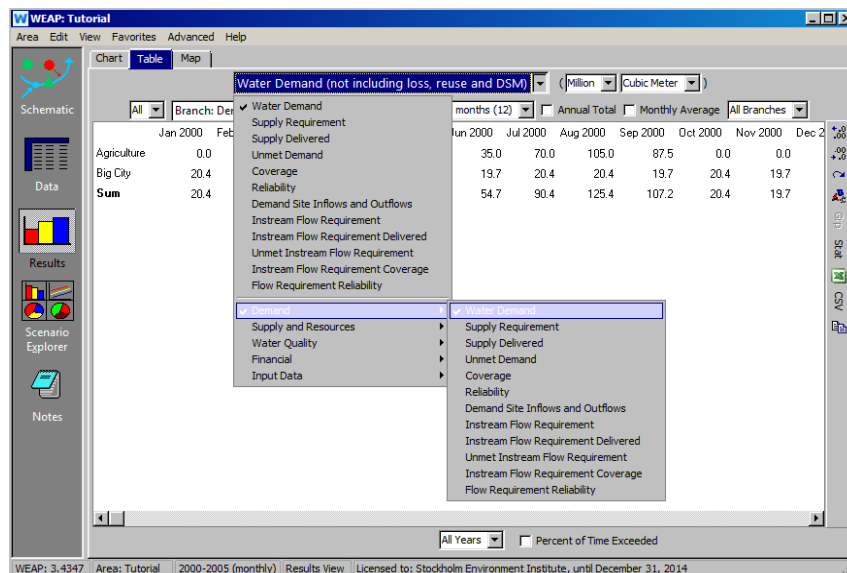
## 13. Run the Model

Click on the “Results” view to start the computation. When asked whether to recalculate, click yes. This will compute the entire model for the Reference Scenario - the default scenario that is generated using Current Accounts information for the period of time specified for the project (here, 2000 to 2005). When the computation is complete, the Results view will appear.



## 14. Check your Results

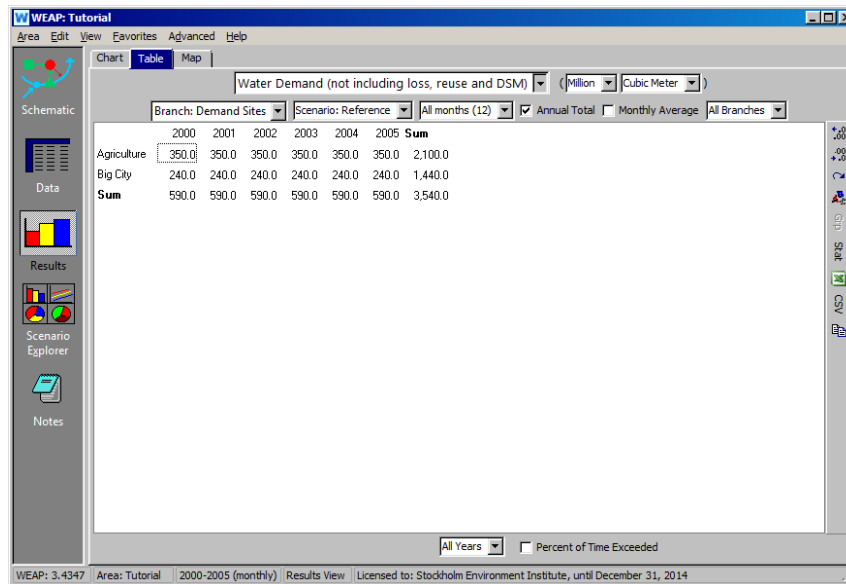
Click on the “Table” tab and select “Demand” and “Water Demand” from the primary variable pull-down menu in the upper center of the window (see below).



Also, click the “Annual Total” Box.

If you have entered all data as listed in previous steps, you should obtain the following annual demand values for each year (2000 to 2005) of the Reference scenario:

*Annual Demand for Agriculture*                       $350 M m^3$   
*Annual Demand for Urban Area*                       $240 M m^3$

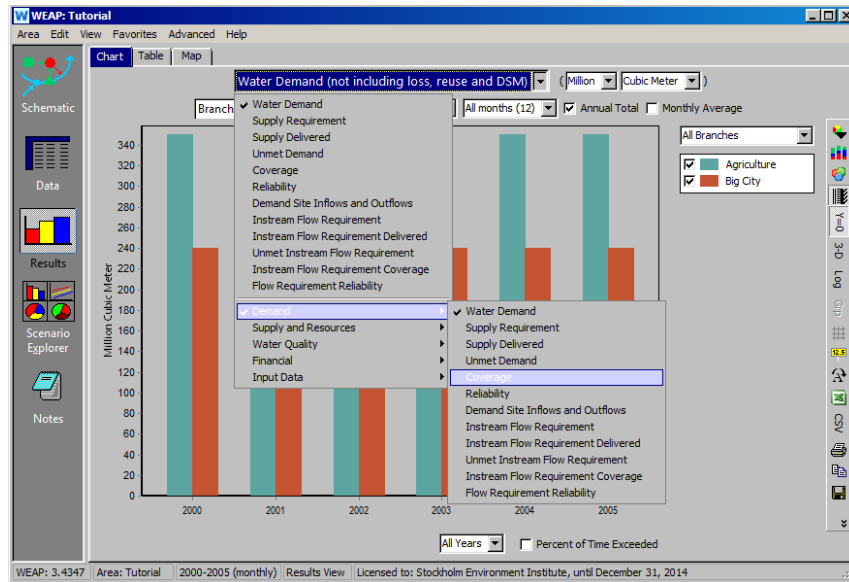


If you do not obtain those values go back to the “Data” view and check your inputs.

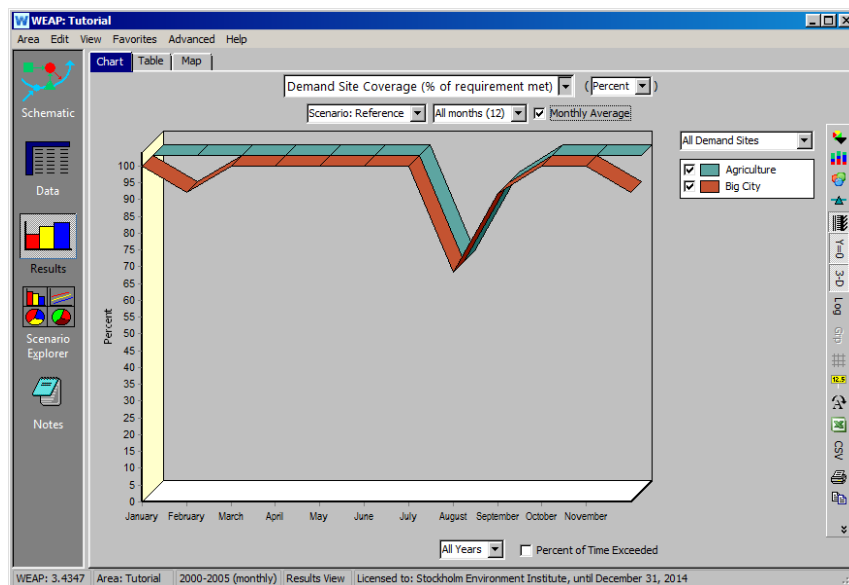
If you obtain an error or warning message read it carefully as it might reveal where in your inputs is the discrepancy, or which step you skipped.

## 15. Look at Additional Results

Now, look at the monthly Demand Coverage rates in graphical form. Click on the “Chart” tab. Select “Coverage” from the primary variable pull-down menu in the upper center of the window. Right now, the Demand variables are shown at the top of the menu, since Demand is checked below. If you were in another variable subsection, such as Supply and Resources, you would have to go into Demand to find the Coverage variable.



Format the graph by selecting the 3-D option on the right side-bar menu, and ensure that “All months” is selected in the pull-down menu above the graph (also keep the “Monthly Average” option checked). Note that the 3-D option allows the viewer to see both data sets even while they overlap. The graph should like the one below.



*During the months of December and February, which have little flow in the river, Big City lacks water, and therefore demands go unmet. We modeled agriculture to only require water March-September, so it registers 100% coverage in the December-February shortage because it has no water demand. Agriculture only has a shortfall in supply in the month of August and September, when the plants require the most*

*water. Note that because Agriculture and Big City both have a supply preference of 1, when there is water shortage they will have equal percentages of unmet demand, assuming they are both demanding water at that time.*



**You can fully customize the way WEAP charts are displayed, as well as print or copy graphs to the clipboard using the toolbox located to the right of the graph.**

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# WEAP

Water Evaluation And Planning System

# Basic Tools

## ***A TUTORIAL ON***

*Creating and Using Key Assumptions* .....42

*Using the Expression Builder*.....45

**October 2023**

**Note:**

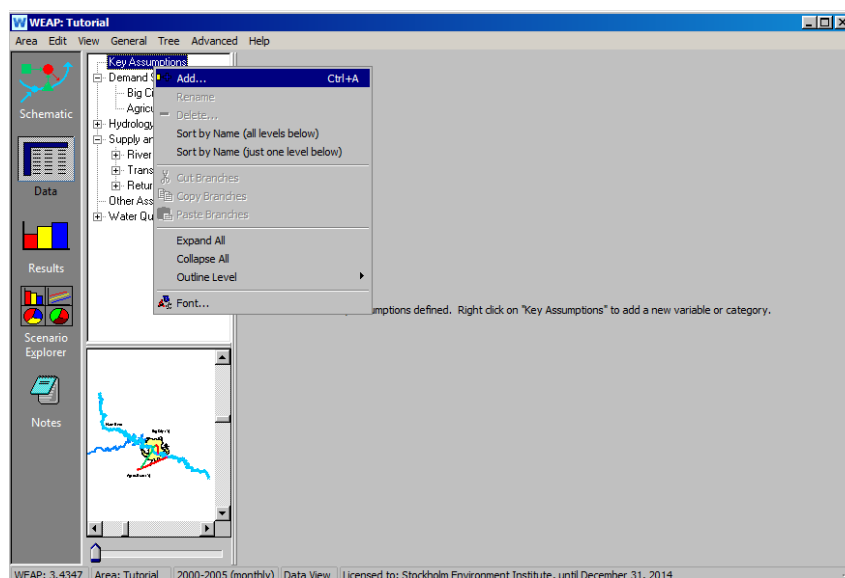
For this module you will need to have completed the previous module (“WEAP in one hour”) or have a basic knowledge of WEAP (creating an area, drawing a model, entering basic data, obtaining first results). To begin this module, go to the Main Menu, select “Revert to Version” and choose the version named “Starting Point for ‘Basic Tools’ module.”

## Creating and Using Key Assumptions

### 1. Using Key Assumptions

Key Assumptions are pieces of data that may be useful to apply across multiple elements. The use of key assumptions is especially worthwhile when the model has a large number of similar objects, for example demand sites, and when performing scenario analyses. In this case, you can easily set all your demand sites to have the same unit domestic consumption. Then, you can create scenarios to vary this consumption without having to edit each and every demand site – simply by changing the key assumption value.

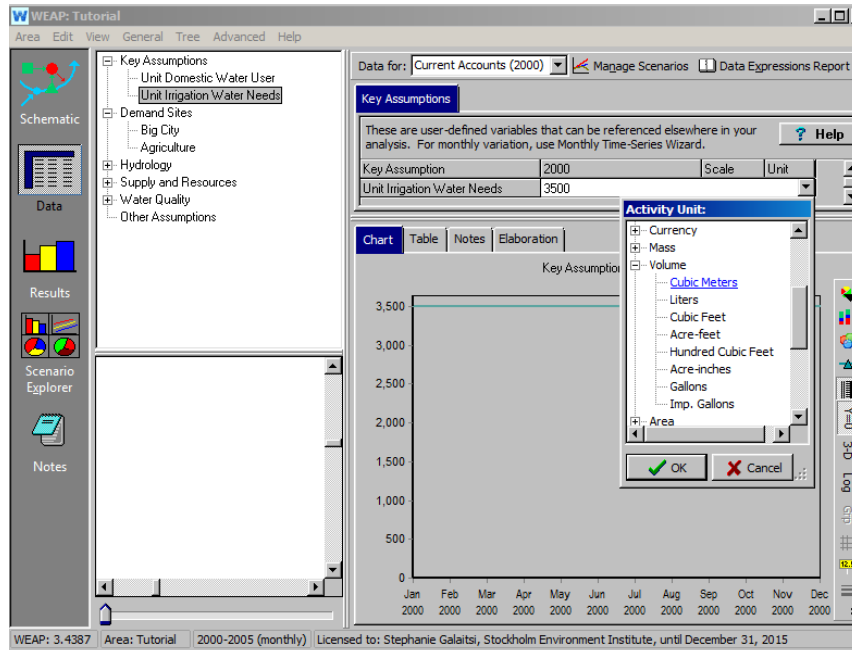
Key Assumptions are created by going to the Data view and right-clicking on the Key Assumptions branch of the Data Tree. Select “Add” - this will create a new Key Assumption variable below the Key Assumption branch.



After clicking Add, you can name your Key assumptions in the Data Tree. Name them and enter the data as follows: (be sure to select the appropriate

units from the Units pull-down menu. Cubic meters will be found under “Volume,”):

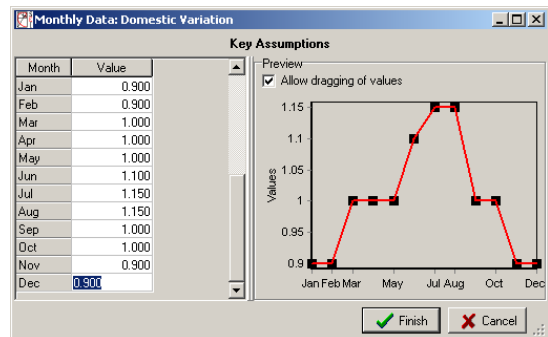
*Unit Domestic Water Use*                      300 m<sup>3</sup>  
*Unit Irrigation Water Needs*                3,500 m<sup>3</sup>



With Key Assumptions, it is important to ensure that the units designated in a Key Assumption variable match the units indicated for the variable as it occurs elsewhere in the data tree. In this case, the 300 m<sup>3</sup> domestic water use matches the 300 m<sup>3</sup>/person use specified in Big City/Water Use/Annual Use Rate. Similarly, the key assumption Unit Irrigation Water Needs matches the units in Agriculture/Water Use/Annual Water Use Rate.

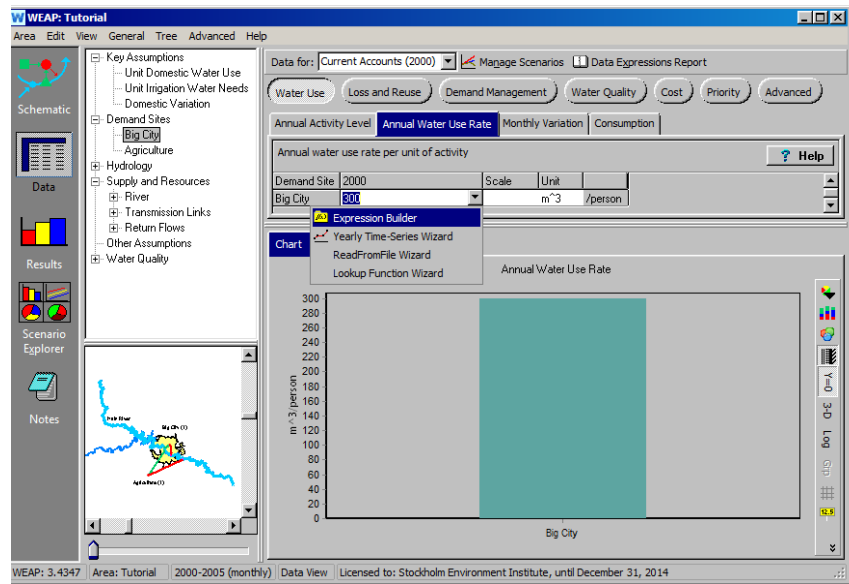
Create one more Key Assumption, Domestic Variation, that is unitless (“No Unit”), and use the Monthly Time Series Wizard to populate it with values:

*Domestic Variation*  
 - Jan to Feb & Nov. to Dec.: 0.9  
 - Mar. to May & Sept. to Oct.: 1.0  
 - June 1.1  
 - Jul, Aug 1.15

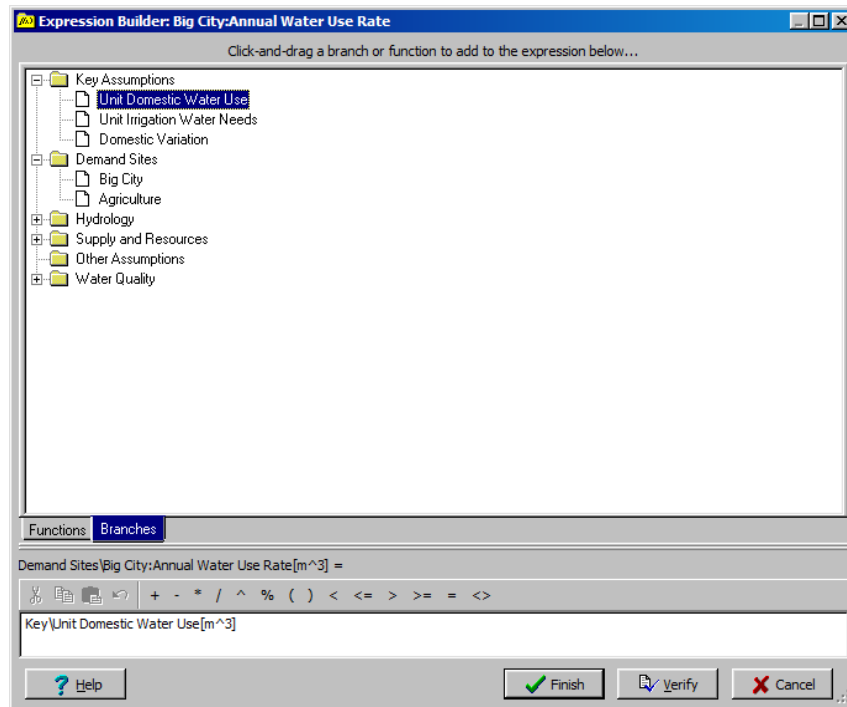


## 2. Creating References to Key Assumption

Create a Key Assumption reference for “Big City Annual Water Use.” Do this by going to the “Annual Water Use Rate” window for Big City in the Data view. Click on the Expression Builder pull-down menu in the space where you entered the “Annual Water Use Rate” (300 m<sup>3</sup>) previously.



In the Expression Builder window, delete the value of 300 from the text field at the bottom of the Expression Builder window, click on the “Branches” tab towards the bottom left of the screen, then click on the “Unit Domestic Water Rate” under Key Assumption (you may have to expand the data tree to see all of the branches) in the Data tree field and drag it down to the text field so it shows up as Key\Unit Domestic Use[m<sup>3</sup>]. Click on “Finish.”



Repeat this procedure to replace the 3500 m<sup>3</sup>/ha water use rate for the “Agriculture” Demand Site with the newly created “Unit Irrigation Water Needs” Key Assumption.

If you check the results now by re-calculating, you should have the same annual total values for demand as obtained in the WEAP in One Hour module:

- Annual Demand for Agriculture 350 M m<sup>3</sup>
- Annual Demand for Urban Area 240 M m<sup>3</sup>

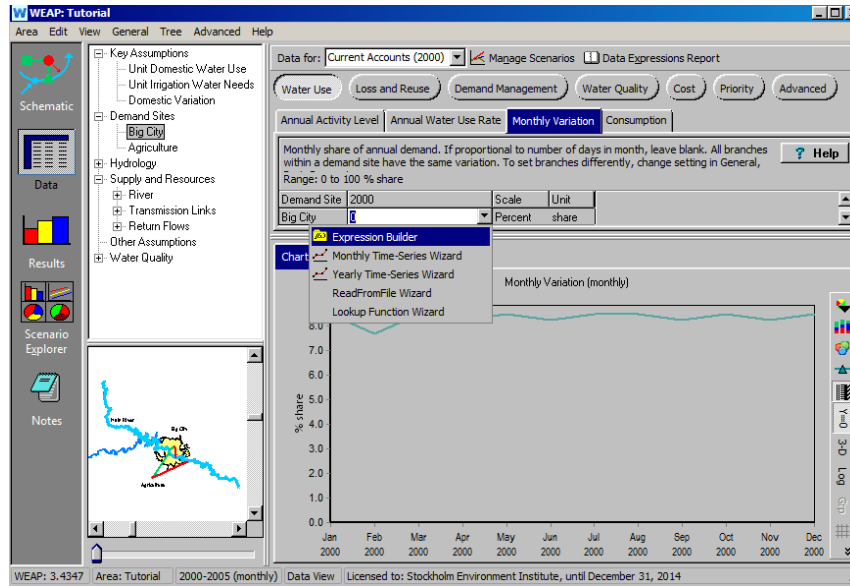


Using the same process, references to other objects' data can also be created. This can be helpful in certain cases. Upon dragging and dropping the object to be referenced from the tree to the expression builder's text field, a list of all available variables appears.

## Using the Expression Builder

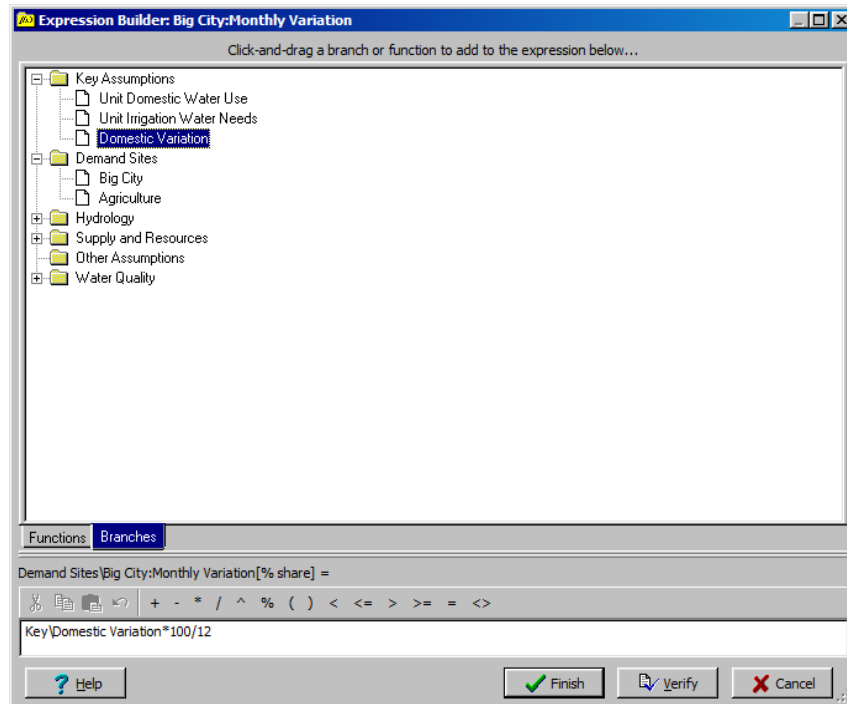
### 3. Creating Mathematical Expressions

You will now alter the monthly variation in water demand for Big City using a mathematical expression. In the Data view, click on the Big City demand site, then “Water Use” and the “Monthly Variation” tab and select the Expression Builder from the pull-down menu in the data entry bar.



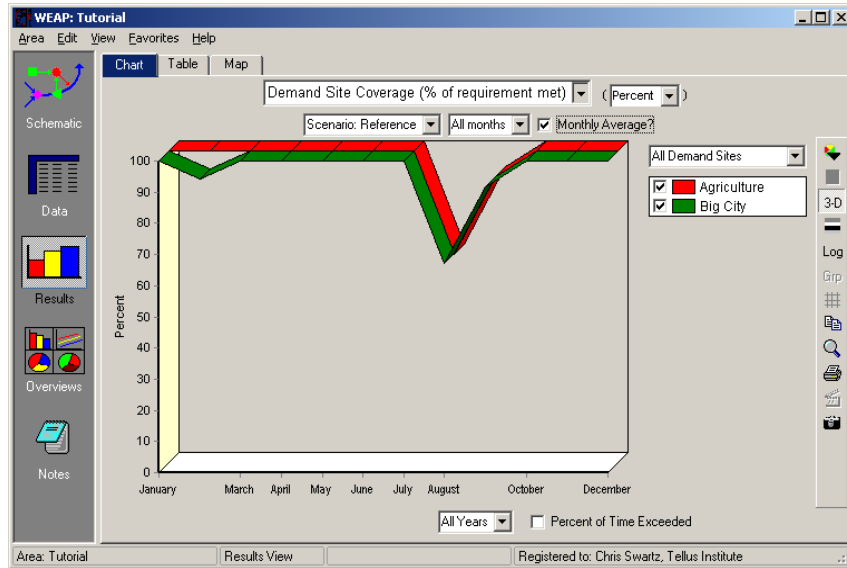
Create the following expression by pulling down the “Domestic Variation” Key Assumption and typing in the modifying terms:

$$\text{Key}\backslash\text{Domestic Variation} * 100 / 12$$

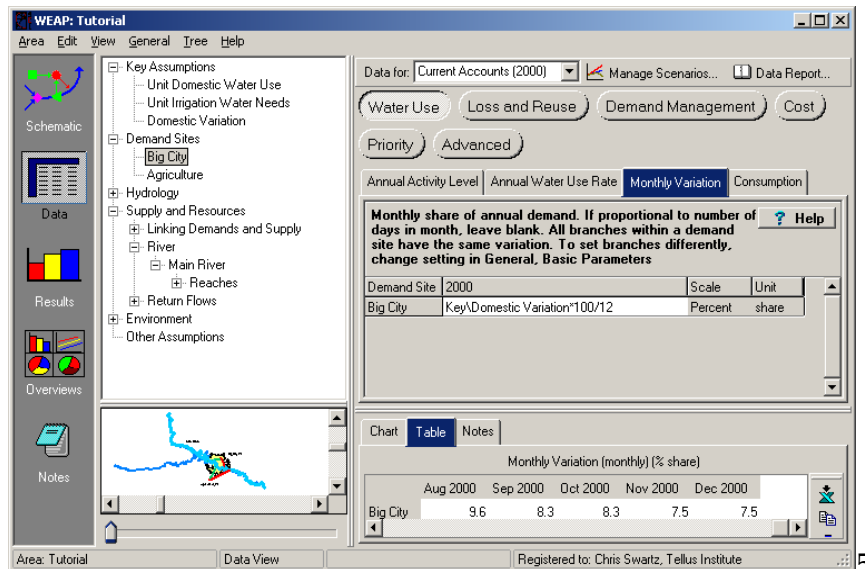
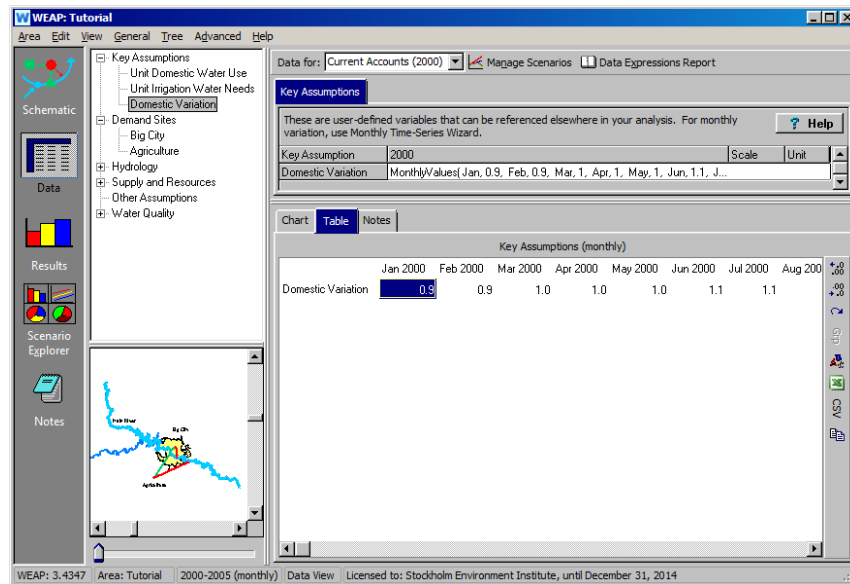


Note that if you had made a mistake in typing the expression, such as entering a space instead of a division sign, an error message would have appeared after clicking “Finish.” You would then be given the opportunity to review and correct the expression. After the correction of an error, you must click “Verify” before “Finish.”

*View the new results for “Demand Site Coverage” after making these changes. Click on the Results view and click on “Yes” to recalculate. The results should appear as below:*



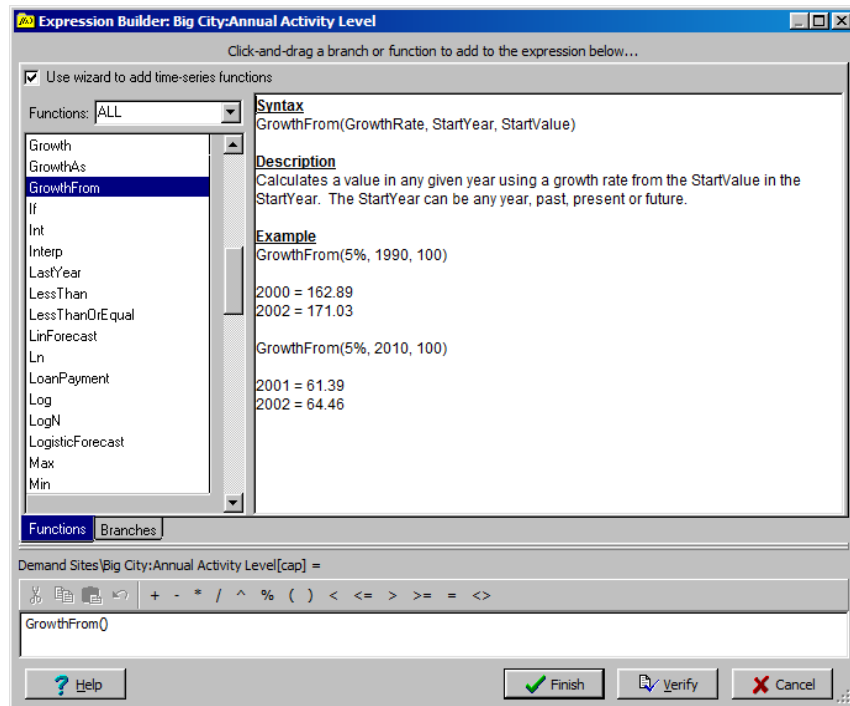
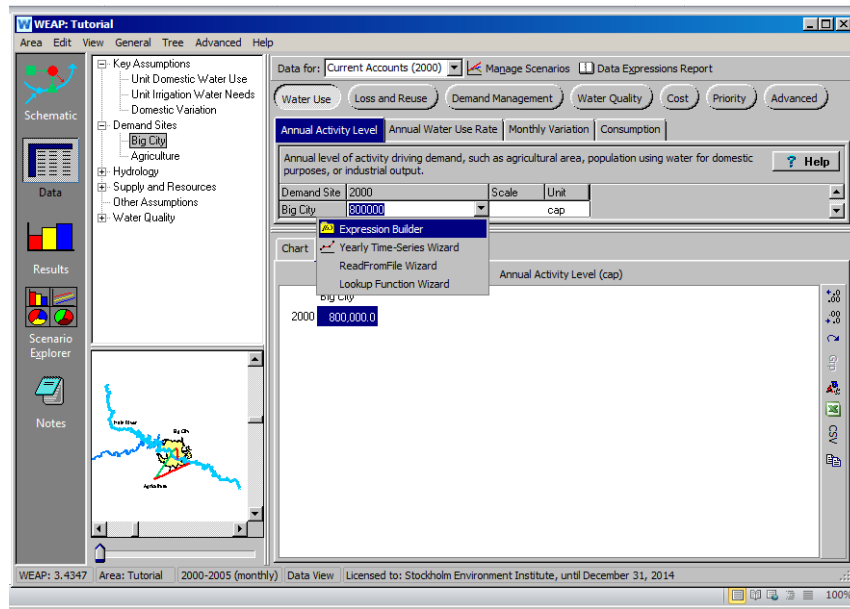
Note that there is no longer unmet demand in December for Big City because the fraction of demand in December decreased from 8.5% (originally based on the number of days in the month) to 7.5% (now based on the expression using the “Domestic Variation” Key Assumption). You can review the numerical values calculated from the “Monthly Variation” expression by selecting the “Table” tab in the data review panel at the bottom of the data window. Remember it is calculated from the original data we entered in the Key Assumptions/Domestic Variation, subjected to the equation we entered in the Expression Builder.



## 4. Using Built-In Functions

We will assume that the current population of Big City (2000) is not known, but we know its population during the last census and the growth estimate. We can use the built-in “GrowthFrom” function to compute the current population of Big City. Do this by selecting the Expression Builder from the pull-down menu in the year 2000 data input field within the “Annual Activity Level” window for Big City. Delete the present value of 800000, click on the “Function” tab rather than the “Branch” tab and drag down into the text field the “GrowthFrom” expression selected from the list of built in expressions.





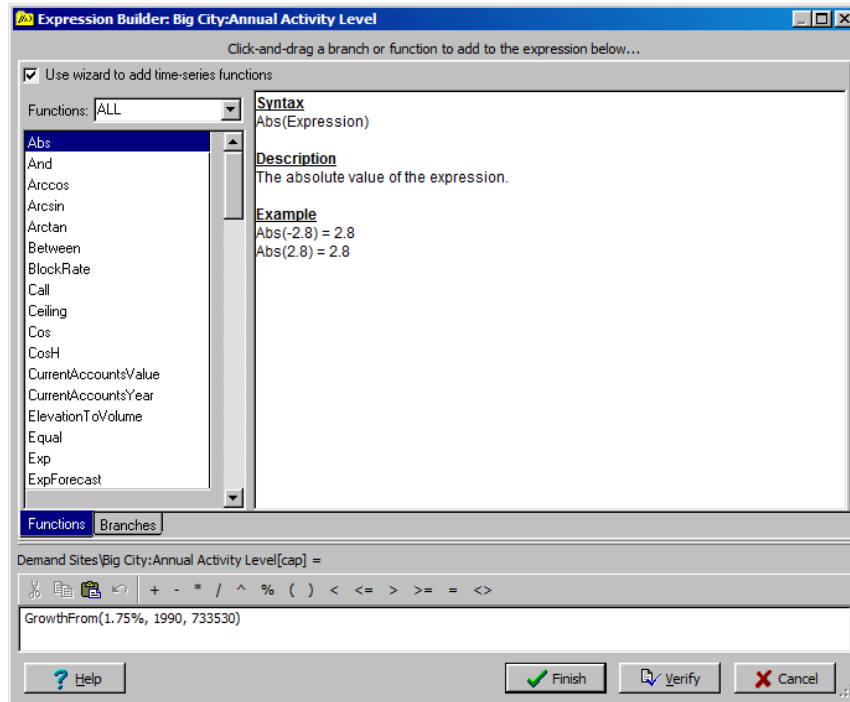
Input the following data into the “GrowthFrom” expression, using the format indicated in the description window next to the expression list.

<i>Date of last Census</i>	<i>1990</i>
<i>Population at last census</i>	<i>733,530</i>
<i>Estimated growth rate</i>	<i>1.75%</i>

This results in the following format for the expression:

*GrowthFrom(1.75%, 1990, 733530)*

Be sure to include the percentage sign in your expression.



The Expression Builder is only a simple way of entering expressions and functions. Savvy users can by-pass it and enter functions, references and mathematical expressions directly in the main Expression window.

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# WEAP

Water Evaluation And Planning System

# Scenarios

## ***A TUTORIAL ON***

*Preparing the Ground for Scenarios* .....52

*Creating the Reference Scenario*.....53

*Creating and Running Scenarios*.....58

*Using the Water Year Method*.....61

**October 2023**

**Note:**

For this module you will need to have completed the previous modules (WEAP in One Hour and Basic Tools) or have a fair knowledge of WEAP (data structure, Key Assumptions, Expression Builder). To begin this module, go to the Main Menu, select “Revert to Version” and choose the version named “Starting Point for ‘Scenarios’ module.”

## Preparing the Ground for Scenarios

### 1. Understand the Structure of Scenarios in WEAP

In WEAP the typical scenario modeling effort consists of three steps. First, a “Current Accounts” year is chosen to serve as the base year of the model; Current Accounts has been what you have been adding data to in the previous modules. A “Reference” scenario is established from the Current Accounts to simulate likely evolution of the system without intervention. Finally, “what-if” scenarios can be created to alter the “Reference Scenario” and evaluate the effects of changes in policies and/or technologies.

*Read the “Scenarios” help topic (under the Data subheading in the Help Contents) for a more detailed description of the WEAP approach.*

### 2. Change the Time Horizon for the Area

In the Data or Schematic view, under the General\Years and Time Steps menu, change the “Time Horizon” of the Area.

<i>Current Accounts Year</i>	<i>2000 (unchanged)</i>
<i>Last Year of Scenarios</i>	<i>2015</i>

### 3. Create an Additional Key Assumption

Create the following key assumption:

<i>Population Growth Rate</i>	<i>2.2</i>
-------------------------------	------------

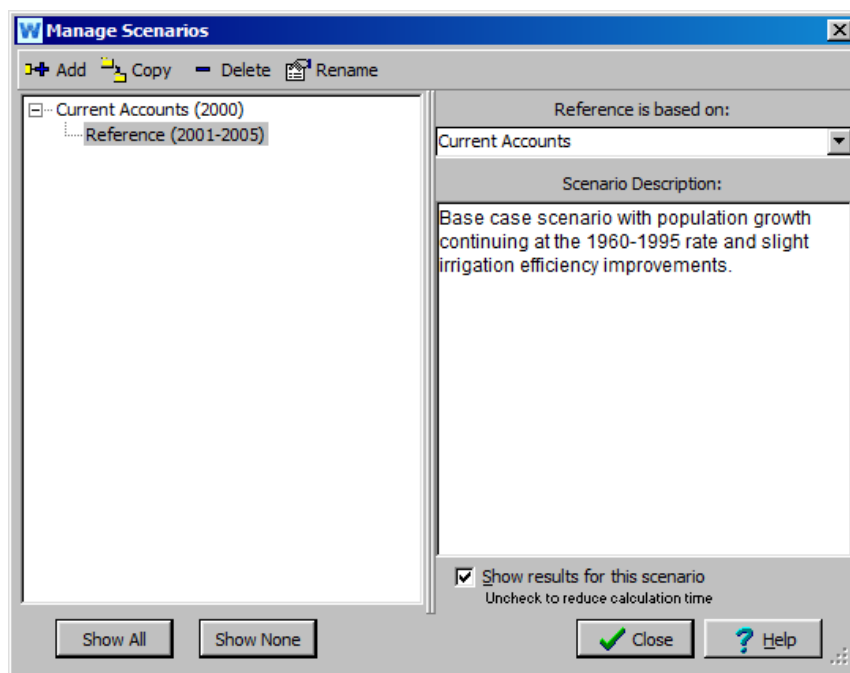
There is no unit for this Key Assumption, but remember to change the “Scale” field to Percent.

# Creating the Reference Scenario

## 4. Describe the Reference Scenario

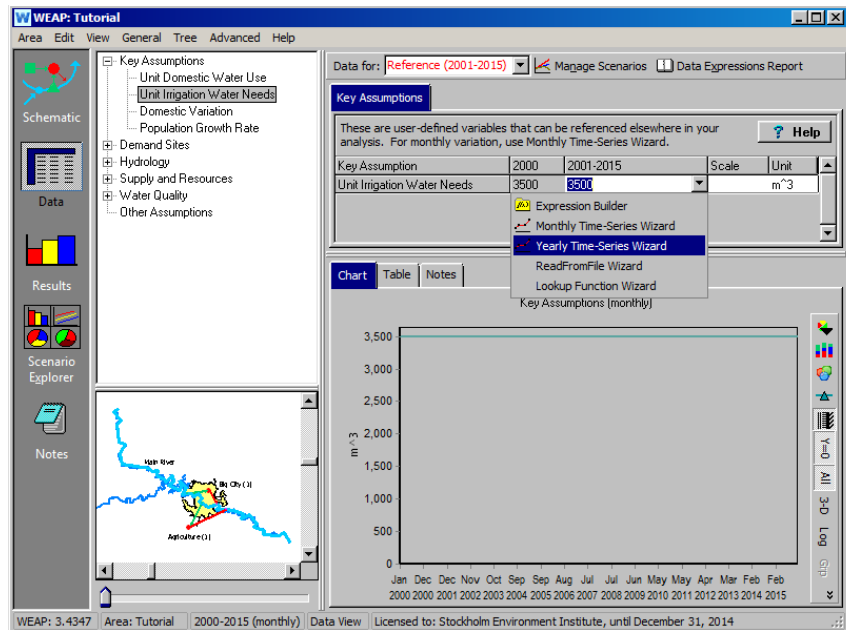
The “Reference” Scenario always exists. Change its description in the Area\Manage Scenarios menu to reflect its actual role. Note that you must be in the Data View or Schematic view to have access to the “Manage Scenarios” option in the Area menu.

*For example, “Base Case Scenario with population growth continuing at the 1960-1995 rate and slight irrigation technology improvement.”*

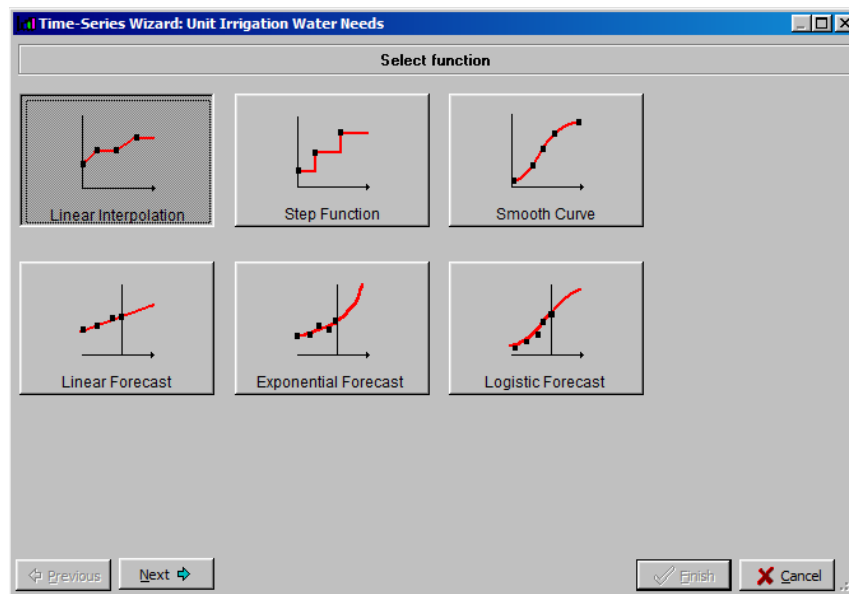


## 5. Change the Unit Irrigation Water Use

In the Data View, change the “Unit Irrigation Water Needs” Key Assumption to reflect a new annual pattern for the period (2001-2015) after the Current Accounts year. To make the change, you will need to select the “Reference” scenario from the drop-down menu at the top of the screen. Use the “Yearly Time-Series Wizard” to construct the time series.



First, select the function “Linear Interpolation” by clicking on it, then click “Next.”



Click on “Enter Data” in the next window, click “Next”, then click “Add” to add the following data to the time series:

*Enter Time-Series Data: Linear Interpolation*

*Data:*

2000 3500

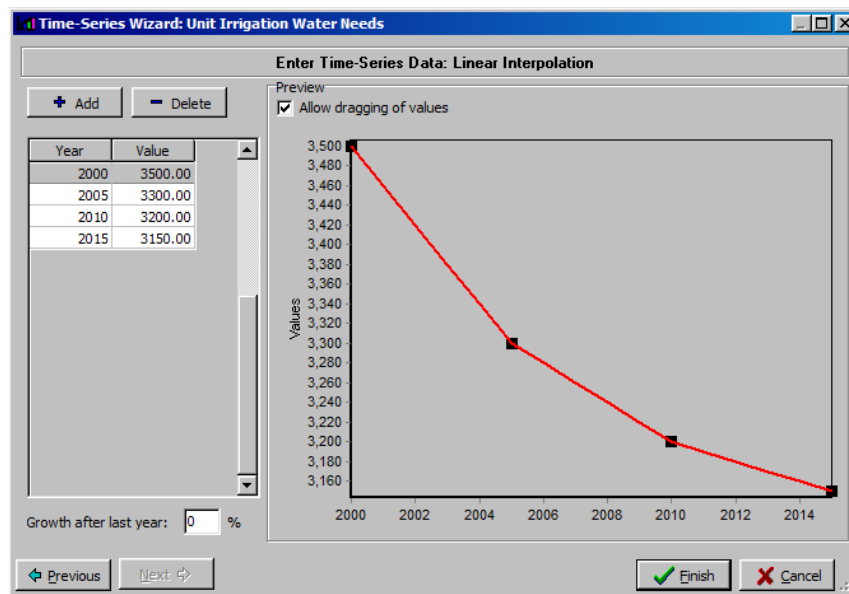
2005 3300

2010 3200

2015 3150

*Growth after last year: 0%*

Note that the first data point, for the year 2000, should already be listed in the data input window because it was input when the “Unit Irrigation Water Needs” Key Assumption was created in the Current Accounts (see Exercise 1 under Creating and Using Key Assumptions, Basic Tools Module).



As you can see while running the Yearly Time Series Wizard, WEAP offers a wide range of techniques to build time series, including importing from Excel files, creating step functions, using forecasting equations etc.



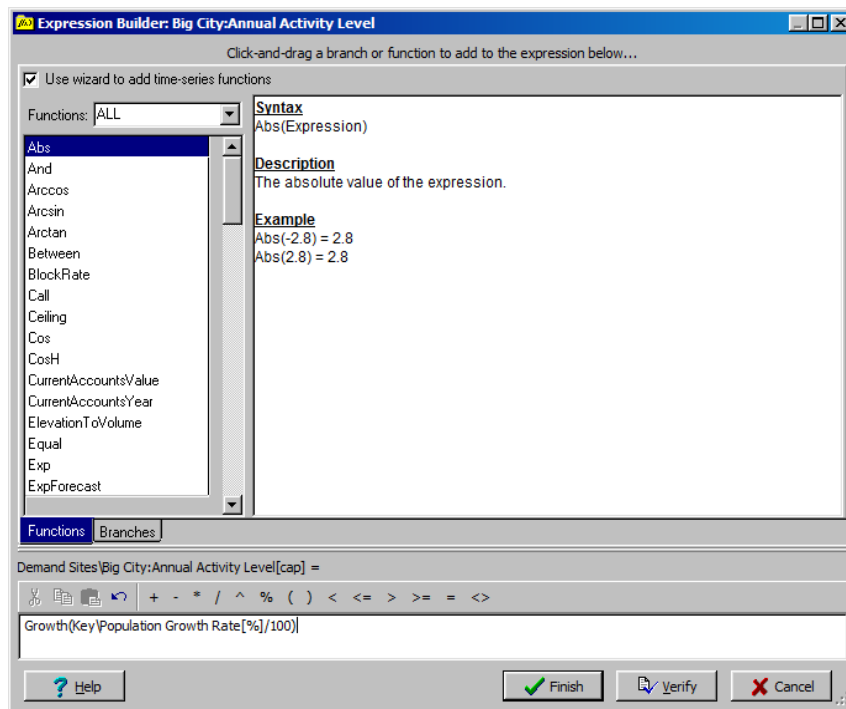
The Yearly Time Series Wizard helps you create expressions. You can also simply type or edit the expression (in this case, “Interp( 2000,3300, 2005,3300, 2010,3200, 2015,3150 )”) without running the wizard, either directly or through the Expression Builder.

## 6. Set the Population Growth

Change the population of Big City to grow by the rate defined by the “Population Growth Rate” Key Assumption defined in an earlier step. Here again you will have to select the “Reference” scenario in the drop-down menu at the top of the Data view.

*Make sure you have the Big City Demand Site and its Annual Activity Level tab selected. Delete the current expression and select the “Growth” function in the Expression Builder in the pull-down menu below the 2001-2015 field (Note that the present expression in this field is the same as that for the Current Accounts year). Then click on the “Branch” tab above the text field. Either double click on the “Population Growth Rate” Key Assumption in the Data Tree, or drag it down into the expression window. Your final function should read “Growth(Key\Population Growth Rate/ 100)”*

*Note that you have to divide the “Population Growth Rate” by 100 in order for WEAP to recognize the value of 2.2 in the Key Assumption as 0.022 in the calculation.*



The same effect could have been modeled without creating a Key Assumption in the first place. We will see however that doing so provides more flexibility when adding other scenarios.

Any value for which no time series is defined for the “Reference” scenario is assumed to remain constant. In our case for example, the Agriculture demand will remain constant until 2015 unless we change this variable as well.

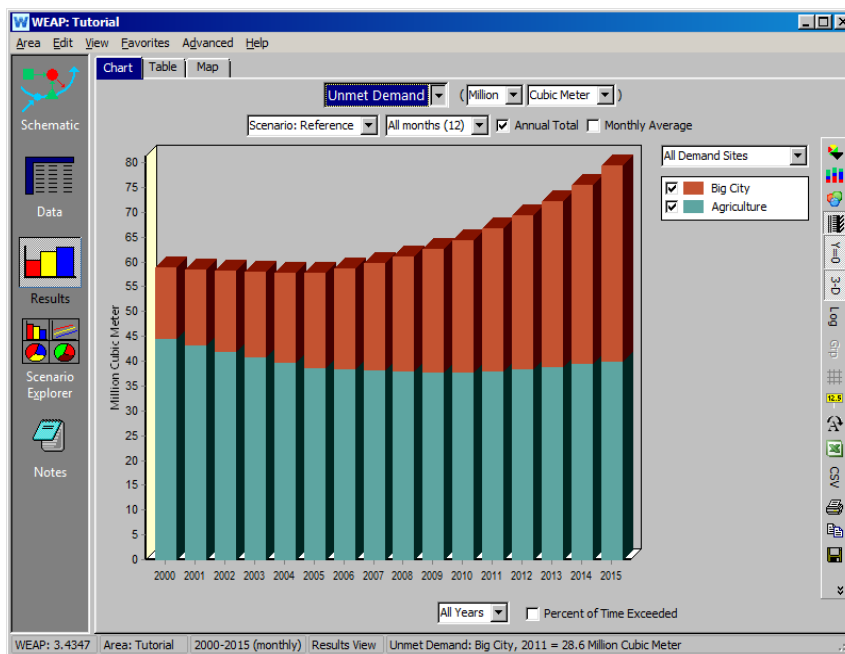
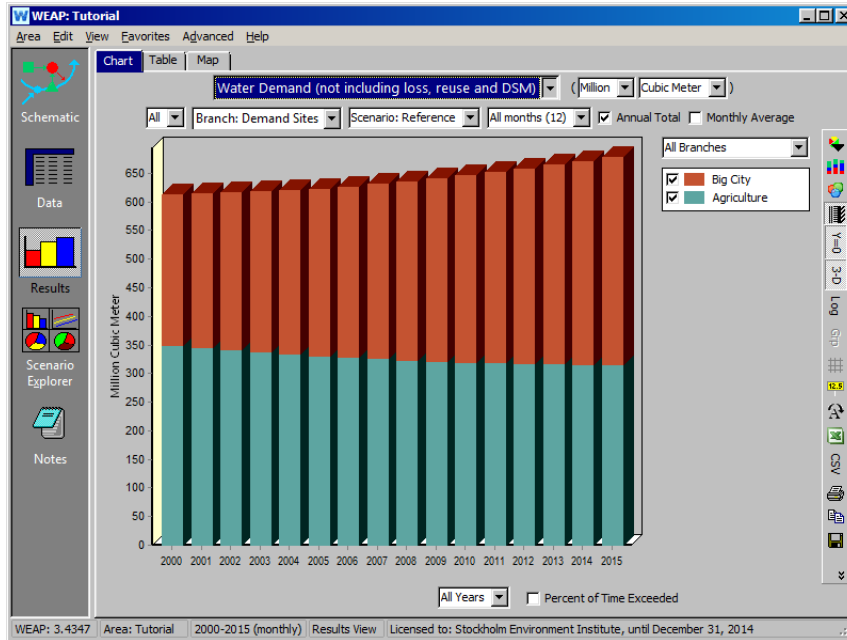


## 7. Run the Reference Scenario

Run the Reference Scenario by clicking the “Results” view. Look at a 3-D graph of “Unmet Demand” (select “Annual Total”) for both demand sites. It should be similar to the figure below. Think about the following points.

*How does the demand evolve compared to the unmet demand?*

*Why is the total unmet demand decreasing at first and then increasing?*

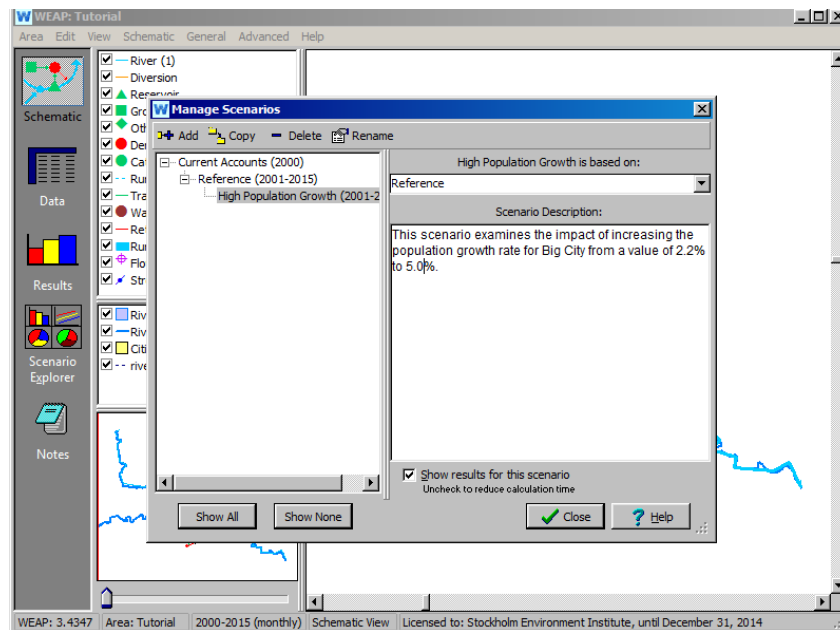


# Creating and Running Scenarios

## 8. Create a New Scenario to Model High Population Growth

Create a new scenario to evaluate the impact of a population growth rate for Big City higher than 2.2% for the period 2001-2015.

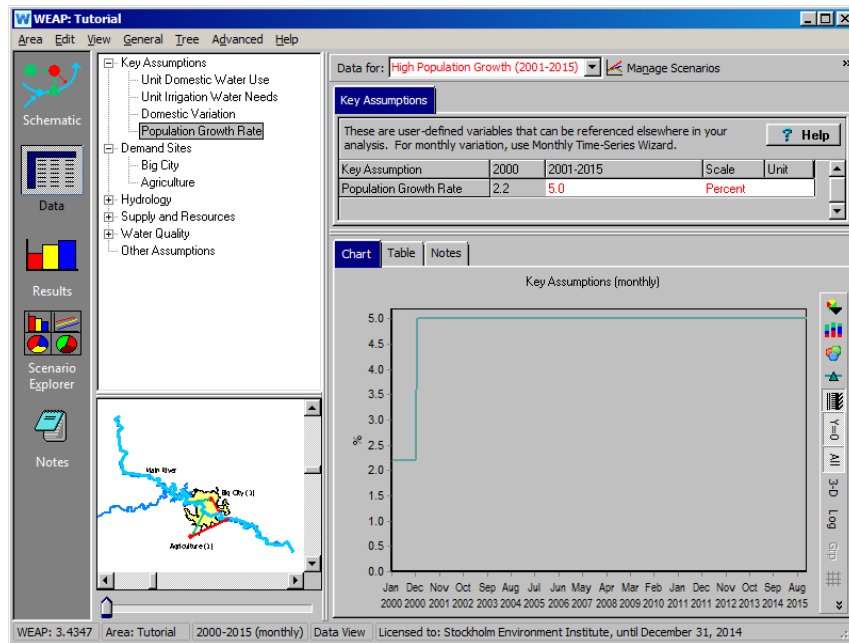
*For this you will have to return to the Data View or the Schematic View. Choose the menu “Area”, “Manage Scenario”, right-click the “Reference” scenario and select “Add.” Name this scenario “High Population Growth” and add the description “This scenario looks at the impact of increasing the population growth rate for Big City from a value of 2.2% to 5.0%.”*



## 9. Enter the Data for this Scenario

Make the following changes in the Data view after having chosen your new scenario in the drop-down menu at the top of the screen:

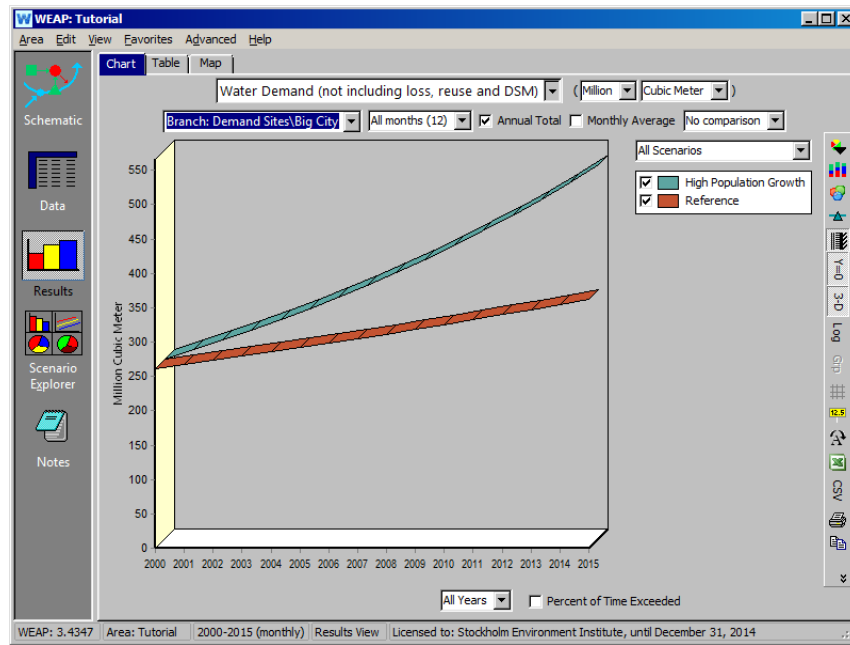
*Select the “Population Growth Rate” Key Assumption and change the value under the 2001-2015 field to 5.0. Note that the color of the data field changes to red after the change - this occurs for any values that are changed to deviate from the “Reference” scenario value.*



## 10. Compare Results: Reference and Higher Population Growth Scenarios

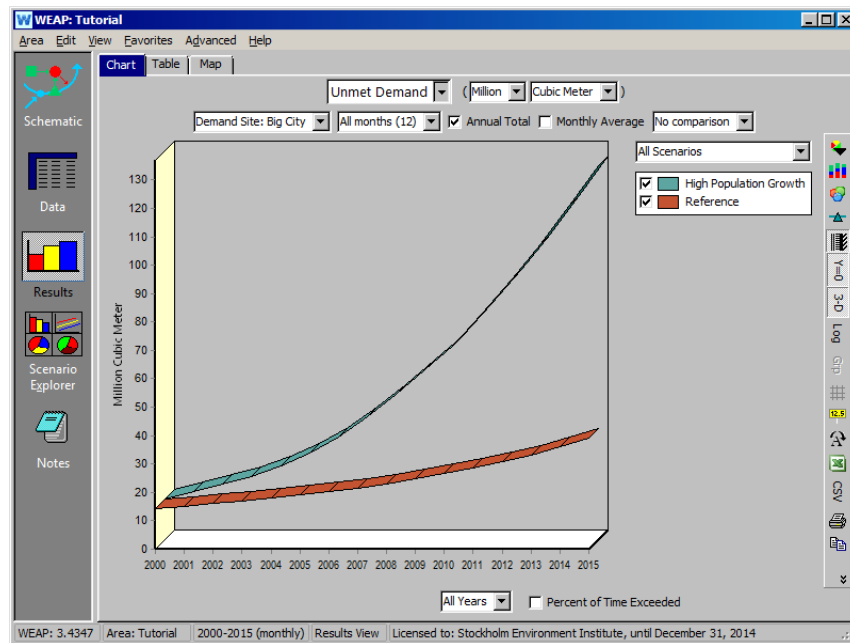
Compare, graphically, the results for the two scenarios we have established so far (Reference and Higher Population Growth).

*For example, select “Water Demand” from the primary variable pull-down menu. Click in the drop-down menu to the right of the chart area (above the graph legend), and select “All Scenarios.” Choose to show only Big City demand by selecting it from the pull-down list in the upper left pull-down menu of the Results window. Your graph should be similar to the one below.*



Note the higher Water Demand for Big City in the “Higher Population Growth” scenario, as expected.

Next, compare “Unmet Demand” for the two scenarios. Use the primary variable pull-down menu to select “Unmet Demand.”



Again, note the higher Unmet Demand for the Higher Population Growth scenario.



When creating many scenarios in the same area, the computation can become lengthy. In this case you can exclude some of the scenarios from the calculation by unchecking the “Show results for this scenario” box in the scenario manager for those scenarios.

## Using the Water Year Method

### 11. Create the Water Year Definitions

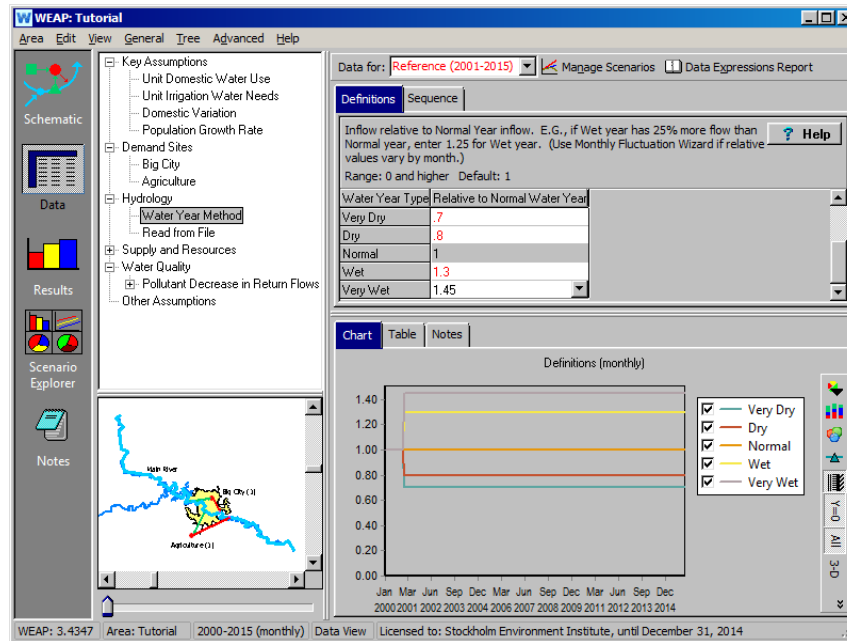
The previous exercise *only varied demand, not supply*. In this step we now want to see how natural variation in climate data (stream flow, rainfall etc.) can be taken into account in WEAP through scenario analyses. We will use the “Water Year Method” as an example. The Water Year Method is a simple means to represent variation in climate data such as streamflow, rainfall, and groundwater recharge. The method first involves defining how different climate regimes (e.g., very dry, dry, very wet) compare relative to a normal year, which is given a value of 1. Dry years have a value less than 1, very wet years have a value larger than 1.

With the “Reference” scenario selected, go into the data view and click on the “Water Year Method” branch under “Hydrology” in the Data tree.

Water Year Type	Relative to Normal Water Year
Very Dry	0.75
Dry	1
Normal	1
Wet	1
Very Wet	1

Select the “Definitions” tab and expand the window, if necessary, to see all five definitions. Enter the following data:

<i>Very Dry</i>	0.7
<i>Dry</i>	0.8
<i>Normal</i>	1.0
<i>Wet</i>	1.3
<i>Very wet</i>	1.45

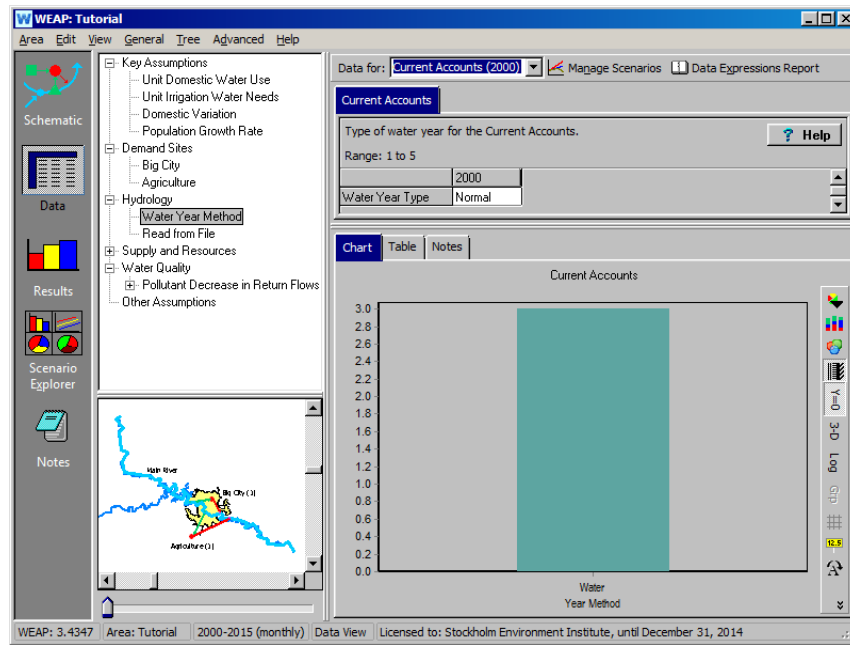


Monthly variations can be entered with the Water Year Monthly Fluctuation Wizard in the drop-down menu.

## 12. Create the Water Year Sequence

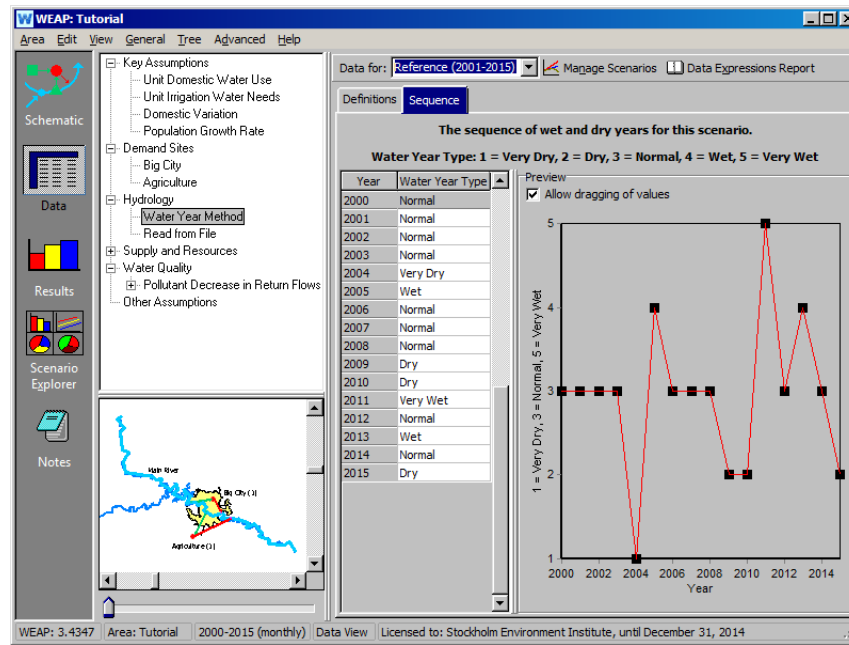
The next step in using the “Water Year Method” is to create the sequence of climatic variation for the scenario period. Each year of the period is assigned one of the climate categories (e.g., wet). Select the “Sequence” tab under the “Water Year Method” branch.

*Set the Current Account as Normal*



Then, select the “Reference” scenario and input the following sequence.

2001-2003 *normal*  
 2004 *very dry*  
 2005 *wet*  
 2006-2008 *normal*  
 2009-2010 *dry*  
 2011 *very wet*  
 2012 *normal*  
 2013 *wet*  
 2014 *normal*  
 2015 *dry*



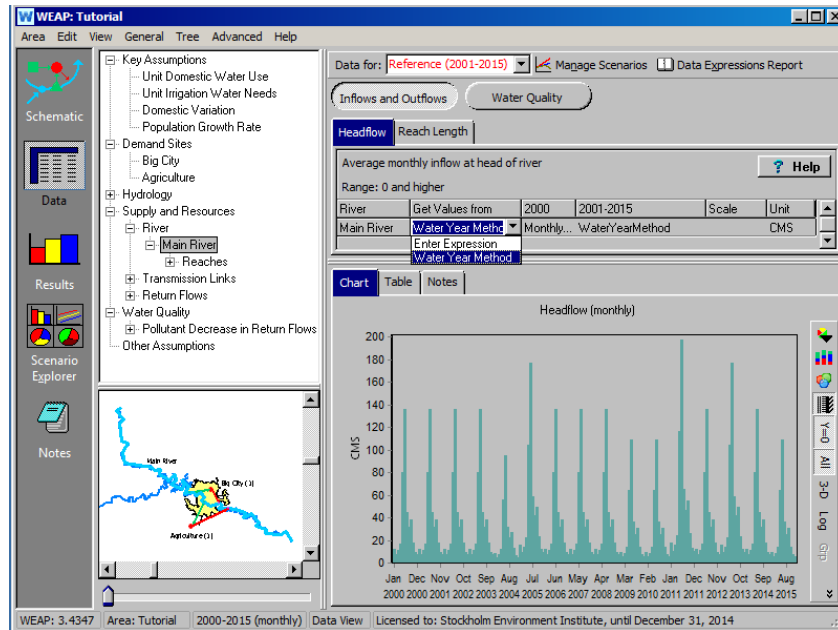
In order to let the inflows to the model (in our case, the headflow of the main river) vary in time, WEAP offers two strategies. If detailed forecasts are available, those can be read using the ReadFromFile function (refer to the Tutorial module on Format and Data for more details). Another method, which is the one presented here, is the “Water Year Method.” Under this method every year in the model’s duration can be defined as normal, wet, very wet, dry or very dry. Different scenarios can then alter the chosen sequence of dry and wet years to assess the impact of natural variation on water resources management.

## 13. Set up the Model to Use the Water Year Method

In the Data tree, change the “Headflow” for the Main River in the “Reference” scenario to use the “Water Year Method.” Note that before, the monthly values of Headflow were the same for the period 2001-2015 as for 2000, the Current Accounts year.

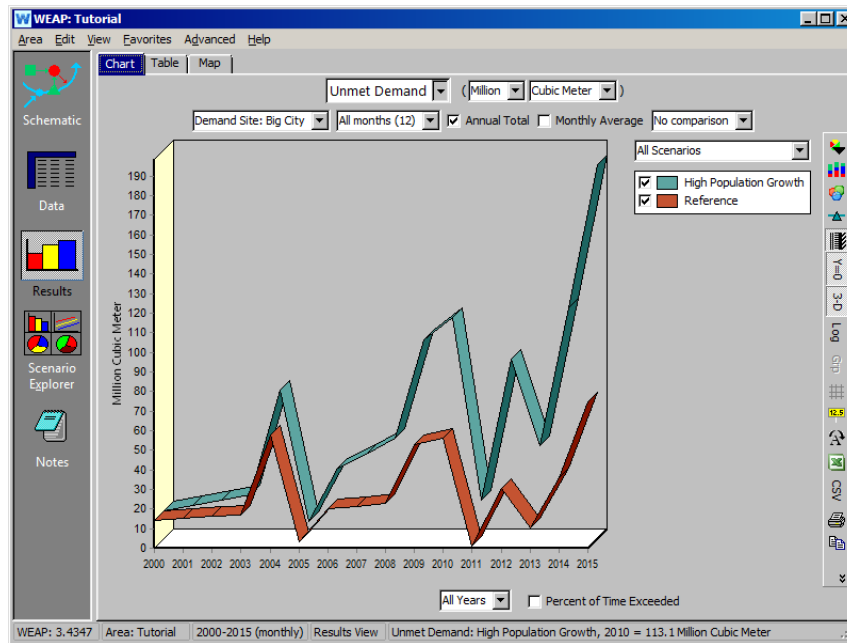
*Use the drop down menu in the “Get Values from” to select this method. You may have to scroll left in this window to get the “Get Values from” field to appear*





## 14. Re-run the Model

Run the model again and compare “Unmet Demand” for the “Reference” and “Higher Population Growth” scenarios, as before (of course, “Water Demand” will not have changed after altering the supply side of the model with the Water Year Method).



Note that Big City “Unmet Demand” for both scenarios is much more erratic using the Water Year Method than assuming a constant headflow to the Main

River, as observed in the previous exercise. In the present case, Unmet Demand varies as the future climate varies. During years wetter or much wetter than normal (2000, the Current Accounts year), Unmet Demand is actually lower than in 2000 for both scenarios, even with the increase in Water Demand from population growth (2.2% for the Reference and 5.0% for the Higher Population Growth scenarios). The increased precipitation, and headflow to the river, mitigates this increased demand in the wetter years.

The opposite occurs in the dry to very dry years, where the population growth is exacerbated by the lower precipitation and headflow in the river in these years. This leads to even higher Unmet Demand than is simulated assuming a constant climate (as performed in the previous exercise).

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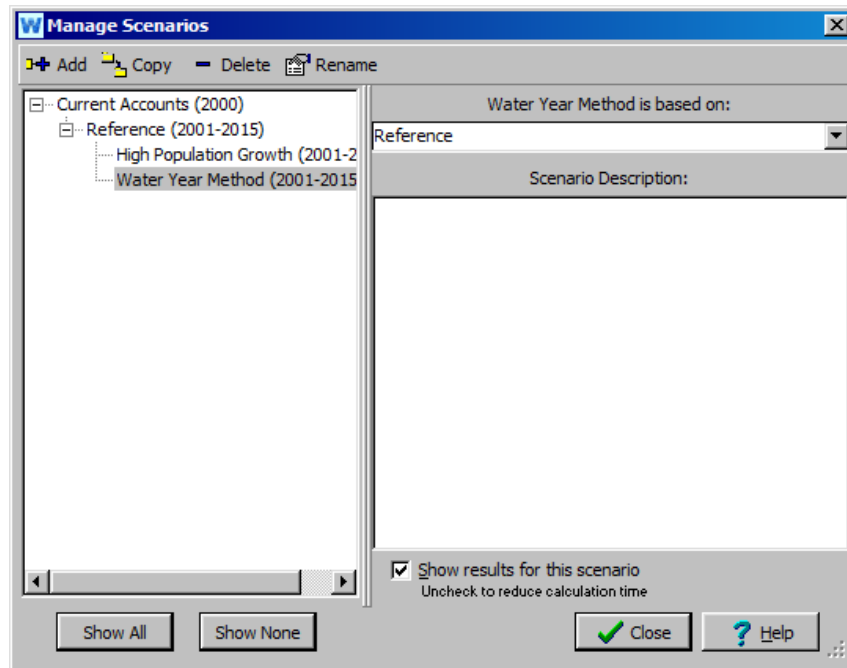
Since unmet demand is the difference between a large demand and a large supply, even a rather small change in the supply at nearly-constant demand can have a very large impact on the unmet demand.



This model does not take any kind of inter-year storage into consideration (reservoirs, groundwater). Therefore, there is no way that the shortage in a dry year can be alleviated by using surplus from previous, wetter years. For more details on how to model storage, refer to the “Refining the Supply” WEAP tutorial module.

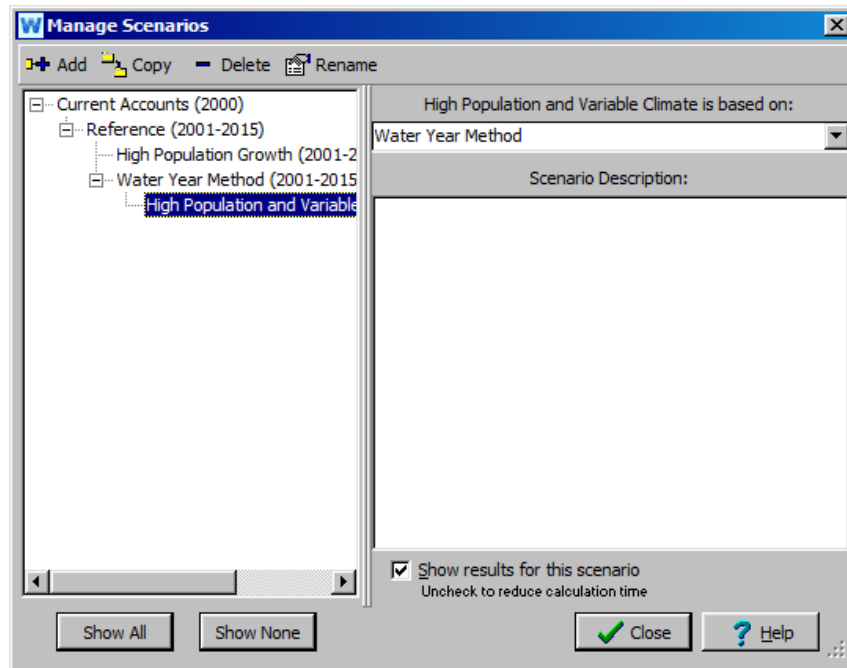
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If you had wanted to compare, *in the same graph in WEAP*, results for the Water Year Method to that generated assuming a constant climate, you could have created a new scenario that used the Water Year Method rather than changing the data in the “Reference” scenario to accommodate the Water Year Method. This new scenario would be inherited from the “Reference” scenario, and the Scenario tree in the “Scenarios Manager would look as follows:



Note that in this case, both the “Reference” (constant climate) and “Water Year Method” scenarios (variable climate) would use a Population Growth Rate equal to 2.2% for Big City, since the “Water Year Method” scenario is inherited from the “Reference” scenario.

If one wanted to compare, in the same WEAP graph, constant climate and variable climate using a 5% Population Growth Rate, you could create another new scenario inherited from the “Water Year Method” scenario and change the “Population Growth Rate” Key Assumption in this scenario to 5%. The tree structure would look as follows:

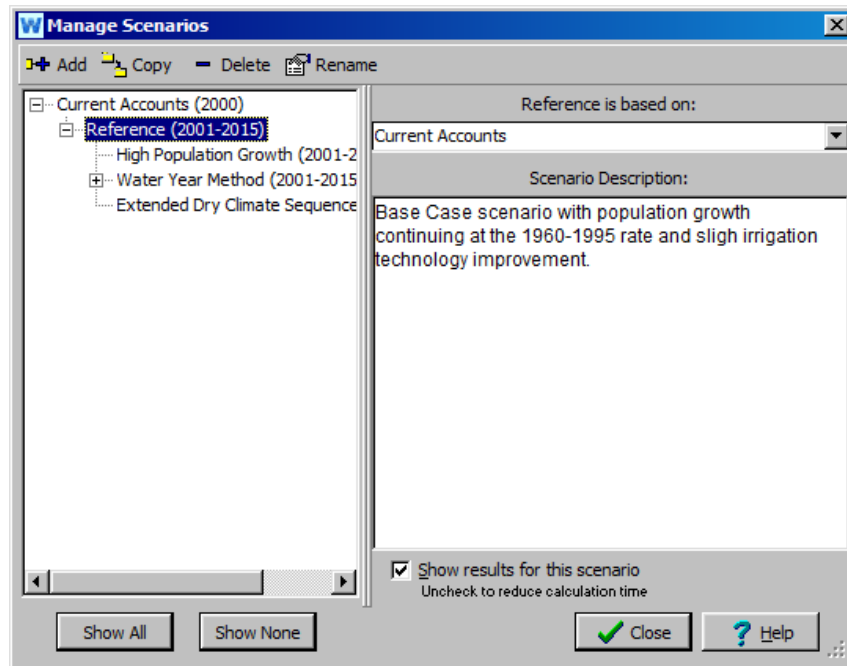


WEAP allows for unlimited versatility in the arrangement of scenarios. Note that you can output results to Excel, which also facilitates results comparisons among scenarios. This feature will be discussed in greater detail in the “Data, Results, and Formatting” module.

## 15. Change Scenario Inheritance

The following example demonstrates the utility of changing scenario inheritance within WEAP.

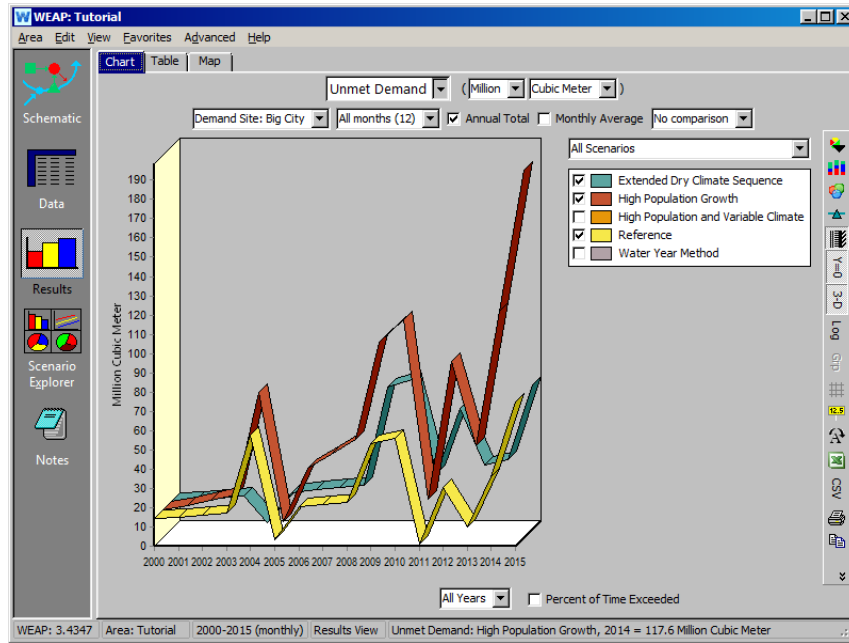
Create a new scenario inherited from the “Reference” scenario, and name it “Extended Dry Climate Sequence.” The scenario tree structure should look as follows:



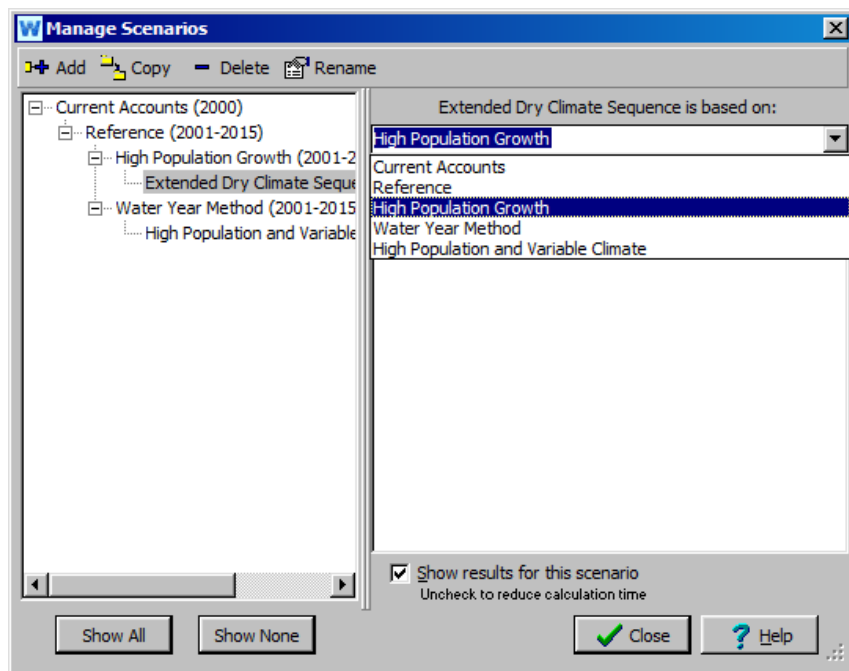
Go to the Data view and select this new scenario for editing. Click on the “Water Year Method” branch of the data tree (below Hydrology) to edit the climate sequence as follows:

2001-2003 *normal*  
 2004 *wet*  
 2005-2008 *normal*  
 2009-2010 *very dry*  
 2011 *normal*  
 2012 *dry*  
 2013 *normal*  
 2014 *normal*  
 2015 *dry*

*The results (shown below) indicate that Big City “Unmet Demand” for the “Extended Dry Climate Sequence” (new climate sequence and a 2.2 % Population Growth Rate) falls somewhat in between those for the “Reference” scenario (original climate sequence and a 2.2 % Population Growth Rate) and the “Higher Population Growth Rate” scenario (original climate sequence, but a 5% Population Growth Rate).*

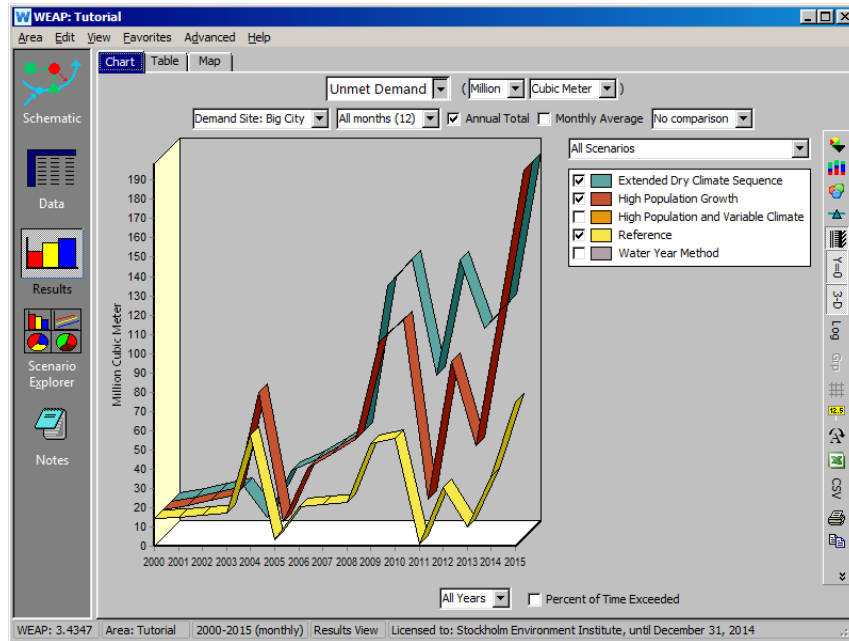


Now, we will change the Scenario Inheritance of the “Extended Dry Climate Sequence” scenario, placing it under the “Higher Population Growth Rate” scenario so that it inherits the 5% Population Growth Rate of that scenario. In the Scenario Manager, select the “Extended Dry Climate Sequence” scenario, click on the drop-down list to the right (below the text saying “Extended Dry Climate Sequence is based on:”) and select “Higher Population Growth” as the new parent scenario.



Now, recalculate the results and look again at “Unmet Demand” for Big City.

*What changes do you notice to the unmet demand for the “Extended Dry Climate Sequence” scenario?*



With the higher population growth rate and dryer climate, Unmet Demand increases substantially.





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**WEAP**

**Water Evaluation And Planning System**

# **Refining the Demand Analysis**

***A TUTORIAL ON***

*Disaggregating Demand* .....74

*Modeling Demand Side Management, Losses  
and Reuse*.....80

*Setting Demand Allocation Priorities*.....89

**October 2023**

**Note:**

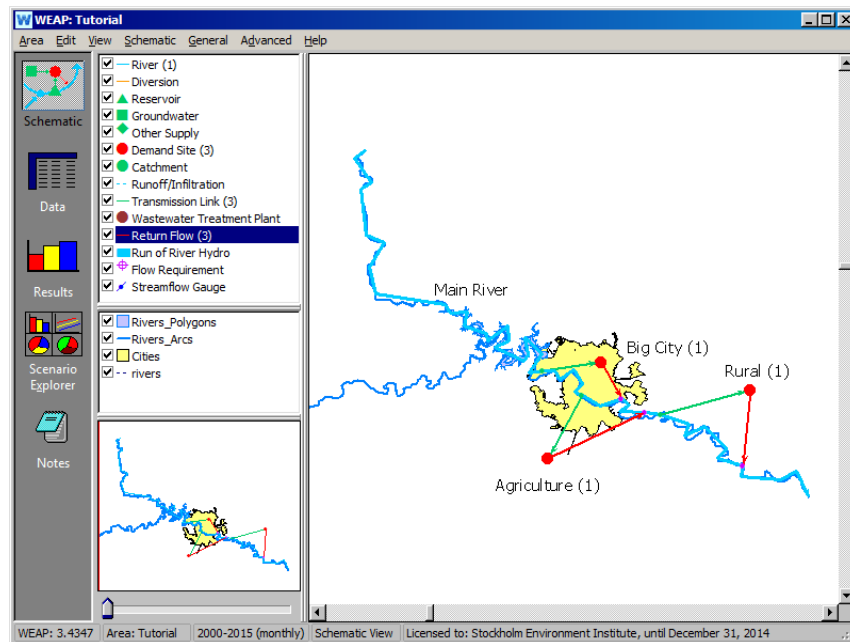
For this module you will need to have completed the previous modules (“WEAP in One Hour, Basic Tools, and Scenarios) or have a fair knowledge of WEAP (data structure, Key Assumptions, Expression Builder, creating scenarios). To begin this module, go to the Main Menu, select “Revert to Version” and choose the version named “Starting Point for all modules after ‘Scenarios’ module.”

## Disaggregating Demand

### 1. Create a new Demand Site

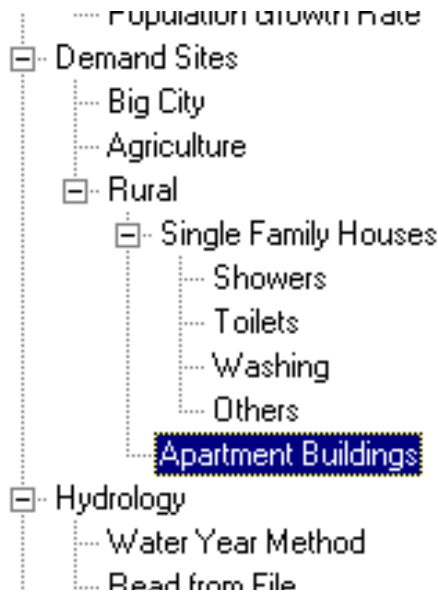
In the Current Accounts, create a new demand site downstream of Big City to simulate rural demand. Name this node “Rural” and give it a *Demand Priority* = 1. Provide a Transmission Link from the Main River positioned downstream of both the Big City and Agriculture Return Flows. *The Supply Preference should be set to 1.* Also provide a Return Flow for Rural that is positioned further downstream.

Your area should now look as follows:

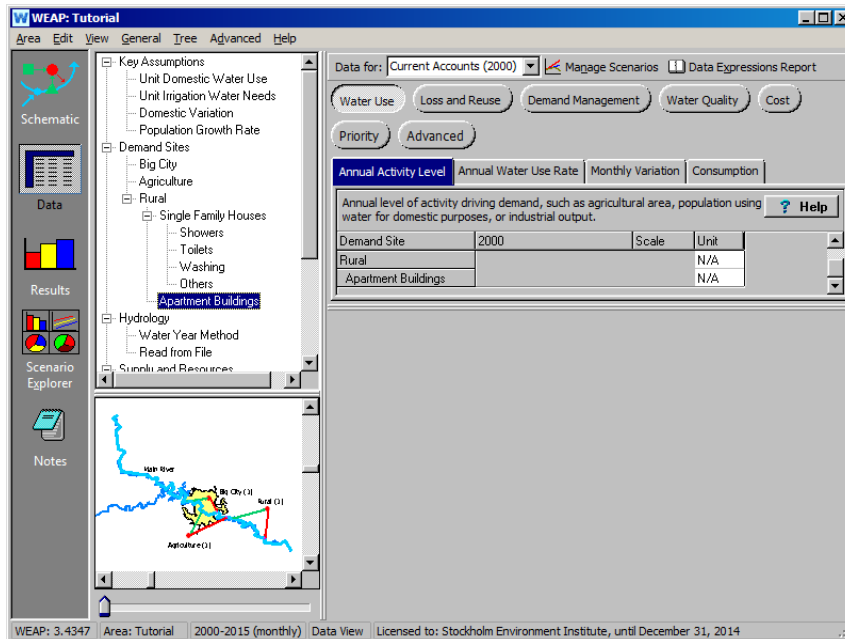


## 2. Create the Data Structure for “Rural” demand node

In order to create a data structure, right-click the “Rural” demand site in the data view tree, and select “Add” to implement the following structure (do not enter any data yet):



Note that “Showers”, “Toilets”, “Washing”, and “Others” are added as sub-branches below “Single Family Houses.”



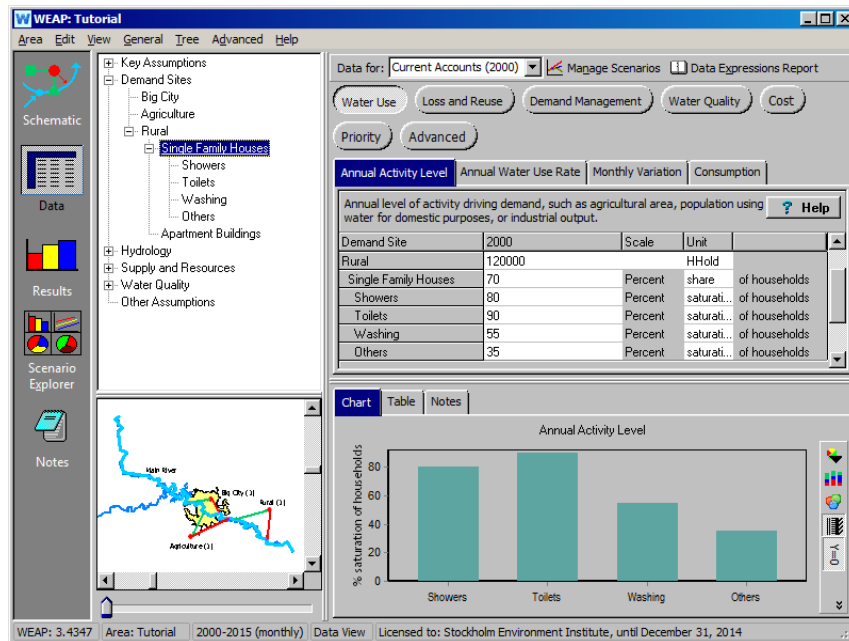
### 3. Enter the Annual Activity Level data

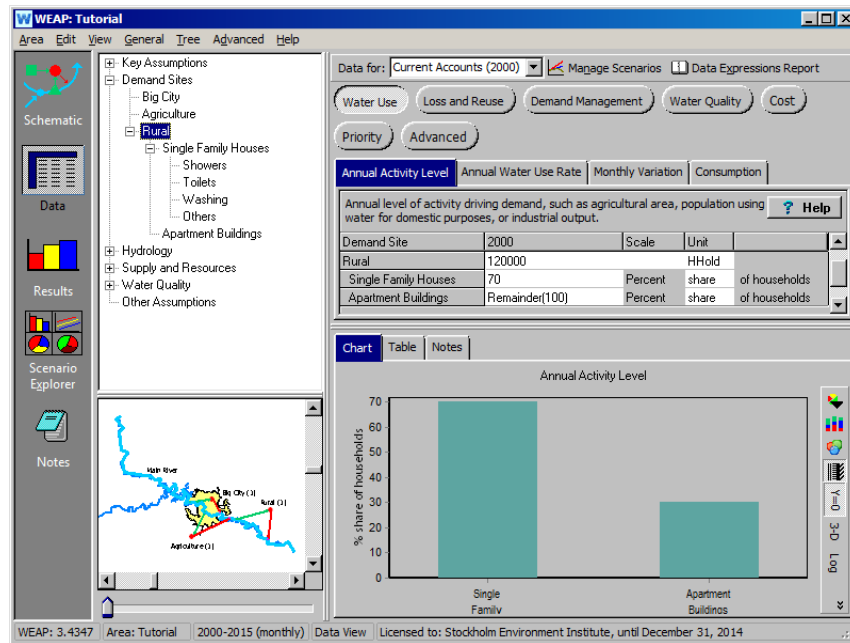
Enter the following data under the Rural Demand Site, Annual Activity Level tab (You will have to click on Single Family House in the Data Tree):

<i>Rural</i>	<i>120,000 Households</i>
<i>Single Family Houses</i>	<i>70% Share</i>
<i>Showers</i>	<i>80% Saturation</i>
<i>Toilets</i>	<i>90% Saturation</i>
<i>Washing</i>	<i>55% Saturation</i>
<i>Others</i>	<i>35% Saturation</i>
<i>Apartment Buildings</i>	<i>Remainder share (use the Expression Builder)</i>



**Share vs. Saturation:** even though both types of percentages are treated mathematically the same by WEAP, they are conceptually different. At a given level of the tree, shares should always sum up to 100%. They also allow the use of the “remainder” function. Saturation indicates the penetration rate for a particular device and is independent of the penetration rate for other devices (i.e., saturation rates for all sub-branches within a given branch do not have to sum to 100.)





#### 4. Enter the Annual Water Use Rate data

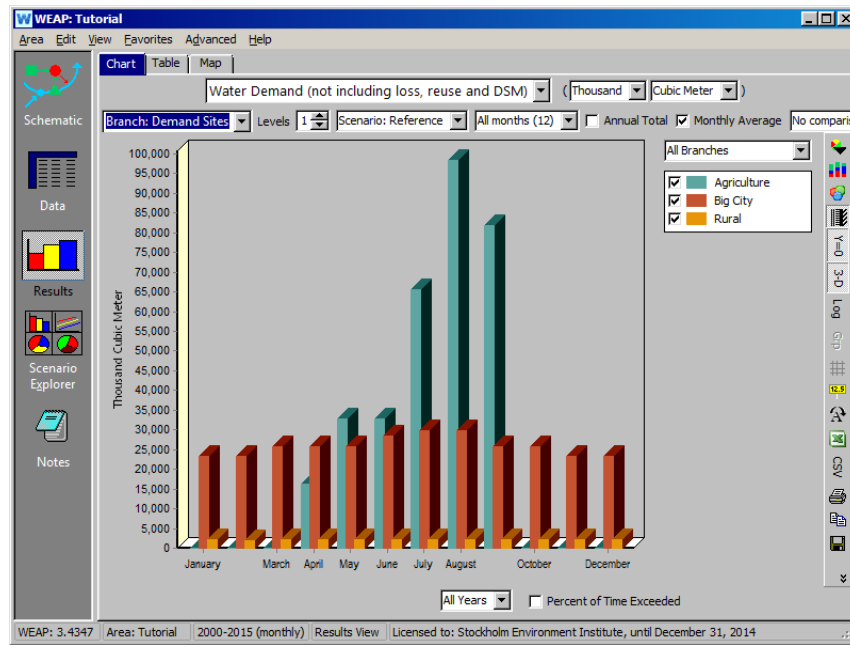
Enter the following data under the “Rural” demand site, “Annual Water Use Rate” tab.

<i>Rural</i>	
<i>Single Family Houses</i>	
<i>Showers</i>	<i>80 m<sup>3</sup> / household</i>
<i>Toilets</i>	<i>120 m<sup>3</sup> / household</i>
<i>Washing</i>	<i>60 m<sup>3</sup> / household</i>
<i>Others</i>	<i>40 m<sup>3</sup> / household</i>
<i>Apartment Buildings</i>	<i>220 m<sup>3</sup> / household</i>
<i>Consumption (in consumption tab)</i>	<i>80%</i>

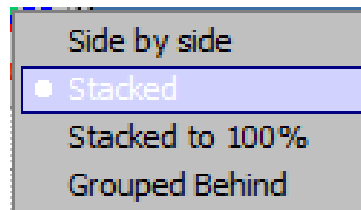
Note that the “Consumption” value is entered for the entire Rural demand node, and not the sub-branches.

#### 5. Check the results

Recalculate your results. In the Results view, choose “Water Demand” as the primary variable from the pull-down menu. Select “All Branches” from the pull-down menu directly above the graph legend. Select 3-D and bar graph as the format using the pull-down menu for the “Chart Type” icon on the vertical graphing toolbar.

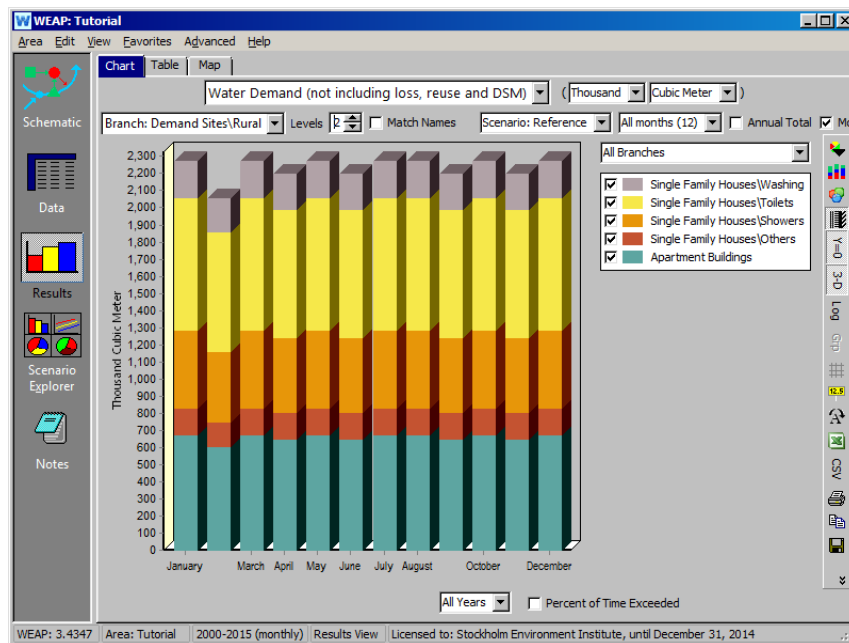
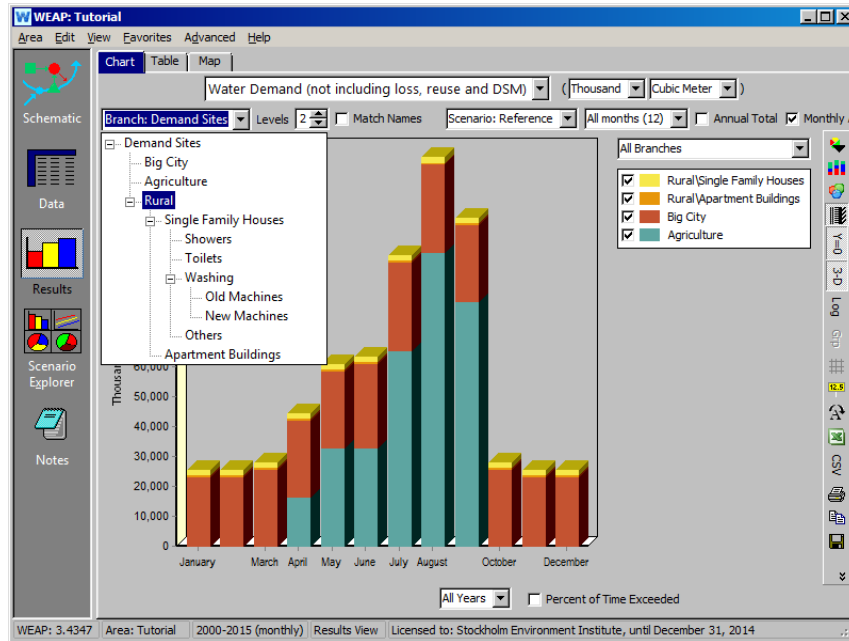


To see the results stacked, click on the bar icon in the far-right menu, and click the option “stacked.”



To view Water Demand results for all of the Rural sub-branches (e.g., Single Family Houses\Showers; Apartment Buildings), select 2 on the “Levels” box (directly above the center of the graph).

Change the branch of demand to the Rural demand.

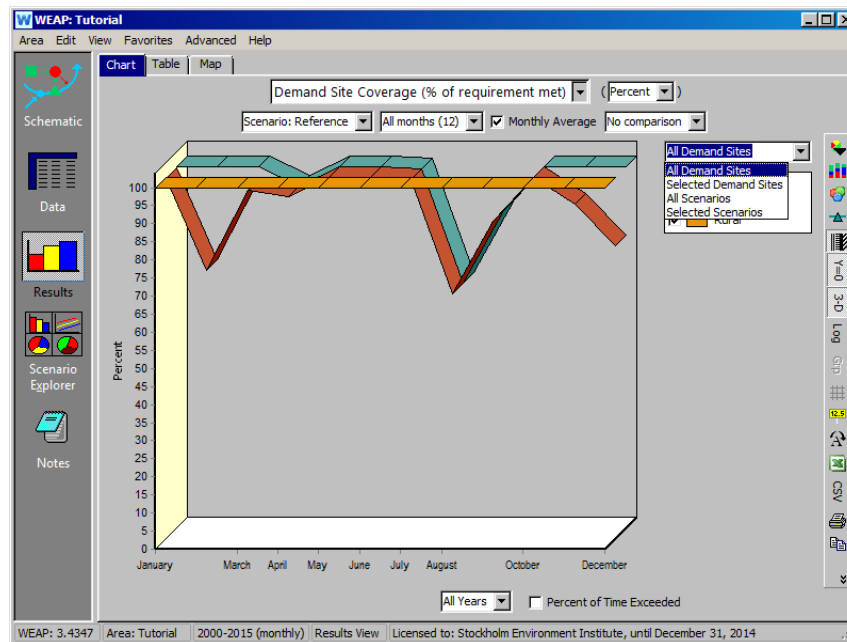


*Do you understand why the Rural demand varies through the year even though we have not entered any variation?*



The variation in Rural demand is due to the fact that WEAP assumes a constant daily demand per day (no monthly demand was specified by the user), so months that have less days (like February) have a lower demand than months that have more days (like January).

Now create a 3-D graph of “Demand Site Coverage” and select all demand sites for presentation (the pull-down menu to do the latter is to the right of the graph; see below).



*Do you understand why Coverage is always 100% for Rural but not for Big City and Agriculture, even though they all have the same demand priority level?*



The Rural withdrawal point is downstream of the return flow point for the Big City, which means there is an additional volume of water available in the river; this return flow can easily cover the rather small Rural demand.

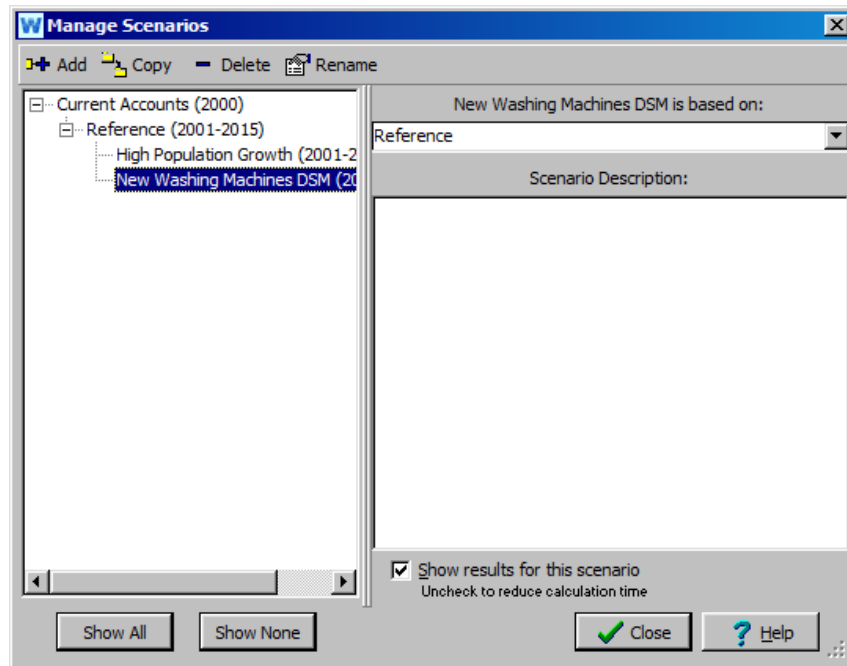
## Modeling Demand Side Management, Losses and Reuse

### 6. Implement Demand Side Management—the disaggregated approach

We will now create a new scenario that explores a demand side management strategy. Call this scenario “New Washing Machines DSM”; it is to be inherited from the “Reference” scenario so it will have the same climate and Big City population growth rate as the “Reference” scenario. We deleted the



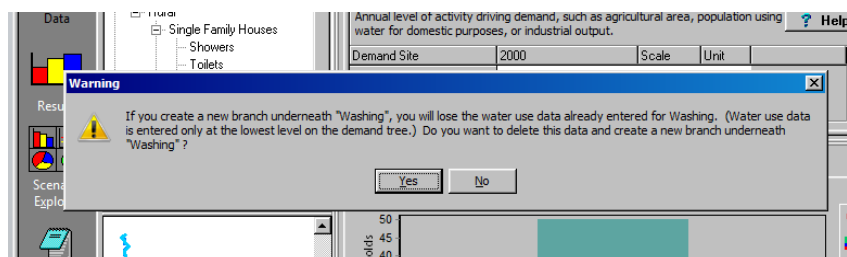
scenarios we are not using by clicking the “delete” button. The scenario tree in the Manage Scenarios window should look like this:



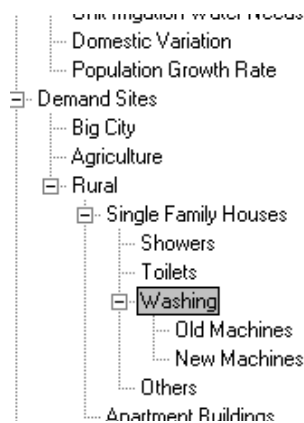
We will assume that a new type of washing machines allows a 1/3 reduction (33.3% less) in washing water consumption. This new scenario will evaluate the impact of this Demand Side Management measure if 50% of the households can be convinced to purchase the water-saving machine.

First, go back to Current Accounts in the Data view, where you will create two new branches (Old Machines and New Machines) in the Rural data structure. Effectively, you are disaggregating the “Washing” variable to now include two new sub-categories. *Note that you must return to Current Accounts because all new data structures must be entered in Current Accounts, even if the variable is not to be activated (i.e., given non-zero activity levels) in the Current Accounts and “Reference” scenario.*

When you go to add the first sub-branch under Washing, you will get the following message:



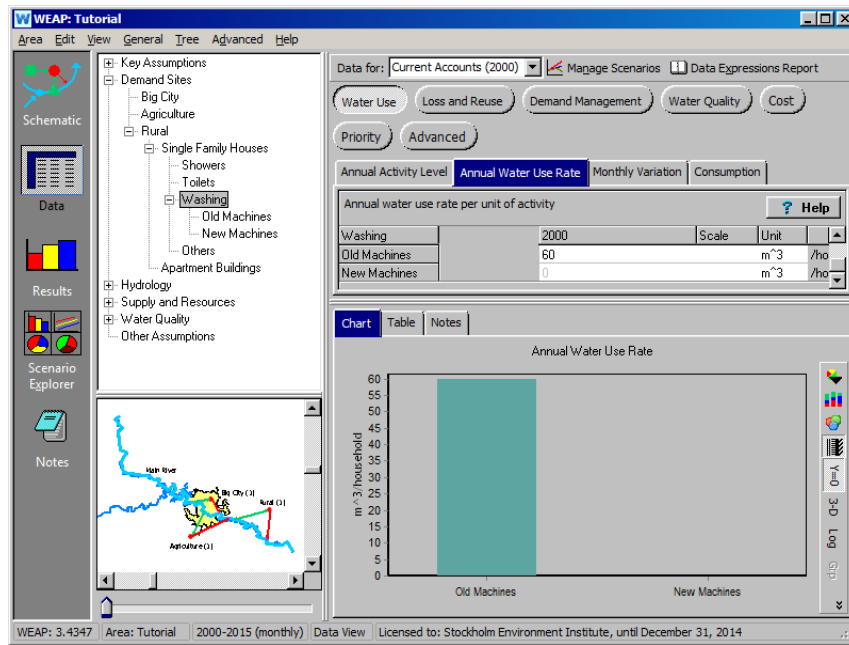
Click “Yes,” and add the following structure:



*Change the units for “Old Machines” and “New Machines” to “Shares.” Under Annual Water Use, reenter the Water Use Rate for Old Machines (60 m<sup>3</sup> / household), as was the value for the original higher-level variable “Washing.”*

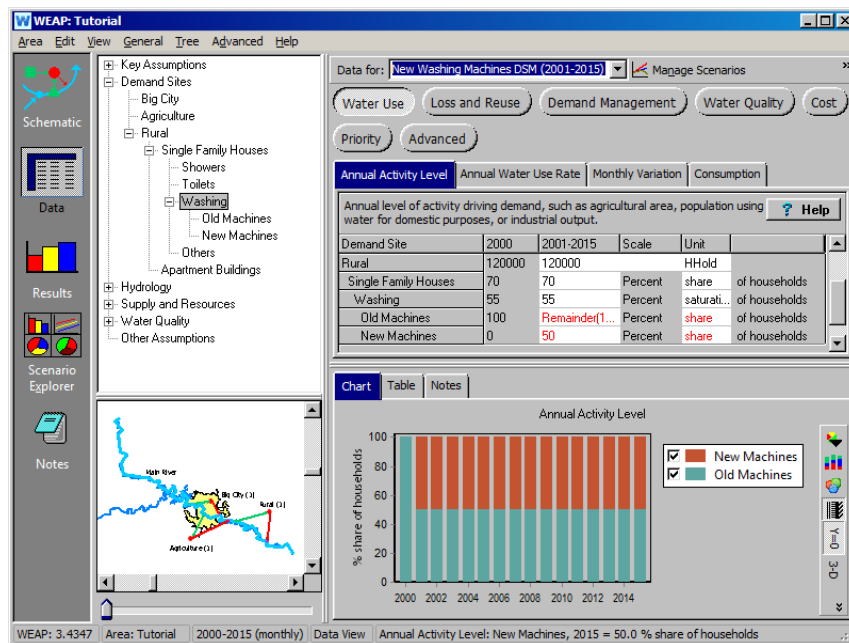
Variable	Value	Scale	Unit
Washing	2000		m <sup>3</sup> /household
Old Machines	60		m <sup>3</sup> /household
New Machines	0		m <sup>3</sup> /household

Enter a value of 100% for the “Old Machines Annual Activity Level.” Leave blank the Annual Activity Level for “New Machines” - this is the same as entering a zero. Remember, you are entering these in the Current Accounts, so you want only the “Old Machines” to be active in the “Reference” scenario. This recreates the same effect as having the aggregated variable “Washing” in the original Current Accounts and “Reference” scenario. The “New Machines” variable will be activated in the “New Washing Machines DSM” scenario (see below).



Now, switch to the “New Washing Machines DSM” scenario.

*Input 50 for New Machines (50% of all washing machines will be the new variety) and Remainder(100) for Old Machines, using the Expression Builder for the latter.*



*You will have to input again the original Water Use Rate for the Old Machines (60 m<sup>3</sup>/household) as well as the new Water Use Rate for the New Machines:*

*Old Machines*                       $60 \text{ m}^3 / \text{household}$   
*New Machines*                       $60 * 0.667 \text{ m}^3 / \text{household}$

*View the data as “Bar,” selected from the top icon on the right hand side.*

Now compare the numerical Water Demand results for the Washing branch of the Rural demand site for the “Reference” and “New Washing Machines DSM” scenarios. In the Results view, click on the Table tab and select the Water Demand variable. Also select “Annual Total” rather than “Monthly Average” and choose 2001 (you can only view numerical results for one individual year at a time when comparing scenarios in the Table view, but this does not present a difficulty for this example, as we do not try to model any growth with time for the Washing variable). Choose Demand Sites\Rural\Washing\Single Family Houses\Washing from the upper left pull-down menu and “All Branches” from the upper right pull-down menu. Select “Reference” and “New Washing Machines DSM” from the pull-down menu at the bottom of the window. The table should look like the following:

	New Washing Machines DSM	Reference
New Machines	924.5	
Old Machines	1,386.0	2,772.0
<b>Sum</b>	<b>2,310.5</b>	<b>2,772.0</b>

Note that the use of the New Machines in 2001 (and all subsequent years in the “New Washing Machines DSM” scenario period) results in about 460,000 m<sup>3</sup> less water demand than if only Old Machines are used (Reference scenario).



Demand-side management (DSM) refers to measures that can be taken on the consumer’s side of the meter to change the amount or timing of water consumption (as compared to the utility company's, or supply, side of the meter).

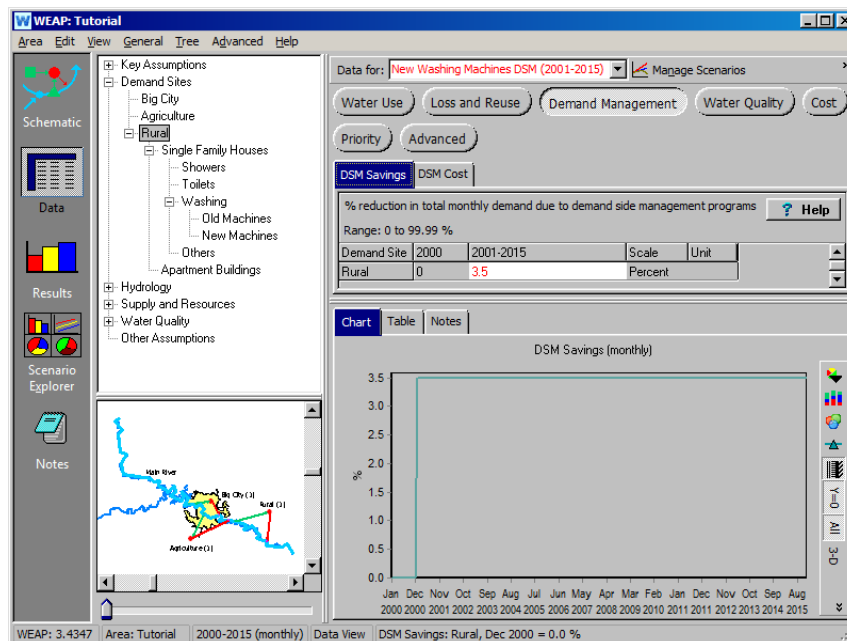
Another way of modeling disaggregated DSM is to reduce the unit consumption for the affected category (in this case washing). There is no right or wrong way to model DSM, although some ways can show more information than others within WEAP.

## 7. Implement Demand Side Management—the aggregated approach

If disaggregated data is not available, an equivalent value of DSM can be computed. In this example, assuming we had not disaggregated the Rural water demand, we could come to the same result by using the “Demand Management” option for this Demand Site in the Data view. In this case the reduction would amount to:

<i>Original contribution of washing to rural water use</i>	<i>2,772/26,316 10.5%</i>
<i>Share of New Machines</i>	<i>50%</i>
<i>Reduction of New Machines</i>	<i>66.6%</i>
<i>Multiplying all of these percentages together =</i>	<i>3.5%</i>

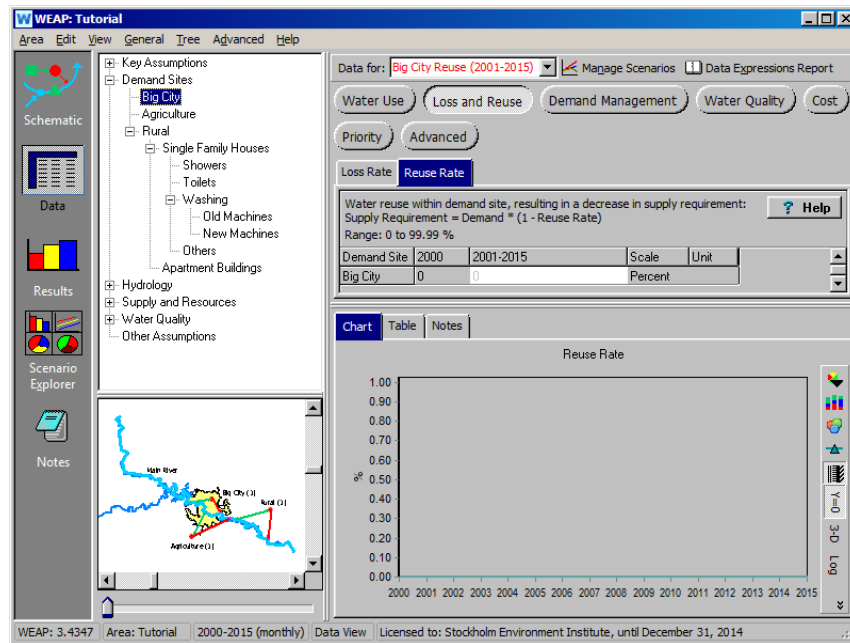
This value could be entered in the “Demand Management/Demand Savings” tab for the Rural branch of a Demand Side Management scenario.



Demand Side Management (DSM) measures are not taken into account in the demand view. To see the effect of a DSM measure, look at the change in Supply Requirement rather than Water Demand.

## 8. Model Reuse

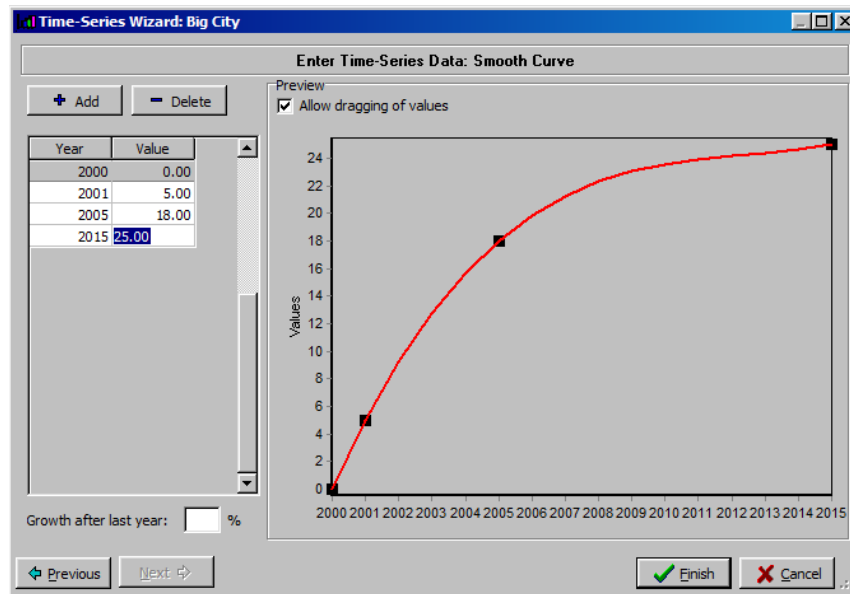
Another water conservation strategy that could be studied with scenarios is water reuse. Create a new scenario inherited from the “Reference” scenario and name it “Big City Reuse.” Make sure you are in this new scenario and click on the Big City branch. Click on the “Loss and Reuse” button and click the “Reuse Rate” tab.



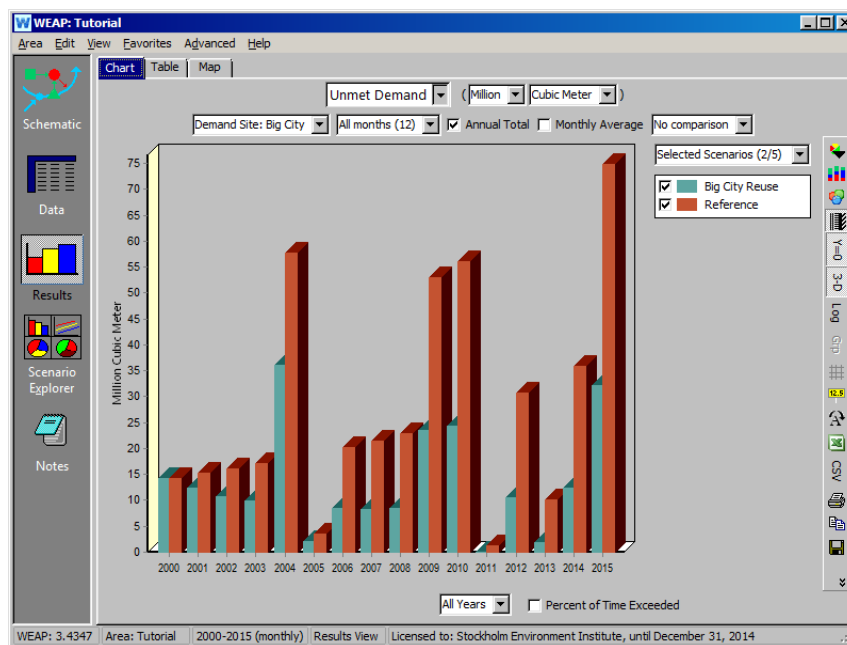
Enter the following expression in the 2001-2015 field using the Expression Builder:

*Smooth(2001,5, 2005,18, 2015,25)*

First, pull the “Smooth” function into the text field of the Expression builder and select “Smooth Curve” from the options. Click “Next” and enter the data values. You should get a plot like the one below. Note that Reuse in the Current Accounts (2000) remains zero. Click “Finish.”



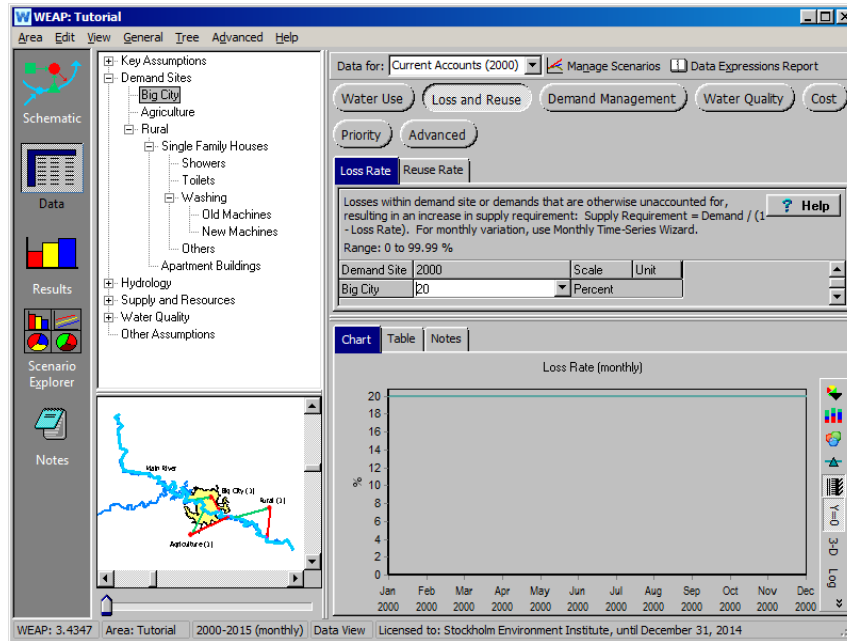
In the Results View, compare Unmet Demand for Big City before (Reference) and after (Big City Reuse) instituting this conservation strategy. You should get the graph below, which shows substantial reductions in Big City Unmet Demand when the water reuse strategy is used.



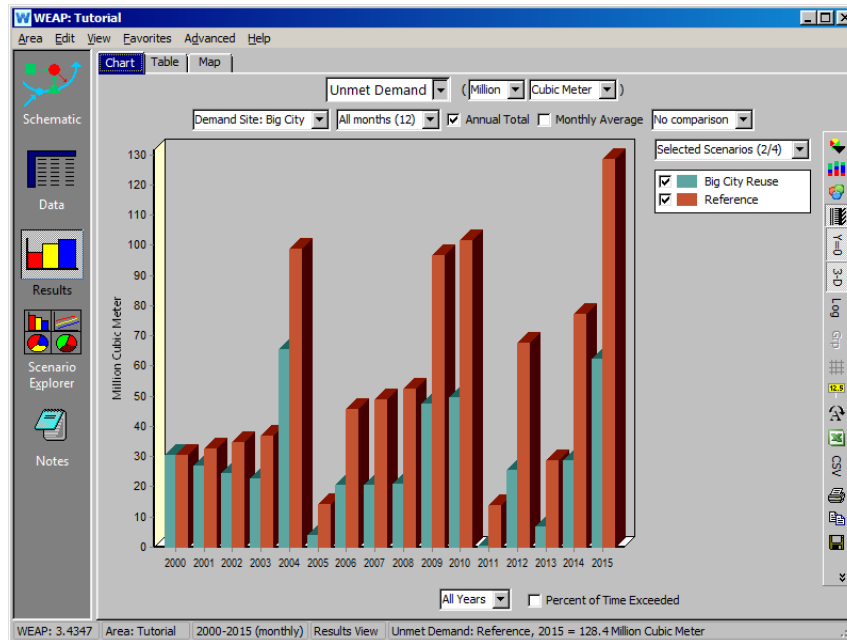
## 9. Model Losses

Re-edit the model to account for a 20% loss rate in the network of Big City. Make this change for the Current Accounts so that it will be carried through

the “Reference” scenario, and as a result of the inheritance feature, throughout all scenarios.



*What happens to the unmet demand for the Big City, both in the “Reference” scenario and the “Big City Reuse” scenario compared to the earlier exercise without losses?*







Losses can happen in Transmission Link, in the Demand Site itself or in the Return flow. Losses in the Transmission Link will affect the supply to the Demand Site. Losses in the Demand Site will affect the required Supply Requirements of this Demand Site. Losses in the Return Flow will only affect the flow returned.

## Setting Demand Allocation Priorities

### 10. Edit Demand Site Priority

Create a new scenario, inherited from the “Reference”, and name it “Changing Demand Priorities.” Change the Demand Priority of the Agriculture Demand Site in the Data view by clicking on the Agriculture branch and then clicking on the Priority button, or by clicking on the node in the Schematic View and selecting “General Info.”

*Change the Demand Priority from 1 to 2.*

The screenshot shows the WEAP Tutorial software interface. The 'Data' view is active, displaying the 'Demand Priority' table for the scenario 'Changing Demand Priorities (2001-2015)'. The table shows the priority for Agriculture changing from 1 in 2000 to 2 in 2001-2015. A chart below the table shows the demand priority over time, with a step function that jumps from 1 to 2 at the start of 2001.

Demand Site	2000	2001:2015
Agriculture	1	2

A demand priority can be any whole number between 1 and 99 (1 is the default) and allows the user to specify the order in which the water requirements of demand sites are satisfied. WEAP will attempt to satisfy the water requirement of a demand site with a demand priority of 1 before a demand site with a demand priority of 2 or greater. If two demand sites have the same priority, WEAP will attempt to satisfy their water requirements equally. Absolute values have no significance for the priority levels; only the relative order matters. For example, if there are two demand sites, the same result will occur if demand priorities are set to 1 and 2 or 1 and 99.

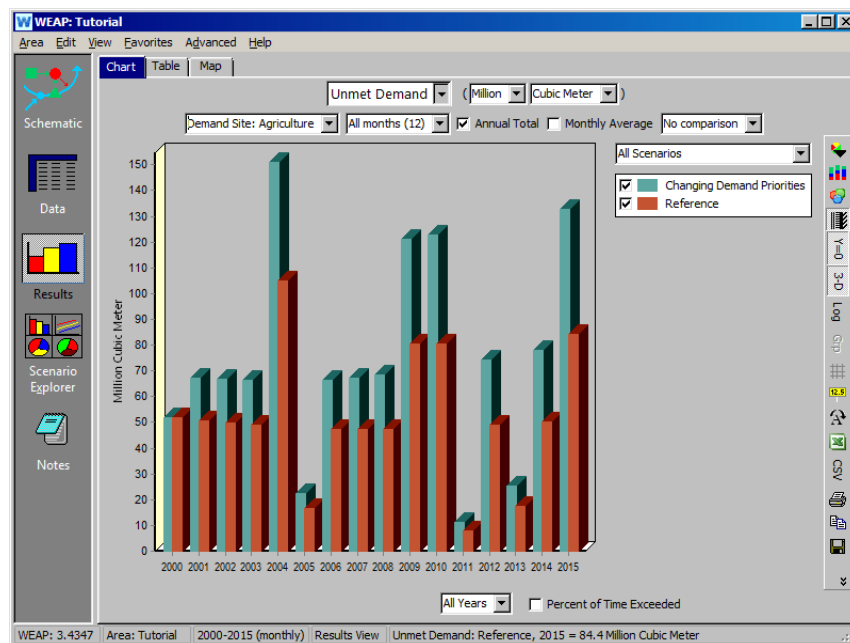


Demand Priorities allow the user to represent in WEAP water allocation as it actually occurs in their system. For example, a downstream farmer may have historical water rights to river water, even though another demand site positioned upstream could extract as much river water as it desired, leaving the farmer with little water in the absence of such water rights. The Demand Priority setting allows the user to set the farmer's priority for water above that of the upstream demand site. Demand Priorities can also change with time or change in a scenario - more advanced subject matter to be dealt with later in the tutorial.

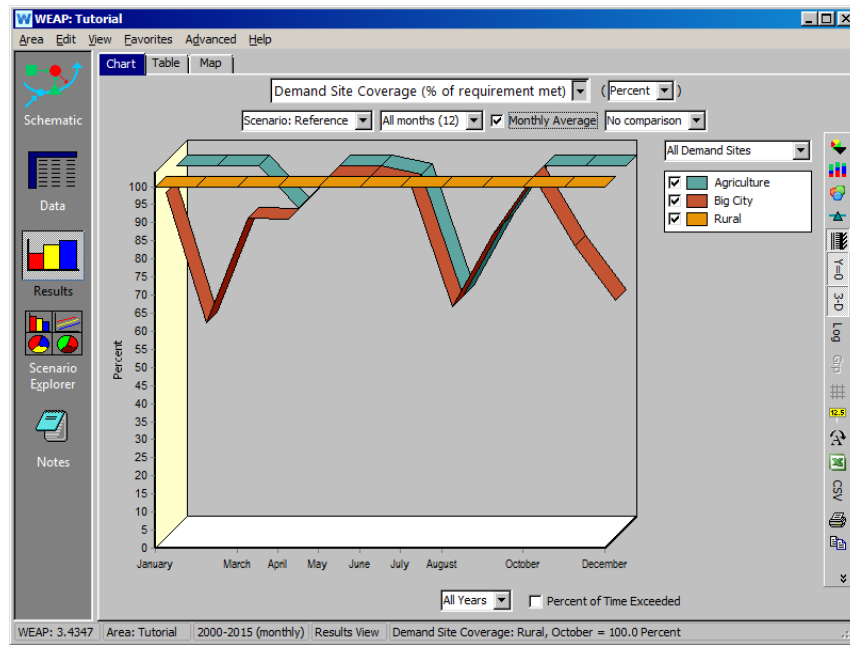
You can also change the Demand Priority in the Data View\”Priority” screen\”Demand Priority” tab.

## 11. Compare Results

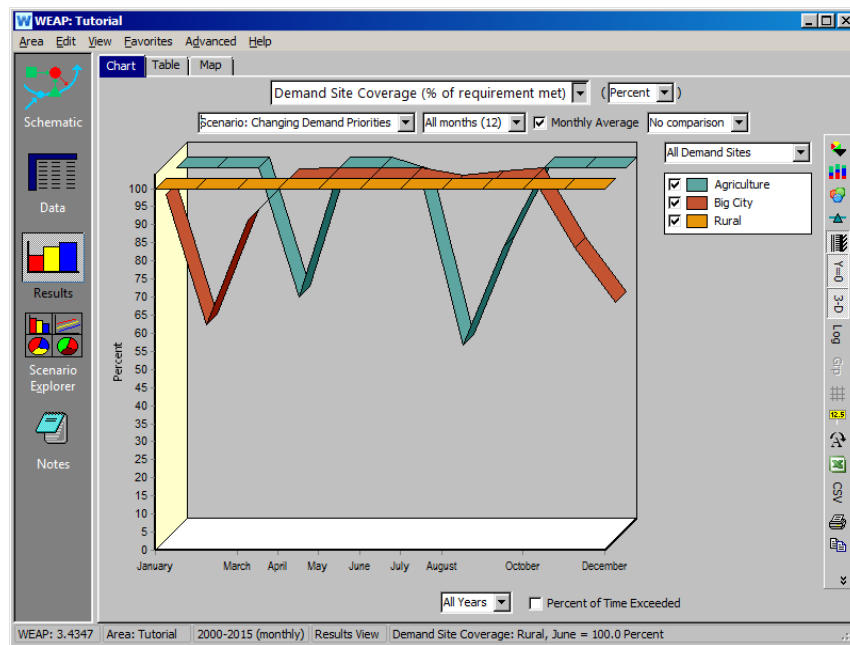
Display graphically the Unmet Demand for Agriculture for the “Reference” and “Changing Demand Priorities” scenarios. It should look like the graph below”:



Notice that the Unmet Demand for Agriculture increases when its Demand Priority is raised to 2. This is because Big City now has preference for having its demand met first. Evidence of this can be observed by generating a graph of the monthly average Demand Coverage for Big City and Agriculture across all years of the Reference scenario.



Now compare these results to the same graph generated for the “Changing Demand Priorities” scenario.



Notice that in the “Reference” scenario, for April and August, both Big City and Agriculture do not get full coverage of their demand because they both compete equally for Main River flow. When Big City is given preference for meeting demand (Changing Demand Priorities scenario), however, its coverage improves relative to Agriculture. At times, coverage is 100% for Agriculture, but not for Big City. That is because there is no Agriculture

demand (primarily observed for the winter months). Note that the Demand Coverage for the Rural demand site is always 100% because the return flows for Big City and Agriculture satisfy the water demand created by the Rural demand site.

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# WEAP

Water Evaluation And Planning System

# Refining the Supply

## ***A TUTORIAL ON***

*Changing Supply Priorities.....94*

*Modeling Reservoir Supply .....97*

*Adding Flow Requirements.....104*

*Modeling Groundwater Resources .....108*

**October 2023**

**Note:**

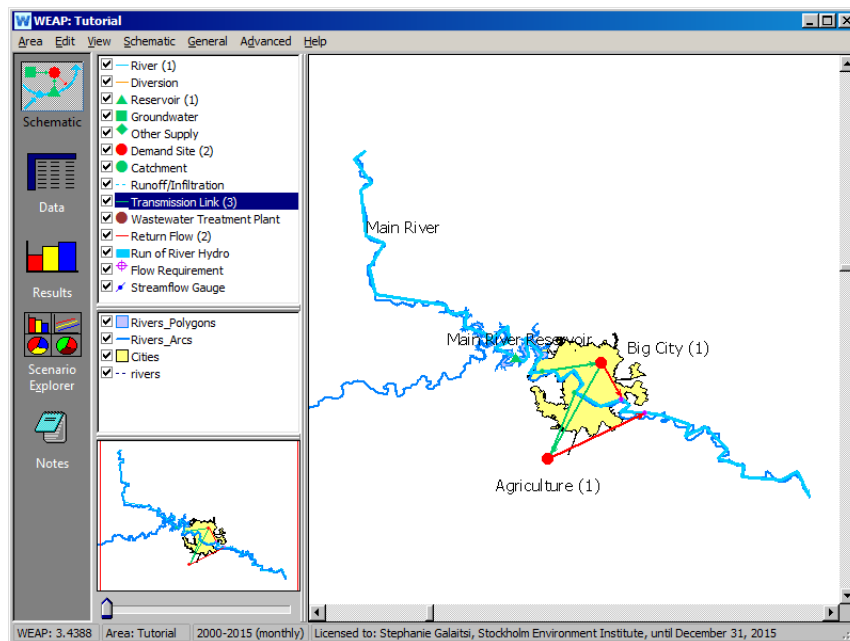
For this module you will need to have completed the previous modules (“WEAP in One Hour, Basic Tools, and Scenarios) or have a fair knowledge of WEAP (data structure, Key Assumptions, Expression Builder, creating scenarios). To begin this module, go to the Main Menu, select “Revert to Version” and choose the version named “Starting point for all modules after ‘Scenarios’ module.”

## Changing Supply Priorities

### 1. Create a new Transmission Link for water reuse

Create a new transmission link starting at the Big City Demand Site and ending at the Agriculture Demand Site. This is a conceptual model of reuse of urban wastewater for agriculture purposes. Set the Supply Preference on this Transmission Link to 2.

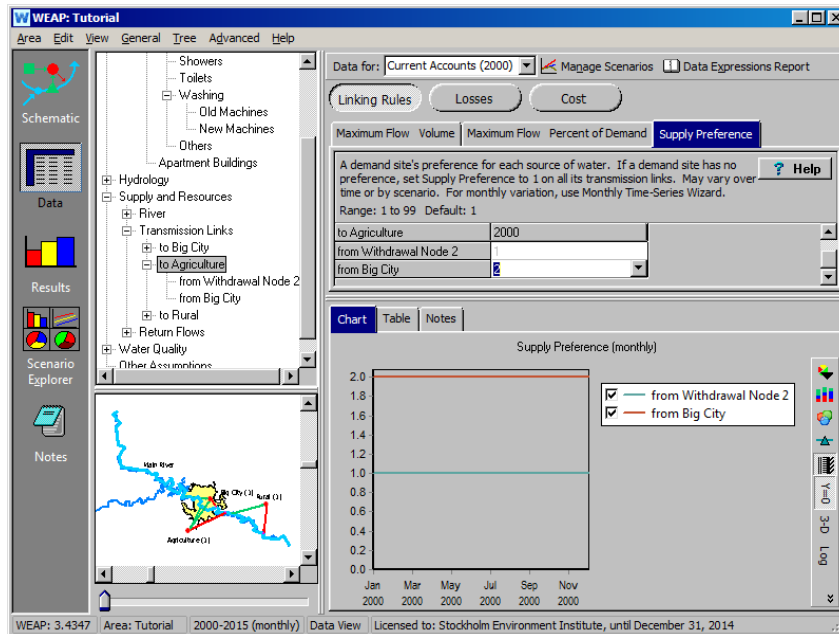
*Supply Preference*                      2



If water quality were a concern, a wastewater treatment plant could have been added to treat the water from Big City before Agriculture received it. Having the treatment plant in the schematic would make it possible to simulate the changes in water quality before and after treatment.

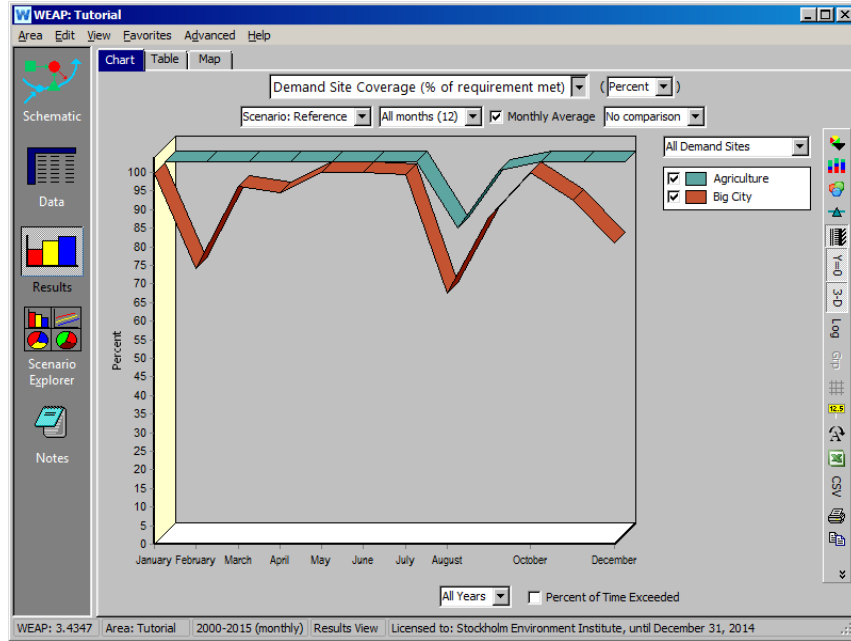
## 2. Results when you change Supply Preferences

Try changing the Supply Preferences of the two links that now supply Agriculture and look at the related results for Demand Site Coverage. To change Supply Preferences, either right click on the Transmission Link in the Schematic view or go to the Data view and click on the appropriate Transmission link below Supply and Resources\Linking Demands and Supply\Agriculture.

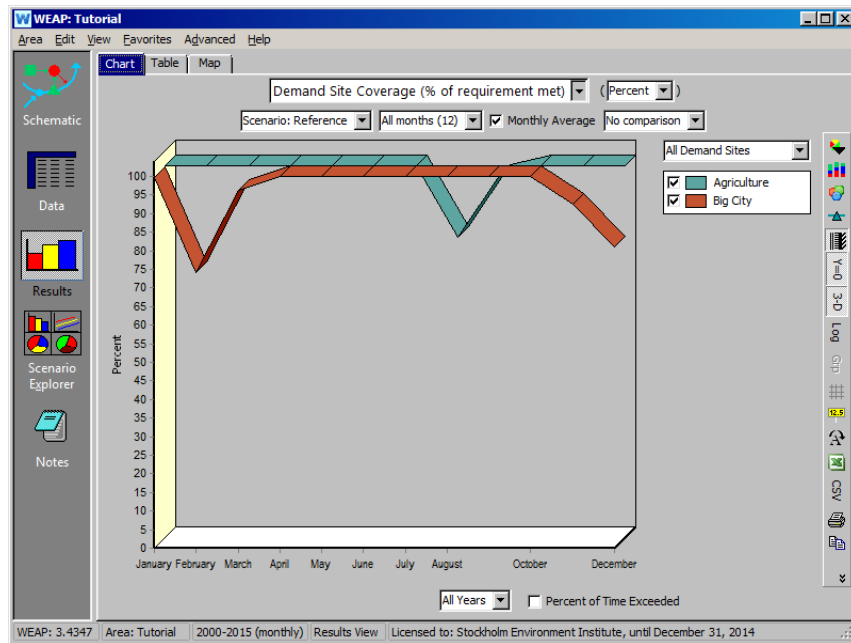


*Try the following combinations:*

*Supply Preferences = 1 from the Main River, 2 from Big City*

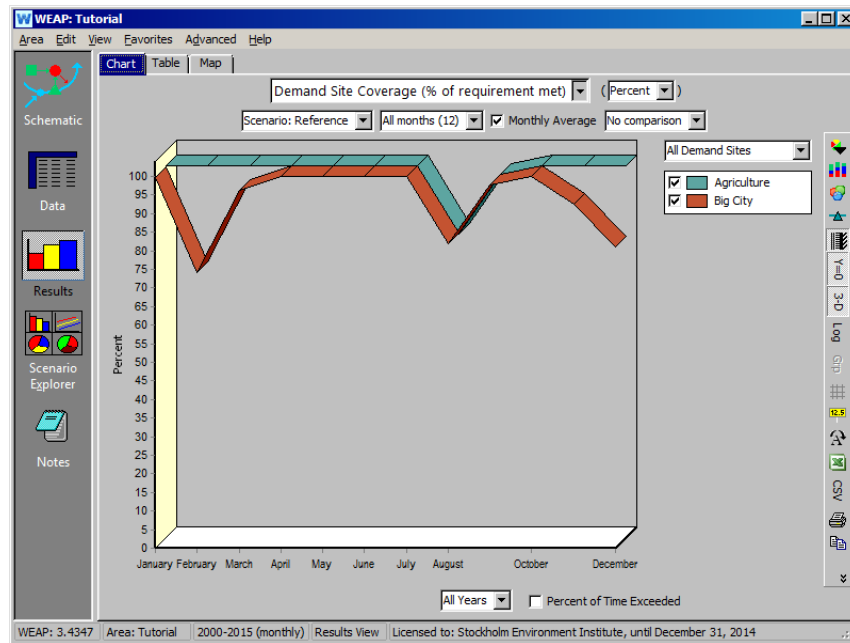


*Supply Preferences = 2 from the Main River, 1 from Big City*





*Supply Preferences = 1 from the Main River and 1 from Big City*



*Do you understand why the differences in Demand Coverage occur when the Supply Preferences are changed?*



You can modify the display of preferences on the schematic by using the “Schematic\Change the Priority View” menu. The “View Allocation Order” option will display the actual priority order in which WEAP computes supply. This is a function of the Supply Preference of the link as well as the Demand Priority of the demand site.

Note that you can study the impact of changing Supply Preferences, like Demand Priorities, by creating alternative scenarios.

### 3. Revert to original model

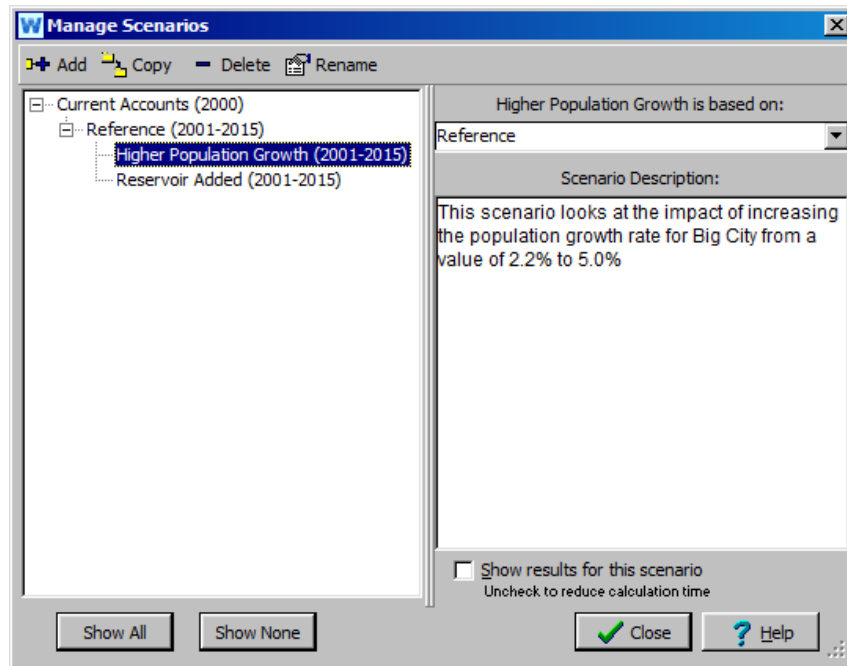
You can do this using the “Revert to Version” option under the Area menu. Choose “Starting point for all modules after “Scenarios” module” as you did at the beginning of this exercise.

## Modeling Reservoir Supply

### 4. Create a Reservoir and enter the related data

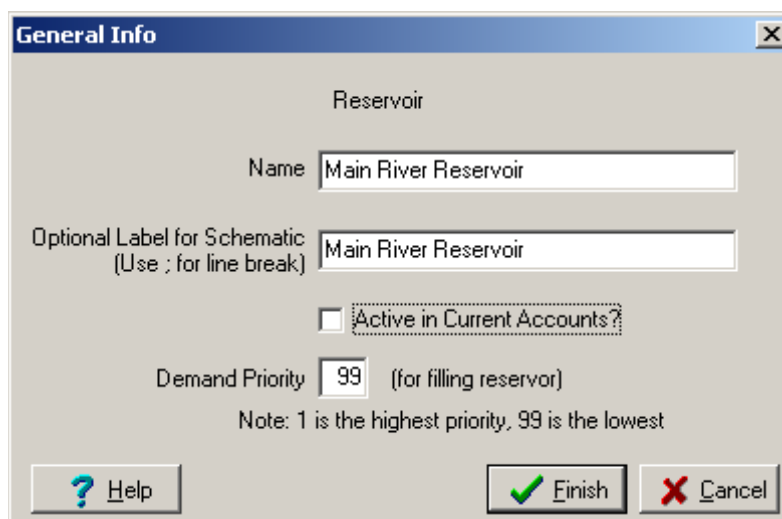
First, create a new scenario inherited from “Reference”, and name it “Reservoir Added.”

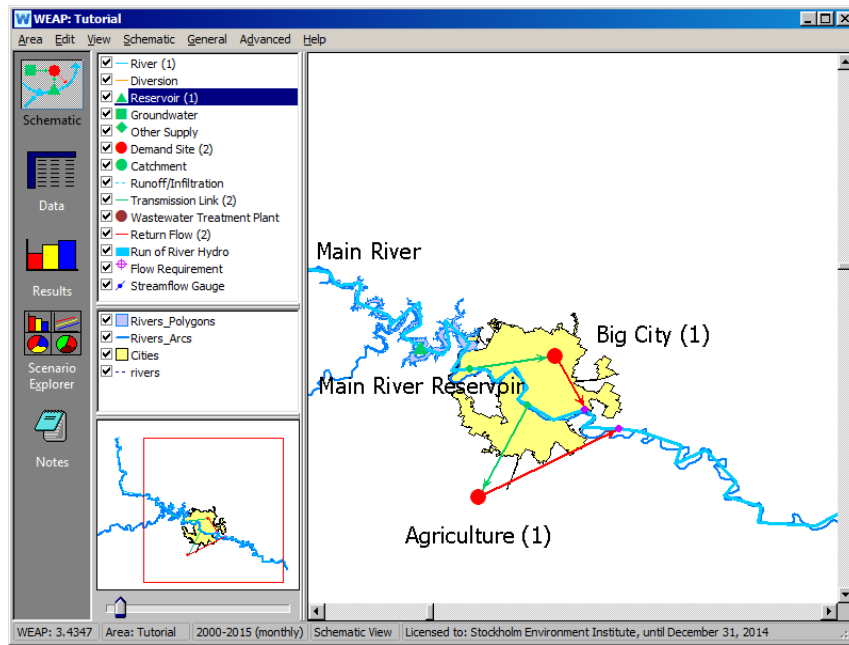
While in Manage Scenarios, highlight the High Population Growth scenario and uncheck the box “show results for this scenario.” This will enable WEAP to make calculations faster.



Then add a reservoir object on the Main River upstream of Big City, and name it “Main River Reservoir.” Unclick the box where it asks if this object is active in Current Accounts.

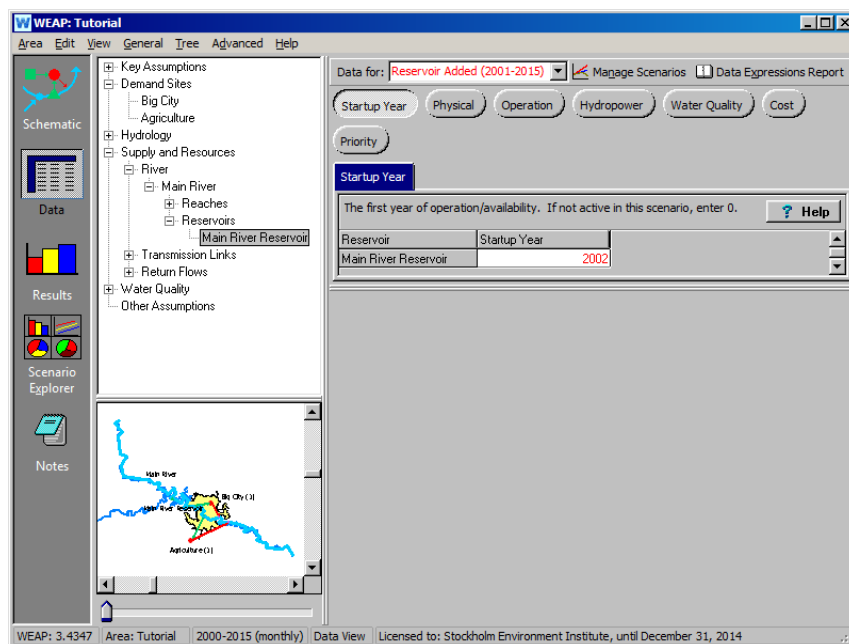
*Leave the Demand Priority at 99 (default).*





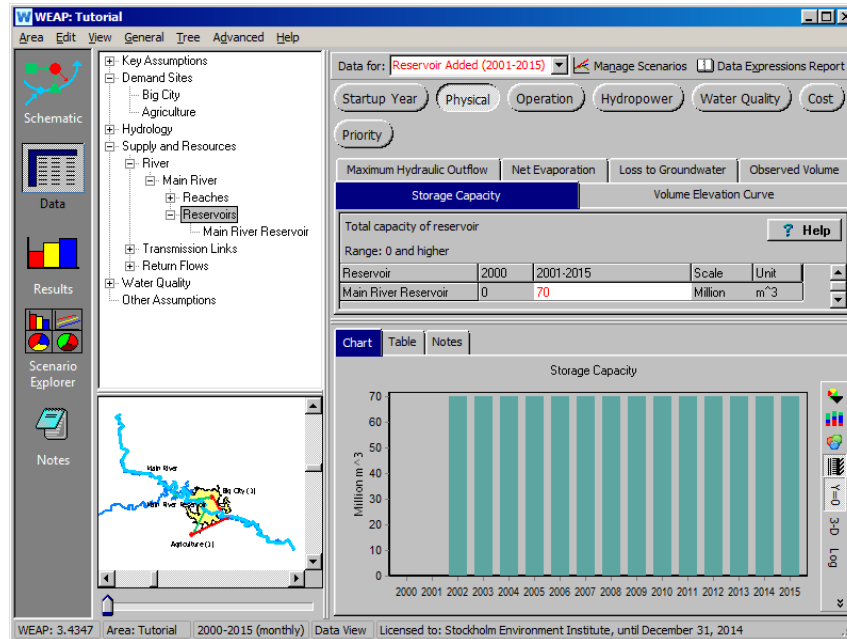
Right click on Main River Reservoir and select “Edit Data.” Select the “Storage Capacity” variable to enter the Data view (Make sure you have the “Reservoir Added” scenario selected). Once you are in the Data view, you will first have to click on the “Startup Year” button before you can alter any other parameters. Note: you may have to click on the data tree before the year will save.

*Choose 2002 as the startup year for Main River Reservoir*



Then click on the “Physical” button and change the following parameters:

*Storage Capacity*                      *70 M m<sup>3</sup>*  
*Note that the Scale is set to “Million”*

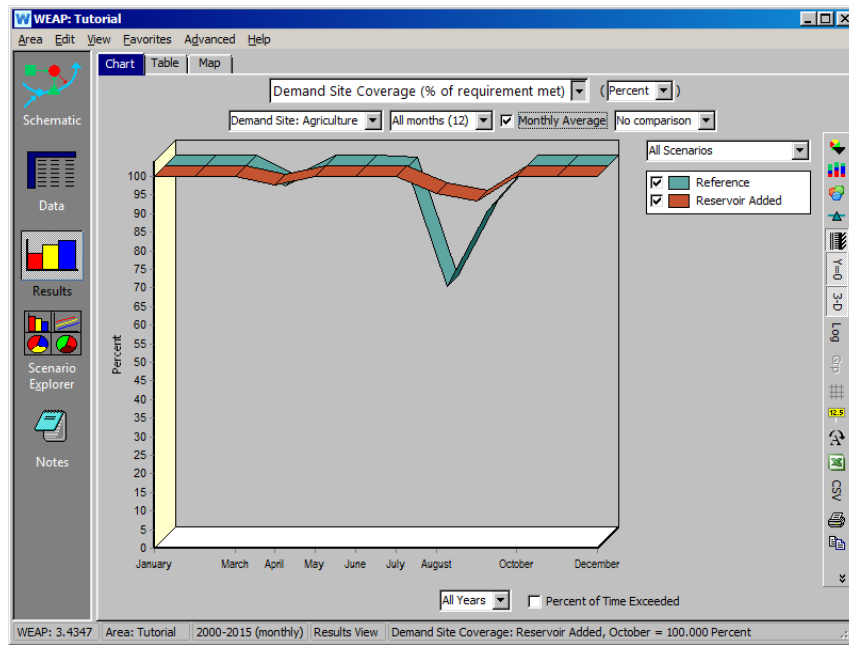


More details about reservoirs operation and hydropower production are provided in the “Reservoirs and Power Production” module of the WEAP tutorial.

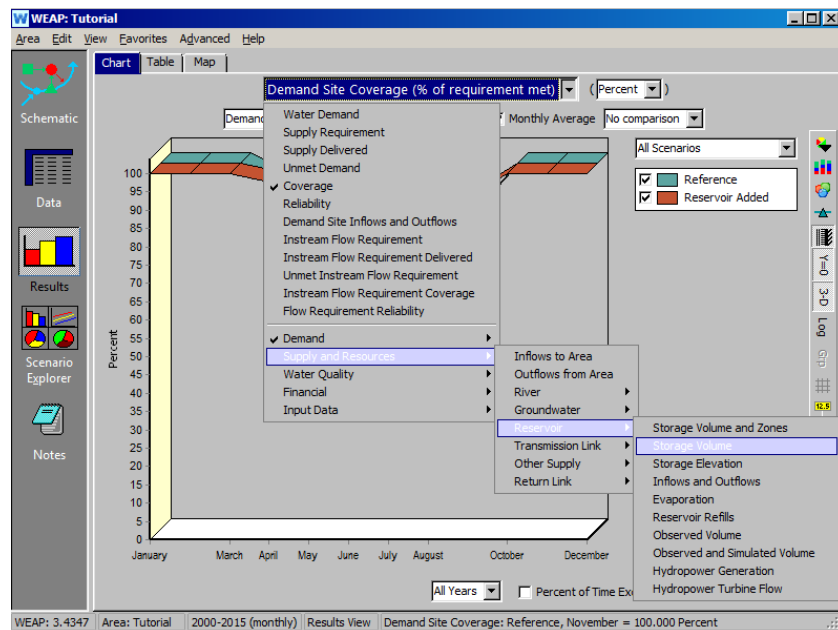
## 5. Run the Model and Evaluate the Results

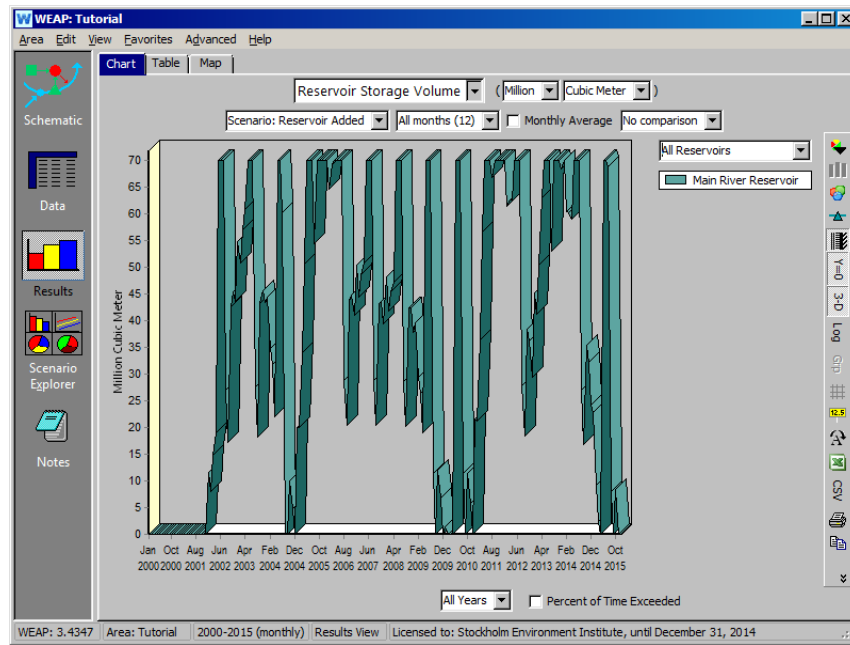
Compare the Demand Site Coverage for Agriculture in the “Reference” and “Reservoir Added” scenarios.

*Demand Coverage: why does Agriculture have higher coverage with the Main River Reservoir in place?*

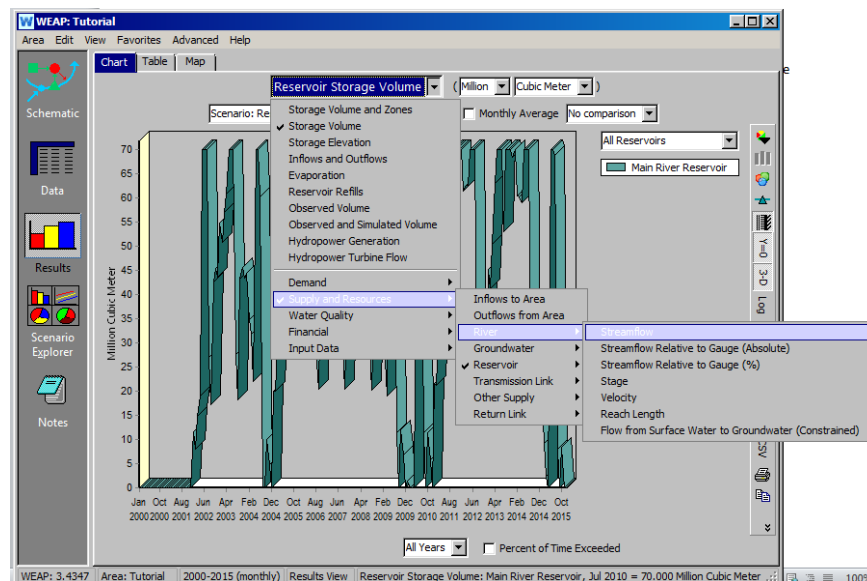


*Reservoir Storage Volume: does the solution of building a reservoir appear to be sustainable? Use the primary variable pull down menu to select Reservoir Storage Volume (under Supply and Resources\Reservoir), and select “All Years” from the pull down menu at the bottom of the graph.*

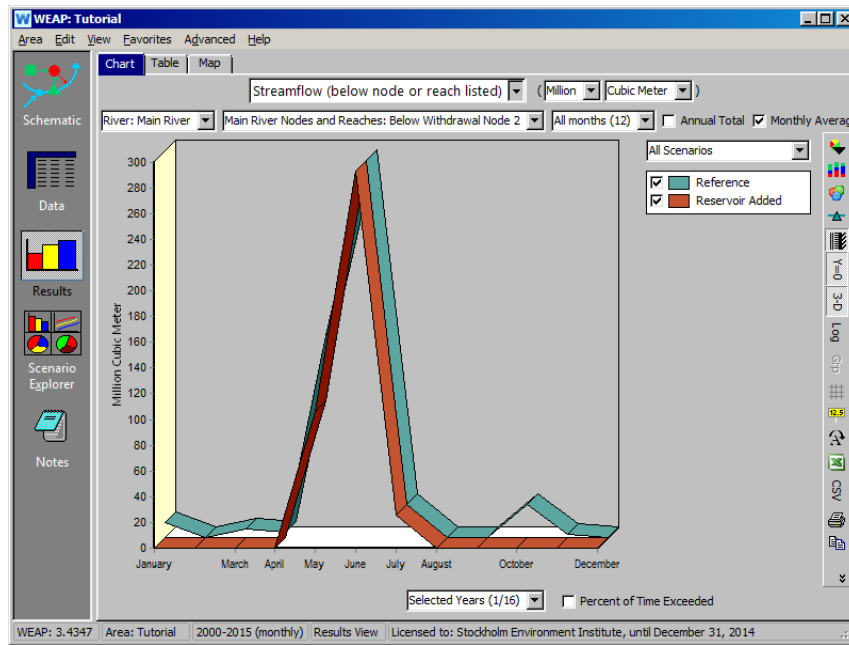




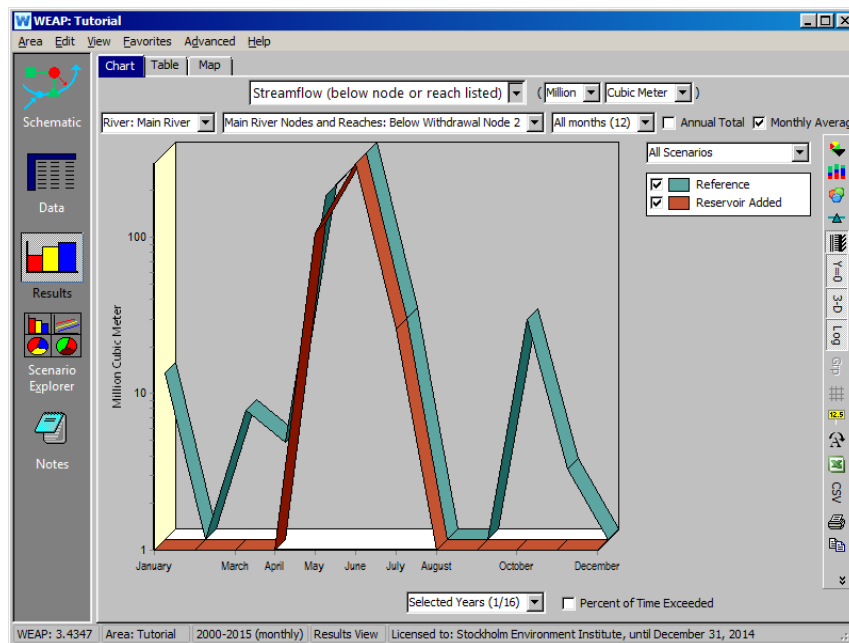
*Flow in the River: how does having the reservoir on the Main River change the flow downstream compared to the Reference scenario? Select Streamflow (under Supply and Resources\River) from the primary variable pull-down menu and click on “Monthly Average.”*



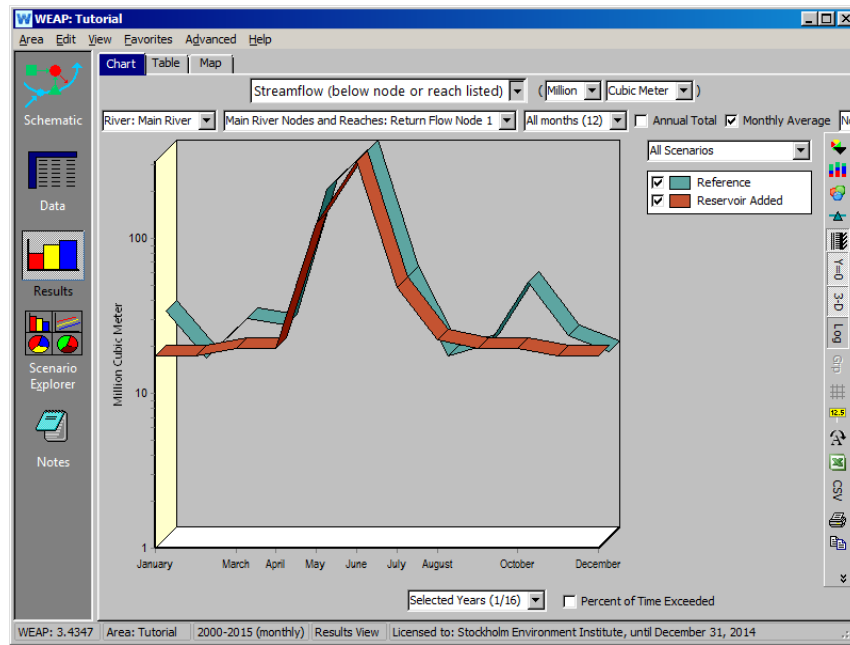
*Choose the year 2002 from the “Selected Years” option on the bottom menu, and choose the reach below Withdrawal Node 2 for comparison.*



You may want to switch to a logarithmic axis (the button is located on the vertical toolbar on the far right) to see more clearly the differences in flow upstream and downstream of the Main River Reservoir.



*Now select the reach below Return Flow Node 1 for comparison. Why is streamflow along this reach more similar for the two scenarios?*



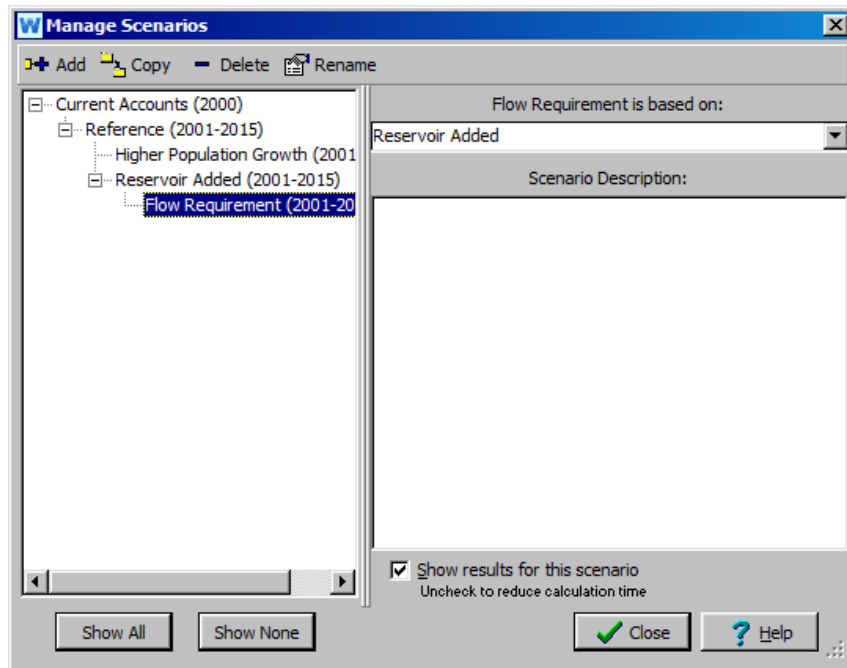
The creation of a large reservoir allows storage of “excess” water during high flow periods to cover water demand during low flow periods. The price to pay is, however, a potentially large impact on the hydrological regime of the river downstream of the reservoir. The Return Flows from Big City and Agriculture provide the flow in the Main River during the spring and winter months. A reservoir’s operation variables and flow requirements can be used to mitigate the reservoir’s downstream impact.

## Adding Flow Requirements

### 6. Create a Flow Requirement

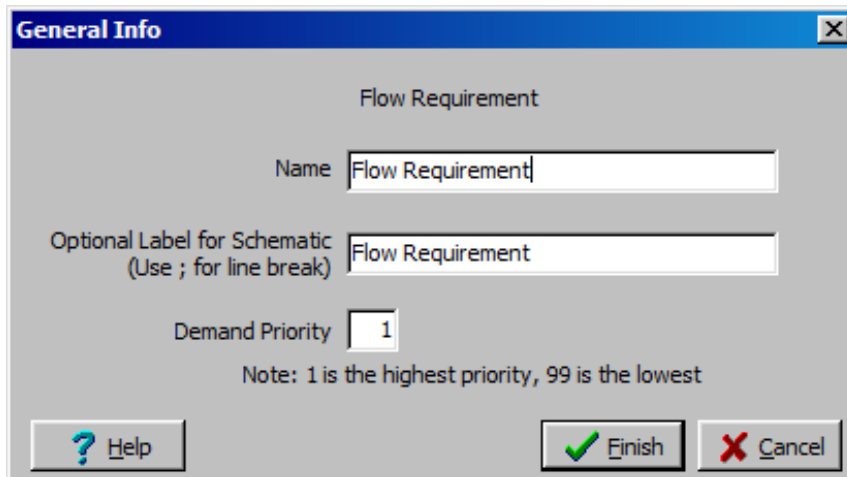
Create another new scenario: “Flow Requirement Added.” This scenario is inherited from the “Reservoir Added” scenario. The scenario tree should look like the one below:





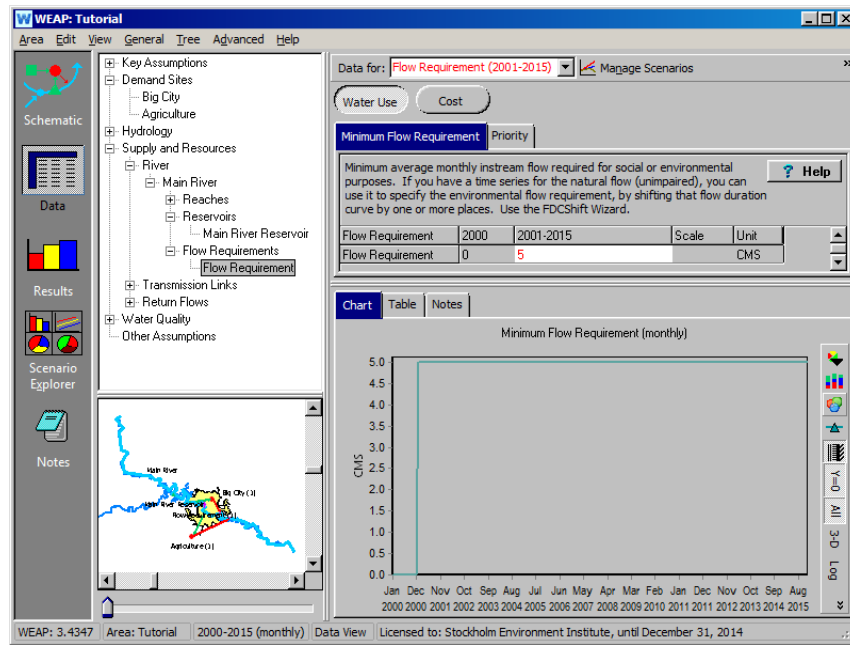
Now add a “Flow Requirement” to the Schematic view below the withdrawal node for the Big City, but upstream of the withdrawal node for Agriculture.

*Demand Priority*                      1 (default)



Right click on the Flow Requirement and select Edit Data\Minimum Flow Requirement. Add the value below (make sure you still have the “Flow Requirement Added” scenario selected):

*Minimum Flow Requirement*    5 CMS

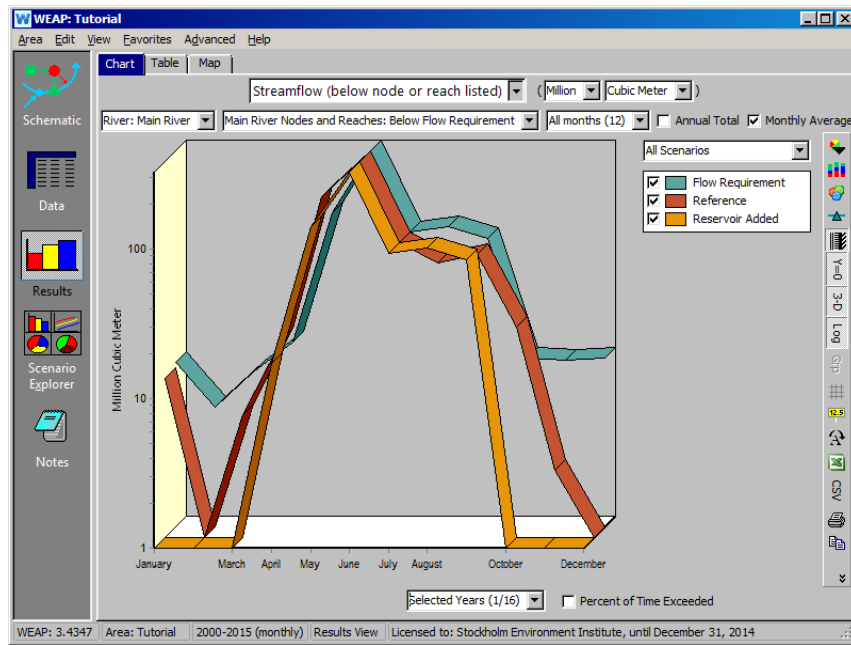


## 7. Run the Model and Evaluate the Results

Look at the results and think about the related questions.

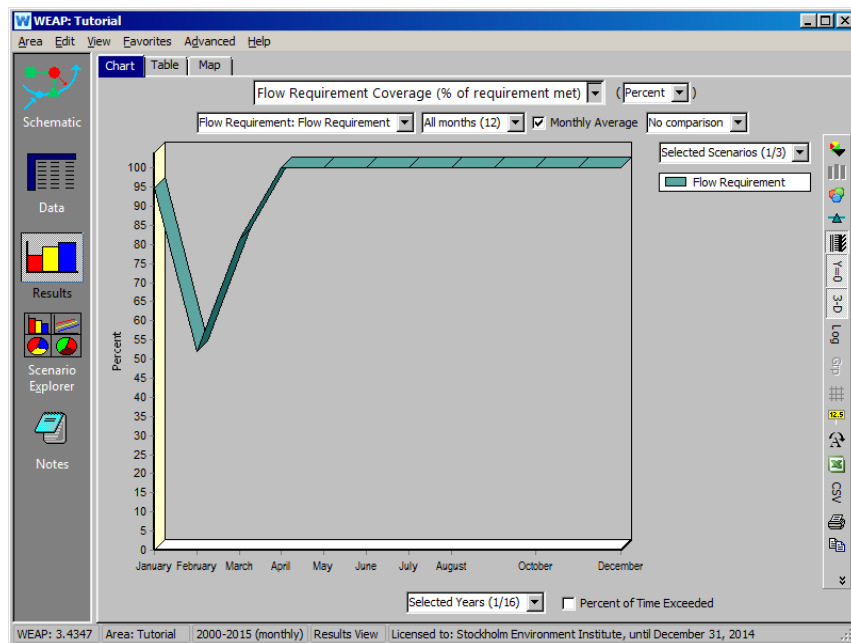
*- How does adding the flow requirement change streamflow in the reach below the flow requirement?*

Compare streamflow below the flow requirement for the “Reference”, “Reservoir Added”, and “Flow Requirement Added” scenarios for the same year (2002). You should obtain a graph like the one below:



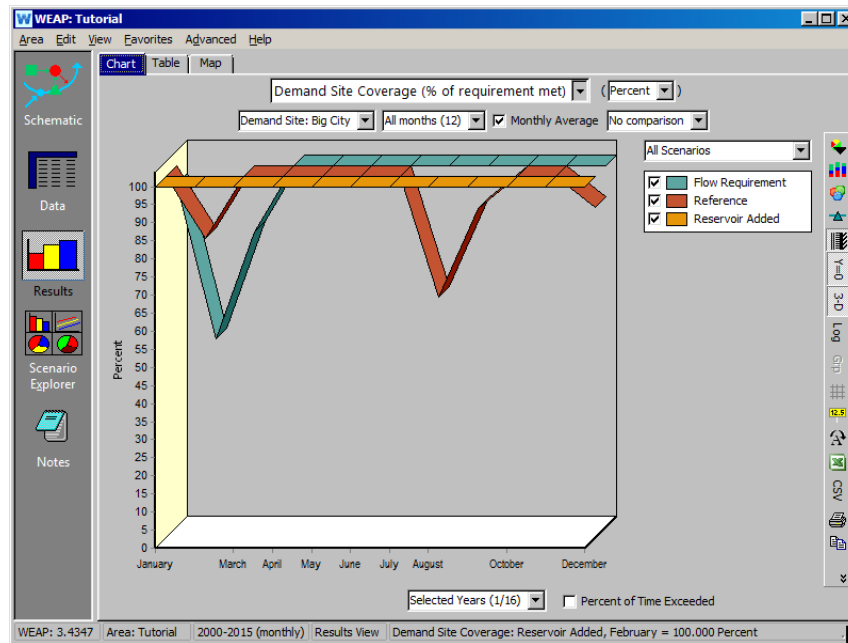
*What is the Flow Requirement coverage?*

You can view these data by selecting “Instream Flow Requirement Coverage” under Demand. (Switch off the logarithmic display for the y axis and select only the “Flow Requirement Added” scenario for viewing).



*Why has the coverage now changed for the Big City?*

Select “Demand Coverage” from the primary variable pull-down menu, select the Big City demand site, and select the “Reference”, “Reservoir Added”, and “Flow Requirement Added” scenarios for viewing.



*Assuming this flow requirement was more important than supplying the Big City, how should the model be changed to ensure that the flow requirement is fulfilled?*

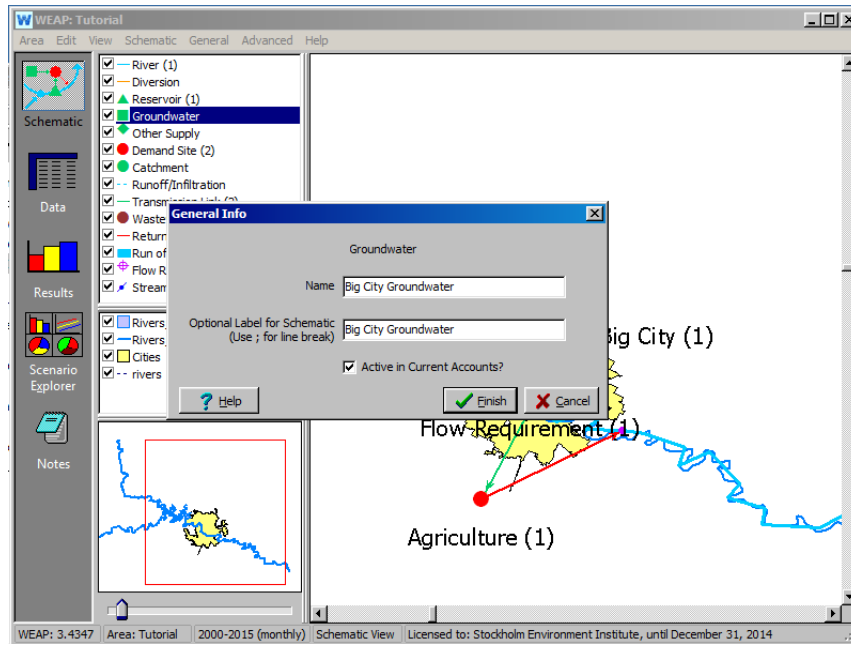


The relative level of Demand Priority for Big City, Agriculture and the Flow Requirement will determine which demand is covered first. To ensure that the Flow Requirement is covered first, change the Demand Priority of Big City to a higher number (lower priority) than for the Flow Requirement, since it is upstream of the Flow Requirement.

## Modeling Groundwater Resources

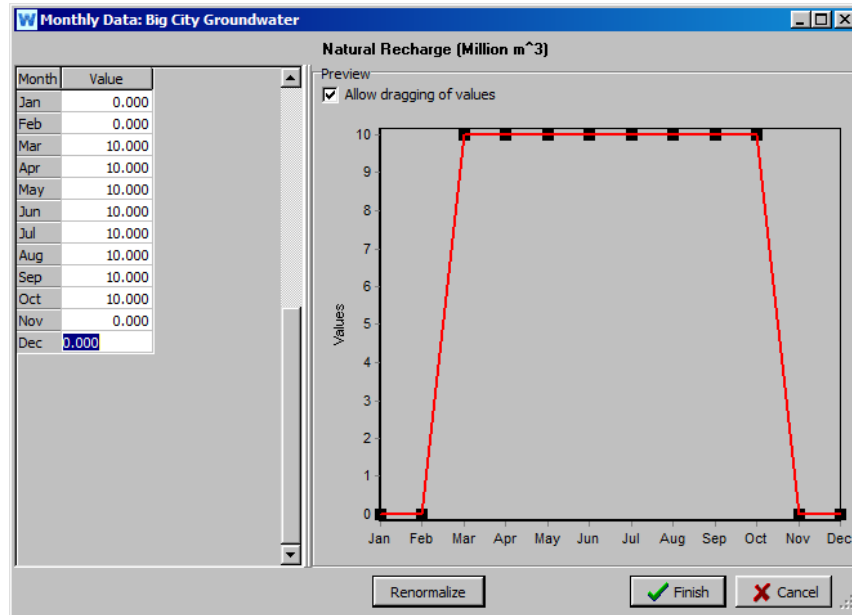
### 8. Create a Groundwater Resource

Create a Groundwater node next to the City and name it “Big City Groundwater.” Also, make it active in Current Accounts.



Give Big City Groundwater the following properties (make sure you are in Current Accounts when entering these data; you will know you are not if there is no tab for Initial Storage):

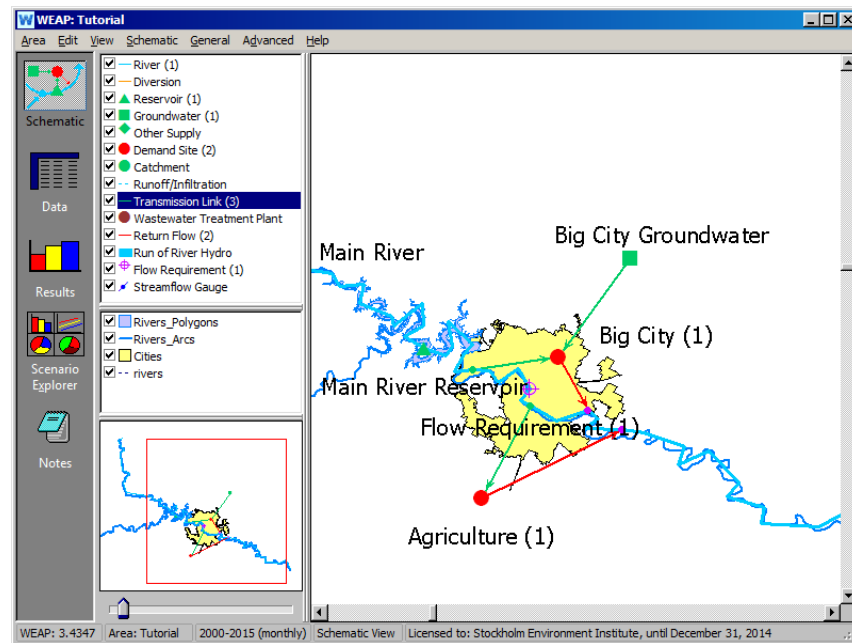
- Storage Capacity* *Unlimited (default, leave empty)*
- Initial Storage* *100M m<sup>3</sup>*
- Natural Recharge (use the Monthly Time Series Wizard, accessed in the field under "2000")*
- Nov. to Feb.* *0M m<sup>3</sup> / month*
- Mar. to Oct.* *10M m<sup>3</sup> / month*



## 9. Connect Big City Groundwater with Big City

Use a Transmission Link to connect Big City Groundwater to the Big City demand site and provide it with a *Supply Preference of 2*.

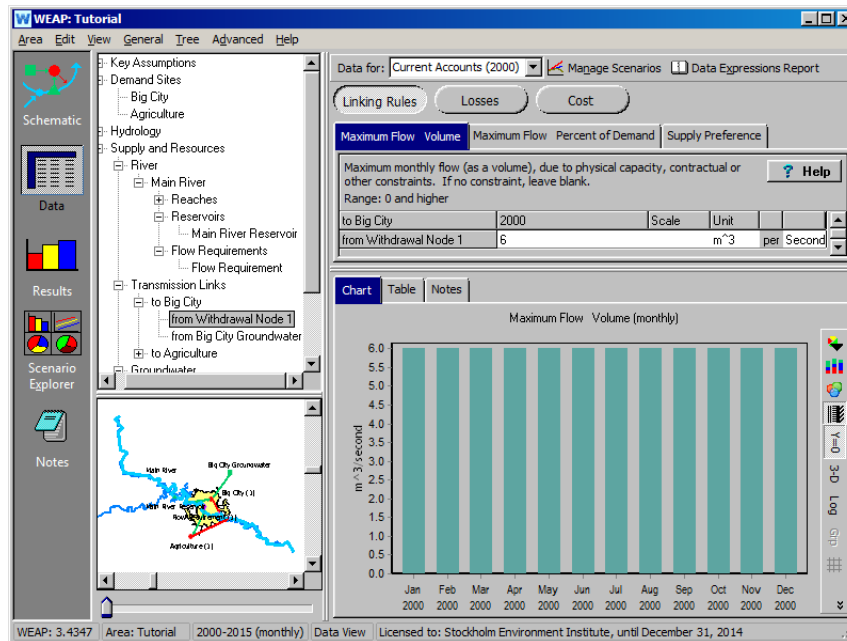
Your model should look similar to the figure below:



## 10. Update the characteristics of the Transmission Link between the Main River and Big City

Change the characteristics of the Transmission Link connecting the Main River (Withdrawal Node 1) and Big City (make sure you are in Current Accounts):

*Supply Preference*                      1 (default)  
*Maximum Flow Volume*              6 m<sup>3</sup>/sec



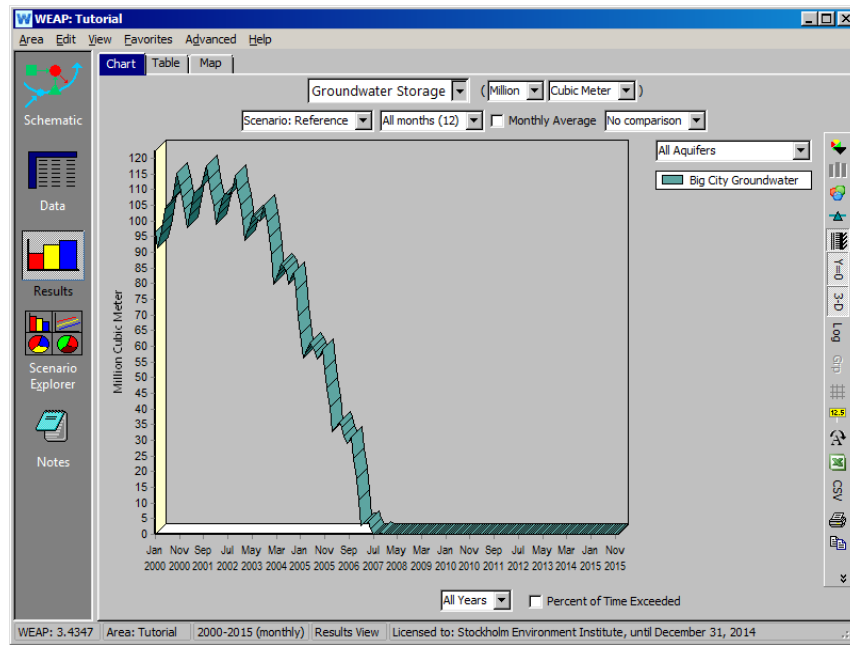
The Maximum Flow Volume or Percent of Demand parameter represents restrictions in the capacity of a resource (due, for example to equipment limits).

## 11. Run the Model and Evaluate the Results

Look at the following results and think about the related questions.

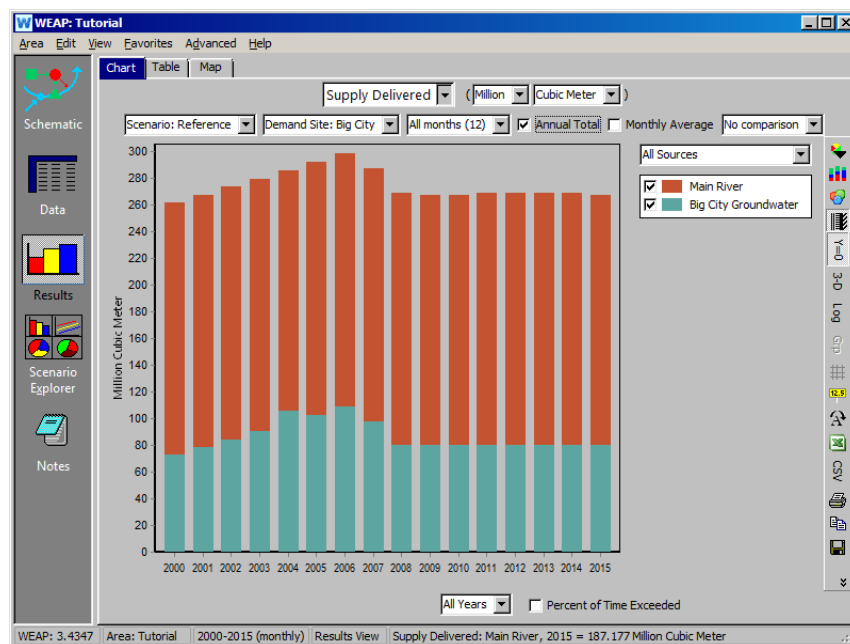
*Is the groundwater extraction required to meet demands under these conditions sustainable?*

To view these results, select “Groundwater Storage” from the pull-down menu under “Supply and Resources\Groundwater.”



*How does the relative use of water from Big City Groundwater and the Main River evolve at the Big City demand site?*

To view these graphical results for Big City specifically, first select “Supply Delivered” under Demand using the primary variable pull-down menu. Then choose “All Sources” in the pull-down menu on the right side of the window above the graph legend. Next, select Big City as the demand site to view using the pull-down menu above the graph. Click on “Annual Total.”







Groundwater recharge and interaction with rainfall and surface water can be modeled rather than entered as inputs. Refer to the “Hydrological Modeling” tutorial for more details.

Other resources can be modeled using the “Other Supply” object, which is characterized by a monthly “production” curve. This object can be used to simulate a desalination plant or inter-basin transfers, for example.

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# WEAP

Water Evaluation And Planning System

# Data, Results and Formatting

***A TUTORIAL ON***

*Exchanging Data* ..... 116

*Importing Time Series* ..... 119

*Working with Results* ..... 123

**October 2023**

**Note:**

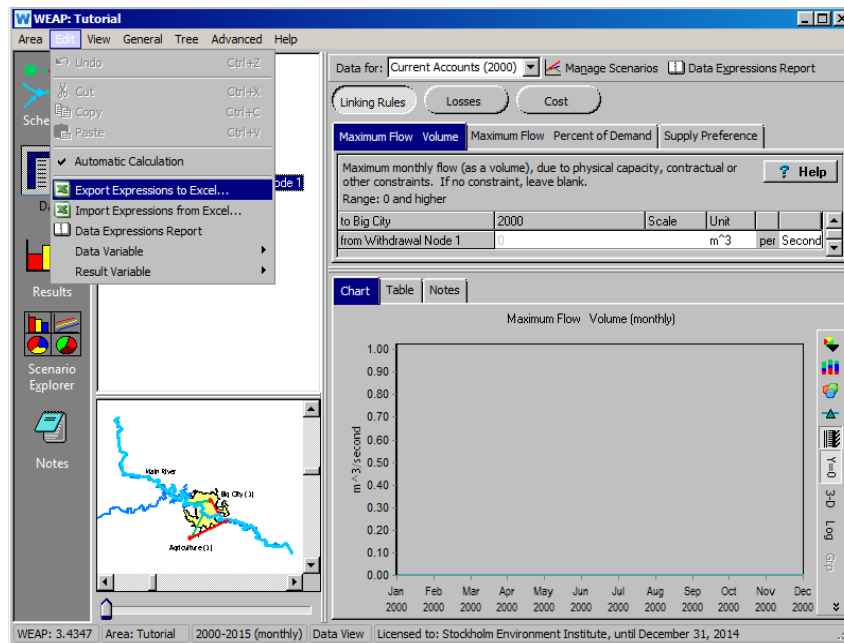
For this module you will need to have completed the previous modules (“WEAP in One Hour, Basic Tools, and Scenarios) or have a fair knowledge of WEAP (data structure, Key Assumptions, Expression Builder, creating scenarios). To begin this module, go to the Main Menu, select “Revert to Version” and choose the version named “Starting point for all modules after ‘Scenarios’ module.”

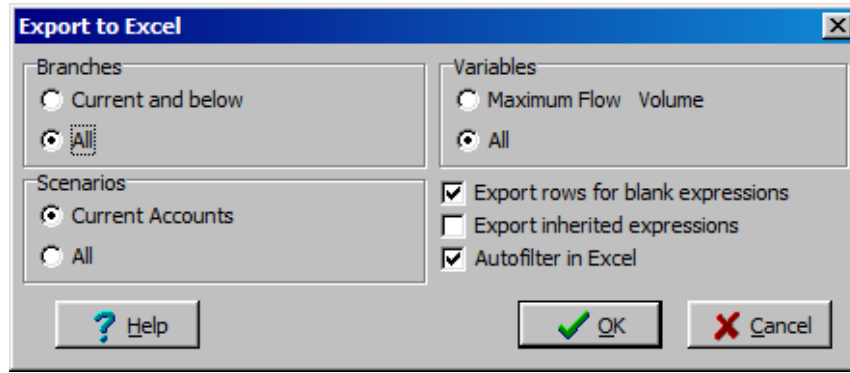
## Exchanging Data

### 1. Export Data to Excel

Export the entire model to Excel by going to the Data view and selecting “Edit”, “Export Expressions to Excel.”

*Export all branches, and all variables of the “Current Accounts” only (don’t export any of the scenarios for this example) to a new workbook. Keep other options at default values.*



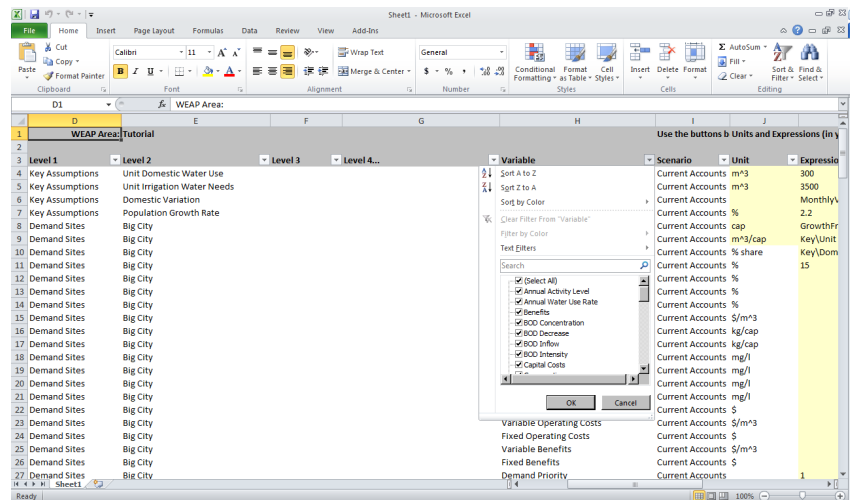


This instruction creates a new Excel workbook that contains all the variables that can be changed in the “Data” view, using the same structure as in the Data tree. In large models, you can choose to export only the current branch and/or variable.

## 2. Use Excel’s Auto Filtering Option

In the Excel Spreadsheet that was created in the previous steps, filter the content to display only the “Consumption” variable. You will probably have to scroll over to the right to see the column in the view.

*Use the arrow to the right of the “variable” header to unselect “select all” and the scroll down to select the “Consumption” variable in the drop-down list.*

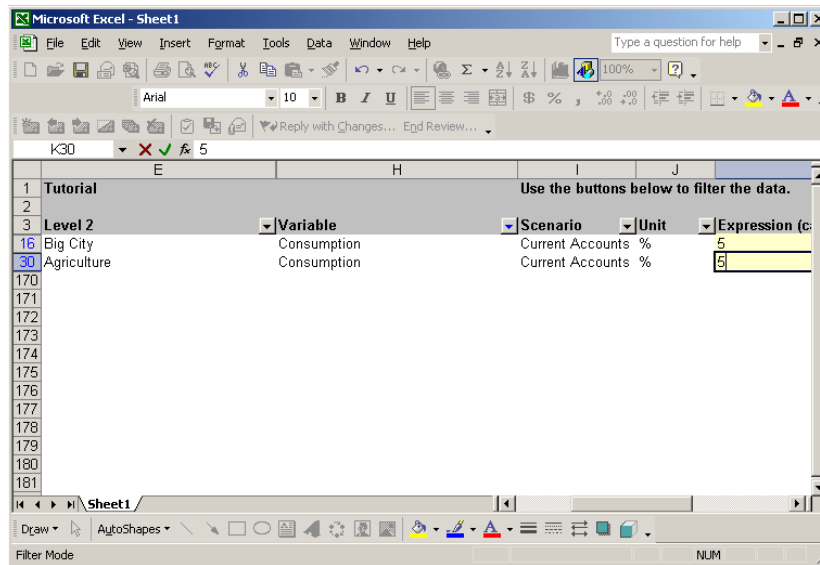


Auto-filtering does not change or erase the data; it only hides the rows that are not of interest. Multiple filters can be used.

### 3. Modify Data

In the Excel spreadsheet that was created in the previous steps, make the following changes in the yellow column (it may be good to hide a few of the columns so that you can see both the variable values and the Demand Sites to which they belong in the same view):

*Big City Consumption*            5% (value was 15 originally)  
*Agriculture Consumption*       5% (value was 90 originally)




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The values entered are not meant to be representative of realistic values, just examples.



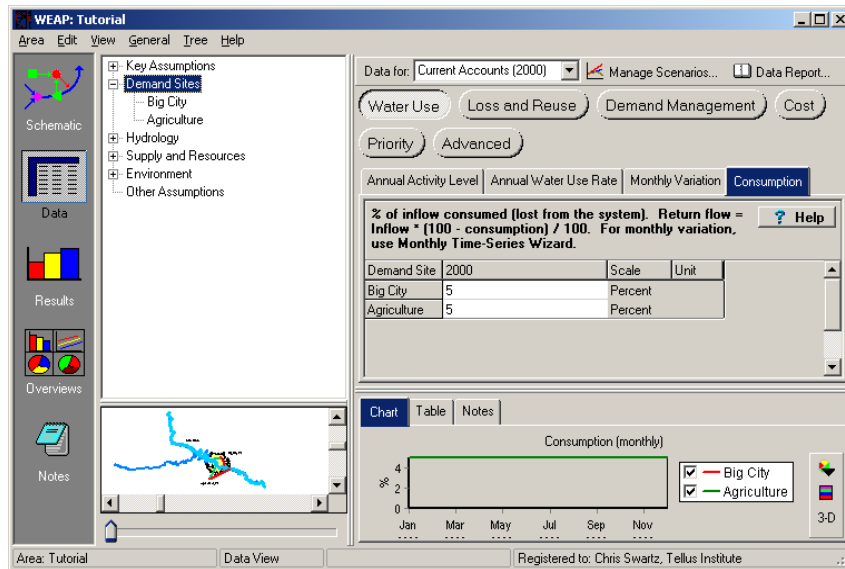
When creating a large model, a quick way to enter a lot of data is to use the Excel Import and Export functions combined with the Excel lookup capabilities. This requires the user to have set up the model in a consistent way (data structure, names), however.

---

### 4. Import the Data from Excel

Re-import the modified data in Excel.

*In WEAP, choose “Edit”, “Import Expressions from Excel...” Check that the Consumption data have been changed in your model.*



WEAP always reads from the Excel file that had the focus last. If you have several Excel files open, you should ensure that the appropriate Excel file is selected before beginning the importation into WEAP.

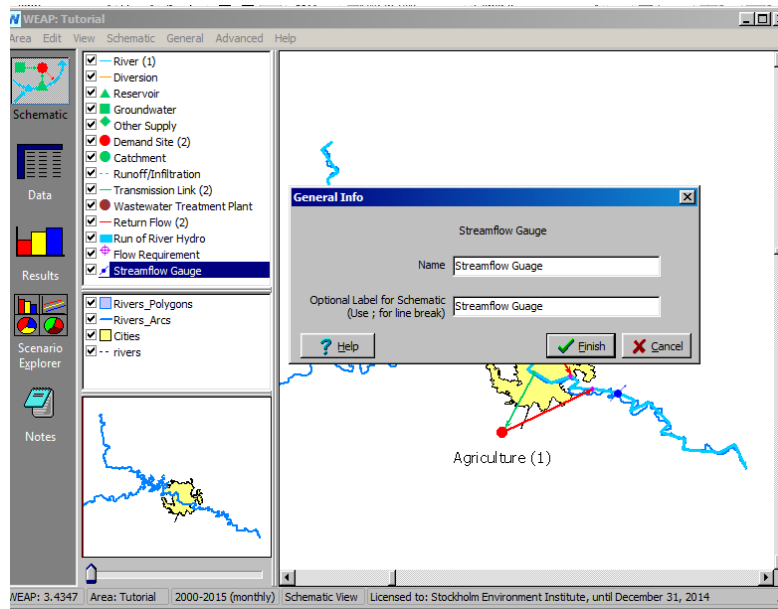
When re-importing into Excel, all rows are read, even those that are filtered out through the auto-filtering options.

## Importing Time Series

### 5. Create a Streamflow Gauge Object

Add a “Streamflow Gauge” object to the model.

*Insert the Streamflow Gauge downstream of the Big City, below the return flow nodes for Agriculture and Big City.*



## 6. Import Text File Data

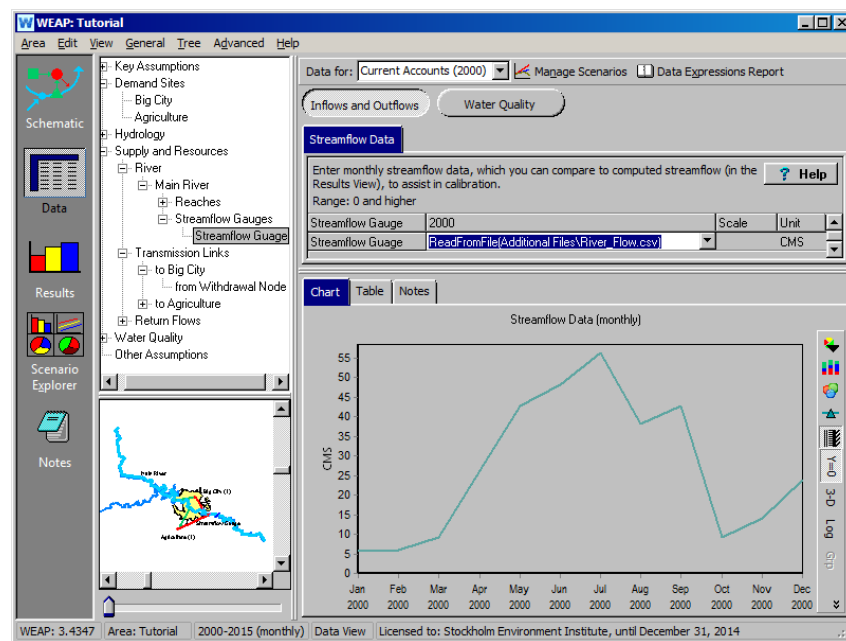
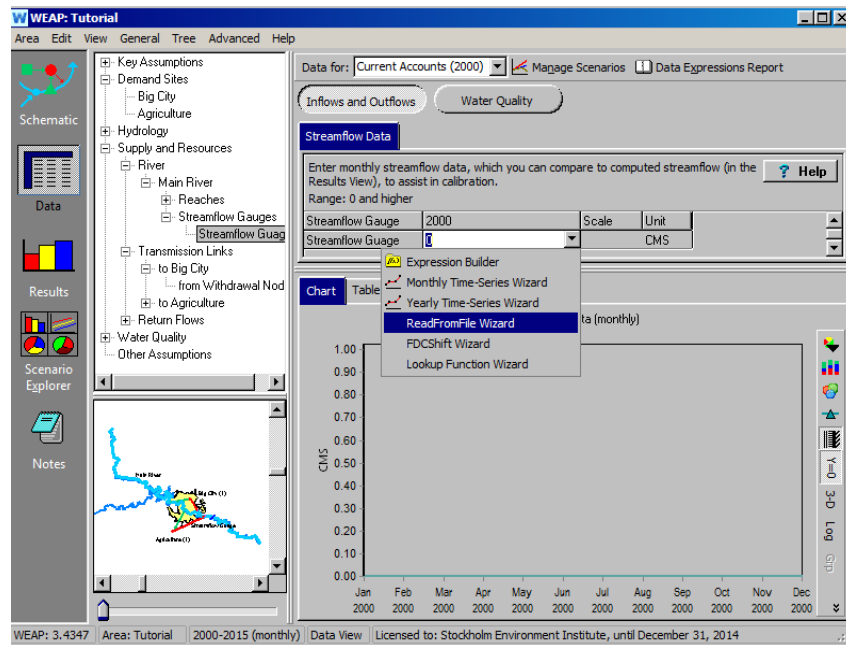
Import streamflow data from a comma-separated text file containing approximately 100 years of streamflow measurements up to 2003. To import the file, use the “ReadFromFile” function in the streamflow gauge’s data tab in the “Supply and Resources\River\Streamflow Gauges” branch of the Data tree.

*Type in the following function, which will read the file from a directory called “Additional Files” located in your area’s folder:*

*“ReadFromFile(Additional Files\River\_Flow.csv)”*

If WEAP cannot find the file, try searching for it using the “ReadFromFile Wizard” in the dropdown menu.





The ReadFromFile function can be used for any variable that requires a time series, monthly or yearly, such as headflow, groundwater recharge, etc.



WEAP will automatically locate the correct year and month and only use that data. If you change the years modeled, WEAP will automatically read the correct data.

More information about the syntax of this function and the format of the data file can be found in the “Read from File” help topic.

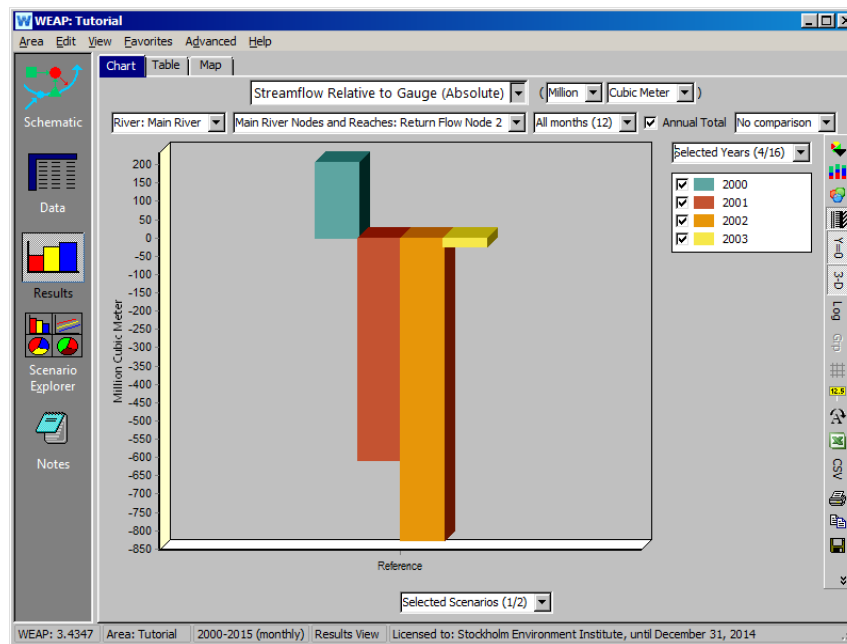
## 7. Compare the Actual and Modeled Streamflow

Recalculate the results and compare the historical streamflow data with the WEAP simulated streamflow. Do this by clicking on the “Chart” tab of the Results view and selecting from the primary variable pull-down menu: Supply and Resources\River\Streamflow Relative to Gauge (Absolute).



WEAP will compare the observed flow at the streamflow gauge to the nearest upstream node. In the case for this example, that node is Return Flow 2 (the Return Flow for Agriculture). Comparing observed and simulated streamflow is one means for the user to assess if the model is representing the system accurately.

Choose “Selected Years” from the pull-down menu below the chart and select 2000, 2001, 2002, and 2003 (the Current Accounts is 2000, and the data file contains no stream gauge data beyond 2003). If the results display both scenarios, change it to the reference scenario only with the pull-down menu to the right of the chart above the legend. To display the years in different colors, use the same pull-down menu above the legend to select “Selected Years.” Choose the Reference scenario. You should see the graph below:



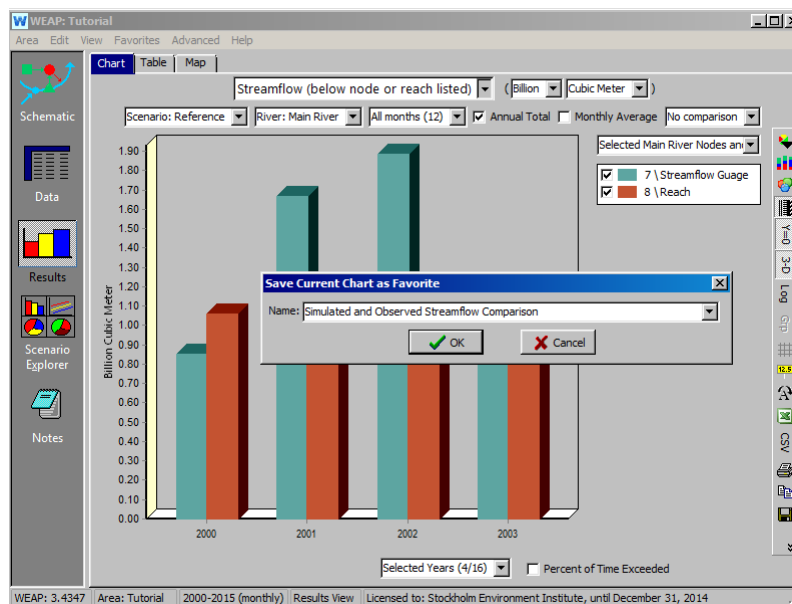
Notice that the simulated streamflow is greater than the observed streamflow in the Current Accounts year (2000) but is less than observed in subsequent years.

# Working with Results

## 8. Create a Favorite Graph

Create a graph of streamflow that shows both the actual flow as recorded at the streamflow gauge and the simulated streamflow at the appropriate node upstream of the streamflow gauge (in this example, below Return Flow Node 2). First, select “Streamflow” from the primary variable pull-down menu. Then select “7 \ Streamflow gauge (gauge)” and “8 \ Reach” from the list that appears when you choose “Selected Main River Nodes and Reaches” from the drop-down menu of the Supply and Resources \ River \ Streamflow chart above the graph legend (see below). Finally, select the years 2000, 2001, 2002, and 2003 to be represented in the graph using the pull-down menu at the bottom of the window.

Save this graph as a favorite by using the “Favorite”, “Save Chart as Favorite” option. Name the file “Simulated and Observed Streamflow Comparison.”



From this point forward, the chart will appear in the list of favorite charts of the Results view.

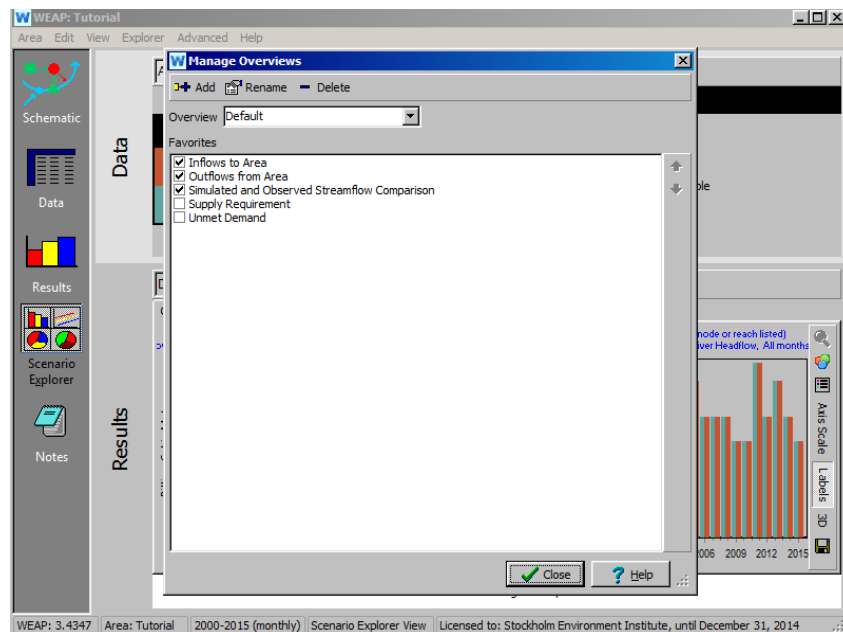


You can also export the data to Excel or to the clipboard, change the format and the display of figures and charts, calculate statistics, group series with the smallest values, etc. from the toolbar located at the right of the “Results” view.

## 9. Create an Overview

An overview displays important charts in the Scenario View like a dashboard. Create an “Overview” displaying the streamflow, inflow, and outflow to area charts.

*Select the “Scenario Explorer” view. Click “Manage.” In the window that appears, select “Inflows to Area”, “Outflows from Area” and the Favorite graph created in the previous step.*

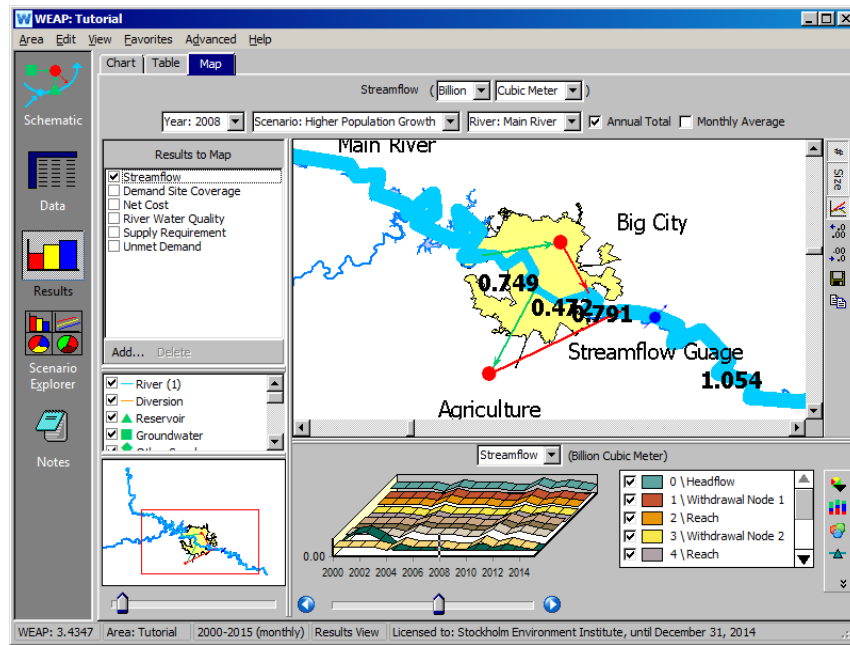


Overviews can be created from any combination of favorites, but the charts need to be created in the “Results” view prior to their integration in an overview. The data underlying overviews can also be displayed in tabular format (select the “Table” tab) and exported to Excel.

## 10. Use the Dynamic Map

Dynamic Results Maps are a quick way to obtain an overview of the results in their temporal context. In the “Results” view, select the “Map” tab and play with the time slider at the bottom of the display to see how the displayed parameters change.


*Try this by selecting the Main River’s streamflow.*



Note that as you pull the slider across the bar, an indicator appears in the graph above the bar to indicate the data selected (for this example, the year 2004 annual total is selected). In the smaller schematic view at the top of the window, the width of the river will increase and decrease with the changing data, and numerical values appear for each of the reaches.

## 11. Export Results to Excel

All results can be readily exported to Excel from the “Results” view. A new workbook is created that contains the results in table format, with the same structure as in WEAP.

*Recall the favorite graph you have created a few steps before by selecting it in the “Favorite” menu of the Results View. Export the related data to Excel by switching to the “Table” tab and hitting the “Export Table to Excel” button (  ) to the right of the screen.*

## 12. Calculate Statistics

You can generate statistics in the Results view for any table. Under “Charts”, display the Reference Scenario Streamflow (annual total) for all reaches of the Main River for all years. Now click on the Table tab and then click on the “Stat” icon on the right vertical menu bar.

Scenario: Reference	River: Main River	All months (12)	Annual Total	Monthly Average	All Main Rive					
		2000	2001	2002	2003	2004	2005	2006	2007	2008
0 \ Headflow		1,084.406	1,084.406	1,084.406	1,084.406	759.083	1,409.725	1,084.406	1,084.406	1,084.406
1 \ Withdrawal Node 1		836.923	832.083	827.143	822.082	531.132	1,121.299	806.410	801.100	795.700
2 \ Reach		836.923	832.083	827.143	822.082	531.132	1,121.299	806.410	801.100	795.700
3 \ Withdrawal Node 2		531.429	529.366	527.218	524.983	291.010	803.437	516.838	513.337	509.770
4 \ Reach		531.429	529.366	527.218	524.983	291.010	803.437	516.838	513.337	509.770
5 \ Return Flow Node 1		766.538	769.073	771.618	774.191	507.563	1,077.441	780.935	782.477	784.040
6 \ Reach		766.538	769.073	771.618	774.191	507.563	1,077.441	780.935	782.477	784.040
7 \ Return Flow Node 2		1,056.757	1,056.654	1,056.547	1,056.435	735.679	1,379.411	1,056.028	1,055.853	1,055.670
7 \ Streamflow gauge		850.070	1,665.330	1,884.132	1,079.598	0.000	0.000	0.000	0.000	0.000
8 \ Reach		1,056.757	1,056.654	1,056.547	1,056.435	735.679	1,379.411	1,056.028	1,055.853	1,055.670

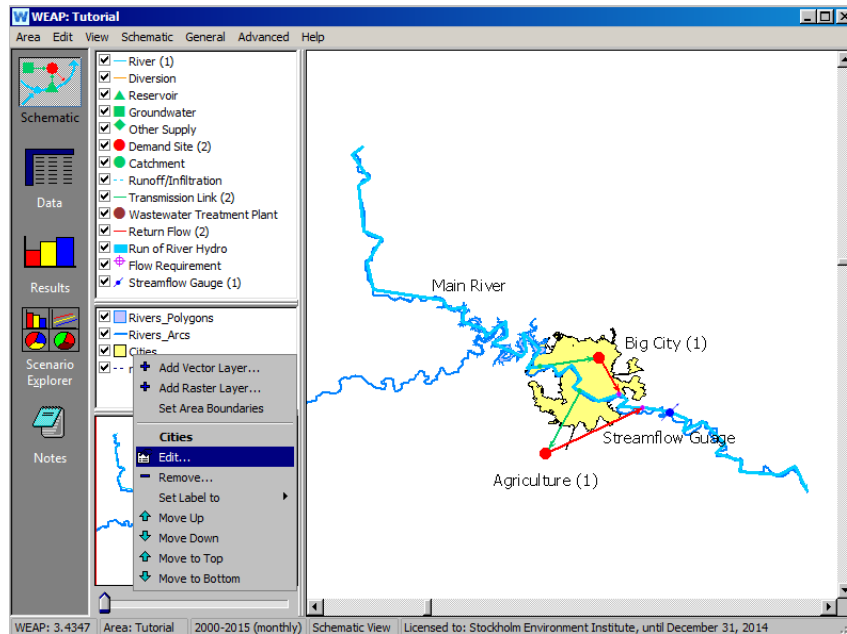
We are provided with statistical values of Min, Max, Mean, Standard Deviation (SD) and Root Mean Square (RMS).

Scenario: Reference	River: Main River	All months (12)	Annual Total	Monthly Average	All Main Rive									
		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
0 \ Headflow		1.084	1.084	1.084	1.084	0.759	1.410	1.084	1.084	1.084	0.868	0.868	1.572	1.084
1 \ Withdrawal Node 1		0.837	0.832	0.827	0.822	0.531	1.121	0.806	0.801	0.796	0.602	0.598	1.241	0.775
2 \ Reach		0.837	0.832	0.827	0.822	0.531	1.121	0.806	0.801	0.796	0.602	0.598	1.241	0.775
3 \ Withdrawal Node 2		0.531	0.529	0.527	0.525	0.291	0.803	0.517	0.513	0.510	0.349	0.346	0.925	0.496
4 \ Reach		0.531	0.529	0.527	0.525	0.291	0.803	0.517	0.513	0.510	0.349	0.346	0.925	0.496
5 \ Return Flow Node 1		0.767	0.769	0.772	0.774	0.508	1.077	0.781	0.782	0.784	0.601	0.602	1.239	0.789
6 \ Reach		0.767	0.769	0.772	0.774	0.508	1.077	0.781	0.782	0.784	0.601	0.602	1.239	0.789
7 \ Return Flow Node 2		1.057	1.057	1.057	1.056	0.736	1.379	1.056	1.056	1.056	0.842	0.841	1.540	1.055
7 \ Streamflow Gauge		0.850	1.665	1.884	1.080	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8 \ Reach		1.057	1.057	1.057	1.056	0.736	1.379	1.056	1.056	1.056	0.842	0.841	1.540	1.055
<b>Min</b>		0.531	0.529	0.527	0.525	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
<b>Max</b>		1.084	1.665	1.884	1.084	0.759	1.410	1.084	1.084	1.084	0.868	0.868	1.572	1.084
<b>Mean</b>		0.832	0.912	0.933	0.852	0.489	1.017	0.740	0.739	0.737	0.565	0.564	1.146	0.732
<b>SD</b>		0.198	0.331	0.389	0.215	0.240	0.418	0.330	0.330	0.330	0.271	0.272	0.464	0.332
<b>RMS</b>		0.853	0.965	1.004	0.876	0.539	1.092	0.804	0.803	0.801	0.621	0.620	1.228	0.796

# Formatting

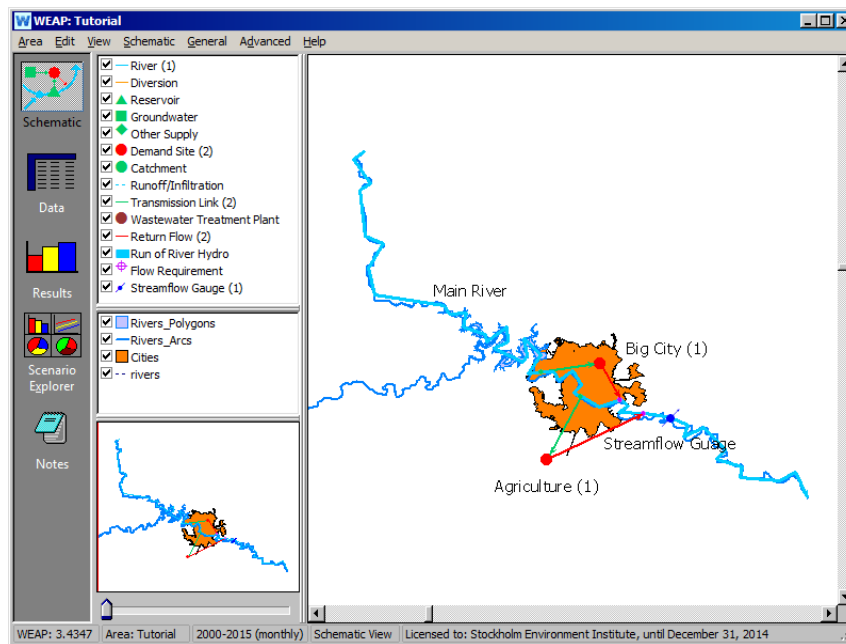
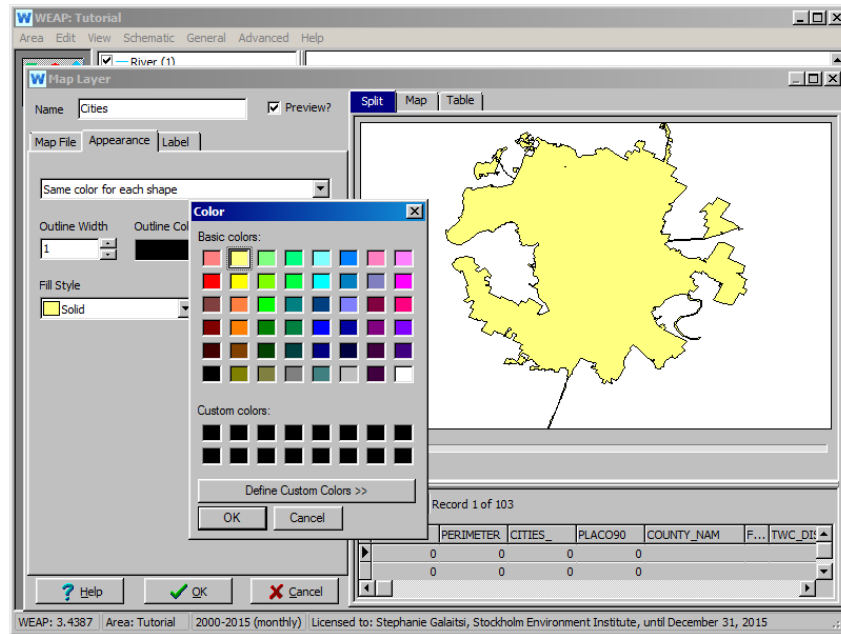
## 13. Change the Appearance of a Background Vector Layer

In the Schematic View, change the color of the polygon for Big City by right-clicking the “Cities” layer in the box below the Element Selection box (see example below), and selecting “Edit.”



In the window that appears, click on the Appearances tab, then click on the “Fill Color” field. A color palette will appear.

*Change the Background color to orange.*



Background vector data can be added by clicking “Add Vector Layer.” WEAP reads vector information in the SHAPEFILE format. This format can be created by most GIS software.

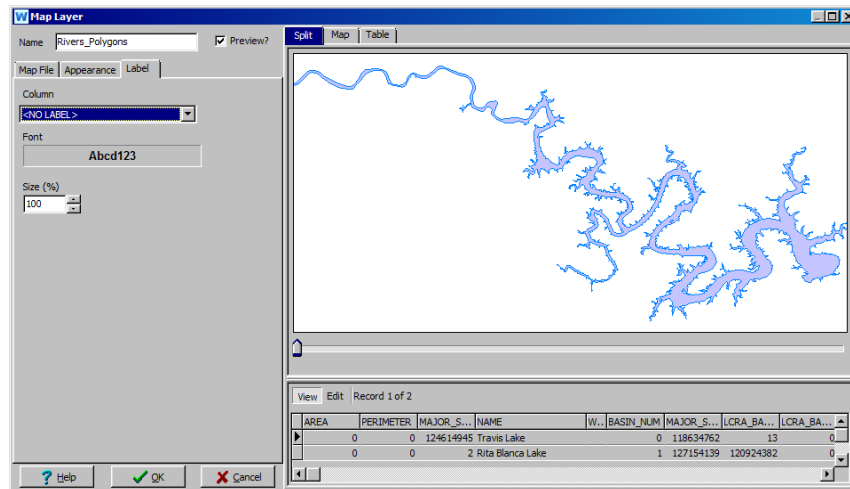


A large amount of georeferenced data (both in vector and raster format) is available on the Internet, sometimes for free; websites such as [www.geographynetwork.com](http://www.geographynetwork.com) or [www.terraserver.com](http://www.terraserver.com) provide good starting points for a search. Keep in mind that some of the downloadable data might need GIS processing before being usable in WEAP, especially to adapt the projection and/or coordinate system.



## 14. Label a Vector Layer

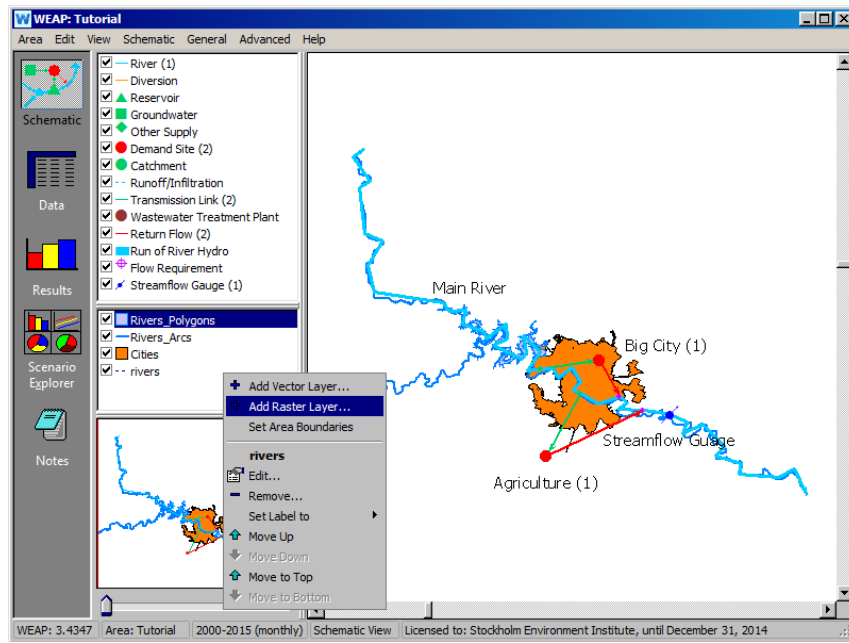
You can edit the labels for the layers - right click on the “Rivers Polygons” layer in the box to the right of the schematic, select “Edit” and choose the “Label” tab. You can also change the size of the labels in this tab by going to the Size field at the bottom of the window.



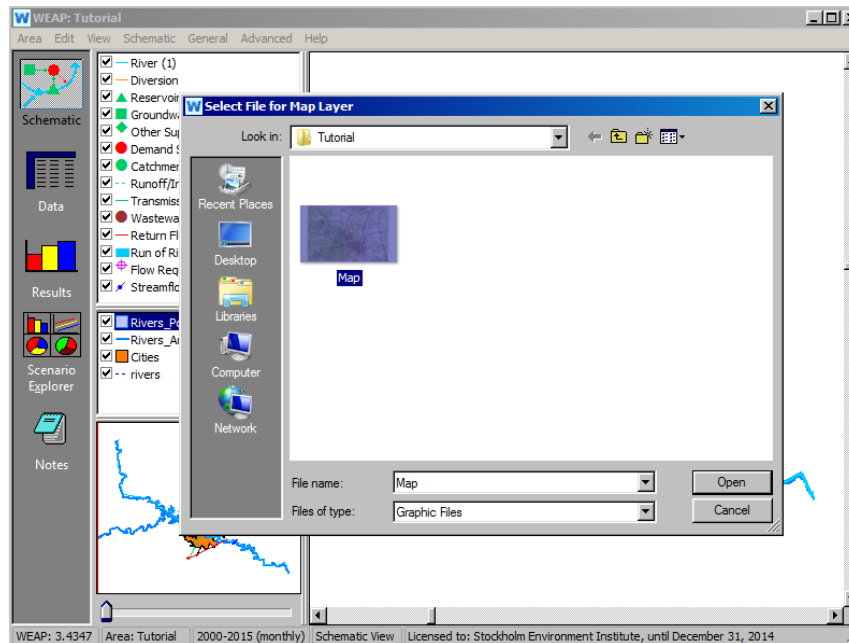
You can also hide layers in the Schematic view by clicking in the small box to the left of the layer name (this makes the check mark disappear also).

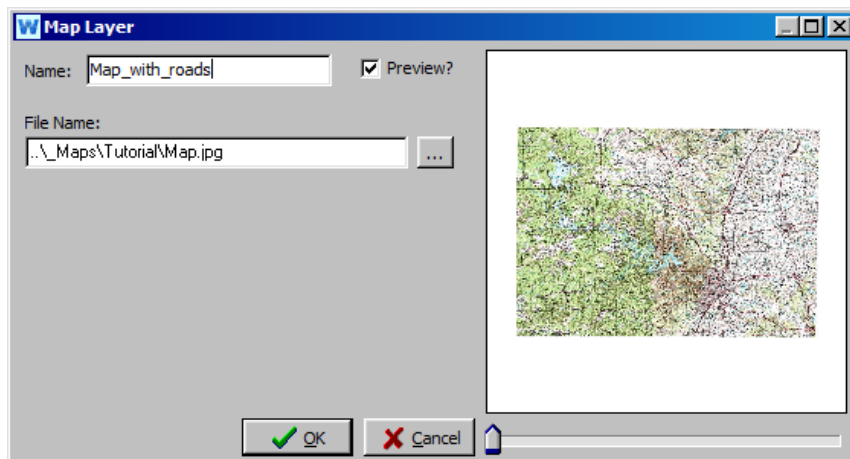
## 15. Add a Raster Layer

In the Schematic view, add a background map of the Big City region by right-clicking in the Layer window (see example below) and selecting “Add Raster Layer.”

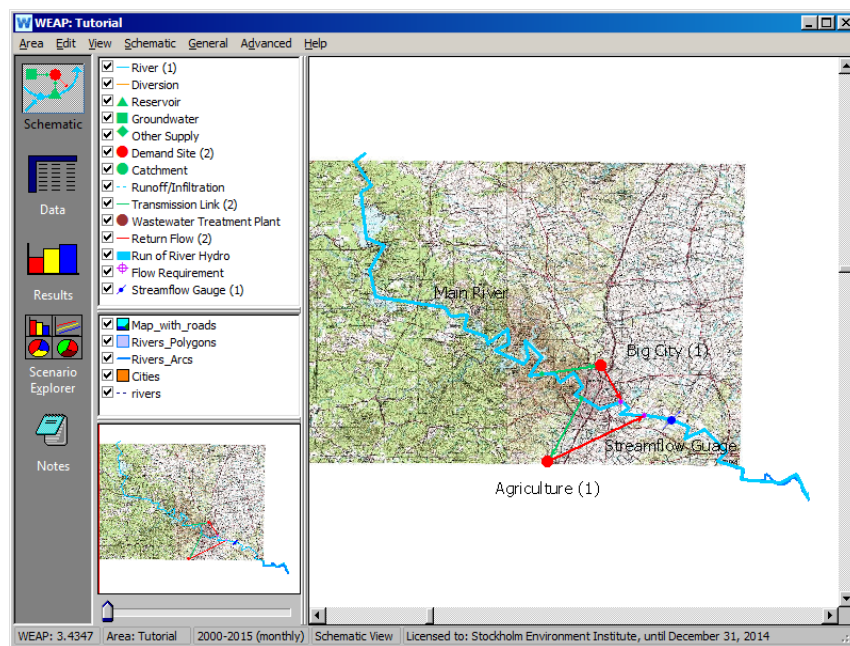


Select the file “Map.jpg” located in the “\_Maps\Tutorial” subdirectory of the WEAP directory (e.g., C:\Program Files\WEAP21\\_Maps\Tutorial). Also enter a descriptive name to appear in the Layer window.

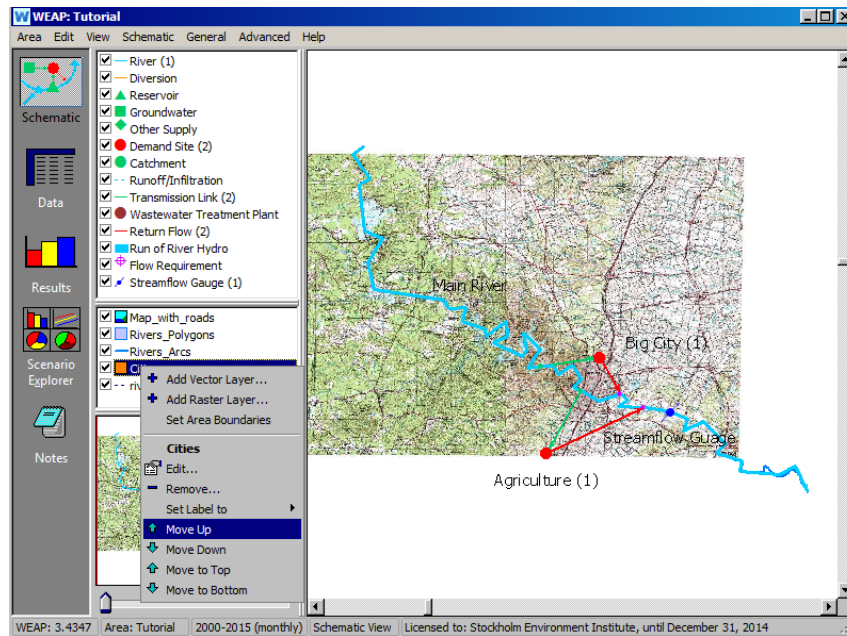




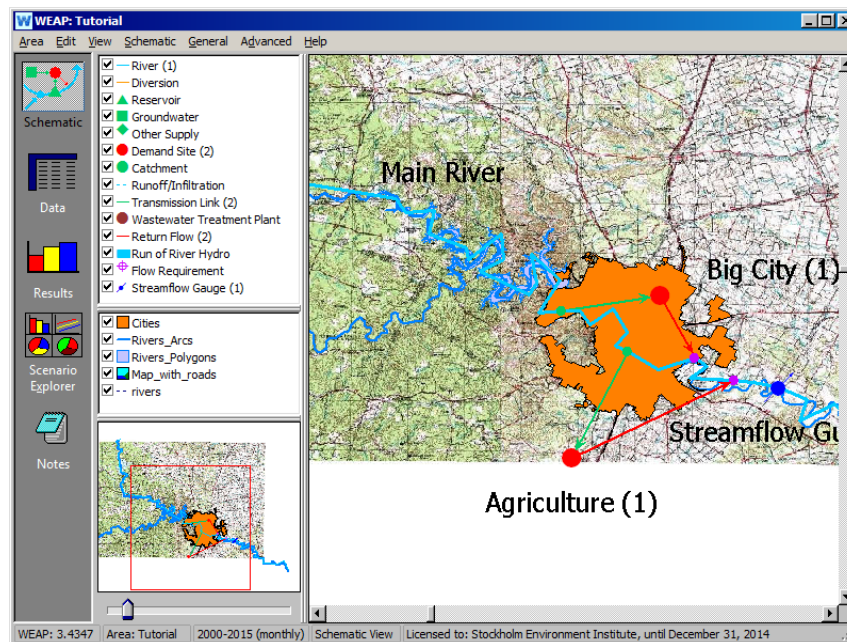
Your map may show up as the first item in the window, placing it on top of the other vectors and shapes.



We want to see the rivers and roads. You can rearrange the schematic layers. Do this by right clicking on a layer and selecting “Move Up” or “Move Down.”



After you have moved your layers, your model should look like so:



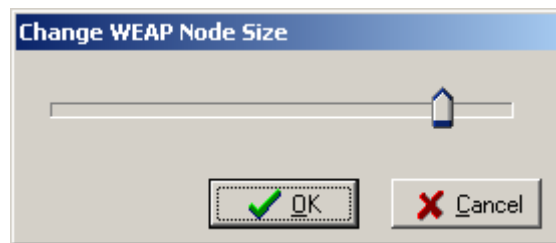
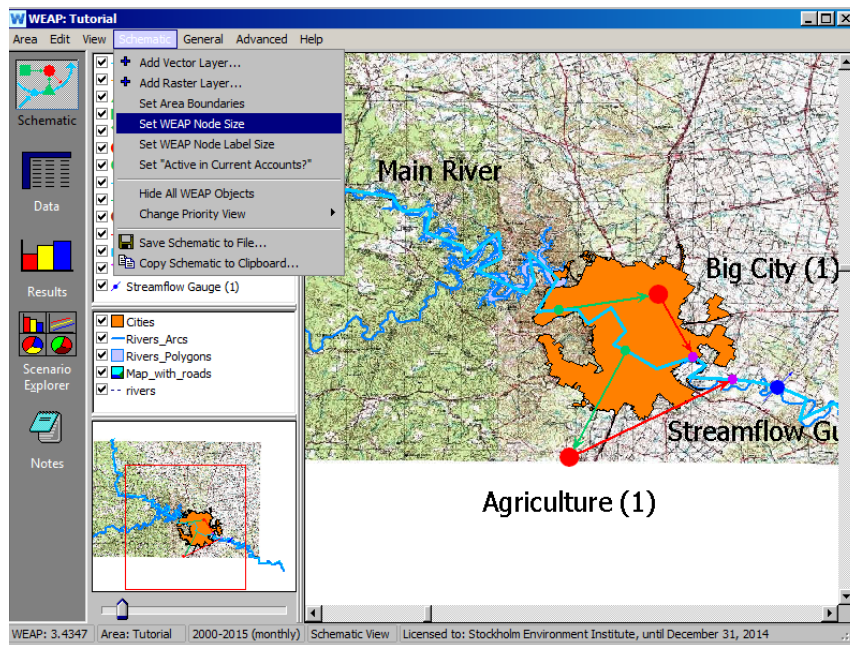
WEAP uses a “world file” to correctly position your raster file for a specific map projection. Those files define the coordinate of one of the corners of the raster and the cell size. They can be created by many standard GIS programs such as ArcView.

The world file must have the same name as the raster file with a “w” added to its extension and be in the same directory. For example, the world file for the above file is called “map.jgw.”

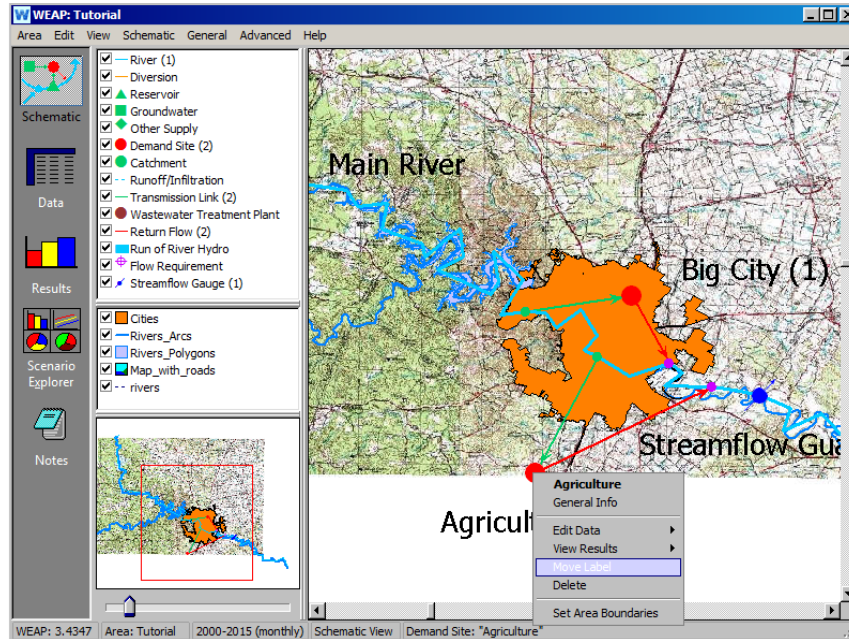
## 16. Move Labels

Complete the formatting of your area by changing the node and label font size and moving around labels.

*Under the Schematic pull-down menu, the “Set WEAP Node Size” and “Set WEAP Node Label Size” menu options can be used to change the size of symbols and labels. For each of these actions, a window with a slider will appear for increasing and decreasing the size of these elements.*



Right-Click on any object and select “Move Label” to move its label.



If you don't want a label to appear for a given object, just right-click that object, select “General Info” and delete the optional label text.



You can copy your map to the clipboard for later use in reports and presentations by selecting “Copy Schematic to Clipboard...” in the “Schematic” menu. The file size indicated in the dialog box corresponds to an uncompressed format. It is usually safe to go with the default level of detail.

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**WEAP**

**Water Evaluation And Planning System**

# **Reservoirs and Power Production**

***A TUTORIAL ON***

*Modeling Reservoir Operation.....136*

*Adding Hydropower Computation.....140*

*Modeling Run-of-River Power Plants.....143*

**October 2023**

**Note:**

For this module you will need to have completed the previous modules (“WEAP in One Hour, Basic Tools, and Scenarios) or have a fair knowledge of WEAP (data structure, Key Assumptions, Expression Builder, creating scenarios). To begin this module, go to the Main Menu, select “Revert to Version” and choose the version named “Starting point for all modules after ‘Scenarios’ module.”

## Modeling Reservoir Operation

### 1. Create a Reservoir

Create a Reservoir on the Lake located upstream of the Big City’s withdrawal from Main River. Name it “Big City Reservoir” and leave it active in Current Accounts.

*Demand Priority*    99 (default)



Entering a Demand Priority of 99 ensures that the reservoir will only fill if all other needs are fulfilled, including downstream demand.

### 2. Enter the Physical Data

Right click on Big City Reservoir to edit data. Enter the following data in the “Physical” window (make sure you are in Current Accounts).

*Storage Capacity*                      70 M m<sup>3</sup>

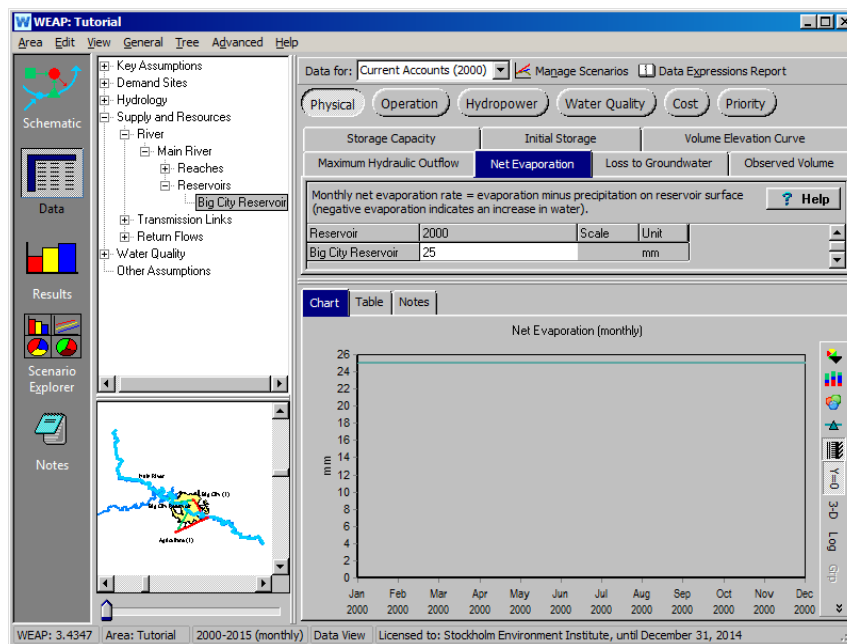
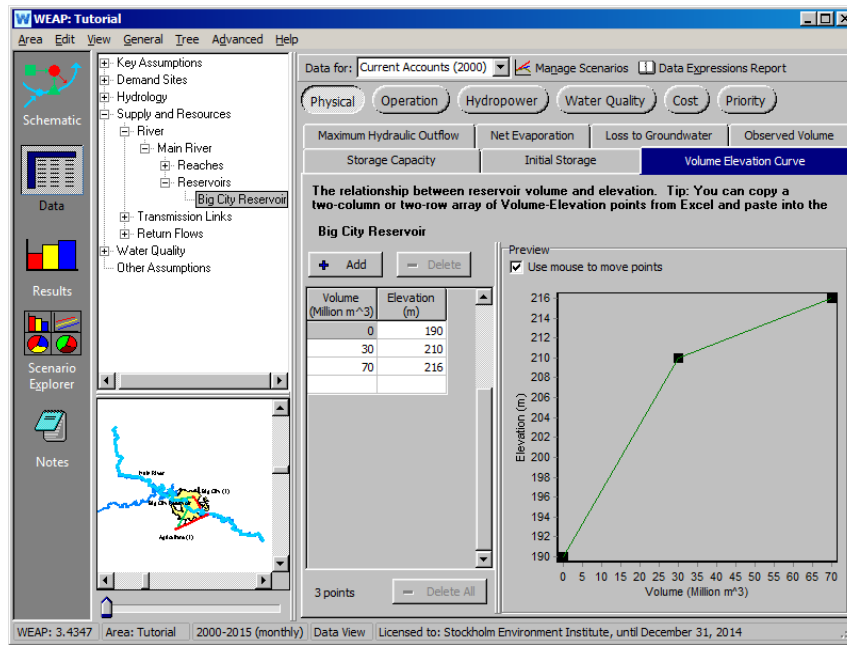
*Initial Storage*                        25 M m<sup>3</sup>

*Volume Elevation Curve*

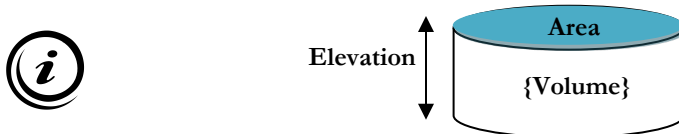
<u>Volume</u>	<u>Elevation</u>
M m <sup>3</sup>	m
0.0	190
30.0	210
70.0	216

*Net Evaporation*    25 mm/month (note that it defaults to monthly measurements)





The “Volume Elevation Curve” is used both to model the surface for evaporation and to compute the head in case hydropower production is simulated. A cylindrical shape is assumed in converting reservoir volume and elevation into reservoir area.

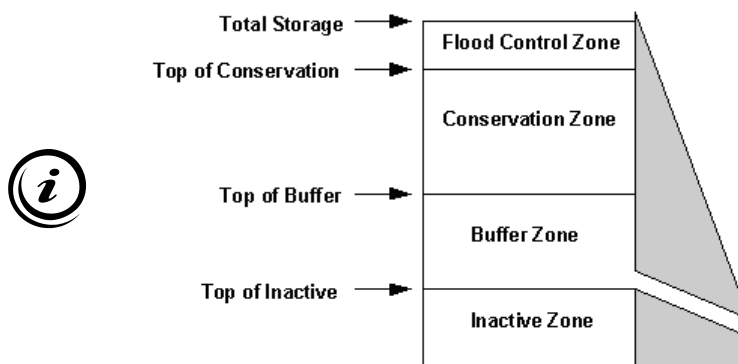
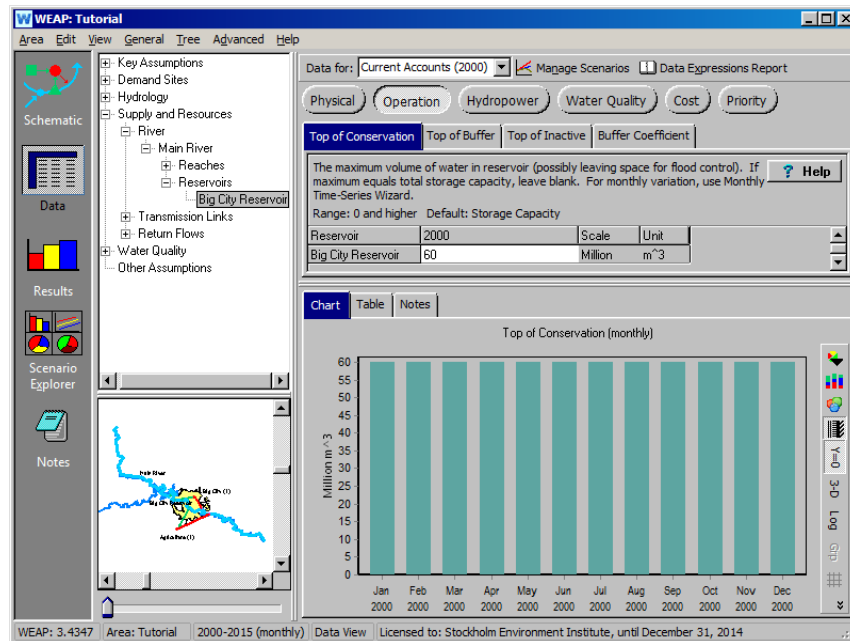


Net evaporation needs to account for both rainfall and evaporation. It can therefore be a positive or a negative number; monthly variations can be modeled using the “Monthly Time Series Wizard.”

### 3. Enter the Operation Data

In the same view, enter the following data in the “Operation” window.

<i>Top of Conservation</i>	<i>60 M m<sup>3</sup></i>
<i>Top of Buffer</i>	<i>40 M m<sup>3</sup></i>
<i>Top of Inactive</i>	<i>5 M m<sup>3</sup></i>
<i>Buffer Coefficient</i>	<i>1.0</i>



As illustrated by the figure to the left, WEAP allows the modeling of advanced reservoir operation through the definition of several zones that have different operational constraints.

More can be learned through the Help file’s “Reservoir Zones and Operation” screen or by clicking on the help button when in the Reservoir’s Operation tab.

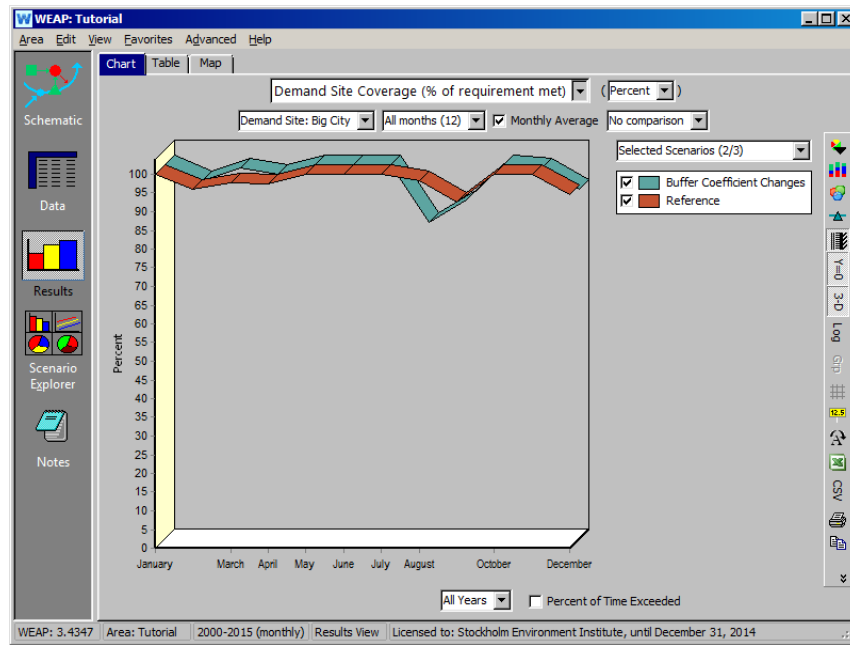
### 4. Understanding the Impact of the Buffer Coefficient

Now create a new scenario inherited from the “Reference” scenario. Name this scenario “Buffer Coefficient Changes.” Then go back to the Data view (make sure that you are in the new scenario you just created) and change the buffer coefficient to 0.1. Click on results to run the new model.

Compare, for the “Reference” and “Buffer Coefficient Changes” scenarios, the results for “Reservoir Storage Volume”, found under the “Supply and Resources\Reservoirs” branch of the primary variable pull-down menu. Select “All Years” from the pull-down menu at the bottom of the graph and click on “Monthly Average” at the top of the graph. Choose the “Reference” scenario and “Buffer Coefficient Changes” scenario for viewing from the pull-down menu above the legend. You can choose “Big City Reservoir” from the pull-down menu directly above the graph.



Also compare results also for Demand Coverage (under the Demand branch). Select the “Reference” and “Buffer Coefficient Changes” scenarios from the pull-down menu above the graph legend. Select “Big City” as the demand site for viewing from the remaining pull-down menu directly above the graph.



The Buffer Coefficient provides a way to regulate water releases when the water level in the reservoir is within the buffer zone (see figure in the information box of the previous step). When this occurs, the monthly release cannot exceed the volume of water in the buffer zone multiplied by this coefficient. In other words, the buffer coefficient is the fraction of the water in the buffer zone available each month for release. Thus, a coefficient close to 1.0 will cause demands to be met more fully while rapidly emptying the buffer zone, while a coefficient close to 0 will leave demands unmet while preserving the storage in the buffer zone. This is why lower Demand Site Coverage is observed for results in the “Buffer Coefficient Changes” scenario above.

## Adding Hydropower Computation

### 5. Understanding the way WEAP models Power Production

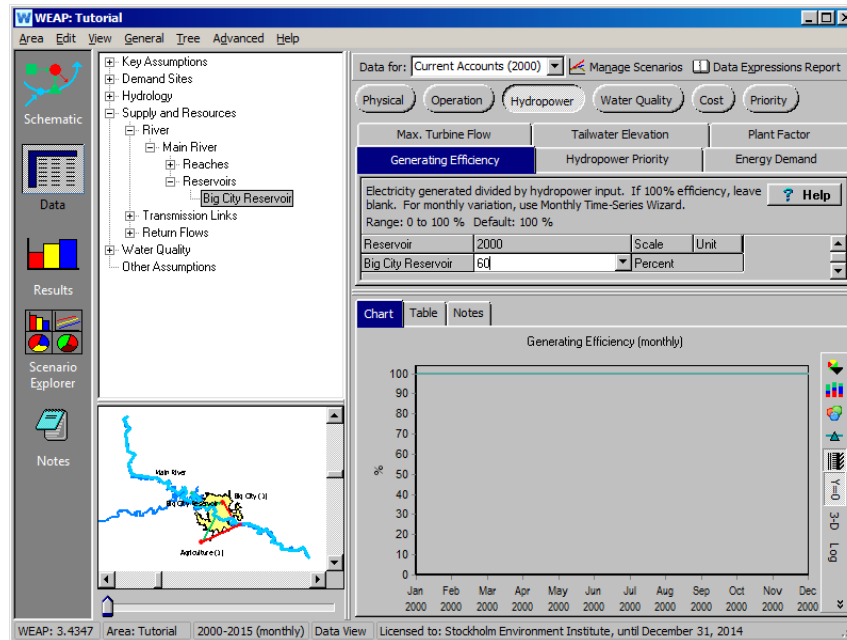
WEAP can model Power Production in three different ways: through on-line reservoirs, through off-line reservoirs, and through run-of-river hydropower plants. In a later module, we will also discuss linking WEAP with a Low Emissions Analysis Platform (LEAP) energy modeling software.

*Refer to the help for more information on each category.*

### 6. Add Power Production Capabilities to Big City Reservoir

In this example we will model an operating reservoir power plant. Enter the following data under the “Hydropower” window for Big City Reservoir in the Current Accounts.

<i>Max Turbine Flow</i>	<i>80 CMS</i>
<i>Tailwater Elevation</i>	<i>195m</i>
<i>Plant Factor</i>	<i>100%</i>
<i>Generating Efficiency</i>	<i>60%</i>

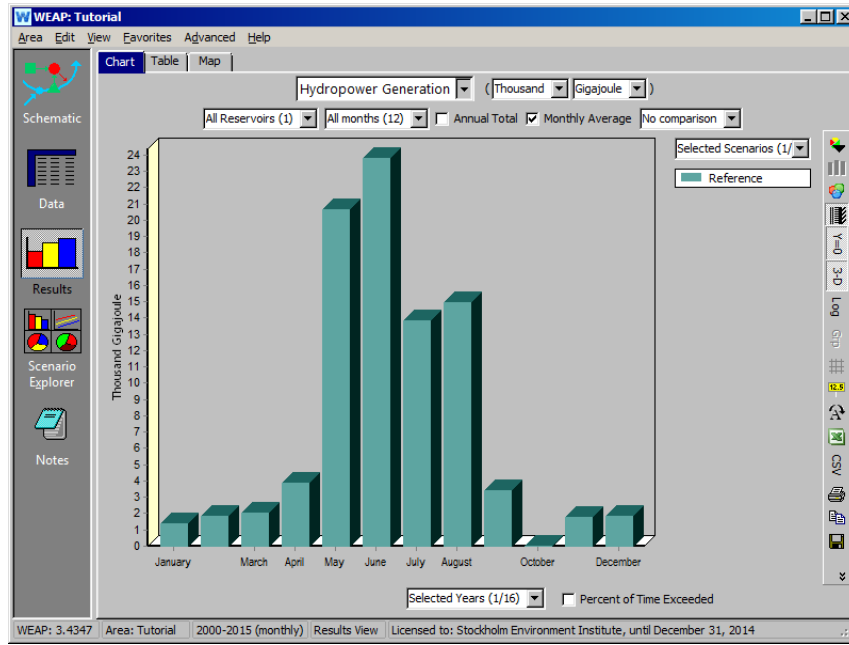


Look at the “Hydropower Calculations” help topic for more information about how WEAP computes power production.

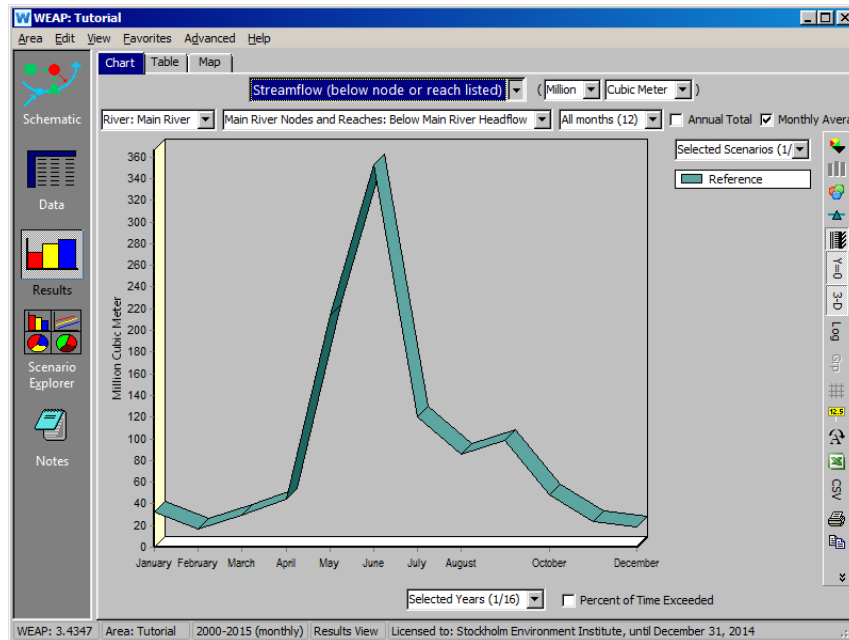
## 7. Compute Hydropower Production and Understand the Results

Run the model and look at the results in the Reference scenario for power production for the year 2000.

*The results can be accessed under the Primary Variable pull-down menu under “Supply and Resources/ Reservoir/ Hydropower.”*



*Do you understand why production levels between May and June are so similar, even though flow in Main River and downstream water release is much greater in June? To confirm this, look at the results for “Streamflow” in the reach above Big City Reservoir (Below Main River Headflow).*





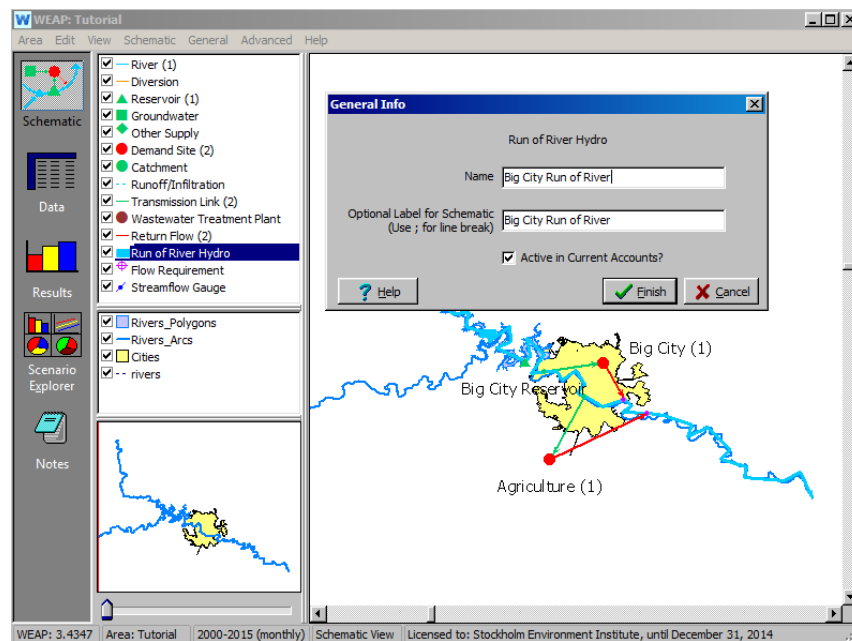
The streamflow that can be processed by the turbine has been capped to 80CMS (see previous step), meaning that even though there is a higher discharge in June, the excess quantity flows downstream without going through the turbine. Hydropower in June would be the same for May and June if not for the fact that the Storage Elevation in Big City Reservoir was slightly lower at the end of April than it was at the end of May (look at the Storage Elevation results to confirm this - these numbers represent the status at the *end* of each month indicated). This effect was slightly offset by the fact that May has 31 days to produce power, whereas June has 30 days, but June still ended up having slightly higher total production.

Off-line, “local” reservoirs’ hydropower production can be modeled in the same way.

## Modeling Run-of-River Power Plants

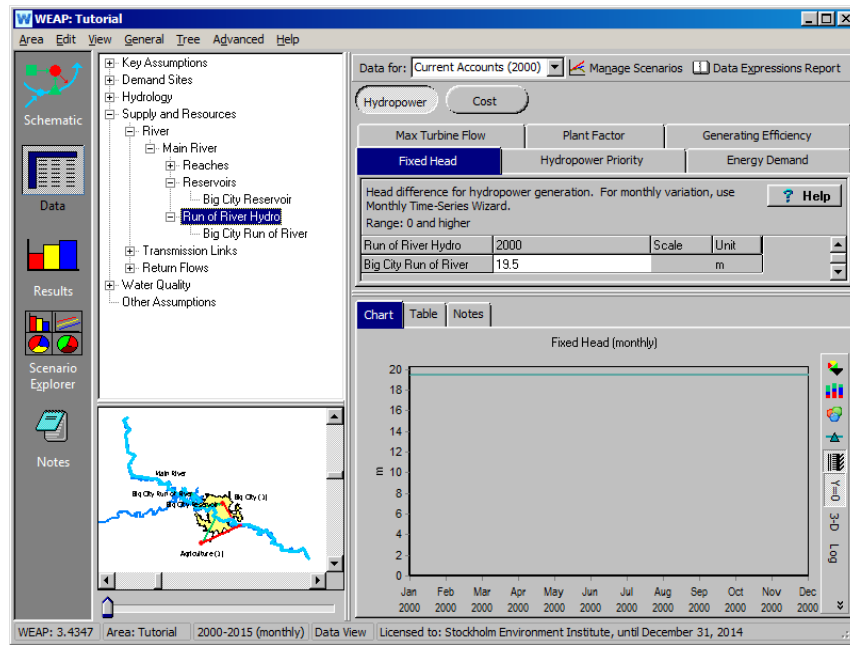
### 8. Create a Run-of-River Hydro Object

Create a Run-of-River Hydro Object on the Main River upstream of the Big City Reservoir created in the previous exercise. Name it “Big City Run of River.”



Enter the following data in the “Supply and Resources\River\Run of River Hydro” branch of the Data tree in the Data View:

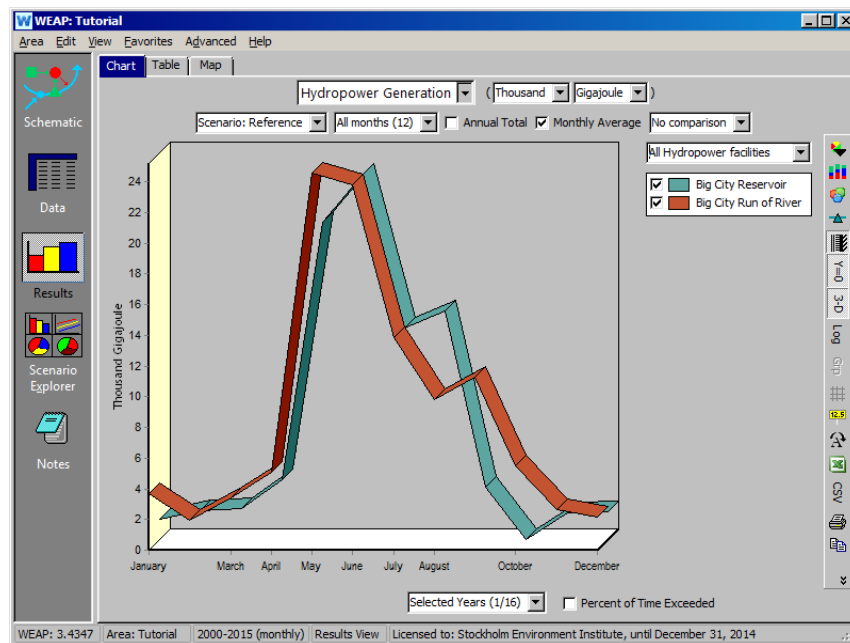
<i>Max Turbine Flow</i>	<i>80 CMS</i>
<i>Plant Factor</i>	<i>100%</i>
<i>Generating Efficiency</i>	<i>60%</i>
<i>Fixed Head</i>	<i>19.5 m</i>



## 9. Run and Compare Results

Run your model and create a graph comparing the power production for the run-of-river and the reservoir power plants. Do this by selecting “All Hydropower” from the pull-down menu above the legend.

*What are the reasons for the differences between both curves?*



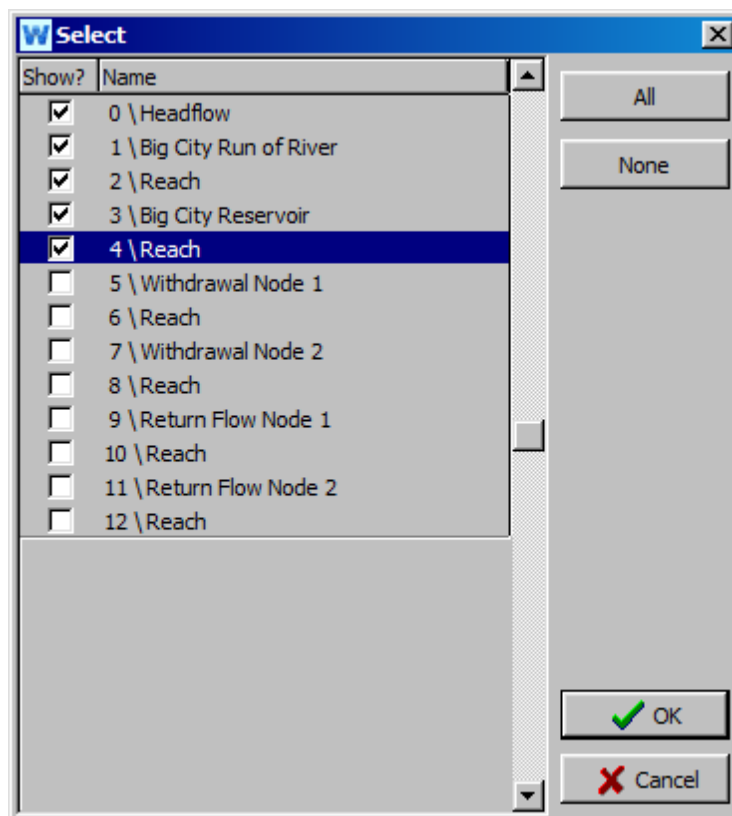




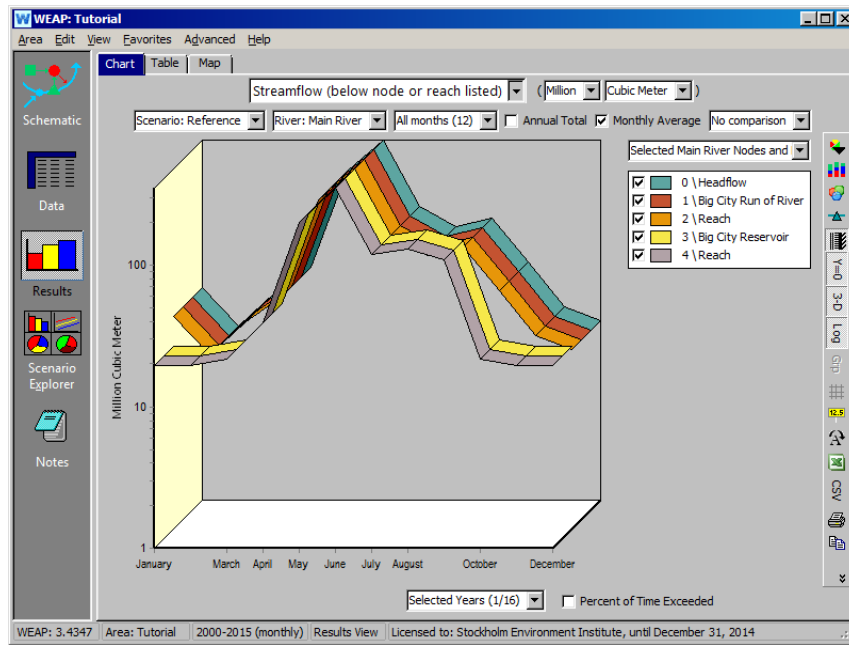
Note that the Run of River hydropower is slightly higher in May than June, in contrast to Big City Reservoir power production. This is due to the additional day available in May compared to June. Run of River hydropower production does not have Storage Elevation as limiting effect, whereas the Reservoir was still filling in May, which decreased the Reservoir production for that month compared to June.

*How does the run-of-river plant influence the streamflow of the river, when compared to the Big City Reservoir plant?*

To view this on the chart, select “Streamflow” from the primary variable pull-down menu and choose “Selected Main River Nodes and Reaches” from the pull-down menu above the legend. Select the following reaches: “0\Headflow”, “1\Big City Run of River”, “2\Reach”, “2\Big City Reservoir”, and “4\Reach” from the list.



We view the results (below) on a logarithmic scale, accessed by clicking on the “Log” icon on the bar on the right.



A reservoir can store water during high flows and release during low flow, thus having a smoothing effect. A run-of-river operation, however, processes whatever water flows in the river at any given point in time. Therefore, it does not affect the shape of the streamflow curve.

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# WEAP

Water Evaluation And Planning System

# Water Quality

## **A TUTORIAL ON**

*Setting up Quality Modeling.....148*

*Entering Water Quality Data.....150*

*Using Water Quality Inflow Constraints for a  
Demand Site .....156*

*Entering Pollution Generating Activity for  
Demand Sites .....158*

*Modeling a Wastewater Treatment Plant.....162*

**October 2023**

**Note:**

For this module you will need to have completed the previous modules (“WEAP in One Hour, Basic Tools, and Scenarios) or have a fair knowledge of WEAP (data structure, Key Assumptions, Expression Builder, creating scenarios). To begin this module, go to the Main Menu, select “Revert to Version” and choose the version named “Starting Point for all modules after ‘Scenarios’ module.”

## Setting up Quality Modeling

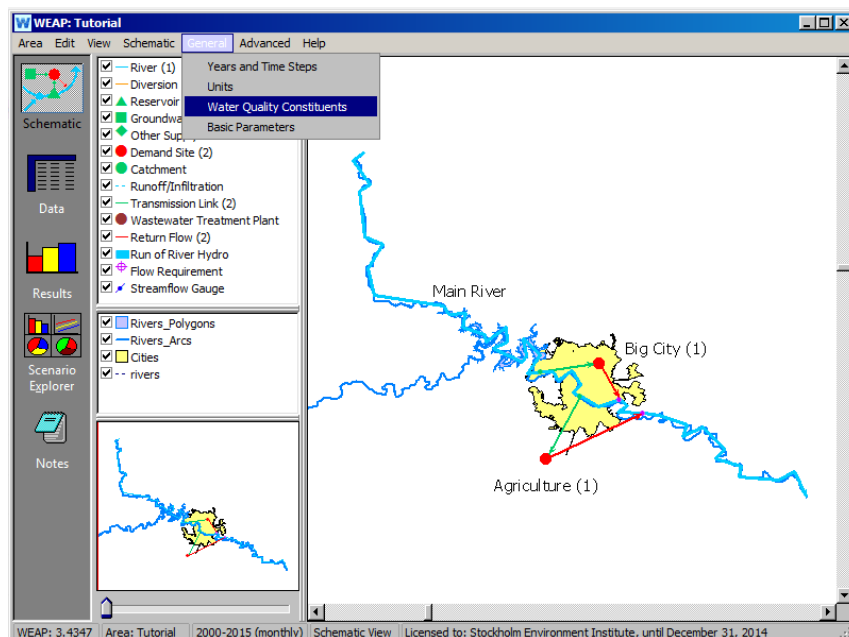
### 1. Understanding Water Quality Modeling in WEAP

WEAP can model both conservative and non-conservative pollutants. Conservative pollutants are modeled through a simple mass balance. Several models are offered for non-conservative pollutants.

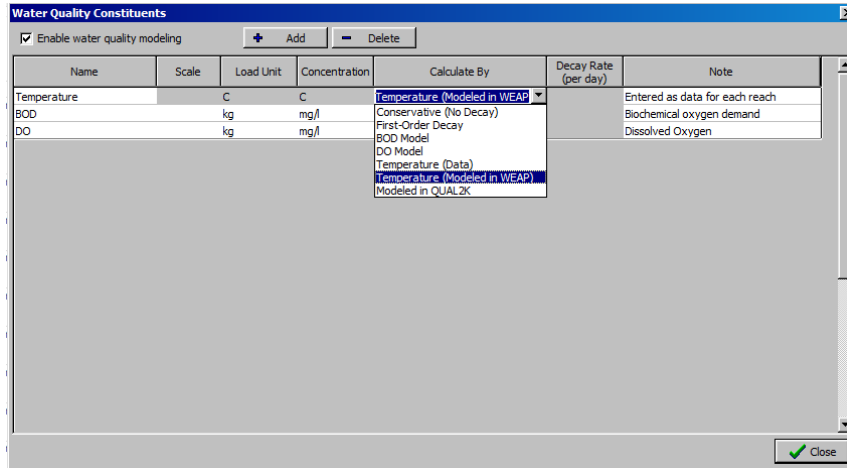
*Read the Water Quality “Getting Started” help topic for a more detailed description of WEAP capabilities.*

### 2. Create a Set of Pollutants

Create a set of pollutants that will be modeled by going to the “General\Water Quality Constituents” menu.

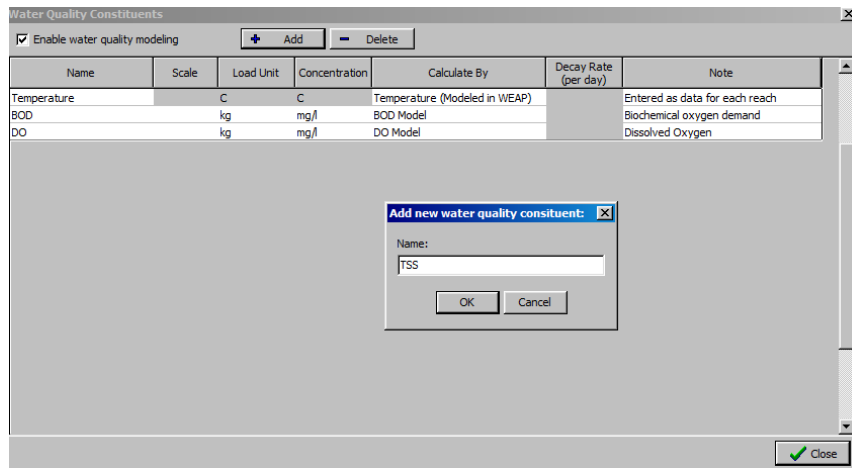


In the dialog box, choose “Temperature” to be calculated by temperature modeled in WEAP, under the “Calculated By” down.



Next, add “TSS” (Total Suspended Solids) and “Salt” to the list of constituents (“BOD” and “DO” should also already be listed):

<i>Name</i>	<i>Calculate by</i>	<i>Decay Rate</i>
<i>Temperature</i>	<i>Temperature (Modeled in WEAP)</i>	
<i>TSS</i>	<i>First-order Decay</i>	<i>0.25 per day</i>
<i>Salt</i>	<i>Conservative (No Decay)</i>	



Water Quality Constituents						
<input checked="" type="checkbox"/> Enable water quality modeling						
<div style="text-align: right;"> <input type="button" value="+ Add"/> <input type="button" value="- Delete"/> </div>						
Name	Scale	Load Unit	Concentration	Calculate By	Decay Rate (per day)	Note
Temperature	C	C		Temperature (Modeled in WEAP)		Entered as data for each reach
BOD	kg	mg/l		BOD Model		Biochemical oxygen demand
DO	kg	mg/l		DO Model		Dissolved Oxygen
TSS	kg	mg/l		First-Order Decay	0.25	
Salt	kg	mg/l		Conservative (No Decay)		



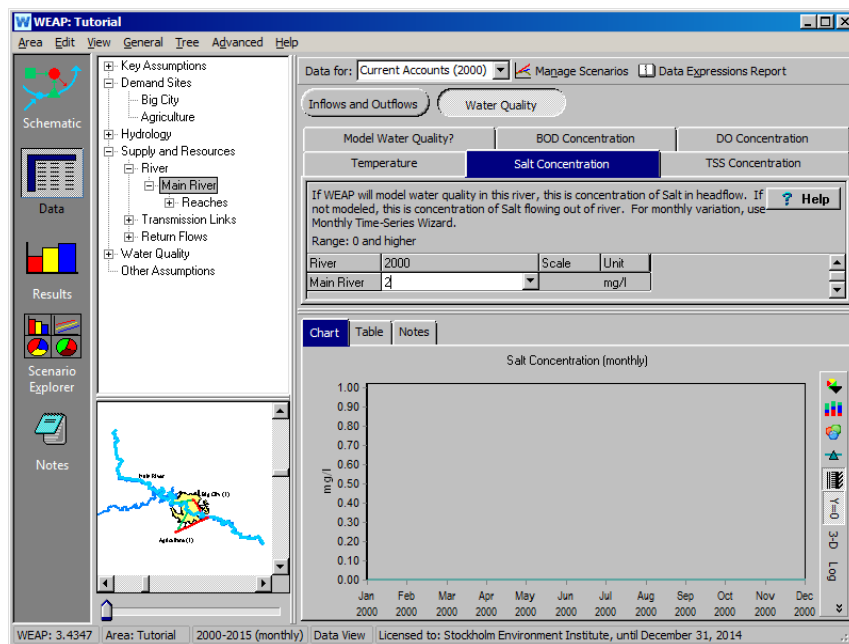
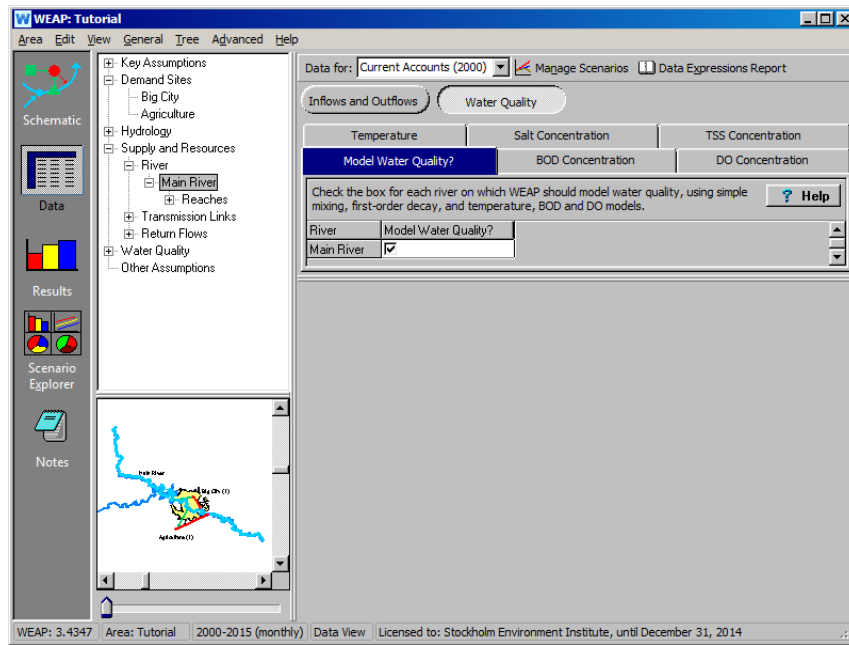
More details are provided on the different models used for BOD and DO models in the “Dissolved Oxygen and Biochemical Oxygen Demand” help topic.

## Entering Water Quality Data

### 3. Enter River Water Quality data

In the Data view tree, select “Supply and Resources\River” and click on the Main River. Then open the “Water Quality” screen and enter the following data, which will represent water quality at the headflow of the river:

<i>Model Water Quality?</i>	<i>YES (check the box)</i>
<i>Temperature</i>	<i>15°C</i>
<i>BOD concentration</i>	<i>5mg/l</i>
<i>DO concentration</i>	<i>8mg/l</i>
<i>TSS concentration</i>	<i>20mg/l</i>
<i>Salt concentration</i>	<i>2mg/l</i>



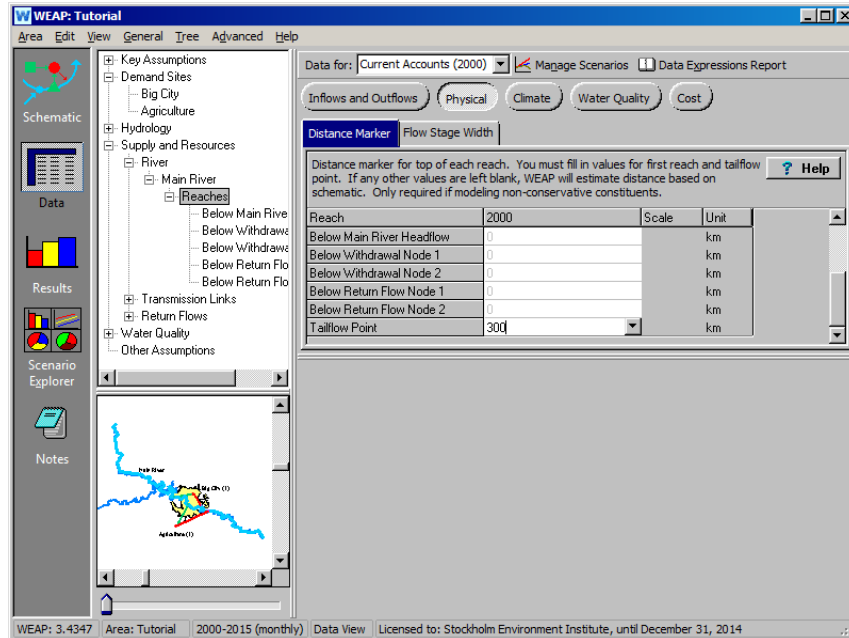
#### 4. Enter River Geometric Characteristics

River geometric characteristics are needed for the various water quality models. They are mainly used to compute velocity/residence time of the water along a reach. In the Data view, select the “Reaches” branch of the Main River and enter the following information under the “Physical” tabs.

*Headflow Distance Marker 0 km*

*Tailflow Distance Marker 300 km*

*Note: intermediate reach lengths will be estimated by WEAP based on the schematic.*



*In the Flow Stage Width tab, use the Wizard by clicking on the drop-down arrow for “Below Main River Headflow” to enter the following data:*

<i>Flow</i>	<i>Stage</i>	<i>Width</i>
0	0.00	0.00
10	3.00	15.00
50	5.00	26.00
100	7.00	35.00
200	9.00	40.00

*Your final formula should read:*

*FlowStageWidthCurve(0,0,0, 10,3,15, 50,5,26, 100,7,35, 200,9,40 )*

*We will assume this section remains constant and leave other reaches empty.*



WEAP: Tutorial

Area Edit View General Tree Tags Advanced Help

Data for: Current Accounts (2000) Manage Scenarios

Inflows and Outflows Physical Climate Water Quality Cost

Distance Marker Flow Stage Width

Enter data relating river stage and width to flow. Use Flow-Stage-Width Wizard. To use values from upstream reach, leave blank. Only required if modeling non-conservative constituents or if linking to MODFLOW.

Reach	2000
Below Main River Headflow	0
Below Withdrawal Node 1	
Below Withdrawal Node 2	
Below Return Flow Node 1	
Below Big City WWTP Return	0
Below Return Flow Node 2	0

WEAP: 2018.0104 (Beta) Area: Tutorial 2000-2015 (monthly) Licensed to: Jack Sieber, Stockholm Environment Institute, until December 31, 2023

Flow-Stage-Width Wizard

Enter data points relating flow to width and stage for reach Below Main River Headflow

Flow [CMS]	Stage [m]	Width [m]	Velocity [m/s]
0.00	0.00	0.00	0.00
10.00	3.00	15.00	0.44
50.00	5.00	26.00	0.79
100.00	7.00	35.00	0.80
200.00	9.00	40.00	1.00

Preview

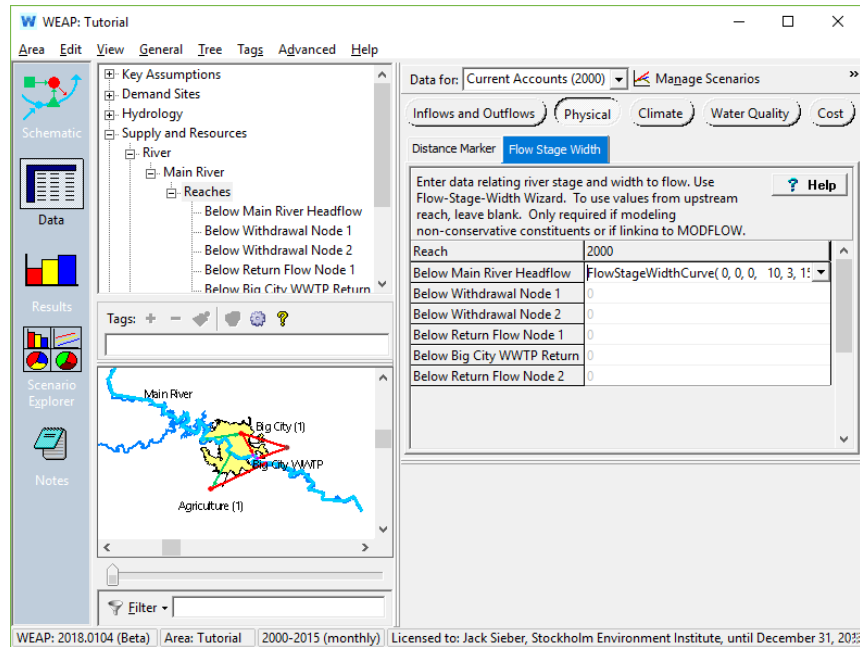
Stage

Width

Velocity

Streambed Shape

Help Finish Cancel

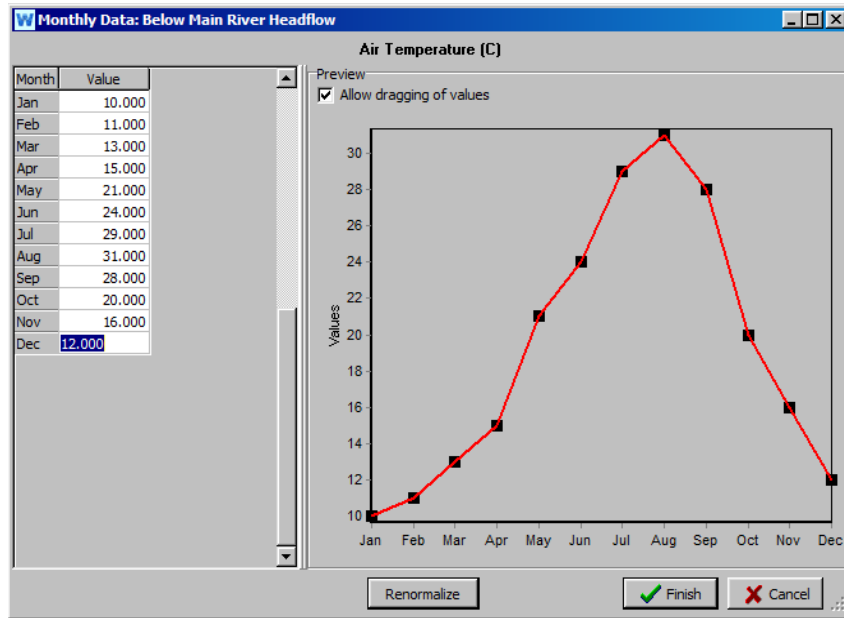


The “Reach Length” tab displayed under the “Inflows and Outflows” category is used only for modeling surface water-groundwater interactions. It represents the length of the reach connected to the groundwater, which may be less than the total length of that reach.

## 5. Enter the Climatic Data

Climatic Data are needed to compute water temperature. Click on the “Climate” button and again select the “Below Main River Headflow” reach. Enter the following climate data (for air temperature, use the Monthly Time Series Wizard):

<i>Air Temperature</i>	
<i>Month</i>	<i>Value (°C)</i>
<i>Jan</i>	<i>10</i>
<i>Feb</i>	<i>11</i>
<i>Mar</i>	<i>13</i>
<i>Apr</i>	<i>15</i>
<i>May</i>	<i>21</i>
<i>Jun</i>	<i>24</i>
<i>Jul</i>	<i>29</i>
<i>Aug</i>	<i>31</i>
<i>Sep</i>	<i>28</i>
<i>Oct</i>	<i>20</i>
<i>Nov</i>	<i>16</i>
<i>Dec</i>	<i>12</i>



Humidity 65%  
 Wind 1 m/s  
 Cloudiness Fraction 1  
 Latitude 30°

*Note: you can enter these values for the first reach and leave the other reaches blank if you want the value to apply to all reaches.*

**WEAP: Tutorial**

Area Edit View General Tree Advanced Help

Data for: Current Accounts (2000) Manage Scenarios Data Expressions Report

Buttons: Inflows and Outflows, Physical, Climate, Water Quality, Cost

Buttons: Air Temperature, Humidity, Wind, Cloudiness Fraction, **Latitude**

Latitude in degrees (required by water temperature model). To use value from upstream reach, leave blank.  
 Range: -90 to 90

Reach	2000
Below Main River Headflow	30
Below Withdrawal Node 1	0
Below Withdrawal Node 2	0
Below Return Flow Node 1	0
Below Return Flow Node 2	0

Buttons: Chart, Table, Notes

Chart: Latitude

The chart displays a single bar for the 'Below Main River' reach with a value of 30 degrees.

Status bar: WEAP: 3.4347 Area: Tutorial 2000-2015 (monthly) Data View Licensed to: Stockholm Environment Institute, until December 31, 2014

# Using Water Quality Inflow Constraints for a Demand Site

## 6. Enter Constraint Data

A demand site may require that its water supply meets certain quality criteria. Create a new scenario inherited from the “Reference” scenario and name it “Big City Water Quality Inflow Constraints.” In the Data view (make sure you are in this new scenario), select the Big City branch of the data tree, and click on the “Water Quality” button. Under the “BOD Inflow” tab, enter the following maximum allowed concentration of BOD:

$$\text{BOD inflow} \qquad 2 \text{ mg/L}$$

## 7. Compare Results

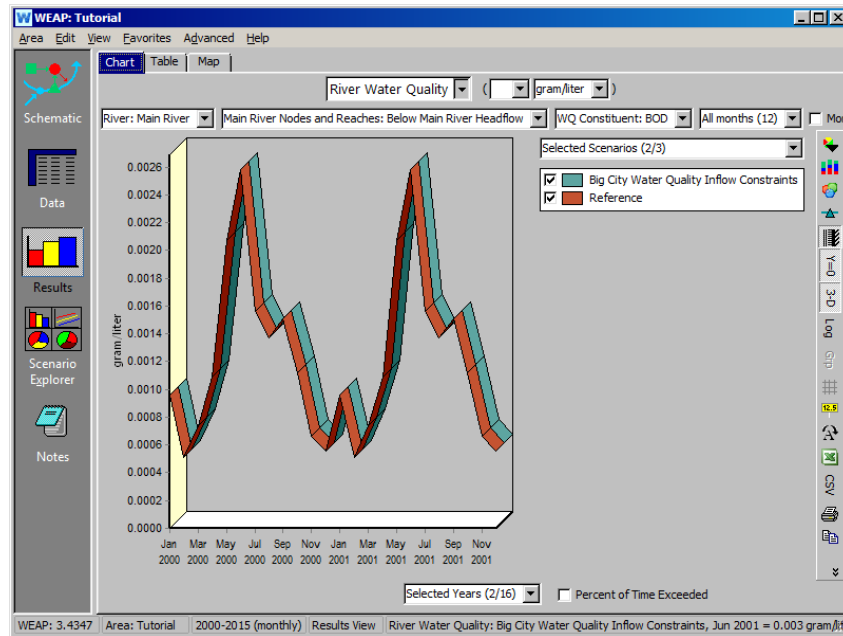
Note that you earlier entered a BOD concentration (5 mg/L) for the Main River Headflow (under Current Accounts), so you can now run the results and compare the output for Big City Demand Site Coverage, with and without this inflow constraint for Big City. For the period 2000 and 2001, a comparison of Big City Demand Site Coverage for the “Reference” and “Big City Water Quality Inflow Constraints” scenarios should look like the following:



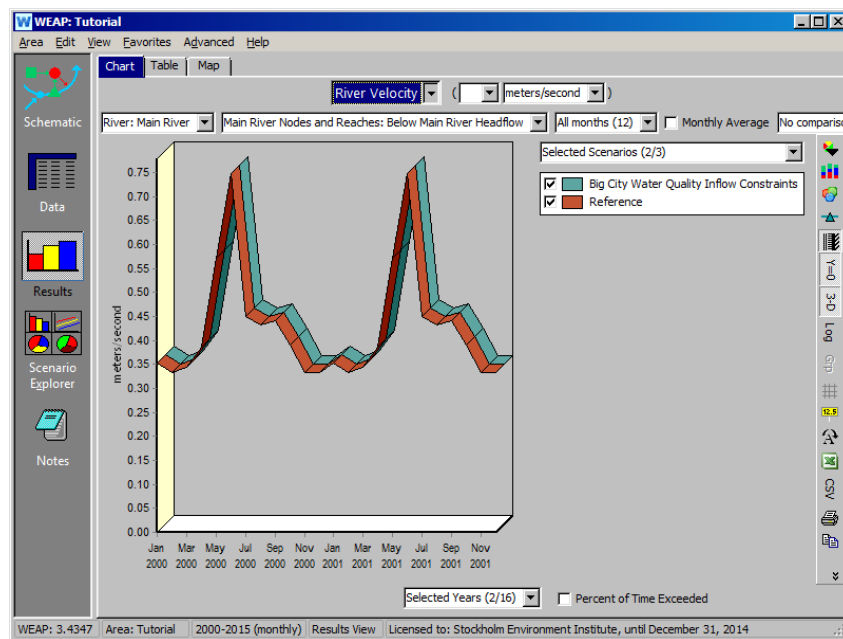
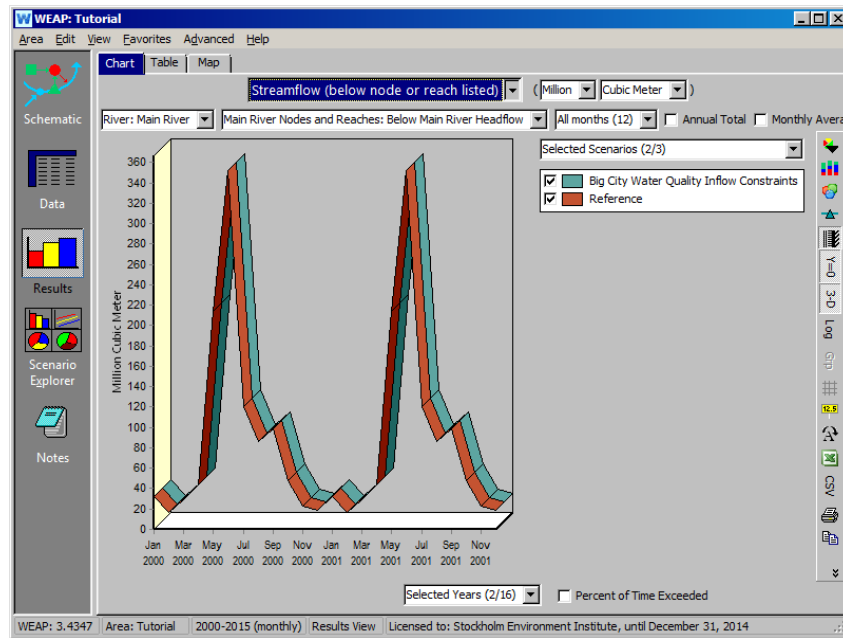
*Why does Big City Coverage drop to zero during June, 2001, in the Inflow Constraint scenario?*



If you look at the BOD concentration (Water Quality, River Water Quality) in the “Below Main River Headflow” reach (pictured below), you will see that BOD rises above the constraint (2 mg/L) for Big City intake during the month of June for both 2000 and 2001. Since the constraint is activated during the scenario period (starting in 2001), coverage for Big City decreases during June 2001, because this demand site will not accept water that falls below the BOD constraint, and no other sources of water other than the Main River have been designated as supplies for Big City.



The simulated temporal pattern of the BOD concentration along this reach of the Main River is a function of degradation, the extent of which is controlled by the residence time of the water in the “Headflow” reach. The longer the residence time in this reach, the more degradation that occurs. The pattern for BOD thus mirrors that of the flow velocity, and streamflow, for the reach (both pictured below).



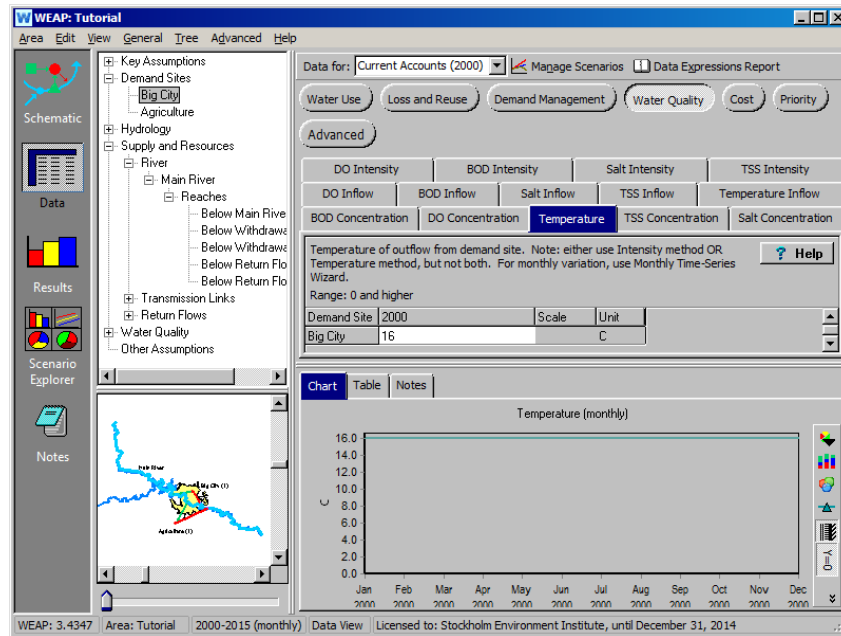
## Entering Pollution Generating Activity for Demand Sites

### 8. Entering Data

We will assume that we know the concentration of pollutants in the outflow (Return Flow) for Big City. Hence, we will use the “Concentration” series of

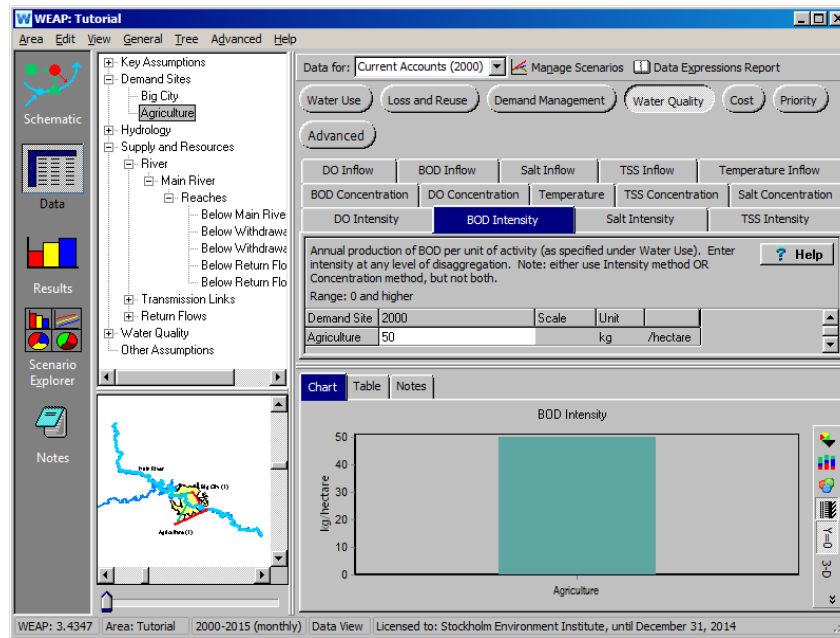
tabs in the “Demand Sites\Big City” branch of the Data tree. Click on the “Water Quality” button and enter the following data (in Current Accounts):

<i>Temperature</i>	<i>16 °C</i>
<i>BOD Concentration</i>	<i>60 mg/l</i>
<i>DO Concentration</i>	<i>3 mg/l</i>
<i>TSS Concentration</i>	<i>5 mg/l</i>
<i>Salt Concentration</i>	<i>10 mg/l</i>



For the Agriculture demand site, we will admit that we do not know the concentration at the outflow, but we do know the pollutant generation intensity. Enter the following data:

<i>BOD intensity</i>	<i>50 kg/ha</i>
<i>DO Intensity</i>	<i>30 kg/ha</i>
<i>TSS Intensity</i>	<i>20 kg/ha</i>
<i>Salt Intensity</i>	<i>2 kg/ha</i>
<i>Temperature</i>	<i>15°C</i>



Pollution outflow from a demand site is only based on each demand site's pollutant concentration or intensity data, not on the water quality of the inflow to the demand site. Note that temperature data can change over time.

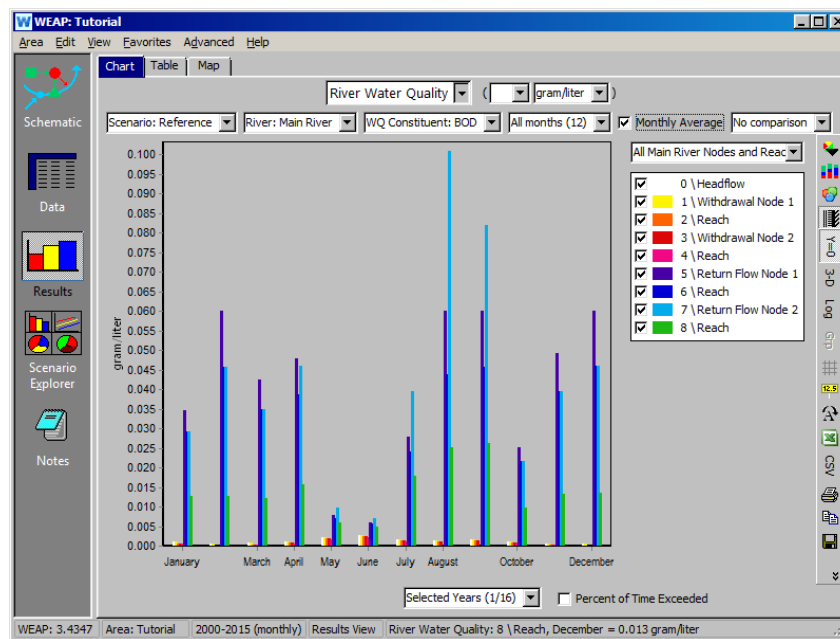
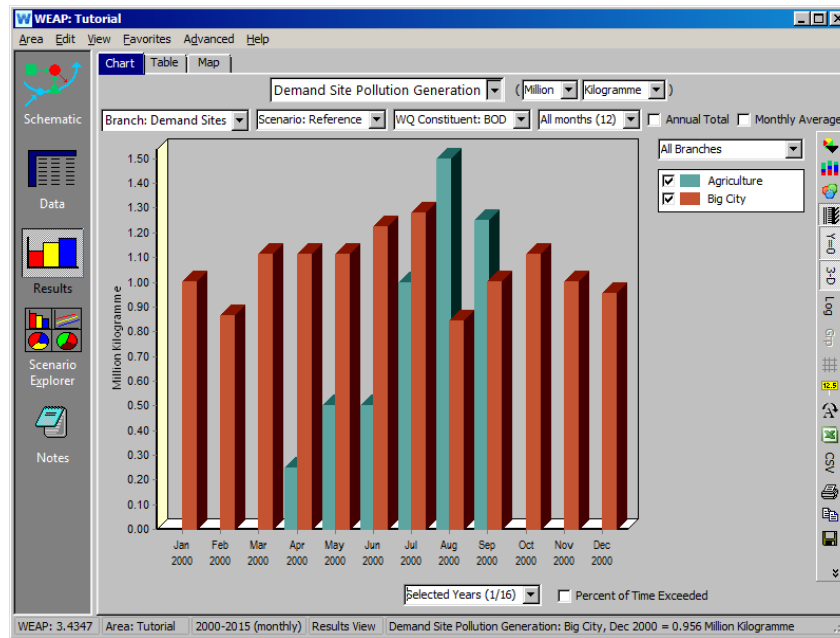
## 9. Evaluate the Results

Run the model and look at the following results for various water quality constituents for the year 2000. Select "Pollution Generation" from the primary variable pull-down menu (under Water Quality):

*Demand Site Pollution Generation*

*River Water Quality (here we switched the colors to "Mac" in the colors option on the bar on the right of the screen)*



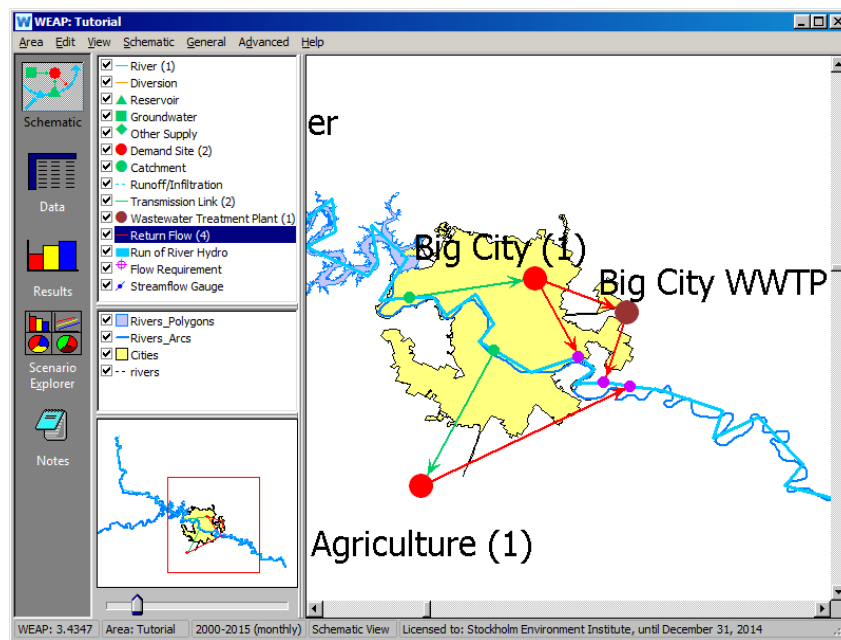


Note that Pollution Generation for Agriculture is confined to the spring and summer months when farming is active.

# Modeling a Wastewater Treatment Plant

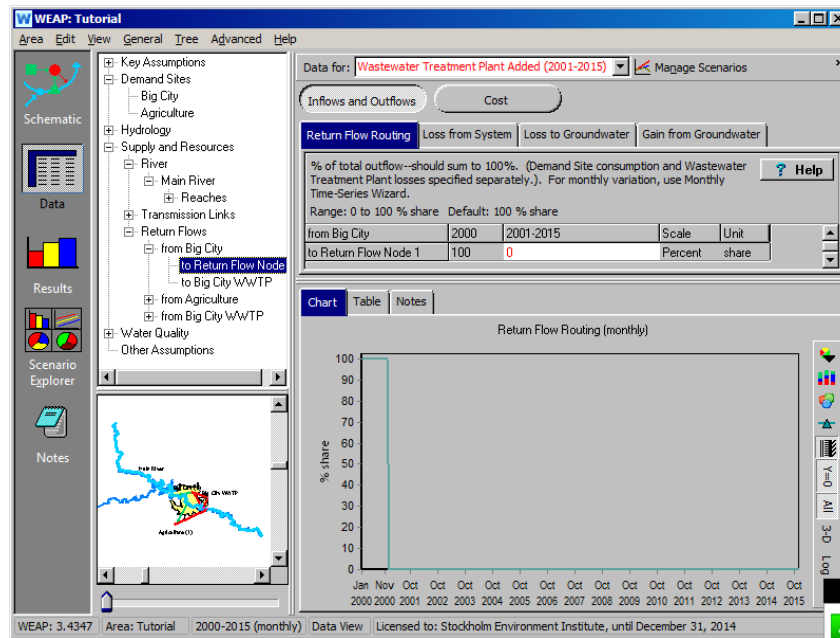
## 10. Create a Wastewater Treatment Plant

Create a new scenario named “Wastewater Treatment Plant Added”- this scenario is inherited from the “Reference.” Then, add a Wastewater Treatment Plant for Big City, name it “Big City WWTP” and make it inactive in Current Accounts, and create a Return Flow Link from the Big City to the WWTP. Keep the existing Return Flow Link from Big City to the river. Also create another return flow from the WWTP to the river. Your model should look similar to the figure below:

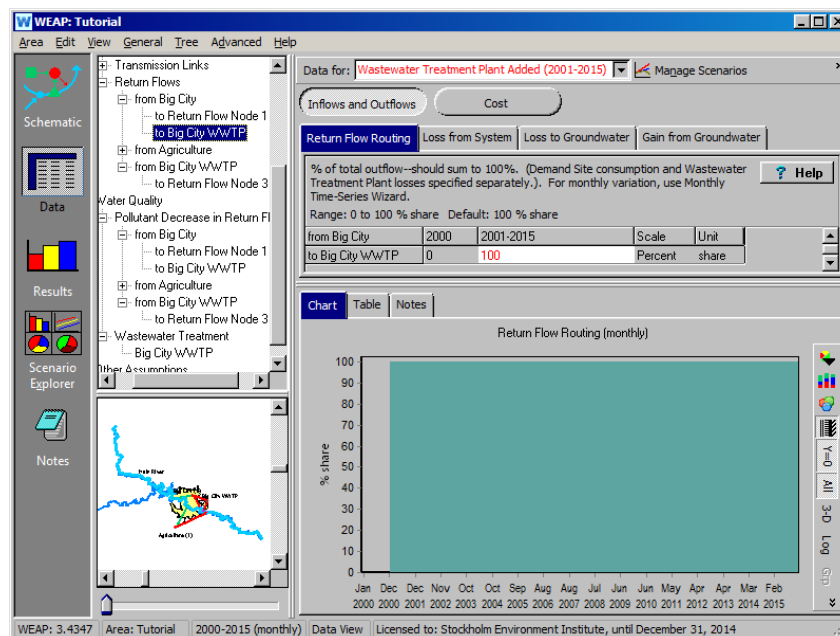


You will have to set the “Return Flow Routing” variables for both links.

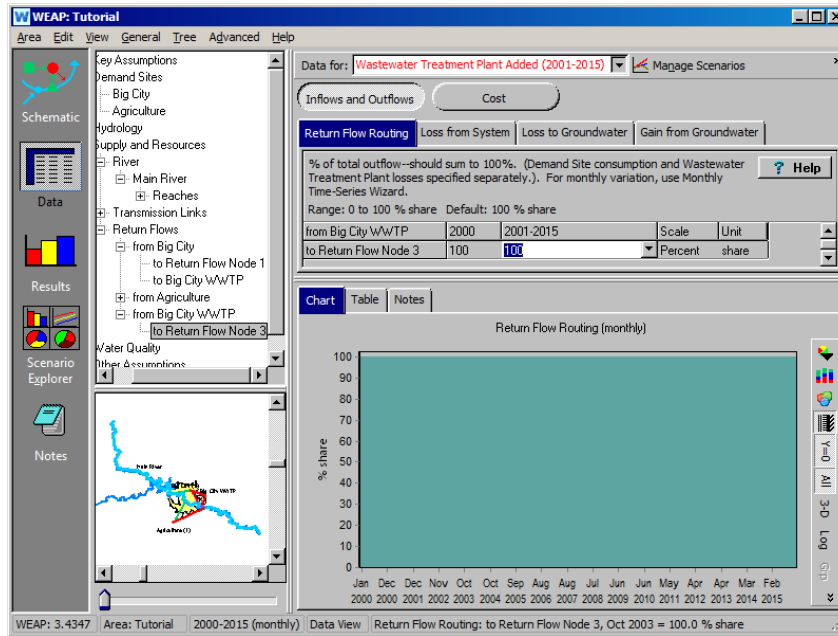
*For the Return Flow from Big City to Main River (Return Flow Node 1), set the Routing to 100% for the Current Accounts year and 0% for years 2001-2015 in the “Wastewater Treatment Plant Added” scenario.*



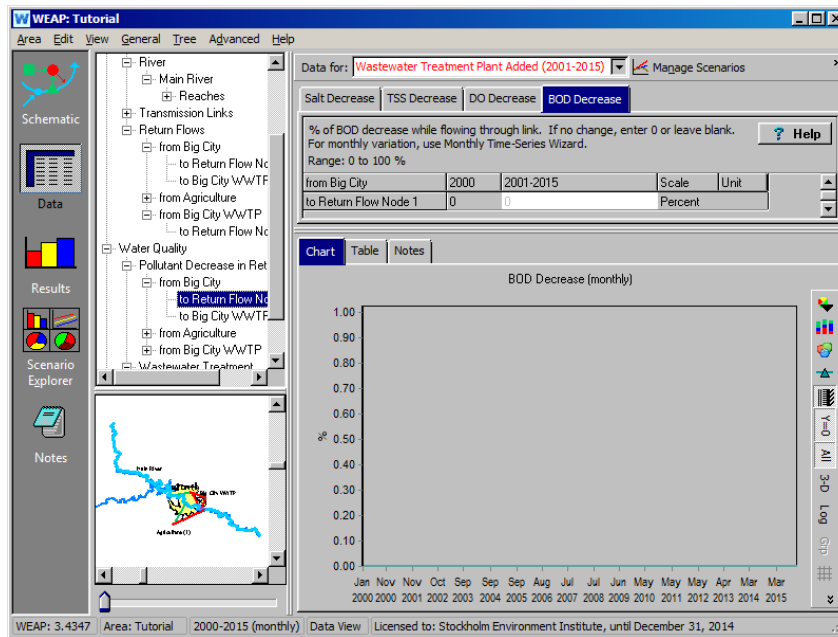
*For the Return Flow from Big City to the Big City WWTP, set the Return Flow to 100% for the years 2001-2015 in the “Wastewater Treatment Plant Added” scenario. Set the return flow to zero in the Current Accounts. Even though it does not yet exist, WEAP will give you errors if the percentages don’t add up to 100% between existing and non-existing infrastructure. See below.*



*Also set the Routing to 100% for the Return Flow from the Big City WWTP to the Main River (Return Flow Node 3). (In Wastewater Treatment Plant Added scenario)*



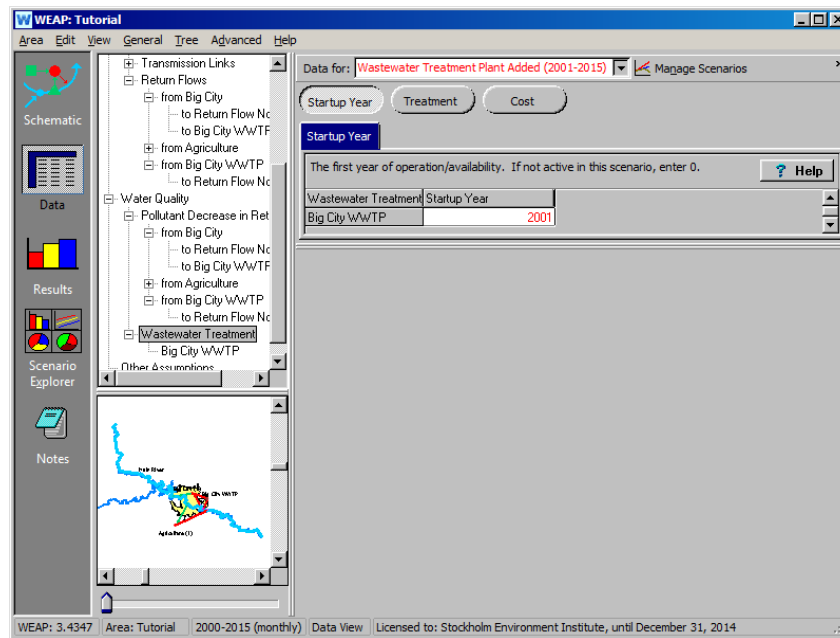
You also have the possibility to set removal rates in the various return flows. This would be useful if, for example, a given pollutant is decomposed by bacteria in the sewer system. These data can be entered under the “Water Quality\Pollutant Decrease in Return Flow” branches for the appropriate return flows (see figure below for example).



## 11. Enter WWTP Data

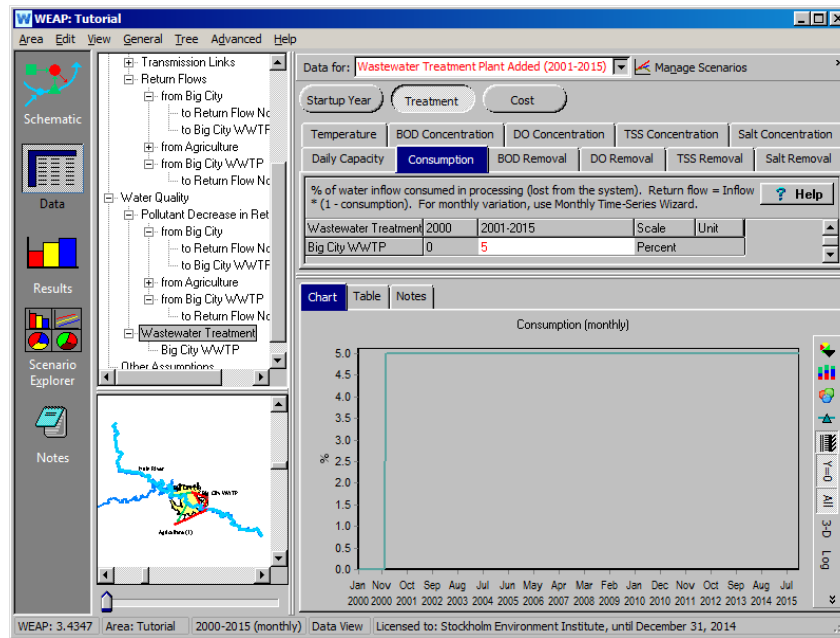
First, enter the “Start Year” by clicking on the “Start Year” button under the “Water Quality\Wastewater Treatment” branch of the data tree for Big City WWTP. Make sure you hit the enter key after entering 2001.

*Start Year*                      *2001*



Also enter the following data under the “Treatment” category (with the “Wastewater Treatment Plant Added” scenario selected):

<i>Consumption</i>	<i>5%</i>
<i>Daily Capacity</i>	<i>2M m<sup>3</sup></i>
<i>BOD Removal</i>	<i>90%</i>
<i>DO Concentration</i>	<i>5mg/l</i>
<i>TSS Removal</i>	<i>80%</i>
<i>Salt Removal</i>	<i>20%</i>
<i>Temperature</i>	<i>15°C</i>



If only part of the wastewater is treated through the WWTP, there are two modeling possibilities. One is to limit the Daily Capacity to whatever amount can actually be treated. In this case the wastewater in excess will be discharged without treatment. In this case, the share of untreated wastewater is not constant, but depends on the total flow.



Another solution is to create an additional return flow going from the demand site straight to the river, by-passing the WWTP. In this case, a constant share can be set to by-pass the WWTP by setting the return flow routing shares accordingly. A combination of both methods is also possible.

## 12. Evaluate the Results

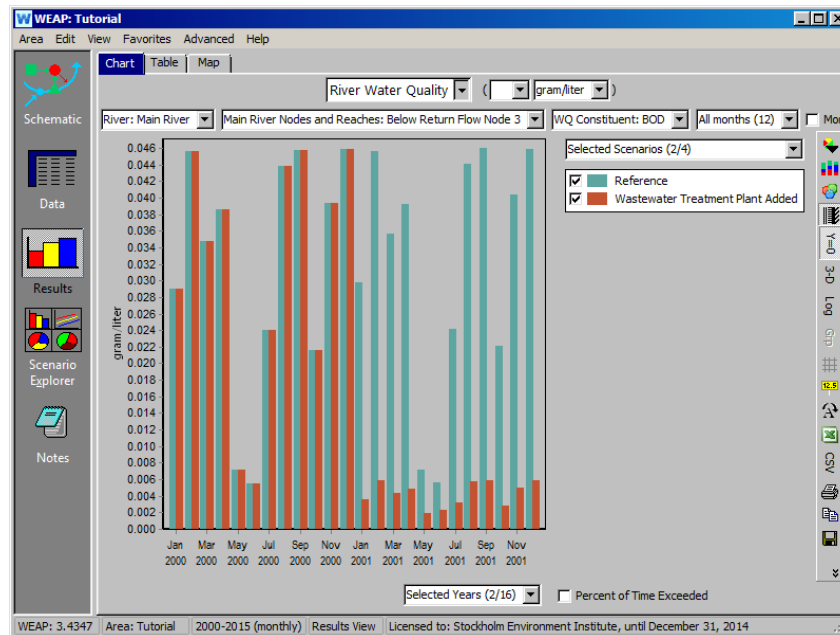
Run the model and look at the following results for BOD in the “Wastewater Treatment Plant Added” scenario, comparing them with the “Reference” scenario values (without a wastewater treatment plant).

*RiverWater Quality (BOD downstream of Big City’s outflow into the river).*

To view these results, first select “River Water Quality” under “Water Quality” in the primary variable pull-down menu. Then choose “Selected Scenarios” under the pull-down menu above the chart legend and select the “Reference” and “Wastewater Treatment Plant Added” scenarios.

Using the pull-down menu at the bottom of the chart, select the years 2000 and 2001 for viewing. Select “Below Return Flow Node 3” (Return Flow Node 3 is the return flow for the WWTP, so you will be looking at water quality in the river just downstream of the outflow from the WWTP) as the Main River reach to view. Select “BOD” as the water quality constituent from

the pull-down menu directly above the chart and unclick the “Monthly Average” button to the far right. Your screen should look like the one below:

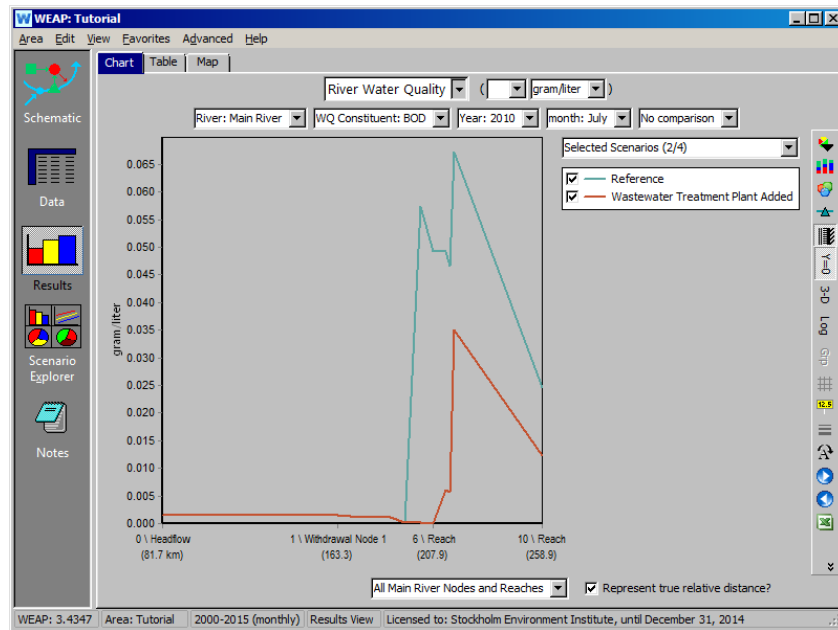


Note that BOD levels decrease substantially in 2001 compared to 2000 in the reach below the return flow from the treatment plant because the plant becomes active that year.

*WEAP can also display water quality results from upstream to downstream.*

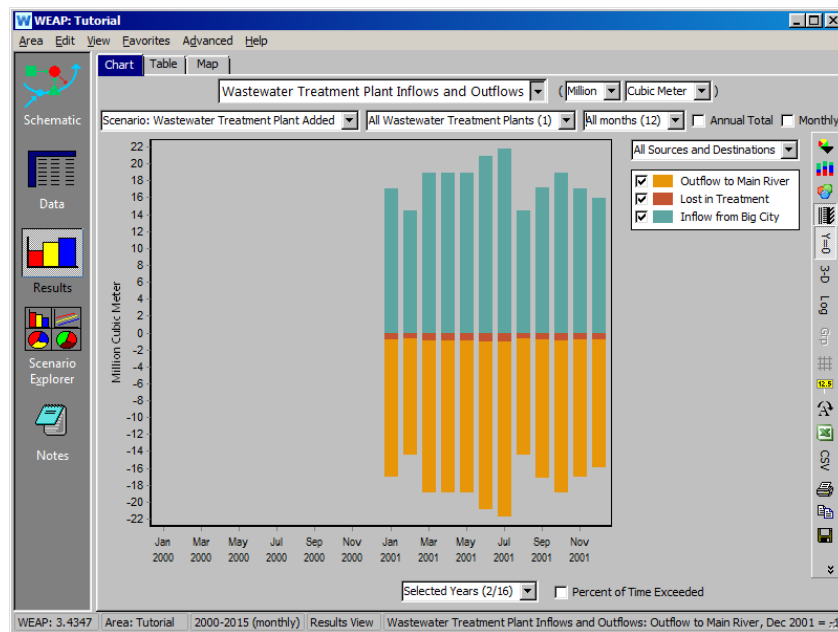
From the bottom menu, choose “All Main River Nodes and Reaches” and check “Represent true relative distance?” This will show all nodes and reaches along the X-axis, with their spacing proportional to their distance downstream (distances shown in parentheses). Select July 2010, as the month and year. For the chart type, select “Line.”

The chart shows that BOD levels rise as BOD-laden return flows enter the river, and decline as the BOD decays as it moves downstream. The effect of the wastewater treatment plant can be clearly seen. Your chart should look like this:



### *Wastewater Treatment Plant Inflows and Outflows.*

Select “Wastewater Treatment Plant Inflows and Outflows” (under Water Quality) from the primary variable pull-down menu and the “Wastewater Treatment Plant Added” scenario from the upper left menu. View “All Months (12)” and in the second icon on the menu bar, select stacked bars.



In this type of chart, the outflows are represented as negative values and inflows are positive values. Note also that the “Lost in Treatment” category represents the flow that is consumed; a consumption rate of 5% was input in the data view for the treatment plant.



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# WEAP

Water Evaluation And Planning System

# Linking WEAP to QUAL2K

***A TUTORIAL ON***

*Linking to QUAL2K*.....170

*Running Scenarios* .....176

**October 2023**

**Note:**

For this module you will need to have completed the previous modules (WEAP in One Hour, Basic Tools, Scenarios, and Water Quality) or have a fair knowledge of WEAP (data structure, Key Assumptions, Expression Builder, creating scenarios). To begin this module, go to the Main Menu, select “Revert to Version” and choose the version named “Starting point for ‘Water Quality with QUAL2K.’” This version enacts necessary files to complete this module.

## Linking to QUAL2K

### 1. Using QUAL2K for Water Quality Modeling in WEAP

In addition to using WEAP’s in-built capacity for water quality modeling, it is possible to use the US EPA QUAL2K modeling framework. This module demonstrates how to use the WEAP/QUAL2K interface, taking the Water Quality module as a starting point. This module is not an introduction to QUAL2K, which requires specialized knowledge, but if you are already using QUAL2K, you should be able to link your QUAL2K file to WEAP after this module.



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QUAL2K is a 1-dimensional, steady state, instream water quality model for well mixed channels (laterally and vertically). Constituents modeled include: ammonia, nitrate, organic and inorganic phosphorous, algae, sediment, pH and pathogens. QUAL2K was developed by Dr. Steve Chapra and his grad students at Tufts University. This module is not an introduction to QUAL2K. Considerable work is required outside of WEAP to calibrate and prepare a QUAL2K file. Refer to the QUAL2K manual for more information. Visit <http://www.epa.gov/athens/wwqtsc/html/qual2k.html> to download or for more information.

---

### 2. Differences Between QUAL2K and WEAP

QUAL2K and WEAP are compatible in their general approach to water quality modeling, but they do some things differently. The important differences are:

- QUAL2K measures distance along a reach from the tail of the reach, while WEAP measures distance from the head.
- QUAL2K allows for diurnal variations in water quality and climate, while WEAP applies the same value to all times of day.
- WEAP is more tolerant of zero or missing values than is QUAL2K.

- QUAL2K and WEAP use different climate parameters. For example, QUAL2K uses dew point, while WEAP uses humidity.
- QUAL2K models many more constituents in much more detail, including two separate CBOD constituents, ammonia, nitrate, organic and inorganic phosphorous, algae, sediment, pH and pathogens (see <http://www.epa.gov/athens/wwqtsc/html/qual2k.html> for more details).

QUAL2K and WEAP are similar in that each treats a river as a sequence of reaches, not necessarily of equal lengths. However, the reach boundaries as defined in QUAL2K and in WEAP need not match. Where reach boundaries do not match, WEAP handles the task of mapping water quality and climate variables, based on distance markers.

Reservoirs present special challenges for water quality modeling. WEAP includes reservoirs, but not for water quality, while QUAL2K includes weirs, but they are not operated. It is recommended that rivers with reservoirs not be linked to QUAL2K, or that they be modeled in two sections—above the reservoir and below the reservoir.

### 3. Link Pollutants to QUAL2K

This module uses the final result from the previous Water Quality module as a starting point. Open the WEAP tutorial (by selecting Area \ Open \ Tutorial from the menu), then selecting Area \ Revert to Version \ Starting point for 'Water Quality' from the menu.

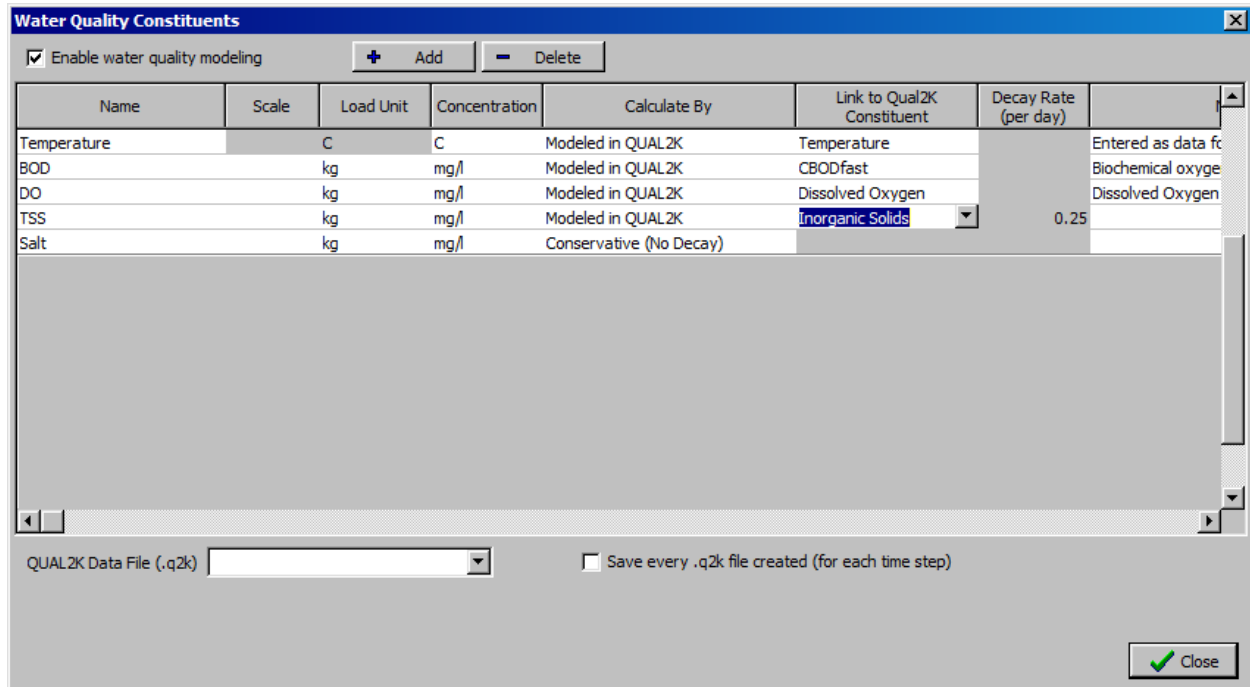
Once the file is ready, change the water quality constituents to point to QUAL2K.

*From the menu, select “General | Water Quality Constituents.”*

*For all of the constituents except Salt, select “Modeled in QUAL2K” in the “Calculated By” drop-down.*

*Link each constituent in WEAP (except salt) to a corresponding QUAL2K constituent: “Temperature” → “Temperature”, “BOD” → “CBOD fast”, “DO” → “Dissolved Oxygen”, “TSS” → “Inorganic Solids.”*

Salinity is not directly modeled in QUAL2K, so it is not linked to a QUAL2K constituent in this example. QUAL2K instead models conductivity, which is an easily measured indicator of salinity.



Next, search for a QUAL2K data file (a file ending in .q2k).

*Look for the new drop-down labeled “QUAL2K Data File (.q2k)” that has appeared at the bottom left of the Water Quality Constituents dialog.*

*Select “< Copy file from another directory >” from the drop-down.*

*Search the Tutorial\Additional Files for the file “Main\_River\_Tutorial.q2k.” If you want to view the QUAL2K file, click the “View” button to open it in the QUAL2K-formatted Excel spreadsheet.*

The Water Quality Constituents Dialog should now look like the following:

Name	Scale	Load Unit	Concentration	Calculate By	Link to Qual2K Constituent	Decay Rate (per day)	
Temperature	C	C	Modeled in QUAL2K	Temperature	Temperature		Entered as data fc
BOD	kg	mg/l	Modeled in QUAL2K	CBODfast	CBODfast		Biochemical oxyge
DO	kg	mg/l	Modeled in QUAL2K	Dissolved Oxygen	Dissolved Oxygen		Dissolved Oxygen
TSS	kg	mg/l	Modeled in QUAL2K	Inorganic Solids	Inorganic Solids	0.25	
Salt	kg	mg/l	Conservative (No Decay)	Conservative (No Decay)	Conservative (No Decay)	0.25	



The QUAL2K file must initially be developed and edited outside of WEAP. WEAP will then modify some of the values, and extract values from QUAL2K after it is run. To view or edit the QUAL2K file, click on the “View” button next to the “QUAL2K Data File (.q2k)” drop-down on the Water Quality Constituents dialog.

## 4. Change Reach Distance Markers

For marking reach distances, QUAL2K assigns the tail of the river a distance of 0, and distance increases upstream. WEAP can measure reach distances either downstream or upstream, but in the previous module distance was measured downstream, opposite the convention for QUAL2K, so the reach distance markers must be changed when linking to QUAL2K.

To set the reach distance markers:

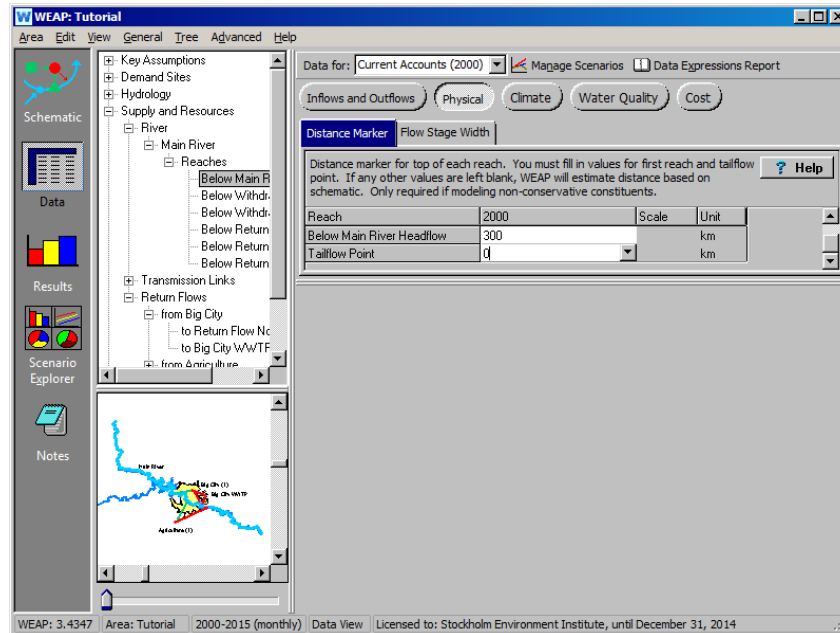
*Go to Data View*

*Navigate to the branch “Supply and Resources\River\Main River\Reaches\Below Main River Headflow.”*

*Click on the “Physical” button.*

*Select the “Distance Marker” tab. (This will only show up in Current Accounts: if you do not see it, switch to Current Accounts in the drop-down at the top of the page.)*

*Set the distance for “Below Main River Headflow” to 300 km, and the distance for “Tailflow Point” to 0 km.*



## 5. Set Dew Point and Cloud Cover

QUAL2K and WEAP use different climate parameters, so some additional climate parameters must be set for QUAL2K. When using QUAL2K for water quality calculations, WEAP changes the list of climate parameters automatically.

While each reach in QUAL2K can have a different climate, for most WEAP applications it is reasonable to assume that the climate is the same on all reaches. In this case, climate parameters only need to be set for the top reach, since for downstream reaches, upstream values are used by default. For this example, two climate parameters will be set: cloud cover and dew point.

Cloud cover is not a climate parameter in WEAP, so there is no corresponding value already in WEAP. For this example, assume that average cloud cover is 30% along the river. To set this:

*Navigate to the branch “Supply and Resources\River\Main River\Reaches\Below Main River Headflow”, if you are not already there.*

*Click on the “Climate” button.*

*Select the “Cloud Cover” tab.*

Type “30” for the value.

Dew point is used by QUAL2K instead of WEAP’s relative humidity parameter. Dew point,  $T_d$ , can be calculated from the air temperature,  $T$ , and relative humidity,  $h_r$  doing the following calculation. First, instead of using air temperature  $T$  directly, use  $x = T/237.7$ . Then calculate dew point using:

$$T_d = 237.7 [17.3 x + (1 + x) \ln h_r] / [17.3 - (1 + x) \ln h_r]$$

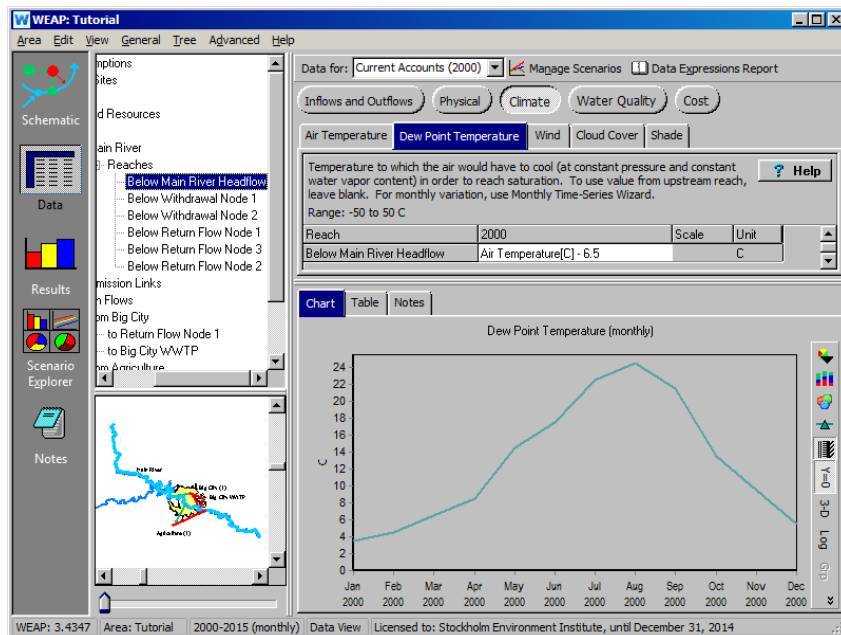
Using this formula, and the values for air temperature (which are different for each month) and relative humidity (65% for every month) in the Water Quality module file, it turns out that dew point is about 6.5°C below air temperature for all months. So, to set dew point:

*Navigate to the branch “Supply and Resources\River\Main River\Reaches\Below Main River Headflow”, if you are not already there.*

*Click on the “Climate” button.*

*Select the “Dew Point Temperature” tab.*

*Either use the Expression Builder or directly type in the formula “Air Temperature - 6.5”, and make sure the units are “C.” Do not type in the [C] as shown below – WEAP will populate that automatically.*



# Running Scenarios

## 6. Run Scenarios

Run the scenario by going to Results View and answering “Yes” to the dialog asking whether to recalculate.

Note that when using QUAL2K, running scenarios can take a long time. Consider reducing the number of scenarios that you calculate at any time.

QUAL2K will not run for months in which streamflow is zero at any point in the river. If this situation occurs in one or more scenarios, add a (small) minimum flow requirement on reaches for which QUAL2K is used to force a flow greater than zero. Here is the error message you might see: “*QUAL2K Error: Error Code 3. This error might be caused a streamflow of zero in the river, which QUAL2K does not allow. Perhaps use a flow requirement below to force a small flow at that point.*” Add a flow requirement to the river immediately upstream from the first return flow node (from Big City), and set the minimum flow requirement in Current Accounts to be 0.1 CMS. Re-run calculations.

## 7. Compare Results

When you have finished running your selected scenarios, compare the results with the results from the previous module. They should be similar, but not identical, because the built-in water quality calculations in WEAP make slightly different assumptions and use different approximations than QUAL2K.



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# WEAP

Water Evaluation And Planning System

# Hydrology

## A TUTORIAL ON

*Modeling Catchments: The Simplified  
Coefficient Method* ..... 178

*Understanding the Soil Moisture Method*..... 183

*Modeling Catchments: The Soil Moisture  
Method*..... 188

*Simulating Surface Water-Groundwater  
Interaction* ..... 194

October 2023

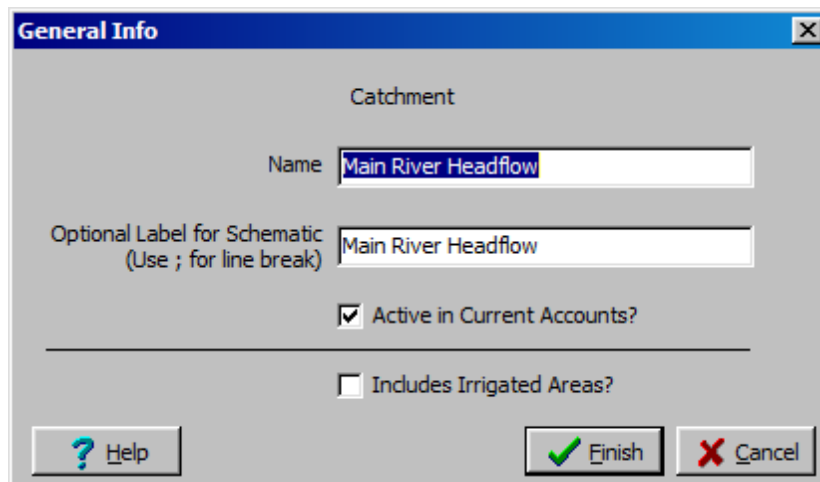
**Note:**

For this module you will need to have completed the previous modules (“WEAP in One Hour, Basic Tools, and Scenarios) or have a fair knowledge of WEAP (data structure, key assumptions, expression builder, creating scenarios). To begin this module, go to the Main Menu, select “Revert to Version” and choose the version named “Starting Point for all modules after ‘Scenarios’ module.”

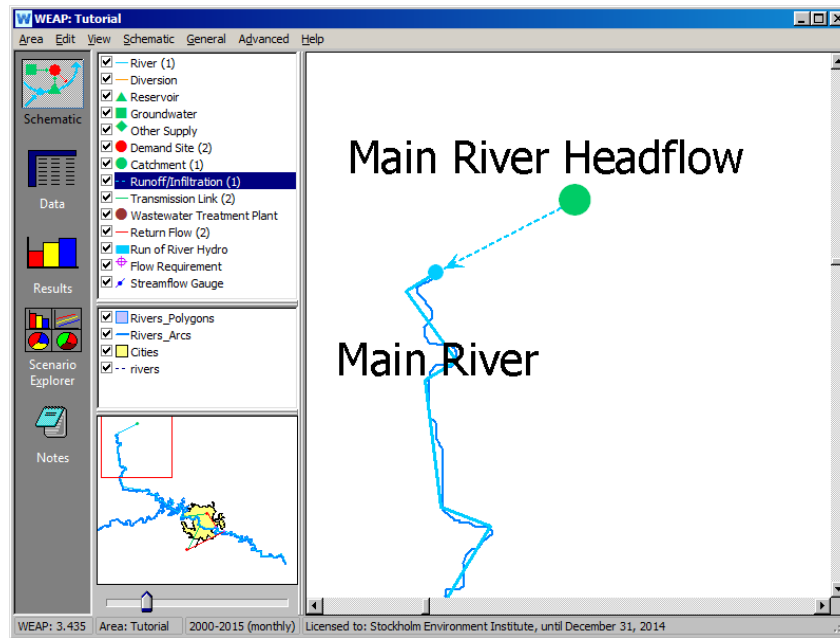
## Modeling Catchments: The Simplified Coefficient Method

### 1. Create a New Catchment

Create a “Catchment” object in the Schematic view to simulate headflow for Main River. Do this by pulling over a Catchment node and locating it near the starting point of the Main River. Name it “Main River Headflow.” Set it to be active in Current Accounts, and leave “Includes Irrigated Areas?” unchecked.

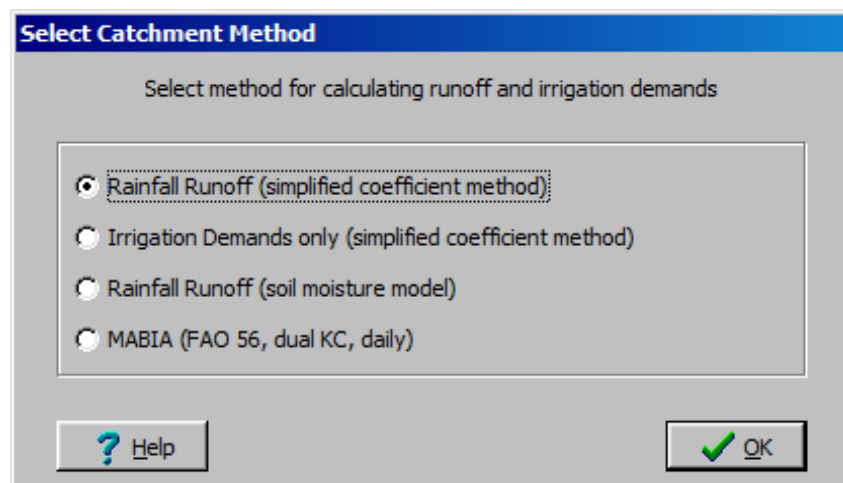


Next draw a Runoff/Infiltration path (dashed blue line) starting from the catchment into the beginning of the Main River.

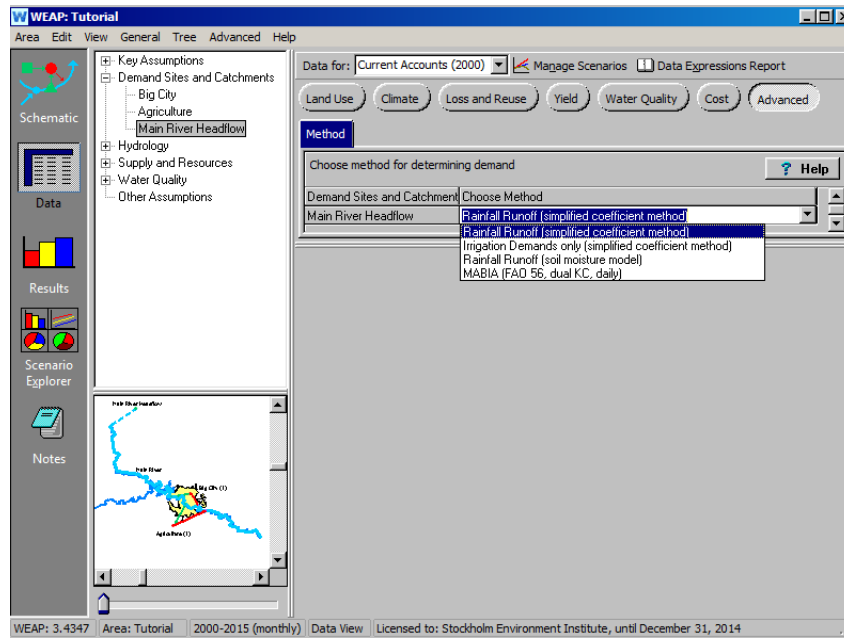


## 2. Create an Appropriate Substructure in the Basin

The first time you right click on the Catchment or select it in the Data Tree, you will get a window that asks you to select a model for the Catchment. Select *Rainfall Runoff (simplified coefficient method)*.

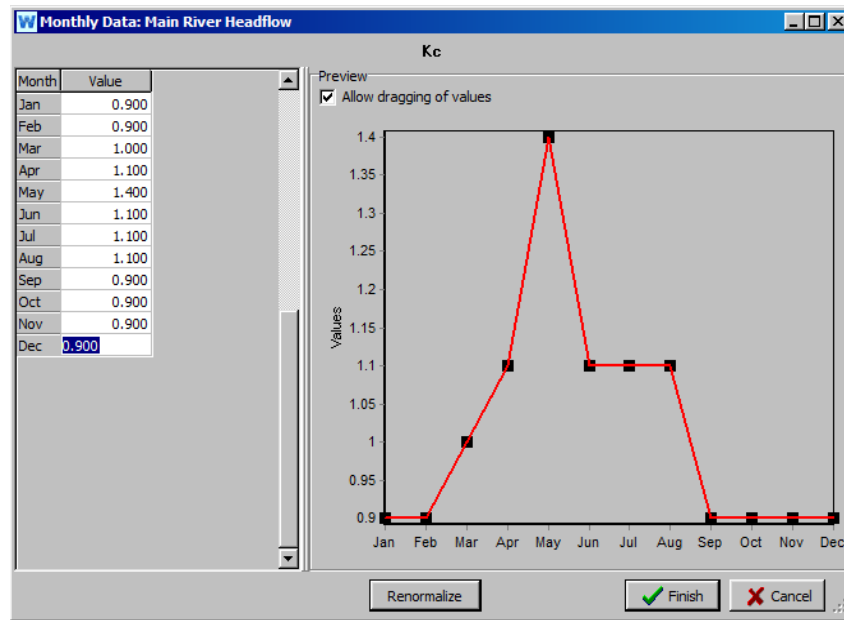


There is also the opportunity to change this selection later by clicking on the “Advanced” tab in the Data view:



In the Data View, select the new catchment under the “Demand Sites and Catchments” branch of the data tree. On the right, click on the “Land Use” button and enter the following data:

<i>Area</i>	<i>10M ha (you will have to choose the units first)</i>
<i>Effective Precipitation</i>	<i>98%</i>
<i>Kc (Crop Coefficients) (use the Monthly Time Series Wizard to input these data)</i>	
<i>Sep to Feb</i>	<i>0.9</i>
<i>March</i>	<i>1.0</i>
<i>April</i>	<i>1.1</i>
<i>May</i>	<i>1.4</i>
<i>Jun to Aug</i>	<i>1.1</i>



Note that if you had clicked “yes” when asked if irrigated areas were to be included in this catchment (under General Info when creating catchment), another button “Irrigation” would have appeared under the catchment in the Data view. This button would have two tabs under it: (1) “Irrigated”, where you would input either a “0” for not irrigated, or a “1” for irrigated for a particular land class; and (2) “Irrigated fraction” where you would specify the fraction of irrigation water supplied to the area that is available for evapotranspiration.

The Rainfall Runoff method is a simple method that computes runoff as the difference between precipitation and a plant’s evapotranspiration. A portion of the precipitation can be set to bypass the evapotranspiration process and go straight into runoff to ensure a base flow (through the “effective precipitation” parameter).

The evapotranspiration is estimated by first entering the reference evapotranspiration, then defining crop coefficients for each type of land use (Kc’s) that multiply the reference evapotranspiration to reflect differences occurring from plant to plant.



More information about this method can be obtained from the FAO Irrigation and Drainage Paper 56, called “Crop Evapotranspiration” and available from the FAO’s website ([www.fao.org](http://www.fao.org)).

Entering an effective precipitation other than 100% is one way of acknowledging the fact that part of the rainfall is not submitted to evapotranspiration during high intensity rainfall events, hence generating a minimal runoff to the river even when the rainfall is lower than the potential evapotranspiration. Another solution is to move to more developed models such as the 2-bucket soil moisture method coupled with Surface Water – Groundwater interaction modeling, as presented later in this module.

### 3. Enter the Climatic Data

Climatic Data are entered at the catchment level (Main River Headflow). Enter the following data under the “Climate” tab using the Monthly Time Series Wizard:

<i>Month</i>	<i>Precip.</i>	<i>ET<sub>ref</sub></i>
<i>Jan</i>	21	42
<i>Feb</i>	37	47
<i>Mar</i>	56	78
<i>Apr</i>	78	86
<i>May</i>	141	131
<i>Jun</i>	114	122
<i>Jul</i>	116	158
<i>Aug</i>	85	140
<i>Sep</i>	69	104
<i>Oct</i>	36	79
<i>Nov</i>	22	43
<i>Dec</i>	13	37



If not available from on-site stations, precipitation data can sometimes be derived from world-wide climate models such as the one developed by Tim Mitchell at the University of East Anglia (<http://www.cru.uea.ac.uk/~timm/data/index.html>). The use of GIS software to extract the appropriate data is required. Such models provide average data in opposition to actual data, implying that the calibration is much more delicate.

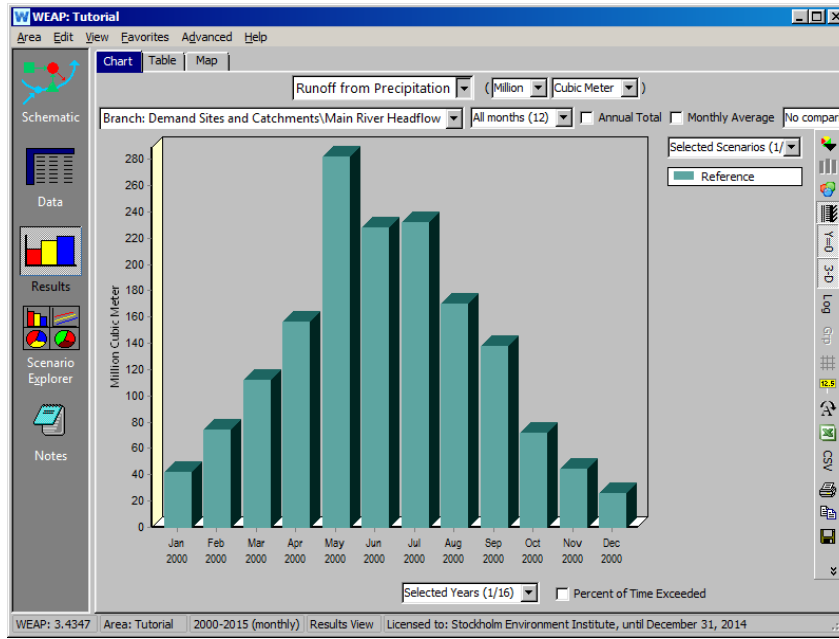
The Reference Evapotranspiration can be determined from a set of climatic and topographic parameters using the Penman-Monteith equation. More details are provided in the FAO publication mentioned earlier. Also, there exist global models of monthly reference evapotranspiration put together by the FAO, available from the FAO’s website.

### 4. Look at the Results

Results for Catchments are in the “Catchment” category in the primary variable pull-down menu.

“Runoff from Precipitation” to the Main River should look similar to the graph below.

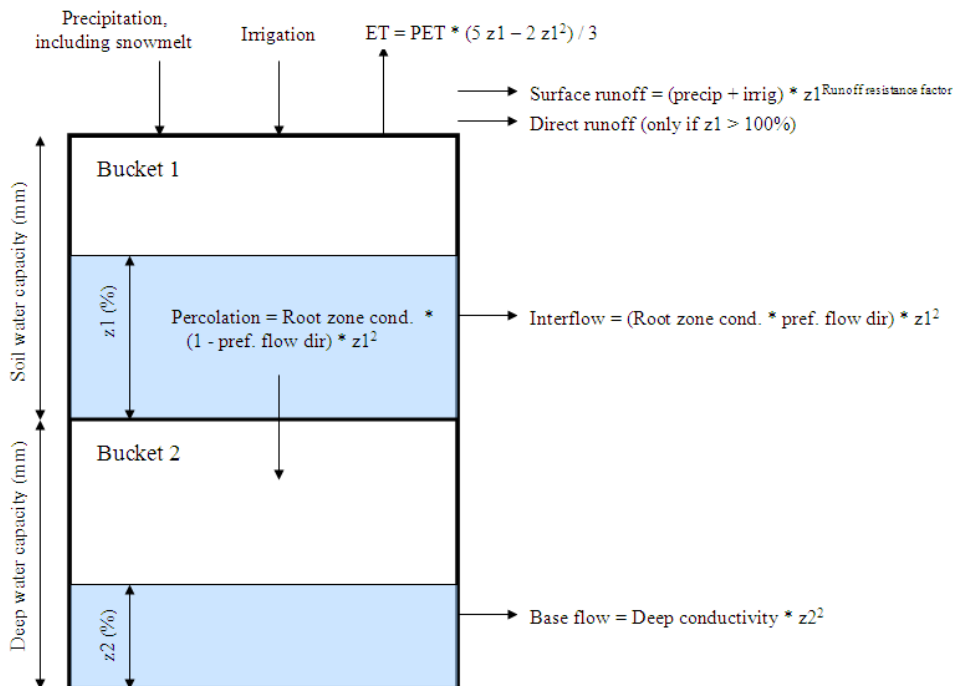
*Select “Selected Scenarios” from the pull-down menu above the graph legend and check off “Reference.” Select “Main River Headflow” as the Demand site/branch from the menu to the upper left of the graph, and the year 2000 from the “Selected Years” option using the menu at the bottom of the graph. Make sure it is for “All Months.”*



# Understanding the Soil Moisture Method

## 5. Physical Structure of the Soil Moisture Method

Below is a picture from the WEAP help menu (topic “Soil Moisture Method”). You can find more details about the calculations in the help menu, but the general parameter operations are summarized below.



The land use and climate parameters of the soil moisture method together determine how much water percolates into the earth, evaporates, or runs off to the river. The following parameters can be changed for each catchment in the Data view under Demand Sites and Catchments. Valid ranges for each parameter are provided in the Catchment Calibration chapter.

#### Land use: Surface parameters

- **Kc:** When it rains, how much water can potentially be evapotranspired by plants?
- **Runoff Resistance Factor:** Of the water that is not evapotranspired, do the conditions on the surface, such as leaf area and slope, encourage or discourage percolation?

#### Land use: Upper Bucket parameters

- **Root Zone Conductivity:** How fast does water move through the upper bucket?
- **Soil Water Capacity:** How much capacity (mm) does the upper bucket have to hold water?
- **Preferred Flow Direction:** As the water travels through the upper bucket, how much of it percolates into the lower bucket, and how much of it runs off and becomes streamflow?
- **Initial Z1:** How full (as a percent of the Soil Water Capacity) is the upper bucket when the model begins?

#### Land use: Lower Bucket parameters

- **Deep Conductivity:** How fast does water move through the lower bucket?
- **Deep Water Capacity:** What is the capacity (mm) of the lower bucket?
- **Initial Z2:** How full (as a percent of the Deep Water Capacity) is the lower bucket when the model begins?

Climate (No differentiation between upper and lower buckets or between different land uses. By default, each of these parameters is specified per catchment and can be further specified per timestep.)

- **Precipitation:** How much precipitation falls?

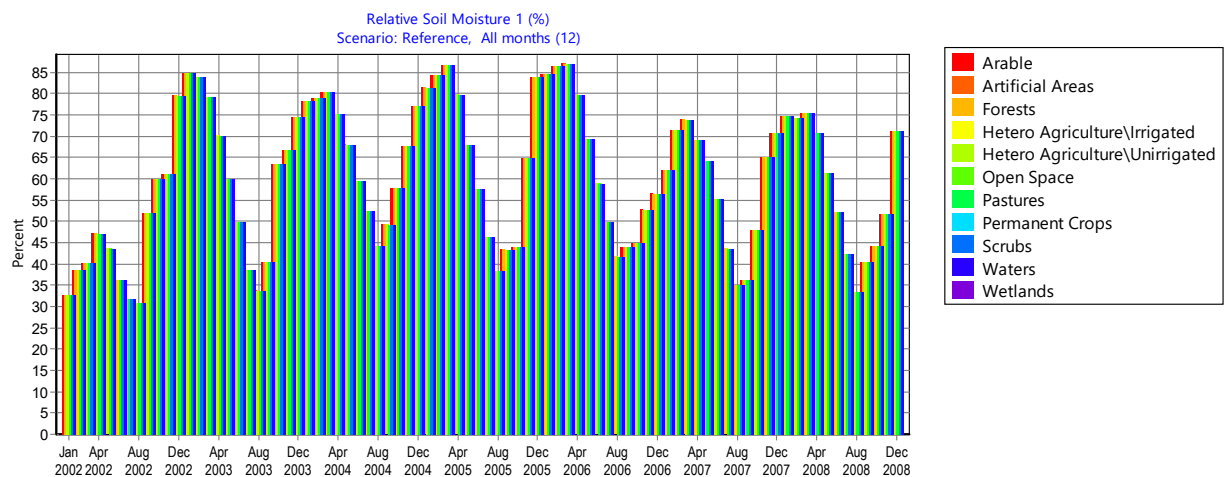


- **Temperature:** What is the average temperature?
- **Humidity:** What is the average relative humidity?
- **Wind:** What is the average wind speed?
- **Cloudiness Fraction:** What fraction of daytime hours are cloudless?
- **Latitude:** At what latitude is the catchment?
- **Freezing Point:** At what temperature does rain turn to snow?
- **Melting Point:** At what temperature does snow melt?
- **Albedo Lower Bound:** What is the albedo (percentage of sun reflected) when snow accumulation is 0?
- **Albedo Upper Bound:** What is the albedo when the snow accumulation is equal to or greater than 10 mm \* the number of days in the timestep? (e.g., 310 mm in January, 280 mm in February, etc.)
- **Albedo:** What is the albedo? (Use only when Albedo Lower and Upper Bound are left blank)
- **Initial Snow:** How much snow (melt water equivalent) is there at the beginning of the first timestep of the model?
- **Snow Accumulation Gauge:** Here you can input historical data of snow accumulation for the catchment, if available.

Irrigation (Note: The following parameters are only available if your catchment is specified to include irrigated areas. See *Modeling Catchments: The Simplified Coefficient Method* in the Hydrology chapter of the Tutorial. The first three parameters can be specified by land use.)

- **Irrigated Area:** Is the land use irrigated (100) or not irrigated (0)?
- **Lower Threshold:** At what soil moisture level should irrigation begin?
- **Upper Threshold:** At what soil moisture level should irrigation cease?
- **Irrigation Use of Runoff:** How much of the runoff can be captured and used for irrigation within the catchment?

- **Initial Z1** (*Data/Demand Sites and Catchments/Catchment Name/Land Use/Initial Z1*). Parameter only available in Current Accounts. In the Soil Moisture Method figure (above) of the upper and lower buckets, the blue area shows how full each bucket is (Z1 for the upper bucket, Z2 for the lower bucket). We need to set the initial conditions for the model, much like a reservoir, because the quantity of water already in the bucket will impact the model (read more about the mathematic expressions in the WEAP Help Menu). The example below shows a model with an initial condition for January 2002 that is likely too low, given the consistency of the other years.



Note that your value for the initial condition will only affect the model for the first year or so—after that, the model adjusts itself. This parameter has a range of 0-100%.

- **Initial Z2.** (*Data/Demand Sites and Catchments/Catchment Name/Land Use/Initial Z2*). The percent of soil moisture for the lower bucket should be relatively stable over time, so you can look at that result to make a guess at the initial condition. Range of 0-100%.
- **Freezing point.** (*Data/Demand Sites and Catchments/Catchment Name/Climate/Freezing Point*). The freezing point determines at what temperature rain becomes snow, delaying infiltration/runoff. This parameter is relevant only for watersheds with snow, and it affects the model only during the months with snow. The value (Celsius) should stay close to zero (WEAP's default value is  $-5^{\circ}$  Celsius).
- **Melting point.** (*Data/Demand Sites and Catchments/Catchment Name/Climate/Melting Point*). This parameter determines when snow turns to water, after which it is subject to all parameters controlling water flow in the catchment. Again, this parameter is only relevant and impactful during the winter and for watersheds

cold enough to have snow. The value should stay close to zero (WEAP's default value is 5° Celsius).

- **Albedo.** (*Data/Demand Sites and Catchments/Catchment Name/Climate/Albedo, .../Albedo Lower Bound, and .../Albedo Upper Bound*). Albedo is the fraction of solar radiation striking a land class that is reflected -- albedo increases as snow depth increases, and can also change over time as snow gets older and dirtier. New snow is very white, and has higher reflectance, whereas snow mixed with soil or dust will have lower albedo. In WEAP, the user can choose limits for high and low albedo values in the system.
- **Irrigated Area.** (*Data/Demand Sites and Catchments/Catchment Name/Irrigation*) Designate any irrigated land use areas. You can select 0% irrigated or 100% irrigated. Catchments with irrigated areas must be connected to water supplies (a river, a groundwater node, etc.) so they have somewhere to draw water from when irrigation is needed.
- **Upper threshold** [of irrigation]. (*Data/Demand sites and Catchments/Catchment Name/Irrigation/Upper Threshold*). This parameter represents the ideal value of soil moisture for the plants. In each time step, WEAP asks “is there enough water in the soil?” If there isn't “enough” (see description of Lower Threshold, below), WEAP will demand water from the connected supply to irrigate the catchment, aiming to provide enough water to reach the upper threshold of soil moisture (if it rains in the same time step, WEAP will probably overshoot the target). Note that all land use types have options for data entry of their upper threshold, but the data are only read by WEAP if the parameter **Irrigated Area** (defined above) is 100% for the respective land use type.
- The **Lower threshold** [of irrigation] specifies each irrigated land use type's tolerance for dryness. If, in a time step, the soil moisture is between the upper and lower threshold, then there is still “enough” soil moisture, and WEAP will not irrigate. WEAP will only irrigate if the soil moisture is lower than the lower threshold, and then it will irrigate as much water as it thinks it necessary to raise the soil moisture to the upper threshold.

To understand the dynamics of the Upper and Lower Thresholds a little bit better, consider the following situations:

Previous Timestep Value (%)	Upper Threshold Value (%)	Lower Threshold Value (%)	WEAP's Action
20 to 100	90	20	None. The soil moisture is tolerable for the plants.
0 to 19	90	20	WEAP provides enough water to raise soil moisture to 90%. Since the gap between 20% and 90% is quite large, this will probably be a large amount of water.
80 to 100	90	80	None.
0 to 79	90	80	WEAP irrigates to raise the soil moisture to 90%. This may be a little bit, if the soil moisture is 79%, or a lot, if the soil moisture is 10% (which would be unusual since it would have to have dropped to that value from the previous time step, which should also have had 80% or more soil moisture).
11 to 100	20	10	None.
0 to 9	20	10	WEAP irrigates up to 20% soil moisture.

Note that the percentage gap between thresholds might be the same (for example, both 80%-90% and 10%-20% have 10% gaps), but with a 10%-20% range, there are more soil moisture values that do not trigger irrigation, while an 80%-90% range will result in greater water needs to maintain prescribed soil moisture.

Similarly, the size of the gap matters—small gaps will produce more frequent irrigation demand (small amounts), whereas large gaps will produce infrequent irrigation demand of very large amounts.



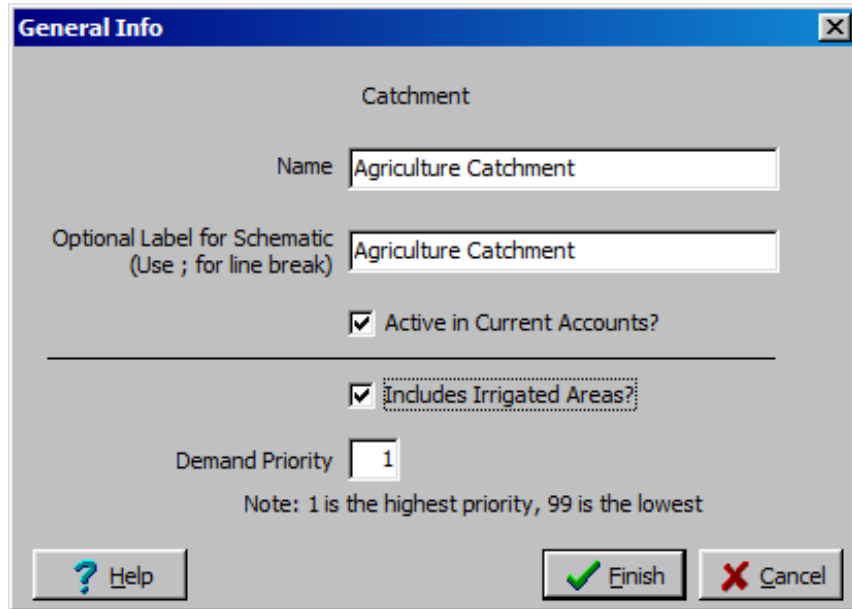
Some of these parameters are profoundly affected by the model time step. For example, the freezing and thawing of soil may occur over days, rather than months.

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## Modeling Catchments: The Soil Moisture Method

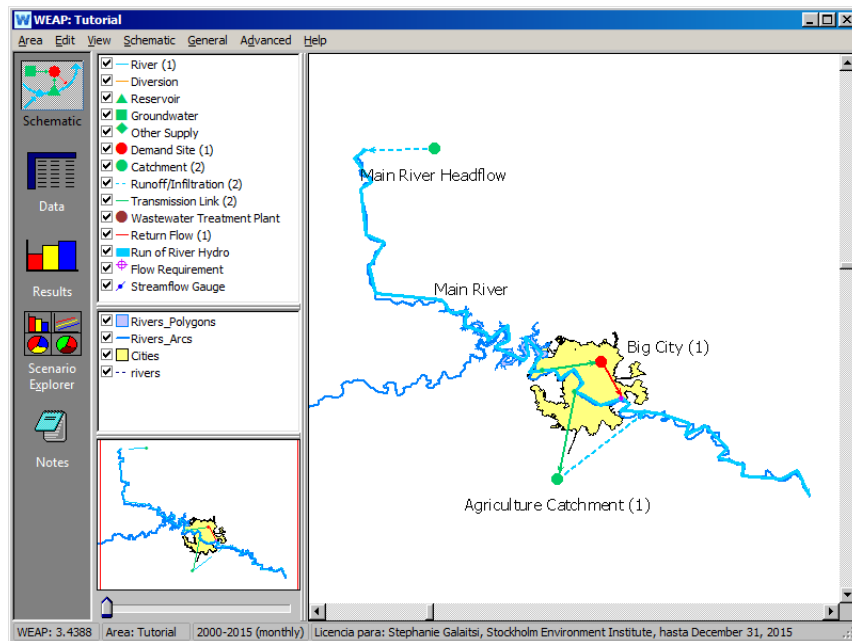
### 6. Replace the Agriculture Demand Site with a Catchment

Delete the Agriculture demand site and create a Catchment in its place. Name it “Agriculture Catchment” and set it Active in Current Accounts, Includes Irrigated Areas, and Demand Priority 1 (the demand priority only appears after you have selected “Includes Irrigated Areas”).



## 7. Connect the New Catchment

Draw a Runoff/Infiltration Link to the Main River below the Return flow node from the Big City. Add a Transmission Link from the Main River (same starting point as the former Agriculture demand site), with a *Supply Preference of 1*. Your model should now look similar to the figure below:





The purpose of this transmission link is to allow supplying irrigated areas with water from the river in case rainfall is insufficient.

## 8. Create sub-structure in the Catchment

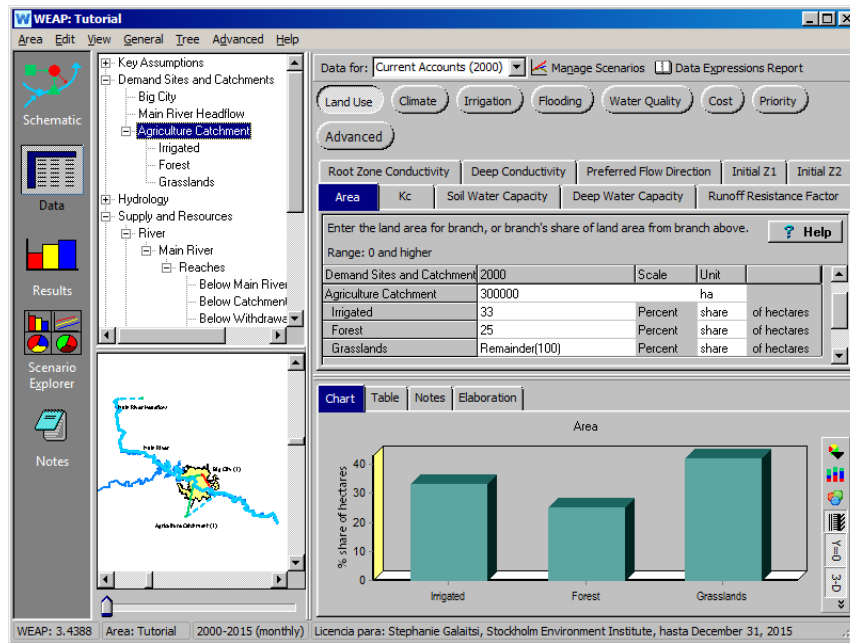
We will assume this catchment has three types of land use. In the Data View, add the following branches to your new catchment by right-clicking it in the data tree and selecting “Add.” (If you select the catchment for editing by right clicking on the node in the schematic view rather than going through the Data view, you will be asked beforehand to choose a simulation method - pick the “Rainfall Runoff (soil moisture method)” method). Add the following branches:

*Irrigated*  
*Forest*  
*Grasslands*

## 9. Enter the Appropriate Land Use Data

Select the Agricultural Catchment in the Data view and pick the “Rainfall Runoff (soil moisture method)” method by clicking on the “Advanced” button (click to the right of “Rainfall Runoff (simplified coefficient method)” and use the arrow to scroll down). Then enter the following data after clicking on the “Land Use” button:

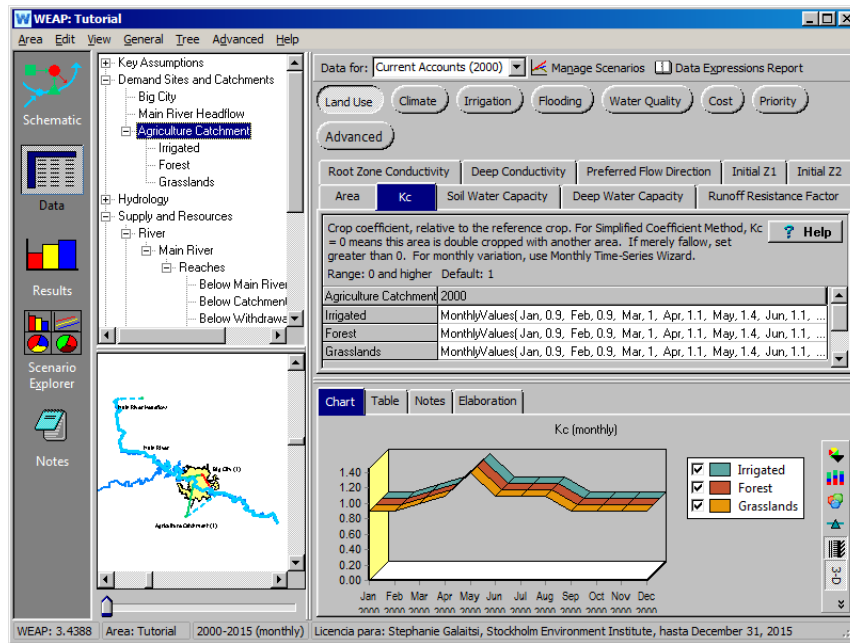
Total Land Area	300,000 ha (you will have to select units first)		
Share of Land Area	Irrigated 33%	Forest 25%	Grasslands Remainder(100)



	<i>Irrigated</i>	<i>Forest</i>	<i>Grasslands</i>
<i>Runoff Resistance Factor</i>	<i>3.6</i>	<i>3.0</i>	<i>1.7</i>
<i>Root Zone Conductivity</i>	<i>60</i>	<i>35</i>	<i>45 mm/month</i>
<i>Preferred Flow Dir.</i>	<i>0.15</i>	<i>0.15</i>	<i>0.15</i>
<i>Initial Z1</i>	<i>50%</i>	<i>20%</i>	<i>20%</i>

The remaining variables are the same for all land classes in the catchment:

<i>Initial Z2</i>	<i>20%</i>
<i>Soil Water Capacity</i>	<i>900 mm</i>
<i>Deep Water Capacity</i>	<i>35,000 mm</i>
<i>Deep Conductivity</i>	<i>240 mm/month</i>
<i>Kc</i>	<i>Use the same values as input for the Main River Headflow catchment in the previous exercise. You can simply copy and paste that expression into the Kc field for the Agriculture Catchment land classes.</i>



The Rainfall Runoff (soil moisture method) method has been developed to provide a simple yet realistic way of modeling hydrological processes with a semi-physical representation. Details about the method and its parameters, as well as calibration procedures, can be found in articles posted to the “publication” section of WEAP’s website ([www.weap21.org](http://www.weap21.org)). The related WEAP help topic provides a description of each parameter and an overview of the model as well. The parameter values displayed above are for illustration purposes only.

## 10. Enter the Appropriate Climate Data

In the same view as in the previous step, select the “Climate” screen and enter the following data:

<i>Precipitation</i>	<i>Use the same precipitation values as input for the Main River Headflow catchment in the previous exercise.</i>
<i>Temperature</i>	<i>MonthlyValues(Jan, 9, Feb, 12, Mar, 16, Apr, 21, May, 24, Jun, 27, Jul, 29, Aug, 29, Sep, 27, Oct, 22, Nov, 16, Dec, 11 )</i>
<i>Humidity</i>	<i>65%</i>
<i>Wind</i>	<i>1m/s</i>
<i>Latitude</i>	<i>30°</i>



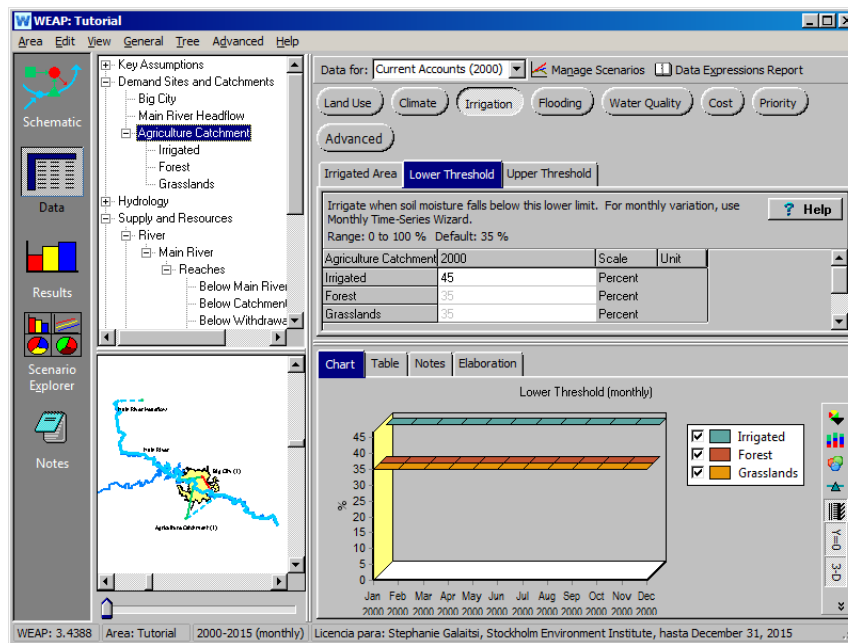
Data about snow coverage are not needed if the basin is not exposed to snow. WEAP determines the appearance of snow based on the temperature and the melting and freezing points parameters. If the last two are left empty, no snow will be allowed to accumulate.



## 11. Set up Irrigated Areas

In the same view as in the previous step, select the “Irrigation” screen and enter the following data:

	<i>Irrigated</i>	<i>Forest</i>	<i>Grasslands</i>
<i>Irrigated Area</i>	100%	0%	0%
<i>Lower Threshold</i>	45%	N/A	N/A
<i>Upper Threshold</i>	55%	N/A	N/A

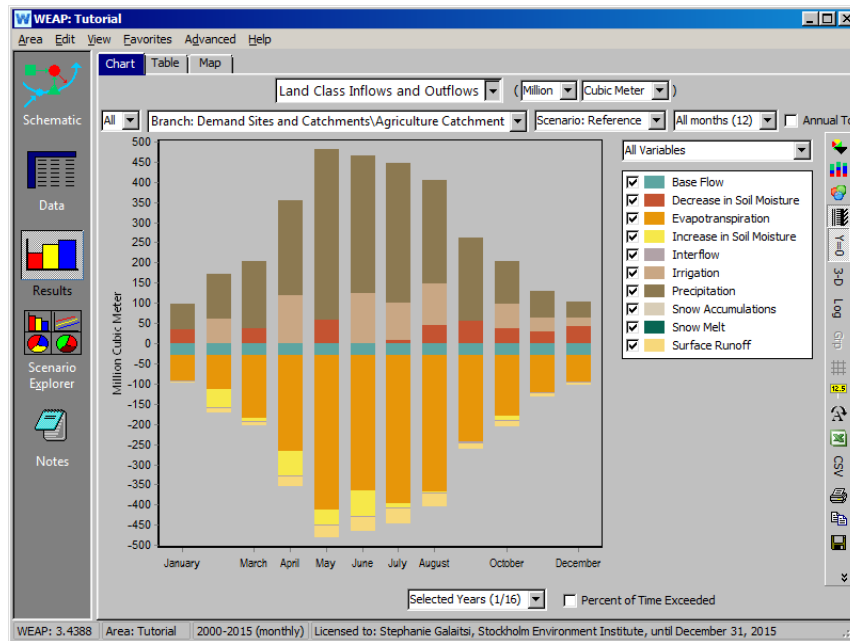


## 12. Look at Results

Look at the following results. Here again, the results are located in the “Catchment” category of the “Results” view.

*Select “Land Class Inflows and Outflows” under the primary variable pull-down menu. Click to view all variables above the chart legend. To view the “Irrigated” segment of the Agriculture catchment, select “Branch: Demand Sites and Catchments\Agriculture Catchment\Irrigated” from the pull-down menu to the upper left of the chart. Choose the year 2000 from the “Selected Years” option using the pull-down menu at the bottom and click on “Monthly Average” to the right of annual total (you may have to expand the screen to see it).*

“Land Class Inflows and Outflows” represents in a very detailed manner the water balance for each land use class. You should obtain a graph similar to the figure below for the “Irrigated” land class inflows and outflows graph:



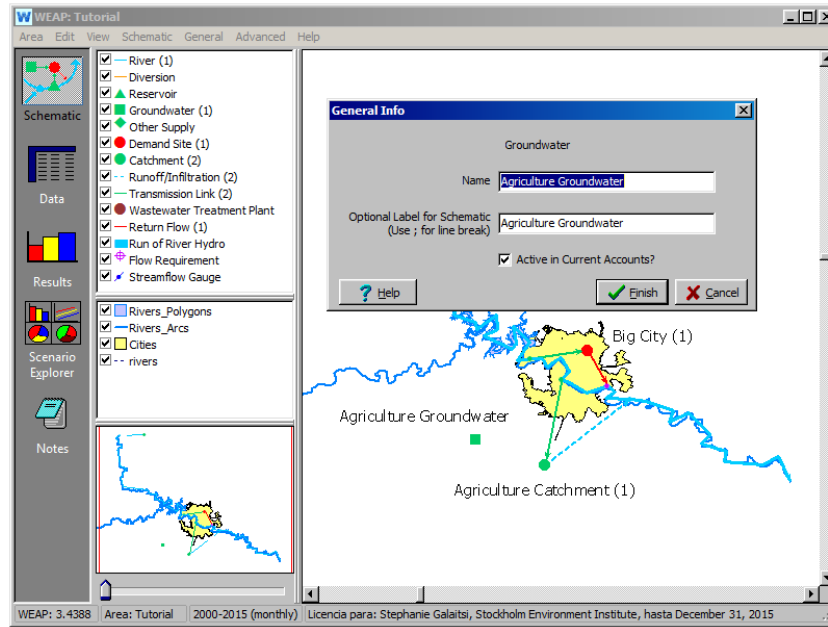
*Change the unit from Cubic Meter to mm. Depth units such as mm are typically more useful when examining or validating results catchment results. Note: you cannot change to a depth unit if “Monthly Average” is checked.*

You can also look at other parameters, such as “Soil Moisture in the upper bucket” (Relative Soil Moisture 1 (%)).

## Simulating Surface Water-Groundwater Interaction

### 13. Create a Groundwater Object

*Create a new “Groundwater” node next to the Agriculture Catchment that you created in the previous exercise. Name it “Agriculture Groundwater.”*



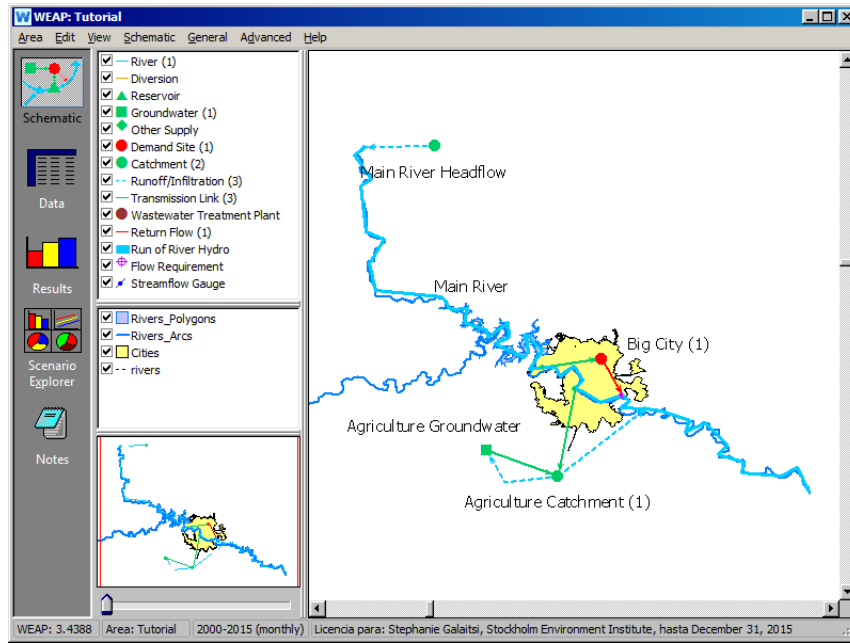
## 14. Connect the Groundwater Object to a Catchment

Create the following connections:

*Transmission Link from Agriculture Groundwater to Agriculture Catchment (Supply Preference 1)*

*Infiltration/Runoff Link from Agriculture Catchment to Agriculture Groundwater.*

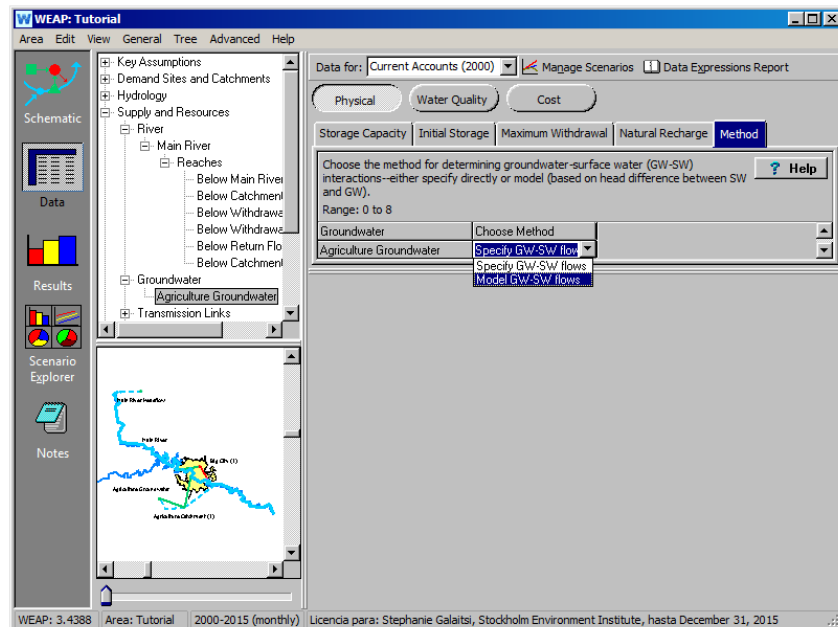
Your model should look similar to the one below:



You can also create the Infiltration/Runoff Link between the catchment and the groundwater node by right-clicking the catchment in the Schematic View, selecting “General Info” and then choosing the groundwater field in the “Infiltration to” drop-down menu.

## 15. Enter the Appropriate Data

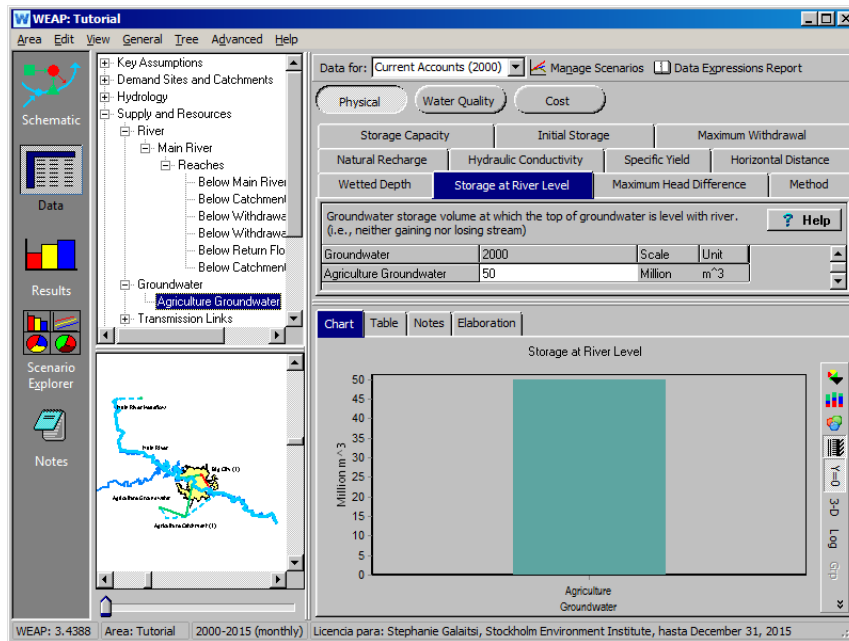
*In the Data View, select Agriculture Groundwater, examine the “Physical” screen and select the “Model GW-SW flows” method from the “Method” tab.*



Switch to the “Water Quality” window and then back to the “Physical” window for the change to take effect (you will now see several new tabs in the “Physical” window. If these do not populate, make sure you are in current accounts).

*Enter the following data (leave blank if nothing is specified) under the appropriate tabs:*

<i>Initial storage</i>	<i>50M m<sup>3</sup></i>
<i>Hydraulic Conductivity</i>	<i>10m/day</i>
<i>Specific Yield</i>	<i>0.1</i>
<i>Horizontal Distance</i>	<i>260m (the extent of the aquifer perpendicular to the river )</i>
<i>Wetted Depth</i>	<i>5m</i>
<i>Storage at River Level</i>	<i>50M m<sup>3</sup></i>

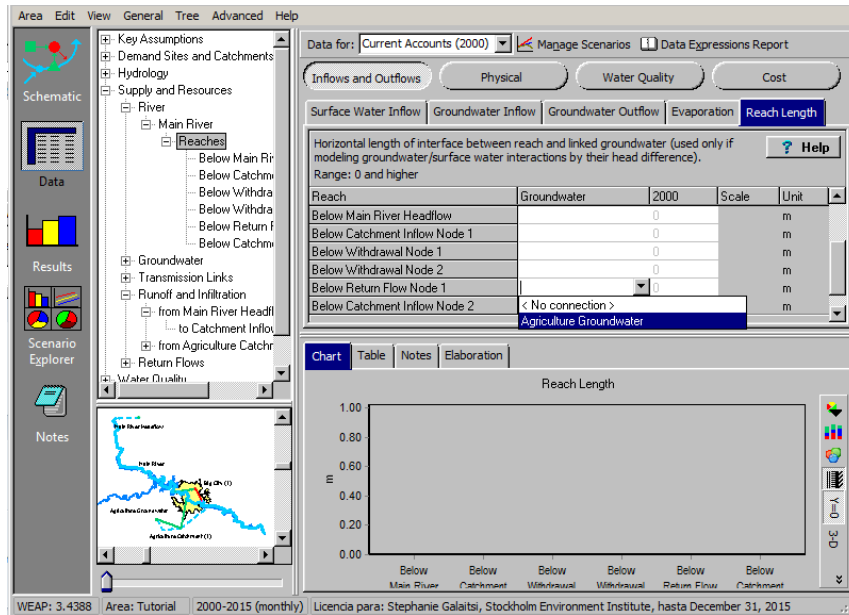


## 16. Select the Reaches that Interact with the Aquifer

*In the Data View’s tree, expand all the reaches of the Main River by clicking on the “+” icon next to it in the “Supply and Resources\River” branch. Select the reach that is below the return flow node from Big City (Return Flow Node 1; you might have to switch to the Schematic view and right-click on the nodes to find the name of that node in your model). Then enter the following data in the “Reach Length” tab for this reach:*

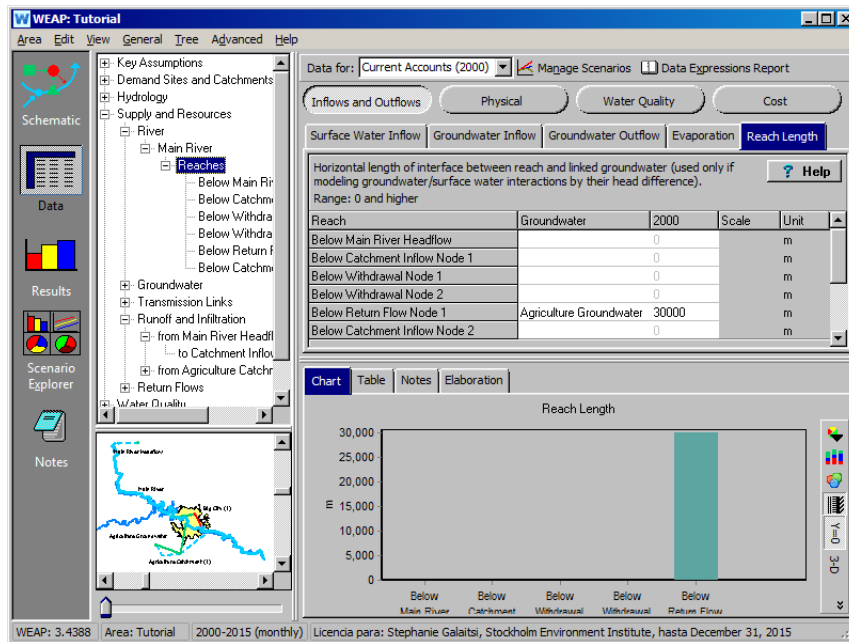
*Groundwater*

*Select “Agriculture Groundwater”*



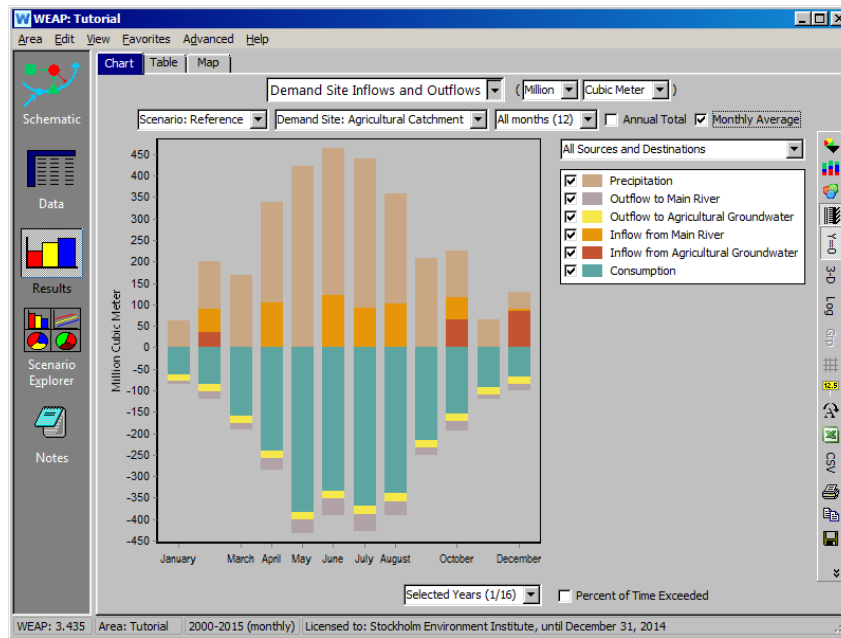
*Reach Length*

*30,000 m*



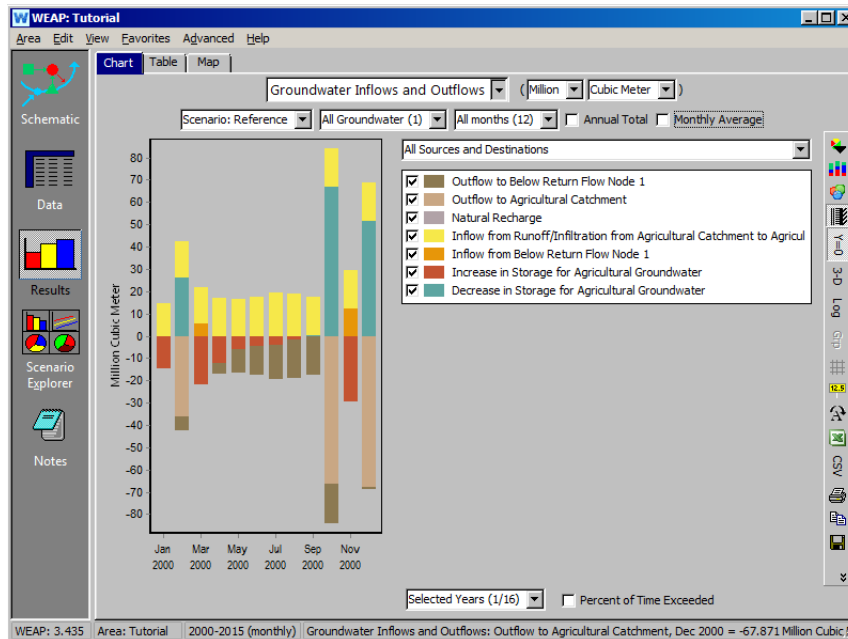
**17. Look at the Results**

*Look at the “Demand Site Inflows and Outflows” in Demand for the Agriculture catchment and select “All Sources and Destinations” for the year 2000.*



Note that these results include “Inflow from Agriculture Groundwater” (due to the designation of the Agriculture Groundwater node as a source to supply irrigation water for the Agriculture Catchment) and “Outflow to Agriculture Groundwater” (due to the creation of a runoff/infiltration link between the two nodes).

*Look also at “Groundwater Inflows and Outflows” (under Supply and Resources\Groundwater) for the year 2000.*





Note that the “Inflow from Upstream” category indicates infiltration of Main River water to Agriculture Groundwater along the river reach you selected earlier. Likewise, “Outflow to Downstream” represents groundwater seepage into the Main River.

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*Look now at the height of groundwater above the river stage. This can be viewed by selecting “Supply and Resources\Groundwater\Height Above River” from the primary variable pull-down menu. Choose “Agriculture Groundwater” from the “Selected Aquifers” option in the pull-down menu above the chart legend.*

---



Note that in the month where groundwater seepage to the Main River occurs (February), the groundwater elevation is higher than the wetted depth of the river as designated in the data (i.e., the difference in elevations is positive). Likewise, when Main River infiltration to groundwater is occurring, the elevation difference is negative.

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# WEAP

Water Evaluation And Planning System

# Catchment Calibration

## ***A TUTORIAL ON***

<i>Gather Observed Data and Select the Model Calibration Locations .....</i>	<i>202</i>
<i>Complete Observed Data and Select the Model Calibration Period .....</i>	<i>204</i>
<i>Visually Assess Model Calibration .....</i>	<i>211</i>
<i>Adjust key parameters and conduct model sensitivity analysis .....</i>	<i>220</i>
<i>Optimize calibration based on visual and statistical assessment.....</i>	<i>236</i>
<i>Model Calibration Tips.....</i>	<i>250</i>

**October 2023**

**Note:**

For this module you will need to have completed the previous modules (WEAP in One Hour, Basic Tools, and Scenarios) or have a fair knowledge of WEAP. It is also a good idea to have completed or reviewed the Hydrology module. To begin this module, go to the Main Menu, select “Revert to Version” and choose the version named “Starting Point for Catchment Calibration Tutorial.”

In this activity, we will demonstrate how to hydrologically calibrate a WEAP model using Rainfall Runoff (soil moisture method) that was introduced in the Hydrology module. The other four catchment methods: Rainfall Runoff (simplified coefficient method); Irrigation demands only (simplified coefficient method); MABIA; and Plant Growth are not covered here. However, many of the same principles apply.

The importance of calibration cannot be overstated. Models represent real-world systems to enable researchers and decision makers to ask questions about the future. A model that does not adequately represent the past will not adequately represent the future, and therefore should not be used to guide decisions in the real world. To ensure that model simulations approximate reality, WEAP models should be calibrated.

The main principal steps used to calibrate a model are:

- 1) Gather observed data and select model calibration locations
- 2) Complete observed data and select the model calibration period
- 3) Visually assess model calibration
- 4) Adjust key parameters and conduct model sensitivity analysis
- 5) Optimize calibration based on visual and statistical assessment

Once the model is calibrated hydrologically calibrate it operationally, adding in major demands and reservoirs and including data on withdrawals, reservoir elevations, groundwater elevations, and downstream flow gauge data.

## Gather Observed Data and Select the Model Calibration Locations

### 1. Gather Observed Data

Note that the principal outcome we used to assess model calibration for WEAP is observed streamflow. The calibration may also include historical observations (or estimates) of snowpack, evapotranspiration, reservoir

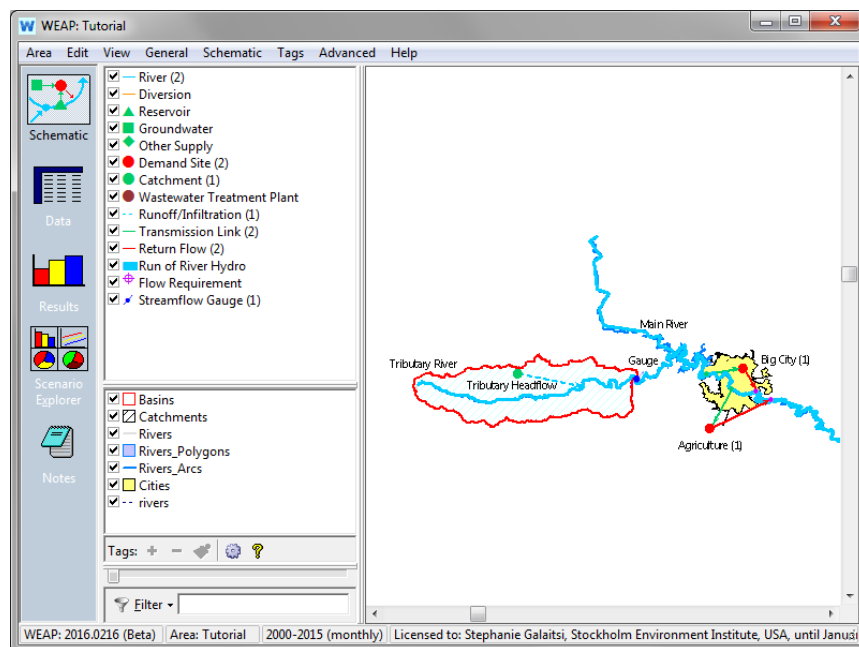
storage, groundwater recharge, and/or groundwater elevation. For this exercise we will look only at streamflow.

For hydrological calibration of the model, ideally begin with unimpaired streamflow data (upstream of major withdrawals or reservoirs) for a 10-year period on a monthly, weekly or daily time step that matches available climatic data, to ensure that the model is calibrated for wet, average and dry years. In this example, we have gathered observed unimpeded monthly streamflow data at the location of “Gauge” as well as monthly climate data for the corresponding catchment. After gathering the data, we saved a file with the data in csv format in the WEAP Areas folder of the project (Tutorial\additional files\SMMdata.csv).

## 2. Select Model Calibration Location(s)

The Schematic View includes a WEAP Catchment object and a shapefile of the catchment area generated using WEAP’s automatic catchment delineation mode.

A catchment is determined by elevation, where the borders of the catchment create a rim of high elevation points that water flows cannot cross. Thus, a catchment denotes an area of land where all surface water from rain, melting snow, or ice converges to a single point at the area’s lowest elevation, known as the “pour point” or “discharge point.” It is this point that determines the shape of a catchment, since a point further downstream would be lower elevation, and thus include a larger area that discharges into it.



In this example, our calibration location is at “Gauge” and we have designed the catchment’s downstream boundary to be at the same point. This way, the catchment’s modeled flow, when calibrated, should match the historical data from the gauge. We have intentionally chosen a gauge location and historical period without upstream demands or reservoirs (unimpaired flows).



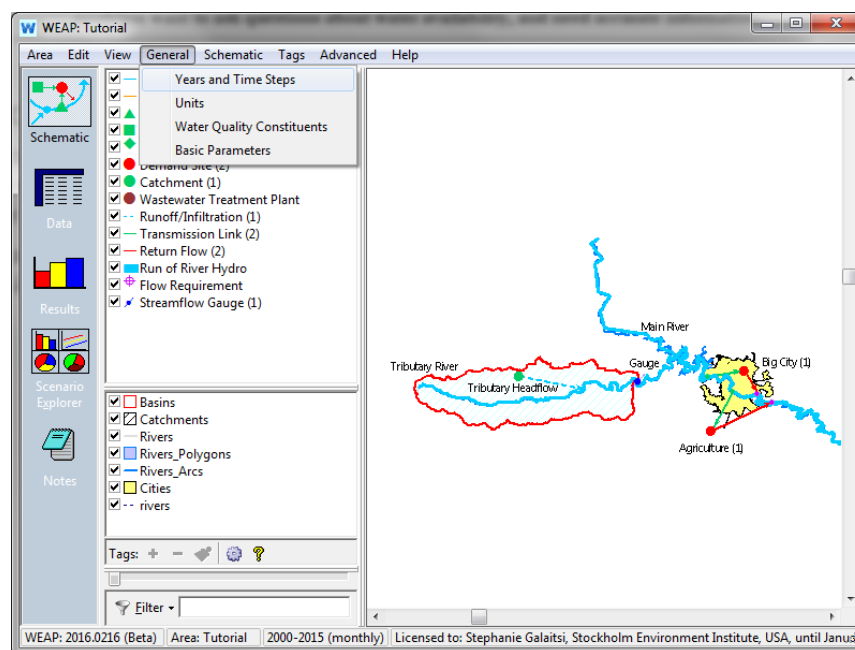
Neither the schematic location of the catchment node nor of the pour point of “Tributary Headflow” affect the flow calculation by WEAP, because WEAP models flow by inputs and outputs. The area of the catchment, over which precipitation falls and accumulates, has a direct impact on catchment hydrology, including inflow to the river. Catchment downstream boundaries should be carefully positioned to allow the model to examine the specific points of interest: the places where modelers need accurate streamflow information.

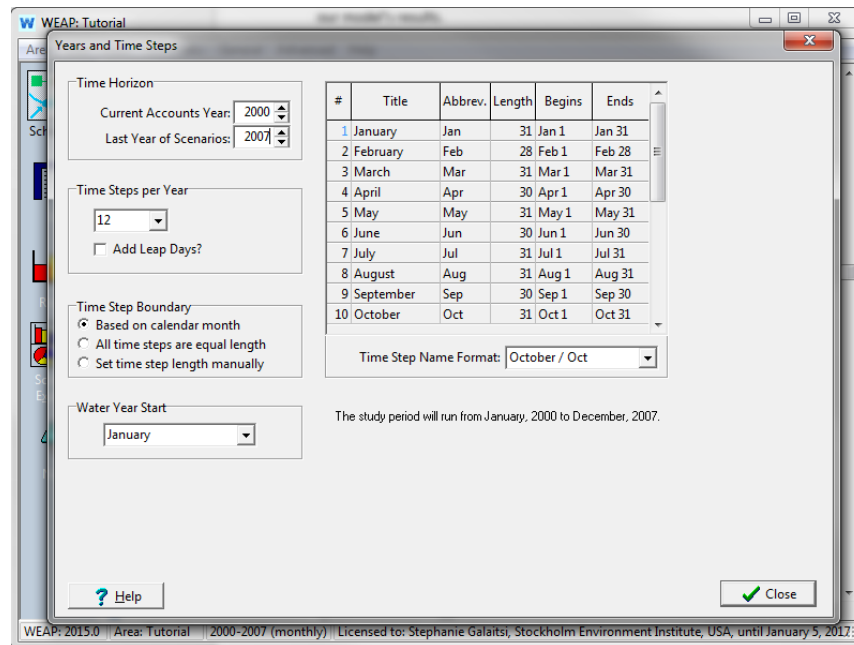
## Complete Observed Data and Select the Model Calibration Period

### 3. Change the Model Timestep

To calibrate our model, we have historical monthly streamflow and climate data available for the years 2000 to 2007. This will be our calibration period. Change the years of the model to match the calibration period.

*Go to Main Menu > General/Year and Time Steps, and change the Time Horizon to be 2000-2007.*

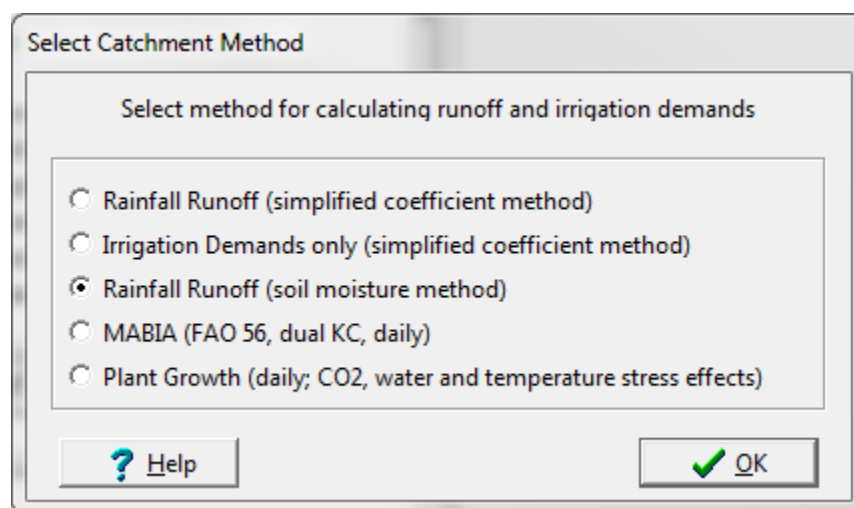




Keep in mind that when you change the initial modeling year (the current accounts year) the initial conditions—for example Population and Land Use—of your model may need to be altered.

#### 4. Select the Catchment Modeling Method

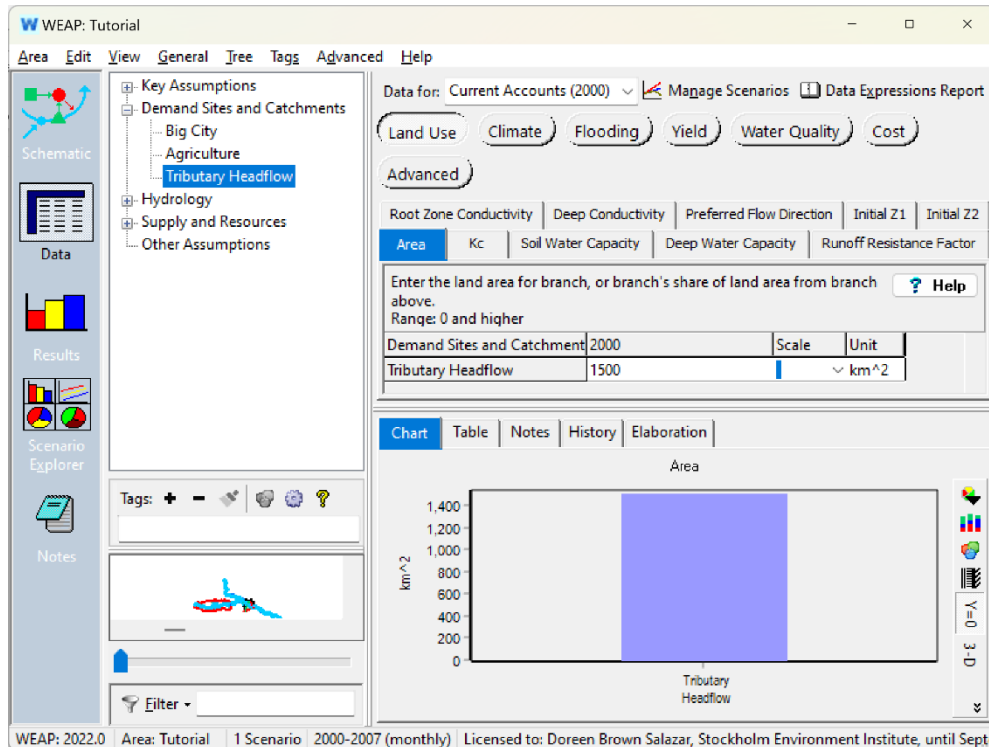
Go to the Data View and click on **Demand Sites and Catchments/Tributary Headflow**. In the window that appears, select the third option for catchment method: “Rainfall Runoff (soil moisture method).”



## 5. Enter the Data

Prior to calibration, it is important to complete observed streamflow data, land use, latitude, precipitation, temperature, and snow accumulation gauge for the time period used for calibration, as they impact model results.

*For the “Tributary Headflow” catchment, under the Land Use category, and the Area tab, enter the value 1500 and set the units to km<sup>2</sup>.*



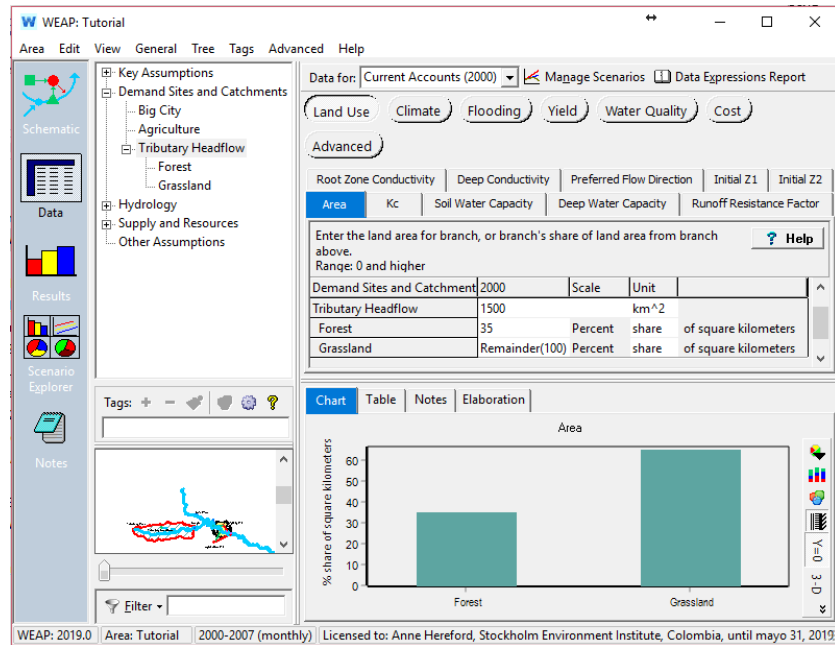
The screenshot shows the WEAP software interface. The 'Area' tab is selected, and the 'Tributary Headflow' catchment is highlighted in the Data View tree. The 'Area' tab is selected, and the value '1500' is entered in the 'Tributary Headflow' field with units set to 'km<sup>2</sup>'. A chart below shows a blue bar representing the area for 'Tributary Headflow'.

Add forest and grassland land cover designations to your catchment.

*Right click on the catchment Tributary Headflow in the Data View tree, select “Add,” and type in the name of your land cover subdivisions: one for forest and one for grassland.*

*Select the units for both to be share [of square kilometers]. Enter a Forest Area of 35%. (Just enter 35 without the percent sign.) Use the Remainder function (which you can type or look up in the Expression Builder) to tell WEAP that the remaining area is grassland. It should read Remainder(100).*

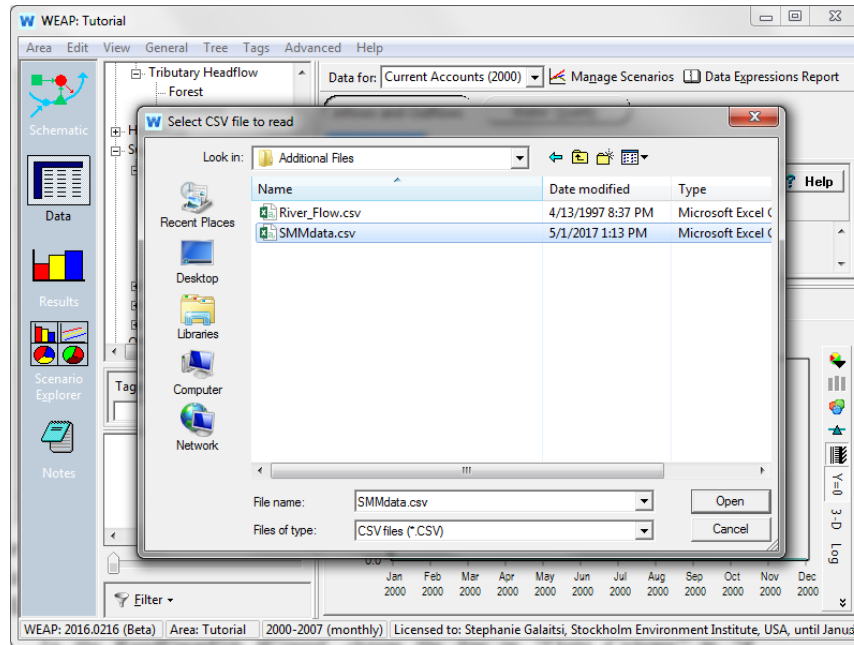
When you have completed these steps, your data and data tree should look the same as below.



*In the Data View, navigate to the Gauge's Streamflow Data (**Supply and Resources/River/Tributary River/Streamflow Gauges/Gauge**).*

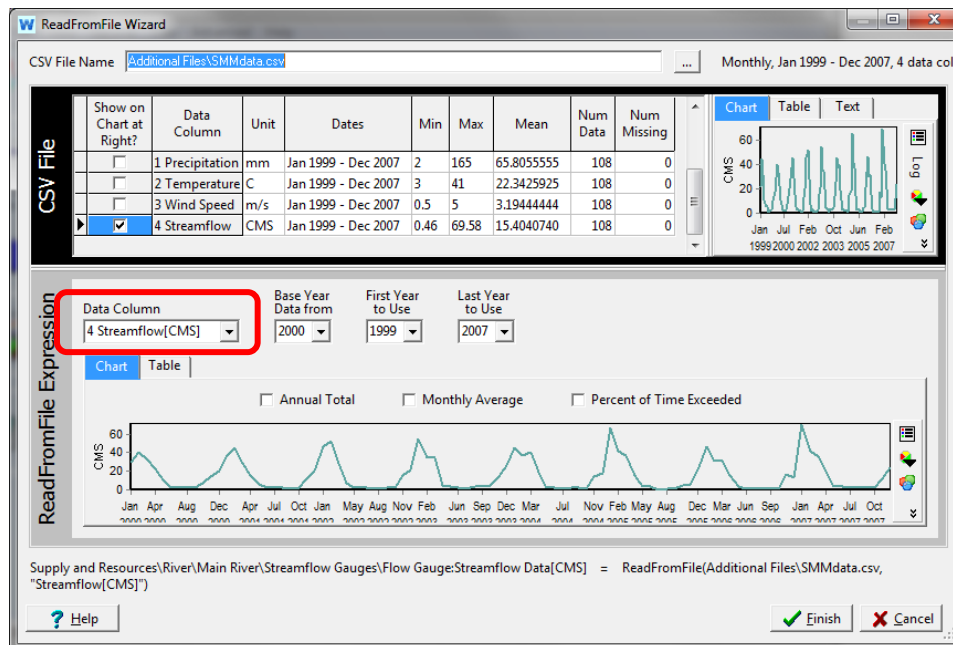
The streamflow gauge does not affect WEAP's calculations; its data are historical observed streamflow from the basin represented in the model. The value of a historical model is the ability to plug in recorded data from the past to compare with data simulated by the model. Historical data can be formatted into a .csv file for upload into WEAP.

*In the Gauge, under **Inflows and Outflows**, click on the white space under the year "2000" and select ReadFromFile Wizard from the dropdown menu. Select the SMMdata.csv file from the Additional Files folder.*



The SMMdata.csv file contains four columns of historical data: Precipitation, Temperature, Wind Speed and Streamflow. We need to make sure the correct information is displayed for the streamflow gauge data.

*In the lower section of the ReadFromFile Wizard, change the line in Data Column to “4 Streamflow[CMS],” and then click the Finish button.*

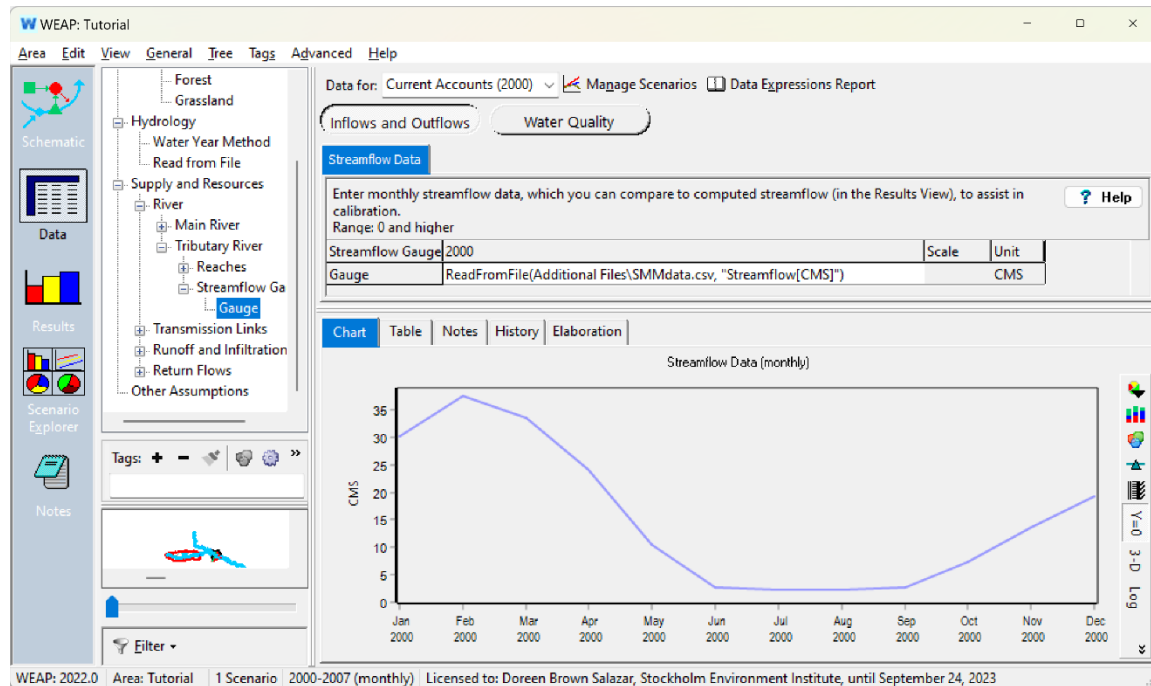






The SMMdata.csv file contains a directive at the top that tells WEAP how to label the different data columns: the text `$Columns = Precipitation[mm], Temperature[C], Wind Speed[m/s], Streamflow[CMS]` tells WEAP the names and units of each data column. For more information about the ReadFromFile Wizard, see the ReadFromFile Wizard video at [www.WEAP21.org/videos](http://www.WEAP21.org/videos).

Your screen should look like this:



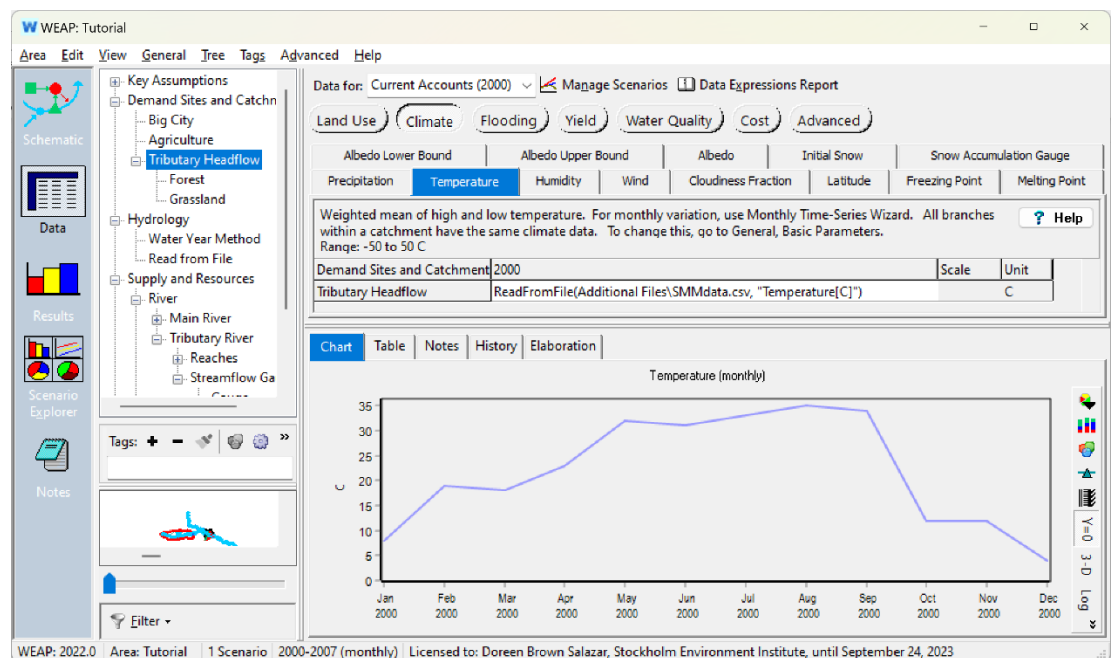
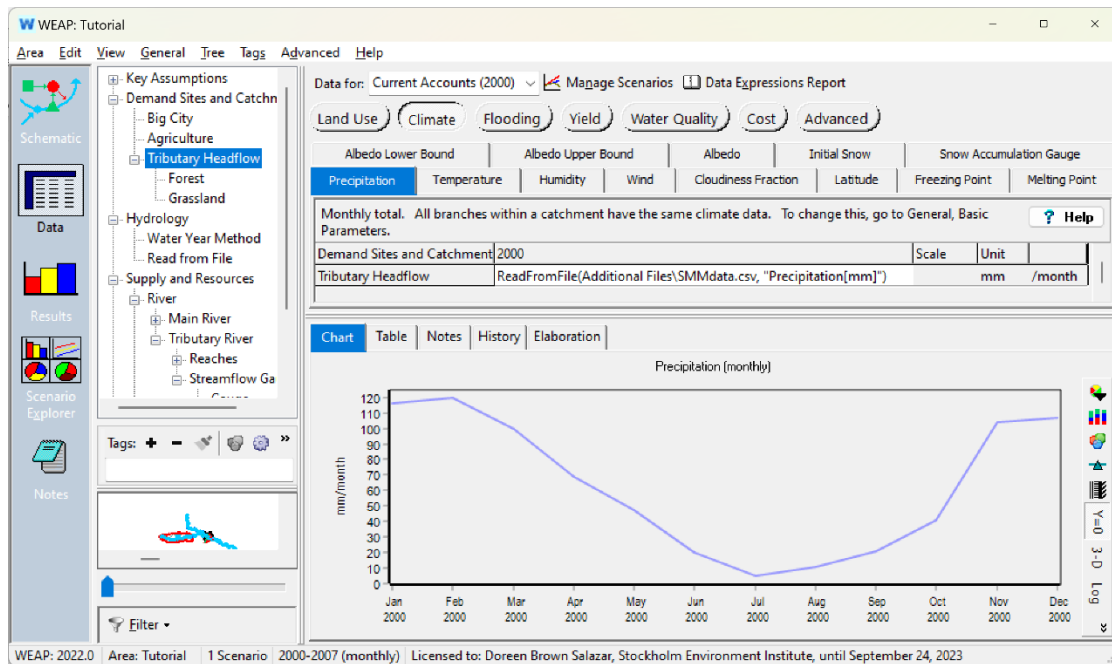
Now we must enter the remaining data in the SMMdata file as climate data for the Tributary catchment. The data are assumed to be representative of the entire catchment, with the exception of some land use data which are specific to certain land use types.

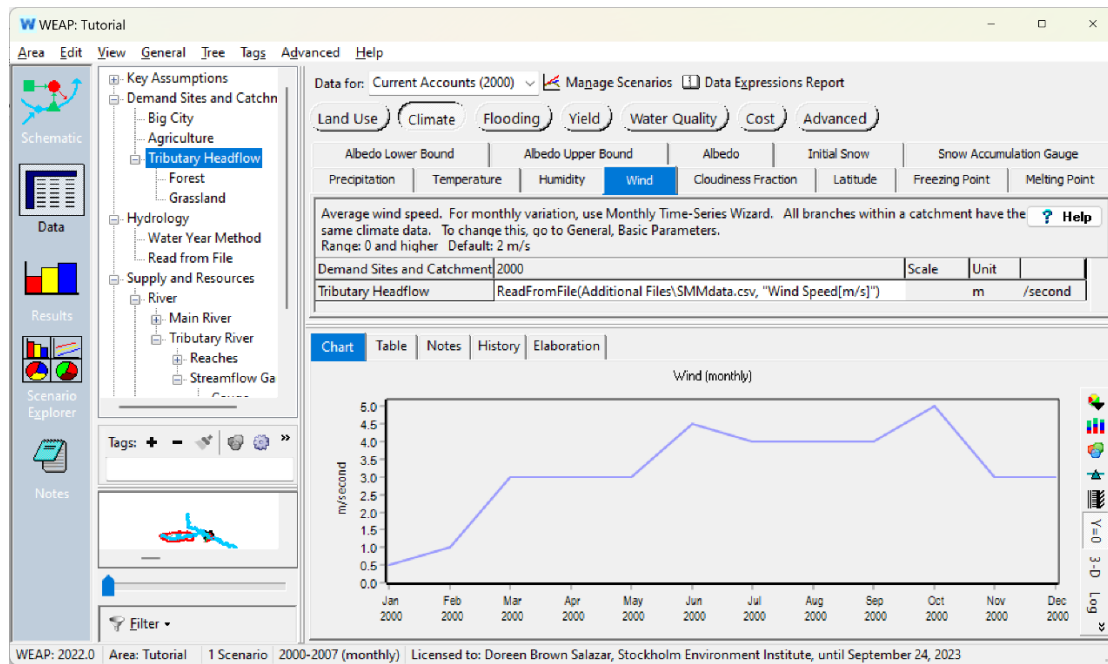


Meteorological stations measure climatic variables such as precipitation, temperature, and windspeed at the location of the station. However, WEAP requires these data to characterize the whole catchment. When possible, it is best to gather data and locations for as many stations as possible. This allows the user to calculate an average value for the whole catchment for each parameter for each time step. In this example, the climatic data in the SMMdata.csv file are assumed to already have been interpolated.

*In the Data View, navigate to the Tributary Headflow catchment under the Climate category to view the climate data. Use the same ReadFromFile Wizard and the SMMdata.csv file to import precipitation, temperature and wind speed data in the Tributary Headflow catchment.*

Always double check the units in your file are the same units that WEAP is using and remember to indicate the correct column. Verify that your graphs match the following graphs.





The *SMMdata.csv* dataset does not include relative humidity. You can use the monthly time series wizard if you have average monthly values for the catchment, but here we will use just one value for the whole year.

*Humidity*                      35 (%)

Finally, WEAP needs to know the latitude of each catchment to estimate potential evapotranspiration. Enter a value of 30.

*Latitude*                        30 (degrees north)

## Visually Assess Model Calibration

Input parameters used by the Soil Moisture Method are discussed in detail in the previous chapter of the Tutorial (Hydrology). The land use and climate parameters are based on historical data and not used for calibration. The default values used by WEAP for the remaining parameters, along with a brief summary of how they impact the model are listed in the following table. As described further in this chapter, the parameters that have the most impact on model calibration are the six shallow soil land use parameters: soil water capacity, runoff resistance factor, Kc, preferred flow direction, root zone conductivity, and initial Z1.

Do not make any adjustments in default values for calibration parameters for now to view the results of an initial, uncalibrated model.

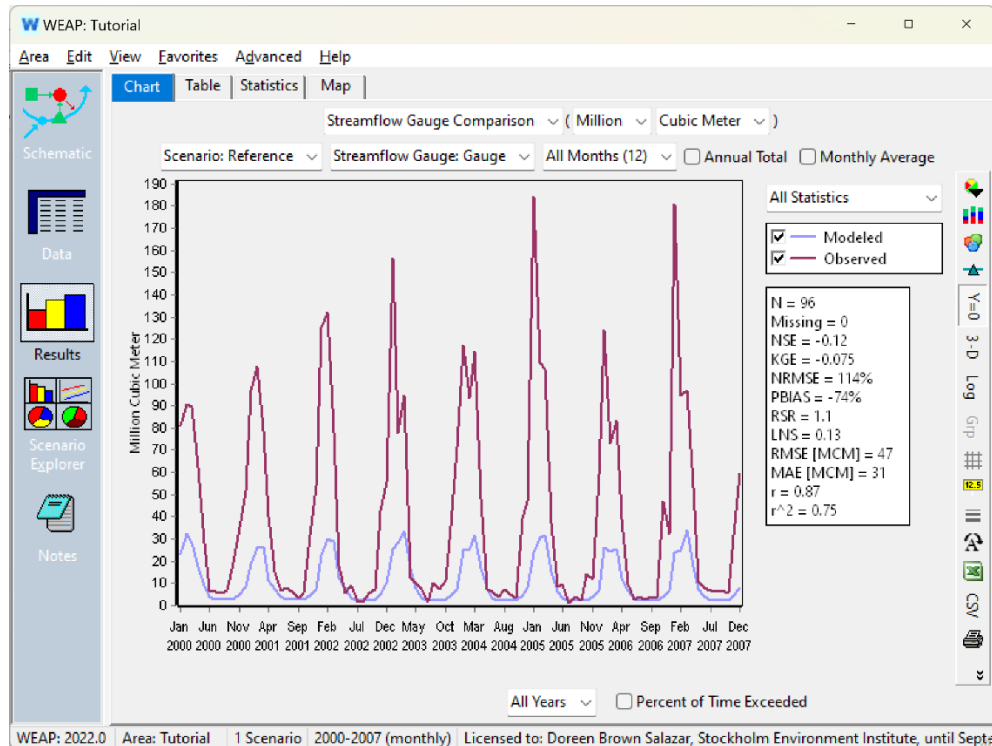
	Parameter	Default Value	Valid Range	Impact on Model
Land Use	<b>Kc</b>	1	0 – ∞	Increasing parameter leads to more evapotranspiration, and thus less water contributing to streamflow.
	<b>Runoff Resistance Factor</b>	2	0 – ∞	Increasing parameter routes less water to streamflow as it instead percolates into the soil. While it is in the soil, more evaporation is possible, and thus less water contributing to streamflow.
	<b>Root Zone Conductivity</b>	20 mm/month	0 – ∞	Increasing parameter shortens travel time for any water in the upper bucket (less evaporation possible, less loss of water from system).
	<b>Soil Water Capacity</b>	1000 mm	0 – ∞	Increasing parameter increases travel time for any water in the upper bucket (more evaporation possible, more loss of water from system)
	<b>Preferred Flow Direction</b>	0.15	0 – 1	0: all water leaving the upper bucket flows to lower bucket, and none to river. 1: all water leaving the upper bucket flows to river, and none to lower bucket.
	<b>Initial Z1</b>	30%	0 – 100	0: Upper bucket begins empty and will retain lots of moisture in the early time-steps. 100: Upper bucket begins at full capacity and will retain little moisture in the early time-steps.
	<b>Deep Conductivity</b>	20 mm/month	0 – ∞	Increasing parameter decreases travel time for any water in the lower bucket before it flows into the river.
	<b>Deep Water Capacity</b>	1000 mm	0 – ∞	Increasing parameter increases travel time for any water in the lower bucket before it flows into the river.
	<b>Initial Z2</b>	30%	0 – 100	0: Lower bucket begins empty and will retain lots of moisture in the early time-steps. 100: Lower bucket begins at full capacity and will retain little moisture in the early time-steps.
Climate	<b>Precipitation, Temperature, Latitude, Snow Accumulation Gauge</b>			These parameters are generally based on historical data and should not be altered during calibration.
	<b>Humidity</b>	0%	0 – 100	Affects evapotranspiration.
	<b>Wind</b>	2 m/s	0 – ∞	Affects evapotranspiration.
	<b>Cloudiness Fraction</b>	1	0 – 1	Affects evapotranspiration. 1=no clouds. 0=completely overcast.
	<b>Freezing Point</b>	-5 °C	-20 – 20	Dictates at what temperature rain becomes snow, delaying infiltration/runoff. Relevant only for catchments with snow and affects the model only during cold months.
	<b>Melting Point</b>	5 °C	-20 – 20	Dictates at what temperature snow becomes water, after which it is subject to all parameters controlling water flow in the catchment. Relevant only for catchments with snow and affects the model only during cold months.
	<b>Initial Snow</b>	0 mm	0 – ∞	Melt water equivalent depth of the snowpack at the beginning of the first timestep of the model.
	<b>Albedo Lower Bound</b>	0.15	0 – 1	Albedo of the surface when snow accumulation is 0. Only used when <i>Albedo</i> variable is left blank.
	<b>Albedo Upper Bound</b>	0.25	0 – 1	Albedo of the surface when snow accumulation is 10 mm*(number of days in the timestep). Only used when <i>Albedo</i> variable is left blank.
	<b>Albedo</b>	Blank	0 – 1	Static value for albedo. If blank, WEAP calculates albedo as a linear function of snow accumulation, between <i>Albedo Lower Bound</i> and <i>Albedo Upper Bound</i> . A lower albedo increases snow melt rate.

## 6. View the Results

*Run the model.*

Compare modeled streamflow with data from the streamflow gauge:

*In the results/chart tab, navigate to **Supply and Resources>River>Streamflow Gauge Comparison**.*



We can see that our modeled river (blue) is not simulating the high flows of the river very well.

## 7. Save Chart as a Favorite

Before we start the calibration process, save this chart as a favorite so we can easily return to it later.

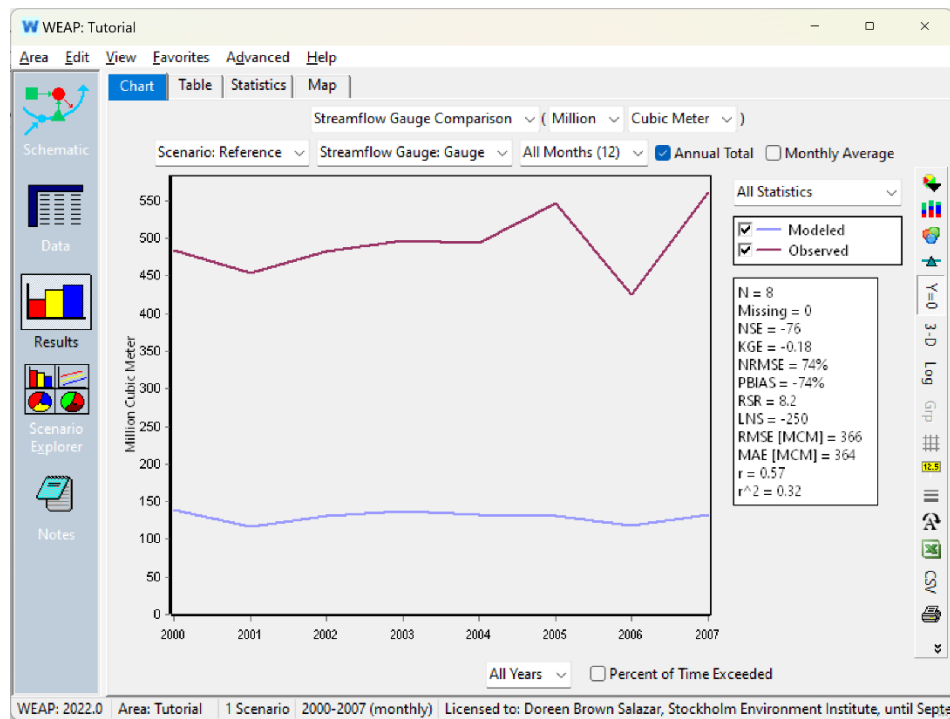
*Go to **Favorites/Save Chart as Favorite...** the default name will be “Streamflow Gauge Comparison”.*

## 8. Explore the Calibration

In the results produced so far, there is not a good fit between the modeled streamflow and the historical streamflow. There is a lot of room for

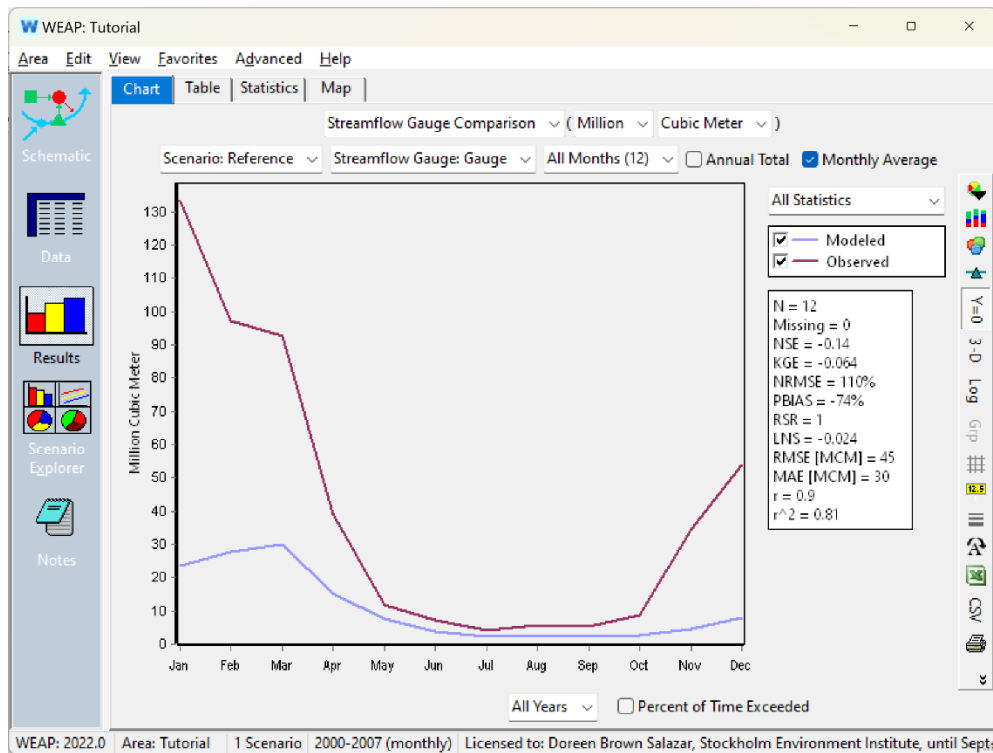
improvement. There are seven charts we recommend considering in the process of calibration:

- 1) The monthly time series for observed and modeled streamflow (generated above). This chart allows us to observe how well the modeled flow matches base flows, wet weather flows, and seasonality for a range of dry and wet years.
- 2) Annual Total of observed and modeled streamflow (while viewing the time series generated above, check the “**Annual Total**” box in the Results View)




The annual total provides a good sense of the general fit of the model over time and of how well the modeled total annual volume of runoff matches observed values. For example, here we see that our modeled flow is much lower, and does not capture annual variations very well, especially the year of low flow in 2006.

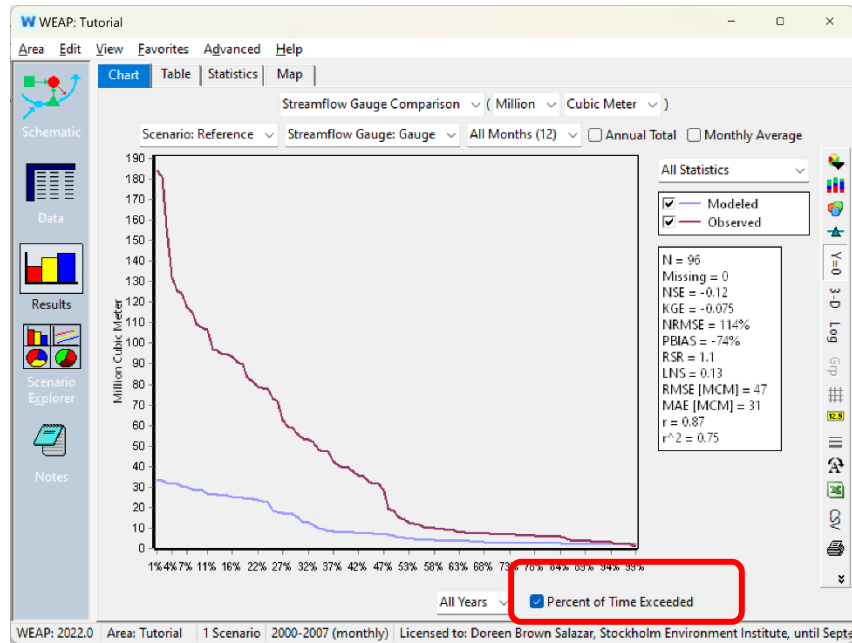
- 3) Monthly Average of observed and modeled streamflow (check the “**Monthly Average**” box in the Results View)



The monthly average shows how the modeled flow values deviate from the historical record, on average, each annual cycle. Here we see that the modeled low flows of the summer are closer to the observed values than the winter modeled high flows, which are considerably underestimated.

*While viewing these results, click on the icon to export results to Excel () on the right side of your screen. Save them on your computer as “Uncalibrated Monthly Average Streamflow Results.” We will review them after our first calibration attempt.*

- 4) Exceedance Probability for observed and modeled streamflow (make sure that neither “*Monthly Average*” nor “*Annual Total*” is checked, and check the box at the bottom right of the Results View that says “*Percent of Time Exceeded.*”)



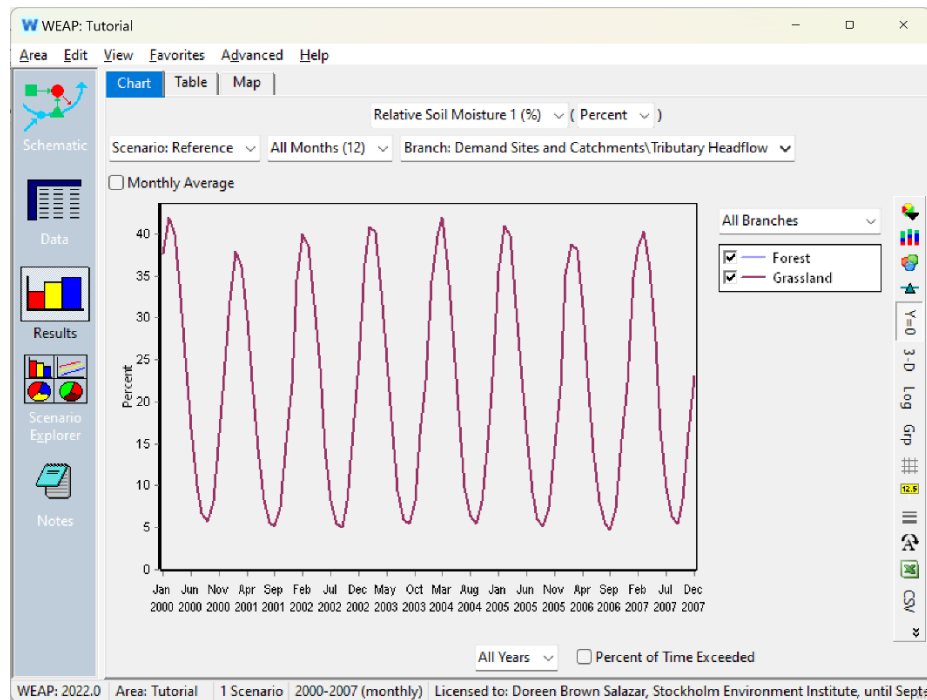
The exceedance probability chart ranks each flow measurement by value, the lowest on the right and the highest on the left, for both the modeled and observed streamflow. The values on the x-axis show the percentage of flows that exceed the values of flow. The modeled and observed streamflow should show a close match of exceedance percentages for the two flow records.

The gauge data charted above suggest that about 48% of flow measurements should be greater than about 34 million m<sup>3</sup>. However, the simulated Basin 1 Runoff shows 0% of flows >34 million m<sup>3</sup>. As we have noted, our model is not currently doing a good job of capturing streamflow, particularly during high-flow periods.

- 5) Relative Soil Moisture 1(%) (In results, navigate to **Catchments/Relative Soil Moisture 1 (%)**. Make sure the Branch selected is “*Tributary Headflow*,”. Be sure that “*Percent of Time Exceeded*” is unchecked.)

Save this chart as a favorite.

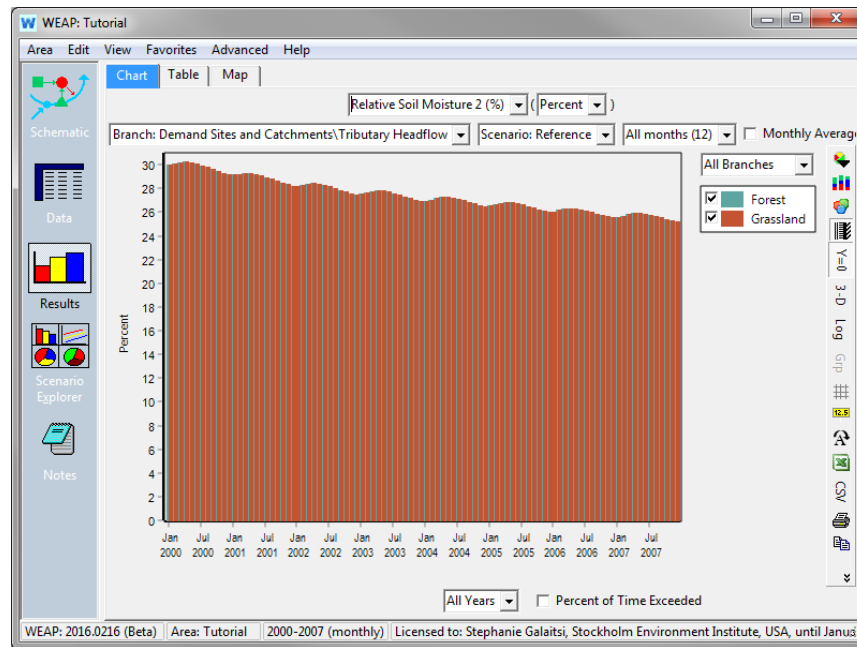




This chart shows a result for the land use dynamics of the modeled catchment. Relative Soil Moisture 1 (%) represents soil moisture in the upper bucket of the catchment soil moisture method's 2-bucket structure. (See Understanding the Soil Moisture Method in the Hydrology Chapter). The catchment's upper bucket is affected by the land use designated in the model as well as by the seasons. Except in extreme circumstances (multi-year droughts), Relative Soil Moisture 1 (%) should remain stable over time, even as it displays seasonal patterns. The current results for the upper bucket are acceptable. Notice that maximum and minimum values are fairly consistent from year to year.

- 6) Relative Soil Moisture 2 (%) (in the Results Menu, just below the Relative Soil Moisture 1 (%) result).

Save this chart as a favorite.




The *Relative Soil Moisture 2 (%)* result shows the soil moisture in the lower bucket of the modeled catchment. The lower bucket is deeper, not affected by land use, and less affected by seasons because of its separation from the surface. Slight seasonal variation is acceptable, and there should be no trend (either increasing or decreasing) over time.

The decreasing trend seen in this lower bucket example could indicate one or more of several problems:

- a. The initial condition for the soil moisture in the lower bucket is too high.
- b. Not enough water is percolating into the lower bucket.
- c. Water is leaving the bucket too quickly, because
  - i. The conductivity is too high.
  - ii. The bucket is too small, so the transport time is very short.

We will explore some of these possibilities as we calibrate.

- 7) Catchment Land Class Inflows and Outflows (still in the catchment results, navigate to “*Land Class Inflows and Outflows.*” View the result as a Monthly Average bar chart and select the bars to be “stacked” using the  icon on the right.)

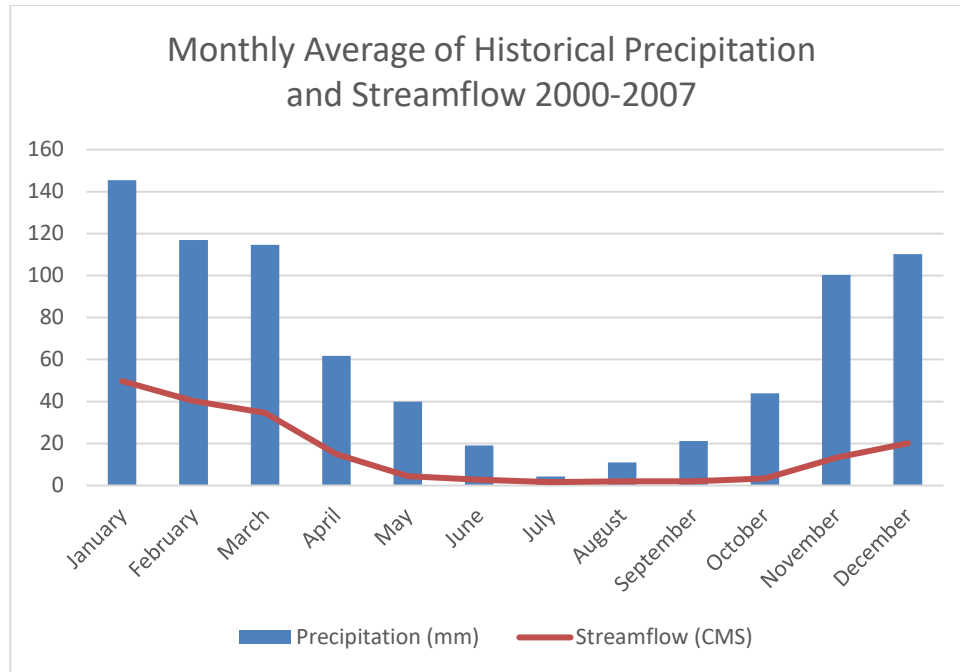


This chart shows the average distribution of the water entering the catchment (values above zero) and how that water leaves (values below zero). We note that there is a large amount of evapotranspiration from February through August, which is water lost from WEAP's accounting system. That could be related to our model's under-representation of streamflow.

Save this chart as a favorite.

Using the information from these seven charts, we can begin to think about changing the parameters of the model to allow WEAP to more accurately model streamflow.

Another way to look at the data that can provide some additional insight on model calibration is to overlay average monthly precipitation and streamflow data. The following figure shows the mean monthly observed runoff and average precipitation for the period 2000-2007.



The hydrograph overlain on precipitation data above reveals a strong correlation between precipitation and runoff and suggests that the system is dominated by the surface runoff component; runoff highly correlated with precipitation is usually because there is little infiltration. The very low baseflows during the dry season suggest a small *Deep Storage Capacity*, often also associated with large seasonal fluctuations in top-bucket storage ( $Z_1$ ), and thus large seasonal variations of soil water availability from very wet (high values of  $Z_1$ ) to very dry (low values of  $Z_1$ ). This is indeed what we already saw in our result *Relative Soil Moisture 1 (%)*.

## Adjust key parameters and conduct model sensitivity analysis

### 9. Change Parameter Values

Prior to making any adjustments in land use calibration parameter values, we'll describe how key land use calibration parameters affect WEAP runoff results and consider what factors might impact those parameters.

Uncalibrated model observations	Relevant Parameters	Impact on Model	Model adjustment to consider
Modeled flows (total annual and maximum monthly) are much lower than observed values	<b>Kc</b>	Increasing parameter leads to more evapotranspiration, and thus less water contributing to streamflow.	Decrease Kc, perhaps seasonally, to reflect lower evapotranspiration and higher runoff. Note that decreasing Kc will impact both peak flows and base flows.
	<b>Runoff Resistance Factor</b>	Increasing parameter routes less water to streamflow as it instead percolates into the soil.	Decrease RRF, to increase the proportion of rainfall directed to runoff. RRF has little impact on base flows.
	<b>Soil Water Capacity</b>	Increasing parameter increases travel time for any water in the upper bucket and decreases streamflow.	Decrease SWC to increase the proportion of rainfall directed to runoff. Note that decreasing SWC will also slightly decrease base flows.
	<b>Preferred Flow Direction</b>	0: all water leaving the upper bucket flows to lower bucket, and none to river. 1: all water leaving the upper bucket flows to river, and none to lower bucket.	Increase PFD to increase the proportion of rainfall directed to runoff. Increasing PFD will decrease base flows.
	<b>Root Zone Conductivity</b>	Increasing parameter shortens travel time for any water in the upper bucket (less evaporation possible, less loss of water from system).	Increase RZC to increase the proportion of rainfall directed to runoff. Increasing RZC will decrease base flows.
Soil moisture in the upper bucket is consistent from year to year	<b>Initial Z1</b>	0: Upper bucket begins empty and will retain lots of moisture in the early time-steps. 100: Upper bucket begins at full capacity and will retain little moisture in the early time-steps.	Make no change!
	<b>Soil Water Capacity</b>		Changes in SWC and RZC will affect consistency of modeled soil moisture in the upper bucket.
	<b>Root Zone Conductivity</b>		
Soil moisture in the lower bucket is decreasing from year to year	<b>Deep Conductivity</b>	Increasing parameter decreases travel time for any water in the lower bucket before it flows into the river.	Lower DC to retain water in the lower bucket.
	<b>Deep Water Capacity</b>	Increasing parameter increases travel time for any water in the lower bucket before it flows into the river.	Increase the DWC to retain water in the lower bucket
	<b>Initial Z2</b>	0: Lower bucket begins empty and will retain lots of moisture in the early time-steps. 100: Lower bucket begins at full capacity and will retain little moisture in the early time-steps.	Increase the value of the initial condition to decrease initial moisture retention and stabilize calculations.

The impacts of these parameters on soil water storage and resulting surface water flow can be appreciated in the summarized soil moisture equation of WEAP, where:

- R = root zone soil water capacity
- Kc = crop coefficient
- RRF = runoff resistance factor
- f = preferred flow direction
- k<sub>s</sub> = root zone conductivity
- S<sub>max</sub> = deep soil water capacity
- k<sub>s2</sub> = deep soil conductivity

### WEAP Hydrology - Soil Moisture Method

<p>Change in Soil Water Storage</p>	<p>= Precipitation - Evapotranspiration</p>	<p>-</p>	<p>Direct Surface Runoff</p>	<p>-</p>	<p>Soil water flow to stream</p>	<p>-</p>	<p>Soil water flow to groundwater</p>
$Rd_j \frac{dz_{1,j}}{dt} = P_s(t) - PET(t)k_{c,j}(t)\left(\frac{5z_{1,j} - 2z_{1,j}^2}{3}\right) - P_s(t)z_{1,j}^{RRF_j} - f_j k_{z,j} z_{1,j}^2 - (1 - f_j)k_{z,j} z_{1,j}^2$							
Shallow Soil Zone	Change in Soil Water Storage	=	Percolation from all sub-branches within catchment	-	Flow to River (i.e. Baseflow)		
Deep Soil Zone	$S_{max} \frac{dz_2}{dt} = \left( \sum_{j=1}^N (1 - f_j)k_{z,j} z_{1,j}^2 \right) - k_{z,2} z_2^2$						

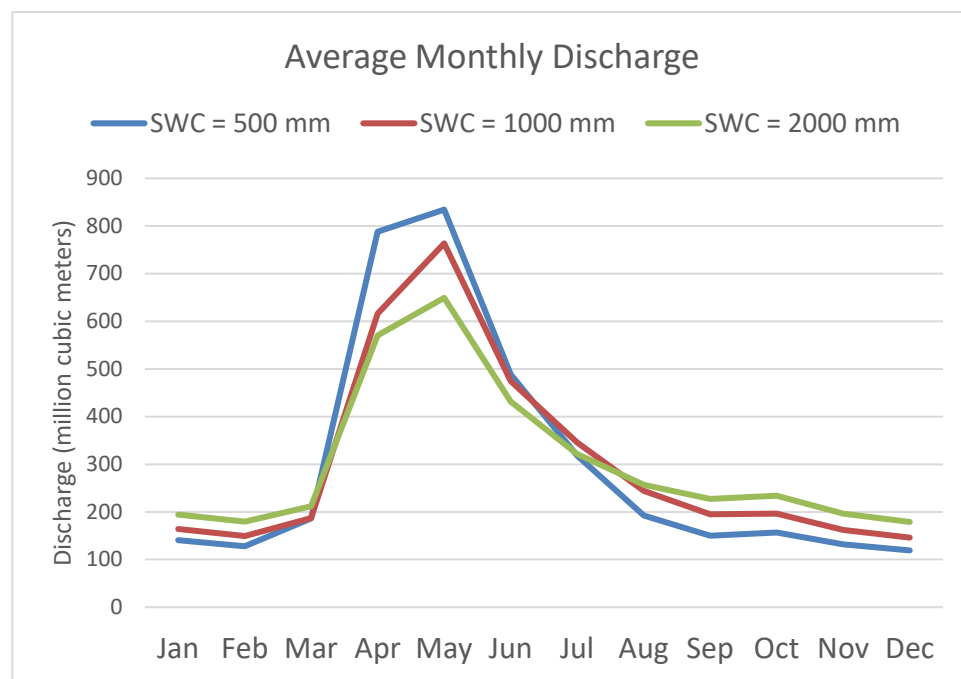
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The table below provides some guidance in considering how land use, crop types, elevation, slope, and geology might impact hydrology as well as their relationship to calibration factors. While it is important to understand the implications of the various calibration parameters, it is also important to understand that some parameters associated with soil moisture accounting are not meant to have rigorous physical meaning; rather they are used to help describe the general hydrologic response of the watershed.

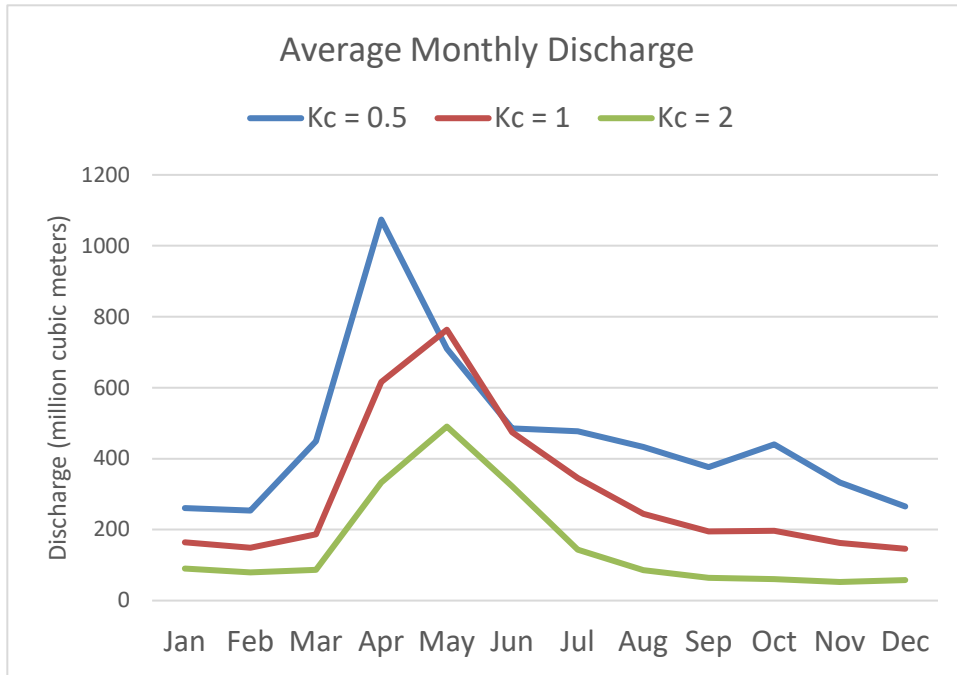
Parameter	Impacting factors
<b>Crop Coefficient, Kc</b>	Land use, crop type, elevation, season (often varies monthly)
<b>Runoff Resistance Factor</b>	Land use, slope, season (can vary monthly)
<b>Root Zone Conductivity</b>	Soil type, elevation
<b>Soil Water Capacity</b>	Soil type, elevation
<b>Preferred Flow Direction</b>	Slope, land use, elevation
<b>Deep Conductivity</b>	Geology, elevation
<b>Deep Water Capacity</b>	Geology, elevation

Model results are more sensitive to changes in some soil calibration parameters than others. Examples of model sensitivity to changes in the parameters are shown in the graphs below.

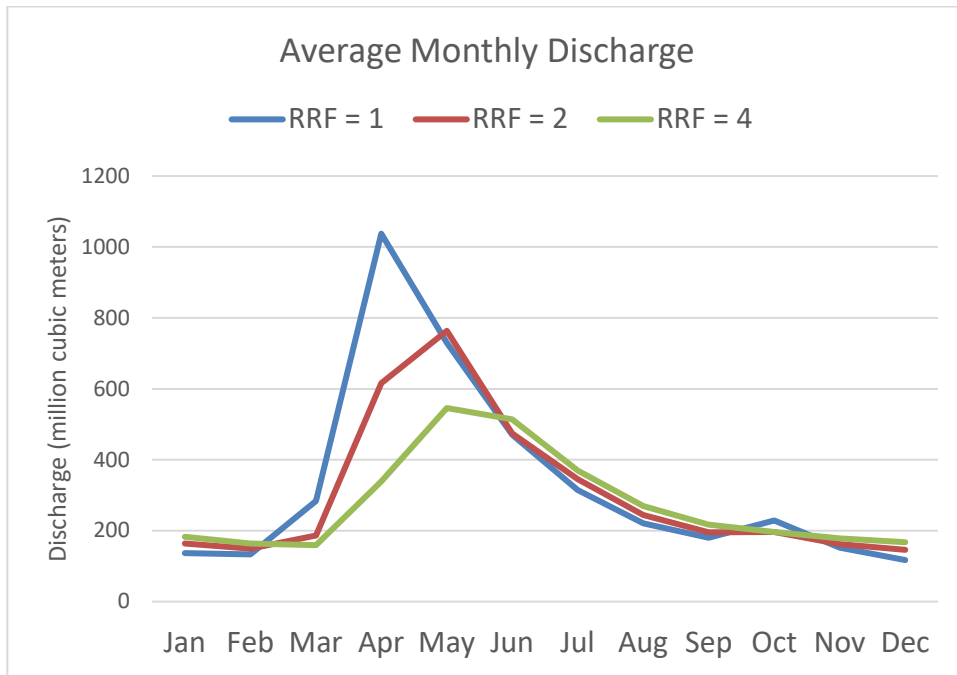
#### Root Zone Soil Water Capacity (SWC)



### Crop Coefficient, Kc

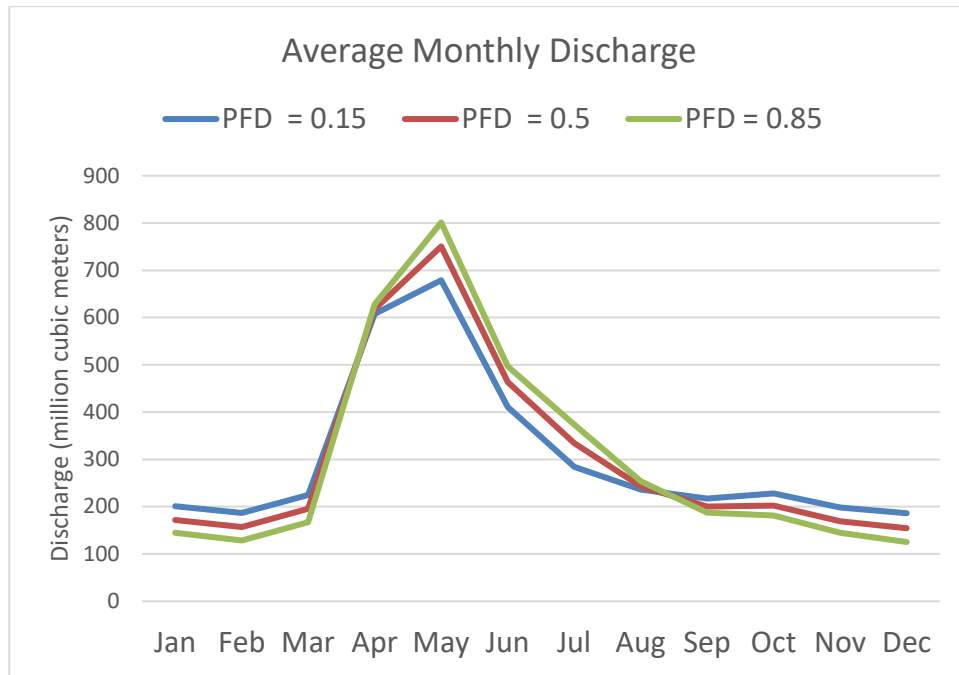


### Runoff Resistance Factor, RRF

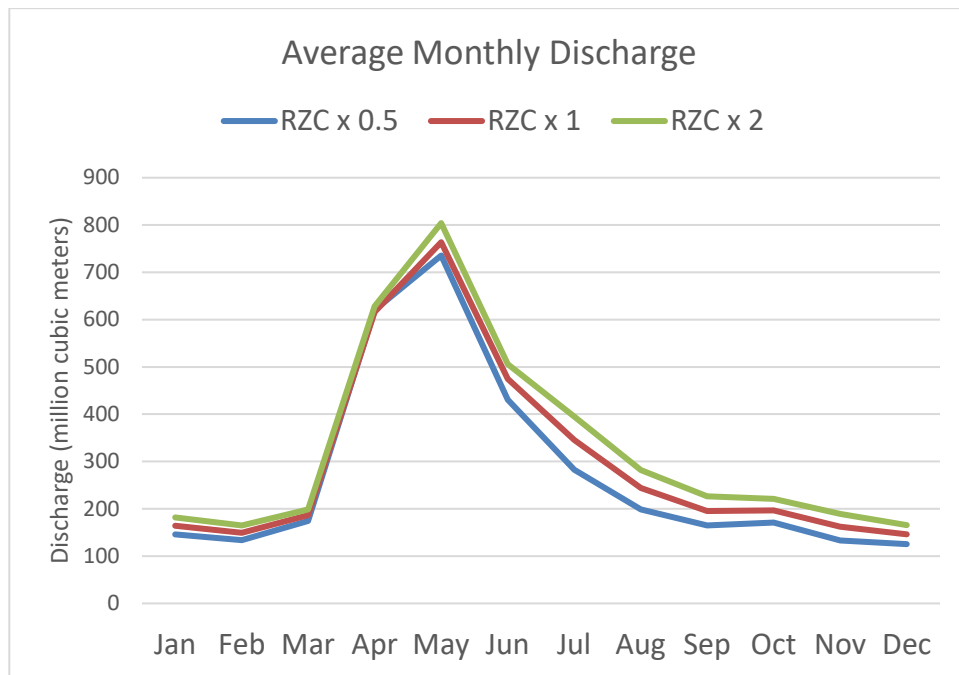




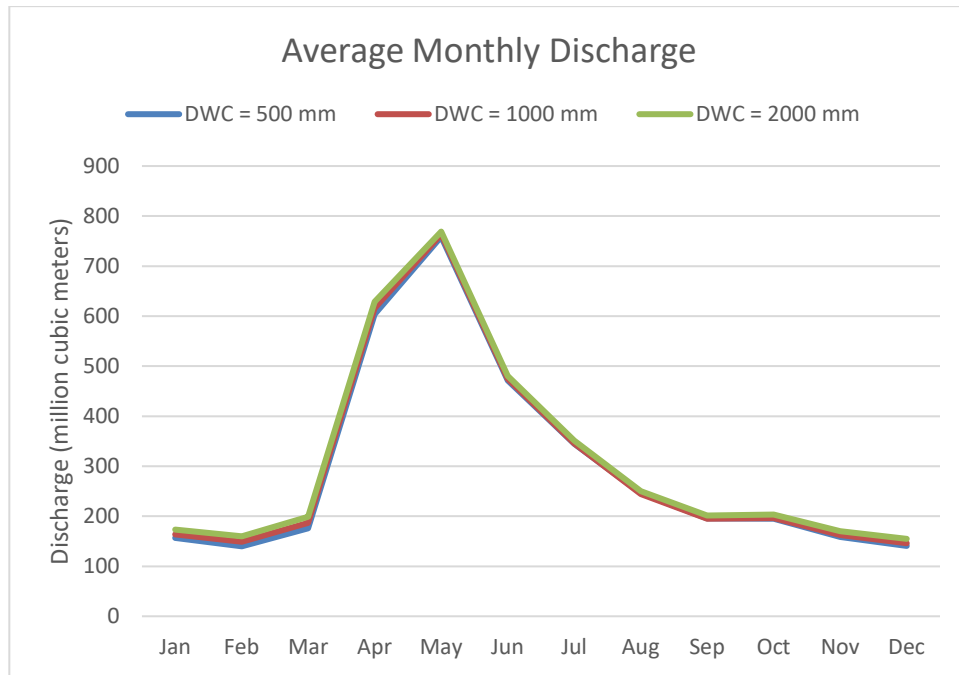
Preferred Flow Direction,  $f$



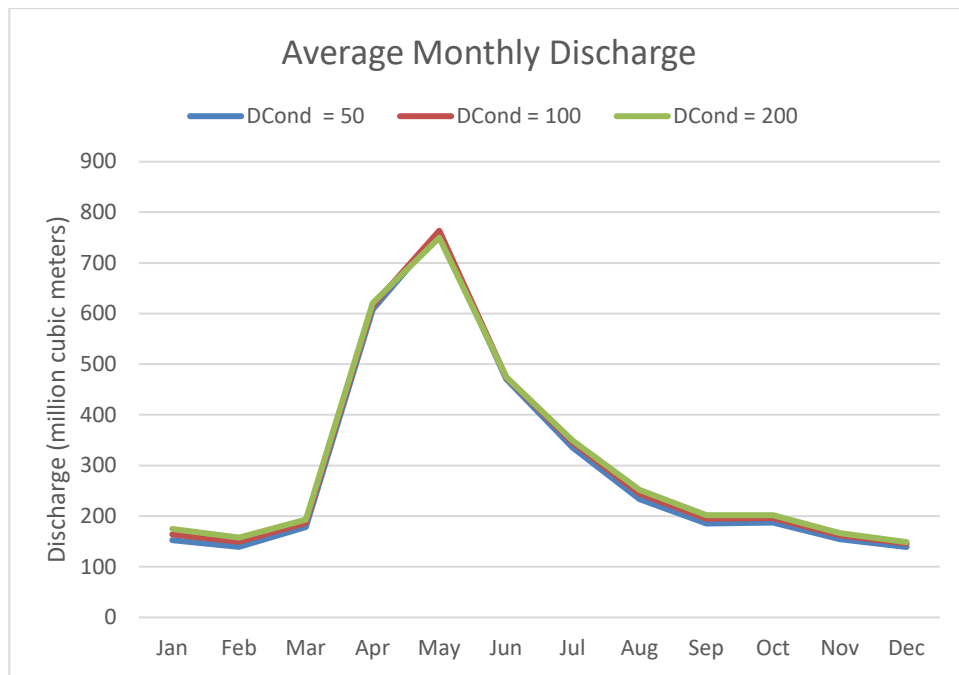
Root Zone Conductivity,  $k_s$



### Deep Soil Water Capacity, Smax



### Deep Conductivity, k<sub>s2</sub>



Now we are ready to begin making changes in land use calibration parameters. We will adjust initial estimates for the hydrologic parameters related to the two land use types in the Tributary Headflow catchment. We will begin with adjusting parameters that affect the upper bucket, focusing on adjusting

parameters to increase the water that the model sends to the river, as modeled streamflow was significantly lower than historical observations.

### 1) *Runoff Resistance Factor*

WEAP gives a default value of 2 for the *Runoff Resistance Factor* of all land use types when a catchment is first added to a model. If we decrease this value, we will increase runoff to the river.

Assume that, for this model, the surface runoff from forest (35% of the area) is usually less than from grasslands (65% of the area), perhaps because the grasslands have a higher average slope in addition to lacking the forest canopy. To characterize this difference, we will use a higher *Runoff Resistance Factor* for forest land than for grassland.

Create a new scenario, “1 runoff resistance factor” (See the Scenarios Chapter to refresh your memory) so that we can evaluate how calibration parameter changes affect model results.

**In the following steps, input parameters for the new “runoff resistance factor” scenario only**

*Forest Runoff Resistance Factor = 3*

*Grassland Runoff Resistance Factor = 1*

The data inputs differentiate between land use type and increase the runoff for the majority of the catchment land area (the grasslands). By increasing direct runoff, the catchment will convert more precipitation to river flow.

Explore model results. We can see that the runoff resistance scenario has higher runoff values than the reference scenario, but wet weather average monthly total flows are still more than two times higher than modeled flows. *You may continue to explore model sensitivity to runoff resistance factors by further adjusting these values.*

## 2) *Soil Water Capacity*

Another way to increase the amount of precipitation converted to river runoff is to reduce the *Soil Water Capacity*. The default value in WEAP is 1000 mm.

Create a new scenario, based on the Runoff Resistance Factor Scenario, named “2 Soil Water Capacity”.

*For the “Soil Water Capacity” scenario, decrease Soil Water Capacity to the following.*

*Forest Soil Water Capacity = 600 mm*

*Grassland Soil Water Capacity = 500 mm*

Explore model results. We can see that the soil water capacity scenario has higher runoff and less evapotranspiration than the reference scenario, but wet weather average monthly total flows are still about two times higher than modeled flows. *You may explore model sensitivity to soil water capacity by further adjusting these values.*

## 3) *Preferred Flow Direction*

Interflow and baseflow are also important contributors to river volume. The month of highest streamflow, according to an average of the flow gauge record for the years 2000-2007, is January (49.7 CMS on average). The lowest is July (1.6 CMS on average), which is likely dominated by baseflow, since there is very little precipitation at that time.

WEAP’s default value for *Preferred Flow Direction* for both land use types is 0.15, which directs only 15% of the water from the upper bucket into the river as interflow (the remaining 85% percolates into the lower bucket). To increase interflow, the user can direct more water from the upper bucket to

flow into the river by increasing the values of the *Preferred Flow Direction* for both land use types.

Create a new scenario named “3 Preferred Flow Direction”, based on the Runoff resistance factor scenario.

*Change the values of Preferred Flow Direction for the Tributary headflow catchment to indicate that horizontal flows dominate; the forested area generates more horizontal flow than grassland.*

*Forest Preferred Flow Direction = 0.7*

*Grassland Preferred Flow Direction = 0.6*

Note that this directs less water to the lower bucket, decreasing the lower bucket’s soil moisture, which was already showing a trend of decline. We will deal with this later.

Explore model results. This adjustment did not have a great impact on model results.

#### 4) *Root Zone Conductivity*

In our initial results for average monthly *Land Class Inflows and Outflows*, we saw that the highest value for interflow was in March (0.7 million m<sup>3</sup>/month). But we also know from our average monthly *Streamflow* results that during the wet season (roughly December-March) the modeled streamflow was too low by 45.9 million m<sup>3</sup>/month (December) to 109.7 million m<sup>3</sup>/month (January). (To obtain these results, subtract modeled streamflow from observed streamflow in the Excel file Monthly Average Streamflow Results.)

Since the hydrograph shows that river runoff is well correlated with precipitation, much of this wet-season river volume should be surface runoff.

We can make an initial guess of the monthly interflow volume based on observed monthly streamflow volumes, and use that guess, combined with an estimate of that the relative storage of the upper bucket (*Z1*), and our estimates of root zone conductivity to mathematically estimate root zone conductivity (see Tips at the end of this chapter). We will adjust the forest and root zone conductivity to match those calculated values. While our mathematical calculations are a sound basis for establishing relationships between parameters, we must be aware of the uncertainty of our baseline assumptions.

*Create a new “4 Root Zone Conductivity” scenario and enter these values in your model for this scenario. The calibration exercise will help suggest how to further change them.*

*Forest Root Zone Conductivity = 23.3 mm/month*

*Grassland Root Zone Conductivity = 27.2 mm/month*

Explore model results. Both base flows and peak flows are still low. In addition to mathematically calculating root zone conductivity, it is worthwhile to explore model sensitivity to this parameter.

#### *5) Deep Water Capacity*

Our initial result for *Relative Soil Moisture 2 (%)* showed a declining trend. Let’s test what happens if we change the default value of lower bucket capacity 1000 mm to 500 mm.

*Create a “5 Deep Water Capacity” scenario, and change the value of*

*Deep Water Capacity = 500 mm*

Explore model results. This adjustment increased the declining trend of *Relative Soil Moisture 2*. We can understand this if we imagine that if the same volume of water were to leave the system as before, it would represent double the percentage of the total volume in the second bucket. However, changing this parameter also will change outflows from the lower bucket. You may explore model sensitivity to this parameter.

#### *6) Deep Conductivity*

You can estimate deep conductivity in a similar way to the method used to calculate root zone conductivity (see Tips at the end of the chapter), by using observed monthly low flow values in million cubic meters per month, the area of the watershed, and relative soil moisture in the bottom bucket.

*Create a “6 Deep Conductivity” Scenario*

*Increase the default Deep Conductivity ( $k_2$ ). value (20 mm/month) to 30 mm/month. This may encourage the lower bucket to run off water faster, which is also encouraged by the fact that we made the bucket smaller.*

*Deep Conductivity = 30 mm/month*

Explore model results. Baseflow values have increased but are still half of modeled flows.

### 7) Crop Coefficient

Crops typically exhibit annual patterns—months when they are growing a lot (and evapotranspiring a lot of water) and months when they are growing little, or not at all, so  $K_c$  is a value that may vary month by month.

However, for our initial calibration we will assume that in this catchment, both the forest and grasslands are perennial and evergreen. We will not adjust  $K_c$ , the evaporation coefficient (or crop coefficient in agricultural context) nor will we vary it by month.

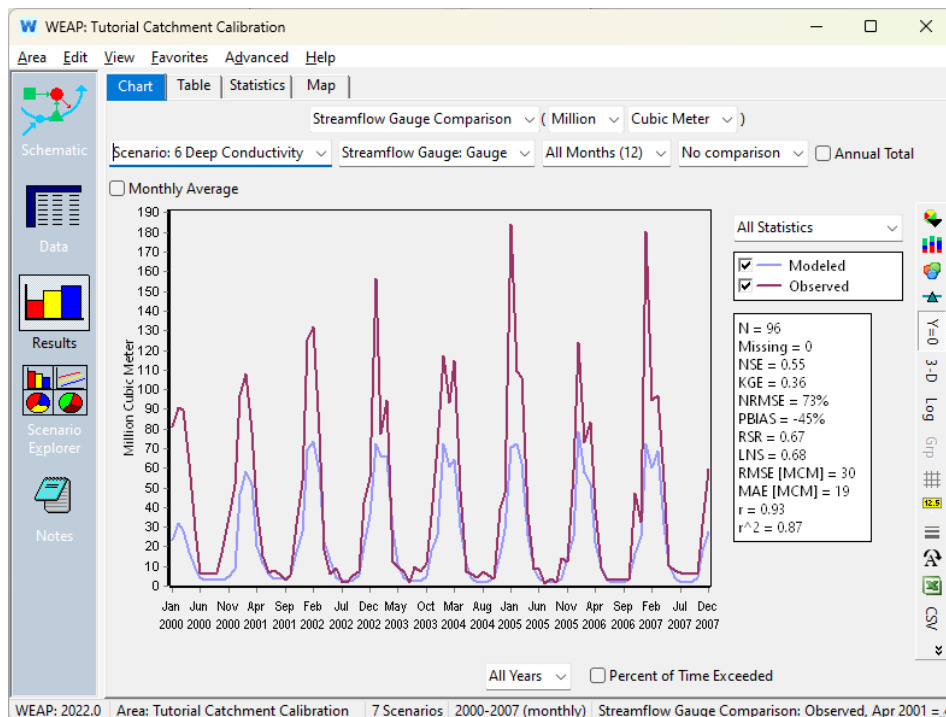


For crops, libraries such as the FAO's single crop coefficient <http://www.fao.org/docrep/x0490e/x0490e0b.htm> are useful in suggesting values for  $K_c$ . However, these values may need to be adjusted depending on the local context of your model.

## 10. View all the Results

*Run the results and look at your favorite chart that you made earlier.*

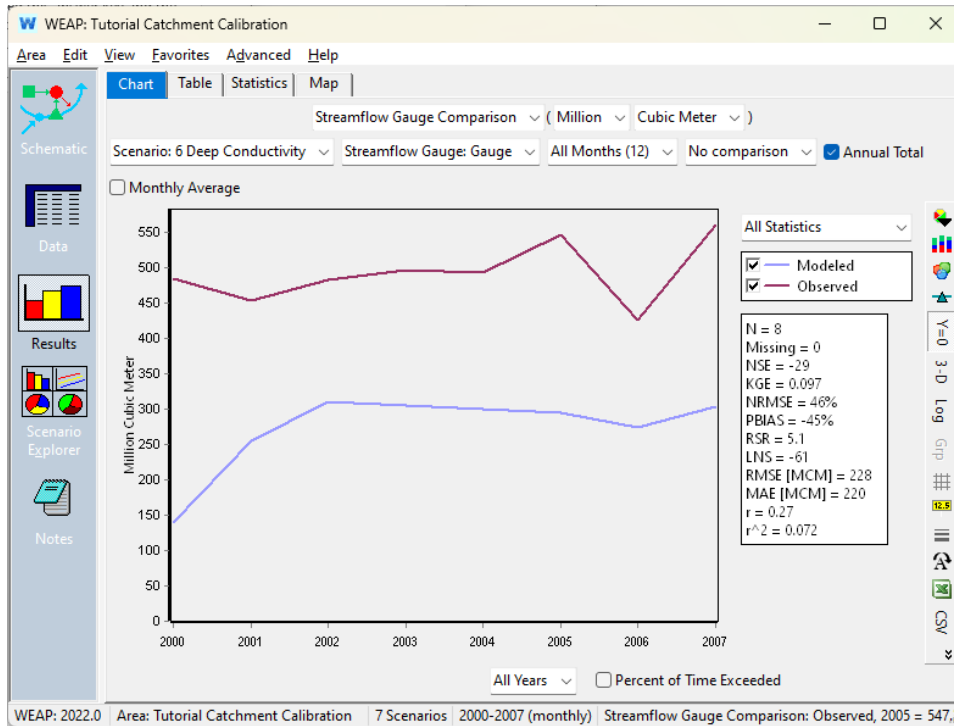
*Go to Favorites in the Main Menu and select "Observed and Modeled Streamflow."*



This looks much better than before. The simulated high flows are higher, though not quite as high as historical data, and the low flows are still approximating historical flows.

If your model does not look like this, you may revert to the version “Answer key for Catchment Calibration Step 1.”

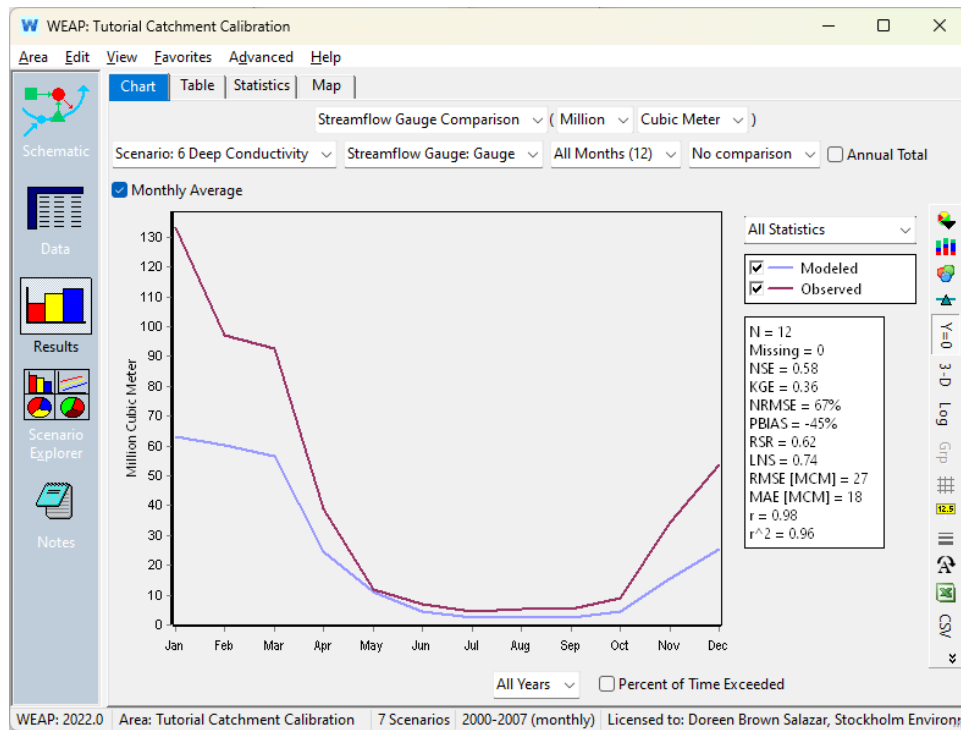
*Check the box for “Annual Total” in the results Chart view.*



The model is still underpredicting streamflow overall, and the annual trends are still not following the observed data very well. Note that modeled values for the base year (2000) are not affected by the parameters changed in our new scenario.

*Check the box for “Monthly Average” for the results.*

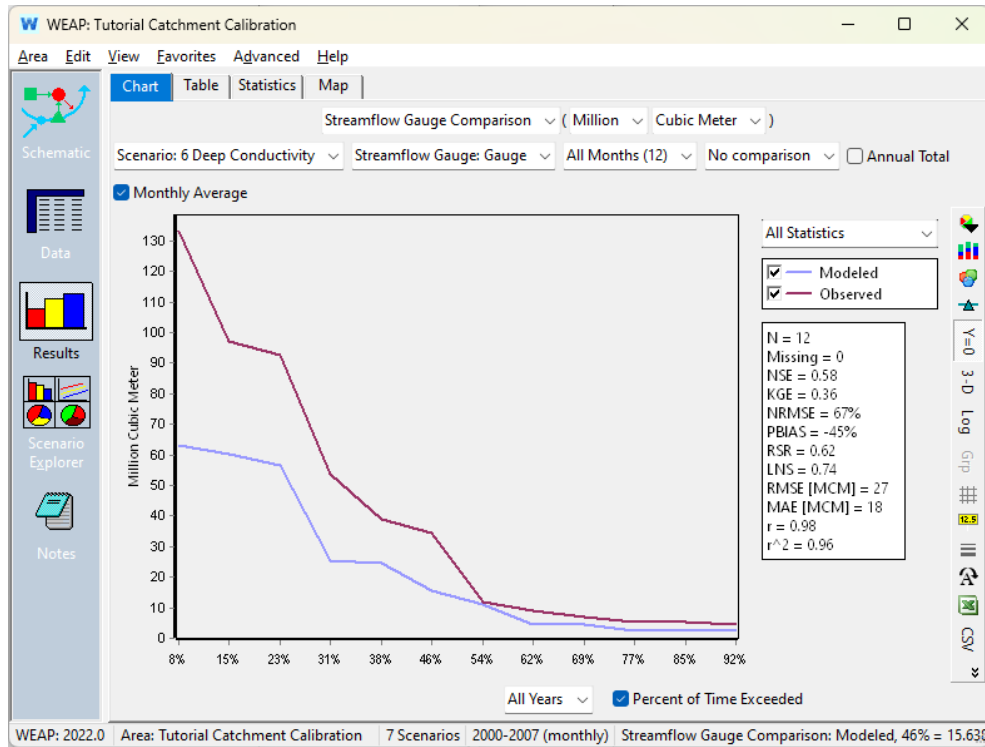




You can compare this to the results you saved earlier in Excel as “*Uncalibrated Monthly Average Streamflow Results*”. The chart above shows us that the model is still underestimating streamflow each month, and that this error is more pronounced during high-flow months. This may be related to how we are modeling runoff.

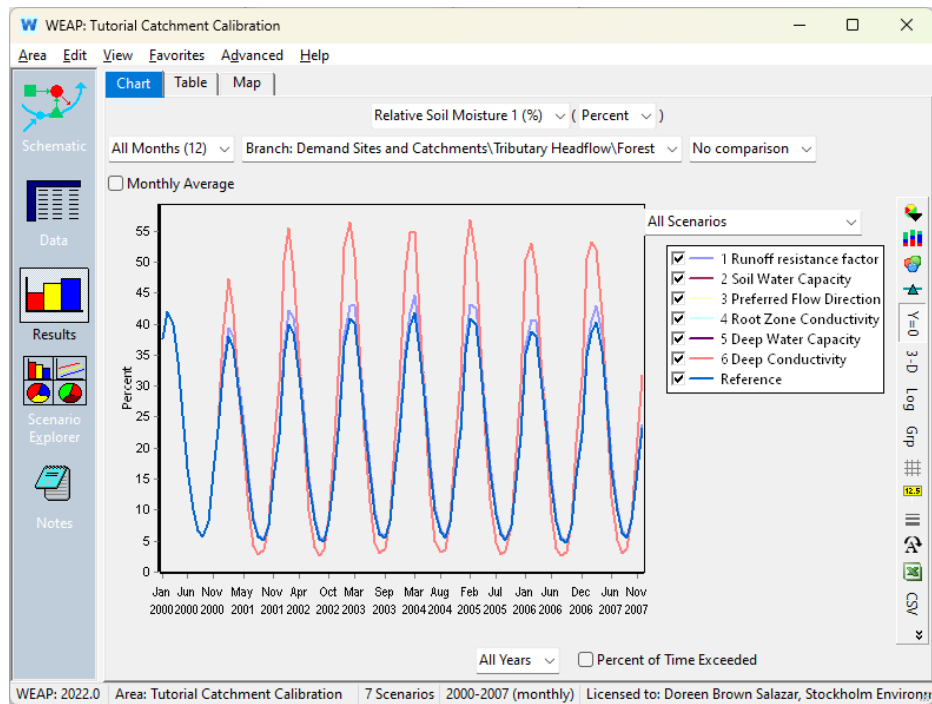
Finally, the flow duration curve can be displayed:

*After unchecking “Monthly Average,” select “Percent of Time Exceeded” at the bottom of the results view.*

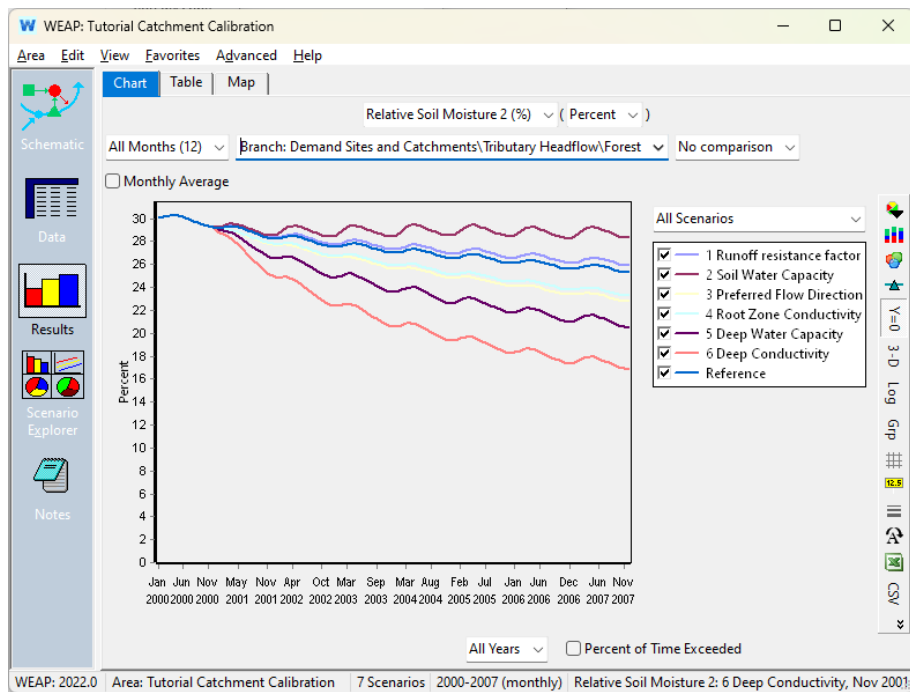


In this chart we can see that the model calculated that streamflow is larger than 10 MCM about 56% of the time, whereas the observed data show that 58% of the time, the streamflow is larger than 10 MCM. For a higher flow, 75 MCM, the model estimates that around 2% of the flows are higher, whereas the data show that the number should be about 25%. Again, we see that our model is underestimating streamflow.

The *Relative Soil Moisture 1 (%)* still shows a stable seasonal trend:



And the *Relative Soil Moisture 2 (%)* initially declines quickly, but the rate of decline decreases so the model could be stabilizing as it progresses. This suggests that it might be a good idea to change the initial condition.



## Optimize calibration based on visual and statistical assessment

Once you have tested the sensitivity of the model to key land use calibration parameters and you are ready to optimize your calibration, you may use statistical parameters to aid you, particularly if you are using automated optimization methods. Note that modeling experts always recommend reviewing results visually as well as reviewing the results of statistical performance metrics.

WEAP includes built-in statistical calculations of the number of data points, the number of missing data points, and ten statistical measures of model calibration (D. N. Moriasi et al., 2007; Ferreira et al., 2020; Gupta et al., 2009; Yoon et al., 2015).

The ideal values and interpretation of these ten built-in statistical measures are summarized in the table below and further described in the text that follows.

Statistical measure	Ideal and acceptable values	Interpretation
Pearson's correlation coefficient, $r$	If $r = 1$ a perfect positive linear relationship exists	describes the degree of collinearity between simulated and measured data
Pearson's coefficient of determination, $r^2$	The ideal value is 1, values of 0.5 to 1 are considered acceptable	is an index of the degree of linear relationship between observed and simulated data
Nash-Sutcliffe Efficiency (NSE)	The ideal value is 1; values > 0.5 = acceptable > 0.6 = desired > 0.7 = good > 0.8 = very good	how well modeled stream flow matches observed streamflow
NSE on Log Transformed Daily Flow (LNS)	The ideal value is 1	same as NSE, but with reduced sensitivity to high and low values
Kling-Gupta Efficiency (KGE)	The ideal value is 1. Desired values are above 0.8.	compiles three metrics: correlation of simulated and observed values, model bias, and simulation of flow variations
Mean Average Error (MAE)	0 indicates a perfect fit, value less than half a standard deviation is considered acceptable	the degree to which modeled and observed flows match
Root Mean Square Error (RMSE)		
Normalized Root Mean Square Error (NRMSE)		
Ratio of the Root Mean Squared Error to the standard deviation (RSR)	An ideal value is zero, but values less than 0.7 are considered good.	a measure of how much simulated flows deviate from observed hydrographs
Percent bias (PBIAS)	An ideal value is zero, but PBias of plus or minus 25% of is considered acceptable	tendency of consistent over or under-estimation of flows / match of simulated to observed total volume

**Pearson's correlation coefficient ( $r$ )** is an index of the degree of linear relationship between observed and simulated data. It ranges from  $-1$  to  $1$ . If  $r = 0$ , no linear relationship exists. If  $r = 1$  or  $-1$ , a perfect positive or negative linear relationship exists.

$$r = \frac{\sum_{i=1}^n (Q_{o(i)} - \overline{Q^{obs}})(Q_i^{sim} - \overline{Q^{sim}})}{\sqrt{\sum_{i=1}^n (Q_i^{obs} - \overline{Q^{obs}})^2 * \sum_{i=1}^n (Q_i^{sim} - \overline{Q^{sim}})^2}}$$

**Pearson's coefficient of determination ( $r^2$ )** also compares simulated and measured data; it describes the proportion of the variance in measured data explained by the model.  $R^2$  ranges from 0 to 1, with higher values indicating less error variance; typically values greater than 0.5 are considered acceptable.

$$r^2 = \left[ \frac{\sum_{i=1}^n (Q_{o(i)} - \overline{Q_{o(i)}})(Q_{c(i)} - \overline{Q_{c(i)}})}{\sqrt{\sum_{i=1}^n (Q_{o(i)} - \overline{Q_{o(i)}})^2 * \sum_{i=1}^n (Q_{c(i)} - \overline{Q_{c(i)}})^2}} \right]^2$$

The **Nash-Sutcliffe Efficiency (NSE)** coefficient is commonly used in hydrological modeling to evaluate how well modeled stream flow matches observed streamflow. The ideal value is 1, values of 0.5 are acceptable; most modelers aim for values that are at or above 0.7.

$$NSE = 1 - \left[ \frac{\sum_{i=1}^n (Q_i^{obs} - Q_i^{sim})^2}{\sum_{i=1}^n (Q_i^{obs} - \overline{Q^{obs}})^2} \right]$$

**NSE on Log Transformed Daily Flow (LNS)** is the NSE calculated with the logarithm of the daily streamflow (LNS). This transformation reduces the sensitivity of NSE to high values and increases its sensitivity to low values.

$$LNS = 1 - \left[ \frac{\sum_{i=1}^n (\log Q_i^{obs} - \log Q_i^{sim})^2}{\sum_{i=1}^n (\log Q_i^{obs} - \overline{\log Q^{obs}})^2} \right]$$

**Kling-Gupta Efficiency (KGE)** aims to capture three different objectives of model calibration: correlation of simulated and observed values, minimization of model bias, and optimum simulation of flow variations. The ideal value is 1; values above 0.8 are desired.

$$KGE = 1 - \sqrt{(r - 1)^2 + (\alpha - 1)^2 + \left(\frac{\overline{Q^{sim}}}{\overline{Q^{obs}}} - 1\right)^2}$$

Where relative variability is defined as:

$$\alpha = \frac{\sum_{i=1}^n (Q_i^{sim} - \overline{Q^{sim}})}{\sum_{i=1}^n (Q_i^{obs} - \overline{Q^{obs}})}$$

**Mean Absolute Error (MAE)** is a simple average of the absolute value of the difference between observed and simulated data. An optimum value would be zero. A value less than half a standard deviation is considered acceptable.

$$MAE = \frac{1}{n} \sum_{i=1}^n |Q_i^{sim} - Q_i^{obs}|$$

**Root Mean Square Error (RMSE)** is a measure of the mean error between simulated and observed flows. An optimum value would be zero. A value less than half a standard deviation is considered acceptable.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (Q_i^{sim} - Q_i^{obs})^2}$$

**Normalized Root Mean Square Error (NRMSE)** is the RMSE divided by the range of observed data. For comparison of model results for the same data using different parameters it provides no additional insights beyond the RMSE alone, but it can be a useful parameter for understanding differences in model performance for wet versus dry years or between different basins.

$$NRMSE = \frac{RMSE}{\text{range of observed data}} = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n (Q_i^{sim} - Q_i^{obs})^2}}{Q_{max}^{obs} - Q_{min}^{obs}}$$

The **ratio of the root mean squared error to the standard deviation (RSR)** is a measure of how much simulated flows deviate from observed hydrographs. An ideal value is zero, but values less than 0.7 are considered acceptable.

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[ \sqrt{\sum_{i=1}^n (Q_i^{obs} - Q_i^{sim})^2} \right]}{\left[ \sqrt{\sum_{i=1}^n (Q_i^{obs} - \overline{Q^{obs}})^2} \right]}$$

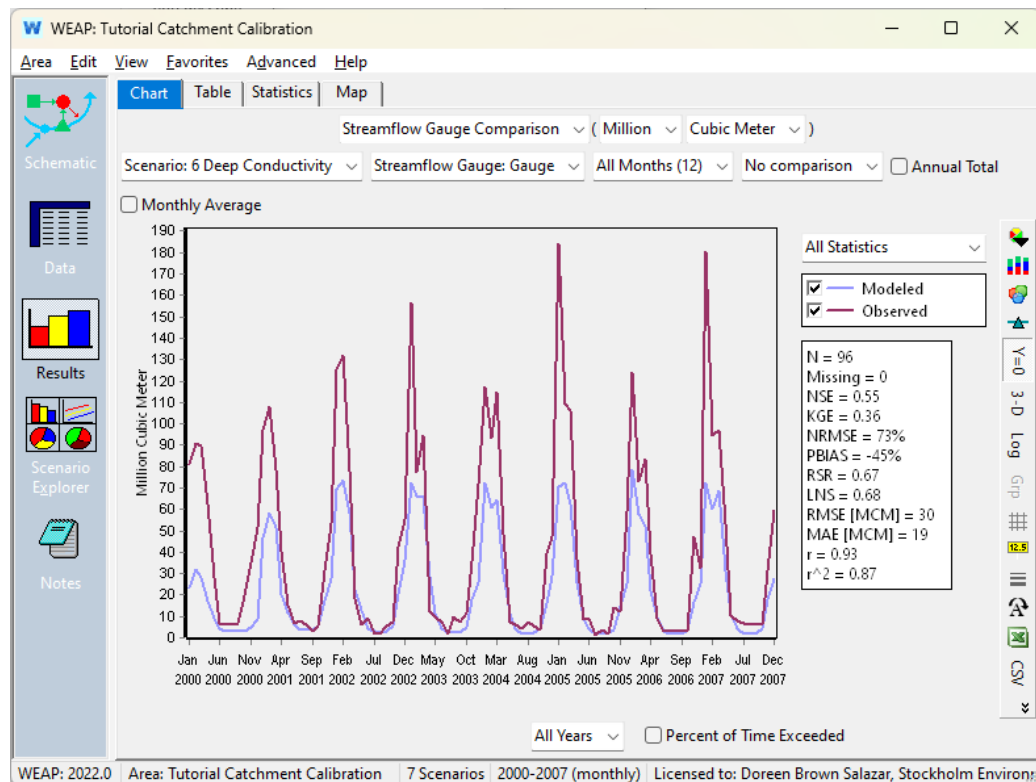
**Percent bias (PBIAS)** is a measure of the model's ability to match the total volume of flow. An ideal value is zero, but PBias of plus or minus 25% of the observed streamflow is considered acceptable.

$$PBIAS = 100 * \left[ \frac{\sum_{i=1}^n (Q_i^{obs} - Q_i^{sim})}{\sum_{i=1}^n (Q_i^{obs})} \right]$$

These ten statistical values are listed to the right of streamflow gauge comparisons in WEAP. Most modelers do not use all of these values for model calibration. They use more than one metric to be sure that their models simulate well: high flows, annual total flow volumes, monthly flow seasonality, and base flows. Studies analyzing the use of metrics for model calibration note that, although  $r$  and  $r^2$  are well-recognized statistics used for many types of models, they are very sensitive to high outliers and insensitive to model bias. Most modelers use metrics such as NSE and KGE to capture seasonal

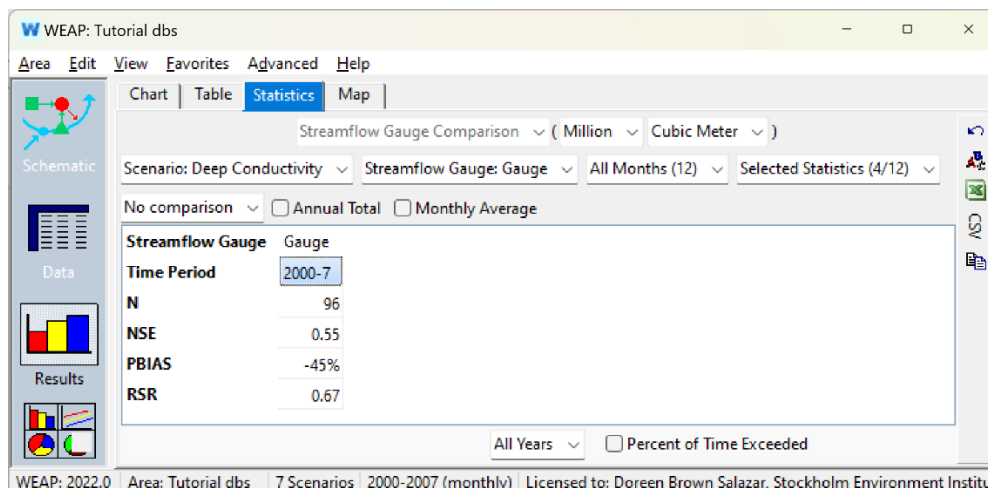
variations, coupled with measures such as MAE or RSR to capture peak flows, and PBIAS to optimize simulation of total annual flows.

Go to the streamflow gauge comparison favorite with “Annual Total” and “Monthly Average” unchecked, and the “Deep Conductivity” scenario: You may select the statistical values displayed by WEAP by clicking on “All Statistics” (on the right), then “Selected statistics”, then checking which parameters you would like WEAP to display. Select N (number of data points), NSE, RSR and PBIAS.



If you then click on the statistics tab (on top) you will see only values for the statistical measures you selected, and you can export the values to excel or a csv by clicking on the Excel icon or CSV on the right. Note that if you select “Annual Total” or “Monthly Average” the number of data points, N, will be the number of years or months, while if you leave both blank, you will include all data. All statistical parameters will be calculated based on these choices. Note that the gold standard for model calibration, and the associated statistics, is the full time series of the model at the smallest time step modeled. However, monthly average statistics may help us to gain insights on model behavior.





If we compare the model results for these statistical values to the desired values, we obtain the following:

Parameter	Model monthly value (N=96)	Model average monthly values (N= 12)	Target values
NSE	0.55	Not applicable	> 0.5 = acceptable > 0.6 = desired > 0.7 = good > 0.8 = very good
PBIAS	-45%	-45%	± < 25% = acceptable
RSR	0.67	0.62	<0.7 = good

There is a lot more work to be done to improve this calibration. Model bias is still particularly low, with the model producing about half observed flows. The NSE and RSR also could use improvement. We included both the monthly and average monthly statistical values to see if these impact statistical results. Note that some statistical values, such as NSE, are not appropriate to use for an average monthly time series.

*Save a version of the model as “Catchment Calibration 1”*

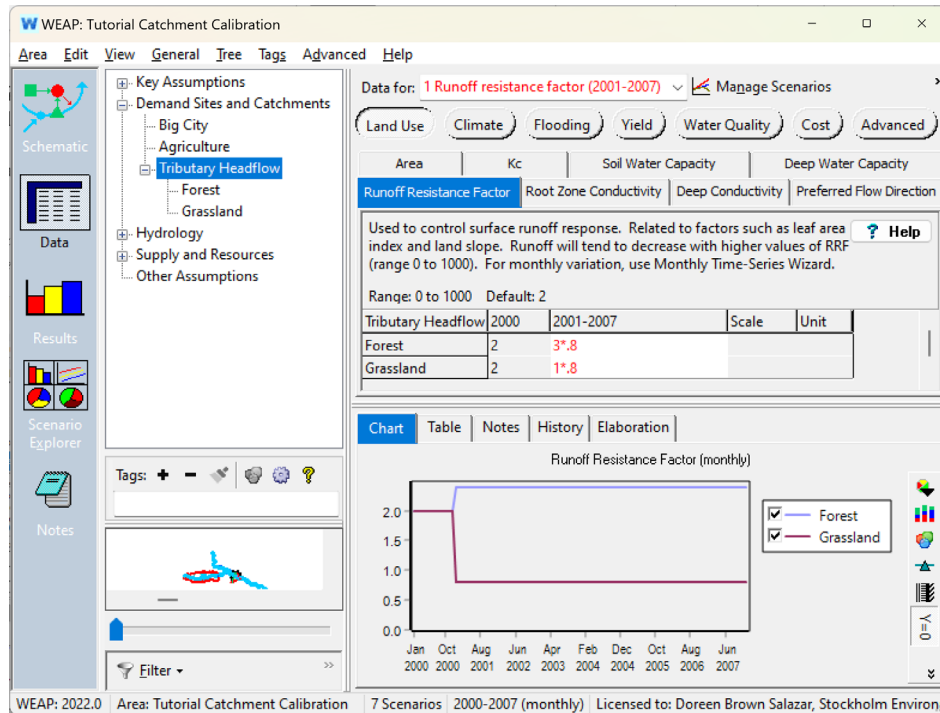
Having viewed the results, we have an idea of what to change.

## 11. Alter Model Parameters

First, because our streamflow is still too low, we will decrease the *Runoff Resistance Factor* by 20%. This will direct more water to runoff to the river immediately. The values were 3 and 1 for forest and grassland, respectively.

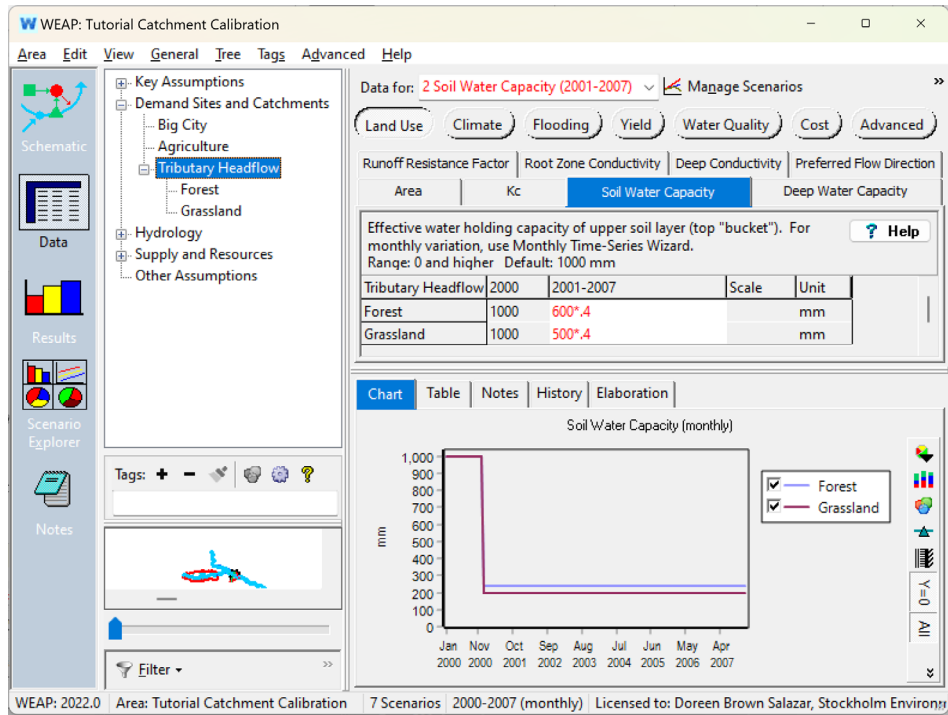
We will edit them using math operations so we can see in WEAP how the new values were calculated.

*In the Data View, multiply Forest and Grassland Runoff Resistance Factor values by 0.8 (in the 1 Runoff Resistance Factor scenario).*



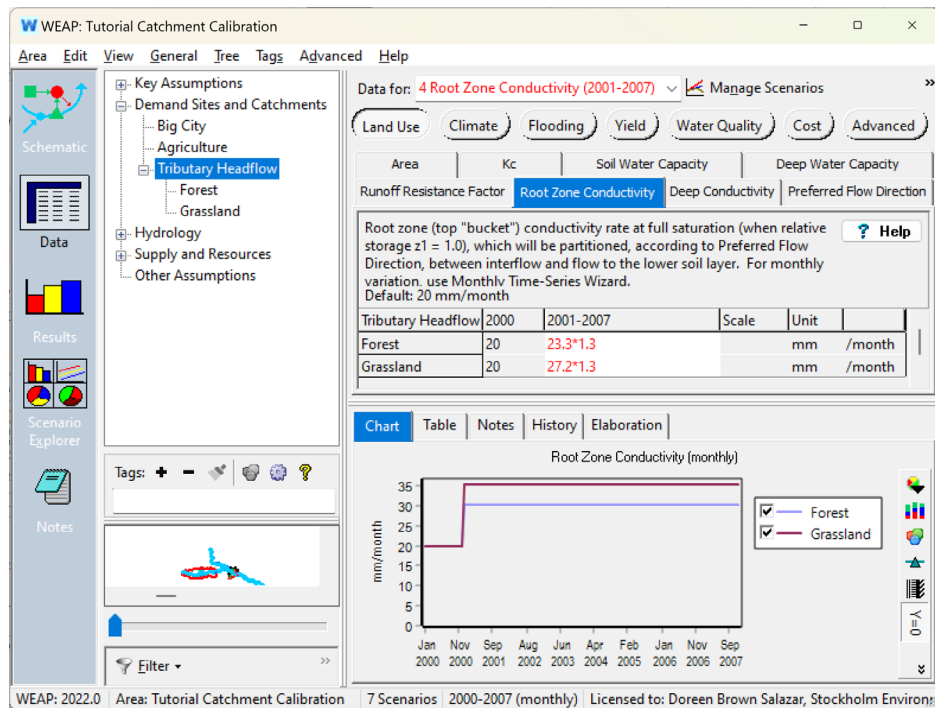
We can also decrease evaporation by speeding up the travel time in the upper bucket. We will start by reducing the values for the *Soil Water Capacity* by 60%. This reduces the amount of water that can be stored, which will encourage more interflow and should increase peak flows and adjust the PBIAS that previously showed underestimation. *Soil Water Capacity* can also make WEAP more responsive to changes on an annual time scale.

*Multiply Forest and Grassland Soil Water Capacity values by 0.4 (in the 2 Soil Water Capacity scenario).*



We will also increase *Root Zone Conductivity* by 30% to encourage faster flow from the top bucket.

*Multiply the Root Zone Conductivity values by 1.3 (in the 4 Root Zone Conductivity scenario).*



Finally, we want the *Relative Soil Moisture 2 (%)* result to be stable over time. We saw that the lower bucket was losing water too quickly, so one response might be to slow the travel time.

*Multiply the Deep Conductivity by 0.4 (in the 6 Deep Conductivity scenario).*

The screenshot shows the WEAP software interface for 'Tutorial Catchment Calibration'. The 'Data for: 6 Deep Conductivity (2001-2007)' is selected. The 'Deep Conductivity' parameter is highlighted in the 'Advanced' tab. The parameter description states: 'Conductivity rate (length/time) of the deep layer (bottom "bucket") at full saturation (when relative storage z2 = 1.0), which controls transmission of baseflow. Baseflow will increase as this parameter increases. For monthly variation, use Monthly Time-Series Wizard. Range: 0.1 and higher Default: 20 mm/month'. The table below shows the parameter values for different scenarios:

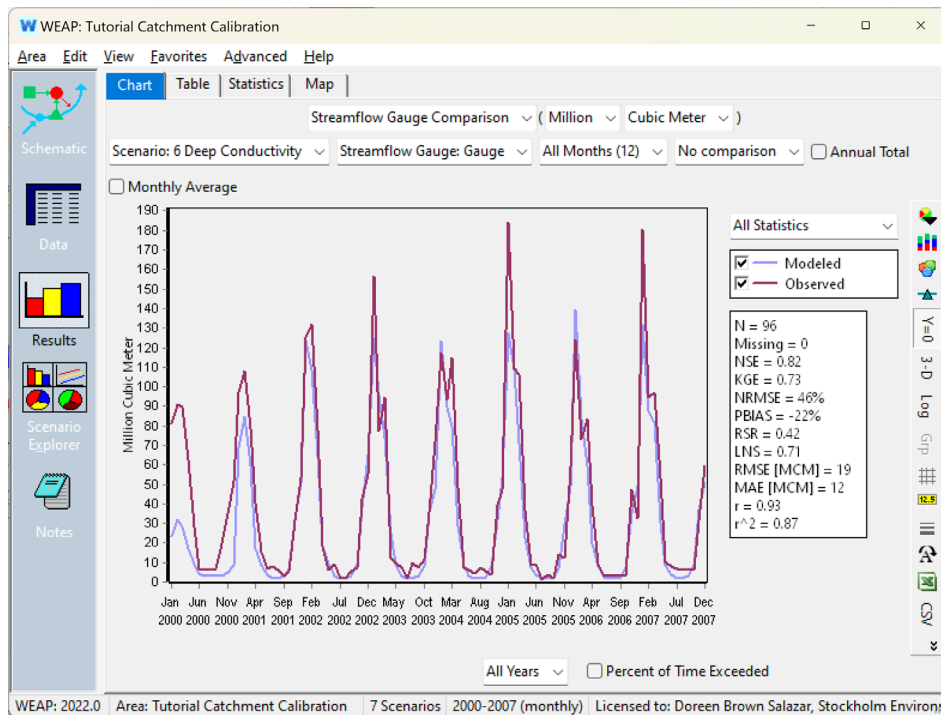
Demand Sites and Catchment	2000	2001-2007	Scale	Unit
Tributary Headflow	20	30.4		mm /month

The chart below shows the 'Deep Conductivity (monthly)' in mm/month. The y-axis ranges from 0 to 20 mm/month. The x-axis shows months from Jan 2000 to Aug 2007. The conductivity is constant at 20 mm/month from Jan 2000 to Aug 2001, then drops to 30.4 mm/month from Sep 2001 to Aug 2007.

## 12. View the Results

Run the results and in the Results View, go to the Favorite Chart for Observed and Modeled Streamflow.

Save a version of this model as “*Calibration 2*”



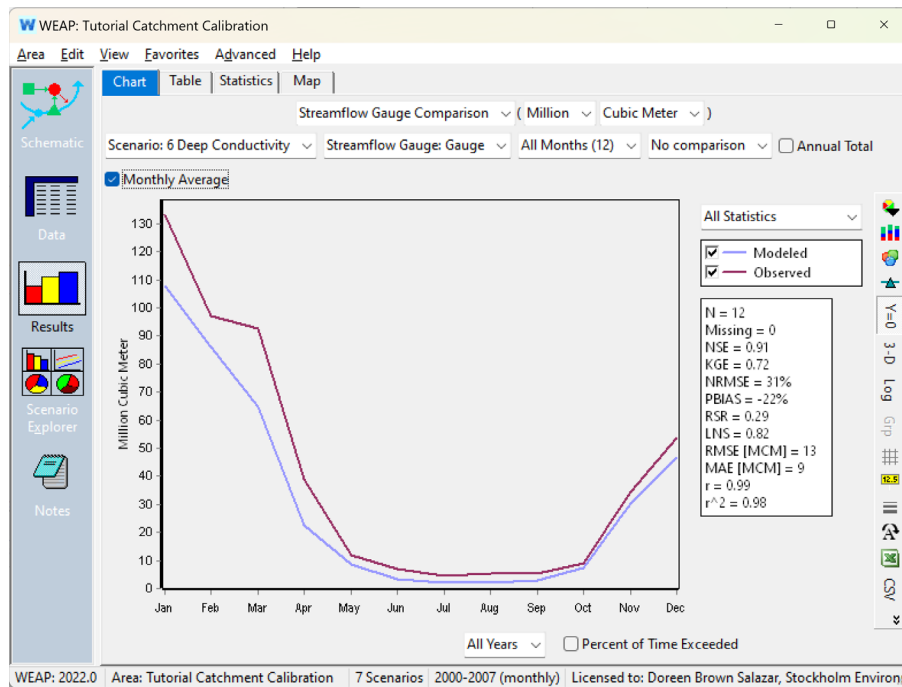
If we look at our statistical evaluation parameters, we can see that our selected evaluation parameters have all improved, and now all fall within the target value ranges. There are always more improvements to be made; you will have to decide how closely your model needs to simulate available historical data and how nearly it should represent known conditions.

Parameter	Previous model monthly value (N=96)	New model monthly value (N=96)	Target values
NSE	0.55	0.82	> 0.6 = desired > 0.7 = good > 0.8 = very good
PBIAS	-45%	-22%	± < 25% = acceptable
RSR	0.67	0.42	<0.7 = good

Save a version of this model as PBIAS -22%

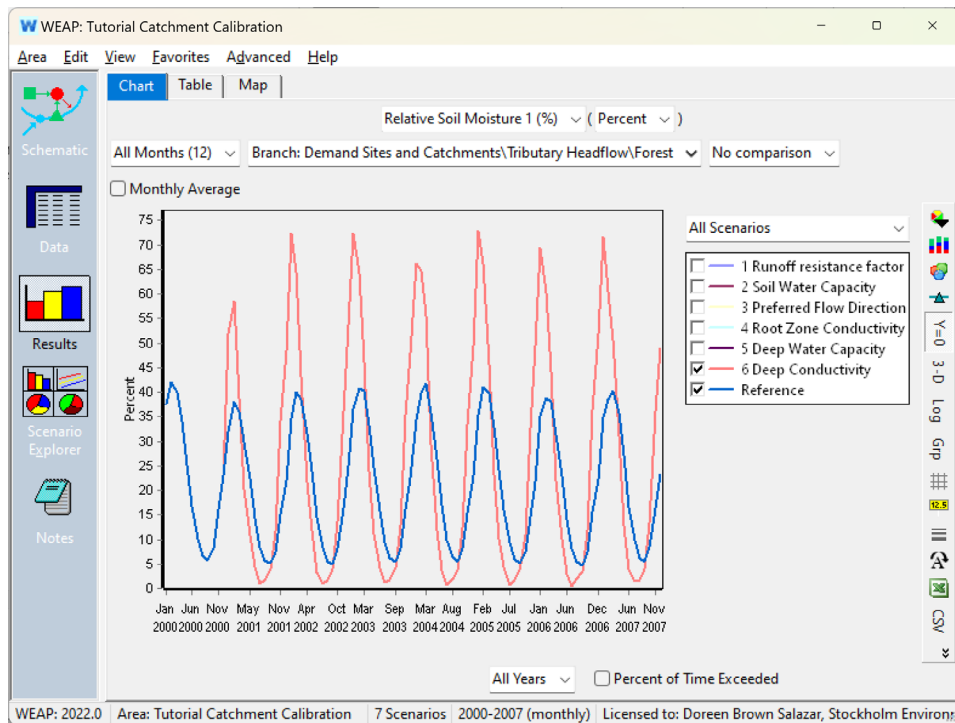
To further understand your model, look at the various charts we used for calibration. For the monthly streamflow gauge comparison chart above, we can see that, interestingly, for some years the peak flows are over-predicted, and other years they are under-predicted. Some years the low flows are very well matched, whereas other years the model under-predicts the low flows.

*Click on the box to see the Monthly Average for the observed and modeled streamflow.*

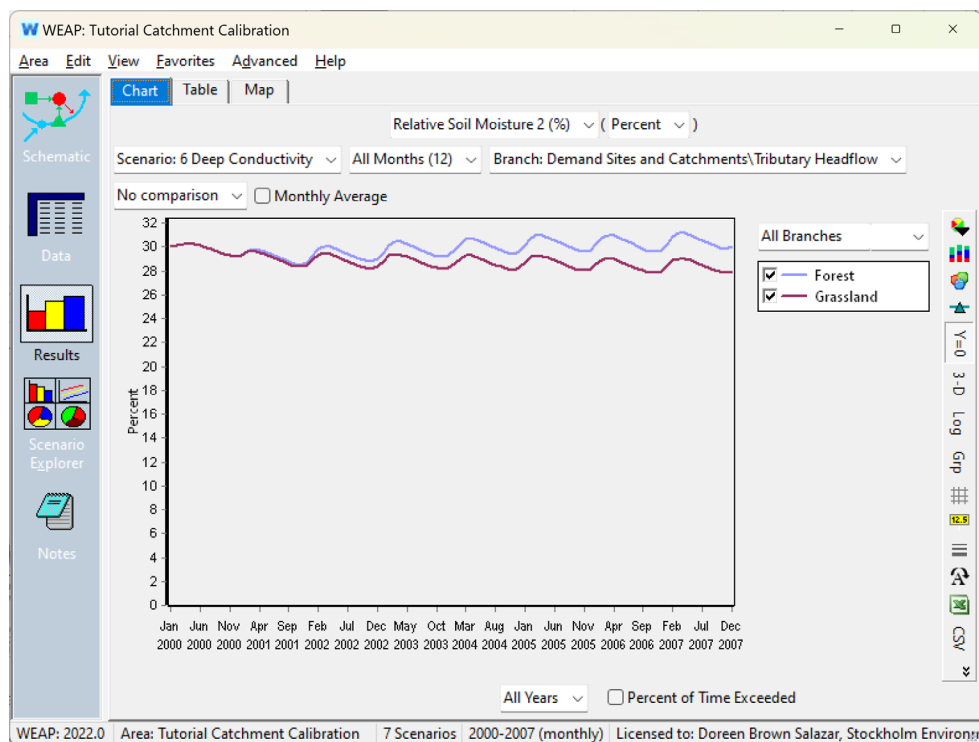


Note that the autumn months show a closer fit, on average, than the rest of the model. This could suggest an opportunity to edit some variables by month, such as the *Runoff Resistance Factor*, or the *K<sub>c</sub>* values for the land use types. Also note that statistical parameters are now calculated for N=12 (the average monthly values).

We can also verify that the cycle of *Relative Soil Moisture 1 (%)* is still stable over time (you will need to uncheck “Monthly Average”).



*Relative Soil Moisture 2 (%)* also appears to be steady, though the results divide the moisture by land use types. These are inevitably different, because they are percolating water differently.



## 13. Identify Compensatory Variables

Our model calibration has been successful, but we would be right to wonder about the factors that we did not change. Could we have obtained similar results by altering different variables? When parameters have different combinations but the same general calibration results, those parameters are called “compensatory.” In WEAP, there are many examples of compensatory parameter combinations. However, the issue at stake remains the same: is the model capturing the dynamics of the streamflow in response to climatic factors?

As an exercise, we can explore what another set of variables might have looked like.

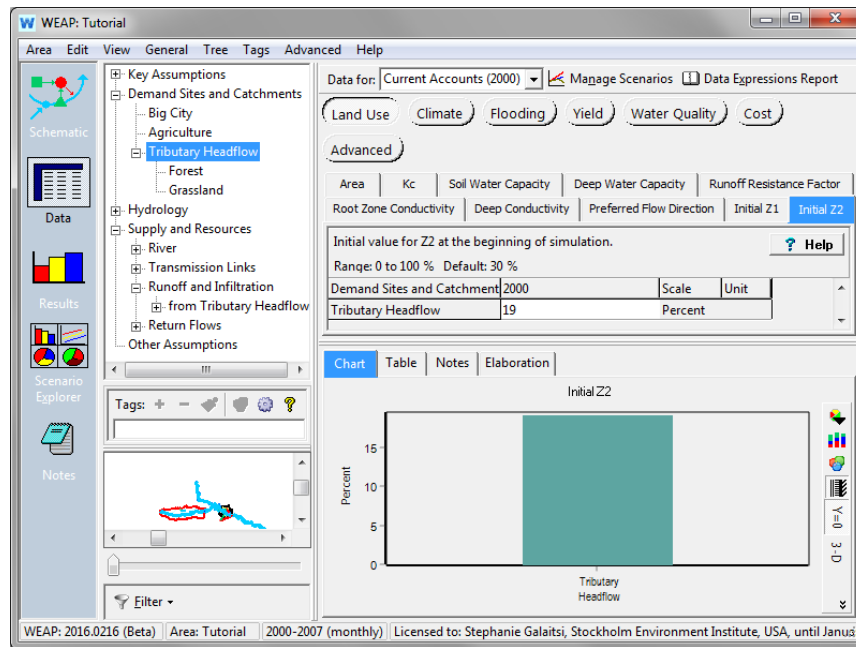
*Return to the Data View and delete the multiplication factor from the Deep Conductivity parameter (in the Deep Conductivity scenario), so the value is once again 30 mm/month.*

We had changed this variable in hopes of providing stability for our result *Relative Soil Moisture 2 (%)*, by slowing the water leaving the catchment, and keeping soil moisture around its initial value of 30%.

Instead, we will assume that the water still has a fast travel time, but the initial soil moisture value was lower.

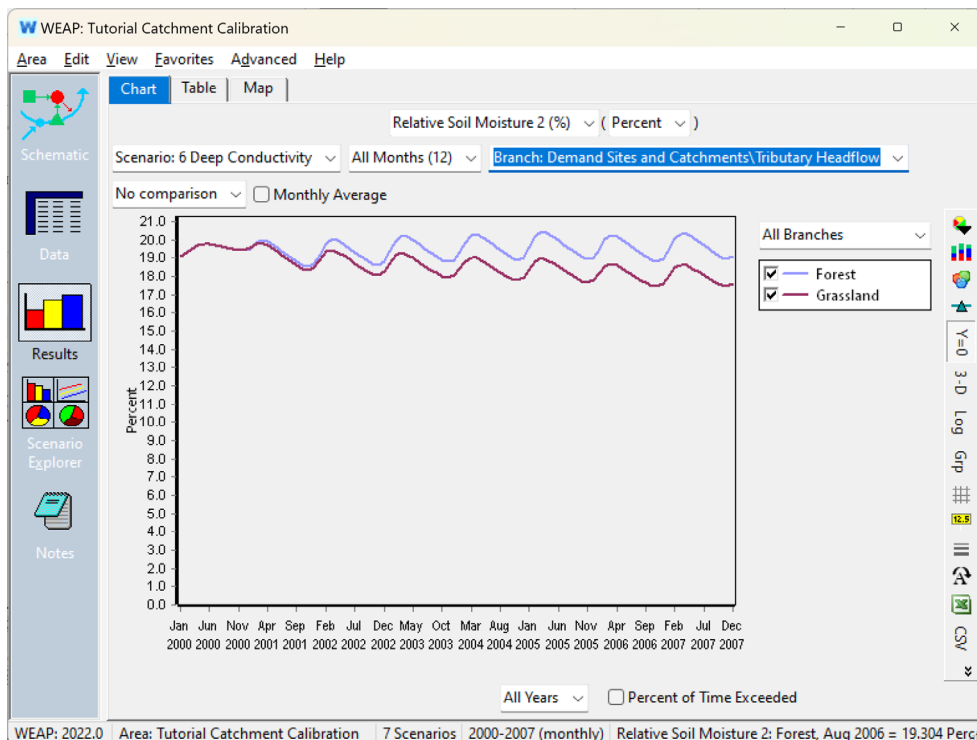
*Change the variable for Initial Z2 to 19% (Note: this variable can only be changed in Current Accounts.)*





Because soil moisture exerts a non-linear impact on travel time in the lower bucket (higher values of soil moisture cause the bucket to expel water faster), specifying a lower soil moisture value in conjunction with a faster conductivity rate is another way to maintain stability in the lower bucket soil moisture.

*Run the results. View the results for Relative Soil Moisture 2 (%).*



This chart looks similar to our prior calibration results.

Did this alteration in the characterization of our lower bucket change statistical results?

*Return to the Favorite Chart for Streamflow Gauge Comparison and view the statistical results.*

Parameter	Calibration 1 model value, monthly	Calibration 2 model value, monthly	Compensatory variable model value, monthly	Target values
NSE	0.55	0.82	0.82	> 0.6 = desired > 0.7 = good > 0.8 = very good
PBIAS	-45%	-22%	-22%	$\pm < 25\%$ = acceptable
RSR	0.67	0.42	0.43	<0.7 = good

The similarity of the results shows that while the different parameter values changed individual results (the soil moisture in the lower bucket over the course of the model), the overall model was not greatly impacted.

In some instances, experienced modelers may be able to consider the model and determine that one set of compensatory parameter values is more realistic than another. In another case, like this one, either set could be equally good, and since they are effectively indistinguishable in terms of the results produced, either can be used within the WEAP model. As the saying goes in English, there are many ways to skin a cat.

## Model Calibration Tips

### 14. Use Relative References and Key Assumptions for Large Models

#### 1) Use Relative References for Parameters for Distinct Land Use Types

Experienced WEAP modelers recommend setting up the model such that a calibration change for one parameter is proportionally reflected in all land use types. This practice of relative references recognizes the impacts that land use type can have, while simplifying changes to the model. An example is illustrated in the following table. Note that preferred flow direction does not use this strategy in this example, as it cannot surpass a value of 1. Knowing how land use types might differ in their hydrologic characteristics requires a good understanding of the area, and ideally measurements, if available. We

also have the option to pick different values for different land use types. Not all variables change according to land use type—for instance, Freezing and Melting temperatures are the same for the whole catchment, and the lower bucket of the Soil Moisture Method is too deep to be affected by land use differences on the surface.

### *Example Hydrologic Calibration Parameter Set Up*

	Kc	Runoff Resistance Factor	Preferred flow direction	Root zone conductivity	Soil Water Capacity
Agriculture	1.1 * Grassland	2	0.85	20	1000
Forest	1.25 * Grassland	2 * Agriculture	0.85	Agriculture	2 * Agriculture
Grassland	1	1.5 * Agriculture	0.85	Agriculture	1.5 * Agriculture
Wetland	1.25 * Grassland	3 * Agriculture	0.5	Agriculture	3 * Agriculture
Urban	0.7 * Grassland	0.5 * Agriculture	0.95	Agriculture	0.5 * Agriculture
Shrubland	Grassland	1.5 * Agriculture	0.85	Agriculture	1.5 * Agriculture
Barren or Sparse Vegetation	0.8 * Grassland	0.75 * Agriculture	0.9	Agriculture	0.75 * Agriculture
Open Water	Grassland	0.2 * Agriculture	0.95	Agriculture	0.2 * Agriculture
Snow and Ice	0.5 * Grassland	0.2 * Agriculture	0.95	Agriculture	0.2 * Agriculture

## 2) Use Key Assumptions for Large Models

It can be tedious to edit values by catchment, especially when working with multiple catchments that might all have the same values within land use type. To ease the calibration process for large models, we recommend structuring your catchment parameters within Key Assumptions. If you are not familiar with Key Assumptions, see the WEAP Tutorial Chapter: Basic Tools. In this way, you can easily edit parameters for multiple catchments at a time.

The more catchments and land use types a model has, the more helpful it will be to structure the Key Assumptions for the calibration process.

## 3) Use the Monthly Time Series Wizard

The default for the parameters is for each to have one value for the entire year. However, it may make sense to change them by month. This introduces an additional 11 values to alter in the calibration process for each parameter. However, not all parameters lend themselves to monthly values; it is the surface that is most affected by seasonal changes.

There are particularly compelling reasons to calibrate the following two variables monthly: Runoff Resistance Factor, and Kc. If foliage and groundcover changes over the course of the year, Kc may vary on a monthly basis and landcover might discourage runoff (a higher Runoff Resistance Factor) during some time steps more than others.

To calibrate based on the monthly values, examining the Monthly Averages in Results will show for which months the model returns below-expected streamflow, and for which months above-expected streamflow.

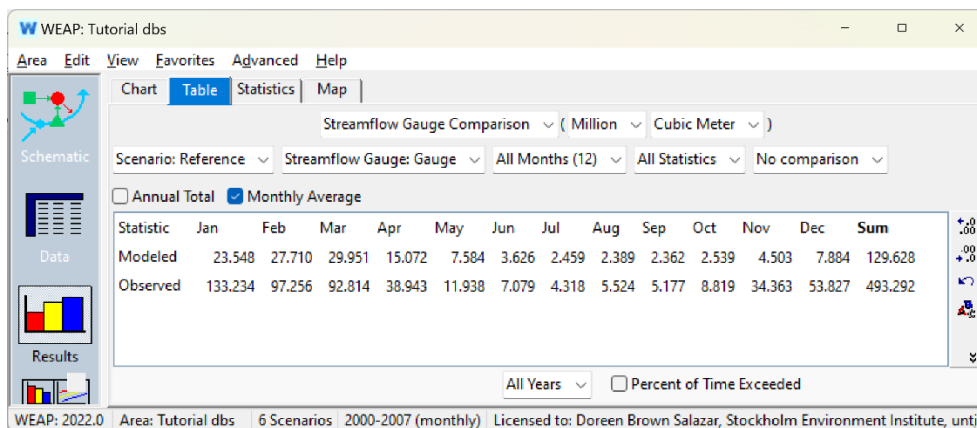
## 15. Use Mathematical Calculations to Estimate Root Zone Conductivity and Deep Conductivity

### 1) Root Zone Conductivity

A process you can use to estimate root zone conductivity is:

- Identify the highest monthly streamflow and the lowest monthly streamflow ( $\text{m}^3/\text{month}$ ) in the observed timeseries.
- Assume the lowest monthly streamflow represents the baseflow.
- Estimate monthly interflow volume ( $\text{m}^3/\text{month}$ ) as a value higher than baseflow and lower than surface water runoff, using the rainfall-runoff hydrograph as a rough guide.
- Divide the interflow volume ( $\text{m}^3/\text{month}$ ) by the area of the basin ( $\text{m}^2$ ) for an estimate of the depth of interflow ( $\text{m}/\text{month}$ ).
- Use the equation:  $Q_i = k_s * Z_1^2$  (where  $Q_i$  is the depth of the interflow,  $k_s$  is the root zone conductivity, and  $Z_1$  is the initial saturation of the first bucket in the Soil Moisture Method).

Review observed average monthly streamflow values in MCM. The highest average monthly streamflow is 133 MCM (January) and the lowest is 4.3 MCM (July). We will assume the baseflow is 4.3 MCM, and calculate surface runoff as 20% of 133, or 27 MCM.



Since the rainfall-runoff hydrograph shows that river runoff is well correlated with precipitation, much of this wet-season river volume should be surface

run-off. We used a starting point assumption of an average monthly interflow component of 12 million m<sup>3</sup> (MCM) during the wet season.

The value 12 million m<sup>3</sup> in an area of 1500 km<sup>2</sup> translates to an equivalent depth of 8 mm/month of interflow:

We then plug this value into the soil moisture method equation that calculates interflow, and use it to calculate root zone conductivity:

Where interflow = 8 mm/mo, *Preferred Flow Direction* = 0.7 (forest) and 0.6 (grasslands), and an estimated *Relative Soil Moisture 1 (%)* value of 70%.

Rearranging the above equation to solve for *Root Zone Conductivity* and plugging in the above values yields a *Root Zone Conductivity* for forest of 23.3 mm/month and for Grassland of 27.2 mm/month.

## 2) *Deep Conductivity*

A similar process can be used for estimating deep conductivity.

If you assume that the entire watershed uniformly supplies the 4.3 MCM of baseflow and divide this low summer volume by the watershed's total area (1500 km<sup>2</sup>), you can estimate the equivalent average baseflow runoff depth as 2.9 mm/month.

We can relate a baseflow runoff depth to *Deep Conductivity* and the square of the layer's relative storage ( $Z_2$ ) using the equation from the soil moisture method:

Looking at the result *Relative Soil Moisture 2 (%)*, it is difficult to guess the stable, average, long-term relative storage of this bottom layer ( $Z_2$ ). Perhaps it has changed now that the *Deep Water Capacity* is halved. Here we will estimate  $Z_2$  to be 30%. We calculate a value of 31 mm/month, and round it to 30 mm/month for our initial estimate of deep conductivity.

## 16. Calibration Optimization Steps

The calibration optimization process should follow these steps:

- 1) Export and copy results into separate document so you can review them after you change the parameters.
- 2) Change parameter values.

- 3) Run Results.
- 4) You might want to save versions of the model as you experiment with changing the parameter values. You can go to **Area/Save Version** to save the ones you think are good. That way, if your calibration efforts produce something that is not an improvement, you can go back to a previous version. It is recommended to save versions without the results because results take up a lot of memory, and they can always be recalculated.
- 5) Repeat until your criteria for calibration are satisfied.
- 6) Quantify the statistical parameters.

The example in this module demonstrated two iterations of the manual calibration process; WEAP's automatic calibration program PEST is introduced in the Snow Hydrology Chapter of this Tutorial.

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# WEAP

Water Evaluation And Planning System

# Snow Hydrology

## **A TUTORIAL ON**

<i>Explore the Pre-Existing Model</i> .....	256
<i>Enter Catchment Climate and Calibration Data</i> .....	258
<i>Explore the Model Sensitivity</i> .....	262
<i>Calibrate with PEST</i> .....	265
<i>Appendix</i> .....	268

**October 2023**

**Note:**

For this module you will need to have completed the previous modules (“WEAP in One Hour, Basic Tools, and Scenarios) or have a fair knowledge of WEAP (data structure, key assumptions, expression builder, creating scenarios). To begin this module, go to the Main Menu, select “Revert to Version” and choose the version named “Starting Point for Snow Hydrology and PEST Calibration module.”

This exercise will familiarize you with WEAP’s snow accumulation and melt routines of the Soil Moisture Method (SMM). In addition, you will learn how to use PEST to help automate the model calibration process. For this exercise, we will model the streamflow produced in a nearby mountain that has snowfall. In general, it is a good idea to divide catchments by elevation bands for entering temperature data because temperature typically decreases with increasing elevation.<sup>1</sup> However, for this example, we assume that there is enough uniformity in the area to warrant building a single catchment, and that there is a snow gauge within the area of this catchment.

## Explore the Pre-Existing Model

When collaborating with other modelers, it is important to know how to explore pre-existing models.

The snow tutorial module is a historical model that uses weekly time steps. This means that we have entered data in the model to accommodate the weekly timestep instead of a monthly timestep.

Using a weekly model assumes that we are looking at a smaller spatial scale than a model with a monthly timestep, because WEAP assumes that it will take one week for water entering the headflow of the model to arrive at the outflow of the model. Weekly and monthly models are thus not generally interchangeable; however, we have made the switch for the purpose of this example.

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<sup>1</sup> Dry air cools at about 10°C/km (the ‘dry adiabatic lapse rate’), while moist air usually cools at less than 6°C/km (the ‘moist adiabatic lapse rate’)



*Go to Main Menu > General/Years and Time Steps*

Years and Time Steps

Time Horizon  
 Current Accounts Year: 1982  
 Last Year of Scenarios: 2000

Time Steps per Year  
 52  
 Add Leap Days?

Time Step Boundary  
 Based on calendar month  
 All time steps are equal length  
 Set time step length manually

Water Year Start  
 Oct 1

#	Title	Abbrev.	Length	Begins	Ends
1	Oct 1	Oct 1	7	Oct 1	Oct 7
2	Oct 8	Oct 8	7	Oct 8	Oct 14
3	Oct 15	Oct 15	7	Oct 15	Oct 21
4	Oct 22	Oct 22	7	Oct 22	Oct 28
5	Oct 29	Oct 29	7	Oct 29	Nov 4
6	Nov 5	Nov 5	7	Nov 5	Nov 11
7	Nov 12	Nov 12	7	Nov 12	Nov 18
8	Nov 19	Nov 19	7	Nov 19	Nov 25
9	Nov 26	Nov 26	7	Nov 26	Dec 2

Time Step Name Format: Oct 1 (first date)

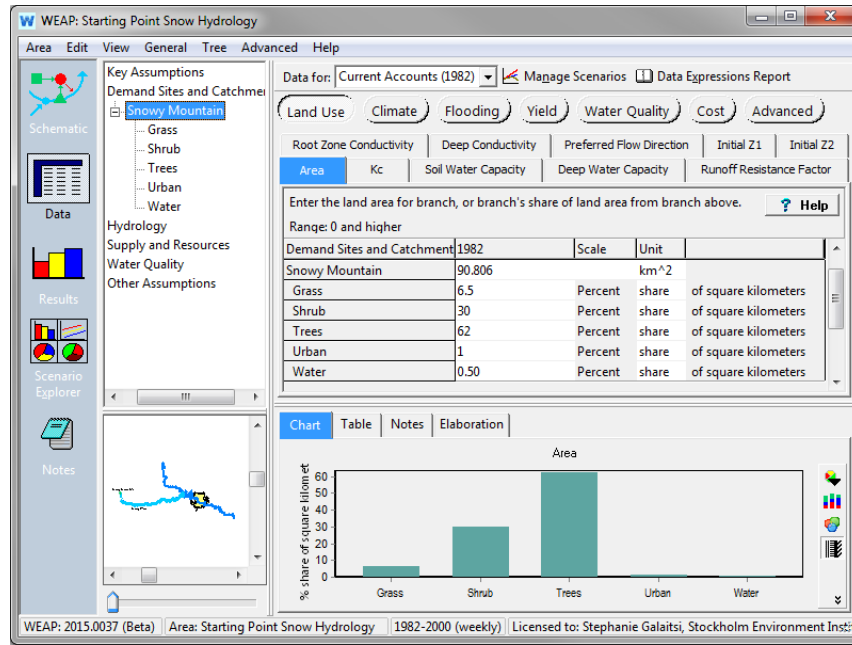
The study period will run from Oct 1, 1981 to Sep 24, 2000.

Help Close

Not only is this a weekly model, but it starts on October 1, 1981. Water years in the United States typically start in October. In the dropdown menu “Time Step Name Format,” the format “Oct 1 (first date)” is selected, but there are other formats available to label the various weeks of the model.

*Close the Years and Time window and go into the Data View to see the data in the catchment “Snowy Mountain.”*

The catchment’s land area is dominated by tree cover (62%).



The variables Area, Kc, Soil Water Capacity, Deep Water Capacity, Deep Conductivity, Preferred Flow, Initial Z1, Initial Z2, Runoff Resistance Factor, and Root Zone Conductivity already have data entered. Most of the root zone (upper bucket) variables have the same value for the different land use types, with the notable exception of the Runoff Resistance Factor.

We also see that under Key Assumptions, there is a new assumption: Albedo, with both NewSnow and OldSnow values (explained below).

## Enter Catchment Climate and Calibration Data

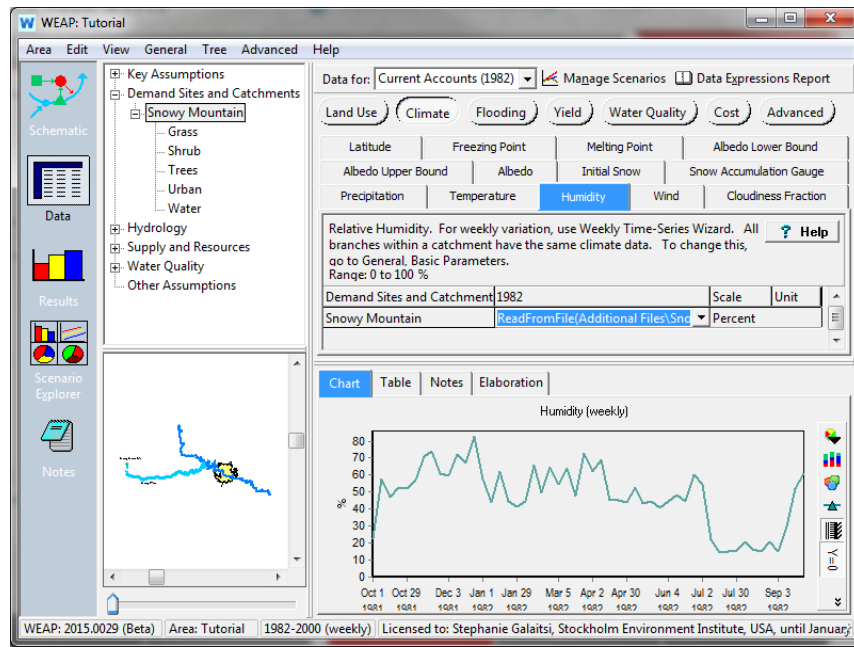
### 1. Enter Climate Data

The climate data can be found in a file called SnowyMountain.csv in the WEAP Tutorial folder\Additional Files. You can look at this file for an example of the data format for a weekly model.

*Use the ReadFromFile function to enter data for precipitation (data column 1), temperature (data column 2) and humidity (data column 3) for Snowy Mountain. You may use the ReadFromFile wizard to help you build the expression or type the expression in directly.*

Relative Humidity. For weekly variation, use Weekly Time-Series Wizard. All branches within a catchment have the same climate data. To change this, go to General, Basic Parameters. Range: 0 to 100 %

Demand Sites and Catchment	1982	Scale	Unit
Snowy Mountain	ReadFromFile(Additional Files\SnowyMountain.csv, "Humidity[%]")	Percent	



*Enter the data for*

*Freezing Point            -5°C (default)*  
*Melting Point             10°C*

Data for wind, cloudiness fraction and latitude are already entered.

Albedo (i.e., surface reflectance) is a very important parameter for snow routines. It controls the net radiation available for snow melt. In this region, albedo of old snow needs to be distinguished from albedo of new snow. Albedo of old snow is lower (as it gets dirtier) than new snow. You must have WEAP version 2016 or newer to access the albedo data tab to enter an expression to control the effect of age of snow on albedo.

*Go to the Albedo data tab. Using the Expression Builder to make an expression, enter the equation:*

*If(PrevTSValue(Snow Depth[m])=0, Albedo Lower Bound,  
 PrevTSValue(Snow Depth[m],1)>PrevTSValue(Snow Depth[m],2),  
 Key\Albedo\NewSnow,  
 Max(PrevTSValue(Albedo)-0.1, Key\Albedo\OldSnow))*

We have now given WEAP instructions for albedo values for three circumstances:

- 1) If previous time step had no snow, then Albedo = Albedo Lower Bound, which defaults to 0.15
- 2) Otherwise, if previous time step had new snow (the snow depth in the previous timestep is greater than two timesteps earlier), then Albedo = “NewSnow” = 0.8
- 3) Otherwise, Albedo = albedo in the previous timestep minus 0.1 (but not less than OldSnow = 0.4).

Note that NewSnow and OldSnow albedo values are in the Key Assumptions and can be changed to help the model better fit the data. The Appendix for this module explains this equation in more detail.

## 2. Enter Observed Snow Data

We will now add snow accumulation data from the Snowy Mountain snow gauge. This gauge is located within the Snowy Mountain catchment.

In the Snowy Mountain Catchment, under Climate > Snow Accumulation Gauge.

*Use the ReadFromFile function to read the data from SnowGauge.csv (in Additional Files of the Tutorial folder)*

Note that this file has missing data, so the “Missing Value Method” in the ReadFromFile Wizard will default to “Mark” which leaves the data value empty. For more, see the Help menu about the ReadFromFile Wizard.

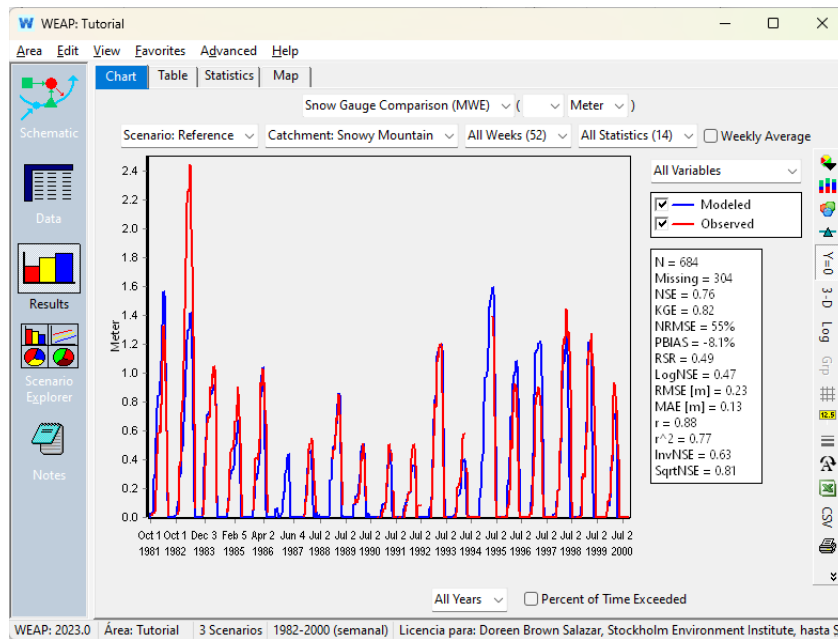
The expression will appear as:

Historic data of snow accumulation (snowpack), to be used in calibration. Measured in melt water equivalent (MWE) depth. For weekly variation, use Weekly Time-Series Wizard. All branches within a catchment have the same climate			
Range: 0 and higher			
Demand Sites and Catchment	Year	Scale	Unit
Snowy Mountain	1982	ReadFromFile(Additional Files\SnowGauge.csv, "SnowGauge[mm]", , , , Mark)	mm

## 3. View the Results

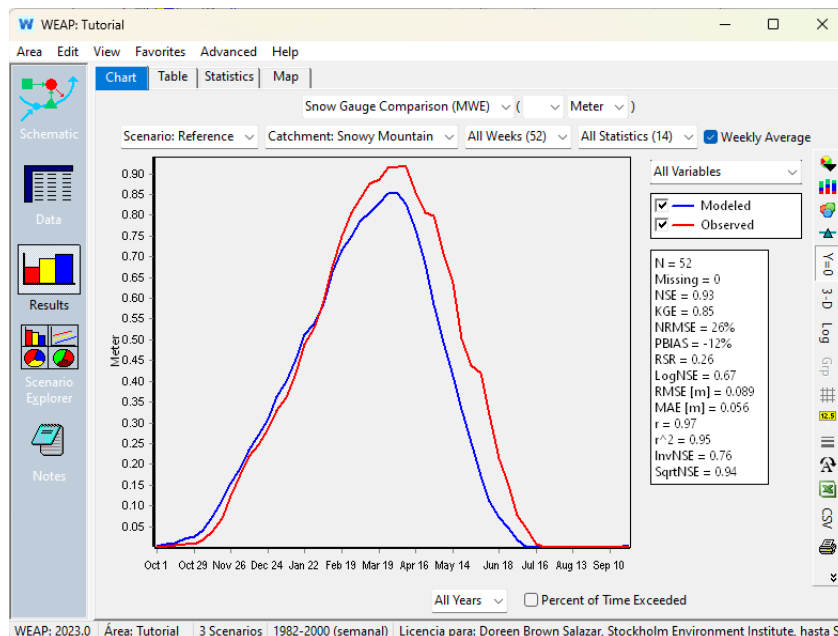
*Run the model results.*

*View the result Catchments/Snow Gauge Comparison*



*Save the chart as a favorite.*

*Look at the same data as a weekly average.*



Here we can see that in general, WEAP’s modeled values for snow depth are too high between October and February and then too low until July, when the snow melts altogether. Compared to the gauge, the model is producing and melting snow too early.

## Explore the Model Sensitivity

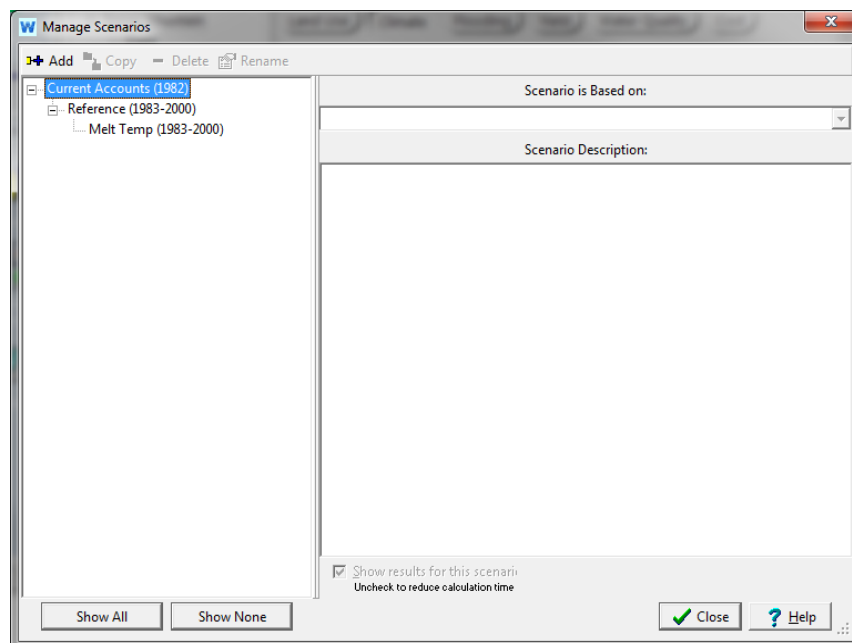
Now that you have a working model you can explore the sensitivity of model results to changes in the parameters.

To explore model sensitivity, you will first create a new scenario in which you will alter parameter values. You will then be able to compare the new scenario results to the “reference” scenario results and see the impacts of changing the parameter values.

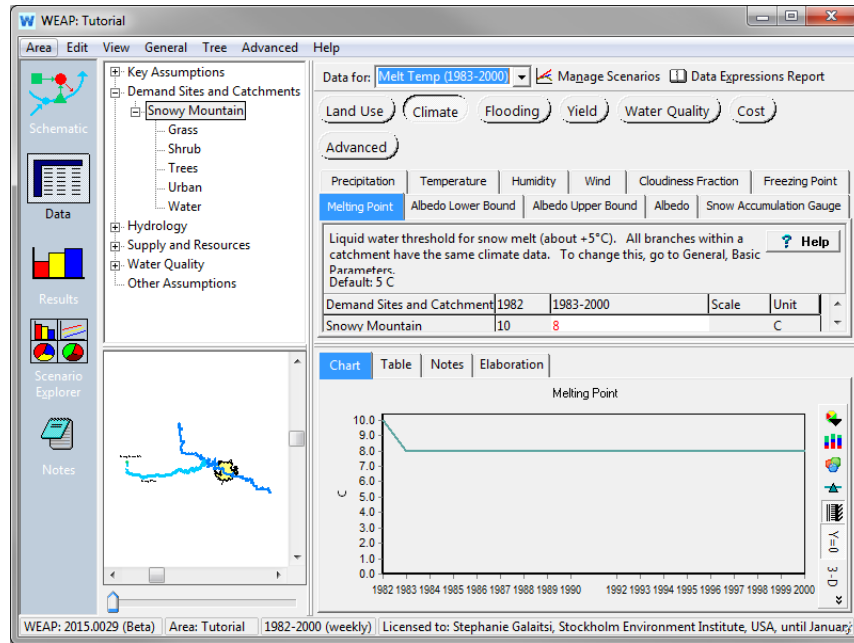
### 4. Manual Changes within a Scenario

We will first examine the impacts of changing the melting point parameter for snow.

*Add a new scenario that inherits from Reference called “Melt Temp.”*



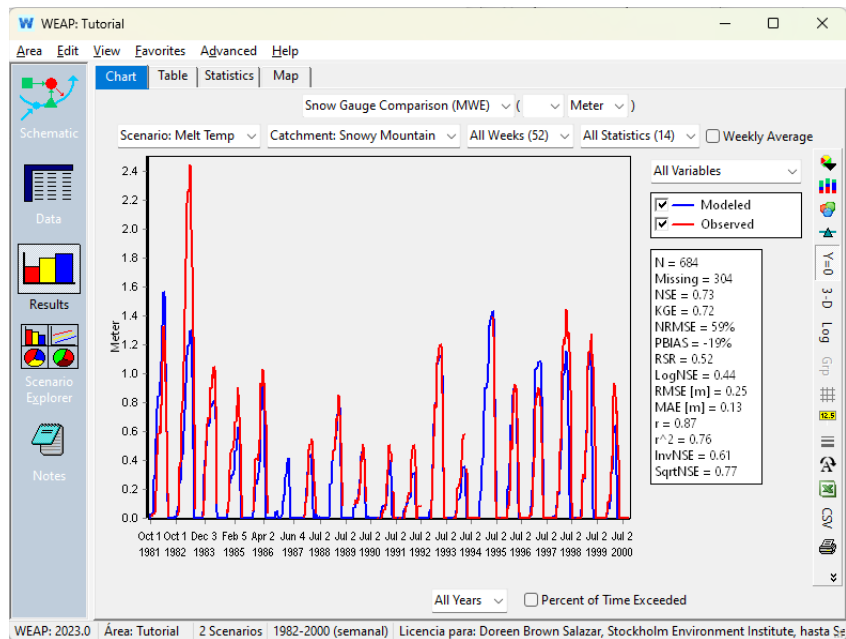
*In the Snowy Mountain catchment, in the Melt Temp scenario, change the “Melting Point” value to 8. Before you run the model, think about how you expect this to change the results.*



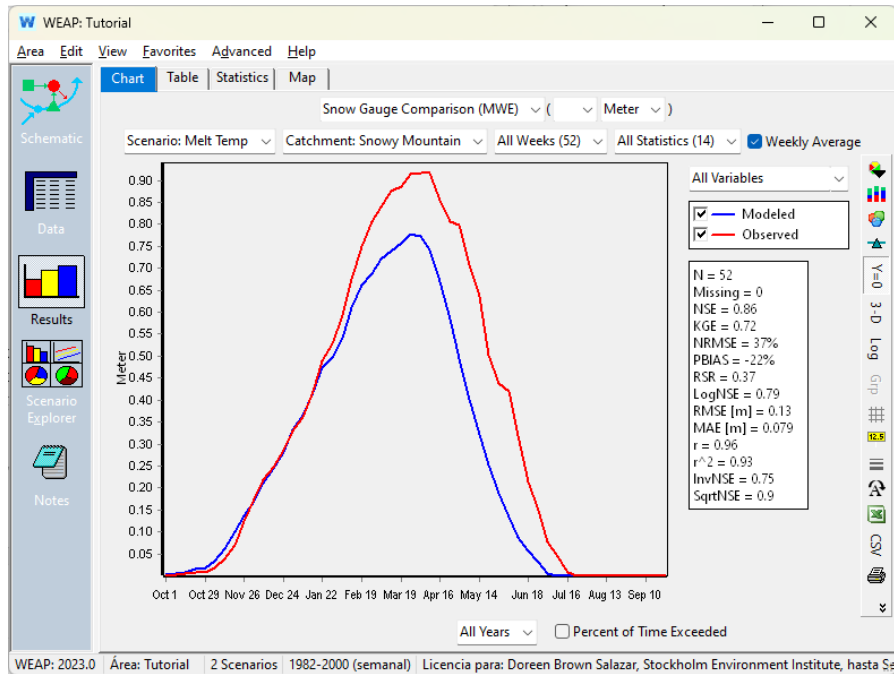
*Run the model by clicking on Results.*

We can compare snow accumulation to the modeled snow for both scenarios.

*Go to Favorites and choose the chart with Snow Gauge Comparison. View the results for the Melt Temp Scenario*

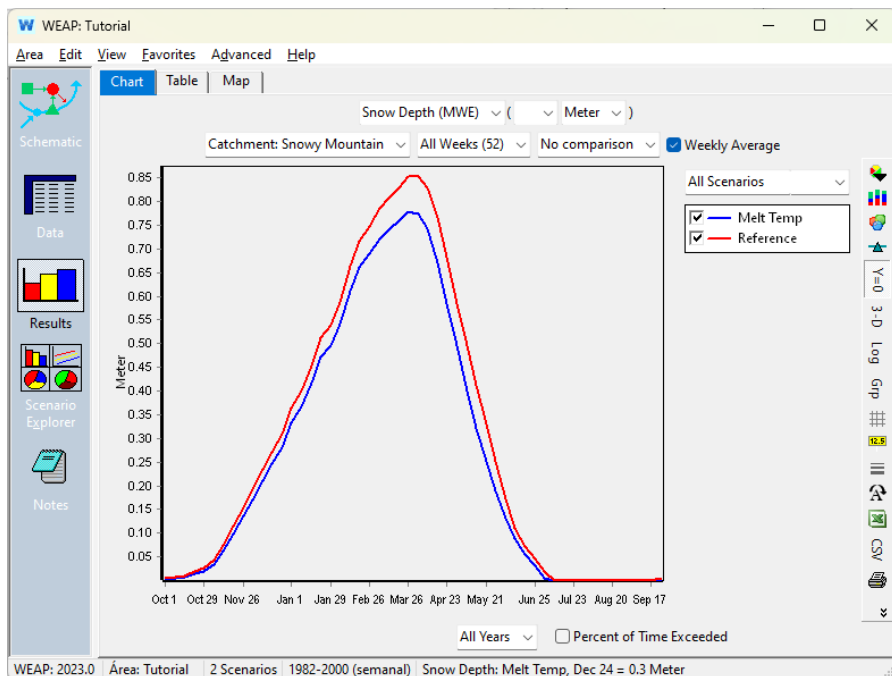


*View as a weekly average.*



The lowered melting temperature reduces the range of temperature in which water can exist as snow. Therefore, the snow accumulation is less. Between October and January, this produces similar results to the snow accumulation gauge, but after January, we see that the snow is melting too early, like the reference scenario. But how do the two scenarios compare to each other?

*Now look at the result “Snow Depth (MWE)”. Choose “All Scenarios” from the dropdown on the right side of the screen.*





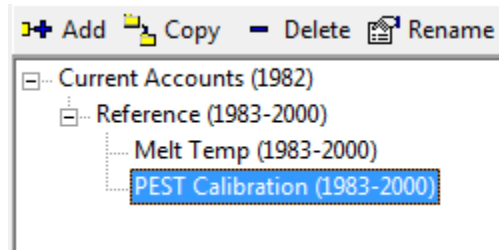
In our “Melt Temp” scenario, the snow is melting even earlier in the year than for the Reference scenario.

When examining the impacts of changing different parameters, it’s useful to start with a fairly substantial change (a few degrees C) to get a sense of how it will affect the model. Then you can select a more appropriate magnitude of change. This activity can be performed for the freezing temperature as well as for changes in other parameters.

## Calibrate with PEST

WEAP links to a parameter estimation tool (PEST) that can help produce results that match historical data records by examining a range of parameter values and combinations thereof. With PEST, the user can select which parameters to calibrate using the historical records available for entry in WEAP: streamflow gauges, catchments with snow depth data and reservoir levels with volume data. A PEST calibration produces combinations of parameter values to enable the model results to approximate the observed data. PEST will not always find the best solutions but can be a good place to start. To learn more about PEST, see the WEAP help menu: (PEST Calibration), or see [www.pesthomepage.org](http://www.pesthomepage.org).

*Create a new scenario called “PEST calibration” that inherits from Reference*



*Open PEST Calibration (Advanced > Pest Calibration).*

*Click + Add to add the Snowy Mountain variables below with the following information:*

<i>Parameter</i>	<i>Lower Bound</i>	<i>Upper Bound</i>	<i>Initial Value</i>
<i>Melting Point</i>	0	10	5
<i>Freezing Point</i>	-10	0	-5

Then select the following:

*Catchments (with snowpack data):*    *Snowy Mountain*

*Years: 1983-2000 (Choose “Selected”, click the button to select All, then deselect ‘82)*

*Scenarios to Calibrate: PEST Calibration*

*Modify Parameters:*

*Current Accounts*

*Unclick*

*Normalize Observation Data*

*Unclick*

Calibration using PEST

Calibration Set: PEST Calibration

Parameters to Calibrate

Parameter	Lower Bound	Upper Bound	Initial Value
Melting Point[C]	0	10	5
Freezing Point[C]	-10	0	-5

Observations to Calibrate To

Streamflow Gauges: None defined

Reservoirs (with observed data): None defined

Catchments (with snowpack data): Snowy Mountain

Years: Selected

Weeks: All

Options

Scenarios to Calibrate: PEST

Modify parameters in Current Accounts also

Normalize observation data

Run PEST after building PEST input files

Buttons: ? Help, ✓ Build Files and Run PEST, ✗ Close

When WEAP normalizes observation data, PEST will use the reciprocal of each observation value as its weight. For example, if the observations were 10, 30 and 25, the weights would be  $1/10$ ,  $1/30$  and  $1/25$ . This weighting will ensure that the larger values, such as flood flows in the river, do not outweigh of the smaller values, such as low flows. This option is essential when simultaneously calibrating different types of observations (e.g.,

streamflow and reservoir storage), because the two types are not comparable (different units, and could be many orders of magnitude different). It is also helpful when calibrating streamflow, so that low flows will have equal weight as high flows. However, we currently have only one record of observation, and we will see what results PEST produces when it is not normalizing large and small flows.

*Click “Build Files and Run PEST”.*

PEST will take control, running the model many times.

Once it stops, results for final parameter values found by PEST will show in the Scenarios Explorer. You can also see them in the Data View for the PEST Calibration Scenario.

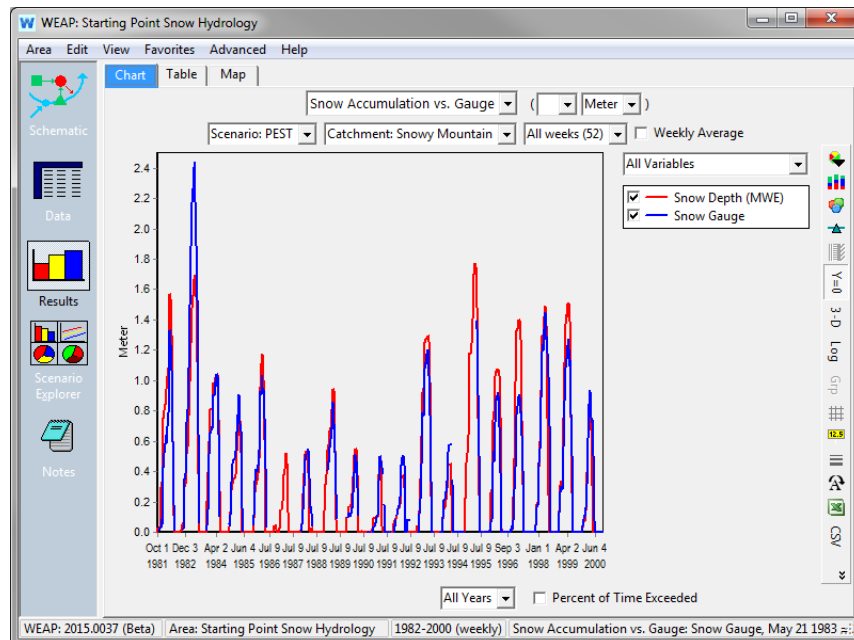
*What were the PEST values for the parameters entered above?*

You may receive slightly different results. Our outputs were:

Parameter	PEST Calibration Value
Melting threshold	6.29
Freezing Threshold	-1.38

*Run the results.*

*How is the snow simulation vs the gauge? Is it better or worse than the Reference (uncalibrated) scenario?*



## Appendix

### Note:

This model used a custom equation for snow albedo evolution. The same equation should NOT be used in other model regions. You will have to figure out what makes sense in your own geographic region and timestep.

Following is an explanation of the snow albedo equation presented in Section 1. .

First, we will tell WEAP that if the previous time step had no snow, WEAP will use an Albedo value of Albedo Lower Bound (which defaults to 0.15). At the start of the model, there is no previous time step, but there is a parameter called “Initial Snow” which WEAP will use as the snow depth of the timestep before the model starts. The user can set this value according to the circumstances in their system at the start of the model’s time period.

To tell WEAP the albedo value for no snow, we will use the “If” statement, in the format *If(test 1, value if test 1 is true, test 2, value if test 2 is true, ..., value if all tests are false)*.

If(PrevTSValue(Snow Depth[m])=0, Albedo Lower Bound,

Now we have to tell WEAP what to do if there was snow in the previous timestep. We want to determine whether there was new snow or old snow, as they have different albedo values. As the *test 2* part of our “If” statement, we will ask WEAP if the snow depth in the previous timestep is greater than the snow depth in the time step prior to that. Values 1 and 2 in this PrevTSValue expression denote how many timesteps previous to look (one or two). In the event that the snow was greater in the most recent time step, WEAP will give Albedo the value of NewSnow from the Key Assumptions, which was 0.8 in this exercise.

If(PrevTSValue(Snow Depth[m])=0, Albedo Lower Bound,  
 PrevTSValue(Snow Depth[m],1)>PrevTSValue(Snow Depth[m],2),  
 Key\Albedo\NewSnow,

However, in the event that there was snow, but it was not new snow, we must tell WEAP how to calculate the Albedo value. This will be the *value if all tests are false* part of the “If” statement. We will ask it to choose the maximum of two values:

- 1) The albedo of the previous time step minus 0.1
- 2) The albedo of the Key Assumption OldSnow (0.4)

If(PrevTSValue(Snow Depth[m])=0, Albedo Lower Bound,  
PrevTSValue(Snow Depth[m],1)>PrevTSValue(Snow Depth[m],2),  
Key\Albedo\NewSnow,  
Max(PrevTSValue(Albedo)-0.1, Key\Albedo\OldSnow))

Therefore, if there is snow on the ground, the value of Albedo will be between 0.4-0.8, depending on how long it has been since the last new snow. After the last snow has melted, the albedo will fall to 0.15.



---

# WEAP

Water Evaluation And Planning System

# Glaciers

## ***A TUTORIAL ON***

<i>Modeling a Glacier .....</i>	<i>272</i>
<i>Enter Catchment Climate .....</i>	<i>273</i>
<i>Effect of Cooling Temperatures .....</i>	<i>276</i>
<i>Effect of Warming Temperatures .....</i>	<i>279</i>
<i>Parameter Sensitivity (Radiation Coefficient).....</i>	<i>282</i>

**October 2023**

**Note:**

For this module you will need to have completed the previous modules (“WEAP in One Hour, Basic Tools, and Scenarios) or have a fair knowledge of WEAP (data structure, key assumptions, expression builder, creating scenarios). To begin this module, go to the Main Menu, select “Revert to Version” and choose the version named “Starting Point for Glacier module.”

In this activity, we will show how severe climate conditions which lead to the accumulation or melt of ice play out in a glacier’s formation or vanishing. After modeling a glacier under one set of conditions, two additional scenarios of cooling and warming conditions are explored. Additionally, a simple sensitivity analysis regarding the radiation coefficient is conducted to investigate the impact of this parameter on glacier melting.

## Modeling a Glacier

For this exercise, we will model the glaciation of an existing snow depth which represents the initial status of the glacier. As we did in the Snow Hydrology exercise, we will assume sufficient regularity in the area for a single-catchment case study.

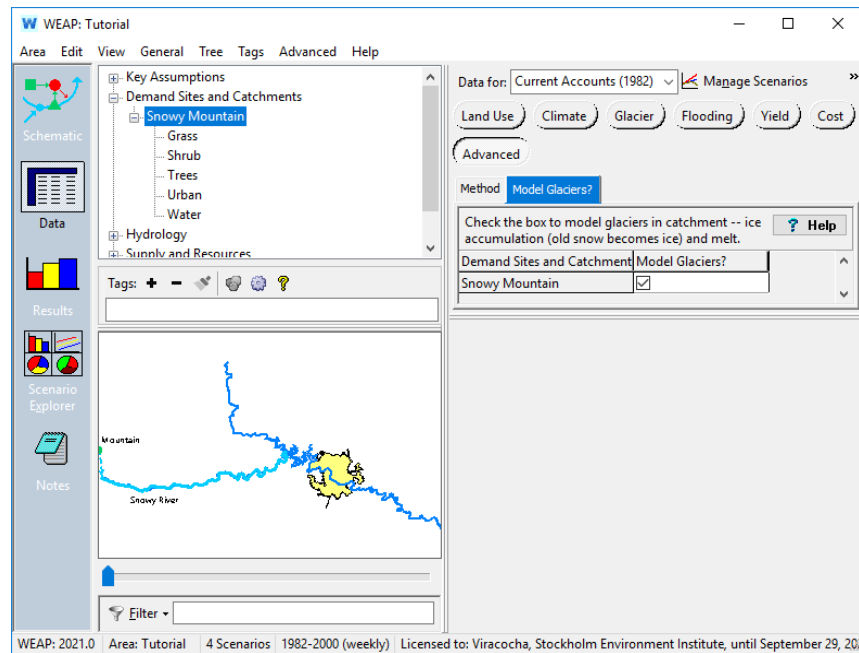
### 1. Set Up the Model to Include Glaciers

With “Snowy Mountain” catchment selected in Data, you should find “Model Glaciers?” under the “Advanced” tab.

*Advanced > Model Glaciers?*

Check the box of “Model Glaciers?”, and you can see now that a new tab called “Glacier” has been generated next to “Climate” tab. (You may need to click on a different tab first for the Glacier tab to appear.)





## Enter Catchment Climate

### 2. Change Modeling Years and Enter Climate Data

The climate data can be found in a file called Glacier.csv in the WEAP Tutorial folder\Additional Files. You can look at this file as an example of a data format for a weekly model. We will be using a weekly model with a water year starting on October 1, as we did with the Snow Hydrology chapter. You will see that the data begins in water year 2011 and ends in 2033.

Change the modeled years to begin in 2012 and end in 2030 (under General\Years and Time Steps).

Set the melting point temperature to 10°C (the default is 5°C), on the Climate tab for Snowy Mountain.

Review the following formula for albedo (also in the climate tab), described and input in the Snow Hydrology chapter:

$$\text{If}(\text{PrevTsv}(\text{Snow Depth}[m])=0, \text{Albedo Lower Bound}, \sim \\ \text{PrevTsv}(\text{Snow Depth}[m], 1) > \text{PrevTsv}(\text{Snow Depth}[m], 2), \sim \\ \text{Key}\backslash\text{Albedo}\backslash\text{NewSnow}, \sim \text{Max}(\text{PrevTsv}(\text{Albedo})-0.1, \\ \text{Key}\backslash\text{Albedo}\backslash\text{OldSnow}))$$

Use the ReadFromFile function to enter data for precipitation (data column 1), temperature (data column 2) and humidity (data column 3) for Snowy Mountain. You may use the ReadFromFile wizard to help you build the expression, or type the expression in directly:

```
ReadFromFile(Additional Files\Glacier.csv, "Precipitation[mm]")
```

```
ReadFromFile(Additional Files\Glacier.csv, "Temperature[C]")
```

```
ReadFromFile(Additional Files\Glacier.csv, "Humidity [%]")
```

We will keep the remaining tabs under “Climate” at the default values.

### 3. Enter Glacier Data

Most of the parameters under the “Glacier” tab already have default values (i.e., Ice Melting Point: 1°C, Radiation Coefficient: 50%, ...). For the sake of this example:

Input an initial Ice Depth of 8 m as shown.

The screenshot shows the WEAP software interface with the 'Glacier' tab selected for the 'Snowy Mountain' catchment. The 'Initial Ice Depth' parameter is set to 8 m. A table below the parameter description shows the value for 'Snowy Mountain' as 8 m. A chart titled 'Initial Ice Depth' shows a single bar for 'Snowy Mountain' with a height of 8.0 m.

Demand Sites and Catchment	2012	Scale	Unit
Snowy Mountain	8		m

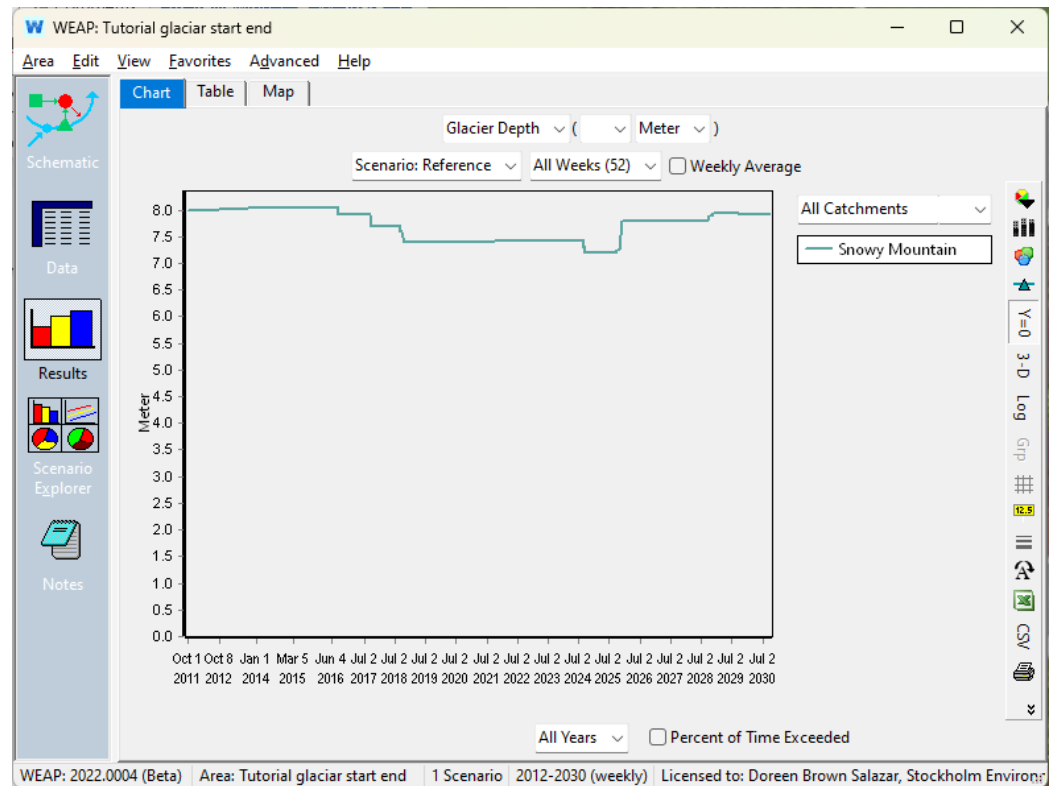
The Scaling Factors (b & c) are two parameters that are used to relate glacial ice volume to glacial area. We will leave them at the default values (1.36 & 0.048) that were derived from an analysis of 144 glaciers around the world (Bahr, D. B., M. F. Meier, and S. D. Peckham, “The physical

basis of glacier volume-area scaling,” J. Geophys. Res. 102 (B9): 20355–20362), 1997.

## 4. View the Results

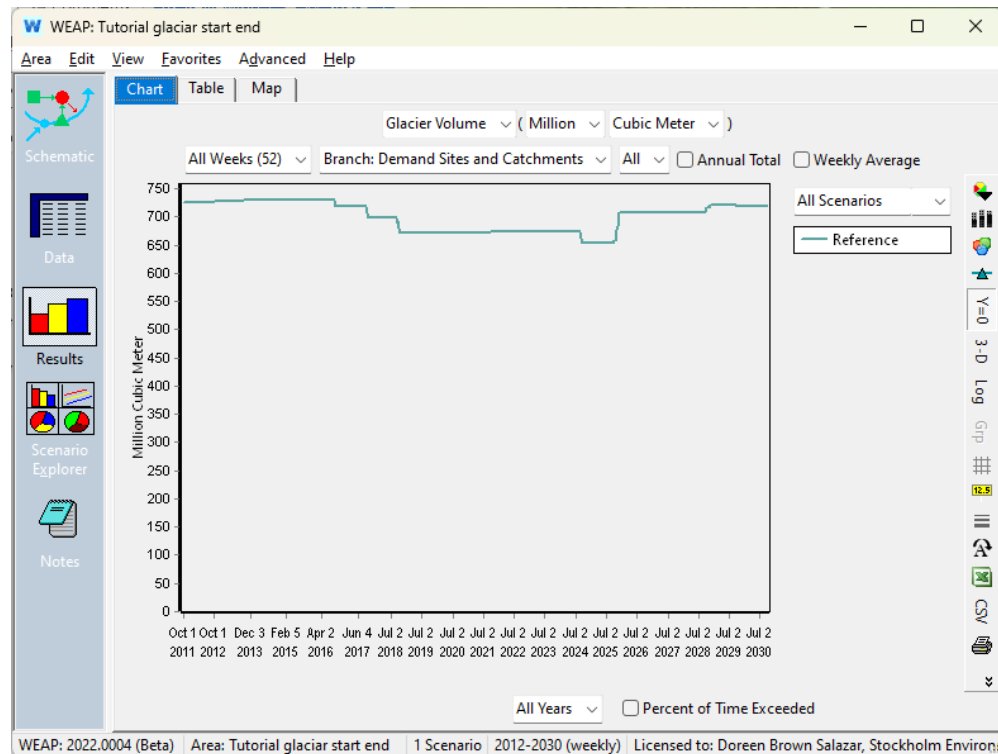
*Run the model.*

*View the result Glacier Depth*



When looking at the glacier depth graph, we conclude that although the depth showed some fluctuations, there is neither an upward nor a downward trend as depth grew and shrank within the approximate range of 7 to 8 meters.

### View the result Glacier Volume



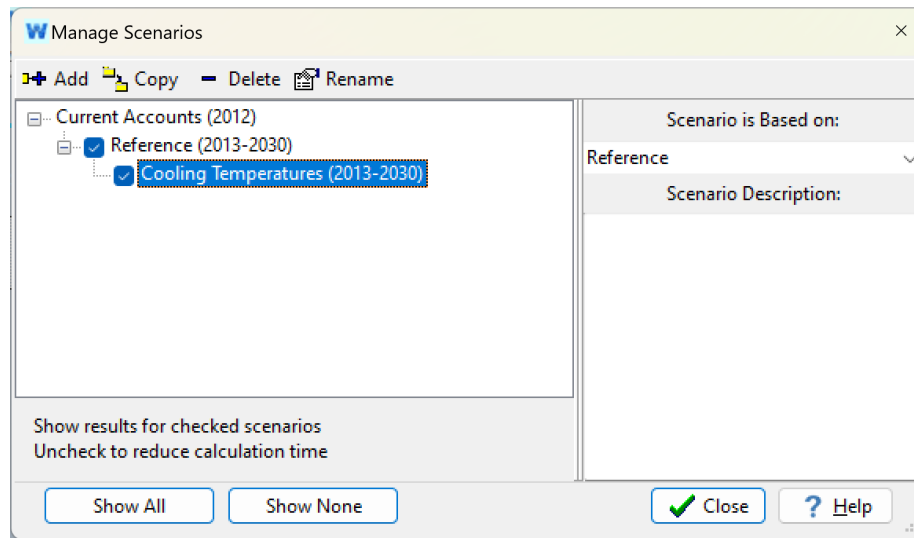
Also, if we look at the timeseries of the glacier volume, we see the same pattern as the depth, with no significant increasing or decreasing trend.

## Effect of Cooling Temperatures

With the uncertainty around climate projections growing, a scenario where cooler conditions would prevail in the future is explored here to model the impact on the glacier dynamics.

### 5. Create a Scenario for Cooling Temperatures

First, we will add a scenario called “Cooling Temperatures” that is based on the “Reference” scenario.



## 6. Enter Climate Data for the Added “Cooling Temperatures”

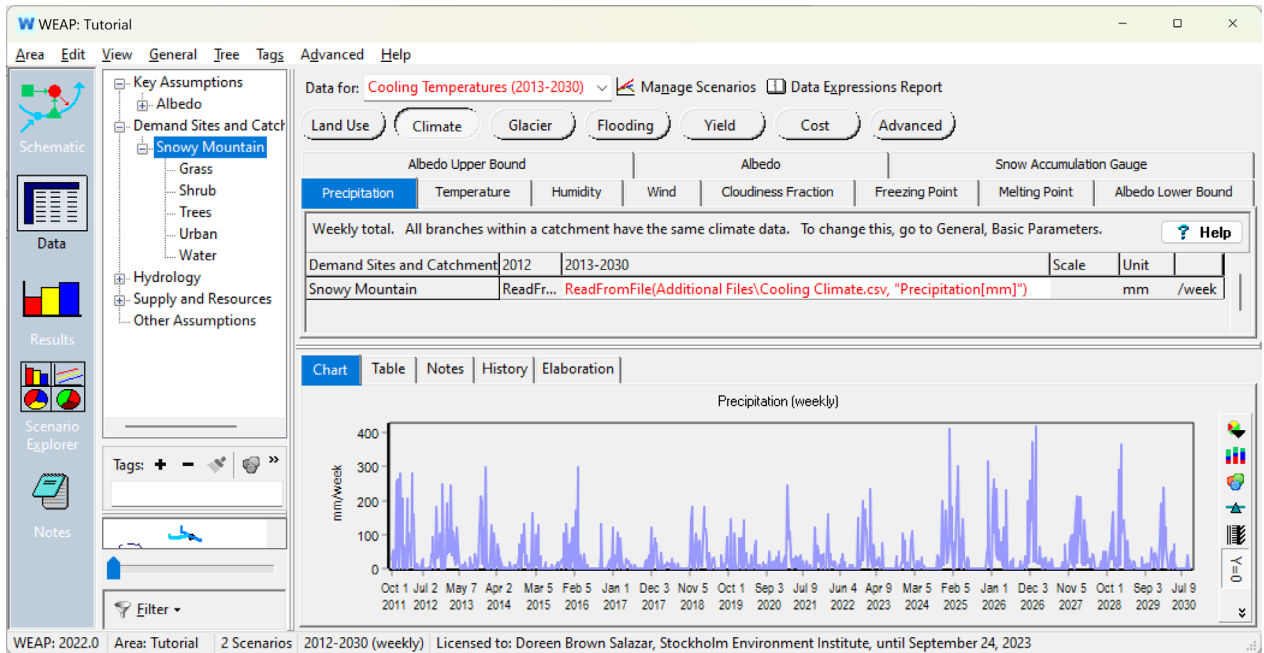
Switch to the “Cooling Temperature” scenario, then add the new climate data, which is in a file called Cooling Climate.csv in the WEAP Tutorial folder\Additional Files and represents a climate that is cooler than that used in the Reference scenario.

*Use the ReadFromFile function to enter data for precipitation (data column 1), temperature (data column 2) and humidity (data column 3) for Snowy Mountain. You may use the ReadFromFile wizard to help you build the expression, or type the expression in directly:*

*ReadFromFile(Additional Files\ Cooling Climate.csv, “Precipitation[mm]”)*

*ReadFromFile(Additional Files\ Cooling Climate.csv, “Temperature[C]”)*

*ReadFromFile(Additional Files\ Cooling Climate.csv, “Humidity [%]”)*

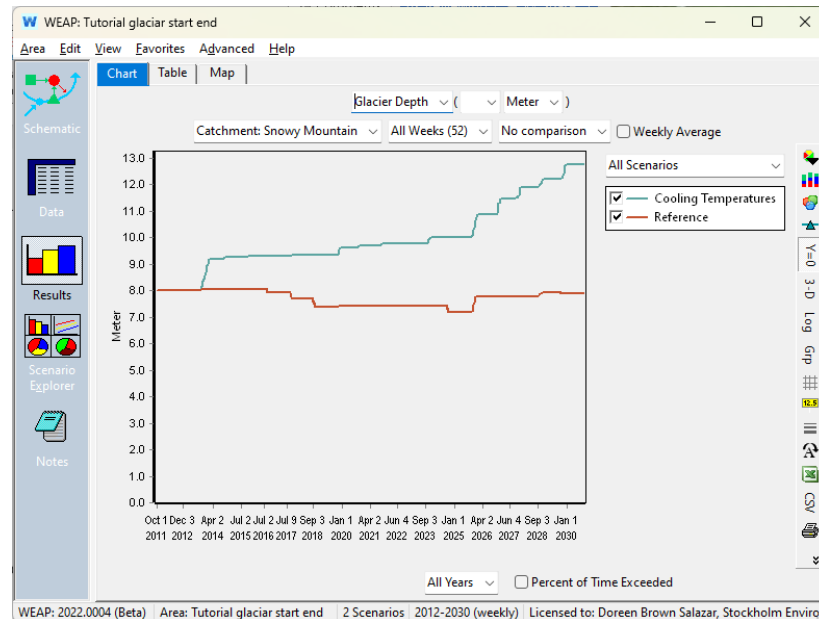


We will keep the remaining tabs under both “Climate” and “Glacier” at the same default values (Note that there will be no need to input an initial glacier depth since it gets inherited from the “Reference” scenario).

## 7. View the Results

*Run the model.*

*View the result Glacier Depth, choosing “All Scenarios” for the legend.*



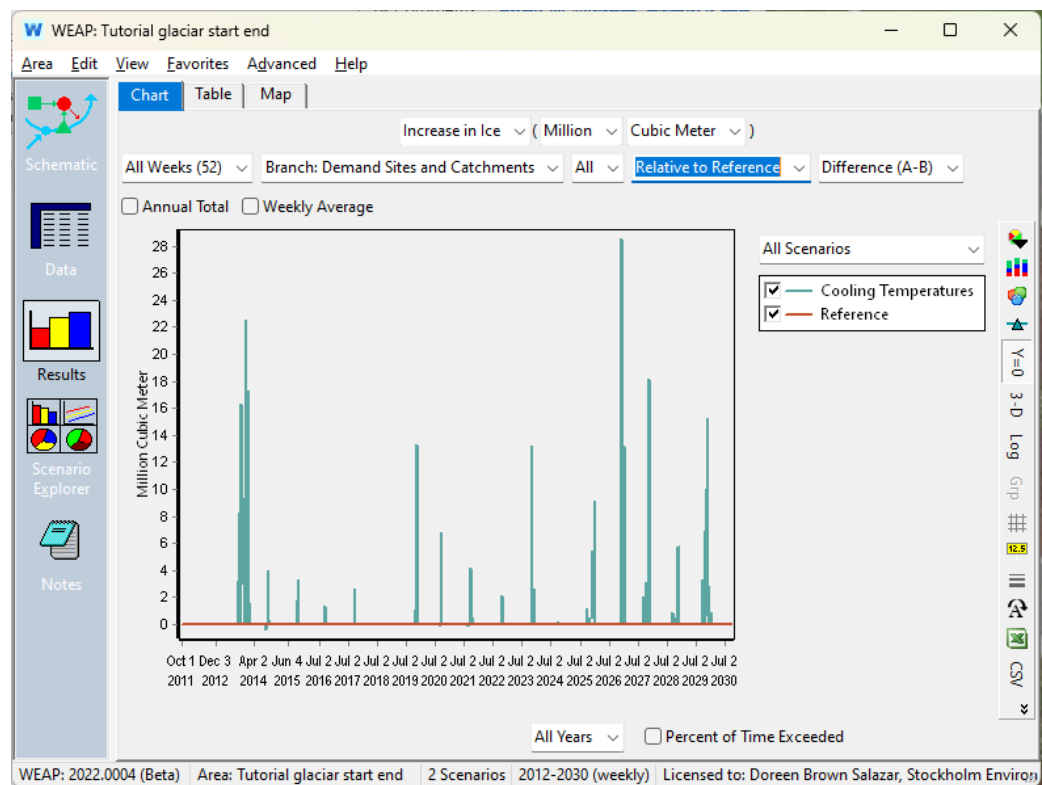
Unlike the “Reference” scenario (in red), where no significant trend was detected, the “Cooling Temperatures” scenario shows a considerable upward trend, with the glacier depth growing from 8 to almost 13 meters during the 20-year interval.

*View the resulting Increase in Ice*

Set a comparison by switching from

*“No Comparison” to “Relative to Reference”*

to show the effect of the cooling conditions on the increase in ice when using the “Reference” scenario as a baseline.



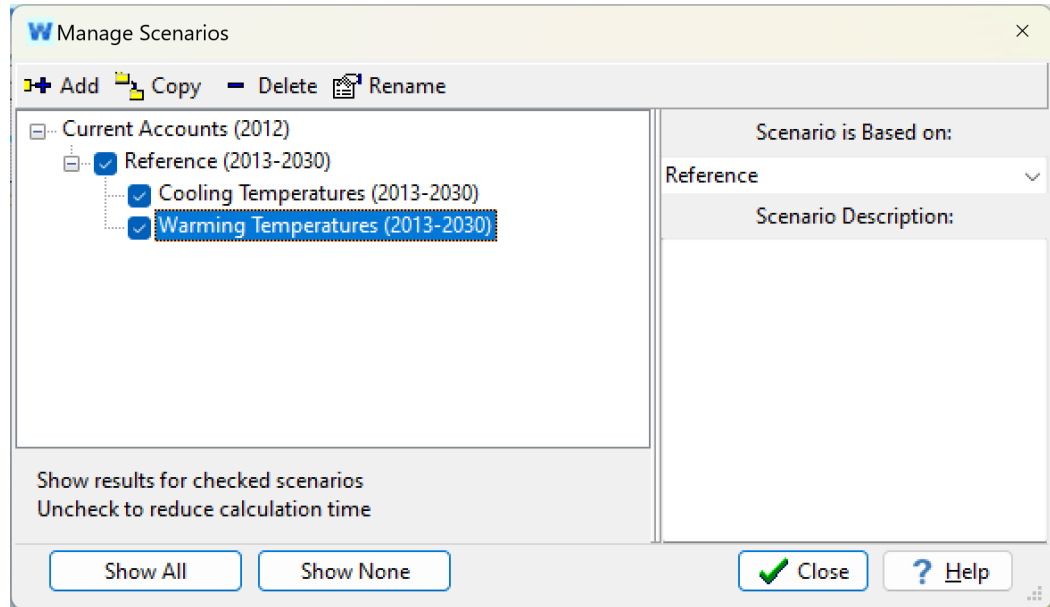
We can clearly see that the cooling conditions have led to the accumulation of considerable amounts of ice within the glacier, with the greatest advances occurring at the end of year 2026.

## Effect of Warming Temperatures

Because a warmer climate is a more likely projection, a scenario where warmer conditions would prevail in the future is explored here to model the impact of the proposed conditions on the glacier dynamics.

## 8. Create a Scenario for Warming Temperatures

First, we will add a scenario called “Warming Temperatures” that is based on the “Reference” scenario.



## 9. Enter Climate Data for the Added “Warming Temperatures”

Switch to the “Warming Temperature” scenario. Then, add the climate data, which is in a file called Warming Climate.csv in the WEAP Tutorial folder\Additional Files.

*Use the ReadFromFile function to enter data for precipitation (data column 1), temperature (data column 2) and humidity (data column 3) for Snowy Mountain. You may use the ReadFromFile wizard to help you build the expression, or type the expression in directly:*

*ReadFromFile(Additional Files\ Warming Climate.csv, “Precipitation[mm]”)*

*ReadFromFile(Additional Files\ Warming Climate.csv, “Temperature[C]”)*

*ReadFromFile(Additional Files\ Warming Climate.csv, “Humidity [%]”)*

We will keep the remaining tabs under both “Climate” and “Glacier” at the same default values.

## 10. View the Results

*Run the model.*



*View the result Glacier Depth*

*Be sure that you have selected “No comparison.”*



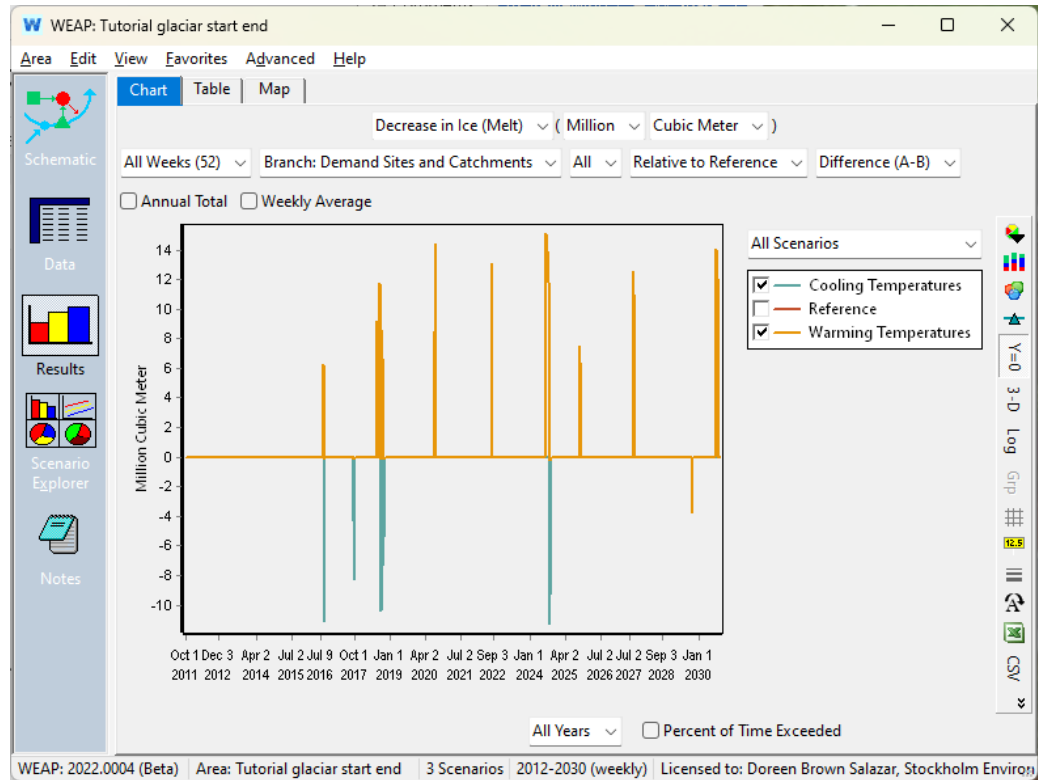
In contrast to the “Cooling Temperatures” scenario, the “Warming Temperature” one leads to a significant downward trend, with the glacier depth shrinking from 8 to below 4 meters during the 20-year interval.

*View the result Decrease in Ice (Melt)*

With only the “Warming Temperatures” and “Cooling Temperatures” scenarios selected, set a comparison by switching from

*“No Comparison” to “Relative to Reference”*

And select “Decrease in Ice (Melt)” to view changes in the volume of ice for each of the two scenarios when compared to the “Reference” scenario.



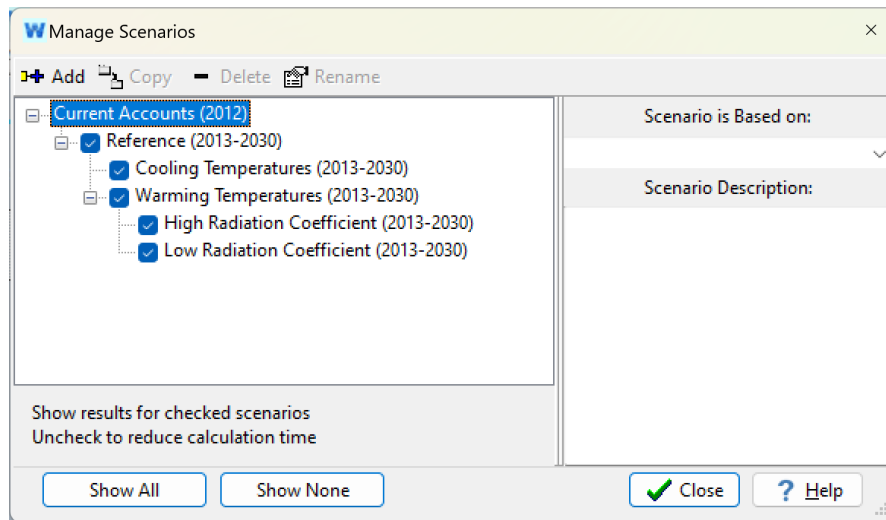
The positive green lines show that the “Warming Temperatures” scenario causes significant amounts of ice to melt in comparison with the “Reference” scenario. The negative blue lines, for the “Cooling Temperatures” scenario, indicate that ice levels increase for this scenario.

## Parameter Sensitivity (Radiation Coefficient)

Since the Warming Temperature scenario is a more realistic script, given the ongoing global warming crisis, the effect of variation of the parameter of radiation coefficient is investigated through a simple sensitivity analysis. Two sub-scenarios based on the Warming Temperatures scenario are added. With a default value of 50% radiation coefficient used in the previous scenario, the effects of using two more extreme points (high and low) are explored, and the outcomes from these values are analyzed.

### 11. Create Scenarios for Different Coefficient Radiation Values

First, we will add 2 scenarios named “High Radiation Coefficient” and “Low Radiation Coefficient”, with both scenarios based on the “Warming Temperatures” scenario.

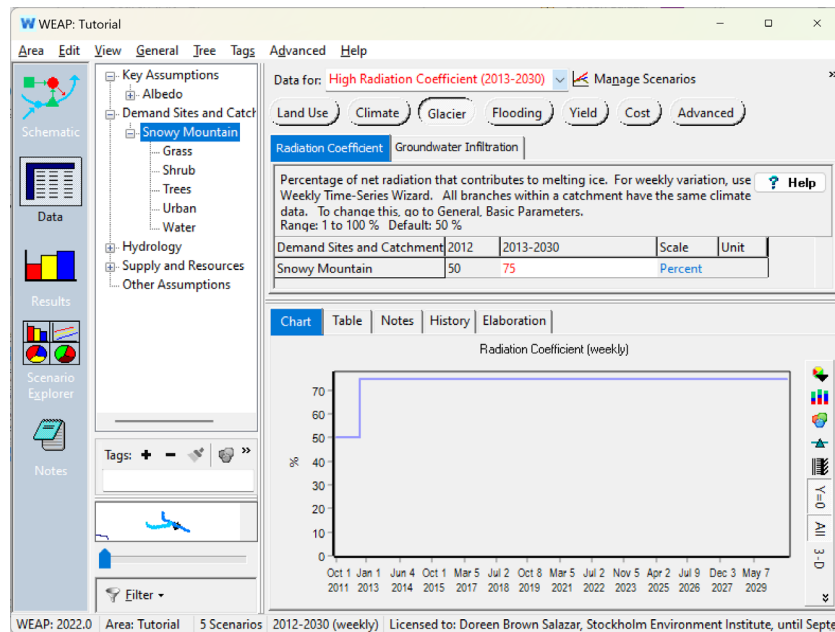


## 12. Enter Data

For these sub-scenarios, climate data will be inherited from the “Warming Temperatures” scenario. However, the only change will be within the glacier data, where the impact of using different values for the radiation coefficient will be explored.

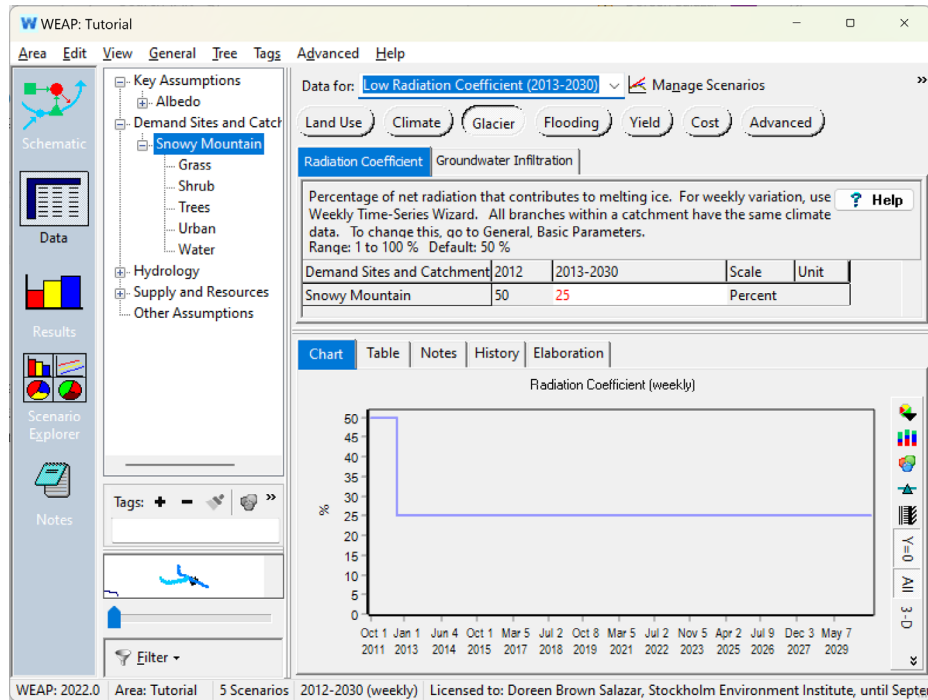
With the “High Radiation Coefficient” scenario selected, we will input a test value of 75% for the radiation coefficient under “Glacier” tab for the data of “Snowy Mountain” Catchment.

*Radiation Coefficient*                      75 %



Switching to the “Low Radiation Coefficient” scenario, we will assign a radiation coefficient value of 25% under “Glacier” tab for the data of “Snowy Mountain” Catchment.

*Radiation Coefficient*                      25 %

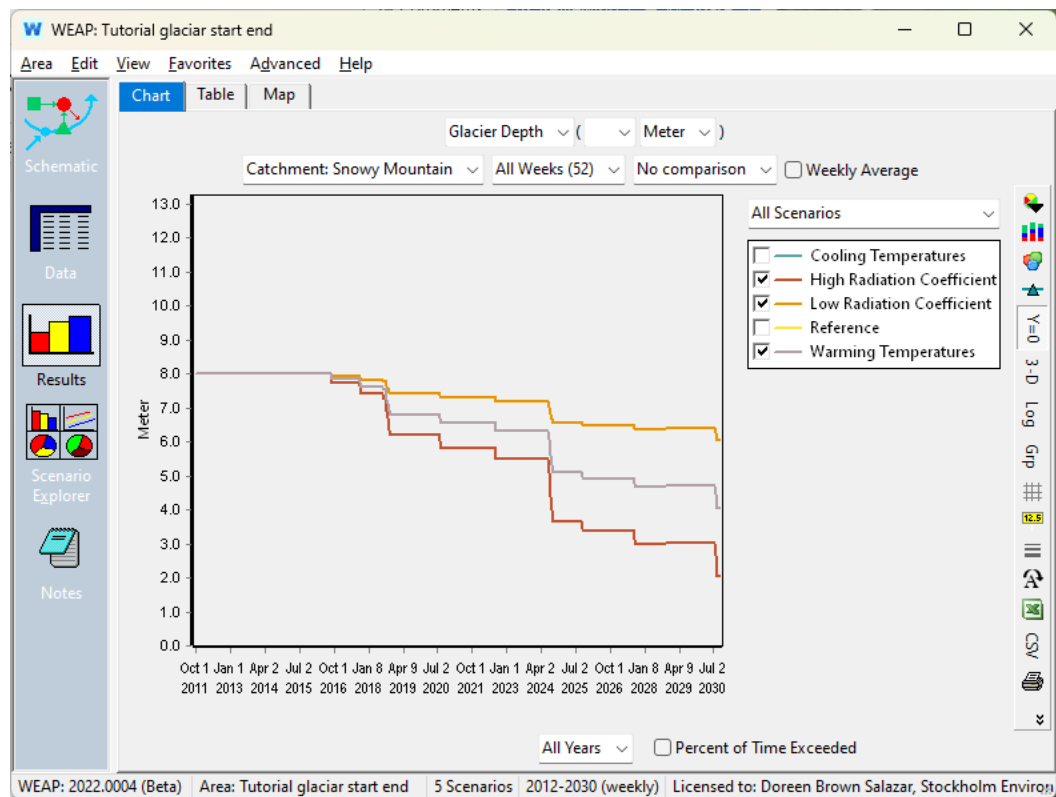


## 13. View the Results

*Run the model.*

*View the result Glacier Depth*

Instead of selecting all the scenarios, select only three of them: Warming Temperatures, High Radiation Coefficient, and Low Radiation Coefficient. Be sure that you have selected “No comparison.”



Although all the three selected scenarios show shrinkages in glacier depth, the rates at which the glacier recedes vary greatly. Under the original “Warming Temperatures” scenario, the glacier takes almost 14 years to recede from 8 to 6 meters. For the “High Radiation Coefficient” scenario, it takes only 10 years to experience the same shrinkage. For the “Low Radiation Coefficient” scenario, the glacier requires the entire 20-year time series to experience the same shrinkage. This shows the huge effect of the radiation coefficient on how fast the glacier could melt.

Some of the factors that impact radiation, and as a result the glacier melt rates, include wind speed, humidity, and sensible heat flux. These factors are known to vary geographically. For instance, higher humidity and wind speed, as in oceanic regions, result in a higher degree day factor (Degree Day Factor is the amount of melting that occurs for each positive degree day). Positive Degree Day sum represents the amount of melt per degree. When ice melt takes place through sublimation, as in terrestrial locations, where dry and high radiation conditions dominate, low degree day factors are common. This happens because there is less available energy for melt, with considerable amounts of energy being consumed through sublimation. Degree day factors can vary significantly at the local scale,

including on the same glacier. For your own analyses, the radiation coefficient will be a calibration parameter you can use to help fit historical observations to your model.

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# WEAP

Water Evaluation And Planning System

# Financial Analysis

## ***A TUTORIAL ON***

*Setting up the Cost and Benefit Model*.....288

*Modeling Cost* .....290

*Modeling Benefits*.....297

**October 2023**

**Note:**

For this module you will need to have completed the previous modules (“WEAP in One Hour, Basic Tools, and Scenarios) or have a fair knowledge of WEAP (data structure, Key Assumptions, Expression Builder, creating scenarios). To begin this module, go to the Main Menu, select “Revert to Version” and choose the version named “Starting Point for all modules after ‘Scenarios’ module.”

## Setting up the Cost and Benefit Model

### 1. Understanding Cost and Benefit Modeling in WEAP

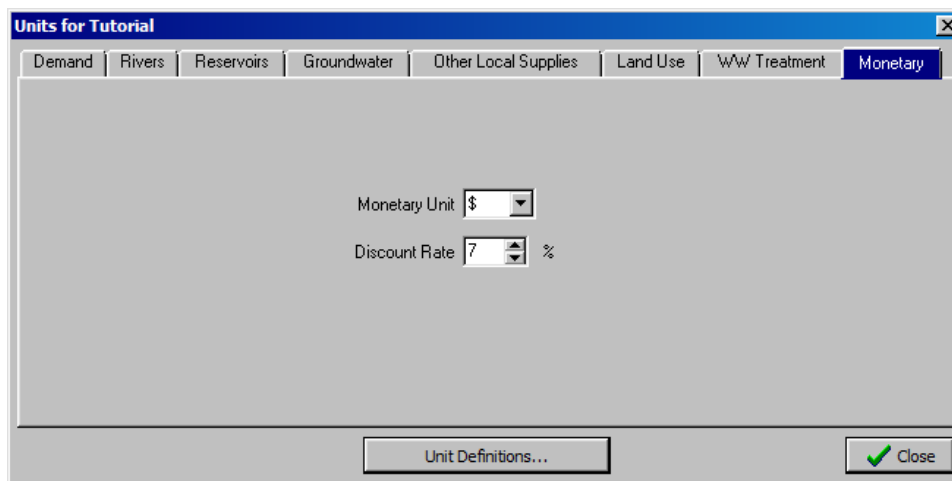
WEAP models three types of costs: Capital Costs, Fixed Operation & Maintenance (O&M) Costs, and Variable O&M Costs. It also models three types of benefits: fixed benefits, variable benefits and electricity revenues. Costs and Benefits can be assigned to any object (e.g., a demand site, river reach, groundwater node, reservoir or hydropower plant).

*For more information on Cost and Benefits, refer to the “Entering Item Cost and Benefits” topic in Help.*

### 2. Setting the Discount Rate

In the “General”, “Units” menu, select the “Monetary” tab and enter the Discount Rate.

*Discount Rate      7%*





The Discount Rate is used to compute net present value and accrue monetary quantities over time. It is different from the interest rate, which must be entered manually for each loan payment computation.



One needs to decide upfront whether the analysis will be done in real or in nominal dollars (with or without considering inflation) since this will have an effect on the discount rate, interest rates and cost & benefit growth.

Determining the Discount Rate is an important matter in economic analyses. Guidelines exist that are based on different methods such as the Weighted Average Cost of Capital (WACC) or Capital Asset Pricing Model (CAP-M). The US government currently recommends a discount rate of 7% for public sector projects (including inflation).

### 3. Changing the Modeling Duration

Cost modeling makes sense mainly if a long time period is being considered. Extend the time period being simulated in WEAP by opening the “General”, “Years and Time Steps” dialog box. Change the “Last Year of Scenarios” variable:

*Last Year of Scenarios*      2025

**Years and Time Steps**

Time Horizon

Current Accounts Year: 2000

Last Year of Scenarios: 2025

Time Steps per Year

12

Add Leap Days?

Time Step Boundary

Based on calendar month

All time steps are equal length

Set time step length manually

Time Step Name Format: October / Oct

Water Year Start

January

#	Title	Abbrev.	Length	Begins	Ends
1	January	Jan	31	Jan 1	Jan 31
2	February	Feb	28	Feb 1	Feb 28
3	March	Mar	31	Mar 1	Mar 31
4	April	Apr	30	Apr 1	Apr 30
5	May	May	31	May 1	May 31
6	June	Jun	30	Jun 1	Jun 30
7	July	Jul	31	Jul 1	Jul 31
8	August	Aug	31	Aug 1	Aug 31
9	September	Sep	30	Sep 1	Sep 30
10	October	Oct	31	Oct 1	Oct 31
11	November	Nov	30	Nov 1	Nov 30

The study period will run from January, 2000 to December, 2025.

Help Close



Changing the “Last Year of Scenarios” will not affect the “Current Accounts”, the base year for all scenarios. It will only affect all the scenarios, including the “Reference” scenario. For more details about WEAP and scenarios, refer to the “Scenarios” module of the tutorial.

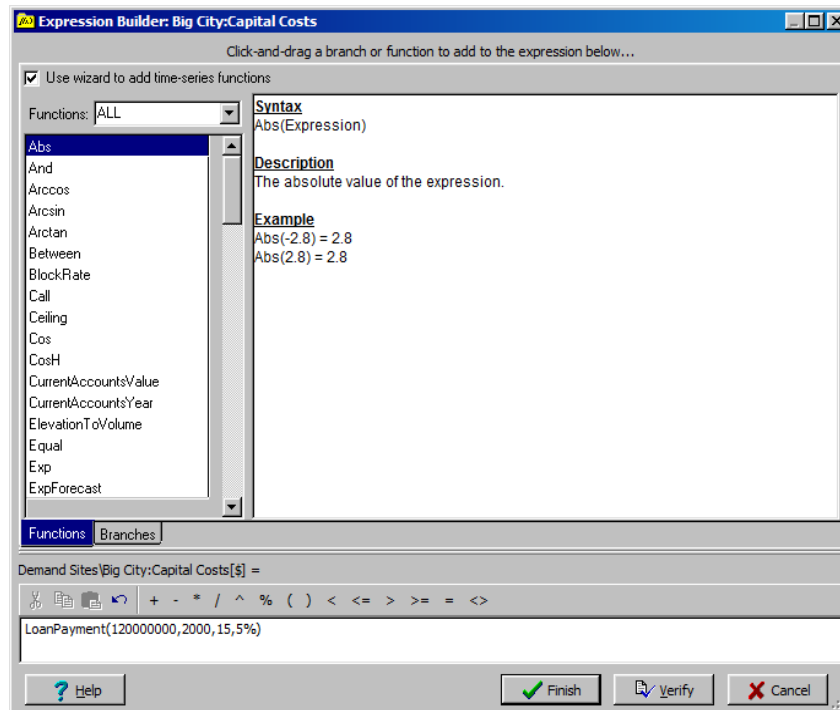
# Modeling Cost

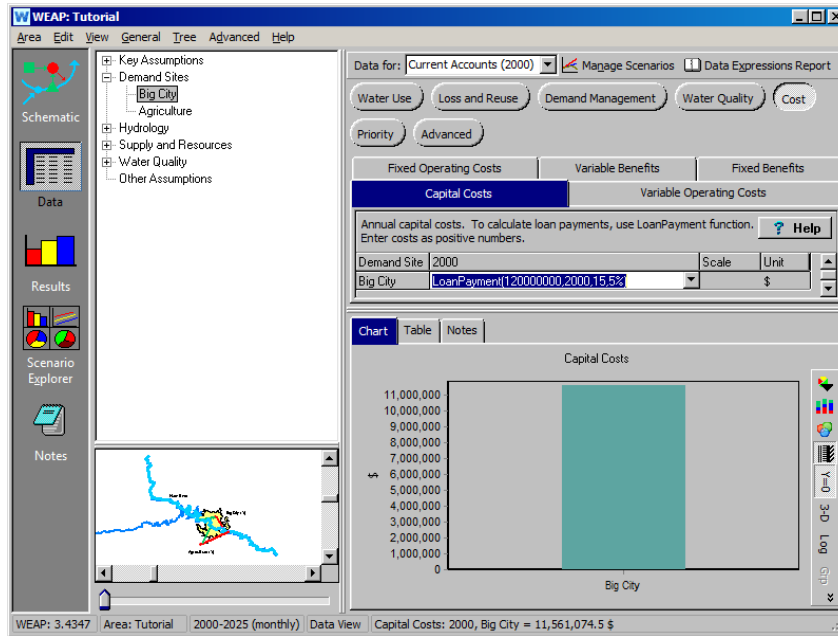
## 4. Enter Demand Site Cost Data

For the Big City demand site, enter the following data (in Current Accounts) in the “Demand Sites” branch of the data tree in the Data view. Click on the “Cost” button and enter under the “Capital Costs” tab:

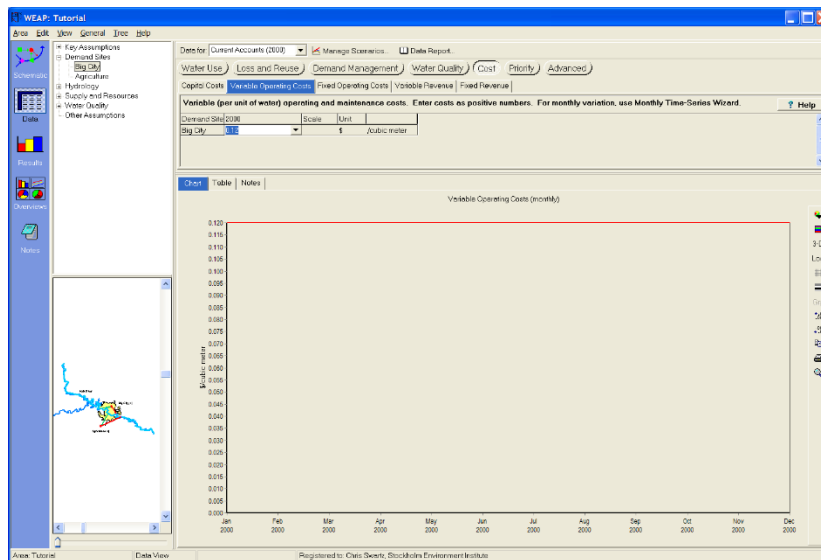
*Capital Costs*      *a loan of 120M\$, occurring in 2000, payback period 15 years, interest rate 5%*

*Use the Expression Builder to select the built-in function “LoanPayment”; pull this function into the expression window and type in the parameters 120000000, 2000, 15, 5% within the parentheses. The expression should look like: “LoanPayment(120000000,2000,15, 5%)”*



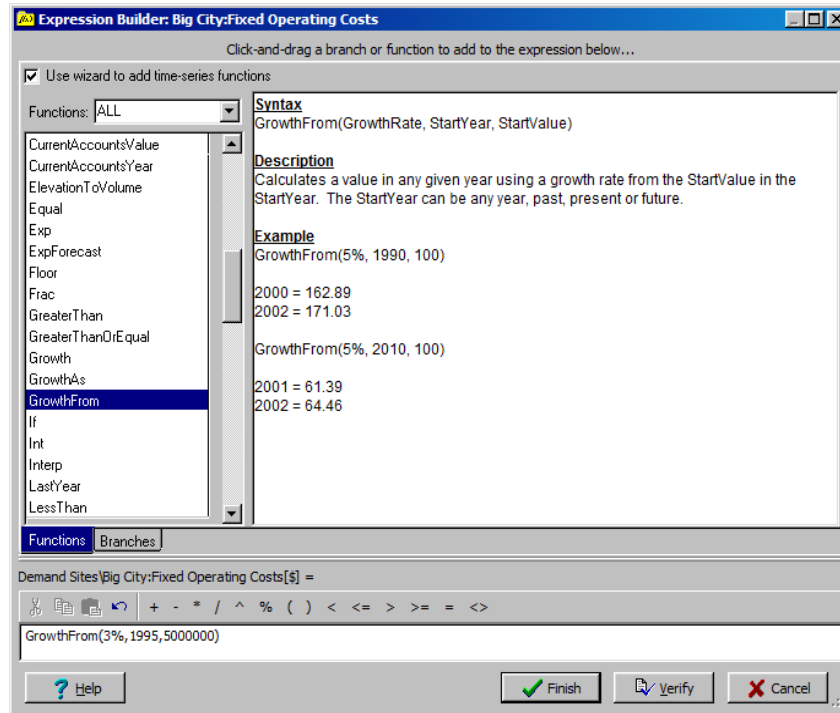


*Variable Operating Costs*                       $0.12\$/m^3$



*Fixed Operating Costs*                      *a yearly value of 5M\$, growing at a 3% rate starting in 1995*

*Use the Expression Builder again, selecting the built-in function "GrowthFrom" and entering the corresponding parameters in the parentheses. The formula should read: "GrowthFrom(3%,1995,5000000)"*

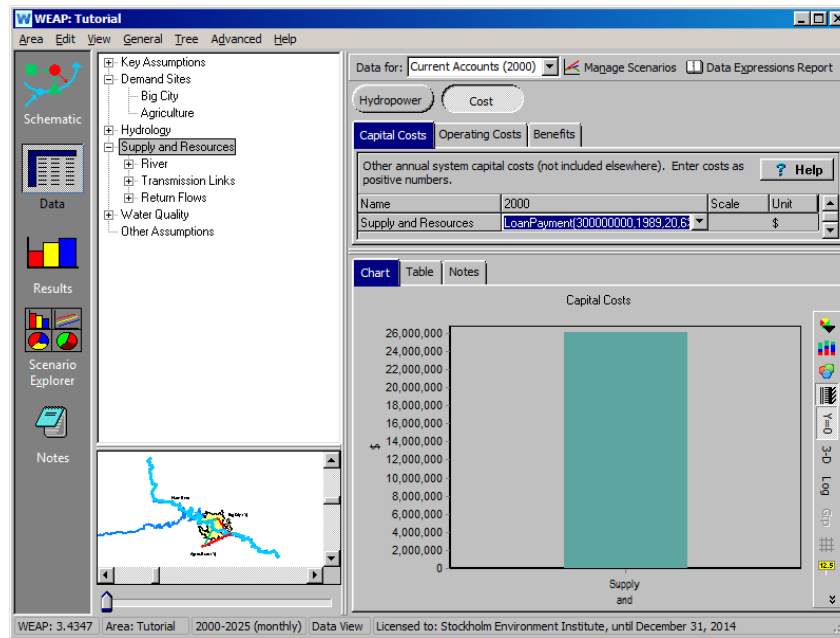


## 5. Enter System-Wide Cost Data

We'll assume that there was a loan made in years earlier than the Current Account (base) year which is still being paid back. We'll assign this cost to the entire system, rather than to a specific object. Enter the following data in the "Supply and Resources" branch of the data tree in the Data view.

*Capital Costs*                      *a loan of 300M\$, occurring in 1989, payback period 20 years, interest rate 6%*

*Again, use the Expression Builder and the "LoanPayment" function. The formula should read "LoanPayment(300000000,1989,20,6%)"*



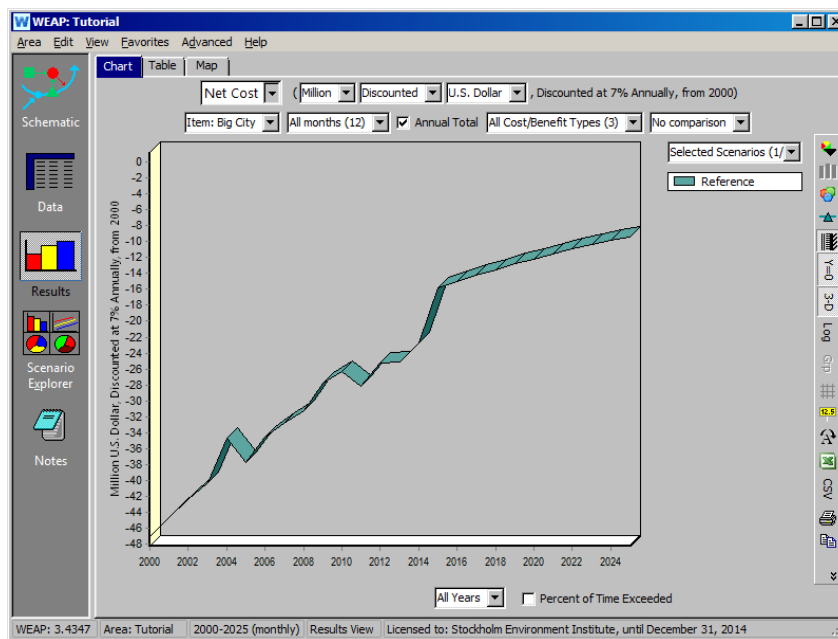
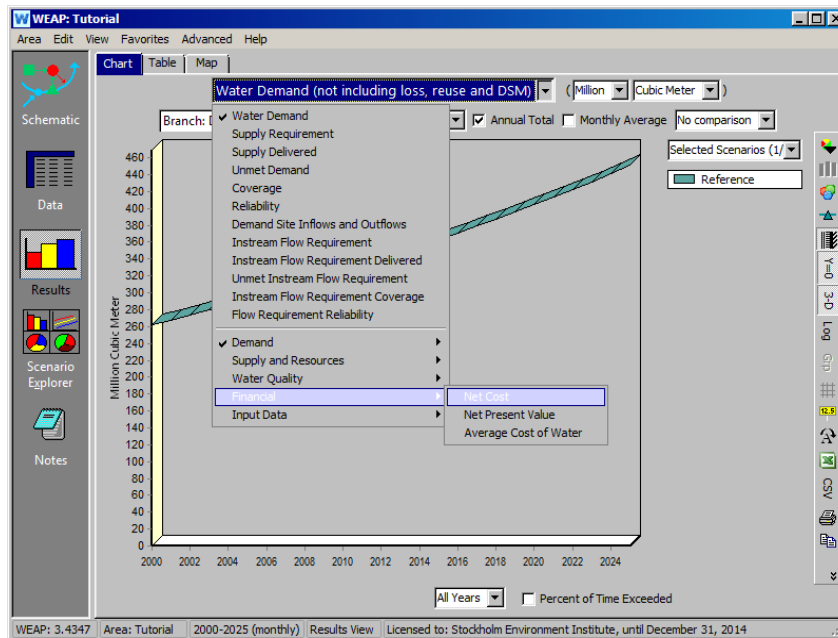
## 6. Evaluate Results

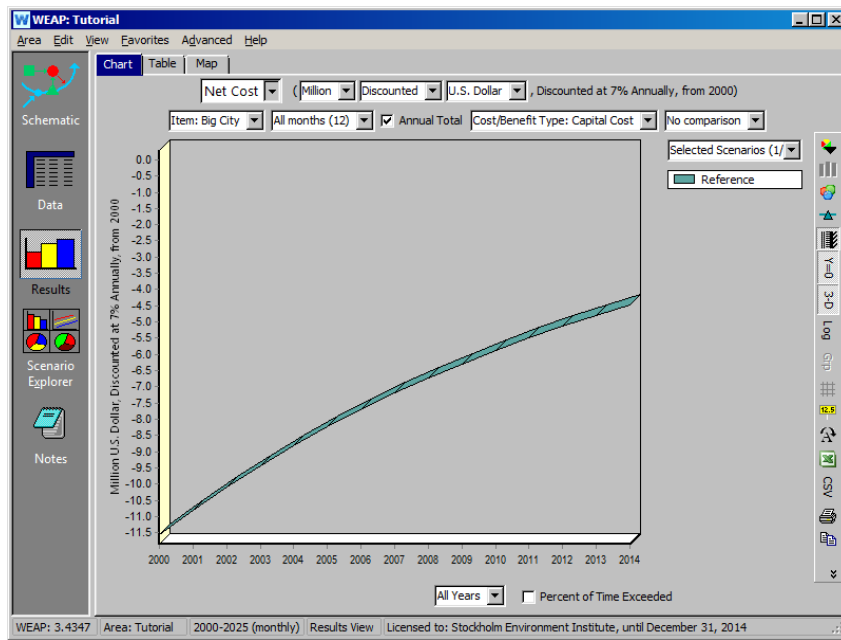
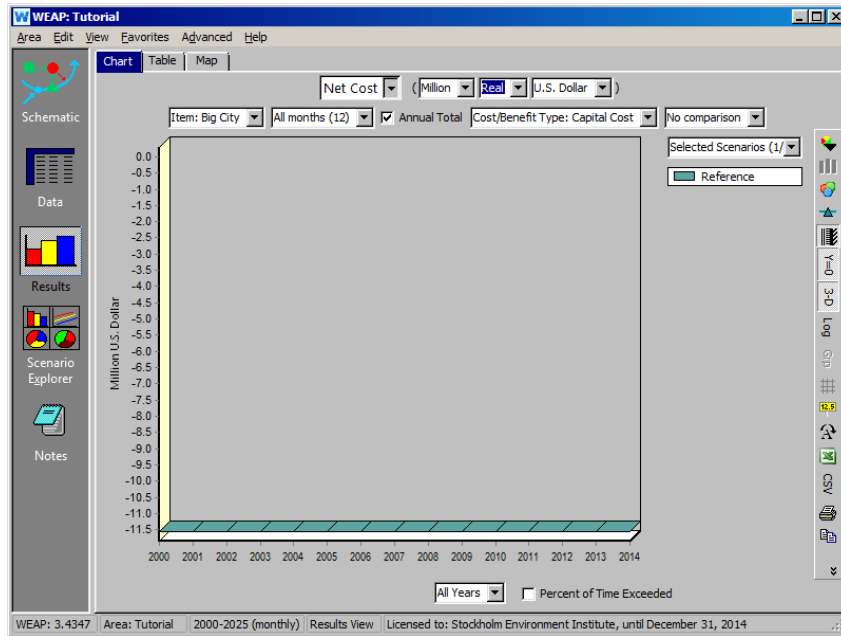
*Run the model and look at the following results:*

*Financial/Net Cost:*

*What is the difference between real and discounted dollar values for the Big City?*

*Select “Financial\Net Cost” from the primary variable pull-down menu and choose Big City from the list of items in the menu to the upper left of the chart. Select “Capital Cost” from the upper right menu. Make sure the “Reference” scenario is selected from the menu above the chart legend. Toggle between the “Real” and “Discounted” options using the menu just to the left of the unit menu (set at U.S. dollars).*



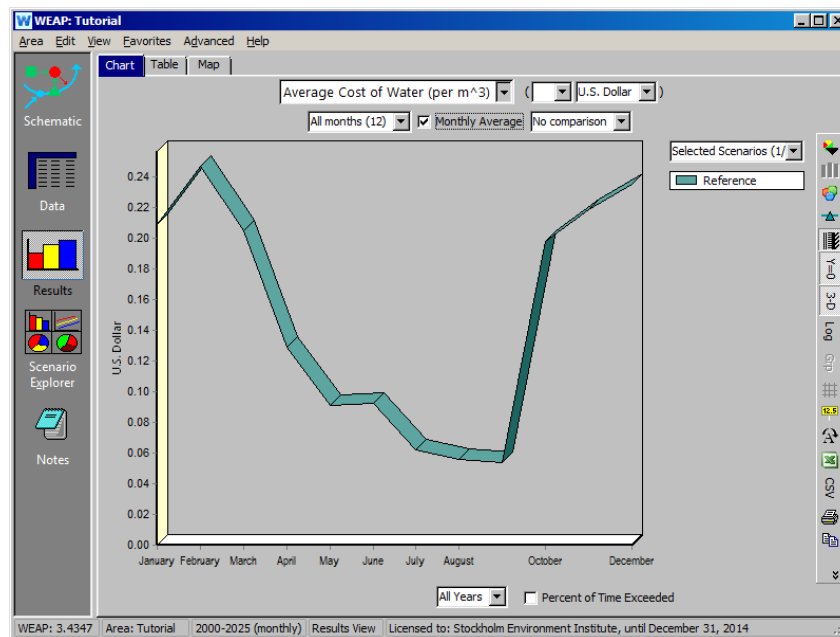
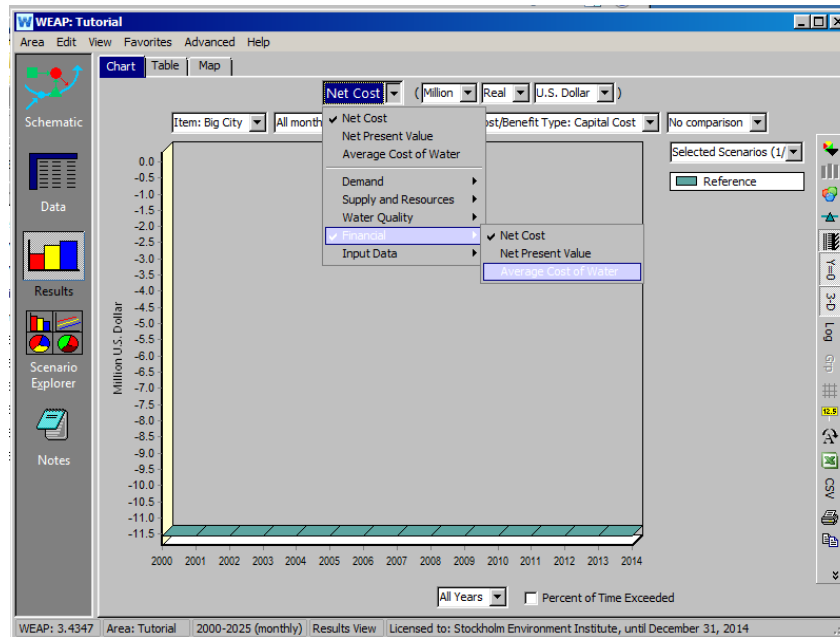


While real dollar are actual dollar values, discounted dollar values have been brought back to their present value using the discount rate. The further in the future the cost occurs, the lower its present value.

### *Average Cost of Water*

*What makes the cost vary on a monthly basis? On an annual basis?*

Select “Financial\Average Cost of Water” from the primary variable pull-down menu. Keep the “Reference” scenario selected and click on “Monthly Average.” You should have a chart like the one below:



Monthly variations in average cost of water occur because of the largely varying consumption of water (especially in the Agriculture area), while fixed costs remain constant. Annual variations are mainly driven by changes in the capital costs (loans are paid back, new loans occur).

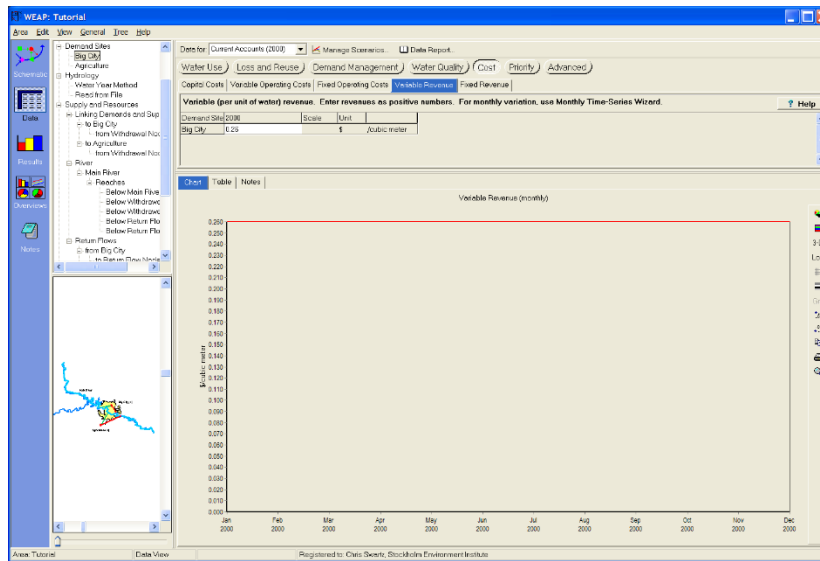


# Modeling Benefits

## 7. Enter Demand Site Benefit

In the “Cost” screen of the Big City Demand Site (Data View), enter the following data, which could, for example, correspond to the price water is sold for.

*Variable Benefit*                       $0.26\$/m^3$



When modeling hydropower reservoirs (refer to the “Reservoir and Hydropower” WEAP tutorial module), one can also enter revenues from electricity generation. The related data-entry tab exists only when pertinent.

## 8. Compare Net Present Cost and Benefit

Display the Net Present Value of the project.

*How do the Net Present Value of the Costs compare to the Net Present Value of the Benefits?*

*In Results View, select “Financial\Net Present Value” from the primary variable pull-down menu, and choose Big City as the item for viewing. You should have a chart like the one below:*



*What does that comparison tell you?*



The Net Present Value of the costs can be compared to that of the benefit to obtain a sense of the economic viability of the system. If the NPV of the costs exceeds the NPV of the benefits, then the system is returning a lower profit than average projects (as defined by the discount rate). If the NPV of the benefits exceed that of the costs, then the systems is generating a profit higher than average projects.

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# WEAP

Water Evaluation And Planning System

# Linking WEAP to MODFLOW

## ***A TUTORIAL ON***

*Linking to MODFLOW* .....300

*Running MODFLOW and Viewing Results* .....330

*Scenario: Increased Population*.....333

*Scenario: Irrigation*.....336

*Scenario: Artificial Recharge* .....342

**October 2023**

**Note:**

For this module you will need to have completed the previous modules (“WEAP in One Hour, Basic Tools, and Scenarios) or have a fair knowledge of WEAP (data structure, Key Assumptions, Expression Builder, creating scenarios) and of MODFLOW. To begin this module, go to the Main Menu, select “Revert to Version” and choose the version named “Starting Point for 'Linking WEAP to MODFLOW module'.”

## Linking to MODFLOW

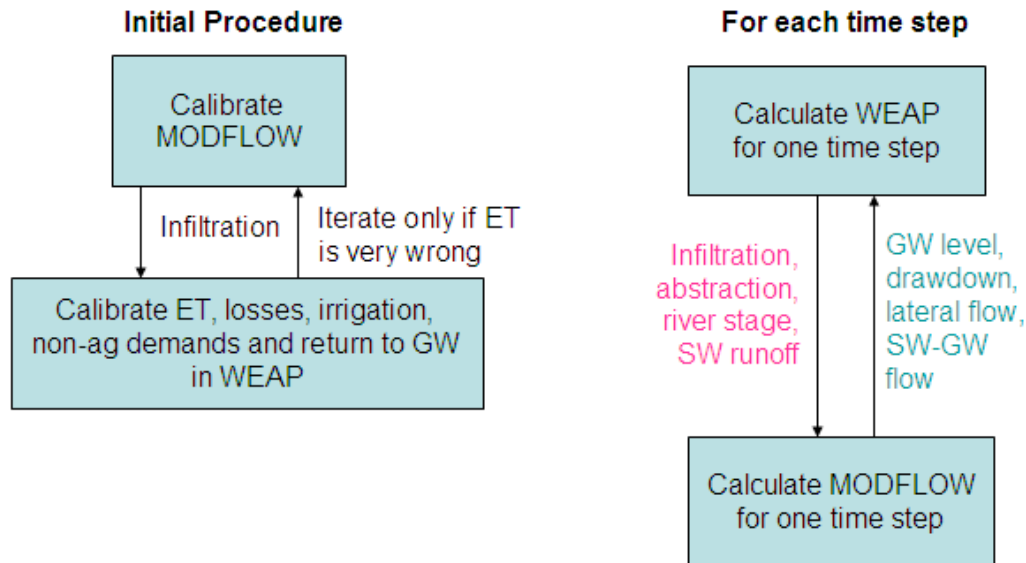
### 1. Using MODFLOW for Groundwater Modeling in WEAP

For situations where the built-in WEAP groundwater model is not sufficiently complex, there is the option to link a WEAP model to a MODFLOW model. MODFLOW is a three-dimensional finite-difference groundwater model created by the U.S. Geological Survey (USGS). When properly linked, data and results flow back and forth between WEAP and MODFLOW for each calculation timestep. With this tight coupling between the models, it is possible to study how changes in local groundwater levels affect the overall system (e.g., groundwater-stream interactions, pumping problems due to drawdown, lateral groundwater recharge) and vice versa (e.g., infiltration and abstraction). However, be advised that building and calibrating a MODFLOW model is not a simple task.

The groundwater models in MODFLOW and WEAP are very different. Whereas a WEAP groundwater node is represented as one large “bucket” with no parameters to describe internal flows, MODFLOW represents groundwater as a multilayered grid of independent cells, each with their own flow parameters and equations that are used to model flows between cells, and across the aquifer boundaries.

When WEAP and MODFLOW are dynamically coupled, WEAP will pause during calculations after each time step to load information (groundwater pumping and recharge, river stage, and surface water runoff, disaggregated to cells) into newly created, temporary MODFLOW input files, run MODFLOW for one stress period/timestep, and then retrieve results (cell heads, storage volume, spring discharges, lateral flow between aquifers, and surface water-groundwater flows (RIV and DRN packages), aggregating cells to river reaches and groundwater nodes) from the MODFLOW output files.

The following chart illustrates the flow of information between WEAP and MODFLOW once the coupling has been done.

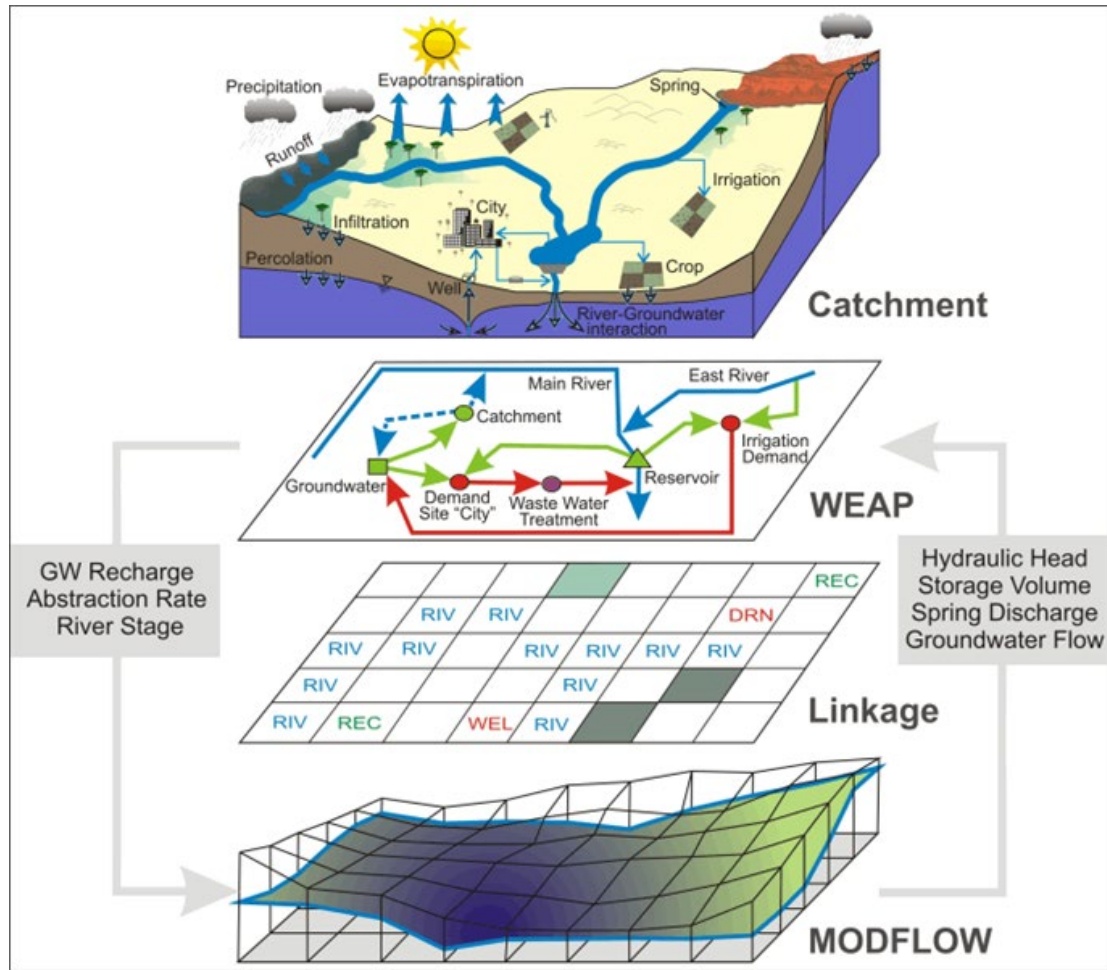


Coupling WEAP and MODFLOW models requires a linkage shapefile (.shp) which can be created using WEAP's built-in tool or a Geographic Information System (GIS). The linkage shapefile is comprised of rectangles; each rectangle represents a cell in the MODFLOW model. Each rectangle has a position defined by row and column number and is labeled with the name of the coinciding WEAP element(s). For example, for a MODFLOW model with 20 rows, 20 columns and 3 layers, there would be 400 features in the shapefile. The attribute table of the linkage shapefile (.dbf) contain fields for MODFLOW cell row number, MODFLOW cell column number, and WEAP groundwater node name. Depending on your model, you might also match some or all of the following: Catchment Name, Land Use Name, Demand Site Name and River Reach Name.

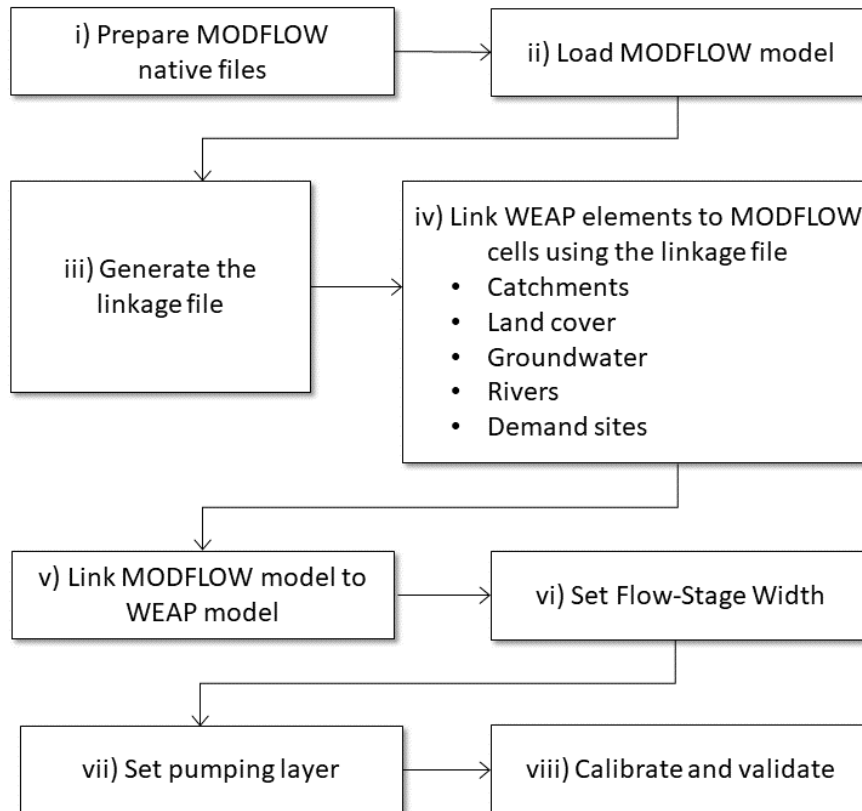
The following diagram <sup>2</sup> shows how the linkage shapefile couples MODFLOW and WEAP models.

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<sup>2</sup> Maloszewski, P., Witczak, S., & Malina, G. (Eds.). (2012). Groundwater Quality Sustainability. <https://doi.org/10.1201/b12715>



There are eight general steps that should be followed to couple the models as shown in the figure:



These steps will be followed and explained through the tutorial.

## 2. Example WEAP Model



This module is not an introduction to MODFLOW, which requires specialized knowledge. Considerable work is required outside of WEAP to calibrate and prepare a MODFLOW model. Refer to the MODFLOW website for more information:

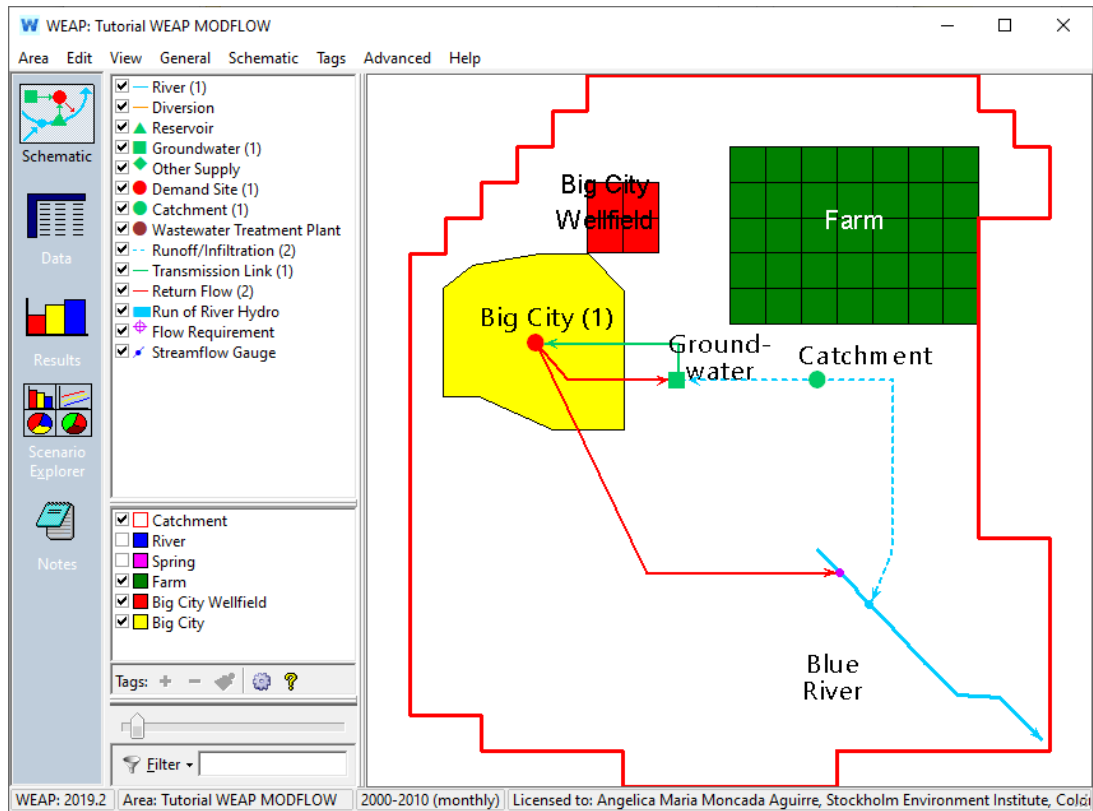
<https://water.usgs.gov/ogw/modflow/>. Be aware that MODFLOW 2000 has been superseded by a newer version, information is available at <http://water.usgs.gov/nrp/gwsoftware/modflow2000/modflow2000.html>.

If you are already using MODFLOW, you should be able to link your MODFLOW model to WEAP after this module.

The sample area used for this module differs from those in previous modules. It includes:

- A city whose supply comes entirely from groundwater and discharges 75% of its wastewater into the river. The other 25% infiltrates into the soil and recharges groundwater.
- A catchment—modeled using Rainfall Runoff (simplified coefficient method)—that includes forest, grassland, agriculture and the city.

- Rainfed agriculture.
- A spring-fed river that receives 50% of the surface runoff from the catchment.
- A groundwater node recharged by the other 50% of the surface runoff from the catchment.



Note that because WEAP does not spatially disaggregate catchments or groundwater nodes; the one catchment node in this example represents the entire area inside the red outline without any information about where in the catchment the various land classes are. The one groundwater node represents the entire aquifer, which extends over the same area as the catchment, and does not include information about where the wellfield for the city is (the red squares labeled Big City Wellfield).

**Note:**

To properly link a MODFLOW model to a WEAP model, localization of wells and land cover classification are needed. Before starting the coupling of the models, cartographic information needs to be processed and analyzed using GIS.



### 3. Loading the MODFLOW Model

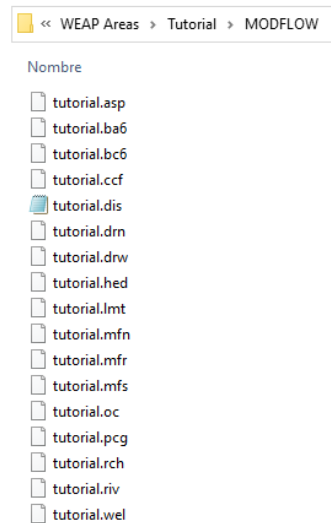
**Note:**

The first step to start linking the models is to prepare the native files of the MODFLOW model. MODFLOW native files can be opened and modified using a text editor. The versions of MODFLOW that WEAP is designed to link to are MODFLOW 2000, 2005, and NWT. A MODFLOW model consists of many different “packages,” most of which are optional. However, not all packages are used or allowed by WEAP. For details on how each package is linked to WEAP, see MODFLOW Link Technical Details.

In addition, you need to consider that models with more than one stress period are allowed, but only data from the first stress period will be used by WEAP. When WEAP writes the new DIS package, the length of the stress period will be changed to match the length of the WEAP timestep. In MODFLOW, the stress period is divided into the number of specified time steps. There is a tradeoff in the choice of number of MODFLOW timesteps. If there are too few the solver may not converge on the correct solution. On the other hand, more timesteps add more computation and slow the model down. If the original MODFLOW stress period length is much longer than the WEAP timestep (e.g., annual vs. monthly), you probably want to reduce the number of MODFLOW timesteps per stress period—it will calculate faster and create smaller files. In general, a daily timestep could be used in MODFLOW. However, if there is rapid change in head it might be wise to use a shorter timestep.

Once you have the MODFLOW native files, the MODFLOW name file (\*.NAM or \*.MFN) and all other allowed package files must be copied into the WEAP area subfolder of your project. It is recommended not to include any MODFLOW result files due to their size.

For this example, the MODFLOW native files were already prepared. The files are contained in a subdirectory named MODFLOW within the Tutorial area subdirectory.



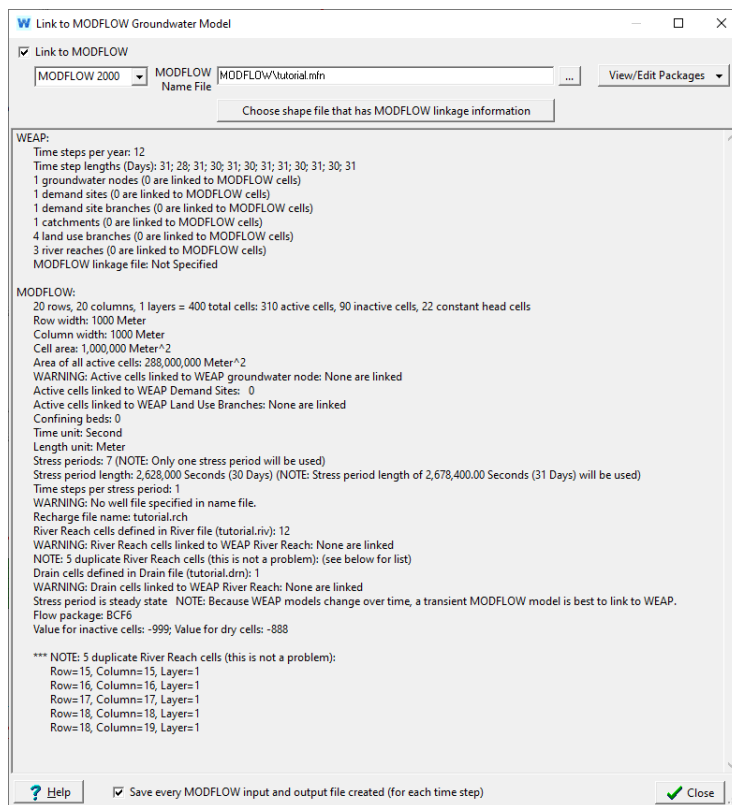
We'll now load a MODFLOW model.

*Go to “Advanced\MODFLOW Link (Groundwater Flow)” on the Main menu.*

*Then, in the “Link to MODFLOW Groundwater Model” window, check the “Link to MODFLOW” checkbox and choose MODFLOW 2000.*

*Next, browse for the “MODFLOW Name File”. Typically, the “Name” file has an extension of .nam or .mfn. For this example, it is **tutorial.mfn**.*

*Review the displayed information of the MODFLOW model.*



After you have specified the MODFLOW version and the name file, WEAP will read in the MODFLOW model and display information about which packages are used under the “View/Edit Packages” button. This button can be used to open and edit the MODFLOW native files.

The name file lists the packages that contain data for the various aspects of the MODFLOW model, such as recharge, pumping and river interactions. Take a look at some of the packages for this model—

*Click on the “View/Edit Packages” button and choose “MODFLOW Name File: tutorial.mfn”. You will see the list of files/packages. Click the cancel button to close the name file and look at another package, such as the “MODFLOW Discretization file: tutorial.dis.” The discretization file contains basic information about the model, such as the number of layers, rows, and columns; and the width of each row and column.*

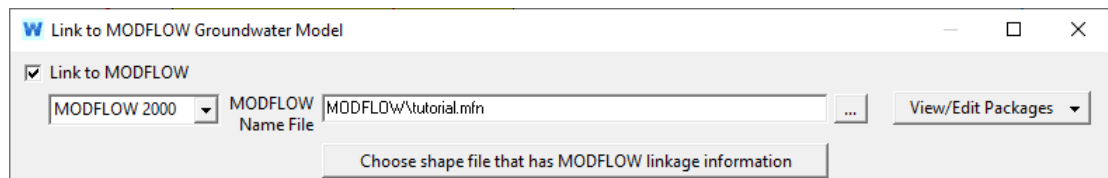
As you can see in the screenshot above, WEAP has read in this information already: 20 rows, 20 columns, 1 layer, and 1000 meters width for both rows and columns.

General information of the MODFLOW model is shown under the MODFLOW heading such as how many rows, columns, layers, active cells, and inactive cells the model has, row and column width, the number of stress

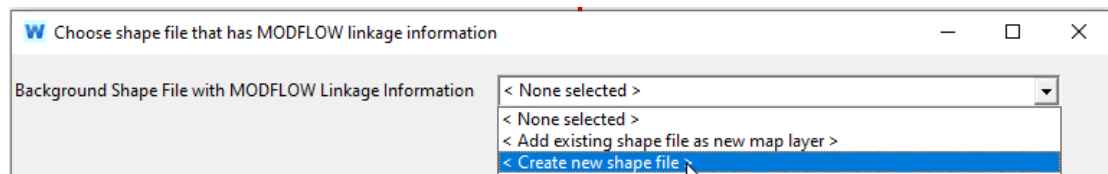
periods, and the value for inactive and dry cells. The same window will show the linked elements once the models are coupled under the WEAP heading. Note that initially WEAP does not know how to link the MODFLOW model to the WEAP model, as can be seen in the screen above, e.g., “WARNING: Active cells linked to WEAP groundwater node: None are linked” and “1 groundwater nodes (0 are linked to MODFLOW cells).”

WEAP’s built-in tool is available on the “Link to MODFLOW Groundwater Model” window when using the “Advanced\MODFLOW Link (Groundwater Flow)” option on the Main menu.

*Click on the “Choose shape file that has MODFLOW linkage information” button.*



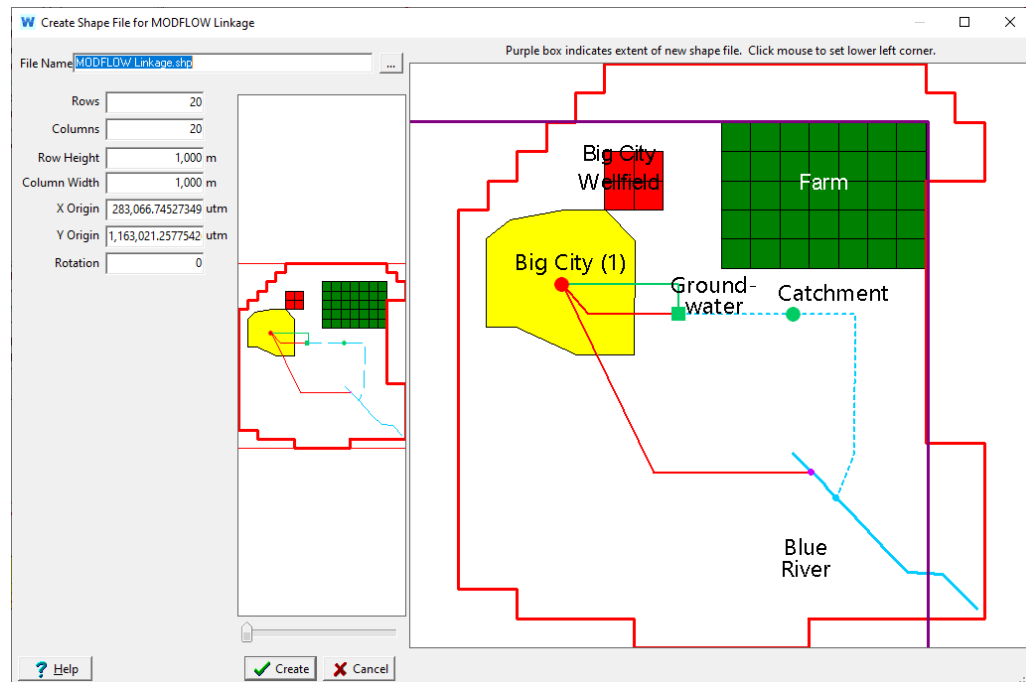
*In the next window, for “Background Shape File with MODFLOW Linkage Information” choose “< Create New Shape File >”.*



In the next window, the File Name box contains the filename for the new shape file. Either use the default filename (“MODFLOW Linkage.shp”) or enter another name. Shape files always have a .shp extension.

*For now, enter “MODFLOW Created Linkage.shp” as the name.*

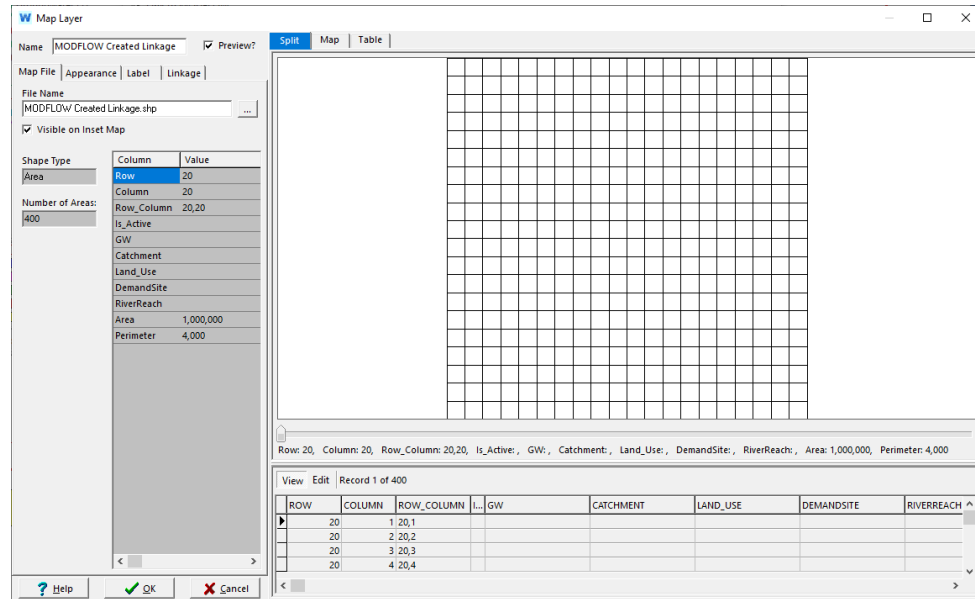
WEAP automatically fills in the number of rows and columns, and the row height and column width, read from the MODFLOW discretization file. However, it is mandatory to enter the origin coordinates of the shape file (X, Y – longitude, latitude), and the rotation angle of the cells to create the linkage shapefile properly. WEAP suggests a pair of origin coordinates based on the extension of your area, these coordinates need to be checked and modified if needed.



If you know the values for latitude, longitude, and rotation, you can enter the numbers directly. If you do not know the values, you can click on the map to set the origin (lower left corner). You will see a purple box on the map that indicates the area of all the cells. As long as you hold down the left mouse key, the purple box will move with the mouse in the lower left corner; release when the box is correctly positioned. You can zoom in on the map (using the zoom slider below the inset map on the left, the mouse wheel, or control-click and drag on the map) to help achieve greater precision in placement of the area.

*Enter 285,000 for X origin, 1,165,000 for Y origin, and 0 for rotation. Click the Create button to create it.*

After the shapefile has been created, WEAP will display it and allow you to customize its appearance on the schematic. If you don't see anything, try changing the Outline Width or Outline Color under Appearance. As you can see from the screen below, the new shape file is a 20x20 grid of 400 cells.



*After customizing the appearance, click the OK button.*

WEAP will add this layer to your Schematic and return you to the “Choose shape file that has MODFLOW linkage information” window.

Apart from WEAP creating the polygon features of the linkage shapefile, it also adds the necessary fields in the attribute table—Row, Column, row and column joined (Row\_Column), active cell indication (Is\_Active), Area, Perimeter and fields for linking WEAP elements (groundwater nodes, catchments and their land cover classes, demand sites, and rivers) to each cell: GW, Catchment, Land\_Use, DemandSite, and RiverReach.

### **Note:**

Fields in the attribute table represent catchments, land cover, groundwater nodes, rivers, and demand sites to be linked. Fields can be customized. Remember to choose GIS-compatible field names, e.g. up to 10 characters long.

When customizing the shapefile appearance (double-click on the map layer), if you uncheck “Visible on Inset Map” the linkage shapefile on the Schematic will draw faster and it will not obscure everything else on the inset map.

By default, the linkage filename created by WEAP is “MODFLOW Linkage.shp” and it will be in your area subdirectory. If you create the linkage shapefile using GIS software, copy it into the WEAP area subdirectory.

The linkage shapefile will also be used to display MODFLOW results in WEAP.

## 4. Linking WEAP elements to MODFLOW Cells Using the Linkage File

**Note:**

This step will guide you through editing the attribute table of the linkage shapefile. A pre-filled shapefile is included in the Tutorial files. If you prefer to use the existing shapefile rather than spending time to fill in all the information in the attribute table, go to step 5.

In general, drinking water (cities), mining and industry water demands are represented by “demand site” elements. Irrigation water demand can be represented by using a “demand site” or a “catchment”. When catchments are used, infiltration into the aquifer due to irrigation can be represented with a Runoff/infiltration link. The water supply comes from surface water and/or wells in an aquifer represented in WEAP as a “groundwater” element. Rivers can be fed by springs and surface runoff from the catchments. At the same time, they can be hydraulically connected to groundwater. In addition, catchments may be characterized in WEAP by land cover classification (e.g. forest, grassland, crops). Return flows from demand sites and infiltration from catchments can be added in the recharge package. This is added evenly only to cells linked to demand sites or catchments—the same cells linked to perform groundwater extraction. By default, cells linked to demand sites and catchments are used for both extraction and recharge of groundwater.

Linking WEAP elements to MODFLOW cells is done by filling in the proper field of the attribute table (catchment, land cover, groundwater, river, and demand site) of each polygon feature with the exact name of the WEAP element to be linked to a particular MODFLOW cell. MODFLOW cells are identified in the linkage shapefile using row and column number.

You may edit this table in several different ways. To edit inside WEAP, right-click on the MODFLOW Linkage map layer, click “Edit” above the attribute table, and type the values directly into the table. You can also prepare the table in Excel and use it in a GIS (make sure WEAP is not open when you edit the attribute table file, or the file will be locked) or directly in any GIS, such as QGIS.

Cells representing wells, rivers, drains, and aquifers in the MODFLOW files can be made into shapefiles. UrbanWellfield.shp, RIVER.shp, SPRING.shp, and Land\_Classes.shp store locations of wells, MODFLOW river cells (RIVER package), drain cells (DRAIN package), and land cover classes of the catchment, respectively. The shapefiles are in the model’s WEAP area folder.

For example, if a groundwater node in WEAP needs to be linked, you first identify the spatial extent of the aquifer in the MODFLOW model. Then, select the polygon features in the linkage file that overlap the aquifer and enter the exact name of the groundwater node in the appropriate attribute table field. Repeat these steps to link catchments, land cover classes, rivers.

**Note:**

- Demand site linkages must be specified for cells representing the aquifer or specific cells representing well locations. (Extraction and infiltration will be applied evenly to all cells).
- Demand site sub-branches can be linked to MODFLOW cells by appending the name of the branch to the name of the demand site in the attribute field for linking demand sites using the following syntax: [Demand site name]\[Sub-branch name]. If you link one sub-branch, you must link them all for that demand site. Also, you must link at the lowest level of disaggregation, not an intermediate level. Do not add any space character before or after the backslash.
- Catchment and land cover, groundwater, and river elements can be linked to one and only one active MODFLOW cell. For a given row and column, every layer will be linked to the same cell. An active MODFLOW cell can be linked to more than one demand site element; to do so you will need to add as many fields as demand site elements to link. This will need to be done when a well is used by more than one user. It is recommended to use a number after the field name (e.g. DemandS1, DemandS2).
- When the River (RIV) MODFLOW package is used, a subset of WEAP's river reaches must be linked. Append the name of the river reach to the name of the river in the attribute field for linking rivers using the following syntax: [River name],[Reach name]. Do not add any space character before or after the comma.
- Before linking MODFLOW drain cells you must identify them using the Drain (DRN) MODFLOW package and add a river to represent each drain. Then, MODFLOW drain cells can be linked in the linkage shapefile following the same procedure as described for rivers.

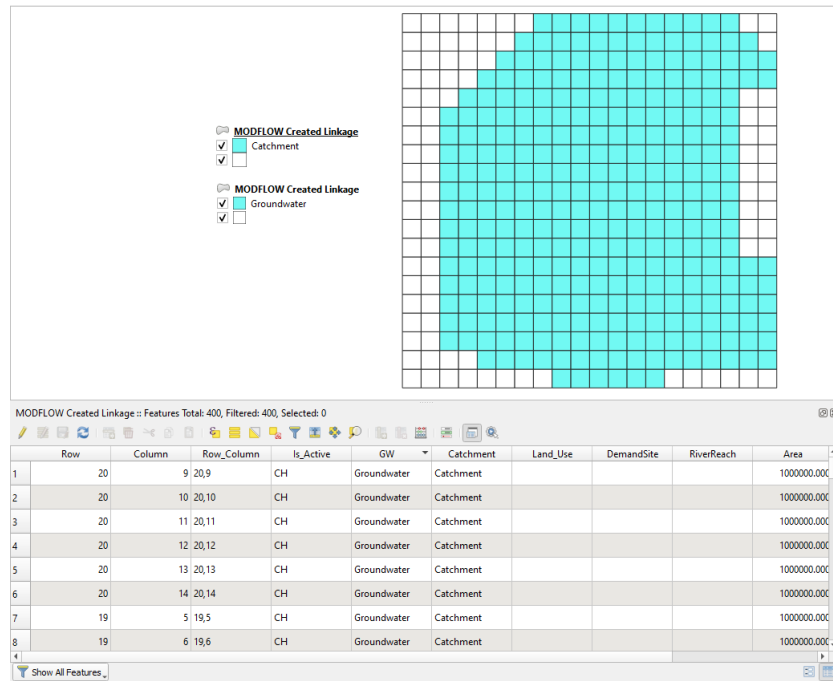
In this WEAP model, there is only one groundwater node to be linked.

*Edit the table using your preferred GIS assigning the name "Groundwater" for each cell that corresponds to an aquifer in the MODFLOW model. In this case, all the active cells represent one aquifer. The name must be entered in the "GW" field of the attribute table.*



*Repeat this process to assign the name of the catchment in the Catchment field. In this case, the catchment cells are the same cells representing the aquifer.*

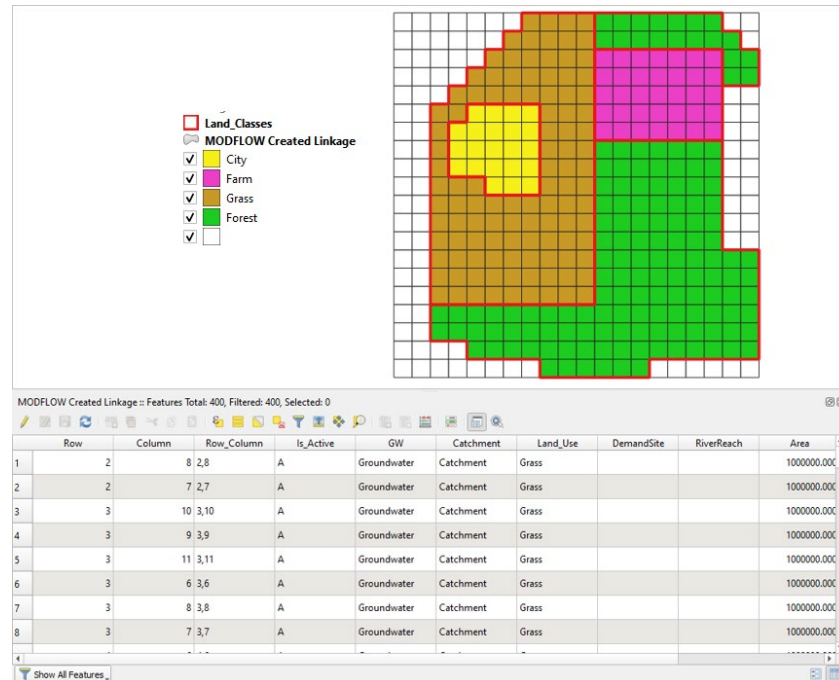
If you use the GW or Catchment field to customize the linkage file appearance in GIS, you will see the following:



The “Select by location” tool in any GIS is useful for selecting specific cells based on their location relative to features in another layer. The file Land\_Classes.shp stores the land cover distribution within the catchment.

*Use the Land\_Classes.shp shapefile to link land cover classes. Fill in the Land\_Use field specifying the land class cover name (Farm, City, Forest, Grass) as appropriate.*

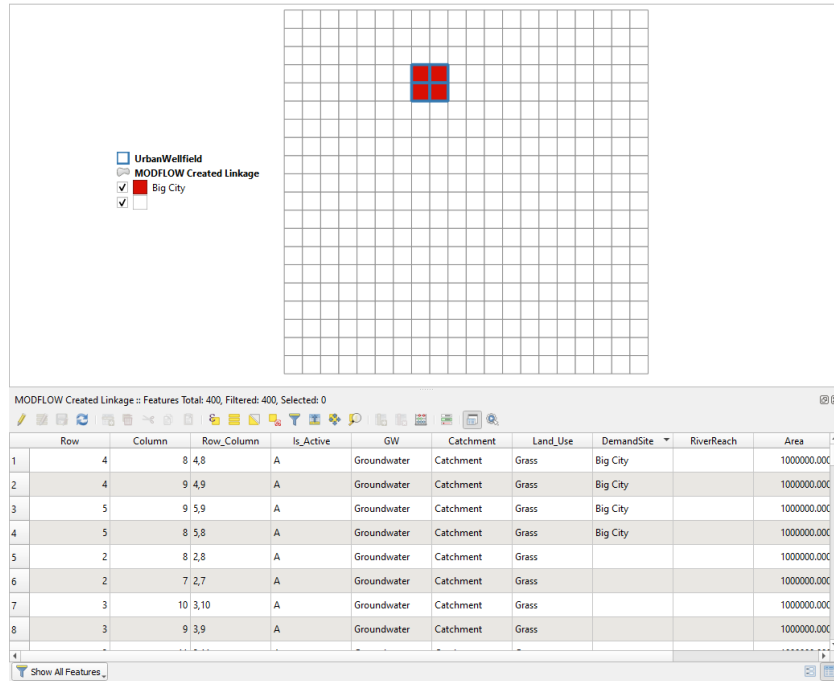
Once you have finished you should have the following:

**Note:**

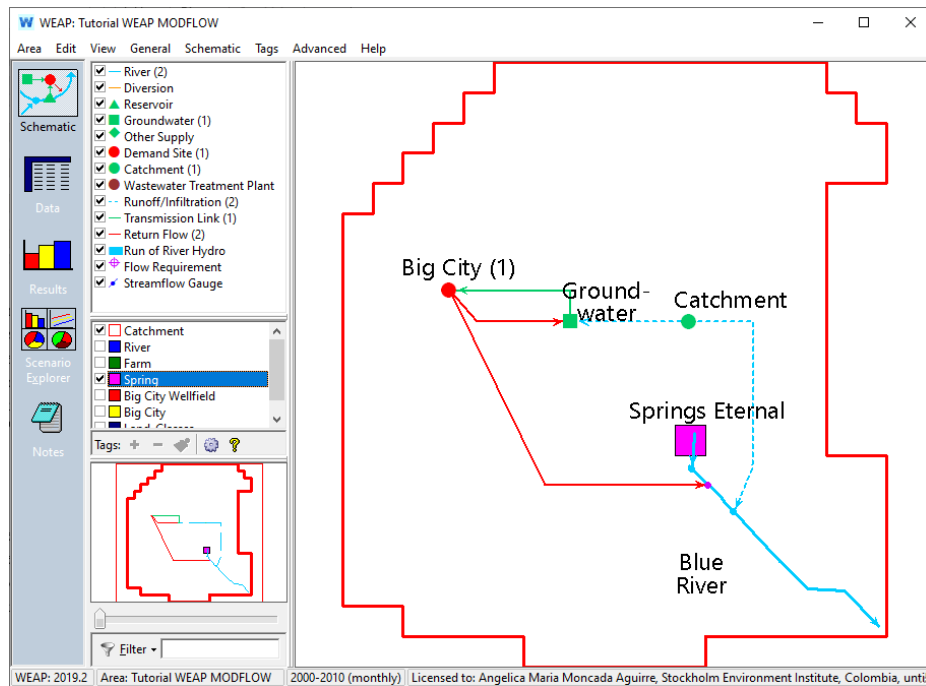
Land cover names in the land cover shapefile may differ from the branch names used in WEAP to define land cover classes within a catchment. WEAP names must be used for filling in the attribute table of the linkage file.

To link the demand site “Big City” the well cells must be identified.

*Use the UrbanWellfield.shp shapefile to assign the demand site name only to the cells with wells (see figure below).*

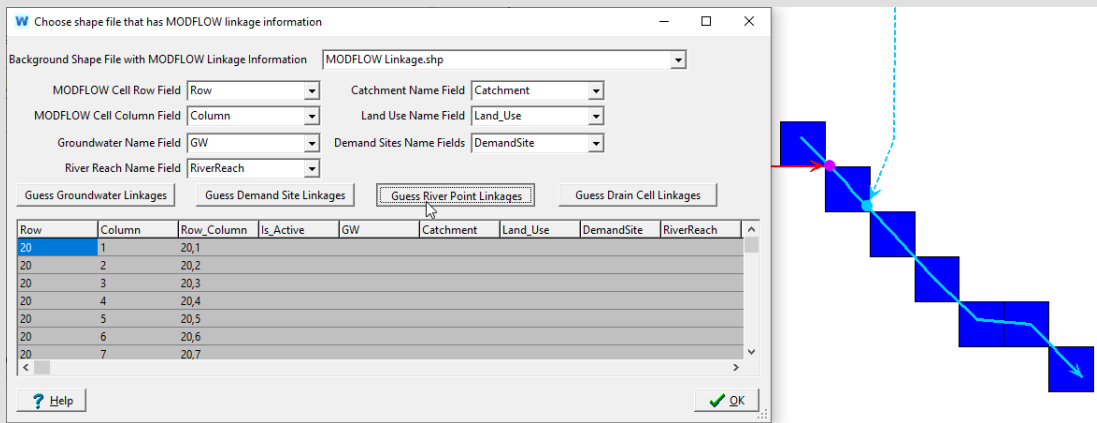


Finally, river reaches must be linked. First, MODFLOW drain cells (DRAIN package) must be identified and a river per drain added in WEAP. Use the SPRING.shp shapefile to check where the MODFLOW drain cells are. Consecutive drain cells are considered a drain. In this case, there is only one drain cell, and a river called “Springs Eternal” (see figure below).



**Note:**

WEAP has a useful tool when filling in the attribute table—the “guess linkages” buttons for groundwater, demand sites, rivers, and drains. WEAP tries to guess which MODFLOW cell could be linked to a WEAP element based on proximity on the schematic. For example, as shown in the figure below, clicking on “Guess River Point Linkages” asks WEAP to identify the closest polygon features in the linkage file that overlap WEAP river reaches and active cells in the River (RIV) package (blue squares). When finished, the river reach names will be written by WEAP into the river shapefile field (e.g. “RiverReach” field).



- Before using this tool, edit the river course or the localization of the WEAP element of interest to match the MODFLOW cells to be linked.
- “Guess River Point Linkages” and “Guess Drain Cell Linkages” buttons will work properly only if the course of the river overlaps the river and drain cells (RIVER and DRAIN packages). When the tool is used, each Demand Site will be linked to only one cell; Groundwater nodes will be linked to all active cells.
- After using this tool, you should review which nodes and cells WEAP has guessed to make sure that they are correct. The easiest way to do this is to display the linkages on the WEAP schematic or in a GIS. If the attribute table has errors, using a GIS to edit the linkage file is recommended.
- All withdrawals from and returns to a groundwater node, demand site, or catchment will be distributed evenly from/to all linked cells.
- River reach names are added to the attribute table considering the WEAP language. If the language is changed, the linkage shapefile will not work. WEAP must be run using the language used to generate the linkage shapefile.

Link the river reaches using the “Guess River Point Linkages” button.

*First, check that your linkage file “MODFLOW Created Linkage.shp” is in WEAP; if not, add it.*

The “Guess River Point Linkages” button is in the “Link to MODFLOW Groundwater Model” window.

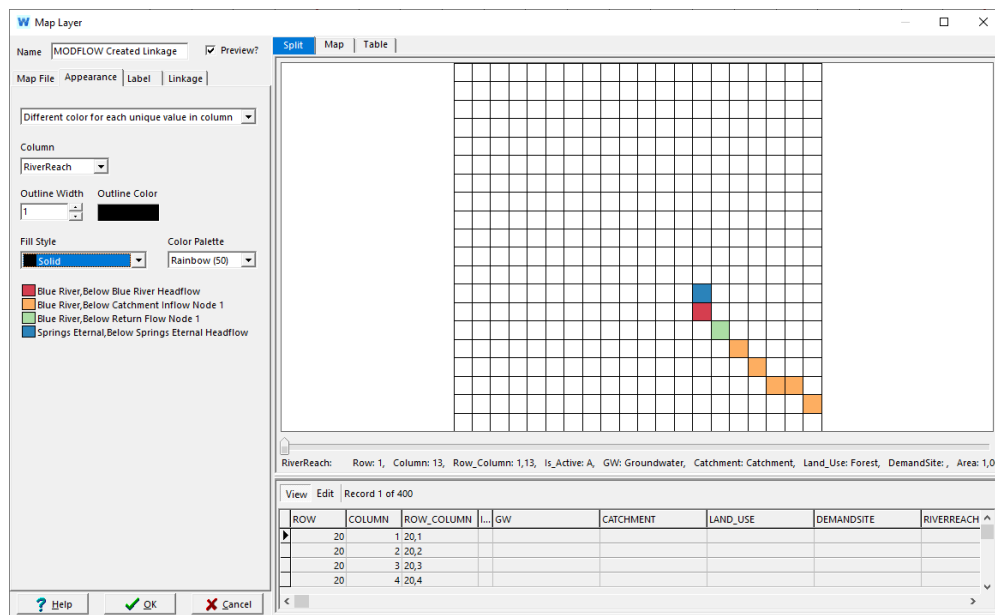
*In the Advanced menu, choose “Link to MODFLOW Groundwater Model”. Then click on “Choose shape file that has MODFLOW linkage information”. In the next window, for “Background Shape File with MODFLOW Linkage Information” choose “MODFLOW Created Linkage.shp”. Next, Click “Guess River Point Linkages”. Select yes on the pop-up window to allow WEAP to overwrite any river reach values already in the shapefile.*

Once this is done, WEAP will indicate how many cells were linked to river reaches.

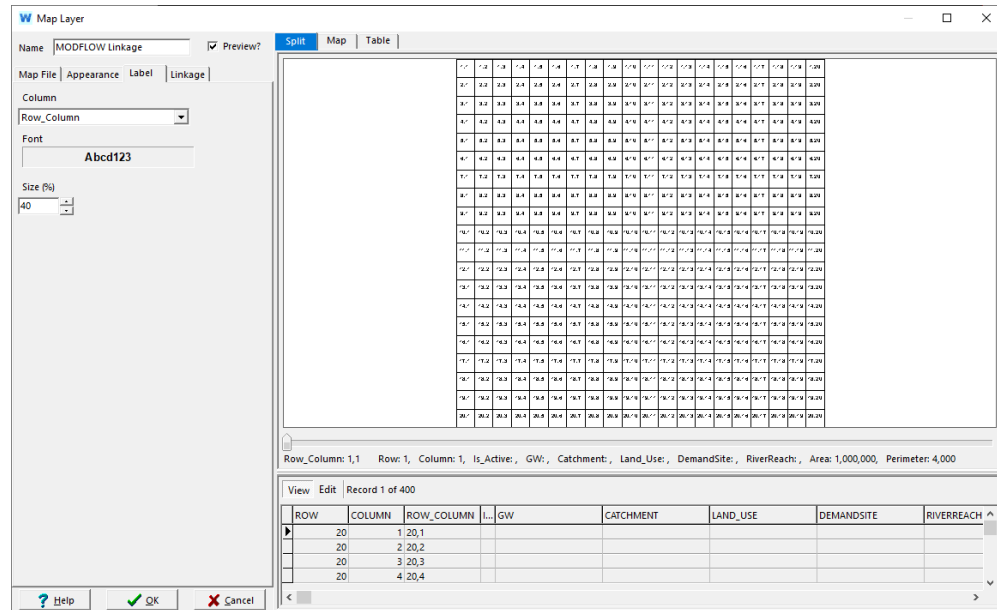
*Repeat the process using the “Guess Drain Cell Linkages” button. Click OK to close the window. Click Close on the “Link to MODFLOW Groundwater Model” window to return to the schematic.*

You can display the river reaches that were linked to MODFLOW Drain and River cells by updating the shapefile appearance (see figure below).

*Right-click MODFLOW Created Linkage shapefile to edit the Map Layer.*



Choose “Row\_Column” for the Column in the Label tab, and set the Size to 40%. Click OK to close the window.

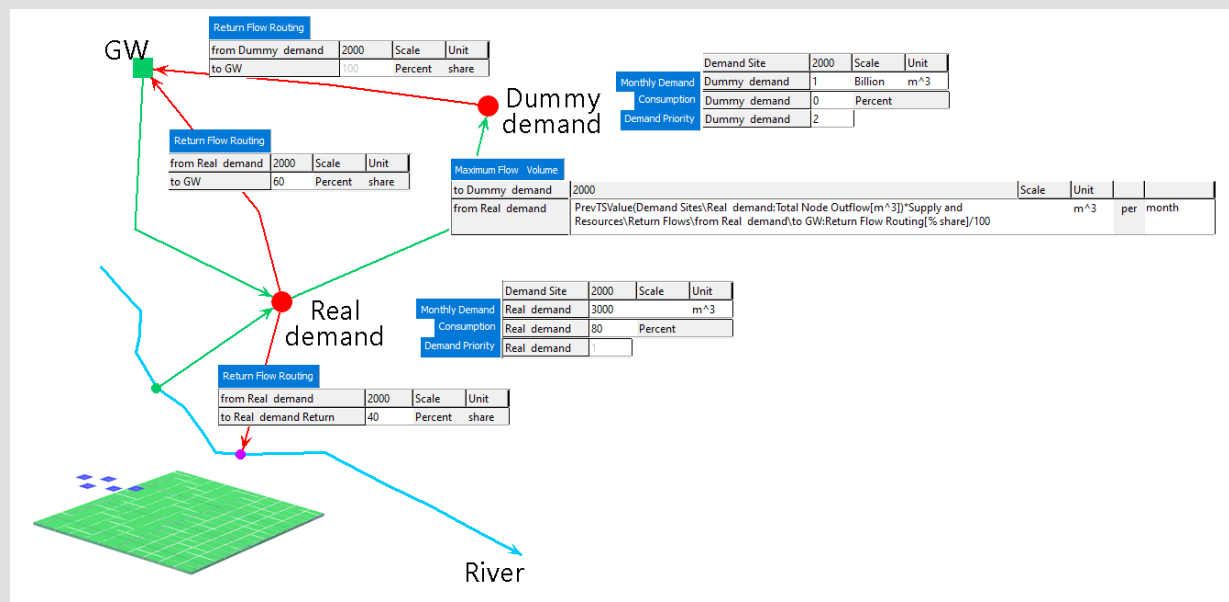


At this point, the linkage shapefile is complete. Names of Groundwater nodes, catchments and land cover classification, demand sites, and river reaches have been added to the attribute table of the linkage shapefile.

If you have completed this section, you can skip ahead to Section 6.

**Note:**

When infiltration is applied to cells without extraction, it is necessary to add a “dummy demand.” An example is shown in the figure below. In this example, well pumping occurs at a small number of cells (blue) while infiltration from water use is distributed over a larger number of cells (green). The demand site named “Real demand” represents the original demand in WEAP and should be connected in the linkage shapefile to the cells shown in blue (representing the location of wells). The demand site “Dummy demand” is the new demand that must be added in WEAP to represent infiltration to different cells and should be connected in the linkage shapefile to the cells shown in green (representing the infiltration area).



“Real demand” can have more than one transmission link or return flow. In the case of more than one return flow, the following expression for “Maximum Flow Volume” must be added in the transmission link from “Real demand” to “Dummy demand”: “PrevTSValue(Demand Sites\[Real Demand Name]):Total Node Outflow[m<sup>3</sup>]\*Supply and Resources\Return Flows\from [Real Demand Name]:\to [Groundwater element name]:Return Flow Routing[% share]/100. The unit of the variable must be changed according to the time step of the model (e.g. month for a monthly model). The above is not necessary if “Real demand” has only one return flow per groundwater element.

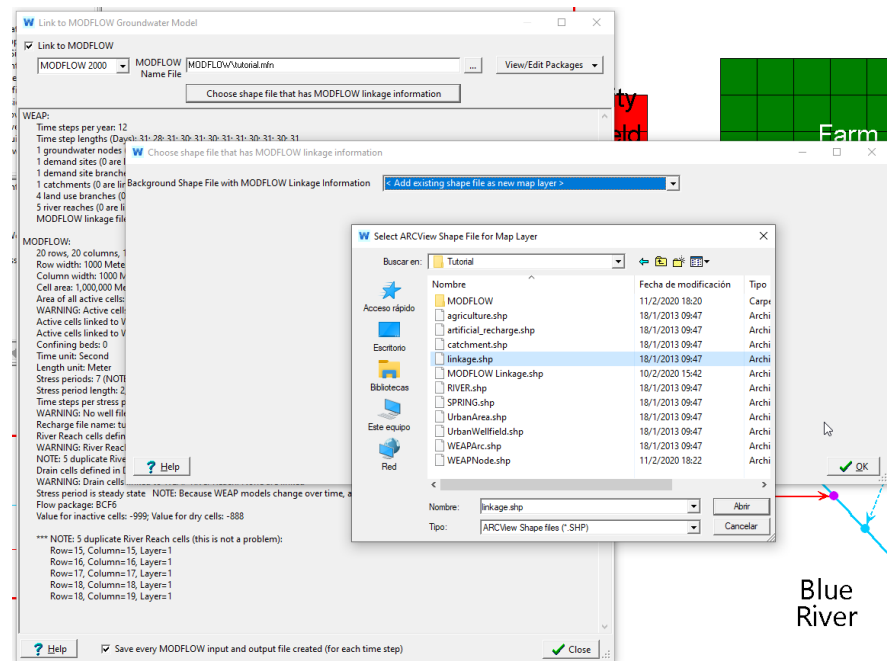
It is important that: a) the priority of “Dummy demand” be lower than that of “Real demand”, b) the water demand of “Dummy demand” be higher at all time steps than that of “Real demand.” (A significantly high value is recommended, such as 1 Billion m<sup>3</sup>.) And c) the “Dummy demand” consumption must be set to 0%.

According to the scheme, although the water demand of the “Dummy demand” is 1 Billion m<sup>3</sup>, WEAP will supply it only with the water not consumed by “Real demand.” In this case, assuming that the water supply of the “Real Demand” was 100% and using the data shown in the figure, the infiltration into the aquifer would be: 3000 m<sup>3</sup>/month (supply)\*20% (100% -consumption)\*60% (return flow routing from the “Real demand” to “GW”) =360 m<sup>3</sup>/month. This result would be the same without the implementation of the “Dummy demand,” but because infiltration is modelled into different cells compared to the extraction (pumping) cells, it is necessary to use this scheme.

## 5. Use an Existing Shapefile

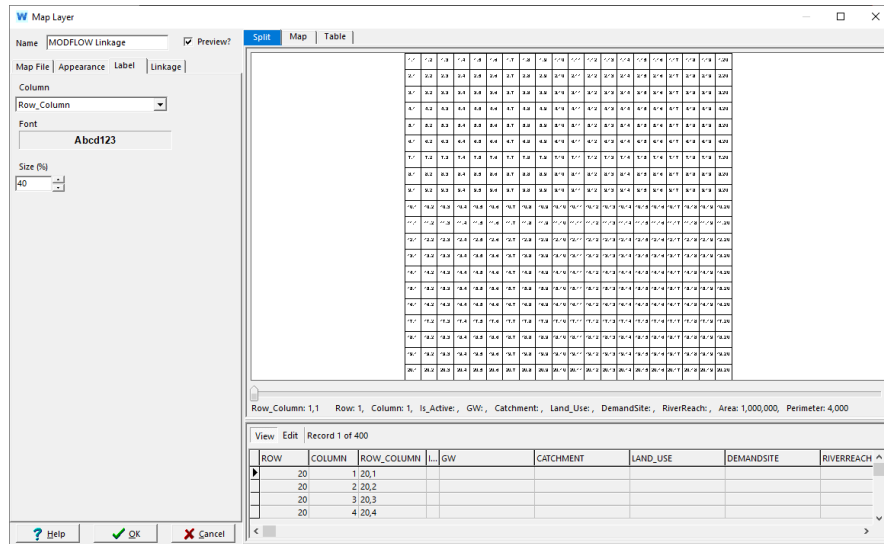
Rather than spending the time now to fill in all the information in the attribute table (as described in the previous section), we can use an existing shape file with all this information already filled in.

*On the “Choose shape file that has MODFLOW linkage information” window, select “< Add existing shape file as new map layer >” for the “Background Shape File with MODFLOW Linkage Information.” In the dialog box that appears, select “linkage.shp” (in the Tutorial directory) as the linkage shapefile to use. Click Open.*

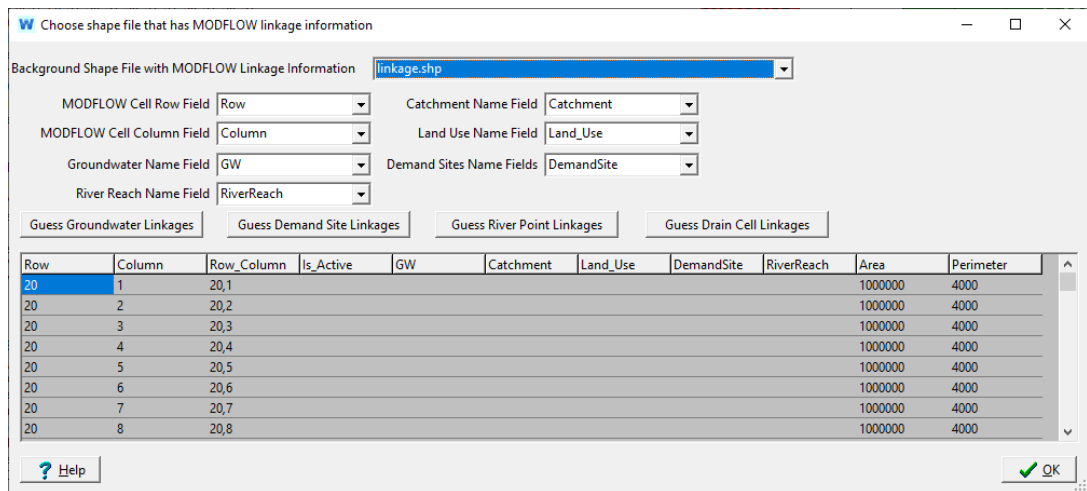


*On the “Map Layer” screen, change the name to “MODFLOW Linkage.” On the “Label” tab, choose “R\_C” for the Column, and set the Size to 40%. Click OK to close the window.*





Now you need to specify which of the fields in the Linkage attribute table will be used for the linkage, and to which MODFLOW and WEAP items they correspond. Based on the attribute table of the linkage shapefile, WEAP automatically guesses which fields are used for what. For example, WEAP has assigned the fields “Row” and “Col” as the MODFLOW row and column values. In fact, in this example, WEAP was able to correctly guess all the fields:



If it did not guess correctly, you would select the appropriate field for each item (e.g., River Reach Name Field is RIVERREACH).

*Click OK to close this window.*

## 6. Verify MODFLOW Model has linked to WEAP Model

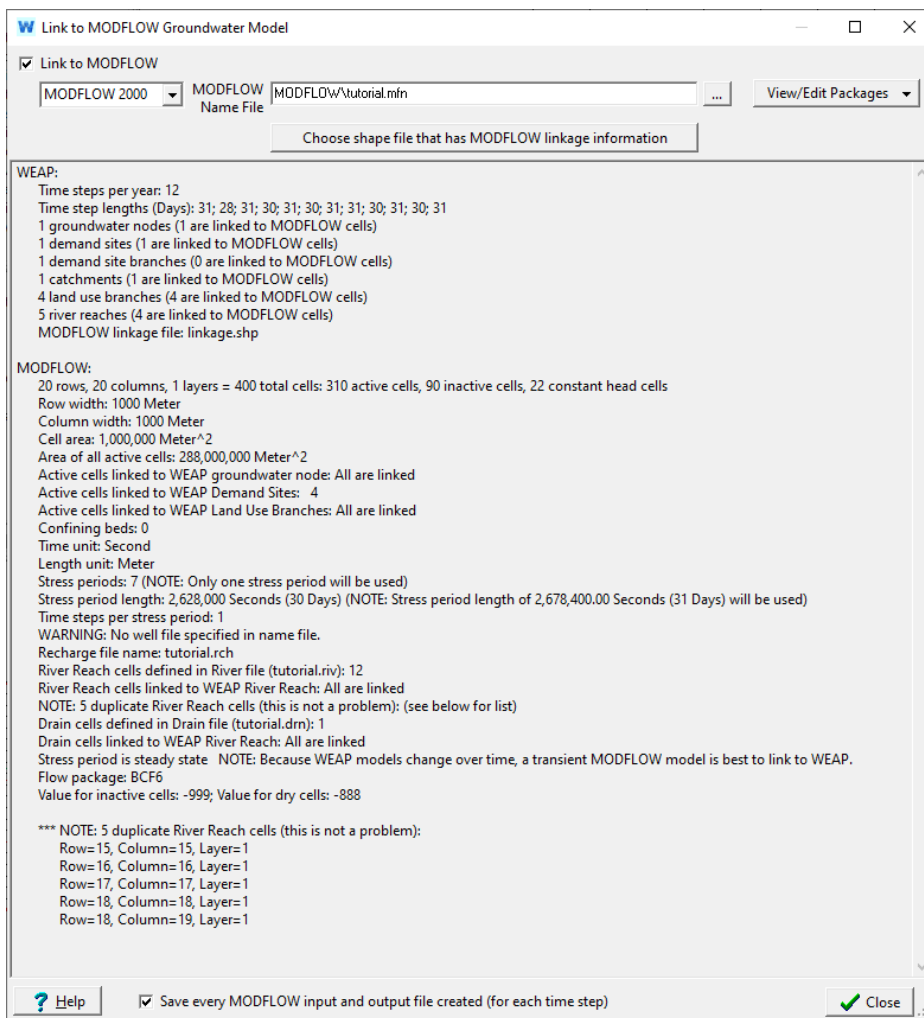
### Note:

- Make sure to check the box at the bottom of the “Link to MODFLOW Groundwater Model” window (“Save every MODFLOW input and output file created”) so that results will be available to view in WEAP and you will be able to run them in MODFLOW to examine the results in more detail, or to make slight changes to the inputs.
- WEAP creates a set of new temporary input files for each timestep and scenario. All temporary filenames start with “!MF!” to distinguish them from other files.
- Any changes you make directly to the temporary input files will be lost the next time WEAP does its calculations, so save them in another directory if you want to preserve them.
- If the MODFLOW model includes confined layers, you can group one or more layers into distinct aquifers for reporting purposes. Click the “Define Aquifers” button to specify how many aquifers exist and which layers correspond to which aquifers. This option is not available if the model has only one layer.

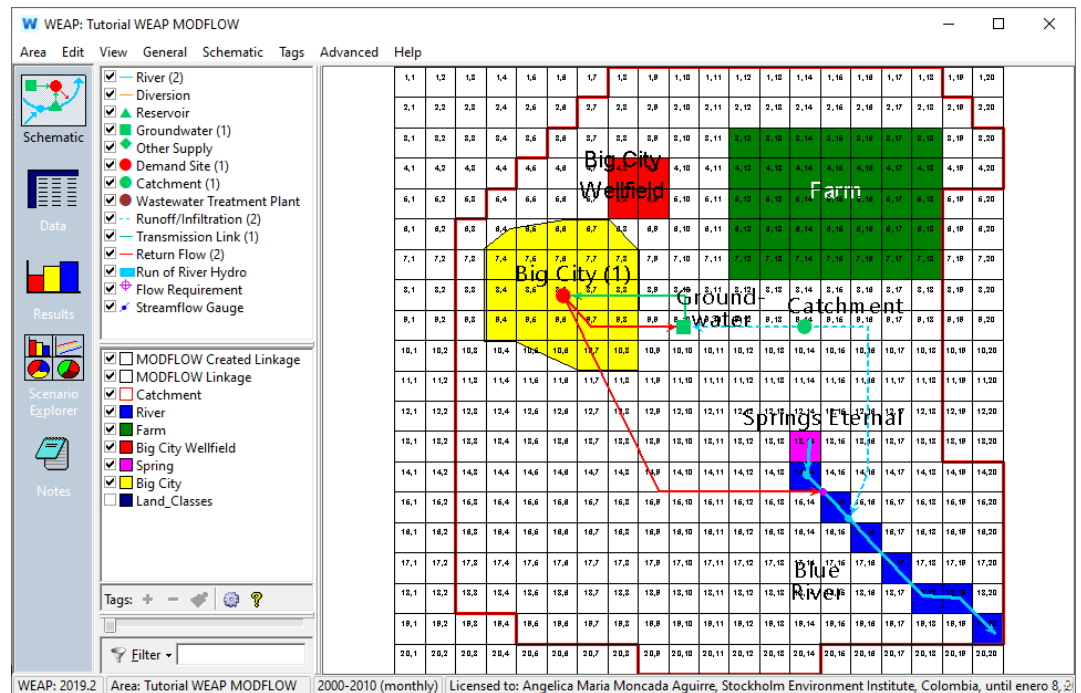
In the “Link to MODFLOW Groundwater Model” window under the WEAP heading, verify how many WEAP elements were linked to MODFLOW cells (the text in parentheses shows this information in the figure below). Not all elements need to be linked; it depends on your model schematic. Note that WEAP reports the linkage shapefile and how many of the WEAP and MODFLOW items have been linked, e.g., “1 groundwater nodes (1 are linked to MODFLOW cells)”.

All active cells must be linked to WEAP elements. This can be verified under the MODFLOW heading as “Active cells linked to WEAP groundwater node: All are linked.”

*Click Close to return to the Schematic.*



Depending on which steps you completed above (Section 4 or Section 5), two layers “MODFLOW Linkage” and “MODFLOW Created Linkage” might now be in the list of background layers in the schematic view, ordered at the top. Note that WEAP can only link to one MODFLOW layer at a time; even though both are shown, WEAP will only extract data from the layer specified in the “Choose Shape File that has MODFLOW Linkage Information” window (In Advanced/MODFLOW Link (Groundwater Flow)/Choose Shape file that has MODFLOW linkage button). If you want to change the order of the layers in the element window, right-click on the layer name and choose “Move Down.”



Take a moment now to view the other information contained in the linkage file.

*Right-click on “MODFLOW linkage” layer, choose “Set label to” and pick one of the other fields, such as “Land\_Class.”*

This will show you which of the four land classes (Grass, City, Forest, Farm) each cell is assigned to. Since the catchment is connected to the groundwater node and modelled by using Rainfall Runoff (simplified coefficient method), the cells linked to the catchment will be recharged by surface runoff from the catchment. Label by “DemandSite” to see from which cells the Big City demand site will pump. These same cells will be recharged by the water discharge of Big City. Label by “GW\_Node” to see which MODFLOW cells are linked to the WEAP groundwater node. Finally, choose the field “RiverReach” to see which cells are linked to the WEAP river reaches of “Blue River”.

Finally, you should review data previously entered as WEAP variables related to groundwater or influenced by surface water–groundwater interaction. The table below shows the list of variables and some considerations:

Element	Variable	Unit	Comments
Catchments- Rainfall Runoff (soil moisture method)	Preferred Flow Direction		In Rainfall Runoff (soil moisture method) mode if the catchment has a runoff infiltration link connected to a groundwater node, this controls flow from the first bucket to the second bucket (0 = 100% horizontal, 1 = 100% vertical).
Demand Sites and Catchments	Consumption	%	Defines the percentage of gross demand that will flow through the return flow link (from the demand site to a river or groundwater node), or through the transmission link (when the demand site is connected to another demand site or to a wastewater treatment plant).
Demand Sites and Catchments including irrigation areas	Demand Priority		Controls the order in which WEAP extracts water from available water sources (rivers, groundwater) to meet demands.
Groundwater	Initial Storage	Million m <sup>3</sup>	Used to track absolute volume of groundwater storage in WEAP but has no effect on MODFLOW results.
Groundwater	Maximum Withdrawal	Million m <sup>3</sup>	Used to set restrictions according to operating rules.
Groundwater	Natural Recharge	Million m <sup>3</sup>	Existing data must be deleted. Leave empty.
Groundwater	Storage Capacity	Million m <sup>3</sup>	Existing data must be deleted. Leave empty.
Reservoirs	Loss to Groundwater	Million m <sup>3</sup>	Existing data must be deleted. Leave empty.  An alternative solution is to include a dummy demand extracting water from the reservoir and discharging it to the groundwater node.
Return Flows	Gain from Groundwater	Million m <sup>3</sup>	Existing data must be deleted. Leave empty.  An alternative solution is to include a dummy demand extracting water from the groundwater node and discharging it to the same discharge point of the demand site where this return flow is connected.
Return Flows	Loss to Groundwater	%	Existing data must be deleted. Leave empty.  An alternative solution is to include a dummy demand extracting water from the demand site and discharging it to the groundwater node.
Return Flows	Return Flow Routing	% share	Defines the percentage of flow that discharges to different elements (rivers, groundwater nodes, wastewater treatment plants).

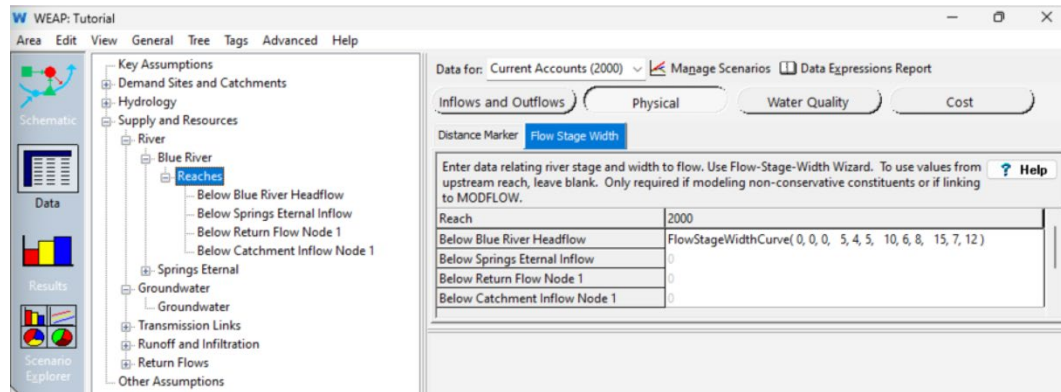
Element	Variable	Unit	Comments
River	Groundwater Inflow	Million m <sup>3</sup>	Deactivated when MODFLOW coupling is being used.  When MODFLOW is not using the River (RIV) or Drain (DRN) package, it does not model surface water–groundwater interaction. An alternative solution is to include a dummy demand extracting water from the groundwater node and discharging it to the river.
River	Groundwater Outflow	%	Deactivated when MODFLOW coupling is being used.  When MODFLOW is not using the River (RIV) or Drain (DRN) package, it does not model surface water–groundwater interaction. An alternative solution is to include a dummy demand extracting water from the river and discharging it to the groundwater node.
Runoff and Infiltration	Groundwater to Groundwater Flow	Million m <sup>3</sup>	Existing data must be deleted. Leave empty.  This is modeled by MODFLOW.
Transmission Links	Loss to Groundwater	%	Existing data must be deleted. Leave empty.  An alternative solution is to include a dummy demand extracting water from the demand site and discharging it to the groundwater node.
Transmission Links	Supply Preference		Defines the preference when a demand site or a catchment with irrigation has multiple sources.

Check that the information entered for Initial Storage, Natural Recharge, and Storage Capacity of the groundwater node are empty.

## 7. Set the Flow-Stage-Width

Surface water–groundwater interaction requires the stage-discharge rating curve, which represents the relationship between the water level and the streamflow at a given point in a river. It is specified as Flow-Stage-Width under the Physical tab. This tab is visible only when a river reach is selected in the data tree.

Go to Data View and then to Supply and Resources/River/Blue River/Reaches/Below Blue River Headflow and review the Flow-Stage-Width data. Note that you'll need to enter your own values when building new models.

**Note:**

The expressions should be filled in for as many river reaches as possible. However, if information is limited, WEAP can calculate the surface water–groundwater interaction by entering the expression only in the first river reach.

## 8. Set Pump Layer

One final step to link the WEAP and MODFLOW models is to specify from which MODFLOW layer the Big City demand site will pump. In general, a demand site or catchment node can pump from a single layer, pump from many layers (in equal or different proportions), or have pumping be handled as negative recharge in the MODFLOW recharge file. Our MODFLOW Linkage has only one data layer (which you can verify in the first line of text under MODFLOW in the Advanced/ MODFLOW Link (Groundwater Flow) window and where the number of rows, columns and layers are reported). Because there is only one layer, the pumping choices are from layer 1, or as negative recharge (enter pump layer = 0 for negative recharge). We want to pump from layer 1.

*Go to the Data View, select “Big City” on the data tree, then click on the “Pumping” category at the top and enter “1” for the Pump Layer.*

The screenshot displays the WEAP software interface for configuring a Pump Layer. The left sidebar shows a tree view of the model structure, with 'Big City' selected under 'Demand Sites and Catchments'. The central panel is titled 'Pump Layer' and contains the following configuration options:

- Data for:** Current Accounts (2000)
- Water Use:** Pumping, Loss and Reuse, Demand Management
- Water Quality:** Cost, Priority, Advanced
- MODFLOW layer(s) from which to pump:** 2000
- Big City:** 1

The right panel shows a chart titled 'Pump Layer (monthly)' with a Y-axis labeled 'Meter' ranging from 0.00 to 1.00. The X-axis shows months from Jan 2000 to Dec 2000. The chart displays a constant value of 1.00 for all months, indicating a constant pumping rate of 1 meter per month.

You have now linked the WEAP model to the MODFLOW model.



**Note:**

Pumping to satisfy demand sites or catchment land classes (irrigation) can either be handled as pumping in the well file, or as negative recharge in the recharge file. When using injection wells for artificial recharge of demand site return flow, specify MODFLOW layer(s) in which to inject water. The pump layer and injection layer are specified in the Data View under the pumping tab for demand sites and under the Irrigation tab for catchments.

- Pump Layer and Injection Layer are only used when linking MODFLOW to WEAP.
- When layer>0 is specified, WEAP will add cells to the well file if they are not already there. Specify layer=255 for a cell to have pumping or injection equally from all layers in that cell. The well package will be modified.
- Leave blank or specify layer=0 for handling withdrawals as negative recharge (pumping) or return flows as positive recharge (injection). The recharge package will be modified.
- Use the PumpLayer function to specify fractions pumped from (pumping) or to (injection) different layers.
- Pumping and injection can vary by scenario and over time.
- Injection Layers can only be used for Demand Site return flows, not for Catchment infiltration.
- If the setting (in General, Basic Parameters) for “MODFLOW Pumping if Dry or Inactive Cells” is “Do not reappportion pumping from dry or inactive cells,” WEAP will reduce groundwater pumping by demand sites and catchments from these drying cells accordingly. This will result in Unmet Demands and will be included in the MODFLOW “Pumping Reduction” reports.
- On the Basic Parameters screen you can choose whether all demand site and catchment subbranches will pump from the same MODFLOW layer or set of layers. For Injection Layer, WEAP will use the same setting as for MODFLOW Pumping for Demand Sites.

# Running MODFLOW and Viewing Results

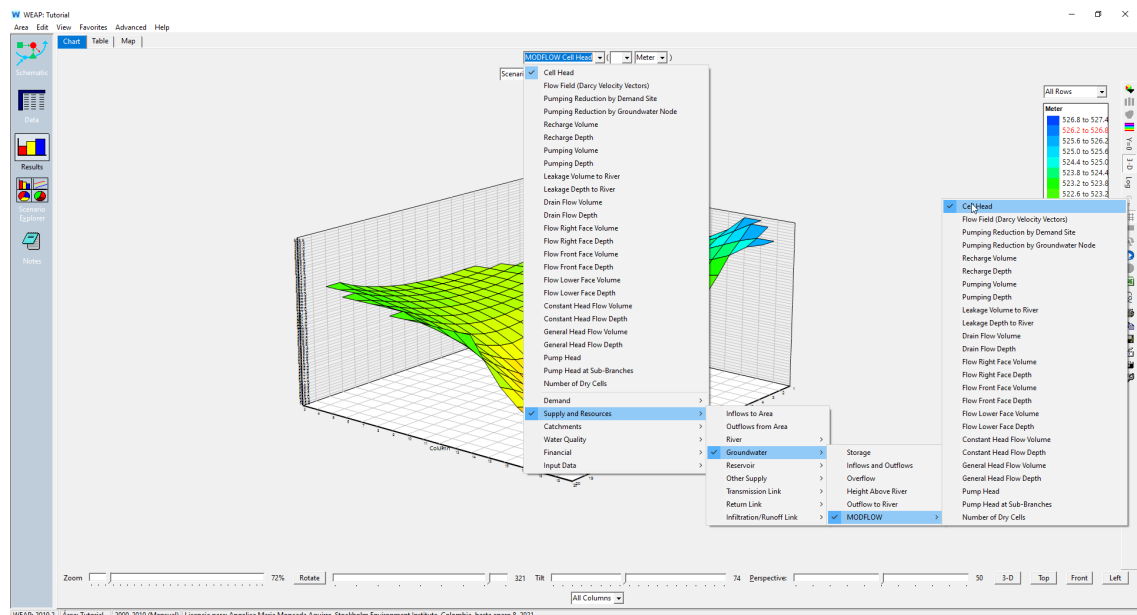
## 9. View Results

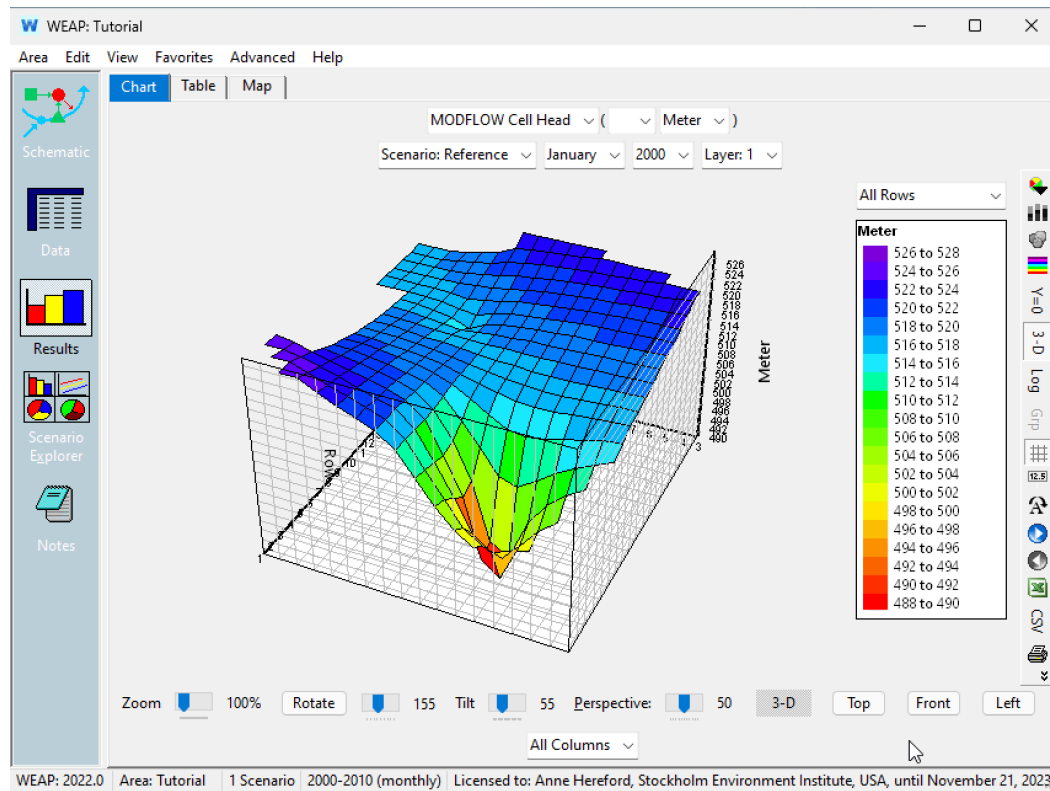
*Click the Results button to calculate and view results. Notice that at each calculation timestep, WEAP runs MODFLOW.*

Results for MODFLOW are in the “Supply and Resources / Groundwater / MODFLOW” category in the pull-down menu just above the chart.

*Look at the results for Supply and Resources / Groundwater / MODFLOW / Cell Head.*

This report shows the vertical head for each MODFLOW cell. Cell head and other MODFLOW results can be overlaid on the map or displayed as a 3-dimensional surface. Make sure that “Surface” is selected as the chart type (the first icon in the menu bar to the right of the legend), and that the “Y=0” button is not selected. The cell head for one timestep is shown (January 2000). Experiment with the sliders below the chart to rotate or tilt the surface. Click the “Rotate” button to animate the chart. Click “3-D” to switch between a 3-D surface and 2-D plan view. You can also click on the 3-D surface and drag the mouse to rotate the view.





*Can you see the impact of pumping from the Big City Wellfield? (This view exaggerates the variation in head—click the “Y=0” button to see a view without vertical exaggeration. It is usually better to turn off Y=0 to highlight differences.)*

In addition to cell head, you can also look at the following results from MODFLOW: Flow Field (Darcy Velocity Vectors), Pumping Reduction (how much pumping has been reduced due to dry cells), Recharge, Pumping, Leakage to River, Drain flow, Flow Right Face (flow from the column to the right/higher column number), Flow Front Face (flow from the row below/higher row number), Flow Lower Face (flow from layer below/higher layer number), Constant Head Flow, Pump Head, Pump Head at Sub-Branches (if linked to Demand Site sub-branches), and Number of Dry Cells. For recharge, positive values represent inflow into the cell, whereas for pumping, drain flow and leakage to river, positive values represent outflow from the cell.

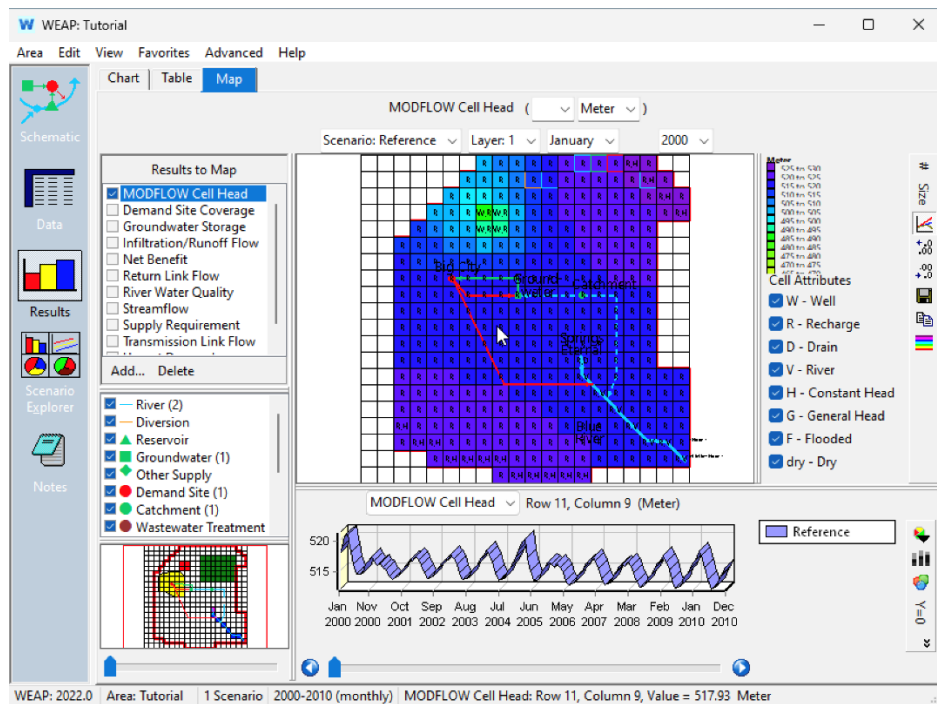
*Click on the Map tab to see the head values on the map, with a graph below.*

*Activate the “Display chart below map” button on the right (x-y plot icon).*

Below the map, a chart shows how head results for a single cell vary over time, one line for each scenario.

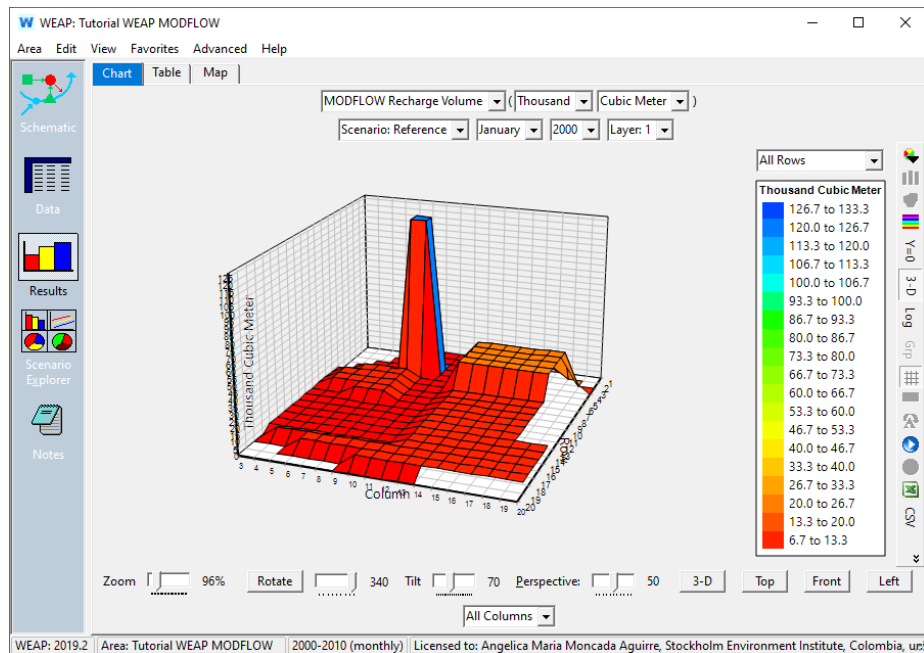
*Click on some of the cells at the Big City Wellfield to see how they vary.*

There is a seasonal fluctuation in cell head (higher in winter, lower in summer) due to increased pumping and lower rainfall in the summer), and an overall trend downward from 2000 to 2010. You can click and drag the mouse over the cells and the graph will update in real-time as you move the mouse. This is a good way to get a quick understanding of how cells in different areas of the model behave differently over time. Note that the option to toggle Y=0 is now at the bottom right menu.



*Look at a few other MODFLOW results, such as Recharge Volume, Pumping, Drain Flow, and Leakage to River.*

Note that pumping and recharge occur on the same cells linked to the “Big City” demand site and the irrigated land area (Farm) of the “Catchment”.



## 10. Calibration and Validation

Calibration and validation should be performed by comparing simulated and observed levels in the exploratory wells. The simulated level in a specific cell can be exported from WEAP by going to the Results View and choosing the variable Supply and Resources \ Groundwater \ MODFLOW \ Cell Head. Graph the time series of simulated and observed levels using a programming language or a spreadsheet such as Microsoft Excel.

A separate section of the Tutorial will guide you through surface water calibration.

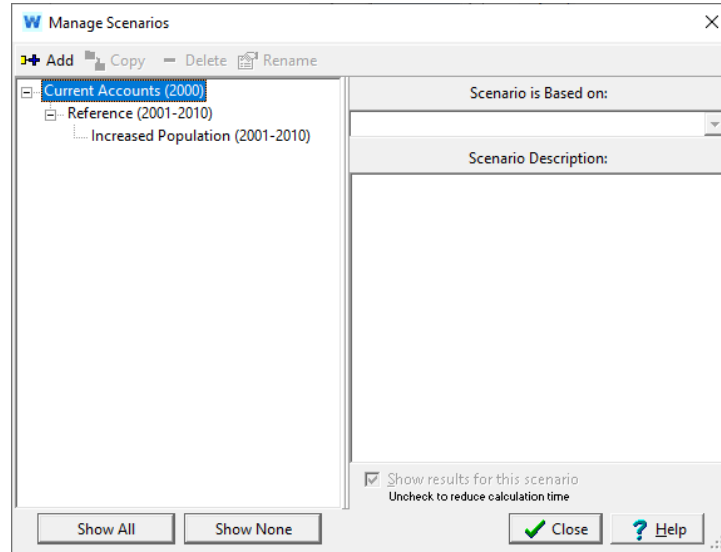
A model can be assumed to be calibrated when the streamflow record obtained from gauge stations is similar to the simulated streamflow in WEAP and the groundwater level recorded in the exploratory wells is similar to the simulated levels in MODFLOW.

## Scenario: Increased Population

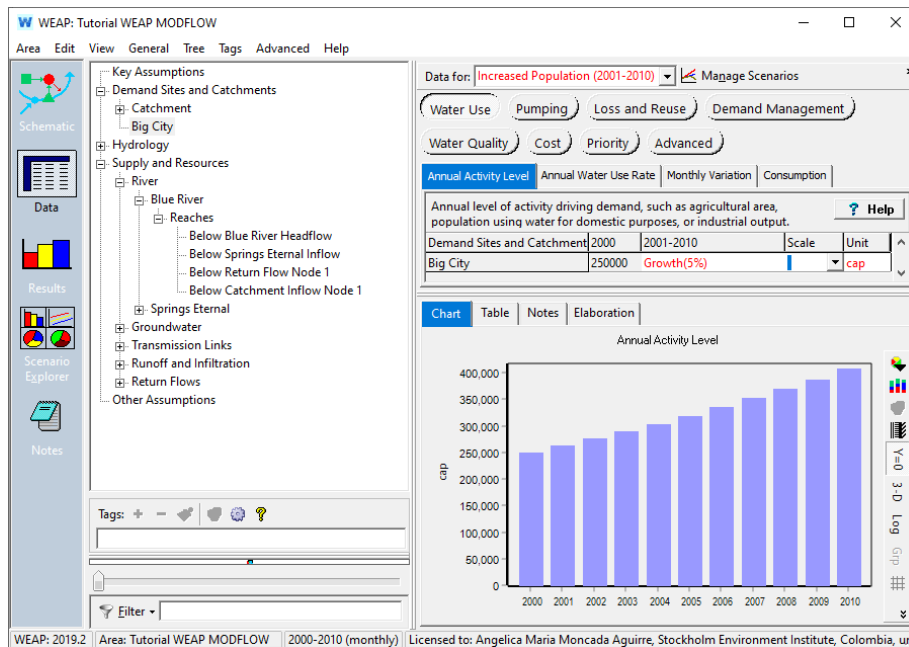
Now that we have a MODFLOW model linked to our WEAP model, we can create some WEAP scenarios and explore how they might affect groundwater.

## 11. Create Scenario

*Switch to the Data View and create a new scenario underneath “Reference.” Call it “Increased Population” (Main menu: Area, Manage Scenarios).*

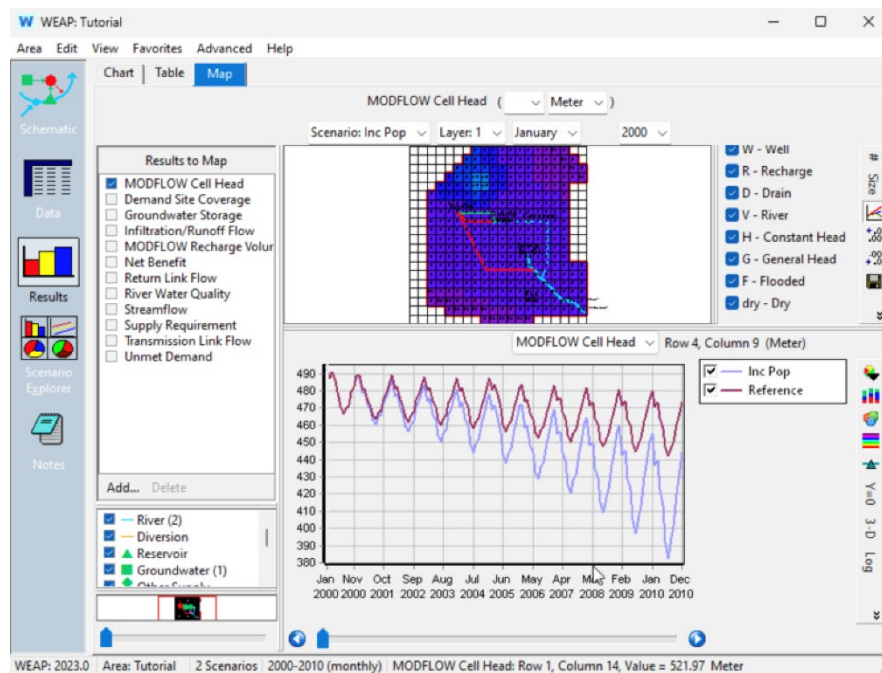


*Under the Water Use tab, change the expression for the Annual Activity Level for Big City from “Growth(1%)” to “Growth(5%)”.*

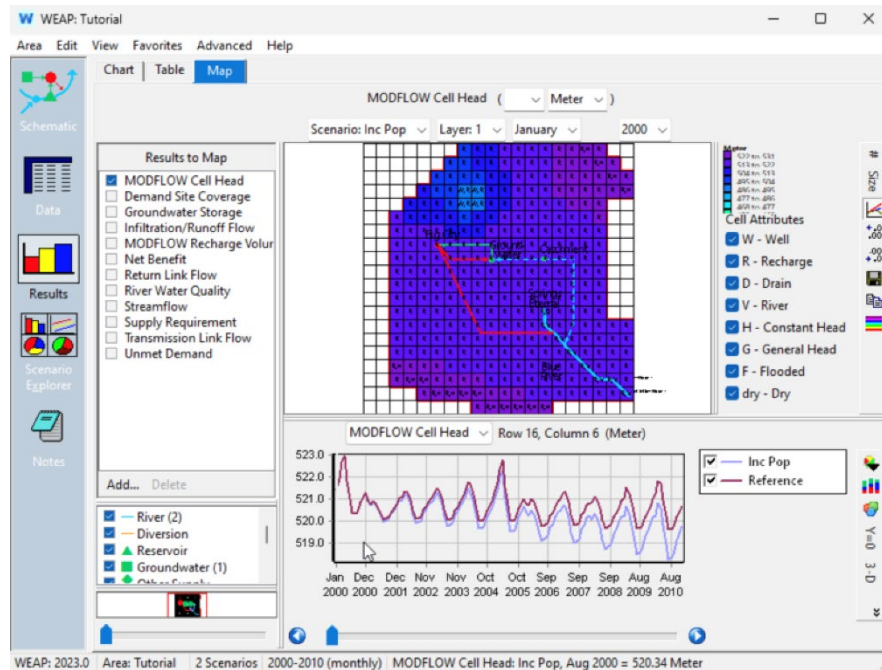


## 12. Evaluate Results

To explore the results, go to Results and look for the impact of the increased pumping from Big City on groundwater levels (Make sure you have selected the following dropdown menu options in the Map view: Scenario: Increased Population, Layer: 1, January, 2000, Row 4, Column 9). As you can see, the slow downward trend of the Reference scenario is accelerated in the Increased Population scenario. This is especially evident in the cells on or near the Big City Wellfield.



The effect, although smaller, can even be seen far away from the wellfield, e.g., in Row 16, Column 6 (in the lower left corner of the model).

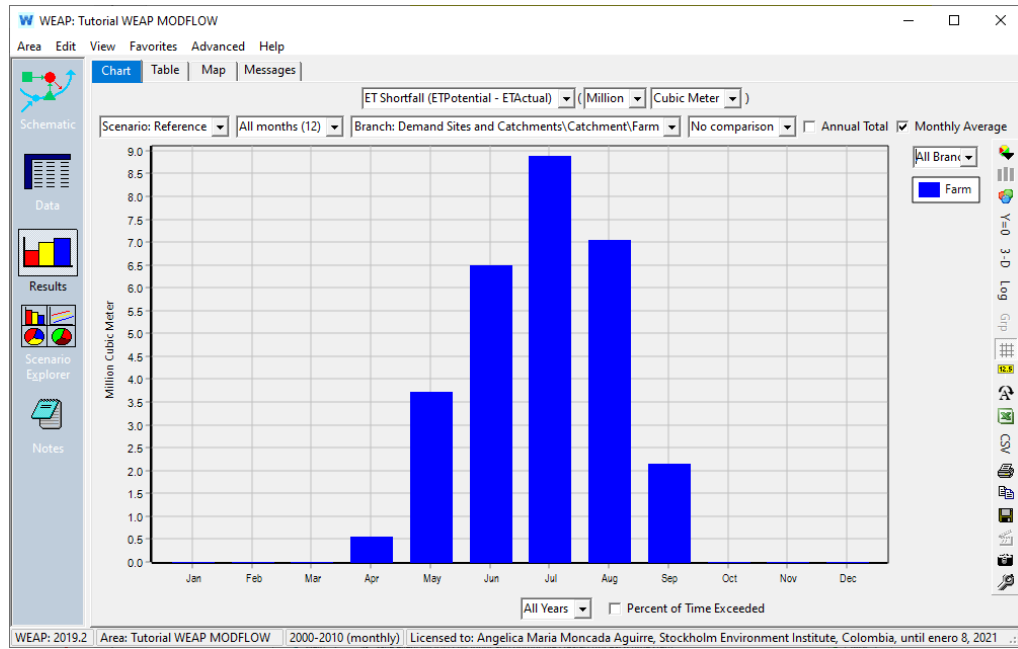


## Scenario: Irrigation

The crops on this Farm are currently rainfed, but there is not enough rainfall in the summer to meet evapotranspiration demand. Look at the results for evapotranspiration shortfall for the Farm branch in the reference scenario.

*In the Chart view, select the following dropdown menu options: Catchments/ET Shortfall, Million, Cubic Meter, Scenario: Reference, All months, Branch: Demand Sites and Catchments/Catchment/Farm, No comparison, Monthly Average. Show All Branches in the legend and All Years (at the bottom of the chart).*

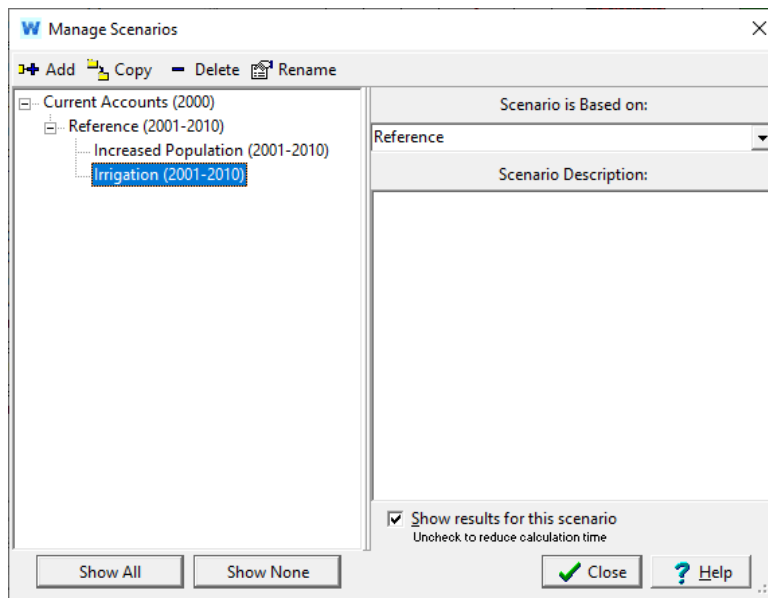




### 13. Create Scenario

Investigate the impact of adding irrigation from groundwater pumping, both on the groundwater levels and on crop yields.

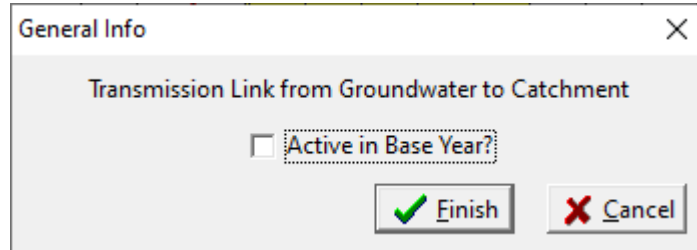
*Switch to the Schematic View and go to Area/Manage Scenarios. Create a new scenario underneath “Reference,” call it “Irrigation.”*



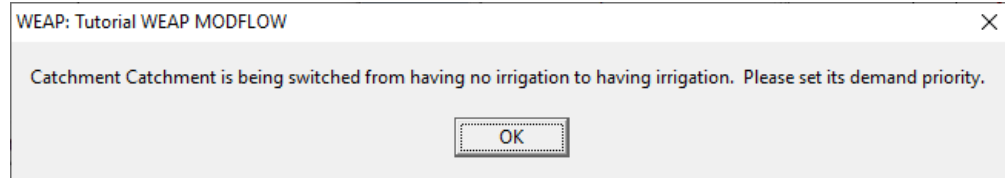
There are several steps to take to activate irrigation for the Farm landclass and for the MODFLOW cells associated with the Farm.

## 14. Add Transmission Link

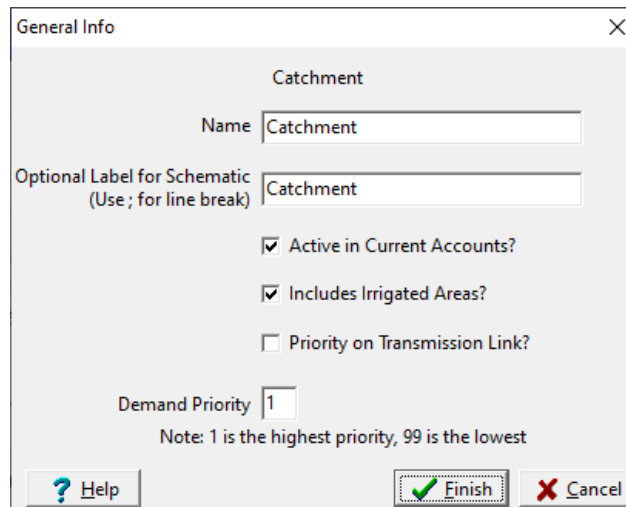
*Add a transmission link from the groundwater node to the catchment, and uncheck “Active in Base Year?”*



When you add this link, WEAP will automatically set the catchment as having irrigation.

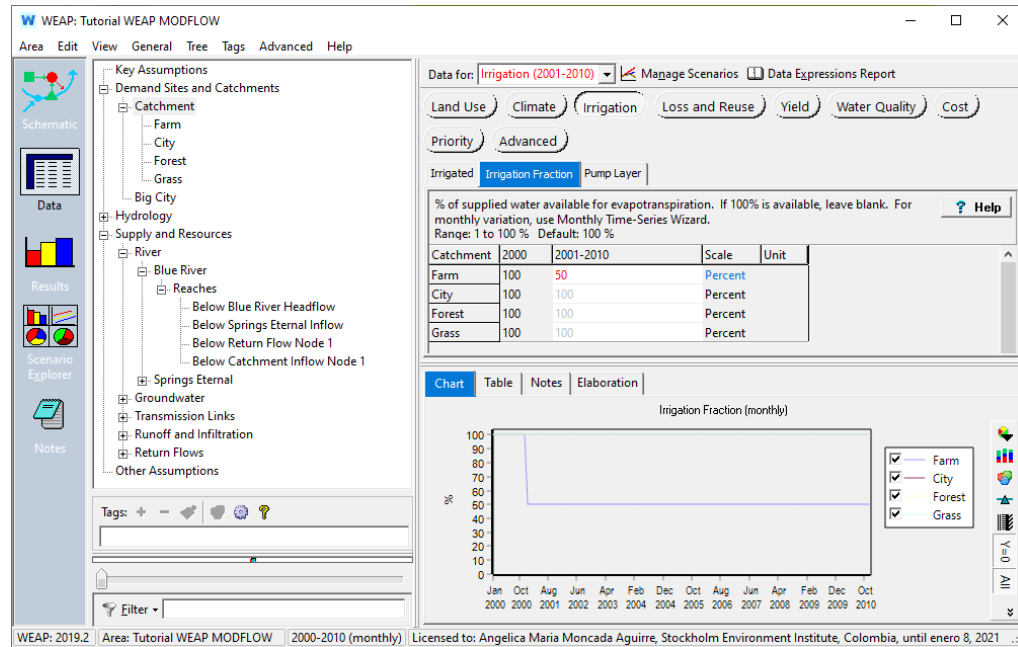


You can leave the priority as 1.

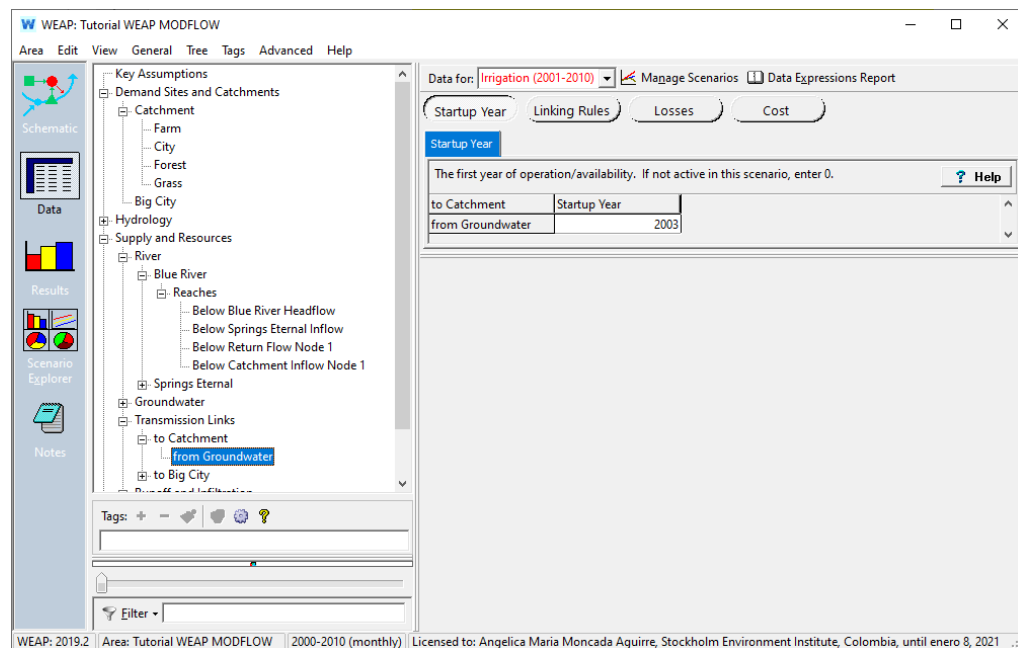


## 15. Set Land Class as Irrigated

*Go to the Data View (make sure that the Irrigation scenario is selected in the “Data for” dropdown box at the top) and change “Irrigated” to 1 for the Farm, and “Irrigation Fraction” to 50 (50% irrigation efficiency).*



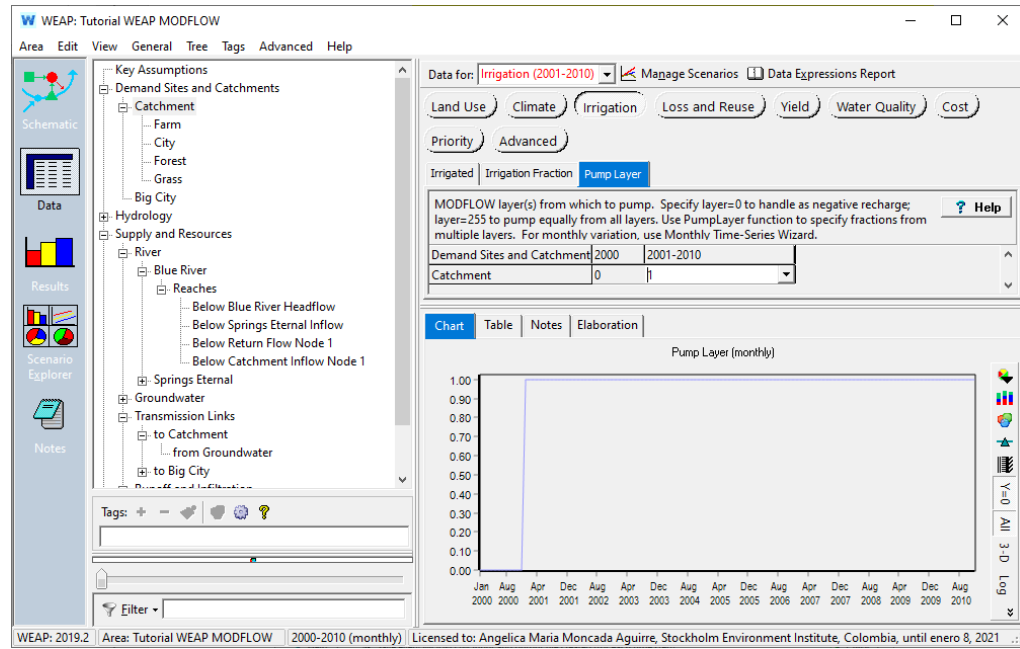
*For the transmission link, set the Startup Year to 2003.*



## 16. Set MODFLOW Layer for Irrigation

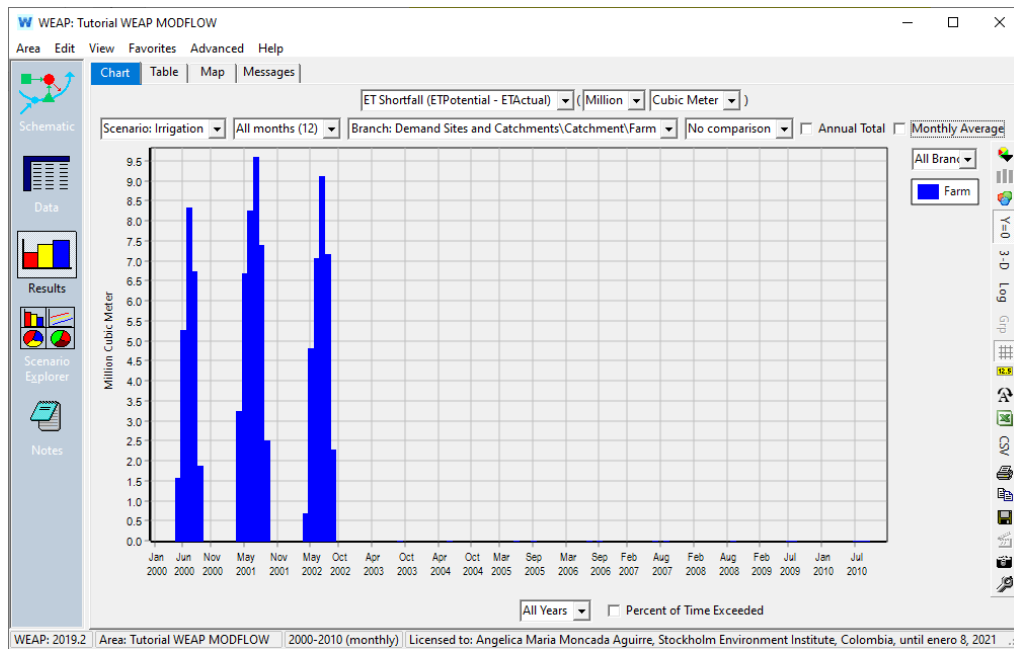
We want MODFLOW to pump the irrigation water from layer 1.

*Click on the “Catchment” branch in the data tree, then click on the “Irrigation” category at the top and the “Pump Layer” variable tab. Enter a value of 1.*



## 17. Evaluate Results

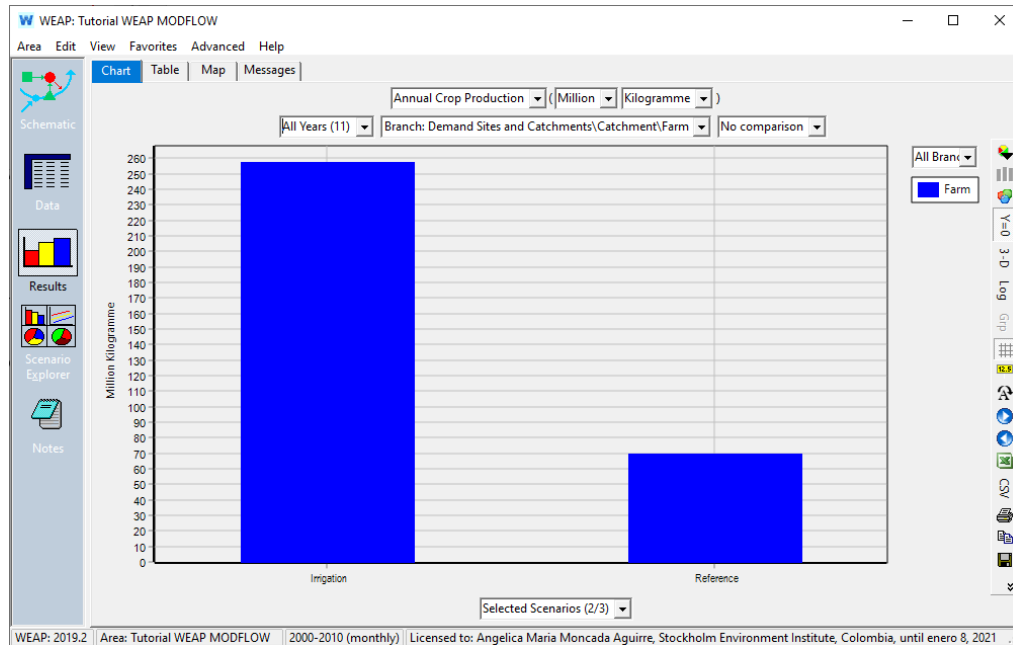
*Go to the Results View. Verify that irrigation begins in 2003, reducing the ET Shortfall to zero. (Remember to uncheck Monthly Average.)*



What happens to crop yields, now that they receive all the water they need?

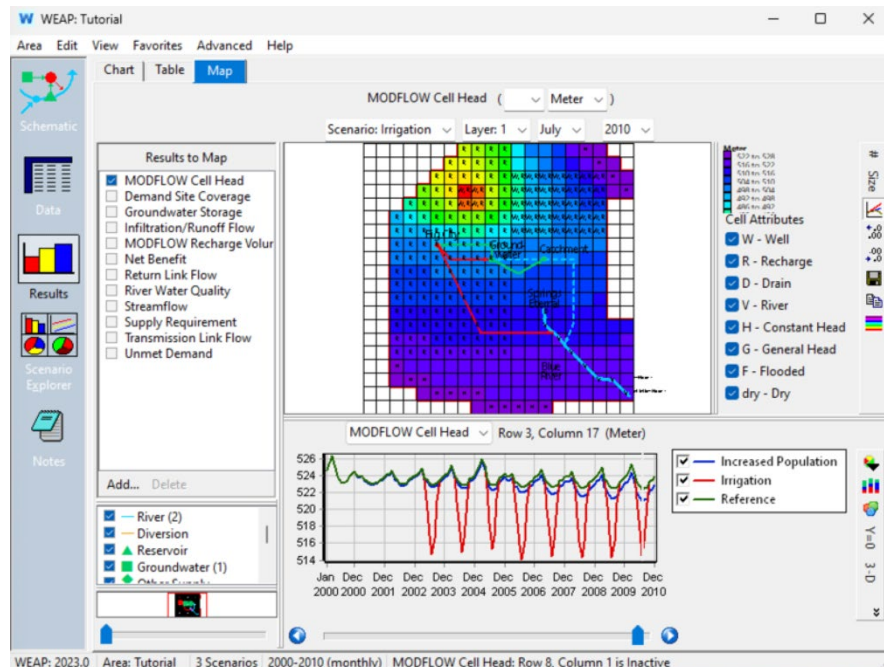
*Look at the Catchment report for Annual crop Production, comparing the yield across scenarios by selecting the Irrigation and Reference Scenarios in the dropdown menu at the*

*bottom and selecting All Branches in the dropdown menu to the right. Make sure you have selected the following dropdown menu options: Million, Kilogram, All Years, Branch: Demand Sites and Catchments/Catchment/Farm, No comparison.*



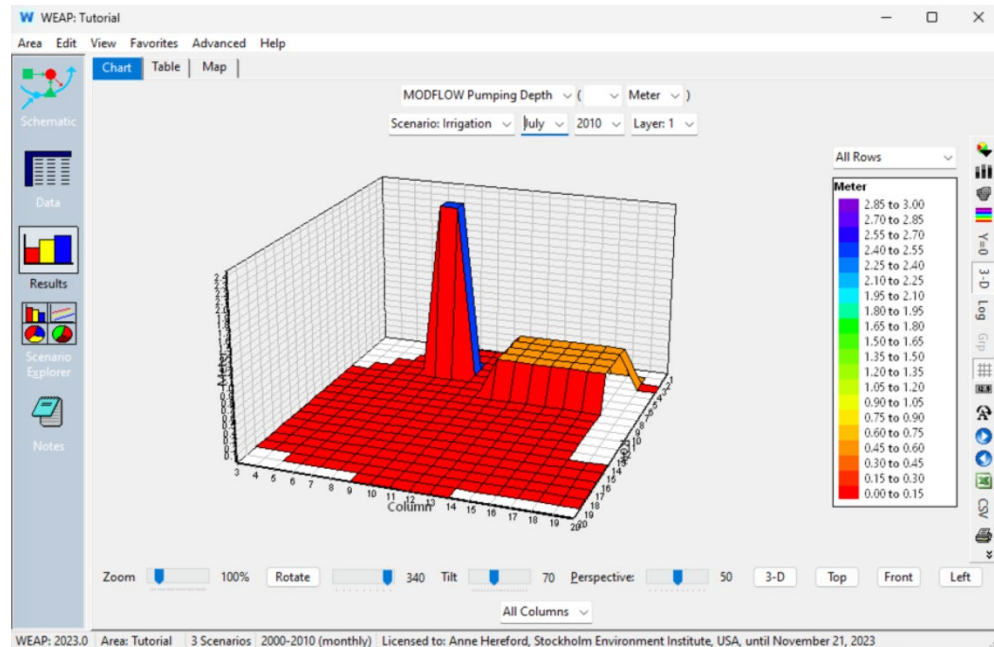
Now look at the impact of irrigation on groundwater.

*View the MODFLOW Cell Head Results for July 2010 on the Map tab. Click on a cell in the map in the Farm to see the largest effect, or a cell far away from the Farm to see a smaller effect.*



Compare the pumping rates for the Farm and for Big City.

*Select the following dropdown menu options: Meter, Scenario: Irrigation, July, 2010, Layer: 1.*



## Scenario: Artificial Recharge

For a final scenario, explore the impact of artificial recharge on groundwater.



Artificial recharge, or “Aquifer Storage and Recovery” (ASR), involves injecting water into an aquifer through wells or by surface spreading and infiltration and then pumping it out when needed. The aquifer essentially functions as a water bank. Deposits are made in times of surplus, typically during the rainy season, and withdrawals occur when available water falls short of demand.

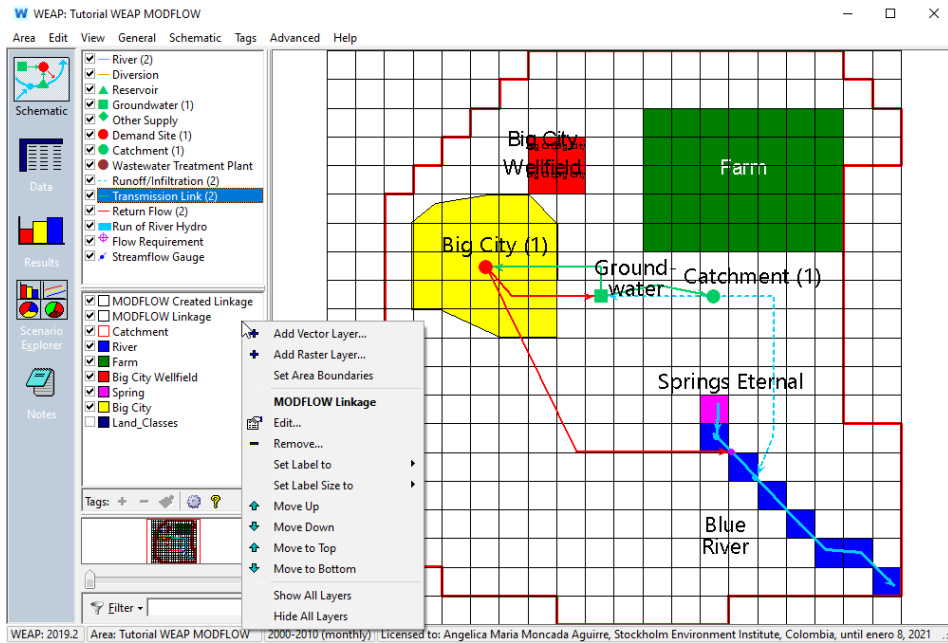
In this example, the water will come from outside the catchment area and not vary seasonally.

### 18. Create Scenario

*Switch to the Schematic View and create a new scenario underneath “Reference,” call it “Artificial Recharge”.*

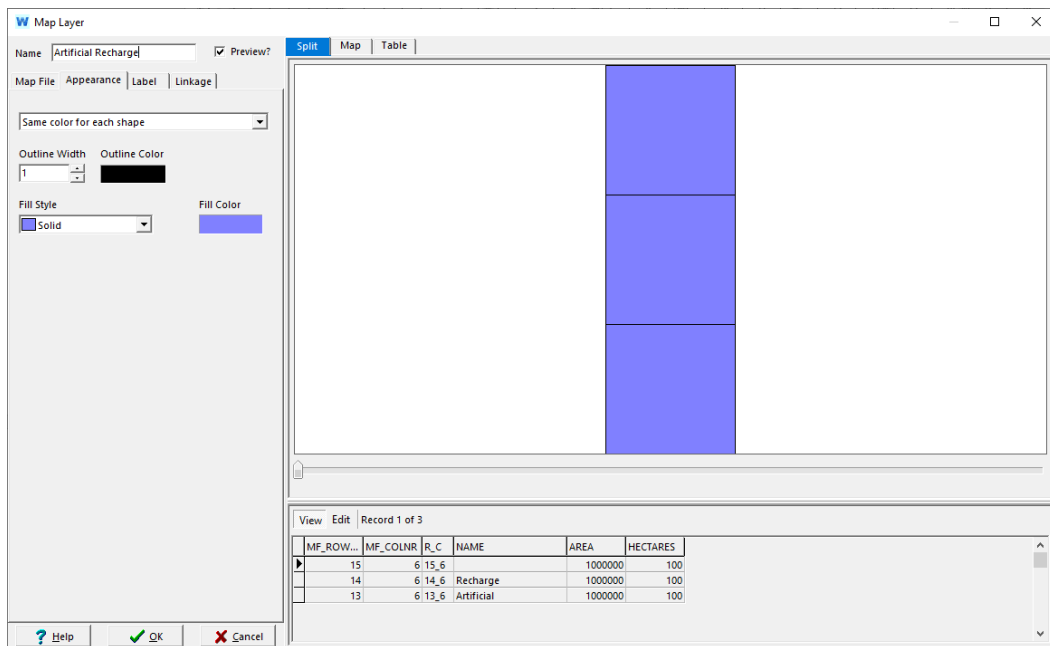
### 19. Load Shapefile Layer

*On the Main Menu, select Schematic, Add Vector Layer.*



Choose the file *artificial\_recharge.shp*. Give it the name “Artificial Recharge” and change its **appearance** so that the Style is “Solid” and the “Fill color” is light blue.

Note that the cells are in column 6, rows 13-15.



## 20. Edit Linkage Shapefile

So that WEAP can tell MODFLOW which cells will receive the artificial recharge, we need to edit the linkage shapefile.

*In the Schematic View, double-click on “MODFLOW Linkage”, select the Table tab and click the Edit button. Scroll down to find the artificial recharge cells: column 6, rows 13, 14 and 15. For these three cells, type into the field labeled DEMANDSITE the name of the artificial recharge demand site: “Artificial Recharge”. Click OK to save changes and return to the schematic view.*

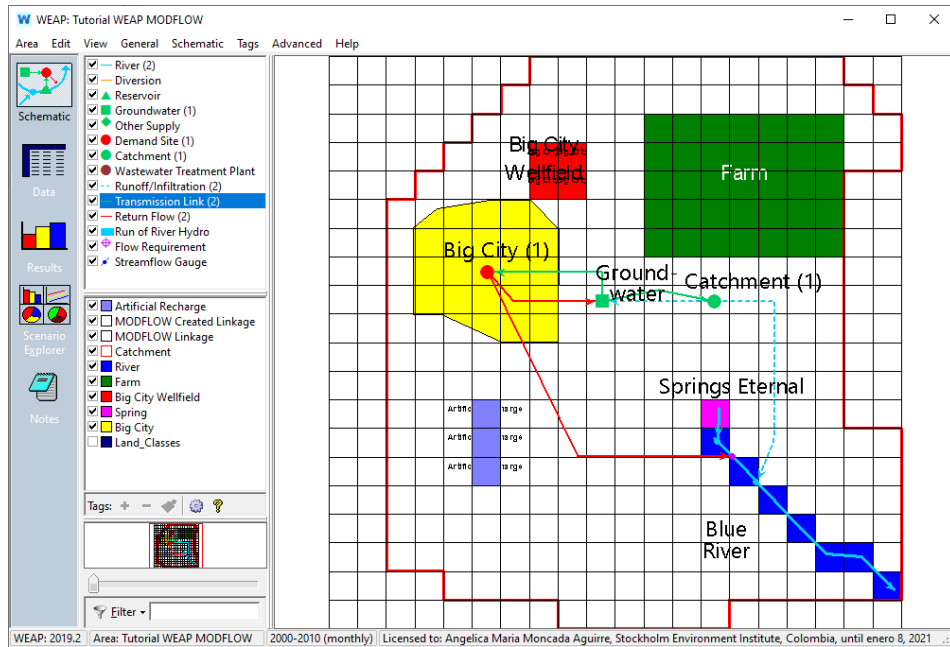
ROW	COLUMN	ROW_COLUMN	GW	CATCHMENT	LAND_USE	DEMANDSITE	RIVERREACH
15	6	15,6	A	Groundwater	Catchment	Grass	Artificial Recharge
15	7	15,7	A	Groundwater	Catchment	Grass	
15	8	15,8	A	Groundwater	Catchment	Grass	
15	9	15,9	A	Groundwater	Catchment	Grass	
15	10	15,10	A	Groundwater	Catchment	Grass	
15	11	15,11	A	Groundwater	Catchment	Grass	
15	12	15,12	A	Groundwater	Catchment	Forest	
15	13	15,13	A	Groundwater	Catchment	Forest	
15	14	15,14	A	Groundwater	Catchment	Forest	
15	15	15,15	A	Groundwater	Catchment	Forest	Blue River,Be
15	16	15,16	A	Groundwater	Catchment	Forest	
15	17	15,17	A	Groundwater	Catchment	Forest	
15	18	15,18	A	Groundwater	Catchment	Forest	
15	19	15,19	A	Groundwater	Catchment	Forest	
15	20	15,20	A	Groundwater	Catchment	Forest	
14		14,1					
14		2 14,2					
14	3	14,3	A	Groundwater	Catchment	Grass	
14	4	14,4	A	Groundwater	Catchment	Grass	
14	5	14,5	A	Groundwater	Catchment	Grass	Artificial Recharge
14	6	14,6	A	Groundwater	Catchment	Grass	
14	7	14,7	A	Groundwater	Catchment	Grass	
14	8	14,8	A	Groundwater	Catchment	Grass	
14	9	14,9	A	Groundwater	Catchment	Grass	
14	10	14,10	A	Groundwater	Catchment	Grass	
14	11	14,11	A	Groundwater	Catchment	Grass	
14	12	14,12	A	Groundwater	Catchment	Forest	
14	13	14,13	A	Groundwater	Catchment	Forest	
14	14	14,14	A	Groundwater	Catchment	Forest	Blue River,Be
14	15	14,15	A	Groundwater	Catchment	Forest	
14	16	14,16	A	Groundwater	Catchment	Forest	
14	17	14,17	A	Groundwater	Catchment	Forest	
14	18	14,18	A	Groundwater	Catchment	Forest	
14	19	14,19	A	Groundwater	Catchment	Forest	
14	20	14,20	A	Groundwater	Catchment	Forest	
13		13,1					
13		2 13,2					
13	3	13,3	A	Groundwater	Catchment	Grass	
13	4	13,4	A	Groundwater	Catchment	Grass	
13	5	13,5	A	Groundwater	Catchment	Grass	
13	6	13,6	A	Groundwater	Catchment	Grass	Artificial Recharge
13	7	13,7	A	Groundwater	Catchment	Grass	
13	8	13,8	A	Groundwater	Catchment	Grass	

Verify this new linkage information:

*Set the label for the MODFLOW Linkage layer to DEMANDSITE.*

You should see the artificial recharge cells labeled, and the Big City Wellfield:

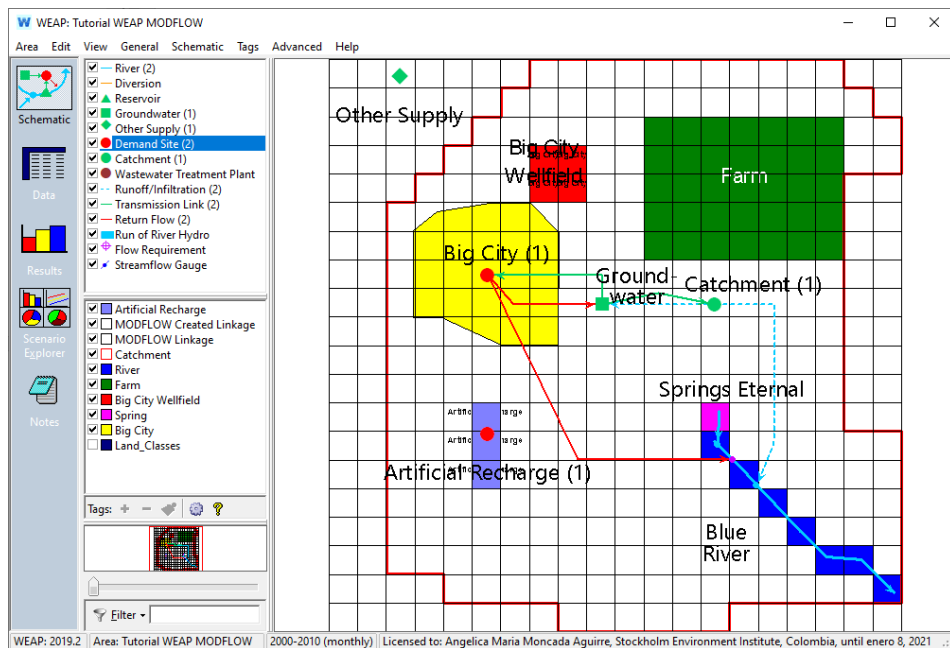




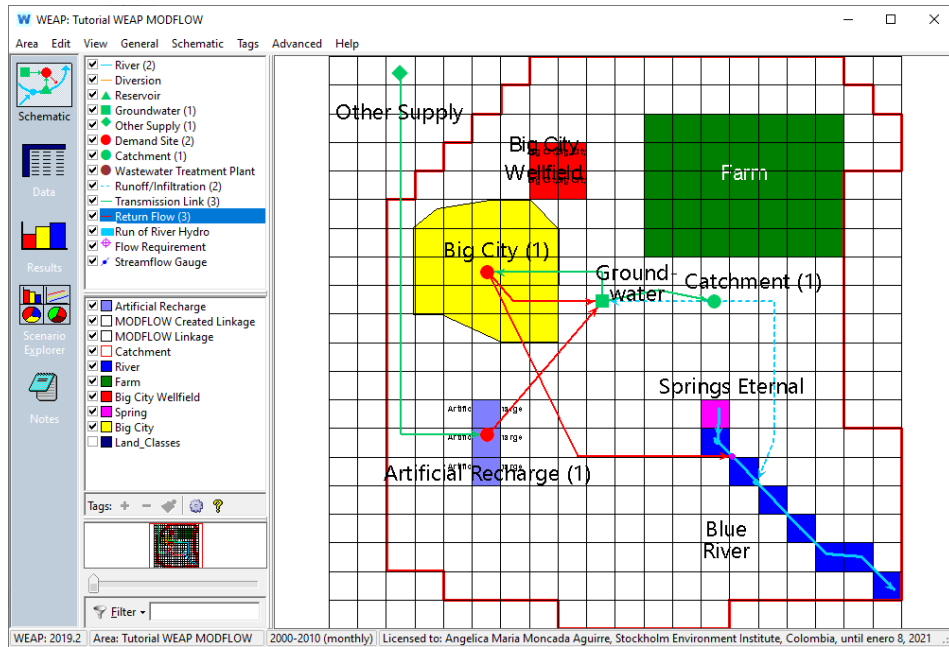
## 21. Create Other Supply and Demand Site

*Create an “other supply” node called “Other Supply” in the upper left corner.*

*Create a new demand site—place it on top of one of the blue artificial recharge cells. Call it “Artificial Recharge” and uncheck “Active in Current Accounts?”*

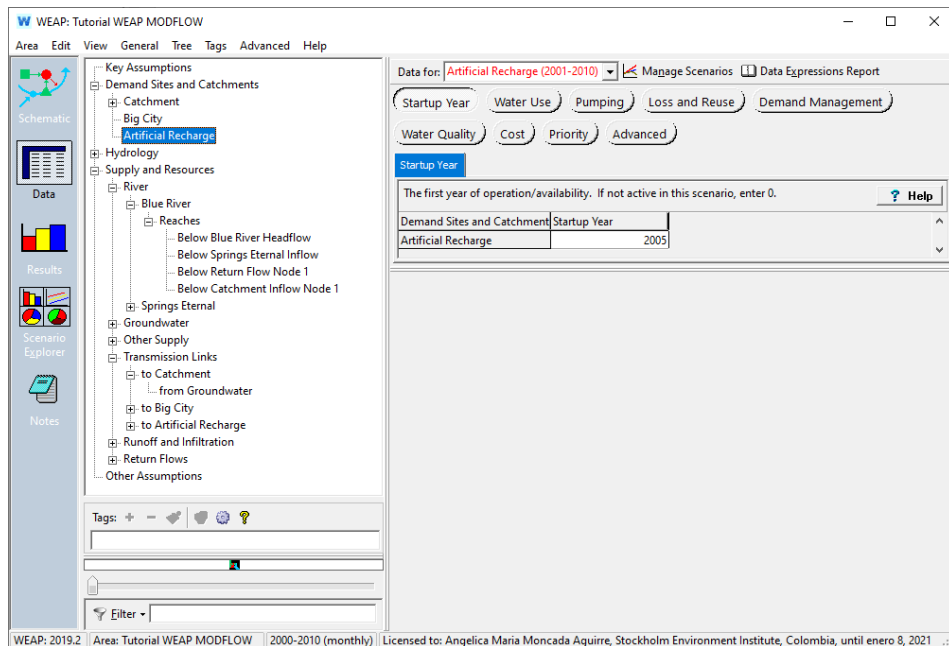


*Add a transmission link from Other Supply to Artificial Recharge. Then add a Return Flow link from Artificial Recharge to the Groundwater node.*

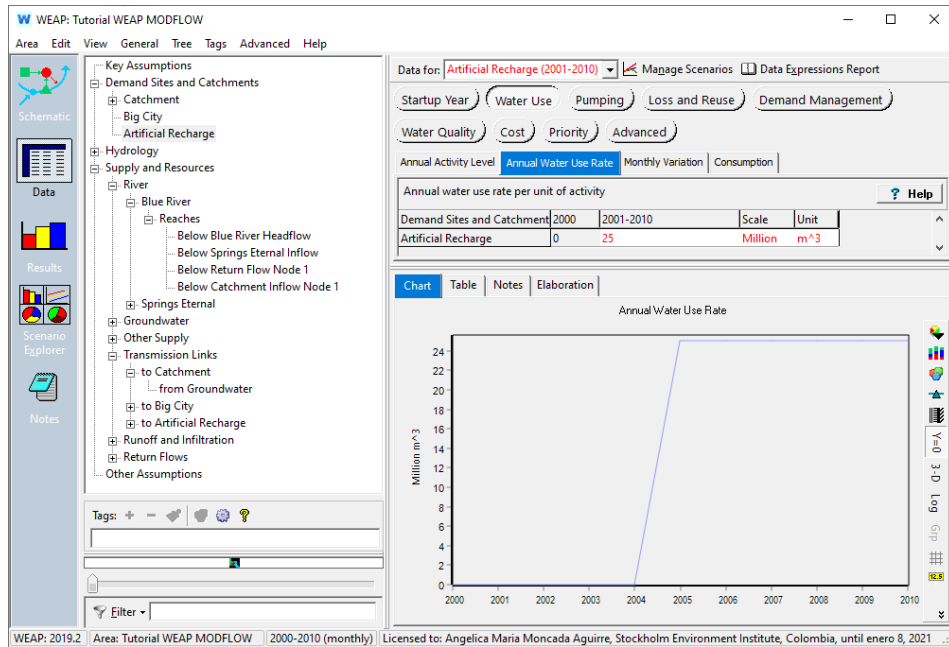


## 22. Enter Supply and Demand Data

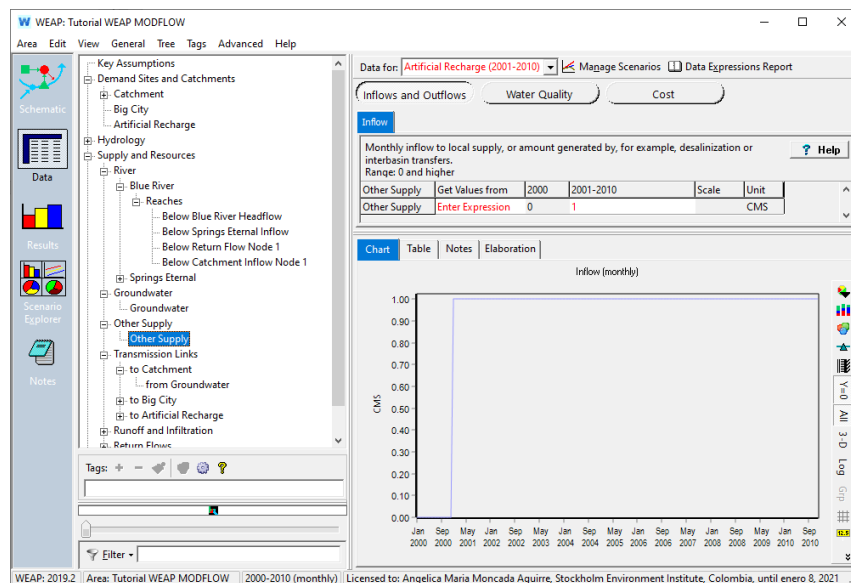
*Go to the Data View, select scenario “Artificial Recharge,” and then click on the branch for demand site Artificial Recharge in the tree. Set the Startup Year to 2005.*



*For Water Use, set the Annual Activity Level to 1 (Tip: First select “No Unit” as the Unit), Annual Water Use Rate to 25 Million cubic meters (the annual capacity of the injection wells), and the Consumption to 0%.*



*Click on the branch for the other supply, and then enter 1 CMS for the inflow.*

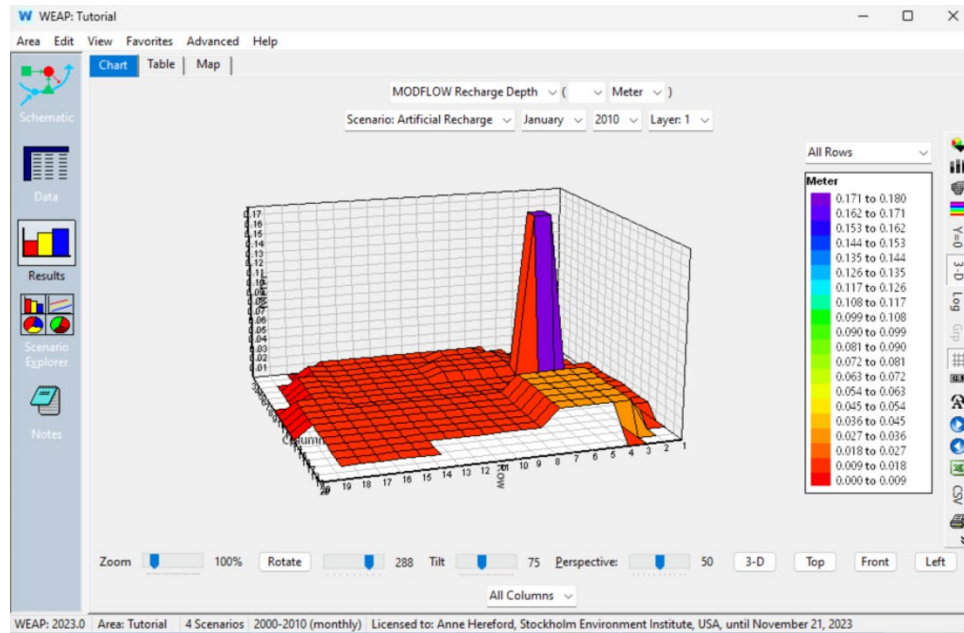


## 23. Evaluate Results

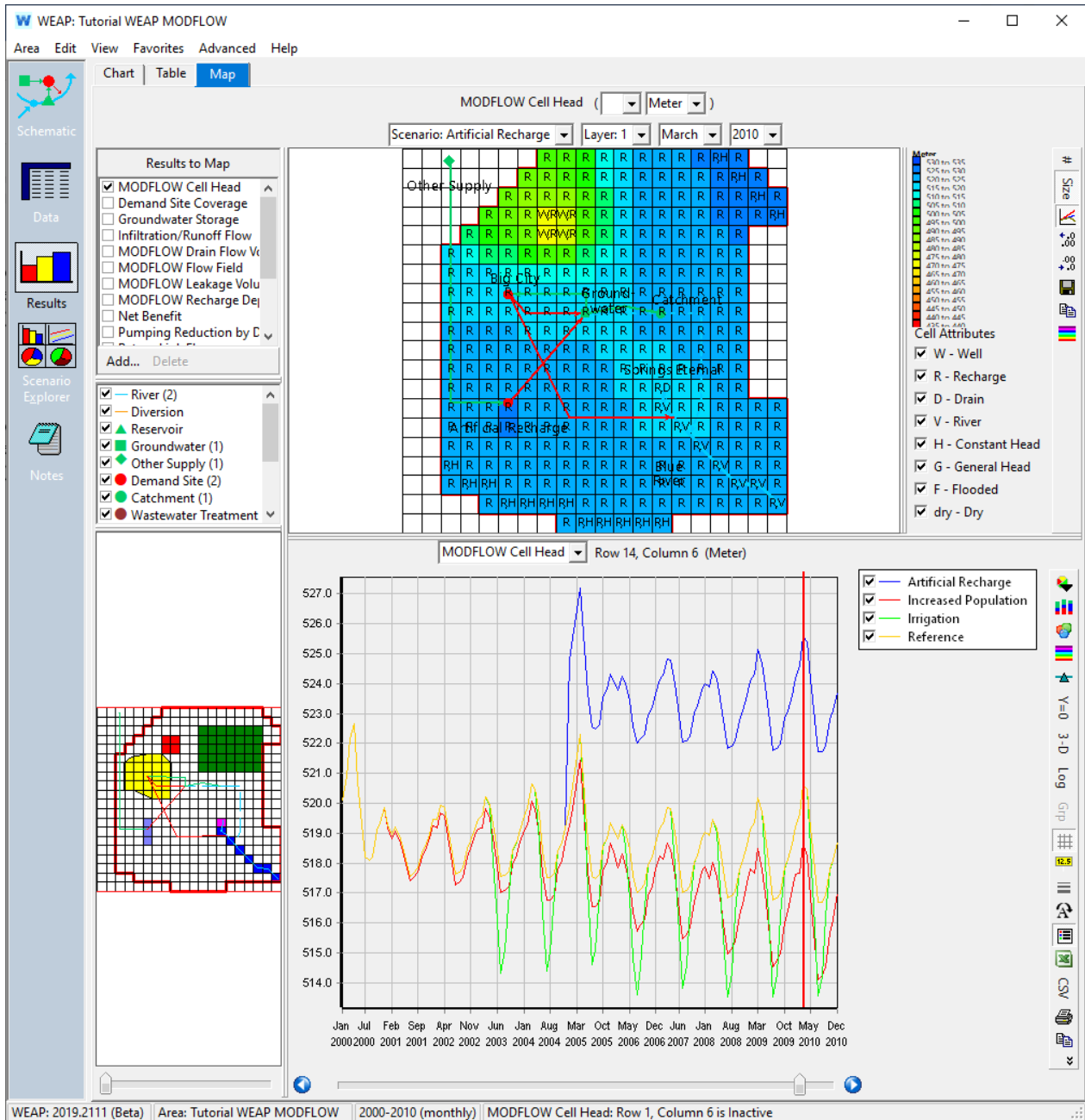
*Run the model and look at results for recharge depth and cell head.*

Make sure you have selected the following dropdown menu options: Meter, Scenario: Artificial Recharge, January, 2010, Layer: 1.

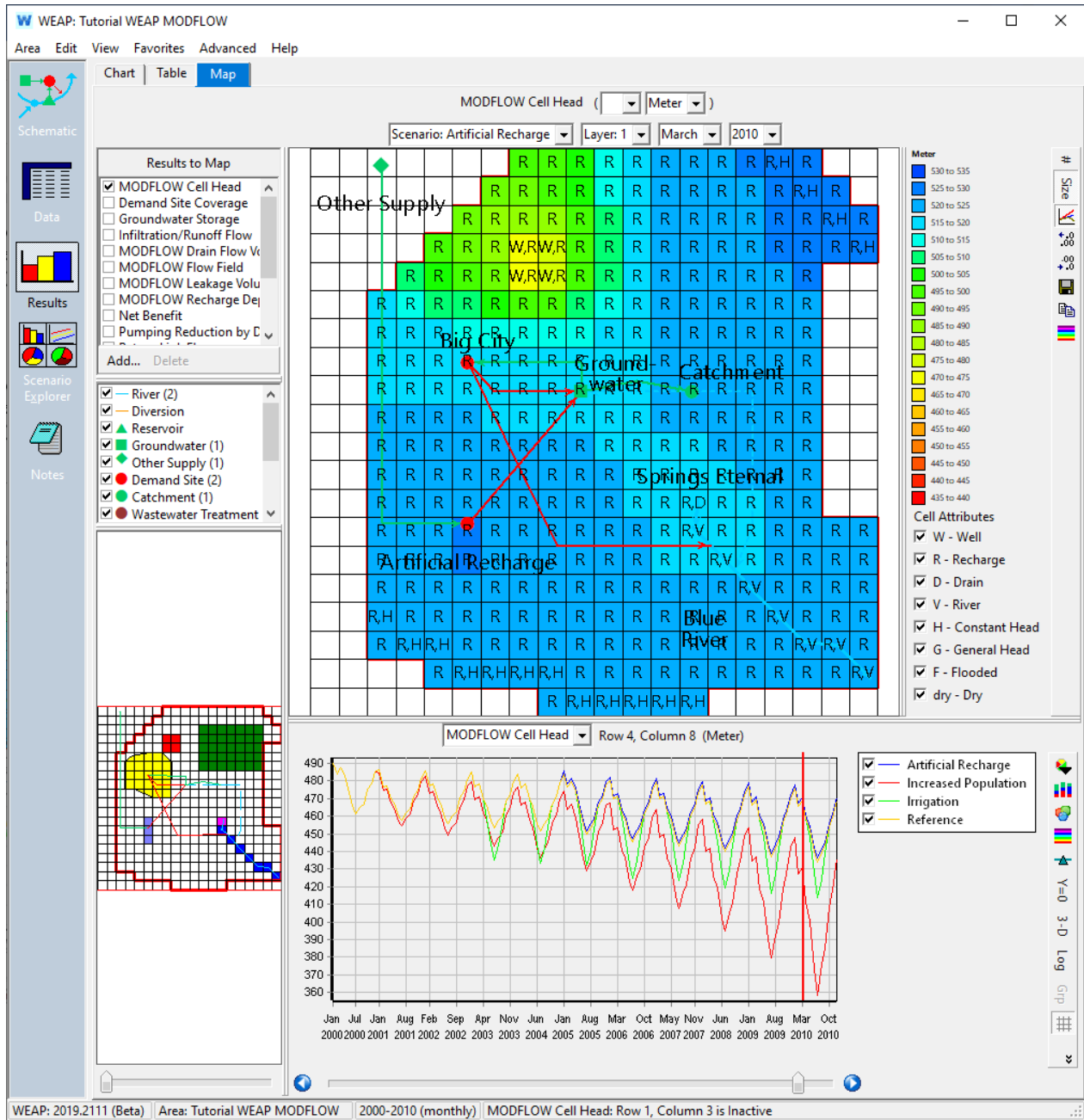
*Does the artificial recharge have much impact on groundwater levels at the recharge site? Is the impact greater closer to the Big City Wellfield or irrigation? Can you think of another site for the artificial recharge that would better alleviate the drawdown from pumping?*

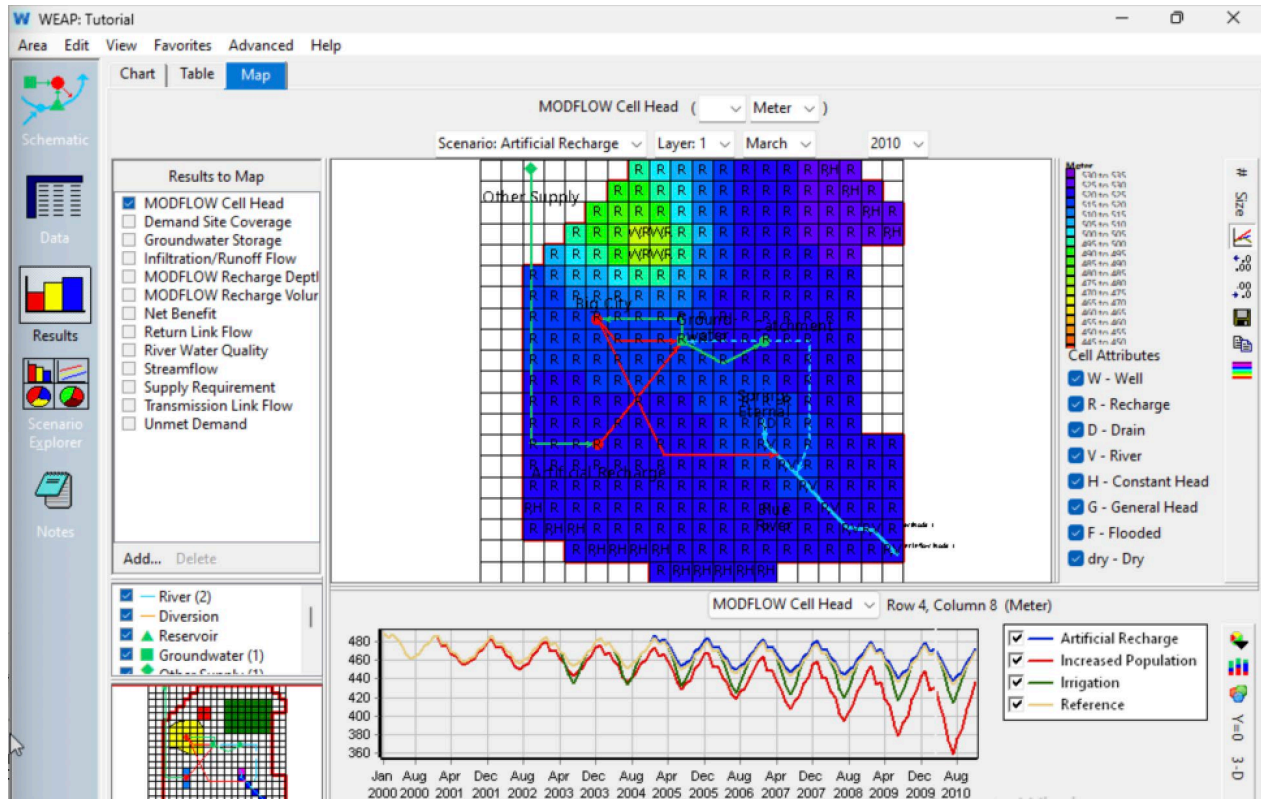


Groundwater levels at the recharge site are much higher than Reference (Select the following dropdown menu options: MODFLOW Cell Head, Meter, Scenario: Artificial Recharge, March, 2010, Layer: 1, Row 14, Column 6):



Groundwater levels by the Wellfield are almost the same as in Reference  
*(Click on the cell at Row 4, Column 8):*









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# WEAP

Water Evaluation And Planning System

# Linking WEAP to LEAP

## **A TUTORIAL ON**

*Linking WEAP and LEAP* .....354

*Scenario: Hydropower Generation from  
WEAP* .....359

*Scenario: Demand for Cooling Water from  
LEAP* .....370

*Scenario: Electricity Demand from WEAP*.....376

**October 2023**

**Note:**

For this module you will need to have completed the previous modules (“WEAP in One Hour, Basic Tools, and Scenarios) or have a fair knowledge of WEAP (data structure, Key Assumptions, Expression Builder, creating scenarios). To begin this module, go to the Main Menu, select “Revert to Version” and choose the version named “Starting Point for 'Linking WEAP to LEAP' module.”

## Linking WEAP and LEAP

### 1. Introduction to LEAP

LEAP, the Low Emissions Analysis Platform, is a widely-used software tool for energy policy analysis and climate change mitigation assessment developed at the Stockholm Environment Institute.

LEAP is an integrated modeling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. It can be used to account for both energy sector and non-energy sector greenhouse gas (GHG) emission sources and sinks. In addition to tracking GHGs, LEAP can also be used to analyze emissions of local and regional air pollutants, making it well-suited to studies of the climate co-benefits of local air pollution reduction.

For more information on LEAP and to download the software, visit <https://leap.sei.org>.

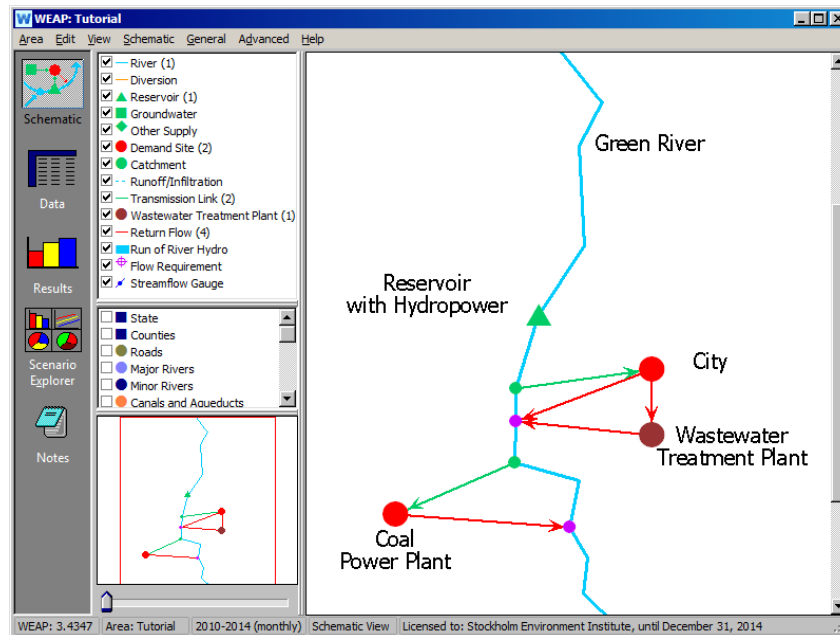
### 2. Coupled Water-Energy Models in WEAP and LEAP

We are going to examine a simple water-energy system; first the water side of the system using WEAP, then the energy side using LEAP. Then we will link the WEAP and LEAP models to examine the interaction between the two sides and see how this interaction influences the results we obtain.

### 3. WEAP Model

In the WEAP “Schematic” view there is a city situated near a river with its own wastewater treatment plant. A reservoir harnesses hydropower from the river. The demand for water comes from two sources: municipal demand from the city, and demand for thermal cooling from a coal power plant also

situated near the river. The municipal demand has the first demand priority (1) compared to the thermal cooling demand (2).



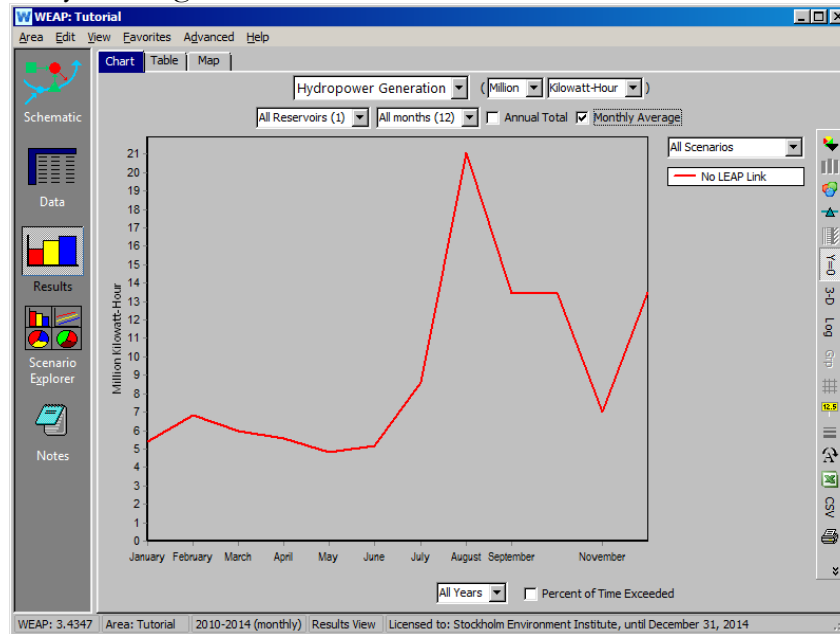
Already we can see links between the water and energy systems in this model. The reservoir and coal power plant utilize water to generate electricity. On the other hand, the wastewater treatment plant uses energy in its treatment process. Energy is also needed for processes like pumping for transmission.

## 4. View WEAP Results

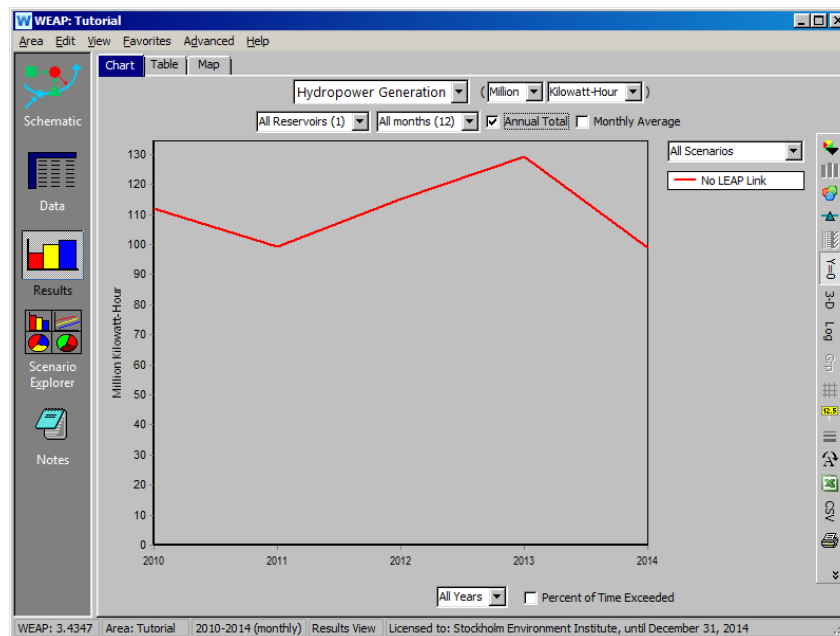
Switch to the “Results” view. Click the pull-down menu at the top left, select “Supply and Resources” > “Reservoir” > “Hydropower Generation.” This allows us to see the variation in hydropower generated by the reservoir over time. Change the unit to Kilowatt-Hour. Remember that you can change the chart type to a line or bar graph by clicking the “Chart Type” button on the right-hand side of the window.

You can also view the monthly average or the annual total hydropower generated by checking the corresponding box at the top of the window. From these options, we can see that hydropower generation peaks during the summer and varies from year to year.

### Monthly Average:



### Annual Total:

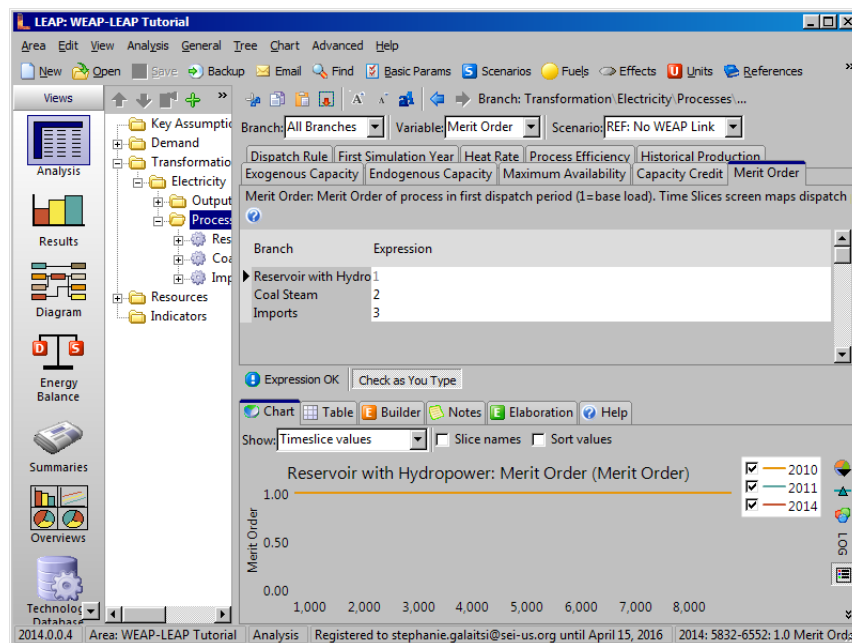


## 5. LEAP Model

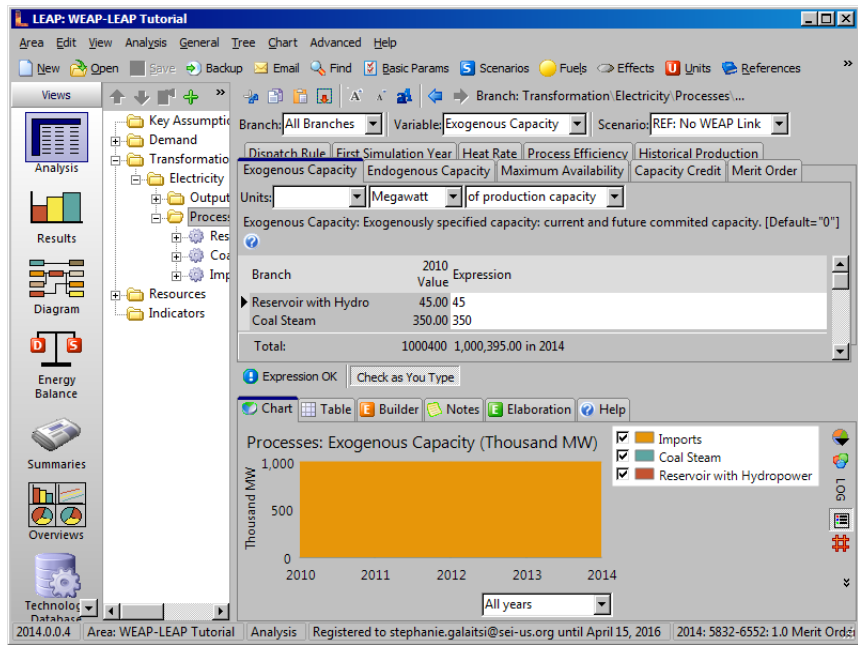
Now we will open the energy modeling program, LEAP, to see the current sources of energy for Big City. Under the Area Menu, open the WEAP-LEAP Tutorial and revert to version “Starting point for WEAP-LEAP Tutorial.”

Open the “Analysis” view in LEAP, which can be found on the left-hand side of the window. This is similar to the “Data” view in WEAP. In the “Scenario” pull-down window toward the top, make sure the “REF: No WEAP Link” scenario is selected.

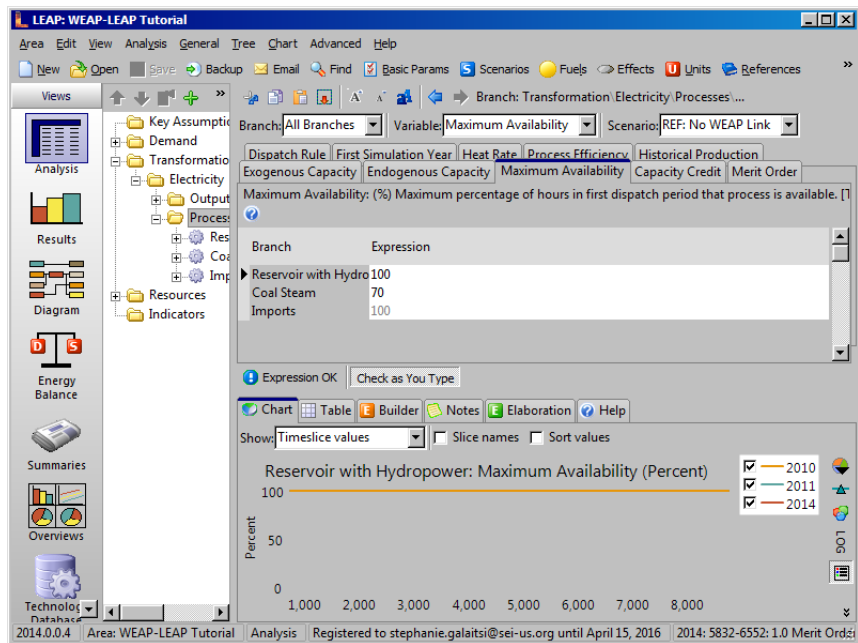
In the Data tree under “Transformation” > “Electricity” > “Processes,” there are three processes that generate electricity: hydropower from the reservoir, the coal steam power plant, and energy imports. If you select the “Merit Order” tab, you can see that hydropower is dispatched first, followed by energy from coal. Any remaining shortfalls are made up with imports, which is last in the merit order.



The energy production capacities for these plants are under the “Exogenous Capacity” tab.



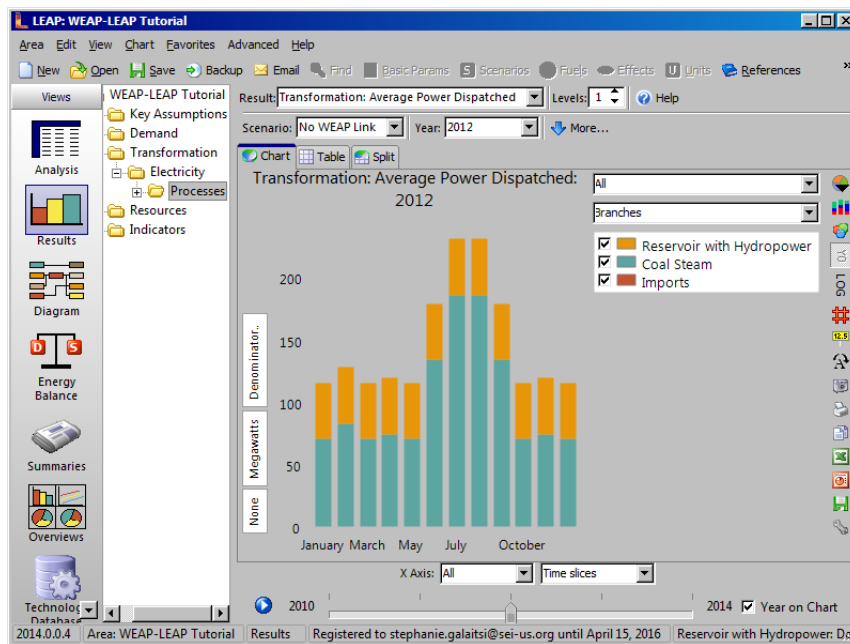
For each energy production process, the portion of maximum energy production that is available can be found under the “Maximum Availability” tab. In the “No WEAP Link” scenario, the maximum availability of the hydropower plant has been entered as 100%. LEAP is assuming that all water demand for hydropower will be met, as it has no information on the amount of water available for hydropower generation.



## 6. View LEAP Results

Switch to the “Results” view, found under the “Analysis” button on the left-hand side of the window. From the top pull-down window, select the variable “Transformation: Average Power Dispatched.”

In 2014 (selected from the right dropdown menu or the bottom scroll bar), almost a third of all electricity produced comes from hydropower, running at its full rated capacity of 45 MW. This is unrealistic if there is insufficient water to satisfy the demand for electricity.

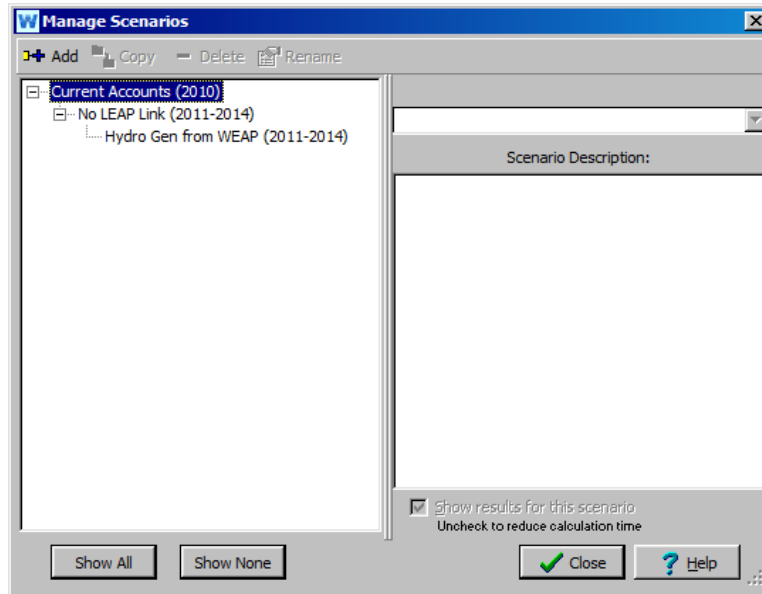


## Scenario: Hydropower Generation from WEAP

In order to have a more realistic representation of hydropower, we will now link LEAP to WEAP, so that LEAP can read the hydropower results calculated by WEAP. In this way, LEAP can determine how much electricity could, in reality, be generated from hydropower.

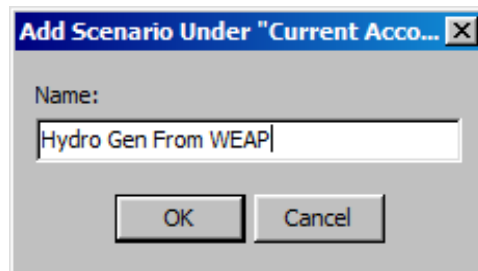
## 7. Create Scenario in WEAP

In WEAP, choose the menu item Area, Manage Scenarios to create a new scenario under the “No LEAP Link” scenario, and name it “Hydro Gen from WEAP.”

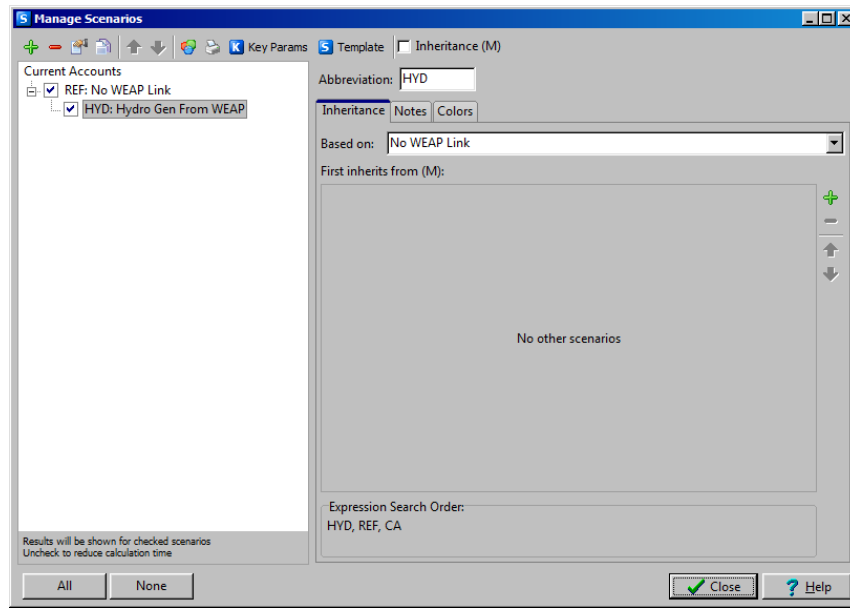


## 8. Create Scenario in LEAP

In LEAP, return to the Analysis View and click the “Scenarios” button (with a blue S icon) toward the top of the window. Add a scenario by clicking the green plus button in the upper left corner, and name the scenario “Hydro Gen from WEAP.” In the “Based on” pull-down window under the Inheritance tab, select “No WEAP Link.” This will ensure that the new scenario inherits the characteristics of the “No WEAP Link” scenario. Close the window.



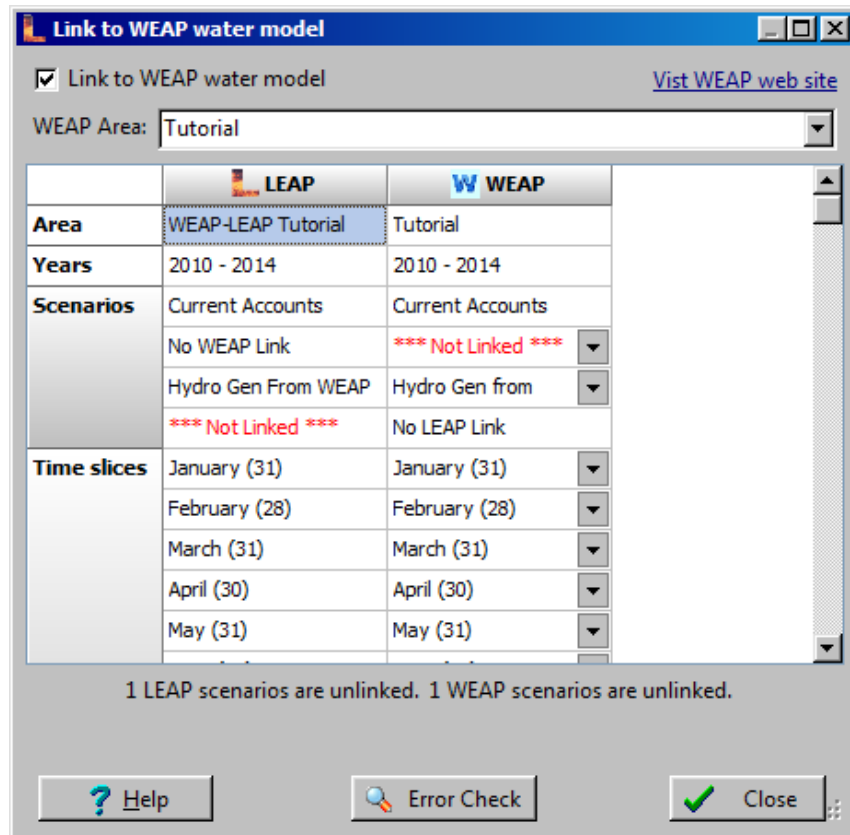




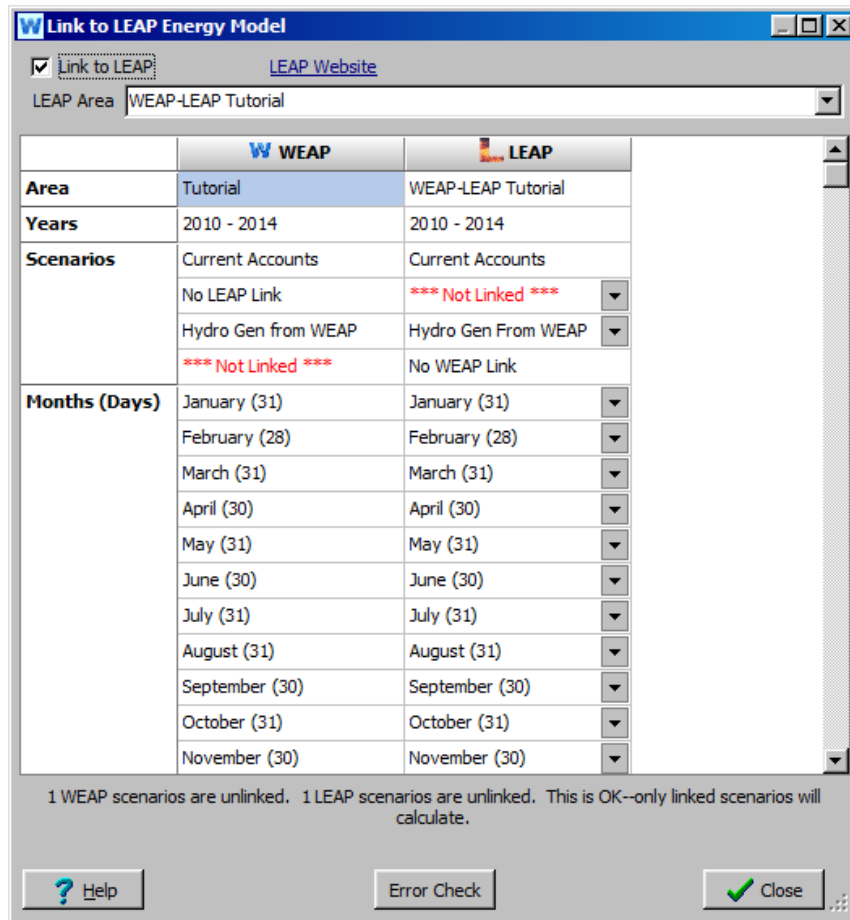
## 9. Linking WEAP and LEAP

In LEAP, go to the Analysis View and then, under the Advanced menu, select “Link to WEAP Water Model.” The window that pops up is the link manager. After checking the box in this window, you associate the LEAP area with the correct WEAP area. It is also where you match LEAP and WEAP scenarios and time steps.

Check the “Link to WEAP water model” box at the top. Where it says *<Select a WEAP Area >*, choose “Tutorial.” When first linked, LEAP or WEAP will attempt to match up the scenarios and timesteps from the two models if they have the same name. The timesteps should all be automatically matched, as well as the “Hydro Gen from WEAP” scenarios. The “No WEAP Link” and “No LEAP Link” scenarios will not link (their names are different), but this is correct—those two scenarios are not linked. You can click the Error Check button to double-check for any errors. Then, close the window.



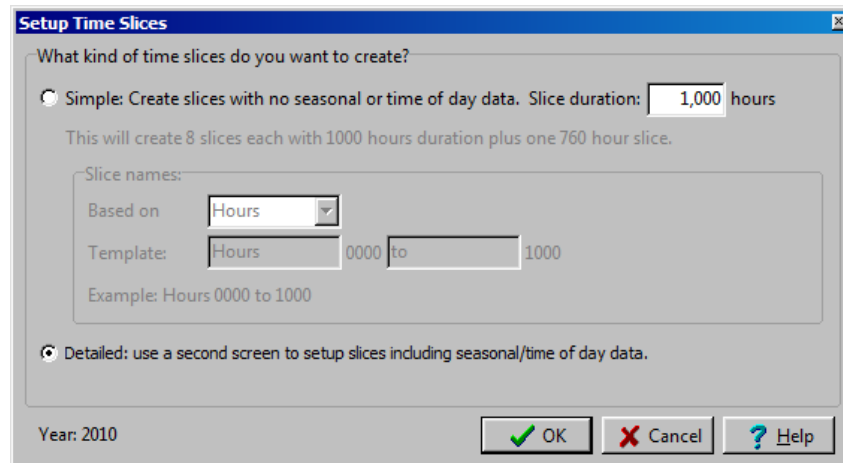
Now we shall follow the same steps for WEAP. In WEAP, under the Advanced menu, select “Link to LEAP Energy Model.” A window just like the LEAP link manager should pop up. Check the “Link to LEAP” box, and verify that the LEAP Area, scenarios and timesteps are linked correctly. Close the window.



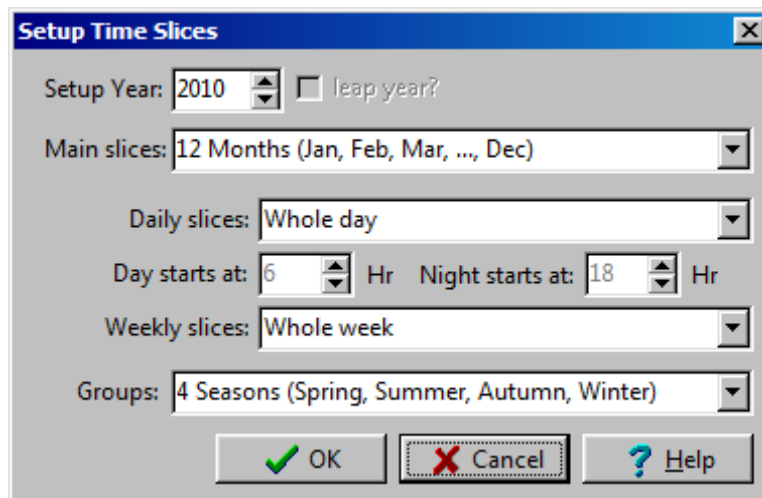
## 10. Time Slices

In this example, the LEAP timeslices have already been set to monthly. But when you create your own LEAP area, you will need to setup the timeslices to match those in the WEAP area to be linked (typically, monthly). In the LEAP Analysis view, go to the “General” menu at the top of the window and select “Time Slices.” If this had been a new area, the default would be 8 seasonal day and night time slices. To change this, click “Setup.”

In the “Setup Time Slices” window that appears, choose “Detailed” and then OK.



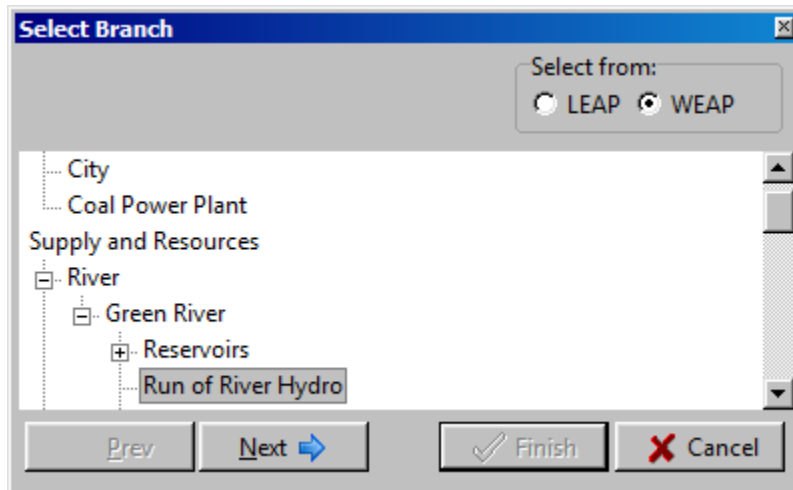
Change “Main slices” to “12 Months.” Make sure “Daily slices” is “Whole day” and “Weekly slices” is “Whole week.” To save these settings, click OK. However, because the time slices are already monthly, you can just click Cancel.



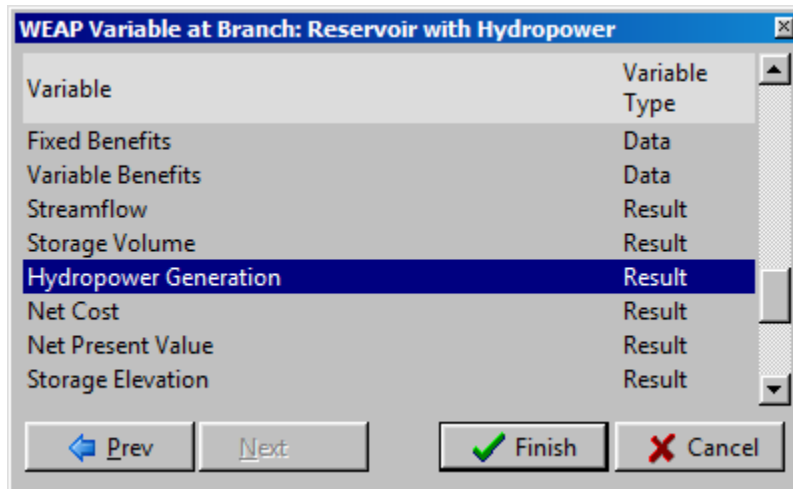
## 11. Reading WEAP Result into LEAP

In the LEAP “Analysis” view, open the Data tree to “Transformation”>“Electricity”>“Processes.” Making sure that the new “Hydro Gen From WEAP” scenario is selected, choose the “Maximum Availability” tab. Select the Reservoir with Hydro branch and click on the Expression Builder tab (shown with an orange E) further down on the screen.

Use the “Branch/Variable” button below the Expressions Builder tab to enter branches from WEAP:



Choose the “Reservoir with Hydropower” branch and click Next.

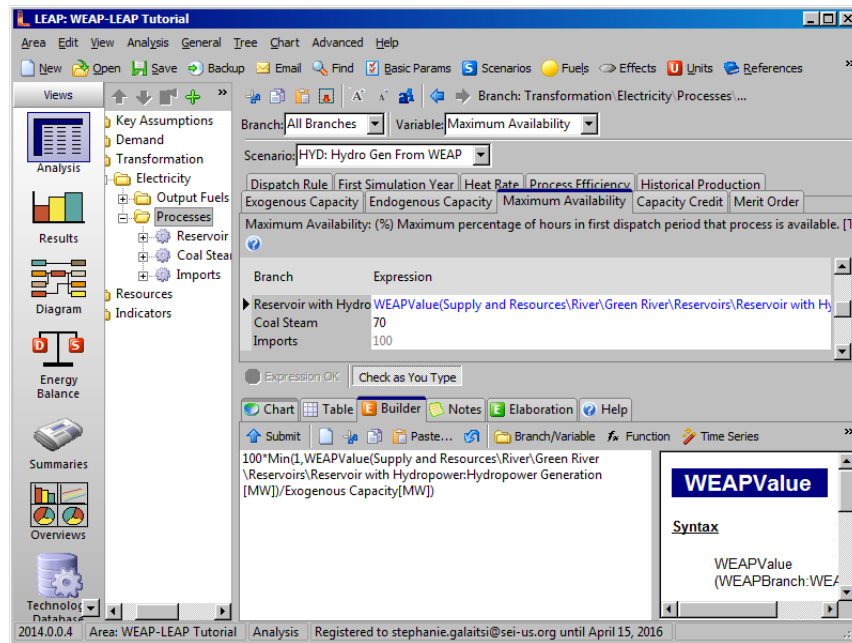


Select the “Hydropower Generation” result variable (you may need to scroll down) and click Finish. You might need to change the unit of “Hydropower Generation” from GJ to MW by specifying in the expression, as shown below.

Fill in the rest of the expression: put  $100 * \text{Min}(1,$  before the `WEAPValue` function and  $)/ \text{Exogenous Capacity}[\text{MW}]$ ) after it. The completed expression should be:

$$100 * \text{Min}(1, \text{WEAPValue}(\text{Supply and Resources} \backslash \text{River} \backslash \text{Green River} \backslash \text{Reservoirs} \backslash \text{Reservoir with Hydropower:Hydropower Generation}[\text{MW}]) / \text{Exogenous Capacity}[\text{MW}])$$

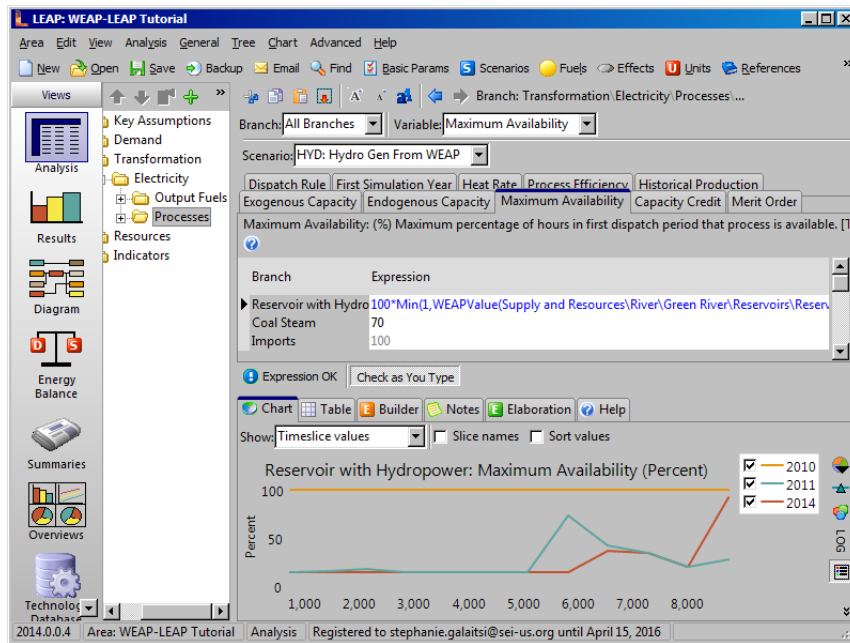
Click the “Submit” button at the top left corner of the Expression Builder.



*Note that you can also type this in. Spaces in names must be included for WEAP and LEAP to recognize the expression.*

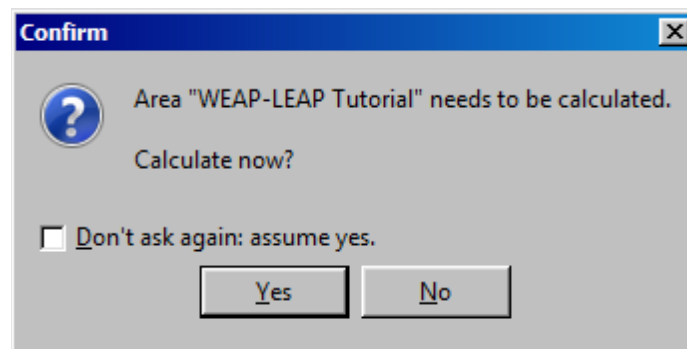
The WEAPValue function tells LEAP to look at data or results calculated by WEAP.

Run results in both WEAP and LEAP and then return to this Reservoir with Hydropower equation. The graph in the Chart tab below the expressions shows that the hydropower maximum availability in 2011 and 2014, as calculated by WEAP, is actually much lower than 100%. This restricts the amount of electricity LEAP can dispatch from hydropower.



## 12. View LEAP Results

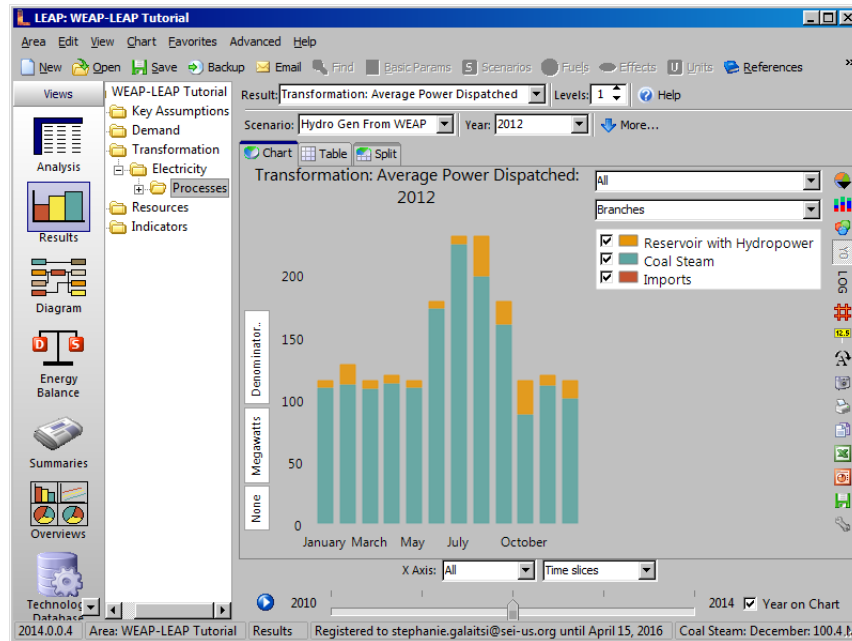
To see how hydropower results from WEAP affects the LEAP electricity dispatch, switch to the “Results” view. Now that WEAP and LEAP are linked and depend upon each other’s results, they will each need to make sure that the other’s results are up to date. In the LEAP confirmation dialog to run calculations, it notes that WEAP also needs to calculate and gives you the option to do that too.



In this initial version of the linked WEAP-LEAP modeling system, the flow of calculations is not fully automatic. In models which have links in both directions, the user is responsible for running the models several times until the system converges, or recognizing the cases where the results diverge or oscillate between two or more different states. We hope to automate this process in future versions.

Note: Your results for this tutorial may not exactly match those shown here, depending on how many times you iterate the calculations in LEAP and WEAP.

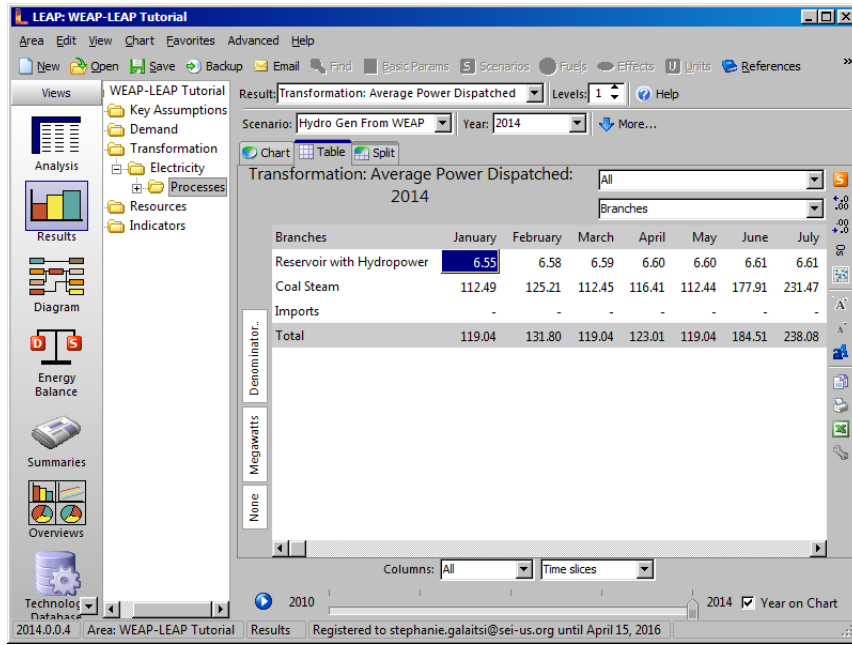
Select the “Transformation: Average Power Dispatched” variable from the pull-down window under the Chart tab. Select the “Hydro Gen from WEAP” scenario from the “Scenario” pull-down window under that. Using the pull-down windows at the right and bottom of the window, select “All Branches” for the vertical axis of the chart, and “All Time Slices” for the horizontal axis.



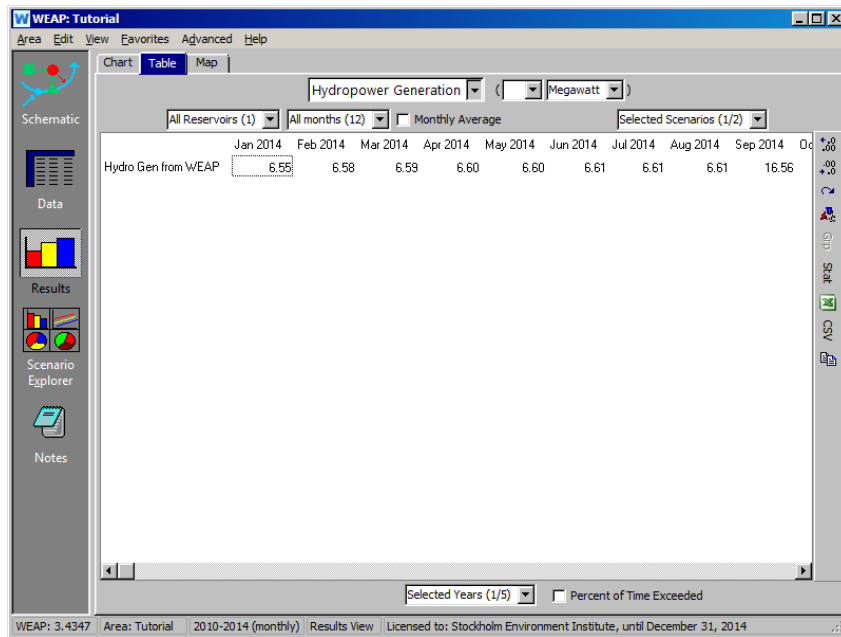
As we can see from the chart, there is much less hydropower and much more coal steam in this scenario due to the restriction given by WEAP.

We can verify that the outputs generated by WEAP indeed match the inputs to LEAP. Switching to the Table tab in the LEAP “Results” view, note that for January 2014, the amount of hydropower generated by the reservoir is 6.55 MW. Note that you may have to change the decimal display by clicking the button on the right. The units can be changed by clicking the vertical Megawatts tab on the left.





In WEAP, under the Table tab of the “Results” view, the value for January 2014 is also 6.55 MW (make sure the units displayed are MW by using the dropdown menu in the upper right).



## Scenario: Demand for Cooling Water from LEAP

As mentioned before, the coal power plant downstream from the city uses cooling water in its electricity generation process. The demand for water from the coal plant is determined by how much electricity it generates in LEAP.

### 13. Create Scenario

Create a new scenario in both WEAP and LEAP named “Cooling Water Demand from LEAP.” The new scenario should inherit the properties of the “Hydro Gen from WEAP” scenario. Check the link manager to ensure that these new scenarios are linked to each other (“Advanced”>“Link to WEAP” or “Link to LEAP” depending on whether you are in LEAP or WEAP).

### 14. Enter Water Use in WEAP

In the WEAP “Data” view, go to the Key Assumption for Cooling Water Requirements per MWH \ Coal Steam on the Data tree, and enter 25000 gal (make sure the “Cooling Water Demand from LEAP” scenario is selected):

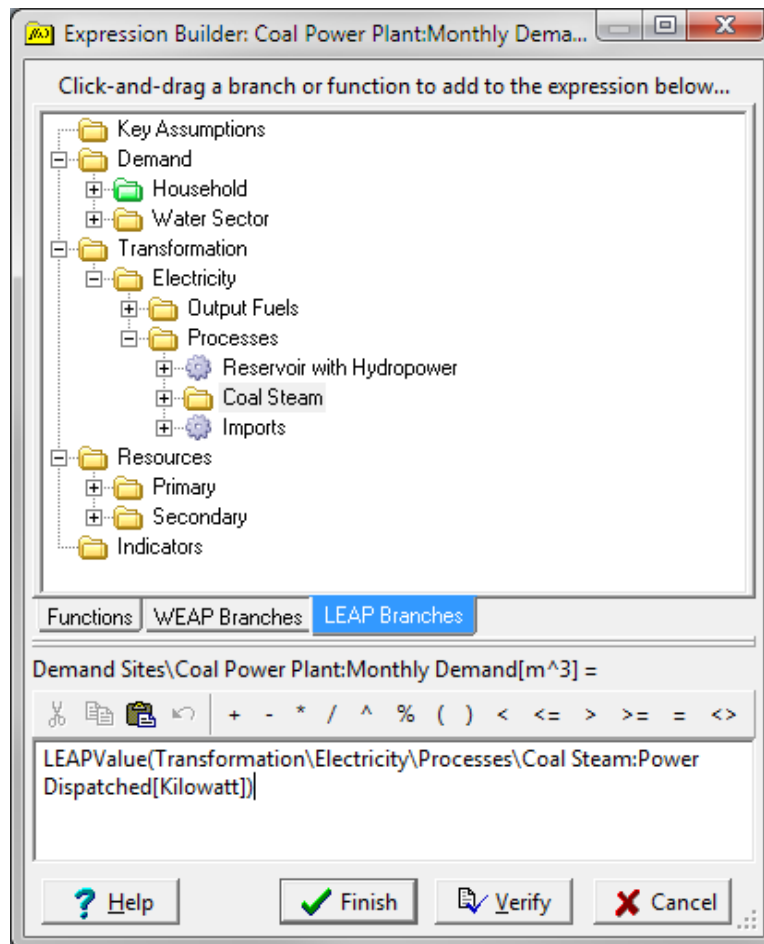
The screenshot shows the WEAP Tutorial software interface. The 'Data' view is active, displaying the 'Key Assumptions' table for the scenario 'Cooling Water Demand from LEAP (2011-2014)'. The table has columns for 'Key Assumption', '2010', '2011-2014', 'Scale', and 'Unit'. The row for 'Cooling Water Requirements per MWH \ Coal Steam' shows a value of 25000 in the '2011-2014' column and 'gal' in the 'Unit' column. Below the table is a chart titled 'Key Assumptions (monthly)' showing a constant value of 25000 gal from 2010 to 2014. The interface also shows a 'Schematic' view on the left and a 'Data Tree' on the right.

Key Assumption	2010	2011-2014	Scale	Unit
Cooling Water Requirements per MWH \ Coal Steam	0	25000		gal

Select Demand Sites \ Coal Power Plant on the tree. On the “Monthly Demand” tab under “Water Use,” enter the following LEAP function:

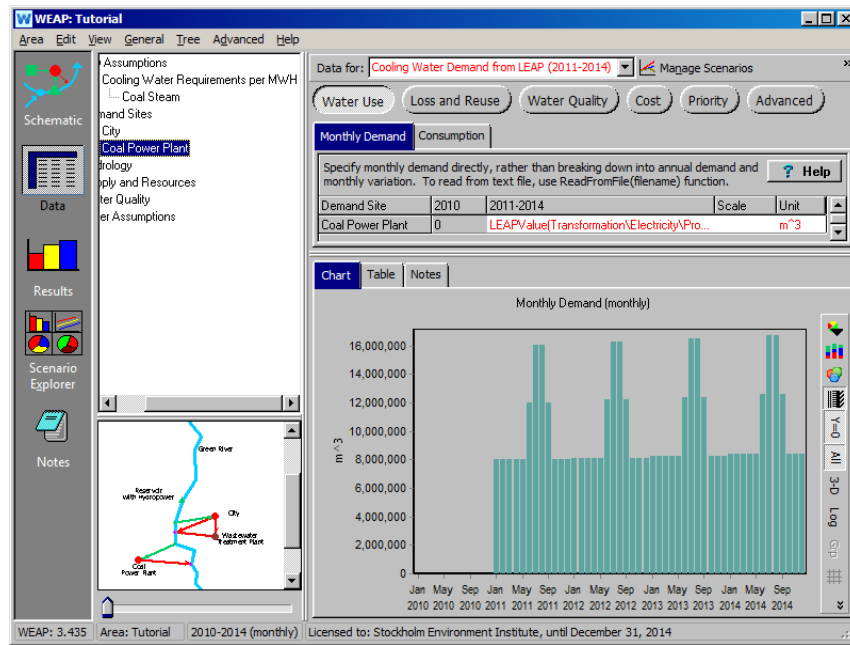
$$LEAPValue(Transformation\Electricity\Processes\Coal\Steam:Average\Power\Dispatched[MW]) * Days * 24 * Key\Cooling\Water\Requirements\per\ MWH\Coal\Steam[m^3]$$
**Note:**

You may use the “LEAP Branches” tab on WEAP’s Expression Builder to help build the LEAPValue part of the expression. If you do, you will need to change the unit from Kilowatt to MW:



Multiplying by  $Days * 24$  converts power (MW) to energy (Megawatt-hours); multiplying by the water requirement per MWH gives the volume of water needed by the coal power plant to function.

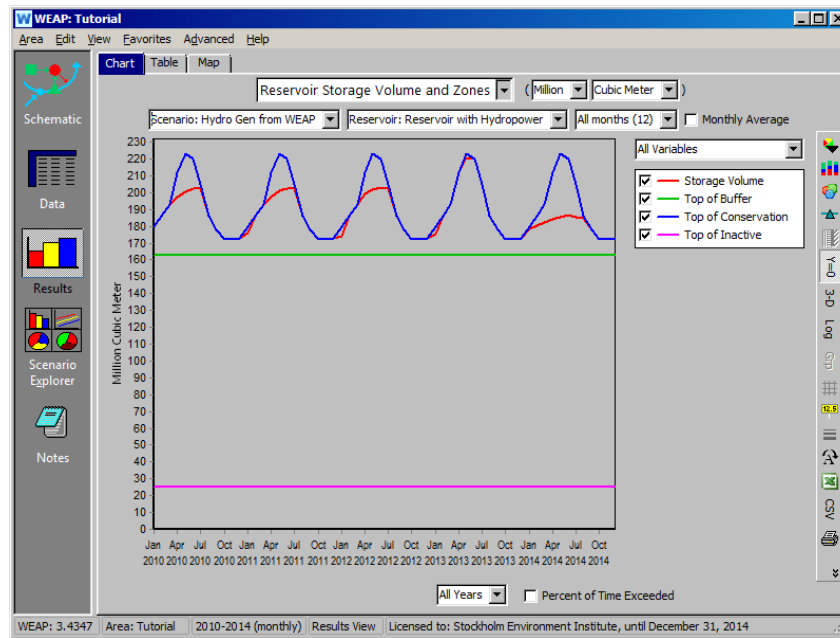
The chart shows the variation in cooling water demand, depending on how much electricity is generated by the coal power plant.



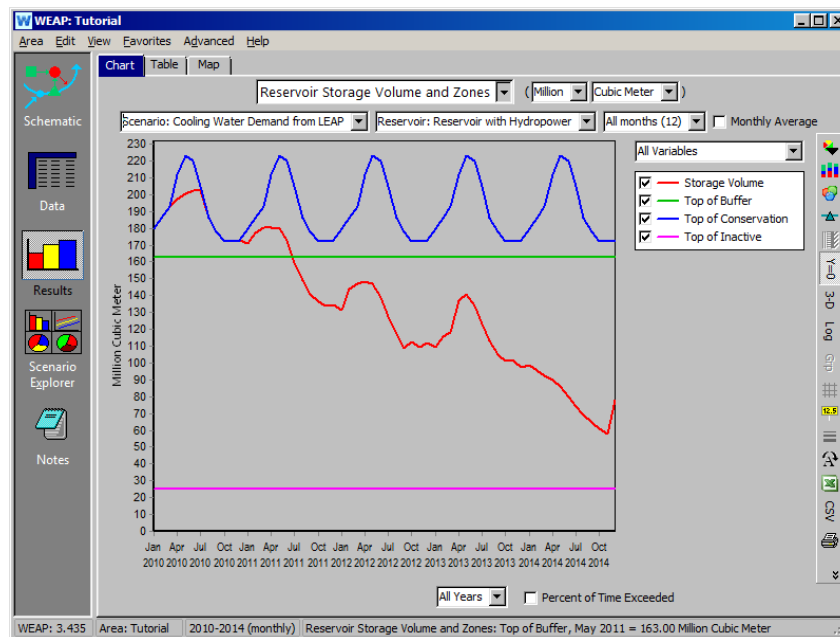
Note: If LEAP has not yet calculated this scenario, you will not see any results here.

## 15. View WEAP Results

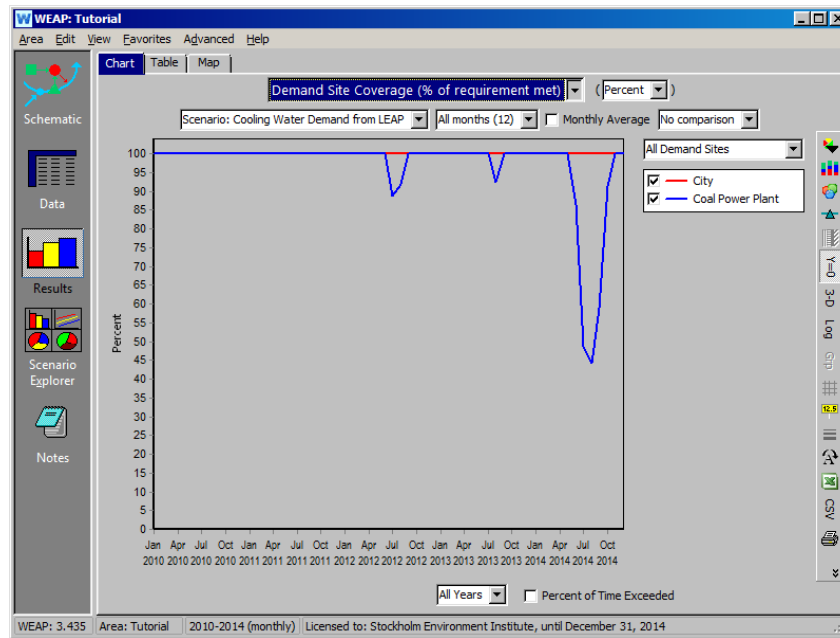
In the “Results” view, select the “Reservoir Storage Volume and Zones” variable in the top pull-down window (“Supply and Resources”>“Reservoir”>“Storage Volume and Zones”). The graph shows the storage volume (red) against the different reservoir zones. Look at it first for Hydro Gen from WEAP for all years.



Change the scenario to “Cooling water demand from WEAP.” Now we can see that the reservoir level dropping lower over time due to the new demand for cooling water.



If we view the “Demand Site Coverage” variable (Demand>Coverage), we observe that demand coverage for the coal plant is less than 100% in several month. This means that there is not enough water to satisfy the coal plant’s demand.



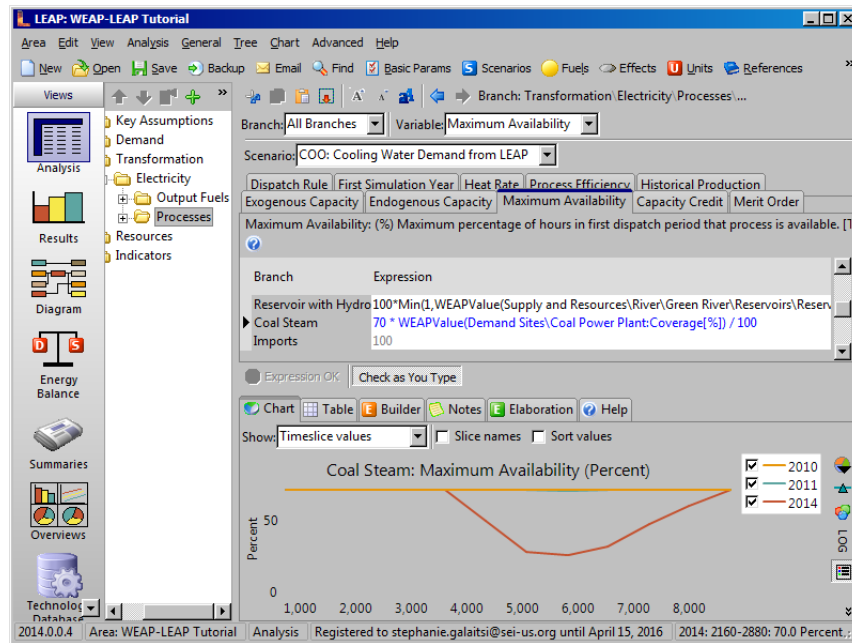
[Results vary]

## 16. Enter WEAP Expression in LEAP

We will now see how this WEAP restriction affects the results in LEAP. Go to the LEAP “Analysis” view and select the “Cooling Water Demand from LEAP” scenario from the pull-down window. Under the “Maximum Availability” tab, enter the following WEAP input expression for the Coal Steam branch:

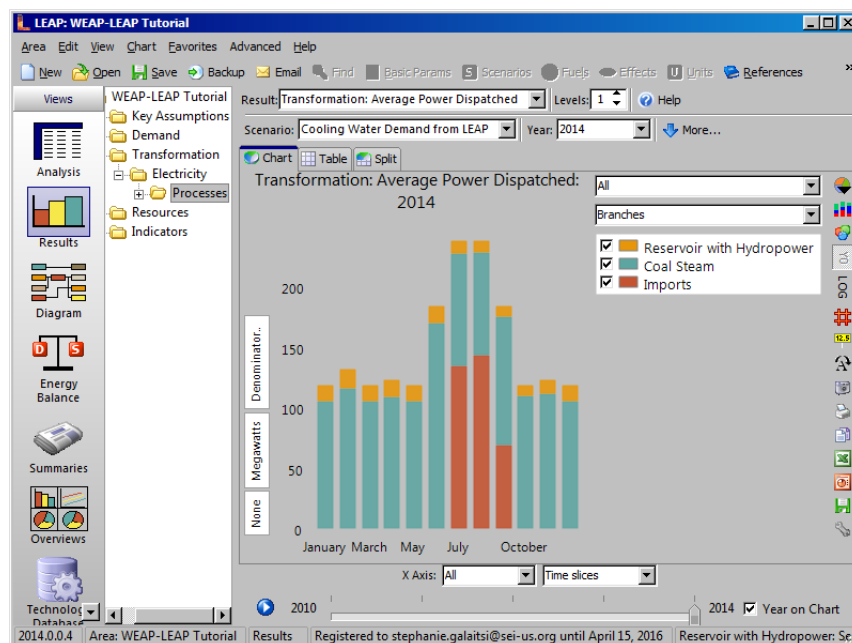
$$70 * WEAPValue(Demand Sites\Coal Power Plant:Coverage[ \% ]) / 100$$

This is the demand coverage for the coal power plant. The chart shows that, in months where the coverage is below 100%, the maximum availability will be less than 70%.



## 17. View Results in LEAP

Switching to the “Results” view, select the “Cooling Water Demand from LEAP” scenario. In 2014, there is insufficient water to satisfy the cooling water demand, which reduces the generating capacity of the coal plant. We can see that at times, imports (in red) are now required to make up for the lack in coverage by hydropower and coal steam.



## Scenario: Electricity Demand from WEAP

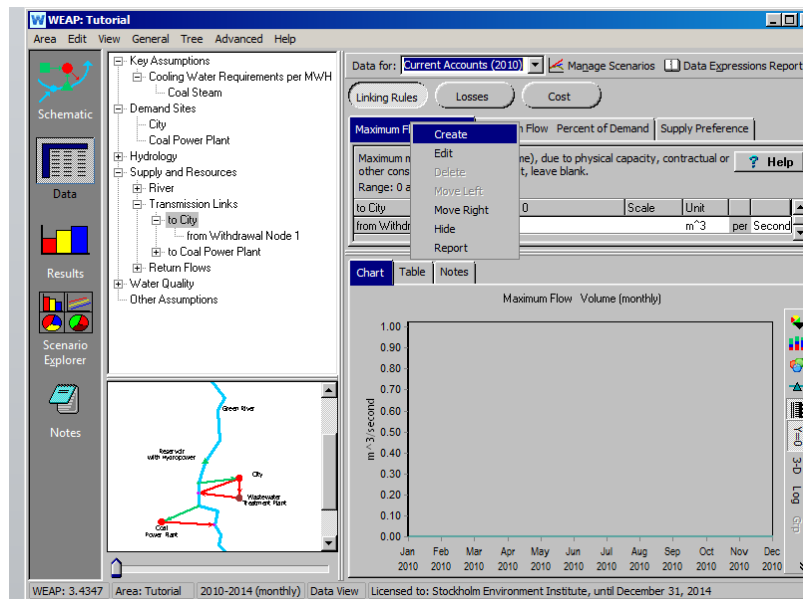
The water sector uses electricity to treat, pump and transmit water. Depending on how much water is used and treated, the demand for electricity changes accordingly.

### 18. Create Scenario in WEAP

In WEAP, create a new scenario called “Electricity Demand from WEAP,” inheriting the characteristics of the “Cooling water demand from LEAP” scenario. Here we are going to focus on two demands for electricity by the water sector.

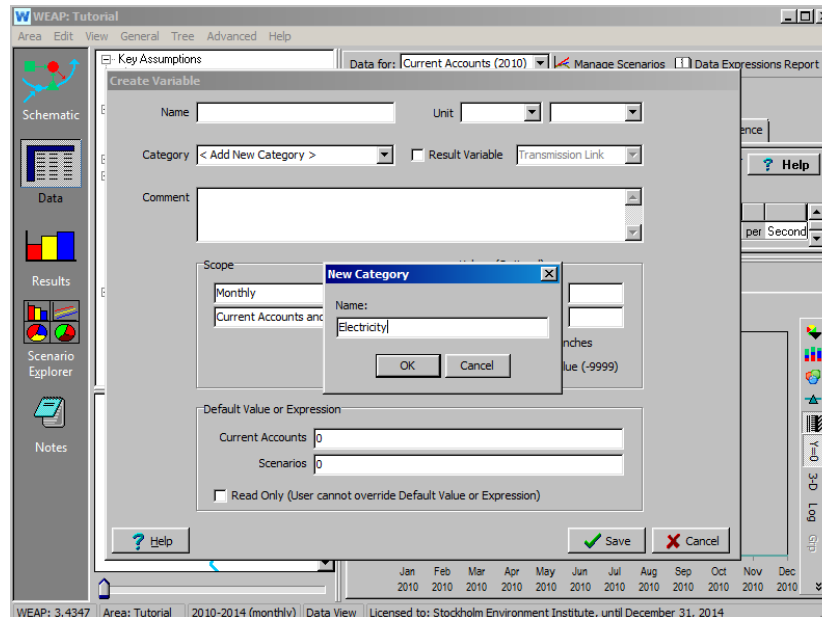
The first is the transmission link from the river to the city. In the Data tree, open “Supply and Resources,” “Transmission Links” and “to City.”

You will create two new user-defined variables, “Electricity per Cubic Meter” and “Total Electricity,” to model electricity used by water pumping and treatment. Right click on an existing variable tab (e.g., Maximum Flow Volume) and choose “Create.”



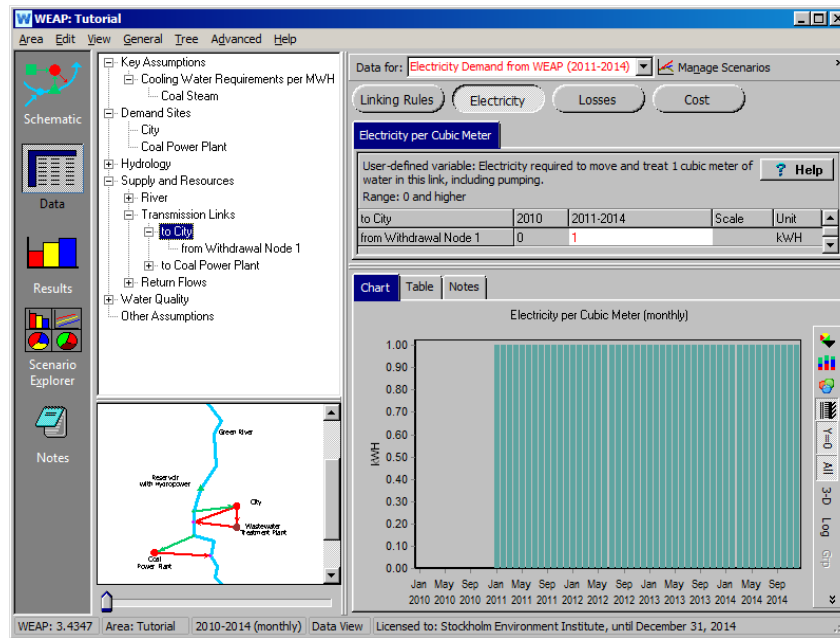
First, create a new category named “Electricity”—select *< Add New Category >* to add it.





Next, enter the following information and click Save:

Once you have created the variable, enter data in the “Electricity Demand from WEAP” scenario for the energy needed for pumping and treatment to the City (*1 kWh / cubic meter*) and the Coal Power Plant (*0.2 kWh / cubic meter*). Tip: just click on the transmission link in the lower left map to jump to that branch in the tree.



Create another variable named “Total Electricity”:

The screenshot shows the 'Create Variable' dialog box in WEAP. The variable name is 'Total Electricity' and the unit is 'kWH'. The category is 'Electricity' and the result variable is 'Transmission Link'. The comment is 'Electricity required to move and treat water flowing through this link, including pumping'. The scope is set to 'Monthly' and 'Current Accounts and Scenarios'. The minimum value is 0 and the maximum value is blank. The 'Sum Across Branches' checkbox is checked, and the 'Allow Missing Value (-9999)' checkbox is unchecked. The default value or expression is 'Electricity per Cubic Meter \* PrevTSValue(Flow)' for both Current Accounts and Scenarios. The 'Read Only' checkbox is checked.

Note: This variable will be a read-only calculated result--the default expression you enter (*Electricity per Cubic Meter \* PrevTSValue(Flow)*) will calculate the total electricity used by the transmission link in the previous timestep. Because this is the default expression, it will be used for all transmission links.

The second electricity demand in this model is from the Wastewater Treatment Plant. Find this in the Data tree under “Water Quality” and “Wastewater Treatment.” We will model it the same way as we did the transmission links. Add two new user-defined variables: “Electricity per Cubic Meter” and “Total Electricity,” with the following definitions:

The 'Edit Variable' dialog box for 'Electricity per Cubic Meter' is shown. The Name field contains 'Electricity per Cubic Meter' and the Unit is set to 'kWh'. The Category is 'Electricity' and the Result Variable is 'Water Quality'. The Comment field contains 'Energy required to treat 1 cubic meter of wastewater'. The Scope is set to 'Monthly' and 'Current Accounts and Scenarios'. The Values (Optional) section has 'Minimum Value' set to '0', 'Maximum Value' is empty, 'Sum Across Branches' is checked, and 'Allow Missing Value (-9999)' is unchecked. The Default Value or Expression section has 'Current Accounts' and 'Scenarios' both set to '0'. The 'Read Only' checkbox is unchecked.

The 'Create Variable' dialog box for 'Total Electricity' is shown. The Name field contains 'Total Electricity' and the Unit is set to 'kWh'. The Category is 'Electricity' and the Result Variable is 'Water Quality'. The Comment field contains 'Energy required to treat all wastewater at this plant'. The Scope is set to 'Monthly' and 'Current Accounts and Scenarios'. The Values (Optional) section has 'Minimum Value' and 'Maximum Value' empty, 'Sum Across Branches' is checked, and 'Allow Missing Value (-9999)' is unchecked. The Default Value or Expression section has 'Current Accounts' set to 'prevTSValue(Wastewater Treatment Plant Total Inflow[m^3])' and 'Scenarios' set to 'Electricity per Cubic Meter[kWh] \* PrevTSValue(Wastewater Treatment Plant Total Inflow[m^3])'. The 'Read Only' checkbox is checked.

The default expression for the read-only result variable Total Electricity is

$$\text{Electricity per Cubic Meter}[kWh] * \text{PrevTSVvalue}(\text{Wastewater Treatment Plant Total Inflow}[m^3])$$

Enter data in the “Electricity per Cubic Meter,” in the “Electricity Demand from WEAP” scenario: *0.1 kWh / cubic meter*.

## 19. Add Key Assumption in WEAP

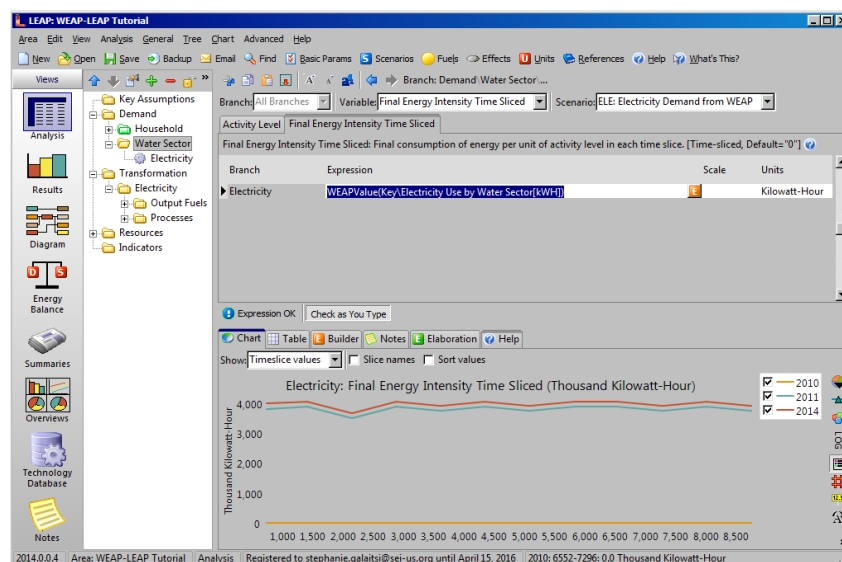
These two electricity demands can be summed up in one key assumption. Add a new key assumption in the Data tree and name it “Electricity Use by Water Sector.” (Right click on the “Key Assumptions” branch and choose “Add,” and select Kilowatt-Hours for the unit.) Enter the following expression in the Current Accounts:

$$(\text{Supply and Resources} \backslash \text{Transmission Links: Total Electricity}[kWh] + \text{Water Quality} \backslash \text{Wastewater Treatment: Total Electricity}[kWh])$$

## 20. Create Scenario in LEAP

Open the “Analysis” view in LEAP and create a scenario named “Electricity Demand from WEAP.” Go to the Link to WEAP screen and link this scenario to the corresponding scenario in WEAP. In the Data tree, go to branch Demand \ Water Sector. Enter this expression in “Final Energy Intensity Time Sliced” (make sure the “Electricity Demand from WEAP” scenario is selected):

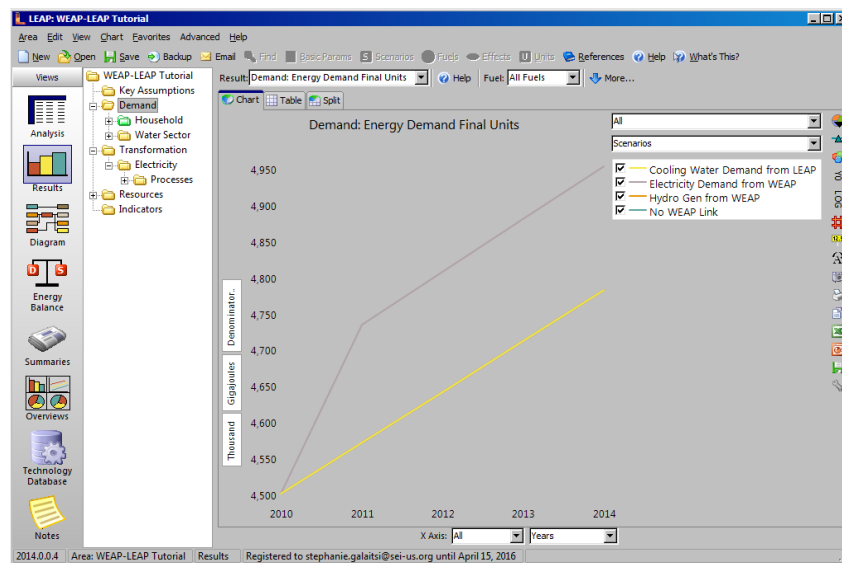
$$\text{WEAPValue}(\text{Key} \backslash \text{Electricity Use by Water Sector}[kWh])$$



You will need to run calculations before you can see these results in the Data View.

## 21. View Results and Compare Scenarios

In the “Results” view of LEAP, you can compare the energy demand across scenarios. Choose the “Energy Demand Final Units” variable from the top pull-down window, and “All Scenarios” for the legend. The “Electricity Demand from WEAP” scenario should show a variation in demand, while the other scenarios show straight lines because they do not take into account the changing electricity demand from the water sector. You may have to click the Y0 icon to the right to see the same view.



In WEAP, look at the results for Reservoir storage by scenario. You may have to run them to or three times to see the following chart. Because of the electricity demand from WEAP, LEAP must dispatch the coal plant more, which increases the cooling water requirement, which further reduces the reservoir level. Even in this simple example, you can see the complexity that can be modeled by linking WEAP and LEAP.

