ESM 121

Water Science
and Management

Mass Balance,
System’s Operation and Water Allocation Policies

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Part I – Continuity Equation: Conservation of Mass

The aim of this exercise is to exercise section is to provide basic concepts of water balance using Pajaro Valley as a case of study. You will perform a simple water balance to estimate inputs ($I_i$) Outputs ($O_t$) and change in storage ($\Delta S_i$) You will estimate these terms considering a simple water supply system: one river, one aquifer and three water users (irrigation, rural and Watsonville city).

Introduction
The water system is shown in Figure 1. The Pajaro Valley aquifer (Green square) supply water to “City of Watsonville”, “Rural” and “Agriculture” water demands. The city of Watsonville discharge their waters to the Watsonville wastewater treatment plant (WTP Watsonville), and from this WTP to the Pajaro river. In this exercise we will learn how to construct a simulation model, and how to evaluate two scenarios, the Baseline scenario (business as usual) and a water Conservation scenario.

![Figure 1](image.png)

Annual Water Mass Balance
The Spreadsheet Ex_3 in the Tab Part 1 - Groundwater shows the annual water demand for the City of Watsonville (Municipal), for rural communities (Rural) and for Agriculture (Agriculture). It also shows the estimated aquifer recharge to the Pajaro aquifer estimated from a groundwater model. In addition, it also has data of the Pajaro River headflow. Consider an initial aquifer storage ($S_0$) of 900,000 acre-feet (AF).
To be turned in:

For the Annual Calculation,

I.- Baseline Scenario

1) Show a table of the calculated aquifer storage (Column I) using a mass balance procedure

\[ S_t - S_{t-1} = I_t - O_t \]

<table>
<thead>
<tr>
<th>Year</th>
<th>Initial Storage</th>
<th>Projected Water Use</th>
<th>Municipal</th>
<th>Ag Water</th>
<th>Irrigation</th>
<th>Recharge</th>
<th>Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>2023</td>
<td>33,000 feet³</td>
<td>4,000 feet³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2024</td>
<td>33,000 feet³</td>
<td>4,000 feet³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2025</td>
<td>33,000 feet³</td>
<td>4,000 feet³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2) Using the same equation estimate the flow of the Pajaro River to the ocean, considering that about 66% of the Municipal demand of Watsonville is a return flow to Pajaro River. Show a table with these results.
II.- Water Savings Scenario

1) Show a table and a graph of the calculated aquifer storage using a mass balance procedure

\[ S_t - S_{t-1} = I_t - O_t \]
2) Using the same equation estimate the flow of the Pajaro River to the ocean, considering that about 66% of the Municipal demand of Watsonville is a return flow to Pajaro River. Show a table with these results.
III.- Comparison of both methods

1) Create a chart (line chart) when you show both aquifer storages.

2) In which scenario the aquifer storage is larger?

3) Why? What terms in the mass balance equation change?

4) Investigate about the concepts of aquifer safe yield and groundwater overdraft?

5) Do the policies of water conservation improve the problem of the overdraft?

6) Is the overdraft problem solved?
7) Take a look at the following figures and mention what other type of problem is causing overdraft?

![Diagram 1](image1.jpg)

a) Historic condition—Groundwater levels above sea level equilibrium level. No wells and no seawater intrusion.

![Diagram 2](image2.jpg)

b) Current stage—Excessive pumping results in long-term decreases in groundwater levels, pushing the salt water wedge closer to the pumping well trying to reach equilibrium.

Do you think the space left in the aquifer storage by fresh water is left empty or is it occupied by other type of liquid?

8) Same questions different figure. Take a look at the following figure and mention what other type of problem is causing overdraft? Explain your reasoning for your answer.

![Image](image3.jpg)

Do you think the space left in the aquifer storage by fresh water is left empty or is it occupied by other type of liquid, or is it compressed? Explain your reasoning for your answer.
Monthly Water Mass Balance

In the lower portion of the spreadsheet Ex_3 tab Part 1 -Groundwater, it shows how to do the same analysis for monthly time steps. You will use the same principles, however, the water demands (Municipal, Rural and Agriculture) and water supplies (Aquifer Recharge and Pajaro River streamflow) are calculated at a monthly time step. For this purpose, you multiply the annual water demand in a given year by the Monthly Water Demand Distribution for that particular water demand.

\[ \text{WaterDemand}_{\text{year.month}}^{\text{User } i} = \text{AnnualWaterDemand}_{\text{year}}^{\text{User } i} \times \text{MonthlyDistribution}_{\text{month}}^{\text{User } i} \]

The table below shows the Monthly Water Demand Distribution percentages.

<table>
<thead>
<tr>
<th>Month</th>
<th>Municipal (%)</th>
<th>Rural (%)</th>
<th>Agriculture (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7%</td>
<td>5%</td>
<td>2%</td>
</tr>
<tr>
<td>2</td>
<td>7%</td>
<td>5%</td>
<td>2%</td>
</tr>
<tr>
<td>3</td>
<td>7%</td>
<td>5%</td>
<td>2%</td>
</tr>
<tr>
<td>4</td>
<td>9%</td>
<td>8%</td>
<td>9%</td>
</tr>
<tr>
<td>5</td>
<td>9%</td>
<td>8%</td>
<td>9%</td>
</tr>
<tr>
<td>6</td>
<td>9%</td>
<td>8%</td>
<td>9%</td>
</tr>
<tr>
<td>7</td>
<td>10%</td>
<td>11%</td>
<td>16%</td>
</tr>
<tr>
<td>8</td>
<td>10%</td>
<td>11%</td>
<td>16%</td>
</tr>
<tr>
<td>9</td>
<td>10%</td>
<td>11%</td>
<td>16%</td>
</tr>
<tr>
<td>10</td>
<td>8%</td>
<td>9%</td>
<td>6%</td>
</tr>
<tr>
<td>11</td>
<td>8%</td>
<td>9%</td>
<td>6%</td>
</tr>
<tr>
<td>12</td>
<td>8%</td>
<td>9%</td>
<td>6%</td>
</tr>
<tr>
<td></td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

As you can see, from the previous equation you need to find the associated water demand for a given year and the monthly distribution at that specific month to multiply both terms. For this purpose, you will use a “look up” function. Go to cell D78 and type the following command:

“=VLOOKUP($B78,$C$11:$F$62,D$73+1,FALSE)*VLOOKUP($C78,$AF$78:$AI$89,D$73+1,FALSE)”
Now, let’s relate the following command with the equation to estimate monthly water demands

\[
\text{WaterDemand}_\text{year,month}^{\text{User } i} = \text{AnnualWaterDemand}_\text{year}^{\text{User } i} \times \text{MonthlyDistribution}_\text{month}^{\text{User } i}
\]

For retrieving the \((\text{AnnualWaterDemand}_\text{year}^{\text{User } i})\), we will use the first Vlookup command. Excel will lookup vertically (“VLookup”) the year value of cell $B78\text{ (in this case 1999) in the first column (it always start looking in the first column) of the table specified by the cell coordinates “}$C$11:$F$62\text{ (the red box in the following figure), and it will retrieve the value of column number 2 (D}$73\text{+1) of the specified table, which is Urban Water Demand, in this case for year 1999 is 7,467. When using this command, make sure to specify the column number that you want values to retrieve, and excel will always use the first column as the column to lookup for numbers, in this case, it will look for the “exact” value in cell B78 on the first column of the table specified, that’s why at the end of the command you need to write “FALSE”.

Similarly, for retrieving the \((\text{MonthlyDistribution}_\text{month}^{\text{User } i})\), we will use the Vlookup command. Excel will lookup vertically (“VLookup”) the year value of cell $C78\text{ (in this case month 1, or January) in the first column of the table specified by the cell coordinates “}$AF$78:$AI$89\text{, and it will retrieve the value of column number 2 (D}$73\text{+1) of the specified table, which is the percentage of water use for Municipal water use, in this case for the month of January (1) is 7%. Remember that it will look for the “exact” value in cell C78 on the first column of the table specified, that’s why at the end of the command you need to write “FALSE”.

"VLOOKUP($B78,$C$11:$F$62,D$73+1,FALSE) VLOOKUP($C78,$AF$78:$AI$89,D$73+1,FALSE)"
For Rural use in cell E78:

```
="=VLOOKUP($B78,$C$11:$F$62,E$73+1,FALSE)*VLOOKUP($C78,$AF$78:$AI$89,E$73+1,FALSE)"
```

For Agriculture use F78:

```
="=VLOOKUP($B78,$C$11:$F$62,F$73+1,FALSE)*VLOOKUP($C78,$AF$78:$AI$89,F$73+1,FALSE)"
```

Results from the Mass Balance model should look like the following picture.
Calculate the aquifer storage for the Baseline and Water Conservation scenarios. Also, calculate the Pajaro River outflow for both scenarios using the same considerations as in the yearly example (66% of the Municipal demand of Watsonville is a return flow to Pajaro River).

To be turned in:

1) Create a chart (line chart) when you show both aquifer storages.
2) What are the differences between the annual calculation and the monthly calculation? Can you identify the seasonality within each year?
3) Does the result changed in terms of groundwater sustainability?
Part II – System's Operation and Water Allocation Policies

The aim of this exercise section is to explore basic concepts of operating and allocation policies. Using the water available for each user, you will define equations that allocate water for the river and among 3 users.

Introduction

The water system is shown in Figure 1. There are 4 main water demands with different water requirements and priorities (Table 1).

<table>
<thead>
<tr>
<th>Priority</th>
<th>Name</th>
<th>Nickname</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>River</td>
<td>(Q_t)</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>User 1</td>
<td>(X_1t)</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>User 2</td>
<td>(X_2t)</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>User 3</td>
<td>(X_3t)</td>
<td>5</td>
</tr>
</tbody>
</table>

![Figure 1](image)

This is description of the water allocation policy for the system shown in Figure 1.

- **River** has the first priority, at least 2 units of water should be left in the river (if available) before the rest of the users can take their water demand. Once the water demand of all the user have been supplied, if there is any water available, then the remaining water will be left in the river.
- **User 3** has the second priority, and once the River has met its demand, then User 3 will take as much water up to meet its water demand, which is 5 units.
- **User 1** and **User 2** share both the 3rd priority in the system. Once River and User 3 have met their water demands, then User 1 and User 2 will take as much water as they can in the same proportion up to their water demand is fulfilled, User 1 = 2.5 units of water and User 2 = 3 units of water.

To solve this exercise of water operation and allocation policy; first, you will estimate the allocation policy (Step 1), and second, you will copy and paste the formulas OR lookup this allocation policy when you are running the calculations (Step 2).
Figure 2. Step 1, water allocation policy and Step 2, mass balance model.
Defining the water allocation policies.

Water User: River

First, let’s start working with River. According to the description provided by the allocation policy, water is left in the River using the following instructions:

“River” has the first priority, at least 2 units of water should be left in the river (if available) before the rest of the users can take their water demand. Once the water demand of all the user have been supplied, if there is any water available, then the remaining water will be left in the river.”

This can be converted into equations as follow:

\[
Q_{River}^t = \begin{cases} 
Q_t^{in} & \text{if } Q_t^{in} < 2 \\
Q_t^{in} - \sum_{i=1}^{1=3} X_{it} & \text{if } Q_t^{in} > 2 + \sum_{i=1}^{1=3} X_{it} \\
2 & \text{if } Q_t^{in} > 2 \text{ and } Q_t^{in} < 2 + \sum_{i=1}^{1=3} X_{it}
\end{cases}
\]

The first condition, \(Q_{River}^t = Q_t^{in}\), refers to “River [..], at least 2 units of water should be left in the river (if available)”, the second condition, \(Q_{River}^t = 2\), refers to “River [..], at least 2 units of water should be left in the river (if available)” and the third condition, \(Q_{River}^t = Q_t^{in} - \sum_{i=1}^{1=3} X_{it}\), refers to “Once the water demand of all the user have been supplied \([2 + \sum_{i=1}^{1=3} X_{it}]\), if there is any water available, then the remaining water will be left in the river.”

Before declaring these equations, it will be easier if we define names to the variables first. Go to cell C54. Then, go to the menu of Formulas and click on “Define Name”. A dialogue window should come out, you should name the variable “River_WD” as a short name of “River Water Demand”. Very important, make sure that in “Scope:” drop down menu you select “Part 2 - River”. By default the “Refers to:” section should be selecting the cell C54 where the cursor is located. If this is not showing, click on the “cells and arrow” icon on the right and select the cell C54. By doing this, you are naming that cell “River_WD” that you will be able to call it like that in excel, cool, isn’t it!
You will have to “Define Name” for the following variables and cells:

<table>
<thead>
<tr>
<th>“Define Name” Variable</th>
<th>Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>River_WD</td>
<td>C54</td>
</tr>
<tr>
<td>X1_WD</td>
<td>D54</td>
</tr>
<tr>
<td>X2_WD</td>
<td>E54</td>
</tr>
<tr>
<td>X3_WD</td>
<td>F54</td>
</tr>
</tbody>
</table>

If you had a problem naming your variables or not selecting the right cell, you can click on the Formulas/Name Manager where you can delete or edit your variables.

Now, let's go to Cell C6 and type the following equation:

The equation in Cell C6 is: “=IF(B6<=River_WD,B6,IF(B6>River_WD+SUM(X1_WD,X2_WD,X3_WD),B6-SUM(X1_WD,X2_WD,X3_WD), River_WD))”
The first part of this equation, grey box, refers to the first condition, the green box refers to the third condition, and if none of the previous conditions applied, then it applies the result from condition 2.

\[
R_{l}R_{W_W}\times = \begin{cases} 
Q_{t} & \text{if } Q_{t}^{in} < 2 \\
2 & \text{if } Q_{t}^{in} > 2 \text{ and } Q_{t}^{in} < 2 + \sum_{i=1}^{3} X_{i} \\
Q_{t}^{in} - \sum_{i=1}^{3} X_{i} & \text{if } Q_{t}^{in} > 2 + \sum_{i=1}^{3} X_{i} 
\end{cases}
\]

Copy and paste this equation for the remaining of the column.
Water User: User 3

According to the description provided by the allocation policy, User 3 has the second priority, and once the River has met its demand, then User 3 will take as much water up to its water demand is fulfilled, which is 5 units.

This can be converted into equations as follow:

\[
X_{3t} = \begin{cases} 
0 & \text{if } Q^{in}_t \leq 2 \\
Q^{in}_t - Q^{River}_t & \text{if } Q^{in}_t > Q^{River}_t \text{ and } Q^{in}_t < Q^{River}_t + X_{3t} \\
5 & \text{if } Q^{in}_t \geq Q^{River}_t + X_{3t} 
\end{cases}
\]

The first condition, \(X_{3t}=0\), refers to "User 3 has the second priority, and once the River has met its demand, then User 3 [...]"; the second condition, \(X_{3t}=5\), refers to "User 3 [...] will take as much water up to meet its water demand, which is 5 units." and the third condition, \(X_{3t}=Q^{in}_t-Q^{River}_t\) refers to "User 3 [...] will take as much water up to its water demand is fulfilled, which is 5 units."

The equation in Cell F6 is: 
"=IF(B6<=River_WD,0,IF(AND(B6>River_WD,B6<River_WD+X3_WD),B6-River_WD,X3_WD))"
The first part of this equation, grey box, refers to the first condition, the green box refers to the third condition, and if none of the previous conditions applied, then it applies the result from condition 2.

\[
X_{3t} = \begin{cases} 
0 & \text{if } Q_t^{in} \leq 2 \\
5 & \text{if } Q_t^{in} \geq Q_t^{River} + X_{3t} \\
Q_t^{in} - Q_t^{River} & \text{if } Q_t^{in} > Q_t^{River} \text{ and } Q_t^{in} < Q_t^{River} + X_{3t}
\end{cases}
\]

Copy and paste this equation for the remaining of the column.
Water User: User 1 and 2
According to the description provided by the allocation policy, User 1 and User 2 share both the 3rd priority in the system. Once River and User 3 have met their water demands, then User 1 and User 2 will take as much water as they can in the same proportion up to meet their water demand, User 1 = 2.5 units of water and User 2 = 3 units of water.

For User 1, this can be converted into equations as follow:

$$X_{1t} = \begin{cases} 
0 & \text{if } Q_t^{in} \leq Q_t^{River} + X_{3t} \\
\left( Q_t^{in} - (Q_t^{River} + X_{3t}) \right) \times \left( \frac{X_{2t}}{X_{1t} + X_{2t}} \right) & \text{if } Q_t^{in} - (Q_t^{River} + X_{3t}) < X_{1t} + X_{2t} \text{ and } Q_t^{in} > Q_t^{River} + X_{3t} \\
2.5 & \text{if } Q_t^{in} - (Q_t^{River} + X_{3t}) > X_{1t} + X_{2t}
\end{cases}$$

For User 2, this description can be converted unto equations as follows:
The first condition, $X_1 = 0$, refers to “Once River and User 3 have met their water demands, then User 1 and User 2 will take [...]”; the second condition, $X_1 = 2.5$, refers to “[...] User 1 and User 2 will take as much water as they can in the same proportion up to meet their water demand, User 1 = 2.5 units of water and User 2 = 3 units of water” and the third condition, refers to “[...] User 1 and User 2 will take as much water as they can in the same proportion up to meet their water demand, User 1 = 2.5 units of water and User 2 = 3 units of water”.

The equation for User 1 in Cell D6 is: 

```
=IF(B6<=River_WD+X3_WD,0,IF(B6-(River_WD+X3_WD)>=X1_WD+X2_WD, X1_WD,(B6-(River_WD+X3_WD))*(X1_WD/(X1_WD+X2_WD))))
```

Figure 9

The first part of this equation, grey box, refers to the first condition, the green box refers to the third condition, and if none of the previous conditions applied, then it applies the result from condition 2.
The equation for *User 2* is very similar to *User 1*, in Cell E6 is: 

```
=IF(B6<=River_WD+X3_WD,0,IF(B6-(River_WD+X3_WD)>=X1_WD+X2_WD,X2_WD,(B6-(River_WD+X3_WD))*(X2_WD/(X1_WD+X2_WD))))
```

Copy and paste this equation for the remaining of the column.

![Figure 10](image1)

The graph should look like:

![Figure 11](image2)
Linking the Water Allocation policy with the Mass Balance Model

There are two methods to use the allocation policy that was just derived into the mass balance model. Use EITHER of the following two methods, but only chose one, the one that you feel more comfortable using.

**First Method**
The easiest way is to select cells C6 to F6 (C6:F6), copy (CTrl+C) and paste the formulas on cells into cells D45 to G45 (D45:G45).

![Figure 12](image1.png)  
Figure 12. On the left, Copy (Ctrl+C) cells C6 to F6, and paste them (Ctrl+V) into cells D45 to G45

And then use these cells (D45:G45) to copy then through the rest of the table.

![Figure 13](image2.png)  
Figure 13
Second Method

The second way to do this, is a little bit more elegant, but still the same principle. This method is used, and it is very helpful, when managing large amount of water users. In this case, what you want is to have control of the water allocating policy in one table (B6:F40) and to recall values from this table in the mass balance model (B59:H79). You can create a “lookup” command that will find the values estimated in the allocation policy table. In cell D59, let’s insert a command that will look up for the value of $Q_{River}$ in the table water allocation table using the following equation:

```
"=VLOOKUP($C59,$B$6:$F$40,2,TRUE)"
```

What the previous command means, is that excel will look up vertically ("VLookup") for the $Q_{River}$ value of cell C59 (in this case 14) in the first column (it always start looking in the first column) of the table specified by the cell coordinates "$B$6:$F$40" (the green box in the following figure), and it will retrieve the value of column number 2 of the specified table, which is $Q_{River}$, in this case for 14 is 3.5. When using this command, make sure to specify the column number that you want values to retrieve, and excel will always use the first column as the column to lookup for numbers, in this case, it will look for the “approximate” value in cell C58 on the first column of the table specified, that’s why at the end of the command you need to write “TRUE”.

![Figure 14](image-url)
For User 1, \( X_{1t} \), use the following equation in cell E59: “=VLOOKUP($C59,$B$6:$F$40,3,TRUE)”

For User 2, \( X_{2t} \), use the following equation in cell F59: “=VLOOKUP($C59,$B$6:$F$40,4,TRUE)”

For User 3, \( X_{3t} \), use the following equation in cell G59: “=VLOOKUP($C59,$B$6:$F$40,5,TRUE)”

Results from the Mass Balance model should look like the following pictures

![Figure 15](image1.png)

![Figure 16](image2.png)

To be turned in:

1) Show a table like the one calculated in Figure 15 and the series of graphs calculated in Figure 16.
**Water Resources Performance Criteria**

Phew, we have done a lot of work to describe the water allocation system for four water demands (River, X1, X2, and X3), imagine in a basin where we have hundreds and sometimes thousands of users! All the previous work quantitatively describes how water is allocated, but it does not give us any performance of the water supply. For estimating the water supply performance, there are four water resources performance criteria used widely in the field: Reliability (in time and volume), Vulnerability, and Resilience. I will show you how to calculate those water resources performance criteria to evaluate the our water resources system.

**Reliability (Time and Volume)**

Have you ever heard in the news about “Water Supply Reliability”? do you remember Governor Brown in our last drought when he talked about “making sure everyone had a reliable water supply during the drought? Water Supply Reliability is a common term used to quantify how frequent a water demand is met (time-based reliability), and how close to the total amount demanded (volumetric reliability). The time based reliability is the portion of time that water demand is fully supplied, or in other words, how frequent a water demand is fully supplied.

To estimate the time based reliability, we need to estimate water supply deficits, which is the difference between the water demand minus the water supplied:

\[
Deficit_t^i = \begin{cases} 
    X_{Demand,t}^i - X_{Supplied,t}^i & \text{if } X_{Demand,t}^i > X_{Supplied,t}^i \\
    0 & \text{if } X_{Demand,t}^i = X_{Supplied,t}^i 
\end{cases}
\]

where: \(X_{Demand,t}^i\) is the water demand for the \(i^{th}\) water user, and \(X_{Supplied,t}^i\) is the water supplied in the \(t^{th}\) time period. Finally, the reliability for the \(i^{th}\) user is:

\[
Reliability(time)^i = \frac{\# \text{ of times } Deficit_t^i = 0}{n}
\]

where \(n\) is the total number of time steps, often used the total number of years or months, depending on the water management unit of time.

The volumetric reliability is the sum of the deficits divided by sum of the water demand. The volumetric reliability express how much water was supplied compared with the total amount of water demanded.

\[
Reliability(volume)^i = \frac{\sum X_{Supplied,t}^i}{\sum X_{Demand,t}^i}
\]

First, let’s calculate the matrix of Water Supply Deficits. As mentioned before, a water supply deficit is the difference between the water demand minus the water supplied. For the River demand, a deficit only exist if the water supplied is less than the water demand (\(Q_{River} = 2\) units of water). Let’s estimate the deficit for year 2020 in cell D87 as follows: “=IF(D59<River_WD,River_WD-D59,0)”
You can count the number of time steps (n), the number of deficits (# of deficits) and the total volume of deficits (Sum of deficits) as follows:

n -> Cell D109: "=COUNT(D87:D107)"
# of deficits -> Cell D110: "=COUNTIF(D87:D107,">0")"
# of NO deficits -> Cell D111: "=COUNTIF(D87:D107,"=0")"
Sum of deficits -> Cell D112: "=SUMIF(D87:D107,">0")"
Sum of Water Demand -> Cell D113: "=River_WD*D109"
Sum of Water Supplied -> Cell D114: "=D113-D112"
According to the equation of reliability in time, we can estimate it as follows:

\[
Reliability(\text{time})^i = \frac{\# \text{ of times Deficit}^i = 0}{n}
\]

Reliability in time -> Cell D116: “=D111/D109”. The time-based reliability means that 95% of the time the water demand of the river can be fully supplied.

According to the equation of volumetric reliability, we can estimate it as follows:

\[
Reliability(\text{volume})^i = \frac{\sum X^i_{\text{Supplied},t}}{\sum X^i_{\text{Demand},t}}
\]

Volumetric Reliability -> Cell D117: “=D114/D113”. The volumetric reliability means that 95% of the volume requested by the River was able to be supplied.
Vulnerability

The performance criterion of vulnerability expresses the severity of the deficits. In summary, it is the average of the water supply deficits, expressed as a percentage of the water demand. Vulnerability can be calculated as follows:

\[
V_{\text{Vulnerability}} = \frac{\sum \text{Deficit}_i}{\text{# of times Deficit}_i > 0 \text{ occurred}} \frac{\text{Water Demand}_i}{\text{Water Demand}}
\]

Vulnerability -> Cell D118: “=(D112/D110)/River_WD”. The vulnerability criterion means that when a deficit happen, on average, the magnitude of the deficit is 100% of the water demanded by the river.

One tricky thing about the Vulnerability is to calculate it when no deficit occur. For this case, the system is considered 0% vulnerable. Thus, the equation in Cell D118 should be changed to account for this peculiar condition as follows: “=IF(D110=0,0,(D112/D110)/River_WD)”.
Resilience

Resilience is the system’s capacity to adapt to changing conditions, resilience must be considered as a statistic that assesses the flexibility of water management policies to adapt to changing conditions. The classic definition of resilience is the probability that a system recovers from a period of failure, e.g., a deficit in water supply. For our specific case, Resilience is the probability that a year of no-deficit follows a year of deficit in the water supply for the $i$th water user. Resilience is a useful statistic to assess the recovery of the system once it has failed. Resilience is expressed as:

$$R_W = \frac{\text{# of times Deficit}_i = 0 \text{ follows Deficit}_i > 0}{\text{# of times Deficit}_i > 0 \text{ occurred}}$$

To estimate Resilience, we need to create a matrix that track the number of times a period of No Deficit follow a period with Deficit. We will always start the first time step with zeros.

For year 2021, we can estimate if the previous year was in a water supply deficit AND this year is not in a deficit in cell I88 as follows: “=IF(AND(D88=0,D87>0),1,0)”. This equation flags (inserting a 1) if the previous year was in a deficit and the current year is not. The following figure shows that only in year
2024 the previous condition is true, meaning that the previous year (2023) was in a water supply deficit and that the current year (2024) it is not.

You can sum all of the times this condition occurs in Cell I109: “=SUM(I87:I107)”

The resilience can be calculated as follows:

\[
Res^t = \frac{\text{# of times } Deficit^t = 0 \text{ follows } Deficit^t > 0}{\text{# of times } Deficit^t > 0 \text{ occurred}}
\]

Resilience -> Cell D119: “=IF(I109=0,1,I109/D110)”. The resilience criterion means the probability that a water demands recovers from a deficit, when they occur. For the River water demand, there is a 100% probability that the system will recover.
One tricky thing about the Resilience is to calculate the resilience of a system when no deficit occur. For this case, the system is considered 100% resilient. Thus, the equation in Cell D119 should be changed to account for this peculiar condition as follows: “=IF(I109=0,1,I109/D110)”.

Water Resources Sustainability Index

Now, think about this: How do you know that a given user is receiving adequately their water demand? So far, we have estimated four performance criteria, but imagine that we start evaluating several alternative water management strategies and all of a sudden some criteria starts going up other going down. Can we estimate a single number (an Index) that summarize the performance of a given water demand? In order to summarize all the performance criteria, we used index that helps synthesizing results. The Water Resources Sustainability Index (SI) is an index that aggregates a set of performance criteria, it is the geometric average of a group of $m$ performance criteria for a given water user $i$: 

$$SI = \sqrt[m]{P_1 \times P_2 \times \cdots \times P_m}$$
\[ S^{I} = \left( \prod_{m=1}^{M} \text{Performance Criteria}^{m} \right)^{1/M} \]

For our case, the SI can be expressed as:

\[ S^{I} = \left[ \text{Rel}(\text{time})^{I} \times \text{Rel}(\text{Volume})^{I} \times \text{Res}^{I} \times (1 - \text{Vuln}^{I}) \right]^{1/4} \]

For the River water demand, the SI can be estimated in Cell D120 as follows:

Cell D120: \( \text{"=(D116*D117*D119*(1-D118))^(1/4)"} \)

<table>
<thead>
<tr>
<th>SUM</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
<td>F</td>
<td>G</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>108</td>
<td></td>
<td></td>
<td>21</td>
<td></td>
<td></td>
<td></td>
<td>Count Resilience=</td>
<td></td>
</tr>
<tr>
<td>109</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>110</td>
<td></td>
<td></td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>111</td>
<td></td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>113</td>
<td></td>
<td></td>
<td>42</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>114</td>
<td></td>
<td></td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>115</td>
<td></td>
<td></td>
<td>Reliability(time)</td>
<td>95%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>116</td>
<td></td>
<td></td>
<td>Reliability (volume)</td>
<td>95%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>117</td>
<td></td>
<td></td>
<td>Vulnerability</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>118</td>
<td></td>
<td></td>
<td>Resilience</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>119</td>
<td></td>
<td></td>
<td>Sustainability Index</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>120</td>
<td></td>
<td></td>
<td></td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 17. Results of the Performance Criteria and Sustainability Index for the River Water demand

For the River water demand, the SI = 0% meaning that it is unsustainable. While the Reliability (in time and volume) is very high (95%) and the resilience is very high (100%), when a deficit occurs, this deficit is very damaging, 100% of the water demand. That’s the reason why the SI = 0%

Instructions

Calculate the deficit matrix for users 1, 2 and 3.

Hint: for year 2020, the deficit can be calculated as follows:
User1 -> Cell E87: \( \text{"=IF(E59<X1\_WD,X1\_WD-E59,0)"} \)
User2 -> Cell F87: \( \text{"=IF(F59<X2\_WD,X2\_WD-F59,0)"} \)
User3 -> Cell G87: \( \text{"=IF(G59<X3\_WD,X3\_WD-G59,0)"} \)

Calculate the following variables for Users 1, 2 and 3: \( n \), \# of deficits, \# of NO deficits, Sum of deficits, Sum of Water Demand, and Sum of Water Supplied
Hint: Remember to use the appropriate water demands for user 1 ($X_1_{WD}$), 2 ($X_2_{WD}$), and 3 ($X_3_{WD}$) in the equation of Sum of Water Demand.

Calculate the resilience matrix for Users 1, 2 and 3.

Estimate the Reliability (time-based and volumetric), Vulnerability, resilience and Water resources Sustainability Index for user 1, 2 and 3.

Hint: Remember to use the appropriate water demands for user 1 ($X_1_{WD}$), 2 ($X_2_{WD}$), and 3 ($X_3_{WD}$) in the equation of Vulnerability.

**To be turned in:**

1) Show table (like figure 17) of the four performance criteria [Reliability(time and volume), vulnerability and resilience) and the Sustainability Index.

2) Change the value of the River water demand ($Q_{River}$) to 4 units in cell C54. Show a table like the one calculated in Figure 15 and the series of graphs calculated in Figure 16.

3) Show table (like figure 17) of the four performance criteria [Reliability(time and volume), vulnerability and resilience) and the Sustainability Index for all water demands for $Q_{River}$ = 4 units. Does the water supply for Users 1, 2 and 3 change? Does it improved or got worse?

4) Calculate the average annual flow coming from upstream ($Q_{In}$) (Average of cells C59:C79). How much the River water demand represent in comparison to the average annual inflows [$River_{WD} / Avg. (Q_{In})$]? Do you think this is enough water so the ecosystem can be sustained? Imagine that from your total monthly income (let say $2,000), this monthly stipend is reduced to the same percentage of water that was left in the river (let say 30% of $2,000 = $600). Can you adequately live with this budget in a month? Do you see any similitude with what we have left to the river? Elaborate why there may be a conflict with human and environmental water supply.
II.- For the River and Reservoir System

Now, you are going to be working with a reservoir system, how exciting!

Before declaring any equation, it will be easier if we define names in this workbook as you did in the previous part of the exercise. Once again, make sure you are in the “Part 2 – Reservoir” sheet. Go to cell C54. Then, go to the menu of Formulas and click on “Define Name”. A dialogue window should come out, you should name the variable “River_WD” as you did before which as a short name of “River Water Demand”. Very important, make sure that in “Scope:” drop down menu you select “Part 2 - Reservoir”. By default the “Refers to:” section should be selecting the cell C54 where the cursor is located. If this is not showing, click on the “cells and arrow” icon on the right and select the cell C54. By doing this, you are naming that cell “River_WD” that you will be able to call it like this worksheet in excel, cool, isn’t it!

You will have to “Define Name” for the following variables and cells:

<table>
<thead>
<tr>
<th>“Define Name” Variable</th>
<th>Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>River_WD</td>
<td>C54</td>
</tr>
<tr>
<td>X1_WD</td>
<td>D54</td>
</tr>
<tr>
<td>X2_WD</td>
<td>E54</td>
</tr>
<tr>
<td>X3_WD</td>
<td>F54</td>
</tr>
<tr>
<td>K</td>
<td>J54</td>
</tr>
<tr>
<td>Hedging</td>
<td>K54</td>
</tr>
</tbody>
</table>

If you had a problem naming your variables or not selecting the right cell, you can click on the Formulas/Name Manager where you can delete or edit your variables.
The same file has a system set up with a reservoir, with capacity $K=25 \text{ units}$, and initial storage $S_0= 7 \text{ units}$, as shown below.

<table>
<thead>
<tr>
<th>Priority</th>
<th>Name</th>
<th>River</th>
<th>User 1</th>
<th>User 2</th>
<th>User 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nickname</td>
<td>$(Q^\text{River}_t)$</td>
<td>$(X_{1t})$</td>
<td>$(X_{2t})$</td>
<td>$(X_{3t})$</td>
</tr>
<tr>
<td></td>
<td>Volume</td>
<td>2</td>
<td>2.5</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 17
The only difference in the allocation policy is that for User 1, User 2 and User 3, you will have to substitute $S_{t-1} + Q_{in}^t$ instead of $Q_{in}^t$ in each of the conditionals. For River, $Q_{River}^t$, the water allocation changes as follow:

$$Q_{River}^t = \begin{cases} 
Q_{in}^t + S_{t-1} & \text{if } Q_{in}^t + S_{t-1} < 2 \\
\frac{2}{2} & \text{if } Q_{in}^t + S_{t-1} \geq 2
\end{cases}$$

In addition, reservoir spills must be calculated (Column G, Cells G6:G40) as follow:

$$Q_{t}^{Spill} = \begin{cases} 
0 & \text{if } S_{t-1} + Q_{in}^t \leq K + Q_{t}^{River} + \sum_{i=1}^{i=3} X_{it} \\
(S_{t-1} + Q_{in}^t) - (K + Q_{t}^{River} + \sum_{i=1}^{i=3} X_{it}) & \text{if } S_{t-1} + Q_{in}^t > K + Q_{t}^{River} + \sum_{i=1}^{i=3} X_{it}
\end{cases}$$

1) Please write down a paragraph explaining in plain words how the operation for River has changed, such as the one used in the River System: “River has the first priority, at least 2 units of water should be left in the river (if available) before the rest of the users can take their water demand. [Insert here how the water allocation policy has changed for River].”
   Hint: In order for the river to receive extra water, does the reservoir have to spill?

2) Calculate the spills (Column G, Cells G6:G40) using the equation provided above.

3) Estimate the table for the water allocation policy (cells B2:H40) and show this table.

4) Estimate in column D the $S_{t-1}+Q_{in}^t$.

5) Use any of the two methods explained above to link the water allocation policy table with the mass balance model for the River (E59:E79), User 1 (F59:F79), User 2 (G59:G79) and User 3 (H59:H79).

6) Using the mass balance equation, estimate the reservoir storage through every time step (I59:I79). Remember that the storage can’t exceed the storage capacity $K=25$ units.

7) Use any of the two methods explained above to link the water allocation policy table with the mass balance model for Reservoir spills (J59:J79),

8) Display the mass balance results, like figure 15 and 16.

9) Similarly, does the water supply for Users 1, 2 and 3 improved if the reservoir is built? Show a comparison of the water supply for both systems (With and without a reservoir $Q_{River}^t = 2$ units in both calculations)
10) What about the River? Does the river improve their water supply?

11) Show table (like figure 17) of the four performance criteria [Reliability(time and volume), vulnerability and resilience) and the Sustainability Index.

12) Did the performance of the systems improved or got worse? Create a table showing a comparison the performance criteria and