S W A T - M O E A

AGRICULTURAL PRODUCTION SYSTEMS OPTIMIZATION TOOL FOR SWAT

User Manual

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Chapter 1. Introduction

This section introduces the User Manual for the SWAT-MOEA (Soil and Water Assessment Tool – Multi-Objective Evolutionary Algorithm), a powerful standalone tool developed to provide optimization capabilities for management practices to SWAT calibrated projects. This manual serves as a comprehensive guide to help you utilize the SWAT-MOEA effectively and efficiently.

SWAT-MOEA integrates the SWAT model with advanced multi-objective optimization techniques, allowing users to explore and identify optimal management strategies for land and water resource management. Whether you are a researcher, water resource manager, or environmental consultant, the SWAT-MOEA enables you to make inform decisions by optimizing complex management scenarios while considering multiple objectives functions.

This user manual provides detailed instructions on each aspect of the SWAT-MOEA, from installation and setup to conducting optimization studies and interpreting results. Through clear explanations, step-by-step procedures, and illustrating examples, we aim to equip you with the knowledge and skills necessary to harness the full potential of SWAT-MOEA for your hydrological modeling projects and optimization needs.

We encourage you to explore the functionalities of SWAT-MOEA, experiment with various optimization scenarios, and leverage its capabilities to address real-world environmental challenges and water resources management. We anticipate the SWAT-MOEA tool will contribute to the achievement of sustainable and efficient management practices for watershed and agricultural systems now, and into the future.

Chapter 2. Install SWAT-MOEA

This chapter is dedicated to guiding users through the steps required in installing the SWAT-MOEA tool. By following these simple instructions, you will be equipped to set up SWAT-MOEA, ensuring a smooth transition into utilizing its features for optimizing the management practices in your SWAT project. Let's begin the installation process to get you up and running with SWAT-MOEA.

2.1 Begin Installation

After downloading SWAT-MOEA, go to your **Downloads** file and **double click** on the *SWAT_MOEA_Installer* (Figure 1). This will prompt the SWAT_MOEA Installer window to appear on your screen (Figure 2).

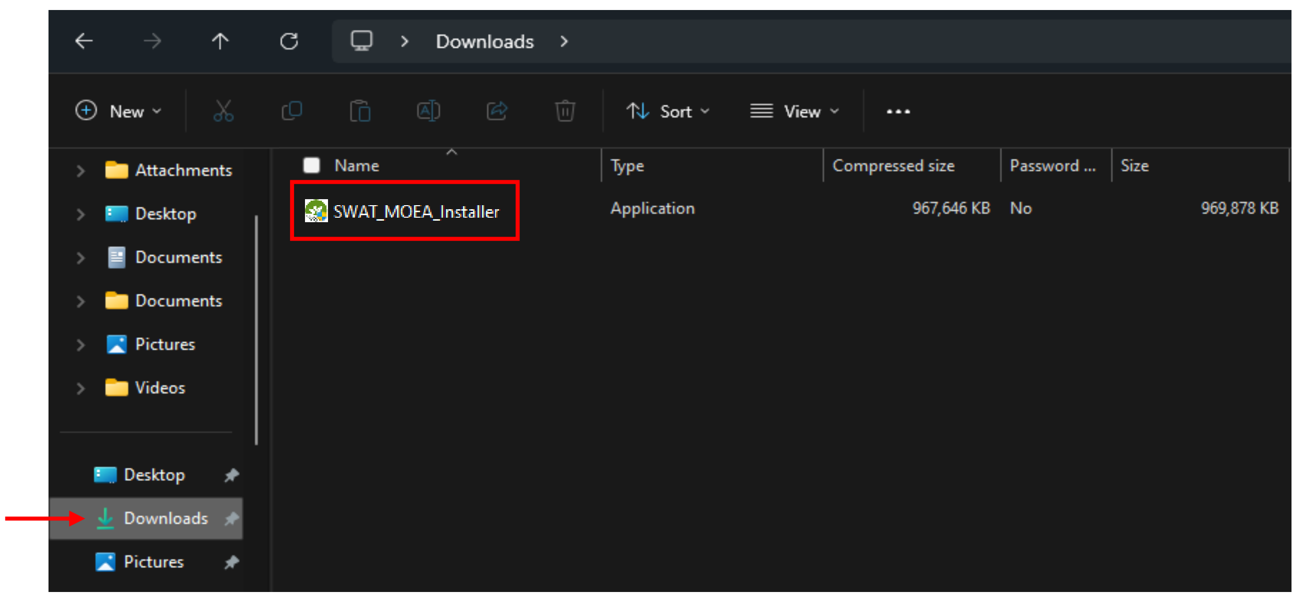


Figure 1. SWAT-MOEA Application

Click on the **Next** button in the SWAT_MOEA Installer window (Figure 2).

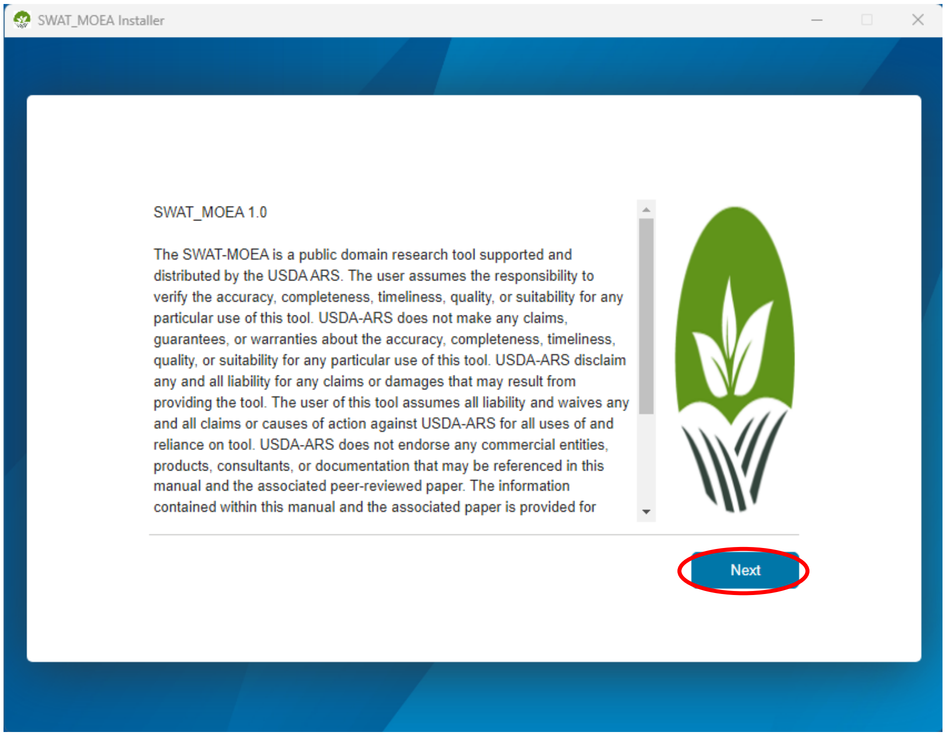


Figure 2. SWAT_MOEA Installer window

The next step requires selecting the destination folder for the SWAT-MOEA tool. You can select the default option (C:\Program Files\USDA-ARS\SWAT_MOEA) or browse to select a different folder (Figure 3).

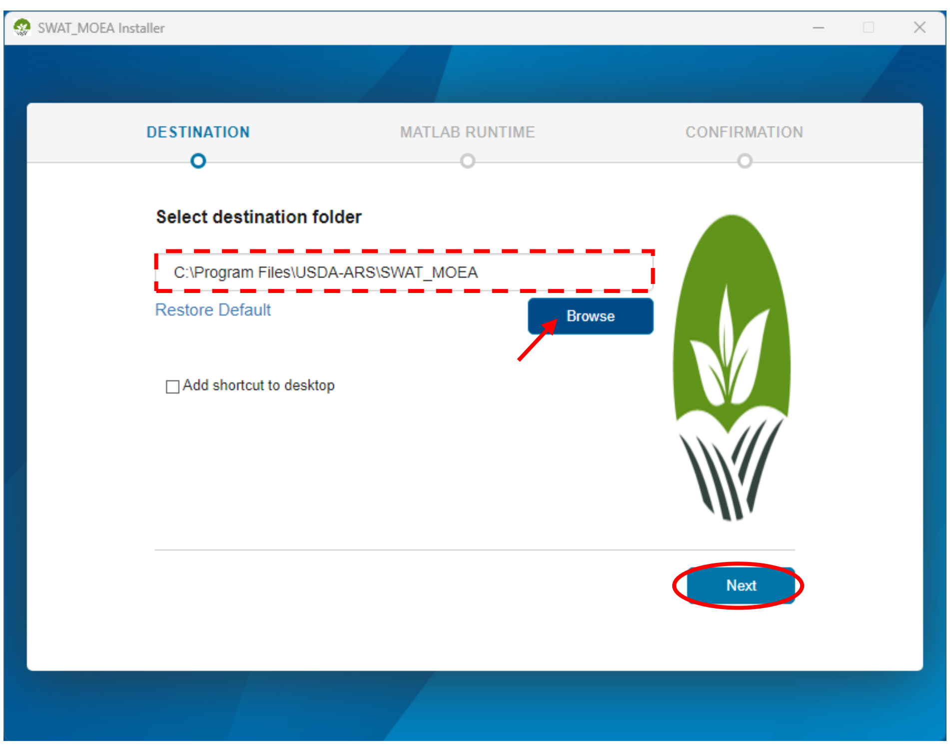


Figure 3. SWAT_MOEA Installer window – SWAT-MOEA tool folder

The next three steps (Figures 4, 5 & 6) involves the installation of MATLAB Runtime. By default, these files will be saved in the C:\Program Files\MATLAB\MATLAB Runtime file or browse to select a different folder (Figure 4). Click the **Next** button.

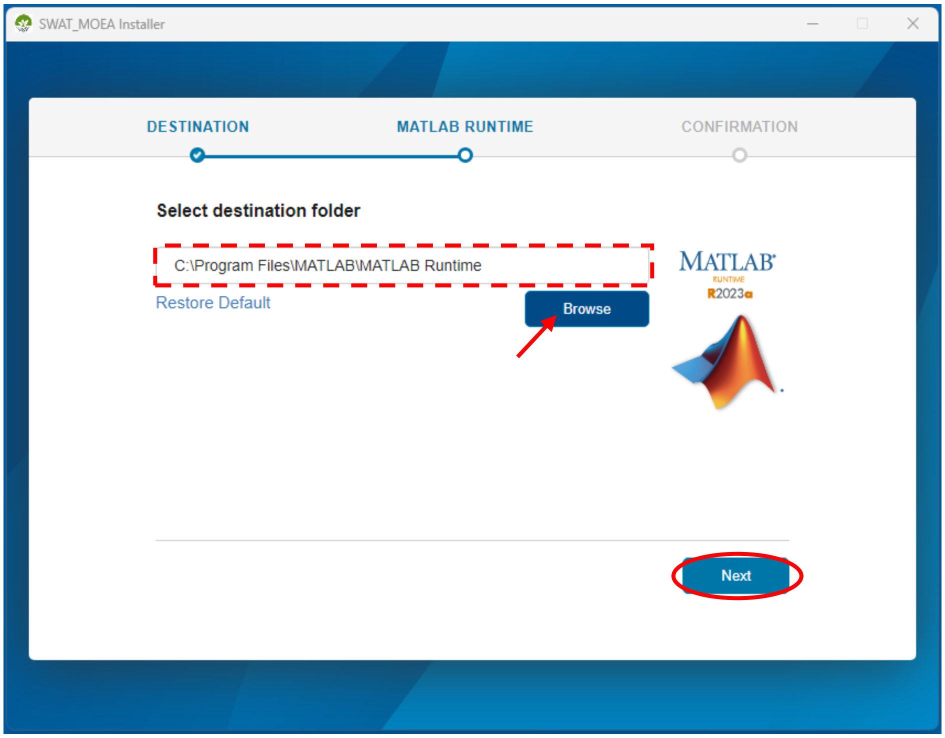


Figure 4. SWAT_MOEA Installer window – MATLAB Runtime Destination

Accept the terms of the license agreement and click the **Next** button (Figure 5).

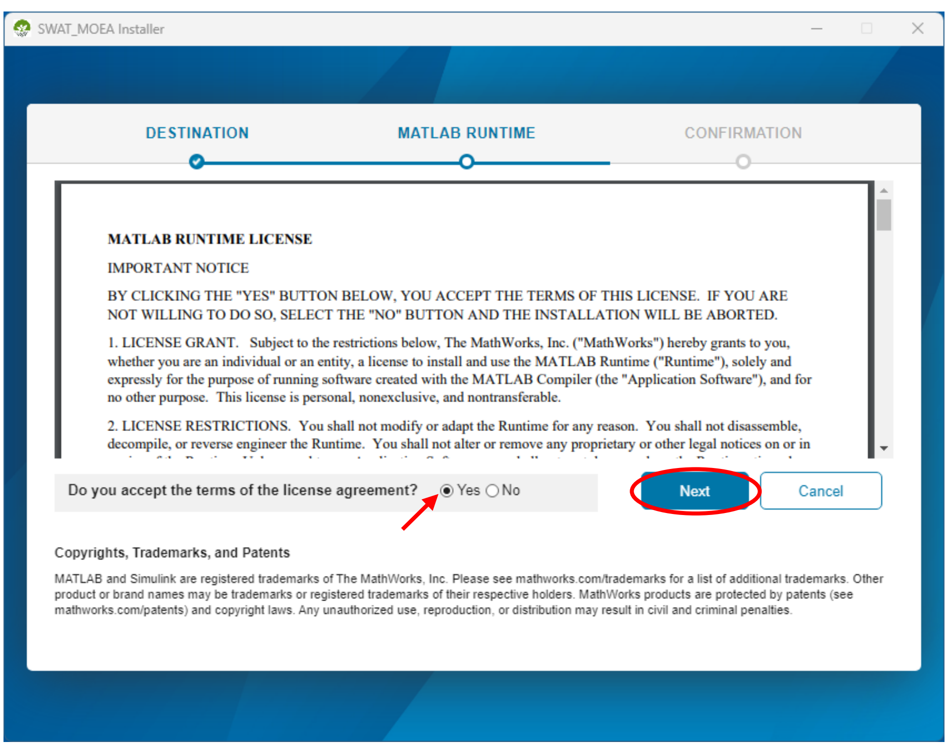


Figure 5. SWAT_MOEA Installer window – MATLAB Runtime

Next, confirm that the selections you made are correct and begin the installation process by clicking the **Begin Install** button (Figure 6).

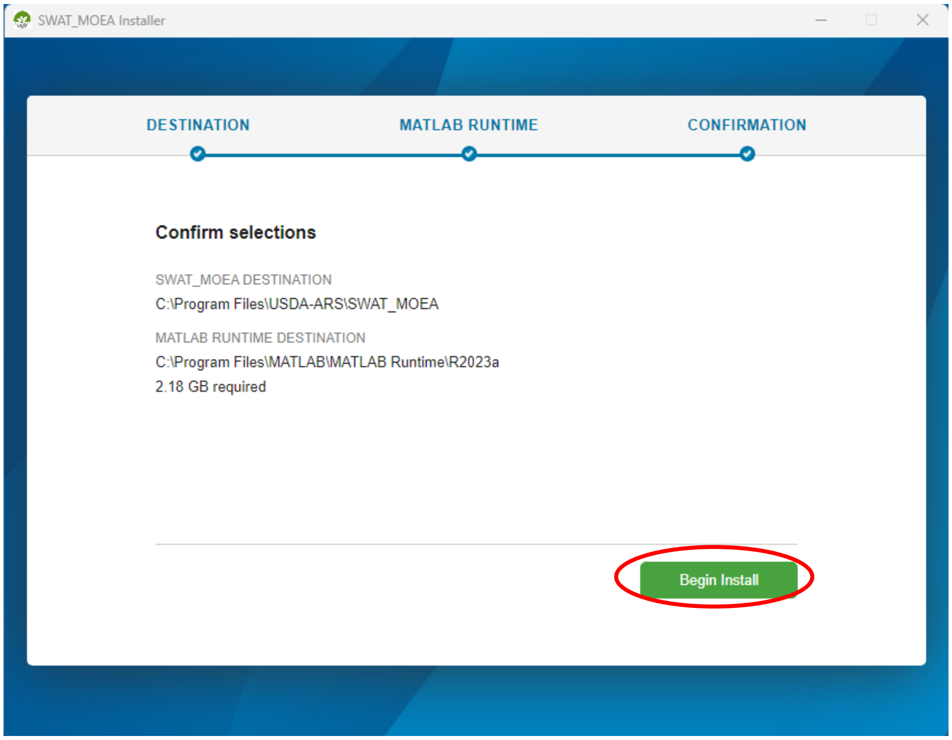


Figure 6. SWAT_MOEA Installer window – Begin Install

Once the SWAT-MOEA installation process is completed, you can close the SWAT_MOEA Installer window (Figure 7).

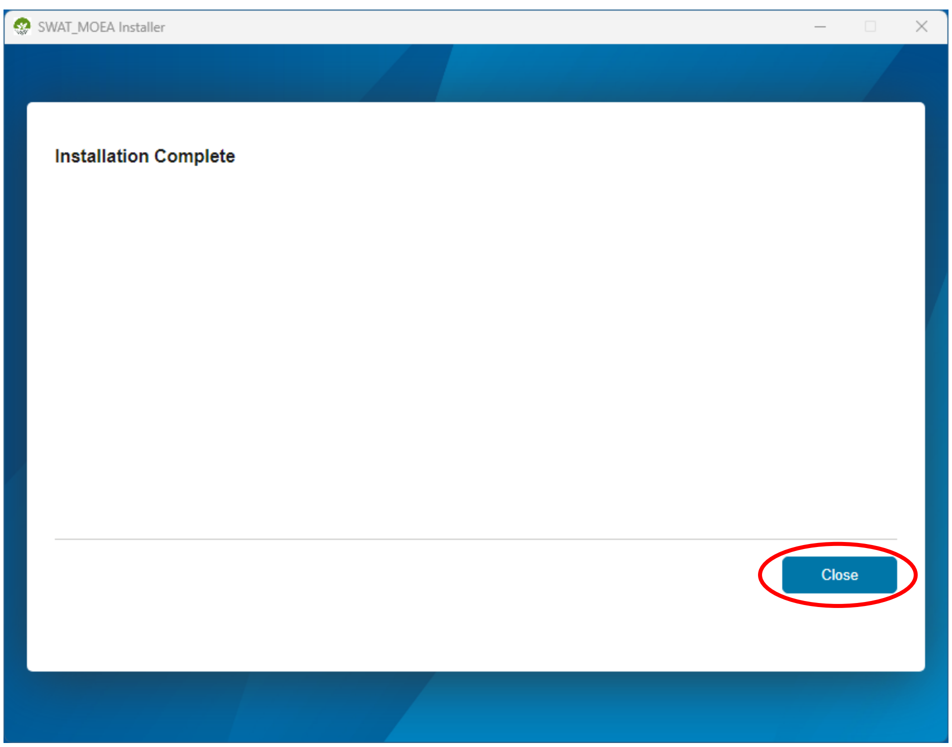


Figure 7. SWAT_MOEA Installer window – Installation Complete

Chapter 3. Project Setup

This chapter is dedicated to demonstrating users the proper setup of SWAT project files to facilitate seamless interaction with SWAT-MOEA. By following these simple steps, you will be able to quickly configure your first SWAT-MOEA project.

3.1 Create new folders

We recommend that you create two separate folders; one for the files require to run SWAT-MOEA tool, and another file to save the results of your SWAT-MOEA Project (Figure 8).

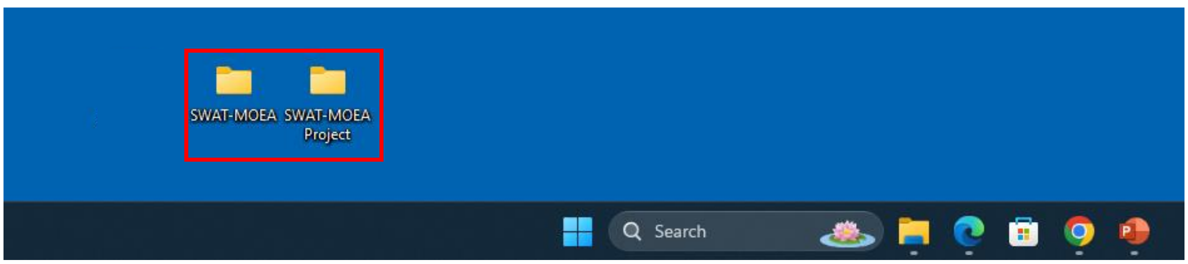


Figure 8. Create two folders

Next, go to **C:\Program Files\USDA-ARS\SWAT_MOEA\application** and **copy/paste** all applications into the **SWAT-MOEA folder.** These should include the SWAT_MOEA application and all different SWAT executable versions (Figure 9).

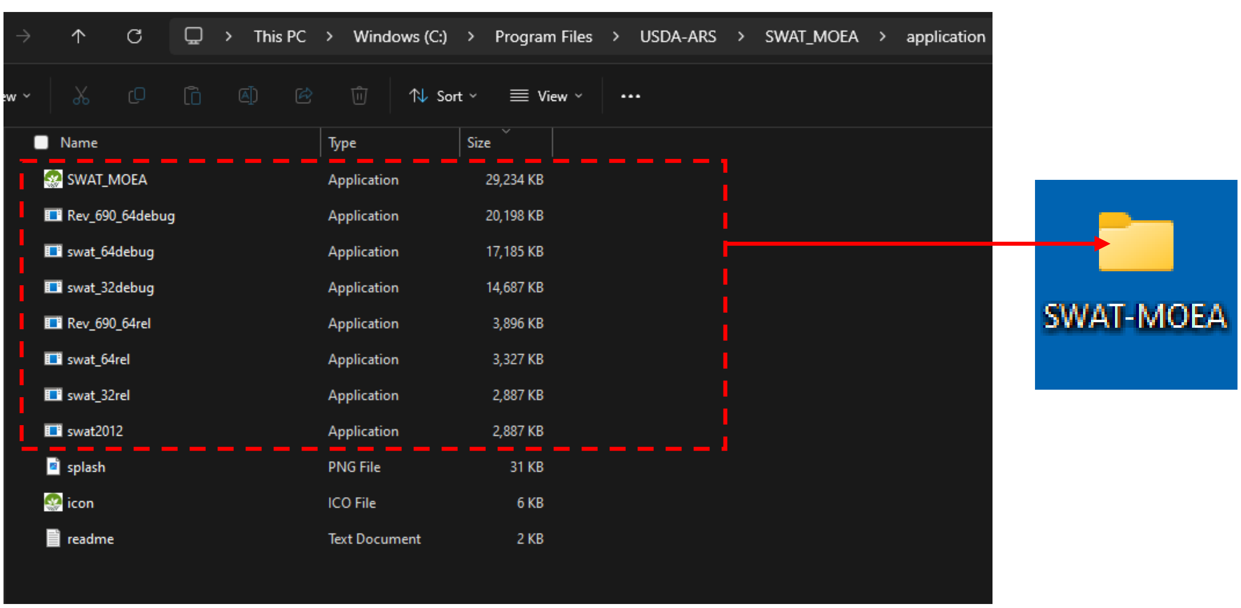


Figure 9. SWAT_MOEA folder – Application files

The **SWAT-MOEA folder** should also include all **SWAT project files, including the shape files.** Make sure you copy/paste these files into the SWAT-MOEA folder (Figure 10).

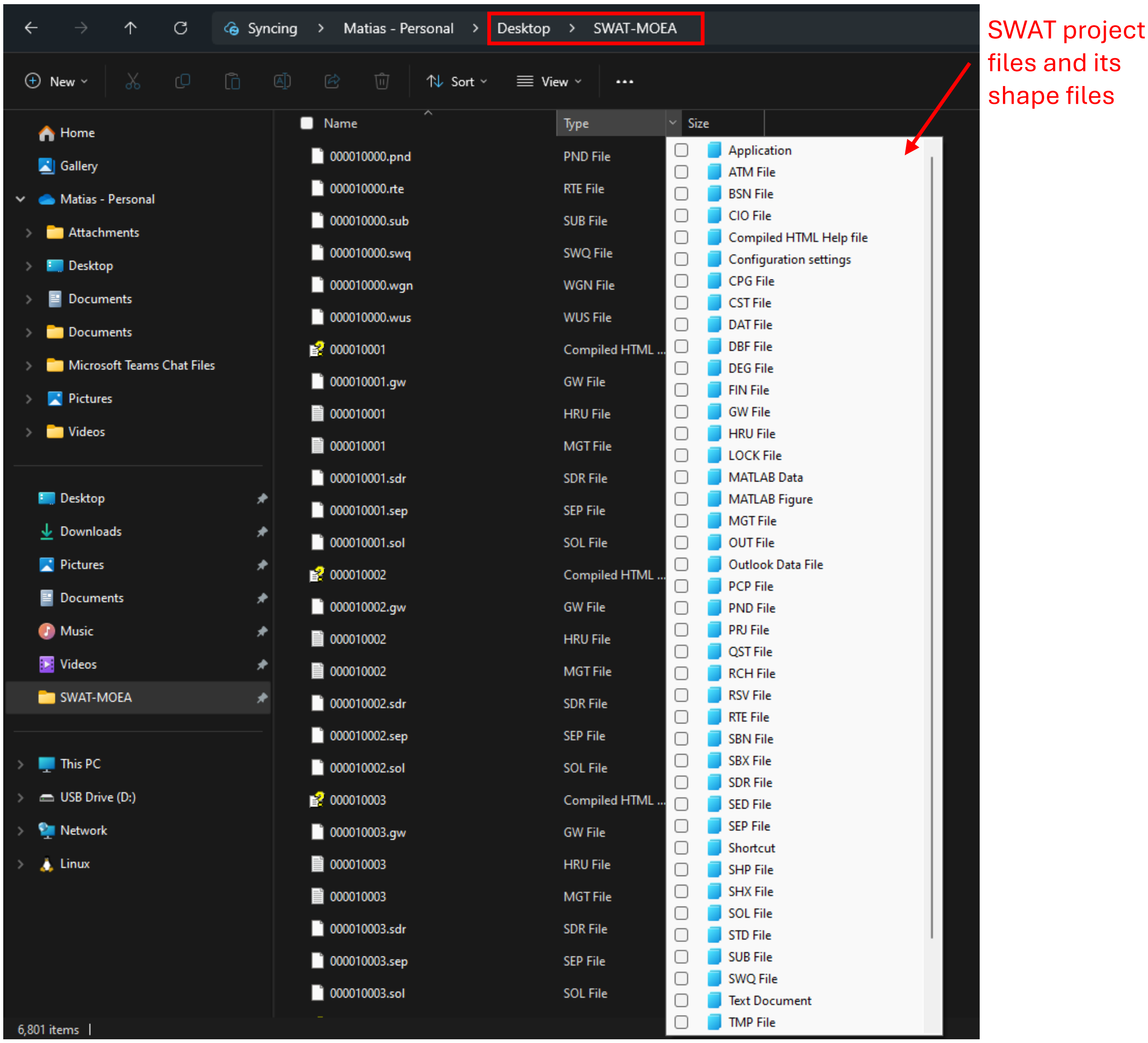


Figure 10. SWAT-MOEA folder – SWAT files

You're all set! To begin your first SWAT-MOEA project, simply **double click** the **SWAT_MOEA application** in the SWAT-MOEA folder (Figure 11).

Figure 11. SWAT-MOEA application

Chapter 4. SWAT-MOEA

This chapter is dedicated to guiding users through the step-by-step utilization of the SWAT-MOEA tool. Here you will find detailed instructions and explanations to help you navigate the functionalities of the software efficiently. Whether you are new to SWAT-MOEA or seeking to enhance your understanding, this chapter aims to provide clear and concise on how to harness the power of this tool in optimizing agricultural management systems using calibrated SWAT projects.

4.1 Begin Project

To start an optimization project in SWAT-MOEA, simply click on the 'BEGIN PROJECT' button in the home page (Figure 12).

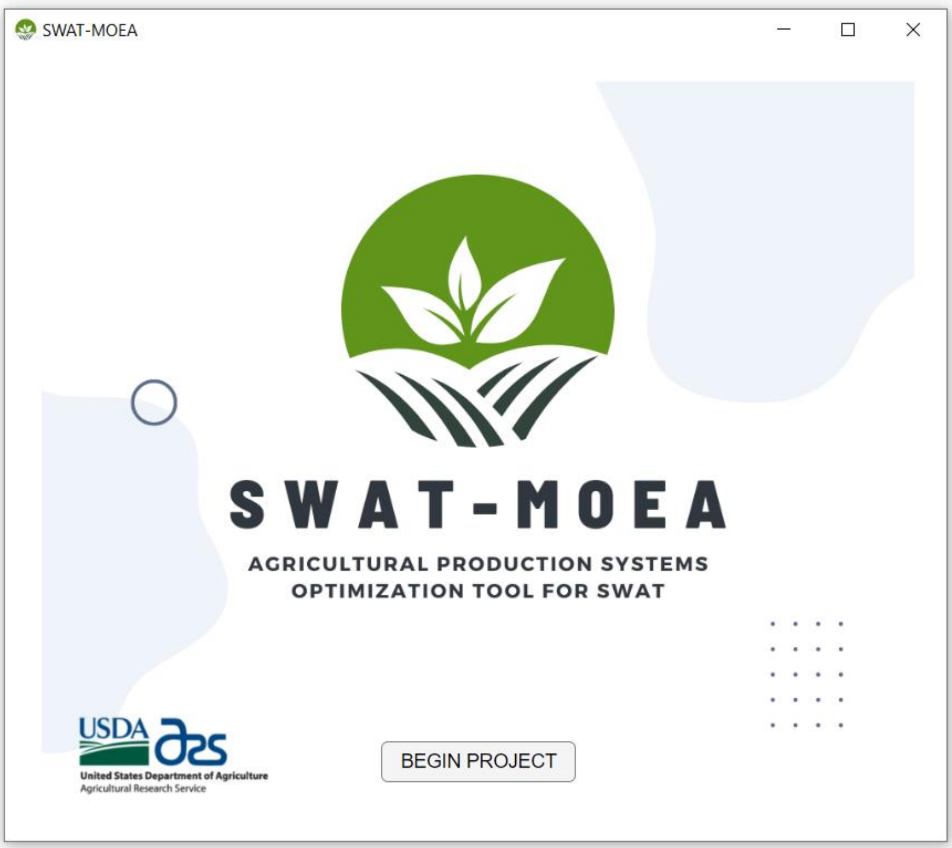


Figure 12. SWAT-MOEA initial window.

4.2 Directory address definition: Saving Optimization Results

When conducting an optimization project within SWAT-MOEA, users are required to indicate the directory address where results will be saved (Figure 13). This window prompts you to type or paste such address.

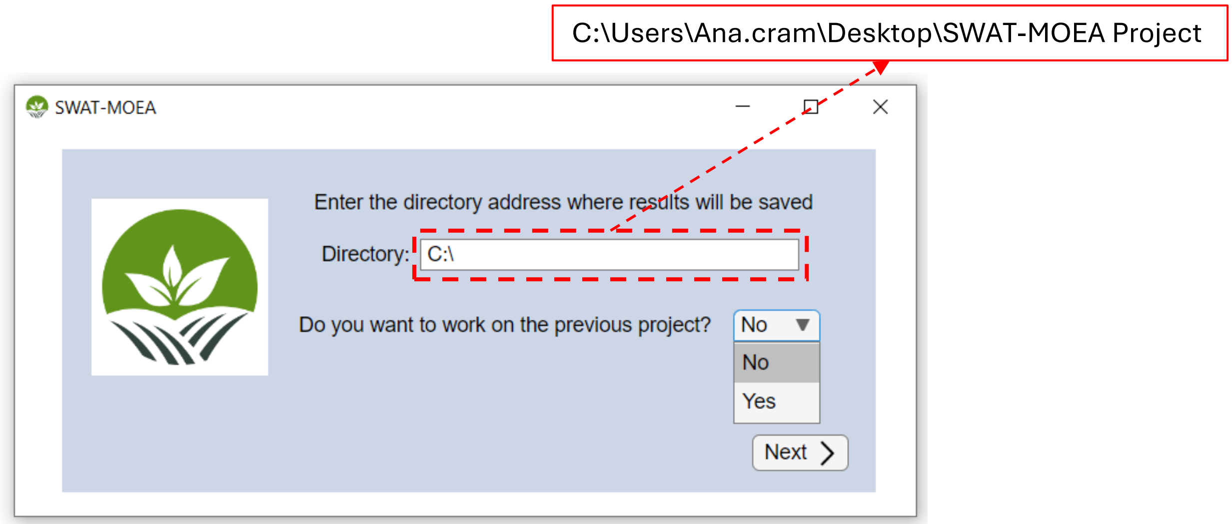


Figure 13. SWAT-MOEA initial window.

Upon completion of the optimization project, you will find several important files in this folder's address. 1) A text file called '*Aspirational Systems*' where all Aspirational Systems (AS) evaluated are saved in SWAT code format; 2) An Excel file called '*SensitivityAnalysis*' where all Pareto solutions are stored; 3) Pareto graphs of suggested solutions; and 4) Geospatial maps of suggested solutions (see chapter 5 for more details).

The SWAT-MOEA tool allows you to upload the last completed project on record. SWAT-MOEA considers a project to be completed when all AS have been executed in SWAT (Section 4.4.6) and the project is ready to proceed to run the MOEA. In this regard, completed projects will include all the setting that will be defined in the following sections.

To upload the previous SWAT-MOEA project, simply select "**Yes**" on the drop-down menu to the question and click "**Next**" to go to the steps describe in Section 4.7.

If you wish to start a new SWAT-MOEA project, select "**No**" on the drop-down menu to the question (Figure 13) and click "**Next**" to go to Section 4.3.

Keep in mind that if an old directory folder address is used in new SWAT-MOEA projects, the files in such folder will be overwritten and previous results will be lost. Make sure you use a different directory folder or save previous SWAT-MOEA result files in a different folder.

4.3 SWAT Executable Selection

Before running optimizations in SWAT-MOEA, it is necessary to specify the SWAT executable version in the simulation intended to study to ensure proper execution of aspirational systems.

SWAT-MOEA offers a variety of SWAT executables for selection. To choose the appropriate one for your simulation, click on the dropdown menu and select the option that corresponds to the executable utilized in your simulation (Figure 14). Then, click "**Next**" to proceed to the next step.

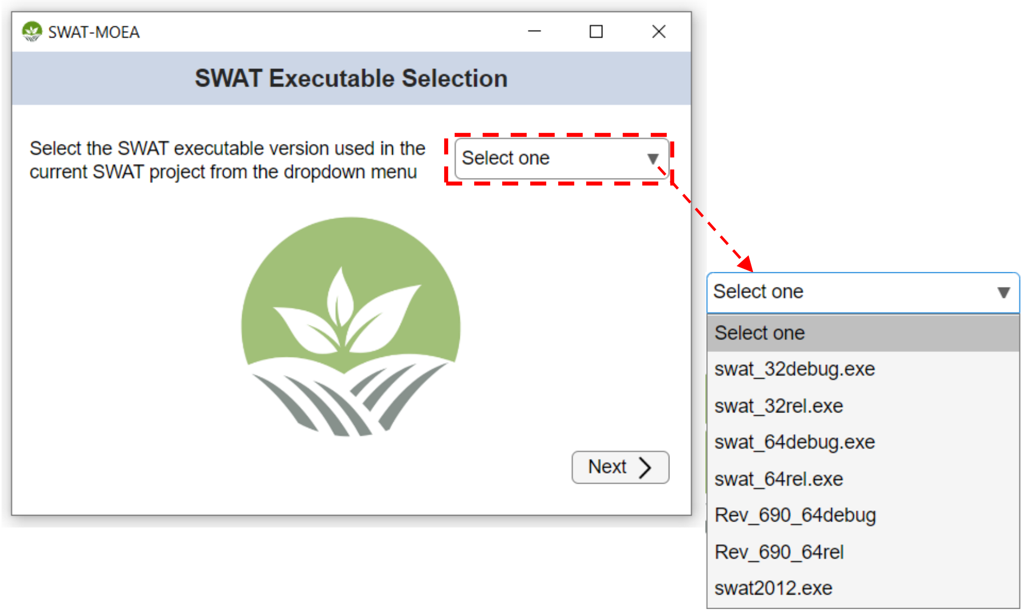


Figure 14. SWAT executable selection.

4.4 Land use definition for optimization

The following step involves selecting Hydrologic Response Units (HRUs) to be included in the optimization study, categorized by land use type. This enables the SWAT-MOEA tool to identify the corresponding SWAT management files (.mgt) for adjusting operation schedules (Figure 15).

```
000010004 - Notepad
File  Edit  Format  View  Help
 .mgt file Watershed HRU:4 Subbasin:1 HRU:4 Luse:GRSG Soil: OK063 Slope: 0-9999 9/7/2018 12:00:00 AM ArcSWAT 2012.10_3.19
               0    | NMGT:Management code
Initial Plant Growth Parameters
               0    | IGRO: Land cover status: 0-none growing; 1-growing
               0    | PLANT_ID: Land cover ID number (IGRO = 1)
            0.00    | LAI_INIT: Initial leaf are index (IGRO = 1)
            0.00    | BIO_INIT: Initial biomass (kg/ha) (IGRO = 1)
            0.00    | PHU_PLT: Number of heat units to bring plant to maturity (IGRO = 1)
General Management Parameters
            0.20    | BIOMIX: Biological mixing efficiency
           68.00    | CN2: Initial SCS CN II value
            1.00    | USLE_P: USLE support practice factor
            0.00    | BIO_MIN: Minimum biomass for grazing (kg/ha)
           0.000    | FILTERW: width of edge of field filter strip (m)
Urban Management Parameters
               0    | IURBAN: urban simulation code, 0-none, 1-USGS, 2-buildup/washoff
               0    | URBLU: urban land type
Irrigation Management Parameters
               0    | IRRSC: irrigation code
               0    | IRRNO: irrigation source location
           0.000    | FLOWMIN: min in-stream flow for irr diversions (m^3/s)
           0.000    | DIVMAX: max irrigation diversion from reach (+mm/-10^4m^3)
           0.000    | FLOWFR: : fraction of flow allowed to be pulled for irr
Tile Drain Management Parameters
           0.000    | DDRAIN: depth to subsurface tile drain (mm)
           0.000    | TDRAIN: time to drain soil to field capacity (hr)
           0.000    | GDRAIN: drain tile lag time (hr)
Management Operations:
               1    | NROT: number of years of rotation
Operation Schedule:
  3 15           3    5          40.00000   0.00
  6  1           5                0.00000
  7  1           6   86           0.00000
  8  1           6   58           0.00000
  9 20           3    5          20.00000   0.00
  9 20           6   61           0.00000
  9 24           6   43           0.00000
  9 25           1   28        1523.27051   0.00      0.00000 0.00    0.00  0.00
 12  1           9   90   45      3.00000   0.47      1.50000
                17
```

Figure 15. SWAT management files (.mgt).

Figure 16 presents the window where SWAT-MOEA allows users to select land use for optimization. You can choose different land use types by **clicking** on one or more 'Plant Codes' listed on the left side of the window. This list encompasses all plant data in SWAT, with the option for users to input additional land use types specific to their SWAT simulation project. To add HRUs with customized land use types, simply **type** the 'Plant Code' at the bottom left of the window and press **Enter**.

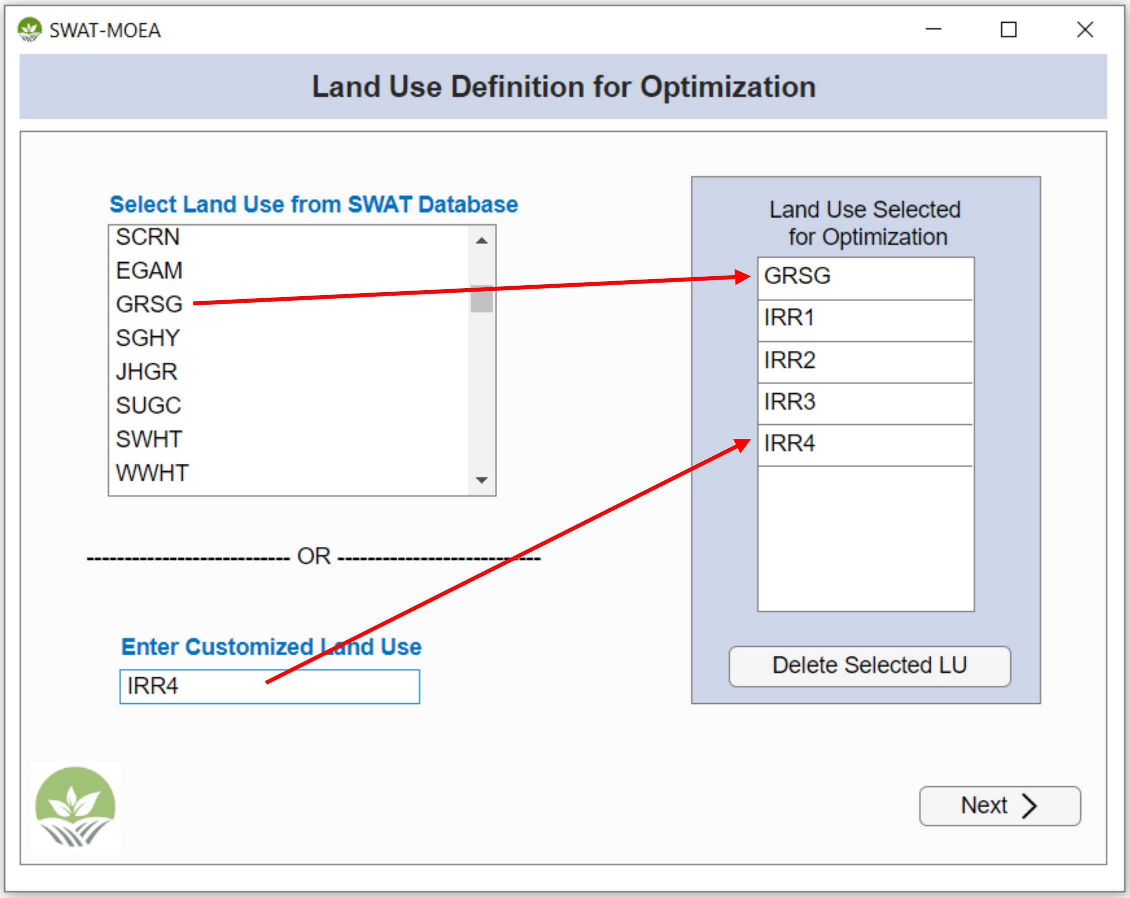


Figure 16. SWAT-MOEA land use definition for optimization.

The table on the right side of the window shows the selected land use types. Once you have finished this step, click on the "**Next**" button at the bottom right to proceed.

Important: It is crucial to select the HRUs that are part of the simulation being used to avoid errors; otherwise, the SWAT-MOEA tool will not locate them in the .mgt files. To remove selected 'Plant Codes' from the table, simply click on them with your mouse and then press the 'Delete Selected LU' bottom at the bottom of the table.

4.5 Definition of Objective Functions

This step involves selecting the optimization objective functions to be evaluated by the MOEA (Figure 17). You have the flexibility to choose multiple objectives for either maximizing and/or minimizing that reflect regional priorities. Your selections will be listed in the tables on the right of the window.

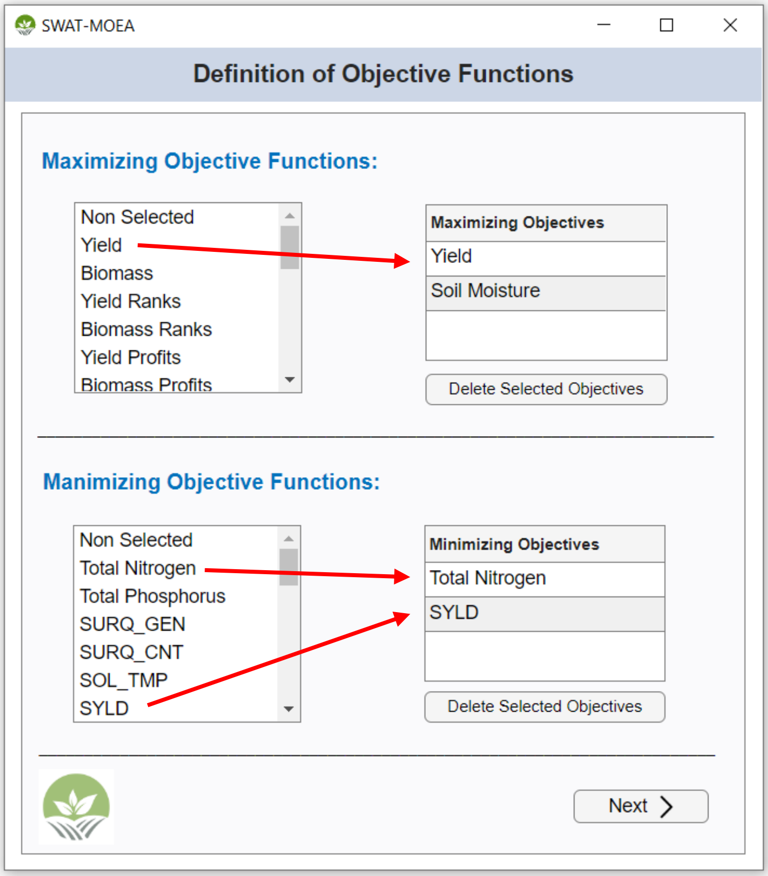


Figure 17. Definition of objective functions.

Here, we will provide a concise overview of how the SWAT-MOEA tool extracts or estimates these values. This extraction process encompasses both the prevailing system, which represents the current simulation, and any additional aspirational systems that the user plans to execute in the subsequent step.

4.4.1 Maximizing Objective Functions

Table 1. provides the complete list of maximizing objective functions available within SWAT-MOEA. These can be broken down into 4 major categories: (a) Productivity; (b) Economics; (c) Environmental; and (d) Water availability/water quantity

Table 1. Maximizing objective functions.

Category	Variable Name	Description
Productivity	Yld[1]	Yield
	Biom[1]	Biomass
	Rank_Yld[2]	Rank Yields
	Rank_Biom[2]	Rank Biomass
Economics	Profit_Yld[3]	Profits from yields
	Profit_Biom[3]	Profits from biomass
Environmental	SOL_TMP[4]	Soil temperature (℃)
	CMUP_KGH[4]	Current soil carbon for first soil layer ($kg\ ha^{-1}$)
	CMTOT_KGH[4]	Current soil carbon integrated -aggregating all soil layers ($kg\ ha^{-1}$)
Water availability/water quantity	Soil Moisture (SM)[5]	SM = SW_END - SW_INIT
	PERC[4]	Water that percolates past the root zone (mm H2O)
	GW_RCHG[4]	Recharge entering aquifers (mm H2O)
	DA_RCHG[4]	Deep aquifer recharge (mm H2O)
	REVAP[4]	Water in the shallow aquifer returning to the root zone in response to a moisture deficit (mm H2O)
	SA_ST[4]	Shallow aquifer storage (mm H2O)
	DA_ST[4]	Deep aquifer storage (mm H2O)
	TLOSS[4]	Transmission losses (mm H2O)
	LATQ[4]	Lateral flow contribution to streamflow (mm H2O)
	GW_Q[4]	Groundwater contribution to streamflow (mm H2O)
	WYLD[4]	Water yield (mm H2O)
	LATQCNT[4]	Lateral flow contributed after pond and wetland losses and after lagging (mm H2O)

[1] Average plant values from the output.std file

[2] Estimated with user-defined ranking weights to intervals of crop production and average plant values from output.std file

[3] Estimated with user's input costs of systems and average plant values from output.std file

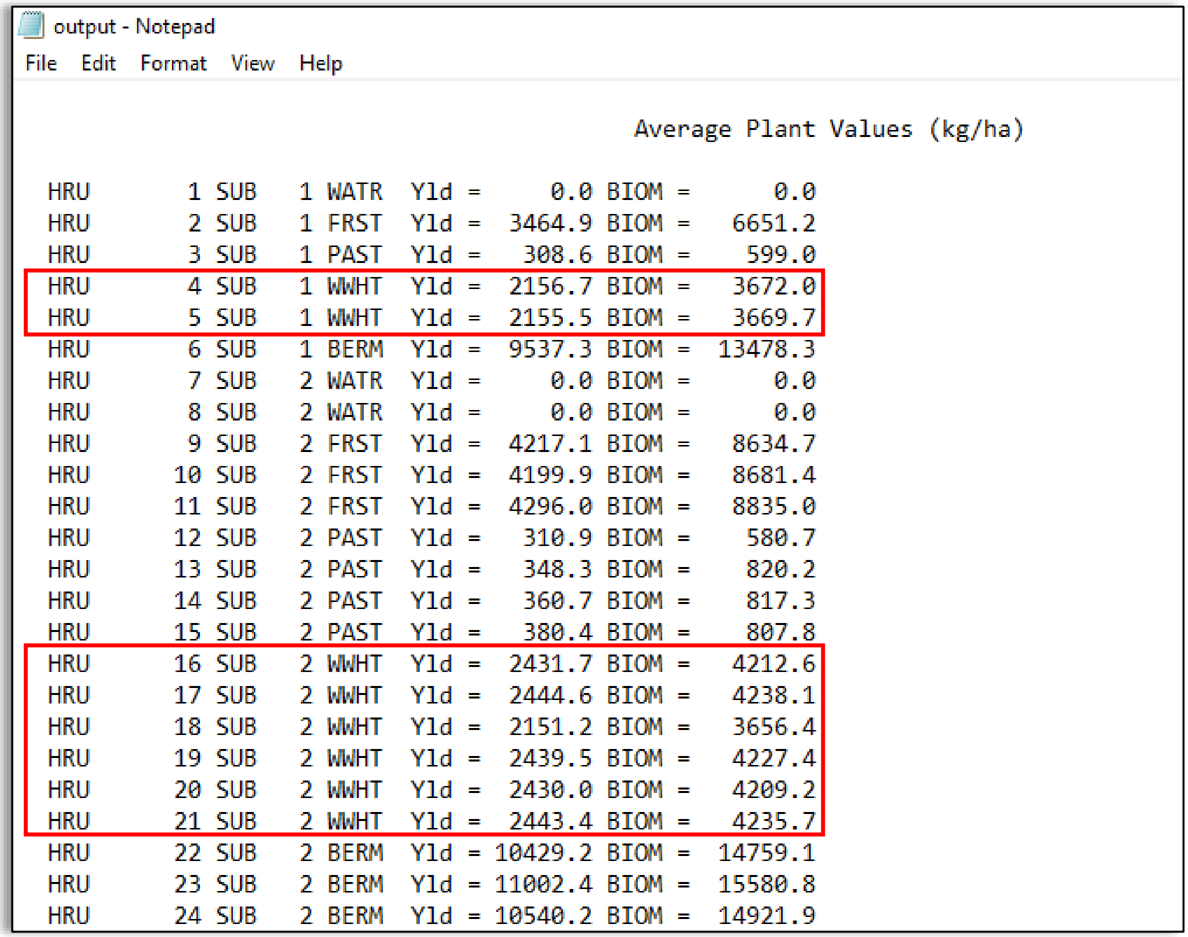
[4] Average variable values from the output.hru file

[5] Sum of variables from the output.hru file

a) Productivity Objectives

The goal of agricultural productivity is to increase crop output values.

When **Yield** and/or **Biomass** objectives are selected, the SWAT-MOEA tool retrieves these values from 'Average Plant Values' section of the *output.std file*, specifically for HRUs selected for optimization (as discussed in Section 4.4; Figure 18).



```
output - Notepad
File  Edit  Format  View  Help

                                    Average Plant Values (kg/ha)

HRU        1 SUB   1 WATR  Yld =     0.0 BIOM =     0.0
HRU        2 SUB   1 FRST  Yld =  3464.9 BIOM =  6651.2
HRU        3 SUB   1 PAST  Yld =   308.6 BIOM =   599.0
HRU        4 SUB   1 WWHT  Yld =  2156.7 BIOM =  3672.0
HRU        5 SUB   1 WWHT  Yld =  2155.5 BIOM =  3669.7
HRU        6 SUB   1 BERM  Yld =  9537.3 BIOM = 13478.3
HRU        7 SUB   2 WATR  Yld =     0.0 BIOM =     0.0
HRU        8 SUB   2 WATR  Yld =     0.0 BIOM =     0.0
HRU        9 SUB   2 FRST  Yld =  4217.1 BIOM =  8634.7
HRU       10 SUB   2 FRST  Yld =  4199.9 BIOM =  8681.4
HRU       11 SUB   2 FRST  Yld =  4296.0 BIOM =  8835.0
HRU       12 SUB   2 PAST  Yld =   310.9 BIOM =   580.7
HRU       13 SUB   2 PAST  Yld =   348.3 BIOM =   820.2
HRU       14 SUB   2 PAST  Yld =   360.7 BIOM =   817.3
HRU       15 SUB   2 PAST  Yld =   380.4 BIOM =   807.8
HRU       16 SUB   2 WWHT  Yld =  2431.7 BIOM =  4212.6
HRU       17 SUB   2 WWHT  Yld =  2444.6 BIOM =  4238.1
HRU       18 SUB   2 WWHT  Yld =  2151.2 BIOM =  3656.4
HRU       19 SUB   2 WWHT  Yld =  2439.5 BIOM =  4227.4
HRU       20 SUB   2 WWHT  Yld =  2430.0 BIOM =  4209.2
HRU       21 SUB   2 WWHT  Yld =  2443.4 BIOM =  4235.7
HRU       22 SUB   2 BERM  Yld = 10429.2 BIOM = 14759.1
HRU       23 SUB   2 BERM  Yld = 11002.4 BIOM = 15580.8
HRU       24 SUB   2 BERM  Yld = 10540.2 BIOM = 14921.9
```

Figure 18. SWAT output.std file.

When **Rank Yield** and/or **Rank Biomass** are selected, new pop-up windows will promptly appear on your screen (Figure 19). In these windows, you can enter your customized intervals of crop production to the predefined rank values, ranging from 0 to 5.

This approach facilitates a normalized comparison of management systems, particularly when comparing different crops across different systems.

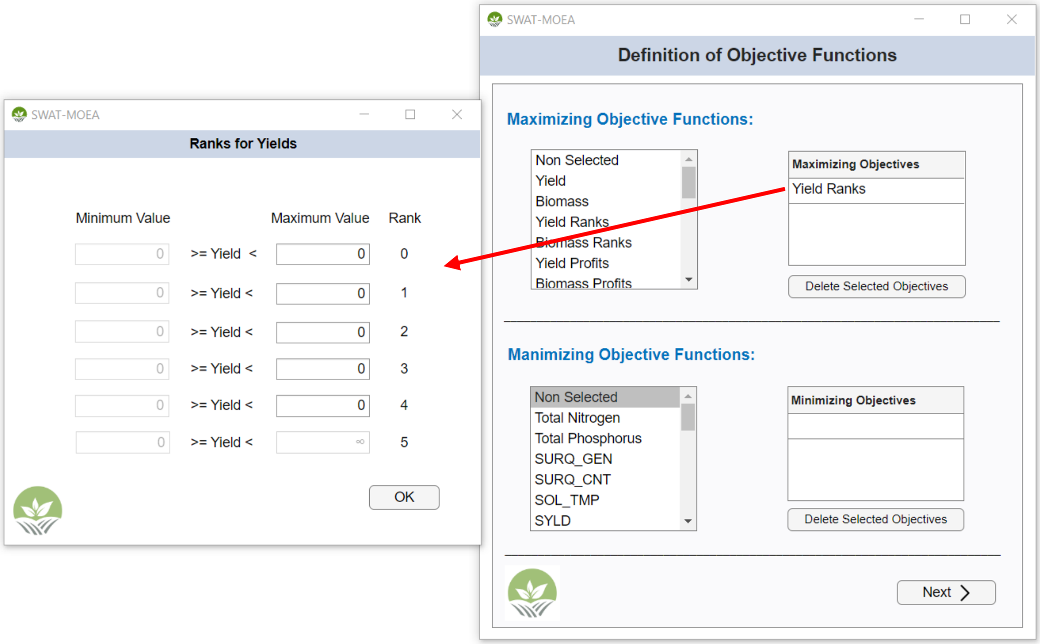


Figure 19. Ranks for yields.

Figure 20 shows how the ranking value operates:

- Rank 0 is assigned to crop production values ranging from 0 to the specified value determined by the user.
- This specified value automatically sets the starting interval for Rank 1.
- Within Rank 1, the user will once again establish the upper bound value.
- This process repeats for subsequential ranks.

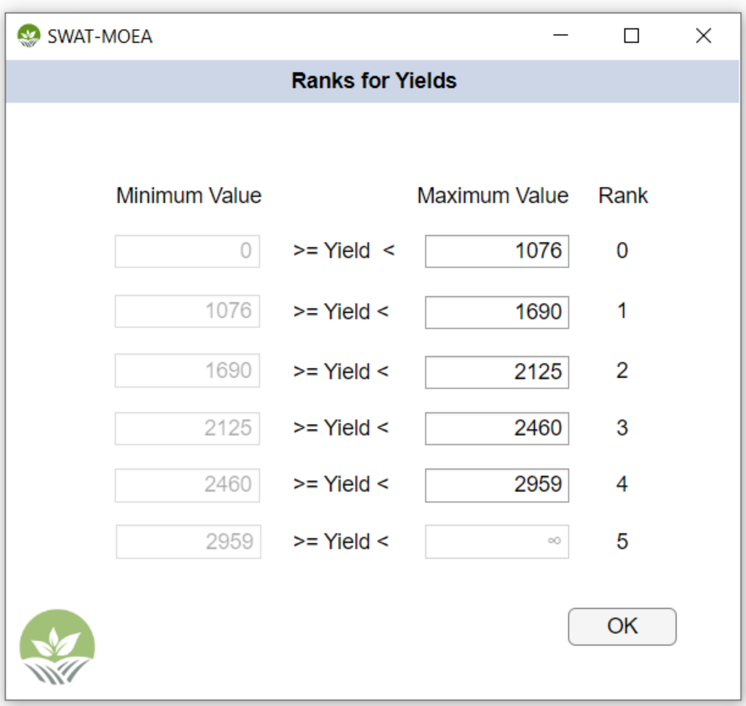


Figure 20. Example of ranks for yields.

Once you are finished setting up these interval values, press the **OK** button.

b) Economic Objectives

An important aspect of crop yields and biomass is their economic value. The objective functions that estimate such economic aspects are Yield Profits and Biomass Profits. When either one of these is selected, new pop-up windows will promptly appear on your screen (Figure 21).

The first window displays a list of crops found in the 'Average Plant Values' section of the *output.std* file. Users are required to input market values corresponding to the crops in HRUs under optimization (as discussed in Section 4.4).

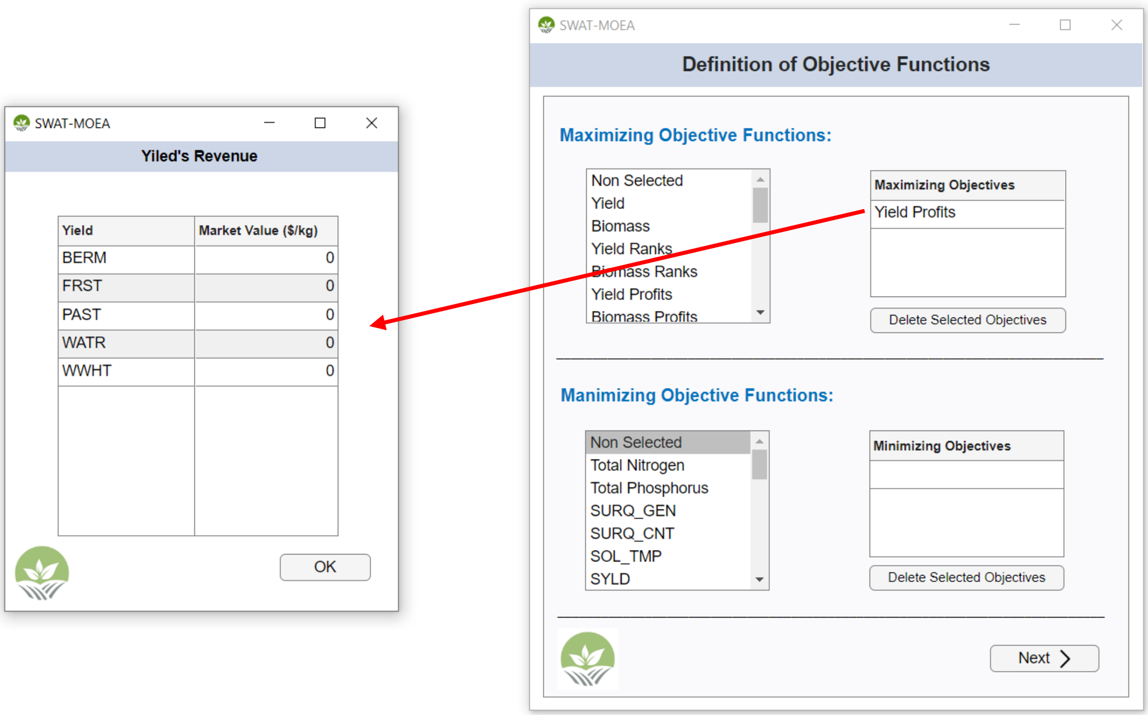


Figure 21. Yield's revenue.

This process enables the SWAT-MOEA tool to estimate the revenue generated from yields or biomass in the prevailing system, or initial simulation. This estimate is achieved by multiplying the market values entered by the user with the 'Average Plant Values' extracted from the *output.std* file (Figure 22).

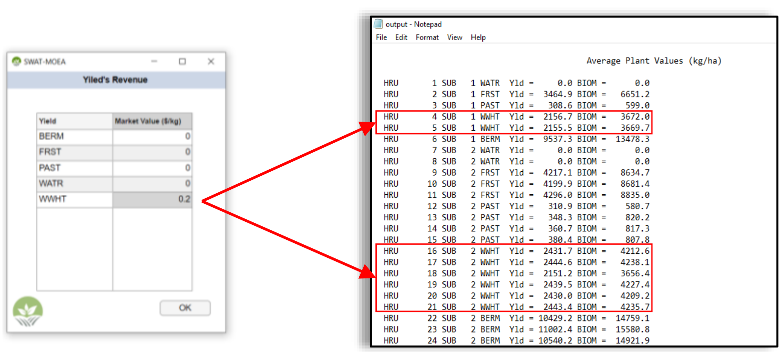
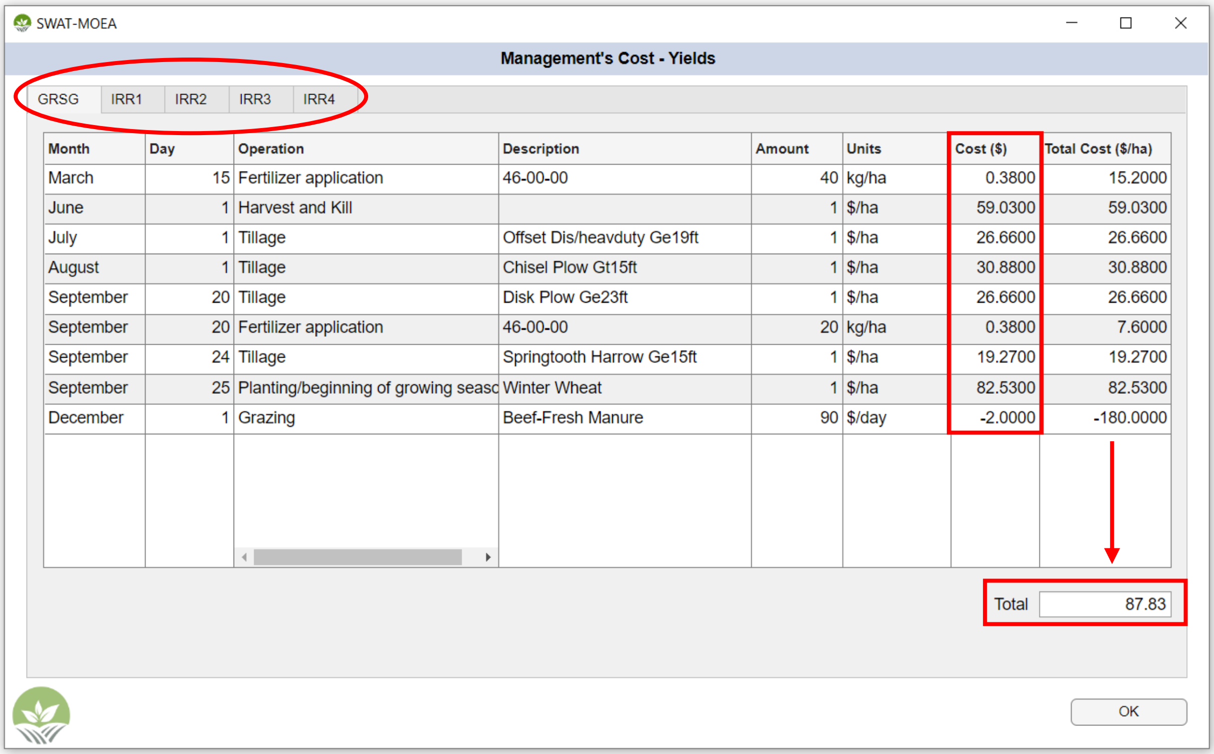


Figure 22. Process to estimate yield's revenue.

After entering market crop values, simply click **OK** to proceed with the next step. This action will prompt a second window to appear on your screen (Figure 23). In this window, the associated costs of the prevailing system will be estimated.

The window displays operation schedules across different tab windows, each corresponding to HRUs previously categorized by land use type (as discussed in Section 4.4). Suggested costs for each operation are also displayed, sourced from the SWAT-MOEA database, or set to 0 if unavailable. Negative cost values denote profit of that operation.



Month	Day	Operation	Description	Amount	Units	Cost ($)	Total Cost ($/ha)
March	15	Fertilizer application	46-00-00	40	kg/ha	0.3800	15.2000
June	1	Harvest and Kill		1	$/ha	59.0300	59.0300
July	1	Tillage	Offset Dis/heavduty Ge19ft	1	$/ha	26.6600	26.6600
August	1	Tillage	Chisel Plow Gt15ft	1	$/ha	30.8800	30.8800
September	20	Tillage	Disk Plow Ge23ft	1	$/ha	26.6600	26.6600
September	20	Fertilizer application	46-00-00	20	kg/ha	0.3800	7.6000
September	24	Tillage	Springtooth Harrow Ge15ft	1	$/ha	19.2700	19.2700
September	25	Planting/beginning of growing seasc	Winter Wheat	1	$/ha	82.5300	82.5300
December	1	Grazing	Beef-Fresh Manure	90	$/day	-2.0000	-180.0000

Figure 23. Management's cost.

Users have the flexibility to edit these cost fields according to their own study requirements. To **modify a cost**, simply **enter the desired value** in the corresponding field.

The total cost for each operation are computed by multiplying the cost of by its quantity. The sum of all total cost is displayed at the bottom right corner, representing the total estimated cost for the prevailing system corresponding to those HRUs.

SWAT-MOEA estimates profits by subtracting estimated costs to the estimated revenue for each HRU.

c) Environmental Objectives

Agricultural management practices can have a positive impact on the environment. The objectives available to maximize listed in Table 1 are extracted from the average values (last values) of the *output.hru* file (Figure 24).

```
1
    SWAT Dec 23 2016    VER 2016/Rev 664                                           0/ 0/   0      0: 0: 0

    General Input/Output section (file.cio):
    9/7/2018 12:00:00 AM ARCGIS-SWAT interface AV

LULC  HRU       GIS  SUB  MGT  MON    AREAkm2  PRECIPmm SNOFALLmm SNOMELTmm     IRRmm     PETmm      ETmm SW_INITmm  SW_ENDmm    PERCmm GW_RCHGmm DA_RCHGmm   REVAPmm  SA_IRRmm
WATR    1 000010001    1    0 1995.93097E-01   922.500     0.000     0.000     0.000  2033.740  1423.618     0.000   116.817     0.000     0.000     0.000     0.000     0.000
FRST    2 000010002    1    0 1995.13331E+00   922.500    20.800    20.800     0.000  1820.703   940.869   175.040   106.872     0.000     0.000     0.000    36.414     0.000
PAST    3 000010003    1    0 1995.66950E+01   922.500    20.800    20.800     0.000  1820.703   720.765   228.178   280.604     7.136     7.054     4.232    36.414     0.000
WWHT    4 000010004    1    0 1995.12113E+01   922.500    20.800    20.800     0.000  1820.703   761.655   230.947   218.166    74.278    71.013    42.608    36.414     0.000
WWHT    5 000010005    1    0 1995.77727E+01   922.500    20.800    20.800     0.000  1820.703   761.608   230.932   218.205    74.148    70.889    42.533    36.414     0.000
BERM    6 000010006    1    0 1995.48817E+00   922.500    20.800    20.800     0.000  1820.703   711.011    85.834    63.120     0.000     0.000     0.000    36.414     0.000
WATR    7 000020001    2    0 1995.21282E-02  1039.900     0.000     0.000     0.000  2021.462  1415.023     0.000   128.024     0.000     0.000     0.000     0.000     0.000
WATR    8 000020002    2    0 1995.33885E+00  1039.900     0.000     0.000     0.000  2021.462  1415.023     0.000   119.874     0.000     0.000     0.000     0.000     0.000
FRST    9 000020003    2    0 1995.84088E-02  1039.900    31.500    31.500     0.000  1796.262   878.977   193.798   133.195    40.741    40.679    24.408    35.925     0.000
FRST   10 000020004    2    0 1995.11609E+00  1039.900    31.500    31.500     0.000  1796.262   886.342   269.027   272.160     7.267     7.231     4.339    35.925     0.000
FRST   11 000020005    2    0 1995.87980E+00  1039.900    31.500    31.500     0.000  1796.262   782.870   285.651   280.270    22.780    22.687    13.612    35.925     0.000
PAST   12 000020006    2    0 1995.18437E+00  1039.900    31.500    31.500     0.000  1796.262   763.894   239.526   274.265    40.713    40.325    24.195    35.925     0.000
PAST   13 000020007    2    0 1995.73545E-01  1039.900    31.500    31.500     0.000  1796.262   700.541   212.520   216.284    36.287    36.130    21.678    35.925     0.000
PAST   14 000020008    2    0 1995.19594E+01  1039.900    31.500    31.500     0.000  1796.262   747.120   285.229   330.483    21.283    20.974    12.585    35.925     0.000
PAST   15 000020009    2    0 1995.80378E+01  1039.900    31.500    31.500     0.000  1796.262   635.723   287.010   331.509    43.371    42.754    25.652    35.925     0.000
WWHT   16 000020010    2    0 1995.32639E+00  1039.900    31.500    31.500     0.000  1796.262   761.135   330.723   305.898    76.290    74.502    44.701    35.925     0.000
WWHT   17 000020011    2    0 1995.24849E+00  1039.900    31.500    31.500     0.000  1796.262   677.601   337.576   307.568    98.923   105.824    63.494    35.925     0.000
WWHT   18 000020012    2    0 1995.17920E+00  1039.900    31.500    31.500     0.000  1796.262   788.065   293.325   224.397   144.838   141.425    84.855    35.925     0.000
WWHT   19 000020013    2    0 1995.10151E+00  1039.900    31.500    31.500     0.000  1796.262   690.278   249.319   195.558   161.362   165.145    99.087    35.925     0.000
WWHT   20 000020014    2    0 1995.26031E+01  1039.900    31.500    31.500     0.000  1796.262   761.095   330.726   305.930    76.286    74.498    44.699    35.925     0.000
WWHT   21 000020015    2    0 1995.20102E+01  1039.900    31.500    31.500     0.000  1796.262   677.769   337.626   307.633    99.073   106.003    63.602    35.925     0.000
BERM   22 000020016    2    0 1995.20261E-02  1039.900    31.500    31.500     0.000  1796.262   802.153    95.142    70.761     0.000     0.000     0.000    35.925     0.000
BERM   23 000020017    2    0 1995.77495E-01  1039.900    31.500    31.500     0.000  1796.262   738.798   112.486    89.335     0.000     0.000     0.000    35.925     0.000
BERM   24 000020018    2    0 1995.17181E+00  1039.900    31.500    31.500     0.000  1796.262   794.617   128.049   105.240     0.000     0.000     0.000    35.925     0.000
BERM   25 000020019    2    0 1995.38221E+00  1039.900    31.500    31.500     0.000  1796.262   743.160   163.124   149.601     0.000     0.000     0.000    35.925     0.000
WWHT   26 000020020    2    0 1995.19146E+00  1039.900    31.500    31.500     0.000  1796.262   761.081   330.695   305.895    76.189    74.405    44.643    35.925     0.000
WWHT   27 000020021    2    0 1995.31302E+00  1039.900    31.500    31.500     0.000  1796.262   679.832   337.967   307.664   100.281   107.463    64.478    35.925     0.000
WWHT   28 000020022    2    0 1995.64427E-01  1039.900    31.500    31.500     0.000  1796.262   761.104   330.746   305.953    76.345    74.555    44.733    35.925     0.000
WATR   29 000030001    3    0 1995.18812E+00   922.500     0.000     0.000     0.000  2033.740  1423.618     0.000   116.817     0.000     0.000     0.000     0.000     0.000
```

Figure 24. SWAT's output.hru file.

d) Water Availability/Water Quantity Objectives

Agricultural management practices can also have a positive impact on water availability and water quantity. The objectives available to maximize, listed in Table 1, are similarly extracted from the *output.hru* file.

Additionally, the SWAT-MOEA tool offers a **Soil Moisture (SM)** objective function, which is the result of subtracting the initial soil water content (SW_INIT) and the end soil water content (SW_END) variables from the *output.hru* file.

SM = SW_END - SW_INIT

4.4.2 Minimizing Objective Functions

Table 2. provides the complete list of minimizing objective functions available within SWAT-MOEA. These can be broken down into 2 categories: (a) Environmental; and (b) Water availability/water quantity.

Table 2. Minimizing objective functions.

Category	Variable Name	Description
Environmental	Total Nitrogen (TN)[5]	TN = ORGN + NSURQ
	Total Phosphorous (TP)[5]	TP = ORGP + SEDP + SOLP
	SURQ_GEN[4]	Surface runoff generated in HRU (mm H2O)
	SURQ_CNT[4]	Surface runoff contribution to streamflow in the main channel (mm H2O)
	SOL_TMP[4]	Soil temperature (℃)
	SYLD[4]	Sediment yield (metric tons/ha)
	ORGN[4]	Organic Nitrogen yield ($\mathrm{kg\ ha^{-1}}$)
	ORGP[4]	Organic Phosphorus yield ($\mathrm{kg\ ha^{-1}}$)
	SEDP[4]	Sediment Phosphorus yield ($\mathrm{kg\ ha^{-1}}$)
	NSURQ[4]	Nitrate in surface runoff ($\mathrm{kg\ ha^{-1}}$)
	NLATQ[4]	Nitrate in lateral flow ($\mathrm{kg\ ha^{-1}}$)
	NO3L[4]	Nitrate leached from the soil profile ($\mathrm{kg\ ha^{-1}}$)
	NO3GW[4]	Nitrate transported into the main channel in the groundwater loading from the HRU ($\mathrm{kg\ ha^{-1}}$)
	SOLP[4]	Soluble phosphorus yield ($\mathrm{kg\ ha^{-1}}$)
	P_WG[4]	Soluble phosphorus transported by groundwater flow into main channel ($\mathrm{kg\ ha^{-1}}$)
	BACTP[4]	Number of persistent bacteria in surface runoff entering reach ($\mathrm{\#cfu\ 100ml^{-1}}$)
	BACTLP[4]	Number of less persistent bacteria in surface runoff entering reach ($\mathrm{\#cfu\ 100ml^{-1}}$)
	TILENO3[4]	Nitrate in tile flow ($\mathrm{kg\ ha^{-1}}$)
	LATNO3[4]	Nitrate-Nitrogen in lateral flow ($\mathrm{kg\ ha^{-1}}$)
	VAP_TILE[4]	Soluble phosphorus leached through the soil profile through cracks ($\mathrm{kg\ ha^{-1}}$)

Water availability/water quantity	IRR[4]	Irrigation (mm H2O)
	PERC[4]	Water that percolates past the root zone (mm H2O)
	GW_RCHG[4]	Recharge entering aquifers (mm H2O)
	DA_RCHG[4]	Deep aquifer recharge (mm H2O)
	SA_IRR[4]	Irrigation from shallow aquifer (mm H2O)
	DA_IRR[4]	Irrigation from deep aquifer (mm H2O)
	QTILE[4]	Drainage tile flow total (mm H2O)

[4] Average variable values from the output.hru file

[5] Sum of variables from the output.hru file

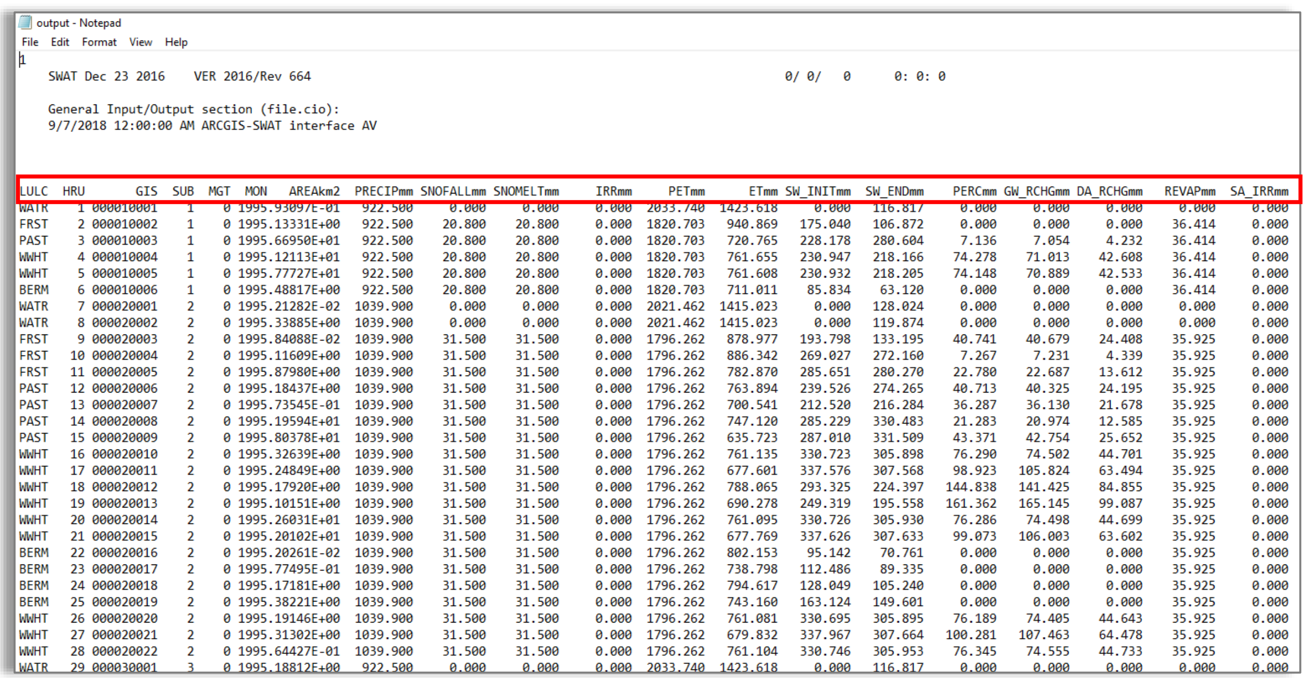
a) Environmental Objectives

Agricultural management practices can have a negative impact on the environment. The objectives available to minimize within SWAT-MOEA listed in Table 2 are also are extracted from the average values (last values) of the *output.hru* file (Figure 25).

Additionally, the SWAT-MOEA tool offers a **Total Nitrogen (TN)** objective function, and a **Total Phosphorus (TP).** These objective functions are estimated with the sum of the following variables in the *output.hru* file:

$$TN=ORGN + NSURQ$$

$$TP=ORGP + SEDP + SOLP$$



LULC	HRU	GIS	SUB	MGT	MON	AREAkm2	PRECIPmm	SNOFALLmm	SNOMELTmm	IRRmm	PETmm	ETmm	SW_INITmm	SW_ENDmm	PERCmm	GW_RCHGmm	DA_RCHGmm	REVAPmm	SA_IRRmm
WATR	1	000010001	1	0	1995	.93097E-01	922.500	0.000	0.000	0.000	2033.740	1423.618	0.000	116.817	0.000	0.000	0.000	0.000	0.000
FRST	2	000010002	1	0	1995	.13331E+00	922.500	20.800	20.800	0.000	1820.703	940.869	175.040	106.872	0.000	0.000	0.000	36.414	0.000
PAST	3	000010003	1	0	1995	.66950E+01	922.500	20.800	20.800	0.000	1820.703	720.765	228.178	280.604	7.136	7.054	4.232	36.414	0.000
WWHT	4	000010004	1	0	1995	.12113E+01	922.500	20.800	20.800	0.000	1820.703	761.655	230.947	218.166	74.278	71.013	42.608	36.414	0.000
WWHT	5	000010005	1	0	1995	.77727E+01	922.500	20.800	20.800	0.000	1820.703	761.608	230.932	218.205	74.148	70.889	42.533	36.414	0.000
BERM	6	000010006	1	0	1995	.48817E+00	922.500	20.800	20.800	0.000	1820.703	711.011	85.834	63.120	0.000	0.000	0.000	36.414	0.000
WATR	7	000020001	2	0	1995	.21282E-02	1039.900	0.000	0.000	0.000	2021.462	1415.023	0.000	128.024	0.000	0.000	0.000	0.000	0.000
WATR	8	000020002	2	0	1995	.33885E+00	1039.900	0.000	0.000	0.000	2021.462	1415.023	0.000	119.874	0.000	0.000	0.000	0.000	0.000
FRST	9	000020003	2	0	1995	.84088E-02	1039.900	31.500	31.500	0.000	1796.262	878.977	193.798	133.195	40.741	40.679	24.408	35.925	0.000
FRST	10	000020004	2	0	1995	.11609E+00	1039.900	31.500	31.500	0.000	1796.262	886.342	269.027	272.160	7.267	7.231	4.339	35.925	0.000
FRST	11	000020005	2	0	1995	.87980E+00	1039.900	31.500	31.500	0.000	1796.262	782.870	285.651	280.270	22.780	22.687	13.612	35.925	0.000
PAST	12	000020006	2	0	1995	.18437E+00	1039.900	31.500	31.500	0.000	1796.262	763.894	239.526	274.265	40.713	40.325	24.195	35.925	0.000
PAST	13	000020007	2	0	1995	.73545E-01	1039.900	31.500	31.500	0.000	1796.262	700.541	212.520	216.284	36.287	36.130	21.678	35.925	0.000
PAST	14	000020008	2	0	1995	.19594E+01	1039.900	31.500	31.500	0.000	1796.262	747.120	285.229	330.483	21.283	20.974	12.585	35.925	0.000
PAST	15	000020009	2	0	1995	.80378E+01	1039.900	31.500	31.500	0.000	1796.262	635.723	287.010	331.509	43.371	42.754	25.652	35.925	0.000
WWHT	16	000020010	2	0	1995	.32639E+00	1039.900	31.500	31.500	0.000	1796.262	761.135	330.723	305.898	76.290	74.502	44.701	35.925	0.000
WWHT	17	000020011	2	0	1995	.24849E+00	1039.900	31.500	31.500	0.000	1796.262	677.601	337.576	307.568	98.923	105.824	63.494	35.925	0.000
WWHT	18	000020012	2	0	1995	.17920E+00	1039.900	31.500	31.500	0.000	1796.262	788.065	293.325	224.397	144.838	141.425	84.855	35.925	0.000
WWHT	19	000020013	2	0	1995	.10151E+00	1039.900	31.500	31.500	0.000	1796.262	690.278	249.319	195.558	161.362	165.145	99.087	35.925	0.000
WWHT	20	000020014	2	0	1995	.26031E+01	1039.900	31.500	31.500	0.000	1796.262	761.095	330.726	305.930	76.286	74.498	44.699	35.925	0.000
WWHT	21	000020015	2	0	1995	.20102E+01	1039.900	31.500	31.500	0.000	1796.262	677.769	337.626	307.633	99.073	106.003	63.602	35.925	0.000
BERM	22	000020016	2	0	1995	.20261E-02	1039.900	31.500	31.500	0.000	1796.262	802.153	95.142	70.761	0.000	0.000	0.000	35.925	0.000
BERM	23	000020017	2	0	1995	.77495E-01	1039.900	31.500	31.500	0.000	1796.262	738.798	112.486	89.335	0.000	0.000	0.000	35.925	0.000
BERM	24	000020018	2	0	1995	.17181E+00	1039.900	31.500	31.500	0.000	1796.262	794.617	128.049	105.240	0.000	0.000	0.000	35.925	0.000
BERM	25	000020019	2	0	1995	.38221E+00	1039.900	31.500	31.500	0.000	1796.262	743.160	163.124	149.601	0.000	0.000	0.000	35.925	0.000
WWHT	26	000020020	2	0	1995	.19146E+00	1039.900	31.500	31.500	0.000	1796.262	761.081	330.695	305.895	76.189	74.405	44.643	35.925	0.000
WWHT	27	000020021	2	0	1995	.31302E+00	1039.900	31.500	31.500	0.000	1796.262	679.832	337.967	307.664	100.281	107.463	64.478	35.925	0.000
WWHT	28	000020022	2	0	1995	.64427E-01	1039.900	31.500	31.500	0.000	1796.262	761.104	330.746	305.953	76.345	74.555	44.733	35.925	0.000
WATR	29	000030001	3	0	1995	.18812E+00	922.500	0.000	0.000	0.000	2033.740	1423.618	0.000	116.817	0.000	0.000	0.000	0.000	0.000

Figure 25. SWAT's output.hru file.

b) Water Availability/Water Quantity Objectives

Agricultural management practices can also have a negative impact on water availability and water quantity. The objectives available to minimize, listed in Table 2, are similarly extracted from the *output.hru* file.

To remove selected objectives from the tables, simply select them with your mouse and then press the 'Delete Selected Objectives' bottom at the bottom of each the table (Figure 26).

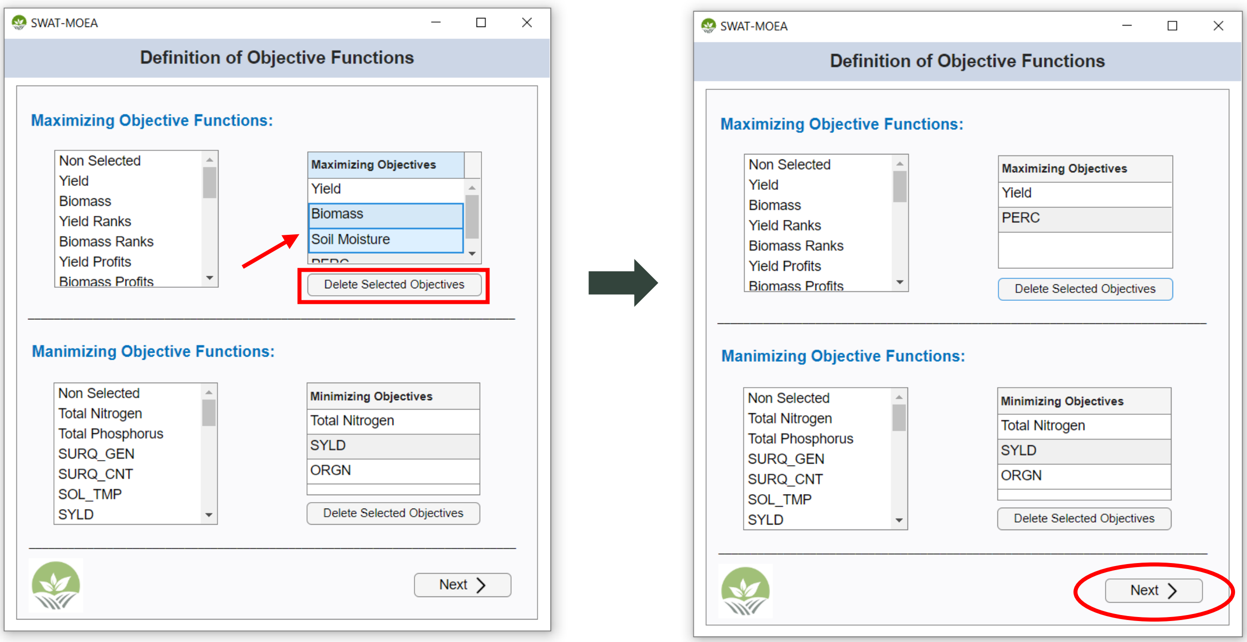


Figure 26. Example on how to use the delete button.

Once you have finished selecting the objectives for your optimization study, click on the "**Next**" button at the bottom right to proceed. This action will prompt the Alternative System Design window to appear on your screen.

4.6 Alternative System Design

This step involves the design of AS for the MOEA analysis (Figure 27). Within this step, you can perform four key actions:

- **Design AS**: This will replace the operation schedules of .mgt files corresponding to HRUs previously categorized by land use type (as discussed in Section 4.4)
- **Estimate Aspirational System Profit**: Input cost and crop market values to calculate the estimated profits of the AS
- **Modify CN2 Values**: Directly adjust the initial CN2 value of .mgt files corresponding to the HRUs previously categorized by land use type (as discussed in Section 4.4)
- **Execute the Designed AS**: Modifications made to .mgt files are executed in SWAT (as defined in Section 4.4)

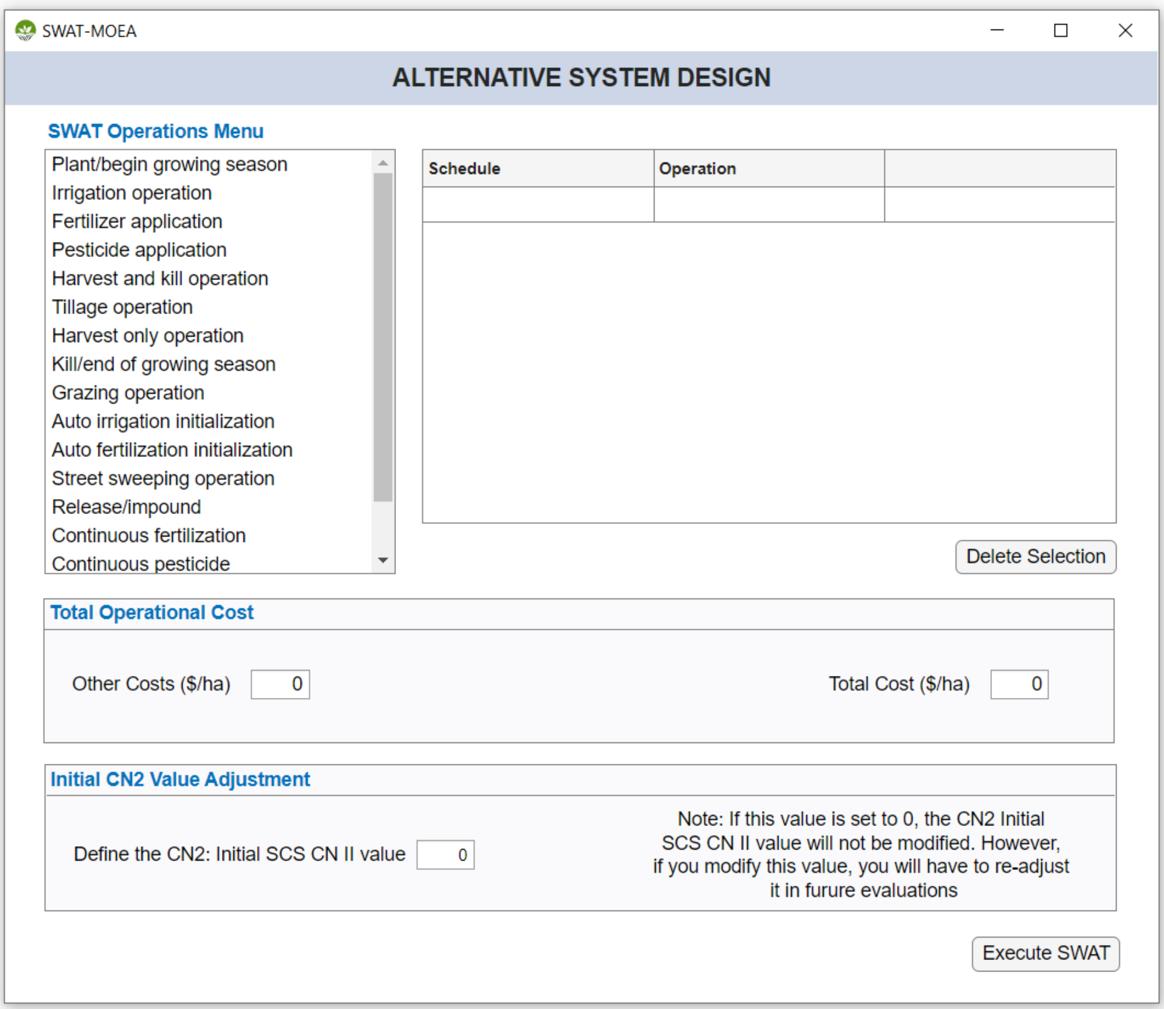


Figure 27. Alternative system design.

4.6.1 Design of AS

The SWAT-MOEA tool facilitates this design process directly from the 'Alternative System Design' window where users have access to the 17 different types of management operations in SWAT, available via the SWAT Operations Menu situated on the left side of this window (Figure 28).

To initiate the alternative system design procedure, simply **select one operation** from the **SWAT Operations Menu**. This action will prompt the corresponding operation window to appear on your screen (Figure 29). Simultaneously, the selected operation will also automatically populate the table on the right-hand side, providing a summary of the alternative system under design. Each operation includes data from SWAT relevant to that specific operation, along with the variables used in SWAT.

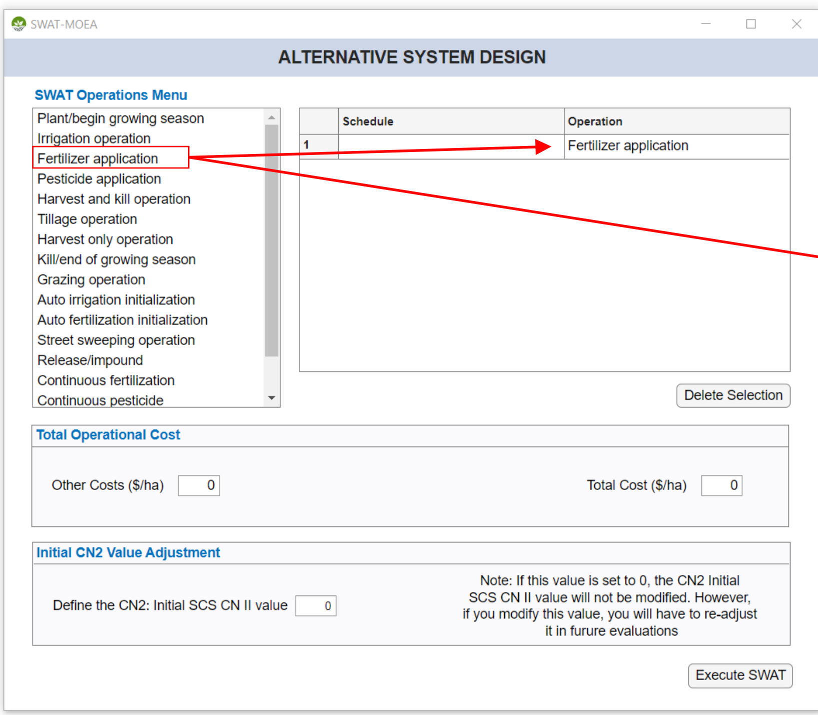


Figure 28. Alternative system design.

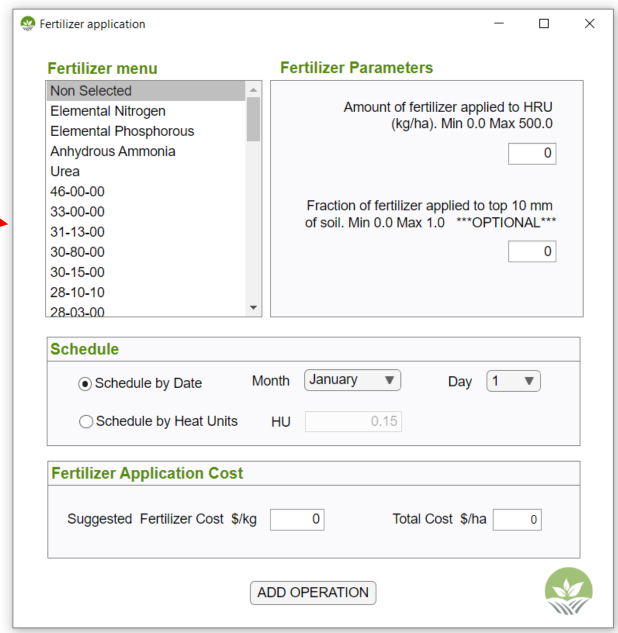


Figure 29. Fertilizer operation.

After entering the required information, simply click on the "**ADD OPERATION**" button (Figure 29). This action will close the current operation window and append the timing of the operation to the table of the Alternative System Design window. Following this, you can proceed to select a different operation you wish to include.

Repeat this step until your AS design is completed.

4.6.2 Estimate Aspirational System Profit

When Yield Profits and/or Biomass Profits are selected as objective functions (as described in Section 4.5), the Operations Application Cost feature becomes available (Figure 30). This enables users to estimate potential costs associated with each operation.

SWAT-MOEA provides suggests costs sourced from its database, where available. However, users retain the flexibility to customize these costs to align with their specific requirements by editing the suggested cost field. This feature allows users to modify the cost estimates according to their unique scenarios and preferences

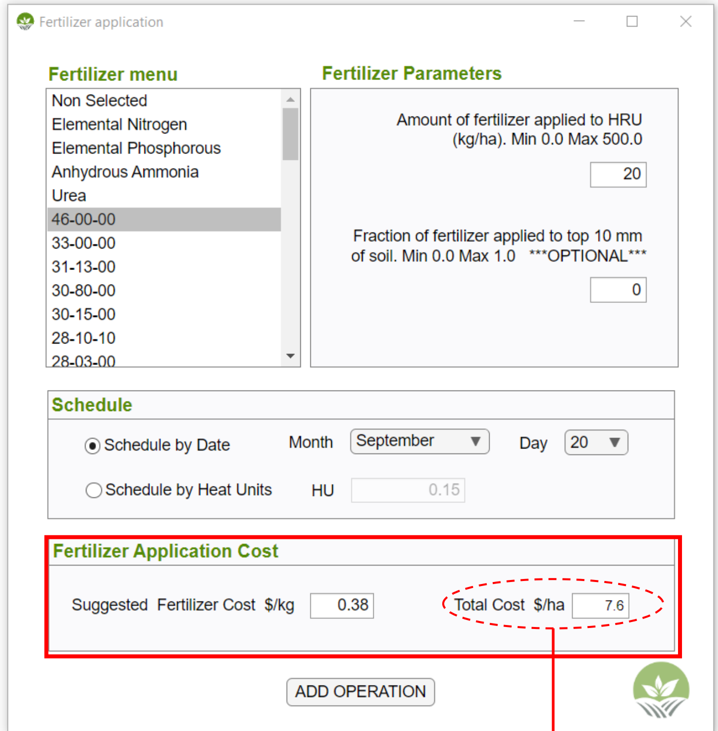


Figure 30. Fertilizer application cost.

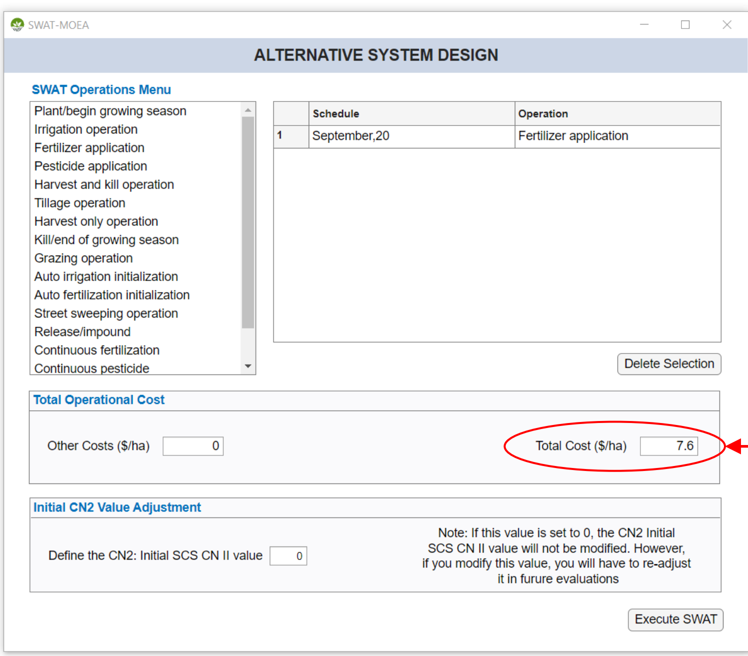


Figure 31. Adding fertilizer application cost to total cost.

The total cost for each operation is then added to the total cost of the AS (Figure 31).

In addition to the operational cost feature, the Plant/begin growing season operation includes a section where users can input current **market values for Yield and/or Biomass** of the specific crop under study (Figure 32).

If the plant being added to the AS design is a cover crop rather than the primary crop under study, ensure that the box at the center of this window is **unchecked**. It is important to note that only one crop can be optimized in this SWAT-MOEA version.

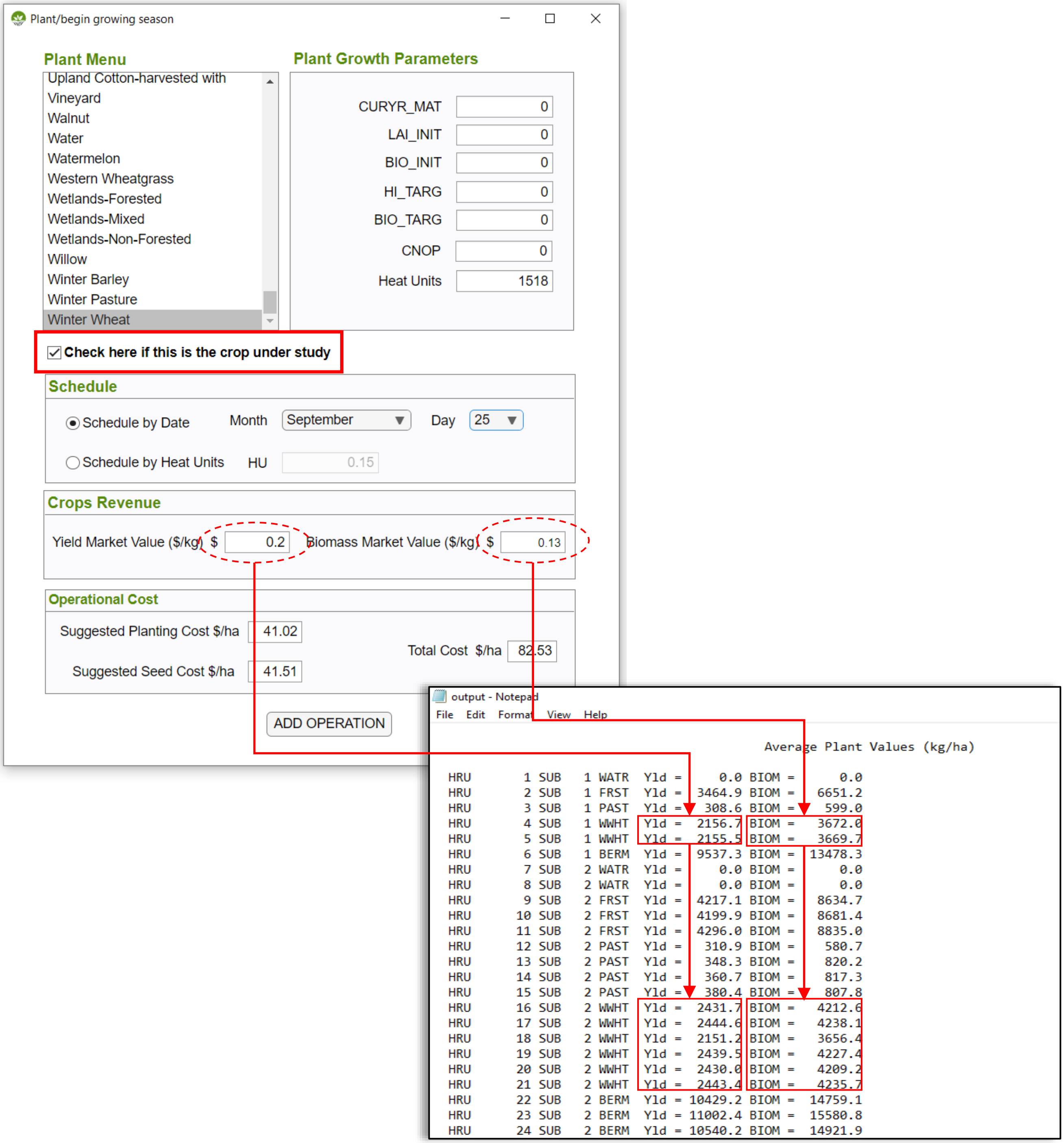


Figure 32. Market values for yields and or biomass.

After completing the entry of all necessary information and parameters in the Plant/begin growing season operation, the total cost associated with this operation will be included in the overall total of the aspirational system design (Figure 33).

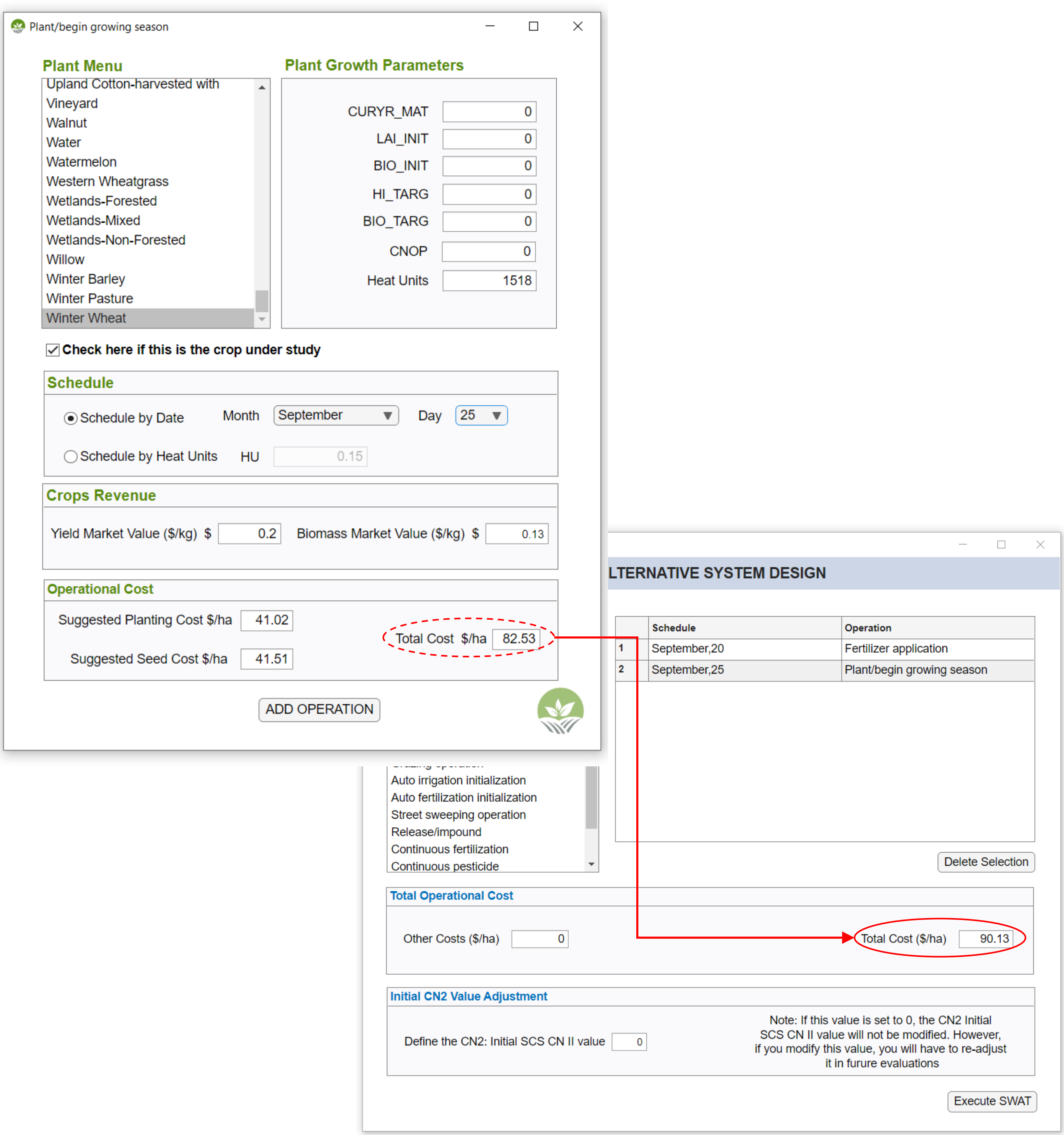


Figure 33. Adding a second operational cost to the total cost.

Finally, any additional costs, such as labor expenses, that may not have been factored into the individual operations can be included in the 'Other Costs' field (Figure 34). The value entered in this field will be incorporated into the overall total of the aspirational system design.

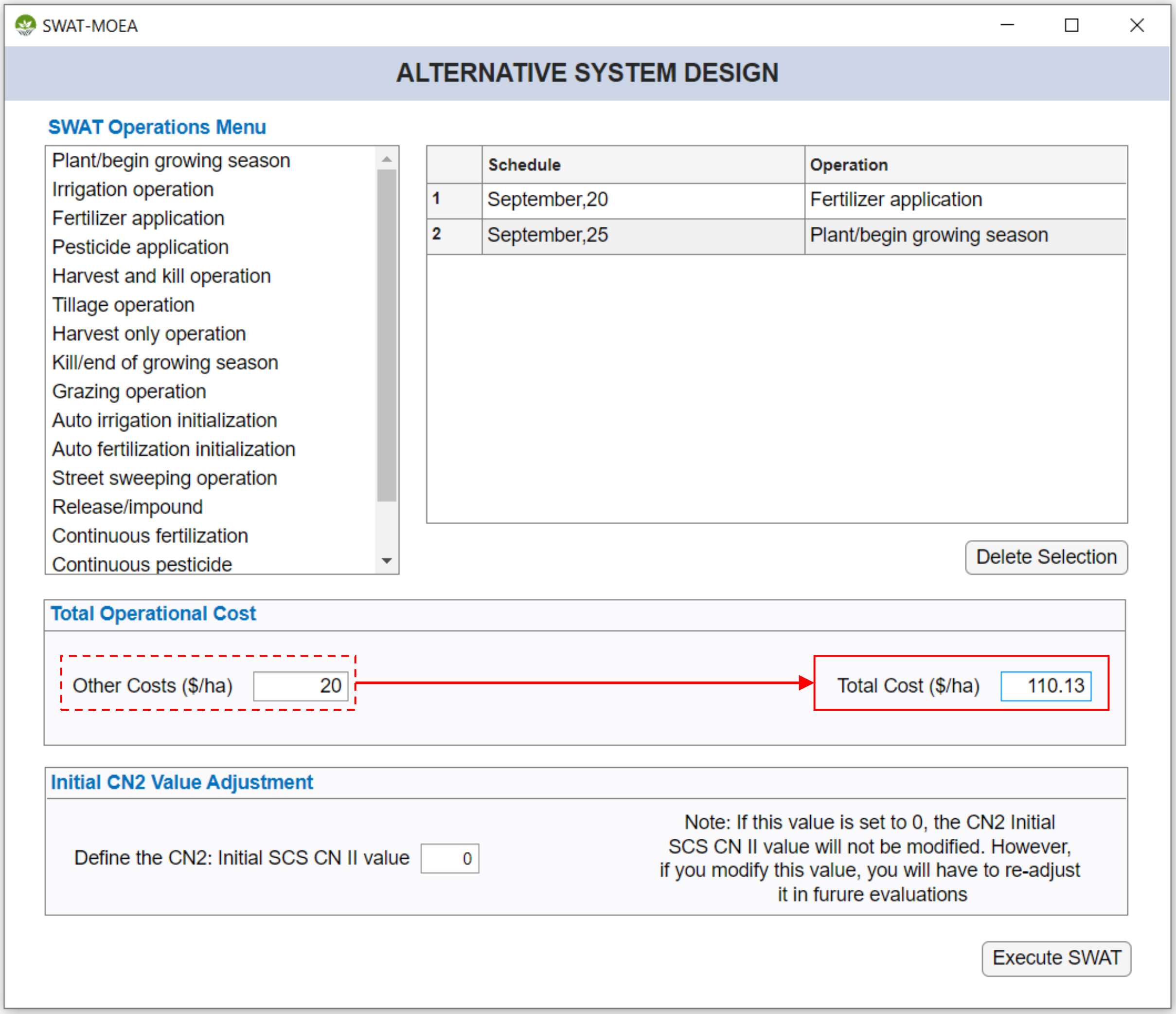


Figure 34. Including additional costs to the total cost.

4.6.3 Modify CN2 Values

The SWAT-MOEA provides users with the option to directly modify the initial CN2 value for the selected HRU management files, avoiding the need to edit the CNOP values in management operations (Figure 35).

To change the initial CN2 value, simply **type the number** in the **Initial CN2Value Adjustment** section located at the bottom of the 'Alternative System Design' window. Setting tis value to 0 will result in no modification to the CN2 value in the .mgt files.

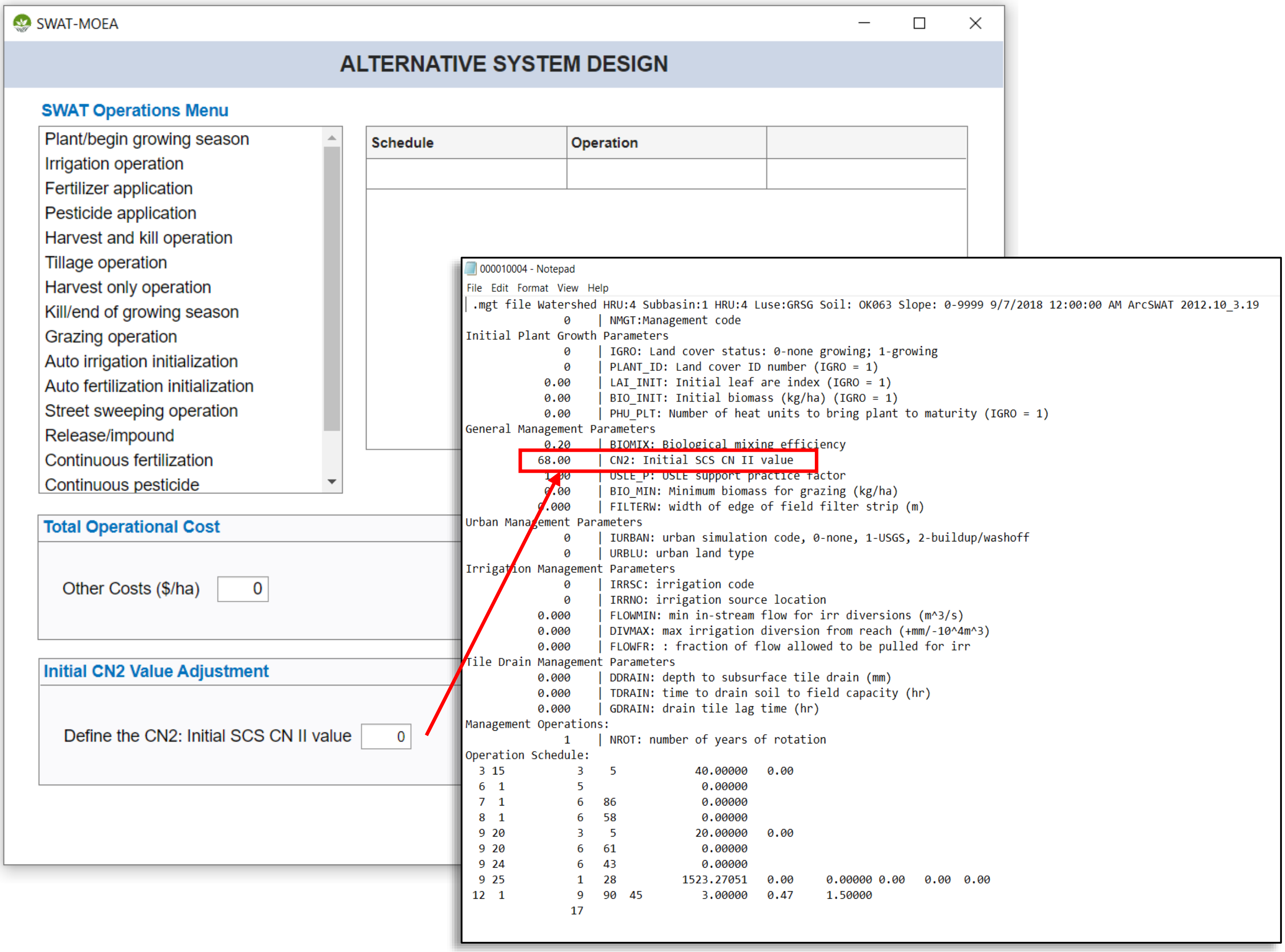


Figure 35. Modification of the CN2 value.

It is important to note that if you change the CN2 value, it will remain the same for future evaluations unless you manually readjust it again in the Initial CN2 Value Adjustment section.

4.6.4 Execute the Designed AS

Once you have completed the aspirational system design, simply click the "**Execute SWAT**" button on the right lower corner of the window (Figure 36). This action triggers the execution of SWAT executable (as defined in Section 4.3), initiating the simulation process. Upon completion of the executable, SWAT-MOEA will extract or estimate the objective functions from the output.std and output.hru files.

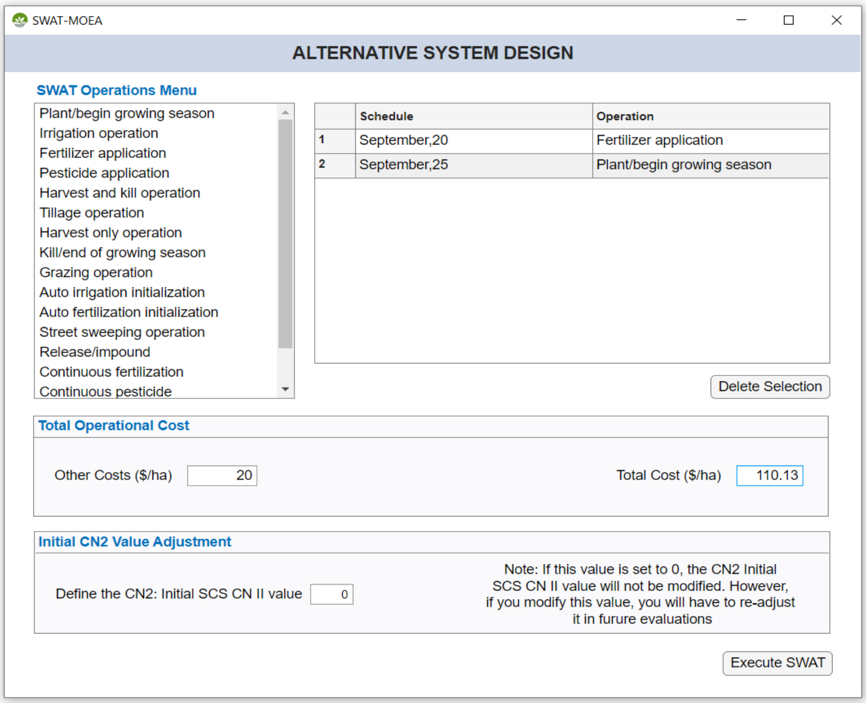


Figure 36. SWAT execution.

Once the simulation process concludes, you will be promoted where you want to design and evaluate a new AS (Figure 37). If you choose "**Yes**", the SWAT-MOEA will return you to the Alternative System Design window, enabling further iterations. However, if you opt for "**No**" the SWAT-MOEA will take to the final step.

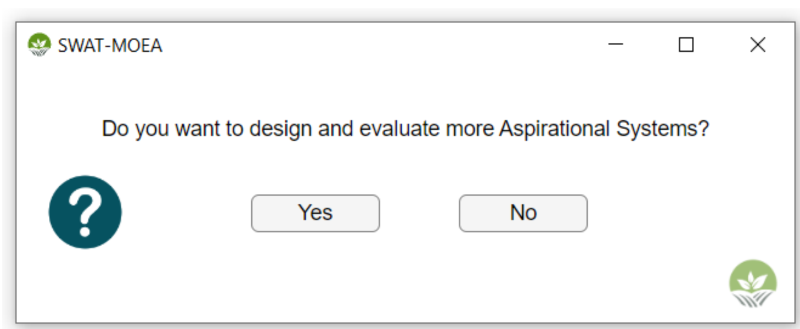


Figure 37. First question window.

At this step, the SWAT-MOEA considers the project setup to be completed.

4.7 MOEA

The final step contains three key components to set up the MOEA:

- **Optimal Subbasins:** Specify the number of subbasins that will undergo optimization within the analysis.
- **System Selection:** Choose the specific system to be considered in the optimization process.
- **MOEA Parameters:** Define the parameters related to the MOEA.

To navigate between these components, simply click on the different tabs provided (Figure 38).

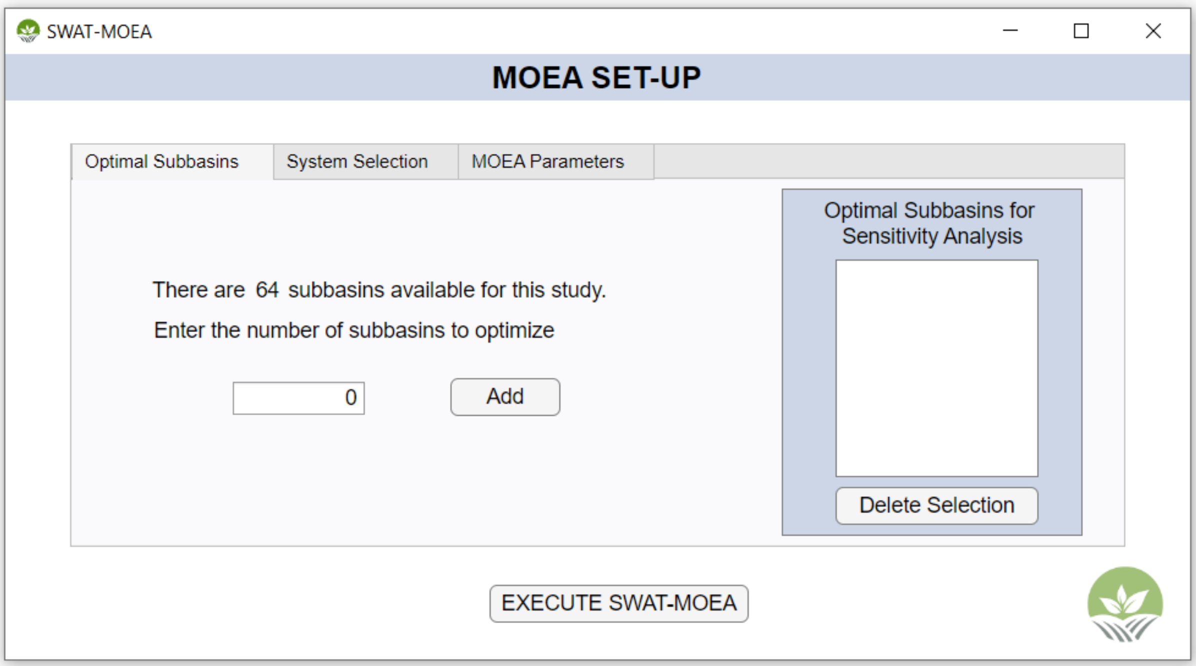


Figure 38. MOEA Setup.

4.7.1 Optimal Subbasins

The Optimal Subbasin tab provides the maximum number of available subbasins, based on the HRUs defined for optimization. This selection allows for the input of multiple subbasins, facilitating sensitivity analysis. The MOEA will use these values to identify subbasins that perform optimally based on defined objective functions and systems selected for the MOEA study.

To add a subbasin number, simply **enter the desired value** in the designated field and **click** the "**Add**" button (Figure 39). The table on the right-hand side will list the optimal subbasins that have been selected for the optimization.

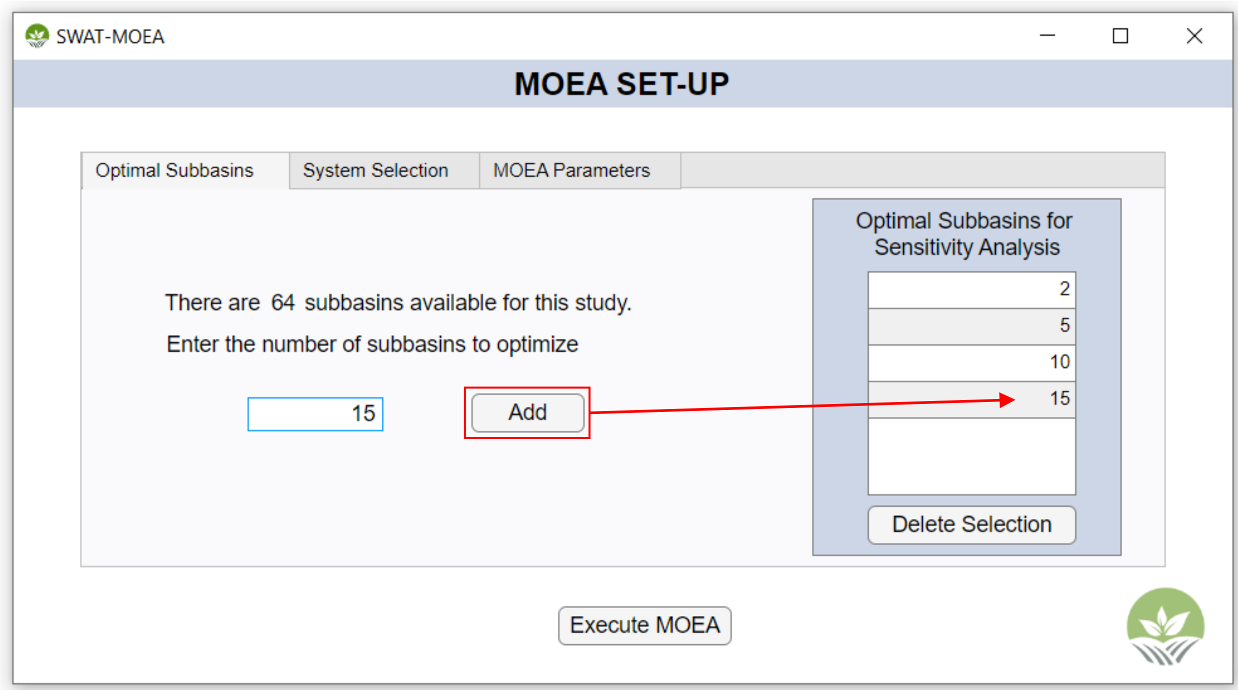


Figure 39. Optimal subbasins.

4.7.2 System selection

The System Selection tab provides the systems available for the optimization study (Figure 40). This includes the PS, as well as the any AS designed in SWAT-MOEA. Users can select from these systems to evaluate various combinations for optimal scenarios.

To make a selection, simply **check** the corresponding box next to each system listed. This allows users to customize and assess different combinations of systems to determine the most effective optimization strategy.

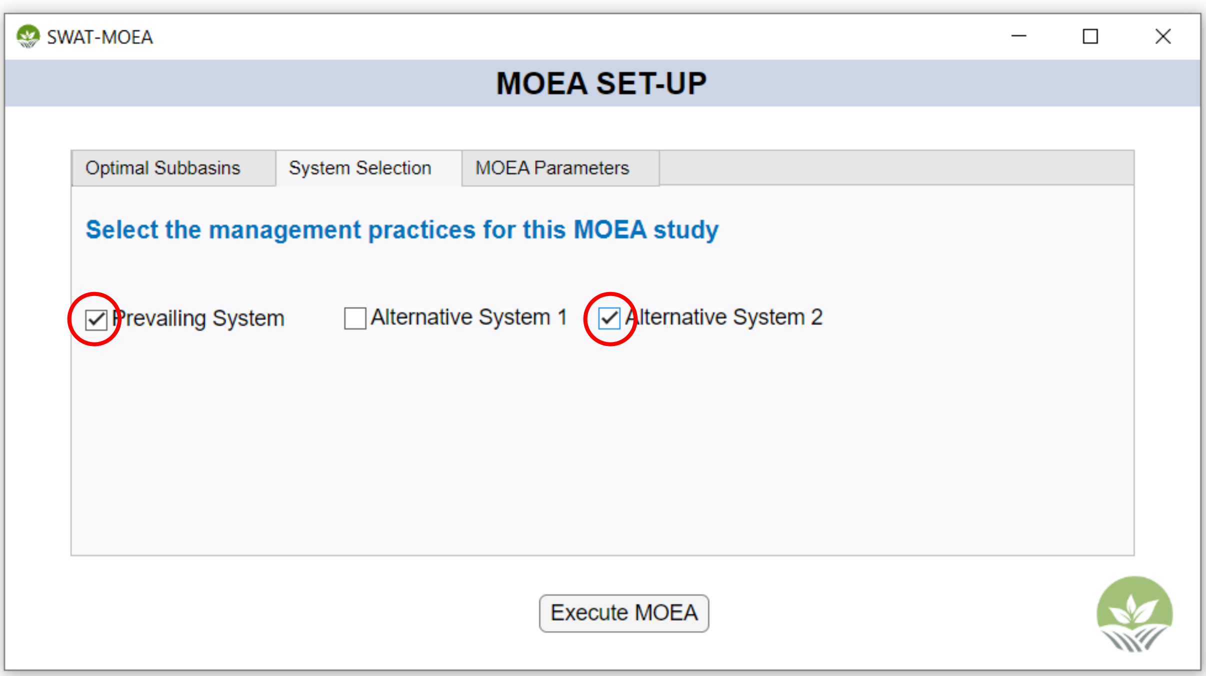


Figure 40. System selection.

4.7.3 MOEA Parameters

The MOEA Parameters tab offers the default setup parameters for the MOEA (Figure 41). User have the flexibility to either **use these default values or customize them** according to their specific study requirements.

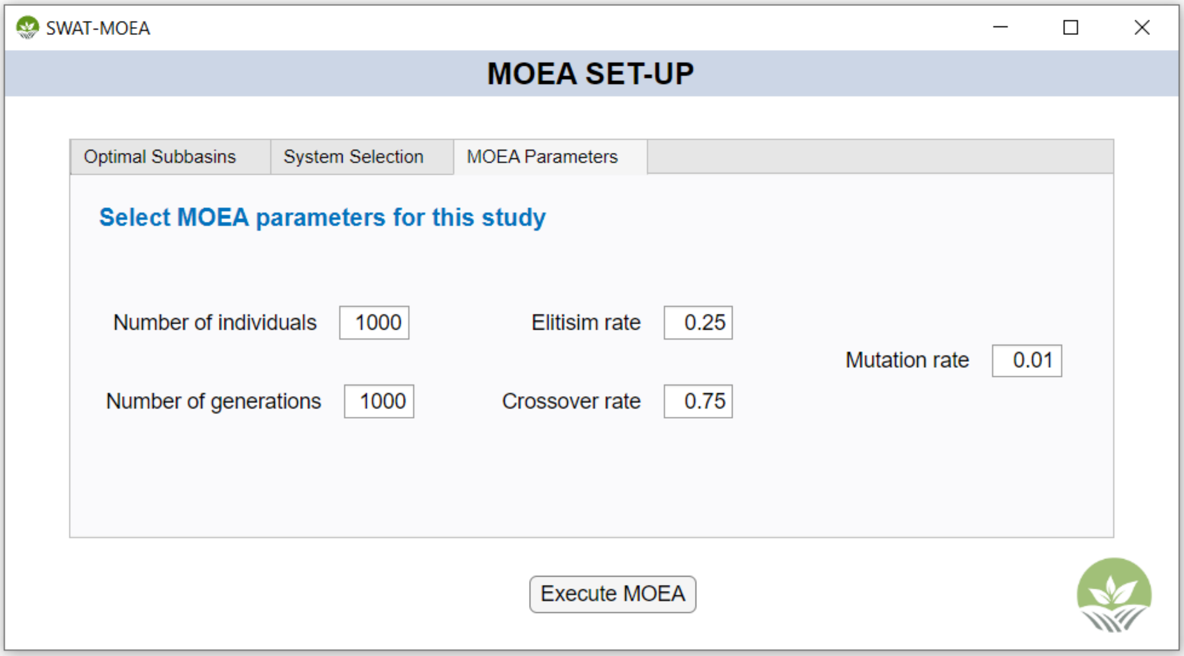


Figure 41. MOEA parameters.

Once you have defined the parameters on these three components, you can initiate the optimization process by clicking the "**Execute MOEA**" button.

Upon initiating the execution of the MOEA, a progress bar will be displayed to provide real-time updates on the progress of the process (Figure 42). This allows users to track the advancement of the study and estimate the time remaining until completion.

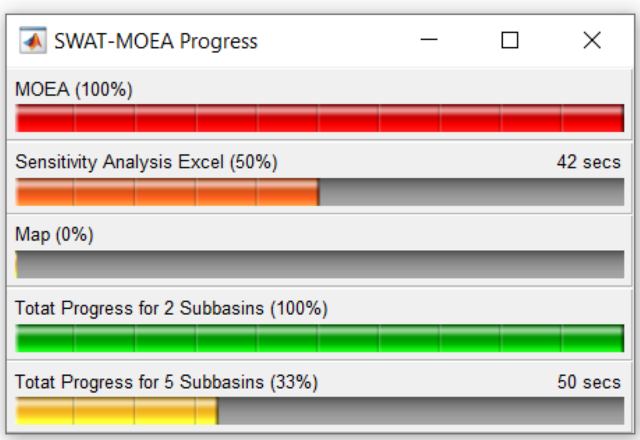


Figure 42. SWAT-MOEA progress.

Upon completion of the study, you will be prompt to decide whether you wish to conduct another MOEA evaluation (Figure 43). If you select "**Yes**", the SWAT-MOEA tool will direct you to the MOEA Set-up window to initiate another evaluation. Alternatively, choosing "**No**" will prompt SWAT-MOEA to compile the final sensitivity analysis results and export them into the Excel file for your revies.

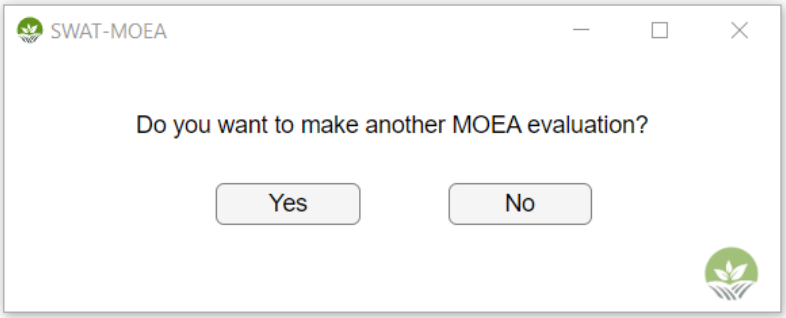


Figure 43. Second question window.

Finaly, the SWAT-MOEA tool will present a notification window indicating that the project has been successfully completed (Figure 44). This window will provide information on where you can locate the results generated by the analysis.

Figure 44. SWAT-MOEA completion notification.

Chapter 5. Results

This chapter is dedicated to the comprehensive analysis and interpretation of the results generated by the SWAT-MOEA tool. Upon completion of your optimization study, SWAT-MOEA produces a variety of files designed to present the outcomes in a structural and insightful manner. Understanding these files is crucial for interpreting the effectiveness of optimal management strategies and making informed decisions based on the optimization objectives.

This chapter aims to equip you with the knowledge to navigate through the results, understanding the significance of each data to apply this understanding to solve real-world environmental and agricultural management challenges.

When the optimization study is completed, you will find three distinctive types of files within the designated results folder (as discussed in Section 4.2; Figure 45).

- Sensitivity Analysis - Excel file
- Alternative Systems - text document
- MATLAB figures

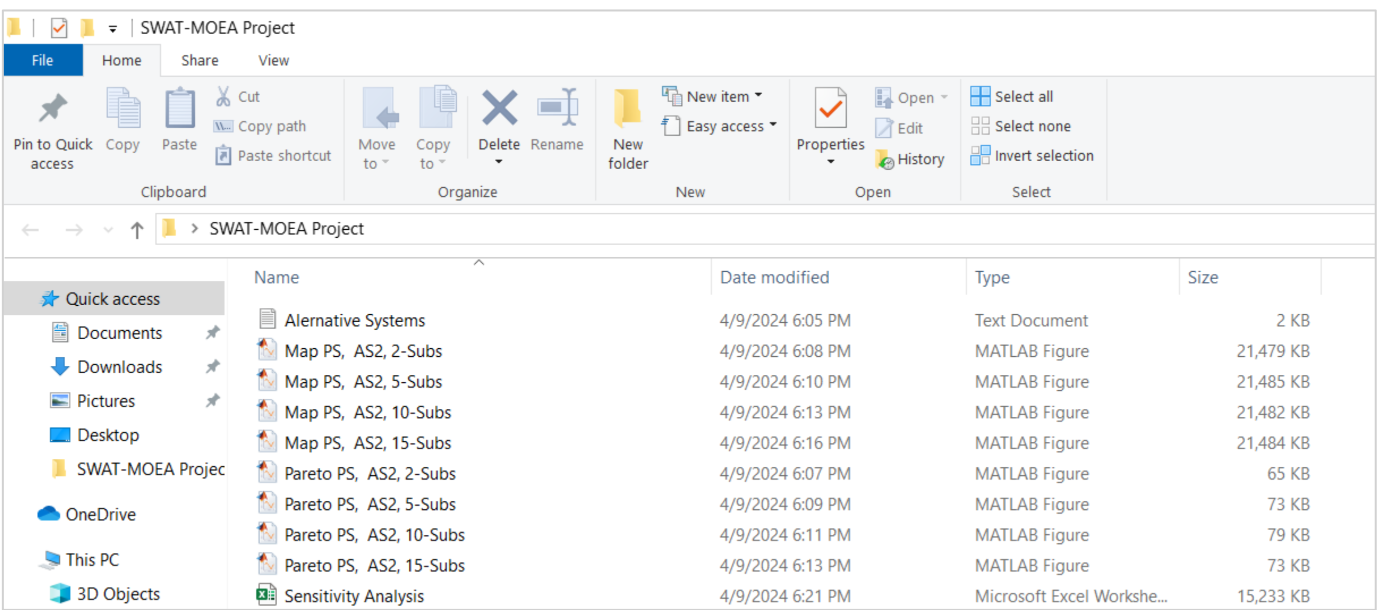


Figure 45. Result's folder.

These files collectively provide comprehensive insights into the optimization results, aiding in informed decision-making and resource management practices. Description of these files are provided in the subsections below.

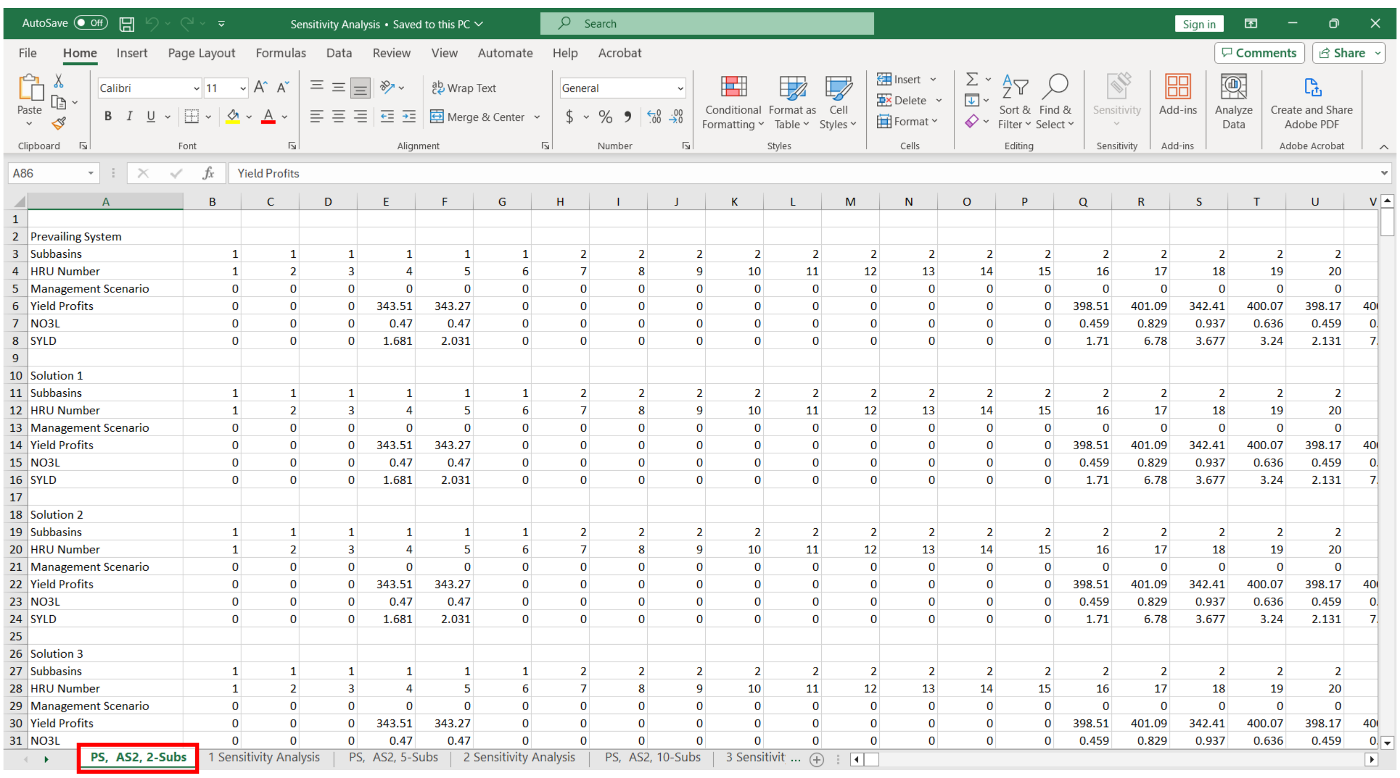
5.1 Sensitivity Analysis Excel file

The Sensitivity Analysis Excel file (Figure 46) contains multiple sheets, which can be categorized into three sets:

- Detailed description of Pareto solutions
- Summary of Pareto solutions
- Summary of all SWAT-MOEA suggested solutions

5.1.1 Detailed description of Pareto solutions

Each sheet within this category provides a comprehensive overview of Pareto solutions, uniquely named after the combination evaluated. For example, the first sheet on the figure called 'PS, AS2, 2-Subs' provides the Pareto solutions for the combination of Prevailing System and Alternative System 2, considering 2 optimal subbasins.

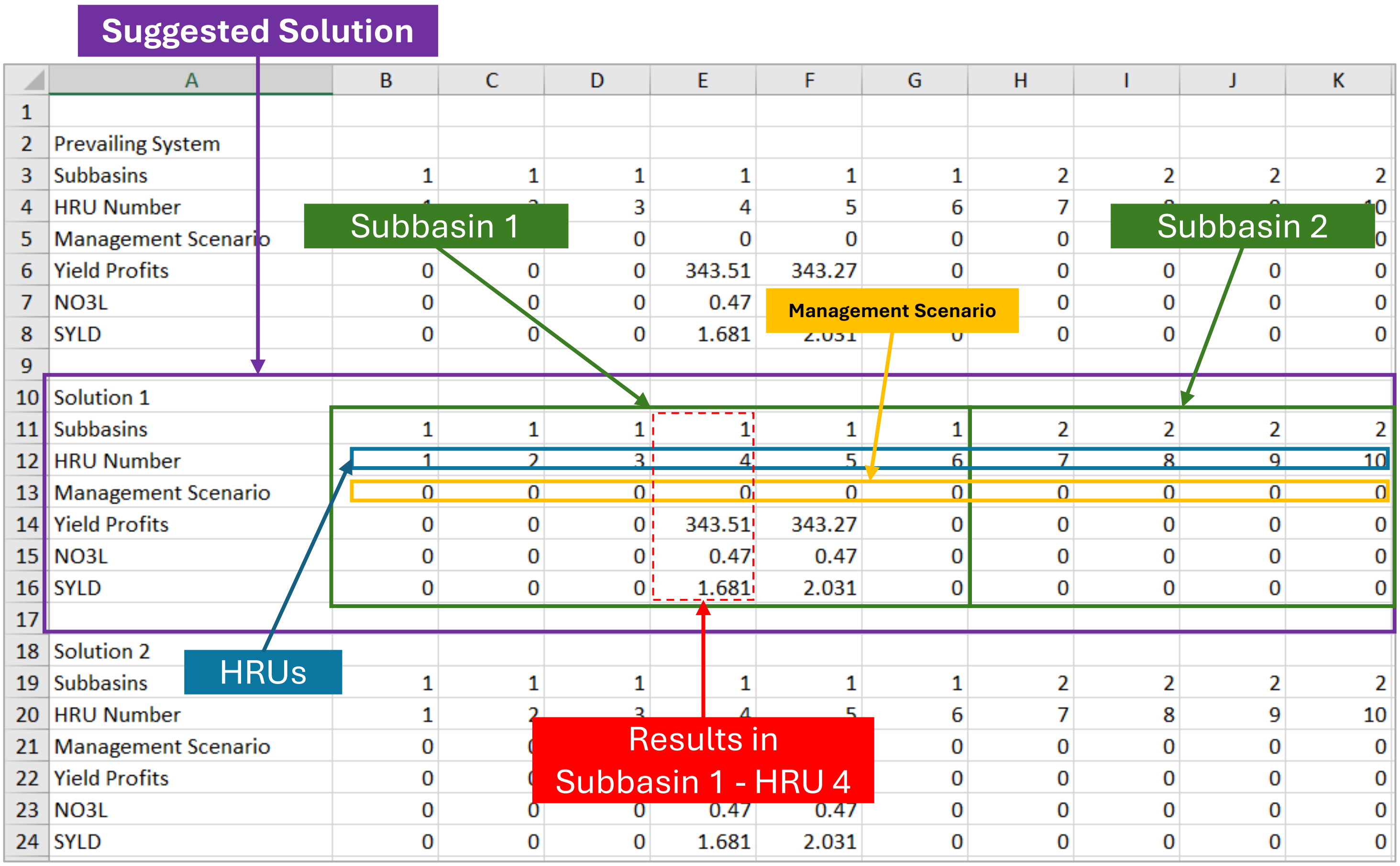


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1																						
2	Prevailing System																					
3	Subbasins	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	
4	HRU Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
5	Management Scenario	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
6	Yield Profits	0	0	0	343.51	343.27	0	0	0	0	0	0	0	0	0	0	398.51	401.09	342.41	400.07	398.17	40
7	NO3L	0	0	0	0.47	0.47	0	0	0	0	0	0	0	0	0	0	0.459	0.829	0.937	0.636	0.459	0
8	SYLD	0	0	0	1.681	2.031	0	0	0	0	0	0	0	0	0	0	1.71	6.78	3.677	3.24	2.131	7
9																						
10	Solution 1																					
11	Subbasins	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	
12	HRU Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
13	Management Scenario	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
14	Yield Profits	0	0	0	343.51	343.27	0	0	0	0	0	0	0	0	0	0	398.51	401.09	342.41	400.07	398.17	40
15	NO3L	0	0	0	0.47	0.47	0	0	0	0	0	0	0	0	0	0	0.459	0.829	0.937	0.636	0.459	0
16	SYLD	0	0	0	1.681	2.031	0	0	0	0	0	0	0	0	0	0	1.71	6.78	3.677	3.24	2.131	7
17																						
18	Solution 2																					
19	Subbasins	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	
20	HRU Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
21	Management Scenario	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
22	Yield Profits	0	0	0	343.51	343.27	0	0	0	0	0	0	0	0	0	0	398.51	401.09	342.41	400.07	398.17	40
23	NO3L	0	0	0	0.47	0.47	0	0	0	0	0	0	0	0	0	0	0.459	0.829	0.937	0.636	0.459	0
24	SYLD	0	0	0	1.681	2.031	0	0	0	0	0	0	0	0	0	0	1.71	6.78	3.677	3.24	2.131	7
25																						
26	Solution 3																					
27	Subbasins	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	
28	HRU Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
29	Management Scenario	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
30	Yield Profits	0	0	0	343.51	343.27	0	0	0	0	0	0	0	0	0	0	398.51	401.09	342.41	400.07	398.17	40
31	NO3L	0	0	0	0.47	0.47	0	0	0	0	0	0	0	0	0	0	0.459	0.829	0.937	0.636	0.459	0

Figure 46. Sensitivity analysis Excel file.

Specific solutions and their corresponding results can be easily identified using the descriptions provided in column A, which also includes the PS outputs. These information includes Subbasin number, HRU number, Management Scenario and the objective functions evaluated. This column serves as a reference point, allowing users to quickly locate and interpret the outcomes of interest within the dataset.

Specific solutions and their corresponding results can be easily identified using the descriptions provided in column A, which also includes the PS outputs (Figure 47). These information includes Subbasin number, HRU number, Management Scenario and the objective functions evaluated, while the output values are displayed in their corresponding row. This column serves as a reference point, allowing users to quickly locate and interpret the outcomes of interest within the dataset.



	A	B	C	D	E	F	G	H	I	J	K
1											
2	Prevailing System										
3	Subbasins	1	1	1	1	1	1	2	2	2	2
4	HRU Number	[illegible]	[illegible]	3	4	5	6	7	[illegible]	[illegible]	[illegible]
5	Management Scenario	[illegible]	[illegible]	0	0	0	0	0	[illegible]	[illegible]	0
6	Yield Profits	0	0	0	343.51	343.27	0	0	0	0	0
7	NO3L	0	0	0	0.47	[illegible]	[illegible]	0	0	0	0
8	SYLD	0	0	0	1.681	[illegible]	[illegible]	0	0	0	0
9											
10	Solution 1										
11	Subbasins	1	1	1	1	1	1	2	2	2	2
12	HRU Number	1	2	3	4	5	6	7	8	9	10
13	Management Scenario	0	0	0	0	0	0	0	0	0	0
14	Yield Profits	0	0	0	343.51	343.27	0	0	0	0	0
15	NO3L	0	0	0	0.47	0.47	0	0	0	0	0
16	SYLD	0	0	0	1.681	2.031	0	0	0	0	0
17											
18	Solution 2										
19	Subbasins	1	1	1	1	1	1	2	2	2	2
20	HRU Number	1	[illegible]	[illegible]	[illegible]	[illegible]	6	7	8	9	10
21	Management Scenario	0	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0
22	Yield Profits	0	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0
23	NO3L	0	0	0	0.47	0.47	0	0	0	0	0
24	SYLD	0	0	0	1.681	2.031	0	0	0	0	0

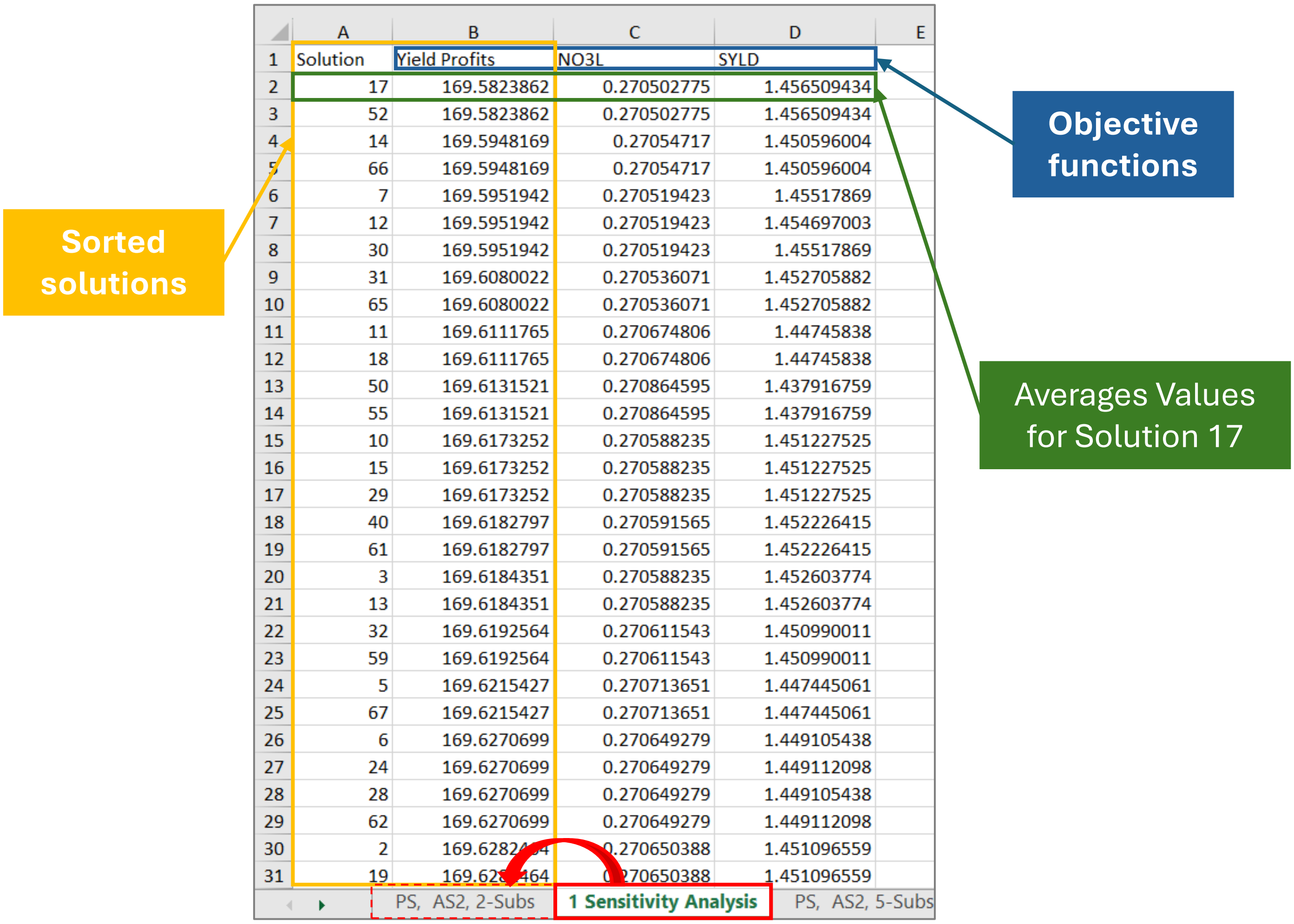
Figure 47. Description of Pareto solutions.

For example, the management scenario was identified as 0 within HRU 4, located in subbasin 1, with results for Yield Profits, NO3L, and SYLD of 343.51, 0.47, and 1.681, respectively. Detailed instruction on interpreting management scenarios will be provided later in this chapter.

Solutions are arranged in order to their proximity to the ideal vector, from closest to farthest, where maximizing and minimizing objectives have vector values of 1 and 0, respectively. Therefore, SWAT-MOEA suggests Solution 1 as it exhibits the closest proximity to the ideal vector.

5.1.2 Summary of Pareto solutions

Within this category, the spreadsheets provide the average values of objective functions for each Pareto solution from the previous sheet (Figure 48). These solutions are sorted based on the values in column B, arranged from smallest to highest. The sheets are named '# Sensitivity Analysis', where the '#' represents the order of the MOEA evaluation.

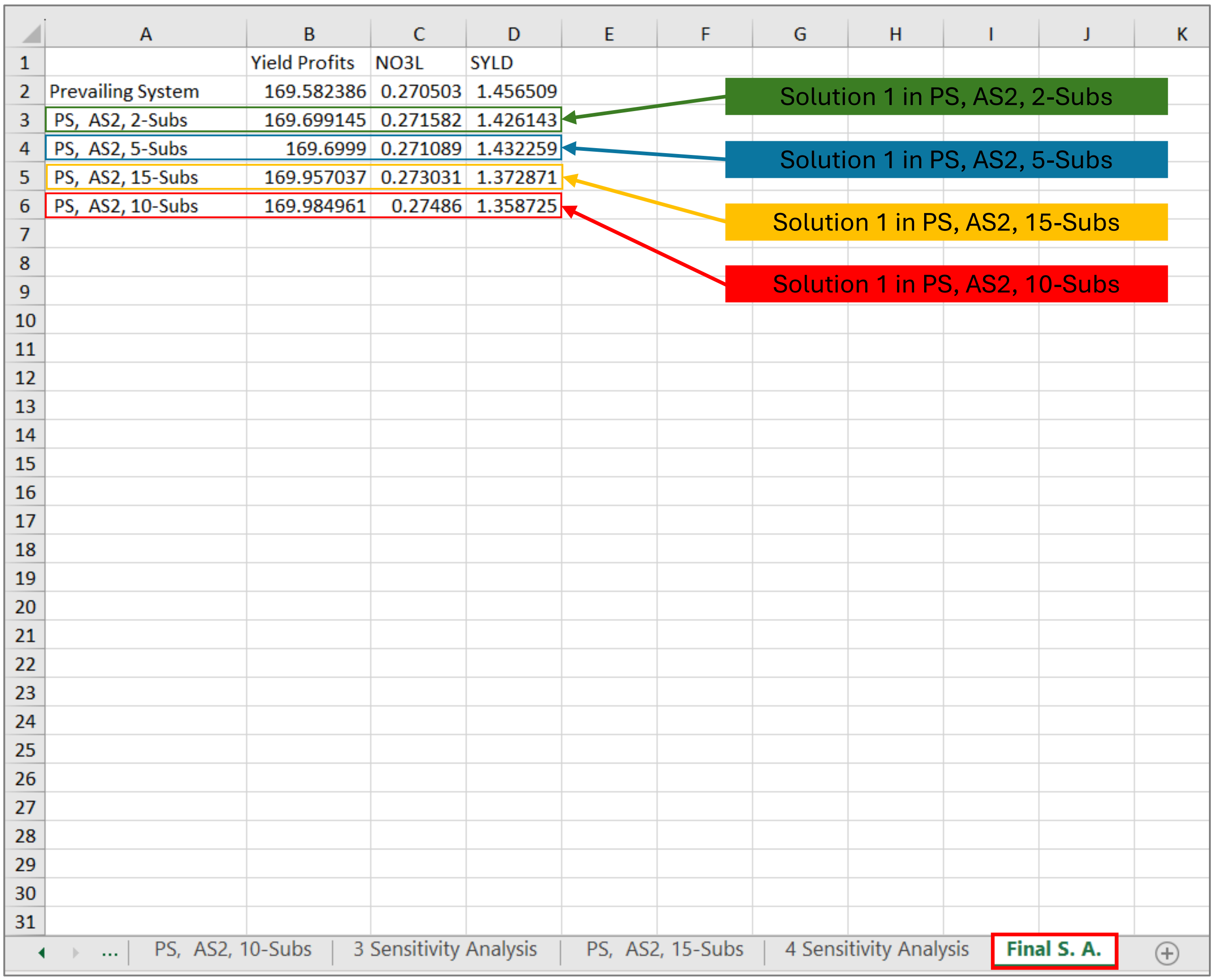


	A	B	C	D
1	Solution	Yield Profits	NO3L	SYLD
2	17	169.5823862	0.270502775	1.456509434
3	52	169.5823862	0.270502775	1.456509434
4	14	169.5948169	0.27054717	1.450596004
5	66	169.5948169	0.27054717	1.450596004
6	7	169.5951942	0.270519423	1.45517869
7	12	169.5951942	0.270519423	1.454697003
8	30	169.5951942	0.270519423	1.45517869
9	31	169.6080022	0.270536071	1.452705882
10	65	169.6080022	0.270536071	1.452705882
11	11	169.6111765	0.270674806	1.44745838
12	18	169.6111765	0.270674806	1.44745838
13	50	169.6131521	0.270864595	1.437916759
14	55	169.6131521	0.270864595	1.437916759
15	10	169.6173252	0.270588235	1.451227525
16	15	169.6173252	0.270588235	1.451227525
17	29	169.6173252	0.270588235	1.451227525
18	40	169.6182797	0.270591565	1.452226415
19	61	169.6182797	0.270591565	1.452226415
20	3	169.6184351	0.270588235	1.452603774
21	13	169.6184351	0.270588235	1.452603774
22	32	169.6192564	0.270611543	1.450990011
23	59	169.6192564	0.270611543	1.450990011
24	5	169.6215427	0.270713651	1.447445061
25	67	169.6215427	0.270713651	1.447445061
26	6	169.6270699	0.270649279	1.449105438
27	24	169.6270699	0.270649279	1.449112098
28	28	169.6270699	0.270649279	1.449105438
29	62	169.6270699	0.270649279	1.449112098
30	2	169.6282[illegible]	0.270650388	1.451096559
31	19	169.62[illegible]464	[illegible]270650388	1.451096559

Figure 48. Description of summary of Pareto solutions.

5.1.3. Summary of SWAT-MOEA suggested solutions

The last spreadsheet in the 'Sensitivity Analysis' Excel file, named 'Final S. A.', provide the average values of objective function associated with all SWAT-MOEA suggested solutions, including the PS (Figure 49). These solutions are arranged in ascending order based on the values in column B, providing a comprehensive overview of the suggested optimization outcomes.

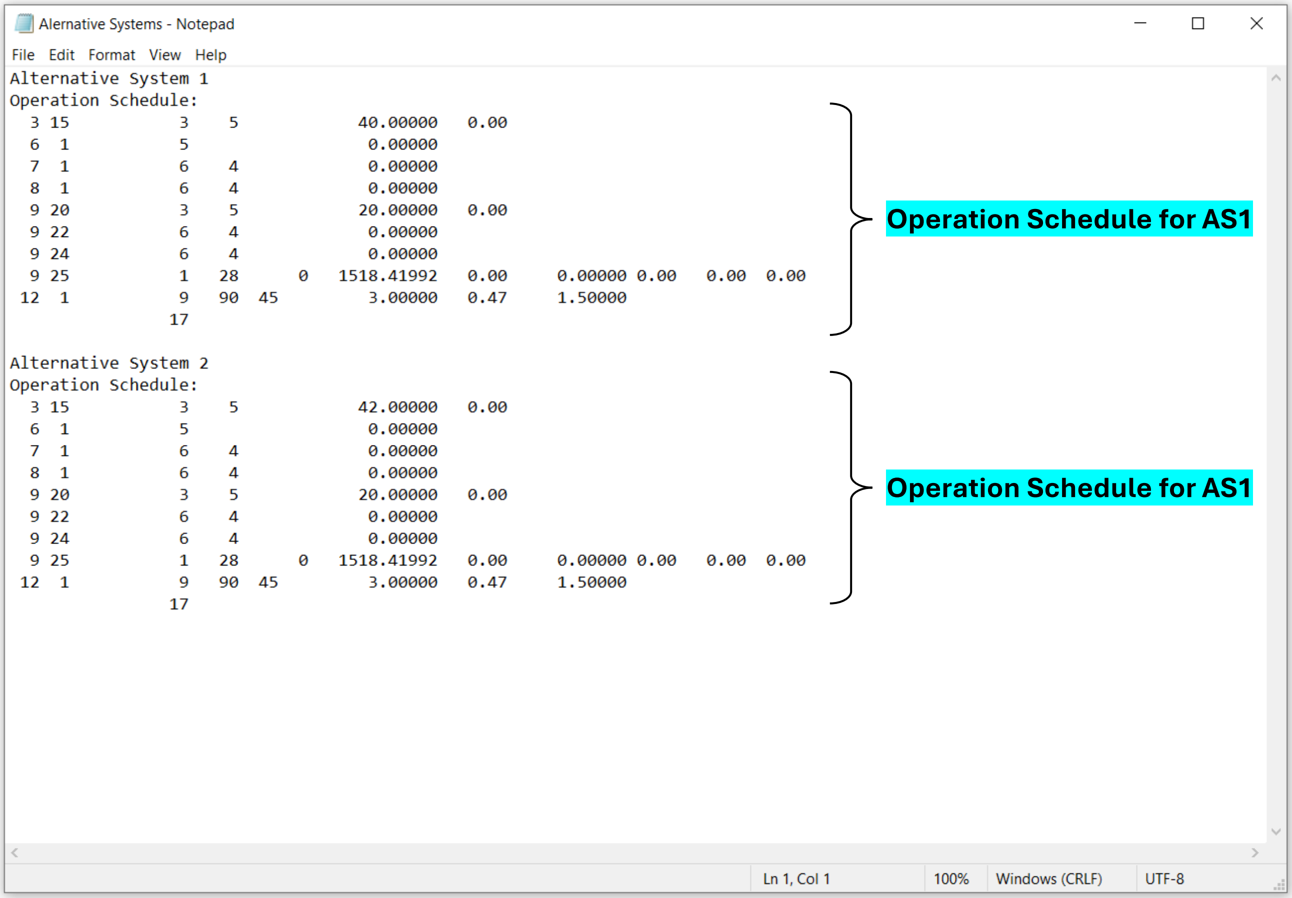


	A	B	C	D
1		Yield Profits	NO3L	SYLD
2	Prevailing System	169.582386	0.270503	1.456509
3	PS, AS2, 2-Subs	169.699145	0.271582	1.426143
4	PS, AS2, 5-Subs	169.6999	0.271089	1.432259
5	PS, AS2, 15-Subs	169.957037	0.273031	1.372871
6	PS, AS2, 10-Subs	169.984961	0.27486	1.358725

Figure 49. Description of '*Final S. A.*' sheet.

5.2 Alternative Systems text file

The Alternative Systems text file contains the operation schedules for the evaluated AS, presented in SWAT code format (Figure 50).



```
Alternative System 1
Operation Schedule:
  3 15          3    5          40.00000   0.00
  6  1          5                0.00000
  7  1          6    4           0.00000
  8  1          6    4           0.00000
  9 20          3    5          20.00000   0.00
  9 22          6    4           0.00000
  9 24          6    4           0.00000
  9 25          1   28      0  1518.41992   0.00      0.00000 0.00    0.00   0.00
 12  1          9   90   45        3.00000   0.47      1.50000
               17

Alternative System 2
Operation Schedule:
  3 15          3    5          42.00000   0.00
  6  1          5                0.00000
  7  1          6    4           0.00000
  8  1          6    4           0.00000
  9 20          3    5          20.00000   0.00
  9 22          6    4           0.00000
  9 24          6    4           0.00000
  9 25          1   28      0  1518.41992   0.00      0.00000 0.00    0.00   0.00
 12  1          9   90   45        3.00000   0.47      1.50000
               17
```


Figure 50. Description of alternative systems text file.

This file serves as a valuable resource, especially when interpreting the management scenarios presented in the Excel file. For a comprehensive understanding of these SWAT codes consult the detailed descriptions provided in Arnold et. al. (2013).

5.3 MATLAB figure file

For each MOEA execution, SWAT-MOEA saves two MATLAB figures. One illustrates the two-dimensional Pareto solutions, denoting the solution suggested with a red asterisk (Figure 51). The second file displays a geospatial map corresponding to this suggested solution (Figure 52).

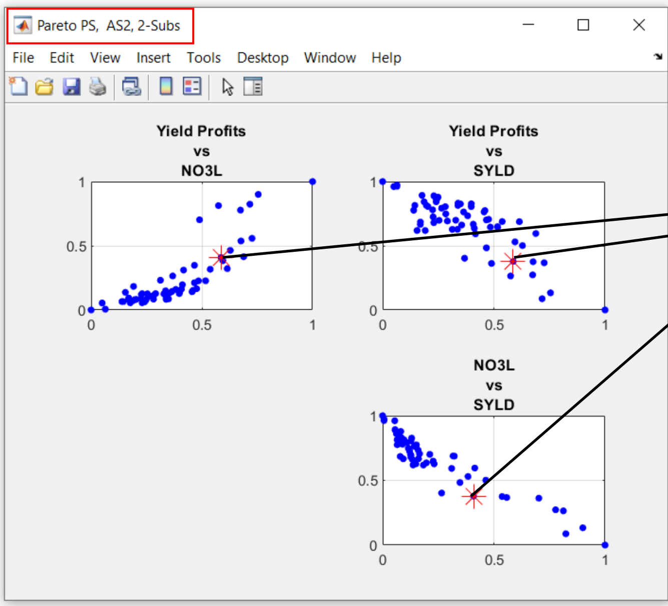


Figure 51. Two-dimensional Pareto graphs.

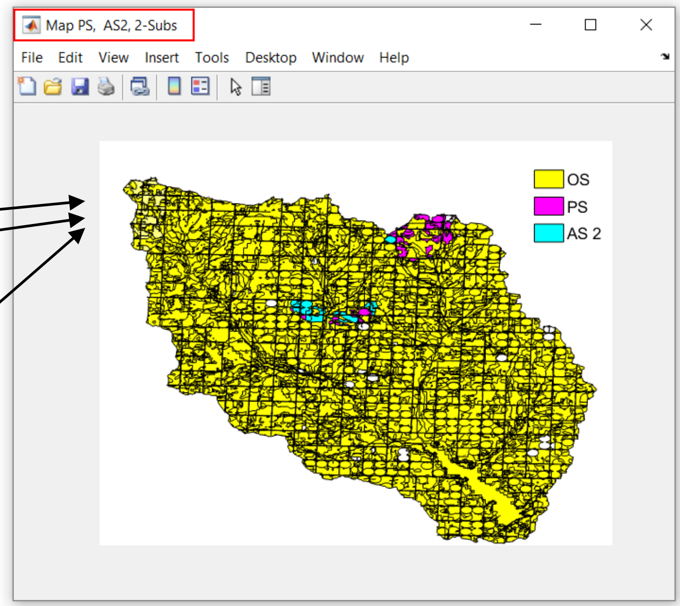


Figure 52. Geospatial map of suggested solution.

Both figures are named after the specific combination executed by the MOEA, providing clear identification and organization of the optimization results.

5.4 Description of Management Scenarios in Excel file

The management scenario represents the spatial placement of systems where:

- 0 values = Not optimal subbasin (prevailing system remains)
- 0.5 values = Prevailing system is optimal
- 1 values = Alternative system 1 is optimal (AS1)
- 2 values = Alternative system 2 is optimal (AS2)
- 3 values = Alternative system 3 is optimal (AS3)

Additionally, zero values in objectives denote that their corresponding HRUs were not included in the optimization based on the land use selected.

For example, in figure 53, Subbasin 24 was identified by the MOEA as an optimal subbasin, in which HRU 242 retains the prevailing system while HRU 243 converts to Alternative System 2.

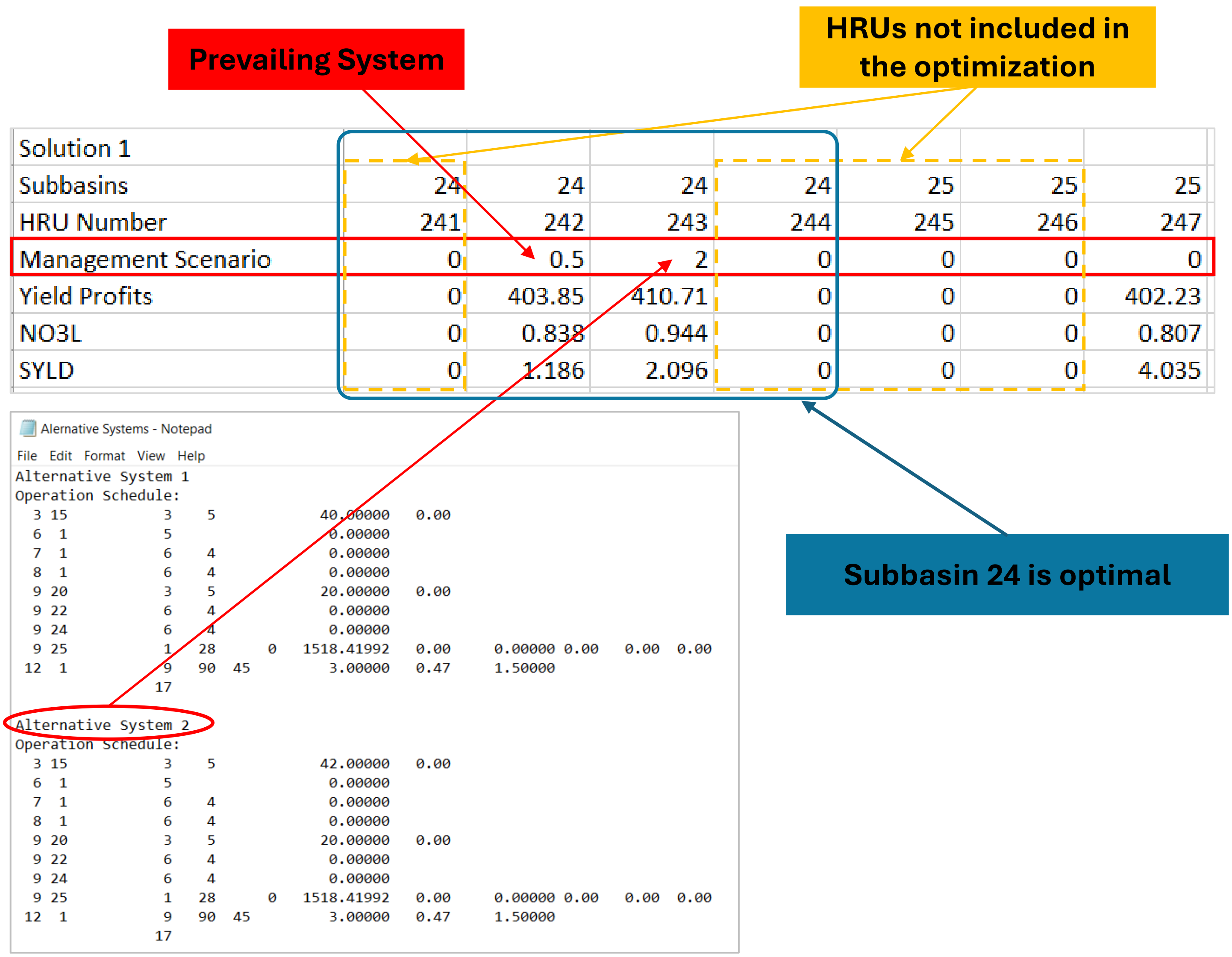


Figure 53. Description of management scenario in Excel file.