User’s Guide: Cost Model for Pumped Storage Hydropower Geomembrane Lining Systems

May 2026

Scott DeNeale[1*]
Antonia Chu[1]
Mustafa Altinakar[2]
Jason Hedien[3]
Vladimir Koritarov[2]

[1]Oak Ridge National Laboratory
[3]Argonne National Laboratory
[3]Stantec Inc.

*Corresponding author: Scott DeNeale (denealest@ornl.gov)

To access the associated Cost Model, visit: https://doi.org/10.21951/PSHgeomembrane/3028450

Contents

List of Figure

List of Tables

1 Model Overview and Assumptions

1.1 Background

Argonne National Laboratory and Oak Ridge National Laboratory have developed the "Cost Model for Pumped Storage Hydropower Geomembrane Lining Systems," with support from Stantec. A prior scoping study of geomembrane lining systems funded by the U.S. Department of Energy produced the HydroWIRES report "Reservoir Lining for Pumped Storage Hydropower," published in 2023 (Hedien et al. 2023), which demonstrated the need for this type of tool. The Microsoft Excel tool, which is publicly available alongside this User Guide, allows users to provide specific input parameters for their PSH reservoirs such as storage volume, surface area, approximate shape, etc., and estimates the costs of various designs of geomembrane lining systems. It aims to provide useful guidance for the preliminary assessment of different liner system costs. This User Guide describes in detail the workflow, the assumptions, as well as the capabilities and limitations of the cost model tool alongside potential use cases as well as exemplary inputs..

The geomembrane lining system cost model is developed for application to closed-loop PSH reservoirs. This Excel-based tool aims to serve as an early-phase cost estimate based on different lining system designs, their components and compositions. It is meant to highlight the differences in cost of different liner system designs and is not meant to serve as an engineering design and/or detailed cost estimate. The tool allows users to provide specific input parameters for their reservoirs and estimate the costs of various designs of geomembrane lining systems. The authors assume no responsibility, and no guarantees are given. Actual costs will vary based on the project and its specific parameters (e.g., size, site location, etc.).

The Excel tool is organized as a series of worksheets focused on different topics. Referring to Figure 1, they are listed below in order alongside their main contents:

- Home: Title, Instructions, Disclaimer
- Project Info & Setup: basic inputs for documentation
- Reservoir Design: calculate lined surface areas (bottom and side slopes) based on shape, depth, bottom length, bottom width, and side slope
  - Introduces formatting for inputs/outputs
  - Includes assumptions and user notes
- Liner System Design: calculates unit costs based on numerous inputs, as well as anchor trench design
- Cost Estimate: calculates component costs and the total cost based on prior calculations
- Glossary: defines acronyms and units used in the model

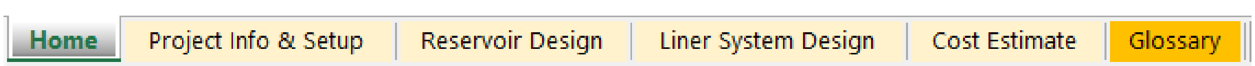


Figure 1. Tabs of the worksheets in the cost estimation spreadsheet.

Sheets are protected with only select content able to be modified. These sheets are intended to be completed sequentially from left to right, and the bottom of each sheet includes a "Home" and a "Previous" and/ or "Next" button for navigation purposes. Instructions and a legend are provided at the top of each sheet, and entries should be made from top to bottom.

Specific instructions are provided in an annotation box when the user clicks on a cell. User-defined inputs determine the calculated output. These values can be overwritten with Custom Inputs made by the user.

The spreadsheet "Cost Model for Pumped Storage Hydropower Geomembrane Lining Systems" was specifically designed to provide a rapid and reliable cost estimate of geomembrane liner systems with a minimum amount of input data to be provided by the user. To achieve this goal, several assumptions had to be made, and several simplifications had to be introduced. Some limitations were also made to ensure the spreadsheet is easy to use and reduce the input data to be entered by the user.

1.2 Reservoir Design

For "Reservoir Design," the user defines the reservoir shape by selecting one of the three reservoir shapes offered in the dropdown menu "Shape" in the worksheet "Reservoir Design": "rectangular," "elliptical/circular," and "non-standard." These reservoir shapes refer to the geometric shape of the plan view of the reservoir bottom. The plan view and the cross-section of rectangular and elliptical/circular reservoirs are conceptually illustrated (not to scale) in Figure 2 and Figure 3, respectively. The definition of input parameters to be entered by the user to allow the spreadsheet to compute surface areas of geomembranes and geotextiles and the lengths of pipes of the drainage system (if selected) are also shown in these figures. The bottom of the non-standard reservoir cannot be represented as a simple geometric shape. Thus, surface areas and pipe lengths needed for cost estimation must be separately entered as custom input.

1) "Rectangular reservoir" has a rectangular-shaped bottom (Figure 2). The user is expected to enter four input parameters under the "INPUT" section of the worksheet "Reservoir Design":

    a) "Height" is the vertical distance in feet from the bottom of the reservoir to the top edge of the reservoir,

    b) "Bottom length" is the length of the rectangular-shaped bottom in feet,

    c) "Bottom width" is the width of the rectangular-shaped bottom in feet, and

    d) "Side slope" is the slope for all side walls. It is dimensionless and defined as m units of horizontal length for one unit of vertical rise.

    Based on these four input parameters, the spreadsheet calculates the following and writes them under the "Calculated" column of the "OUTPUT" section:

    a) "Reservoir bottom lined surface area," which is the surface area in ft^2 of the reservoir bottom lined with the geomembrane liner.

    b) "Reservoir side slope lined surface area," which is the surface area in ft^2 of the side walls of the reservoir lined with the geomembrane liner.

    c) "Combined reservoir lined surface area," which is the sum of the "Reservoir bottom lined surface area" and the "Reservoir side slope lined surface area." It is also in units of in ft^2. It is important to note that the "Combined reservoir lined surface area" does not consider the extension of the geomembrane to anchor it in an anchor trench (this is accounted for separately in the "Liner System Design" worksheet).

    d) "Total volume of lined reservoir" is the volume of the reservoir when it is filled to the top edge of the reservoir, i.e., top edge of the side walls. It is provided in both ft^3 and acre-ft. This is only provided for reference and is not used in cost calculations.

    There are two special cases to be considered:

- When the same value is entered for "Bottom length" and "Bottom width," the reservoir bottom becomes a square.
- Specifying the "Side slope" as null or "0" corresponds to vertical side walls.

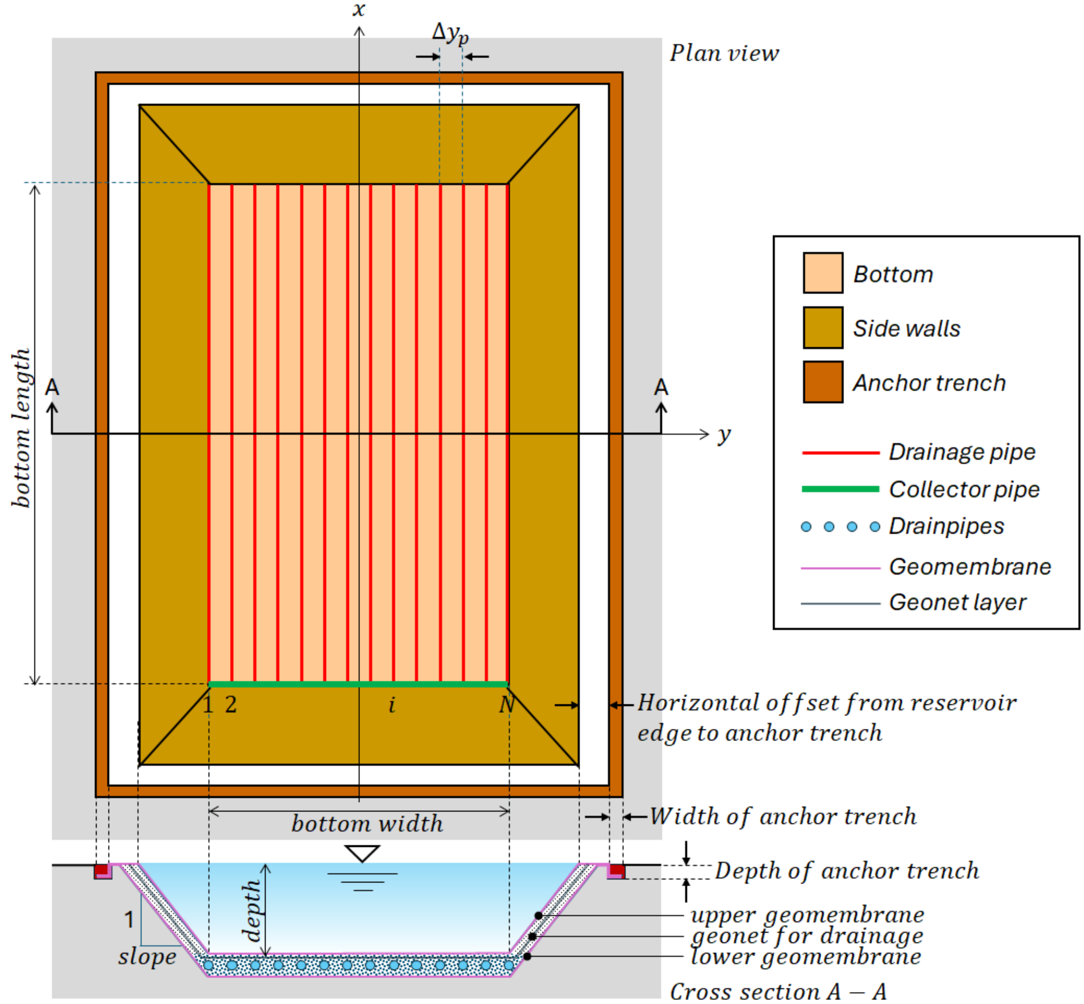


Figure 2. Plan view and cross-section of the rectangular reservoir (not to scale) showing the definition of the variables and the drainage pipe layout used for cost estimation.

2) "Elliptical/Circular" has an ellipse-shaped bottom (Figure 3). The user is expected to enter four input parameters under the "INPUT" section of the worksheet "Reservoir Design":

   a) "Height" is the vertical distance in feet from the bottom of the reservoir to the top edge of the reservoir,

   b) "Bottom length" is the length of the elliptical bottom, which is equal to two times the semi-major axis of the ellipse,

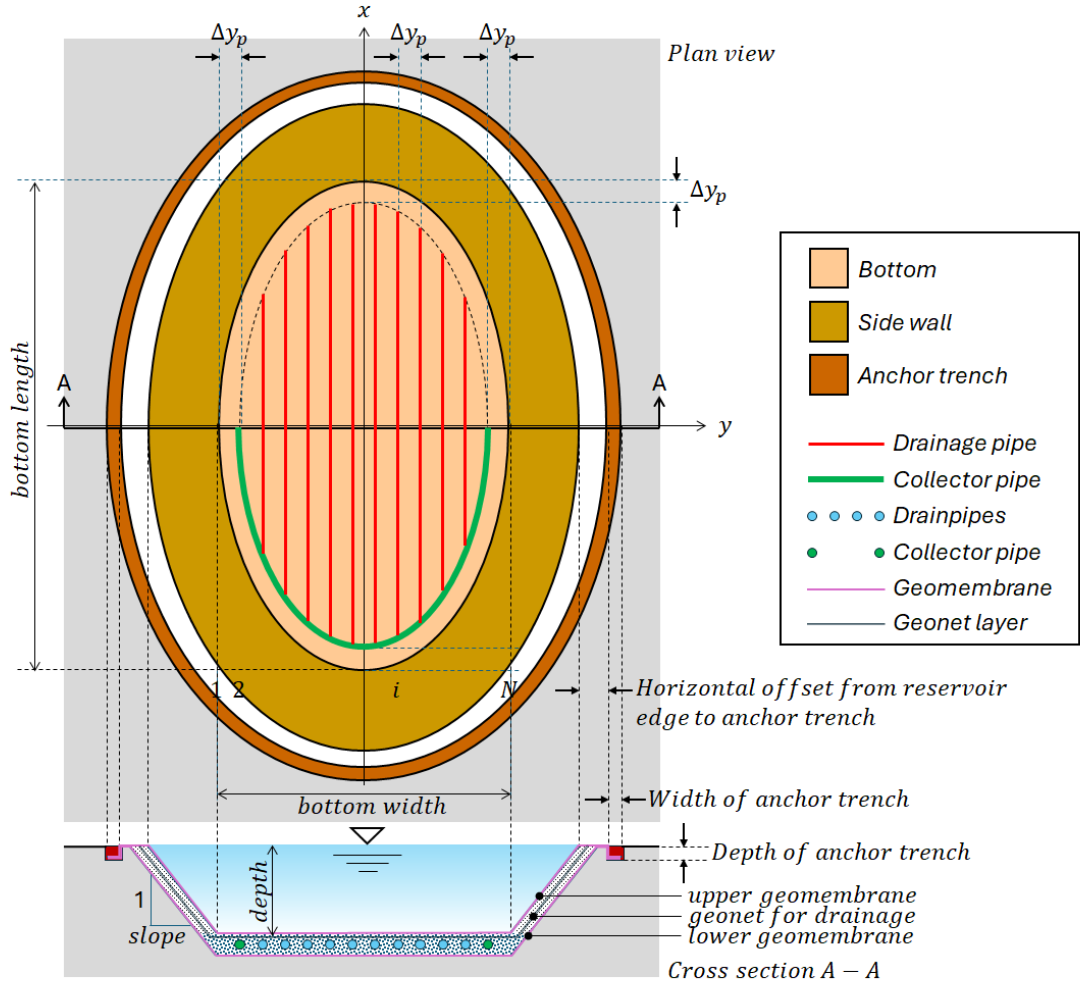


Figure 3. Plan view and cross-section of the elliptical/circular reservoir (not to scale) showing the definition of the variables and the drainage pipe layout used for cost estimation.

c) "Bottom width" is the width of the elliptical bottom, which is equal to two times the semi-minor axis of the ellipse, and

d) "Side slope" is the slope for the curved side wall around the perimeter. It is dimensionless and defined as m units of horizontal length for one unit of vertical rise.

Based on these four input parameters, the spreadsheet calculates the following and writes them under the "Calculated" column of the "OUTPUT" section:

a) "Reservoir bottom lined surface area," which is the surface area in ft^2 of the elliptic reservoir bottom lined with the geomembrane liner.

b) "Reservoir side slope lined surface area," which is the surface area in ft^2 of the curved side walls of the reservoir lined with the geomembrane liner.

c) "Combined reservoir lined surface area," which is the sum of the "Reservoir bottom lined surface area" and the "Reservoir side slope lined surface area." It is also in units of in ft^2. It is important to note that the "Combined reservoir lined surface area" does not consider extension of the geomembrane to anchor it in an anchor trench (this is accounted for separately in the "Liner System Design" worksheet.

d) "Total volume of lined reservoir," which is the volume of the reservoir when it is filled to the top edge of the reservoir, i.e., the top edge of the side walls. It is provided in both ft^3 and acre-ft. This is only provided for reference and is not used in cost calculations.

There are two special cases to be considered:

- When the same value is entered for "Bottom length" and "Bottom width," the reservoir bottom becomes a circle.
- Specifying the "Side slope" as null or "0" corresponds to vertical side walls.

3) "Non-standard" reservoir has a bottom that cannot be defined as a simple geometric shape. The side walls may also have different slopes. Thus, the spreadsheet does not automatically calculate the surface areas or the volume. By selecting this option, the user is required to enter the following two surface areas, which must have been previously determined by the user under the "Custom Input" column of the "OUTPUT" section:

a) "Reservoir bottom lined surface area," which is the surface area in ft^2 of the reservoir bottom lined with the geomembrane liner, and

b) "Reservoir side slope lined surface area," which is the surface area in ft^2 of the side walls of the reservoir lined with the geomembrane liner.

Optionally, the user can also enter the "Total volume of lined reservoir" in ft^3 and/or acre-ft in the "Custom Input" column of the "OUTPUT" section. The entered values are only for reference. They are not used in cost estimates.

The user assumes the responsibility of providing accurate values for reservoir surface areas, and optionally for volume, based on the engineering calculations. The entered values are not verified in the spreadsheet.

1.3 Liner System Design

Following the "Reservoir Design" worksheet, the "Liner System Design" worksheet takes various prior inputs combined with additional inputs to determine design parameters and unit costs for the geomembrane, geotextile, drainage and leak detection layer, and cover layer portions of the system.

In addition to the previously assessed bottom and side portions of the lining system based on reservoir geometry, the geomembrane lining system may also include an anchor trench for which additional material needs to be considered. This additional surface area needed to extend the material (geomembrane and geotextile) to the anchor trench is entered separately in the "Liner System Design" worksheet. If an anchor trench is used with a rectangular or elliptical reservoir, the user should answer "yes" to the question, "Anchor trench used?" under the "INPUT: User-defined" column of the "Liner System Design" worksheet and then enter three parameters under the same column (see Figure 2 and Figure 3):

a) "Horizontal offset from reservoir edge to anchor trench," which is the distance in ft from the top edge of the reservoir to the edge of the anchor trench. The spreadsheet assumes that the anchor trench follows the shape of the top edge of the reservoir at this user-specified distance around the entire perimeter.

b) "Depth of anchor trench," which is the depth of the anchor trench. The trench is assumed to have a constant depth around the entire perimeter of the reservoir.

c) "Width of anchor trench," which is the width of the anchor trench. The trench is assumed to have a constant width around the entire perimeter of the reservoir.

The spreadsheet assumes that the geomembrane extends from the top edge of the reservoir to the anchor trench, covering the entire depth of the trench on the reservoir side and the entire bottom of the trench. Thus, the length of the additional geomembrane system material needed to anchor the geomembrane in the trench is equal to the sum of the above three user-specified parameters, which are assumed to be the same around the entire perimeter of the reservoir.

To calculate the "Liner surface area for anchoring" under the "User-defined" column of the "INPUT" section, the spreadsheet assumes that the geomembrane for the side wall is extended by a distance equal to the sum of the three parameters, specified above, using the user-specified side slope.

If the "non-standard" reservoir shape was selected in the worksheet "Reservoir Design," the user is expected to directly enter the "Liner surface area for anchoring" in ft^2 under the "INPUT: Custom Input" column of the 'Liner System Design" section of the "Liner System Design" worksheet.

Under the "Liner System Design" worksheet, the user can also specify whether the geomembrane lining system uses a single or double geomembrane barrier layer. Depending on the selection, for each geomembrane layer, the user specifies the type of the geomembrane and its thickness (in mil).

In calculating the cost of the geomembrane, regardless of the top or bottom geomembrane layer, the spreadsheet always uses the same surface areas (either calculated or user-specified) of the bottom, sides, and additional anchoring material. No consideration is given to the thickness of the layers making up the geomembrane lining system (such as the drainage layer or the cover layer, etc.).

In the "Liner System Design" worksheet, the user can also specify up to six geotextile layers and enter a rating between 500 and 700 g/m^2 separately for the bottom, side slopes, and anchoring in the trench. In calculating the cost of the geotextile, regardless of the geotextile in the geomembrane lining system, the spreadsheet again uses the same surface areas (either calculated or user-specified) of the bottom, sides, and additional anchoring material.

Often, the manufacturer delivers the geomembrane and geotextile to the jobsite in rolls of a specified width. These rolls are then deployed in the jobsite with an overlapping between the adjacent rolls for welding them together. The spreadsheet does not consider the additional material that would be needed because of the overlapping between adjacent rolls. The cost estimations for all geomembrane and geotextile layers are carried out using the sum of the "Liner system bottom surface area," "Liner system side slope surface area," and, if an anchor trench is used, "Liner surface area for anchoring." These surface areas are calculated by the spreadsheet for rectangular and elliptical/circular reservoirs. For non-standard reservoirs, they can be entered by the user after calculating them based on the engineering calculations.

A drainage and leak detection layer can also be selected in the "Liner System Design" input. This layer assumes the installation of a geonet and a network of perforated drainage pipes laid out under the bottom of the reservoir[1] according to a predefined layout based on its shape. The drainage pipe network consists of a number of rows of drainpipes (with the specified user-defined spacing between them), which are laid out parallel to the longer axis of the reservoir bottom. At the downstream end of the long axis of the reservoir, the drainpipes discharge into a collector pipe that evacuates drained water away from the

[1] It is recommended to construct the bottom of the reservoir with a 2 to 3% slope in the longitudinal direction and 3 to 5% slope in the lateral direction to facilitate the evacuation of drainage water and gases under the lining system. These details are considered in the final design of the reservoir. They have no bearing on the present cost estimation methodology.

reservoir. The pipe layouts used for rectangular and elliptical/circular reservoirs are shown in Figure 2 and Figure 3, respectively.

The only input required from the user is the "Spacing between drainage pipes" in feet. Based on this input entered by the user, the spreadsheet calculates the "Drainage pipe length (total)" and the "Collector pipe length (total)" in units of feet according to the appropriate layout. If the non-standard reservoir option has been selected, the user directly enters the values for the "Drainage pipe length (total)" and the "Collector pipe length (total)" under the "Custom Input" column. Multiplication of these pipe lengths with the corresponding unit costs (dollars per foot) gives the cost of the pipes for the drainage layer. The unit costs for the drainage pipes and collector pipes are assigned by default by the spreadsheet, but the user can change them to custom values.

1.4 Liner System Assumptions and Limitations

The following additional assumptions and limitations hold in calculating the cost of the liner system:

1) The calculated costs refer to unit prices in 2024 dollars based on rough assumptions using limited available information. Rates incorporate material, assumed transportation, and installation costs and should be used with caution. In cases where raw unit costs were obtained in 2018 dollars, an escalation factor of 1.28 was used to increase the unit costs by 28% to 2024 dollars, based on the U.S. Army Corps of Engineers CWCCIS Indices for the 03 Reservoirs feature code for 2Q18 and 2Q24.

2) The cost of preparing the support layer is not included in the estimation of the geomembrane liner cost.

3) The cost of constructing the anchor trench is not included in the estimation of the geomembrane liner cost.

4) The estimation of the geomembrane liner cost does not consider the special detail work needed around pipe connections, concrete appurtenances, etc.

5) Geomembranes and geotextiles are assumed to cover the full reservoir bottom and side slope surface areas, as well as the anchored trench surface area.

6) During the installation, adjacent geomembrane rolls have to be overlapped 4 to 6 inches for the creation of seams by welding (for thermoplastic geomembranes) or by using special chemicals or two-sided tapes (for thermoset geomembranes). The additional material required for overlapping is relatively small and negligible. It is not considered in calculating the surface areas of geomembranes or geotextiles.

7) The geonet surface area is assumed to cover the full bottom reservoir surface area.

8) The cost of the cover layer is calculated based on the user-specified cover layer thicknesses for the bottom and the side slopes. The user enters the thicknesses in inches for "Cover layer thickness (bottom)" and "Cover layer thickness (side slopes)" under the "User-defined" column of the "Cover Layer: INPUT" section. Thus, the cover layer is assumed to have the same thickness and same gradation over the entire height of the side wall and around the entire perimeter of the reservoir. Section 2.4.4 in Hedien at al. (2023) discusses the design of the cover layer on the side slope. Section 2.4.5 in the same document discusses the minimum conductivity of the cover layer to prevent excessive pore pressure during rapid drawdown and filling operations. If a cover layer with a tapered

thickness is used, the user may calculate and provide an average thickness for the entire height of the side wall.

9) If the height of the side slope is greater than a critical value, the tensile stresses in the selected geomembrane due to its own weight and the weight of the overlaying layers may be excessive. In such cases, berms should be provided on the side slope to keep the effective slope length below a critical value (see Figure 3.22 in Hedien et al. 2023). The present spreadsheet does not consider the construction of any berms.

1.5 Results

The "Cost Estimate" worksheet provides calculated output from the prior model inputs. Again, the calculated costs can be overridden by the user. The model provides a "Total geomembrane cost," "Total geotextile cost," "Total drainage & leak detection layer cost," and "Total cover layer cost," as well as a "TOTAL LINING SYSTEM COST." The results are provided tabularly as well as in a pie chart. Given the model's setup, a user can easily modify inputs or provide custom inputs to alter the design and test model sensitivity while exploring cost impacts and design alternatives.

Oak Ridge National Laboratory

2 Example Walkthrough

Model Basics

- Layout of worksheets *(optional, custom inputs included throughout model)*
    - Home: title, instructions, disclaimer
    - Project Info & Setup: basic inputs for documentation
    - Reservoir Design: calculate lined surface areas (bottom and side slopes) based on shape, height, bottom length, bottom width, and side slope
        - Introduces formatting for inputs/outputs (see legend below in Figure 4)
        - Includes assumptions and user notes
    - Liner System Design: calculates anchor trench liner surface area; calculates unit costs based on numerous inputs
    - Cost Estimate: calculates component and total costs based on prior calculations
    - Glossary: defines acronyms and units used in the model
    - Sheets are protected with only select content able to be modified.
- Note that you may encounter a "Check Performance" notification about a slow workbook. This can be disregarded.

The cells of the worksheets are colored to guide the user according to the legend shown in Figure 4.

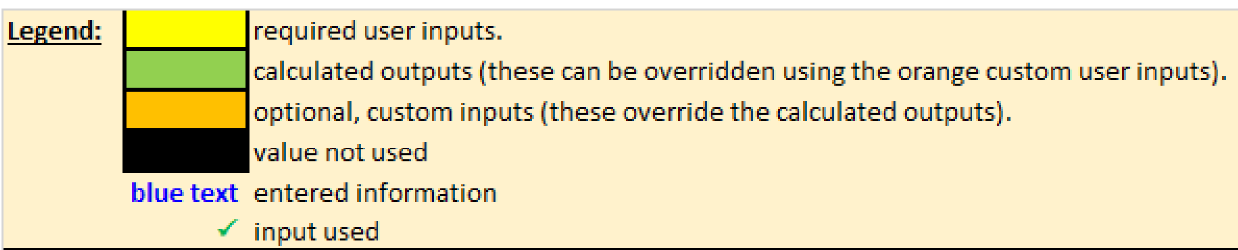


Figure 4. Legend used in cost model worksheets.

Example

The following example is provided to demonstrate the use of the model. A more detailed, step-wise walkthrough will be made available in a User Guide that will be published at a later date.

Step 1: Upon opening the model, the "Home" page will be displayed (Figure 5). No user input is required on this worksheet.

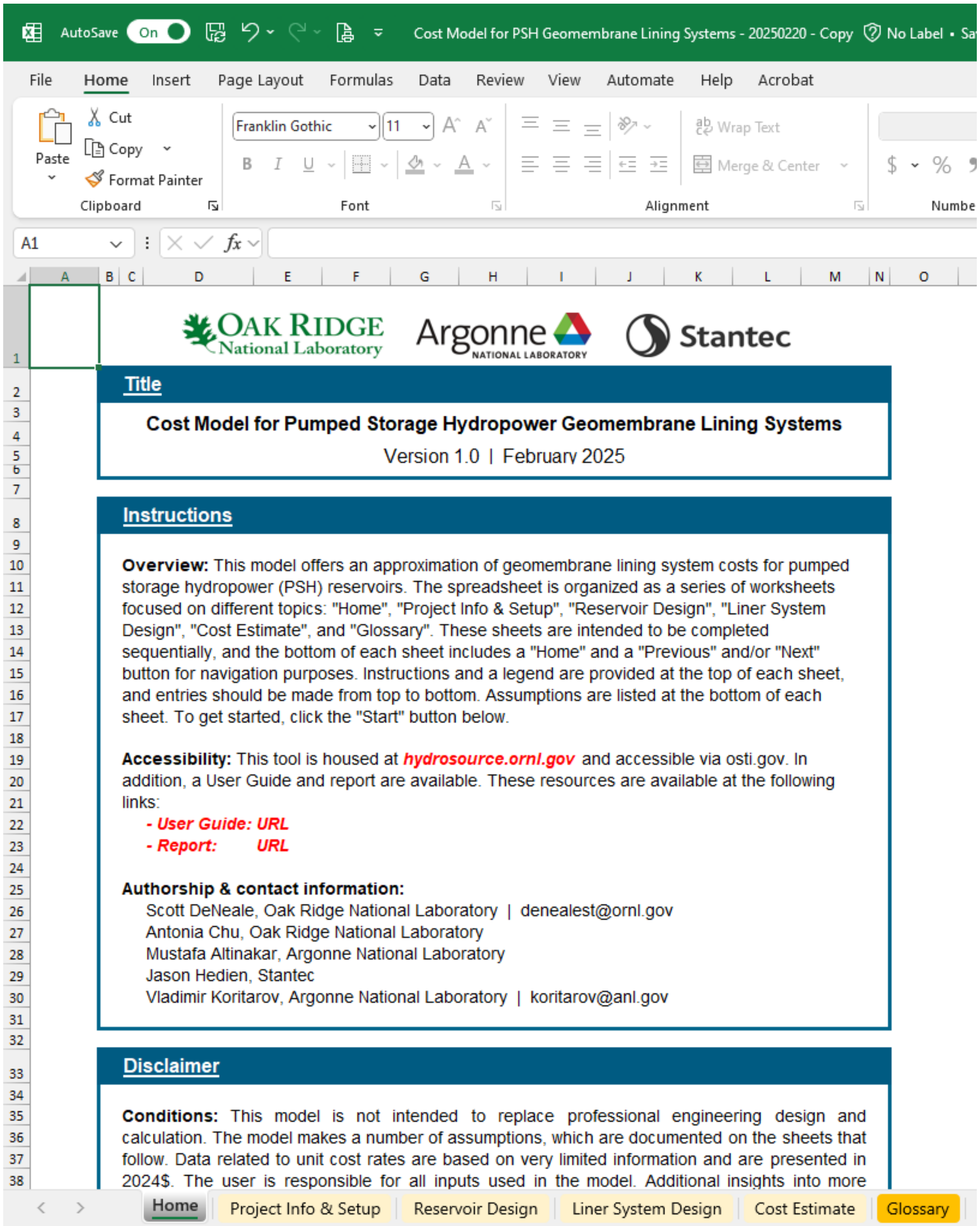


Figure 5. "Home" page.

Step 2: Click the "Start" button to move to the next sheet, which is "Project Info & Setup" (Figure 6).

Step 3: Enter project information for project "Oak Ridge Example" located in Oak Ridge, Tennessee. The project includes modeling the cost for a single upper reservoir in a closed-loop configuration, with Scott DeNeale as the contact.

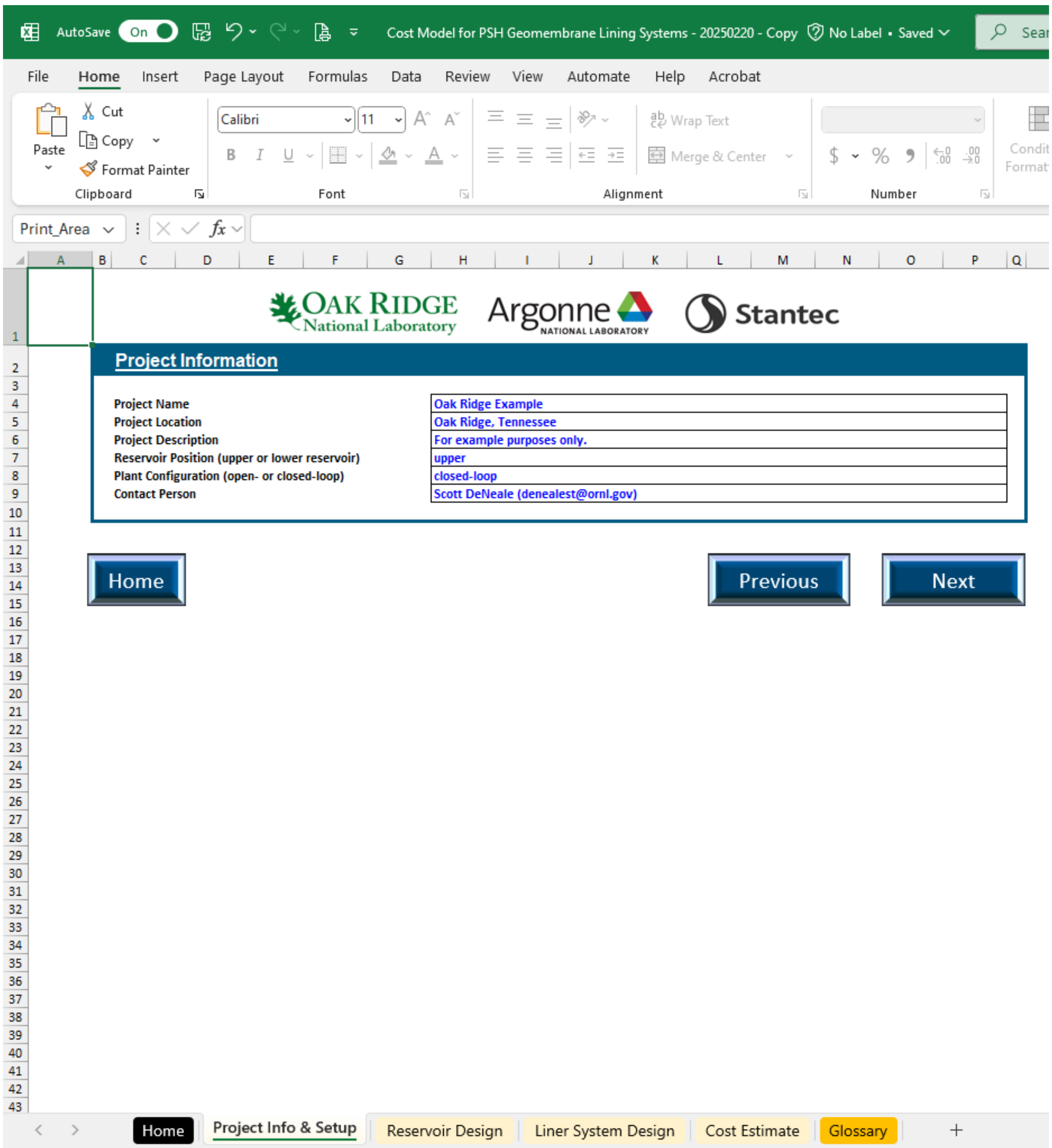


Figure 6. "Project Info & Setup" page.

Step 4: Click the "Next" button to move to the next sheet named "Reservoir Design" (Figure 7).

Step 5: Enter reservoir design information, including the following "required user inputs" (in yellow):

- Shape: elliptical/circular
- Height: 50 ft
- Bottom length: 1,000 ft
- Bottom width: 500 ft
- Side slope: 2.00

Step 6: Notice the calculated outputs (in green):

- Reservoir bottom lined surface area: 392,699 ft^2
- Reservoir side slope lined surface area: 305,141 ft^2
- Total reservoir lined surface area: 697,840 ft^2
- Total volume of lined reservoir: 26,023,829 ft^3 (597 acre-ft)

Step 7: Enter custom inputs to round up to the nearest thousand square feet for the bottom and side slope lined surface areas (in orange cells K25 and K26). Notice the total reservoir lined surface area is now 698,000 ft^2 and a Warning has been issued in red text in Row 28.

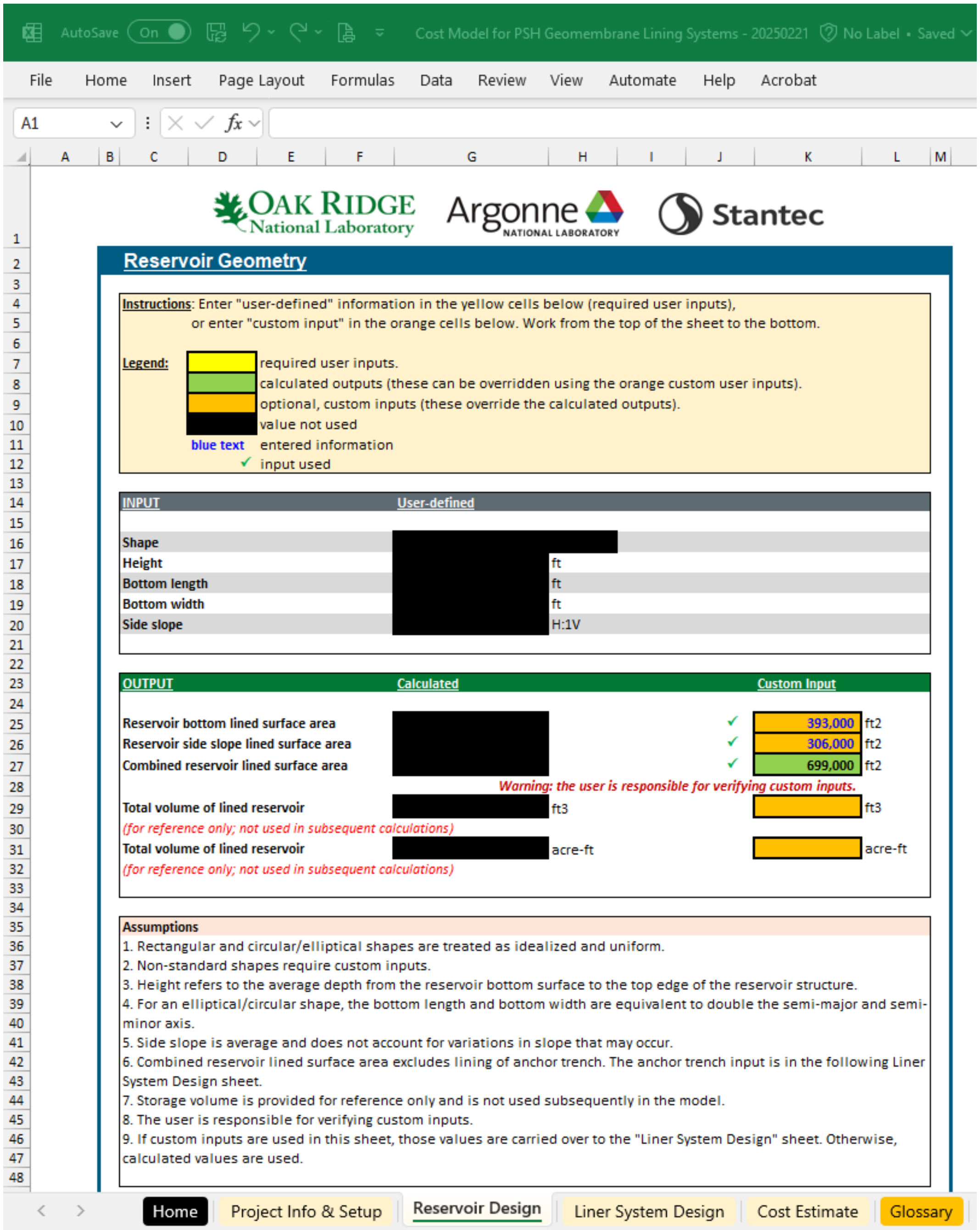


Figure 7. "Reservoir Design" page.

Step 8: Click the "Next" button to move to the next sheet named "Liner System Design" (Figure 8).

Step 9: Enter liner system design information, including the following "required user inputs" (in yellow):

- Anchor trench used?: Yes
- Horizontal offset from reservoir edge to anchor trench: 5 ft
- Depth of anchor trench: 2 ft
- Width of anchor trench: 2 ft

- Geomembrane, single or double?: Single
- Geotextile used?: Yes
- Drainage & leak detection layer used?: Yes
- Cover layer used?: Yes

Step 10: Enter geomembrane information, including the following "required user inputs" (in yellow):

- Layer 1 material (bottom): HDPE
- Layer 1 thickness (bottom): 60 mil
- Layer 1 material (side slopes): HDPE
- Layer 1 thickness (side slopes): 80 mil
- Layer 1 material (anchor trench): HDPE
- Layer 1 thickness (anchor trench): 60 mil
- Notice the Layer 2 cells are colored black (since only a single geomembrane is selected) and not included in subsequent calculations.
- Notice the output below: $0.56/ft^2 for the layer 1 unit cost (bottom) and $0.66/ft^2 for the layer 1 unit cost (side slopes).

Oak Ridge National Laboratory

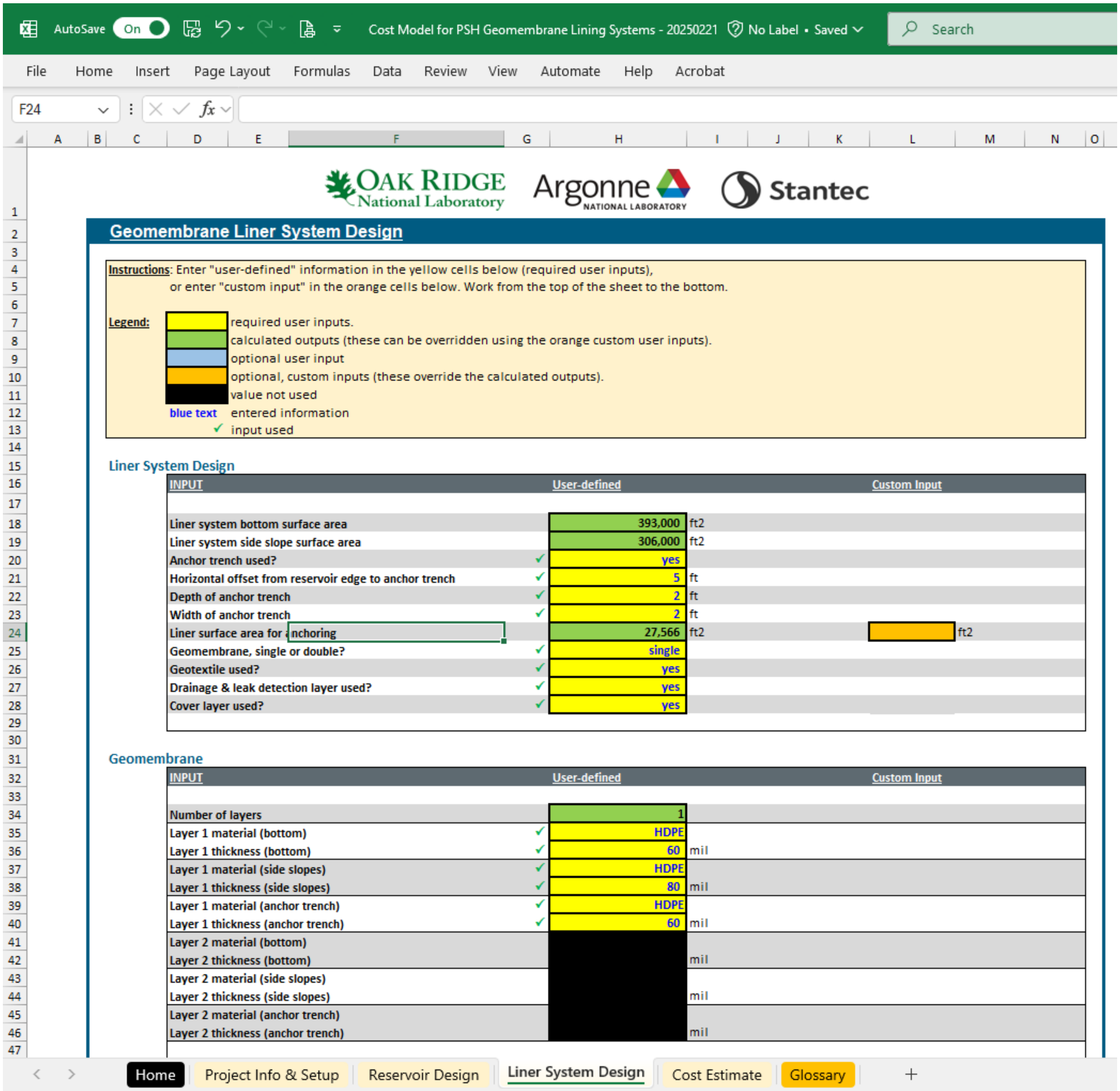


Figure 8. "Liner System Design" page (screenshot 1 of 3).

Step 11: Enter custom inputs (in orange cells L51 through L53) for unit costs for geomembrane layer 1 (bottom) of $0.60, (side slopes) of $0.70, and (anchor trench) of $0.60 (Figure 9).

Step 12: Referring to Figure 9, enter geotextile information, including the following "required user inputs" (in yellow):

- Number of layers: 2
- Layer 1 rating (bottom): 500 g/m^2
- Layer 1 rating (side slopes): 700 g/m^2
- Layer 1 rating (anchor trench): 500 g/m^2
- Layer 2 rating (bottom): 500 g/m^2
- Layer 2 rating (side slopes): 700 g/m^2
- Layer 2 rating (anchor trench): 500 g/m^2
- Notice the calculated output for unit costs: \$0.51, \$0.77, \$0.51 for the different geometric sections, respectively. Let us keep these values (no need to enter custom input in cells L85:L90).

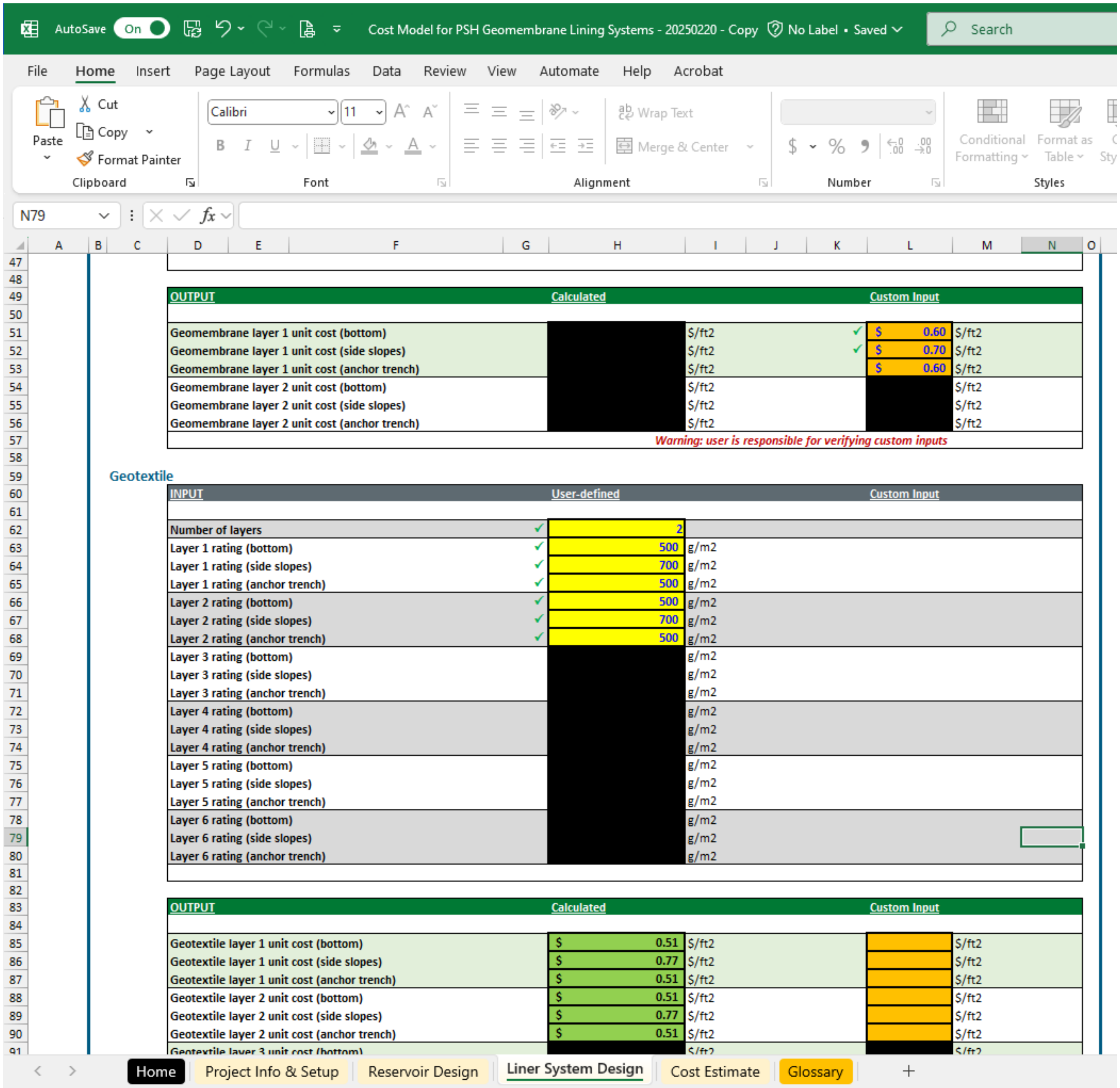


Figure 9. "Liner System Design" page (screenshot 2 of 3).

Step 13: Referring to Figure 10, enter drainage and leak detection layer information, including the following "required user inputs" (in yellow):

- Spacing between drainage pipes: 100 ft

Step 14: Notice the calculated drainage pipe length (1,508 ft) and collector pipe length (909 ft). Unit costs shown are default values.

Step 15: Notice that in Figure 10, the Support Layer is listed as "Not included in cost calculation." This decision is being made by the project team, given that the support layer is a standard, engineered feature of any reservoir system and is not unique to a geomembrane lining system. It is assumed as a separate project cost, outside the scope of the lining system.

Step 16: Referring to Figure 10, enter cover layer information, including the following "required user inputs" (in yellow):

- Cover layer thickness (bottom): 20 inches
- Cover layer thickness (side slopes) 30 inches

Step 17: Notice the calculated cover layer outputs of 24,259 yd^3 bottom layer volume, 28,333 yd^3 side slope layer volume, \$34.56/yd^3 bottom unit cost, and \$32.96/yd^3 side slope unit cost. Let us keep these values.

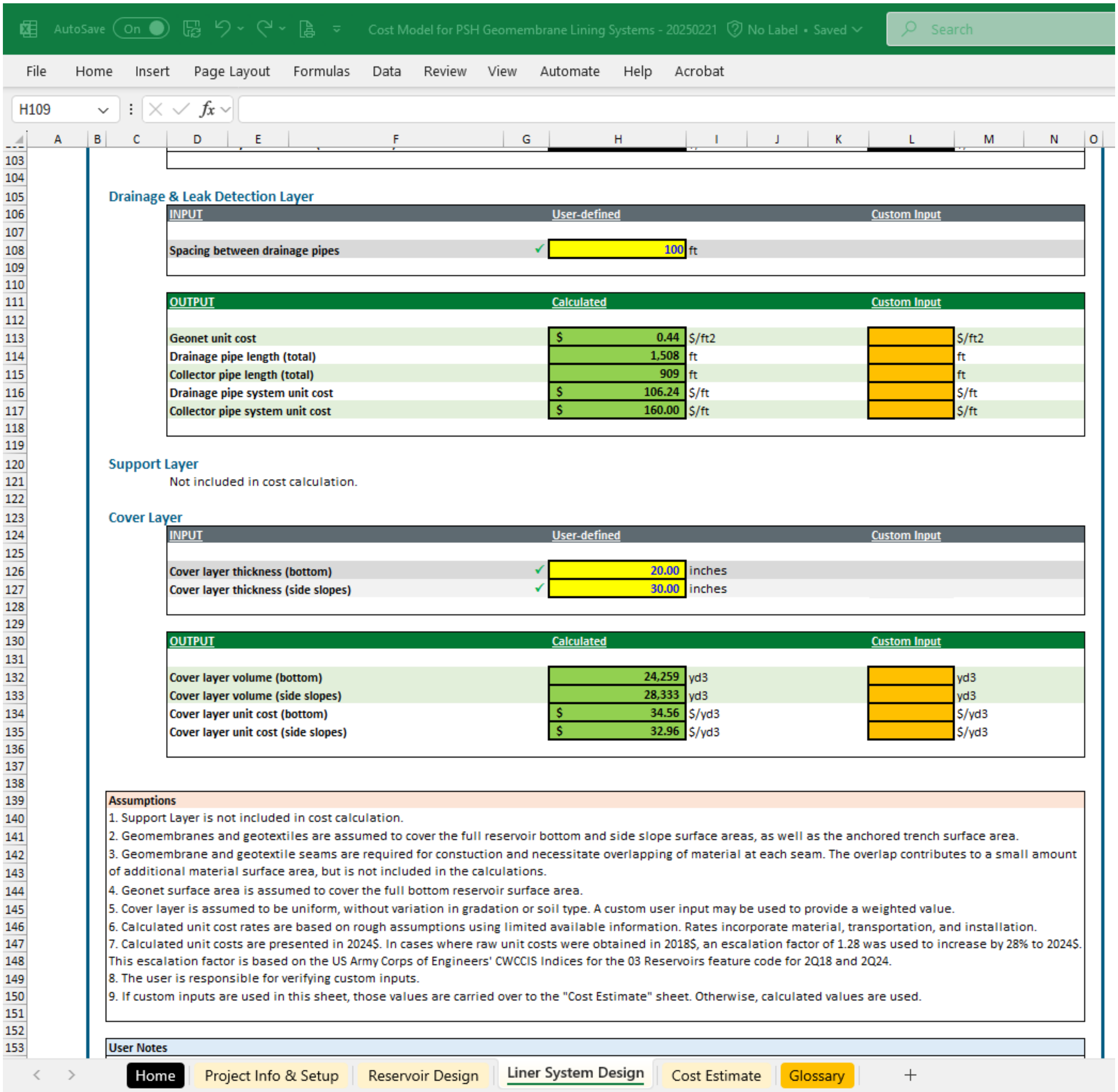


Figure 10. "Liner System Design" page (screenshot 3 of 3).

Step 18: Click the "Next" button to move to the next sheet, named "Cost Estimate" (Figure 11).

Step 19: Referring to Figure 11and Figure 12, notice the calculated costs for all components. Let us keep these and not enter any custom inputs (i.e., leave Column L alone). The following component and total costs are calculated:

- Total geomembrane cost: $466,539
- Total geotextile cost: 900,675
- Total drainage & leak detection layer cost: $609,932
- Total cover layer cost: $1,772,238
- Total lining system cost: $3,749,385

Step 20: In Figure 12, notice the pie chart and overall cost distribution.

Step 21: END

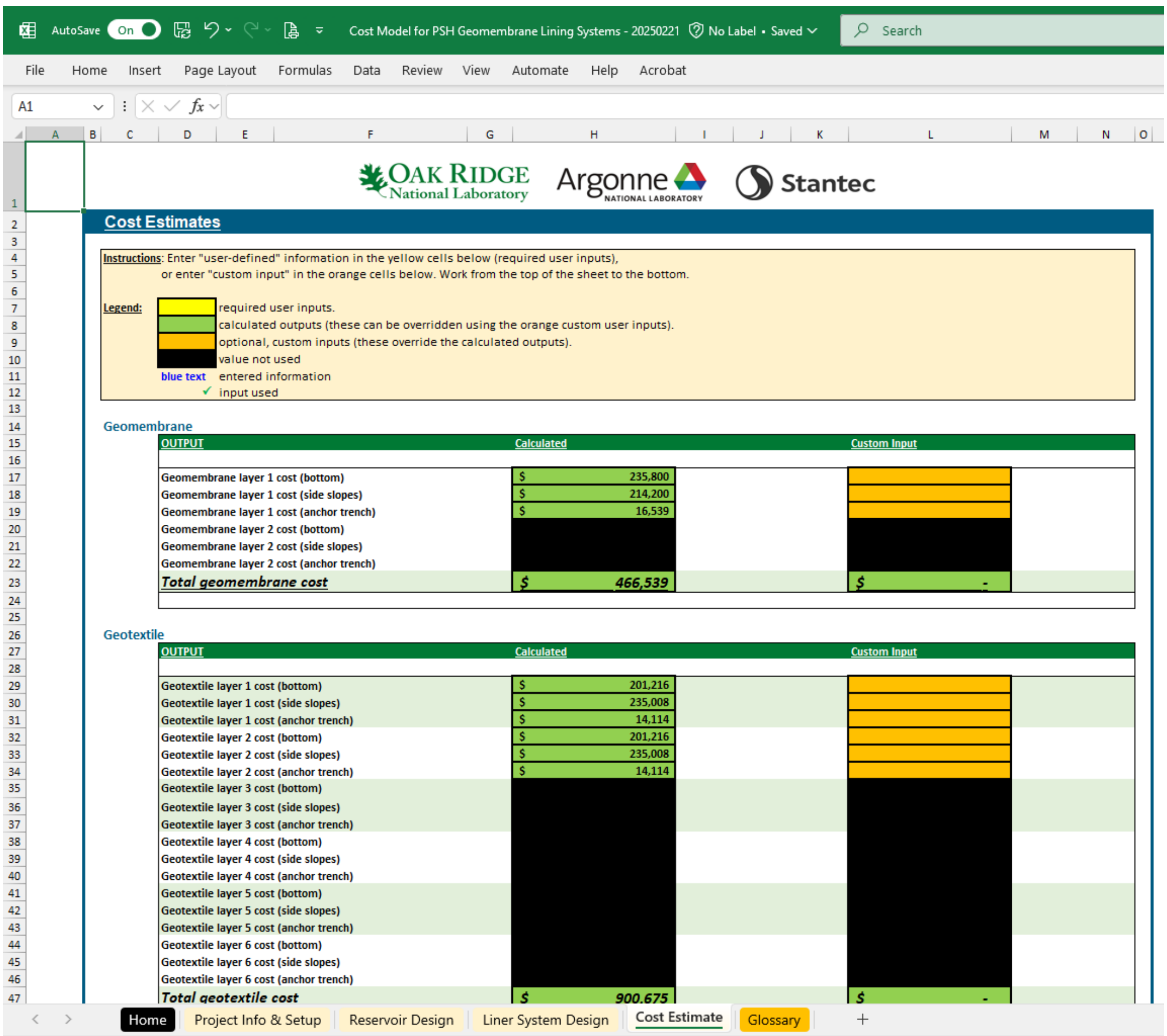


Figure 11. "Cost Estimate" page (screenshot 1 of 2).

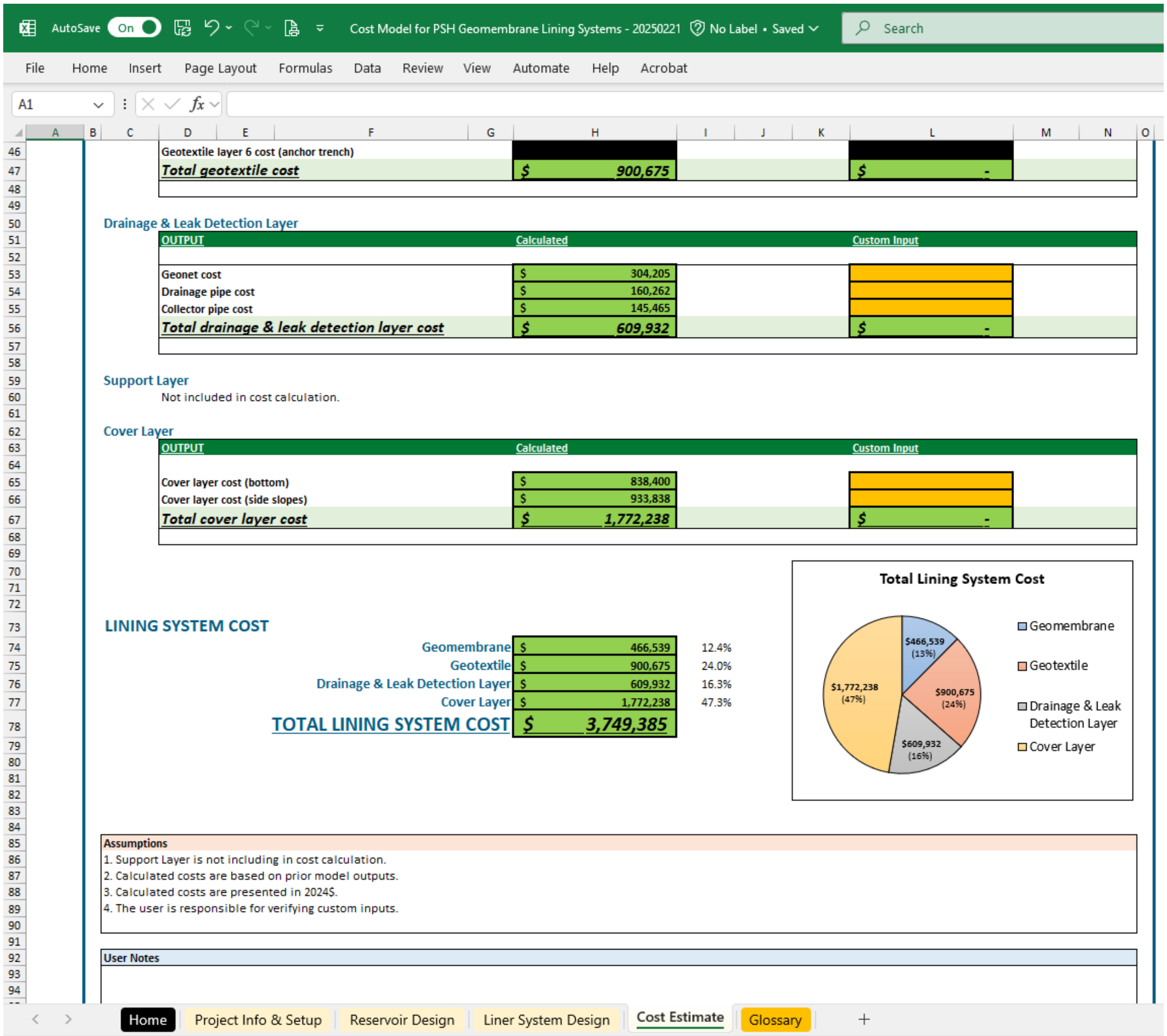


Figure 12. "Cost Estimate" page (screenshot 2 of 2).

3 Sensitivity Analysis for Example Walkthrough

An example (Scenario A) PSH reservoir geomembrane lining system is presented in Section 2 that exhibits the following input features:

- Reservoir Design
    - Shape: elliptical/circular
    - Height: 50 ft
    - Bottom length: 1,000 ft
    - Bottom width: 500 ft
    - Side slope: 2.00
- Liner System Design
    - (custom) Reservoir bottom lined surface area: 393,000 ft^2
    - (custom) Reservoir side slope lined surface area: 305,000 ft^2
    - (custom) Total reservoir lined surface area: 698,000 ft^2
    - Anchor trench used?: Yes
    - Horizontal offset from reservoir edge to anchor trench: 5 ft
    - Depth of anchor trench: 2 ft
    - Width of anchor trench: 2 ft
    - Geomembrane, single or double?: Single
    - Geotextile used?: Yes
    - Drainage & leak detection layer used?: Yes
    - Cover layer used?: Yes
    - Geomembrane
        - Layer 1 material (bottom): HDPE
        - Layer 1 thickness (bottom): 60 mil
        - Layer 1 material (side slopes): HDPE
        - Layer 1 thickness (side slopes): 80 mil
        - Layer 1 material (anchor trench): HDPE
        - Layer 1 thickness (anchor trench): 60 mil
        - (custom) geomembrane layer 1 unit cost (bottom) of $0.60, (side slopes) of $0.70, and (anchor trench) of $0.60
    - Geotextile
        - Number of layers: 2
        - Layer 1 rating (bottom): 500 g/m^2
        - Layer 1 rating (side slopes): 700 g/m^2
        - Layer 1 rating (anchor trench): 500 g/m^2
        - Layer 2 rating (bottom): 500 g/m^2
        - Layer 2 rating (side slopes): 700 g/m^2
        - Layer 2 rating (anchor trench): 500 g/m^2
    - Drainage and leak detection layer spacing between drainage pipes: 100 ft
    - Cover layer
        - Cover layer thickness (bottom): 20 inches
        - Cover layer thickness (side slopes) 30 inches

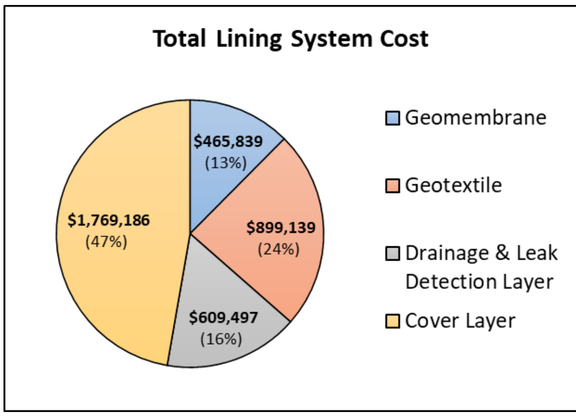
For this example (Scenario A), the total cost breakdown is as follows:

- Total geomembrane cost: $465,839
- Total geotextile cost: $899,139
- Total drainage & leak detection layer cost: $609,497
- Total cover layer cost: $1,769,186

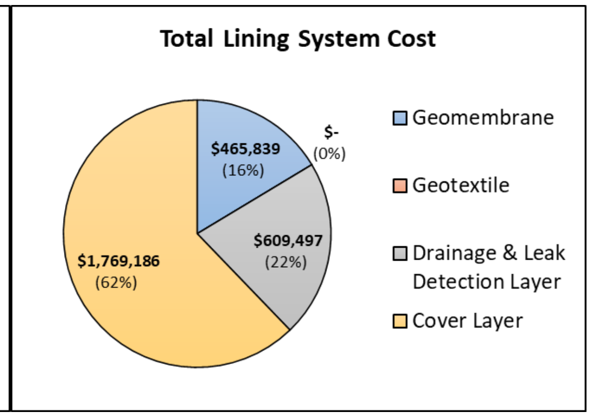
- Total lining system cost: $3,743,662

Table 1. Comparison of costs of different cost items in different scenarios for the example walkthrough

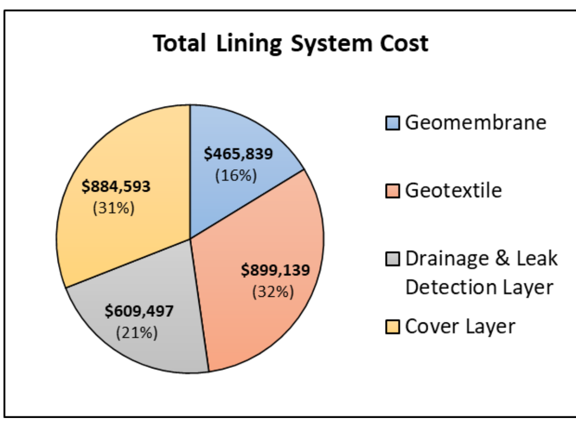
Component Cost	Scenario A	Scenario B	Scenario C	Scenario D
Total geomembrane cost	$465,839	$465,839	$465,839	$586,694
Total geotextile cost	$899,139	$0	$899,139	$1,130,998
Total drainage & leak detection layer cost	$609,497	$609,497	$609,497	$1,100,416
Total cover layer cost	$1,769,186	$1,769,186	$884,593	$2,226,335
Total lining system cost	$3,743,662	$2,844,522	$2,859,068	$5,044,442
Total lining system cost change (%)	*baseline*	*-24%*	*-24%*	*+35%*



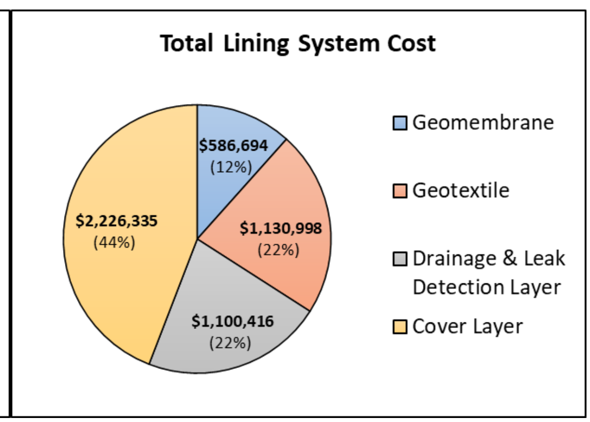
Scenario A



Scenario B



Scenario C



Scenario D

Figure 13. Pie charts showing the distribution of costs between different components of the total cost for the example walkthrough as shown in Table 1.

We will now conduct sensitivity analysis to modify various input parameters to assess the implications on component and overall system costs:

- Scenario A: see above example.
- Scenario B: same as Scenario A, but using no geotextile.
- Scenario C: same as Scenario A, but using half the volume of cover layer material (10-inch-thick bottom cover layer and 15-inch-thick side slope cover layer).
- Scenario D: same as Scenario A, but using a rectangular reservoir shape with no other changes to input geometry.

The results of these different scenarios are provided in Table 1 with cost breakdown pie charts in Figure 13. Note that for Scenario D, the total lined surface area increased by 26% compared with Scenario A.