# CaptureMF6– Estimate stream and evapotranspiration capture with simple MODFLOW6 models

Regulators such as Nevada Division of Water Resources (NDWR) need to estimate capture of streamflow by pumping (Nevada State Engineer, 2021). Analytical and numerical models have been deemed appropriate tools by NDWR for estimating capture from withdrawals of a groundwater right. Analytical models facilitate rapid analysis because input requirements are minimal. Numerical models can better approximate heterogeneous hydraulic properties and discharges to streams and phreatophytes (Barlow and Leake, 2012), but analyses generally are not rapid.

The Glover solution (Jenkins, 1968) likely is the most frequently applied analytical model, because spreadsheet solutions have been readily available (Hunt, 2005; Environment Canterbury, 2024). The Glover solution, like many other analytical solutions, assumes an infinite, homogenous, and isotropic aquifer that is penetrated fully by a straight-line stream and pumping well. These superficially concerning assumptions are not the primary limitation.

Analytical estimates primarily are limited by not simultaneously simulating potential capture from streams and evapotranspiration. Other analytical solutions more thoroughly characterize connection between aquifer and stream (Hunt, 2003), but do not simulate distributed discharge as evapotranspiration. This is a significant limitation where pumped water comes from storage and capture of discharge to streams and evaporation.

Simultaneous capture from streams and evapotranspiration can be analyzed rapidly with simplified numerical models that are created, executed, and synthesized with the current version of the ***CaptureMF6*** workbook. Aquifer, evapotranspiration area, and stream are defined with simple geometries and homogeneous properties to limit input requirements. Aquifer and evapotranspiration area extents are defined by lengths and widths. These areas are centered where pumping wells are projected on a straight-line approximation of the stream that bisects the aquifer (Figure 1). Lateral discretization is limited to specifying uniform, square cells in the evapotranspiration area and expanding row heights and column widths by a single multiplier to the aquifer extents (Figure 1). Vertical discretization is fixed at thicknesses of 1 and 99 ft in layers 1 and 2, respectively.

Simple, numerical models created by the ***CaptureMF6*** workbook simulate change from pumping with the same superposition assumptions in the Glover solution (Jenkins, 1968). All initial heads are 0 ft and heads are 0 ft in single stream that is simulated with constant-head package (Langevin, et.al., 2017). The straight-line stream is simulated in layer 1 of a single column that spans all rows. This straight-line approximation is a regressed fit to the user-specified stream segment (Figure 1).

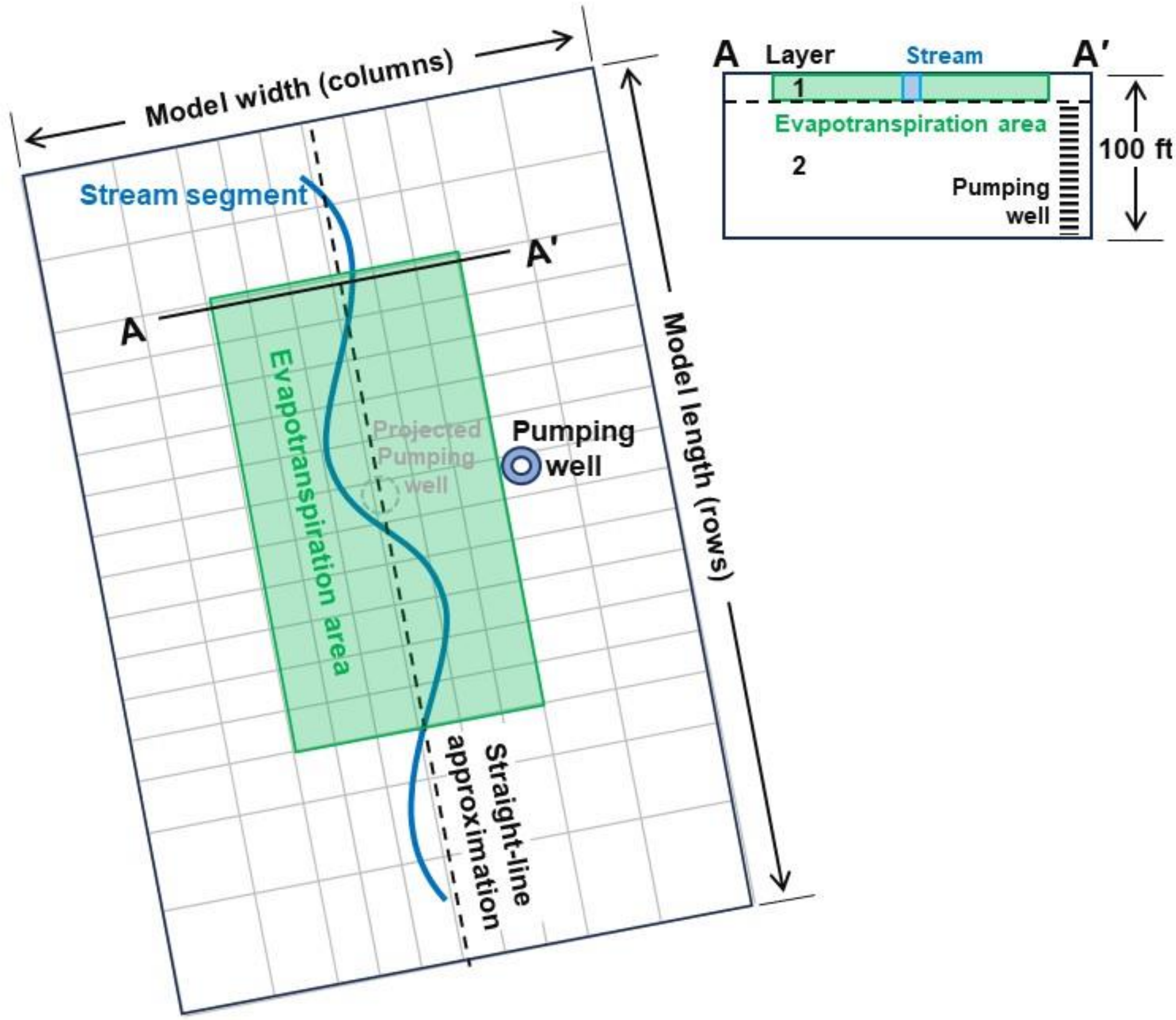



**Figure 1.—** Simplified MODFLOW6 template for analyzing stream and evapotranspiration capture from proposed pumping.

Capture from the evapotranspiration area is rate limited and is simulated with two MODFLOW packages, evapotranspiration (EVT) and well (WEL) (Langevin, et.al., 2017). This capture-limited boundary limits the total capture of discharge to the maximum evapotranspiration rate after simulated drawdown exceeds the extinction depth of evapotranspiration (Halford and Plume, 2011; p. 35). The WEL package simulates injection of water into a model cell, while EVT package simulates removal of water from the same model cell. Injection from the WEL package equals cell area times maximum evapotranspiration rate to balance discharge from the EVT package in the same cell. No capture occurs initially when simulated head is 0 and equals the elevation of the ET surface. As simulated water levels decline, injected volumes do not change, while EVT discharge decreases. Capture from the evapotranspiration area is the sum of volumes injected with the WEL package and discharged with the EVT package. Cells in WEL and EVT packages are assigned to layer 1 (Figure 1).

Pumping wells are simulated with a second WEL package. Pumpage is assigned to the nearest cell that contains mapped coordinates and is assigned vertically to layer 2 (Figure 1). Pumping rates are specified in acre-feet per year (acre-ft/yr).

Significant hydraulic properties and evapotranspiration parameters are defined with ranges so potential capture can be estimated with multiple models. These parameters are horizontal hydraulic conductivity (Kx), specific yield (Sy), maximum evapotranspiration rate (ETr), and extinction depth of evapotranspiration (ETd). Synthesizing multiple MODFLOW6 model results in a new workbook facilitates rapidly viewing effects of tested parameters on stream and evapotranspiration capture. Ratio of horizontal to vertical hydraulic conductivity and specific storage were specified because these parameters are less significant than Kx, Sy, ETr, and ETd.

## *Pine Creek example*

Estimating capture from a stream and evapotranspiration area will be illustrated with an example from Pine Valley, hydrographic area (HA) 053 (Figure 2). A total of 6.6 acre-ft/yr was proposed to be pumped from four points of diversion that ranged between 2,400 and 3,500 ft from Pine Creek. Maximum stream capture ranged between 5 and 6 acre-ft/yr with a Glover analysis and transmissivity estimates between 900 and 2,300 ft²/d (Braumiller, 2023). This exceeded the annual pumping exemption of 5 acre-ft in section 3C of order 1329 (Nevada State Engineer, 2021), which prompted further analysis.

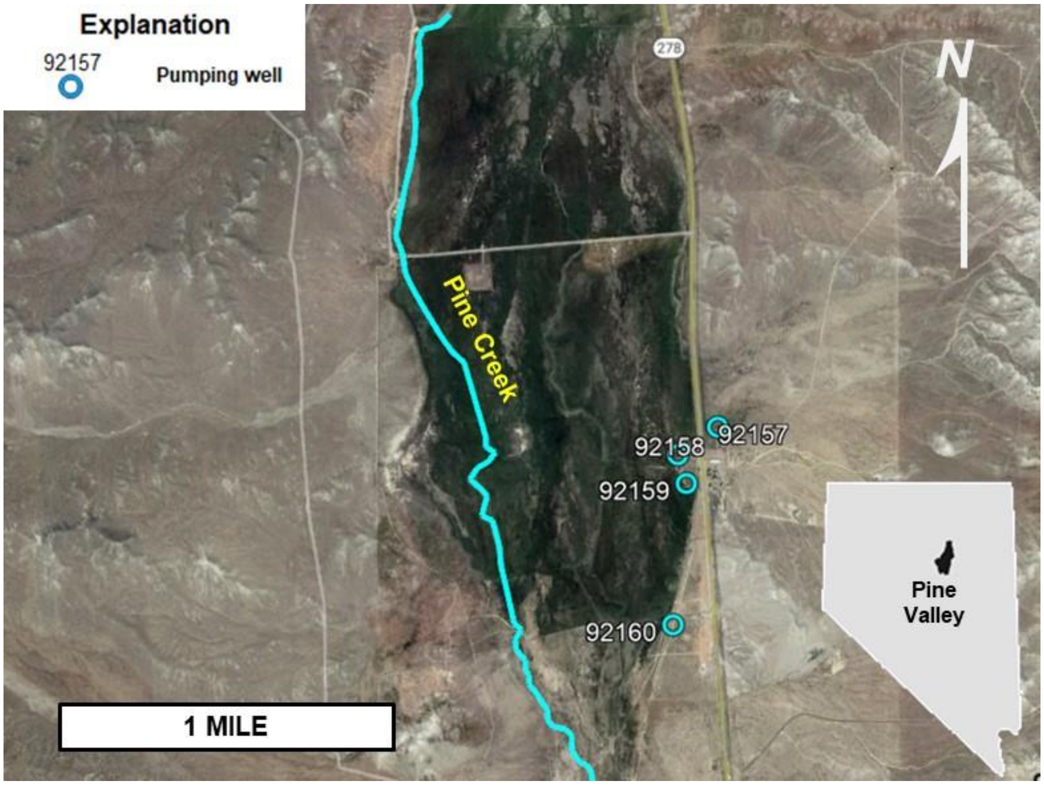



**Figure 2.—** Example of estimating capture from Pine Creek and evapotranspiration from four points of diversion in Pine Valley HA053.

Capture from evapotranspiration at the Pine Creek site is likely with greater than 0.5 mi of evapotranspiration area between Pine Creek and proposed points of diversion (Figure 2). About 4,000 acres of groundwater evapotranspiration (ETgw) were mapped between 4 mi upstream and 3 mi downstream of the proposed points of diversion (Huntington, et.al., 2022). Annual estimated ETgw rates ranged between <0.1 and 2.8 ft and averaged 0.6 ft (Figure 3). More probable rates for half the ETgw discharge ranged between 0.5 and 0.9 feet per year (ft/yr).

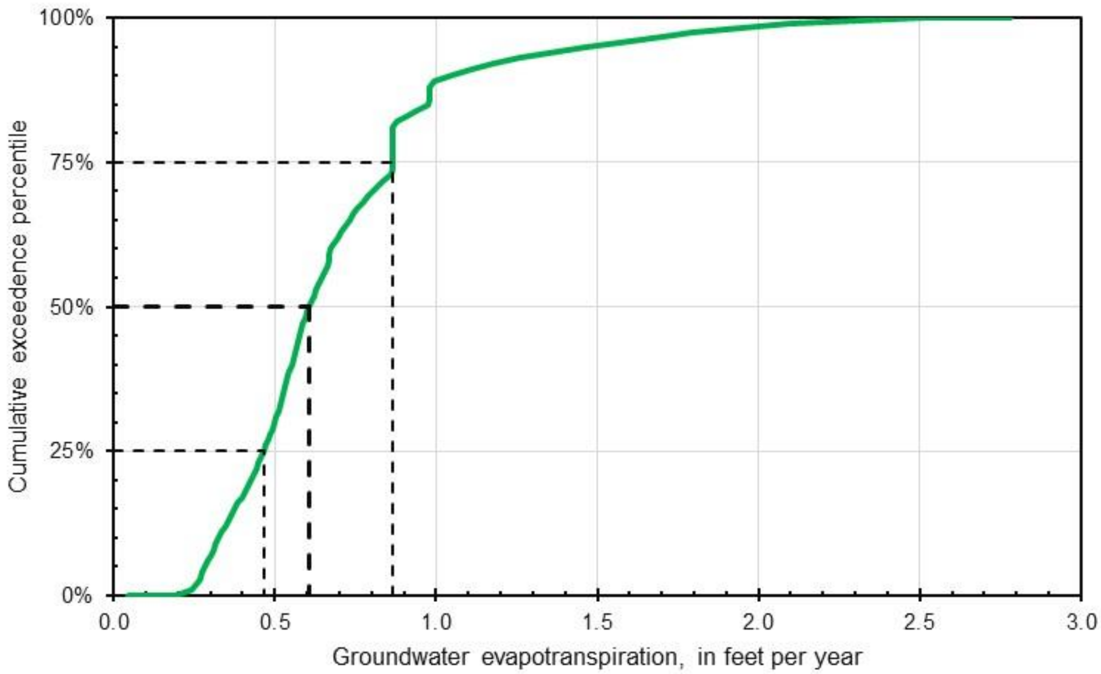



**Figure 3.—** Cumulative groundwater evapotranspiration rates from 4,000 acres upstream and downstream of the Pine Creek site.

Pine Creek site was reanalyzed using the ***CaptureMF6*** workbook so that capture from evapotranspiration could be estimated in addition to stream capture from Pine Creek (Figure 4). Transmissivity ranged between 900 and 2,300 $ft^2/d$ as in the previous Glover analysis (Braumiller, 2023). Specific yield ranged between 0.1 and 0.2. Maximum evapotranspiration rate ranged between 0.5 and 0.9 ft/yr. Extinction depth of evapotranspiration ranged between 3 and 9 ft.

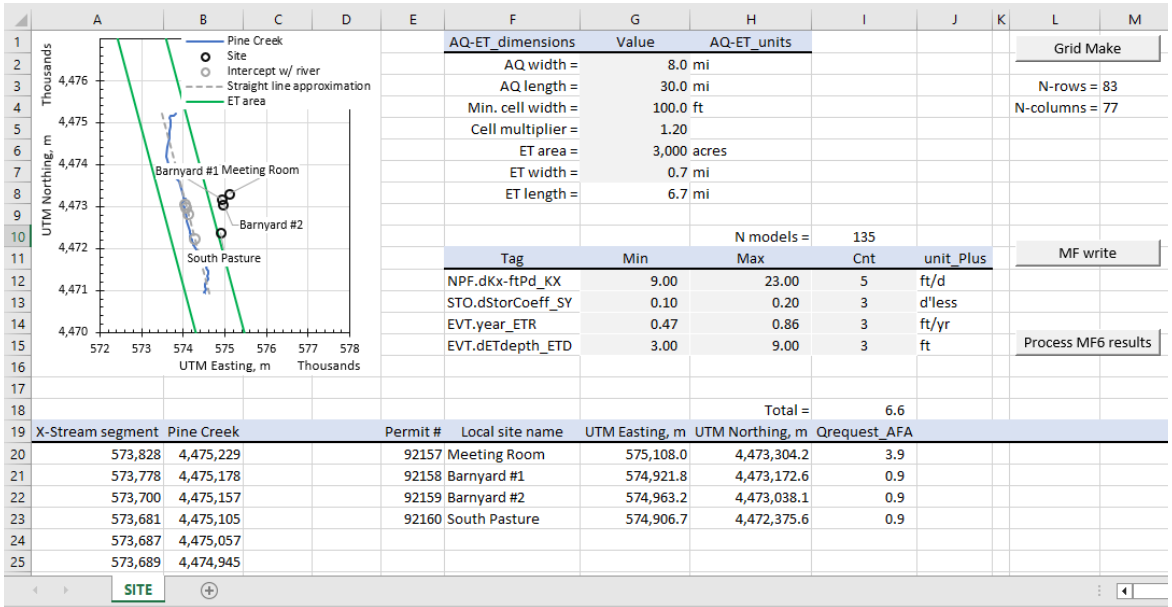



**Figure 4.—** SITE page in CaptureMF6 workbook, where stream segment and pumping wells are specified along with aquifer dimensions and hydraulic properties.

Annual stream and evapotranspiration capture averaged 3.4 and 2.5 acre-ft, respectively, in the ***CaptureMF6*** analysis (Figure 5). Total annual capture of 5.9 acre-ft from the ***CaptureMF6*** analysis was similar to capture estimates from the previous Glover analysis (Braumiller, 2023). Results primarily differed because the ***CaptureMF6*** analysis more realistically simulated evapotranspiration capture.

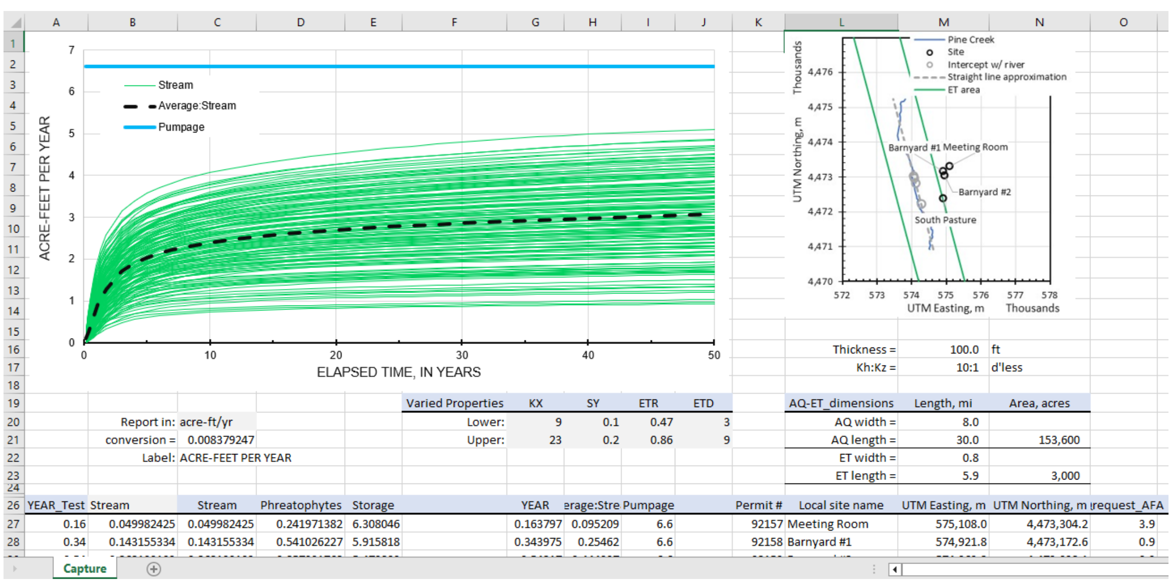



**Figure 5.—** New workbook that summarizes simulated capture from stream and phreatophytes.

The file CaptureMF6.v1.zip contains,

- ***.\CaptureMF6\CaptureMF6.v1.xlsm*** – Workbook with macros for,
  1.) Defining stream, ET area, and wells in user-defined MF6 grid;
  2.) Writing family of alternative MF6 models is individual folders and batch files to execute all MF6 models; and
  3.) Reading all MF6 model results, reducing output frequency, and synthesizing results in a new workbook.
- ***ET-Freq.xlsx*** – Auxiliary workbook for estimating range of groundwater evapotranspiration (ETgw) rates from raster rates in OpenET (Huntington, et.al., 2022).
- ***.\bin\MF6.exe*** – MF6 version 6.0.4 executable.
- **CaptureMF6-EXPLAIN.v1.pdf** – Explanatory document

Zip file can be downloaded with the following link https://halfordhydrology.com/capturemf6/.

## *Revisions*

February 9, 2024 —Revisions through version 1 are initial release.

## *Suggested Citation*

Halford, Keith, 2024, CaptureMF6—Estimate stream and evapotranspiration capture with simple MODFLOW6 models, version 2, Halford Hydrology LLC web page, accessed February 2024, at https://halfordhydrology.com/capturemf6/

## *References*


Barlow, P.M., and Leake, S.A., 2012, Streamflow depletion by wells—Understanding and managing the effects of groundwater pumping on streamflow: U.S. Geological Survey Circular 1376, 84 p. http://pubs.usgs.gov/circ/1376/

Braumiller, S., 2023, Capture analysis for applications 92157-92160 by Nevada Gold Mins, LLC in Pine Valley Hydrographic Basin (HA 053), memorandum from Nevada Department of Water Resources, October 25,2023, 12 p.

Environment Canterbury, 2024, Groundwater tools and resources, Environment Canterbury Regional Council web page, accessed February 2024, https://www.ecan.govt.nz/your-region/your-environment/water/tools-and-resources/

Glover, R.E., and Balmer, C.G., 1954, River depletion resulting from pumping a well near a river: American Geophysical Union Trans., v. 35, pt. 3, p. 468-470.

Halford, K.J., and Plume, R.W., 2011, Potential effects of groundwater pumping on water levels, phreatophytes, and spring discharges in Spring and Snake Valleys, White Pine County, Nevada, and adjacent areas in Nevada and Utah: U.S. Geological Survey Scientific Investigations Report 2011-5032, 52 p. https://doi.org/10.3133/sir20115032

Hunt, B, 2003, Unsteady stream depletion when pumping from semi-confined aquifer. Journal of Hydrologic Engineering 8, no. 1: 12-19.

Hunt, B., 2005, Visual Basic Programs for Spreadsheet Analysis. Groundwater, 43: 138-141. https://doi.org/10.1111/j.1745-6584.2005.tb02293.x

Huntington, J. L., Bromley, M., Minor, B., Morton, C. G., and Smith, G., 2022, Groundwater Discharge from Phreatophyte Vegetation, Humboldt River Basin, Nevada, Desert Research Institute Publication No. 41288, prepared for Nevada Department of Conservation and Natural Resources, Division of Water Resource, 46 p. https://www.dri.edu/project/humboldt-etg/

Jenkins, C.T., 1968, Computation of rate and volume of stream depletion by wells: U.S. Geological Survey Techniques and Methods, book 4, chap. D1, 17 p., https://pubs.usgs.gov/twri/twri4d1

Langevin, C.D., Hughes, J.D., Banta, E.R., Niswonger, R.G., Panday, Sorab, and Provost, A.M., 2017, Documentation for the MODFLOW 6 Groundwater Flow Model: U.S. Geological Survey Techniques and Methods, book 6, chap. A55, 197 p., https://doi.org/10.3133/tm6A55.

Nevada State Engineer, 2021, State Engineer's Order No. 1329— Establishing Interim Procedures for Managing Groundwater Appropriations to Prevent the Increase of Capture and Conflict with Rights Decreed Pursuant to the Humboldt River Adjudication, Carson City, Office of the State Engineer of the State of Nevada, 13 p., http://images.water.nv.gov/images/Orders/1329o.pdf

Theis, C.V., 1940, The source of water derived from wells—Essential factors controlling the response of an aquifer to development: Civil Engineering, v. 10, no. 5, p. 277–280.

## CaptureMF6 Workbook

Capture from proposed pumping is analyzed on the SITE page in the CaptureMF6 workbook (Figure 6). Discretized stream segment and pumping wells are specified in columns **A:B** and **E:I**, respectively. Aquifer extent, evaporation area, and model grid guidelines are defined in a table (**F1:H8**). Ranges of hydraulic properties and evapotranspiration parameters and sampling frequency are defined in another table (**F11:J15**). Controls for creating model grid, writing MODFLOW6 models, executing models, and synthesizing model results are in columns **L:M**. Two additional supporting pages CONTROL and Capture exist and normally are hidden.

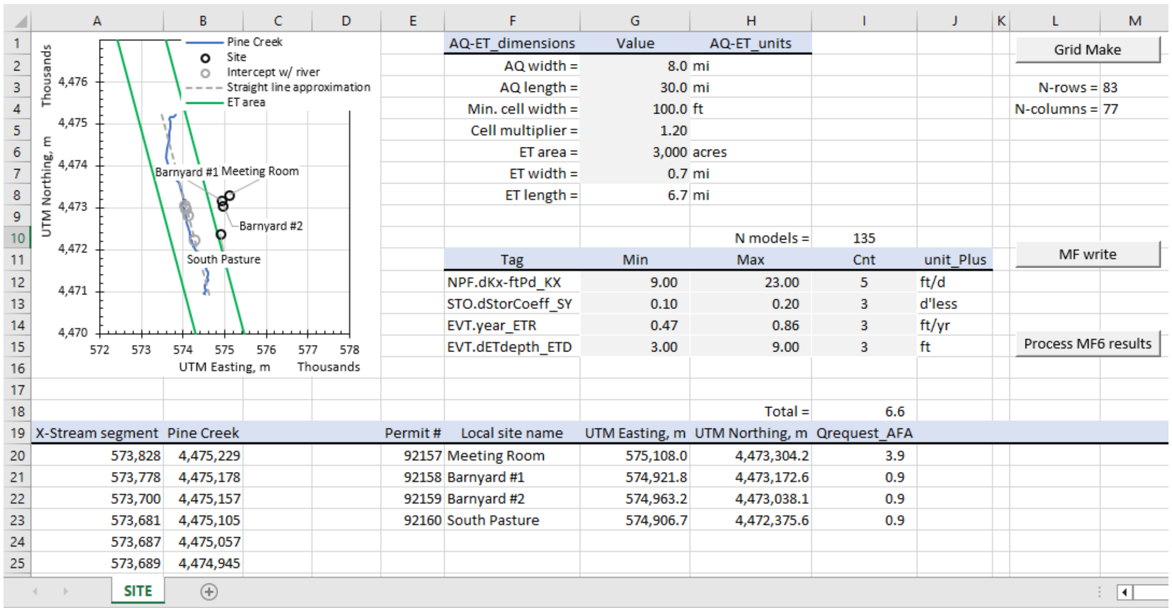


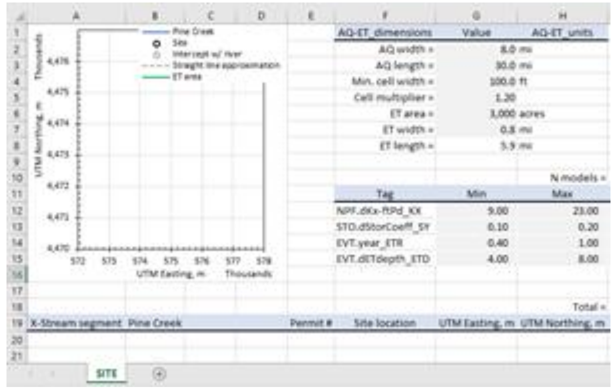

**Figure 6.—** SITE page in CaptureMF6 workbook, where stream segment and pumping wells are specified along with aquifer dimensions and hydraulic properties.

Step-by-step use of the CaptureMF6 workbook is illustrated with the Pine Creek example in the following four tables, *Specify Site, Grid Make, MF write,* and *Process MF6 results*.

### *Specify Site*

Map is blank without stream segment (**A20:B319**) or wells (**E20:I100**) specified.

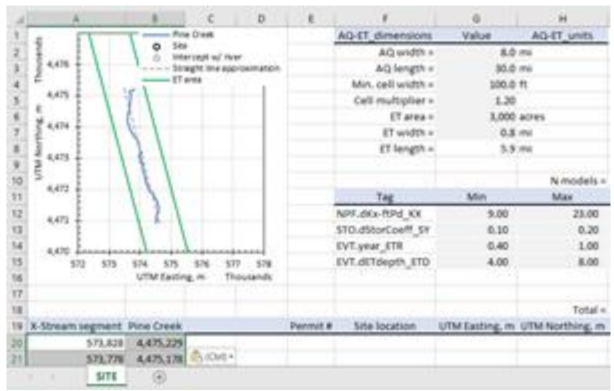
Both stream segment and wells are specified in UTM meters, which is in zone 11 for Pine Creek example.



Paste stream segment as values to **A20.**

Stream segment appears on map along with straight-line approximation of stream and edges of ET area.

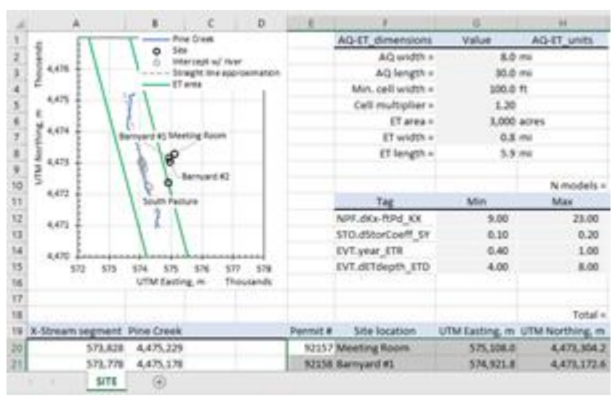
Minimum and maximum extents of X and Y axes likely will need to be revised for another site.



Paste table of wells as values to **E20.**

Columns **E:I** should be Permit number, Local site name, UTM easting and northing in meters, and proposed annual pumpage in acre-feet.

Wells will appear on map chart with local site name.



Aquifer dimensions are specified in **G2:G3** in miles.

ET area, in acres, is specified in **G6**. Width of ET area is specified in **G7** in miles. Length of ET area is computed.

ET area will be divided into square model cells that are the minimum cell width (**G4**) on each side.

| | F | G | H |
|---|---|---|---|
| 1 | AQ-ET_dimensions | Value | AQ-ET_units |
| 2 | AQ width = | 8.0 | mi |
| 3 | AQ length = | 30.0 | mi |
| 4 | Min. cell width = | 100.0 | ft |
| 5 | Cell multiplier = | 1.20 | |
| 6 | ET area = | 3,000 | acres |
| 7 | ET width = | 0.8 | mi |
| 8 | ET length = | 5.9 | mi |

SITE

Hydraulic property and evapotranspiration parameter ranges are defined in **G11:H15**.

Minimums in column **G** and Maximums in column **H**.

Sampling frequency is specified in column **I** with total number of MODFLOW6 models reported in **I10**.

| | F | G | H | I | J |
|---|---|---|---|---|---|
| 10 | | | N models = | 16 | |
| 11 | Tag | Min | Max | Cnt | unit_Plus |
| 12 | NPF.dKx-ftPd_KX | 9.00 | 23.00 | 2 | ft/d |
| 13 | STO.dStorCoeff_SY | 0.10 | 0.20 | 2 | d'less |
| 14 | EVT.year_ETR | 0.40 | 1.00 | 2 | ft/yr |
| 15 | EVT.dETdepth_ETD | 4.00 | 8.00 | 2 | ft |

SITE

Total number of MODFLOW6 models increases quickly with increased sampling frequency.

Writing, executing and synthesizing about 100 models of 100 rows of 100 columns takes about 5 minutes.

| | F | G | H | I | J |
|---|---|---|---|---|---|
| 10 | | | N models = | 135 | |
| 11 | Tag | Min | Max | Cnt | unit_Plus |
| 12 | NPF.dKx-ftPd_KX | 9.00 | 23.00 | 5 | ft/d |
| 13 | STO.dStorCoeff_SY | 0.10 | 0.20 | 3 | d'less |
| 14 | EVT.year_ETR | 0.40 | 1.00 | 3 | ft/yr |
| 15 | EVT.dETdepth_ETD | 4.00 | 8.00 | 3 | ft |

SITE

Sampling frequency of 1 can be specified.

The parameter value will equal the average of minimum and maximum values in columns **G & H**.

| | F | G | H | I | J |
|---|---|---|---|---|---|
| 10 | | | N models = | 5 | |
| 11 | Tag | Min | Max | Cnt | unit_Plus |
| 12 | NPF.dKx-ftPd_KX | 9.00 | 23.00 | 5 | ft/d |
| 13 | STO.dStorCoeff_SY | 0.10 | 0.20 | 1 | d'less |
| 14 | EVT.year_ETR | 0.40 | 1.00 | 1 | ft/yr |
| 15 | EVT.dETdepth_ETD | 4.00 | 8.00 | 1 | ft |

SITE

***Grid Make***

Model discretization primarily is adjusted by changing,
Minimum cell width (**G4**) and
Cell multiplier (**G5**).

ET area is divided into square model cells that are the minimum cell width (**G4**) on each side.

Cells expand by cell multiplier (**G5**) from outer edges of ET area to edges of model extent.

| | F | G | H |
|---|---|---|---|
| 1 | AQ-ET_dimensions | Value | AQ-ET_units |
| 2 | AQ width = | 8.0 | mi |
| 3 | AQ length = | 30.0 | mi |
| 4 | Min. cell width = | 100.0 | ft |
| 5 | Cell multiplier = | 1.20 | |
| 6 | ET area = | 3,000 | acres |
| 7 | ET width = | 0.8 | mi |
| 8 | ET length = | 5.9 | mi |

SITE

Click “Grid Make” to compute new grid.

Model dimensions are 83 rows of 82 columns with,
Minimum cell width (**G4**) = 100 ft and
Cell multiplier (**G5**) = 1.20.

| | L | M |
|---|---|---|
| 1 | Grid Make | |
| 2 | | |
| 3 | N-rows = | 83 |
| 4 | N-columns = | 82 |
| 5 | | |

SITE

Reduce,
Minimum cell width (**G4**) to 50 ft and
Cell multiplier (**G5**) to 1.10

| | F | G | H |
|---|---|---|---|
| 1 | AQ-ET_dimensions | Value | AQ-ET_units |
| 2 | AQ width = | 8.0 | mi |
| 3 | AQ length = | 30.0 | mi |
| 4 | Min. cell width = | 50.0 | ft |
| 5 | Cell multiplier = | 1.10 | |
| 6 | ET area = | 3,000 | acres |
| 7 | ET width = | 0.8 | mi |
| 8 | ET length = | 5.9 | mi |

SITE

Click “Grid Make” to compute new grid.

Model dimensions are 161 rows of 160 columns with,
Minimum cell width (**G4**) = 50 ft and
Cell multiplier (**G5**) = 1.10.

| | L | M |
|---|---|---|
| 1 | Grid Make | |
| 2 | | |
| 3 | N-rows = | 161 |
| 4 | N-columns = | 160 |
| 5 | | |

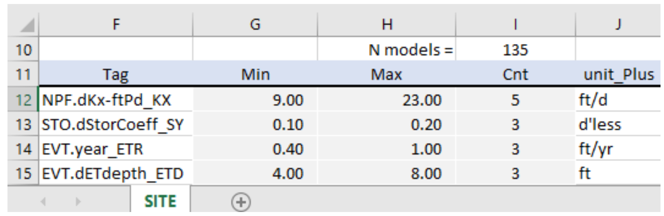
SITE

***MF write***

Parameter table defines ranges of hydraulic properties and evapotranspiration parameters in **G11:H15** with sampling frequency specified in column **I**.

Parameters in this example are,
Kx: 9, 12.5, 16, 19.5, & 23 ft/d
Sy: 0.10, 0.15, & 0.20.
ETr: 0.4, 0.7, & 1.0 ft/yr
ETd: 4, 6, & 8 ft

A total of 135 (**I10**) MODFLOW6 models will be created.

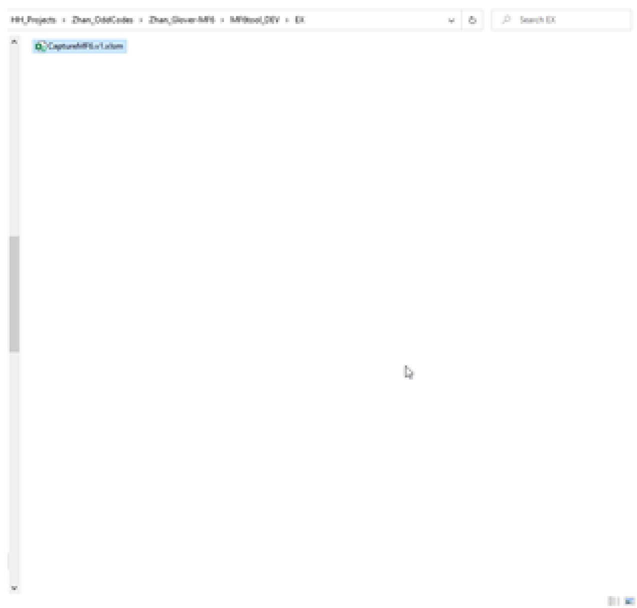


| | F | G | H | I | J |
|---|---|---|---|---|---|
| 10 | | | N models = | 135 | |
| 11 | Tag | Min | Max | Cnt | unit_Plus |
| 12 | NPF.dKx-ftPd_KX | 9.00 | 23.00 | 5 | ft/d |
| 13 | STO.dStorCoeff_SY | 0.10 | 0.20 | 3 | d'less |
| 14 | EVT.year_ETR | 0.40 | 1.00 | 3 | ft/yr |
| 15 | EVT.dETdepth_ETD | 4.00 | 8.00 | 3 | ft |

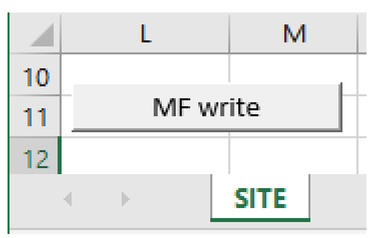
SITE

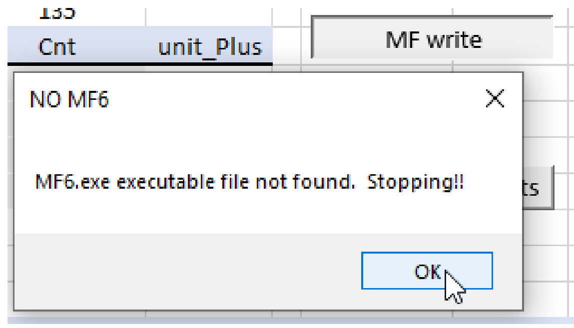
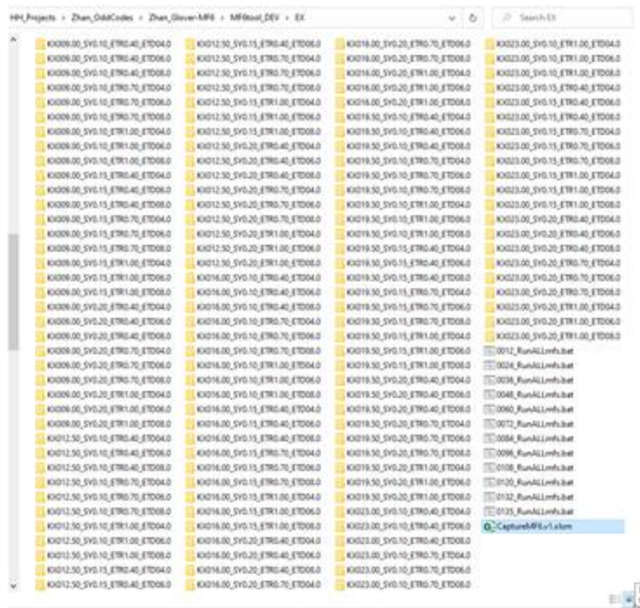
Folder with CaptureMF6 workbook contains just the workbook prior to creating MODFLOW6 model folders.

Each model is in a subfolder with parameter values summarized in each subfolder name.

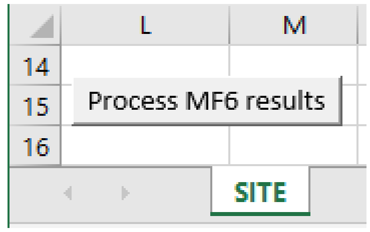
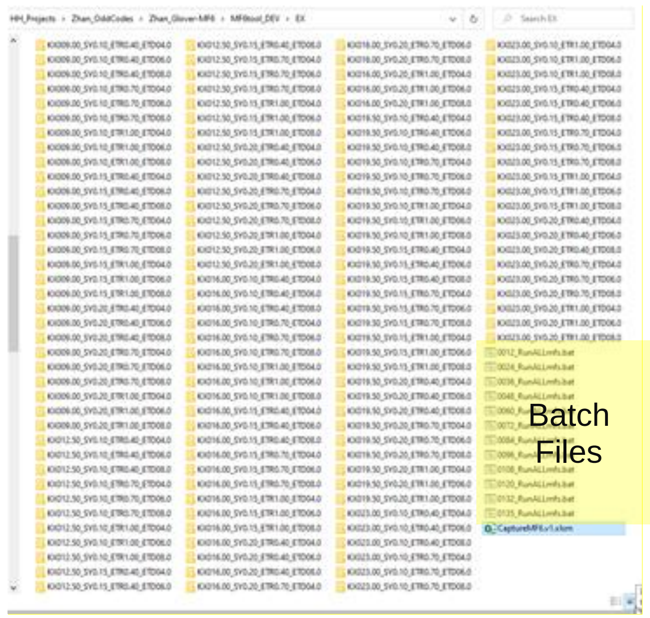
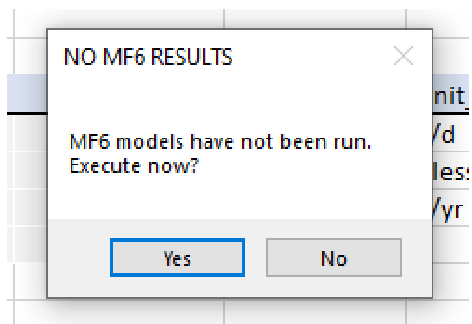
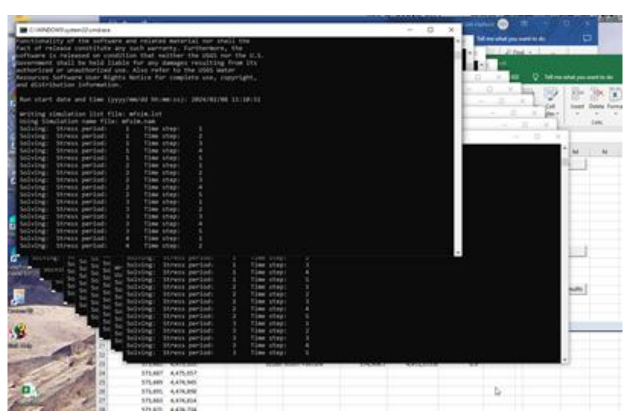


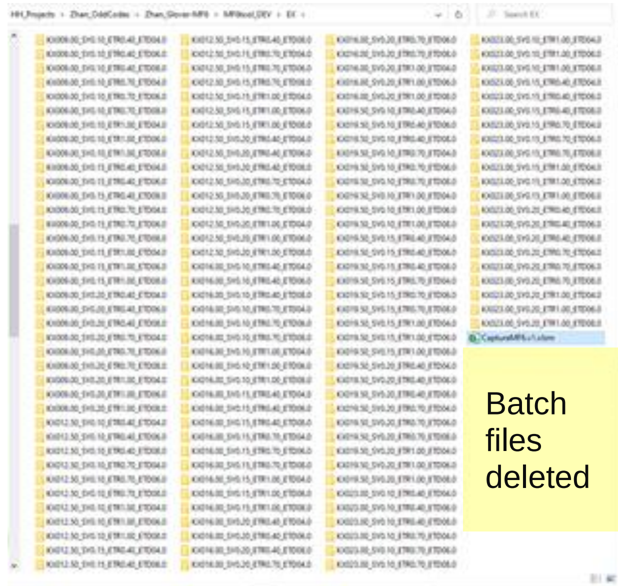
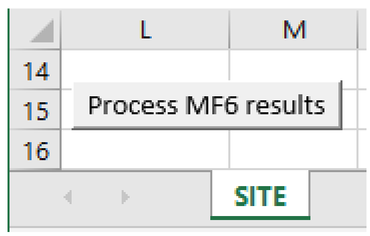
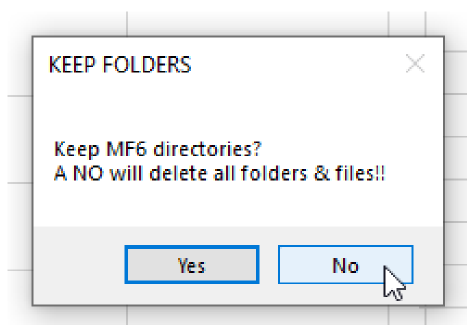
Click “MF write” to generate 135 subfolders with MODFLOW6 model input files and batch files to execute all models.

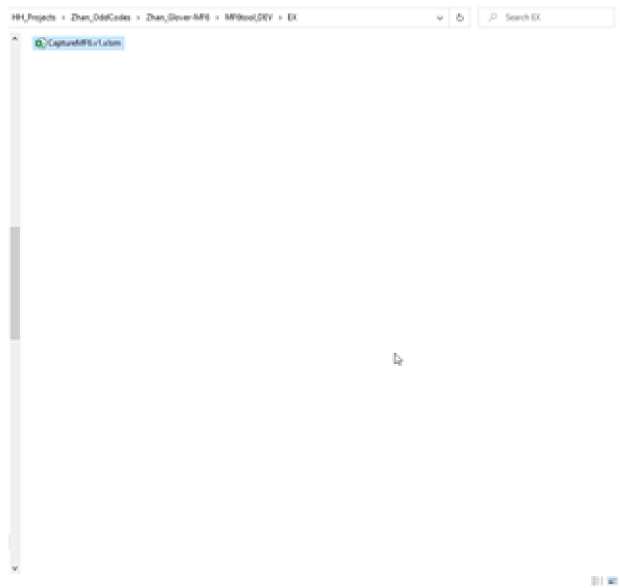
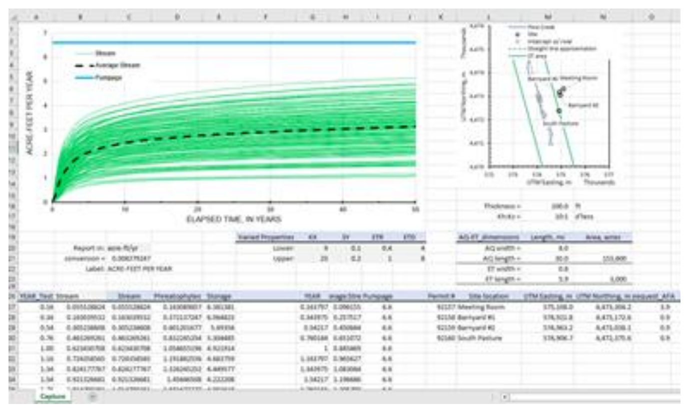
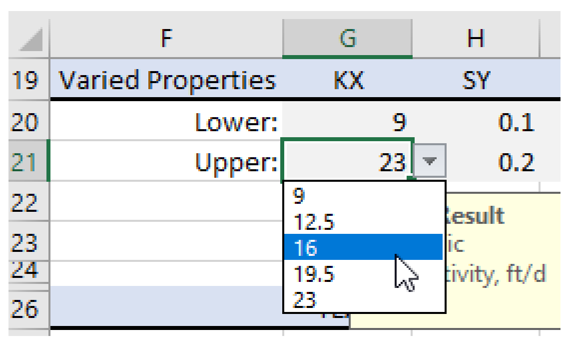


| | |
|---|---|
| Process will fail if a MF6.exe file is not found in a parallel directory, this directory, or a subdirectory.<br>Download a copy of [MF6]() and add to folder if absent. |  |
| 135 subfolders were created with MODFLOW6 model input files.<br>Multiple batch files also were created to execute all models. The number of batch files varies with the number of processors on a given machine.<br>Each subfolder contains a MODFLOW6 model with parameter values summarized in each subfolder name. |  |

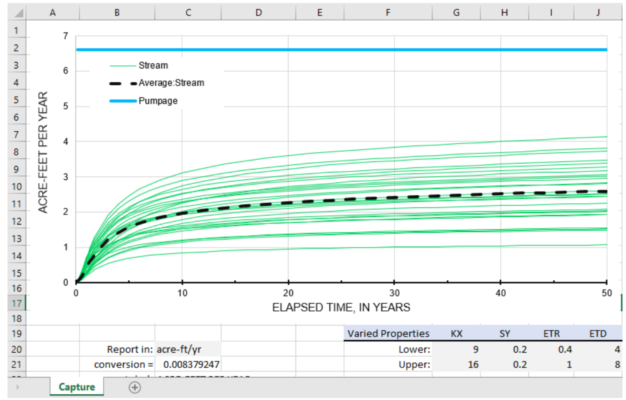
*__Process MF6 results__*

| | |
|---|---|
| Click “Process MF6 results” to either execute the MODFLOW6 models or synthesize the model results. |  |
| Multiple batch files with names of ***????_RunALLmfs.bat*** will exist in the target folder if the MODFLOW6 models have not been executed.<br>A batch file will exist for each processor if enough models were created,<br>N-models > 4*number_of_processors<br>A minimum of 4 model calls per batch file is required. |  |
| A “NO MF6 RESULTS” message appears if a ***????_RunALLmfs.bat*** file exists in the folder with the CaptureMF6 workbook.<br>Click ***Yes*** and the models will be executed. |  |
| A command prompt will appear for each batch file and execute MODFLOW6 models assigned to each batch file. |  |

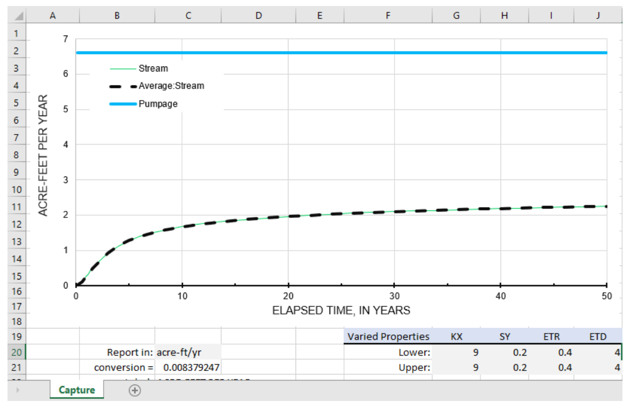
| | |
|---|---|
| All ***????_RunALLmfs.bat*** batch files are deleted after the MODFLOW6 models have been executed. |  |
| Click “Process MF6 results” after executing the MODFLOW6 models.<br>Model results will be imported and synthesized in a new workbook. |  |
| A “KEEP FOLDERS” message will appear.<br>Click ***Yes*** to retain model subfolders. This is the default option.<br>Click ***No*** to delete all models and subfolders. |  |

| | |
|---|---|
| All files and subfolders created by CaptureMF6 workbook and MODFLOW6 are deleted after responding ***No*** to “KEEP FOLDERS” message. |  |
| New workbook that summarizes simulated capture from stream and phreatophytes. |  |
| Bounds on each varied property can be adjusted in the new workbook. |   |

Individual and average capture results are limited to models within the minimum and maximum ranges specified in **G20:J21**.

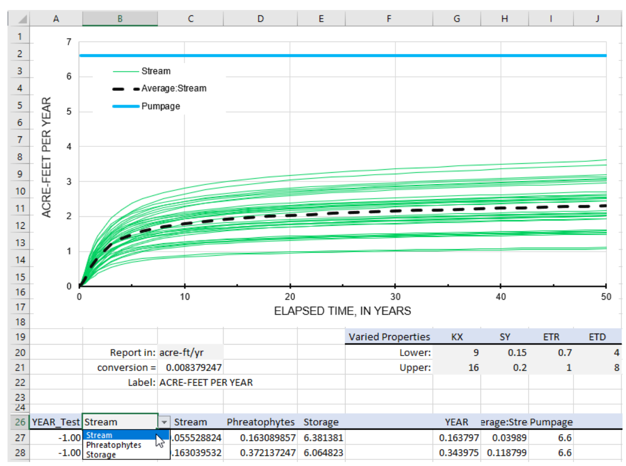


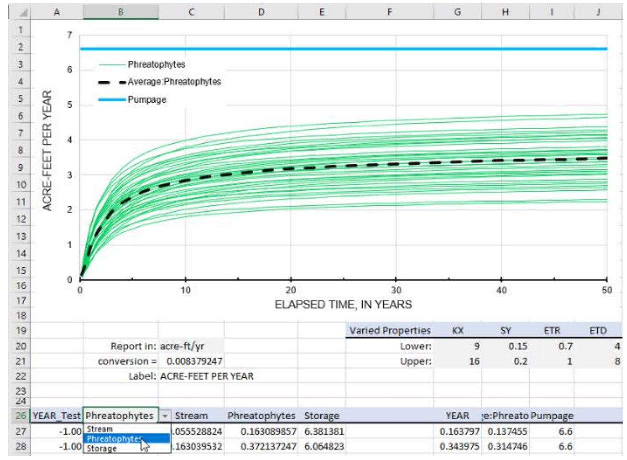
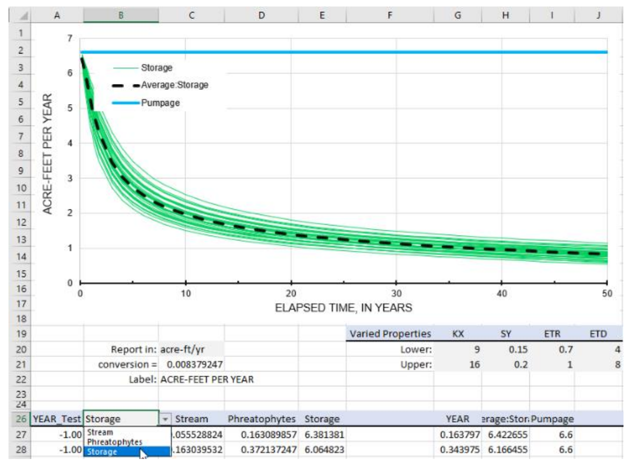

Results are limited to a single simulation where minimum and maximum values are equal for all 4 parameters in **G20:J21**.




Capture from the stream is the default view.

Other sources of water to wells can be viewed by changing selection in **B26**.



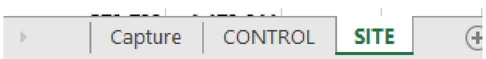
| | |
|---|---|
| Capture from the evapotranspiration area is displayed if *Phreatophytes* is selected in **B26**. |  |
| Water released from storage is displayed if *Storage* is selected in **B26**. |  |

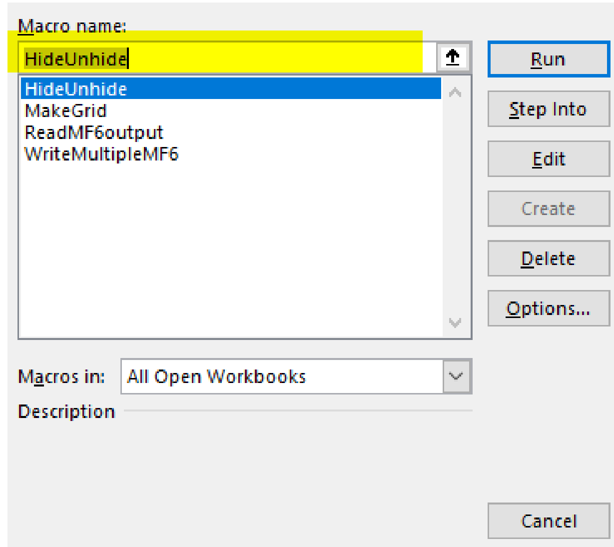
***Optional changes on CONTROL page***

Macro HideUnhide will either reveal all worksheets or hide all sheets except the SITE page.

Will view either,


or




Frequency of MODFLOW output in results workbook can be altered with the table in **B8:C11**.

More times and simulated values are retained as filter frequency in column C is reduced.