Development of a MODFLOW Tool for Delineation of Stream Depletion Zones

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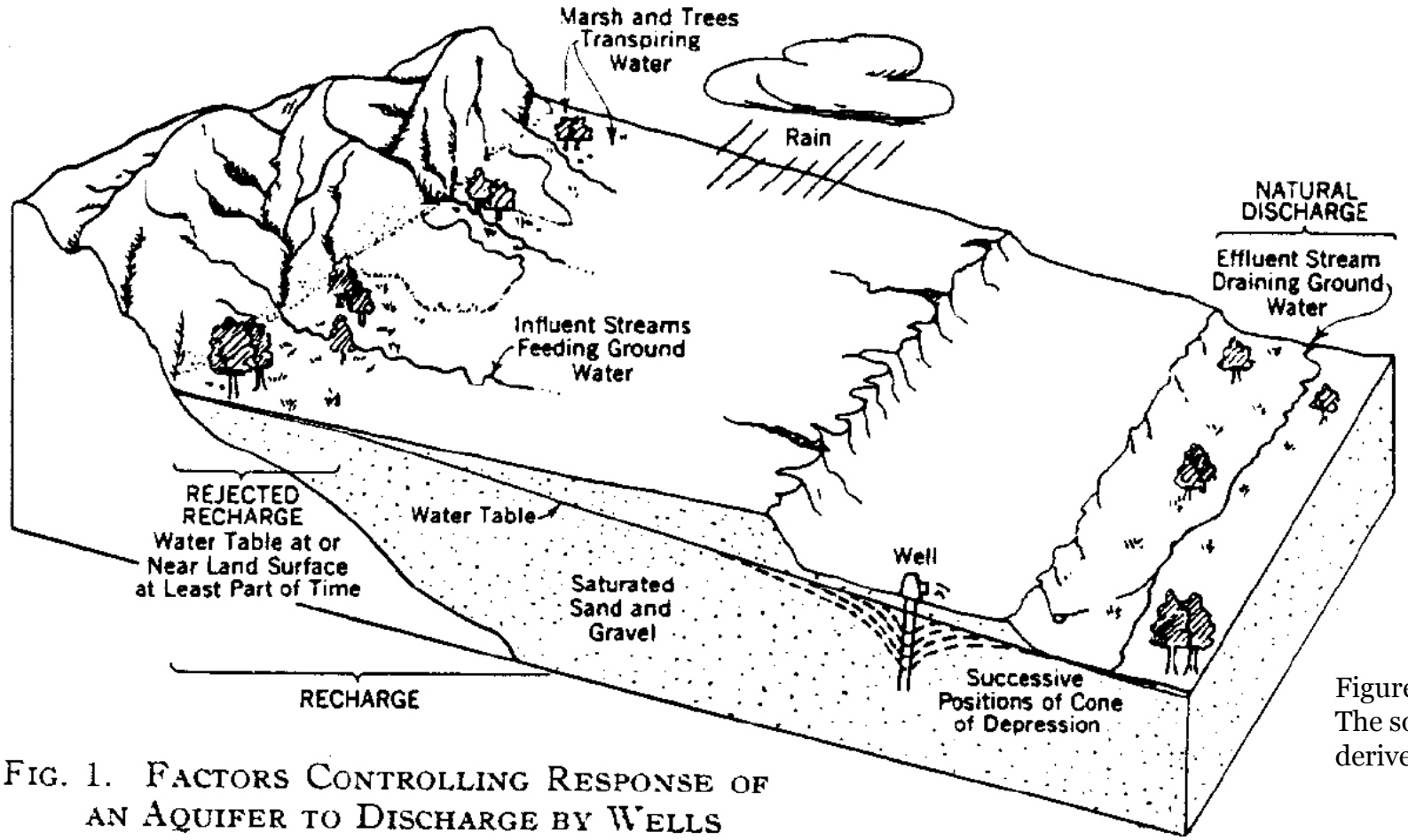


FIG. 1. FACTORS CONTROLLING RESPONSE OF AN AQUIFER TO DISCHARGE BY WELLS

Figure from Theis, 1941
The source of water derived from wells

- In order to maintain long-term equilibrium, water removed by a well must be offset by either induced recharge to the aquifer, or a decrease in the aquifer discharge (Theis, 1941; Bredehoeft et al., 1982)

What is a Stream Depletion Zone?

- "Stream depletion means either direct depletion of the stream or reduction of ground-water flow to the stream" (Jenkins, 1968)

Stream Depletion Zone (SDZ) – A 3-dimensional zone based on a depletion threshold.

MCA 85-2-102: "…an area where *hydrogeologic modeling* concludes that as a result of a ground water withdrawal, the surface water would be depleted by a rate equal to at least 30% of the ground water withdrawn within 30 days after the first day a well or developed spring is pumped at a rate of 35 gallons a minute."

MCA 85-2-306: "…a permit is not required before appropriating ground water by means of a well or developed spring…

- when the appropriation is *outside* a stream depletion zone, is 35 gallons a minute or less, and does not exceed 10 acre-feet a year,
- when the appropriation is *within* a stream depletion zone, is 20 gallons a minute or less, and does not exceed 2 acre-feet a year"

How Stream Depletion is Calculated from MODFLOW Results – Numerical Model

Numerical modeling allows for more complex settings.

```
 HEAD WILL BE SAVED ON UNIT  730 AT END OF TIME STEP   30, STRESS PERIOD    1
1
  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP   30, STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                IN:
           ---                                ---
             STORAGE =       2152.4048          STORAGE =          28.9307
      CONSTANT HEAD =    11984761.0000   CONSTANT HEAD =      399494.7812
      RIVER LEAKAGE =           0.0000   RIVER LEAKAGE =           0.0000

            TOTAL IN =    11986913.0000         TOTAL IN =      399523.7188

          OUT:                               OUT:
          ----                               ----
             STORAGE =        386.2915          STORAGE =           1.4648
      CONSTANT HEAD =          0.0000   CONSTANT HEAD =           0.0000
      RIVER LEAKAGE =    12468073.0000   RIVER LEAKAGE =      415601.8125

           TOTAL OUT =    12468459.0000         TOTAL OUT =      415603.2812

            IN - OUT =     -481546.0000          IN - OUT =      -16079.5625

 PERCENT DISCREPANCY =          -3.94   PERCENT DISCREPANCY =          -3.95
```

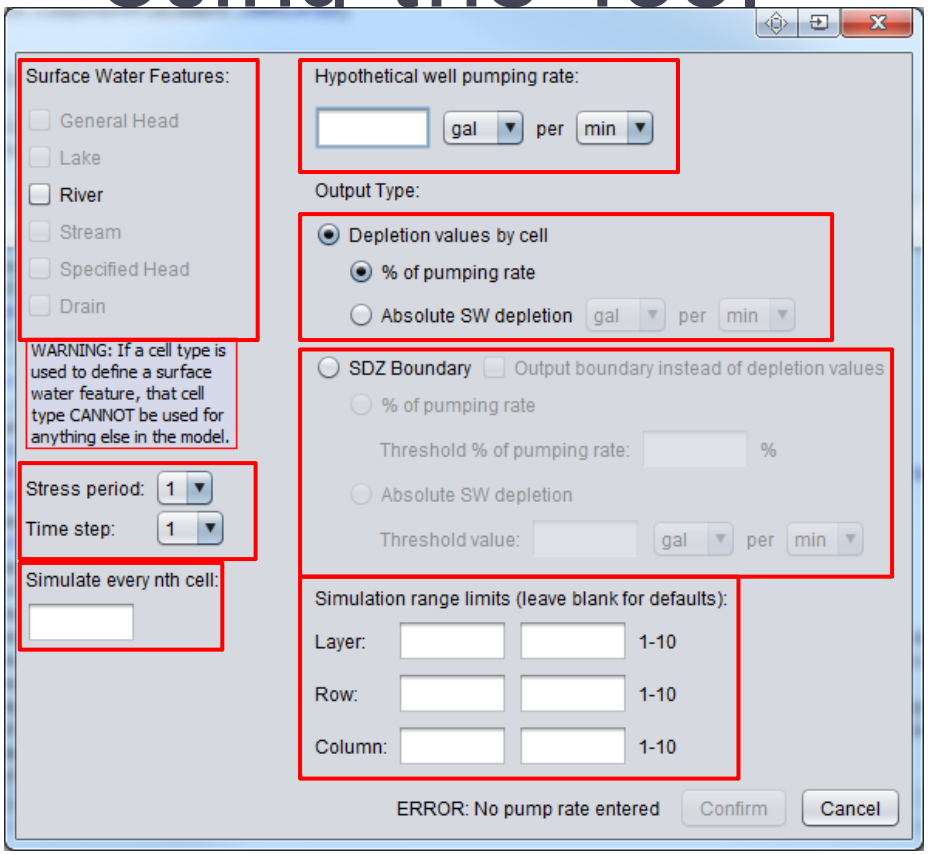
```
T  730 AT END OF TIME STEP   30, STRESS PERIOD    1

TIRE MODEL AT END OF TIME STEP   30, STRESS PERIOD   1
-----------------------------------------------------

   L**3       RATES FOR THIS TIME STEP      L**3/T
              ------------------------

                        IN:
                        ---
12022698.0000             STORAGE =      399986.5000
       0.0000      CONSTANT HEAD =           0.0000
       0.0000              WELLS =           0.0000
       0.0000      RIVER LEAKAGE =           0.0000

12022698.0000            TOTAL IN =      399986.5000

                       OUT:
                       ----
     338.1958             STORAGE =           0.0000
       0.0000      CONSTANT HEAD =           0.0000
  202140.0000              WELLS =        6738.0000
12297468.0000      RIVER LEAKAGE =      409431.5000

12499946.0000           TOTAL OUT =      416169.5000

 -477248.0000            IN - OUT =      -16183.0000

      -3.89   PERCENT DISCREPANCY =          -3.97
```

415,602 ft^3/d – 409,432 ft^3/d = 6170 ft^3/d

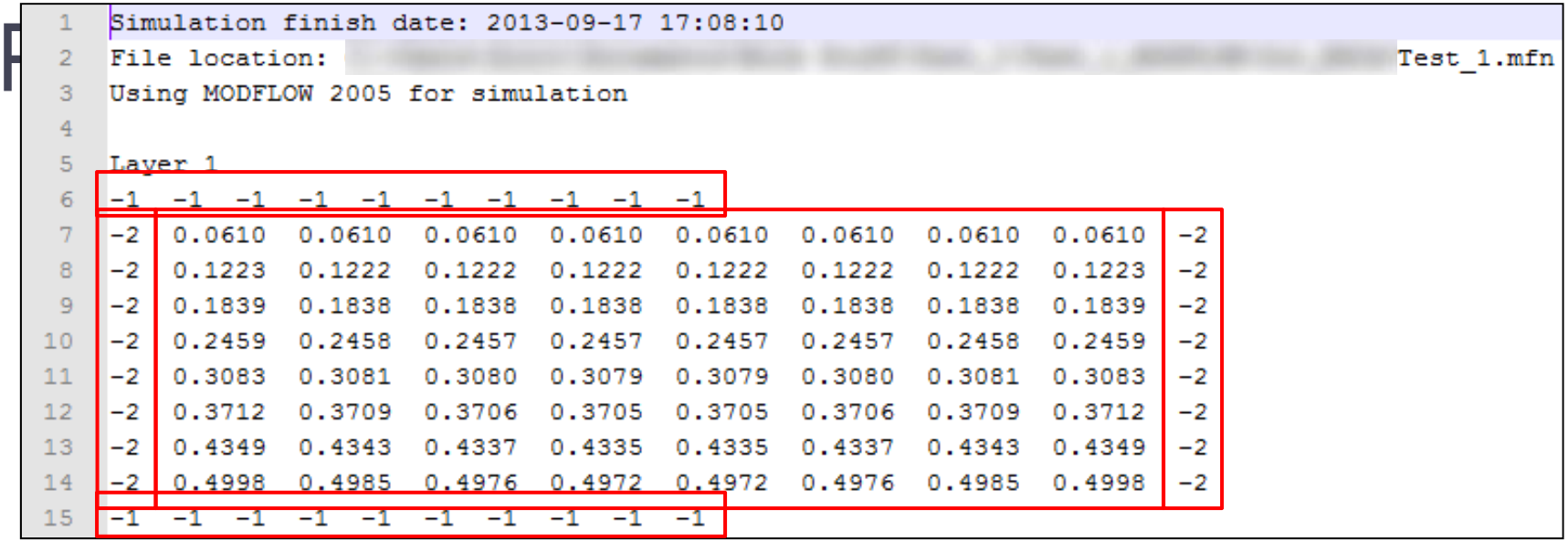
6170 ft^3/d ÷ 6738 ft^3/d = 91.6%

Testing a particular location is easy.
Testing every location to develop a SDZ would be extremely inefficient.

Using the Tool



- Load native MODFLOW file
- Run Baseline
- Select surface water features
- Stress period/time steps
- Well pumping rate
- Brute-Force Method
- Recursive Method
  - Works out from "seed" cells until results are below a threshold
- n^{th} cell
- Simulation Range Limits

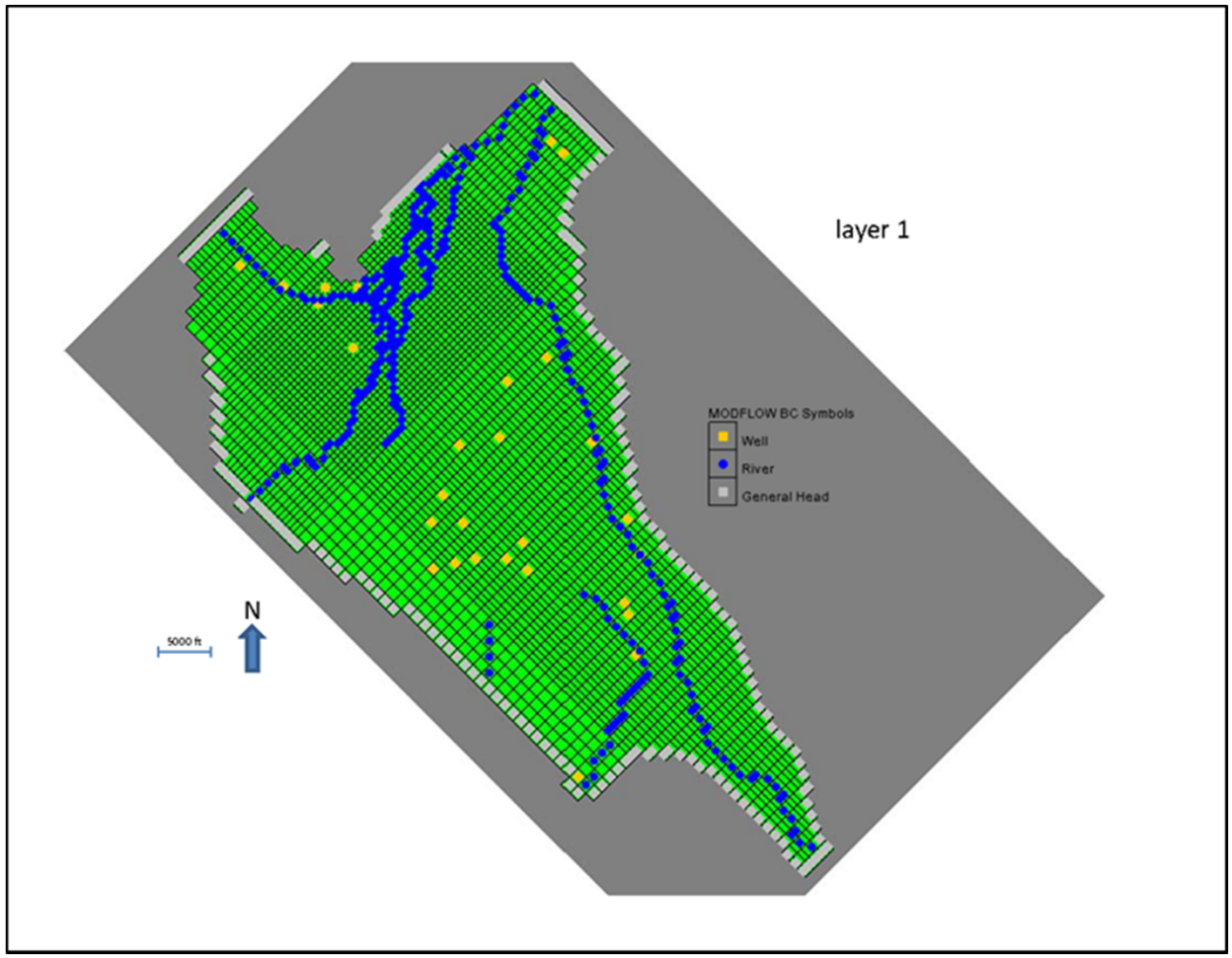


```
Simulation finish date: 2013-09-17 17:08:10
File location:                                                    Test_1.mfn
Using MODFLOW 2005 for simulation

Layer 1
-1  -1  -1  -1  -1  -1  -1  -1  -1  -1
-2  0.0610  0.0610  0.0610  0.0610  0.0610  0.0610  0.0610  0.0610  -2
-2  0.1223  0.1222  0.1222  0.1222  0.1222  0.1222  0.1222  0.1223  -2
-2  0.1839  0.1838  0.1838  0.1838  0.1838  0.1838  0.1838  0.1839  -2
-2  0.2459  0.2458  0.2457  0.2457  0.2457  0.2457  0.2458  0.2459  -2
-2  0.3083  0.3081  0.3080  0.3079  0.3079  0.3080  0.3081  0.3083  -2
-2  0.3712  0.3709  0.3706  0.3705  0.3705  0.3706  0.3709  0.3712  -2
-2  0.4349  0.4343  0.4337  0.4335  0.4335  0.4337  0.4343  0.4349  -2
-2  0.4998  0.4985  0.4976  0.4972  0.4972  0.4976  0.4985  0.4998  -2
-1  -1  -1  -1  -1  -1  -1  -1  -1  -1
```

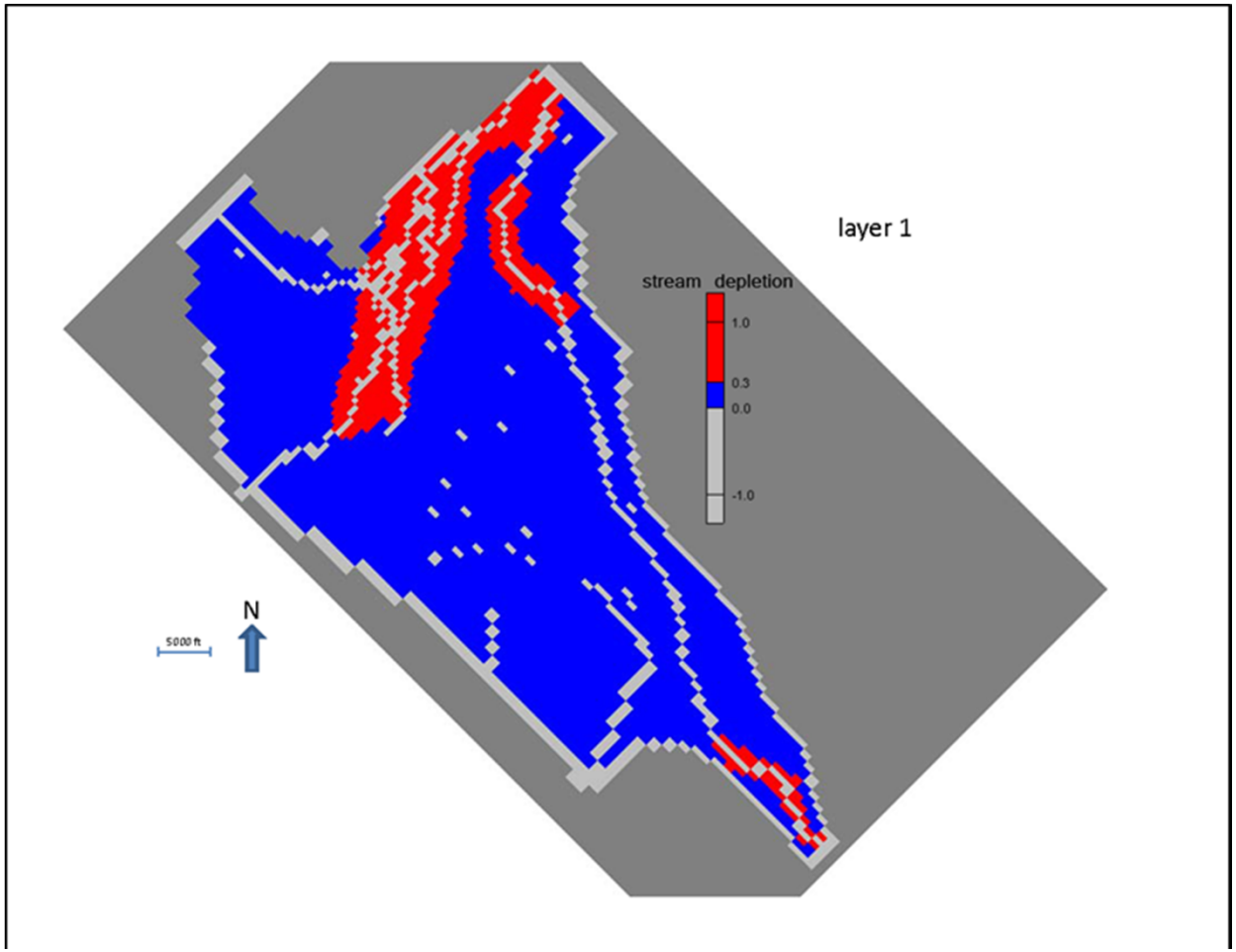
- Tab delimited – Easily imported into Excel
- Results by cell
  - -1: Inactive and/or featured cell
  - -2: Cell outside user limits
  - -888: Dry cell detected during simulation
  - -999: Error during simulation
  - Positive value: Calculated depletion value

Results using a Pre-Existing Model

(Uthman and Beck, 1998)



Results using a Pre-Existing Model
SDZ defined by q/Q>30% after 30 days



High Performance Computer (HPC)

- Trade off due to high “overhead” per batch
  - 30 sec startup
- Small models run quicker on desktop
- All the desktop options are available
- Need to submit batches
  - Brute-Force Method
    - User defined size
    - 32 cells per batch, with a maximum of 512 cores (16 batches) works well
      - MTech HPC has 704 cores
  - Recursive Method
    - User defined “chunk” size
      - 6x6x6 cell chunks (up to 216 cells) work well for MTech HPC
    - Chunk faces are evaluated for propagation

Run Times

- Non-HPC run times using a 4 core processer
  - Brute-Force Method
    - 7,000 cells – 11 minutes
    - 250,000 cells – 4 days
  - Recursive Method
    - 7,000 cells – 2 minutes
    - 250,000 cells – 16 hours
- HPC run times – 250,000 cells
  - Brute-Force Method – 6 hours
  - Recursive Method – 1.5 hours

Conclusions

- Stream Depletion Zones (SDZs) will need to be developed in some areas of Montana.
- Other states have similar laws.
- If a properly designed and calibrated MODFLOW model is available for the area, it can be used to define the SDZ.
  - Be aware of the effects of boundaries.
- The SDZTool allows for automation of the stream depletion calculations
  - A 250,000 cell model can be run in 1.5 hrs on the HPC
- Critical evaluation of the initial model, and the results will be required.


Questions?