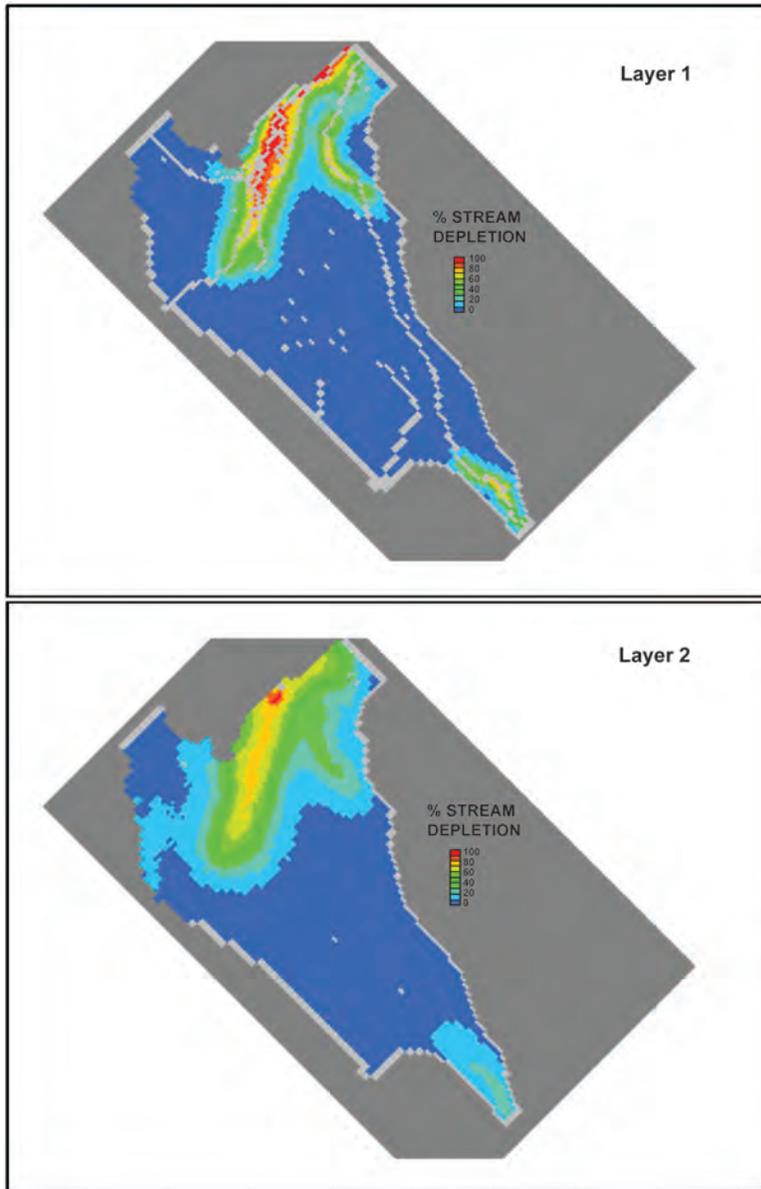


**A MODFLOW TOOL TO DEFINE BOUNDARIES OF A STREAM DEPLETION ZONE**



**Andrew Bobst and Scott Fleener**  
Montana Bureau of Mines and Geology  
Ground Water Investigations Program

Open-File Report 655  
November 2014



**A MODFLOW TOOL TO DEFINE BOUNDARIES OF A STREAM DEPLETION ZONE**

**Andrew Bobst and Scott Fleener**

**Montana Bureau of Mines and Geology  
Ground Water Investigations Program**

**Montana Bureau of Mines and Geology Open-File Report 655**

**October 2014**





# CONTENTS

Abstract .....	1
Introduction.....	1
Calculating Stream Depletion by Analytical Methods .....	2
Calculating Stream Depletion by Numerical Methods .....	2
Developing an SDZ Map using Numerical Modeling .....	3
Comparison to the Jenkins Method (1968).....	3
Effects of “Artificial Boundaries” .....	6
Pumping Rate Independence .....	7
An Example Using a Pre-Existing MODFLOW Model.....	7
Conclusions.....	9
Acknowledgments .....	13
References .....	13
Appendix A: Using the Tool.....	15
Installation Instructions.....	17
Procedure for Use.....	17

## FIGURES

Figure 1. This flow chart shows the process that the SDZTool and the user follow to determine stream depletion.....	4
Figure 2. This model was used to compare stream depletion calculations from the numerical model to analytical solutions .....	5
Figure 3. Stream depletion values as a percentage of the pumping rate were calculated manually using MODFLOW, using the SDZTool with MODFLOW, and using the Jenkins analytical method.....	6
Figure 4. The calculated stream depletion as a percentage of the pumping rate is somewhat dependent on the pumping rate .....	9
Figure 5. The Upper Beaverhead model uses two layers and includes general head boundaries, rivers, and wells to represent the system .....	10
Figure 6. Results from the SDZTool show that stream depletion is greatest near the Beaverhead River, with some depletion along Blacktail Deer Creek.....	11
Figure 7. Results from the SDZTool can be contoured to show a SDZ .....	12

## TABLES

Table 1. Comparison of stream depletion as a percentage of the pumping rate.....	6
Table 2. Comparison of calculated stream depletion at different pumping rates .....	8



## ABSTRACT

Stream depletion zones (SDZs) are mappable three-dimensional zones, defined by a percentage of a well's pumping rate that would have otherwise been stream flow. Such a percentage is defined after a specified time of constant pumping. Analytical methods of defining these zones must substantially simplify the hydrogeologic system. In situations where there are variable aquifer properties, simplified analytical answers may provide poor results. Analytical methods also only provide a stream depletion value for a particular point, so developing an SDZ map would require many calculations and be quite inefficient. Numerical groundwater models, such as MODFLOW, allow for a more complex representation of the hydrogeologic system; however, the process for mapping an SDZ would require testing the effects of adding a well one cell at a time. For this reason the SDZTool has been developed to automate the calculation of stream depletion using existing MODFLOW-2000 or MODFLOW-2005 numerical groundwater models. Results from this tool are comparable to simplified analytical solutions for models developed to follow the assumptions of the analytical methods. Use of this tool on a pre-existing MODFLOW model shows that the extent of calculated SDZs is similar to that calculated using analytical methods.

## INTRODUCTION

When a well removes water from an aquifer, the hydraulic system must be rebalanced by induced recharge to the aquifer, or a decrease in groundwater discharge (Theis, 1940; Bredehoeft and others, 1982). If the imbalance is made up by induced recharge from a stream or by a decrease in groundwater discharge to a stream, the well has caused stream depletion (Jenkins, 1968). The factors that determine the magnitude and timing of stream depletion are (1) the distance to the stream and the degree to which the stream and the aquifer are connected; (2) the distance to, amount, and distribution of recharge; (3) the distribution of transmissivity and storativity in the aquifer; and (4) the duration and magnitude of water withdrawal from the well (Theis, 1940; Hantush, 1965).

The amount of stream depletion anticipated to result from a proposed well can be calculated if sufficient hydrogeologic information is available. This can be done analytically (e.g., Glover and Balmer, 1954; Hantush, 1965; Jenkins, 1968; Hunt, 1999, 2003; Butler and others, 2001) or numerically (e.g., Leake and others, 2005, 2008; Neupauer and Gribling, 2012). While such a calculation is useful to evaluate stream depletion from a single well, calculating stream depletion from many well locations can be done more efficiently if a map of stream depletion is developed for an aquifer using a specified pumping rate and pumping duration. When such a map includes a particular threshold value,

the area that will have the greatest short-term effect on stream flow is called the stream depletion zone (SDZ; Metesh, 2012).

The Montana Legislature passed a law defining SDZs in 2013. The intent of this law was to establish a zone where reduction of well discharge would reduce stream depletion in a short period of time. Within an established SDZ wells that are exempt from the formal water rights permitting process (aka exempt wells) would be limited to a total annual diversion of 2 acre-ft, and would be limited to a maximum withdrawal rate of 20 gallons per minute (gpm). Exempt wells outside of SDZs are allowed to divert up to 10 acre-ft per year, and are limited to a maximum withdrawal rate of 35 gpm. Under the Montana law an SDZ is "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." The Montana Department of Natural Resources and Conservation is currently developing rules to define the methods that will be used to establish SDZs. Several other western states have adopted similar laws to recognize the interconnection between surface water and groundwater, and to facilitate their integrated management.

## CALCULATING STREAM DEPLETION BY ANALYTICAL METHODS

Analytical methods employ a single governing equation derived under a specific set of assumptions. The analytical method described by Jenkins (1968) is widely used, and it incorporates much of the previous work (Theis, 1941; Glover and Balmer, 1954). Jenkins (1968) identified the following assumptions related to using this method:

1. The transmissivity of the aquifer ( $T$ ) does not change with time. Thus, for a water-table aquifer, drawdown is considered to be negligible when compared to the saturated thickness.
2. The temperature of the stream is assumed to be constant and to be the same as the temperature of the water in the aquifer.
3. The aquifer is isotropic, homogeneous, and semi-infinite in areal extent.
4. The stream that forms a boundary is straight and fully penetrates the aquifer.
5. Water is released instantaneously from storage.
6. The well is open to the full saturated thickness of the aquifer.
7. The pumping rate is steady during any period of pumping.

Also implicit in this method are the assumptions that there is only one well, one stream, one aquifer, that the streambed is at least as permeable as the aquifer, that any recharge to the aquifer occurs a semi-infinite distance away, and that regardless of aquifer properties the specified pumping rate can be maintained. Other work has attempted to remove some of the more restrictive assumptions, such as no streambed resistance (Hantush, 1965), fully penetrating streams (Hunt, 1999, 2004; Zlotnik and Huang, 1999; Butler and others, 2001) and steady pumping rates (Darama, 2001); however, substantial simplification of the hydrogeologic system is required to use analytical methods. Aquifer properties often change spatially, hydrologic boundaries may be encountered (e.g., no-flow), the saturated thickness may change substantially due to pumping, rivers are rarely straight, the wells

may not be fully penetrating, there may be multiple wells or streams, and recharge may occur close to the area analyzed.

## CALCULATING STREAM DEPLETION BY NUMERICAL METHODS

Numerical models can incorporate a more complex representation of the hydrogeologic system than analytical models. Numerical models can allow for spatial variability in aquifer properties, hydrologic boundaries, changing saturated thickness with pumping, sinuous rivers, partly penetrating wells, simulation of multiple wells and multiple streams, and recharge near the area being tested. Numerical models are limited by the requirement that space and time must be discretized, so solutions are only available at predetermined locations and times. This discretization also results in some truncation error as the differential equations of groundwater flow are replaced by algebraic equations. Numerical models also do not give a precise answer. Numerical models use successive approximation techniques to get near to an answer; however, they never arrive at a single "correct" answer. Due to their complexity, numerical models must be calibrated relative to field data and observations; however, if there were substantial conceptual errors during the development of the model, it is still mathematically possible for the model to calibrate, but to be a poor representation of the hydrogeologic system. For this reason detailed monitoring data and a well-developed conceptual model (including a detailed groundwater budget) are needed if a numerical model is expected to reasonably approximate a particular hydrogeologic system (Anderson and Woessner, 1992).

If a properly developed and calibrated numerical model is available for an area, the stream depletion resulting from a hypothetical well at any particular location within the model can be estimated (for example, Leake and others, 2005, 2008, 2012). Such an estimate would require less simplification of the hydrogeologic system than would be needed to use an analytical solution.

The most commonly used numerical groundwater flow model is MODFLOW (Harbaugh, 2005), which is a finite difference model. The basic steps for calculating stream depletion from a single well in

MODFLOW model are:

1. Run the model without the well for the specified time period, and save the baseline water budget information. This information is stored by MODFLOW in the \*.out file.
2. Add the subject well, rerun the model, and save the revised water budget information.
3. Compare the baseline water budget to the revised water budget and note any differences. Any change in the net flux to surface water features represents stream depletion. Divide the stream depletion by the well's pumping rate to get the percentage of pumped water that is from stream depletion. This is equivalent to the  $q/Q$  value used by Jenkins (1968).

## **DEVELOPING AN SDZ MAP USING NUMERICAL MODELING**

Calculating stream depletion from a single well using a numerical model is relatively simple; however, developing an SDZ map by manually testing the effects of a well in every cell of a model would be inefficient and time consuming (Leake and others, 2010). To address this problem requires development of a general purpose computer program that automates the procedure of mapping stream depletion (Leake and others, 2010). This paper documents such a program that has been developed for MODFLOW-2000 and MODFLOW-2005 (Harbaugh and others, 2000; Harbaugh, 2005). The current version is SDZTool\_1.0.1. The process followed by the SDZTool is similar to the process outlined in the "Calculating Stream Depletion by Numerical Methods" section above, and is shown schematically in figure 1. The results of the SDZTool are saved as results for each cell, in column, row, layer format. Details regarding use of the SDZTool are included in appendix A.

It is much more efficient to test many well locations using an automated process. A computer is well suited for this repetitive task, and can do each run much more rapidly than a person. There is also a substantially lower chance of error when the process is automated. Since the testing of each hypothetical well location is completely independent of the results for any other run, this process

can be run in parallel by as many processors as are available.

To increase efficiency, the SDZTool also includes options for limiting the number of cells to be tested. The nth cell option allows cells to be skipped by only testing every nth cell (e.g., enter 5 to test every 5th cell). The range limits allow testing to be limited to a specified range of layers, rows, and columns. These options can also be combined.

Work is ongoing regarding further optimization. One potential approach is to have the program calculate stream depletion starting in cells closest to surface-water features and then systematically calculating depletion in cells further away, until a particular depletion threshold is reached. Another approach is to format the program to work on a high-performance computer (HPC). For example, the HPC at Montana Tech has 512 cores, compared to the 8 cores commonly included on modern desktop computers, so the SDZ analysis could theoretically run 64 times faster on the HPC.

## **COMPARISON TO THE JENKINS METHOD (1968)**

The analytical solution for stream depletion developed by Jenkins (1968) is widely used. For example, it was used to develop the "Colorado Model" (Schroeder, 1987), and is included in STRM-DEPL08 (Reeves, 2008; <http://mi.water.usgs.gov/software/groundwater/CalculateWell/index.html>). This model is for a fully penetrating stream with no streambed resistance. The assumptions required to follow the Jenkins method were presented in the "Calculating Stream Depletion by Analytical Methods" section. Assumptions 1, 3, 4, 6, and 7 could differ using a numerical approach, but to compare the results from the SDZTool to the Jenkins method (1968), a numerical MODFLOW model was developed to simulate the Jenkins assumptions. A model with a 500 x 500 x 1 cell grid [200 ft thick and 100,000 ft (18.9 mi) along each horizontal edge] was constructed. Specified head cells with head set to 200 ft were assigned along the east and west edges of the model, and a river with stage set to 199 ft was located straight down the middle (fig. 2).

The Jenkins assumptions were simulated by:

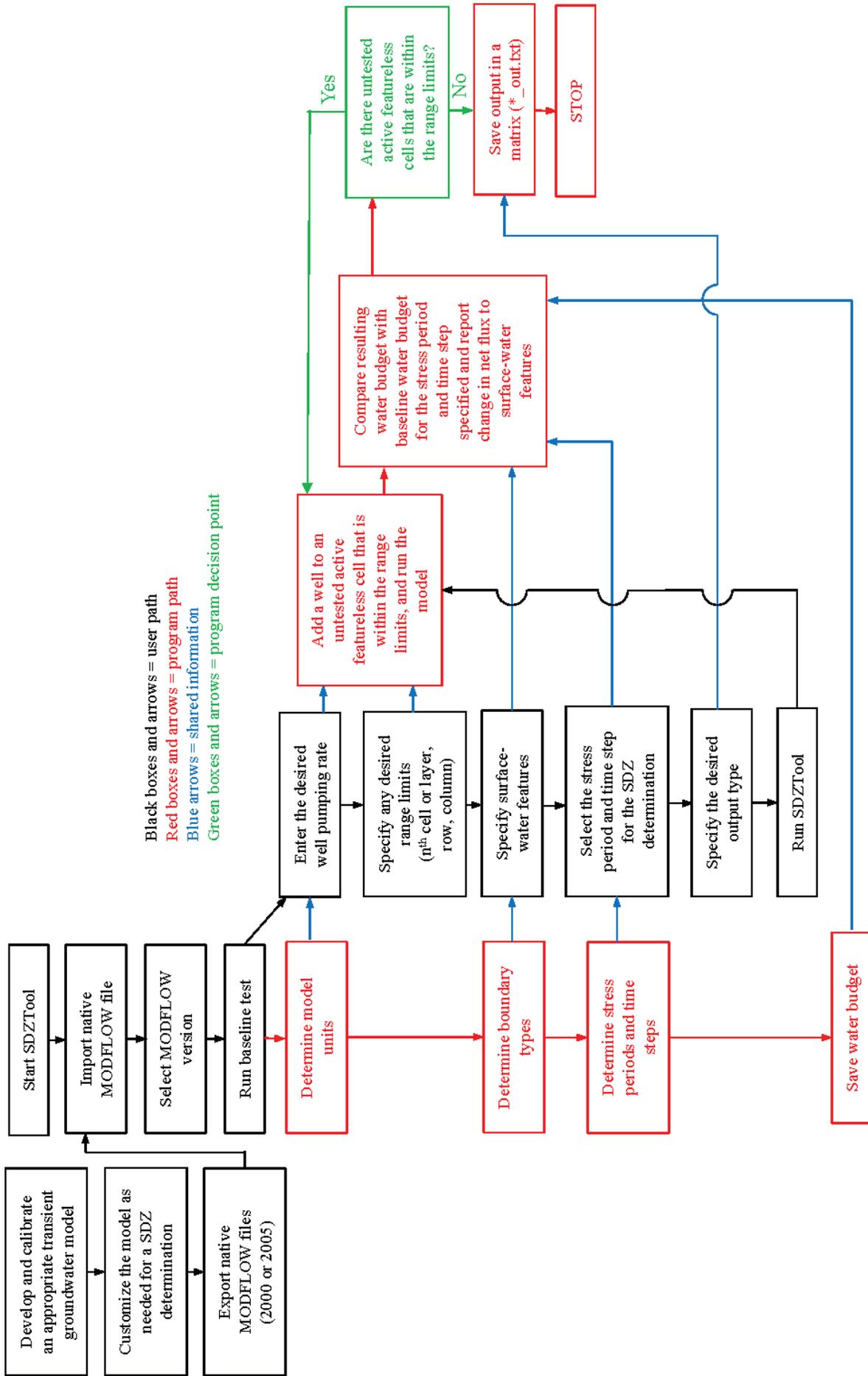


Figure 1. This flow chart shows the process that the SDZTool and the user follow to determine stream depletion.

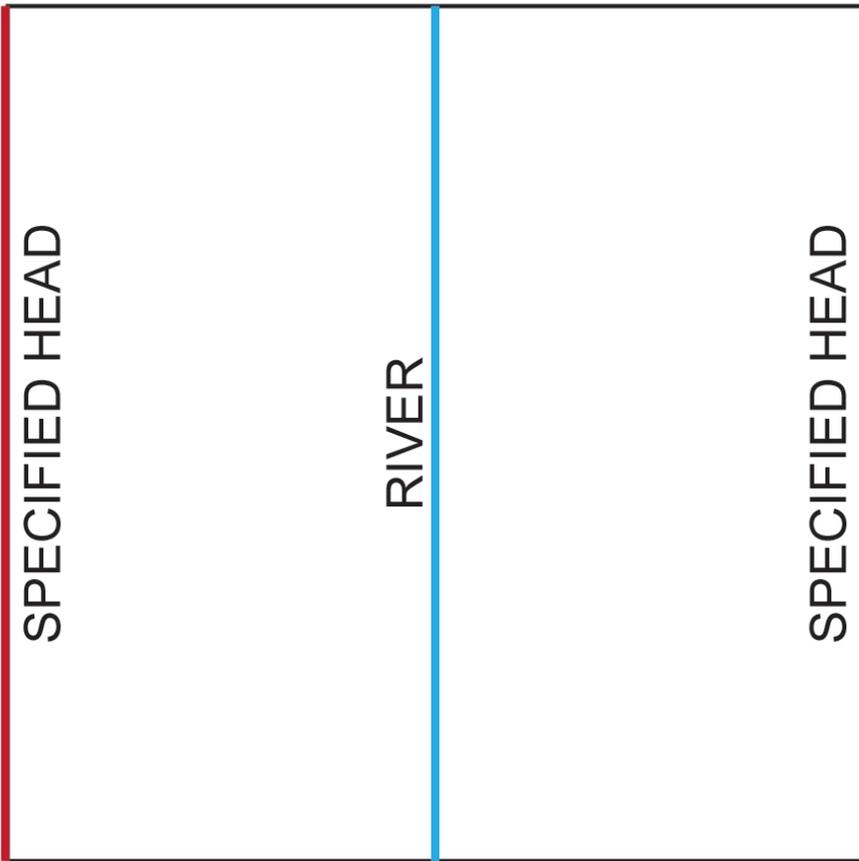


Figure 2. This model (shown in map view) was used to compare stream depletion calculations from the numerical model to analytical solutions. The model grid is 100,000 ft on each horizontal edge.

*Assumption 1:* Making the aquifer thick (b=200 ft) relative to the anticipated drawdown, permeable (K=500 ft/d), and with a reasonably high specific yield ( $S_y=0.1$ ) so that drawdown is small relative to aquifer thickness.

*Assumption 3:* Making the aquifer isotropic, homogeneous, and very large horizontally (100,000 ft x 100,000 ft).

*Assumption 4:* Making the stream (river) straight and fully penetrating. Full penetration was achieved by having a 1-layer model and high streambed conductance (5,000,000 ft<sup>2</sup>/d).

*Assumption 6:* Using a 1-layer model.

*Assumption 7:* Using a steady pumping schedule [35 gpm (6,738 ft<sup>3</sup>/d) for 30 days].

When this model was completed it was

tested by manually placing wells within the grid at specific locations so that the results could be compared to the Jenkins (1968) method (table 1). The numerical model was run for 30 days with one stress period and 30 1-day time steps. The results were similar to, but slightly less than, the Jenkins method (0.2–0.6% difference). As discussed below, these slightly lower values likely result from the slight reduction in saturated thickness caused by pumping at 35 gpm. The SDZTool was also used to calculate stream depletion, which produced results that were the same as those for the manually tested cells (table 1, fig. 3).

### EFFECTS OF “ARTIFICIAL BOUNDARIES”

Artificial boundaries can create unrealistic predictions in numerical models. As noted by Leake and others (2010): “model boundaries that do not represent physical features in a way that they would respond to pumping stress...are problematic in calculations of capture because they can affect calculation of

Table 1. Comparison of stream depletion as a percentage of the pumping rate (35 gpm).

Distance from Stream (ft)	Jenkins Method (STRMDEPL08)	MODFLOW	
		Manual	SDZTool
800	91.8%	91.6%	91.6%
1,600	83.6%	83.3%	83.3%
2,400	75.7%	75.3%	75.3%
3,200	67.9%	67.4%	67.4%
4,000	60.6%	60.0%	60.0%
4,800	53.5%	53.0%	53.0%
5,600	47.0%	46.4%	46.4%
6,400	40.9%	40.3%	40.3%
7,200	35.3%	34.7%	34.8%
8,000	30.2%	29.7%	29.7%
8,800	25.6%	25.2%	25.2%
9,600	21.5%	21.1%	21.1%

*Note.* STRMDEPL08 results from <http://mi.water.usgs.gov/software/groundwater/CalculateWell/index.html>.

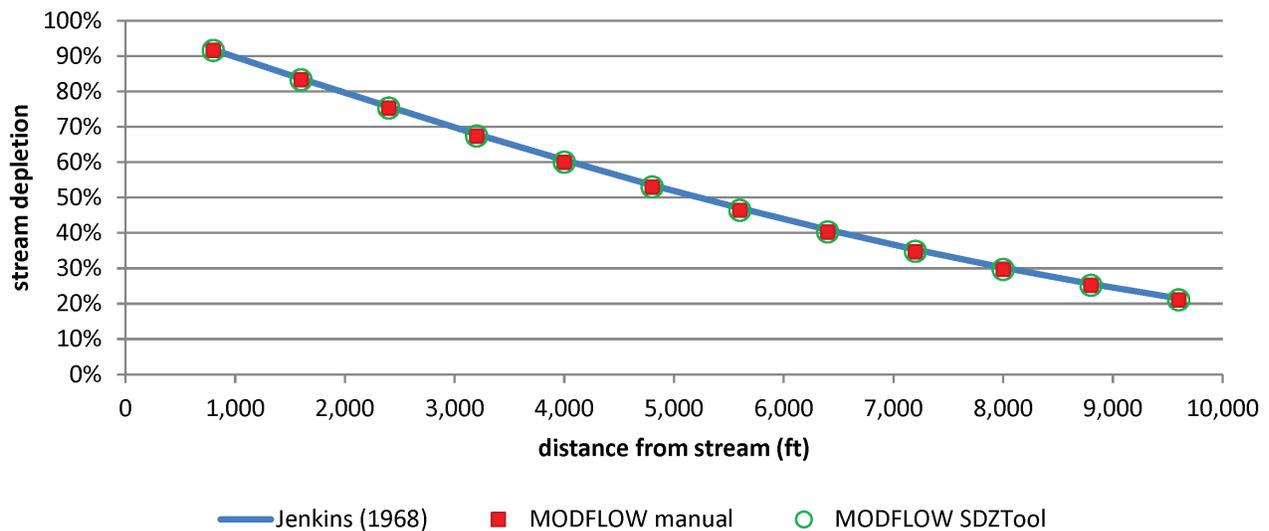


Figure 3. Stream depletion values as a percentage of the pumping rate were calculated manually using MODFLOW, the SDZTool with MODFLOW, and the Jenkins analytical method (table 1). The MODFLOW model was constructed to simulate the assumptions of the Jenkins method. Results from all three methods are comparable.

capture from actual physical features represented with head dependent boundaries.” As such, care should be taken when specified head or specified flux (including no-flow) boundaries are used. Leake and others (2010) suggest stream depletion should not be mapped for locations where the flow from such boundaries is greater than 10% of the well pumping rate.

## PUMPING RATE INDEPENDENCE

If the Jenkins method (1968) is used, the calculated stream depletion as a percentage of the pumping rate is independent of pumping rate because the solution is for stream depletion relative to the pumping rate ( $q/Q$ , where  $q$  is the stream depletion rate and  $Q$  is the pumping rate). However, the magnitude of depletion (i.e., cfs of stream flow) is directly proportional to the pumping rate.

In some cases the rate to use may be predetermined (e.g., 35 gpm for the Montana SDZ law); however, use of the predetermined rate may not be applicable to local hydrologic conditions. For example, 35 gpm may cause excessive drawdown in low-yield aquifers and cause some model cells to go dry (e.g., in granitic bedrock). In these cases, a different pumping rate needs to be used if stream depletion values are to be calculated for local conditions. As such, a robust evaluation of a method to estimate stream depletion should include the effect of using different pumping rates.

The numerical model described above (fig. 2) was tested under various pumping rates. In the numerical model the  $K$  is 500 ft/d, the saturated thickness is 200 ft ( $T=100,000$  ft<sup>2</sup>/d; 748,000 gpd/ft), the storativity is 0.1, and the well is pumped for 30 days. The well was located 1,600 ft from the stream, and pumping rates between 0.1 and 50,000 gpm were simulated. Stream depletion as a percentage of the pumping rate ranged from 83.2% to 89.9% (table 2, fig. 4). As a comparison, the stream depletion from the Jenkins method as a percentage of the pumping rate was 83.6%. The model results show that there are several effects from the pumping rate. Very low pumping rates appear to approach steady-state more quickly, resulting in a somewhat higher percentage of the withdrawal coming from the stream. If it is assumed that the stream is the only source where the withdrawal from the well can be supplied, stream depletion would be 100% at steady-state (Jenkins, 1968; Reeves, 2008). Variations in pumping rate within a reasonable range for the aquifer result in fairly minor changes in calculated stream depletion, so long as flow mechanisms remain the same. For example, the calculated stream depletion only changes by about 1% between 1 and 100 gpm; however, once a portion of the river starts losing water to the aquifer, the calculated stream depletion changes by 2.4% between 100 and 150 gpm (fig. 4, table 2).

The pumping rate dependence of stream deple-

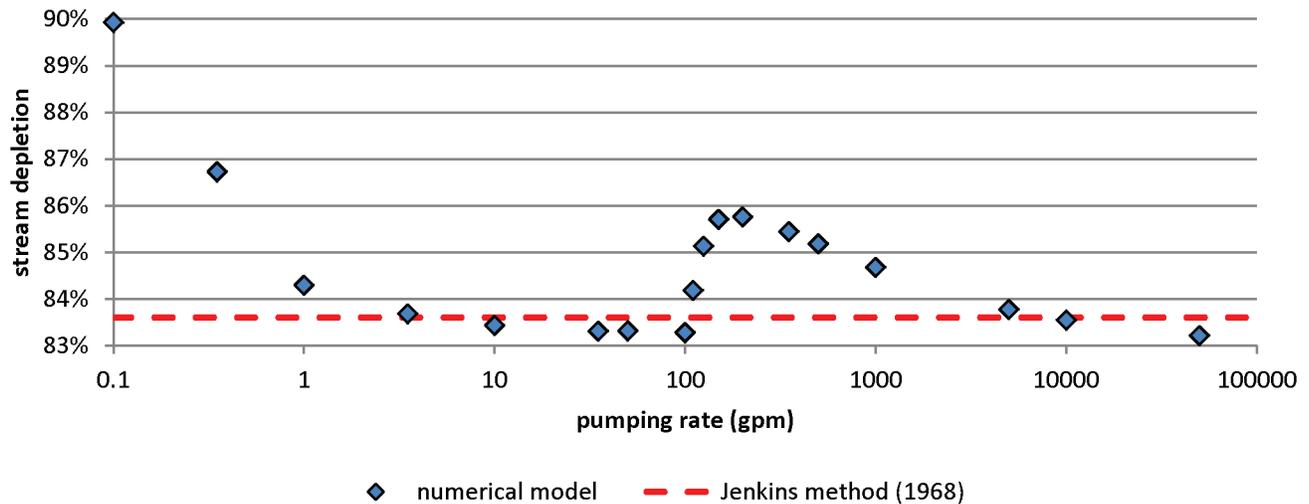


Figure 4. The calculated stream depletion as a percentage of the pumping rate is somewhat dependent on the pumping rate. Very low pumping rates result in somewhat higher stream depletion values, which appear to be due to the system being closer to steady-state. A 2.5% increase occurs when there is a change to drawing water to the aquifer from the stream rather than intercepting it before it reaches the stream.

tion is particularly important where there are low-permeability aquifers where cells would go dry at the normally prescribed rate (e.g., 35 gpm). In such cases a lower rate reflective of local hydrogeologic conditions could be needed, resulting in a slight change in the calculated value of stream depletion. If a rate lower than normally prescribed must be used, the highest pumping rate that will not dry the cell should be used. Several pumping rates should also be evaluated so that the direction and magnitude of the difference between the effects from prescribed rate and the modified rate can be estimated.

### AN EXAMPLE USING A PRE-EXISTING MODFLOW MODEL

Uthman and Beck (1998) developed a numerical groundwater model for the Upper Beaverhead Basin near Dillon, Montana, using MODFLOW-88 (fig. 5). This was a two-layer model with cell sizes ranging from 500 x 500 ft to 1000 x 1000 ft. The model included active and inactive cells. General-head boundaries were used to simulate mountain front recharge and groundwater flow into the basin from the alluvium of Blacktail Deer Creek, the Beaverhead River, and Rattlesnake Creek. A general-head boundary was also used to simulate groundwater discharge from the basin into the alluvium of the Beaverhead River. River cells were used to simulate the Beaverhead River, Blacktail Deer, Rattlesnake, Sheep, and Small Horn Creeks, and Poindexter and

VanCamp Sloughs. Recharge was assigned as 10% of precipitation plus irrigation recharge, minus evapotranspiration. Wells with high pumping rates were simulated using the well package. This model had 57 stress periods 8 to 31 days in duration.

To adapt this model for use with the SDZTool, the model files were converted to MODFLOW-2000 using GMS 9.1 (Aquaveo, 2013), and a single 30-day stress period with 10 time steps was used. Values from the original stress period 1 (30 days from April 1 to April 30, 1993) were used for all sources, sinks, and boundaries. After these minor modifications, native MODFLOW-2000 files were exported. The SDZTool was used to calculate percent stream depletion for each active featureless cell in the model that would result if a well was pumped continuously for 30 days at 35 gpm. This model contained 7,076 active featureless cells, and these calculations required about 9 min using a 4-core processor.

The results were viewed by importing them into GMS for visualization (fig. 6). The results show that there are areas of higher stream depletion rates near the Beaverhead River and Blacktail Deer Creek.

The results can also be viewed as an SDZ, where areas are either above or below 30% (fig. 7). While such a map can be drawn, it should be noted that it has no regulatory implications at this time, since

Table 2. Comparison of calculated stream depletion at different pumping rates.

Pumping Rate (gpm)	Pumping Rate (ft <sup>3</sup> /d)	River Out (ft <sup>3</sup> /d)	River In (ft <sup>3</sup> /d)	Net River Out (ft <sup>3</sup> /d)	River Change (ft <sup>3</sup> /d)	Groundwater Elevation at the Pumping Well (ft)	Drawdown (ft)	Drawdown as % of Saturated Thickness	Stream Depletion as % of Pumping Rate
0	0	415,602	0	415,602	0	199.0323	0.0000	0.00000%	0.0%
0.10	19	415,584	0	415,584	17	199.0321	0.00014	0.00007%	89.9%
0.35	67	415,543	0	415,543	58	199.0318	0.00047	0.00024%	86.7%
1.0	193	415,439	0	415,439	162	199.0309	0.00134	0.00067%	84.3%
3.5	674	415,038	0	415,038	564	199.0276	0.00468	0.00235%	83.7%
10	1,925	413,996	0	413,996	1,606	199.0189	0.01340	0.00673%	83.4%
35	6,738	409,988	0	409,988	5,613	198.9967	0.03555	0.01786%	83.3%
50	9,626	407,582	0	407,582	8,020	198.9653	0.06695	0.03364%	83.3%
100	19,251	399,569	0	399,569	16,032	198.8983	0.13392	0.06729%	83.3%
110	21,176	397,917	143	397,774	17,827	198.8849	0.14732	0.07402%	84.2%
125	24,064	395,911	795	395,115	20,486	198.8648	0.16742	0.08412%	85.1%
150	28,877	393,182	2,330	390,852	24,750	198.8313	0.20093	0.10095%	85.7%
200	38,503	388,976	6,393	382,583	33,019	198.7643	0.26794	0.13462%	85.8%
350	67,380	380,218	22,189	358,030	57,572	198.5631	0.46911	0.23570%	85.4%
500	96,257	374,123	40,516	333,607	81,995	198.3618	0.67050	0.33688%	85.2%
1,000	192,513	361,065	108,480	252,585	163,017	197.6890	1.34326	0.67490%	84.7%
5,000	962,567	326,434	717,198	-390,764	806,366	192.2222	6.81003	3.42157%	83.8%
10,000	1,925,134	310,808	1,503,598	-1,192,790	1,608,392	185.1615	13.87074	6.96909%	83.5%
50,000	9,625,668	275,557	7,870,071	-7,594,514	8,010,115	113.0155	86.01675	43.21749%	83.2%

Note. The well is 1600 ft from the river. These calculations were developed from the model developed for testing relative to the Jenkins model (fig. 2). The Jenkins method predicts the percent of the pumped water derived from stream depletion to be 83.6%.

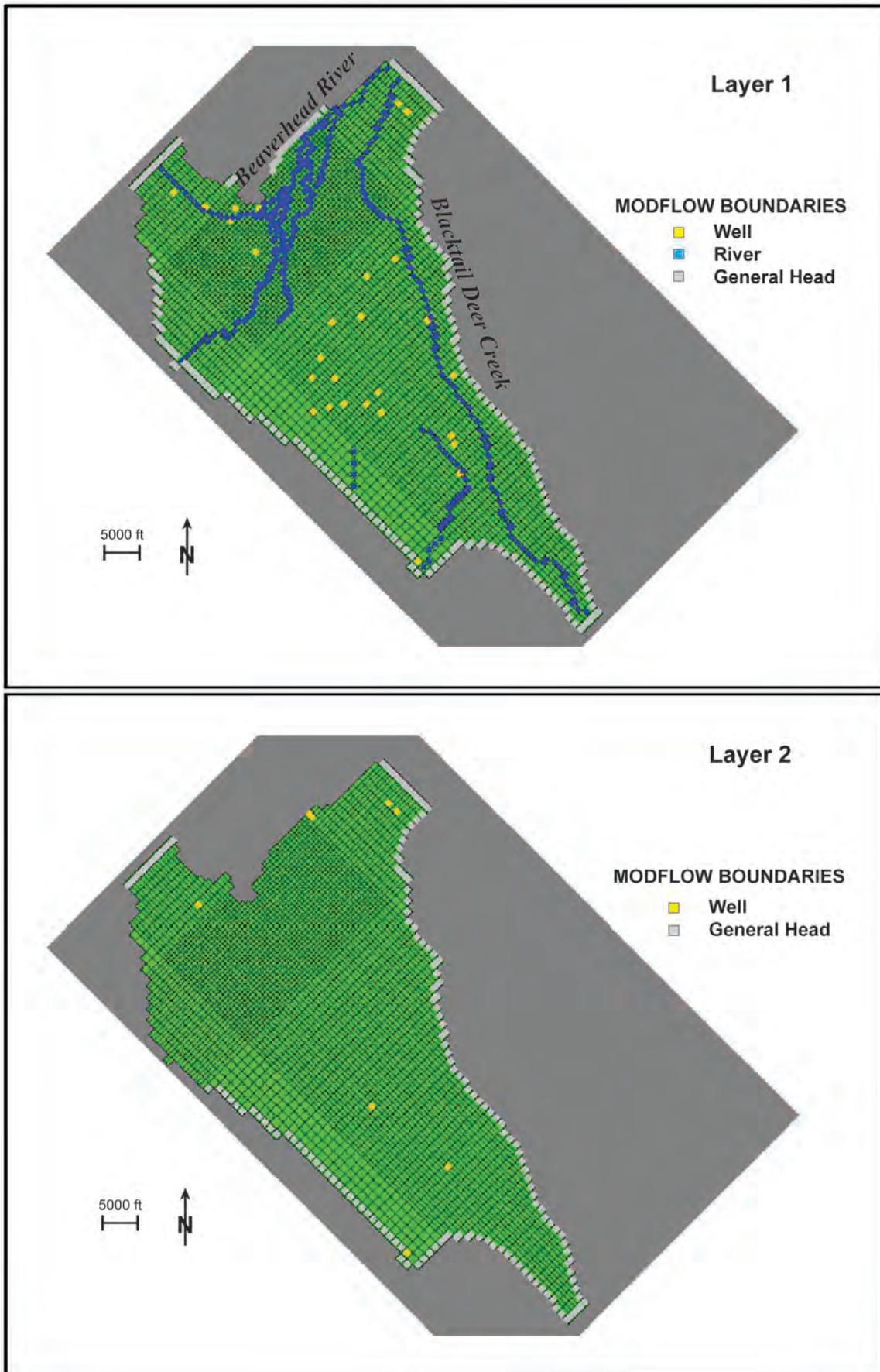


Figure 5. The Upper Beaverhead model (Uthman and Beck, 1998) uses two layers and includes general head boundaries, rivers, and wells to represent the system. Recharge is also applied. There are 7,076 active featureless cells in this model (green cells). Dark gray cells are inactive.

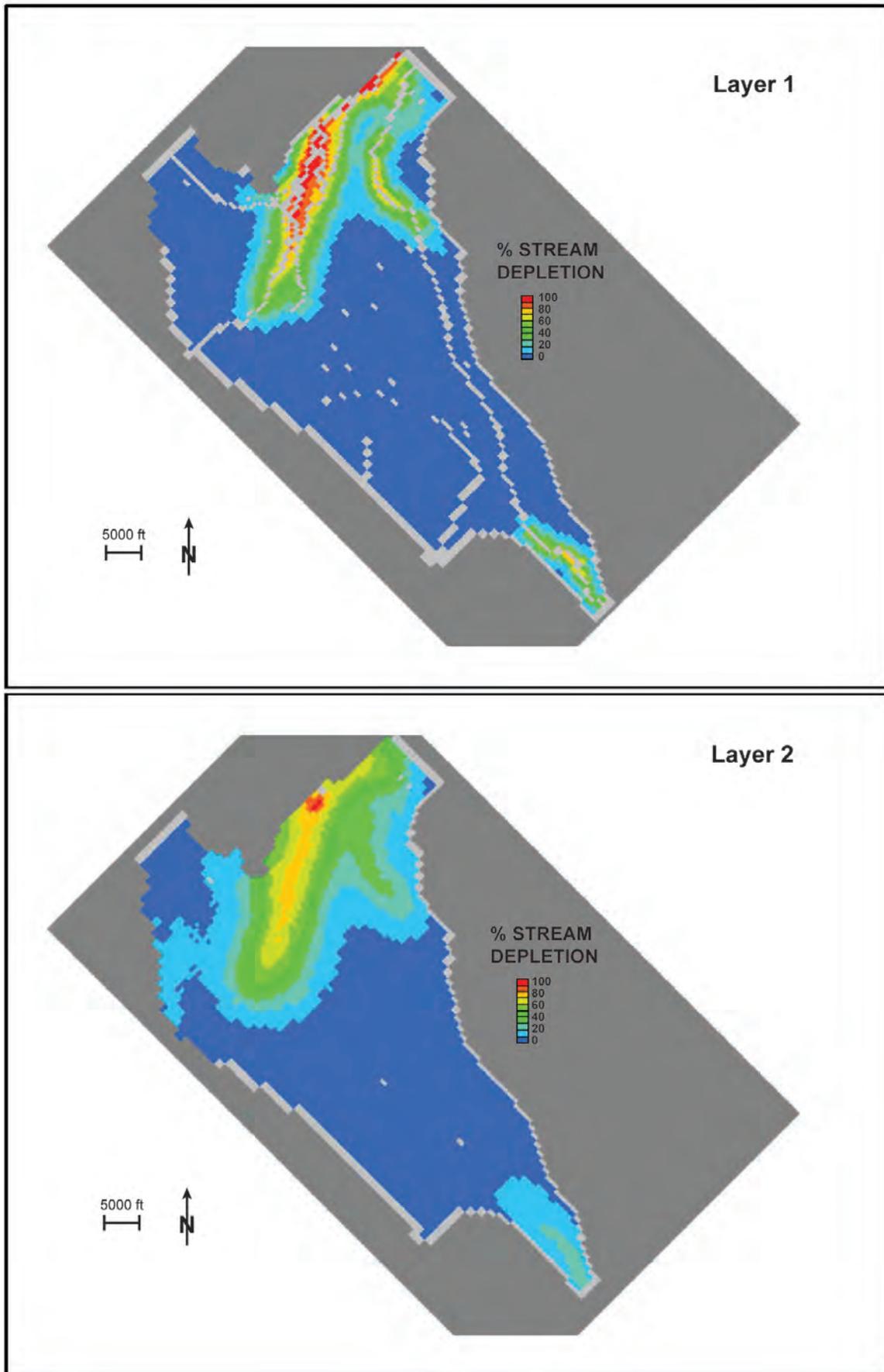


Figure 6. Results from the SDZTool show that stream depletion is greatest near the Beaverhead River, with some depletion along Blacktail Deer Creek. Depletion is greater in layer 1 than in layer 2. Light gray cells were not tested because they contain features (such as wells or rivers) or are inactive. Dark gray cells are inactive.

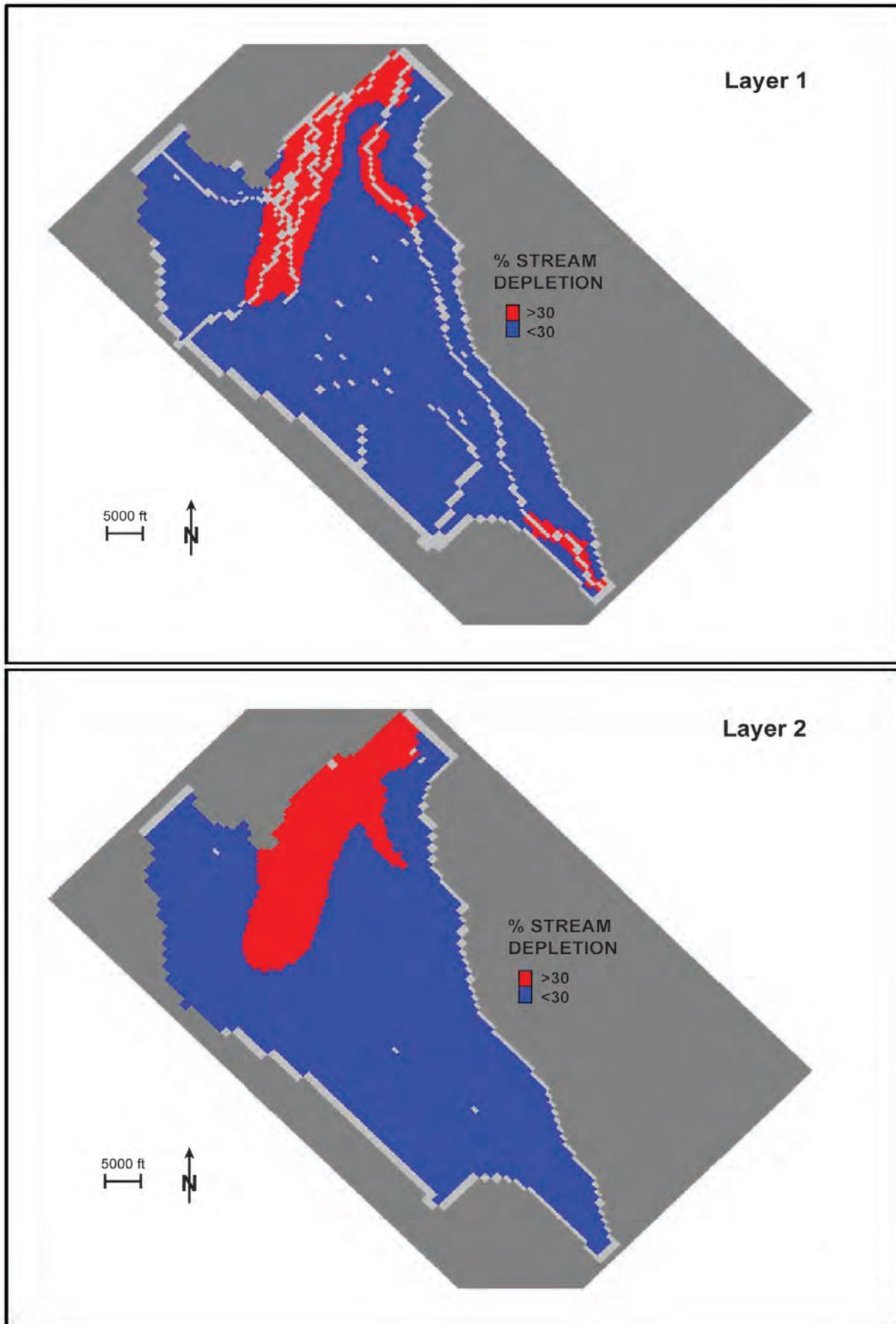


Figure 7. Results from the SDZTool can be contoured to show a SDZ (30% or greater is red). For such a result to be meaningful regulatory bodies would need to conduct detailed evaluation of the model used, and the results. Light gray cells were not tested because they contain features (such as wells or rivers) or are inactive. Dark gray cells are inactive.

any model used for this purpose, and the results, would need to be evaluated in detail by the appropriate regulatory agencies. An interesting result of viewing the results in this way is that the zone in the southeast corner, along Blacktail Deer Creek, is only in layer 1. In this area pumping from layer 2 is insufficient to cause stream depletion values to be above 30%. This serves to emphasize that SDZs are three-dimensional. Also note that near the junction of Blacktail Deer Creek and the Beaverhead River, the SDZ is discontinuous in layer 1, while it is smaller but contiguous in layer 2.

## CONCLUSIONS

Calculating stream depletion values over an area, or delineating SDZs, can be accomplished using the SDZTool, if an appropriate and properly calibrated MODFLOW-2000 or MODFLOW-2005 numerical model is available for the area. Any model used for this purpose should be carefully evaluated to ensure that it provides a realistic representation of the system. The SDZTool results must also be carefully evaluated to ensure unrealistic values are not being calculated. Such a result could occur near boundaries. For most models the SDZTool will provide results for the entire model in a reasonable amount of time. When large models are tested it is advisable to test a subset of the cells (nth cell option) and then limit the range of cells to be tested, or be able to have a computer run the program for up to several weeks. Since the calculations can be run in parallel, it is planned that a future version will be developed for use on a high-performance computer. Also, while the current version (1.0.1) uses the simple approach of testing the effects to surface water by testing a well in every (or every nth) active featureless cell in the specified range, future versions may be able to limit the number of cells that need to be tested by using the definition of the SDZ and testing only those cells closest to surface-water features.

## ACKNOWLEDGMENTS

The gracious assistance provided by many individuals is appreciated. In particular, Keith Vertanen from the Montana Tech Computer Science and Software Engineering Department assisted with the development of conceptual approaches to design-

ing the SDZTool. Kirk Waren and Julie Butler from the MBMG assisted by testing the SDZTool, and provided suggestions for improving its function. John Metesh from the MBMG provided much of the background work that led to this project being undertaken. John Wheaton's support for this project is also appreciated. We also thank Robert Sedgewick and Keven Wayne, who allowed their StdDraw java library to be used for debugging.

## REFERENCES

- Aquaveo, 2013, Aquaveo Groundwater Modeling System (GMS) version 9.1.1.0; 5/7/13.
- Anderson, M., and Woessner, W., 1992, Applied groundwater modeling: Simulation of flow and advective transport: San Diego, Academic Press, 381 p.
- Bredehoeft, J.D., Papadopulos, S.S., and Copper, H.H. Jr., 1982, Groundwater: The water budget myth, in Scientific basis of water-resources management, ed. National Research Council (U.S.), Geophysical Study Committee, National Academy Press, Washington DC, p. 51–57.
- Butler, J.J., Zlotnik, V.A., and Tsou, M.-S., 2001, Drawdown and stream depletion produced by pumping in the vicinity of a partially penetrating stream: *Ground Water*, v. 39, no. 5, p. 651–659.
- Darama, Y., 2001, An analytical solution for stream depletion by cyclic pumping of wells near streams with semipervious beds: *Ground Water*, v. 39, no. 1, p. 79–86.
- Glover, R.E., and Balmer, C.G., 1954, River depletion resulting from pumping a well near a river: *American Geophysical Union Transactions*, v. 35, pt. 3, p. 468–470.
- Hantush, M.S., 1965, Wells near streams with semipervious beds: *Journal of Geophysical Research*, v. 70, no. 12, p. 2829–2838.
- Harbaugh, A.W., 2005, MODFLOW-2005, the U.S. Geological Survey modular ground-water model—The Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16.

- Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.
- Hunt, B., 1999, Unsteady stream depletion from ground water pumping: *Ground Water*, v. 37, no. 1, p. 98–102.
- Hunt, B., 2003, Unsteady stream depletion when pumping from semiconfined aquifer: *Journal of Hydrologic Engineering*, v. 8, no. 1, p. 12–19.
- Jenkins, C.T., 1968, Computation of rate and volume of stream depletion by wells: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chap. D1, 17 p.
- Leake, S.A., Hoffmann, J.P., and Dickinson, J.E., 2005, Numerical ground-water change model of the C aquifer and effects of ground-water withdrawals on stream depletion in selected reaches of Clear Creek, Chevelon Creek, and the Little Colorado River, northeastern Arizona: U.S. Geological Survey Scientific Investigations Report 2005-5277, 29 p.
- Leake, S.A., Hoffmann, J.P., and Dickinson, J.E., 2005, Numerical ground-water change model of the C aquifer and effects of ground-water withdrawals on stream depletion in selected reaches of Clear Creek, Chevelon Creek, and the Little Colorado River, northeastern Arizona, U.S. Geological Survey Scientific Investigations Report 2005-5277, 29 p.
- Leake, S.A., Pool, D.R., and Leenhouts, J.M., 2008, Simulated effects of groundwater-water withdrawals and artificial recharge on discharge to streams, springs, and riparian vegetation in the Sierra Vista subwatershed of the Upper San Pedro Basin, southeastern Arizona, U.S. Geological Survey Scientific Investigations Report 2008-5207, 14 p.
- Leake, S.A., Reeves, H.W., and Dickinson, J.E., 2010, A new capture fraction method to map how pumpage affects surface water flow: *Ground Water*, v. 48, no. 5, p. 690–700.
- Leake, S.A., and Gungle, B., 2012, Evaluation of simulations to understand effects of groundwater development and artificial recharge on the surface water and riparian vegetation Sierra Vista subwatershed, Upper San Pedro Basin, Arizona: U.S. Geological Survey Open-File Report 2012-1206, 11 p.
- Metesh, J., 2012, Hydrogeology related to exempt wells in Montana: A report to the 2010–2012 Water Policy Interim Committee of the Montana Legislature: Montana Bureau of Mines and Geology Open-File Report 612, 24 p.
- Neupauer, R.M., and Griebing, S.A., 2012, Adjoint simulation of stream depletion due to aquifer pumping: *Ground Water*, v. 50, no. 5, p. 746–753.
- Reeves, H.W., 2008, STRMDEPL08—An extended version of STRMDEPL with additional analytical solutions to calculate streamflow depletion by nearby pumping wells: U.S. Geological Survey Open-File Report 2008-1166, 22 p.
- Schroeder, D.R., 1987, Analytical stream depletion model: Office of the State Engineer, Colorado Division of Water Resources, Ground Water Software Publication No. 1.
- 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.
- Theis, C.V., 1941, The effect of a well on the flow of a nearby stream: *American Geophysical Union Transactions*, v. 22, pt. 3, p. 734–738.
- Uthman, W., and Beck, J., 1998, Hydrogeology of the Upper Beaverhead Basin near Dillon, Montana: Montana Bureau of Mines and Geology Open-File Report 384, 549 p.
- Zlotnik, V.A., and Huang, H., 1999, Effect of shallow penetration and streambed sediments on aquifer response to stream state fluctuations (analytical model): *Ground Water*, v. 37, no. 4, p. 599–605.



**APPENDIX A**  
**USING THE TOOL**



## APPENDIX A—INSTALLATION INSTRUCTIONS AND PROCEDURES FOR USE

### Installation Instructions

SDZTool was written as a Java™ Archive file (\*.jar) and then packed into an executable file. As such, the SDZTool program itself does not need to be installed, but just needs to be accessible. Ensure that the Java™ version is up to date (<http://java.com/en/download/index.jsp>). MODFLOW-2000 and/or MODFLOW-2005 need to be installed (whichever the initial MODFLOW model used) because the SDZTool will use one of these programs to run the native MODFLOW files. The native MODFLOW files should be tested using MODFLOW off the command line to ensure that they will run properly. Other programs to read and visualize the results (text readers, spreadsheets, and GUI interfaces for MODFLOW) are useful, but not necessary. The SDZ software can be obtained by contacting the lead author ([abobst@mtech.edu](mailto:abobst@mtech.edu)).

### Procedure for Use

(1) *Double click on the SDZTool\_1.0.1 executable file.*

This will cause a new window to open. This window is the status box that will track what the program has done, and provide information to the user. There is only one option for the user, and that is to click on the “New Simulation” button at the bottom.

(2) *Click on “New Simulation” button.*

This will cause a new window to open. The first input is to map to the native MODFLOW file for the model that will be tested using the “Select File” button. The user must select the \*.nam or \*.mfn file for the model. Next the user must select the version of MODFLOW that the model uses. MODFLOW-2005 is the default, but MODFLOW-2000 is also supported. Once these selections are made the user clicks on the “Run Baseline Test” button.

(3) *Click on “Run Baseline Test” button.*

When the baseline test is run the tool runs the model with no modification, and reads from the \*.out (or \*.lst), \*.glo if it exists, and \*.ba6 files and reports the extent of the grid, the units that are used in the model, the possible surface-water features in the model, the number of stress periods

and time steps, and the number of active cells that do not contain features. The active featureless cells are the cells that will be tested. The tool saves the output from this run since it will be used as the baseline run to calculate depletion from adding wells. A new box with several features opens at the end of the baseline test. This box includes:

(a) **Surface-Water Features:** Select the features that represent the surface waters to be tested in the model. The tool reads the result of the baseline test to make the features that may be surface-water features selectable; however, the user must define which particular features are intended to represent surface water. Note that if a cell type is used to define a surface-water feature, it cannot be used for other purposes in the model. For example, if specified head cells are used to represent a lake, they cannot also be used to define an upgradient boundary. This is due to the tool using the budget information from the \*.out file to calculate stream depletion.

(b) **Stress period and time step:** Based on the baseline test, the tool asks the user which time step of which stress period is to be evaluated. This guides the tool to the budget information in the \*.out file that will be used for calculating stream depletion. For example, if one stress period with 30 1-day time steps were used in the model and the stream depletion after 30 days needed to be evaluated, stress period one and time step 30 would be selected.

(c) **Simulate every nth cell:** This option allows the user to define if all cells are tested (blank), or if some subset will be tested based on skipping a number of cells. For example, if the user wanted to test every 5th cell, a 5 would be entered in this box. This can allow for significantly shorter run times while still providing distributed results, which is particularly useful when assessing if the model is set up properly, and for determining if only a limited range of cells needs to be tested (see below).

(d) **Hypothetical pumping rate:** Enter the pumping rate of the hypothetical pumping wells. Units can be selected from the dropdown menus; the default is gallons per minute (gpm). Since the tool reads the units from the baseline test, conversions will occur automatically.

(e) Output type: “Depletion values by cell” will be selected by default, and the choice is between “% of pumping rate” and “Absolute SW depletion.” The “% of pumping rate” option will return a decimal value of the reduction of stream flow relative to the pumping rate of the well. Multiply this value by 100 to get a true percentage. The “Absolute SW depletion” will return the change in flow in the surface-water features as a result of pumping the well (e.g., cfs reduction in stream flow).

(f) Simulation range limits: These options allow for a subset of cells to be tested based on defining a range of layers, rows, and columns. This can dramatically reduce the number of cells that need to be tested; however, it is advisable that the nth cell option be used first to determine the appropriate ranges to use, and the results should be carefully reviewed to ensure that effects are not artificially truncated.

The results file will be saved in the folder where the native MODFLOW files are located. It is a text (\*.txt) file written as a tab delimited file, with a value for each cell. Cells that were inactive or contained features are assigned “-1,” cells that were not tested due to user limits (nth cell or limited range) are assigned “-2,” and dry cells are assigned “-888.” Each layer is reported separately. This file can be easily imported into standard spreadsheets (e.g., Excel) and most graphical user interfaces (e.g., GMS).

*(4) Click on “Confirm” button.*

The tool will begin running MODFLOW. In the status box, the tool reports the number of active featureless cells that will be tested, the estimated running time (based on the baseline run time), and the number of threads being used. As noted by Leake and others (2010), each run is independent and completely parallelizable, so the tool will spawn multiple threads that will run independently through however many CPU cores are available to the Java™ Virtual Machine. This is usually the same as the number of CPU cores the computer has. As each thread finishes its task it is reported, and when the last thread finishes the program reports “SDZ simulation completed.” The actual runtime and the location of the output file are also reported. The name of the output file is based on the model file name, the date and time of the run, and ends with “\_out.txt.” A status bar and a tally of completed cells allow progress to be monitored. A line of text at the bottom of the box reports the cell that has most recently been completed as a column, row, layer value. The tool begins in (1,1,1) and progresses through columns, rows, and then layers. If the pumping rate specified causes dry cells, the tool will report the number of simulations that result in dry cells. A warning box at the end of the run will also inform of dry cells.