Appendix 4: Groundwater Optimization Modeling

Technical Memorandum

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Subject: Metro Pumping Optimization 3
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1.0 Introduction

This technical memorandum describes the optimization of pumping in the seven-county metropolitan area. The goal of the optimization was to maximize total pumping from existing permitted wells while meeting constraints on baseflow, hydraulic head, flow direction, and flux to/from surface water features as specified by the Metropolitan Council. The optimization uses the steady-state version of the Twin Cities Metropolitan Area Groundwater Flow Model, Version 3.0 (Metro Model 3; Metropolitan Council, 2014)

Optimizations described in technical memorandums dated August 15, 2014 and October 13, 2014 (Barr, 2014a and Barr, 2014b), herein referred to as Optimization 1 and Optimization 2, are similar and complimentary to the optimization described in this technical memorandum, herein referred to as Optimization 3.

2.0 Optimization Software, GWM-VI

The Groundwater Management (GWM) Process for MODFLOW, developed by the USGS (Ahlfeld et al., 2000), was used for the optimization. The version used was GWM-VI (Banta and Ahlfeld, 2013) which allows for parallel processing. No changes were made to the source code of GWM-VI for implementation of this project. All optimization algorithms described in Banta and Ahlfeld (2013) and Ahlfeld et al. (2005) are implemented with no change. However, several pre- and post-processing steps were used to overcome hardwired limitations on the type of constraints available with the standard GWM-VI implementation and are discussed in Section 2.3. Optimizations utilizing GWM-VI require two main inputs: decision variables and constraints; each is discussed below.

2.1 Decision variables

Decision variables are quantifiable controls that are to be determined by the GWM-VI optimization algorithms (Ahlfeld et al., 2000). Decision variables for both Optimizations 1, 2, and 3 were identical and were provided to us by Metropolitan Council. They include existing permitted wells in the seven-county metropolitan area open to any aquifer, except the Mt. Simon Hinckley aquifer, and with use codes from the SWUDS database shown in Table 1. A total of 2,074 wells were included in the optimization. The goal of the optimization was to maximize the objective function, which is essentially the sum of the pumping from all decision variable wells.

Table 1. SWUDS use codes for decision variable wells included in the optimization

Use Code	Description	Use Code	Description
211	Municipal	248	Non-metallic processing
212	Private waterworks	249	Industrial processing
213	Commercial and Institutional	263	Quarry dewatering
215	Fire protection	264	Sand/gravel pit dewatering
229	Power generation	266	Dewatering
232	Institutions	271	Pollution containment
241	Agricultural processing	277	Sewage treatment
242	Pulp and paper processing	289	Non-crop irrigation
246	Petroleum-chemical processing, ethanol	290	Major crop irrigation
247	Metal processing		

2.2 Constraints

Constraints impose restrictions on the values that can be taken by the decision variables (Ahlfeld et al., 2000). Three types of constraints were used: hydraulic head, flux between groundwater and surface-water features (baseflow and basin leakage and/or gain), and groundwater flow-direction. In general, Optimization 3 and Optimization 2 are constrained significantly less than Optimization 1. A summary of constraints imposed for each optimization is shown in Table 2 and details describing each constraint type are presented below.

Table 2. Comparison of constraints between Optimization 1, 2, and 3

Constraint Type	Optimization 1	Optimization 2	Optimization 3
Drawdown from available head for confined bedrock aquifers above the Mt. Simon-Hinckley	75%	75%	50%
Drawdown in the Mt. Simon-Hinckley aquifer	1 foot	1 foot	1 foot
Drawdown at groundwater dependent surface-water features (cancerous fens)	1 foot	1 foot	1 foot
Change in net baseflow to trout streams	-10%	-10%	-10%
Change in net baseflow to other river reaches	Not included	-15%	-15%
Change in net baseflow to the Mississippi River	Not included	-15%	-25%
Change in net groundwater flux for high and outstanding biodiversity	Not included	-15%	-15%
Change in net groundwater flux to potentially vulnerable lakes with wide littoral zone	Not included	-10%	-10%
Change in net groundwater flux for remaining lakes at grouped by Township	Not Included	-15%	-15%
Change in flow directions at site of groundwater contamination	10 degrees	10 degrees	10 degrees

Optimization 1 constrained the flux between groundwater and surface water for trout streams only. As described in more detail below, Optimizations 2 and 3 constrained the flux between groundwater and surface water for all lakes, streams, and wetlands simulated by Metro Model 3 within the seven-county metropolitan area.

2.2.1 Hydraulic Head Constraints

Hydraulic head constraints were used to impose three conditions on the optimization: 1) hydraulic head in confined bedrock aquifers can't drop below a "safe yield" threshold, 2) hydraulic head in the Mt. Simon–Hinckley aquifer can't drop more than 1 foot from the baseline condition, and 3) hydraulic head at groundwater dependent surface-water features (e.g. calcareous fens) can't drop more than 1 foot from the baseline condition. Hydraulic head, representing "safe yield" thresholds, were defined as:

$$SafeYieldHead=(Hb-Z)*0.50+Z$$

Where:

H_b is the base head condition for the aquifer, defined using pumping from the Metro Model 2;
Z is the elevation of the top of the aquifer

The base condition from which drawdown for the Mt. Simon-Hinckley aquifer and groundwater dependent surface-water features were determined was the hydraulic head from the steady-state version of the Metro Model 3.

Hydraulic head constraints representing "safe yield" and limits on drawdown of the Mt. Simon-Hinckley aquifer were implemented at the cell location (row and column) of all pumping wells in the seven-county metro area. Including these head constraints in every model cell is not practicable as it would dramatically increase the total run time for the optimization. These head constraints are more likely to be violated at the location of high pumping stress, compared to distances far from the wells. Vertically, at each cell location, constraints were included only for model layers representing bedrock aquifers being pumped and layers above these aquifers. For example, if the Prairie du Chien is being pumped and lower aquifers are not being pumped, "safe yield" constraints were only included for the Prairie du Chien and St. Peter aquifer, not the deeper aquifers.

2.2.2 Flux between groundwater and surface-water features

All surface-water features in the Metro Model 3 are simulated using the River Package for MODFLOW. The River Package simulates the exchange of water between groundwater and surface water. River Package boundary cells were compiled into groups and the water fluxes into or out of the boundary cells were tracked and summarized for each group. Constraints were imposed to limit the change in flux from the baseline condition resulting from increased pumping. The baseline condition used was the flux simulated with the steady-state version of Metro Model 3.

Groundwater flux to all streams (baseflow) in the seven-county metropolitan area was constrained for the optimization (Figure 1). Each stream was divided into reaches approximately 5 miles in length. Baseflows for trout stream reaches are not allowed to be reduced by more than 10 percent from the baseline conditions. Baseflows for all other reaches, with the exception of the Mississippi River, are not allowed to be reduced more than 15 percent from baseline conditions. Baseflows for the Mississippi River were allowed to be reduced up to 25 percent. A total of 13 trout stream baseflow constraints and 79 non-trout stream baseflow constraints were imposed for the optimization.

River boundary cells that intersect sites of high and outstanding biodiversity identified by the Minnesota County Biological Survey (2013) were grouped together (Figure 1). The groundwater flux into these features was not allowed to decrease more than 15 percent and/or flux out of these features was not allowed to increase more than 15 percent from the baseline simulation. A total of 108 biodiversity area constraints were imposed.

River Package boundary cells that represent lakes identified as being potentially vulnerable to groundwater pumping and having a wide littoral zone (Barr, 2010) were grouped together (Figure 1).

Lakes are considered to have a wide littoral zone if they are less than five feet deep over more than 20 percent of the total surface area. These lakes have a greater potential of being negatively impacted by reductions in stage. For these lakes (68 in the seven county metropolitan area), the water flux out was not allowed to increase more than 10 percent and/or the groundwater flux into these lakes was not allowed to decrease more than 10 percent.

All remaining River Package boundary cells that were not included in groups described above were grouped based on the public land survey township they are located in (Figure 1). This resulted in an additional 103 constraints. For these grouped boundary cells, the total groundwater flux in was not allowed to be reduced by more than 15 percent and/or total water flux out was not allowed to increase more than 15 percent. Grouping these River Package cells, rather than imposing constraints on individual cells or surface water features, was necessary to help keep the total number of constraints to a manageable level to maintain reasonable solution times for the optimization algorithm.

2.2.3 Flow Direction Constraints

Flow direction constraints for Optimizations 1, 2, and 3 are identical and were included for areas of existing groundwater contamination provided by the Metropolitan Council. The flow direction in the vicinity of these contamination areas was not allowed to deviate from the baseline condition by more than 10 degrees. The baseline condition used was the flow direction simulated with the steady-state version of Metro Model 3.

2.3 Substitution of MMProc

GWM-VI uses a stand-alone executable, *MMProc.exe*, to write MODFLOW input files, execute MODFLOW, and extract head and cell-by-cell flow values from MODFLOW output files. *MMProc.exe* is hardwired to only read output from a small number of MODFLOW packages. Two major limitations of *MMProc.exe* necessitated the development of a separate and much more flexible pre- and post-processor: inability to read/write data for the River Package, and implementation of groundwater flow-direction constraints. Pre- and post-processing for Optimization 2 and Optimization 3 are identical. Pre- and post-processing Optimization 1 involved less constraints associated with River Package boundary cells. Description of the pre- and post-processing steps described in the technical memo from August 14, 2014 and is repeated below for completeness.

A python script, *pyMMProc.py*, was developed to handle the capabilities of *MMProc.exe* while being more flexible and allowing use of the River Package and flow-direction constraints. A comparison of how *MMProc.exe* and *pyMMProc.py* interact with GWM-VI and MODFLOW is shown on Figure 2a and Figure 2b.

The source code for this script is provided with the project deliverables and is documented internally. A brief description of how the script works is provided below for those not familiar with the python programing language.

GWM-VI creates a file called *MMProc.in.jtf* at the start of an optimization run that acts as a template file for well pumping rates. Throughout the optimization, GWM-VI (or a runner program called *jrunner* if running in parallel mode) uses *MMProc.in.jtf* to create a file called *MMProc.in* which contains pumping rates for MODFLOW to use. Updated pumping rates are pulled from *MMProc.in* and used by *pyMMProc.py* to generate a new Well (WEL) Package and Revised Multi-Node Well (MNW2) Package files for MODFLOW. *pyMMProc.py* then executes MODFLOW.

After MODFLOW is completed, *pyMMProc.py* extracts hydraulic head and river flux data from MODFLOW output files associated with the head and river observation packages. Selected hydraulic head data are used to calculate groundwater flow-directions by solving a three-point problem. The deviation in groundwater flow direction from a provided base condition is then determined. The change in river flux from the base condition is also calculated. All hydraulic head, change in flow direction, and change in river flux are written to a file called *Simulated_Values.out* which is read directly by GWM-VI.

pyMMproc.py also checks to make sure that MODFLOW converged and that no pumping rates were reduced by the MNW2 or Upstream Weighting (UPW) Package. Convergence status and pumping rate status are written to a file called *modflow.status* which is read directly by GWM-VI.

The use of pyMMproc.py necessitates slight modifications on how GWM-VI input files are set up that may not be initially intuitive. Input files were set up to treat all constraints, including baseflow and flow-direction constraints as head constraints. All constraint types are included in the head constraints (HEDCON) input file. This was necessary due to GWM-VI only supporting the Stream Package, whereas the Metro Model 3 uses the River Package. If GWM-VI input files were set up using the stream constraints (STRMCON) input file, GWM-VI would expect to find a Steam Package, which does not exist for Metro Model 3.

2.4 Limitations of GWM-VI

During the course of this optimization several hindrances were encountered that relate to the GWM-VI software. We have notified the developers of GWM-VI about these issues; however, there is currently no timeline for fixing them. A discussion of these issues and current workarounds to each are described below.

1.) **Solving of the linear program (LP) is not optimized or parallelized**. The SLP solver used by GWM-VI has two main phases: 1) calculation of the response matrix, which requires MODFLOW to be run once for every decision variable and 2) solving the LP. Previous versions of GMW (prior to GWM-VI) were not able to run is a parallel or distributed fashion. So, calculation of the response matrix was by far the most time consuming phase of solving the optimization problem. With the introduction of parallel processing in GWM-VI, calculation of the response matrix can be completed in a fraction of the time previously required, given that enough processors are available. During this project, we used up to 75 processors for calculating the response matrix. Solving the LP is not parallelized and must be completed on a single processor. The solution time for a single LP problem is roughly proportional to the number of constraints cubed.

2.) **Pumping from multi-node wells being reduced.** Wells simulated with the MNW2 Package can have their pumping rate automatically reduced if the head in the well or surrounding aquifer drops to levels that would not be able to supply the specified pumping rate for a well. This is an unfavorable occurrence for the GWM-VI algorithms because constraints may be met only because the pumping was automatically reduced by MODFLOW. GWM-VI overcomes this issue by checking information in the *modflow.status* file written by MMproc (or pyMMproc). If any wells have their pumping reduced it is indicated in the *modflow.status* file and GWM-VI automatically reduces pumping rates for all wells based on equation 73 in Ahlfeld (2005) and attempts an additional MODFLOW simulation. This continues iteratively until all MNW2 wells pump at the specified rates. The problem with this approach is that all wells have their pumping reduced if just a single MNW2 well is causing a problem. So, if many iterations of reducing pumping from all wells are required to prevent a single MNW2 well from pumping at a rate less than specified there is very little change in the total pumping.

Overcoming this issue required stopping GWM-VI at each iteration of the SLP solver and adjusting pumping rates wells that were causing problems. Implementing this process dramatically increased progress of the optimization. The process of adjusting pumping rates was automated for Optimization 2 and Optimization 3 but still required manually stopping and restarting GWM-VI at each iteration.

3.0 Results of Optimization

3.1 Pumping Rates

Total optimized pumping from the wells included in the optimization is 374 million gallons per day (MGD). This represents a 43-percent increase in the base pumping of 261 MGD, which is the pumping from the steady-state version of the Metro Model 3 and represents average pumping from 2003 to 2011. A comparison of optimized total pumping rates for Optimizations 1, 2, and 3 is shown in Table 3.

Table 3. Comparison of results from Optimization 1, 2, and 3.

Optimization	Total optimized pumping (MGD)
1	743
2	368
3	374

Further analysis of the optimized pumping is beyond the scope of this project but it is our understanding that it will be completed by the Metropolitan Council. However, we have tried to provide the Metropolitan Council with some insight, based on what we learned during the optimization process and a cursory inspection of the results. A discussion is provided in Section 4.0 below.

3.2 Binding constraints and shadow prices

While 5,237 constraints were imposed for the optimization, only a subset actually controls the formulation of an optimal solution. These constraints are said to "bind" the solution because they prevent decision variables (well pumping) from taking values that would further improve the optimization. Each binding constraint has a "shadow price" which reflects how sensitive the optimization is to the constraint. For additional discussion of binding constraints and shadow prices the reader is referred to Ahlfeld et al. (2005) pg. 51. Binding constraints and associated shadow prices calculated by GWM-VI during the last iteration of the optimization are presented in Attachment A. A total of 184 (out of 5,237 total) constraints were found to be binding. Overall, baseflow constraints (trout and other streams) were the most sensitive, constituting 12 of the top 30 constraints with the largest shadow price. Change in flux on the township and range scale constituted 9 of the top 30 constraints with the largest shadow price. Table A2 summarizes binding constraints by constraint type. Figure 3 shows the spatial distribution of binding constraints.

4.0 Discussion

Analysis of the optimization results are not part of the scope of this project and it is our understanding that such analysis is planned to be completed by Metropolitan Council staff. However, the following observations were noted during this project and may warrant further review, discussion, or follow-up optimization.

1.) Optimization 1 showed large increases in pumping sustained by induced leakage from River Package boundary cells. Significantly increasing the constraints imposed on River Boundary cells for Optimization 2 greatly reduced these issues, and hence reduced the total optimized pumping volumes. Optimization 3 imposed strictor constraints regarding safe yield (50% available head vs.

75% available head) and less restrictive constraints on baseflow to the Mississippi River. Overall Optimization 3 resulted in slightly more pumping than Optimization 2, primarly because the optimization is very sensitive to constraints imposed on baseflow of the Mississippi River. There may still be areas where induced leakage may be occurring beyond sustainable levels but are highly local and smaller than the scale to which we can impose constraints.

2.) Many of the constraints with the largest shadow price (see Section 3.2) are reaches of the Mississippi River. A constraint imposing no more than a 25 percent reduction in baseflow from baseline conditions was used for these reaches. Because these reaches are major groundwater discharge zones for the region, many wells, particularly in the deeper aquifers, affect baseflow to these reaches by capturing flow that would go to the river under lower pumping conditions. It should be noted that the constraint imposed does not represent a 25 percent reduction in total flow; the vast majority of flow comes from upstream. Allowing for a greater reduction in baseflow to these reaches would result in a higher optimized pumping volume, potentially significantly higher given the magnitude of the shadow price for these constraints.

3.) For some communities, the optimized pumping scheme results in municipal pumping being reduced to nearly zero. The reality and feasibility of such a scenario is uncertain.

4.) This type of optimization is very non-linear and typically non-unique. It is very likely that different distributions may result in nearly identical total pumping. We believe the addition of more constraints for Optimizations 2 and 3 has helped move toward the more unique solution. However, the level of uniqueness has not been quantified.

Limitations of the model, optimization, and choice of wells and constraints should be carefully considered when using these results for long-term planning. The optimization was limited to only existing wells and assumes that conditions have reached steady-state. New wells, added in undeveloped areas or aquifers, would certainly increase the total pumping of the region while still meeting imposed constraints. Also, in certain areas local concerns such as well interference or impacts to surface waters not accurately simulated at the scale of the Metro Model 3 may be deemed unacceptable even though all constraints imposed were met.

5.0 References

Ahlfeld, D.P., Barlow, P.M. and Mulligan, A.E., 2005. GWM—A ground-water management process for the U.S. Geological Survey modular ground-water model (MODFLOW-2000): U.S. Geological Survey Open-File Report 2005-1072, 124p.

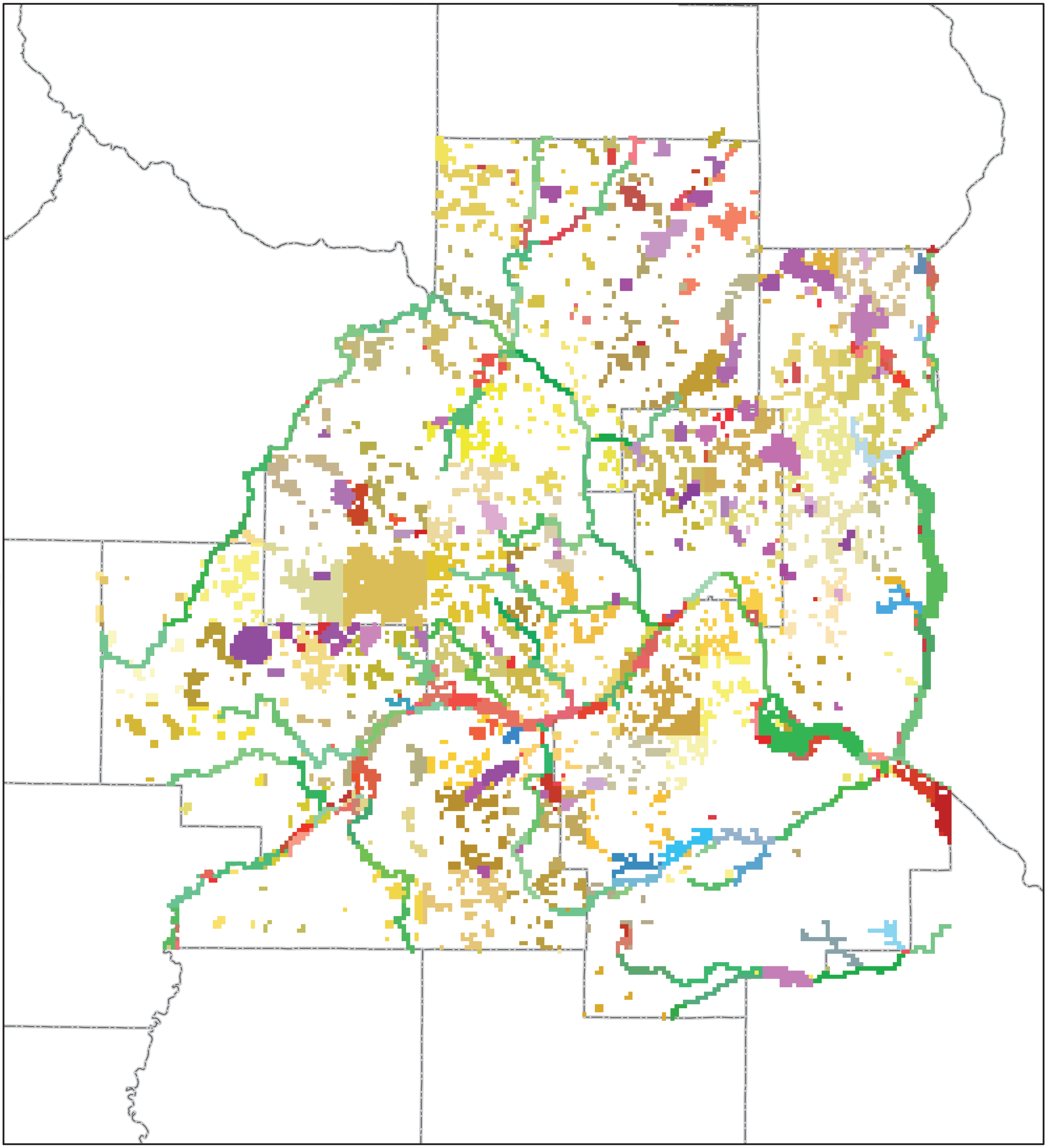
Banta, E.R. and Ahlfeld, D.P., 2013. GWM-VI—Groundwater Management with parallel processing for multiple MODFLOW versions: U.S. Geological Survey Techniques and Methods, book 6, chap. A48, 33p.

Barr Engineering. 2014a. Metro Pumping Optimization, Technical Memorandum from Evan Christianson and Ray Wuolo to Lanya Ross, Anneka LaBelle, and Ali Elhassan, August 15, 2014.

Barr Engineering. 2014b. Metro Pumping Optimization 2, Technical Memorandum from Evan Christianson and Ray Wuolo to Lanya Ross, Anneka LaBelle, and Eli Elhassan, October 13, 2014.

Metropolitan Council, 2014. Twin Cities Metropolitan Area Regional Groundwater Flow Model, Version 3.0. Prepared by Barr Engineering. Metropolitan Council: Saint Paul, MN.

Minnesota County Biological Survey. 2013. MBS Sites of Biodiversity Significance, Minnesota Department of Natural Resources, Division of Ecological Resources, shapefile geospatial data.



River Packge Boundary Cell Constraints

- Biodiversity Area
- Stream/River
- Trout Stream
- Township Range Group
- Vulnerable Basin

N

Miles

10 0

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Figure 1

RIVER PACKAGE BOUNDRY
CELL CONSTRAINTS
Pumping Optimization 3
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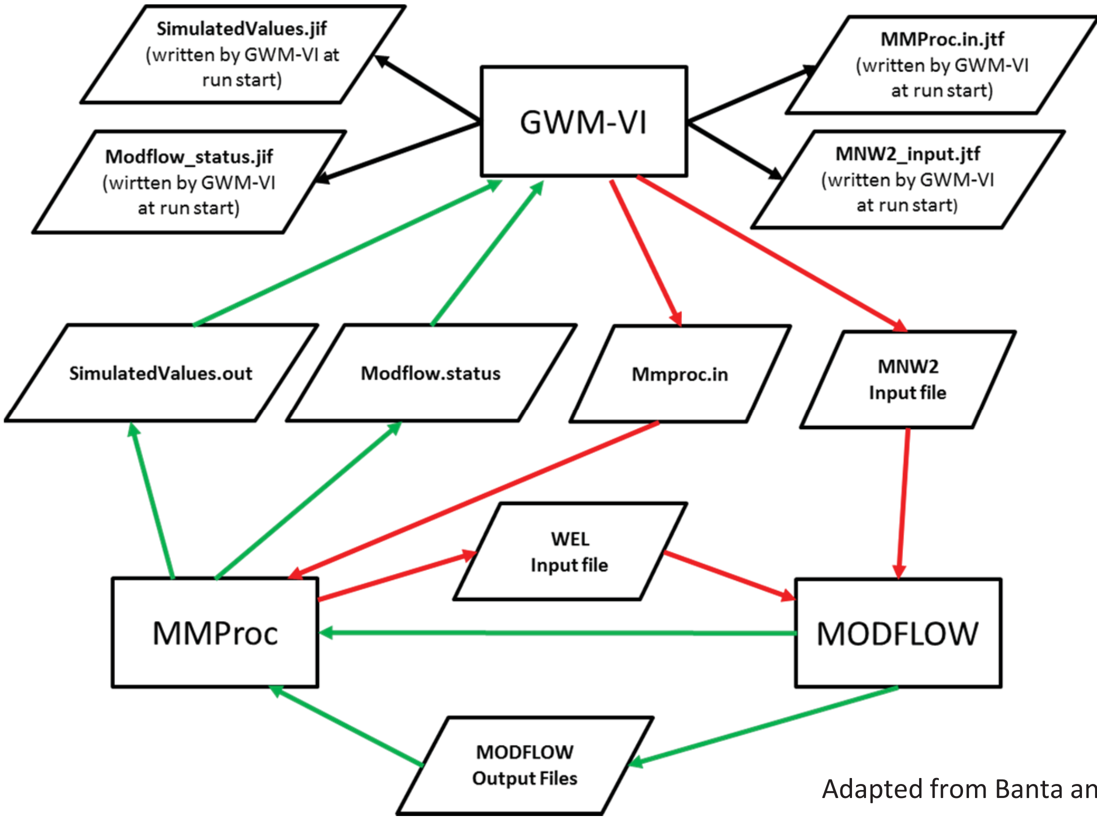
1a. Interaction of MMProc with GWM-VI and MODFLOW



Adapted from Banta and Ahlfeld, 2013

1b. Interaction of pyMMProc with GWM-VI and MODFLOW

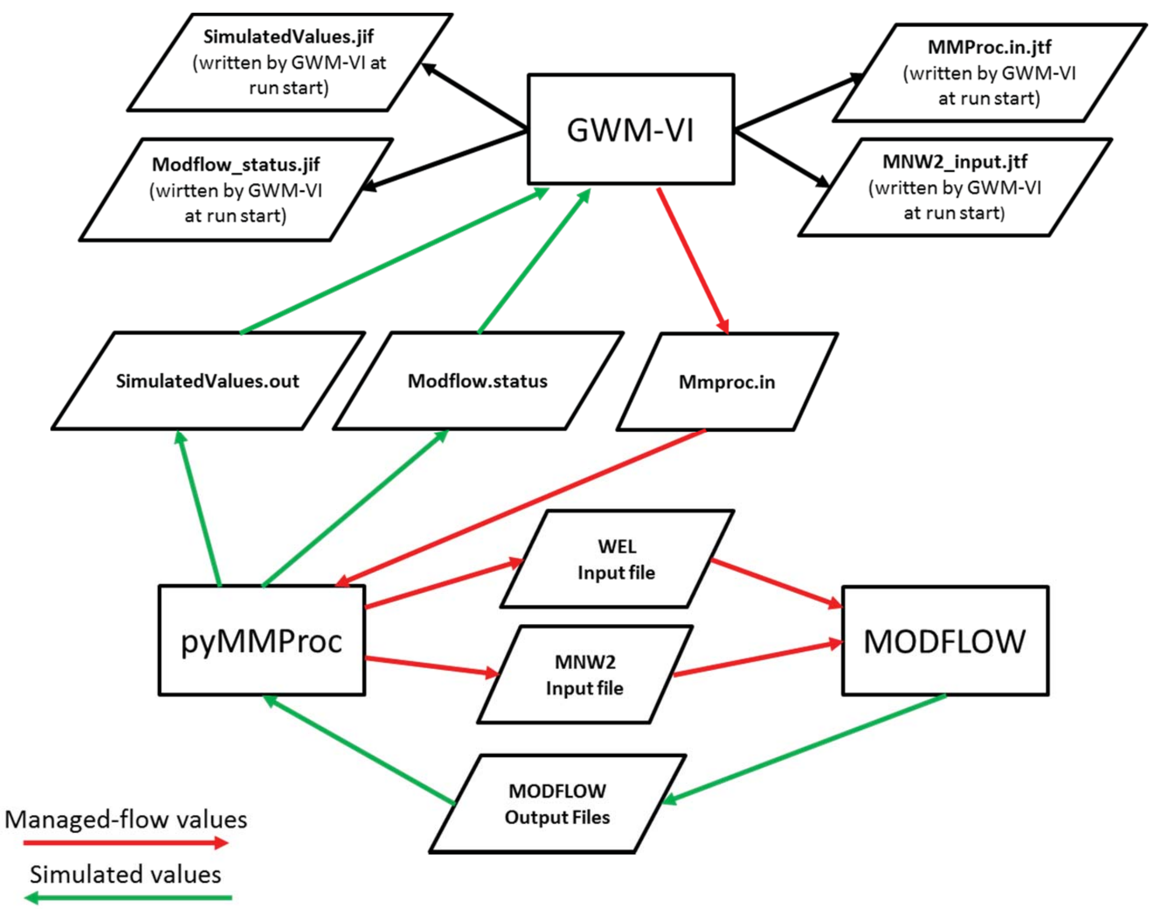


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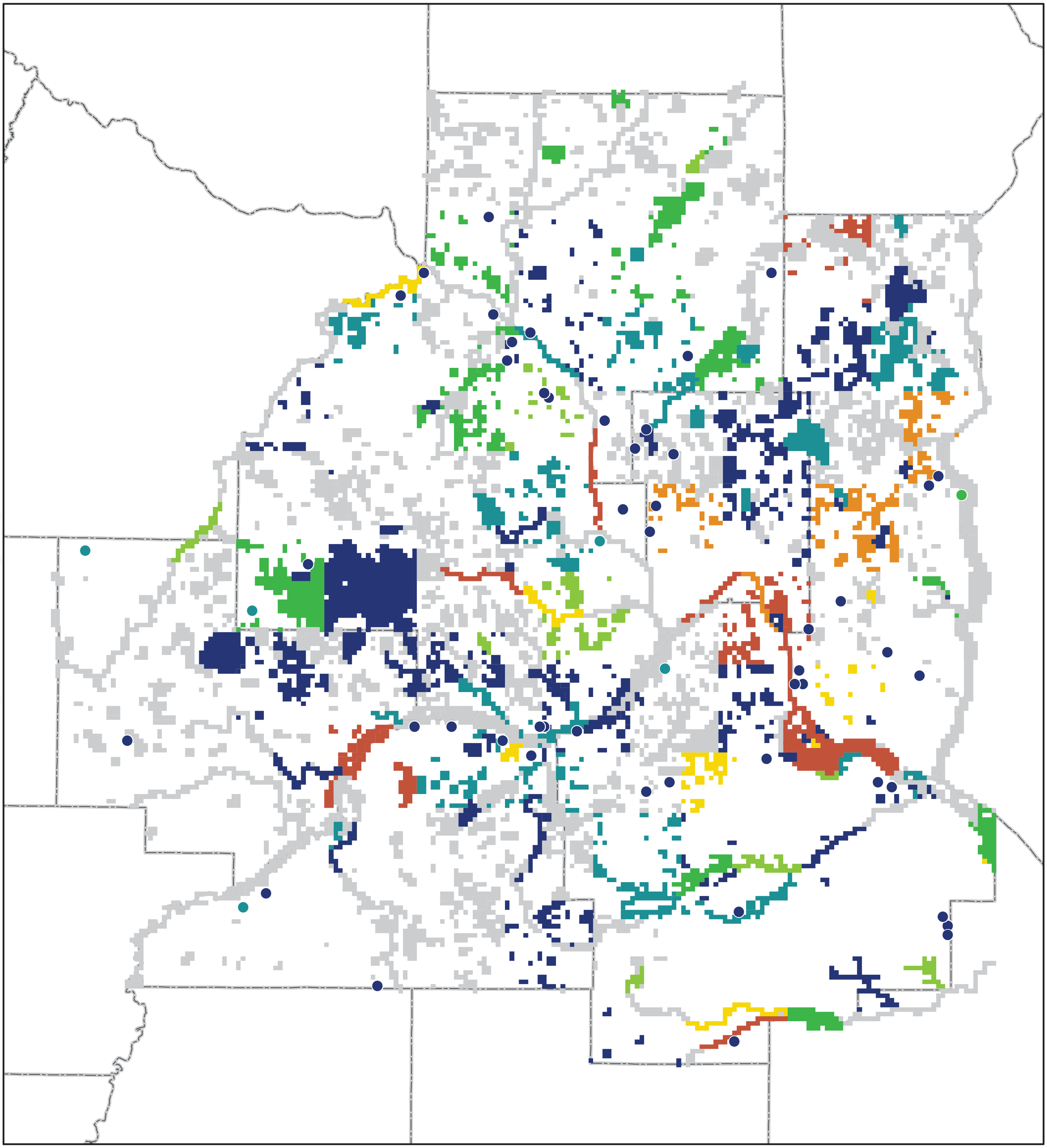
Figure 2

Comparison of MMProc and pyMMProc interaction with GWM-VI and MODFLOW
Pumping Optimization 3
Metropolitan Council



Binding Hydraulic Head and Safe Yield Constraints

Shadow Price

- > 1.50e+008
- 1.26e+008 - 1.50e+008
- 1.01e+008 - 1.25e+008
- 7.51e+007 - 1.00e+008
- 5.01e+007 - 7.50e+007
- 2.51e+007 - 5.00e+007
- < 2.50e+007

Binding River Boundary Constraints

Shadow Price

- > 1.50e+008
- 1.26e+008 - 1.50e+008
- 1.01e+008 - 1.25e+008
- 7.51e+007 - 1.00e+008
- 5.01e+007 - 7.50e+007
- 2.51e+007 - 5.00e+007
- < 2.50e+007
- Non-Binding River Cells

N

Miles
0 2.5 5

Figure 3

BINDING CONSTRAINTS
Pumping Optimization 3
Metropolitan Council

Attachment A

Binding Constraints and Shadow Prices

Table A-1

Binding Constraints and Shadow Price

Constraint Name	Description	Row	Col	Absolute Shadow Price
Riv_016	Mississippi River (Downtown St. Paul)	--	--	3.14E+08
Riv_013	Mississippi River (N. Minneapolis, Fridley, Brooklyn Center)	--	--	2.96E+08
T28_R22	Township 28, Range 22	--	--	2.56E+08
T32_R21	Township 32 Range 21	--	--	2.04E+08
Riv_165	Mississippi River / Sping Lake	--	--	2.00E+08
T115_R23	Township 115, Range 23	--	--	1.84E+08
Riv_018	Mississippi River (S. St. Paul, Invergrove Heights, Newport, St. Paul Park)	--	--	1.81E+08
Riv_136	Cannon River (Northfield, Randolph)	--	--	1.73E+08
Vul_083	Crosby Lake	--	--	1.62E+08
Riv_120	Minnehaha Creek (Minnetonka, Hopkins, St. Louis Park)	--	--	1.57E+08
Riv_055	Minnesota River (Chaska, Carver)	--	--	1.54E+08
T29_R21	Township 29 Range 21	--	--	1.50E+08
Riv_017	Mississippi River (St. Paul)	--	--	1.48E+08
T30_R20	Township 30 Range 20	--	--	1.33E+08
T29_R23	Township 29 Range 23	--	--	1.32E+08
Riv_135	Chub Creek	--	--	1.20E+08
Vul_023	Powers Lake	--	--	1.14E+08
Trout_03	Eagle Creek	--	--	1.13E+08
T27_R21	Township 27 Range 21	--	--	1.12E+08
T115_R19	Township 115 Range 19	--	--	1.12E+08
Bio_083	Ravenna 17	--	--	1.11E+08
Riv_121	Minnehaha Creek (St. Louis Park, Edina)	--	--	1.05E+08
Riv_033	Crow River (Rogers, St. Michael)	--	--	1.04E+08
Trout_07	Trout Brook	--	--	9.39E+07
Trout_12	Vermillion River (Empire)	--	--	9.00E+07
Riv_041	Crow River (Watertown, Delano)	--	--	8.60E+07
Bio_026	Rice Lake Natural Area	--	--	8.50E+07
T119_R21	Township 119 Range 21	--	--	8.19E+07
Bio_038	Chub Lake South	--	--	8.06E+07
Vul_066	Bryant Lake	--	--	7.91E+07
T28_R24	Township 28 Range 24	--	--	7.70E+07
Bio_031	Sedil East	--	--	7.61E+07
Bio_009	Mud Hen Lake Area	--	--	7.44E+07
Riv_113	Elm Creek (Maple Grove, Champlin, Dayton)	--	--	7.42E+07
T119_R22	Township 119 Range 22	--	--	7.40E+07
T32_R23	Township 32 Range 23	--	--	7.29E+07
T114_R16	Township 114 Range 16	--	--	6.85E+07
T31_R22	Township 31 Range 22	--	--	6.78E+07
Trout_11	Vermillion River (Farmington, Empire Twp)	--	--	6.76E+07
T32_R25	Township 32 Range 25	--	--	6.69E+07
Vul_005	Coon Lake	--	--	6.65E+07
T117_R24	Township 117 Range 24	--	--	6.53E+07
Bio_068	Linwood 5 Natural Area	--	--	5.99E+07
Vul_004	Byllesby Lake	--	--	5.63E+07
T28_R20	Township 28 Range 20	--	--	5.57E+07
Vul_016	George Lake	--	--	5.33E+07
T34_R23	Township 34 Range 23	--	--	5.29E+07
CM207_296	Mt. Simon Hinckley	207	296	5.07E+07
T29_R24	Township 29 Range 24	--	--	4.71E+07
Vul_064	Centerville Lake	--	--	4.62E+07
Vul_035	Medicine Lake	--	--	4.48E+07
Bio_002	Ninninger West	--	--	4.35E+07
Vul_065	Ham Lake	--	--	4.31E+07
Riv_011	Mississippi River (Champlin, Coon Rapids, Brooklyn Park)	--	--	4.22E+07
T115_R21	Township 115 Range 21	--	--	4.11E+07
Riv_148	S. Branch Vermillion River (Castle Rock Twp.)	--	--	4.10E+07
T113_R19	Township 113 Range 19	--	--	3.88E+07
Trout_13	S. Branch Vermillion R. (Castle Rock Twp, Empire Twp., Vermillion Twp.)	--	--	3.88E+07
T120_R23	Township 120 Range 23	--	--	3.82E+07
T31_R20	Township 31 Range 20	--	--	3.74E+07
CM296_141	Mt. Simon Hinckley	296	141	3.48E+07
Vul_058	Gervais Lake	--	--	3.42E+07
Bio_007	St. Lawrence 13	--	--	3.32E+07
Trout_09	Vermillion River (Eureka Twp.)	--	--	3.29E+07
Riv_115	Rice Creek (Mounds View, Arden Hills, Shoreview)	--	--	3.26E+07
CM219_107	Mt. Simon Hinckley	219	107	3.19E+07
Bio_074	Conley Lake Backwaters	--	--	3.17E+07
Vul_003	Turtle Lake	--	--	3.13E+07
Bio_078	North Ninninger 34	--	--	3.12E+07
Trout_10	Vermillion River (Lakeville, Farmington)	--	--	3.07E+07

Table A-1
Binding Constraints and Shadow Price

Constraint Name	Description	Row	Col	Absolute Shadow Price
Vul_089	Bone Lake	--	--	3.06E+07
T31_R23	Township 31 Range 23	--	--	3.02E+07
Vul_047	White Bear Lake	--	--	2.94E+07
Vul_001	DeMontreville Lake	--	--	2.92E+07
Bio_015	Nine Mile Creek	--	--	2.85E+07
T114_R20	Township 114 Range 20	--	--	2.83E+07
CM232_143	Mt. Simon Hinckley	232	143	2.73E+07
T115_R22	Township 115 Range 22	--	--	2.72E+07
GWSW1	Gun Club Lake South	--	--	2.67E+07
Riv_126	Purgatory Creek	--	--	2.62E+07
Trout_01	Assumption Creek	--	--	2.60E+07
CM217_218	Mt. Simon Hinckley	127	218	2.60E+07
T118_R21	Township 118 Range 21	--	--	2.56E+07
Riv_132	Unnamed (Burnsville)	--	--	2.48E+07
T117_R23	Township 117 Range 23	--	--	2.40E+07
Riv_097	Carver Creek	--	--	2.30E+07
Bio_099	Empire 15	--	--	2.25E+07
Riv_150	Vermillion River (Vermillion)	--	--	2.23E+07
Vul_062	Hannan Lake	--	--	2.12E+07
T29_R22	Township 9 Range 22	--	--	2.12E+07
Bio_066	East Rosemount 18	--	--	2.11E+07
Trout_06	Pine Creek	--	--	2.03E+07
T27_R22	Township 27 Range 22	--	--	1.88E+07
Riv_118	Basset Creek (Plymouth, Golden Valley)	--	--	1.85E+07
CM260_116	Mt. Simon Hinckley	260	116	1.80E+07
T119_R24	Township 119 Range 24	--	--	1.77E+07
Vul_050	Upper Prior Lake	--	--	1.72E+07
Vul_049	Unnamed (Cottage Grove)	--	--	1.69E+07
Vul_009	Long Lake	--	--	1.68E+07
Bio_019	Dean's Lake	--	--	1.64E+07
T32_R24	Township 32 Range 24	--	--	1.61E+07
Vul_021	Big Marine Lake	--	--	1.57E+07
T114_R18	Township 114 Range 18	--	--	1.53E+07
T115_R17	Township 115 Range 17	--	--	1.51E+07
CM264_254	Mt. Simon Hinckley	264	254	1.34E+07
T116_R22	Township 116 Range 22	--	--	1.19E+07
Riv_124	Nine Mile Creek	--	--	1.19E+07
Riv_100	Sand Creek (Jordan)	--	--	1.09E+07
T114_R19	Township 114 Range 19	--	--	1.09E+07
CM159_255	Mt. Simon Hinckley	159	255	1.07E+07
Bio_097	Camp Hduhapi	--	--	1.05E+07
Riv_146	Unnamed (Empire Twp.)	--	--	9.37E+06
CM257_178	Mt. Simon Hinckley	257	178	8.48E+06
Bio_060	Pigs Eye SNA	--	--	8.25E+06
GWSW4	Savage Fen	--	--	7.92E+06
T120_R21	Township 120 Range 21	--	--	7.80E+06
T112_R17	Township 112 Range 17	--	--	7.23E+06
Bio_091	Belwin Gravel Pit	--	--	6.81E+06
Riv_102	Credit River (Credit River Twp, Savage)	--	--	6.14E+06
Vul_039	Minnewashta Lake	--	--	6.03E+06
T30_R22	Township 30 Range 22	--	--	5.85E+06
T31_R21	Township 31 Range 21	--	--	5.53E+06
Vul_014	Lake Waconia	--	--	5.33E+06
T113_R21	Township 113 Range 21	--	--	5.08E+06
OP325_247	Praire du Chein Group	--	--	4.82E+06
CM177_237	Mt. Simon Hinckley	177	237	4.59E+06
CM168_195	Mt. Simon Hinckley	168	195	4.55E+06
T112_R20	Township 112 Range 20	--	--	4.42E+06
OP257_186	Praire du Chein Group	--	--	4.21E+06
Bio_058	Black Dog Lake area	--	--	4.16E+06
CM313_170	Mt. Simon Hinckley	313	170	4.05E+06
Vul_029	Olsen Lake	--	--	3.92E+06
T27_R24	Township 27 Range 24	--	--	2.98E+06
CM222_155	Mt. Simon Hinckley	222	155	2.96E+06
Bio_107	Grey Cloud Dunes East	--	--	2.78E+06
T31_R24	Township 31 Range 24	--	--	2.78E+06
Riv_127	Riley Creek (Chanhassen, Eden Prairie)	--	--	2.60E+06
Vul_025	Lotus Lake	--	--	2.56E+06
Bio_087	Wilder Forest	--	--	2.46E+06
CM178_198	Mt. Simon Hinckley	178	198	2.35E+06

Table A-1
Binding Constraints and Shadow Price

Constraint Name	Description	Row	Col	Absolute Shadow Price
Riv_131	Unnamed (Eagan)	--	--	2.23E+06
Vul_028	Dutch Lake	--	--	1.92E+06
Vul_008	Lake Elmo	--	--	1.81E+06
Bio_076	Savage Fen, Credit River	--	--	1.75E+06
CM191_219	Mt. Simon Hinckley	191	219	1.44E+06
CJ269_278	Jordan Sandstone	269	278	1.16E+06
Vul_088	Weaver Lake	--	--	8.04E+05
CJ203_291	Jordan Sandstone	203	291	7.44E+05
Vul_011	Smetana Lake	--	--	7.12E+05
Vul_078	Pleasant Lake	--	--	6.14E+05
Vul_027	Murphy Lake	--	--	5.92E+05
CT293_146	Tunnel City	293	146	4.41E+05
Bio_072	Grey Cloud Dunes West	--	--	4.35E+05
CT159_180	Tunnel City	159	180	3.57E+05
OP236_263	Praire du Chein Group	236	263	2.94E+05
CJ205_289	Jordan Sandstone	205	289	2.87E+05
CJ246_287	Jordan Sandstone	246	287	2.82E+05
CT147_194	Tunnel City	147	194	2.74E+05
CJ270_281	Jordan Sandstone	270	281	2.70E+05
T116_R24	Township 116 Range 24	--	--	2.52E+05
CT164_175	Tunnel City	164	175	2.05E+05
FlowDir3	TCAAP Plume (St Anthony, Minneapolis)	--	--	165000.00
FlowDir2	TCAAP Plume (New Brighton)	--	--	145000.00
CJ300_293	Jordan Sandstone	300	293	1.26E+05
CJ302_293	Jordan Sandstone	302	293	9.49E+04
OP258_213	Praire du Chein Group	258	213	9.02E+04
CJ264_254	Jordan Sandstone	264	254	7.80E+04
CT172_203	Tunnel City	172	203	7.27E+04
OP257_205	Praire du Chein Group	257	205	6.08E+04
OP241_280	Praire du Chein Group	241	280	6.04E+04
OP257_206	Praire du Chein Group	257	206	5.96E+04
OP297_248	Praire du Chein Group	297	245	4.33E+04
OP269_233	Praire du Chein Group	269	233	3.57E+04
CT185_206	Tunnel City	185	206	3.13E+04
CJ298_292	Jordan Sandstone	298	292	2.09E+04
CT186_207	Tunnel City	186	207	1.88E+04
Riv_114	Rice Creek (Fridley)	--	--	1.41E+04
CJ230_270	Jordan Sandstone	230	270	1.20E+04
CT260_197	Tunnel City	260	197	9.75E+03
CT174_199	Tunnel City	174	199	7.56E+03
OP271_228	Praire du Chein Group	271	228	6.83E+03
FlowDir7	St. Paul Park Refinery	--	--	6450.00
CT279_287	Tunnel City	279	287	3.31E+03
CT186_206	Tunnel City	186	206	2.53E+03

Color Key

- Trout streams baseflow constraint
- Non-trout streams baselfow constraint
- Groundwater dependent features hydraulic head constraint (calcerous fens)
- Flow direction constraint
- Mt. Simon-Hinckley aquifer change in hydraulic head constraint
- Safe yield for confined bedrock aquifers constraint
- Surface water flux constraint (Township and Range groups)
- Vulnerable surface water features with wide litoral zone constraint
- Sites of high biodiversity constraint

Table A-2

Summary of Binding Constraints by Constraint Type

Group	Sum Total Shadow Price	Percent Total Shadow Price	Number of Constraints with Shadow Price	Average Shadow Price	Rank of Average Shadow Price
Township Range	2.47E+09	33.66%	45	5.49E+07	3
Stream/River	2.39E+09	32.48%	28	8.52E+07	1
Vulnerable Surface Water Basin	9.32E+08	12.69%	29	3.21E+07	5
Biodiversity Area	7.52E+08	10.24%	22	3.42E+07	4
Trout Stream	5.13E+08	6.99%	9	5.70E+07	2
Mt. Simon Hinckley Hydraulic Head	2.41E+08	3.28%	15	1.61E+07	7
Groundwater Dependent Feature (Fen)	3.46E+07	0.47%	2	1.73E+07	6
Safe Yield for Confined Bedrock Aquifer	1.42E+07	0.19%	31	4.57E+05	8
Flow Direction	3.16E+05	0.00%	3	1.05E+05	9