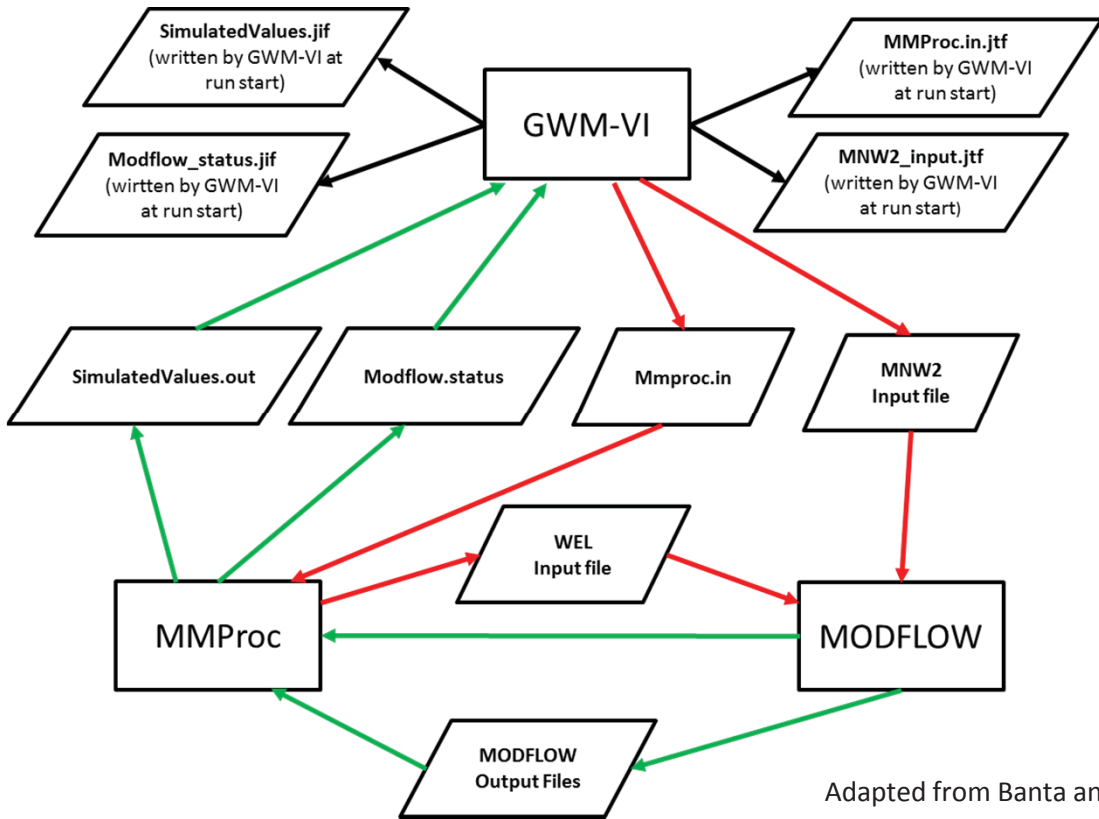


1a. Interaction of MMProc with GWM-VI and MODFLOW



Adapted from Banta and Ahlfeld, 2013

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

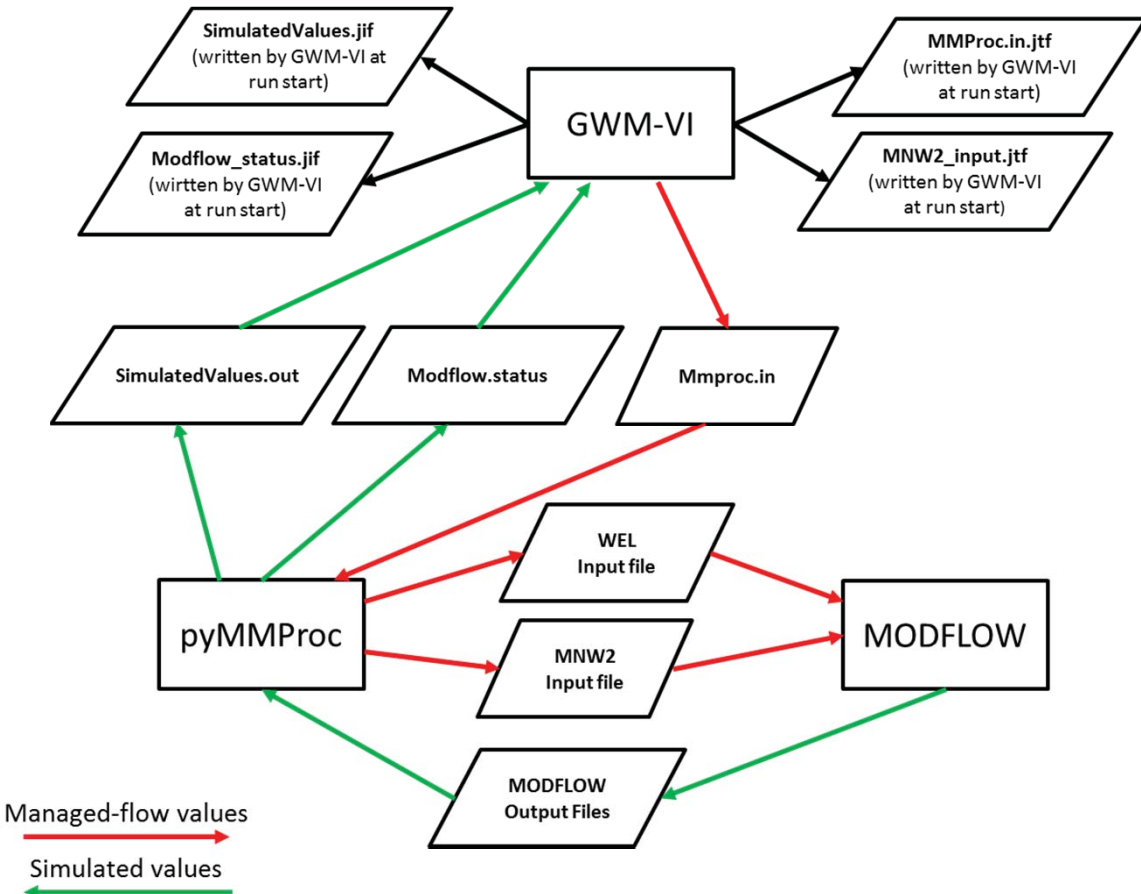
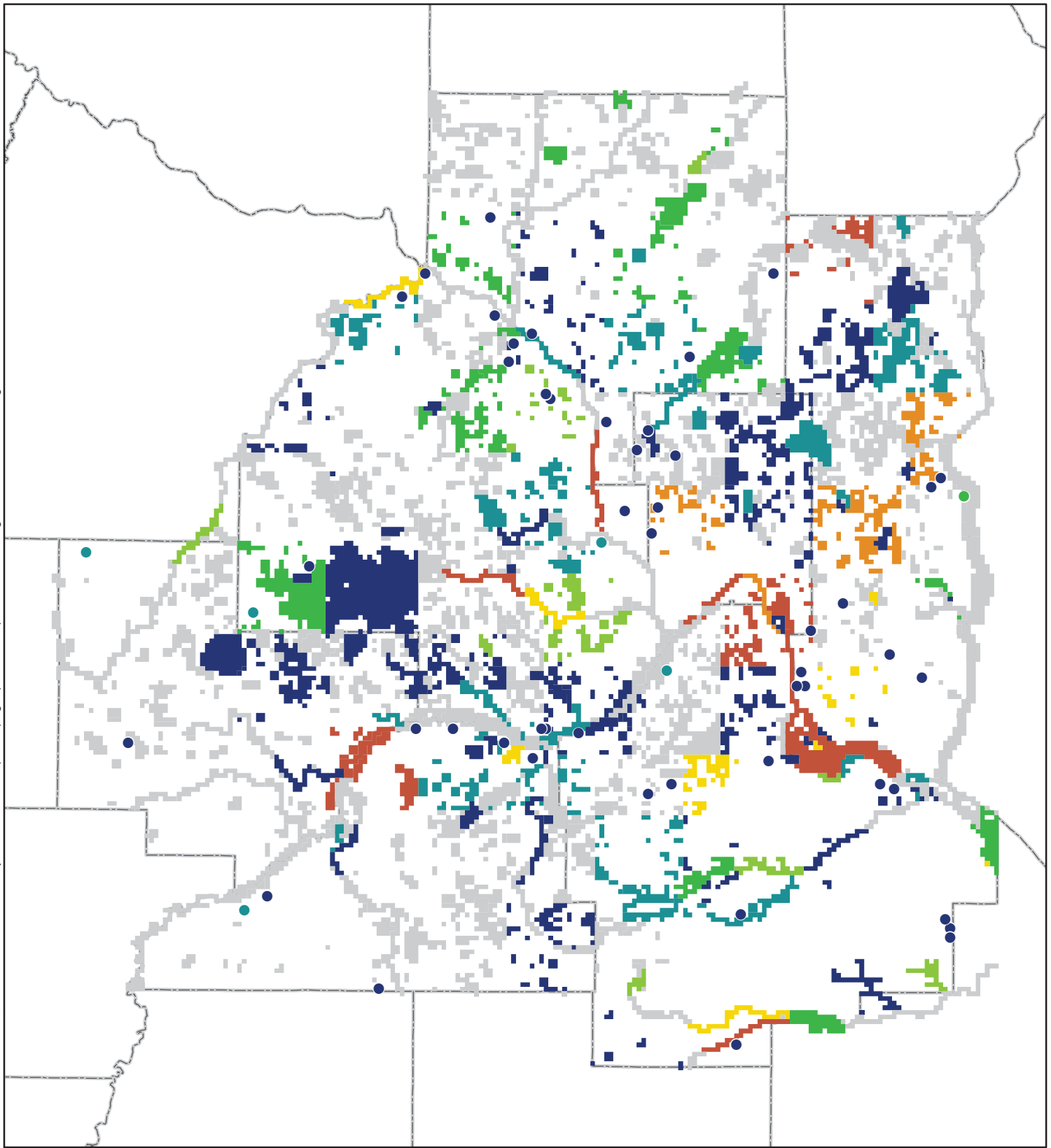


Figure 2

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



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 baseflow 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 littoral 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