Ravine Lake Water Quality Modeling and Management Report

Final Report **June 21, 2013**

Houston Engineering Inc.

South Washington Watershed District

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Acronyms and Abbreviations List

Chl-*a*	Chlorophyll-*a*
CAMP	Citizen-Assisted Lake Monitoring Program
DO	Dissolved Oxygen
HEC-RAS	Hydrologic Engineering Center River Analysis System
HEI	Houston Engineering, Inc.
LA	Load Allocation
MnDNR	Minnesota Department of Natural Resources
MOS	Margin of Safety
MPCA	Minnesota Pollution Control Agency
MR	Minnesota Rules
MSP	Minneapolis-St. Paul Airport
NCHF	North Central Hardwood Forest
OHWL	Ordinary High Water Level
P8	Predicting Polluting Particle Passage thru Pits, Puddles, & Ponds
SD	Secchi Depth
SWMM	Storm Water Management Model
SWWD	South Washington Watershed District
TMDL	Total Maximum Daily Load
TP	Total Phosphorus
TSI	Trophic State Index
WCBP	Western Corn Belt Plains
WMP	Watershed Management Plan
WLA	Wasteload Allocation

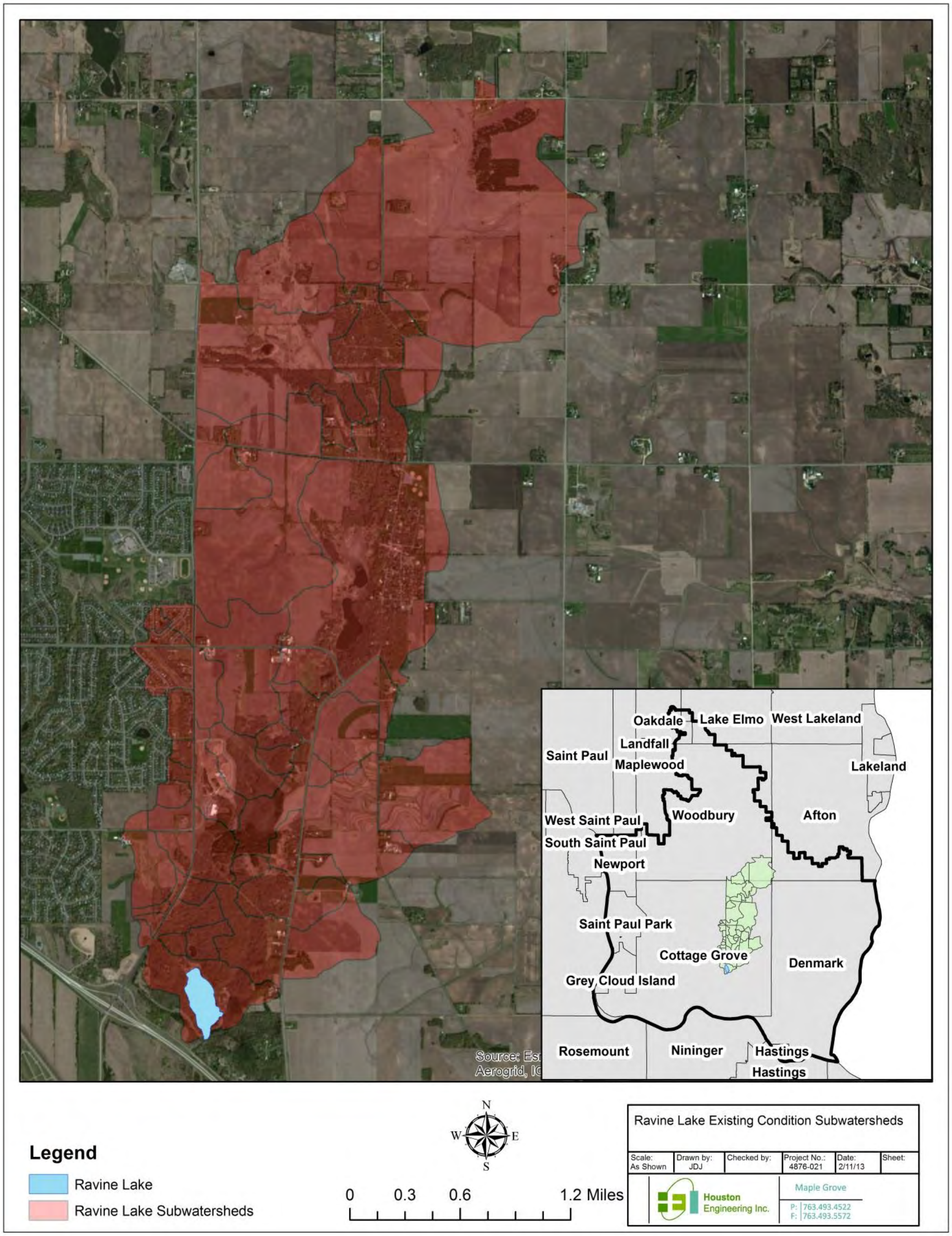
1.0 INTRODUCTION

Ravine Lake is located within southern Washington County in the Minneapolis-St. Paul metropolitan area of eastern Minnesota (see **Figure 1**). The lake is managed, locally, by the South Washington Watershed District (SWWD). In 2006, Ravine Lake was placed on the Minnesota Pollution Control Agency's (MPCA) List of Impaired Waters (i.e., 303(d) list) for nutrient eutrophication/biological indicators. Ravine Lake is currently listed in Category 5 with no Total Maximum Daily Load (TMDL) plan having been approved. In an effort to develop a management plan for Ravine Lake that encompasses both current conditions and anticipated future development, the SWWD requested the assistance of Houston Engineering, Inc. (HEI) to evaluate existing data and develop a series of models to describe the stresses imposed upon Ravine Lake. By determining the current, future, and maximum allowable total phosphorus loads to Ravine Lake, options for load reduction management are assessed. The overall analyses are necessary to establish the load capacity to Ravine Lake and allocate nonpoint source subwatershed loads, thereby establishing a basis to manage the lake and its watershed.

This report presents an assessment of the water quality for Ravine Lake, including the estimated water budget and total phosphorus mass balance for nine years of monitoring data, 2002-2010. A watershed loading and in-lake eutrophication response model were created for the summer growing season (June 1 through September 30) using monitoring data for model calibration and validation. Once the model was calibrated and validated, a long-term precipitation record was used within the watershed model to simulate 50-years of runoff volume and load. The watershed runoff and load, along with other external sources, were then used as input to the receiving water model to develop the phosphorus loading capacity for Ravine Lake. Multiple model runs for various load reduction scenarios were completed to guide future management strategies to achieve both the State numeric water quality standard and the SWWD's water quality goal for total phosphorus concentrations in Ravine Lake.

As a second step, the in-lake eutrophication response model was coupled with inputs from a long-term watershed loading model simulating a proposed future development scenario. This analysis allowed for the comparison of lake response under the two scenarios (i.e., existing and future conditions) and also provided a basis for discussing implementation strategies for reducing lake impacts during future development.

Figure 1. Ravine Lake watershed location and existing subwatersheds



2.0 LAKE INFORMATION

2.1 Lake Description

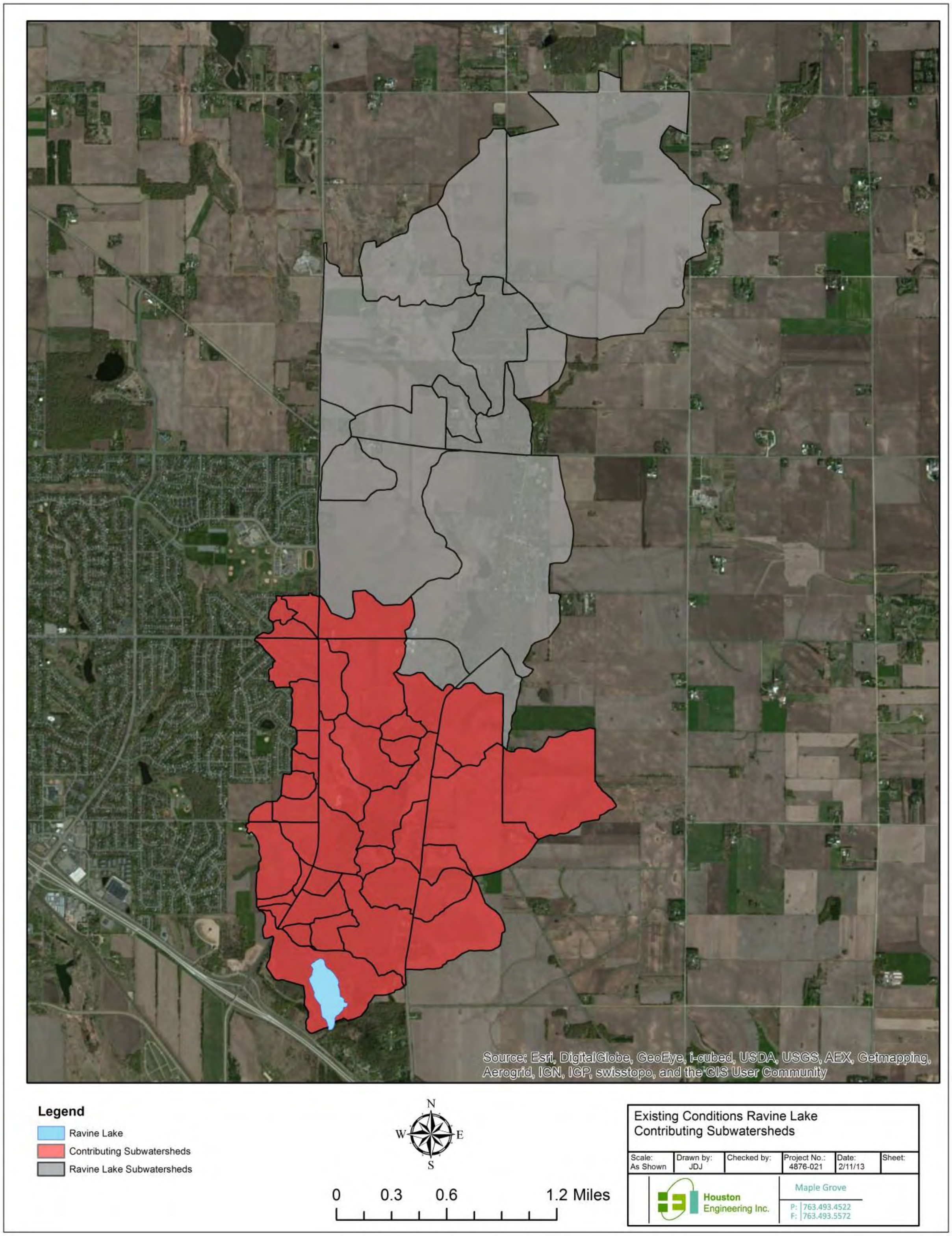
Ravine Lake is a 26.4-acre lake located within the City of Cottage Grove within Cottage Grove Regional Park. It has a maximum depth of 16 feet. Ravine Lake's watershed includes upland and ravine areas and ultimately drains (through Ravine Lake) to the Mississippi River. The watershed is approximately 4,336 acres; however, the Existing Conditions Stormwater Management Model (SWMM) (HDR, 2012a) of the watershed indicates hydraulic breakpoints exist and that only about 1,704 acres of the watershed currently contribute surface water flow and pollutant loading to Ravine Lake (**Figure 2**) under a 100-year event. The 50-years of simulation performed in the Ravine Lake watershed loading model, created for this project (see report in **Appendix A**), confirms this contributing area. The contributing subwatersheds consist primarily of developed urban area to the west, wooded ravine in the central portion, and farmland to the east. Public access to Ravine Lake is possible by means of Cottage Grove Ravine Regional Park. The lake is used for wildlife viewing, fishing, and aesthetics. Non-motorized boating is allowed on the lake.

Ravine Lake is identified by the Minnesota Department of Natural Resources (MnDNR) as Public Water No. 82-0087-00 (water quality data for the lake is improperly stored and reported under ID # 82-0086-00). Water levels within the lake have been controlled by various engineered (outlet) structures during this study period. The water levels on Ravine Lake are currently controlled by a 24-inch culvert on the southern end of the lake, installed in July of 2011. The culvert has upstream and downstream invert elevations of 768.50 and 768.00 (NAVD 1929), respectively. Prior to July 2011, the Ravine Lake outlet was controlled by an 18-inch culvert. The Ordinary High Water Level (OHWL) for Ravine Lake has been set by the MnDNR at an elevation of 770.7 feet (NAVD 1929). The lake shows a general increase in water level beginning in 2007 followed by a general decrease beginning in 2011. A memo by Howard R. Green Company (HR Green) indicates that the culvert discharging from Ravine Lake was found to be crushed in July of 2009 and not conveying flow (HR Green, 2010). Discussions with Washington County confirmed that the culvert has experienced various degrees of blockage since as early as 1990 and that the water level rise beginning in 2007 is likely due to nearly complete blockage of the culvert at that time (Polehna, 2013). This condition caused occasional flooding issues along the roadway over the culvert. Washington County staff also confirmed that the channel downstream of Ravine Lake has been maintained by clearing, grubbing, and excavation of sedimentation throughout the study period. The new 24-inch culvert was installed by Washington County in July of 2011 (SWWD, 2013). Based on this information, HEI has made the following assumptions regarding outflow from Ravine Lake:

- From 2002-2007, 50% of the flow area was obstructed in the culvert;
- From 2008-2010, 75% of the flow area was obstructed in the culvert; and
- Data from 2011 (new 24-inch culvert) was not used in this analysis.

Water quality samples have been collected, by the Washington Conservation District as part of the Metropolitan Council's Citizen-Assisted Lake Monitoring Program (CAMP), in Ravine Lake from 1998-2012. According to modeling completed in this study, Ravine Lake has an average hydraulic residence time of approximately 8 months.

Figure 2. Ravine Lake Existing Conditions contributing subwatersheds



2.2 Classification

According to the SWWD Watershed Management Plan (WMP), Ravine Lake is managed (by the SWWD) as a Class B water (SWWD, 2007). Class B waters generally demonstrate a reasonable chance of attaining the in-lake phosphorus goal established by the SWWD and of meeting the designated uses. Class B lakes are defined as generally exhibiting long-term phosphorus concentrations between 60 and 100 parts per billion (ppb) for the summer growing season. The natural lake ecosystem of Class B lakes may be considered as moderately disturbed. Lakes classified as Class B are those that may support some fishery, but are also well suited for supporting wildlife, aesthetic enjoyment, and boating or other special purposes (SWWD, 2007).

The MPCA classifies Ravine Lake as a Class 2B water. Minnesota Rules (MR) 7050.0222 state that Class 2B surface waters shall be such as to permit the propagation and maintenance of a healthy community of cool or warm water sport or commercial fish and associated aquatic life, and their habitats. These waters shall be suitable for aquatic recreation of all kinds, including bathing, for which the waters may be usable. This class of surface water is not protected as a source of drinking water.

With a maximum depth of 16 feet and more than 80% of the lake shallow enough to support emergent and submerged rooted aquatic plants (i.e., littoral), Ravine Lake is considered a shallow lake. The contributing watershed for the lake is located entirely in the Western Corn Belt Plains (WCBP) ecoregion; however, given the lake's proximity to the North Central Hardwood Forest (NCHF) ecoregion and the primary characteristics of its watershed, the MPCA has decided that NCHF water quality standards will apply. As such, applicable state Class 2B conventional water quality standards for shallow lakes in the NCHF Ecoregion include dissolved oxygen (DO), pH, temperature, and eutrophication (total phosphorus [TP], chlorophyll-*a* [chl-*a*], and Secchi depth [SD]). TP is the primary stressor causing the use impairment. The applicable MPCA eutrophication numeric standards, expressed as the June 1 through September 30 average value for a near-surface (epilimnetic) samples, are: 1) TP should not exceed 60 micrograms per liter (µg/L); 2) chl-*a* should not exceed 20 µg/L; and 3) SD should not be less than 1.0 meter. Eutrophication standards are compared to data averaged over the summer season (June through September). Exceedance of the TP and either the chl-*a* or SD standard is required to indicate an impaired condition. This report shows analyses for all three parameters. However, the focus of the loading capacity calculations is solely based on TP concentrations in each of the lakes, since meeting the TP standard will result in MPCA considering the lake unimpaired.

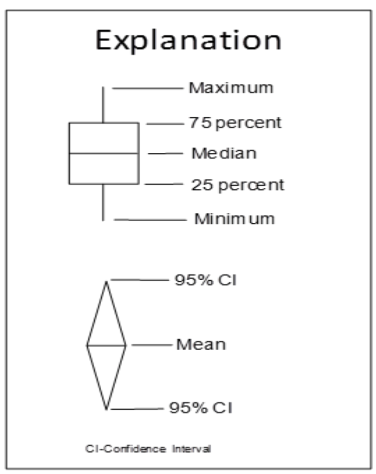
2.3 Existing Water Quality

The water quality of Ravine Lake has been assessed through monitoring since 1998. All samples were collected in the upper three feet of the lake. Monitoring of Ravine Lake continues through support from the SWWD and Metropolitan Council and is performed by the Washington Conservation District. For the purposes of this study, water quality and surface water flow data were needed to simulate conditions within the watershed and Ravine

Lake. The time period used for model development, calibration, and validation includes data from June 1 through September 30 (summer season) from 2002 through 2010 (study period). The summer season is used to be consistent with the averaging period for the state's numeric water quality standards.

This section summarizes the available water quality data for Ravine Lake. A table is included, which presents the mean and median TP, chl-*a*, and SD for Ravine Lake, calculated for the summer season. Also included in the table are the respective Carlson Trophic State Index (TSI) values, computed using the mean summer season value for each parameter (Carlson, 1977). Finally, graphs are presented to illustrate the monitoring data statistically. All data are summarized using box and whisker plots. **Figure 3** shows how to interpret these plots. The box-shaped figure represents the data using non-parametric statistics. The top of the box represents the value that 75 percent of observations are at or below, while the bottom of the box represents the value that 25 percent of all observations are at or below. The line through the middle is the median value. The minimum and maximum values (excluding outliers) are represented by the lower and upper ends of the lines (i.e., whiskers) extending from the box. Outliers are defined as any value that falls above or below the median by 1.5 times the height of the box (interquartile range) and are marked by dots on the plot. The diamond shape figure represents the data using parametric statistics, with the center line representing the mean value and the top and bottom of the diamond representing the upper and lower values of the 95 percent CI, respectively.

Figure 3. Interpretation of box and whisker plots.



Graphs are provided for TP concentration, chl-*a* concentration, and SD data collected during the summer season throughout the past 12 years (1998-2012). Water quality data for Ravine Lake is summarized in **Table 1** and displayed in **Figure 4** through **Figure 6**.

Table 1. Water quality statistics for Ravine Lake.

Year	Total Phosphorus			Chlorophyll-*a*			Secchi Disk Transparency		
	n	(ug/L)		n	(ug/L)		n	(meters)	
		Mean	Median		Mean	Median		Mean	Median
Concentrations									
1998	9	174.4	170.0	---	---	---	9	0.54	0.50
1999	10	75.0	75.0	---	---	---	10	1.04	0.85
2000	8	98.8	95.0	---	---	---	8	0.54	0.45
2001	8	121.3	120.0	8	33.81	38.00	8	0.28	0.30
2002	9	108.3	107.0	9	71.00	69.00	9	0.33	0.30
2003	6	64.5	58.0	7	31.93	30.00	8	0.69	0.55
2004	9	62.7	53.0	9	30.89	25.00	9	0.67	0.60
2005	9	50.9	46.0	9	26.17	24.00	9	1.81	1.68
2006	4	118.0	124.0	4	29.50	29.50	4	1.56	1.68
2007	4	59.0	57.5	4	15.78	16.00	4	1.79	1.83
2008	5	80.8	74.0	5	23.00	19.00	5	2.29	2.29
2009	4	52.5	51.5	4	12.50	10.10	4	2.59	2.59
2010	4	72.3	68.5	4	28.35	19.50	4	1.46	1.25
2011	4	68.0	72.0	4	45.98	37.00	4	2.17	1.83
2012	5	106.0	85.0	5	105.40	66.00	5	1.10	1.07

Trophic State Index Computed from Mean Concentrations			
	Total Phosphorus TSI	**Chlorophyll-*a* TSI**	**Secchi Disk TSI**
1998	79	---	69
1999	66	---	59
2000	70	---	69
2001	73	65	78
2002	72	72	76
2003	64	65	65
2004	64	64	66
2005	61	63	51
2006	73	64	54
2007	63	58	52
2008	67	61	48
2009	61	55	46
2010	66	63	55
2011	65	68	49
2012	71	76	59

Figure 4. Ravine Lake historic seasonal TP concentrations.

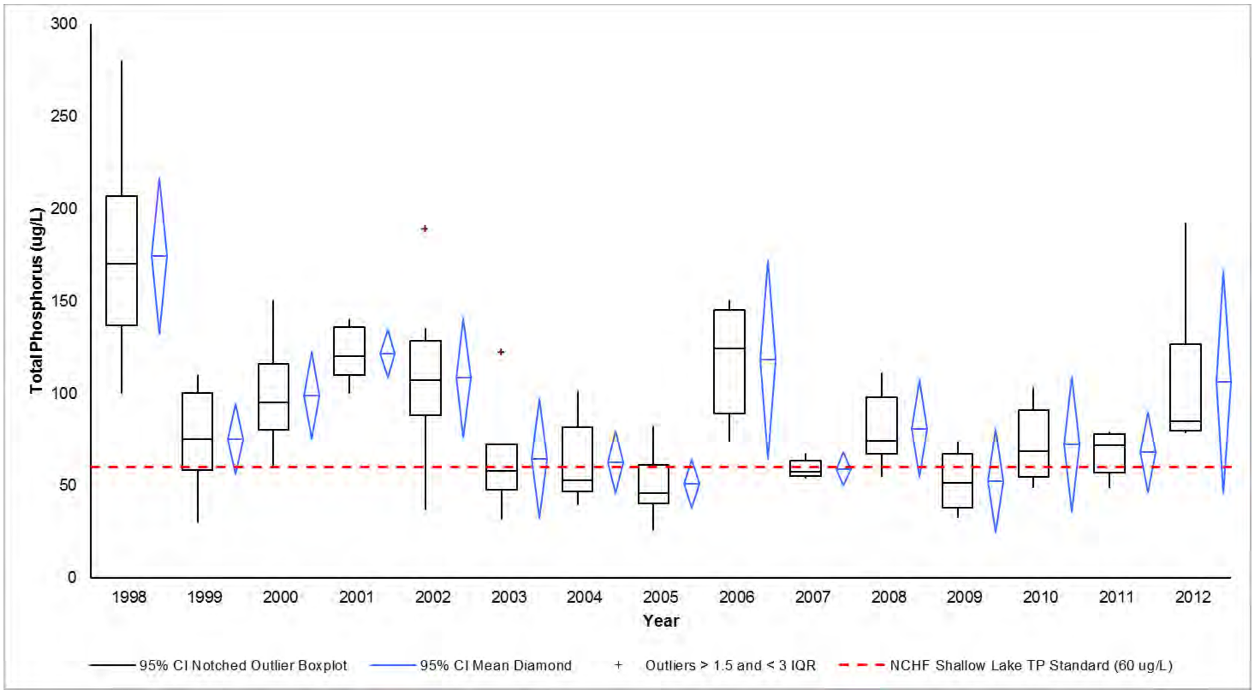


Figure 5. Ravine Lake historic seasonal chl-*a* concentrations.

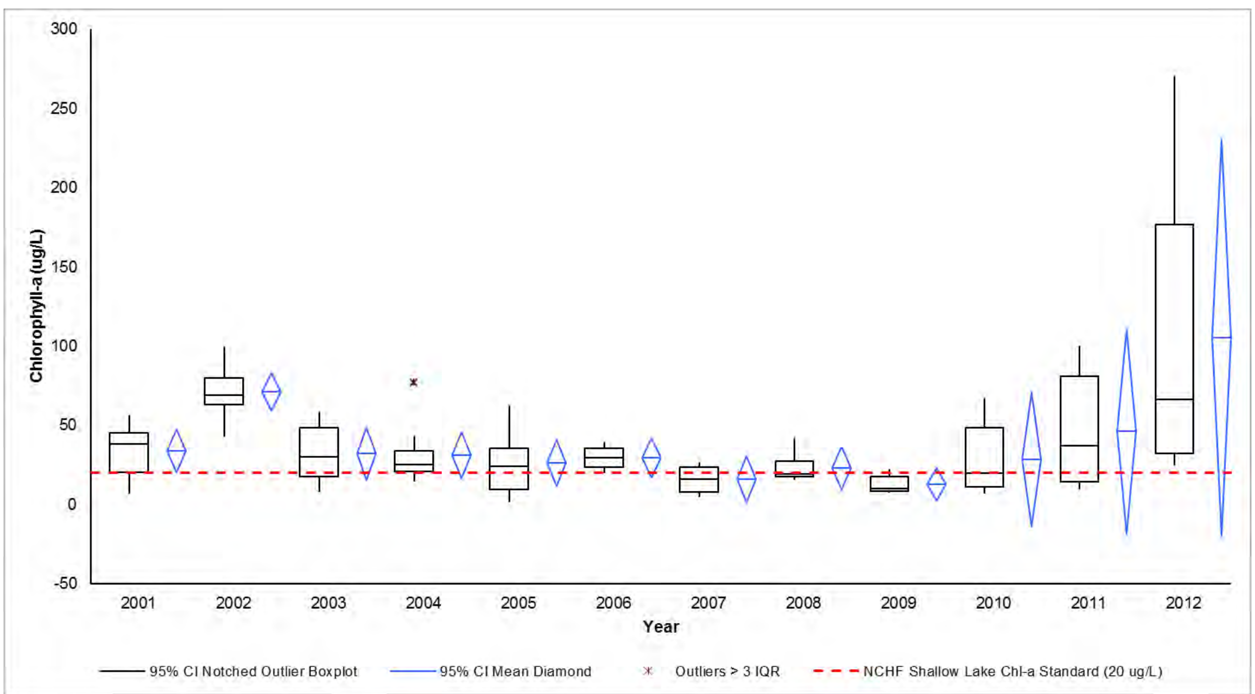


Figure 6. Ravine Lake historic seasonal SD values.

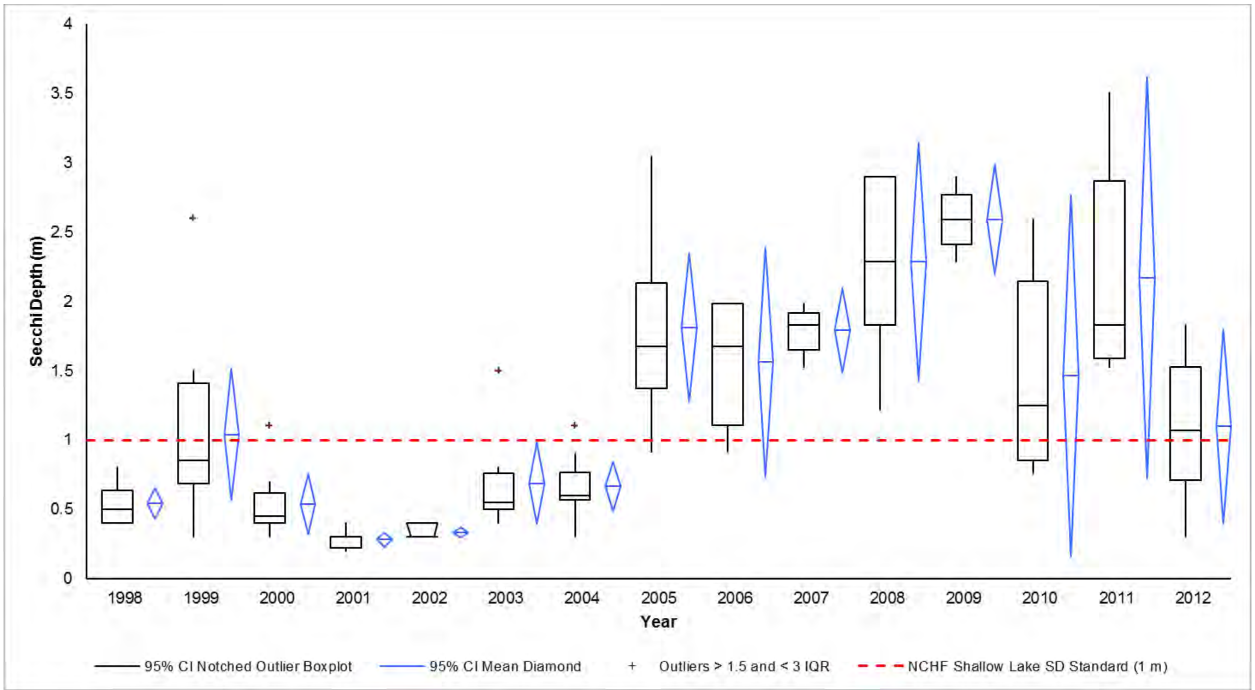
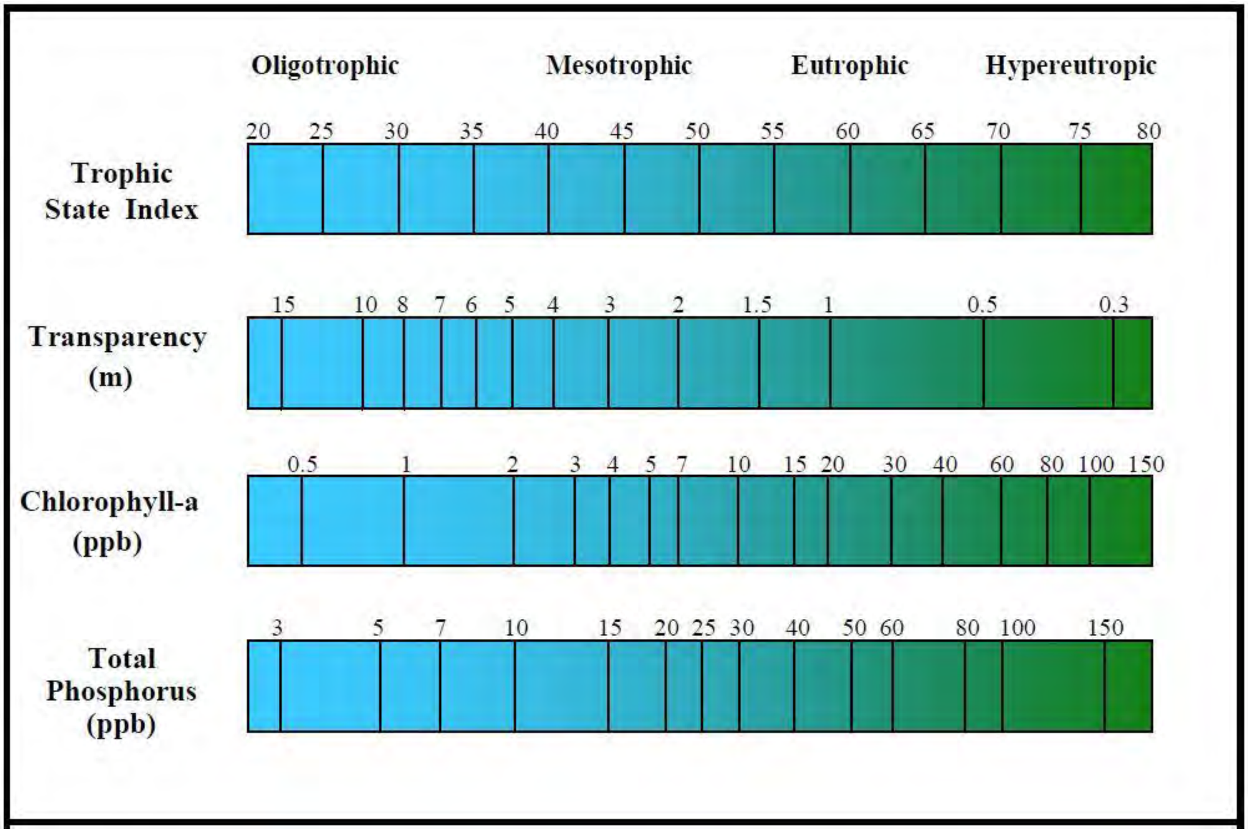


Figure 4 shows that average seasonal phosphorus concentrations in Ravine Lake have fluctuated above and below the state water quality standard throughout the past 14-years. Recently, elevated years include 2006 and 2012. **Figure 5** shows chl-*a* concentrations have also fluctuated near the state water quality standard with an increase beginning in 2011. **Figure 6** shows that seasonal average SD values were below the state water quality standard from 1998 – 2004 and have increased above the standard beginning in 2005.

Figure 7 shows the range of TSI values and lake eutrophication state in comparison to the range of TP, chl-*a*, and SD values. The TSI values in **Table 1** show Ravine Lake generally ranging from eutrophic to hypereutrophic, with some values showing mesotrophic. The values indicate disagreement between the status shown by the TP, chl-*a*, and SD values suggesting that additional factors may be present in the lake that cannot be explained solely by the relationship between these three parameters. Such factors may include the mixing characteristics of the lake (i.e., the fetch), the low disturbance of substrate, or the type and amount of algae present.

Figure 7. TSI value reference figure (MPCA, 2005)



2.4 Water Budget

A water budget is an accounting of the amount of water entering and leaving a lake over a given time period. The time period used to develop the water budget in this study is the summer seasons of the study period, corresponding to the averaging period of the state numeric standards. The amount of water moving in and out of a system varies from year-to-year, dictated primarily by the seasonal precipitation occurring in the area. The water budget is important to quantify because different sources of water can contain different quantities of pollutants and the amount of water entering and leaving the lake determines the hydraulic residence time, which impacts the eutrophication response. The water budget is also important because it is used during hydrologic and water quality modeling for model calibration and validation purposes.

A water budget accounts for "gains" in water to the lake (*i.e.*, precipitation, runoff and groundwater inflow) as well as "losses" (*i.e.,* evaporation, surface outflow, and groundwater outflow). Each of these affects the volume of water in the lake (storage). This section describes how the various terms of the water budget were computed for Ravine Lake. The final water budget is presented in **Section 2.4.8**.

2.4.1 Tributary Inflow

Tributary inflow is defined as any inflow originating from another upstream waterbody. Under the conditions addressed in this study (50-years of simulation), all of the overland water entering Ravine Lake is from watershed runoff; therefore Ravine Lake does not have any tributary inflow.

2.4.2 Surface Water Runoff

The amount of surface water runoff entering Ravine Lake during the summer season of the study period was estimated using the Predicting Polluting Particle Passage thru Pits, Puddles, & Ponds (P8) model developed for the watershed. Additional information on the P8 models developed for the Ravine Lake watershed are summarized in the *Ravine Lake Watershed P8 Modeling* report, included as **Appendix A**. Surface water runoff refers to any surface water that eventually enters the lake via overland flow, either from the immediate Ravine Lake subwatershed (i.e., direct drainage) or through the upland drainage network (i.e, through the storm sewer system). The Ravine Lake watershed P8 model was run from 1962 through 2011 and annual surface water runoff volumes to Ravine Lake were extracted and compiled to determine the seasonal contribution to the lake. Results for the study period are shown in **Table 2**.

Table 2. Ravine Lake water budget seasonal volumes.

Year	Surface Water Runoff (acre-feet)	Precipitation (acre-feet)	Evaporation (acre-feet)	Change in Storage (acre-feet)	Surface Outflow (acre-feet)	Net Groundwater and Error (acre-feet)
2002	266	55	50	6	316	50
2003	47	22	57	14	361	363
2004	54	26	54	-23	318	269
2005	69	35	60	-1	72	27
2006	64	30	60	-5	74	34
2007	211	46	62	8	261	75
2008	44	22	59	7	300	299
2009	56	26	56	-2	327	298
2010	121	43	53	26	370	285

2.4.3 Precipitation

Long-term precipitation records (1962-2011) from the first-order weather monitoring station located at the Minneapolis St-Paul airport (MSP) were used as forcing data in the P8 watershed model developed under this study. They were also used to estimate the amount of water falling on the surface of Ravine Lake as precipitation during the study period. The mean summer season precipitation observed at MSP during this 50-year period (i.e., the time period used in setting the loading capacity of the lake, discussed in **Section 3.4**) was 14.7 inches. By comparison, a summer season precipitation totals for 2002-2010 range from 10.0 inches in 2008 to 25.1 inches in

2002. When the seasonal rainfall depths are applied to the area of Ravine Lake, the seasonal precipitation volumes associated with these rainfall depths are determined and shown in **Table 2**.

2.4.4 Evaporation

Evaporation can be an important component of the water budget, particularly for shallow lakes with small watersheds. Evaporation volumes were estimated using the combined aerodynamic and energy balance method. The method is derived from both physical and empirical relationships and accounts for many of the influencing meteorological parameters. Three methods were analyzed, including the Lake Hefner #1 and #2 and the Meyer methods. The results of these methods were averaged to determine the yearly evaporation, from Ravine Lake, during the study period.

Each method requires the following meteorological data: air temperature, wind speed, and water vapor pressure (expressed as dew point). Daily meteorological data from the MSP station was used for this analysis. The methods also require daily water temperature data, which was estimated by forming a linear regression between known lake water temperature data and corresponding air temperature data and applying the regression to create a daily water temperature dataset. Evaporation was calculated on a daily time step and summed over the summer season. Summer season evaporation totals were calculated for each of the years in the study period. The estimated evaporation depths (in inches per summer season) for each year of the study period were determined and applied to the surface area of Ravine Lake to determine a summer season evaporation volume (acre-feet). The results are shown in the **Table 2.**

2.4.5 Change in Storage

Change in storage (increase or decrease) was estimated using measured lake levels obtained from the MnDNR LakeFinder website and the lake surface area. Observed water level values were linearly interpolated between measurements to estimate daily values. The changes in storage were estimated from the difference in lake levels between June 1 and September 30 of each year. An increase in water level over the season is interpreted as a positive change in storage value; likewise a decrease in water level represents a negative change in storage value. The seasonal change in storage volumes are shown in **Table 2**.

2.4.6 Surface Outflow

Surface outflow volumes for Ravine Lake were estimated using daily lake levels (**Section 2.4.5**) combined with stage-discharge curves generated for the outlet culvert assumptions discussed in **Section 2.1**. The stage-discharge curves were generated by creating a Hydrologic Engineering Center River Analysis System (HEC-RAS) model to simulate outflow from the lake. The HEC-RAS model includes the outflow culvert (under various configurations) and the downstream control structures and channels. The two scenarios described in **Section 2.1** (a 50% and 75% obstructed 18” culvert) were applied to the HEC-RAS model and stage-discharge curves were generated for each scenario. These curves have been included in **Appendix B**. The stage-discharge curves for the scenarios where then applied to the corresponding lake level data sets, during the corresponding years, to generate seasonal outflow volumes. As indicated in **Section 2.1** the 50% obstruction discharge curve was used for 2002-2007 and the 75% obstruction curve was used for 2008-2010. The estimated seasonal surface outflow volumes for the water budget are shown in **Table 2**.

2.4.7 Net Groundwater & Error

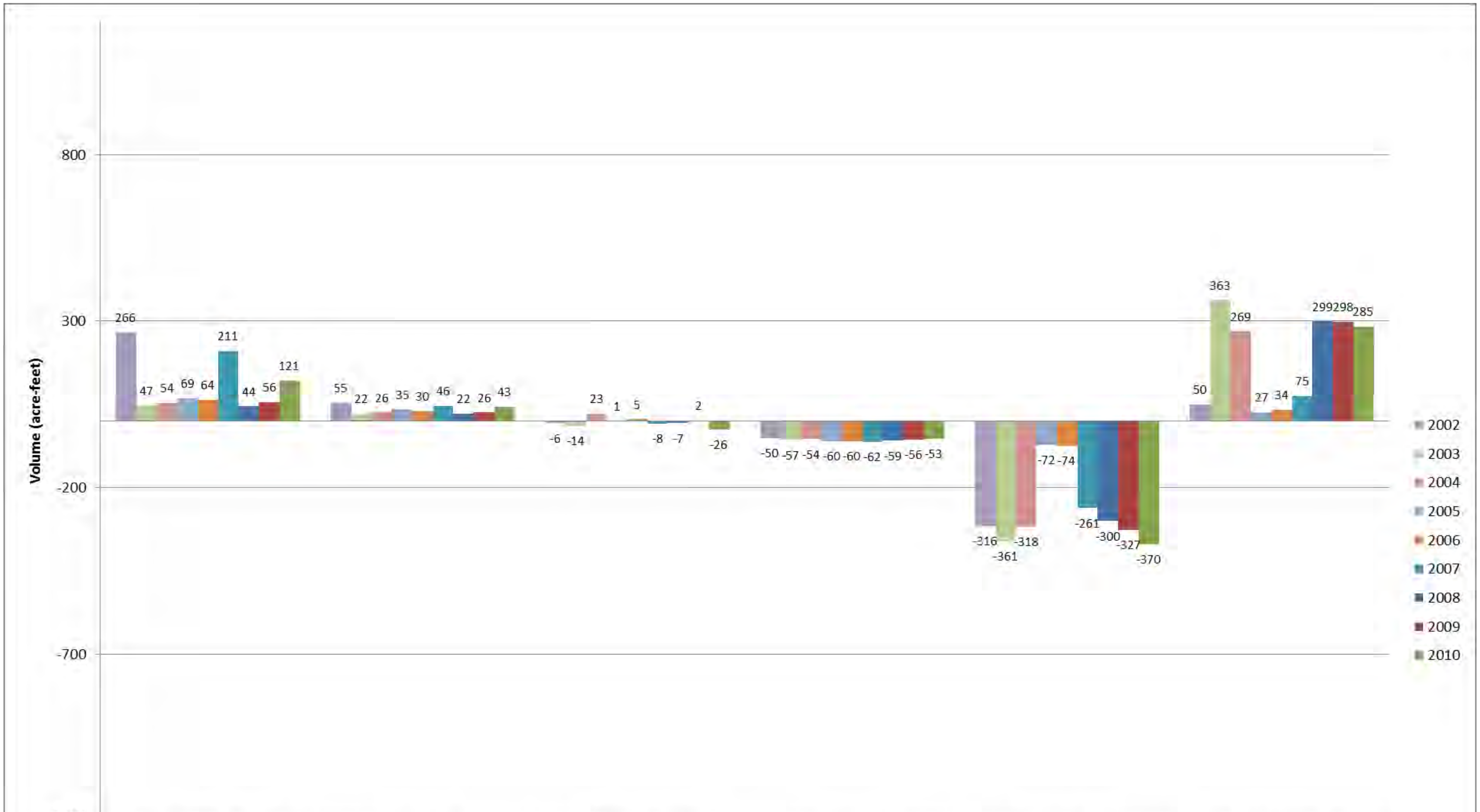
Information about groundwater interaction within the overall watershed of Ravine Lake is limited. Groundwater inflow is known to be an important part of the water budget for Ravine Lake (SWWD, 2013), but quantifiable data on its impact is largely unavailable. The Comprehensive Lake Management Plan for Ravine Lake (McComas, 2003) estimates an annual groundwater influx of 25 acre-feet. However, discussion with the SWWD indicates that this value is uncertain and also that groundwater inflow rates are likely seasonal; rates likely correspond to upland groundwater levels, dropping in the summer and rebounding in the fall (SWWD, 2013). A large-scale assessment of groundwater resources in Washington County determined that Ravine Lake is considered a “flow-through” lake with respect to groundwater interaction. This indicates that the lake is in direct hydraulic connection with the regional water table but without an outlet that significantly removes the inflowing groundwater. Groundwater flows into the lake primarily in the upgradient areas but discharge back into the water-table system on the downstream end, resulting in nearly a net zero groundwater balance. During the course of the year, there can be situations when the lake is “gaining” or “losing” with respect to groundwater but on average, groundwater flows through (Barr, 2005). The exact extents that Barr used to define Ravine Lake for their study are unknown (i.e., if they included the wetlands and channels downstream of the outlet culvert to be part of Ravine Lake or not). It is notable, that discussions with the SWWD indicate that water leaving Ravine Lake (through the outlet culvert) rarely reaches the culvert passing under MN 61, approximately 1000 channel feet downstream of the outlet culvert. If Barr considered this area as part of the Ravine Lake system, the flow-through nature they describe is possible.

For the purposes of this modeling, Ravine Lake is considered to be the main waterbody upstream of the outlet culvert. Given the qualitative nature of the available groundwater information for the lake, the net groundwater term for the water budget developed was combined with the error term. In general, the combined groundwater/error term was then computed from the remaining terms in the balance equations (net groundwater + error = inputs - outputs). The computed seasonal net groundwater & error volumes are shown in **Table 2**. In most years, this term makes up a significant component of the water balance equation.

2.4.8 Estimated Water Budgets

The estimated seasonal water budget for Ravine Lake is shown in the **Figure 8**. The budget was estimated as described in the sections above.

Figure 8. Ravine Lake seasonal water budget.



	Surface Water Runoff	Precipitation	Change In Storage	Evaporation	Surface Outflow	Net Groundwater & Error
2002	266	55	-6	-50	-316	50
2003	47	22	-14	-57	-361	363
2004	54	26	23	-54	-318	269
2005	69	35	1	-60	-72	27
2006	64	30	5	-60	-74	34
2007	211	46	-8	-62	-261	75
2008	44	22	-7	-59	-300	299
2009	56	26	2	-56	-327	298
2010	121	43	-26	-53	-370	285

2.5 Total Phosphorus Nutrient Budget

Along with accounting for the amount of water entering and leaving Ravine Lake, it is necessary to account for the amount of nutrients by developing a TP budget (mass balance). Nutrient amounts are expressed as loads, in units of mass per time (e.g. kg/season or lb/season), and are estimated by considering the concentration of a substance in the water and the amount of that water entering and exiting the waterbody over a period of time. In the case of this study, the substance/nutrient considered is phosphorus. This section describes how the various components of the TP budget for Ravine Lake were estimated. The overall budget results are presented in **Section 2.5.6**.

2.5.1 Tributary and Surface Water Runoff Loading

Loads entering Ravine Lake include nutrients entering through tributary inflows as well as surface water runoff. As noted in **Section 2.4.1**, Ravine Lake does not experience any tributary inflow (under the modeled conditions) and thus no tributary inflow loading. The amount of surface water runoff loading to Ravine Lake during the summer seasons of the study period were estimated using the P8 model developed for the watershed. The resulting estimated loads are summarized in **Table 3**.

Table 3. Ravine Lake TP nutrient budget seasonal masses.

Year	Local Runoff Loading (kg)	Atmospheric Deposition (kg)	Internal Loading (kg)	Retained Mass & Error (net out) (kg)	Surface Outflow (kg)
2002	109	2	21	90	42
2003	22	1	21	15	29
2004	26	1	21	24	25
2005	34	2	21	52	5
2006	27	2	21	39	11
2007	110	2	21	114	19
2008	24	1	21	16	30
2009	25	2	21	27	21
2010	52	2	21	42	33

2.5.2 Atmospheric Deposition

The annual atmospheric deposition rate for the watershed encompassing Ravine Lake was determined to be 0.29 kg/hectare/yr (Barr 2007). In order to estimate atmospheric deposition during the summer seasons of the study period, it was assumed that the amount of TP from atmospheric deposition is driven solely by precipitation and that the TP concentration of precipitation remains constant throughout the year. Using the precipitation data from the hydrologic budget, a ratio of summer season precipitation to annual precipitation was calculated for each year in the study period. For example, in 2002 the summer season total precipitation was 25.1 inches and the annual precipitation was 36.1 inches; therefore the ratio for 2002 is 0.70 and is applied to the annual deposition to determine seasonal deposition. Summer season atmospheric loadings for the study period were computed by applying the respective ratios to the annual atmosphere deposition rate of 0.29 kg/hectare/yr. The estimated seasonal TP atmospheric loading to Ravine Lake is summarized in **Table 3**.

2.5.3 Internal Loading

Internal TP loads to the lake were estimated using information developed by the Rice Creek Watershed District (RCWD), also in the Twin Cities Metropolitan area. The RCWD retained the U.S. Army Corps of Engineer's Eau Galle Lab to measure the sediment phosphorus release rates in 30 of their lakes, in the laboratory, under oxic and anoxic conditions. The phosphorus release rate in Ravine Lake was estimated assuming a long-term average summer season internal release rate, consistent with those found in the RCWD, of 1.62 milligrams per square meter per day. This internal release rate was estimated and used in the previous SWWD studies (Colby, Markgrafs, Armstrong, and Wilmes Lakes). The value is the median rate observed in 23 lakes in the RCWD, characterized as both shallow and relatively urban. The release rate was applied over an area equal to the surface area of Ravine Lake, resulting in a conservative estimate of the amount of sediments contributing loading. The internal loading of Ravine Lake was assumed to remain constant (21 kg/season) during each summer season throughout the study period. The resulting internal phosphorus loading is summarized in **Table 3**.

2.5.4 Retained Mass & Error

Other in-lake processes (sedimentation, groundwater loading, nutrient uptake, etc.) were not explicitly accounted for in the TP nutrient balance of Ravine Lake, but rather estimated with the retained mass & error term in the nutrient balance equations (retained mass + error = TP inputs – TP outputs). However, the CNET in-lake response model does account for the sedimentation term in its simulations. The retained mass & error TP loading is shown in **Table 3.**

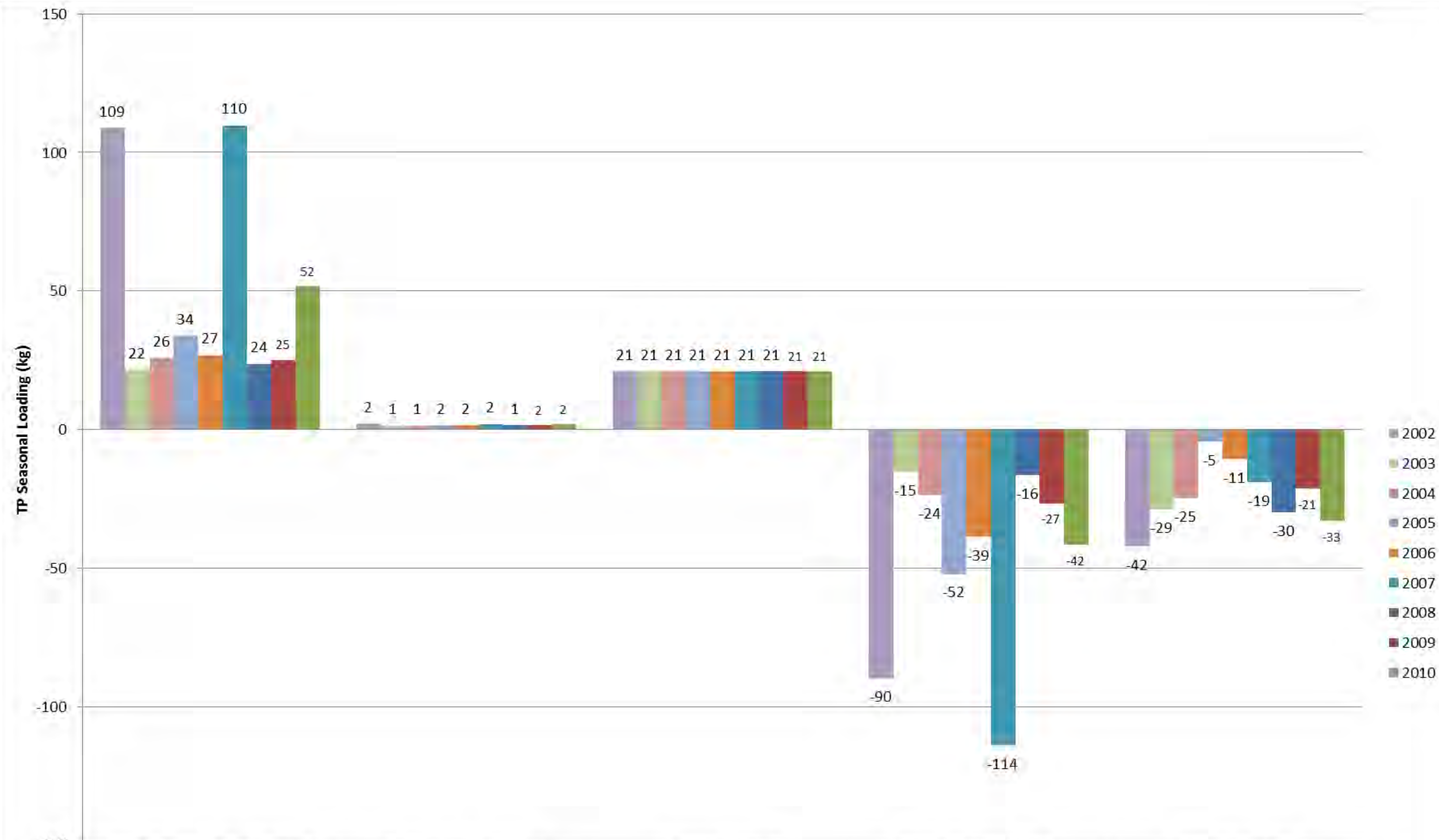
2.5.5 Surface Outflow

The TP load exiting Ravine Lake was estimated by applying the mean summer season TP concentration in Ravine Lake to the estimated summer season outflow during each year. Resultant surface outflow loads are shown in **Table 3**.

2.5.6 Estimated Total Phosphorus Nutrient Budget

Using the results of **Sections 2.5.1** through **2.5.5**, the summer season TP mass balances for Ravine Lake was estimated for the study period. The results are shown in **Figure 9**.

Figure 9. Ravine Lake seasonal TP nutrient balance.



	Surface Water Runoff Loading	Atmospheric Deposition	Internal Loading	Retained Mass & Error	Surface Outflow
2002	109	2	21	-90	-42
2003	22	1	21	-15	-29
2004	26	1	21	-24	-25
2005	34	2	21	-52	-5
2006	27	2	21	-39	-11
2007	110	2	21	-114	-19
2008	24	1	21	-16	-30
2009	25	2	21	-27	-21
2010	52	2	21	-42	-33

3.0 MODEL DEVELOPMENT AND APPLICATION

3.1 Modeling Goals and Technical Objectives

The modeling goals and technical objectives establish the anticipated uses, technical methods, and outcomes (products) of the model. Identification of the goals and objectives early in the process are essential for conducting a successful modeling effort. The following section describes these goals and objectives.

Modeling goals are general statements reflecting the overall expectations or outcomes from the model development and application process. Technical objectives are specific to the water quality problem being addressed and should incorporate the applicable temporal and spatial scales to be addressed by the model (e.g., water quality problems related to short-term episodic event or long-term conditions). For example, a modeling goal might be to establish nutrient loads and the load reductions needed to achieve water quality goals for a particular lake. The corresponding technical objectives may include assessing the eutrophication response of the lake at each lake inlet and outlet for the average monthly condition.

The two primary types of water quality modeling for this project can be broadly categorized as watershed (*i.e*., landscape) and receiving water modeling. The water quality goals and technical objectives for the modeling components of the Ravine Lake Management Plan project are the same as those presented for the Powers Lake Pilot Project, as described in Tables 1 and 2 of a Technical Memorandum to the SWWD dated January 28, 2010. These goals and objectives can be generally described as understanding the response of the lakes to excess nutrients, both in terms of the amount of algae and the clarity of the lake.

3.2 Watershed Modeling

The movement of water and TP from the watershed into Ravine Lake was determined using two P8 models developed as part of this project. The Existing Conditions and Future Conditions models incorporate a number of factors that encompass inflow, outflow, and the movement of sediment-related particles (including TP) through a watershed. The P8 models were used to estimate the seasonal total runoff volume and TP loading to Ravine Lake over a 50-year continuous period. Results of these simulations were then used as inputs to the receiving water model described in **Section 3.3**, which was developed to compute the loading capacity of Ravine Lake.

The routing information and most other required inputs for the P8 models were adopted from two existing SWWD SWMM models. The Ravine Lake watershed P8 model was calibrated using a combination of 1979 SWMM model outputs for runoff and land class-based literature values for unit area loading. The models were checked for reasonability by comparing unit runoff and TP loads to FLUX analysis of a similar nearby watershed and by comparing subwatershed runoff concentrations to land class-based literature values. More information on the development of the Ravine Lake P8 models is included in **Appendix A**.

3.3 Receiving Water Modeling

Two CNET models were created to simulate the eutrophication response within Ravine Lake. CNET is a modified version of the receiving water model BATHTUB, which was created by the U.S. Army Corps of Engineers (USACE). CNET is a spreadsheet model currently available as a Beta version from Dr. William W. Walker. The primary modifications to the CNET model implemented during this study were: 1) the use of empirically derived regression relationships specific to Ravine Lake derived from monitoring data to estimate the response of chl-*a* and SD to TP; and 2) the implementation of a Monte Carlo approach allowing selected modeling parameters and inputs to vary based upon known statistical distributions and correlations, resulting in statistically distributed forecasting. The Monte Carlo approach generates a distribution of the annual mean concentrations reflecting the uncertainty in the model parameters and normal variability in inputs. The Existing Conditions CNET model simulates current in-lake response based on watershed inputs from the Existing Conditions P8 model. Similarly, the Future Conditions CNET model modifies the Existing Conditions CNET model by substituting Future Conditions P8 model watershed inputs.

To perform the Monte Carlo simulation using the CNET models, the models were operated via Crystal Ball. Crystal Ball is proprietary software developed by Oracle and is used for Monte Carlo or stochastic simulation and analysis. Stochastic modeling is an approach where model parameters and input values are allowed to vary according to their statistical distribution and therefore their probability of occurrence. This allows the effect of parameter uncertainty and normal variability in the inputs to be quantified when computing the model outputs.

The Crystal Ball software allows for multiple probabilistic simulations to be entered into the model. For the Ravine Lake study, 1000 trials were used, with each trial representing a different permutation of model parameters and input values within the bounds established by the statistical distributions. The Monte Carlo simulation results in a computed distribution of model outputs. The stochastic approach reflects the variability in model parameters and inputs, and allows explicit determination of their effect on the mean values and the expression of model results as risk. **Section 3.3.1** and **Section 3.3.2** describes the details of the Existing Conditions and Future Conditions CNET model development for Ravine Lake, including the variable values in the Monte Carlo simulation and the statistical distributions for each varying parameter within the model. The inputs to the CNET models that do not follow a statistical distribution were held constant throughout all model simulations.

3.3.1 Existing Conditions Ravine Lake CNET Model Development

The Existing Conditions CNET model was developed first and surface water inflow and loading modifications were made to create the Future Conditions CNET model, discussed in **Section 3.3.2**. **Table 4** shows the model inputs used in the Existing Conditions Ravine Lake Monte Carlo simulation and the statistical distributions for each parameter used.

Table 4. Model inputs used in the Monte Carlo Analysis for Ravine Lake Existing Conditions Model.

Model Input	Statistical Distribution	Basis for Distribution	Distribution Truncated at Extreme Values?	Correlation	
				Considered?	Input Correlated With
Precipitation	Beta	1962 – 2011 MSP National Weather Service Station*	Yes	Yes	Surface runoff (0.97) Surface load (0.96) Atmospheric Load (.72)
Evaporation	Weibull	1962 – 2011 computed from regression with MSP National Weather Service Station air temperature data*	Yes	No	---
Atmospheric Load	Logistic	1962 – 2001 computed using seasonal precipitation ratio and constant annual atmospheric deposition	Yes	Yes	Precipitation (0.72)
Surface Water Runoff Volume	Lognormal	1962 – 2011 calibrated Existing Conditions P8 model*	Yes	Yes	Precipitation (0.97) Surface Load (0.98)
Surface Runoff TP Load	Lognormal	1962 – 2011 calibrated Existing Conditions P8 model*	Yes	Yes	Precipitation (0.96) Surface Runoff Volume (0.98)
Storage & Groundwater	Triangular	2002 – 2010 annual water balance values	Yes	No	---

Notes:
All distributions truncated at the minimum and maximum values in the time period noted.
Distributions chosen are best fit for the time period of seasonal values.
Correlation coefficients were derived from actual data.
Value in parentheses is correlation coefficient as determined by Crystal Ball.
A triangular distribution was chosen for storage and groundwater based on limited data set (2002-2010).
See Appendix C for the statistical distribution parameters.
Statistical distributions were the best fit distribution, as determined by the Crystal Ball software.
* Values for 1987 were removed from the distributions for these variables due the extremity of the hydrology during this year and its impact on skewing the modeled distribution.

Prior to completing the Monte Carlo modeling analysis, the Existing Conditions CNET model was calibrated to 2006-2010 average summer season mean TP, chl-*a*, and SD and validated for 2002-2005 average summer season data. The modeling used the seasonal water budget and TP mass balance around the lake as described in **Sections 2.4.8 and 2.5.6**. The following CNET models were used in the simulations:

- Total phosphorus sedimentation model: Canfield & Bachman (1981), Natural Lakes
- Chlorophyll-*a* response model: P, Light, Flushing

- Secchi Disk Transparency response model: Secchi vs. Chl-*a* and Turbidity

The CNET model calibration is performed by adjusting each sedimentation and response models' calibration coefficient to reduce the errors between observed and simulated values. For the SD response model, a non-algal turbidity factor (α) of 0.7 was used; this was determined using the non-algal turbidity relationship presented by Walker (2006) and empirical data collected in Ravine Lake. Calibration and validation to multiple year averages ensures an in-lake response model that best represents long-term average conditions in Ravine Lake, which is appropriate for computing the loading capacity. **Table 5** and **Table 6** show the results of model calibration and validation, respectively.

Table 5. Ravine Lake Existing Conditions CNET Model calibration results for an average of the 2006-2010 summer seasons (June through September) mean concentrations.

	Calibration Coefficient	Measured	Modeled	Absolute Difference	Percent Difference
Total Phosphorus	1.32	75.1 ppb	70.1 ppb	5.0 ppb	-6.7%
Chlorophyll-a	0.8	18.8 ppb	24.9 ppb	6.1 ppb	32.4%
Secchi Disk	1.47	1.93 m	1.11 m	0.82 m	-42.5%

Table 6. Ravine Lake Existing Conditions CNET Model validation results for 2002-2005 summer season (June through September) mean concentrations.

	Measured	Modeled	Absolute Difference	Percent Difference
Total Phosphorus	66.0 ppb	70.1 ppb	4.1 ppb	6.2%
Chlorophyll-a	37.0 ppb	24.9 ppb	12.1 ppb	-32.7%
Secchi Disk	0.78 m	1.11 m	0.33 m	42.3%

3.3.2 Future Conditions Ravine Lake CNET Model Development

The primary difference between the Existing Conditions and Future Conditions CNET models is the P8 model-derived results (surface water runoff volume and surface runoff TP load) used to define the statistical distribution of model inputs used in the Monte Carlo simulation. All other input distributions remained the same between the CNET models. **Table 7** shows the model inputs used in the Future Conditions Ravine Lake Monte Carlo simulation and the statistical distributions for each parameter used.

Table 7. Model inputs used in the Monte Carlo Analysis for Ravine Lake Future Conditions Model.

Model Input	Statistical Distribution	Basis for Distribution	Distribution Truncated at Extreme Values?	Correlation	
				Considered?	Input Correlated With
Precipitation	Beta	1962 – 2011 MSP National Weather Service Station*	Yes	Yes	Surface runoff (0.96) Surface load (0.97) Atmospheric Load (.72)
Evaporation	Weibull	1962 – 2011 computed from regression with MSP National Weather Service Station air temperature data*	Yes	No	---
Atmospheric Load	Logistic	1962 – 2001 computed using seasonal precipitation ratio and constant annual atmospheric deposition	Yes	Yes	Precipitation (0.72)
Surface Water Runoff Volume	Lognormal	1962 – 2011 Future Conditions P8 model*	Yes	Yes	Precipitation (0.96) Surface Load (0.99)
Surface Runoff TP Load	Lognormal	1962 – 2011 Future Conditions P8 model*	Yes	Yes	Precipitation (0.97) Surface Runoff Volume (0.99)
Storage & Groundwater	Triangular	2002 – 2010 annual water balance values	Yes	No	---

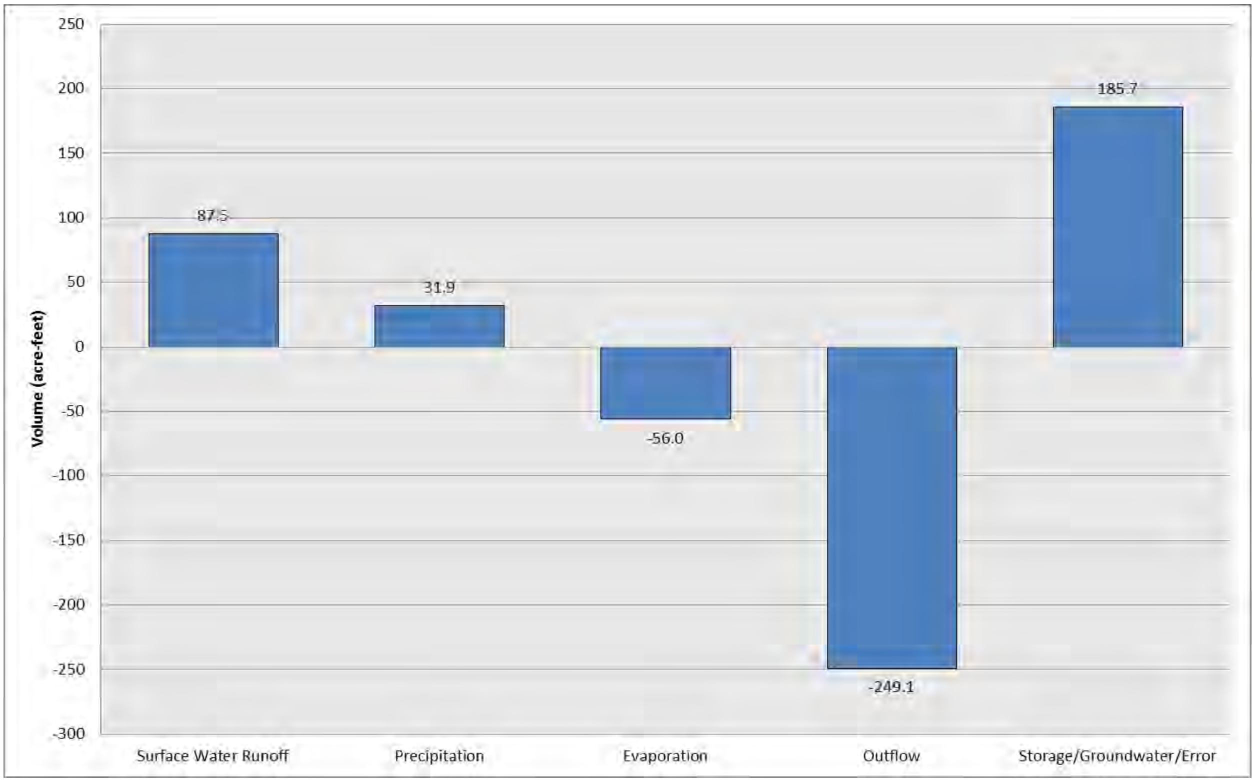
Notes:
All distributions truncated at the minimum and maximum values in the time period noted.
Distributions chosen are best fit for the time period of seasonal values.
Correlation coefficients were derived from actual data.
Value in parentheses is correlation coefficient as determined by Crystal Ball.
A triangular distribution was chosen for storage and groundwater based on limited data set (2002-2010).
See Appendix C for the statistical distribution parameters.
Statistical distributions were the best fit distribution, as determined by the Crystal Ball software.
* Values for 1987 were removed from the distributions for these variables due the extremity of the hydrology during this year and its impact on skewing the modeled distribution.

3.4 Modeling Loading Capacity

Average values and statistical distributions for a 50-year period of record (1962-2011) representing long-term conditions were used in the water and nutrient budgets to develop the loading capacities and TP load allocations for Ravine Lake. Model inputs were determined using data and methods shown in **Table 4** and **Table 5** in **Section 3.3**. Long-term average internal TP loading rates were simulated as 21 kg/season as discussed in **Section 2.5.3**. The groundwater inflow, change in storage, and error terms were combined in the long-term average CNET modeling.

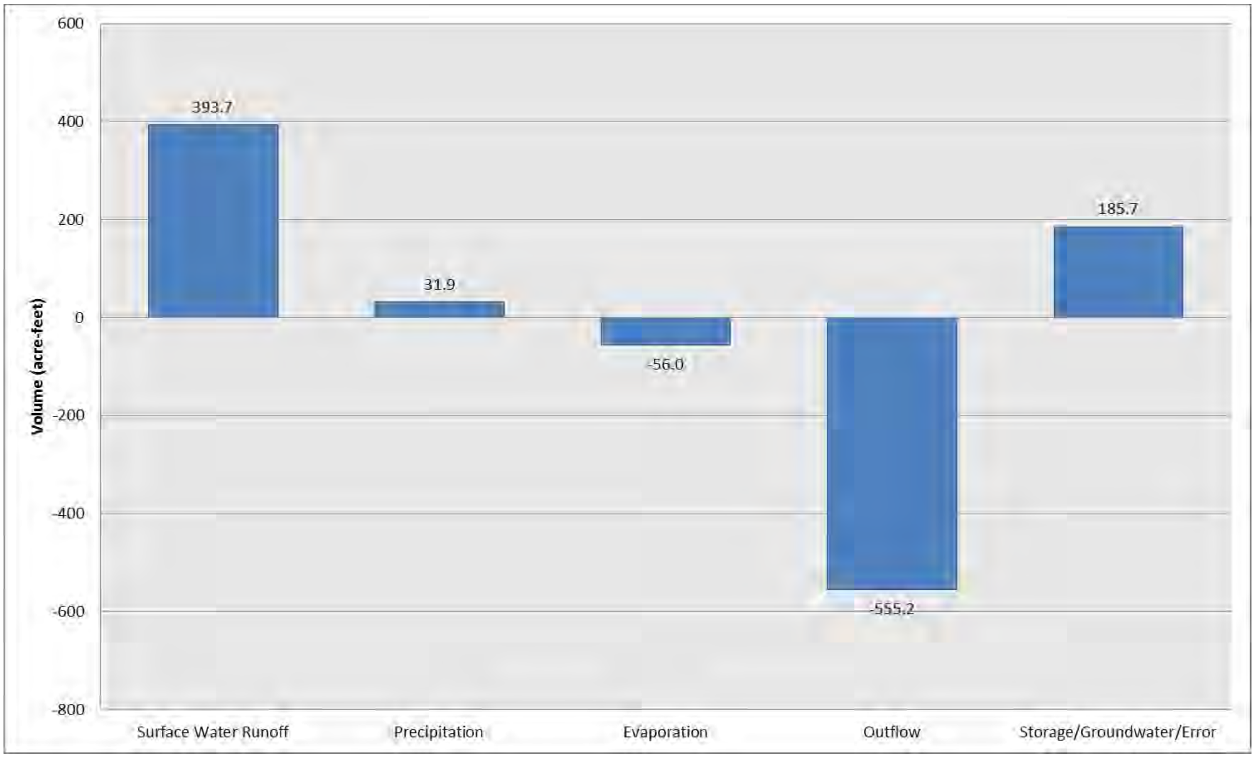
A nine-year average (2002-2010) was used based on the water budget discussed in **Section 2.4.8**. The surface water outflow from Ravine Lake was computed by the CNET models and checked with outflows developed in **Section 2.4.8** as part of the water budget. The CNET long-term average hydrologic budgets for the Existing and Future Conditions Ravine Lake models are shown in **Figure 10** and **Figure 11**, respectively. Results of the modeling and the impacts of various load reductions are discussed in the following section.

Figure 10. CNET long-term average (50-yr) Existing Conditions Ravine Lake summer season water budget.



HoustonEngineering Inc.

Figure 11. CNET long-term average (50-yr) Future Conditions Ravine Lake summer season water budget.



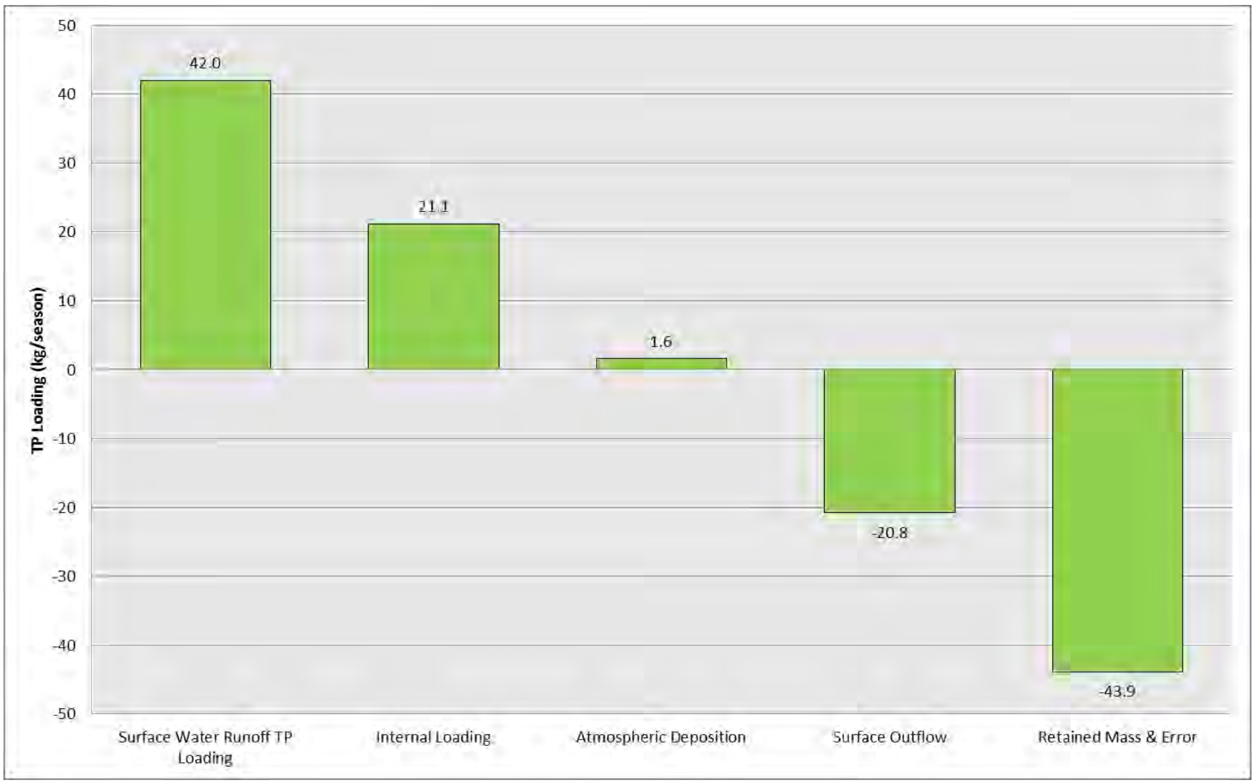
4.0 EUTROPHICATION RESPONSE AND LOADING CAPACITY

To simulate the load reductions and therefore the maximum allowable load (loading capacity) needed to achieve the State water quality standards in Ravine Lake under both the existing and future conditions, a series of model simulations were performed using the Existing Conditions and Future Conditions CNET models. Each simulation reduced the total amount of TP entering Ravine Lake during the summer season, computing the anticipated eutrophication response within the lake. The goal of the modeling was to identify the loading capacity of Ravine Lake (i.e., the maximum allowable TP load to the system that maintains the State water quality standards) during the June 1 – September 30 summer season. Consistent with MPCA guidance (MPCA, 2007), it is assumed that if a lake meets the State's TP water quality standard that chl-*a* and SD within the system will respond accordingly and eventually also reach the State-defined goals (even if the results of the CNET modeling do not predict this result). This approach assumes that data collected and extensively analyzed by the MPCA during standards development provides a more accurate estimate of how lakes will respond when moved from an impaired to unimpaired state than the relationships that exist within the CNET program. In addition to analyzing each TP load reductions' ability to meet the State water quality standards, the ability to meet SWWD goals for Ravine Lake was also assessed. SWWD's goals for the lake are addressed in their Watershed Management Plan and state that the desired TSI values for the lake are between 63 and 66, corresponding to a range in TP concentrations from 59.2 to 72.9 ug/l.

4.1 Ravine Lake Existing Conditions CNET Modeling Response

Figure 12 shows the long-term average TP mass balance of Ravine Lake as computed in the Existing Conditions CNET model. This mass balance is based on the 50-year average (1962-2011) model inputs. Under this analysis, results show that Ravine Lake currently receives a total summer season TP loading of approximately 64.6 kg. About 42 kg of that TP comes from surface water runoff; the other major source of TP is from internal load at 21.1 kg. The CNET model then computes that (on average) 20.8 kg TP/season is removed from the system.

Figure 12. CNET long-term average (50-yr) Existing Conditions Ravine Lake summer season TP mass balance.



4.1.1 Ravine Lake Eutrophication Response

Figure 13 through **Figure 18** and **Table 8** are a result of the Existing Conditions Monte Carlo simulation and show the effects of reducing existing summer season TP loads to Ravine Lake on the summer mean TP, chl-*a* and SD within the lake. Loads were reduced incrementally within the CNET model and assumed to come from the surface water runoff loading component of the mass balance. Results are presented both in terms of the average seasonal mean concentrations (as shown by the column graphs) and the predicted distributions of seasonal mean concentrations (shown as series of lines, where each line represents a different surface water runoff TP loading to the lake). It is important to note that the average load based on the Monte Carlo simulation is slightly different than the 50-year average (63 kg vs. 64.6 kg). This is due to the nature of the statistical distributions used in the

Monte Carlo simulation. Under the Monte Carlo simulation, an average of approximately 40 kg of the loading comes from surface water runoff.

Figure 13. Existing Conditions Ravine Lake summer season mean TP concentrations under select load reduction scenarios; Current Conditions = 63 kg/season.

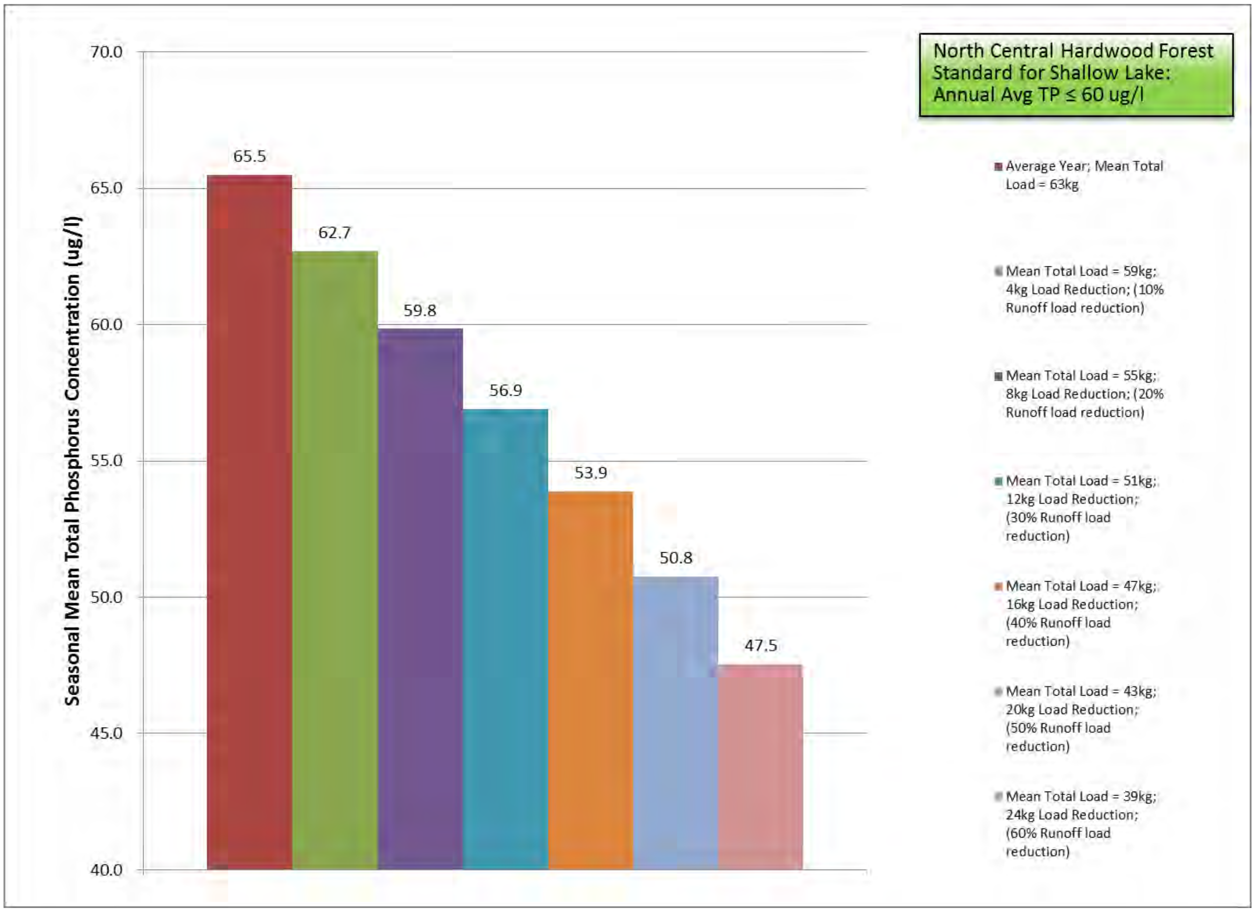


Figure 14. Existing Conditions Ravine Lake frequency distribution of summer season mean TP concentrations resulting from select load reduction scenarios; Current Conditions = 63 kg/season.

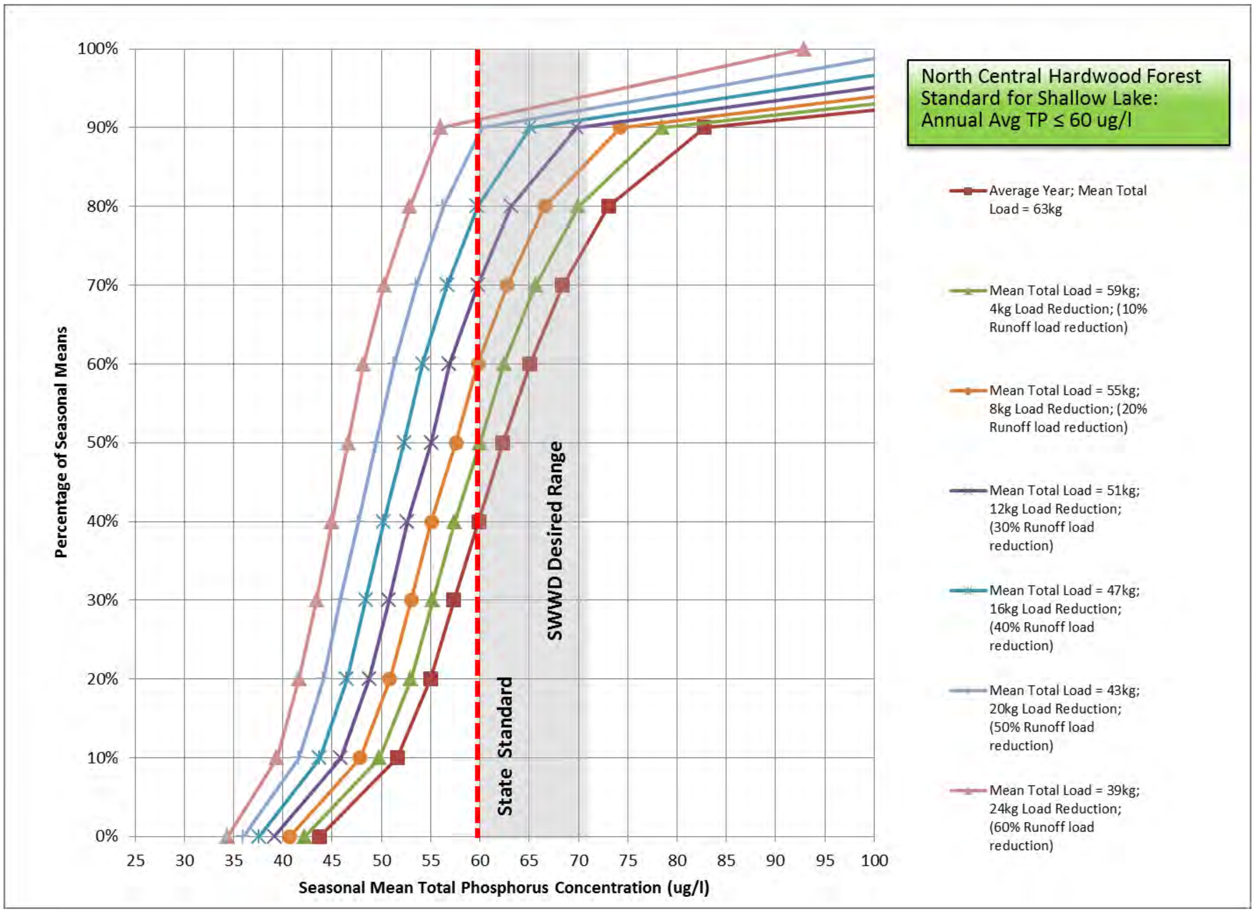


Table 8. Existing Conditions Monte Carlo simulation TP loading reduction results.

Non-Exceedance Percentile	Average Summer Season TP Concentration (ug/L) (current)	Average Summer Season TP Concentrations (ug/L) for Load Reduction from Current Load; Average Summer Season					
		4 kg	8 kg	12 kg	16 kg	20 kg	24 kg
Mean	65.5	62.7	59.8	56.9	53.9	50.8	47.5
0%	43.7	42.2	40.7	39.2	37.6	36.0	34.4
10%	51.6	49.8	47.8	45.9	43.7	41.6	39.4
20%	55.0	53.0	50.8	48.8	46.5	44.1	41.6
30%	57.3	55.2	53.1	50.8	48.4	45.8	43.4
40%	59.9	57.4	55.1	52.7	50.2	47.6	45.0
50%	62.3	60.0	57.6	55.1	52.3	49.5	46.6
60%	65.1	62.5	59.8	56.9	54.2	51.3	48.2
70%	68.4	65.7	62.8	59.8	56.7	53.5	50.3
80%	73.1	70.0	66.6	63.2	59.8	56.3	52.9
90%	82.8	78.5	74.3	69.8	65.1	60.2	56.0
100%	159.8	149.9	139.6	128.8	117.5	105.6	92.9

Figure 15. Existing Conditions Ravine Lake summer season mean chl-*a* concentrations under select load reduction scenarios; Current Conditions = 63 kg/season.

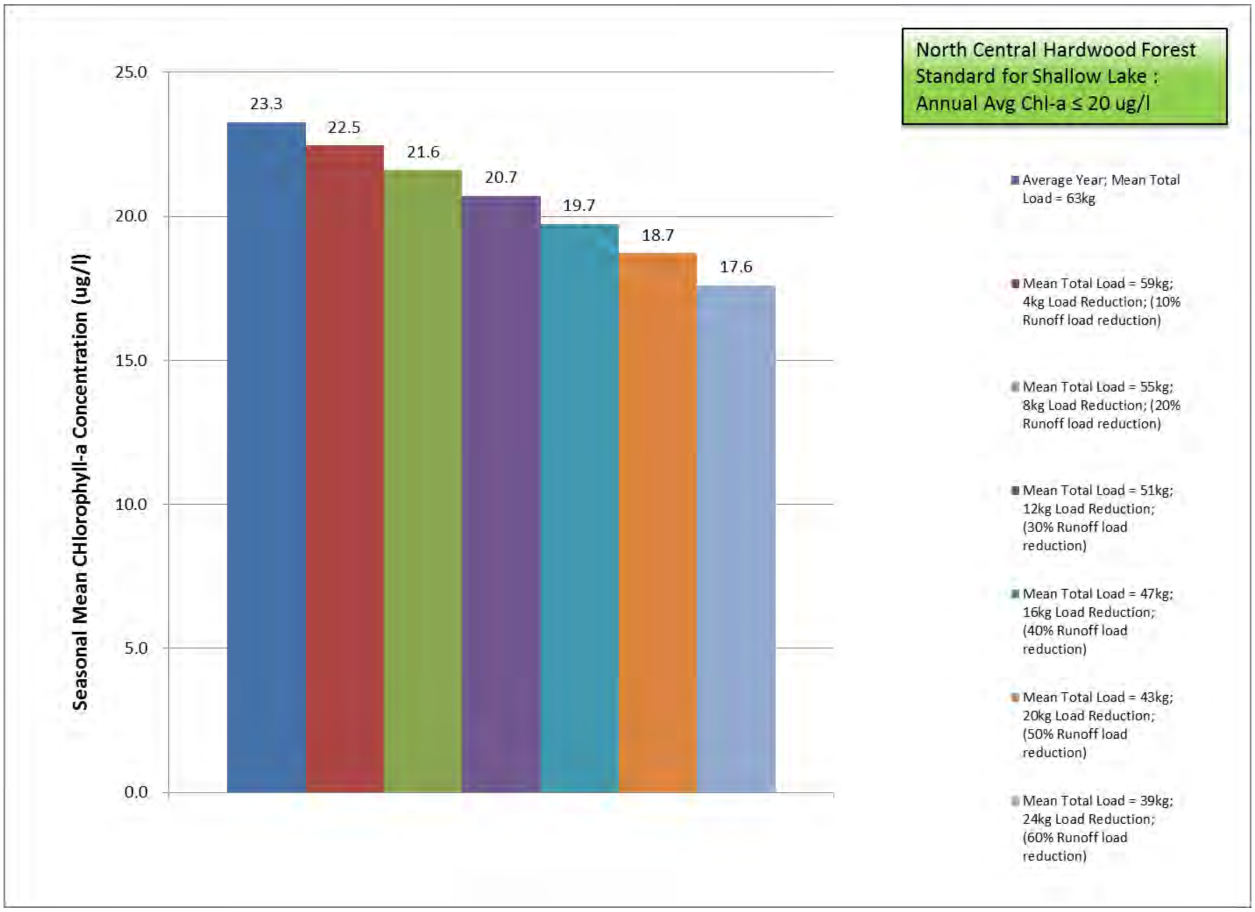


Figure 16. Existing Conditions Ravine Lake frequency distribution of summer season mean chl-*a* concentrations under select load reduction scenarios; Current Conditions = 63 kg/season.

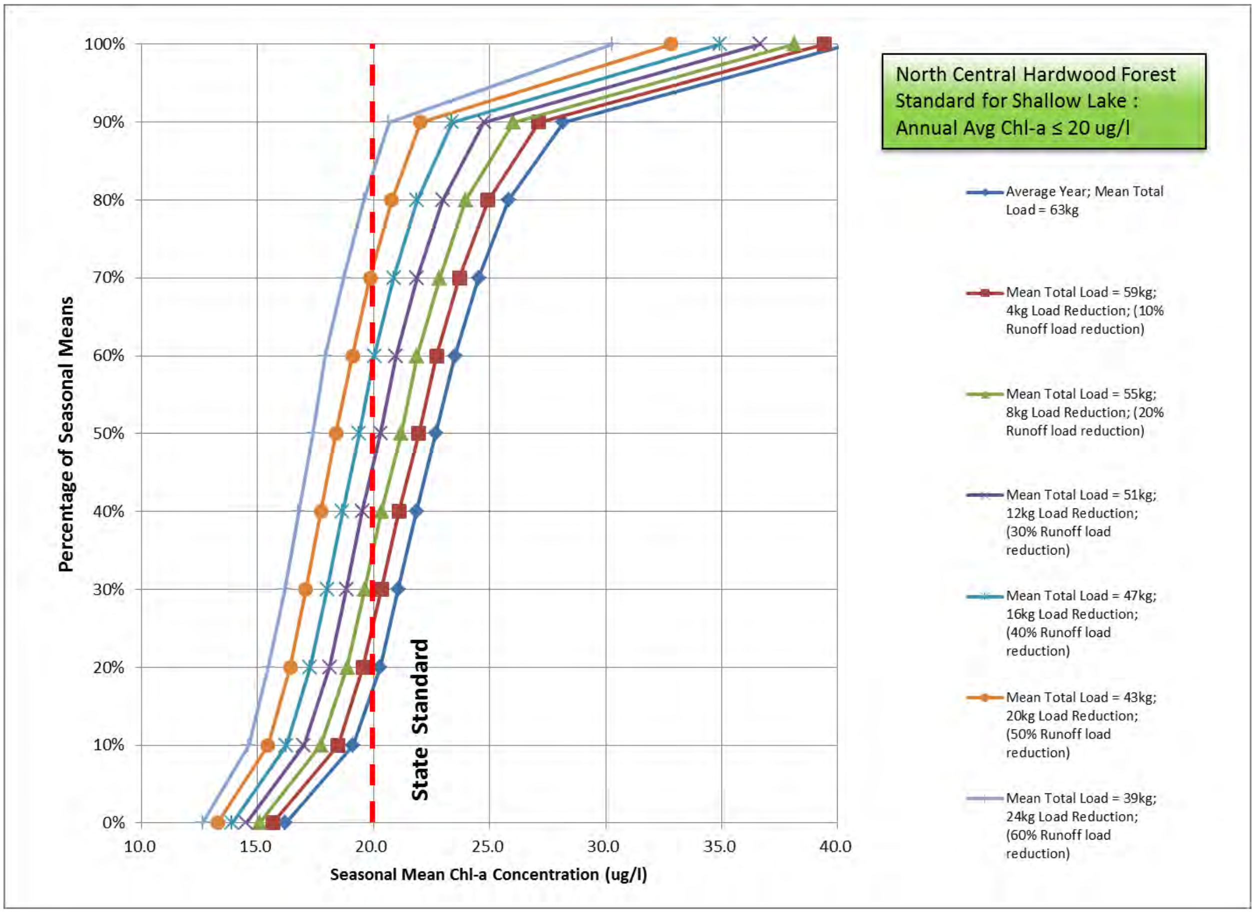


Figure 17. Existing Conditions Ravine Lake summer season mean secchi disk depth under select load reduction scenarios; Current Conditions = 63 kg/season.

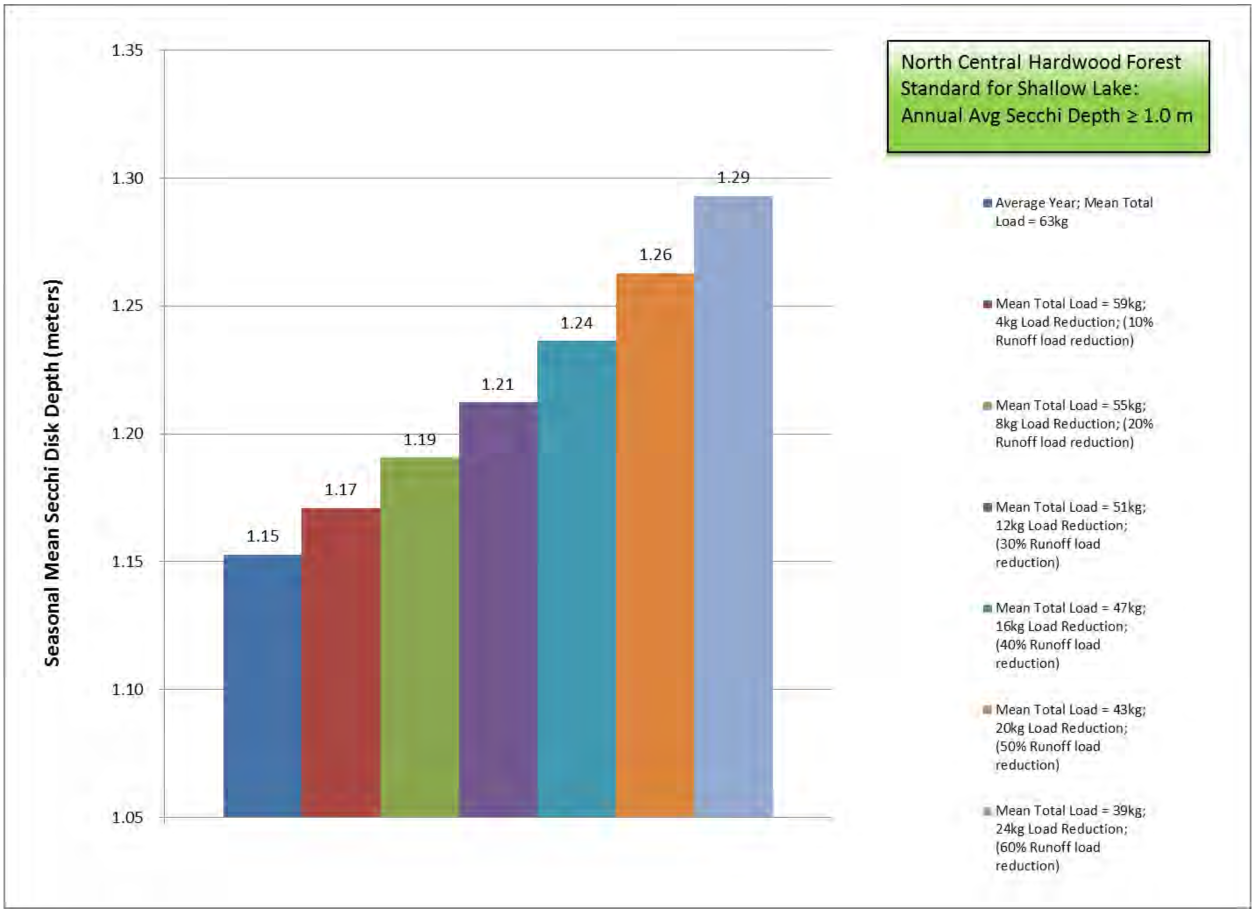
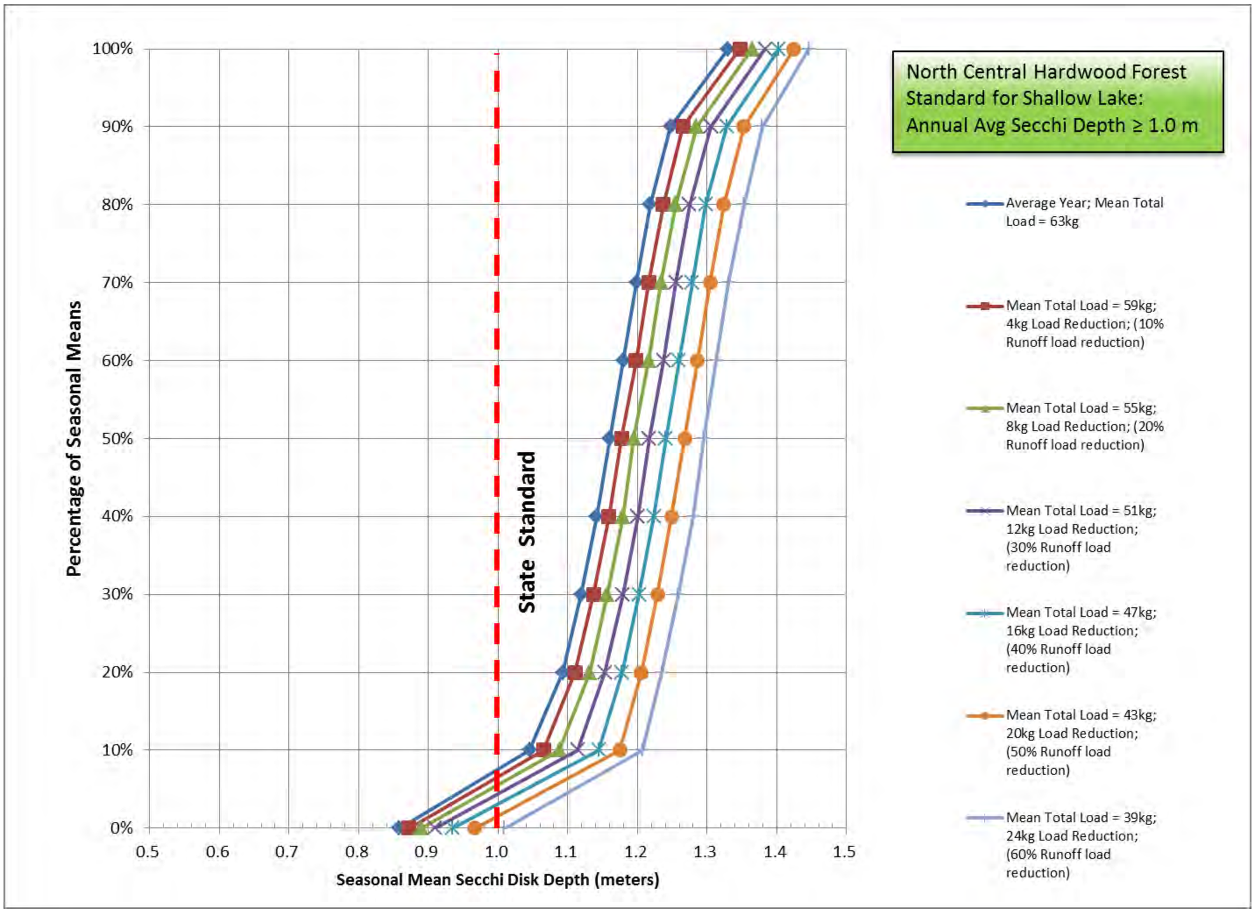


Figure 18. Existing Conditions Ravine Lake frequency distribution of summer season mean secchi disk depth under select load reduction scenarios; Current Conditions = 63 kg/season.



4.1.2 Ravine Lake Loading Capacity under Existing Conditions

The loading capacity is defined as the maximum allowable TP load to a lake that can occur while still achieving the in-lake TP water quality numeric standard of the MPCA, 60 ug/l. The SWWD also has a goal for Ravine Lake that the TSI value range between 63 and 66, correlating to a TP concentration of 59.2-72.9 ug/l. Since the State standard 60 ug/l is generally more stringent than the SWWD's goal, it will be the basis for computing the allowable load to the lake. Although this study is not, technically a TMDL study, the function of a loading capacity defined here replicates that developed under a TMDL. Given the similarity between this work and a TMDL, the loading capacity computed for Ravine Lake is allocated between non-point sources (i.e., the load allocation – LA – in a TMDL study), point sources (i.e., the wasteload allocation – WLA – in a TMDL study), and a margin of safety (MOS). The LA component of the loading capacity includes existing and future nonpoint sources (i.e., atmospheric deposition and internal load); the WLA component includes storm-sewered and overland runoff from the Ravine Lake watershed. The

MOS used is an explicit expression, intended to reflect the lack of knowledge and uncertainty in establishing the load capacity.

In this study, the loading capacity of Ravine Lake was computed using a stochastic approach based on the hydrology and water quality simulated by the P8 and CNET modeling. The loading capacity (allowable load) of the lake was defined as that which reduces the seasonal mean TP concentration for the 50th percentile non-exceedance value to under the MPCA numeric standard (60 ug/l). Since the loading capacity of Ravine Lake is computed using a stochastic approach (which takes uncertainty and variability into consideration), the MOS was computed as 5% of the allowable load.

Results of the loading capacity analysis are shown in **Figure 14**. The red line at 60 ug/L represents the average summer season TP concentration eutrophication standard for the protection of lake quality in shallow Class 2 surface waters in the NCHF ecoregion. Likewise, the shaded area shows the range of desired concentrations based on the SWWD's desired TSI range for Ravine Lake. **Table 8** shows the values used to produce **Figure 14**. Results of this analysis show that the loading capacity of Ravine Lake under existing conditions is 55 kg/season. Achieving this load would require an 8 kg (20%) reduction in the summer season surface water runoff TP load. **Table 9** shows the load allocations that would be employed if Ravine Lake were to be evaluated as a TMDL-listed water body. The summer season daily values presented in **Table 9** were computed based on seasonal values shown in **Figure 14** and **Table 8**.

Table 9. Existing Conditions Ravine Lake Loading Capacity to Meet State Water Quality Standards.

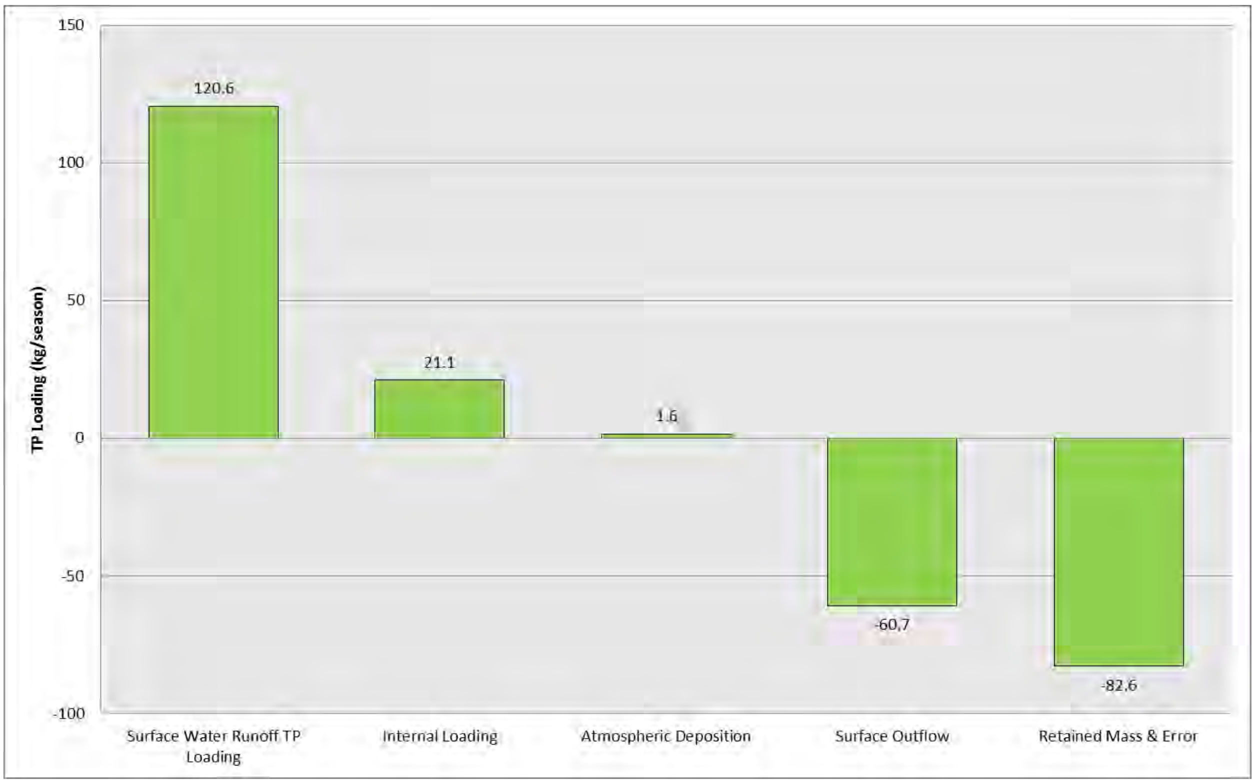
	Loading (kg/day)	**=**	**Load Allocation (kg/day)**	**+**	**Wasteload Allocation (kg/day)**	**+**	**Margin of Safety (kg/day)**
Current Condition (63 kg; 122 days)	0.516	=	0.188	+	0.328	+	0
Goal: 60 ug/L (55 kg; 122 days)	0.451	=	0.188	+	0.240	+	0.023

As summarized in **Table 9**, it is estimated that the current 0.516 kg/day summer season TP load to Ravine Lake would have to be reduced to 0.451 kg/day. Under this scenario, the wasteload allocation (storm-sewered runoff from the watershed) would have to be reduced from 0.328 to 0.240 kg/day (40 to 29 kg/season), allowing for the 5% MOS. The wasteload allocation represents what is considered a technically feasible reduction through the installation of best management practices (BMPs) as the watershed further develops. If the entire load reduction is achieved through reductions in WLA, then no reduction in LA is necessary, which is comprised of both atmospheric and internal loading from the phosphorus-laden bottom sediments. In reality any combination of WLA and LA equaling 0.428 kg/day is able to achieve the loading capacity.

4.2 Ravine Lake Future Conditions CNET Modeling Response

Figure 19 shows the long-term average TP mass balance of Ravine Lake as computed in the Future Conditions CNET model. Results estimate that Ravine Lake would receive a total summer season TP loading of approximately 143.3 kg under this scenario. About 120.6 kg of that TP comes from surface water runoff; the other major source of TP remains the internal load at 21.1 kg. The CNET model estimates that 60.7 kg/season TP is removed (on average) from the system.

Figure 19. CNET long-term average (50-yr) Future Conditions Ravine Lake summer season TP mass balance.



4.2.1 Ravine Lake Eutrophication Response

Figure 20 through **Figure 25** and **Table 10** show the effects of reducing the simulated future summer season TP loads to Ravine Lake on the summer mean TP, chl-*a* and SD within the lake (based on the Future Conditions CNET model). Loads were reduced incrementally within the CNET model and assumed to come from the surface water runoff loading component of the mass balance. Results are presented both in terms of the average seasonal mean concentrations (as shown by the column graphs) and the predicted distributions of seasonal mean concentrations (shown as series of lines, where each line represents a different surface water runoff TP loading to the lake). As was the case with the Existing Conditions simulation, the simulated average load is slightly different compared to the 50-year average (140 kg vs. 143.3 kg). This is again due to the nature of the input statistical distributions used in the simulation. The average seasonal surface water loading in the Monte Carlo simulations is approximately 117 kg.

Figure 20. Future Conditions Ravine Lake summer season mean TP concentrations under select load reduction scenarios; Future Conditions = 140 kg/season.

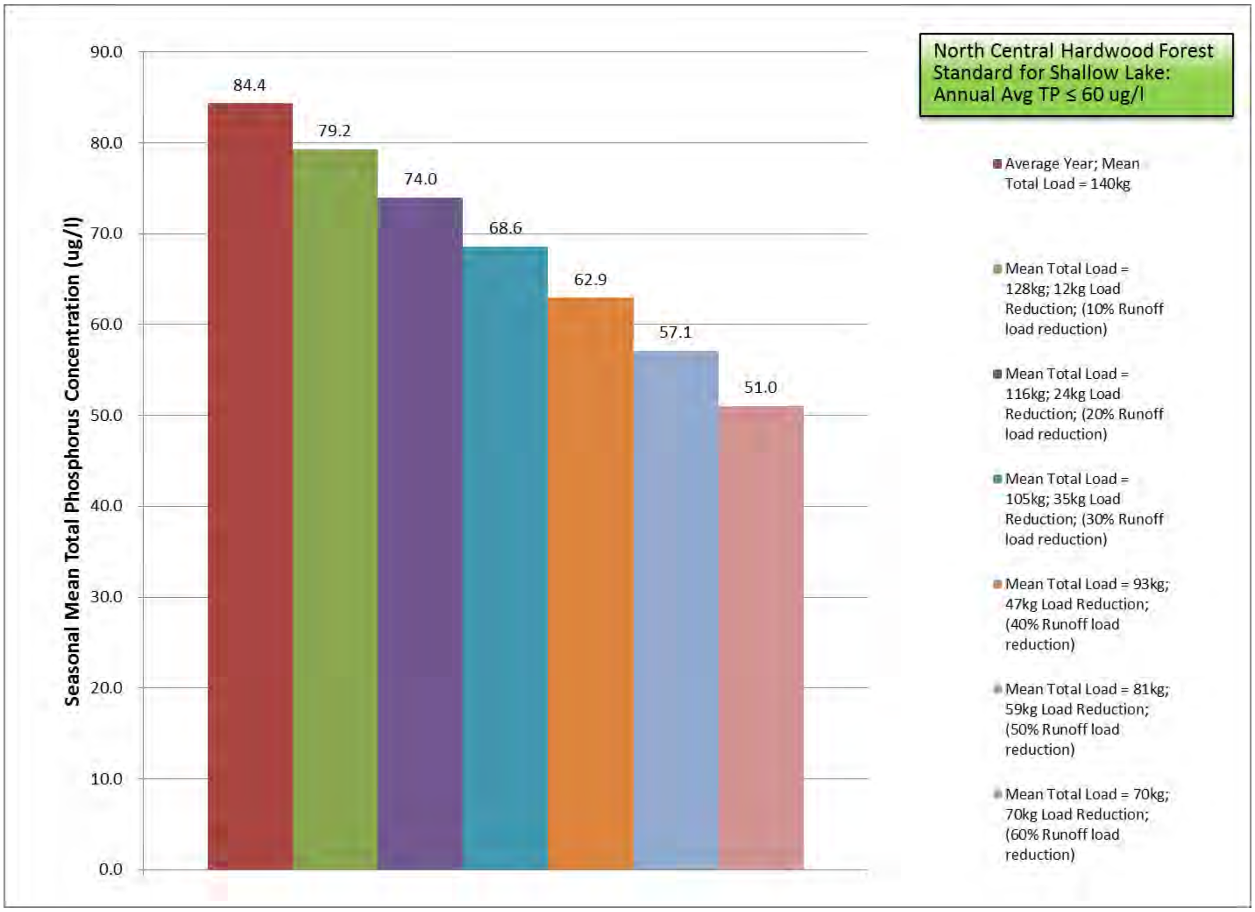


Figure 21. Future Conditions Ravine Lake frequency distribution of summer season mean TP concentrations resulting from select load reduction scenarios; Future Conditions = 140 kg/season.

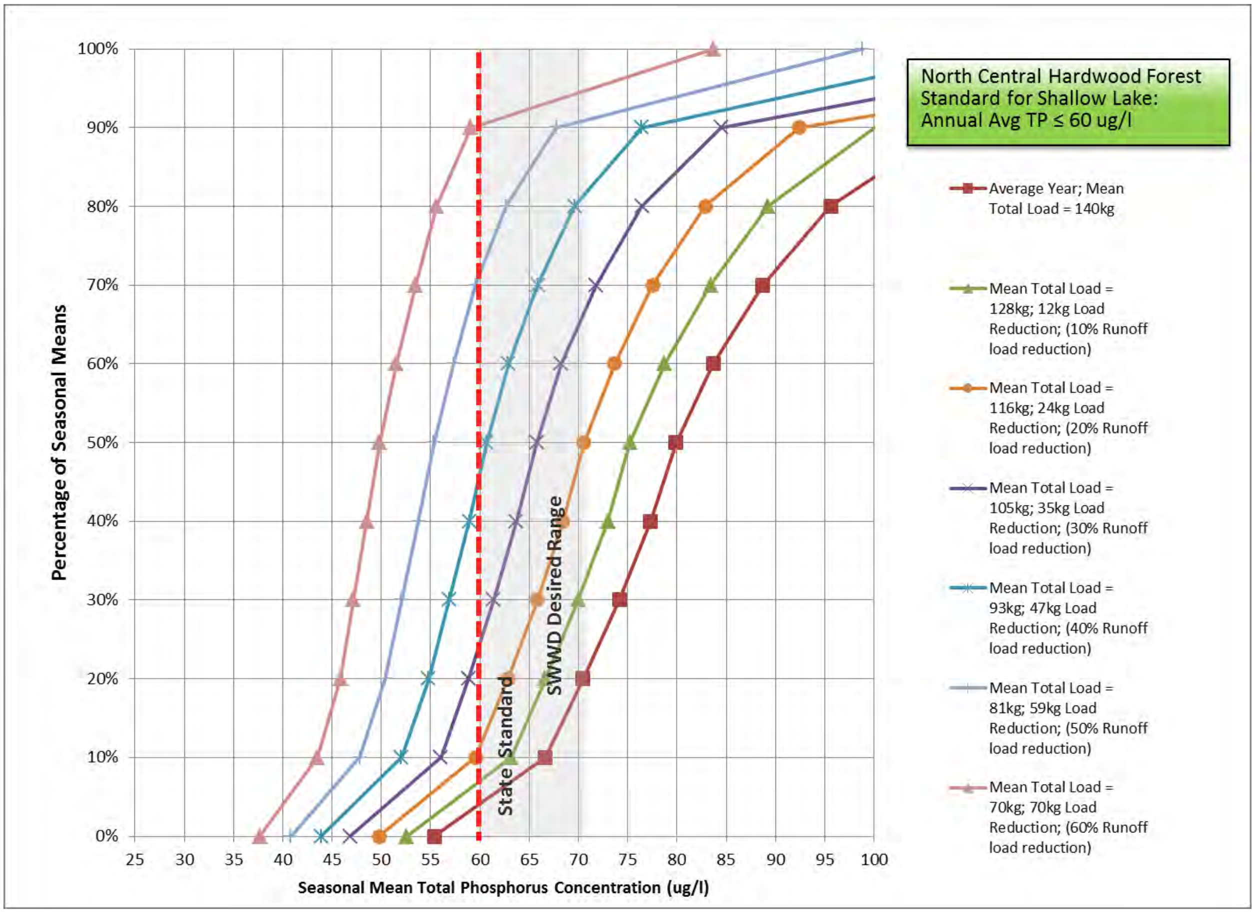


Table 10. Future Conditions Monte Carlo simulation TP loading reduction results.

Non-Exceedance Percentile	Average Summer Season TP Concentration (ug/L) (current)	Average Summer Season TP Concentrations (ug/L) for Load Reduction from Current Load; Average Summer Season					
		12 kg	24 kg	35 kg	47 kg	59 kg	70 kg
Mean	84.4	79.2	74.0	68.6	62.9	57.1	51.0
0%	55.4	52.6	49.8	46.9	43.9	40.8	37.7
10%	66.6	63.2	59.6	56.0	52.0	47.8	43.5
20%	70.5	66.6	62.8	58.9	54.8	50.4	45.8
30%	74.1	70.0	65.8	61.4	56.9	52.0	47.1
40%	77.3	73.0	68.4	63.7	58.9	53.8	48.5
50%	79.9	75.2	70.6	65.8	60.7	55.4	49.8
60%	83.7	78.8	73.7	68.2	62.9	57.3	51.5
70%	88.7	83.4	77.6	71.8	65.9	59.6	53.5
80%	95.6	89.3	82.9	76.5	69.6	62.7	55.6
90%	82.8	100.1	92.4	84.5	76.5	67.8	59.1
100%	159.8	153.4	140.5	127.1	113.3	98.9	83.8

Figure 22. Future Conditions Ravine Lake summer season mean chl-*a* concentrations under select load reduction scenarios; Future Conditions = 140 kg/season.

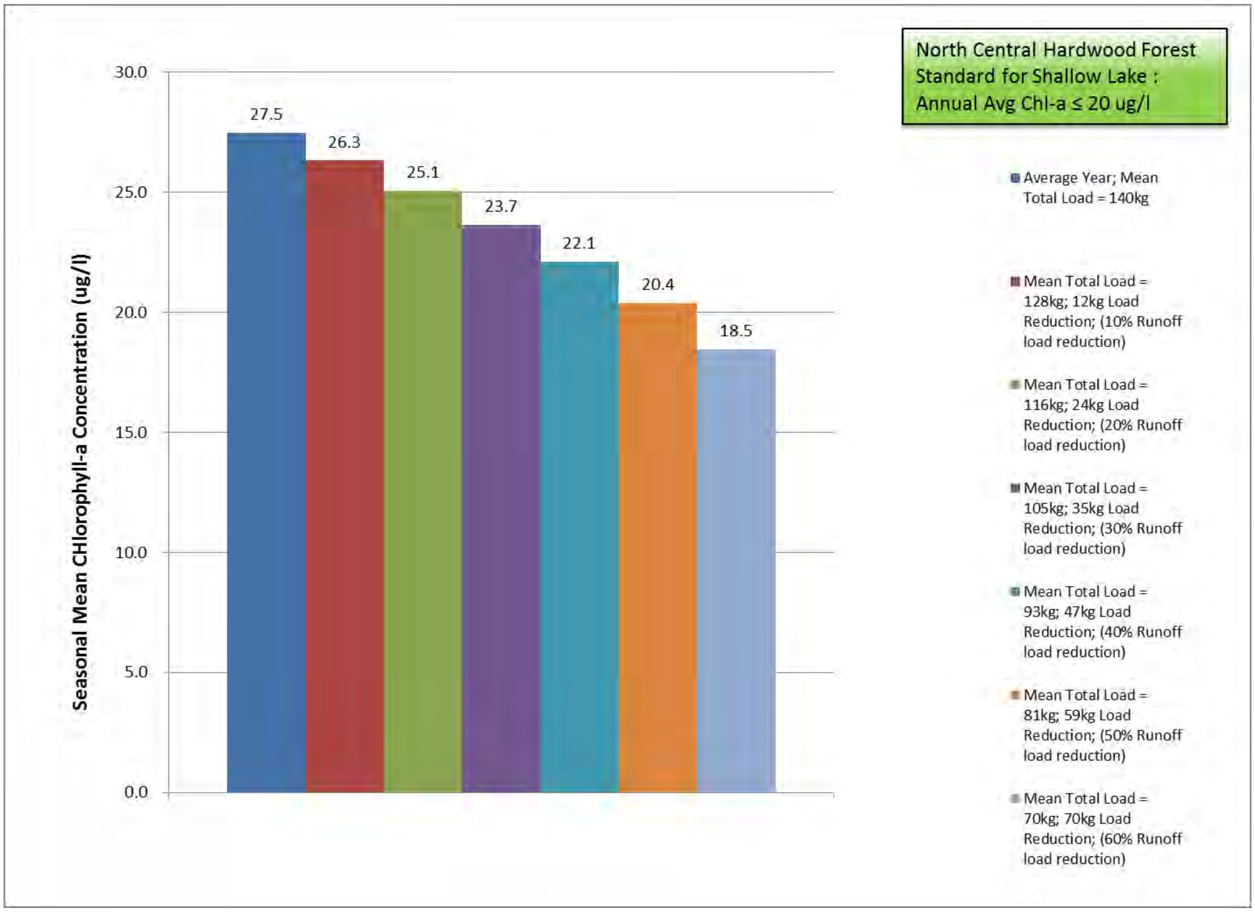


Figure 23. Future Conditions Ravine Lake frequency distribution of summer season mean chl-*a* concentrations under select load reduction scenarios; Future Conditions = 140 kg/season.

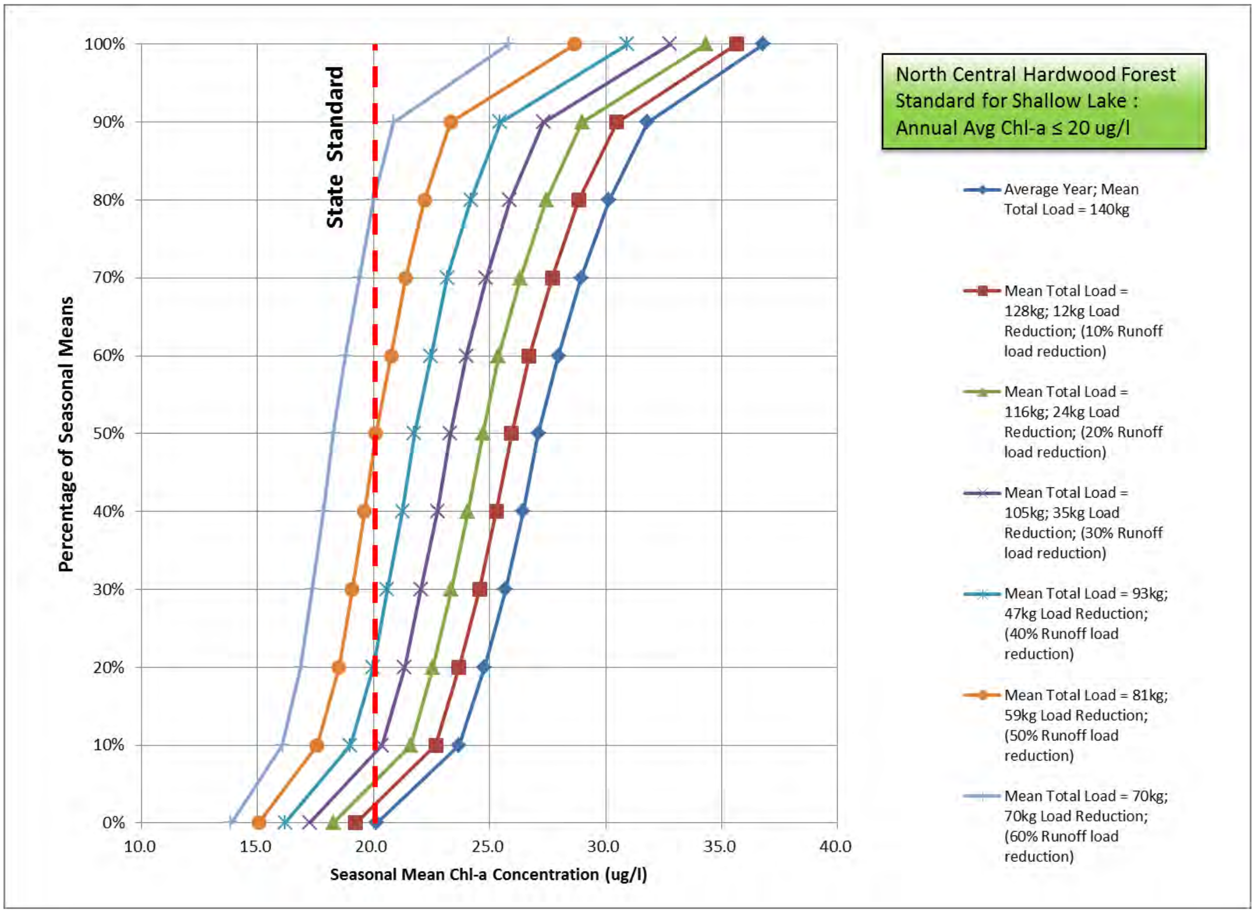


Figure 24. Future Conditions Ravine Lake summer season mean secchi disk depth under select load reduction scenarios; Future Conditions = 140 kg/season.

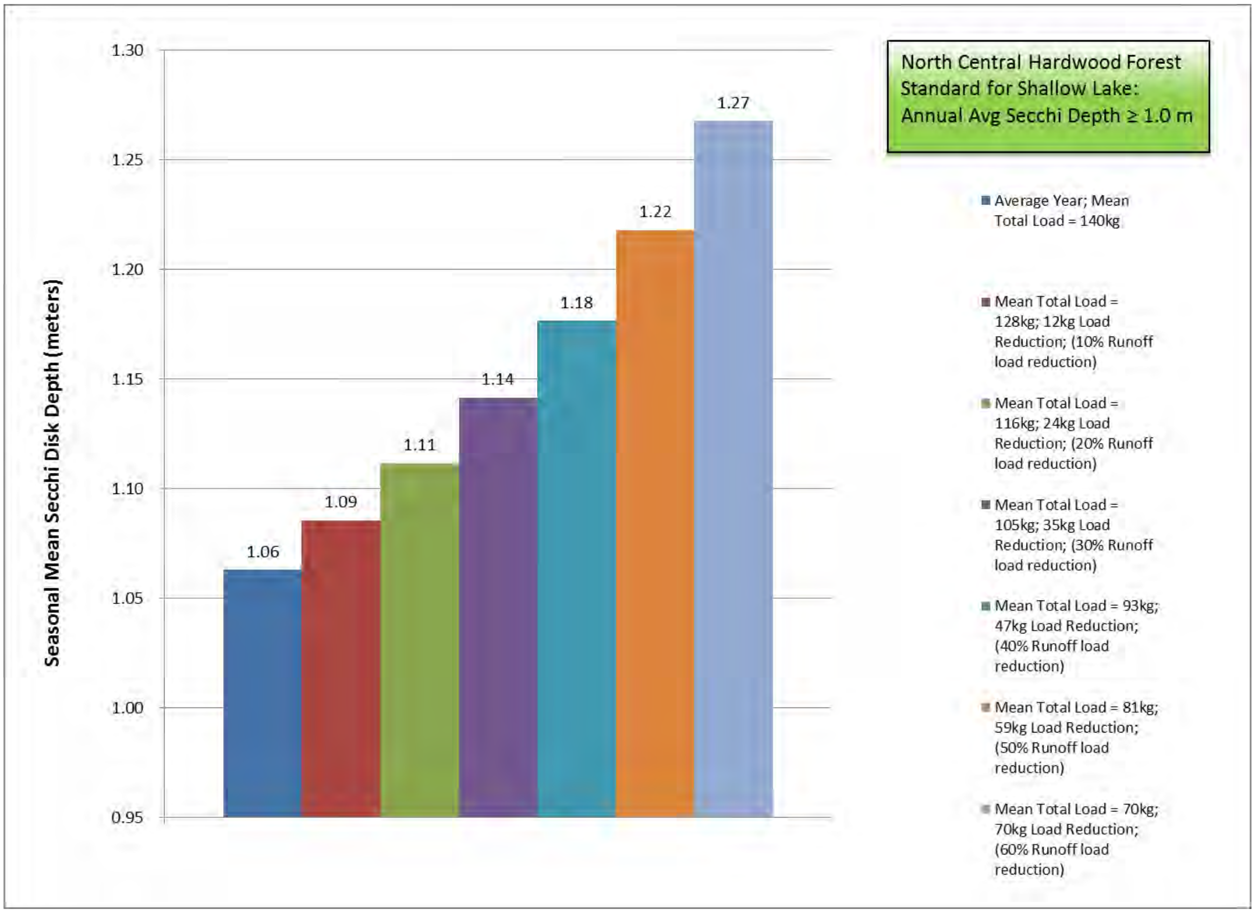
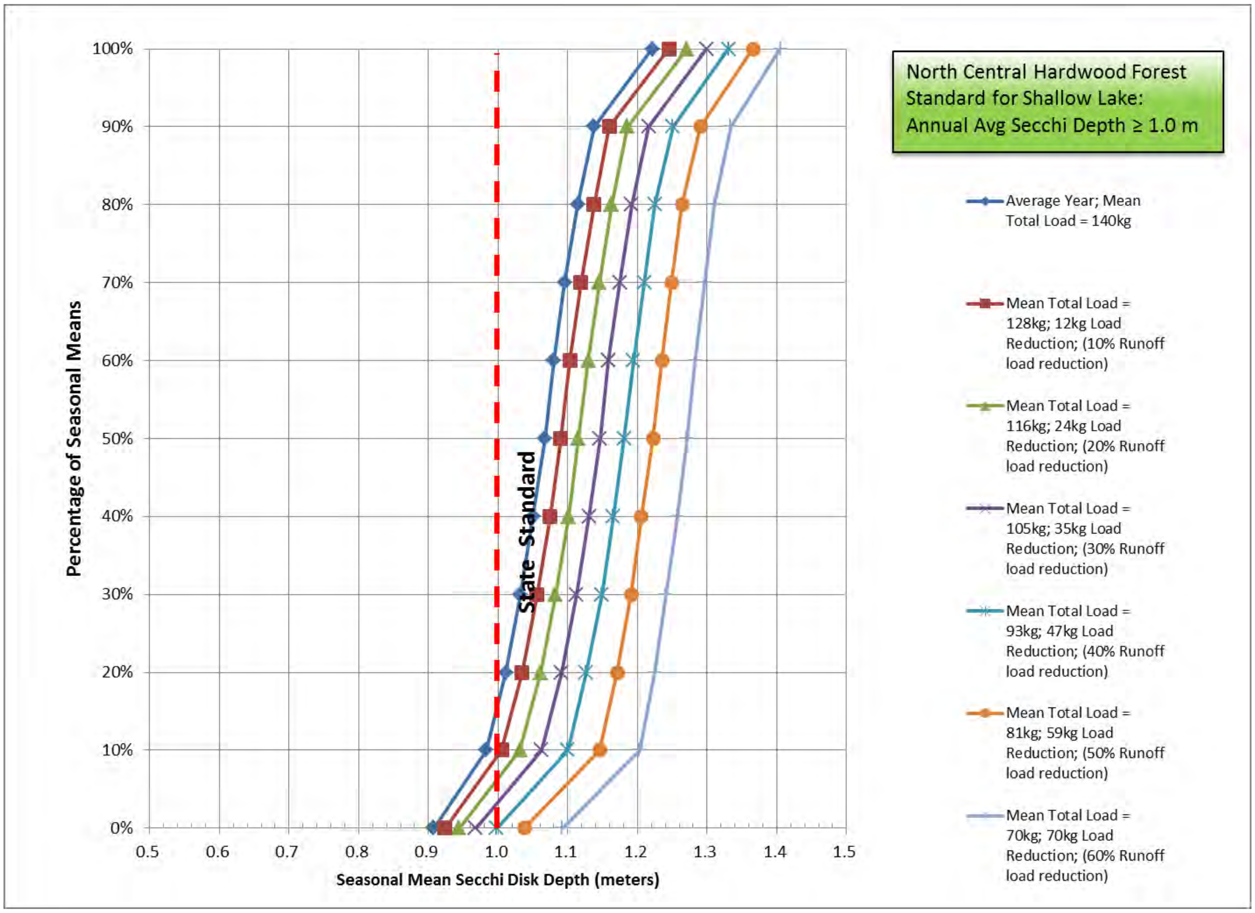


Figure 25. Future Conditions Ravine Lake frequency distribution of summer season mean secchi disk depth under select load reduction scenarios; Future Conditions = 140 kg/season.



4.2.2 Ravine Lake Loading Capacity under Future Conditions

A similar loading capacity analysis was performed using the results of the Future Conditions model. Results of the loading capacity analysis are shown in **Figure 21**. The red line at 60 ug/L represents the average summer season TP concentration eutrophication standard for the protection of lake quality in Class 2 surface waters in the NCHF ecoregion. Likewise, the shaded area shows the range of desired concentrations based on the SWWD's desired TSI values for Ravine Lake. **Table 10** shows the values used to produce **Figure 21**. Results of this analysis show that the loading capacity of Ravine Lake under the future condition scenario is 81 kg/season, requiring a 59 kg (50%) reduction in the summer season surface water runoff TP loading. The loading capacity of the lake under the future condition is higher than that under the existing condition (81 kg/season vs. 55 kg/season) since the lake is also receiving more water under the future condition and the hydraulic residence time drops from an average of approximately 9 months to 4 months; the eutrophication response in the lake is altered due to this change.

5.0 IMPLEMENTATION TO ACHIEVE THE LOADING CAPACITY

5.1 Existing Conditions

There are any number of implementation scenarios under which the loading capacity of Ravine Lake (under existing conditions) can be achieved. The information presented in **Section 4.1.2** assumes that all of the required load reduction in the watershed will come from watershed-based BMPs, as these are typically easier to implement than reductions in internal lake TP loading. However, in reality, any combination of watershed-based and in-lake load reductions that achieve an average summer season loading of 0.421 kg/day will meet the loading capacity of the lake.

Assuming the SWWD will first focus implementation efforts on the watershed, the surface water TP loading in the Ravine Lake watershed needs to be reduced by approximately 28% (this includes the 5% MOS as detailed in **Table 9**) to achieve State water quality standards. Innumerable watershed-based BMP implementation scenarios could be employed to achieve these reductions. **Figure 26** shows the simulated 50-year average annual TP yields (from the Existing Conditions model) for the subwatersheds in the study area. Results in this map show the estimated untreated (i.e., not routed through the modeled devices) yields and include values from the outlier year of 1987. While not directly comparable to the water quality standards set by the SWWD in their WMP (since the yields are not routed; SWWD, 2007), these values are useful in identifying priority management areas in the watershed by highlighting those subwatersheds where higher vs. lower TP yields are seen.

Figure 27 shows the amount of TP exiting each modeled device on an average annual basis (based on the 50-years of results). These results can be useful in identifying devices where large amounts of TP are released downstream, highlighting devices that may need additional treatment added or implemented upstream. **Figure 27** also reiterates information shown in **Figure 2**, indicating that a large portion of the Ravine Lake watershed (including the area upstream of Vandeberg Lake and two subwatersheds south of the lake that flow north) is non-contributing to Ravine Lake under existing conditions. Average annual TP outflows from Vandeberg Lake are simulated as zero.

Figure 26. Existing Conditions Model 50-Year Average Subwatershed (Untreated) Unit TP Yield Values

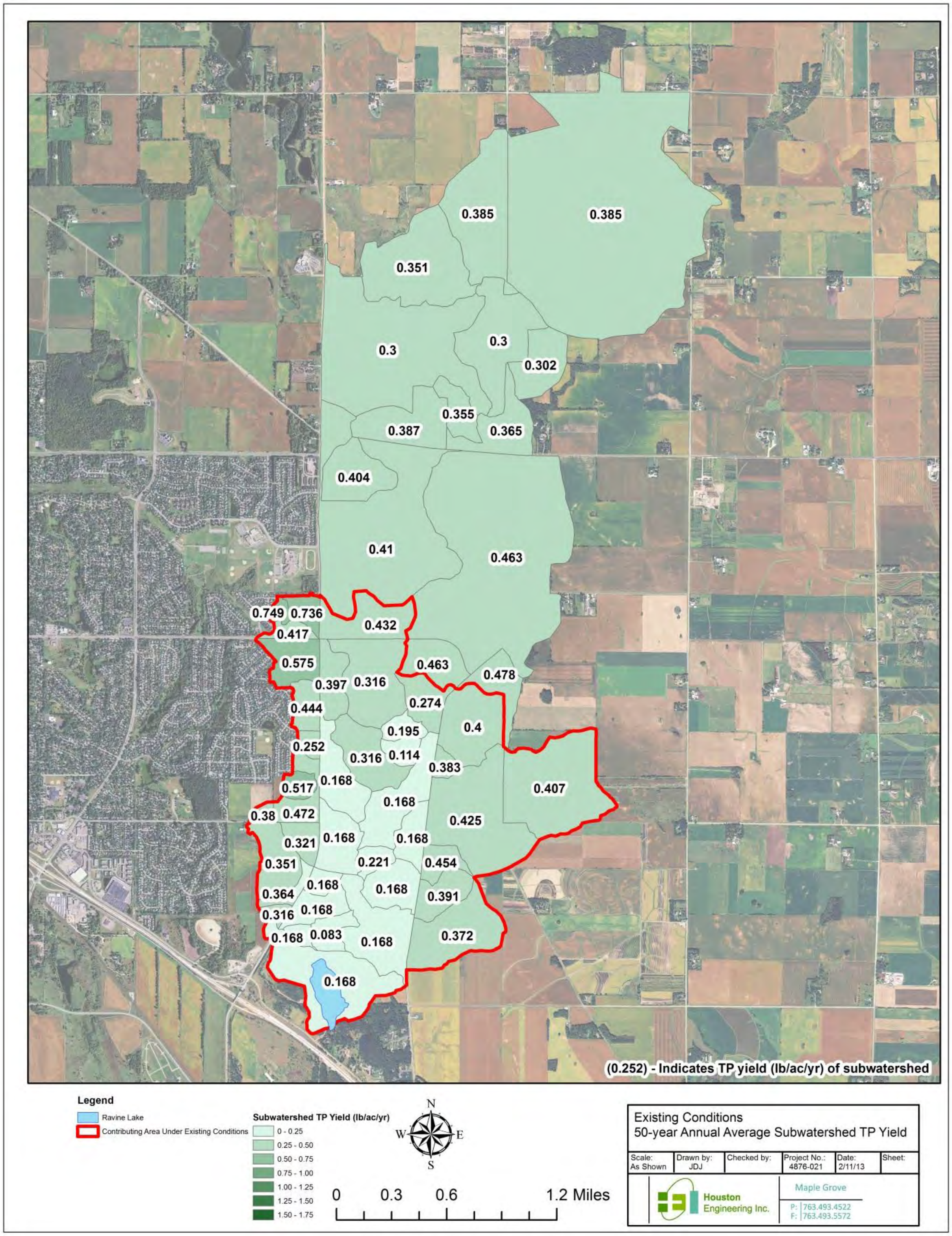
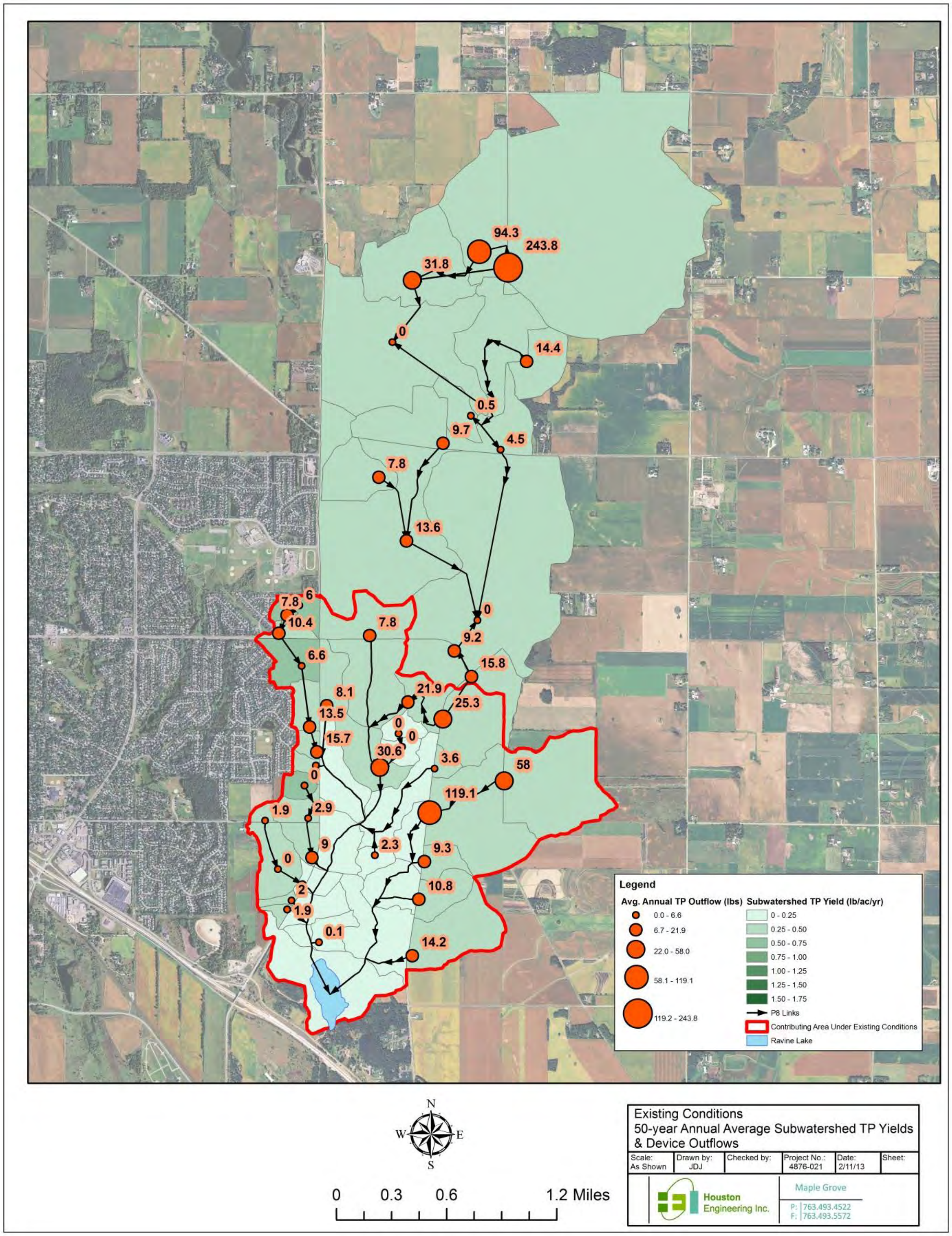


Figure 27. Existing Conditions Model 50-Year Average Device TP Outflow (lbs/year)



The SWWD WMP identifies acceptable annual (treated) unit loads within the Ravine Lake watershed of 0.04 lbs/ac/year (SWWD, 2007). Results of this analysis can be used to update that number to an acceptable annual (treated) surface water TP loading rate of 0.093 lb/ac/year, based on the summer season surface water runoff load allocation (**Table 9**) of 29 kg, a contributing area of 1,704 acres, and an average seasonal TP loading:annual TP loading ratio of 2.49 (computed from the Existing Conditions P8 model outputs). Comparing this result to the TP unit yields shown in **Figure 26** provides an estimate of the amount of TP treatment required in each subwatershed.

5.2 Future Conditions

The SWWD's WMP identifies a stormwater runoff volume standard that new developments "maintain the annual average predevelopment infiltration capacity of the site". The application of this standard is to maintain "the total runoff volume determined from typical climatic conditions", judged using precipitation data from 1979 (SWWD, 2007). As discussed in the P8 modeling report, included as **Appendix A**, results of the Future Conditions model show significant changes in the Ravine Lake watershed under the future conditions scenario. **Table 11** summarizes some of these differences, showing the increased volume of surface water that is forecasted to reach Ravine Lake, as well as the increased surface water TP loads.

Table 11. Ravine Lake input comparison between Existing Conditions and Future Conditions P8 models.

	Existing Conditions Model	Future Conditions Model
% Developed*	8.7%	38.4%
Contributing Area (acres)	1,704	2,944
1979		
Summer Seasonal Volume (acre-feet)	74	353
Summer Seasonal TP Load (lbs)	73	210
Annual Volume (acre-feet)	393	1,419
Annual TP Load (lbs)	239	606
Annual Unit Runoff (in/acre)	2.77	5.78
Annual Unit TP Load (lb/acre)	0.14	0.21
1962-2011		
Average Summer Seasonal Volume (acre-feet)	103	429
Average Summer Seasonal TP Load (lbs)	186	416
Average Annual Volume (acre-feet)	262	982
Average Annual TP Load (lbs)	281	696
Average Annual Unit Runoff (in/acre)	1.84	4.00
Average Annual Unit TP Load (lb/acre)	0.16	0.24

* Developed includes only land classified as "urban", based on entire Ravine Lake watershed

Figure 28 shows the simulated future 50-year average annual TP yields (from the Future Conditions model) for the subwatersheds in the study area. Similar to what's shown in **Figure 26**, results in this map show the estimated untreated yields and include values from the outlier year of 1987. **Figure 29** shows the amount of TP exiting each modeled device on an average annual basis. Comparing the results shown in **Figure 28** with those in **Figure 26** provides insight on where the additional flows simulated in the future conditions scenario originate.

As detailed in **Section 4.2.2**, the loading capacity of Ravine Lake under the future condition scenario increases to 81 kg/season due to the additional flows reaching the lake and the subsequent reduction in residence time. Per the District's standards, however, this magnitude of additional flow to the lake should not be allowed to occur, due to the need for stormwater runoff volume control. **Figure 30** and **Figure 31** show the (untreated) unit runoff values during 1979 per the Existing Conditions and Future Conditions P8 models, respectively, highlighting those areas where large increases in unit runoff due to future development are seen. **Figure 32** and **Figure 33** show the amount of surface water exiting each modeled device during 1979, highlighting those devices where large increases in flows are seen between the Existing and Future Conditions models. As discussed in the P8 modeling report (**Appendix A**), two main changes in the hydraulics between existing and future conditions are responsible for the increased flows (and also the increase in the lake's contributing area): the inclusion of a pump at Vandeberg Lake (EW1-2A) and the addition of a 72" pipe connecting model device CP4-3 (in the west-central part of the watershed) to RL2-15C. A comparison of **Figure 32** and **Figure 33** shows this change. **Figure 32** shows the area north and two subwatersheds south of Vandeberg Lake as non-contributing (under the existing condition). **Figure 33** shows considerable flow volume leaving Vandeberg Lake and CP4-3 in 1979 (under the future condition).

Figure 28. Future Conditions Model 50-Year Average Subwatershed (Untreated) Unit TP Yield Values

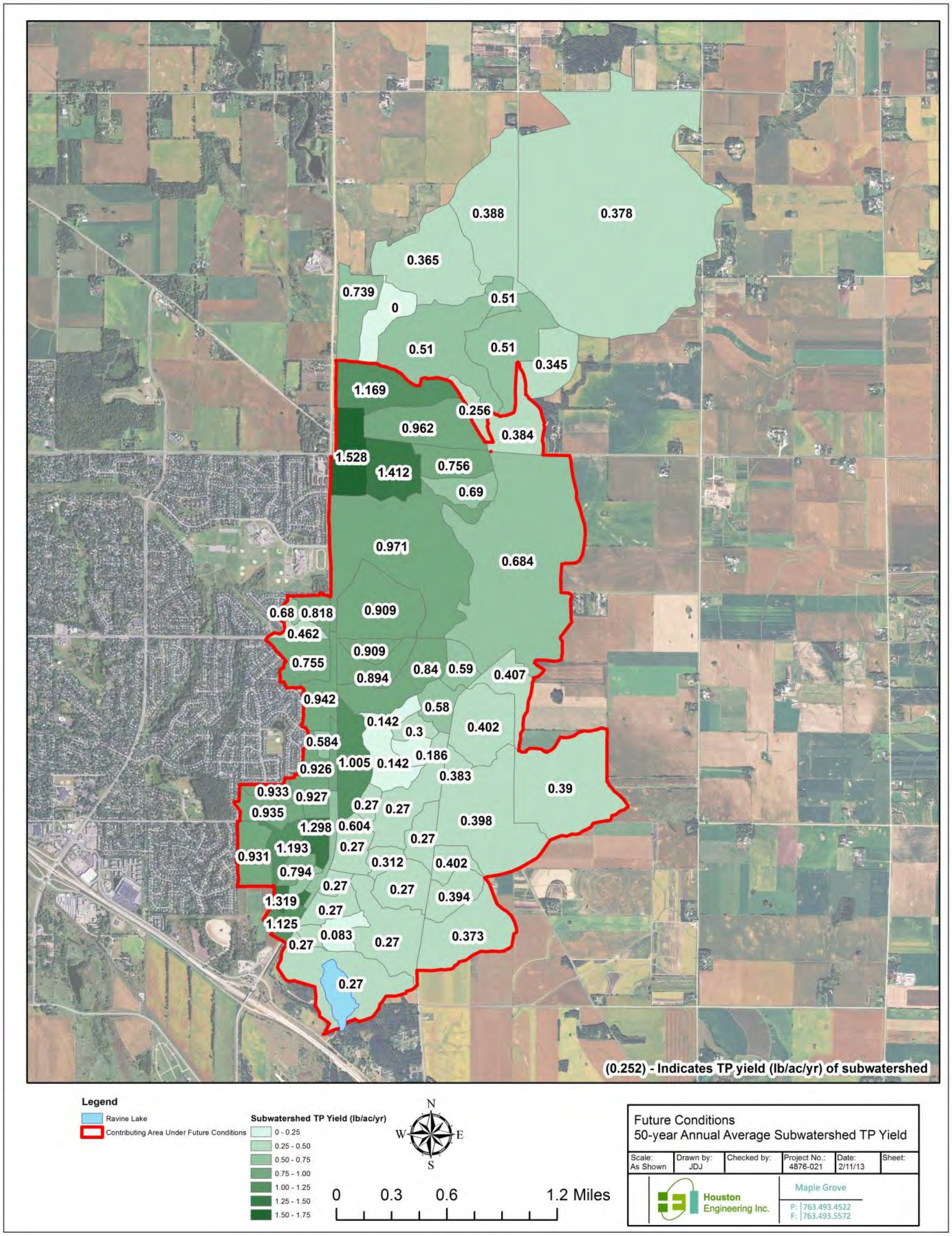


Figure 29. Future Conditions Model 50-Year Average Device TP Outflow (lbs/year)

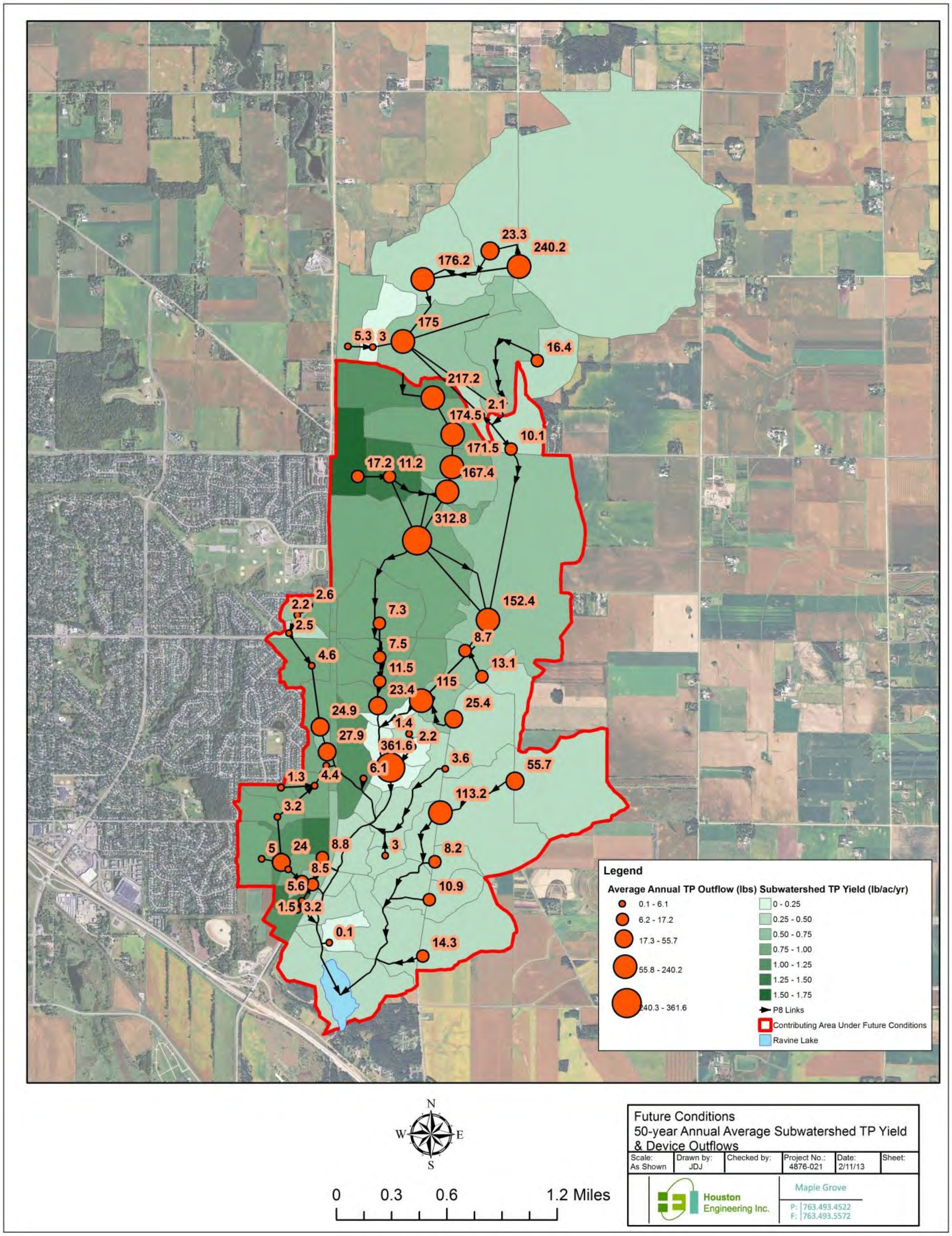


Figure 30. Existing Conditions Model 1979 Subwatershed (Untreated) Unit Runoff Values

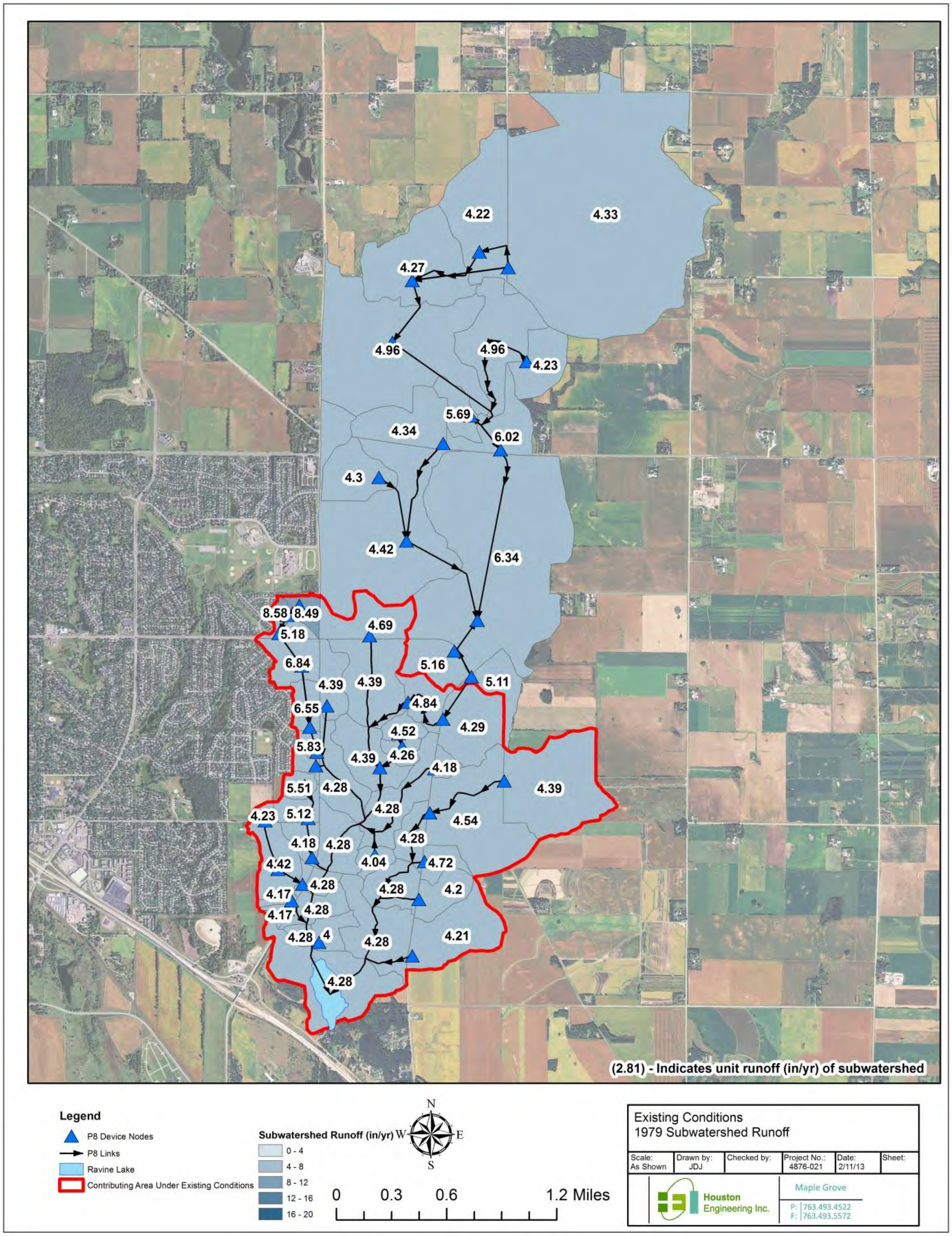


Figure 31. Future Conditions Model 1979 Subwatershed (Untreated) Unit Runoff Values

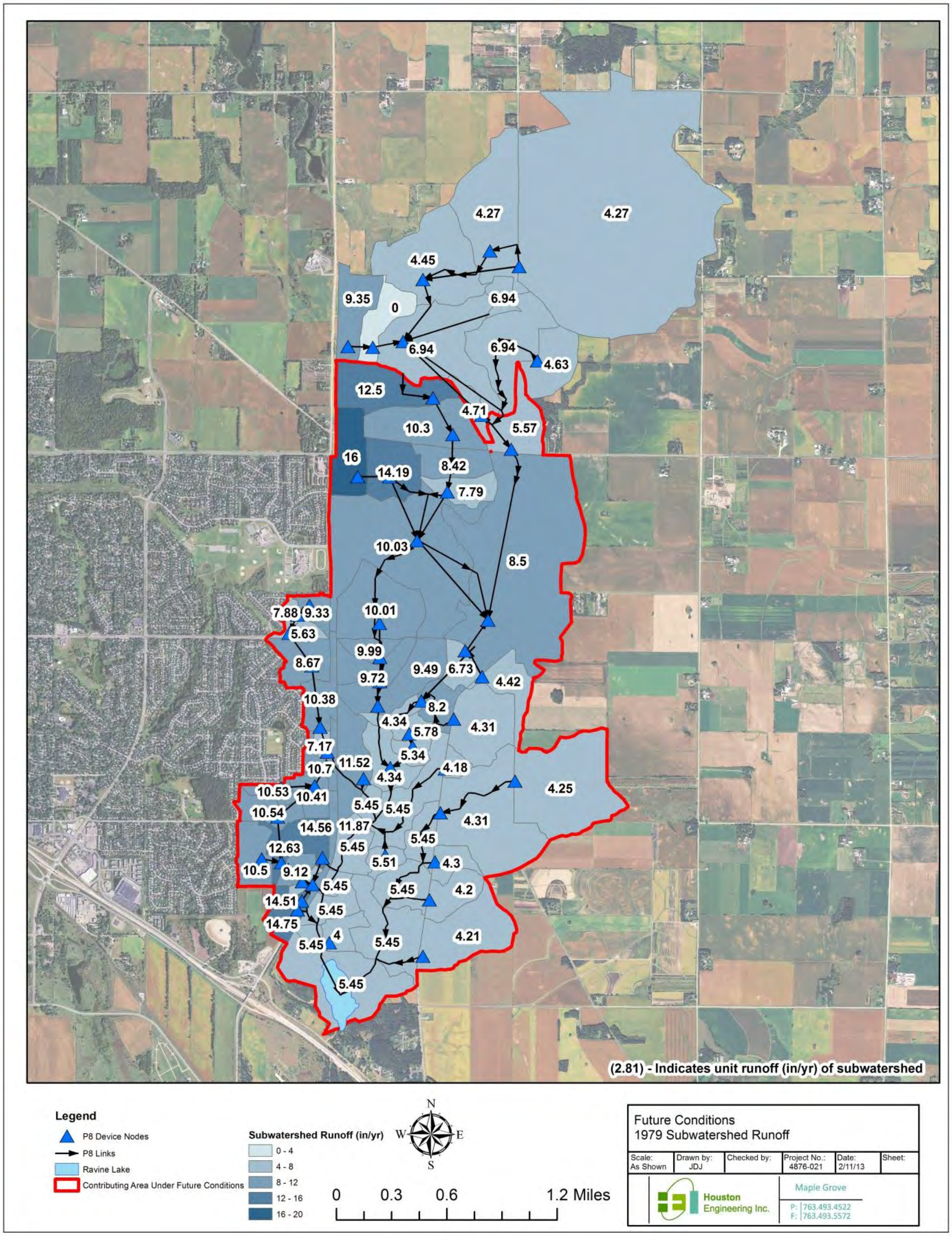


Figure 32. Existing Conditions Model 1979 Device Surface Water Outflow

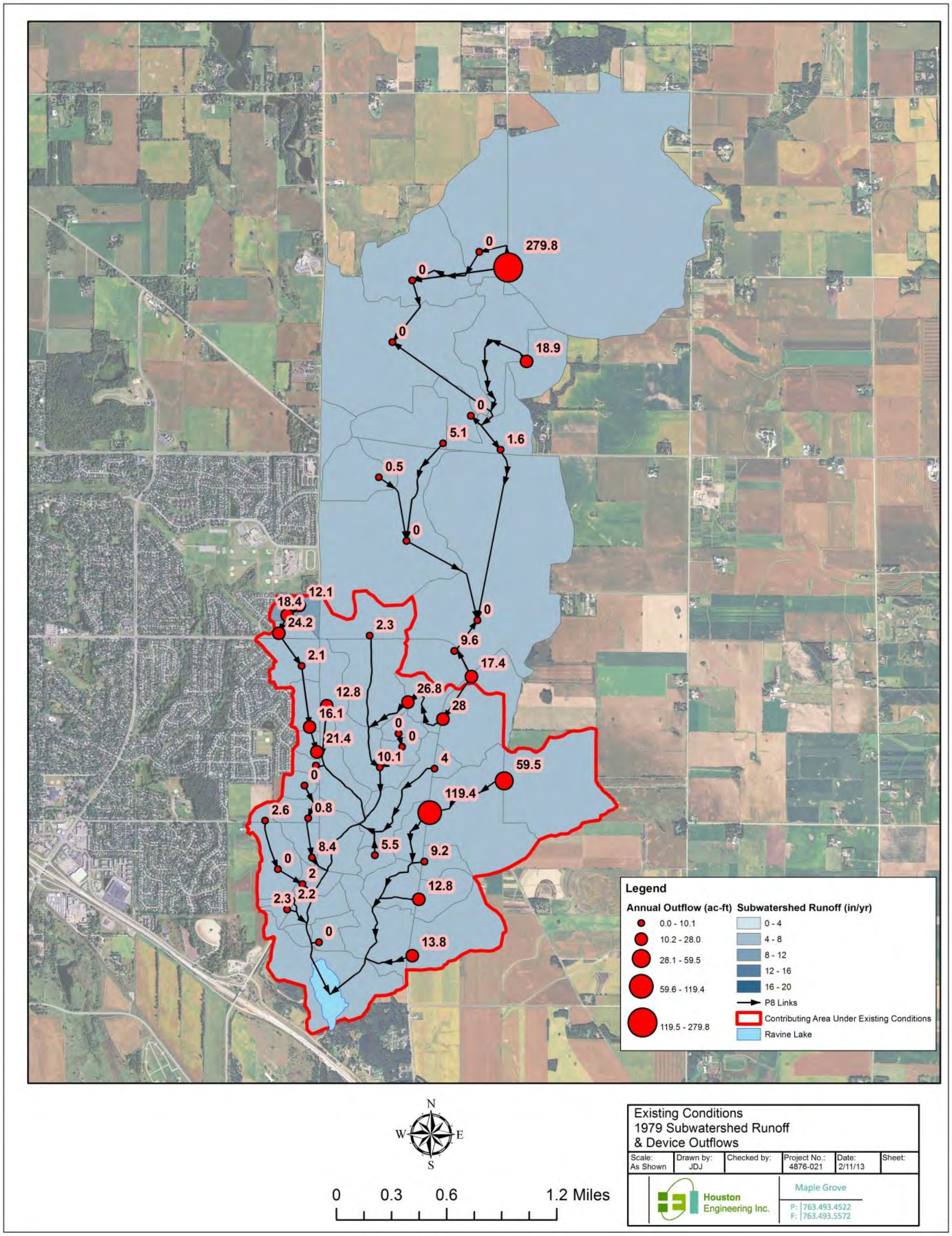
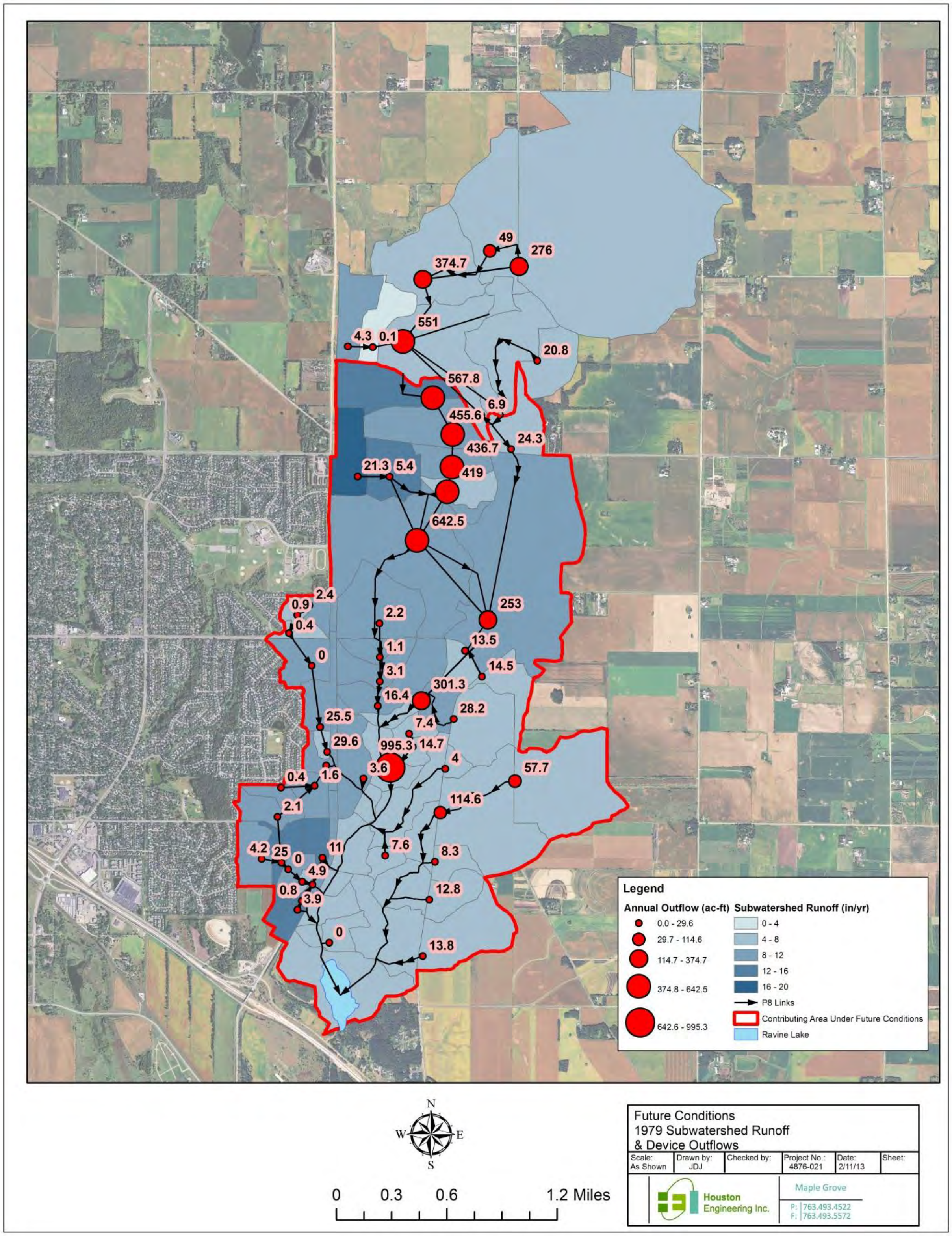


Figure 33. Future Conditions Model 1979 Device Surface Water Outflow



5.2.1 Adjusted Infiltration Watershed and CNET Models

To account for SWWD's stormwater runoff volume standard, the Future Conditions P8 model was modified to simulate additional treatment in key areas of the Ravine Lake watershed with a goal of matching their simulated future and existing runoff volumes in 1979. This new model was called the Adjusted Infiltration P8 model, since the additional treatment was simulated by (artificially) increasing infiltration rates in select model devices to simulate volume control.

The purpose of the Adjusted Infiltration model is to simulate the Existing Conditions model runoff conditions to Ravine Lake (in 1979), given the Future Conditions subwatershed, treatment devices, and land classification. In order to do this, the 1979 runoff volumes simulated with the Existing Conditions model were compared to those from the Future Conditions model. It is important to note that while some watersheds remain unchanged in size and locations (cropland to the east and north), others (developed areas to the south and west) differ considerably (see the appendix in the P8 Modeling Report, in **Appendix A**, for more information on this). Professional judgment was used in evaluating overlapping subwatersheds and identifying locations at which to make the existing vs. future conditions comparisons. Devices outflows were compared and reductions in outflows were made by increasing infiltration rates within the devices in the Future Conditions model until similar 1979 outflows were achieved. By doing this, similar inflows into Ravine Lake under existing and future conditions are also achieved. The final simulated infiltration rates in the Adjusted Infiltration model varied by device, with a maximum simulated value of 2 in/hour. The intention of simulating increased infiltration was not to imply that the devices would actually be designed to this performance, but rather that a similar amount of treatment would be achieved within the subwatersheds draining to these devices through any number of different treatment options.

Results of the model adjustments are shown in **Table 12**; the Adjusted Infiltration P8 Model shows a 1% difference between simulated volumes into Ravine Lake under existing and future conditions during 1979 (this was considered sufficient for the purposes of this work). Due to the proposed future development in the Adjusted Infiltration P8 Model, the concentration of TP in the surface water entering Ravine Lake increased resulting in increased surface water TP loading to the lake under this scenario (**Table 12**).

Table 12. Ravine Lake input comparison between Existing Conditions and Adjusted Infiltration P8 models.

	Existing Conditions Model	Adjusted Infiltration Model
Contributing Area (acres)[1]	1,704	2,944
1979		
Summer Seasonal Volume (acre-feet)	74	101
Summer Seasonal TP Load (lbs)	73	103
Annual Volume (acre-feet)	393	398
Annual TP Load (lbs)	239	279
Annual Unit Runoff (in/acre)	2.77	2.80
Annual Unit TP Load (lb/acre)	0.14	0.16
1962-2011		
Average Summer Seasonal Volume (acre-feet)	103	146
Average Summer Seasonal TP Load (lbs)	186	279
Average Annual Volume (acre-feet)	262	313
Average Annual TP Load (lbs)	281	391
Average Annual Unit Runoff (in/acre)	1.84	1.28
Average Annual Unit TP Load (lb/acre)	0.16	0.13

[1] contributing area defined as any area that contributes flow that eventually enters Ravine Lake during the 50-year time period of model simulation. For the Adjusted Infiltration model, the contributing area value of 2,944 acres includes areas upstream of both CP4-3 and Vandeberg Lake.

Results of the Adjusted Infiltration P8 model are shown in **Figure 34** and **Figure 35**. As mentioned in the discussion of the Future Conditions model, the main changes between existing and future condition hydrology in the Ravine Lake Watershed (under this two scenarios) result from previously non-contributing areas in the upper part of the watershed now contributing flow. The main locations of this increased flow are at device CP4-3 and Vandeberg Lake (device EW1-2A). Although the Adjusted Infiltration model was developed to match outflows (between existing and future conditions) at these locations in 1979, the 50-year average outflow from these devices is still greater than zero (**Figure 34**). Examining the annual outflow from these devices shows that CP4-3 regularly contributes flow downstream during the simulated model period (outflows are non-zero for 37 of the 50-years of simulation; the average annual outflow is 15 acre-feet/year). However, Vandeberg Lake only contributes flow downstream three times in the 50-year period (one of those time is in 1987, which has been noted as an outlier in the model). For certain management purposes, the SWWD may decide to consider the subwatersheds draining through Vandeberg Lake as not contributing to Ravine Lake; the Ravine Lake contributing area under such a scenario would be 2,422 acres (including areas downstream of CP4-3 and Vandeberg Lake as well as those upstream of CP4-3). The contributing areas shown in **Figure 34** and **Figure 35** reflect the 2,422 acre area.

Figure 34. Adjusted Infiltration Model 50-Year Average Device Stormwater Outflow (acre-feet/year)

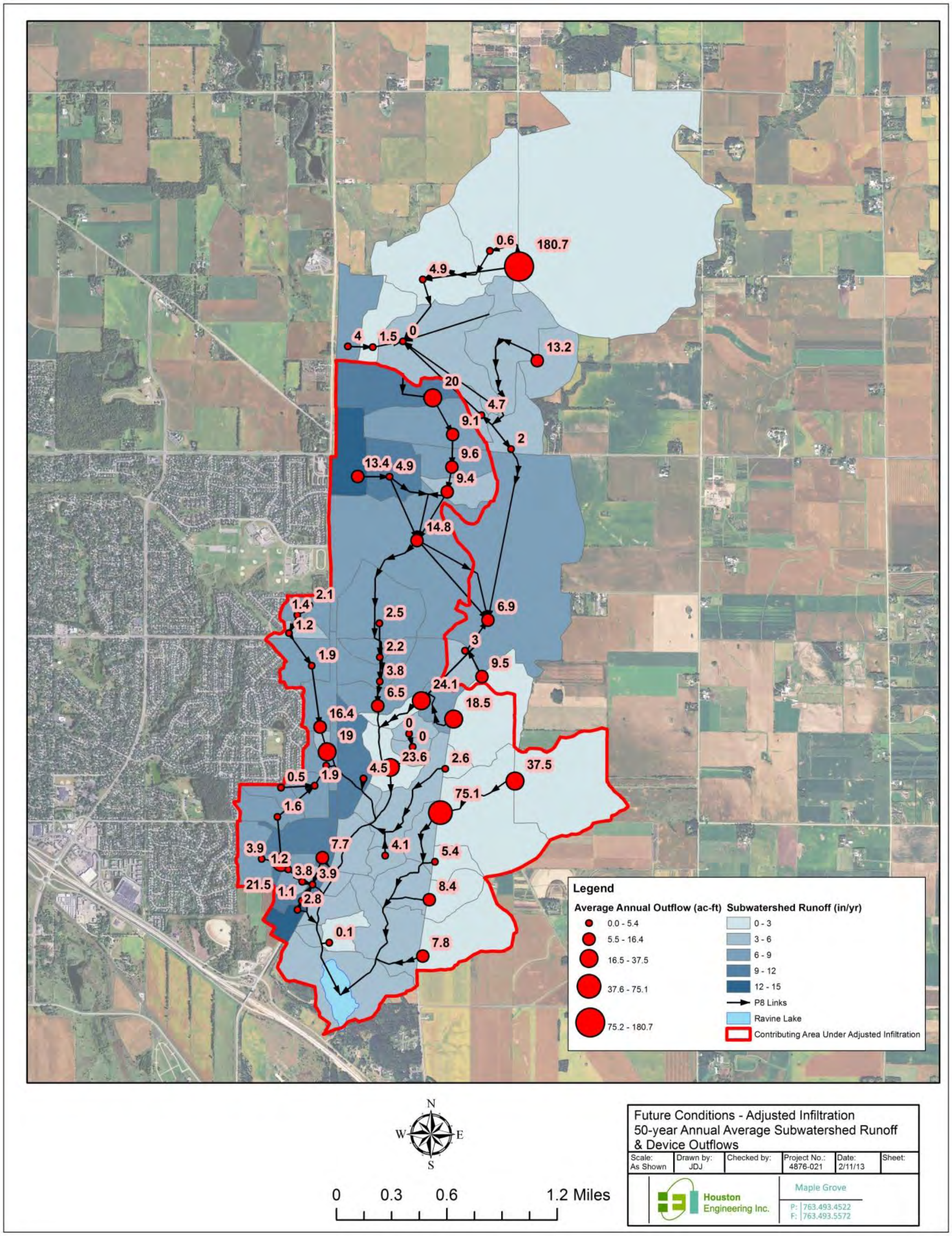
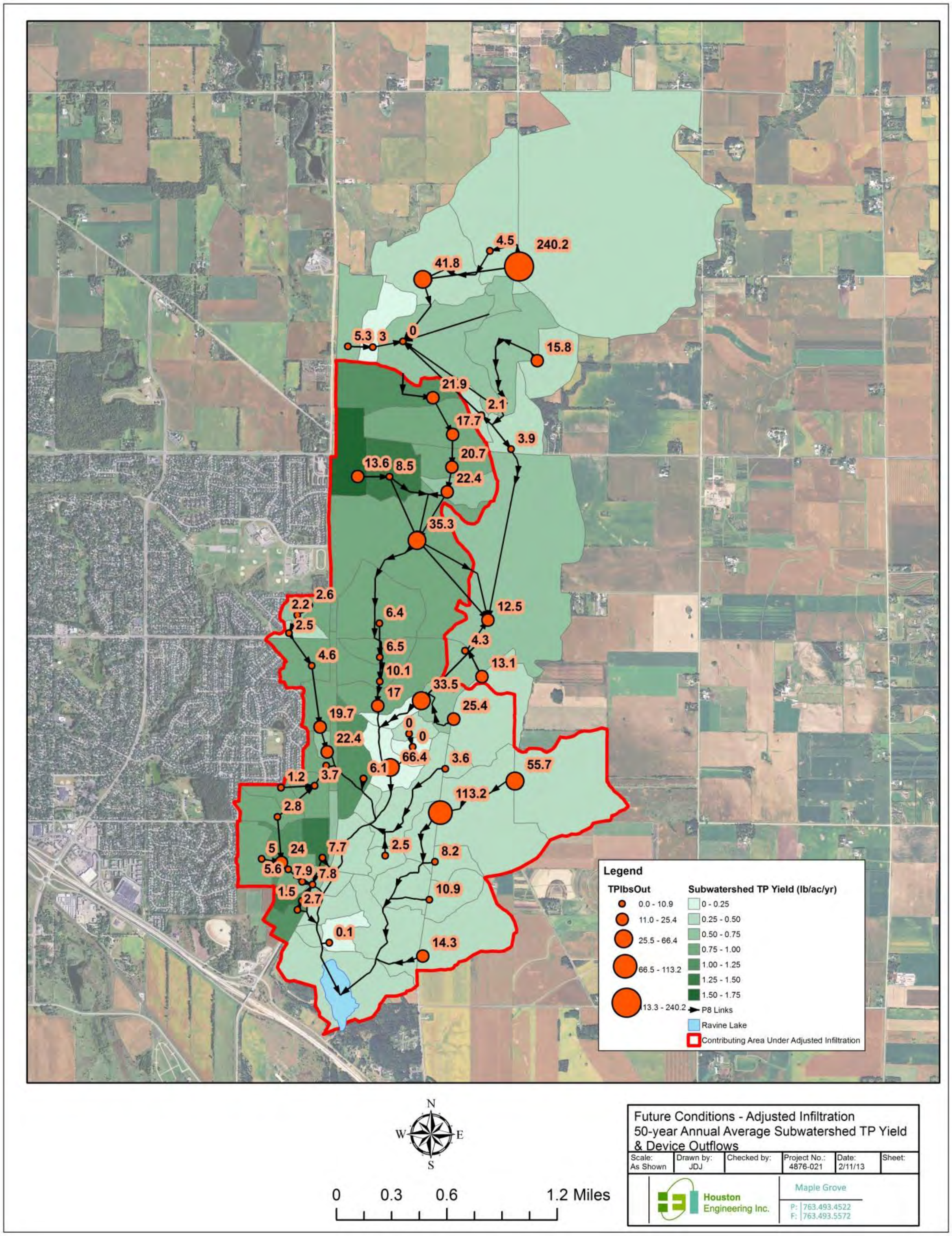


Figure 35. Adjusted Infiltration Model 50-Year Average Device TP Outflow (lbs/year)



An Adjusted Infiltration CNET model was developed to simulate the impacts of the Adjusted Infiltration watershed scenario on eutrophication dynamics in Ravine Lake. Similar to what was done with the Future Conditions CNET model, the only model inputs that differ between the Adjusted Infiltration CNET model and Existing Conditions CNET model are the surface water runoff volume and surface runoff TP load distributions, which were updated within outputs from the Adjusted Infiltration P8 model. All other input distributions remain consistent with those of the Existing Conditions and Future Conditions models. **Table 13** shows the model inputs used in the Adjusted Infiltration Ravine Lake Monte Carlo simulation and the statistical distributions for each parameter used.

Table 13. Model inputs used in the Monte Carlo Analysis for Ravine Lake Adjusted Infiltration Model.

Model Input	Statistical Distribution	Basis for Distribution	Distribution Truncated at Extreme Values?	Correlation	
				Considered?	Input Correlated With
Precipitation	Beta	1962 – 2011 MSP National Weather Service Station*	Yes	Yes	Surface runoff (0.97) Surface load (0.97) Atmospheric Load (0.72)
Evaporation	Weibull	1962 – 2011 computed from regression with MSP National Weather Service Station air temperature data*	Yes	No	---
Atmospheric Load	Logistic	1962 – 2001 computed using seasonal precipitation ratio and constant annual atmospheric deposition	Yes	Yes	Precipitation (0.72)
Surface Water Runoff Volume	Lognormal	1962 – 2011 Adjusted Infiltration P8 model*	Yes	Yes	Precipitation (0.97) Surface Load (0.97)
Surface Runoff TP Load	Lognormal	1962 – 2011 Adjusted Infiltration P8 model*	Yes	Yes	Precipitation (0.97) Surface Runoff Volume (0.97)
Storage & Groundwater	Triangular	2002 – 2010 annual water balance values	Yes	No	---

Notes:
All distributions truncated at the minimum and maximum values in the time period noted.
Distributions chosen are best fit for the time period of seasonal values.
Correlation coefficients were derived from actual data.
Value in parentheses is correlation coefficient as determined by Crystal Ball.
A triangular distribution was chosen for storage and groundwater based on limited data set (2002-2010).
See Appendix C for the statistical distribution parameters.
Statistical distributions were the best fit distribution, as determined by the Crystal Ball software.
* Values for 1987 were removed from the distributions for these variables due the extremity of the hydrology during this year and its impact on skewing the modeled distribution.

5.2.1.1 Ravine Lake Eutrophication Response

Figure 36 through **Figure 41** and **Table 14** show the effects of reducing the simulated summer season TP loads to Ravine Lake under the Adjusted Infiltration scenario. Loads were reduced incrementally within the CNET model and assumed to come from the surface water runoff loading component of the mass balance. Results are presented both in terms of the average seasonal mean concentrations (as shown by the column graphs) and the predicted distributions of seasonal mean concentrations (shown as series of lines, where each line represents a different surface water runoff TP loading to the lake). The originally simulated average seasonal TP loading into Ravine Lake under the Adjusted Infiltration scenario is 78 kg, with an average of approximately 55 kg of that loading coming from surface water.

Figure 36. Adjusted Infiltration Ravine Lake summer season mean TP concentrations under select load reduction scenarios; Simulated Conditions = 78 kg/season.

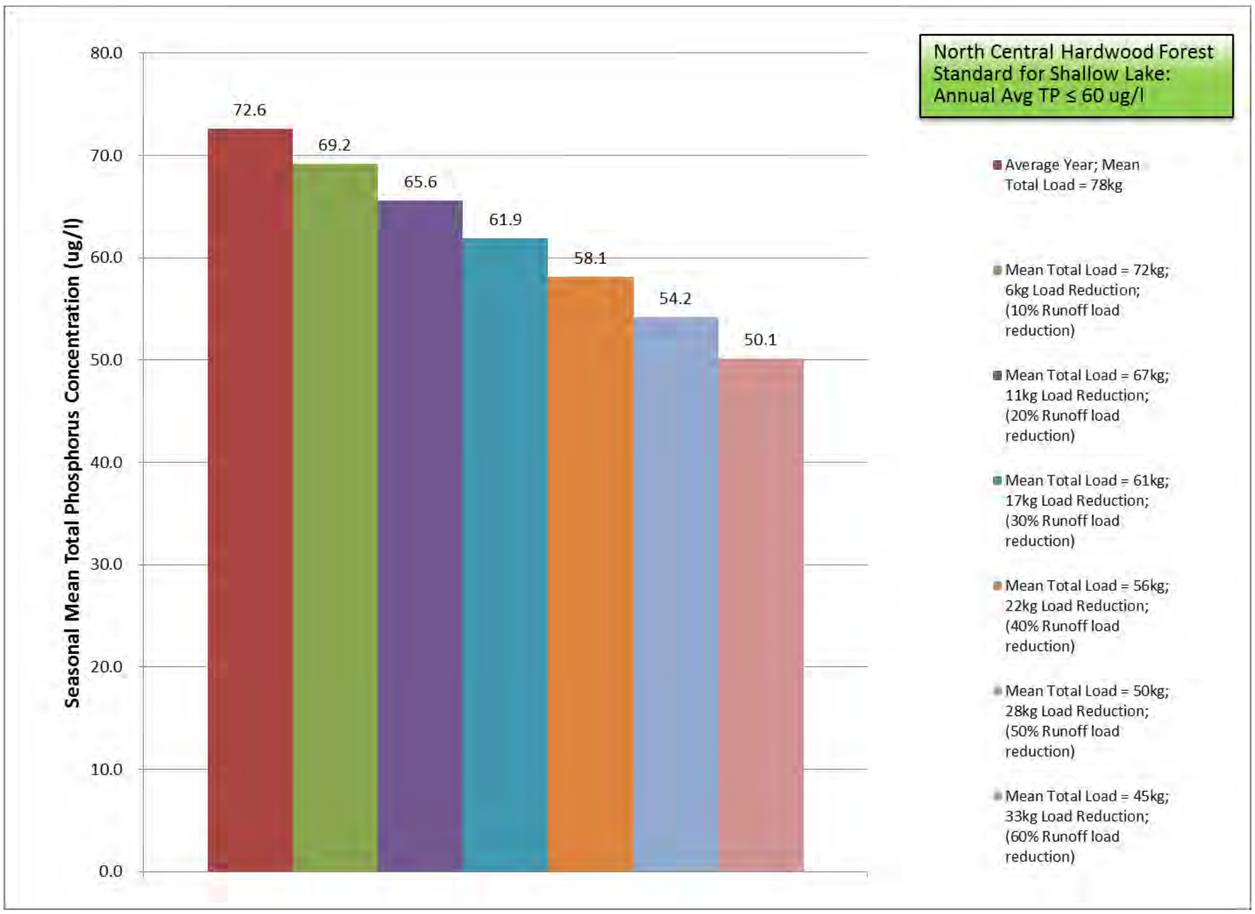


Figure 37. Adjusted Infiltration Ravine Lake frequency distribution of summer season mean TP concentrations resulting from select load reduction scenarios; Current Conditions = 78 kg/season.

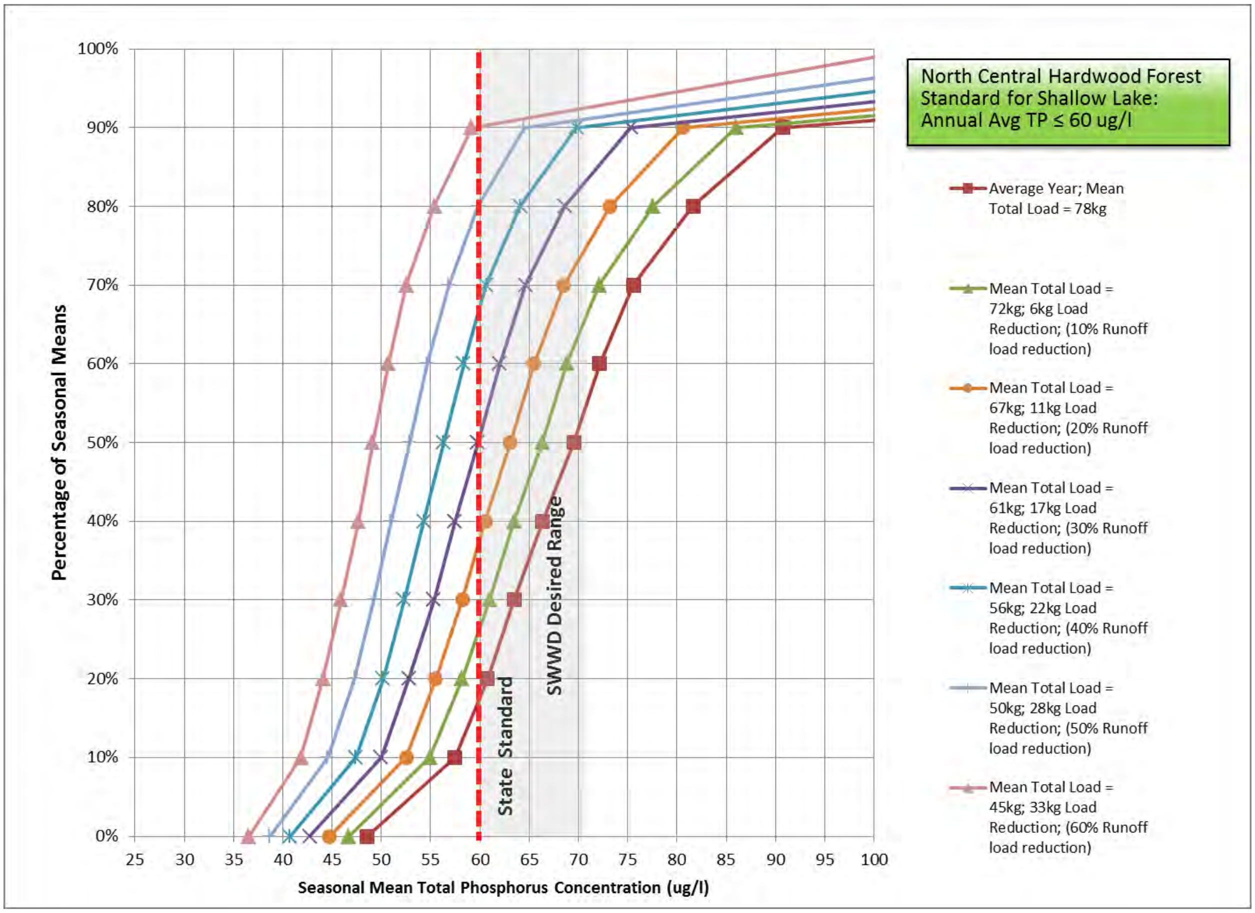


Table 14. Adjusted Infiltration Conditions Monte Carlo simulation TP loading reduction results.

Non-Exceedance Percentile	Average Summer Season TP Concentration (ug/L) (current)	Average Summer Season TP Concentrations (ug/L) for Load Reduction from Simulated Load; Average Summer Season					
		6 kg	11 kg	17 kg	22 kg	28 kg	33 kg
Mean	72.6	69.2	65.6	61.9	58.1	54.2	50.1
0%	48.6	46.7	44.7	42.8	40.7	38.7	36.6
10%	57.5	54.9	52.5	50.0	47.4	44.6	41.8
20%	60.8	58.2	55.5	52.8	50.2	47.3	44.1
30%	63.5	61.0	58.2	55.3	52.3	49.2	45.9
40%	66.4	63.5	60.6	57.5	54.3	51.0	47.7
50%	69.6	66.3	63.1	59.8	56.3	52.8	49.1
60%	72.1	68.8	65.5	62.0	58.4	54.6	50.7
70%	75.6	72.1	68.5	64.6	60.6	56.8	52.5
80%	81.6	77.6	73.2	68.7	64.1	59.8	55.4
90%	90.7	86.0	80.6	75.3	69.8	64.5	59.2
100%	188.6	176.2	163.4	149.9	135.7	120.8	104.9

Figure 38. Adjusted Infiltration Ravine Lake summer season mean chl-*a* concentrations under select load reduction scenarios; Simulated Conditions = 78 kg/season.

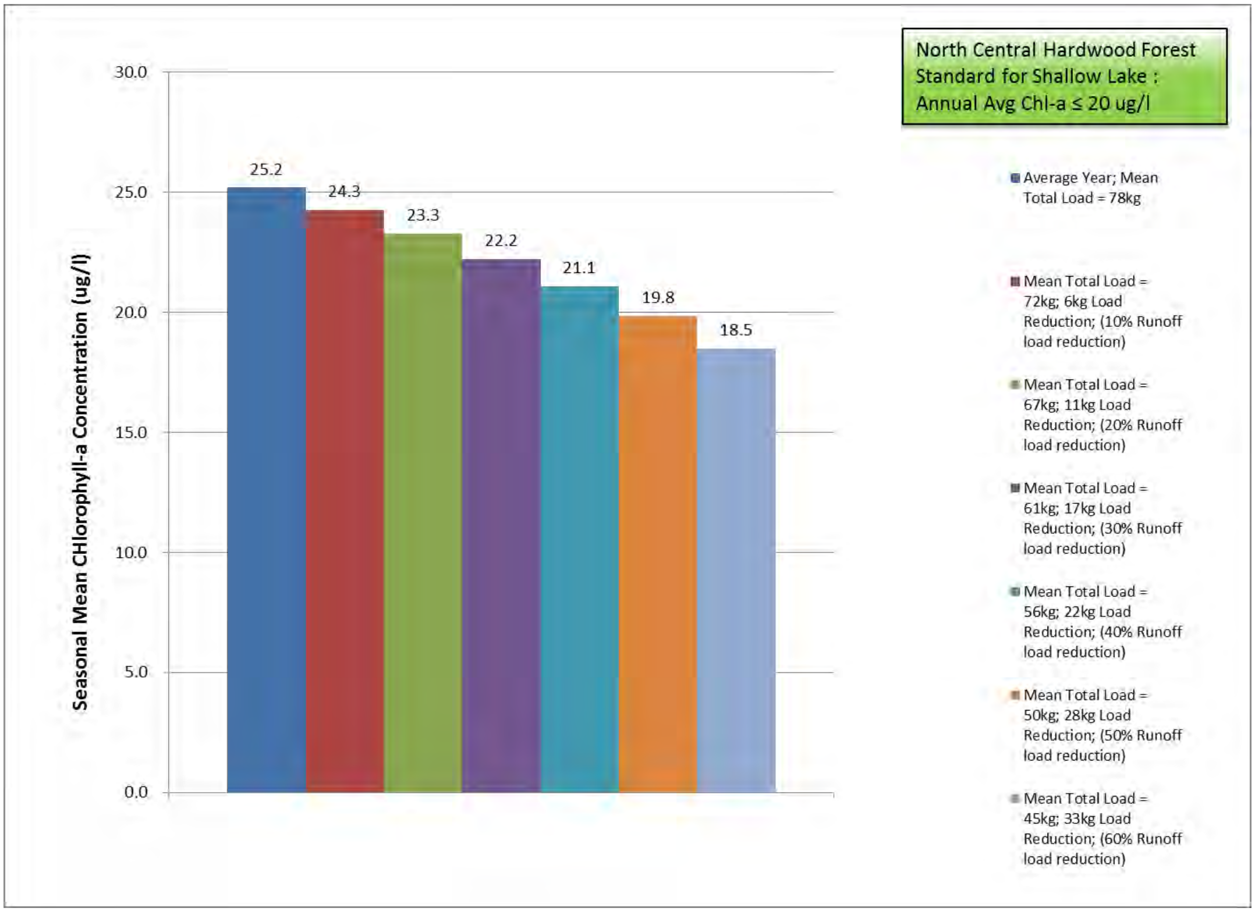


Figure 39. Adjusted Infiltration Ravine Lake frequency distribution of summer season mean chl-*a* concentrations under select load reduction scenarios; Simulated Conditions = 78 kg/season.

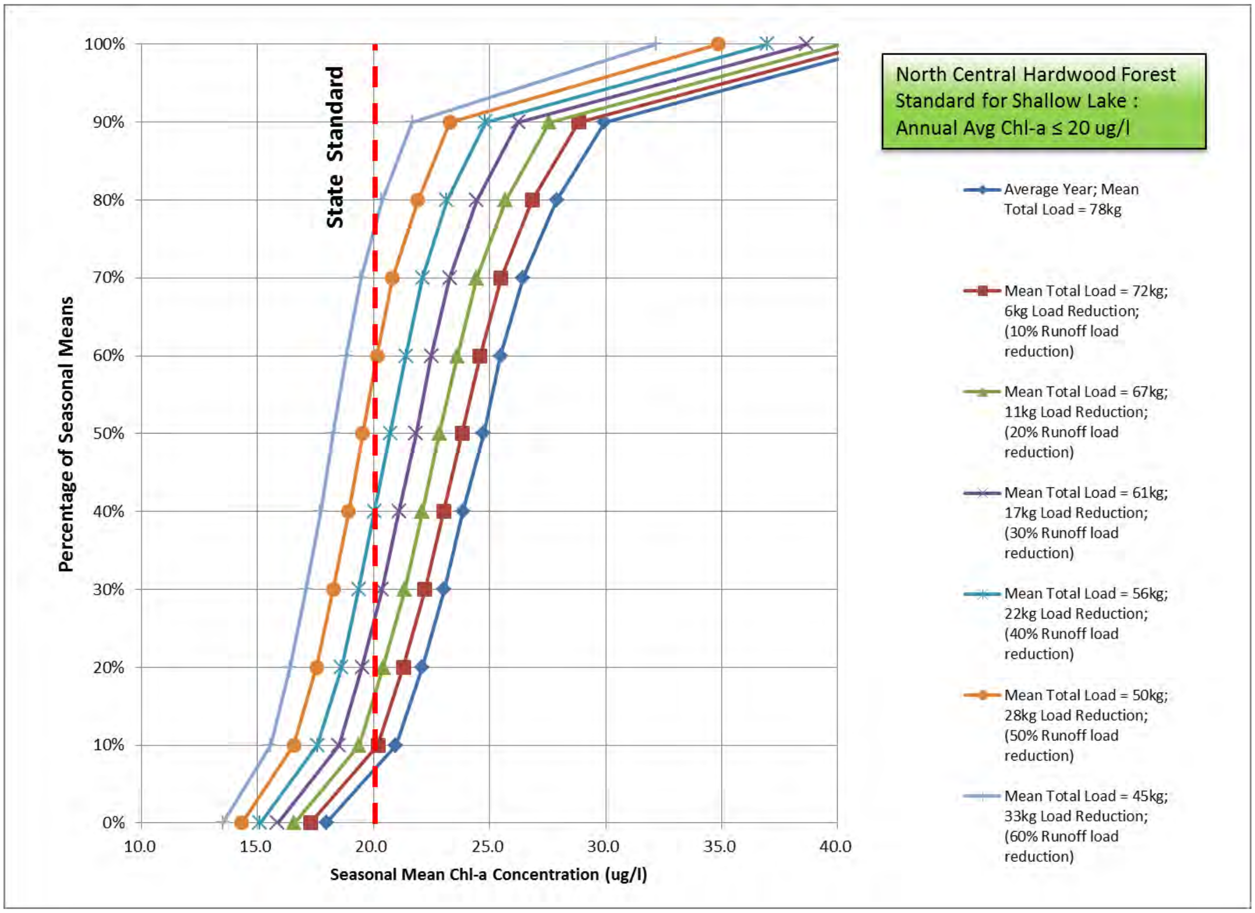


Figure 40. Adjusted Infiltration Ravine Lake summer season mean secchi disk depth under select load reduction scenarios; Simulated Conditions = 78 kg/season.

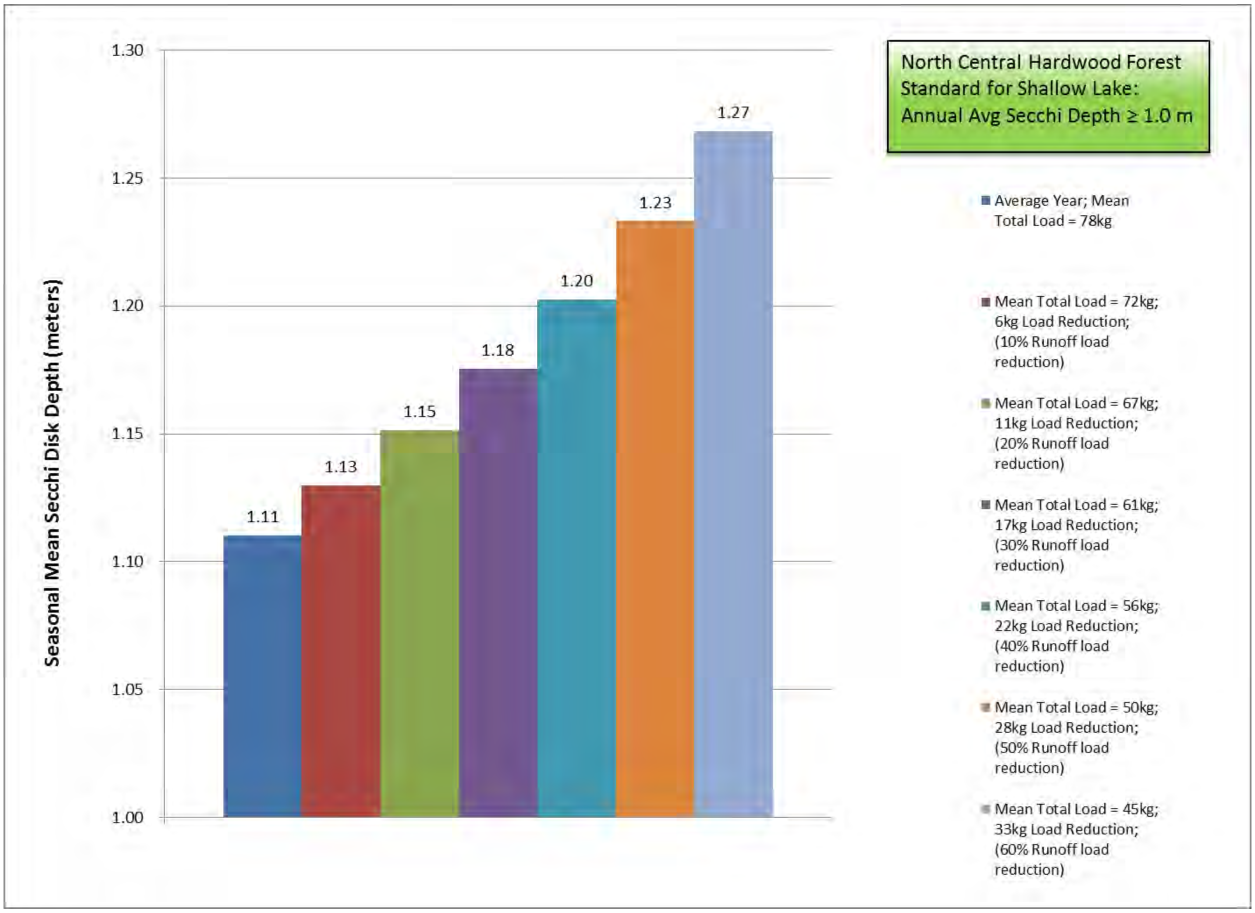
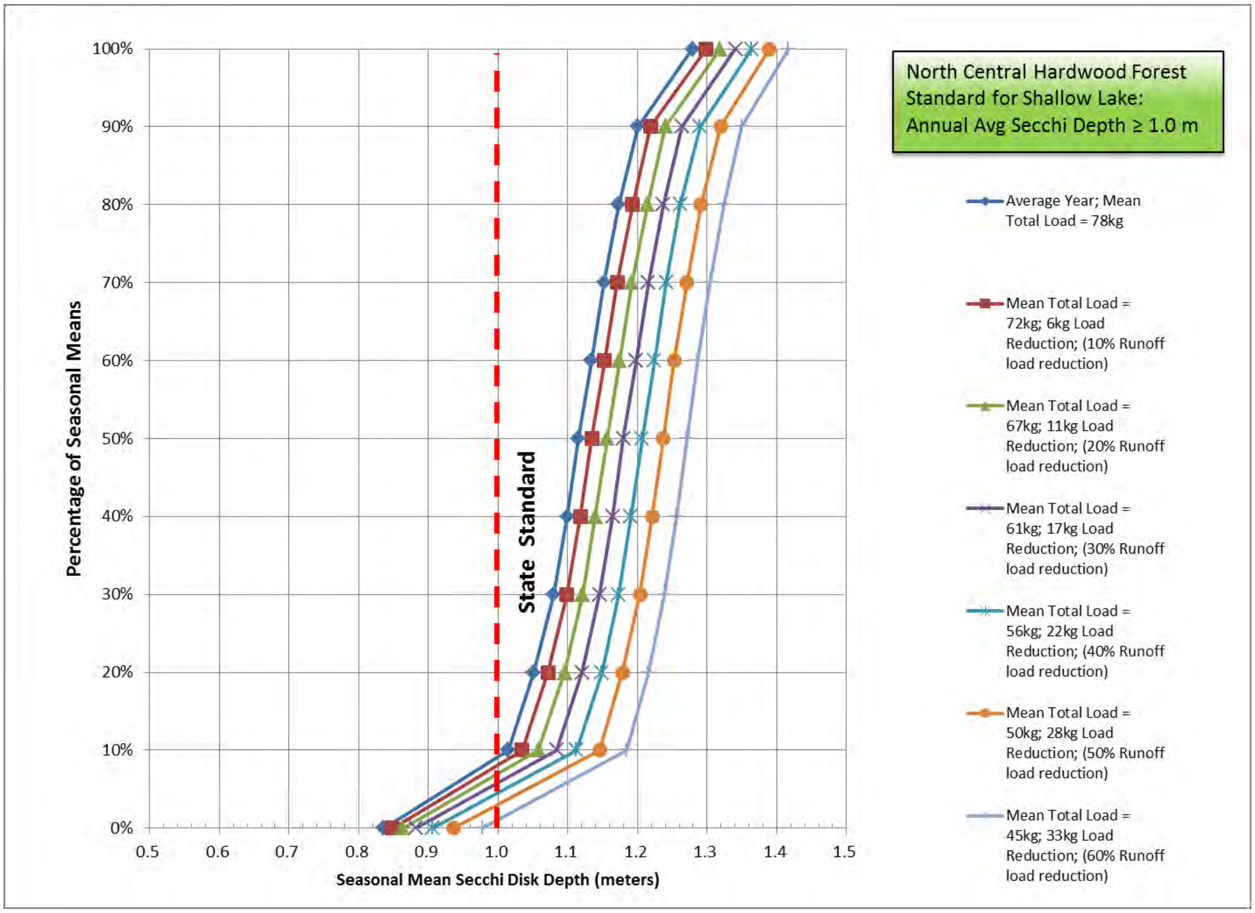


Figure 41. Adjusted Infiltration Ravine Lake frequency distribution of summer season mean secchi disk depth under select load reduction scenarios; Simulated Conditions = 78 kg/season.



5.2.1.2 Ravine Lake Loading Capacity under the Adjusted Infiltration Scenario

Results of the loading capacity analysis under the Adjusted Infiltration scenario are shown in **Figure 37**. The red line at 60 ug/L represents the average summer season TP concentration eutrophication standard for the protection of lake quality in Class 2 surface waters in the NCHF ecoregion. Likewise, the shaded area shows the range of desired concentrations based on the SWWD's desired TSI values for Ravine Lake. **Table 14** shows the values used to produce **Figure 37**. Results of this analysis show that the loading capacity of Ravine Lake under the Adjusted Infiltration scenario is 56 kg/season, requiring a 22 kg (40%) reduction in the summer season surface water runoff TP loading. The loading capacity of the lake under the this scenario is slightly higher than that under the existing condition (56 kg/season vs. 55 kg/season) since the lake is receiving slightly more water, on average (**Table 12**), and the hydraulic residence time drops from an average of approximately 9 months to 8 months. **Table 15** shows the load allocations that would be employed if Ravine Lake were to be evaluated as a TMDL-listed water body under this scenario.

Table 15. Adjusted Infiltration Conditions Ravine Lake Loading Capacity to Meet State Water Quality Standards.

	Loading (kg/day)	=	Load Allocation (kg/day)	+	Wasteload Allocation (kg/day)	+	Margin of Safety (kg/day)
Current Condition (78 kg; 122 days)	0.639	=	0.188	+	0.451	+	0
Goal: 60 ug/L (56 kg; 122 days)	0.459	=	0.188	+	0.248	+	0.023

As summarized in **Table 15**, it is estimated that the simulated 0.639 kg/day summer season TP load to Ravine Lake would have to be reduced to 0.459 kg/day to meet the State water quality standard. Under this scenario, the wasteload allocation (storm-sewered runoff from the watershed) would have to be reduced from 0.451 to 0.248 kg/day (55 to 33 kg/season), allowing for the 5% MOS. If the entire load reduction were achieved through reductions in WLA, then no reduction in LA would be necessary. In reality any combination of WLA and LA equaling 0.436 kg/day would achieve the loading capacity.

5.3 Implications for SWWD Standards

As mentioned above, the SWWD currently has standards governing the amount of water that's permitted to leave new developments (the stormwater runoff volume standard) and also the maximum allowable TP load from areas contributing to downstream lakes. The Adjusted Infiltration scenario was developed to simulate the SWWD's stormwater runoff volume standard, managing the increase in surface water flows (due to new development) to Ravine Lake. Results of this analysis were summarized in **Section 5.2.1**.

SWWD's current maximum allowable TP loading standard dictates that areas contributing to Ravine Lake not exceed the average loading of 0.04 lbs/acre/year. The results of this Ravine Lake modeling and management analysis can be used to update the Ravine Lake Watershed TP loading standard; options for a new standard are presented in **Table 16** for consideration by the SWWD.

Under existing conditions, with 1,704 acres contributing surface water flow and TP loading to Ravine Lake, the new maximum allowable TP loading standard for the Ravine Lake Watershed was computed at 0.093 lbs/acre/year. Using results of the Adjusted Infiltration scenario (which simulates compliance with the SWWD's stormwater runoff volume standard), the loading capacity of the lake increases slightly and the contributing area of the watershed also increases. For the purposes of standard development, a contributing area of 2,422 acres was used for the Adjusted Infiltration scenario. This area includes all subwatersheds that drain through the treatment device at CP4-3, but not those draining through Vandeberg Lake (see **Figure 34**). As mentioned in **Section 5.2.1**, according to the Adjusted Infiltration P8 model, Vandeberg Lake only contributes flow to Ravine Lake during three of 50 years simulated, representing extreme hydrologic conditions; neither the State of Minnesota nor SWWD manage water quality to these extreme events, so the contributing area under non-extreme conditions was used for this calculation. The resultant maximum allowable TP load under the Adjusted Infiltration Condition is 0.075 lbs/acre/year.

Table 16. Updated Maximum Allowable TP Loading Standards for the Ravine Lake Watershed.

	Existing Conditions	Adjusted Infiltration Condition
Loading Capacity (kg/season)	55	56
Allocated Stormwater Loading (kg/season)	29	33
Season to Annual conversion	2.49	2.49
Annual Allocated Stormwater Load (kg/year)	72.2	82.2
Contributing Area (acres)	1,704	2,422[1]
Suggested TP Loading Standard (kg/year)	0.042	0.034
Suggested TP Loading Standard (lb/year)	0.093	0.075

[1] *includes subwatershed draining through CP4-3, but not those draining through Vandeberg Lake.*

6.0 SUMMARY OF RESULTS

The purpose of the Ravine Lake Management Plan project was to develop a management plan for Ravine Lake, located within Ravine Lake Regional Park, Cottage Grove, MN. The lake is currently listed as impaired for excess nutrients by the State of Minnesota and significant development is planned for its watershed in the coming years. The contents of this report detail the analyses that were performed to compute the loading capacity of Ravine Lake (i.e., the amount of TP that can enter the lake, while meeting State water quality standards) under both existing and future conditions. Information on simulated subwatershed surface water runoff and TP yield was provided for both existing and future conditions, giving insight on priority areas for treatment. Estimated surface water outflows and TP loadings from each modeled device (under existing and future conditions) were also provided; these results highlight areas where additional treatment may be needed.

The SWWD has standards governing the amount of water that's permitted to leave new developments (the stormwater runoff volume standard) and also the maximum allowable TP load from areas contributing to downstream lakes. The final outcome of the work was to provide updated standards for consideration by the SWWD, based on the results of this modeling analysis.

7.0 REFERENCES

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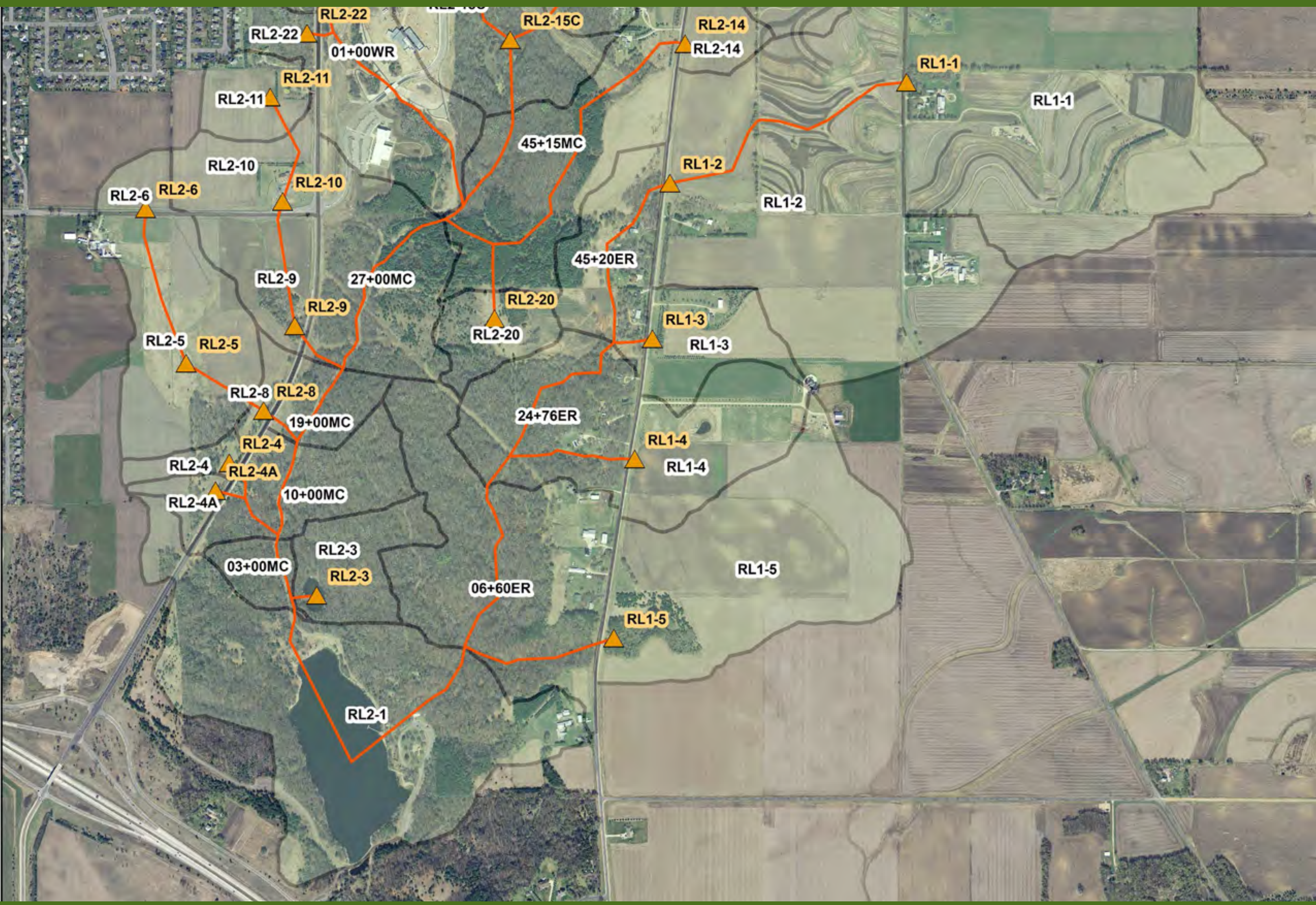
APPENDIX A

P8 Modeling Report

Ravine Lake Watershed P8 Modeling Report



Final Report **June 21, 2013**

Houston Engineering Inc.

South Washington WATERSHED District

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Acronyms and Abbreviations List

AUAR	Alternative Urban Areawide Review
CLFLWD	Comfort Lake Forest Lake Watershed District
CN	Curve Number
DEM	Digital Elevation Model
LIDAR	Light Detection and Ranging
MSP	Minneapolis-St. Paul
NLCD	National Land Cover Dataset
NURP	National Urban Runoff Program
P8	Predicting Polluting Particle Passage thru Pits, Puddles, & Ponds
SWMM	Storm Water Management Model
SWWD	South Washington Watershed District
TP	Total Phosphorus
TSS	Total Suspended Solids
UAL	Unit Area Load
USEPA	United States Environmental Protection Agency

1 INTRODUCTION

The Ravine Lake watershed encompasses the central portion of the South Washington Watershed District (SWWD), as shown in **Figure 1**. Watershed modeling of the Ravine Lake watershed was performed using Version 3.4 of the Program for Predicting Polluting Particle Passage thru Pits, Puddles, & Ponds (P8) Model[1] to develop the surface water runoff volume, total suspended sediment (TSS) load, and total phosphorus (TP) load components of the long-term hydrologic budget and mass balance for the area. Two P8 models were created; each based on existing SWWD Storm Water Management Model (SWMM)[2] models, obtained from HDR Engineering, Inc. (HDR). The first P8 model is an Existing Conditions Model; the second model is a Future Conditions Model.[3] Both models are referred to as the Ravine Lake watershed P8 models, hereafter. The models are representative of the watershed year-round; however, hydrologic calibrations to the models are performed using data from April-October when the watershed is hydrologically active. The P8 models were developed using National Urban Runoff Program (NURP) data and provide pollutant loading estimates based on data collected as part of the NURP program. The models track pollutant loading by building up particles on impervious surfaces, washing off the particles through precipitation-driven runoff, and routing the runoff volumes and loads downstream through treatment devices (modeled as ponds, infiltration basins, pipes, etc.). The pollutant removal efficiency of each device is then applied and pollutants not removed are routed downstream through the simulated watershed. This report serves as documentation for the development of the Ravine Lake watershed P8 models, including the modeling methods, data sources, and results.

2 DERIVATION OF MODEL INPUTS

The P8 models require user input relative to local precipitation and temperature, watershed characteristics, water quality parameters, and treatment device geometry. For both Ravine Lake watershed P8 models, the routing information and most other required inputs were adopted from corresponding SWMM models. These SWMM models were developed for the SWWD as part of the Central Draw Project.[4]

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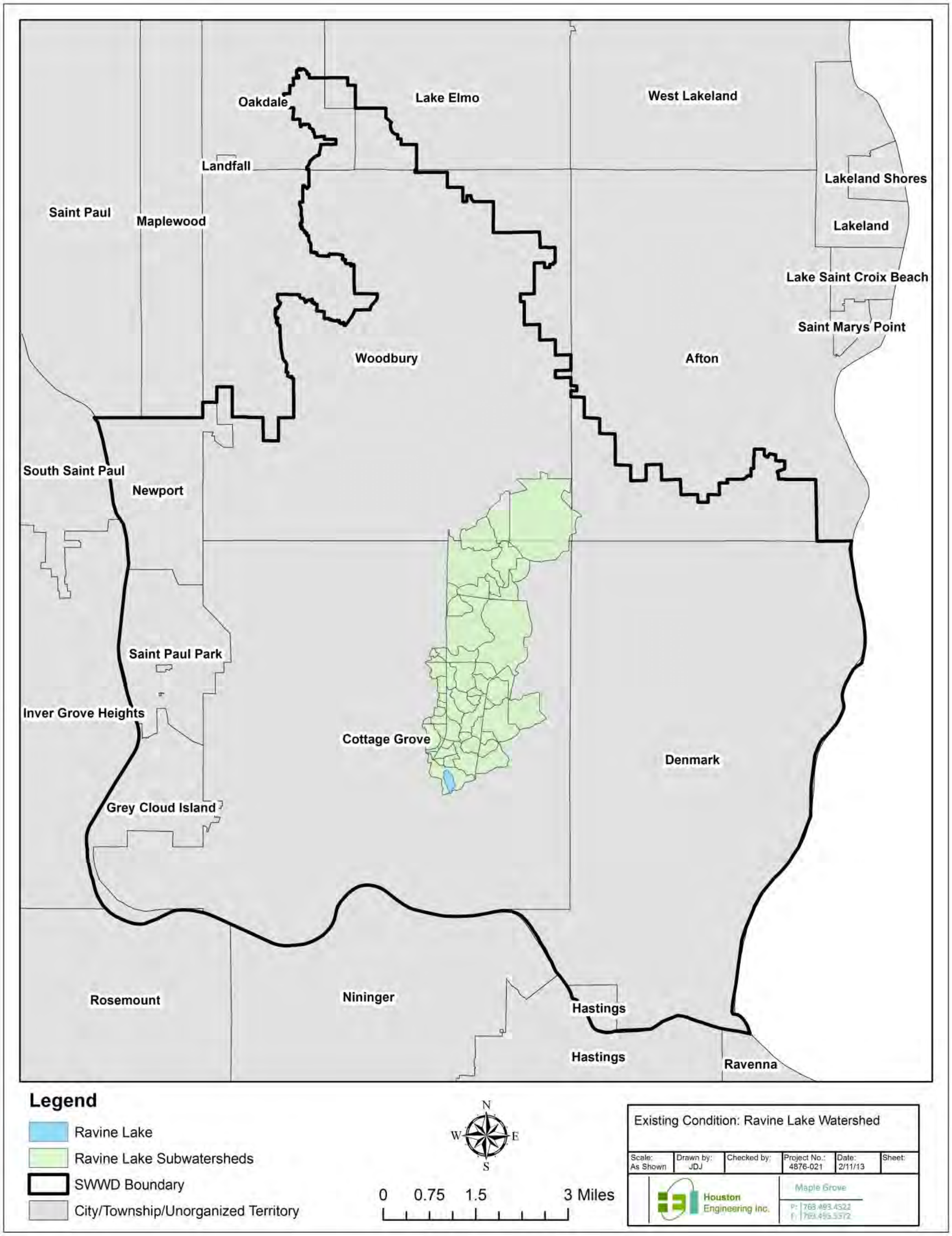
[1] http://wwwalker.net/p8/
[2] http://www.xpsoftware.com/products/xpswmm/
[3] This model is also known as the Ultimate Build-out Condition and is based, in part, on the East Ravine Alternative Urban Areawide Review and Mitigation Plan, developed for the City of Cottage Grove; the version of the model used for this work was provided, to HEI, on May 13th, 2013.
[4] XP-SWMM models developed for the "Central Draw Project and Flood Storage Area Maps," by HDR Engineering, Inc., June 2002.

Figure 1. Existing Conditions Ravine Lake Watershed.



The following sections discuss the data extracted from the SWMM models, as well as the selection of other input parameters specific to the P8 models during the model calibration process. Any input parameters not specifically discussed within this report remain the same as the P8 models' default values.

2.1 Precipitation and Temperature

The P8 models require hourly precipitation and daily temperature data to be input for hydrologic simulation. For the Ravine Lake watershed models, these data were obtained at the Minneapolis-St. Paul (MSP) airport, the closest meteorological station (approximately 20 miles away) with sufficient data to perform long-term model simulations. For this work, data from 1949 through 2011 were used.

2.2 Watershed Characteristics

The Ravine Lake watershed boundaries were adopted from the aforementioned SWMM models. The Existing Conditions and Future Conditions models have a total of 55 and 68 subwatersheds, respectively, that contribute to Ravine Lake and are included within the P8 models.

The imperviousness fractions for each subwatershed were also adopted from the respective SWMM models. These fractions were determined to be reasonable by comparing them to impervious surface datasets obtained from the University of Minnesota's Remote Sensing and Geospatial Analysis Laboratory.[5]

The SWMM models were developed using Horton's Infiltration Method for pervious surfaces with depression storage. In contrast, P8 model calculations use the Curve Number (CN) Method to generate pervious surface runoff without depression storage. A pervious CN of 61 was selected for use in both P8 models, representative of grassed areas in good condition with Hydrologic Soil Group B soils. According the SWWD Watershed Management Plan,[6] this accurately represents conditions throughout the majority of the Ravine Lake watershed.

Additional watershed parameters used as model calibration parameters include the impervious area runoff coefficient, impervious depression storage, and portion of the total impervious area assumed to be directly-connected (e.g. to a curb, storm sewer, or other stormwater conveyance facility). All impervious surfaces were assumed to be un-swept.

[5] http://land.umn.edu/

[6] South Washington Watershed District Watershed Management Plan, Chapter 8, prepared by Houston Engineering, Inc. June 2007.

2.3 Treatment Devices

The P8 model hydraulic networks (used to route water through the watershed) and the locations and characteristics of storage nodes and outlet locations were also adopted from the SWMM models. However, due to P8 model requirements, some assumptions were needed to estimate the available storage in the treatment devices (BMPs, ponds, wetlands, and other nodes where pollutant removal occurs). The hydraulic component of the SWMM model requires only the flood pool volume (volume above the outlet) be defined. Often the permanent pool volumes (volume below the outlet) in SWMM models are undefined. P8 requires that both the permanent and flood pools be accurately defined. Permanent (when available) and flood pool volumes are defined in SWMM using elevation-area curves for each storage node. Each of the individual storage nodes in the SWMM models were examined to determine whether or not their elevation-area curve included the permanent pool and whether the entirety of that pool was defined. This determination was made using the SWMM elevation-area curve, the invert elevation of the outlet structure, a two-foot contour map developed using a Light Detection and Ranging (LIDAR) Digital Elevation Model (DEM), and aerial photographs. In cases where the SWMM model invert matched the bottom contour elevation, the SWMM-defined permanent pool was used. If the SWMM model invert was above the bottom contour elevation, the elevation-area curve was extended using the contours to include the additional storage. The presence and location of wetlands were determined using the National Wetland Inventory (NWI) and the permanent pool was extended 1.5 feet below the contour surface; open waters were determined using the Public Water Inventory (PWI) and the permanent pool was extended 3 feet below the contoured water surface.

The flood pool volumes were defined as all additional storage in the elevation-area curves above the outlet or permanent pool elevation. A 10-year, 24-hour duration precipitation event was run in the SWMM model to check that none of the high water elevations exceeded the flood pool elevations.

Existing Conditions Model infiltration rates applied to storage nodes were determined as follows:

- Storage nodes that appeared dry on aerial photos and had no permanent pool storage were given no infiltration.
- Storage nodes that appeared dry on aerial photos and had permanent pool storage were given an infiltration rate of 0.6 in/hr, based on typical values for the region.[7]
- Storage nodes that had open water, permanent pool storage, and an outlet were given no infiltration rate.
- Storage nodes that had open water and no outlet were given an infiltration rate ranging from 0-0.6 in/hr, chosen by running the model long-term to maintain apparent water level elevations based on aerial photographs. This is the case for isolated waterbodies that maintain standing water year round.

[7] 2005 Infiltration Monitoring Program Final Report. Emmons and Oliver Resources, Inc. February 23, 2006.

For the Future Conditions Model, devices located in the modified/developed areas of the watershed were given infiltration rates based on available device information found in the City of Cottage Grove East Ravine Alternative Urban Areawide Review (AUAR) Stormwater Management Report.[8] All other infiltration rates or devices not implicitly defined in the report remained the same based on assumptions made for the Existing Conditions Model.

Wetlands controlled by an outlet structure were modeled as ponds in the P8 model and assigned a particle removal scale factor of 3, as recommended in the P8 documentation to account for the effects of vegetation on particle removal rates.

2.4 Water Quality Particle Parameters and Components

The P8 default NURP 50 particle file was selected for model development. The NURP 50 represents typical concentrations and particle settling velocities for a number of stormwater pollutants. The component concentrations in the file were calibrated by the original model developers to the 50th percentile (median) values compiled in the U.S. Environmental Protection Agency's (USEPA) NURP. [9]

P8 provides particle compositions (mg/kg) for various particle classes. During calibration, the scale factor for particles was adjusted as the mechanism for calibrating the model to expected annual loads (methods for developing expected annual loads is discussed in **Section 3.2**).

3 MODEL CALIBRATION AND VALIDATION

No flow or water quality monitoring data exists within the Ravine Lake watershed itself. Therefore, other sources of information were used to calibrate and check the reasonability of the P8 model results.

The Ravine Lake watershed P8 models were calibrated/validated by comparing simulated and expected unit runoff and TP/TSS yield values. Expected values for surface water hydrology were developed from the corresponding SWMM models. Although no formal documentation for these SWMM models exists, the models have been accepted by the SWWD and serve as the basis for various planning efforts. It was, therefore, deemed reasonable to assume that the models provide realistic watershed runoff values. Expected TP yield values were developed using literature value for given land use types.[10] The Ravine Lake watershed is unique in that it currently has very little urban area, where the use of the P8 model is most reliable. Additionally, many areas within the watershed

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[8] Report, "Cottage Grove East Ravine AUAR and Mitigation Plan. Stormwater Management", Appendix D. June 14, 2005, Emmons & Olivier Resources (EOR)
[9] "P8 Urban Catchment Model Program Documentation ," William W. Walker, October 1990.
[10] Memorandum, "Summary of Recommended Unit Area Load Values." LimnoTech. May 30, 2007.

undergo significant infiltration. The chosen calibration/validation approach was designed to overcome these challenges and still obtain realistic results. The calibration and validation procedure was as follows:

1. Calibrate the hydrology of the subwatersheds using expected surface water runoff volumes;
2. Calibrate the TP and TSS yields from the subwatersheds using expected values;
3. Compare the total watershed unit runoff at Ravine Lake to a similar nearby watershed; and
4. Compare the total unit TP load at Ravine Lake to that of a similar nearby watershed.

3.1 Calibration of Subwatershed Hydrology

Calibration of the P8 models centered on model simulations during the growing season of 1979, deemed a "typical" year for precipitation by the SWWD. Total rainfall for 1979 was 35.6 inches, which was slightly greater than the long-term average of 29 inches but rainfall intervals are very typical of average conditions in timing, duration, and intensity.[11] Rainfall records from the gauge at the MSP International Airport for the 1979 growing season were applied to the SWMM model to estimate subwatershed runoff volumes from April through October. The same time period was simulated in the P8 models and the runoff volumes from each subwatershed were compared to the SWMM model results. **Figure 2** and **Figure 3** show that the uncalibrated model results for both the Existing and Future Condition P8 models are consistently about 60% higher than the SWMM model results. This indicates a global model parameter adjustment is needed.

[11] "Report on Development of Groundwater Flow Model of Southern Washington County," Barr Engineering, June 2005

Figure 2. Percent difference in 1979 watershed runoff volume for Existing Conditions P8 model compared to SWMM model, prior to P8 calibration.

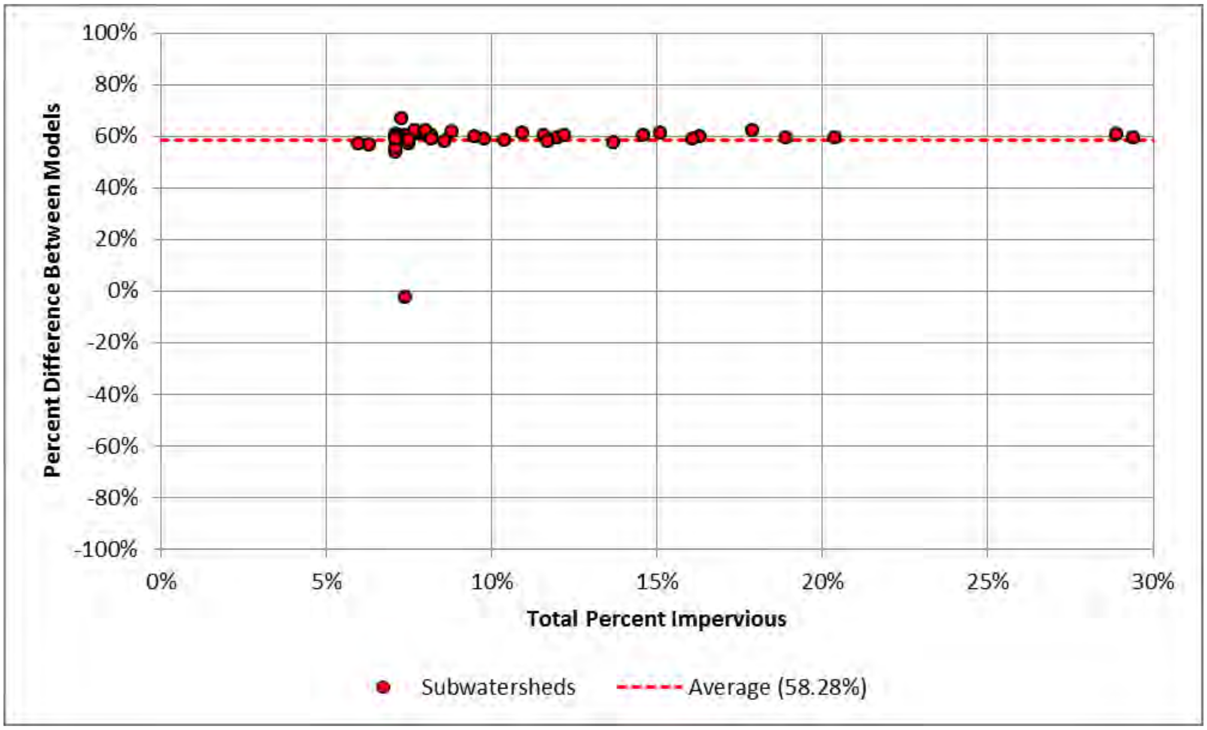
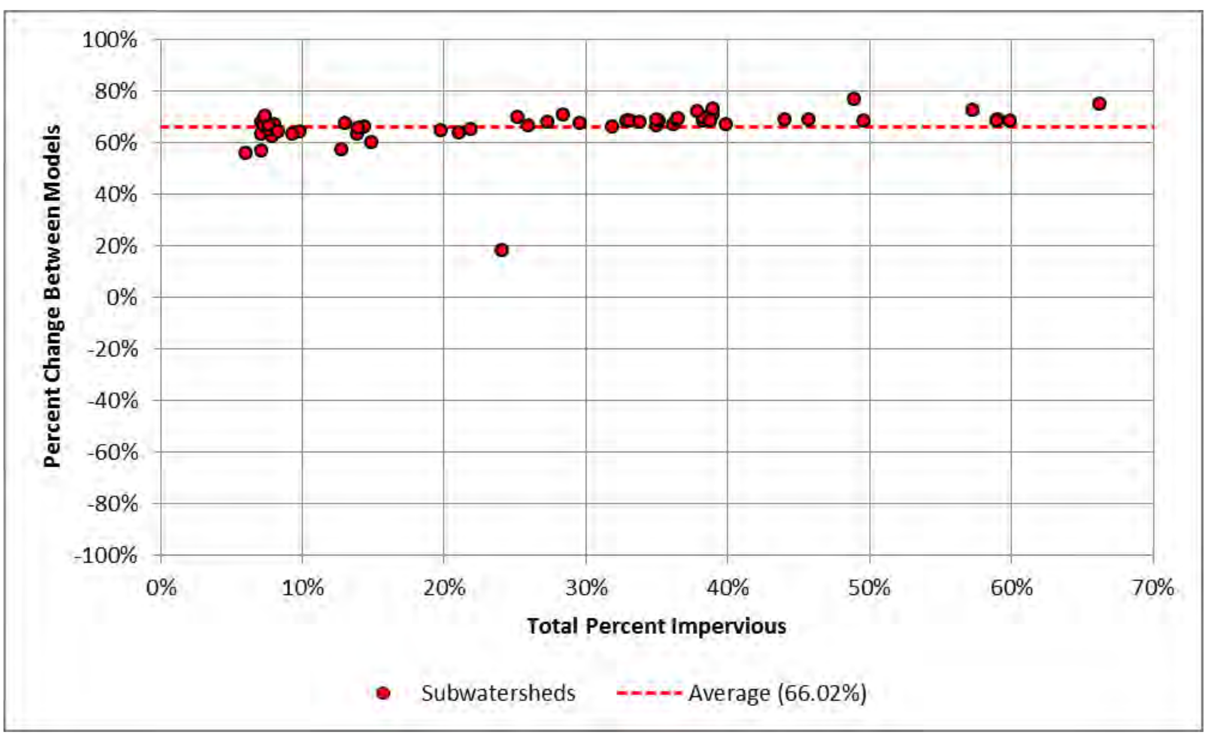


Figure 3. Percent difference in 1979 watershed runoff volume for Future Conditions P8 model compared to SWMM model, prior to P8 calibration.



The most downstream subwatershed, immediately surrounding Ravine Lake, appears as an outlier in **Figure 2** and **Figure 3**. In the P8 models, the area representing the lake (a large percentage of the subwatershed area), was removed from the model because only inflows to the lake from the subwatershed are needed for the in-lake model being developed under this work. Direct precipitation to Ravine Lake will be introduced during the in-lake modeling. As a result, when comparing to the SWMM model results, these appear as outliers.

The procedure for calibrating the P8 models included modification of the impervious runoff coefficient (default of 1) and the relative percentages of directly and indirectly connected impervious. Because most of the subwatersheds are relatively rural, and those that have more urban characteristics are still not highly developed, it was found that designating 30% of the impervious area as indirectly connected was defensible and improved the calibration. In addition, the impervious runoff coefficient was lowered slightly to 0.9. The resulting calibrated subwatershed runoff results for both the Existing and Future Conditions P8 models are shown in **Figure 4** and **Figure 5**.

Figure 4. Percent difference in 1979 watershed runoff volume for Existing Conditions P8 model compared to SWMM model, after P8 calibration.

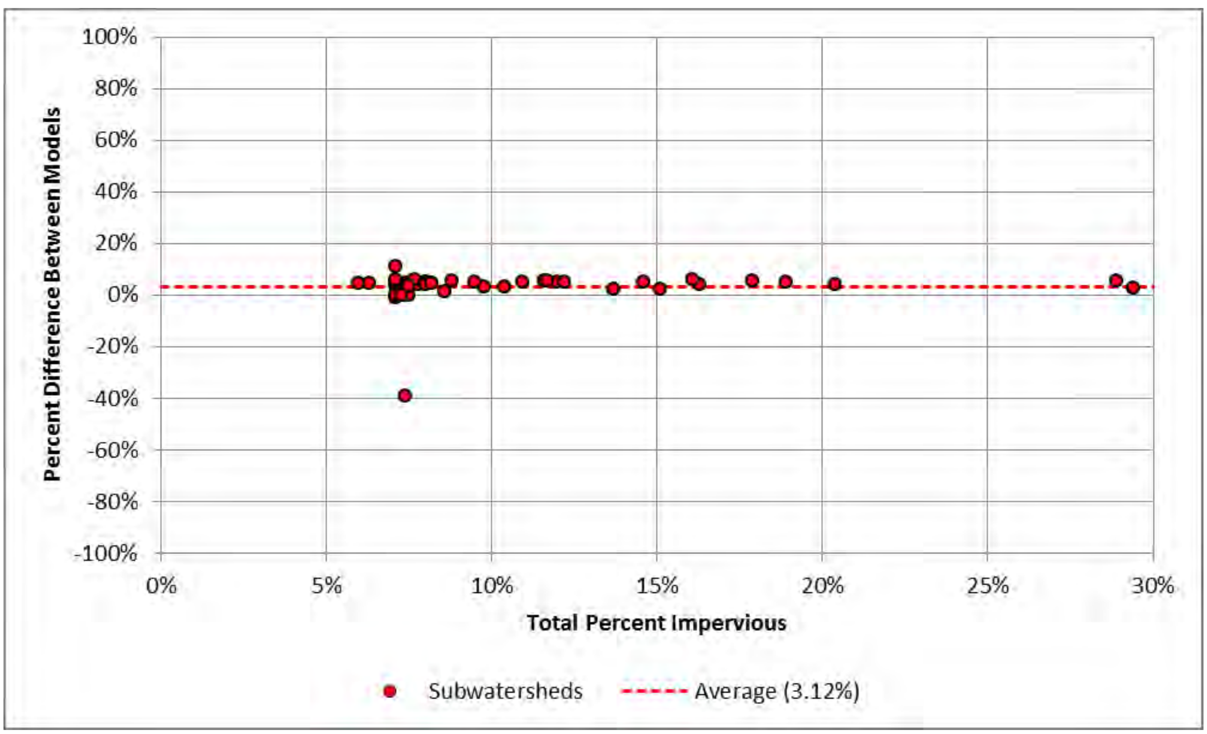
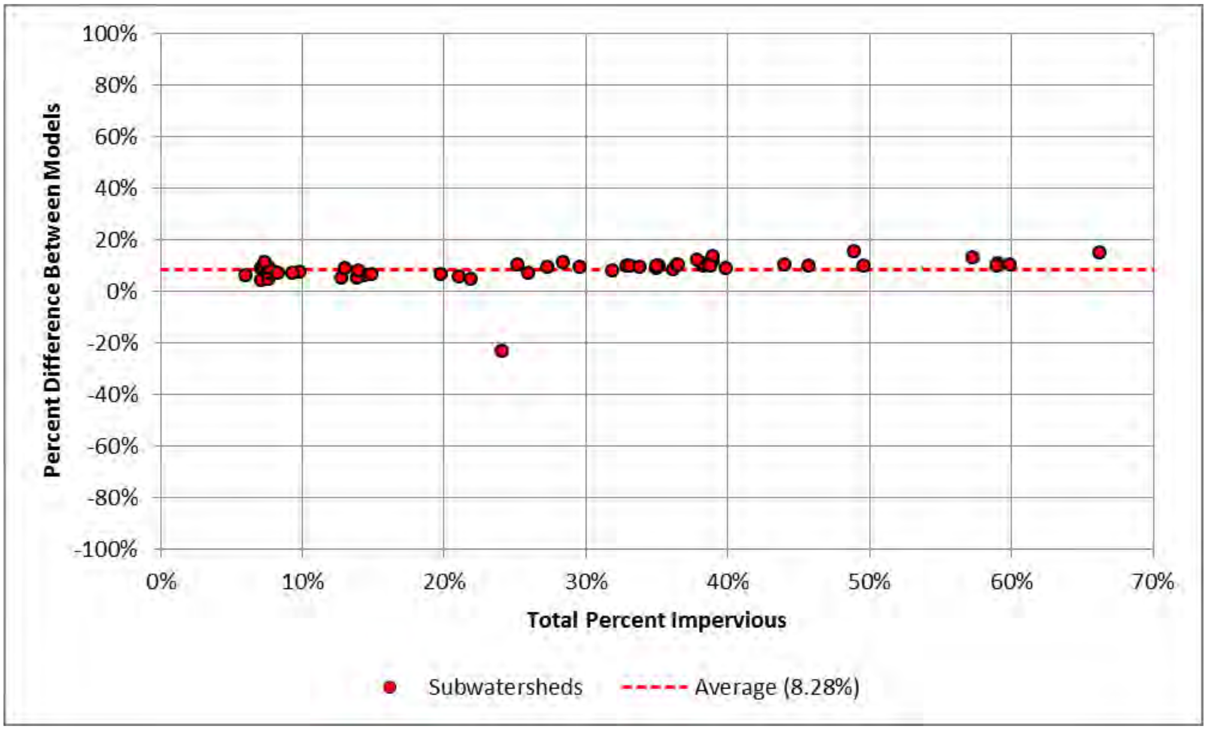


Figure 5. Percent difference in 1979 watershed runoff volume for Future Conditions P8 model compared to SWMM model, after P8 calibration.



3.2 Calibration of Subwatershed Total Phosphorus Yield

Different land use types produce varying yields of surface water pollutants. The P8 model pollutant yields were, therefore, calibrated by land use type throughout the watershed.

Using the 2006 National Land Cover Dataset (NLCD) for the Conterminous United States, land classes in the Existing Conditions model subwatersheds were categorized into three simplified P8 land classes: cropland, urban, and forest. The simplified land class categories are shown in **Table 1**. **Figure 6** shows a comparison of the 2006 NLCD land classes to the simplified P8 land classes in the Ravine Lake watershed.

For the Future Conditions model, the Existing Conditions model land class data was modified based on future land use data generated by Hoisington Koegler Group, Inc. (HKGI) and used in the development of the SWMM model. This data is consistent with future land use projections presented in the City of Cottage Grove East Ravine AUAR report.[12] Based on the geospatial data received for this effort, the following types of future development were classified as urban land use:

- areas with 1-12+ dwelling units per acre;
- 2-acre unsewered lots;
- civic/civic campus areas;
- commercial areas;
- easements; and
- mixed use areas.

All other future development areas remained unchanged from the Existing Conditions Model. **Figure 7** shows a comparison of the combined 2006 NLCD and future development land classes to simplified P8 land classes in the Ravine Lake watershed.

Table 1. P8 Model land classifications for 2006 NLCD land classes.

Simplified P8 Land Class	2006 NLCD Land Class
Cropland	Cultivated Crops
	Pasture/Hay
Forest	Deciduous Forest
	Emergent Herbaceous Wetlands
	Evergreen Forest
	Grassland/Herbaceous
	Mixed Forest
	Shrub/Scrub
Urban	Developed High Intensity
	Developed, Low Intensity
	Developed, Medium Intensity
	Developed, Open Space

[12] Report, “Cottage Grove East Ravine, AUAR. Stormwater Management”, Figure 6. June 14, 2005, Emmons & Olivier Resources (EOR)

Figure 6. Land class simplification for the Existing Conditions P8 model.

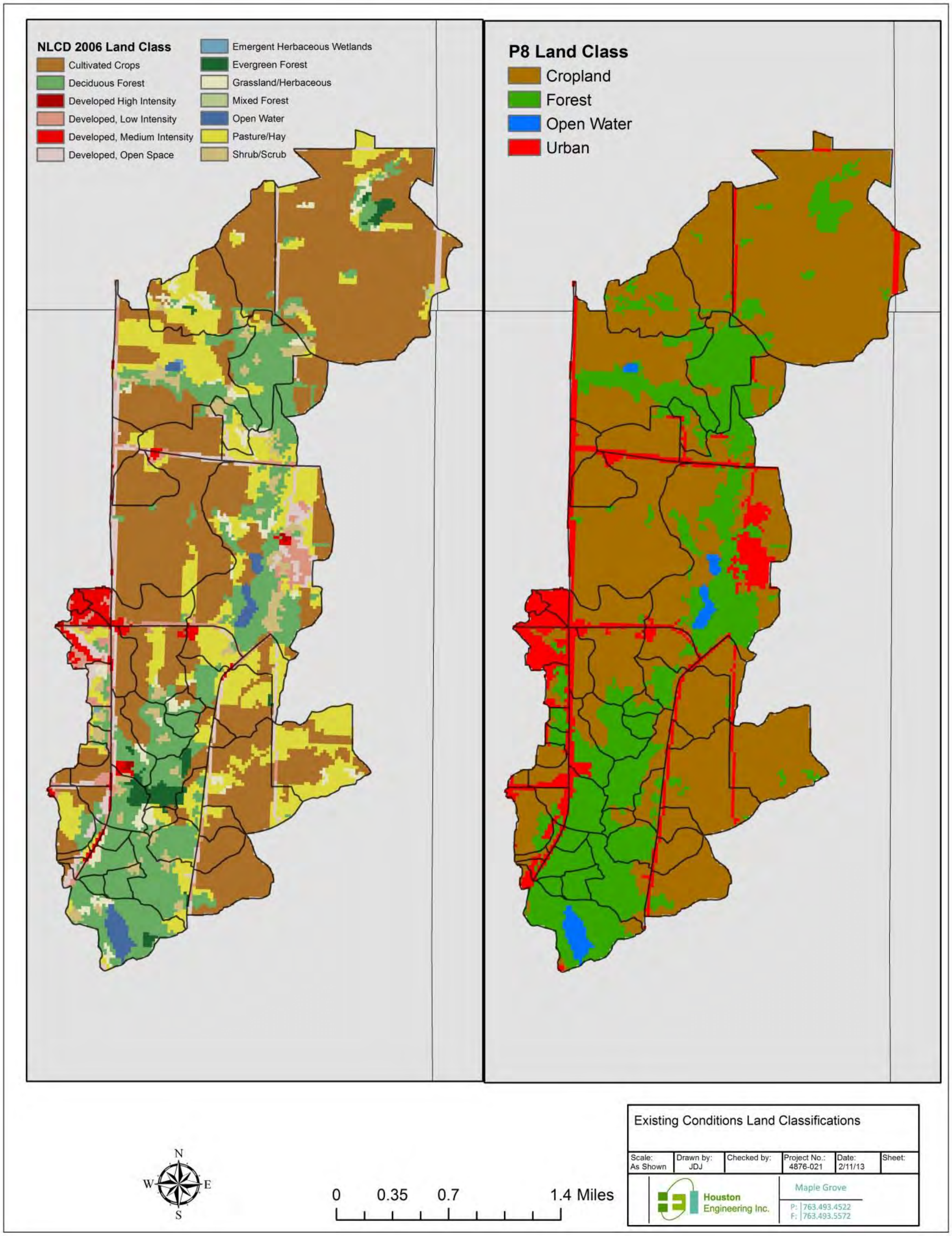
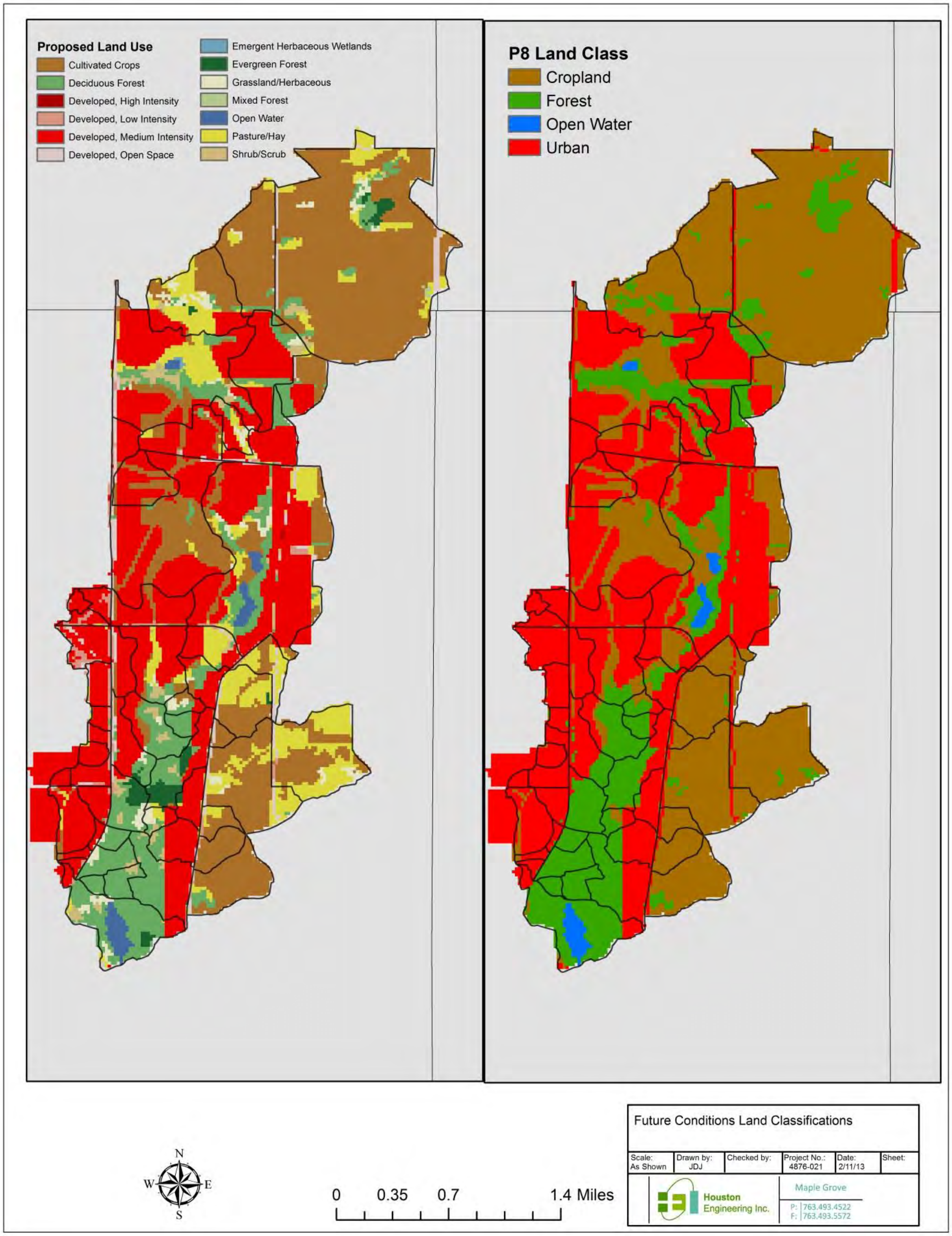


Figure 7. Land class simplification for the Future Conditions P8 model.



To calibrate the models for simulated nutrient loadings, the 50-year average subwatershed TP yields from the models were compared to literature value TP yields summarized in a 2007 study for the Comfort Lake Forest Lake Watershed District (CLFLWD).[13] The yields in the CLFWD study are widely based on the study "Detailed Assessment of Phosphorus Sources to Minnesota Watersheds".[14] The expected yield values are given in **Table 2**. An area-weighted, expected TP yield was then computed for each modeled subwatershed combining the percent cropland, forest, and urban area in each subwatershed with the literature yield values. Results were then compared to model outputs for calibration. For example, if a subwatershed in the model contains 12% cropland, 30% forest, and 58% urban area, using the literature values in **Table 2**, the expected TP yield from that subwatershed would be 0.66 lbs/ac/yr. **Figure 8** and **Figure 9** show a comparison of the modeled versus expected subwatershed TP yields for the uncalibrated P8 models. The points are displayed as a function of the percent of each subwatersheds' dominant land class (i.e., greatest percentage of cropland, forest, or urban).

To calibrate the models, particle load scale factors were adjusted for each of the three simplified land classes and an area-weighted particle load scale factor was calculated for and applied to each subwatershed. The same general particle load scale factors were used in both models; these values are shown in **Table 2.** Also shown in **Table 2** is the average percent difference between the modeled and expected results, by land use type, for the calibrated models. The comparison shows particularly high errors for TP loading in urban areas of the Existing Conditions model. This is a result of using the same particle load scale factor for each model. Because the urban land class in the Existing Conditions model represent so little area, this was deemed acceptable.

Table 2. Subwatershed TP yield calibration data.

			Existing Conditions Model	Future Conditions Model
Land Use	Literature UAL[13] (lbs TP/ac/yr)	General Particle Load Scale Factor	% Difference between P8 Model and UAL TP Loading	% Difference between P8 Model and UAL TP Loading
Cropland	0.34	1.8	2.7	-1.7
Forest	0.07	0.4	16.6	-2.3
Urban	1.03	1.45	-39.7	0.3

[13] Memorandum, "Summary of Recommended Unit Area Load Values." LimnoTech. May 30, 2007.
[14] Memorandum, "Detailed Assessment of Phosphorus Sources to Minnesota Watersheds." Minnesota Pollution Control Agency. February 2004.

Figure 10 and **Figure 11** show a comparison of both models, following subwatershed TP yield calibration. The figures display the percent difference between the predicted and modeled TP yields for each subwatershed.

Figure 8. Existing Conditions Model, comparison of simulated and expected P8 subwatershed TP yields, prior to calibration.

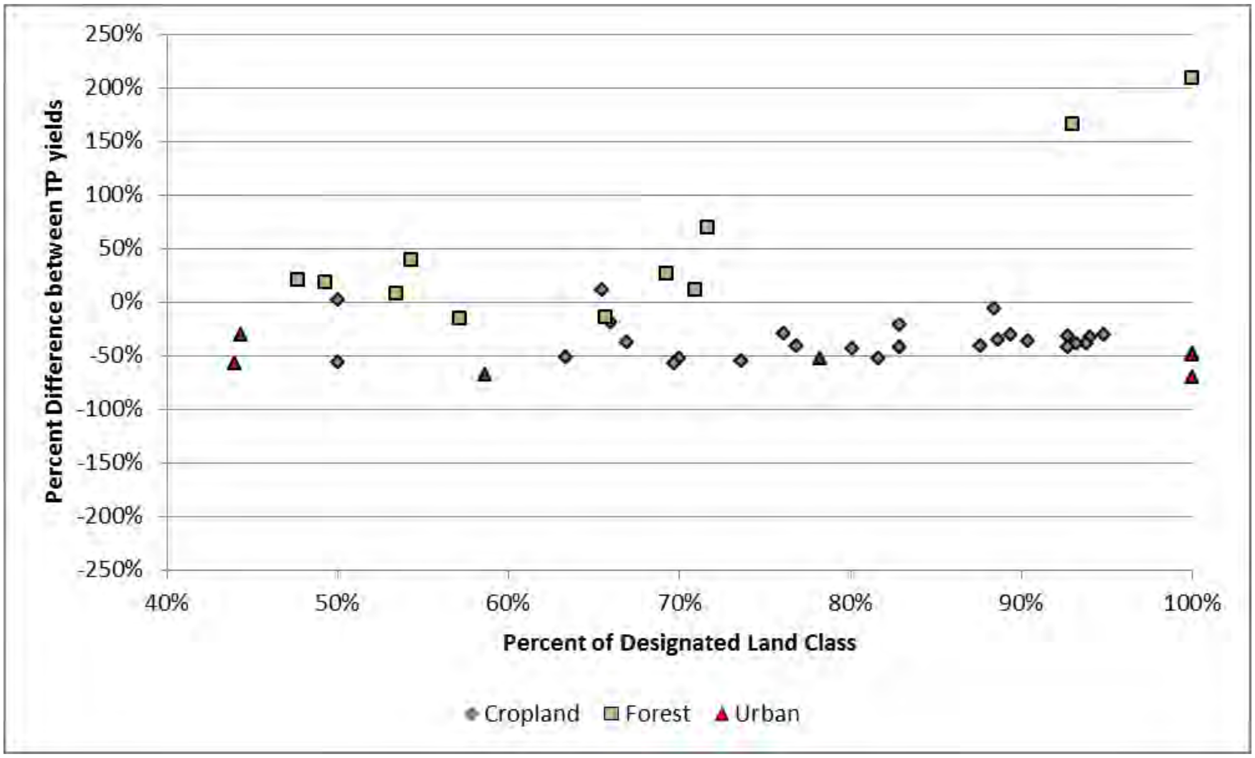


Figure 9. Future Conditions Model, comparison of simulated and expected P8 subwatershed TP yields, prior to calibration.

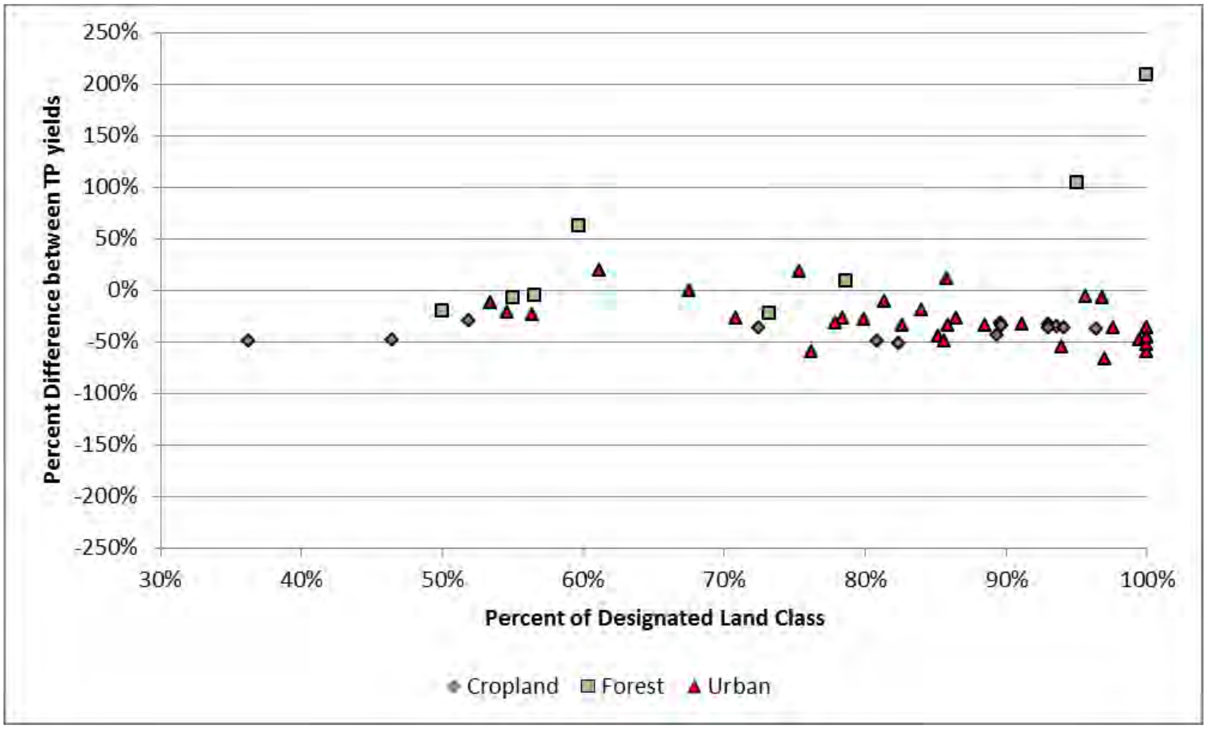


Figure 10. Existing Conditions Model, comparison of simulated and expected P8 subwatershed TP yields, after calibration.

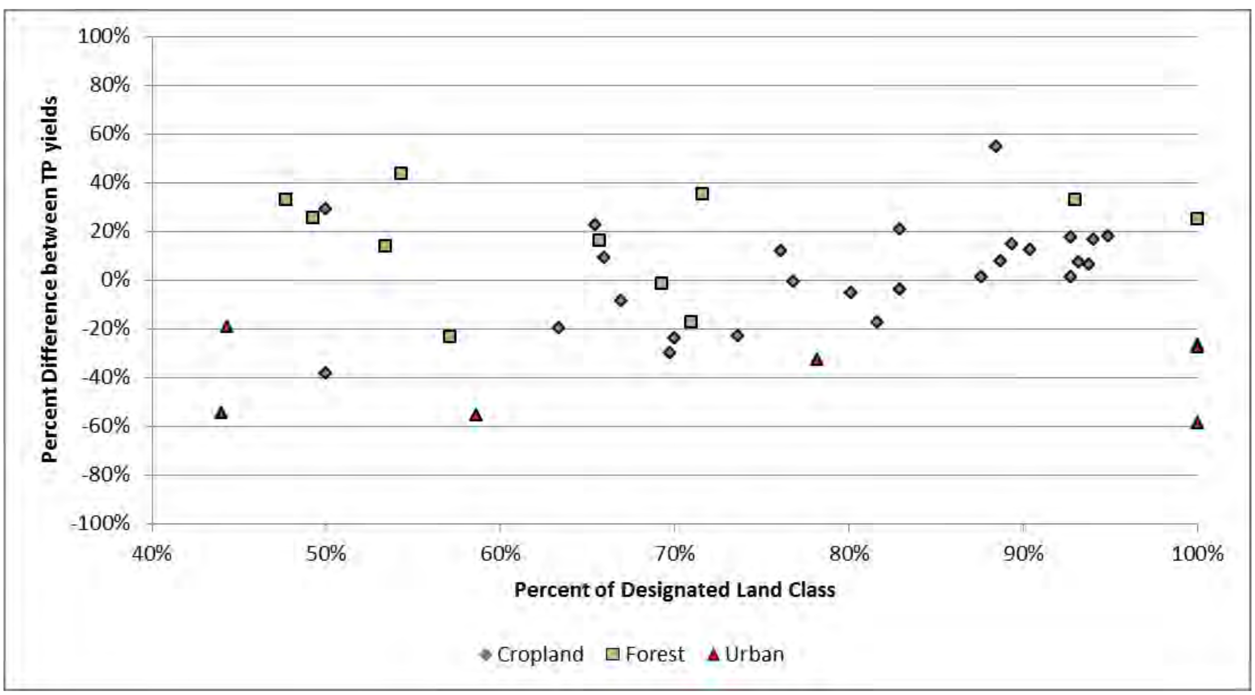
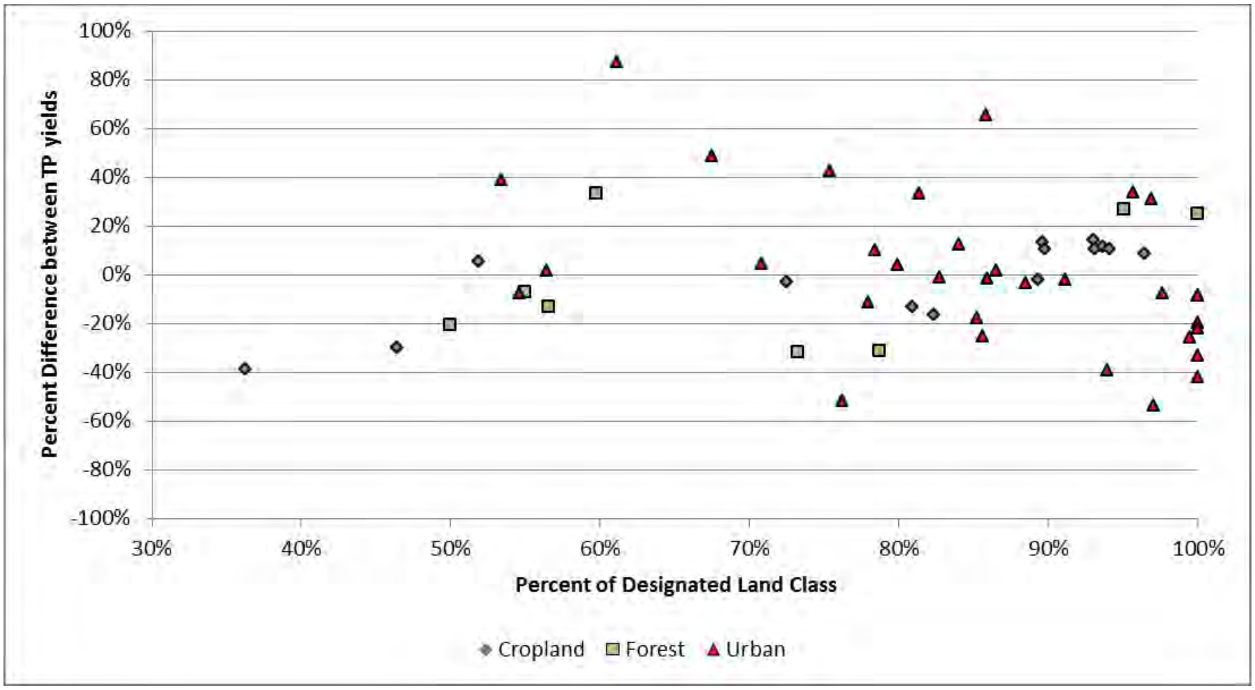


Figure 11. Future Conditions Model, comparison of simulated and expected P8 subwatershed TP yields, after calibration.



3.3 Comparison of Unit Runoff and TP Load at Assessment Location

A secondary check of the reasonability of the long-term P8 modeling results was performed using data from the nearby Trout Brook monitoring site. It was necessary to use data from the Trout Brook watershed for this secondary check since limitations in the SWMM models (e.g., no consideration of infiltration in the watershed) do not allow them to be used for estimating runoff at downstream assessment locations on a long-term continuous basis and because no observed flow or water quality data exists in the Ravine Lake watershed. The Trout Brook monitoring site is located east of Ravine Lake near Afton State Park (**Figure 12**) and maintained by the SWWD. A FLUX[15] analysis carried out by the SWWD reported runoff volumes and TP loads for the Trout Brook watershed for 2011. Loading from the analysis includes only the portion of the watershed upstream of the monitoring site. The FLUX analysis and contributing watershed area were used to calculate a unit runoff and TP unit loading for the Trout Brook watershed. The unit runoff and unit TP loading were then calculated for the Ravine Lake watershed and the two results were compared.

The subwatersheds in the Existing Conditions Model have a total area of 4,336 acres. However, the routing of the area (based on the SWMM model) indicates that hydraulic breakpoints exist in the model, dividing the overall model into three isolated sections. These sections are shown in **Figure 13**. Under the existing conditions, only 1,704 acres of the Ravine Lake watershed actually drain (via surface water) to Ravine Lake. For this secondary check, only the area routing to Ravine Lake was included in the unit volume and load calculation.

The Existing Conditions P8 model was run for 2011 and unit runoff and unit TP loading values, for this portion of the watershed, were computed. **Table 3** shows the results of this analysis, comparing the modeled and observed runoff/loading values.

Table 3. Unit runoff and loading comparison between Trout Brook and Ravine Lake watersheds.

Watershed	Area (acres)	2011 Volume Inflow (ac-ft)	2011 TP Load (lbs)	2011 Unit Runoff (in/ac)	2011 Unit TP Load (lb/ac)
Trout Brook (FLUX)	4,250	1,061	915	3.0	0.22
Ravine Lake (P8)	1,704	295	171	2.1	0.10

The results of the model comparison indicate that the Ravine Lake P8 model unit runoff and TP unit load are lower, but similar, to those of the Trout Brook FLUX analysis. This comparison assumes that both watersheds behave the same hydraulically; particularly the retention within the watershed. Higher retention combined with infiltration in

[15] Email from John Loomis, SWWD. February 20, 2013.

the Ravine Lake watershed would result in lower unit runoff and loading values. Cursory review of the Trout Brook watershed in comparison to the Ravine Lake watershed indicates this may be the case.

A similar comparison of the Future Conditions Model was not performed because the future conditions include dissimilar hydraulic routing; previously isolated subwatersheds are hydraulically connected subwatersheds that route to Ravine Lake. This hydraulic connectivity is unlike that of the Trout Brook watershed and could substantially skew the results of a comparison. Additionally, the Future Conditions Model of the Ravine Lake watershed is substantially more developed than the Trout Brook watershed. For these reasons, a secondary comparison of the Future Conditions model was not performed.

Figure 12. Ravine Lake and Trout Brook watersheds.

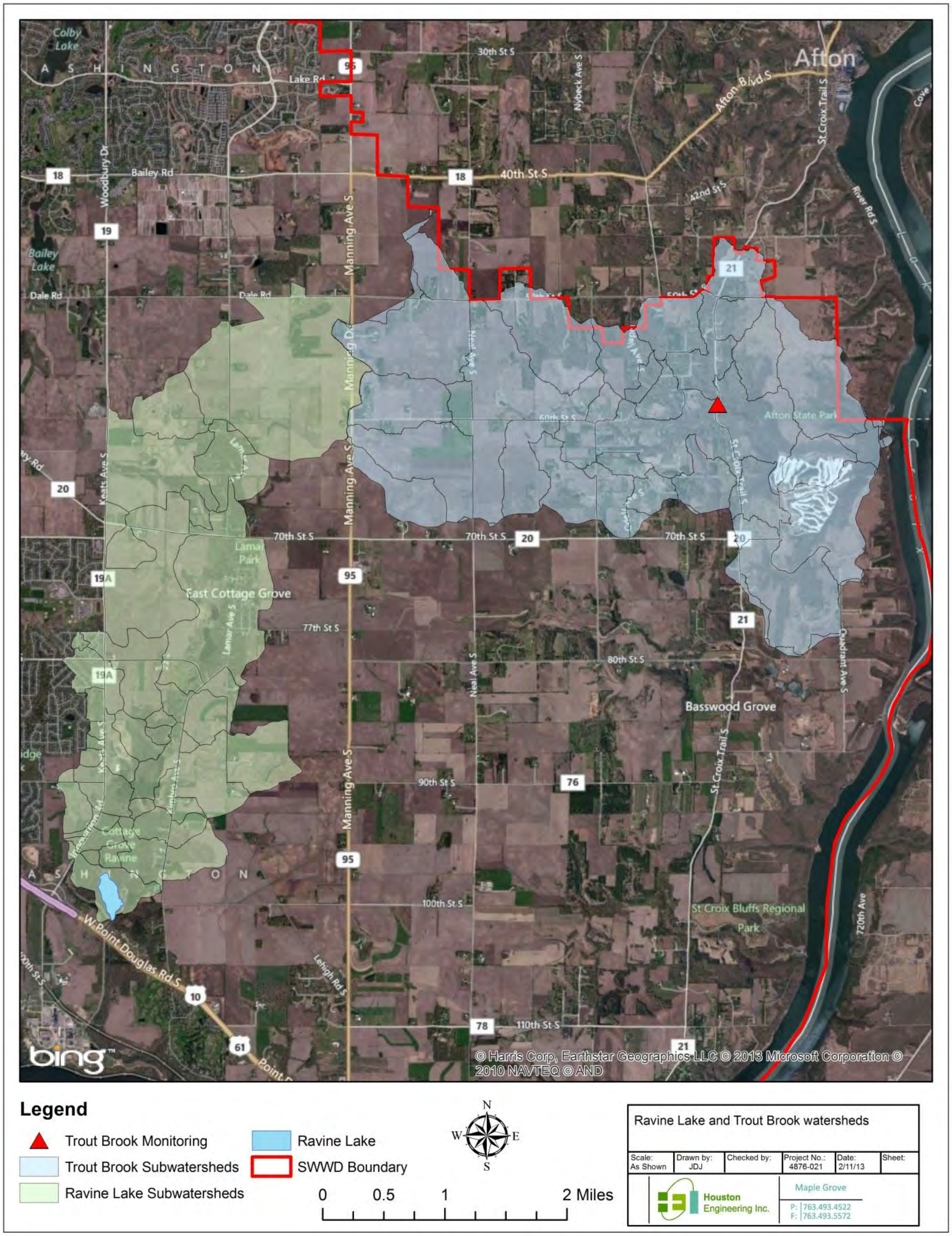
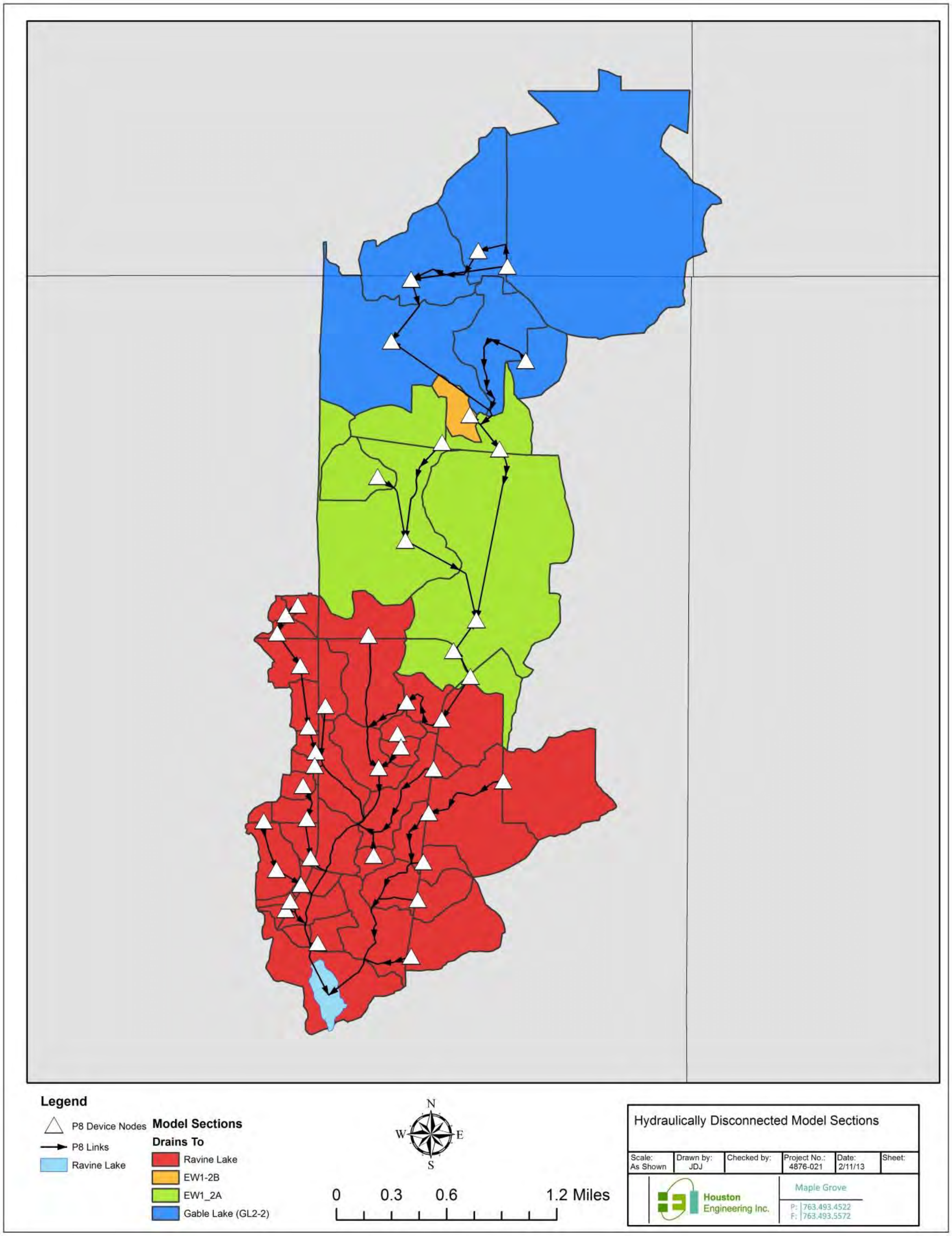


Figure 13. Hydraulically-isolated sections of the Existing Conditions P8 model.



3.4 Subwatershed Concentration Comparison

An additional check for model reasonability was performed by evaluating long-term subwatershed runoff concentrations for TP and TSS. The models were run over a 50-year period and the average subwatershed runoff concentrations for TP and TSS were compared to literature values[16] based on the dominant (> 66%) land class (cropland, forest, or urban) in the area. The results are shown in **Table 4**.

Table 4. Subwatershed runoff concentration comparison.

Dominant Land Class	Existing Conditions Model		Future Conditions Model		Literature Values	
	TP (ug/L)	TSS (ug/L)	TP (ug/L)	TSS (ug/L)	TP (ug/L)	TSS (ug/L)
Cropland	0.6	192	0.6	198	0.12-0.21	ND
Forest	0.1	45	0.1	45	0.02-0.03	ND
Urban	0.5	152	0.5	151	0.05-9.4	3-3,577

ND - No Data

Results of the comparison indicate that the Existing and Future Conditions models are producing subwatershed TP and TSS concentrations that are similar amongst models. Cropland and forest TP yields are slightly higher than literature values in this case, but within the expected error due to modeling assumptions and assumptions in summarizing the data (i.e., by major land use category within each subwatershed). Urban yield values are within the expected ranges.

4 MODEL RESULTS & DISCUSSION

Several key differences exist between the Existing and Future Conditions models that result in significant changes in the surface water and pollutant loading to Ravine Lake, both on an annual and long-term average basis. This section presents a comparison of these differences and identifies root causes within the models.

Table 5 presents a summary of the simulated hydrology, for existing and future modeled conditions, for overall flow entering Ravine Lake; results are provided for both 1979 alone and on a 50-year (1962-2011) average annual basis. Results are also presented on a summer seasonal (June-September) and annual basis. It's notable that the early to mid-1980s had a series of particularly wet years in the area, resulting in extremely high (simulated) surface water runoffs and TP loads in 1987. The long-term average results shown in **Table 5** include the 1987 outliers in the

[16] Lin, J. P. (2004). "Review of published export coefficient and event mean concentration (EMC) data," ERDC TN-WRAP-04-3, U.S. Army Engineer Research and Development Center, Vicksburg, MS, 15 pp.

averages presented. Future users of these results may want to remove the 1987 outliers (depending on the goals of their use) to represent conditions in the watershed.

As summarized in **Table 5,** the contributing area to Ravine Lake increases by approximately 73% between the existing and simulated future condition. In addition, the developed area has increased by more than 400%, approximately doubling unit runoff values on both the short- (i.e., 1979) and long-term (i.e., 50-year average) basis. Contributing area for each of the models is defined as including any subwatersheds that are both hydraulically connected to Ravine Lake in the model and have outflow via these connections during the 50-year simulation. Developed area is defined as any area that has been classified as “urban” (see **Figure 6** and **Figure 7**). Annual unit runoff values were computed by dividing the simulated annual runoff volume by the contributing area.

In addition to summarizing the differences in surface water volumes that reach Ravine Lake under the existing and future conditions, **Table 5** also summarize the differences in the TP loads that reach the lake under the two scenarios. Again, increases in total loading and annual unit loading to the lake are seen. Annual unit TP loads were computed as the annual TP load divided by the contributing area.

Table 5. Ravine Lake input comparison between Existing Conditions and Future Conditions P8 models.

	Existing Conditions Model	Future Conditions Model
% Developed*	8.7%	38.4%
Contributing Area (acres)	1,704	2,944
1979		
Summer Seasonal Volume (acre-feet)	73.7	353.2
Summer Seasonal TP Load (lbs)	72.5	209.6
Annual Volume (acre-feet)	392.8	1,419.2
Annual TP Load (lbs)	238.8	606.1
Annual Unit Runoff (in/acre)	2.77	5.78
Annual Unit TP Load (lb/acre)	0.14	0.21
1962-2011		
Average Summer Seasonal Volume (acre-feet)	103.2	428.8
Average Summer Seasonal TP Load (lbs)	185.7	415.8
Average Annual Volume (acre-feet)	261.6	981.7
Average Annual TP Load (lbs)	280.6	695.5
Average Annual Unit Runoff (in/acre)	1.84	4.00
Average Annual Unit TP Load (lb/acre)	0.16	0.24

* Developed includes only land classified as "urban", based on entire Ravine Lake watershed

The increased contributing area in the Future Conditions model can be attributed to the increased hydraulic connectivity of the watershed, predominantly caused by the inclusion of a pump at Van de Berg Lake (EW1-2A) and the addition of a 72” pipe connecting CP4-3 to RL2-15C. Figures showing the Existing Conditions and Future Conditions model subwatersheds, devices, and connections are included as **Figure A1** and **Figure A2** in the **Appendix**. This increase in contributing area is partially responsible for the (simulated) increase in surface water inflow to Ravine Lake between the two scenarios.

Several key outflow locations within the watershed were used to track increases in flow volume between the two model scenarios. The 72” pipe that’s included in the Future Conditions model at CP4-3 introduces an additional average annual runoff volume of approximately 445 ac-ft to the area contributing to Ravine Lake. Devices in the Future Conditions model, downstream of CP4-3, do not have sufficient infiltration to reduce this volume before it enters Ravine Lake. Likewise, the pump at Van de Berg Lake (EW1-2A) introduces an average annual runoff volume of approximately 202 ac-ft, also with limited downstream infiltration. These two connections account for nearly two-thirds of the surface water volume increase to Ravine Lake. Additional drainage area added in the Future Conditions scenario, particularly in the increased-development areas to the west, result in increased subwatershed outflow that may not be compensated by downstream infiltration. The remaining increase in flows and loads to Ravine Lake is a function of the general combination of increased development (impervious runoff), lack of infiltration, and increase in contributing area.

As indicated in **Figure 6** and **Figure 7**, the developed portion of the watershed increases from the Existing to Future condition, particularly in the southwestern portion of the watershed, contributing to Ravine Lake. This increase in development is the primary cause for the higher unit runoff values shown in **Table 5**. **Figure A3**, **Figure A4** and **Table A1** in the **Appendix** show the 50-year average annual untreated unit runoff values (in/yr) for each subwatershed in both the Existing and Future Conditions models. These untreated values show the runoff that is yielded from the landscape in each area, not the amount that is routed through best management practices or other devices in the model. Also included in the table and in **Figure A5** and **Figure A6** are the 50-year average annual subwatershed unit TP yields (i.e., the amount of the TP yielded from the landscape in each area, not accounting for treatment in BMPs/devices before the load moves downstream). The unit runoff and TP loading values are calculated by the P8 models for each simulated device; therefore, multiple watersheds draining to the same device are attributed the same unit runoff and unit yield value. As noted previously, certain subwatersheds show considerable increases in simulated unit runoff and unit yield values between the Existing and Future Conditions scenarios; these increases are particularly notable in the areas draining to CP4-3 and the newly-developed subwatersheds to west. According to USGS[17], typical mean annual runoff values for the region are between 6-7 inches per year. The Existing Conditions model shows values near this in the developed areas (urban), with lower values (2-4 inches per year) in the forested and cropland areas. The Future Conditions model shows values greater (as high as 13.3 inches per year) than the USGS average on many areas (predominantly in the newly developed areas) with lower values in the forest and cropland areas (see **Appendix**). **Figure A7** and **Figure A8** show the simulated (untreated) unit runoff values under 1979 conditions.

5 CONCLUSION

This report documents the creation of two Ravine Lake watershed models, developed to represent the existing and future conditions of the area. The models were created using P8 and simulate the surface water runoff volume and pollutant load components of the long-term hydrologic budget and mass balance for the area. The models were developed from, and largely based on, two existing event-based hydraulic SWMM models created for the SWWD. The Future Conditions model included pond infiltration rates similar to those reported in the City of Cottage Grove AUAR study. The P8 models were calibrated using SWMM model runoff volumes from the hydrologically-active period (April-October) as well as literature values for UALs. Additionally, unit runoff and TP loading model results were compared to an adjacent watershed FLUX estimates and subwatershed runoff concentrations were compared to land class-based literature values. The results of the two models, evaluated for 1979 and on a 50-year average basis are reviewed and discussed, identifying specific changes in simulated surface water volume and TP loads to Ravine Lake under the two scenarios. The resulting models can be used to estimate pollutant loading throughout the watershed and ultimately into Ravine Lake, given existing and future conditions for watershed management purposes.

[17] USGS Techniques for Estimating the Magnitude and Frequency of Peak Flow on Small Streams in Minnesota Based on Data through Water Year 2005. Scientific Investigation Report 2009-5250. http://pubs.usgs.gov/sir/2009/5250/pdf/sir2009-5250.pdf

6 APPENDIX A

Figure A1: Existing Conditions Model Framework

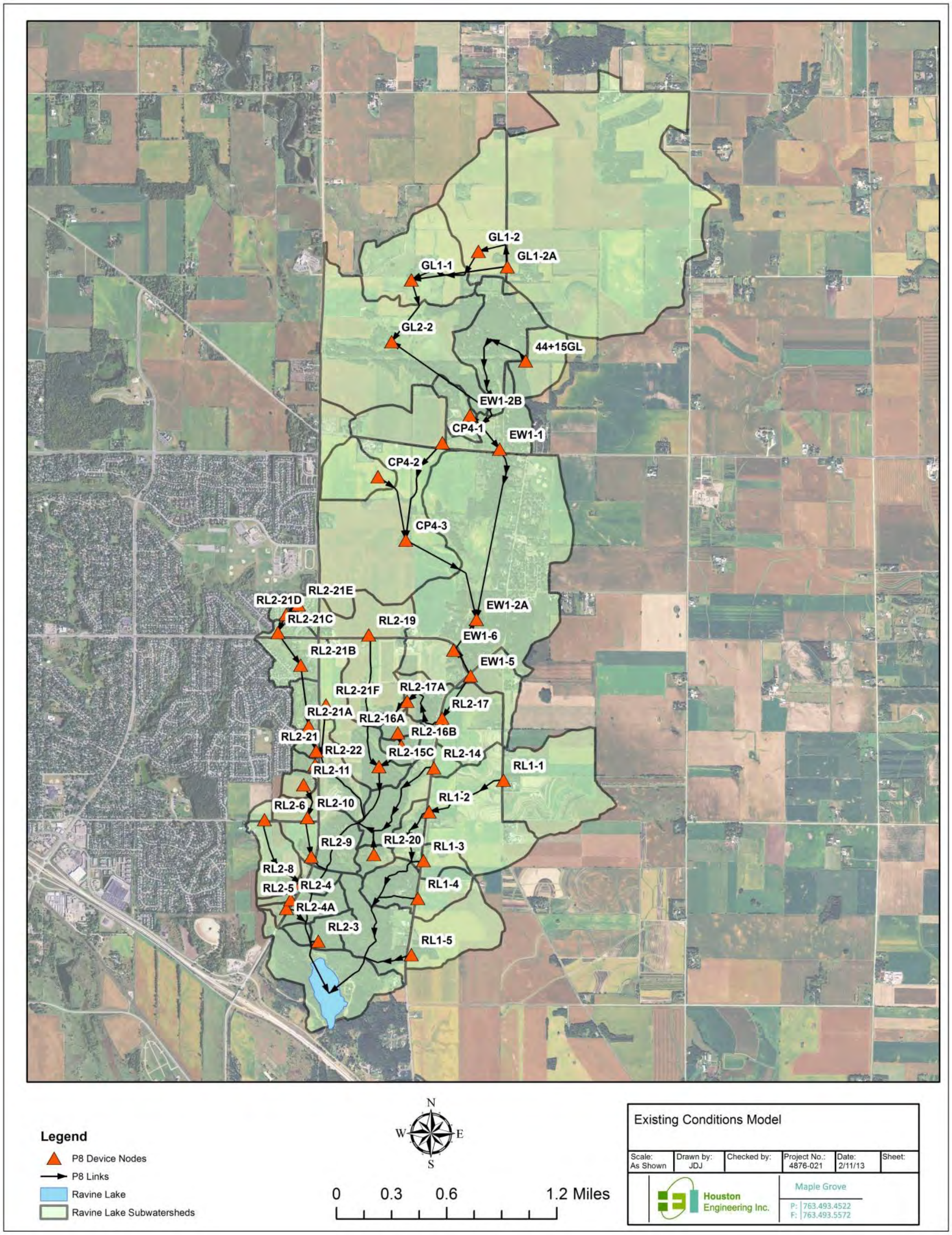


Figure A2: Future Conditions Model Framework

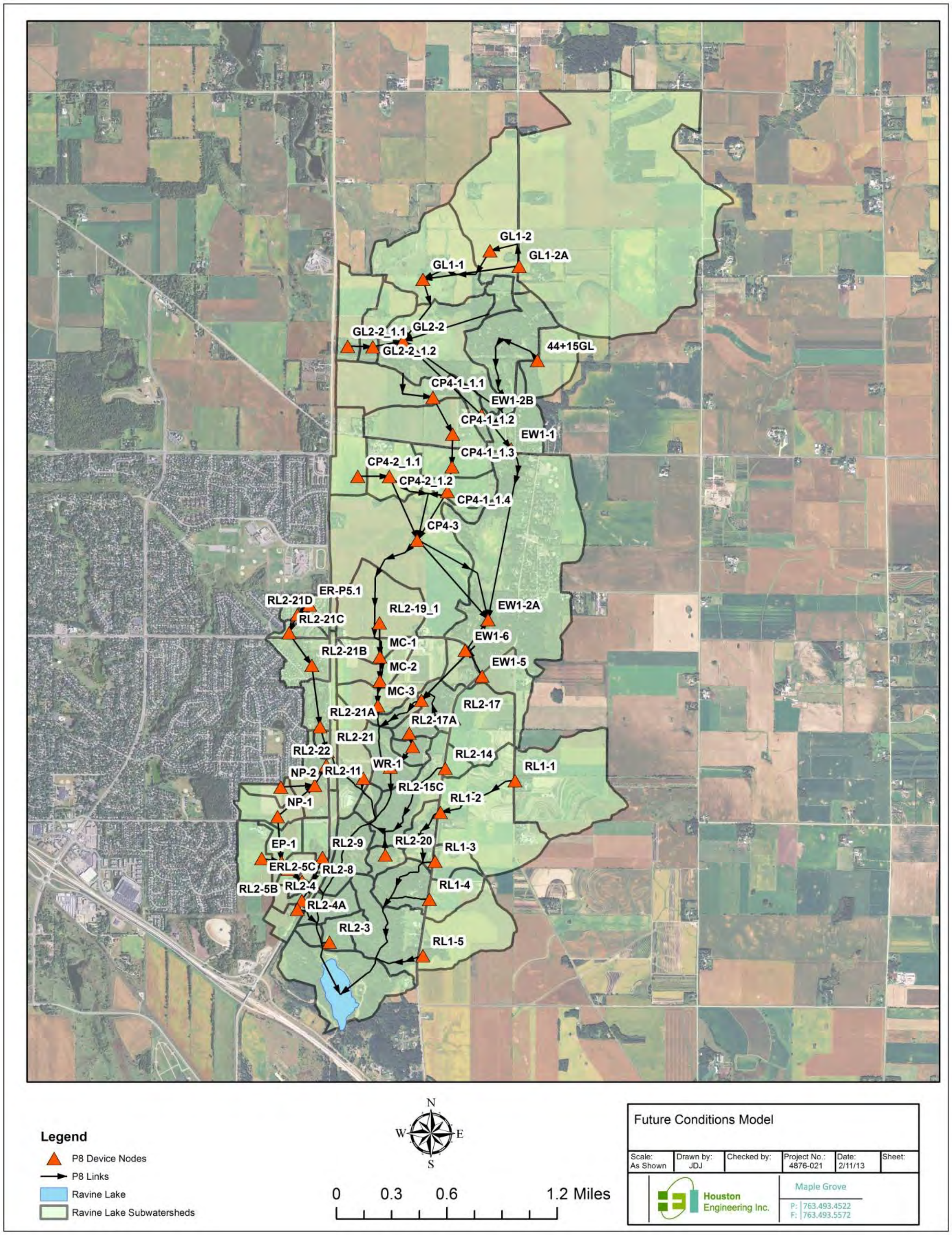


Figure A3: Existing Conditions Model 50-Year Average Subwatershed (Untreated) Unit Runoff Values

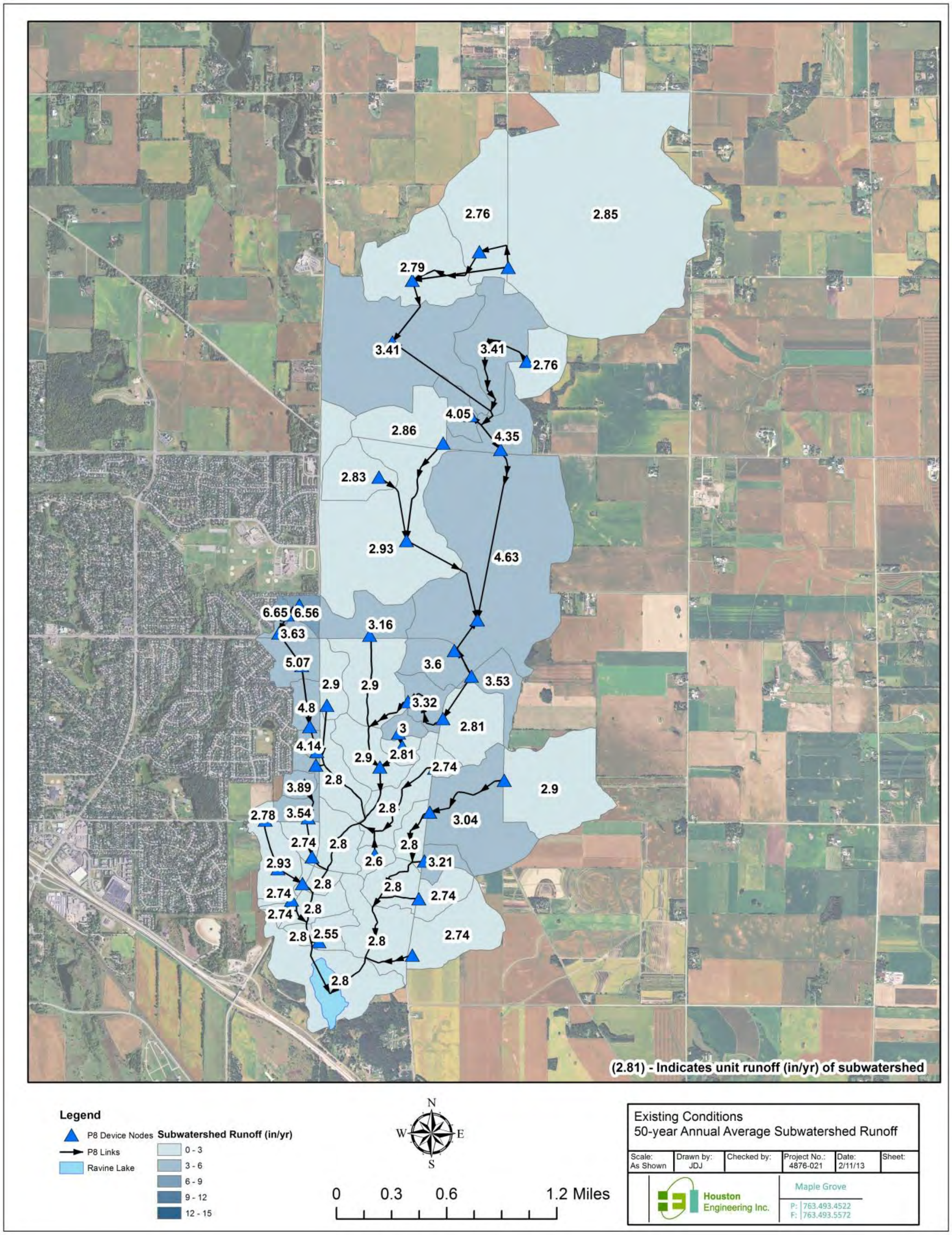


Figure A4: Future Conditions Model 50-Year Average Subwatershed (Untreated) Unit Runoff Values

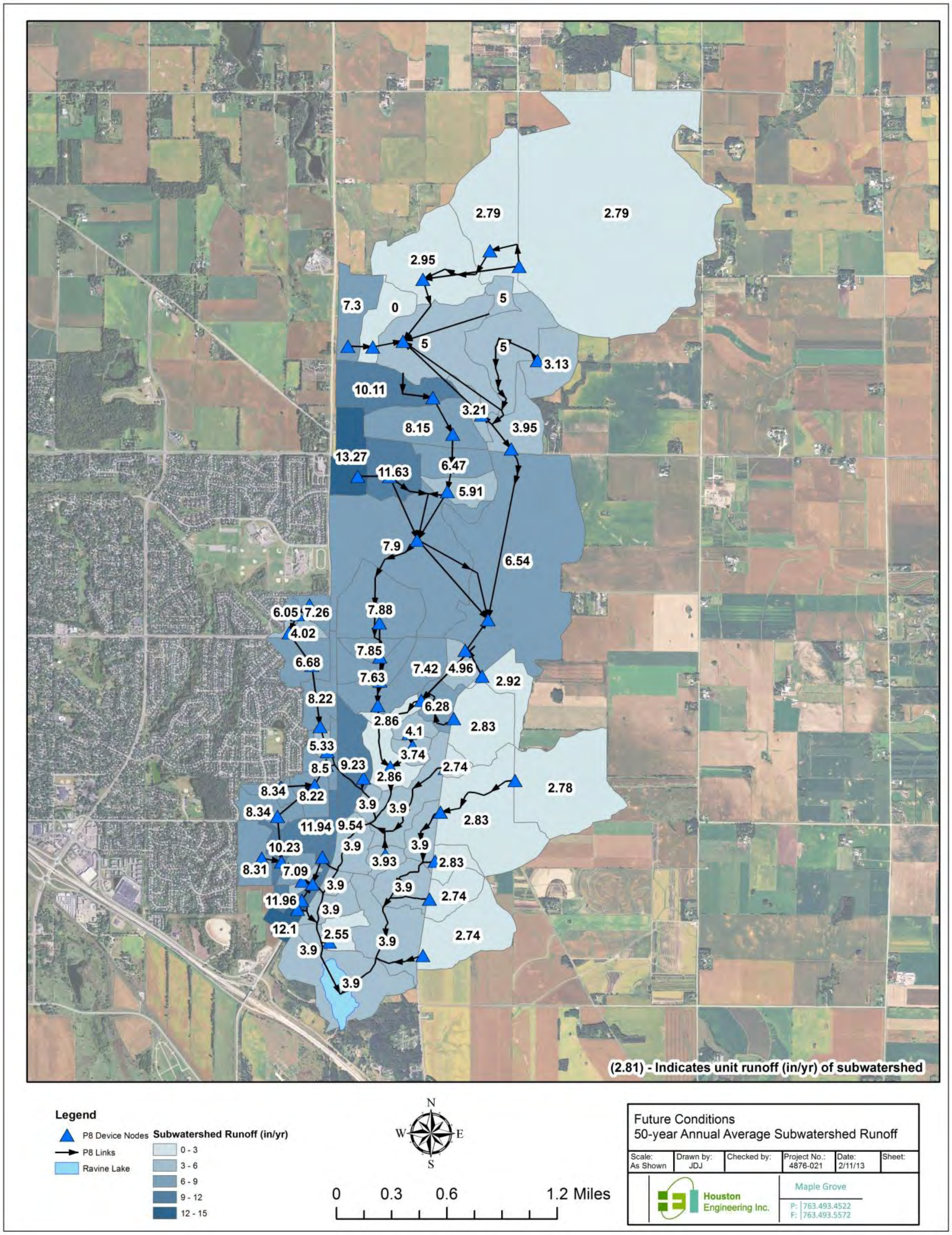


Figure A5: Existing Conditions Model 50-Year Average Subwatershed (Untreated) Unit TP Yield Values

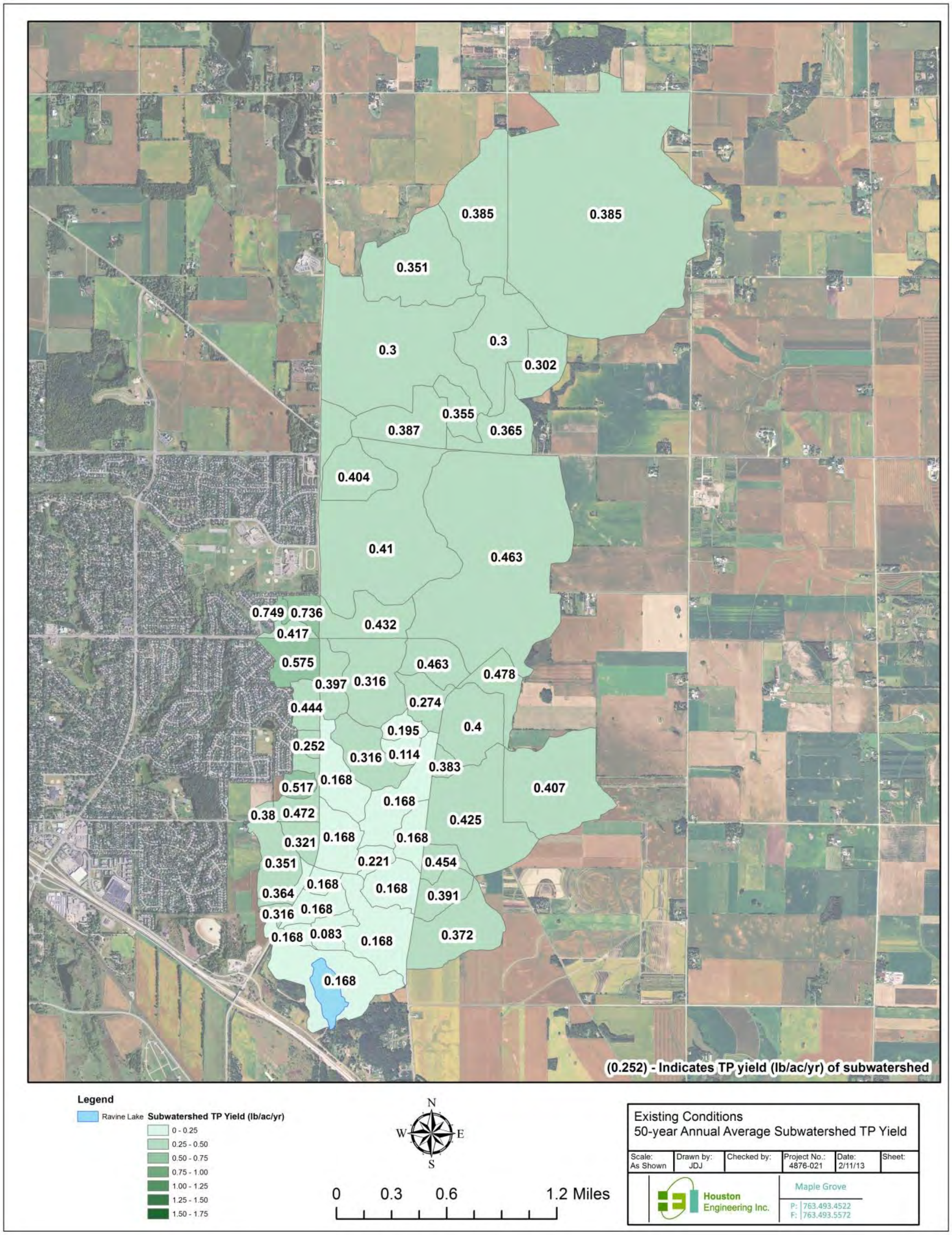


Figure A6: Future Conditions Model 50-Year Average Subwatershed (Untreated) Unit TP Yield Values

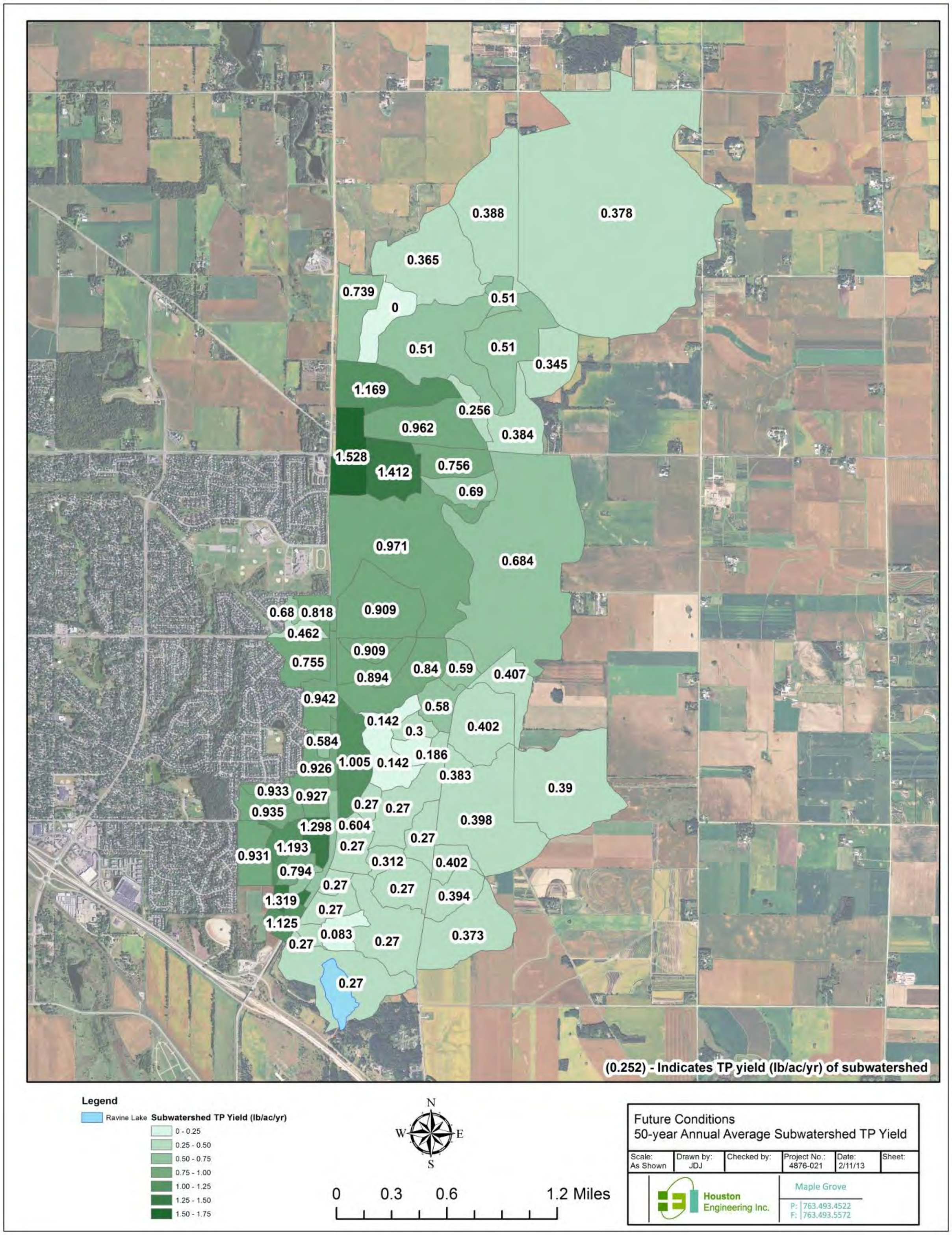


Figure A7: Existing Conditions Model 1979 Subwatershed (Untreated) Unit Runoff Values

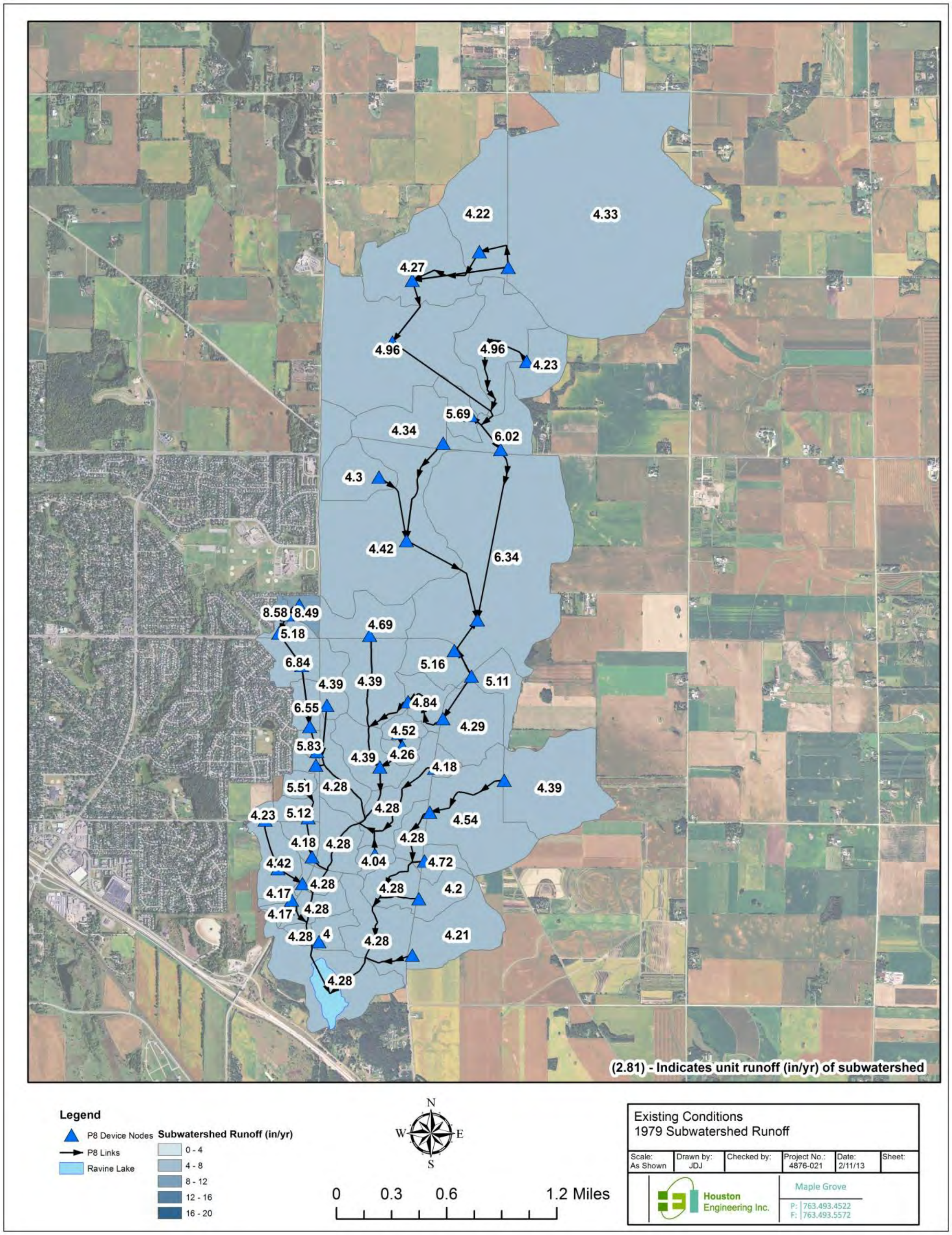


Figure A8: Future Conditions Model 1979 Subwatershed (Untreated) Unit Runoff Values

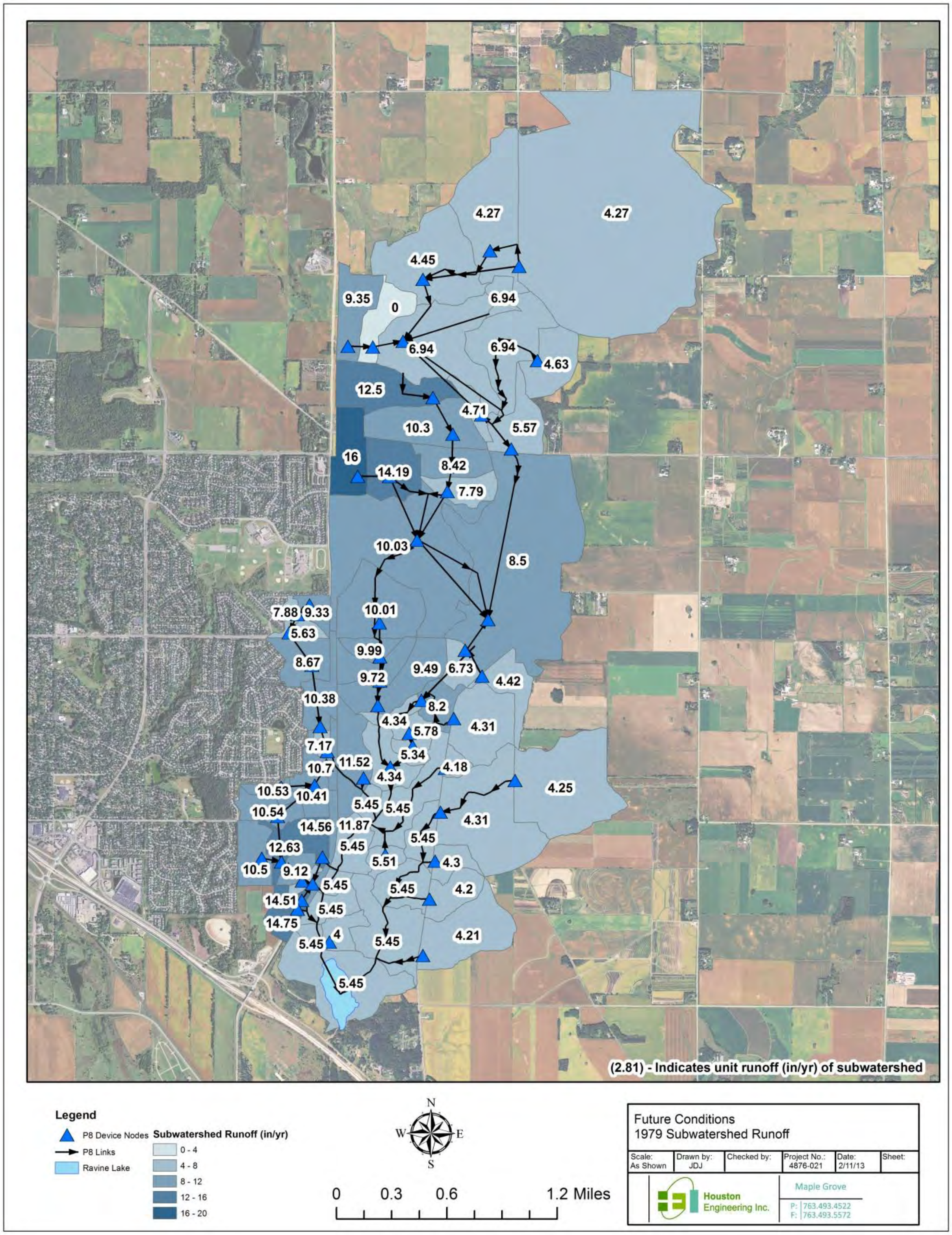


Table A1: Existing and Future Conditions (Untreated) Unit Runoff and Unit TP Yield values for 50-year Annual Average.

Existing Conditions Model				Future Conditions Model			
Model Watershed	Model Receiving Device	Unit Runoff (in/yr)	Unit TP Load (lb/yr)	Model Watershed	Model Receiving Device	Unit Runoff (in/yr)	Unit TP Load (lb/yr)
01+00WR	RL2-1	2.8	0.17	01+00WR	RL2-1	3.9	0.27
03+00MC	RL2-1	2.8	0.17	03+00MC	RL2-1	3.9	0.27
05+38GL	GL2-2	3.4	0.30	05+38GL	GL2-2	5.0	0.51
06+60ER	RL2-1	2.8	0.17	06+60ER	RL2-1	3.9	0.27
10+00MC	RL2-1	2.8	0.17	10+00MC	RL2-1	3.9	0.27
19+00MC	RL2-1	2.8	0.17	19+00MC	RL2-1	3.9	0.27
24+76ER	RL2-1	2.8	0.17	24+76ER	RL2-1	3.9	0.27
27+00MC	RL2-1	2.8	0.17	27+00MC	RL2-1	3.9	0.27
44+15GL	44+15GL	2.8	0.30	44+15GL	44+15GL	3.1	0.35
45+15MC	RL2-1	2.8	0.17	45+15MC	RL2-1	3.9	0.27
45+20ER	RL2-1	2.8	0.17	45+20ER	RL2-1	3.9	0.27
76+00MC	RL2-15C	2.9	0.32	76+00MC	RL2-15C	2.9	0.14
CP4-1	CP4-1	2.9	0.39	CP4-1_1.1	CP4-1_1.1	10.1	1.17
CP4-2	CP4-2	2.8	0.40	CP4-1_1.2	CP4-1_1.2	8.2	0.96
CP4-3	CP4-3	2.9	0.41	CP4-1_1.3	CP4-1_1.3	6.5	0.76
EW1-1	EW1-1	4.4	0.37	CP4-1_1.4	CP4-1_1.4	5.9	0.69
EW1-2A	EW1-2A	4.6	0.46	CP4-2_1.1	CP4-2_1.1	13.3	1.53
EW1-2B	EW1-2B	4.1	0.36	CP4-2_1.2	CP4-2_1.2	11.6	1.41
EW1-5	EW1-5	3.5	0.48	CP4-3	CP4-3	7.9	0.97
EW1-6	EW1-6	3.6	0.46	EP-1	EP-1	8.3	0.93
GL1-1	GL1-1	2.8	0.35	ER-P5.1	ER-P5.1	7.3	0.82
GL1-2	GL1-2	2.8	0.39	ERL2-5A	ERL2-5A	10.2	1.19
GL1-2A	GL1-2A	2.9	0.39	ERL2-5C	ERL2-5C	5.2	0.59
GL2-2	GL2-2	3.4	0.30	EW1-1	EW1-1	4.0	0.38
RL1-1	RL1-1	2.9	0.41	EW1-2A	EW1-2A	6.5	0.68
RL1-2	RL1-2	3.0	0.43	EW1-2B	EW1-2B	3.2	0.26
RL1-3	RL1-3	3.2	0.45	EW1-5	EW1-5	2.9	0.41
RL1-4	RL1-4	2.7	0.39	EW1-6	EW1-6	5.0	0.59
RL1-5	RL1-5	2.7	0.37	GL1-1	GL1-1	3.0	0.37
RL2-1	RL2-1	2.8	0.17	GL1-2	GL1-2	2.8	0.39
RL2-10	RL2-10	3.5	0.47	GL1-2A	GL1-2A	2.8	0.38
RL2-11	RL2-11	3.9	0.52	GL2-2	GL2-2	5.0	0.51
RL2-14	RL2-14	2.7	0.38	GL2-2_1.1	GL2-2_1.1	7.3	0.74
RL2-15C	RL2-15C	2.9	0.32	GL2-2_1.2	GL2-2_1.2	0.0	0.00
RL2-16A	RL2-16A	3.0	0.20	GL2-2_1.3	GL2-2	5.0	0.51
RL2-16B	RL2-16B	2.8	0.11	MC-1	MC-1	7.9	0.91
RL2-17	RL2-17	2.8	0.40	MC-2	MC-2	7.6	0.89
RL2-17A	RL2-17A	3.3	0.27	MC-3	MC-3	7.4	0.84
RL2-19	RL2-19	3.2	0.43	NP-1	NP-1	8.3	0.94
RL2-20	RL2-20	2.6	0.22	NP-2	NP-2	8.3	0.93
RL2-21	RL2-21	4.1	0.25	RL1-1	RL1-1	2.8	0.39
RL2-21A	RL2-21A	4.8	0.44	RL1-2	RL1-2	2.8	0.40
RL2-21B	RL2-21B	5.1	0.58	RL1-3	RL1-3	2.8	0.40
RL2-21C	RL2-21C	3.6	0.42	RL1-4	RL1-4	2.7	0.39
RL2-21D	RL2-21D	6.7	0.75	RL1-5	RL1-5	2.7	0.37
RL2-21E	RL2-21E	6.6	0.74	RL2-1	RL2-1	3.9	0.27
RL2-21F	RL2-21F	2.9	0.40	RL2-11	RL2-11	8.2	0.93
RL2-22	RL2-22	4.3	0.30	RL2-14	RL2-14	2.7	0.38
RL2-3	RL2-3	2.6	0.08	RL2-15C	RL2-15C	2.9	0.14
RL2-4	RL2-4	2.7	0.36	RL2-16A	RL2-16A	4.1	0.30
RL2-4A	RL2-4A	2.7	0.32	RL2-16B	RL2-16B	3.7	0.19
RL2-5	RL2-5	2.9	0.35	RL2-17	RL2-17	2.8	0.40
RL2-6	RL2-6	2.8	0.38	RL2-17A	RL2-17A	6.3	0.58
RL2-8	RL2-8	2.7	0.24	RL2-19_1	RL2-19_1	7.9	0.91
RL2-9	RL2-9	2.7	0.32	RL2-20	RL2-20	3.9	0.31
				RL2-21	RL2-21	5.3	0.58
				RL2-21A	RL2-21A	8.2	0.94
				RL2-21B	RL2-21B	6.7	0.76
				RL2-21C	RL2-21C	4.0	0.46
				RL2-21D	RL2-21D	6.1	0.68
				RL2-22	RL2-22	8.5	0.93
				RL2-3	RL2-3	2.6	0.08
				RL2-4	RL2-4	12.0	1.32
				RL2-4A	RL2-4A	12.1	1.13
				RL2-5B	RL2-5B	7.1	0.79
				RL2-8	RL2-8	9.5	0.60
				RL2-9	RL2-9	11.9	1.30
				WR-1	WR-1	9.2	1.01

APPENDIX B

HEC-RAS Stage Discharge Curves

18" Culvert		24" Culvert		18" Culvert - 50% Obstructed		18" Culvert - 75% Obstructed		18" Culvert High N-value	
Elevation	Flow (cfs)	Elevation	Flow (cfs)	Elevation	Flow (cfs)	Elevation	Flow (cfs)	Elevation	Flow (cfs)
770.61	0.00	770.61	0.00	770.61	0.00	770.61	0.00	770.61	0.00
770.62	0.01	770.62	0.01	770.62	0.01	770.62	0.01	770.62	0.01
770.63	0.02	770.63	0.02	770.63	0.02	770.63	0.01	770.63	0.02
770.64	0.03	770.64	0.03	770.64	0.02	770.64	0.02	770.64	0.03
770.65	0.03	770.65	0.03	770.65	0.03	770.65	0.03	770.65	0.03
770.66	0.04	770.66	0.04	770.66	0.04	770.66	0.04	770.66	0.04
770.67	0.05	770.67	0.05	770.67	0.05	770.67	0.04	770.67	0.05
770.68	0.06	770.68	0.06	770.68	0.06	770.68	0.05	770.68	0.06
770.69	0.07	770.69	0.07	770.69	0.07	770.69	0.06	770.69	0.07
770.7	0.08	770.7	0.08	770.7	0.07	770.7	0.07	770.7	0.08
770.71	0.08	770.71	0.09	770.71	0.08	770.71	0.07	770.71	0.08
770.72	0.09	770.72	0.09	770.72	0.09	770.72	0.08	770.72	0.09
770.73	0.10	770.73	0.10	770.73	0.10	770.73	0.09	770.73	0.10
770.74	0.11	770.74	0.11	770.74	0.11	770.74	0.10	770.74	0.11
770.75	0.12	770.75	0.12	770.75	0.12	770.75	0.10	770.75	0.12
770.76	0.13	770.76	0.13	770.76	0.12	770.76	0.11	770.76	0.13
770.77	0.14	770.77	0.14	770.77	0.13	770.77	0.12	770.77	0.13
770.78	0.14	770.78	0.14	770.78	0.14	770.78	0.13	770.78	0.14
770.79	0.15	770.79	0.15	770.79	0.15	770.79	0.13	770.79	0.15
770.8	0.16	770.8	0.16	770.8	0.16	770.8	0.14	770.8	0.16
770.81	0.17	770.81	0.17	770.81	0.17	770.81	0.15	770.81	0.17
770.82	0.18	770.82	0.18	770.82	0.17	770.82	0.16	770.82	0.18
770.83	0.19	770.83	0.19	770.83	0.18	770.83	0.16	770.83	0.18
770.84	0.19	770.84	0.20	770.84	0.19	770.84	0.17	770.84	0.19
770.85	0.20	770.85	0.20	770.85	0.20	770.85	0.18	770.85	0.20
770.86	0.21	770.86	0.21	770.86	0.21	770.86	0.19	770.86	0.21
770.87	0.22	770.87	0.22	770.87	0.22	770.87	0.19	770.87	0.22
770.88	0.23	770.88	0.23	770.88	0.22	770.88	0.20	770.88	0.23
770.89	0.24	770.89	0.24	770.89	0.23	770.89	0.21	770.89	0.24
770.9	0.25	770.9	0.25	770.9	0.24	770.9	0.21	770.9	0.24
770.91	0.26	770.91	0.26	770.91	0.25	770.91	0.22	770.91	0.25
770.92	0.28	770.92	0.28	770.92	0.26	770.92	0.23	770.92	0.27
770.93	0.30	770.93	0.30	770.93	0.28	770.93	0.24	770.93	0.29
770.94	0.32	770.94	0.32	770.94	0.30	770.94	0.24	770.94	0.30
770.95	0.34	770.95	0.34	770.95	0.31	770.95	0.25	770.95	0.32
770.96	0.35	770.96	0.36	770.96	0.33	770.96	0.26	770.96	0.33
770.97	0.37	770.97	0.38	770.97	0.35	770.97	0.27	770.97	0.35
770.98	0.39	770.98	0.40	770.98	0.36	770.98	0.28	770.98	0.37
770.99	0.41	770.99	0.42	770.99	0.38	770.99	0.29	770.99	0.38
771	0.43	771	0.44	771	0.40	771	0.30	771	0.40
771.01	0.45	771.01	0.46	771.01	0.41	771.01	0.31	771.01	0.42
771.02	0.47	771.02	0.48	771.02	0.43	771.02	0.32	771.02	0.43
771.03	0.49	771.03	0.50	771.03	0.45	771.03	0.33	771.03	0.45
771.04	0.51	771.04	0.52	771.04	0.46	771.04	0.34	771.04	0.46
771.05	0.53	771.05	0.55	771.05	0.48	771.05	0.35	771.05	0.48
771.06	0.56	771.06	0.58	771.06	0.50	771.06	0.36	771.06	0.50
771.07	0.59	771.07	0.61	771.07	0.52	771.07	0.37	771.07	0.52
771.08	0.61	771.08	0.63	771.08	0.53	771.08	0.38	771.08	0.54
771.09	0.64	771.09	0.66	771.09	0.55	771.09	0.39	771.09	0.56
771.1	0.66	771.1	0.69	771.1	0.57	771.1	0.40	771.1	0.58
771.11	0.69	771.11	0.72	771.11	0.59	771.11	0.41	771.11	0.60
771.12	0.71	771.12	0.74	771.12	0.61	771.12	0.42	771.12	0.62
771.13	0.74	771.13	0.77	771.13	0.63	771.13	0.43	771.13	0.64
771.14	0.77	771.14	0.80	771.14	0.64	771.14	0.44	771.14	0.66
771.15	0.79	771.15	0.83	771.15	0.66	771.15	0.45	771.15	0.68
771.16	0.82	771.16	0.85	771.16	0.68	771.16	0.46	771.16	0.70
771.17	0.84	771.17	0.88	771.17	0.70	771.17	0.47	771.17	0.72
771.18	0.87	771.18	0.91	771.18	0.72	771.18	0.48	771.18	0.75
771.19	0.89	771.19	0.94	771.19	0.74	771.19	0.49	771.19	0.77
771.2	0.92	771.2	0.96	771.2	0.75	771.2	0.49	771.2	0.79
771.21	0.95	771.21	0.99	771.21	0.77	771.21	0.50	771.21	0.81
771.22	0.97	771.22	1.02	771.22	0.79	771.22	0.51	771.22	0.83

771.23	1.00	771.23	1.06	771.23	0.81	771.23	0.52	771.23	0.85
771.24	1.03	771.24	1.09	771.24	0.83	771.24	0.52	771.24	0.87
771.25	1.05	771.25	1.13	771.25	0.85	771.25	0.53	771.25	0.89
771.26	1.08	771.26	1.16	771.26	0.87	771.26	0.54	771.26	0.91
771.27	1.11	771.27	1.20	771.27	0.88	771.27	0.55	771.27	0.93
771.28	1.14	771.28	1.23	771.28	0.90	771.28	0.55	771.28	0.95
771.29	1.17	771.29	1.27	771.29	0.92	771.29	0.56	771.29	0.98
771.3	1.20	771.3	1.30	771.3	0.94	771.3	0.57	771.3	1.00
771.31	1.23	771.31	1.34	771.31	0.96	771.31	0.57	771.31	1.02
771.32	1.26	771.32	1.37	771.32	0.98	771.32	0.58	771.32	1.05
771.33	1.29	771.33	1.41	771.33	0.99	771.33	0.59	771.33	1.07
771.34	1.32	771.34	1.44	771.34	1.01	771.34	0.60	771.34	1.10
771.35	1.35	771.35	1.47	771.35	1.03	771.35	0.60	771.35	1.12
771.36	1.38	771.36	1.51	771.36	1.04	771.36	0.61	771.36	1.15
771.37	1.41	771.37	1.54	771.37	1.06	771.37	0.62	771.37	1.17
771.38	1.43	771.38	1.58	771.38	1.07	771.38	0.62	771.38	1.20
771.39	1.46	771.39	1.61	771.39	1.09	771.39	0.63	771.39	1.22
771.4	1.49	771.4	1.65	771.4	1.10	771.4	0.64	771.4	1.25
771.41	1.52	771.41	1.68	771.41	1.12	771.41	0.65	771.41	1.27
771.42	1.55	771.42	1.72	771.42	1.13	771.42	0.65	771.42	1.30
771.43	1.58	771.43	1.75	771.43	1.15	771.43	0.66	771.43	1.32
771.44	1.61	771.44	1.79	771.44	1.17	771.44	0.67	771.44	1.35
771.45	1.64	771.45	1.82	771.45	1.18	771.45	0.67	771.45	1.37
771.46	1.67	771.46	1.86	771.46	1.20	771.46	0.68	771.46	1.40
771.47	1.70	771.47	1.89	771.47	1.21	771.47	0.69	771.47	1.42
771.48	1.73	771.48	1.93	771.48	1.23	771.48	0.70	771.48	1.45
771.49	1.76	771.49	1.96	771.49	1.24	771.49	0.70	771.49	1.47
771.5	1.79	771.5	2.00	771.5	1.26	771.5	0.71	771.5	1.50
771.51	1.81	771.51	2.03	771.51	1.27	771.51	0.72	771.51	1.52
771.52	1.84	771.52	2.07	771.52	1.29	771.52	0.72	771.52	1.55
771.53	1.87	771.53	2.11	771.53	1.31	771.53	0.73	771.53	1.57
771.54	1.90	771.54	2.15	771.54	1.32	771.54	0.74	771.54	1.60
771.55	1.93	771.55	2.18	771.55	1.34	771.55	0.75	771.55	1.62
771.56	1.96	771.56	2.22	771.56	1.35	771.56	0.75	771.56	1.65
771.57	1.99	771.57	2.26	771.57	1.37	771.57	0.76	771.57	1.67
771.58	2.02	771.58	2.30	771.58	1.38	771.58	0.77	771.58	1.70
771.59	2.05	771.59	2.34	771.59	1.40	771.59	0.77	771.59	1.72
771.6	2.07	771.6	2.37	771.6	1.41	771.6	0.78	771.6	1.75
771.61	2.10	771.61	2.41	771.61	1.43	771.61	0.79	771.61	1.77
771.62	2.13	771.62	2.45	771.62	1.44	771.62	0.80	771.62	1.80
771.63	2.16	771.63	2.49	771.63	1.46	771.63	0.80	771.63	1.82
771.64	2.19	771.64	2.52	771.64	1.48	771.64	0.81	771.64	1.85
771.65	2.22	771.65	2.56	771.65	1.49	771.65	0.82	771.65	1.88
771.66	2.24	771.66	2.60	771.66	1.51	771.66	0.82	771.66	1.90
771.67	2.27	771.67	2.64	771.67	1.52	771.67	0.83	771.67	1.93
771.68	2.30	771.68	2.68	771.68	1.54	771.68	0.84	771.68	1.95
771.69	2.33	771.69	2.71	771.69	1.55	771.69	0.85	771.69	1.98
771.7	2.36	771.7	2.75	771.7	1.57	771.7	0.85	771.7	2.00
771.71	2.38	771.71	2.79	771.71	1.58	771.71	0.86	771.71	2.03
771.72	2.41	771.72	2.83	771.72	1.60	771.72	0.87	771.72	2.05
771.73	2.44	771.73	2.86	771.73	1.61	771.73	0.87	771.73	2.07
771.74	2.47	771.74	2.90	771.74	1.63	771.74	0.88	771.74	2.10
771.75	2.50	771.75	2.94	771.75	1.65	771.75	0.89	771.75	2.12
771.76	2.52	771.76	2.98	771.76	1.66	771.76	0.89	771.76	2.15
771.77	2.55	771.77	3.01	771.77	1.68	771.77	0.90	771.77	2.17
771.78	2.58	771.78	3.05	771.78	1.69	771.78	0.91	771.78	2.20
771.79	2.61	771.79	3.09	771.79	1.71	771.79	0.92	771.79	2.22
771.8	2.64	771.8	3.12	771.8	1.72	771.8	0.92	771.8	2.24
771.81	2.67	771.81	3.16	771.81	1.74	771.81	0.93	771.81	2.27
771.82	2.69	771.82	3.19	771.82	1.75	771.82	0.94	771.82	2.29
771.83	2.72	771.83	3.23	771.83	1.77	771.83	0.94	771.83	2.32
771.84	2.75	771.84	3.26	771.84	1.78	771.84	0.95	771.84	2.34
771.85	2.78	771.85	3.30	771.85	1.80	771.85	0.96	771.85	2.37
771.86	2.81	771.86	3.33	771.86	1.82	771.86	0.97	771.86	2.39
771.87	2.83	771.87	3.37	771.87	1.83	771.87	0.97	771.87	2.41
771.88	2.86	771.88	3.40	771.88	1.85	771.88	0.98	771.88	2.44

771.89	2.89	771.89	3.44	771.89	1.86	771.89	0.99	771.89	2.46
771.9	2.92	771.9	3.48	771.9	1.88	771.9	0.99	771.9	2.49
771.91	2.95	771.91	3.51	771.91	1.89	771.91	1.00	771.91	2.51
771.92	2.98	771.92	3.55	771.92	1.91	771.92	1.02	771.92	2.54
771.93	3.00	771.93	3.58	771.93	1.92	771.93	1.03	771.93	2.56
771.94	3.03	771.94	3.62	771.94	1.94	771.94	1.04	771.94	2.59
771.95	3.05	771.95	3.65	771.95	1.95	771.95	1.06	771.95	2.61
771.96	3.08	771.96	3.69	771.96	1.97	771.96	1.07	771.96	2.63
771.97	3.10	771.97	3.72	771.97	1.99	771.97	1.08	771.97	2.66
771.98	3.13	771.98	3.76	771.98	2.00	771.98	1.10	771.98	2.68
771.99	3.15	771.99	3.79	771.99	2.02	771.99	1.11	771.99	2.71
772	3.17	772	3.83	772	2.03	772	1.12	772	2.73
772.01	3.20	772.01	3.87	772.01	2.05	772.01	1.14	772.01	2.76
772.02	3.22	772.02	3.90	772.02	2.06	772.02	1.15	772.02	2.78
772.03	3.25	772.03	3.94	772.03	2.08	772.03	1.16	772.03	2.80
772.04	3.27	772.04	3.97	772.04	2.09	772.04	1.18	772.04	2.83
772.05	3.30	772.05	4.01	772.05	2.11	772.05	1.19	772.05	2.85
772.06	3.32	772.06	4.03	772.06	2.12	772.06	1.21	772.06	2.88
772.07	3.35	772.07	4.06	772.07	2.14	772.07	1.22	772.07	2.90
772.08	3.37	772.08	4.09	772.08	2.15	772.08	1.23	772.08	2.93
772.09	3.39	772.09	4.11	772.09	2.17	772.09	1.25	772.09	2.95
772.1	3.42	772.1	4.14	772.1	2.18	772.1	1.26	772.1	2.98
772.11	3.44	772.11	4.17	772.11	2.19	772.11	1.27	772.11	3.00
772.12	3.47	772.12	4.20	772.12	2.21	772.12	1.29	772.12	3.02
772.13	3.49	772.13	4.22	772.13	2.22	772.13	1.30	772.13	3.04
772.14	3.52	772.14	4.25	772.14	2.24	772.14	1.31	772.14	3.06
772.15	3.54	772.15	4.28	772.15	2.25	772.15	1.33	772.15	3.08
772.16	3.57	772.16	4.31	772.16	2.27	772.16	1.34	772.16	3.10
772.17	3.59	772.17	4.33	772.17	2.28	772.17	1.35	772.17	3.12
772.18	3.61	772.18	4.36	772.18	2.30	772.18	1.37	772.18	3.14
772.19	3.64	772.19	4.39	772.19	2.31	772.19	1.38	772.19	3.16
772.2	3.66	772.2	4.41	772.2	2.33	772.2	1.39	772.2	3.18
772.21	3.69	772.21	4.44	772.21	2.34	772.21	1.41	772.21	3.20
772.22	3.71	772.22	4.47	772.22	2.36	772.22	1.42	772.22	3.22
772.23	3.74	772.23	4.50	772.23	2.37	772.23	1.43	772.23	3.24
772.24	3.76	772.24	4.52	772.24	2.39	772.24	1.45	772.24	3.26
772.25	3.79	772.25	4.55	772.25	2.40	772.25	1.46	772.25	3.28
772.26	3.81	772.26	4.58	772.26	2.42	772.26	1.47	772.26	3.30
772.27	3.84	772.27	4.61	772.27	2.43	772.27	1.49	772.27	3.32
772.28	3.86	772.28	4.63	772.28	2.45	772.28	1.50	772.28	3.34
772.29	3.88	772.29	4.66	772.29	2.46	772.29	1.52	772.29	3.36
772.3	3.91	772.3	4.69	772.3	2.48	772.3	1.53	772.3	3.38
772.31	3.93	772.31	4.71	772.31	2.49	772.31	1.54	772.31	3.40
772.32	3.96	772.32	4.74	772.32	2.51	772.32	1.56	772.32	3.42
772.33	3.98	772.33	4.77	772.33	2.52	772.33	1.57	772.33	3.44
772.34	4.01	772.34	4.80	772.34	2.54	772.34	1.58	772.34	3.46
772.35	4.04	772.35	4.82	772.35	2.55	772.35	1.60	772.35	3.48
772.36	4.07	772.36	4.85	772.36	2.57	772.36	1.61	772.36	3.49
772.37	4.10	772.37	4.88	772.37	2.58	772.37	1.62	772.37	3.51
772.38	4.13	772.38	4.90	772.38	2.60	772.38	1.64	772.38	3.53
772.39	4.17	772.39	4.93	772.39	2.61	772.39	1.65	772.39	3.55
772.4	4.20	772.4	4.96	772.4	2.63	772.4	1.66	772.4	3.57
772.41	4.23	772.41	4.99	772.41	2.64	772.41	1.68	772.41	3.59
772.42	4.26	772.42	5.01	772.42	2.66	772.42	1.69	772.42	3.61
772.43	4.29	772.43	5.04	772.43	2.67	772.43	1.70	772.43	3.63
772.44	4.32	772.44	5.06	772.44	2.69	772.44	1.72	772.44	3.65
772.45	4.35	772.45	5.09	772.45	2.70	772.45	1.73	772.45	3.67
772.46	4.38	772.46	5.11	772.46	2.72	772.46	1.74	772.46	3.69
772.47	4.42	772.47	5.13	772.47	2.73	772.47	1.76	772.47	3.71
772.48	4.45	772.48	5.16	772.48	2.75	772.48	1.77	772.48	3.73
772.49	4.48	772.49	5.18	772.49	2.76	772.49	1.78	772.49	3.75
772.5	4.51	772.5	5.21	772.5	2.78	772.5	1.80	772.5	3.77
772.51	4.54	772.51	5.23	772.51	2.79	772.51	1.81	772.51	3.79
772.52	4.57	772.52	5.26	772.52	2.81	772.52	1.82	772.52	3.81
772.53	4.60	772.53	5.28	772.53	2.82	772.53	1.84	772.53	3.83
772.54	4.64	772.54	5.30	772.54	2.84	772.54	1.85	772.54	3.85

772.55	4.67	772.55	5.33	772.55	2.85	772.55	1.87	772.55	3.87
772.56	4.70	772.56	5.35	772.56	2.87	772.56	1.88	772.56	3.89
772.57	4.73	772.57	5.38	772.57	2.88	772.57	1.89	772.57	3.91
772.58	4.76	772.58	5.40	772.58	2.90	772.58	1.91	772.58	3.93
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772.6	4.82	772.6	5.45	772.6	2.93	772.6	1.93	772.6	3.97
772.61	4.86	772.61	5.48	772.61	2.94	772.61	1.95	772.61	3.99
772.62	4.89	772.62	5.50	772.62	2.96	772.62	1.96	772.62	4.06
772.63	4.92	772.63	5.52	772.63	2.97	772.63	1.97	772.63	4.18
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772.67	5.05	772.67	5.62	772.67	5.07	772.67	5.07	772.67	4.67
772.68	5.08	772.68	5.65	772.68	5.10	772.68	5.10	772.68	4.79
772.69	5.12	772.69	5.67	772.69	5.14	772.69	5.14	772.69	4.91
772.7	5.15	772.7	5.69	772.7	5.17	772.7	5.17	772.7	5.01
772.71	5.19	772.71	5.72	772.71	5.20	772.71	5.20	772.71	5.04
772.72	5.22	772.72	5.74	772.72	5.24	772.72	5.24	772.72	5.07
772.73	5.25	772.73	5.77	772.73	5.27	772.73	5.27	772.73	5.10
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772.76	5.36	772.76	5.84	772.76	5.38	772.76	5.38	772.76	5.18
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772.78	5.43	772.78	5.89	772.78	5.44	772.78	5.44	772.78	5.24
772.79	5.46	772.79	5.91	772.79	5.48	772.79	5.48	772.79	5.27
772.8	5.50	772.8	5.94	772.8	5.51	772.8	5.51	772.8	5.30
772.81	5.53	772.81	5.96	772.81	5.55	772.81	5.55	772.81	5.33
772.82	5.57	772.82	5.99	772.82	5.58	772.82	5.58	772.82	5.36
772.83	5.60	772.83	6.01	772.83	5.61	772.83	5.61	772.83	5.39
772.84	5.63	772.84	6.04	772.84	5.65	772.84	5.65	772.84	5.42
772.85	5.67	772.85	6.06	772.85	5.68	772.85	5.68	772.85	5.45
772.86	5.70	772.86	6.08	772.86	5.72	772.86	5.72	772.86	5.48
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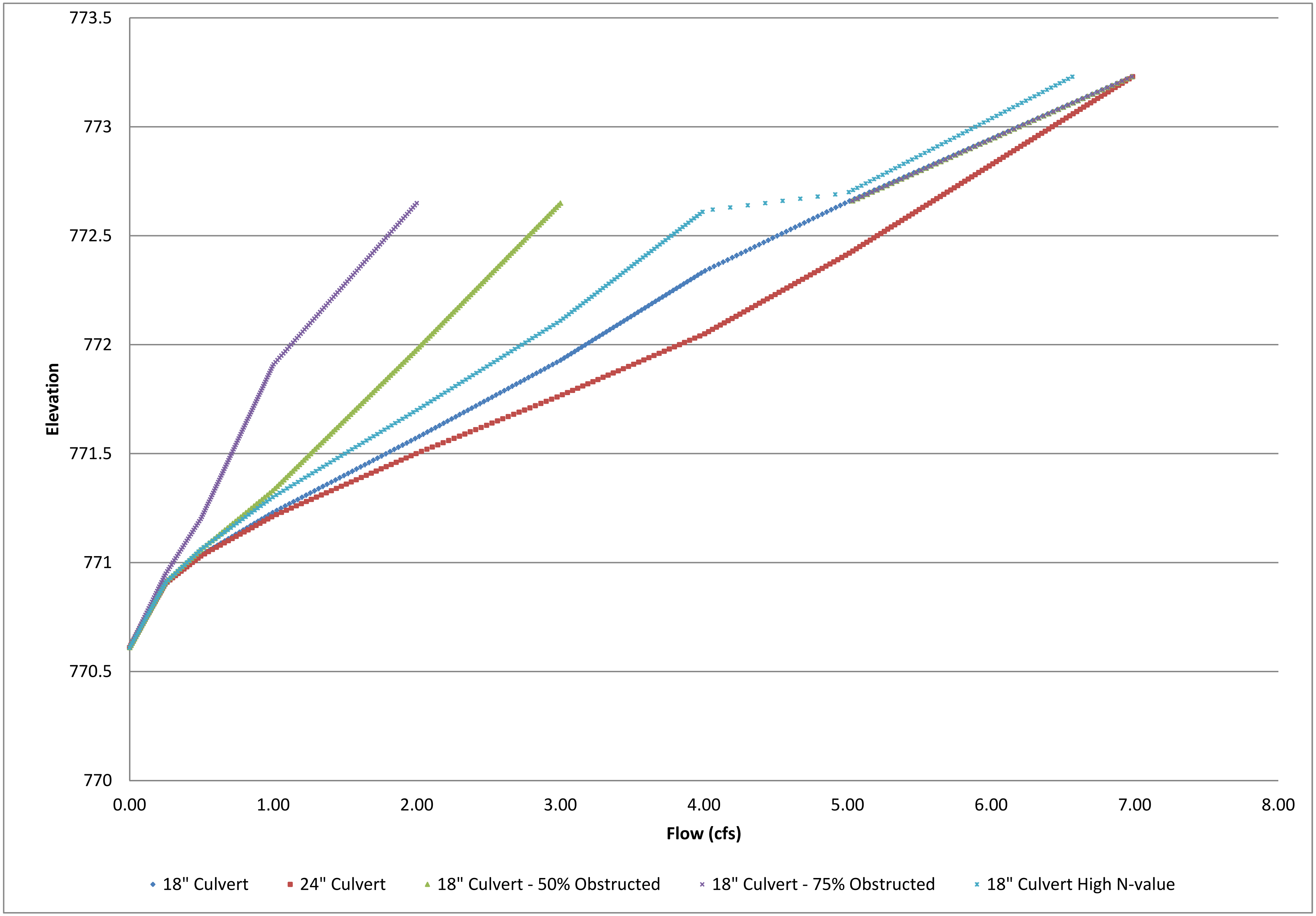
772.89	5.81	772.89	6.16	772.89	5.82	772.89	5.82	772.89	5.57
772.9	5.84	772.9	6.18	772.9	5.85	772.9	5.85	772.9	5.60
772.91	5.88	772.91	6.21	772.91	5.89	772.91	5.89	772.91	5.63
772.92	5.91	772.92	6.23	772.92	5.92	772.92	5.92	772.92	5.65
772.93	5.94	772.93	6.25	772.93	5.96	772.93	5.96	772.93	5.68
772.94	5.98	772.94	6.28	772.94	5.99	772.94	5.99	772.94	5.71
772.95	6.01	772.95	6.30	772.95	6.02	772.95	6.02	772.95	5.74
772.96	6.05	772.96	6.33	772.96	6.06	772.96	6.06	772.96	5.77
772.97	6.08	772.97	6.35	772.97	6.09	772.97	6.09	772.97	5.80
772.98	6.12	772.98	6.38	772.98	6.13	772.98	6.13	772.98	5.83
772.99	6.15	772.99	6.40	772.99	6.16	772.99	6.16	772.99	5.86
773	6.19	773	6.43	773	6.19	773	6.19	773	5.89
773.01	6.22	773.01	6.45	773.01	6.23	773.01	6.23	773.01	5.92
773.02	6.26	773.02	6.47	773.02	6.26	773.02	6.26	773.02	5.95
773.03	6.29	773.03	6.50	773.03	6.30	773.03	6.30	773.03	5.98
773.04	6.32	773.04	6.52	773.04	6.33	773.04	6.33	773.04	6.01
773.05	6.36	773.05	6.55	773.05	6.37	773.05	6.37	773.05	6.04
773.06	6.39	773.06	6.57	773.06	6.40	773.06	6.40	773.06	6.07
773.07	6.43	773.07	6.60	773.07	6.43	773.07	6.43	773.07	6.10
773.08	6.46	773.08	6.62	773.08	6.47	773.08	6.47	773.08	6.12
773.09	6.50	773.09	6.64	773.09	6.50	773.09	6.50	773.09	6.15
773.1	6.53	773.1	6.67	773.1	6.54	773.1	6.54	773.1	6.18
773.11	6.57	773.11	6.69	773.11	6.57	773.11	6.57	773.11	6.21
773.12	6.60	773.12	6.72	773.12	6.60	773.12	6.60	773.12	6.24
773.13	6.63	773.13	6.74	773.13	6.64	773.13	6.64	773.13	6.27
773.14	6.67	773.14	6.77	773.14	6.67	773.14	6.67	773.14	6.30
773.15	6.70	773.15	6.79	773.15	6.71	773.15	6.71	773.15	6.33
773.16	6.74	773.16	6.82	773.16	6.74	773.16	6.74	773.16	6.36
773.17	6.77	773.17	6.84	773.17	6.77	773.17	6.78	773.17	6.39
773.18	6.81	773.18	6.86	773.18	6.81	773.18	6.81	773.18	6.42
773.19	6.84	773.19	6.89	773.19	6.84	773.19	6.84	773.19	6.45
773.2	6.88	773.2	6.91	773.2	6.88	773.2	6.88	773.2	6.48

773.21	6.91	773.21	6.94	773.21	6.91	773.21	6.91	773.21	6.51
773.22	6.94	773.22	6.96	773.22	6.95	773.22	6.95	773.22	6.54
773.23	6.98	773.23	6.99	773.23	6.98	773.23	6.98	773.23	6.57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771
770.5
770
Elevation
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
Flow (cfs)
18" Culvert
24" Culvert
18" Culvert - 50% Obstructed
18" Culvert - 75% Obstructed
18" Culvert High N-value

APPENDIX C

Statistical Distribution Parameters

Crystal Ball Report - Assumptions
Simulation started on 5/7/2013 at 9:24 AM
Simulation stopped on 5/7/2013 at 9:24 AM

Run preferences:	
Number of trials run	1,000
Monte Carlo	
Random seed	
Precision control on	
Confidence level	95.00%
Run statistics:	
Total running time (sec)	1.11
Trials/second (average)	901
Random numbers per sec	5,405
Crystal Ball data:	
Assumptions	6
Correlations	4
Correlated groups	1
Decision variables	0
Forecasts	59

Assumptions

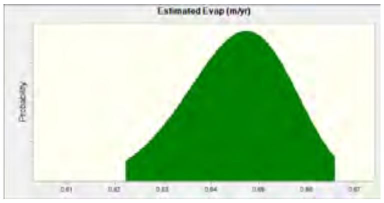
Worksheet: [CNET - Ravine Lake - Existing - Final.xls]MODEL

Assumption: Estimated Evap (m/yr) — Cell: O16

Weibull distribution with parameters:

Location	0.60
Scale	0.05
Shape	5.198577351

Selected range is from 0.62 to 0.67

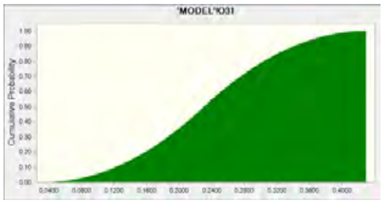


Assumption: O31 — Cell: O31

Triangular distribution with parameters:

Minimum	0.0350
Likeliest	0.2290
Maximum	0.4300

Selected range is from 0.0350 to 0.4300

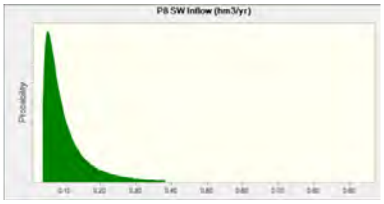


Assumption: P8 SW Inflow (hm3/yr) — Cell: O24

Lognormal distribution with parameters:

Location	0.03
Mean	0.11
Std. Dev.	0.09

Selected range is from 0.04 to 0.38



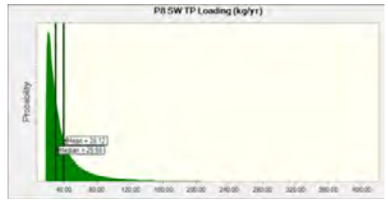
Correlated with:	Coefficient
P8 SW TP Loading (kg/yr) (O26)	0.98
Summer Precip (in/summer) (O15)	0.97

Assumption: P8 SW TP Loading (kg/yr) **Cell: O26**

Lognormal distribution with parameters:

Location	16.65
Mean	40.48
Std. Dev.	36.89

Selected range is from 17.35 to 250.38



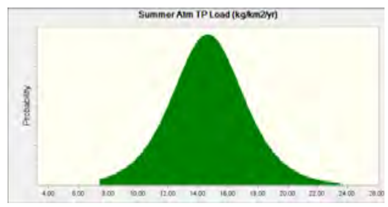
Correlated with:	Coefficient
Summer Precip (in/summer) (O15)	0.96
P8 SW Inflow (hm3/yr) (O24)	0.98

Assumption: Summer Atm TP Load (kg/km2/yr) **Cell: O20**

Logistic distribution with parameters:

Mean	14.65
Scale	1.57

Selected range is from 7.39 to 23.50



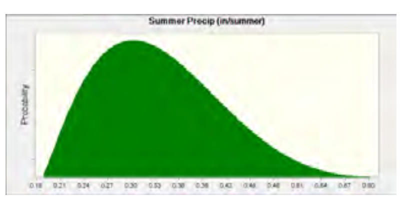
Correlated with:	Coefficient
Summer Precip (in/summer) (O15)	0.72

Assumption: Summer Precip (in/summer) **Cell: O15**

Beta distribution with parameters:

Minimum	0.19	(='Precip&Atm Load'!I59)
Maximum	0.64	(='Precip&Atm Load'!I60)
Alpha	2.24157362	
Beta	4.670265732	

Selected range is from 0.19 to 0.64



Assumption: Summer Precip (in/summer) (cont'd) **Cell: O15**

Correlated with:	Coefficient
P8 SW TP Loading (kg/yr) (O26)	0.96
Summer Atm TP Load (kg/km2/yr) (O20)	0.72
P8 SW Inflow (hm3/yr) (O24)	0.97

End of Assumptions

Crystal Ball Report - Assumptions
Simulation started on 5/28/2013 at 11:36 AM
Simulation stopped on 5/28/2013 at 11:36 AM

Run preferences:	
Number of trials run	1,000
Monte Carlo	
Random seed	
Precision control on	
Confidence level	95.00%
Run statistics:	
Total running time (sec)	1.16
Trials/second (average)	861
Random numbers per sec	5,168
Crystal Ball data:	
Assumptions	6
Correlations	4
Correlated groups	1
Decision variables	0
Forecasts	59

Assumptions

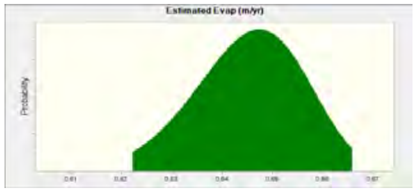
Worksheet: [CNET - Ravine Lake - Future.xls]MODEL

Assumption: Estimated Evap (m/yr) **Cell: O16**

Weibull distribution with parameters:

Location	0.60
Scale	0.05
Shape	5.198577351

Selected range is from 0.62 to 0.67

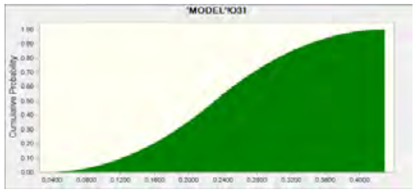


Assumption: O31 **Cell: O31**

Triangular distribution with parameters:

Minimum	0.0350
Likeliest	0.2290
Maximum	0.4300

Selected range is from 0.0350 to 0.4300

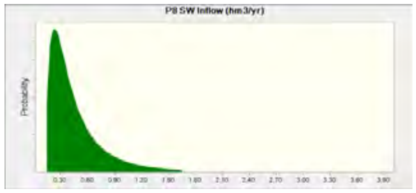


Assumption: P8 SW Inflow (hm3/yr) **Cell: O24**

Lognormal distribution with parameters:

Location	0.10
Mean	0.49
Std. Dev.	0.41

Selected range is from 0.14 to 1.65



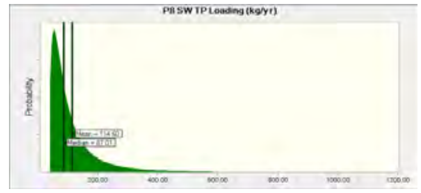
Correlated with:	Coefficient
P8 SW TP Loading (kg/yr) (O26)	0.99
Summer Precip (in/summer) (O15)	0.96

Assumption: P8 SW TP Loading (kg/yr) **Cell: O26**

Lognormal distribution with parameters:

Location	35.27
Mean	120.67
Std. Dev.	111.87

Selected range is from 39.92 to 584.68



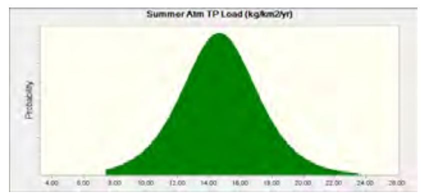
Correlated with:	Coefficient
Summer Precip (in/summer) (O15)	0.97
P8 SW Inflow (hm3/yr) (O24)	0.99

Assumption: Summer Atm TP Load (kg/km2/yr) **Cell: O20**

Logistic distribution with parameters:

Mean	14.65
Scale	1.57

Selected range is from 7.39 to 23.50



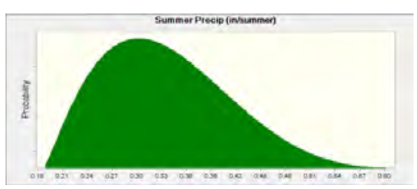
Correlated with:	Coefficient
Summer Precip (in/summer) (O15)	0.72

Assumption: Summer Precip (in/summer) **Cell: O15**

Beta distribution with parameters:

Minimum	0.19	(='Precip&Atm Load'!I59)
Maximum	0.64	(='Precip&Atm Load'!I60)
Alpha	2.24157362	
Beta	4.670265732	

Selected range is from 0.19 to 0.64



Assumption: Summer Precip (in/summer) (cont'd) **Cell: O15**

Correlated with:	Coefficient
P8 SW TP Loading (kg/yr) (O26)	0.97
Summer Atm TP Load (kg/km2/yr) (O20)	0.72
P8 SW Inflow (hm3/yr) (O24)	0.96

End of Assumptions

Crystal Ball Report - Assumptions
Simulation started on 6/3/2013 at 3:50 PM
Simulation stopped on 6/3/2013 at 3:50 PM

Run preferences:	
Number of trials run	1,000
Monte Carlo	
Random seed	
Precision control on	
Confidence level	95.00%
Run statistics:	
Total running time (sec)	1.24
Trials/second (average)	807
Random numbers per sec	4,842
Crystal Ball data:	
Assumptions	6
Correlations	4
Correlated groups	1
Decision variables	0
Forecasts	59

Assumptions

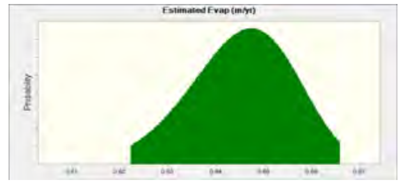
Worksheet: [CNET - Ravine Lake - Future - Inf Adj.xls]MODEL

Assumption: Estimated Evap (m/yr) **Cell: O16**

Weibull distribution with parameters:

Location	0.60
Scale	0.05
Shape	5.198577351

Selected range is from 0.62 to 0.67

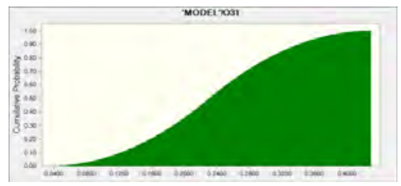


Assumption: O31 **Cell: O31**

Triangular distribution with parameters:

Minimum	0.0350
Likeliest	0.2290
Maximum	0.4300

Selected range is from 0.0350 to 0.4300

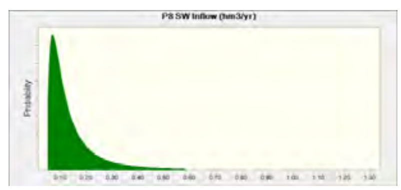


Assumption: P8 SW Inflow (hm3/yr) **Cell: O24**

Lognormal distribution with parameters:

Location	0.04
Mean	0.14
Std. Dev.	0.13

Selected range is from 0.05 to 0.58



Correlated with:	Coefficient
P8 SW TP Loading (kg/yr) (O26)	0.97
Summer Precip (in/summer) (O15)	0.97

Assumption: P8 SW TP Loading (kg/yr) **Cell: O26**

Lognormal distribution with parameters:

Location	22.53
Mean	55.22
Std. Dev.	49.14

Selected range is from 23.59 to 396.89

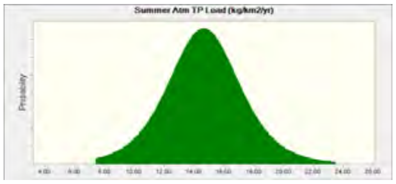
Correlated with:	Coefficient
Summer Precip (in/summer) (O15)	0.97
P8 SW Inflow (hm3/yr) (O24)	0.97

Assumption: Summer Atm TP Load (kg/km2/yr) **Cell: O20**

Logistic distribution with parameters:

Mean	14.65
Scale	1.57

Selected range is from 7.39 to 23.50



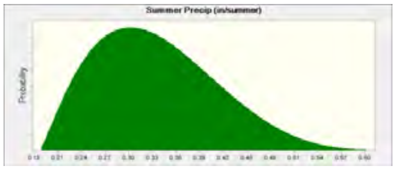
Correlated with:	Coefficient
Summer Precip (in/summer) (O15)	0.72

Assumption: Summer Precip (in/summer) **Cell: O15**

Beta distribution with parameters:

Minimum	0.19	(='Precip&Atm Load'!I59)
Maximum	0.64	(='Precip&Atm Load'!I60)
Alpha	2.24157362	
Beta	4.670265732	

Selected range is from 0.19 to 0.64



Assumption: Summer Precip (in/summer) (cont'd) **Cell: O15**

Correlated with:	Coefficient
P8 SW TP Loading (kg/yr) (O26)	0.97
Summer Atm TP Load (kg/km2/yr) (O20)	0.72
P8 SW Inflow (hm3/yr) (O24)	0.97

End of Assumptions