Appendix C

Development of Lake Water Budgets and Lake Water Budget Figures
Development of CLFLWD’s water budgets for 2004, 2003, 2006 balanced the flows in and out of lakes (Water Cycle elements) and change in storage in lakes, according to the following Water Budget Equation:

\[ \text{INPUTS} = \text{OUTPUTS} + \Delta \text{STORAGE} \]

The flows into and out of the individual lakes in the CLFLWD include tributary streamflow (also referred to as basin runoff), CLFLWD groundwater flows, landlocked subwatershed groundwater flows, precipitation on the lake surface, evaporation from the lake surface, and connecting channel flows.
The CLFLWD water budget makes use of both the monitoring data and XP-SWMM modeling results. Since even calibrated model results do not substitute for logical thinking or other types of data collection and analysis, the water budget is locked into the monitoring data at specific monitoring locations. The observed volumetric discharges were distributed to the contributing components. The first distribution was on the basis of direct calculation of water budget components (precipitation, evaporation, change in storage and CLFLWD groundwater), using methodologies described below. The final distributions took the remaining volumes and distributed them on the basis of relative XP-SWMM model predictions.

**DIRECT CALCULATIONS**

**Precipitation**
Fifteen-minute precipitation observations, as monitored by Washington Conservation District, were converted to an annual precipitation value. Each lake surface area in the Water Budget was assigned the nearest monitored precipitation record by implementing the Thiessen polygons method. If a lake’s surface area was to be assigned to multiple gages, the respective lake surface area for each rain gauge was calculated using GIS. This is how the annual volume of precipitation for the water budget was calculated. These volumes were utilized in the lake response model [in the spreadsheet column titled “Precipitation (direct)” (inflow)].

**Evaporation**
St. Paul Campus Climatological Observatory (21-8450-6) monthly pan evaporation (inches) observations from 2004, 2003, 2006 were converted to lake evaporation using a pan coefficient of 74.5% (Hydrology Guide for Minnesota for CLFLWD.) Then they were adjusted to represent the CLFLWD values for 2004, 2003, 2006 by the same ratio of mean monthly lake evaporation of St. Paul Campus to CLFLWD from the Hydrology Guide for Minnesota. The St. Paul Campus Climatological Observatory has monthly values for May thru September, and values for April (21-30) and October (1-10.) The Hydrology Guide for Minnesota CLFLWD values were used for mid-autumn, winter and mid-spring (October 11 thru April 20.) These evaporation rates and the lake surface area were directly used to calculate the annual volume of evaporation for the water budget. This is how the annual volume of precipitation for the water budget was calculated. These volumes were utilized in the lake response model [in the spreadsheet column titled “Evaporation from Lake” (outflow)].

**Change in Storage**
Changes in a Lake’s water level represents a change in water availability or the volume of water stored. Water-level changes are the result of several natural factors and also are influenced by human activities. These factors and activities operate in timescales that range from hours to decades. The primary natural factors affecting lake levels are the amount of inflow received by each lake and the outflow characteristics of the outlet channels. Influential human factors include diversions into or out of the basin, dredging of outlet channels, and modification of outlet structures. Seasonal fluctuations reflect the annual hydrologic cycle, which is characterized by higher water levels during the spring and early summer and lower water levels during the remainder of the year. (Wilcox, 2007) One-year fluctuations in storage was calculated for the Water Budget by comparing the DNR lake finder lake levels on the 6 lakes with data (Comfort Lake, Little Comfort Lake, Forest Lake, Sylvan Lake, Bone Lake, and Shields Lake.) These volumes were utilized in the lake response model [in the spreadsheet column titled “Change in Storage” if value is positive (outflow), if value is negative (inflow)].
CLFLWD Groundwater
According to the Washington Co 2003 report on Groundwater the CLFLWD is situated in two types of groundwater zones; recharge and discharge. Groundwater discharge and recharge zones were not explicitly modeled in XP-SWMM, but explicitly incorporated into the Water Budgets.

Forest Lake and west thereof are in a groundwater discharge zone, classified because it is underlain by thick Des Moines lobe till deposits. The groundwater is “typically” close to the surface and interacting by discharging into or thru the lakes and streams (water is leaving the aquifers and flowing to the surface.) The discharge zone is monitored at monitoring stations 4, 5, 6, 7 and 8.

East of Forest Lake is typically a groundwater recharge zone associated with outwash plains. Groundwater recharge zones, in contrast, with a greater depth to groundwater and lakes and streams loosing waters to the groundwater (water from precipitation is transmitted downward to an aquifer.) The recharge zone is monitored at monitoring stations 1, 2 and 3.

Groundwater divides, like surface water divides (watershed divides,) indicate a distinct groundwater flow regions where groundwater flow moves in opposite directions along the divide. It is common (when aquifers are shallow and strongly influenced by surface water flow) that groundwater divides coincide with surface water divides.
We assume the net CLFLWD groundwater flows is zero at the Comfort Lake outlet. Then calculate the depth of runoff at the Comfort Lake outlet (5.86-inches) as the CLFLWD’s average runoff depth. The deviation from average runoff depth can be attributed to CLFLWD recharge and discharge groundwater flows. In the recharge zone, Bone Lake discharge was adjusted upward by 1,247 acre-ft, this volume was lost to groundwater. In the discharge zone, watershed runoffs were adjusted downward by 1,247 acre-ft, this volume was gained by groundwater. Groundwater gain/losses in the water budgets were specific to lakes, and recharges and discharges were estimated as function of total lake surface area. The rate of groundwater recharge seepage was 22.6-inches per lake-acre, and the rate of groundwater discharge seepage was 4.7-inches per lake-acre.

These volumes were utilized in the lake response model [in the spreadsheet columns titled “Regional Groundwater Outflow” (outflow), and “Regional Groundwater Inflow” (inflow)].

**RELATIVE XP-SWMM MODEL PREDICTIONS**

After the calculated portions of the water budget are determined, the final distributions of the remaining volumes were distributed on the basis of relative XP-SWMM model predictions. For various locations in the CLFLWD, subwatershed direct runoff was tabulated and summarized (from XP-SWMM model RUNOFF block.) Similarly for various outlet/channel locations in the CLFLWD, volumetric discharges were tabulated (from XP-SWMM model HYDRAULICS block.) The ratios of runoff to discharge and discharge to discharge (at different locations) were used to distribute flows.

**Bone Lake Example**

For all receiving waters upstream of a monitoring location (this example is for the Bone Lake outlet), the ratio of *model predicted* subwatershed runoff to *monitored* discharge (in 2004 the “runoff/discharge” ratio is 0.491). This runoff/discharge ratio is used to determine the amount of discharge by way of the subwatershed’s outlet. In the case of Sea Lake (landlocked), it is by way of groundwater (140 acre-ft) because the 2004 XP-SWMM simulation predicts subwatershed runoff of 285 acre-ft and an outlet discharge of 0 acre-ft. The XP-SWMMM model doesn’t simulate groundwater interactions, and if there isn’t an outlet discharge by way of surface drainage, it has to be via near surface groundwater discharge. Sea Lake’s water surface level doesn’t increase all year long in response to rainfall, as the model is predicting, but rather fluctuates around the normal water level.
(This assumption held true for landlocked subwatersheds after comparison of model predicted Sylvan lake water surface levels to MN DNR Lake finder data for Sylvan Lake lake ID = 82008000.) Comparison of water surface levels indicates that the groundwater hydraulic gradient would direct this groundwater from from Sea Lake to Bone Lake. The model predicted values at Sea Lake (along with ratios from Moody Lake, Lendt Lake, Third Lake, and other landlocked subwatersheds) are used to determine the outflow volume for the water budget. Then calculated values were balanced in the budget to calculate the subwatershed specific runoff volumes. These calculations were repeated for all monitoring locations for 2004 (benchmark conditions,) 2003 (wet conditions,) and 2006 (dry conditions).

**Landlocked Subwatershed Groundwater**

In all cases this was calculated by monitoring location-specific runoff/discharge ratios, as described in the Bone Lake example. These landlocked volumes were utilized in the lake response model [in the spreadsheet columns titled “Discharge via Groundwater” (outflow) and “Flow from Upstream Lakes via Ground Water” (inflow)].

Landlocked subwatersheds are completely enclosed so that surficial runoff does not leave the subwatershed. The localized runoff typically collects at the lowest elevation (wetland or lake.) The water is accounted in our Water Budget either as discharges to groundwater or as plant uptake, infiltration, evaporation, or transpiration. Furthermore the Washington Co 2003 report characterizes Forest Lake, Shields and Bone Lakes as precipitation flow-through lakes with low connectivity to groundwater. Sylvan Lake was characterized as a groundwater flow though lake with high connectivity to groundwater.

The groundwater in the Water Budget attributed to “upstream lakes” represents water leaving an upstream lake that is landlocked (e.g. Sea Lake, Nielson Lake, Elwell Lake, Sylvan Lake, and Clear Lake) by way of groundwater and entering the Water Budget down gradient of regional groundwater flows.

**Connecting Channel Flows**

In cases where connecting channel flows are not monitored, these water budget volumes were calculated by monitoring location-specific runoff/discharge ratios, as described in the Bone Lake example. These volumes were utilized in the lake response model [in the spreadsheet columns titled “Discharge through outlet” (outflow) and “Flow from upstream lakes via surface” (inflow)].

**Basin Runoff**

In all cases basin runoff volumes were calculated by Water Budget Equation difference, as described in the Bone Lake example. After water budget components were defined, these volumes were calculated and tabulated in the lake response spreadsheet titled “Watershed Runoff” (inflow).

**REFERENCES**


Lake Water Budget Figures
Lake Water Budget

The diagram represents the water budget for School Lake. The inputs and outputs are measured in acre-feet. The key parameters include:

- Evaporation from Lake
- Discharge through Outlet
- Discharge via Groundwater
- Watershed Runoff
- Precipitation (direct)
- Flow from Upstream Lakes via Surface
- Flow from Upstream Lakes via Groundwater
- Regional Groundwater Inflow
- Change in Storage