

DEVELOPMENT OF A MONTHLY WATERSHED SALT MODEL

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By

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BIOGRAPHICAL SKETCH

Michael Liu is a Masters of Environmental Engineering student in the department of Biological and Environmental Engineering at Cornell University. Prior to his Master's Degree he obtained a Bachelor's of Science in Environmental Engineering from Cornell University and worked in the Peace Corps in Uganda.

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INTRODUCTION

Road Salt is sodium chloride that is used as a deicing agent throughout Northern America and Europe during the winter time. The use of road salt started in the 1940s and its use, especially throughout the Northern America, has increased rapidly due to widespread availability and ease of use (Kelly et al., 2008). Usage of road salt is also correlated with increased development of impervious surfaces, human activity and human population density, all of which have been increasing throughout Northern America since the 1940s.

Increased uses of road salt leads to higher concentrations of chloride in the environment's waterways and groundwater. This may be of concern due to sodium chloride's negative effects on the environment, its contamination in drinking water and its corrosive effects on public infrastructure (Kelly et al., 2008). However road salt is not the only anthropogenic source of chloride. Other sources include water softeners, septic and sewage effluent, rock weathering, and dry and wet deposition.

There have been a number of salt models on watersheds. Kelly et al. (2008) created a yearly model for rural watershed that tracks the concentrations of chloride within the groundwater and streams. The model was tested on East Wappinger Creek in Dutchess County, N.Y. from 1955-2005. Shaw et al. (2012) also created a yearly watershed salt model based off of a simple mixing model to calculate the chloride concentrations in a small rural watershed. They used the Fall Creek Watershed in Tompkins county from 1973-2003 as a study site. Oberts (2000) created a runoff model to determine how snowmelt and road salt interact during rain events and snow events on different impervious and pervious surfaces.

This report details the development of a monthly road salt model for a small watershed. Given various watershed parameter inputs and precipitation data the model determines the concentrations of sodium and chloride in the watershed's stream and groundwater at a monthly timescale. The study site used was East Wappinger Creek in Dutchess County, NY.

METHODS

REPLICATION OF THE KELLY ET AL. YEARLY SALT MODEL

The model described in the Kelly et al. paper uses known and approximated yearly salt input data and yearly precipitation data to model the concentration of chloride within East Wappinger Creek (Kelly et al., 2008). Replicating this model in a spreadsheet provides the basis for a monthly model.

Inputs

The Kelly et al. study period begins at 1955 and ends 2005. Yearly precipitation data inputs used to recreate the model were taken from National Oceanic and Atmospheric Administration (NOAA, 2015). Evapotranspiration is assumed to be 50% of precipitation. Salt runoff is accounted for by a 10 percent “bypass” factor which assumes that 10 percent of all road salt bypasses the groundwater and enters the stream directly. All the remaining road salt, and other salt sources are assumed to enter groundwater. The study takes into account various sodium chloride inputs including road salt, water softener, sewage and septic system effluent, and rock weathering.

From 1955 to 1985 road salt is assumed to be a linear increase from 0 in 1955 to 767.6 thousand kilograms in 1985. Road salt input from 1985 onward is based on collected data.

Water Softeners are assumed to be used in all households within the watershed. Given an average household size, water softener used per household per year, average water hardness, and average water usage per household the amount of chloride and sodium used for water softening may be determined. First the total households must be calculated (equation 1) by dividing the total population by household size:

$$HH_{total} = \frac{P_{total}}{HH_{size}} \quad (1)$$

Where

$$\begin{aligned} P_{total} &= \text{Total Population (persons)} \\ HH_{size} &= \text{Household Size } \left(\frac{\text{Persons}}{\text{Household}} \right) \\ HH_{total} &= \text{Total Households (Households)} \end{aligned}$$

Then the average water hardness is calculated in grains per household per day. First, household water usage is calculated (equation 2) and then is multiplied by average water hardness to obtain grains per household (equation 3).

$$Water_{HH} = HH_{size} * Water_{person} \quad (2)$$

$$Grains_{HH} = Water_{HH} * Hardness \quad (3)$$

Where

$$Water_{person} = \text{Water usage per person per day} \left(\frac{L}{\text{person} * \text{day}} \right)$$

$$Water_{HH} = \text{Water usage per household per day} \left(\frac{L}{\text{household} * \text{day}} \right)$$

$$Grains_{HH} = \text{Grains of hardness per household per day} \left(\frac{\text{Grains}}{\text{Household} * \text{day}} \right)$$

$$\text{Hardness} = \text{Average water hardness} \left(\frac{\text{Grains}}{L} \right)$$

The daily household grain production is then multiplied by 365 to create a yearly number and then divided by an average water softener removal rate and multiplied by total households to obtain the total NaCl used in water softener in the watershed (equation 4):

$$Softener_{NaCl} = \frac{(Grains_{HH} * 365 \frac{days}{year})}{Softener_{removal}} * HH_{total} \quad (4)$$

Where

$$Softener_{NaCl} = \text{Total NaCl used in Water Softener in the watershed per year} \left(\frac{kg}{yr} \right)$$

$$Softener_{removal} = \text{Average Water Softener Removal Rate} \left(\frac{\text{grains}}{kg \text{ NaCl}} \right)$$

Total sodium and chloride inputs from septic systems and sewage treatment are obtained by the summing all chloride usage from human excrement, household waste, and sewage treatment and then multiplying it by the total watershed population (equation 5):

$$Waste_{Cl} = (Waste_{Excrement} + Waste_{Household} + Waste_{Sewage}) * P_{total} \quad (5)$$

Where

$$Waste_{Excrement} = \text{Chloride waste from human excrement} \left(\frac{kg}{\text{person} * \text{yr}} \right)$$

$$Waste_{Household} = \text{Chloride waste from household products} \left(\frac{kg}{\text{person} * \text{yr}} \right)$$

$$Waste_{sewage} = \text{Chloride waste from sewage treatment} \left(\frac{kg}{\text{person} * \text{yr}} \right)$$

Chloride inputs from rock weathering were estimated by using chloride concentration measurements from 1905, before the use of water softeners, and road salt.

Each of these inputs are calculated for each year from 1955 to 2005. Each input is then summed to provide a total chloride and total sodium yearly input into the watershed.

Model

To emulate a small watershed, the model assumes that all precipitation that has not gone towards evapotranspiration enters the groundwater pool, which is fixed at a constant of 5 meters. Thus the amount of precipitation that enters the groundwater pool is also the amount of groundwater that leaves the pool and enters the stream.

A mass balance is utilized and total chloride masses in the groundwater pool, entering the groundwater pool, and leaving the groundwater pool are calculated. The yearly mass of chloride that enters the pool is the sum of the yearly masses of the different chloride sources. The yearly mass of road salt is multiplied by .9 to account for the 10 percent bypass factor (Equation 6).

$$Total_{Cl,t} = .9 * Road\ Salt_{Cl,t} + Softener_{Cl} + Waste_{Cl} + Weathering_{Cl} \quad (6)$$

Where

$$Total_{Cl,t} = \text{Total mass of Chloride entering the GW pool during year } t$$

The new mass of chloride in the groundwater pool will then be the mass of chloride that flows in the groundwater pool added with the mass of chloride in the groundwater pool from the year before and subtracted by the mass of chloride that has flowed through the groundwater pool into the streams (Equation 7).

$$M_{GWpool,t+1} = Total_{Cl,t+1} + M_{GWpool,t} - M_{GWflowthrough,t} \quad (7)$$

Where

$$M_{GWpool,t+1} = \text{Mass of chloride in the GW pool at the beginning of year } t + 1 \text{ (kg)}$$

$$M_{GWflowthrough,t} = \text{Mass of chloride that flows out of the GW pool during year } t \text{ (kg)}$$

This will give the groundwater pool a new chloride concentration. This is the chloride concentration of the groundwater that will exit the pool the next year (Equation 8). The volume of the groundwater pool is kept at a constant since the height is kept at a constant of 5 meters and the area of the watershed does not change (Equation 9). From the volume of the water that exits the groundwater pool, a new mass of chloride that enters the streams may be calculated (Equation 10). The volume of water that flows through the groundwater pool is the precipitation minus evapotranspiration which is kept at a constant 50% of precipitation for that year (Equation 11).

$$C_{GWpool,t} = \frac{M_{GWpool,t}}{V_{GWpool}} \quad (8)$$

$$V_{GWpool} = A_{Watershed} * GW_{constant} \quad (9)$$

$$M_{Flowthrough,t} = V_{Flowthrough,t} * C_{GWPool,t} \quad (10)$$

$$V_{Flowthrough,t} = P_t - P_t * .5 \quad (11)$$

Where

$C_{GWpool,t}$ = Concentration of the GW pool during year t (kg/m³)

$A_{Watershed}$ = Area of watershed (m²)

$GW_{constant}$ = Groundwater constant of 5m

V_{GWpool} = Volume of groundwater pool (m³)

$V_{Flowthrough,t}$ = Volume of water that flows through the GW pool (m³)

$M_{Flowthrough,t}$ = Mass of chloride that flows through the GW pool (kg)

P_t = Precipitation (m³)

When this mass is summed with the bypass and divided by the stream volume the sodium and chloride concentration may be obtained (Equation 12). The yearly stream volume is the volume of water that flows through the groundwater pool ($V_{Flowthrough,t}$).

$$C_{Stream,t} = \frac{M_{Flowthrough,t} + 1 * RoadSalt_{Cl}}{V_{Flowthrough}} \quad (12)$$

Where

$C_{Stream,t}$ = Concentration of Chloride in stream at year t (kg/m³)

After implementation of the yearly model in a spreadsheet, a sensitivity analysis was performed to identify the role of possible errors in bypass rate and streamflows. The percent of road salt that bypassed the groundwater after the year 1995 was changed from 10 percent to 20, 30 and 40 percent

and changes in chloride concentration in the streams were noted. Streamflow after 1995 was also reduced by 10, 20 and 30 percent and resulting chloride concentrations in the stream were noted.

MONTHLY MODEL

Model Description

A monthly model was developed to evaluate impacts of road salt on chloride concentrations in streams throughout the year. The yearly model that was developed by Kelly is used as a foundation. The 10 percent bypass assumption was changed and monthly runoff, runoff chloride concentrations and chloride masses in runoff were calculated.

To achieve this the two programs were utilized, the Generalized Watershed Loading Functions (GWLF) (Haith et al., 2010) and the BEERunoff program (BEE Software Services, 2003). The GWLF is able to take daily precipitation data and other watershed parameters to calculate monthly streamflow and groundwater discharge thus eliminating the need for evapotranspiration and monthly precipitation data. The BEERunoff program is able to take daily precipitation and various watershed parameters to return runoff associated with snowmelt. Given snowmelt runoff and concentration of chloride the mass of road salt that runs off into the stream and bypasses the groundwater pool can be calculated. In addition the streamflow is no longer assumed to be the groundwater discharge (or known groundwater flow through in the yearly model) but is taken from the results of the GWLF.

The monthly mass balance is similar to the yearly model. Instead of working on a yearly basis the model now works on a monthly basis. Calculations of the input sources remain the same as the yearly model. However the results are now divided by 12 to give a monthly chloride output instead of a yearly one. The total chloride output for each year is calculated. Instead of accounting for a 10 percent bypass in the road salt, the monthly road salt entering the GW pool is now calculated by subtracting the monthly mass of chloride that runs off into the stream from the monthly applied road salt (Equation 13). The mass of chloride in the runoff is calculated by multiplying the volume of snowmelt runoff with an average concentration of chloride in wintertime road runoff as shown in Equation 14.

$$RoadSalt_{Cl,GW,t} = RoadSalt_{Cl,t} - M_{Cl,Runoff,t} \quad (13)$$

Where

$RoadSalt_{Cl,GW,t}$ = Mass of Chloride from Road Salt entering the GW in month t (kg)

$RoadSalt_{Cl,t}$ = Mass of Chloride from applied road salt in month t (kg)

$M_{Cl,Runoff}$ = Mass of Chloride from road runoff in month t (kg)

$$M_{Cl,Runoff} = Snowrunoff_t * C_{Cl,runoff} \quad (13a)$$

$$Total_{Cl,t} = Road\ Salt_{Cl,GW,t} + Softener_{Cl} + Waste_{Cl} + Weathering_{Cl} \quad (13b)$$

Where

$Snowrunoff_t$ = volume of snowmelt runoff in month t (m³)

$C_{Cl,runoff}$ = average concentration of snowmelt runoff ($\frac{kg}{m^3}$)

$C_{Cl,runoff}$ is assumed to be 230 mg/L or .23 kg/m³ as found in the Oberst paper (Oberst et. al., 2000). $Snowrunoff_t$ is an output of the BEERunoff program. The total mass of chloride in the groundwater at the beginning of month t+1 is given by Equation 14.

$$M_{GWpool,t+1} = Total_{Cl,t+1} + M_{GWpool,t} - M_{flowthrough,t} \quad (14)$$

The concentration of chloride in the groundwater pool may be calculated by dividing the mass of chloride in the groundwater pool by the volume of water in the groundwater pool, whose height is kept at a constant of 5m (equation 15).

$$C_{GWpool,t+1} = \frac{M_{GWpool,t+1}}{V_{GWpool}} \quad (15)$$

The mass of chloride leaving the groundwater pool from the groundwater discharge in month t+1 is calculated by multiplying the concentration of chloride in the groundwater pool by the groundwater discharge and adding it with the mass of chloride that bypassed the groundwater pool through the runoff (Equation 16).

$$M_{flowthrough,t+1} = C_{GWpool,t+1} * V_{flowthrough,t+1} + M_{Cl,Runoff,t+1} \quad (16)$$

The concentration of chloride in the streams may be calculated by dividing the mass of chloride in the groundwater discharge with the monthly streamflow volume. The monthly $V_{flowthrough,t+1}$ and streamflow were obtained from GWLF output.

GENERALIZED WATERSHED LOADING FUNCTION (GWLF)

The Generalized Watershed Loading Function is meant for estimating nonpoint sources of nitrogen and phosphorous pollution within streamflow. To achieve this the GWLF calculates watersheds monthly streamflow and groundwater discharge which are needed for a monthly salt model. Doing so would eliminate the need for an assumed evapotranspiration of .5 of the precipitation. Thus, the monthly model only takes advantage of a portion of the GWLF. The calculations of nitrogen and phosphorus are unnecessary for this model.

Inputs

The GWLF requires inputs for daily weather, transport, and nutrients to run. Because nutrient data are not pertinent to a monthly salt model these were left as zero where possible. This would not affect the groundwater discharge and streamflow calculations. Weather data involves daily temperature and precipitation along with the number of days in each month.

The transport data involved numerous parameters about the watershed including: the number of rural and urban land uses, recession constant, seepage constant, initial unsaturated zone available moisture, initial shallow saturated zone moisture, initial snow depth, watershed sediment delivery ratio, available water capacity of the unsaturated zone and antecedent precipitation for the first five days preceding the simulation. Inputs also include each month's name and each month's evapotranspiration cover coefficient, daylight hours per day, erosivity coefficient and growing season indicator. Each land use indicated in the input must include land use area, runoff curve number, and Universal Soil Loss Equation product KLSCP. Similar to the nutrient data, wherever possible zeros were used as input data in the transport data. Universal Soil Loss Equation product KLSCP was inputted as zero. Curve numbers for the East Wappinger Creek watershed were obtained through the Dutchess County Agriculture profile (USDA, 2012).

Model Description

The GWLF takes the streamflow to consist of the total watershed runoff and the groundwater discharge from the shallow saturated zone. Runoff from each source area is calculated with equation 17:

$$Q_{kt} = \frac{(R_t + M_t - 2 * DS_{kt})^2}{R_t + M_t + 8 * DS_{kt}} \quad (17)$$

Where:

Q_{kt} = Runoff from source area k on day t (cm)

R_t = Rainfall on day t (cm)

M_t = Snowmelt on day t (cm)

DS_{kt} = Detention parameter for source area k on day t (cm)

Precipitation is assumed to be rain on days where temperature is above 0 degrees Celsius and snowfall on days below 0 degrees Celsius. Snowmelt is computed through equation 18:

$$M_t = .45 * T_t \text{ for } T_t > 0 \quad (18)$$

Where:

T_t = Daily mean air temperature in (C)

The detention parameter DS_{kt} is a function of the curve number (Equation 19):

$$DS_{kt} = \frac{2540}{CN_{kt}} - 25.4 \quad (19)$$

Where

CN_{kt} = the curve number at source area k at day t

The curve numbers are dependent on the antecedent moisture condition. The curve numbers for different conditions $CN1_k$, $CN2_k$, or $CN3_k$ are dependent on if the antecedent moisture condition is 1 (driest), 2 (average) or 3 (wettest). The antecedent moisture conditions are different for dormant and growing seasons and are specified in the inputs. The curve number for particular day t is linearly dependent on the antecedent precipitation as shown in Figure 1. The Antecedent precipitation is a function of the rainfall and snowmelt of the previous five days (Equation 20).

$$A_t = \sum_{n=t-5}^{t-1} (R_n + M_n) \quad (20)$$

Where

A_t = Antecedent precipitation (cm)

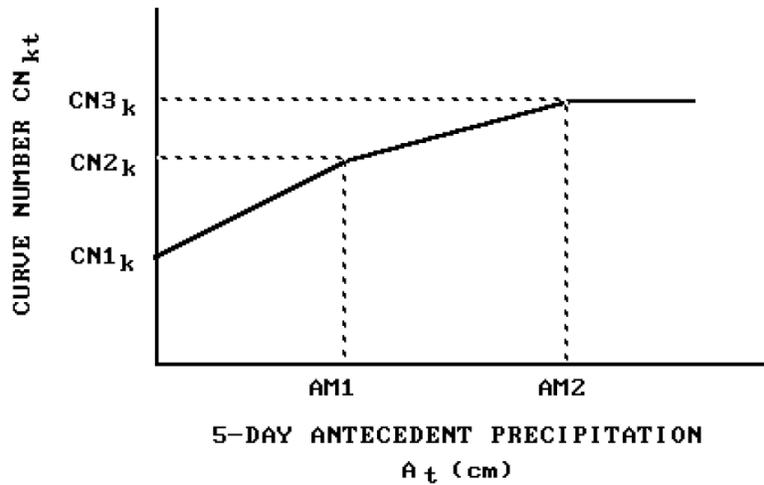


Figure 1- Curve Number versus Antecedent Precipitation

Curve Numbers 1 and 3 may be calculated from Curve Number 2 (Equations 21 and 22) while Curve Number 2 is an input for the GWLF.

$$CN1_k = \frac{CN2_k}{2.334 - 0.01334 * CN2_k} \quad (21)$$

$$CN3_k = \frac{CN2_k}{0.4036 + 0.0059 * CN2_k} \quad (22)$$

Where

$CN1_k, CN2_k,$ and $CN3_k$ = Curve numbers for source area K

To calculate groundwater discharge, first the daily water balance of the unsaturated and shallow saturated zones must be established:

The unsaturated zones moisture, U_t , is calculated through a water balance (Equation 23):

$$U_{t+1} = U_t + R_t + M_t - Q_t - E_t - PC_t \quad (23)$$

Where

PC_t = Percolation during day t (cm)

U_t = Unsaturated zone moisture at beginning of day t (cm)

E_t = Evapotranspiration during day t (cm)

The shallow saturated zone moisture, S_t , is also calculated through a water balance (Equation 24):

$$S_{t+1} = S_t + PC_t - G_t - D_t \quad (24)$$

Where

D_t = Seepage flow to the deep saturated zone on day t (cm)

S_t = Shallow saturated zone moisture at the beginning of day t (cm)

G_t = Groundwater discharge during day t (cm)

Percolation, PC_t , is calculated with Equation 25:

$$PC_t = \text{Max}(0, U_t + R_t + M_t - Q_t - E_t - U^*) \quad (25)$$

Where

U^* =Available Soil Water Capacity

Evapotranspiration is calculated with Equation 26:

$$E_t = \text{Min}(CV_t * PE_t, U_t + R_t + M_t - Q_t) \quad (26)$$

Where

CV_t =the cover coefficient for day t

PE_t =Potential Evapotranspiration during day t (cm)

Potential Evapotranspiration is then calculated with Equation 27:

$$PE_t = \frac{0.021 * H_t^2 * e_t}{T_t + 273} \quad (27)$$

Where

H_t =number of daylight hours in day t

e_t =saturated water vapor pressure in day t (mbar)

T_t =Temperature on day t (Celsius)

The saturated water vapor pressure is calculated with equation 28:

$$e_t = 33.8639[(0.00738 * T_t + 0.8072)^8 - 0.000019(1.8T_t + 48) + 0.001316], T_t \geq 0 \quad (28)$$

Deep Seepage is calculated through equation 29:

$$D_t = s * S_t \quad (29)$$

Where

s = groundwater seepage constant

Groundwater discharge on day t is calculated with Equation 30:

$$G_t = r * S_t \quad (30)$$

Where

r = groundwater recession constant

BEERUNOFF PROGRAM

The BEERunoff program models daily surface runoff in the same fashion as GWLF – Equations 17-22. A part of the BEERunoff output provides snowmelt runoff, or runoff during days of snowmelt. The BEERunoff program was executed for the total area of roads, approximately 977540 m² (Kelly et al.), in the East Wappinger Creek Watershed to determine the amount of snowmelt that runs off roads and enters storm drains, bypassing the groundwater pool. With an average chloride concentration of 230 mg/L (Oberts, 2000), the mass of chloride that bypasses the groundwater pool may be determined. This replaces the 10 percent bypass assumption made in the yearly model.

INPUTS

The BEERunoff program requires weather data inputs that include daily temperature, daily precipitation, and days in each month that are modeled, and date of each day. Inputs regarding the watershed parameters include the Curve number CN2, the antecedent moisture limits 1 and 2 for dormant and growing seasons and indications on whether a month is a dormant or growing season.

RESULTS AND DISCUSSION

Yearly Model

The replication of the yearly model developed by Kelly et al. (Figure 2) and the model results from Kelly et al. article (Figure 3) are similar. A steady increase from 1955 to 1995 with a sharp increase in chloride concentration near the late 90s. The replicated yearly model followed very closely with the observed chloride stream concentration. Prior to the mid-90s the replicated model also followed the modeled chloride concentration as well.

The yearly model had various limitations to the user as discussed earlier. The evapotranspiration was kept at a constant of .5 of the precipitation and bypass was kept at a constant of 10 percent. The nature of the yearly model did not allow for evaluation of how chloride concentration adjusted throughout the seasons of the year.

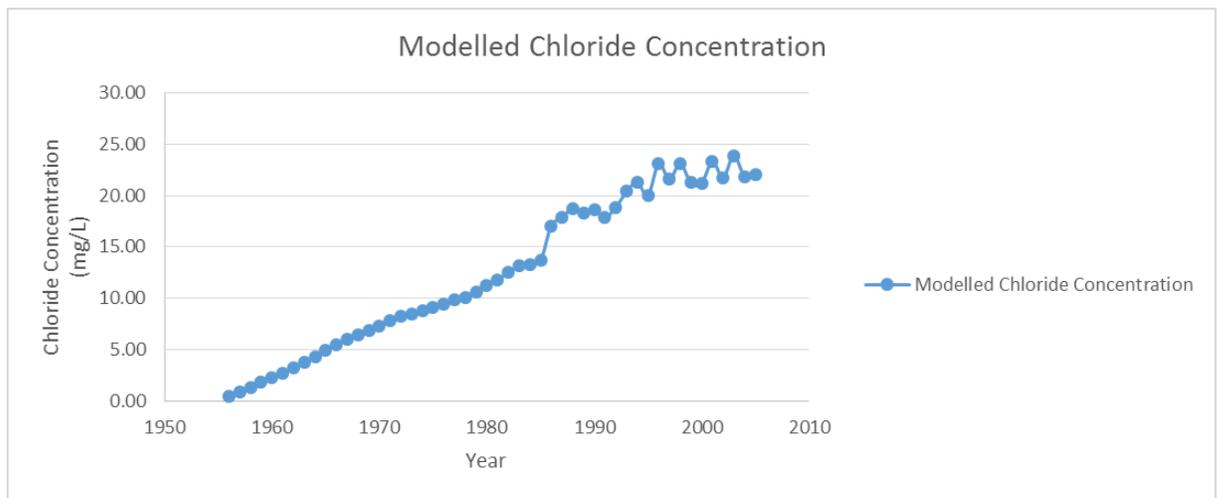


Figure 2- Replicated Model results of Chloride Concentration vs. Year in East Wappinger Creek

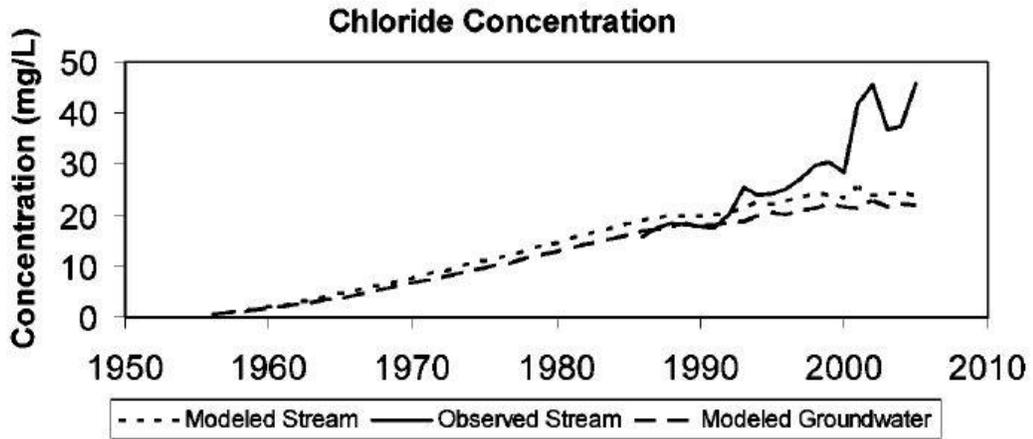


Figure 3- Model Results of Chloride Concentration vs. Year in East Wappinger Creek by Kelly et al.

A sensitivity analysis of the replicated model was performed. Streamflow was reduced by 20, 40, 60, and 80 percent after 1995 (Figure 4) while bypass was increase from 10 percent to 20, 30, and 50 percent (Figure 5). With both alterations in the streamflow and road salt bypass, the chloride concentration in the streams increase and have more variance, especially in the case of road salt bypass.

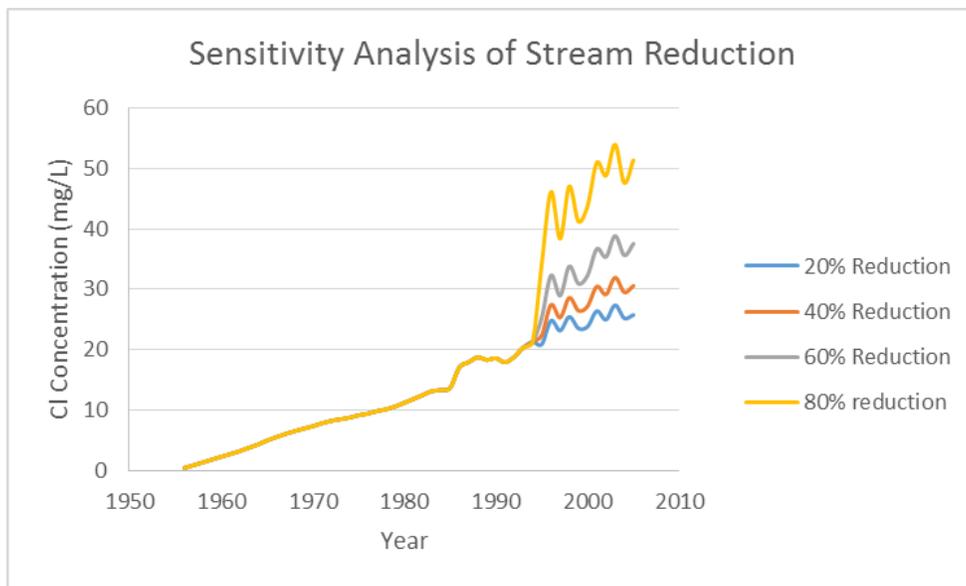


Figure 4- Streamflow Sensitivity Analysis for Yearly Model

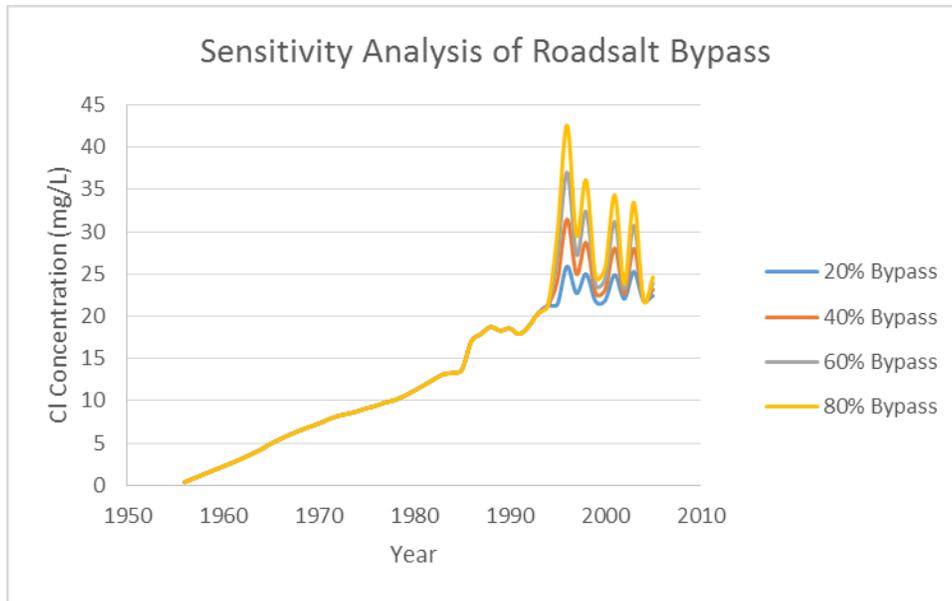


Figure 5- Bypass Sensitivity Analysis for Yearly Model

MONTHLY MODEL

First, to test the accuracy of the GWLF, the streamflow outputs of the GWLF were compared with gathered stream data from the USGS (USGS, 2015). These comparisons are shown in Figure 6. A R^2 value of .76 was achieved.

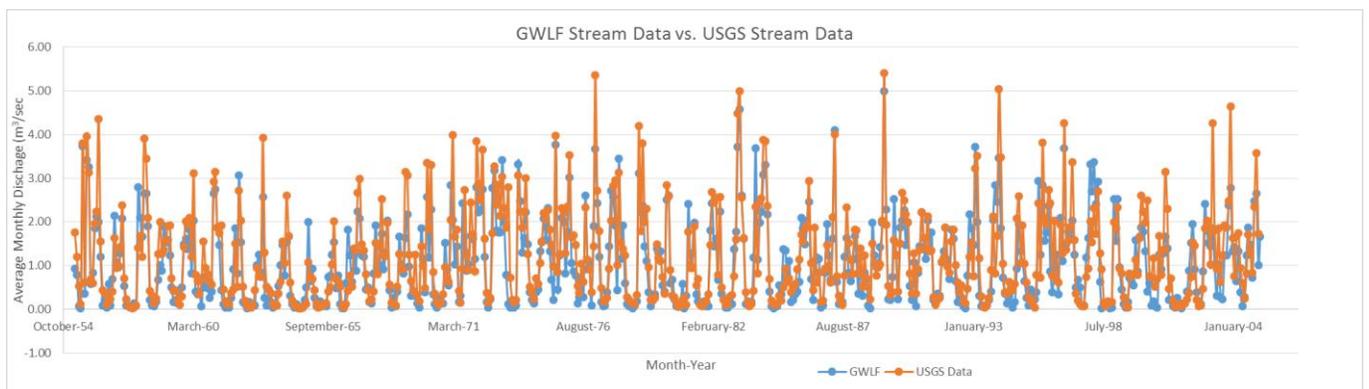


Figure 6- Comparing Average Monthly Discharge vs. time between GWLF Stream Data and USGS Stream Data

Figure 7 is the monthly model which utilizes the GWLF outputs for monthly groundwater discharge and streamflow but not the BEERunoff outputs of snowmelt. Thus this graph still incorporates

a 10 percent road salt bypass assumption. The chloride concentrations seem to be slightly lower than the concentrations in yearly replicated model.

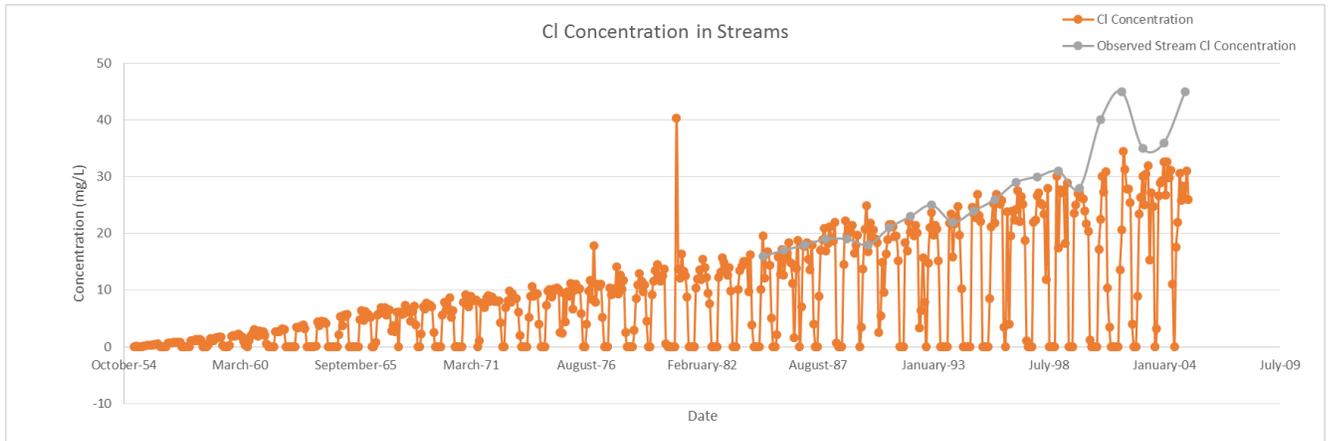


Figure 7- Monthly Chloride Concentration vs. Time with GWLF alterations. Still with a 10% road salt bypass

Figure 8 is the monthly model that utilizes both the outputs for the GWLF and the outputs for the BEERunoff function. Thus the model incorporates uses the groundwater discharge and streamflow from GWLF as well as the snowmelt runoff from the BEERunoff model. With the addition of the BEERunoff outputs into the model there is a slight increase in the chloride concentration.

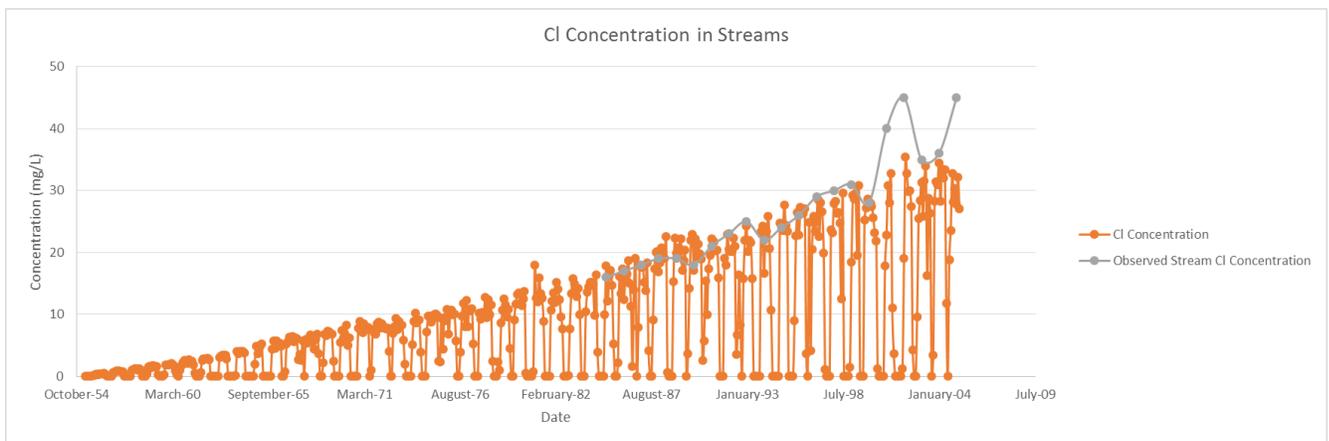


Figure 8- Monthly Chloride Concentration vs. Time with GWLF alterations and BEERunoff alterations

SUMMARY AND CONCLUSION

To create a basis for the monthly watershed salt model, the yearly salt model described in the Kelly et al. paper was replicated. Inputs to the model were changed and the time step was altered from a yearly interval to a monthly interval. The outputs of the Generalized Watershed Loading Function and the BEERunoff Function used as inputs for the new monthly watershed salt model. Results of the replicated yearly model and the monthly model were compared with the observed data from the Kelly et al. paper. Trends in the chloride concentration within streams and similar and consistent amongst the replicated yearly model and the monthly model. The monthly model outputs using the 10 percent bypass and using the BEERunoff snowmelt runoff are very similar suggesting that the “10 percent bypass” is an accurate assumption in a small watershed. Another explanation is on months when road salt is applied, that the mass of salt in the snowmelt runoff is much smaller than the mass of salt that leaves the groundwater pool. The mass of salt that enters the stream from the groundwater pool is, on average, 25 times greater than the salt that enters the stream from snowmelt runoff.

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