

EROSION AND WEATHERING PROCESSES IN THE DELAWARE RIVER BASIN

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ABSTRACT

Total suspended sediments and the total dissolved solids (TDS) from three river gaging stations, near Delaware Water Gap, Riegelsville and Trenton on the Delaware River measured by the USGS were used to estimate the physical erosion, chemical weathering and total denudation rates of the Delaware River Basin. The denudation rates are 28 and 128 tons/km²/yr for the upper stream and downstream stretches. Overall, the chemical weathering is more prominent in the basin than the physical weathering due to the low gradient of the region and sufficient moisture levels in the regional soil. The total suspended sediments are high during March and April when snow melting and ground thawing occur, and low during the summer when the river discharge is low. The response of TDS to the river discharge is more complicated. Overall, higher temperatures increases the chemical weathering, and low discharge increases the ion concentration in the water. The saturation indices calculated using the WATEQ4F program indicate that calcite and dolomite are more saturated in the summer, while silica and halite show opposite patterns. While the saturation index of silica may be explained by its thermodynamic property, the saturation index of the halite that deviates from the normal pattern is thought to be related with the application of winter deicing salt in the region.

Soil cores were also collected from four sites in the basin. Data from a 15-foot soil core indicates that weight percentage of quartz decreases with depth, while the weight percentage of feldspar increases. Various mineral types and abundance were also recognized from other shallow soil cores. These diverse mineral patterns reflect the diverse ion species in the river basin.

INTRODUCTION

Because of the effect of weathering on water quality and landscape in a basin, there are always interests in better understanding the weathering processes (Blum et al.,

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1998, Braun et al., 2005, Grosbois et al., 2000, White and Blum, 1995, White and Brantley, 2003). Various methods, from mass balance, isotope analysis, lab experiment to computer modeling, have been used in the erosion and weathering studies (Roy et al., 1999, Moon et al., 2007, Yuan et al., 2007). During recent years, because of the detrimental effect of sulfate, nitrate and road salts on the ecosystem, the buffering capacities of various weathering processes have become the focuses of some of the studies as well (Douglas et al., 2002, Witfield et al., 2006, Lerman and Wu 2006, Moncoulon et al., 2004, da Goncalves and Bonotto, 2004).

Progresses have been made on understanding how the chemical weathering of soils and bedrock responds to different environmental factors such as temperature, pH and landscape (Riebe et al., 2004, White and Fernando, 1995, White and Brantley, 2003). However, because of the climatic, geographic and geologic variations of regions, weathering can be significantly different from region to region. The relationship developed for the chemical ions also can be different (Braun et al., 2005, Millot et al., 2003). In addition, there has not been a thorough study of the weathering processes and the effect of anthropogenic loadings in the Delaware River Basin (DRB). Therefore, this project intends to provide an initial investigation on the weathering processes in the DRB (Figure 1).

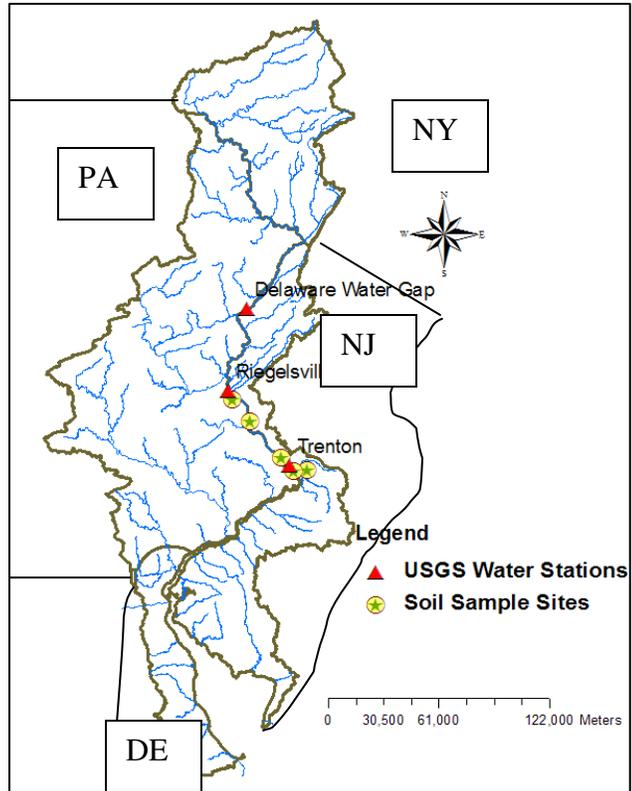


Figure 1. Locations of soil sample sites and three USGS water stations in the Delaware River Basin, including State lines of NJ, NY, PA, DE

RESEARCH METHOD

Total Denudation Rate

Total denudation rate of the DRB is the sum of its physical erosion and chemical weathering rates. Physical erosion is calculated as the average of the total suspended sediments normalized by the catchment area of the basin up to that particular outlet station. The suspended sediments are the sediment particles that were removed by the river water from the basin.

Chemical weathering rate is calculated as the product of total dissolved solids (TDS) and the discharge of the river water, with this product being normalized by the catchment area (Yuan et al., 2007, Douglas, 2006). The TDS is approximated by the sum of the concentrations of major cations, including the Ca^{2+} , Mg^{2+} , Na^+ , K^+ , HCO_3^- , SO_4^{2-} , Cl^- and silica in the system, mainly the first 7 ions. This approach has been practiced in many previous studies (Riebe et al., 2004, Ryu et al., 2008, Roy et al., 1999, Yuan et al., 2007, Karim and Veizer, 2000).

Seasonal Variations of Erosion Rate

Because discharge and precipitation change seasonally, the physical removal of sediments and chemical dissolution of the ions, which are related to discharge and precipitation, will change seasonally. The total loadings of suspended sediments reflect the amount of physical erosion, and the total dissolved major ions reflect the chemical weathering of the rocks and soil in the basin. The monthly averages were calculated by adding all the sample data collected in a particular month for all the years that data are available. Also, in order to examine the relationship between the water temperature and dissolved silica concentration, a simple linear correlation was calculated.

Saturation Indices of Mineral Species

Saturation index is a term that is used to describe the dissolution state of a mineral in water. It is calculated as the log ion activity product of the dissolution reaction divided by the equilibrium constant of a reaction (Drever, 1997). For example, for the dissolution of gypsum, the saturation indices equation is given as,

$$\text{Saturation Index} = \log \frac{IAP}{K_{sp}} = \log \frac{(a_{ca^{2+}} a_{so_4^{2-}})_{solution}}{K_{sp(gypsum)}}$$

where *IAP* is Ion Activity Product and K_{sp} is equilibrium constant of the reaction equation. The ratio of *IAP* and K_{sp} can also be normalized by the number of ions to obtain the saturation ratio (Zhang and Nacollas, 1990).

The WATEQ4F (Ball and Nodstrom, 1991) which evaluates the distribution and the saturation level of each species for each element was used to calculate the saturation index of each species. The program uses the measured ion concentrations of a water system as input.

Soil Mineral Patterns of the Area

Soil cores were collected from five sites in the basin (fig 1). A 15-foot core collected at the Naval Air Warfare Center (NAWC), West Trenton site was obtained from the USGS Trenton office. Two-foot shallow soil cores were collected from four sites along Route 29 near the Delaware River. The soil sample's X-ray powder diffraction spectra were collected. RockJock6 (Eberl, 2003) was used to quantify weight percentage of the soil minerals based on the X-ray spectra of the soil and rock minerals. Mertens et al. (2006) recommended the RockJock program to be the "method of choice" for the soil clay mineral analysis based on the X-ray spectra. Weight abundances of soil minerals are the bases for mass balance analyses of the chemical weathering.

RESULTS

Denudation Rate of the DRB

The Delaware Water Gap is the most upstream station, Riegelsville is the middle station, and Trenton is the most downstream station. The Delaware River becomes tidal in less than a mile below the Trenton station (Figure 1). Total suspended sediments generally increase with river discharge. During 1945-82, the mean annual suspended sediments at the Trenton station ranged from 50 to 6500 tons per day (Figure 2).

Concentrations of the major ions, calcium, magnesium, potassium, and silica, which resulted from the chemical weathering, fluctuated annually in response to river discharge. However, they did not show a significantly trend from 1945 to 2008 (Figure 3).

Concentrations of sodium and chloride increased by 2 to 4 times as a result of increased application of the winter deicing salt (Sun et al., 2006, Lucarino and Sun, 2007). Also, the molar concentration of chloride has risen above the sodium concentration in the last 20 years. This reversal of concentrations may indicate that sodium derived from weathering of albite to kaolinite, which was considered the sole source of sodium (Blum et al., 1998), has become less significant in relation to the artificial input of sodium from the deicing salt. Sulfate concentration shows a low and decreasing trend since the 1970s. This decline may be related to the clean-air act passed by Congress in 1970's which

Table 1. Denudation rates calculated from the suspended sediments and total dissolved solid at three gage stations of the Delaware River: near Delaware Water Gap, Riegelsville and Trenton stations..

Stations	Physical Erosion Tons/km ² /yr	Chemical Weathering Tons/km ² /yr	Total Denudation Tons/km ² /yr	Data Period /Source
Water Gap	11.47	16.94	28.41	Physical:1964-65, 1971-72; Chemical: 1965-68
Riegelsville	---	77.79	---	Chemical: 1960-78; 1991-2008
Trenton	41.71	86.34	128.04	Physical: 1950-82; Chemical: 1944-2008
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Panola Min. GA	14±2	---	23±3	Source: Riebe et al., (2004).
Nicols Peak, S. Sierra Nevada	127±12	---	111±13	Source: Riebe et al., (2004).

resulted in the reduction of the dry wet depositions of sulfate in the basin. However, this decline also may be related to the change of equilibrium balance brought by the increased use of NaCl in the basin (Lucarino and Sun, 2007). Biocarbonate data at the three stations were recorded for less than 10 years by USGS. Because of the positive linear relationship between the concentration of biocarbonate and the concentrations of calcium and magnesium (with R² from 0.5 to 0.96), one can deduce that the concentration of biocarbonate probably did not have a significant trend based on the concentrations of calcium and magnesium (fig. 3). The high concentration of silica during the mid 1950's, may be caused by floods that exposed unweathered bedrock with the removal of thick

sediment deposits (Figure 3). However, there is the possibility of an imbalance brought about by increased NaCl concentrations that cause a change in the weathering rates of orthoclase, plagioclase and other silicates. Data from the two precipitation stations in the basin collected between 1981 and 2006 by National Atmospheric Deposition Program, show the atmospheric depositions of ions, compared with the ion concentrations in the river, are insignificant. Therefore, the main sources of ions in the river are the chemical weathering of rocks and the deicing salt applied in the basin.

Comparing the denudation rate at Trenton, Water Gap and Riegelsville (Table 1),

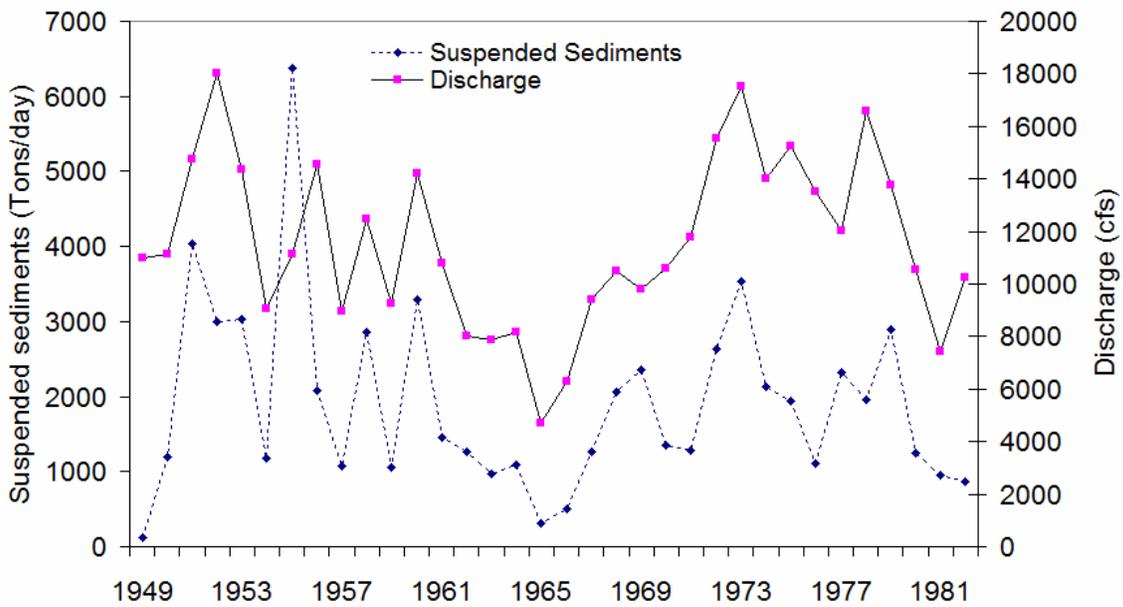


Figure 2. Annual average suspended sediments and discharge of the Delaware River at Trenton station.

it is apparent that the chemical weathering increases downstream. This change might reflect the changing underlying geology and the slopes of drained area from upstream to downstream regions. The denudation rates of 28 and 128 tons/km²/year are comparable with the data from studies in other regions by Riebe et al. (2004). Because Trenton station is located downstream and it drains nearly the whole basin, its denudation rate is more representative of the whole Delaware River basin.

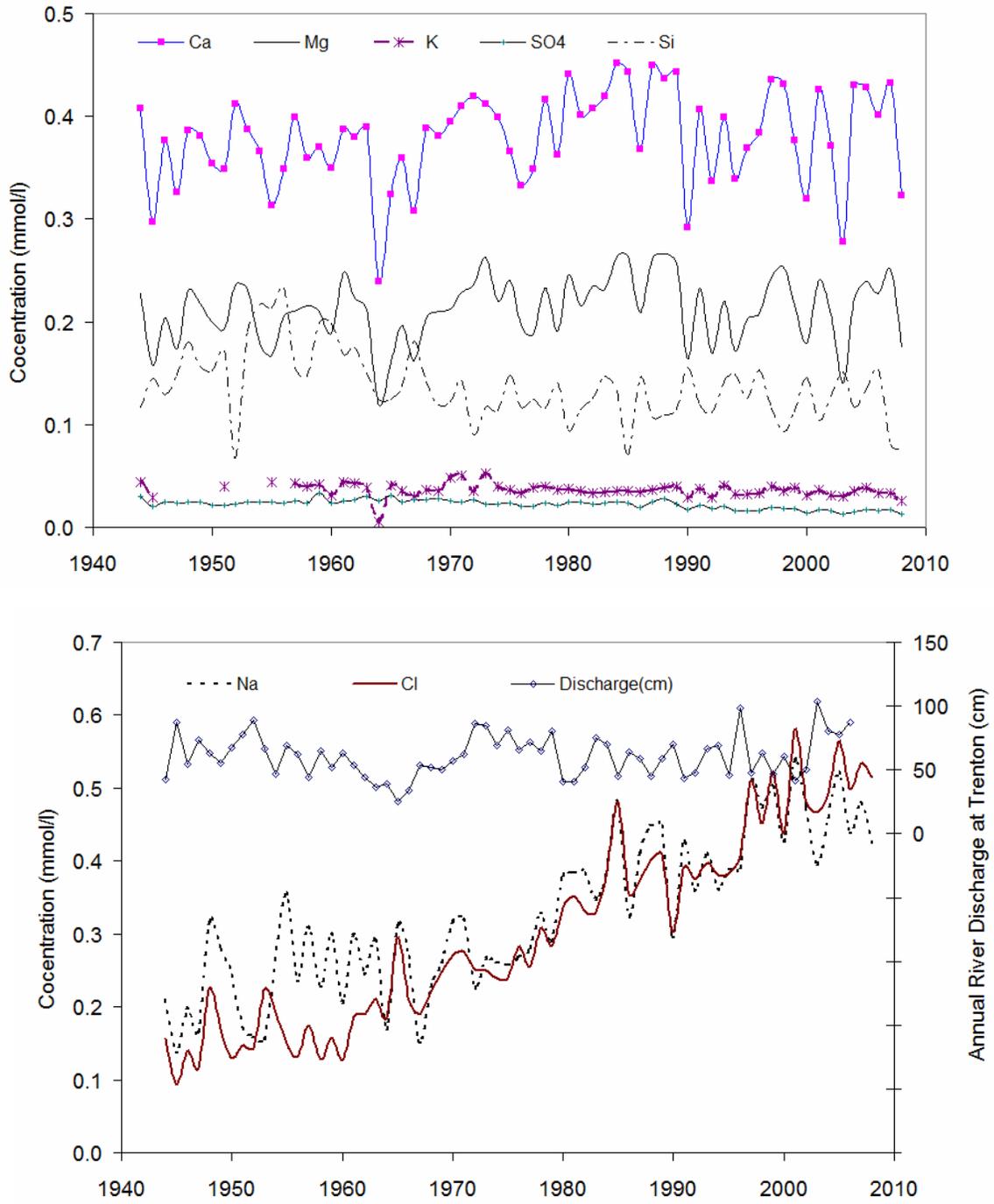


Figure 3. Average monthly concentration trends of major ions and discharge of the Delaware River at Trenton station. Upper panel, Ca, Mg, K, SO₄ and Si; lower panel, Na, Cl and the normalized discharge.

Seasonal Variation of Erosion Rate

Changes of suspended sediment rates in the Delaware River corresponded mainly to the increase and decrease of river discharge. This implies that suspended sediment loading is larger during March and April when the snow-melting and ground thawing

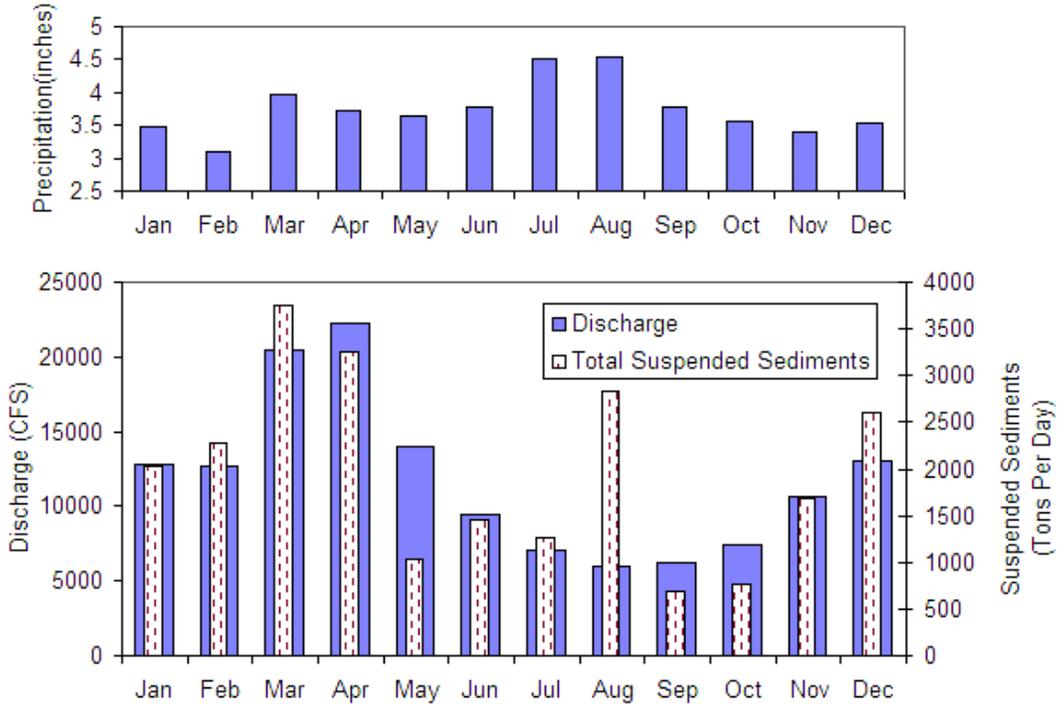


Figure 4. Average monthly suspended sediment loads vs. average NJ precipitation and discharge of the Delaware River at Trenton station.

occur (Figure 4). However, because of the large amount of precipitation in August, the total sediment loading can increase significantly in August in response to the flash flooding, such as the spike of total suspended sediments observed in 1955 (fig. 2). The average suspended sediments of August from 1950 to 1982 for Trenton station is 2830 tons/km²/year (Figure 4). However, excluding the sediment loading spike of August 1955, the average sediment loading of August during this same period from 1950 to 1982 will be only 707 tons/km²/year at Trenton station, which is similar to the average sediment loadings for July and September.

The concentrations of the seven major ions except silica correlate inversely with the discharge of the river (Figure 5). They are low when the discharges are high in March and April, and high in the summer when the river discharges are low. The monthly

concentrations of silica are high in the winter period and low in the summer and fall periods, and have a negative correlation with temperature. This might indicate that the solubility of silica may be responding to the temperature differently from the other ions (Moon et al., 2007). However, the silica concentration generally increases with

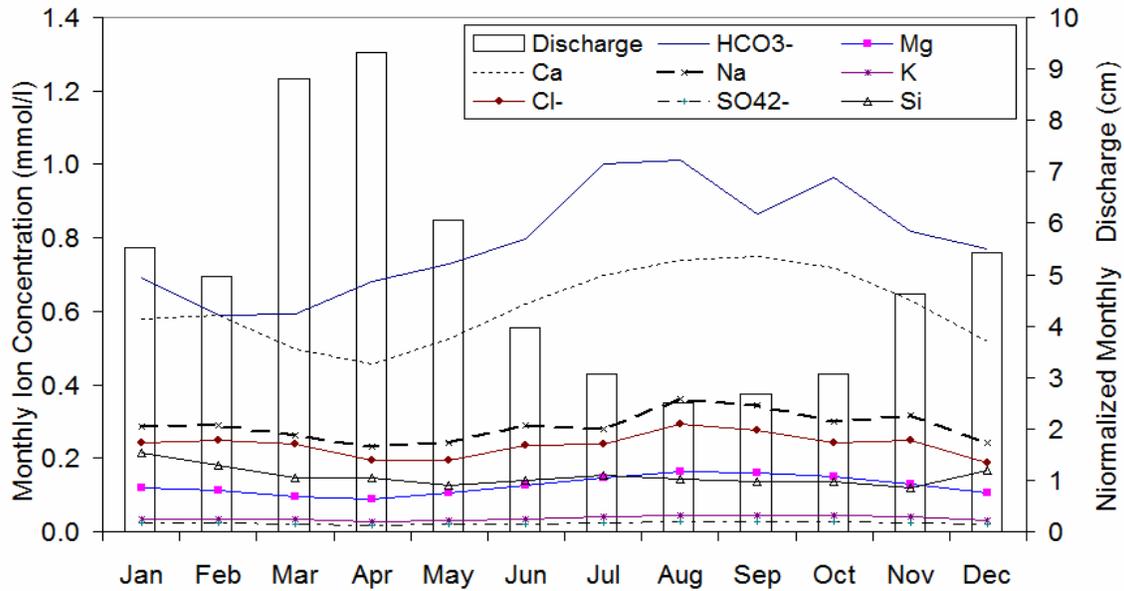


Figure 5. Seasonal variation of ion concentrations vs. discharge of the Delaware River at Trenton station.

temperature from most of the previous studies (White and Blum, 1995). The total TDS loading (TDS x discharge), which is the total weight of the major ions including silica, shows a similar changing pattern as the total suspended sediment (Figure 4), with a small loading in the summer months and a relative large loading in the spring months.

Saturation Indices of Minerals in Water

The saturation index (SI) was calculated for the period between 1970 and 2008 for each station when the data are available, with the river chemistry as the input for the WATEQ4F program. Saturation indices of 50 mineral species were given by the program output. Only the average SI of a few minerals that are related with the road salt, sulfate atmospheric loading and two other common weathering products, calcite and amorphous silica are identified here (Figure 6). For calcite, it is near saturation in August, which corresponds to its higher molar concentration in the summer (Figure 5). Halite (NaCl)

shows a slightly higher SI in February than in August. This seasonal change of halite might be related to the deicing salt application in the winter as discussed in the previous section. But overall, the halite saturation in the water is still very low as indicated by their large negative SI (Figure 6). The SI of amorphous silica shows a trend that is opposite of calcite. It is more saturated in February than in August. The seasonal trend of gypsum's SI is similar to that of the calcite, with a high SI in August. However, there are obvious differences between the SI of the data at the Delaware Water Gap and Trenton stations. Their differences might reflect the differences in their underlying geology and the atmospheric deposition.

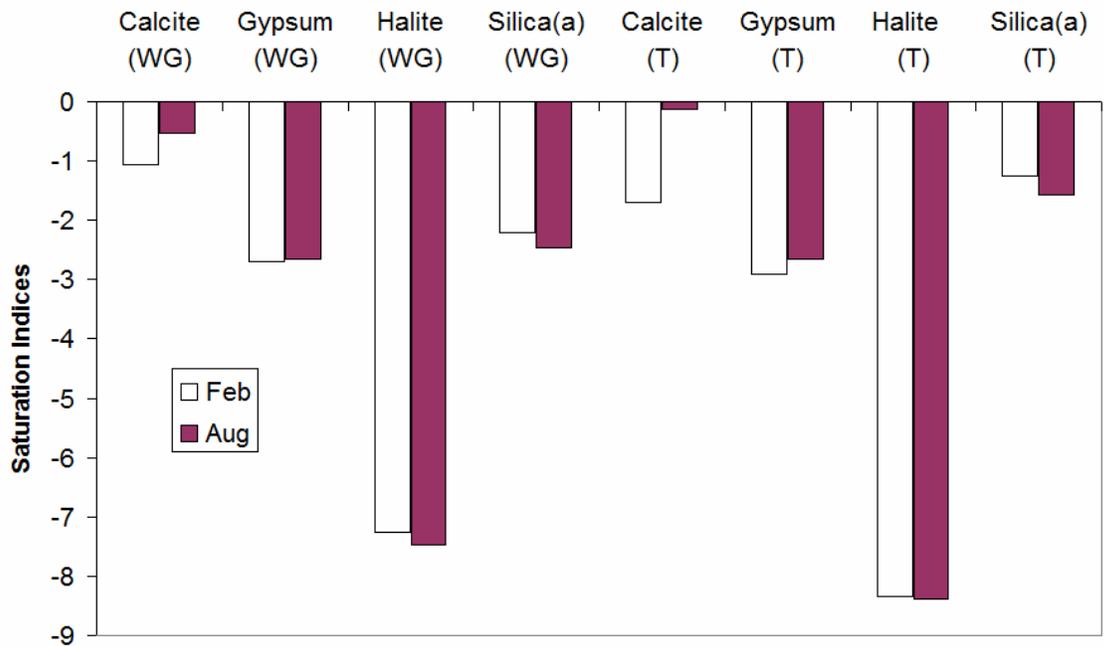


Figure 6. Saturation indices of calcite, gypsum, amorphous silica and halite from Delaware Water Gap (WG) and Trenton (T) stations in February and August.

MINERAL WEATHERING IN THE AREA

The mineral weight percent of soils samples for four soil cores are given in Table 2. The mineral weight abundance of the NAWC core shows that the weight abundance of quartz decreases with depth, while weight abundance of feldspar increases with depth. Relatively, there is more plagioclase feldspar in the samples. The change of weight

abundance of clay minerals with depth depends on the specific type of mineral dominant and varied weight abundances for clay minerals. This diverse mineral weight

Table 2. Mineral weight percent abundance of the study sites

NAWC, Naval Air Warfare Center, West Trenton; Stock, Stockton Elementary School ground; Park, Washington Crossing Park; Diosite, diorite road cut on Route 29.

Depth →	NAWC West Trenton Site, Depths below Land surface in Feet							Other Sites		
	0	2	3.8	7.9	10	11.8	15.8	Stock	PARK	Diosite
Quartz	45.16	46.32	42.40	7.08	0.00	1.96	14.07	35.08	0.00	8.56
K-feldspar	10.56	3.02	7.51	21.81	25.29	16.11	3.42	12.87	2.48	8.35
Na,Ca feldspar	3.06	7.28	14.78	7.27	23.76	42.51	48.94	15.49	23.04	35.69
Calcite	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11
Dolomite	0.54	0.00	0.17	0.07	0.13	0.00	0.00	0.25	0.90	0.29
Pyrite	0.00	0.03	0.09	0.13	0.00	0.40	0.17	0.02	0.97	0.43
Gypsum	1.33	0.58	0.00	0.49	0.34	0.00	0.88	0.67	0.00	1.01
Magnetite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.73	0.01
Hematite	0.00	0.07	0.34	0.10	0.00	3.76	5.03	0.58	2.16	0.10
Goethite	1.72	1.75	1.66	0.89	0.80	0.00	0.26	1.21	0.00	1.27
Kaolinite	6.29	4.88	5.00	11.59	6.51	0.09	0.60	1.96	0.00	7.59
Smectite	20.56	18.40	19.04	28.43	22.37	18.20	11.86	9.98	20.28	16.17
Illite	2.16	5.08	1.24	4.63	19.28	12.58	0.00	5.03	5.09	2.01
Biotite	1.91	1.69	1.35	2.68	0.00	0.00	0.14	6.35	8.78	4.31
Chlorite	3.32	3.34	0.80	5.83	1.51	1.66	0.20	9.88	33.03	11.80
Muscovite	3.36	7.56	5.61	8.99	0.00	2.71	14.42	0.40	2.54	2.31

abundance from various soil sites including some of our earlier studies (Sun et al., 2008) reflects the diverse ion concentrations in the DRB.

Even though the weight abundance of carbonate minerals, calcite and dolomite are only a small portion of the soil mineral mass, because of the relative large amount of calcium, and magnesium in the river water, they still might play a large role in the mass

balance calculation of calcium and magnesium in the Delaware River based on similar studies conducted by other researchers (Blum et al, 1998, Grosbois et al, 2000).

SUMMARY AND CONCLUSIONS

Denudation rates in the Delaware River Basin vary from upper stream to downstream. Overall, the chemical weathering is prominent due to the high moisture level and longer soil water residence time in the DRB. The total denudation rates of 28 and 128 tons/km²/yr are comparable to the rates obtained from other regions of the country. The major ion concentrations are usually high in the summer with a sequence of Ca>Mg>Na>K. Concentration of silica shows a slightly different trend. Because of the anthropogenic contribution of the winter deicing salt, the concentrations of Na and Cl have nearly quadrupled during 1945-2007. The weight abundance of soil minerals changes with soil depth. Overall, there is more quartz near the surface and more feldspar at depth, which could reflect the decreasing level of mineral weathering with depth.

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