Effects of Annual Precipitation on Heavy Metals in Runoff from Soils in the U.S. Great Plains

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ABSTRACT

Deterioration of natural water resources due to runoff from agricultural land is a major problem in the U.S. Great Plains. Changes in earth climate can create heavy storms and alter precipitation patterns which would affect the element concentrations in runoff. A 2-year study (dry and wet year) was conducted to assess the impact of annual precipitation on element concentrations in runoff from soils and element loadings to Salt Creek in the Roca watershed, Nebraska. Both dissolved and sediment-associated forms of five elements (Al, Fe, Mn, Cu, and Zn) were determined in runoff. The amount of dissolved element in runoff for the wet year was greater than the dry year. Except for Zn, the total amount of element associated with sediment was greater than that found in dissolved form. The Mehlich3 extraction was applied to determine the reactive fraction of element in sediment. A small fraction of element associated with sediment was in reactive form, ranging from 1 to 33% of the total element content. The sum of both the reactive fraction of element in sediment and amount of element dissolved in water were used to calculate the total Bioactive Element Concentration (BEC) in runoff. For the dry year, the total BEC in runoff was 424, 349, 387, 5.2, and 26.8 μg/L for Al, Fe, Mn, Cu, and Zn, respectively. The corresponding total BEC for the wet year was 622, 479, 114, 3.7, and 19.8 μg/L, respectively. Further, the Bioactive Element Loading (BEL) into Salt Creek was greater for the wet year than the dry year. Aluminum, Fe, and Mn contributed to the greatest BEL into the surface water body while Zn and Cu had the least contribution. We concluded that greater precipitation during the wet year would increase the negative impact of runoff from soils and BEL to surface water systems in the U.S. Great Plains.

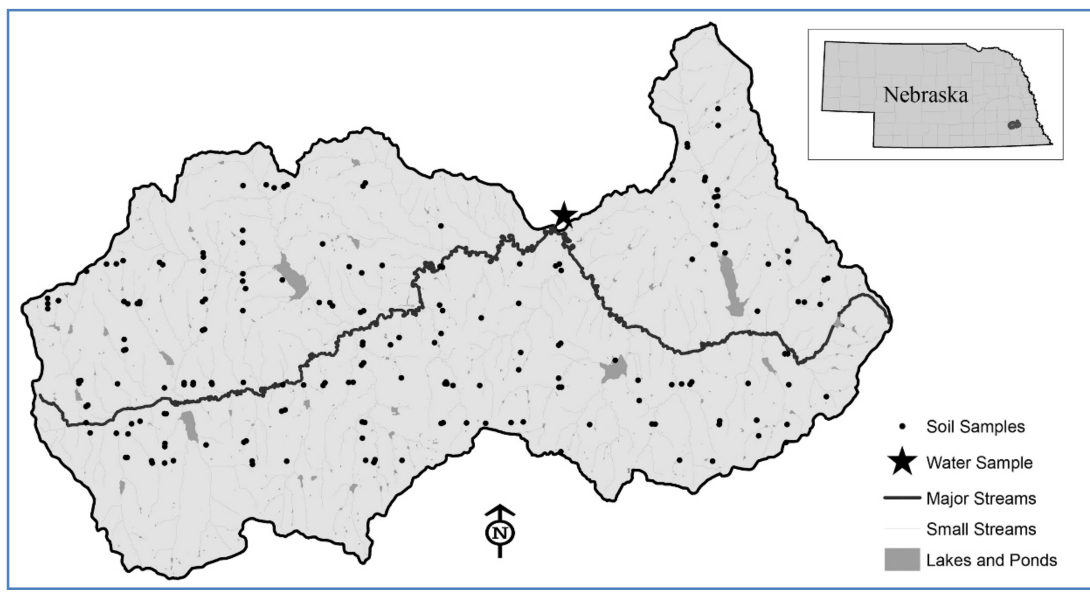

Figure 1. Soil and water sampling locations and the 43,286-ha drainage area in Roca watershed, Lancaster County, Nebraska.

Table 1. Classification and some properties (mean ± standard deviation) for the 14 major soils under crop and grass covers in the Roca watershed, Lancaster County, Nebraska.

Soil	Classification	Land over	Clay (%)	OC (%)	CEC (Cmol/kg)	pH-water
Burchard	Fine-loamy, mixed,	Crop	24.75 ±5.79	2.47 ±0.27	19.55 ±3.72	6.43 ±1.08
	mesic Typic Argiudolls	Grass	24.75 ±2.34	2.47 ±0.48	19.55 ±1.31	6.43 ±0.79
Crete	Fine, montmorillonitic,	Crop	27.13 ±3.93	2.07 ±0.21	21.00 ±3.19	5.95 ±0.80
	mesic Pachic Argiustolls	Grass	29.47 ±3.78	2.89 ±0.82	24.87 ±4.73	6.05 ±0.27
Judson	Fine-silty, mixed,	Crop	27.80 ±4.12	2.13 ±0.58	20.45 ±3.37	6.40 ±1.10
	mesic Cumulic Hapludolls	Grass	27.07 ±2.24	1.92 ±0.43	20.90 ±1.12	6.15 ±0.69
Kennebec	Fine-silty, mixed,	Crop	25.00 ±4.33	1.96 ±0.24	19.98 ±3.10	5.97 ±1.03
	mesic Cumulic Hapludolls	Grass	25.08 ±2.36	2.45 ±0.36	22.12 ±1.12	6.20 ±0.69
Mayberry	Fine, montmorillonitic,	Crop	28.58 ±6.80	1.57 ±0.50	20.23 ±4.52	5.97 ±1.24
	mesic Aquic Argiudolls	Grass	32.80 ±3.88	2.04 ±0.66	25.53 ±2.17	6.33 ±0.58
Morrill	Fine-loamy, mixed,	Crop	32.97 ±5.76	1.75 ±0.35	21.47 ±3.36	5.12 ±0.56
	mesic Typic Argiudolls	Grass	29.98 ±7.29	2.23 ±0.56	22.47 ±3.84	6.22 ±0.34
Nodaway	Fine-silty, mixed, nonacid,	Crop	25.35 ±1.62	2.21 ±0.71	20.60 ±2.45	5.42 ±0.90
	mesic Mollic Udifluvents	Grass	27.30 ±7.24	2.21 ±1.01	22.88 ±7.90	6.38 ±0.89
Pawnee-PaC2	Fine, montmorillonitic,	Crop	33.42 ±5.55	1.73 ±0.08	24.23 ±5.31	5.68 ±0.97
	mesic Aquic Argiudolls	Grass	30.03 ±5.45	2.18 ±0.62	23.07 ±3.97	5.93 ±0.25
Pawnee-PaD2	Fine, montmorillonitic,	Crop	33.68 ±4.89	1.64 ±0.35	23.48 ±3.05	5.50 ±0.47
	mesic Aquic Argiudolls	Grass	29.45 ±4.78	2.26 ±0.53	22.82 ±3.66	6.20 ±0.31
Shelby	Fine-loamy, mixed,	Crop	30.07 ±6.03	1.52 ±0.38	21.88 ±3.75	5.93 ±0.64
	mesic Typic Argiudolls	Grass	26.62 ±5.05	1.74 ±0.41	20.13 ±3.24	6.88 ±0.86
Steinauer	Fine-loamy, mixed (calcareous),	Crop	32.68 ±4.40	1.39 ±0.36	23.12 ±2.16	6.78 ±0.87
	mesic Typic Udorthents	Grass	23.03 ±8.53	2.27 ±0.54	18.58 ±5.47	6.75 ±0.80
Wymore-WtB	Fine, montmorillonitic,	Crop	35.50 ±4.16	2.30 ±0.48	25.83 ±1.67	5.65 ±0.80
	mesic Aquic Argiudolls	Grass	33.72 ±3.53	2.82 ±1.21	26.68 ±4.67	6.22 ±0.82
Wymore-WtC2	Fine, montmorillonitic,	Crop	36.62 ±3.50	1.98 ±0.16	26.07 ±3.44	5.35 ±0.52
	mesic Aquic Argiudolls	Grass	36.97 ±4.78	1.86 ±0.27	27.48 ±3.58	6.33 ±0.68
Wymore-WtD3	Fine, montmorillonitic,	Crop	38.73 ±3.88	1.80 ±0.18	27.45 ±3.30	5.43 ±0.77
	mesic Aquic Argiudolls	Grass	37.82 ±5.17	2.02 ±0.75	27.72 ±4.10	6.32 ±0.74

INTRODUCTION

Climate change has resulted in changing patterns of precipitation in the globally observed data. These changing precipitation patterns would affect runoff and soil moisture and thus could affect the quality of surface waters. Understanding the transport of elements from agricultural land to surface water bodies as affected by climate change is important for adaptation. Moreover, the knowledge of dissolved and sediment associated forms of elements and their effects on water quality could improve land management practices and minimize the impact on water resources.

Elements such as Al, Fe, Mn, Cu, and Zn are present in several chemical forms in soil, which are water soluble, adsorbed on colloidal inorganic surfaces, complexed with organic materials, and associated with inorganic minerals (i.e., oxides, hydroxides, carbonates, aluminosilicates). At high concentrations, most of these elements have detrimental effects on living organisms. The bioavailability and environmental impact is dependent upon the amount of element dissolved in soil solution, which is controlled by soil properties.

The goal of this 2-year project was to study the effects of annual precipitation on the concentration of elements in surface runoff entering natural water systems in the Platte River basin, Nebraska which is located in the north central region of the U.S. Great Plains. The Roca watershed (Platte River basin) was selected for this study, and five elements were investigated (Al, Fe, Mn, Cu, and Zn). The specific objectives were to assess the effects of annual precipitation on: i) the dissolved and sediment-associated forms of elements in runoff water, ii) elements loss by runoff from watershed soils, and iii) the impact of element loading to Salt Creek from runoff.

MATERIALS and METHODS

Study Area

The Roca watershed is located in the southeastern section of the Platte River basin in Lancaster County, Nebraska (Fig. 1). The drainage area encompasses 43,286 hectares (106,880 acres) of agricultural land in the southern part of Lancaster County. The main stream through the Roca watershed is Salt Creek. Eleven soil series (Burchard, Crete, Judson, Kennebec, Mayberry, Morrall, Nodaway, Pawnee, Shelby, Steinauer, and Wymore) accounted for 92% of the agricultural land and are the soils that will be used in this study. The historic record shows a mean annual precipitation of 729 mm (28.7 inches) for Lancaster County where the Roca watershed is located. In the present study, the 2009 annual precipitation was below average at 586 mm (23.08 inches) and above average for 2010 at 874 mm (34.42 inches).

Soil, Sediment and Water Sampling and Analysis

Soil samples were collected from the 14 soil map units and analyzed by methods described in Soil Survey Investigations Report (SSIR) No. 42 (USDA-NRCS, 2004). Taxonomic classifications and selected properties for the 14 soils under crop and grass in the Roca watershed, Lancaster County, Nebraska is presented in Table 1. During the period from March through November for both 2009 and 2010, 35 weekly stream water samples and suspended sediments were collected from Salt Creek and analyzed for dissolved and total elements. We used the USEPA geochemical equilibrium speciation model to calculate the concentration/activity of dissolved chemical species related to the five elements (Al, Fe, Mn, Cu, and Zn) in the stream water.

RESULTS and DISCUSSION

Water Flow and Suspended Sediment

There was an annual water flow into the Salt Creek (Roca town) of 10.1 and 46.1 million m3 for the dry and wet year, respectively. For the dry year, the weekly sediment loading into Salt Creek ranged from 0.01 to 729 metric tons, with an annual average of 47.9 metric tons/week. The wet year values gave an annual loading of 8933 metric tons (more than five times the amount of sediment measured during the dry year). The wet year sediment loading was equivalent to an annual loss from soils of 206 kg/ha in the watershed. The 2-year average of sediment loss from soils in the watershed was 122 kg/ha/yr. The predicted average runoff from soil during the dry year was 268 m^3/ha/yr, which produced an annual runoff of 10.7 million m^3 for all soils in the watershed. The corresponding predicted average runoff from soil for the wet year was greater at 1,300 m^3/ha/yr, which generated an annual runoff of 51.8 million m^3 for the entire watershed.

Elements in Salt Creek Water

Dissolved and sediment-associated forms of the five elements (Al, Fe, Mn, Cu, and Zn) were measured weekly (kg) in Salt Creek at the Roca monitoring station during the dry and wet years. Table 2 shows the annual amount (kg) of different forms of the five elements in runoff generated from Roca watershed during the dry and wet year. In general, both dissolved and sediment-associated element forms were greater for the wet than the dry year. Also, most of elements were found in water during and after storm events. Figure 2 shows the Al amount (kg) in dissolved (Fig. 2a) and sediment-associated forms (Fig. 2b) measured from weekly water samples in Salt Creek during the dry and wet years. The amount of dissolved Al measured in Salt Creek during the dry year had a large range between a minimum of 0.1 kg/week and a maximum of 1,767 kg/week with an average of 105 kg/week and produced an annual amount of 3,691 kg. The corresponding amount of dissolved Al in water for the wet year was greater than the dry year. It ranged from a minimum of 1.27 kg/week to a maximum of 8,097 kg/week with an average of 718 kg/week which gave an annual amount of 25,131 kg. The wet year had almost 7 times the amount of dissolved Al than that found in Salt Creek water during the dry year. Almost all of the dissolved Al in water was in the form of single Al hydroxide species: $Al(OH)_4$ [-1], accounted for 99.3 and 98.9% of the total dissolved Al for the dry and wet year, respectively.

Environmental Impact

The total bioactive element concentration in Salt Creek during the dry year was 424, 349, 387, 5.21, and 26.8 μg/L, for Al, Fe, Mn, Cu, and Zn, respectively. The corresponding total bioactive element concentration for the wet year was 622, 479, 114, 3.68, and 19.8 μg/L, respectively. The bioactive Cu and Zn concentrations found in Salt Creek for both the dry and wet years were lower than the value of Cu (15 μg/L) and Zn (64 μg/L) concentrations in natural surface waters of the U.S. The maximum permissible limit for Fe, Mn, Cu, and Zn in U.S. drinking water is 300, 50, 1300, and 7,400 μg/L, respectively while no limit has been recommended for Al (USEPA, 2002). The bioactive element concentrations found in Salt Creek were much lower than the maximum permissible value for Cu and Zn in drinking water. However, it appears that both bioactive Fe and Mn concentrations in Salt Creek have exceeded the permissible limit for drinking water during the two years. With respect to aquatic life, the USEPA (2002) recommended two criteria to determine the quality of freshwater: i) the Criterion Maximum Concentration (CMC) and ii) the Criterion Continuous Concentration (CCC). The bioactive Al concentration in Salt Creek for both dry and wet years have exceeded the USEPA recommended CCC for the quality of freshwater. But, the Al concentrations found in Salt Creek were below the recommended CMC. These data indicated that Al concentration determined in Salt Creek during the 2-year study (424 to 622 μg/L) could adversely affect the aquatic life from long term exposure. On the other hand, none of the other four elements investigated (Fe, Mn, Cu, and Zn) has exceeded the recommended USEPA criteria for surface freshwater bodies.

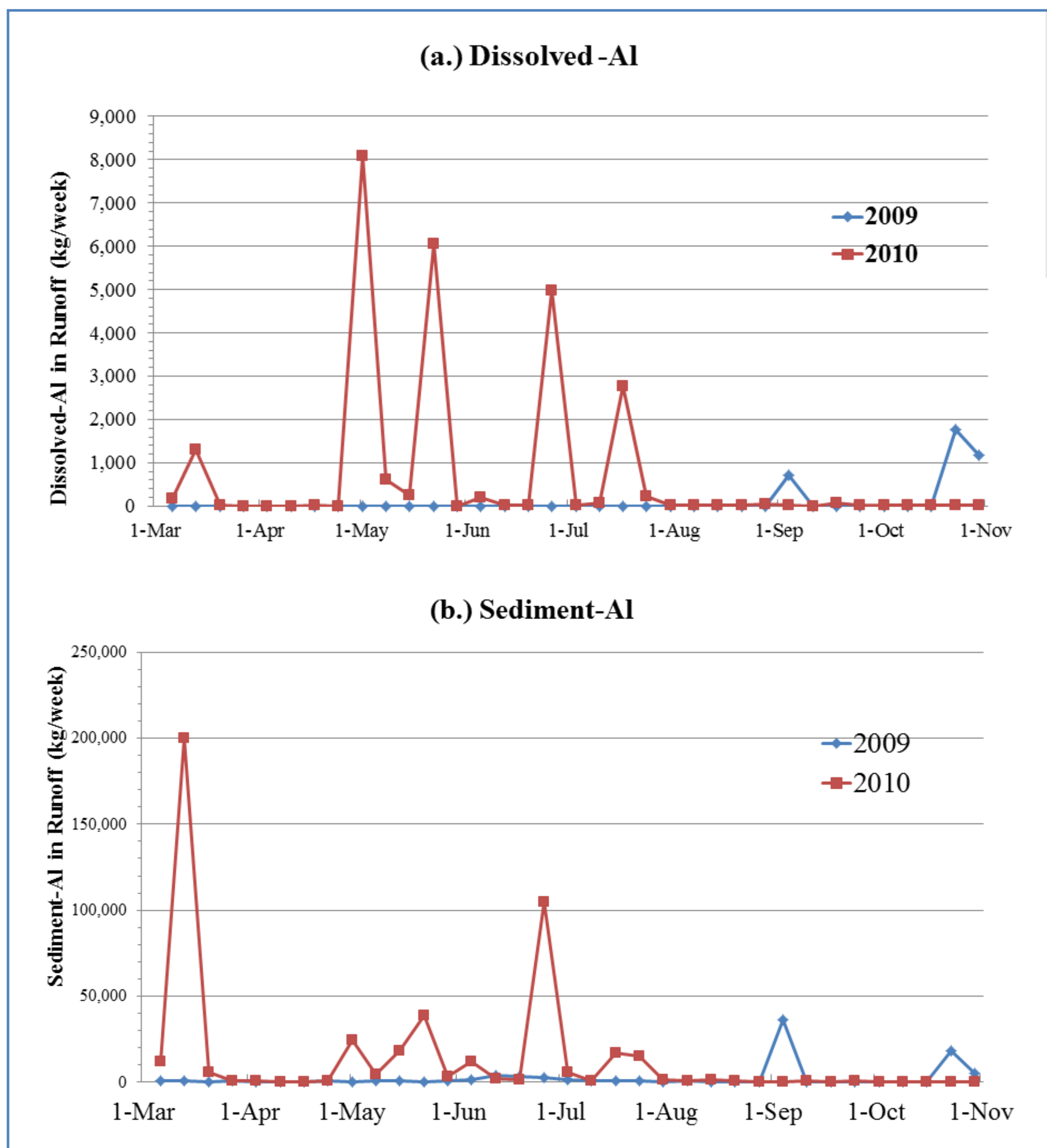

Figure 2. Aluminum amount in dissolved (a) and sediment-associated form (b), measured from weekly water samples in Salt Creek.

Table 2. The annual amount (kg) of different forms of aluminum, iron, manganese, copper, and zinc (mean ± standard deviation) in runoff generated from Roca watershed during the dry 2009 and wet 2010.

Element	Form	2009 (kg)	2010
Aluminum (Al)	Dissolved	3,691 ±369	25,131 ±1,870
	Sediment	83,516 ±6,669	478,692 ±37,569
	Reactive	585 ±50	3555 ±293
Iron (Fe)	Dissolved	2,881 ±284	18,301 ±1,371
	Sediment	27,347 ±2,162	167,781 ±13,704
	Reactive	643 ±52	3,792 ±296
Manganese (Mn)	Dissolved	3,603 ±63	3,912 ±255
	Sediment	912 ±72	4,893 ±369
	Reactive	298 ±24	1,350 ±94
Copper (Cu)	Dissolved	47.7 ±2.06	145.7 ±7.0
	Sediment	19.7 ±1.50	146.1 ±11.3
	Reactive	4.9 ±0.42	24.1 ±2.0
Zinc (Zn)	Dissolved	263.0 ±5.24	887.0 ±70.8
	Sediment	86.4 ±6.50	535.0 ±42.5
	Reactive	6.8 ±0.62	27.0 ±1.9

CONCLUSIONS

The concentration and species of dissolved Al, Cu, and Zn measured in the Salt Creek stream water are not expected to have any adverse effect on human and animal health. However, the relatively high concentration of Fe and Mn in stream water has exceeded the permissible limit for U.S. drinking water. Further, the Al concentrations determined in water (424 to 622 μg/L) suggests that aquatic life in Salt Creek could be harmed from long term exposure. On the other hand, none of the other four elements investigated (Fe, Mn, Cu, and Zn) have exceeded the recommended USEPA criteria for surface freshwater. In general, both the amount of elements in dissolved form and those associated with suspended sediments in runoff were greater for the wet year than the dry year. We concluded that greater precipitation during the wet year increased the five metal element loadings into Salt Creek and the negative impact of runoff from agricultural land on surface water quality.

REFERENCES

USDA-NRCS (2004): Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42, Version No. 4. USDA-NRCS, Washington, D.C.

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