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SEWAGE SLUDGE APPLICATION IN SEMIARID GRASSLANDS: EFFECTS ON RUNOFF AND SURFACE WATER QUALITY

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INTRODUCTION

Approximately 6 million metric tons of municipal sewage sludge are produced annually in the United States alone (U.S. Environmental Protection Agency 1990). In many large urban areas of the Southwest, including the city of Albuquerque, New Mexico, liquid waste is processed in a sewage treatment plant. This process greatly improves the quality of effluent leaving the plant, but disposal of the solid, sewage sludge-extracted wastes remains a problem. Presently, Albuquerque's sewage sludge is applied over large acreages of rangeland set aside specifically for disposal purposes and tilled into the subsoil. Safe, economically feasible disposal of the sludge, not rehabilitation of the rangeland affected, is the city's main objective.

A primary concern limiting the use of sludge as a soil amendment is the potential introduction of contaminants into the environment, including surface and groundwater resources. Yet sewage sludge has been successfully used as a fertilizer and mulch for agricultural purposes (Berglund et al. 1984; Catroux et al. 1981) and in mined land reclamation efforts (Sopper and Kerr 1979). Recently, a pioneering study has shown that degraded rangeland responds favorably to the application of sewage sludge as a fertilizer and organic matter amendment (Fresquez et al. 1990a). The results of this preliminary study further showed that a one-time surface application of 22.5 to 45.0 Mg ha^{-1} (10-20 tons/acre) of anaerobically digested sewage sludge did not lead to contamination of soil or plant tissue (Fresquez et al. 1990b, 1991).

Runoff and erosion on hillslopes increase with decreasing vegetative cover and increasing slope gradient. Both factors are recognized as important parameters in existing erosion prediction equations and models (Wischmeier and Smith 1978; Alberts et al. 1989; Hernandez et al. 1989). Vegetative cover disrupts overland flow on hillslopes and promotes greater infiltration while reducing runoff.

Much of the southwestern rangelands experienced heavy livestock grazing over the past century, leading to a substantial reduction in total plant cover and density (Dortignac and Hickey 1963). Thus, any successful attempt at increasing vegetative cover (canopy cover, canopy height, and residue or litter cover) in New Mexico rangeland should lead to reduced runoff and sediment yields.

Rogers and Schumm (1991) conducted an experimental study on changes in runoff and sediment yield resulting from changing vegetative cover from 43% to 0% on a 10% slope. Their data showed that sediment yield increased as vegetative cover was decreased from 43% to 15%, but below 15%, further reduction in vegetative cover did not increase sediment yield appreciably. We believe applying sewage sludge to New Mexico rangeland will reduce erosion from hillslopes because favorable vegetative response (increased biomass production, basal and canopy cover) will increase surface roughness and soil stability. These factors in turn should lead to reduced runoff on degraded rangeland.

The specific objectives of our research were: 1) to evaluate differences in runoff yield induced by natural and simulated rainfall in sludge-amended (treated) and unamended (control) plots in a semiarid grassland, and 2) to determine the extent of transfer of potential sludge-borne contaminants within the immediate area of sludge application by surface runoff.

This paper reports the differences in runoff quantity and runoff water quality measured on rangeland treated with sewage sludge and untreated rangeland during the initial growing season following sludge application. Continued research at the site will address the changes in soil properties and vegetation induced by the sludge treatment and the subsequent effects of these changes on surface hydrology.

STUDY SITE DESCRIPTION

The study was established on a sloping alluvial fan located within the Sevilleta National Wildlife Refuge (Fig. 1). The refuge, managed by the U.S.D.I. Fish and Wildlife Service, provides an excellent opportunity to compare treatment effects within rangeland because the area is completely fenced off, public access is restricted, and livestock grazing is prohibited.

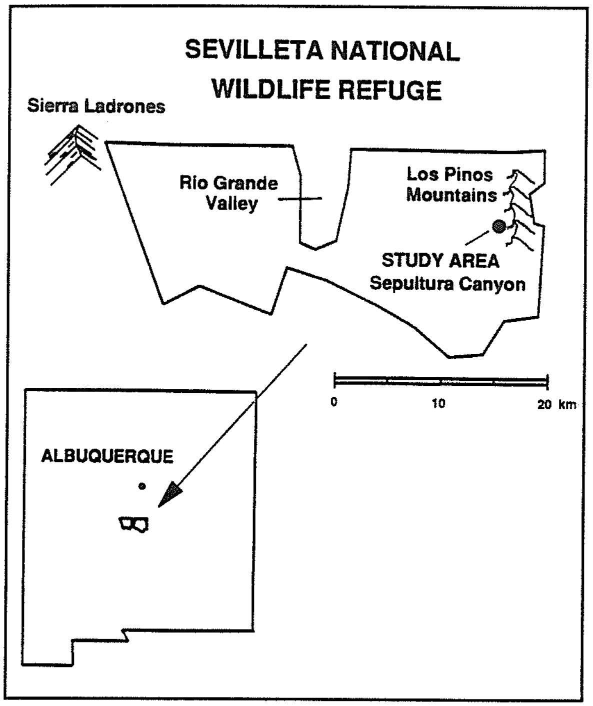

Figure 1. Location of the sludge application study within the Sevilleta National Wildlife Refuge.

Climate at the Sevilleta National Wildlife Refuge is arid to semiarid with mean annual precipitation ranging from 200 to 250 mm (personal communication, Doug Moore, Research Associate, Dept. of Biology, University of New Mexico, Sevilleta Refuge LTER Meteorological Investigations). Summers are relatively hot and winters are cool. Vegetation within the refuge is dominated by semiarid grassland and shrubland at low elevations in the Rio Grande Valley. Pinyon-juniper stands dominate the vegetation at high elevations.

The soils at the study site have been mapped as components of the Harvey-Dean association, 1%-9% slopes (U.S.D.A. Soil Conservation Service 1988). The Harvey and Dean soils are both deep and well drained. The Harvey soil is classified as fine-loamy, mixed, mesic Ustollic Calciorthid; the Dean soil is classified as fine-loamy, carbonatic, mesic Ustollic Calciorthid. The soils are formed in alluvium and colluvium derived primarily from limestone, and both have been strongly influenced by eolian processes. Surface soil textures range from gravelly fine sandy loam to very fine sandy loam. Subsoil horizons range in texture from sandy clay loam to gravelly loam.

STUDY DESIGN

Within the Sevilleta Refuge, a blue grama/hairy grama (*Bouteloua gracilis/B. hirsuta*) dominated community was selected for study on both a moderately sloping and strongly sloping component of a stable alluvial fan. The site is located along the flanks of the Los Pinos Mountains at the mouth of Sepultura Canyon (Fig. 1). Three pairs of runoff plots, each consisting of a treated (sludge-amended) and a control (no sludge) plot, 10-m long and 3-m wide, were established within each of the slope gradient classes (Fig. 2). The three paired plots established at the lower component of the landscape (6% slope gradient) were designated as 1L-T (for treated or sludge-amended) and 1L-C (for control), 2L-T and 2L-C, and 3L-T and 3L-C. The three paired plots located in the upper (high) portion of the study area (10%-11% slope gradient) were designated as plots 1H-T and 1H-C, 2H-T and 2H-C, and 3H-T and 3H-C.

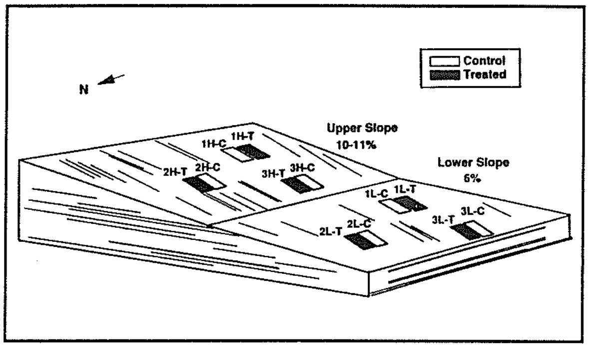

Figure 2. Experimental layout of sewage sludge-amended plots (treated) and unamended (control) plots within two landscape components at the Sevilleta Refuge study site. (not to scale)

The sludge treatment, applied in early April 1991, consisted of a one-time surface amendment of 45 Mg ha^{-1} (20 t $acre^{-1}$ on an oven-dry basis) of municipal sewage sludge provided by the City of Albuquerque. The City's anaerobically digested and mechanically de-watered sewage sludge, at approximately 17% dry solids (82.5% water), is gelatinous and thus relatively easy to transport and handle.

The plots were bordered by 15-cm (6-inch) aluminum flashing to exclude external runoff. Runoff within the borders was collected in reservoirs (galvanized steel livestock tanks, 1800-liter capacity) buried at the base of the plots. The tanks were positioned with a 1% drop in slope across the base of the plot to facilitate water measurements and sampling following small runoff events. Soil was back-filled and tamped around each tank. Gaps between plot boundaries and tank edges were lined with concrete to prevent leakage and loss of runoff water. Each tank was calibrated by recording the level of water in the tank at each sequential addition of a known amount of water. Water-sealed plywood lids were placed over the tanks to prevent direct precipitation into the tanks and minimize evaporation following rainfall events.

Total precipitation occurring during summer storms was measured with two standard rain gauges (rainfall collection buckets). Additionally, a self-activating recording rain gauge was installed at the site on August 1, 1991, allowing measurements of storm intensity (mm hr^{-1}) for subsequent events.

A large rainfall simulator was used in September 1991 to allow observations of response to high-intensity rainfall under controlled conditions (Ward 1986). The rainfall simulator consisted of 15 sprinklers mounted on 3-m standpipes. The simulator distributed water simultaneously to each plot in a pair so infiltration and runoff yield could be observed and recorded on the two plots concurrently.

We evaluated the sludge's water absorption capability during the rainfall simulation by placing 30 g to 50 g of air-dry sludge on five 30-cm^2 screen mesh platforms located along the plot boundaries; the samples received the same amount of precipitation as the plots. The samples were collected immediately after the rainfall simulation runs and placed in airtight tin containers. Five additional sludge samples were collected before rainfall simulation to assess the field moisture content of the sludge prior to wetting.

Samples of runoff water, obtained after stirring the contents in the collection reservoirs to uniformity, were collected in acid-washed plastic bottles after each major rainfall event and immediately following each rainfall simulation run. The samples were then transported to the lab in an ice chest for subsequent nitrate and metal analyses. Samples tested for nitrate were preserved with concentrated sulfuric acid (2.0 ml H_2SO_4 per liter of water sample) and those tested for metal concentrations were preserved with concentrated nitric acid (5.0 ml

HNO_3^- per liter of water sample). All water samples were analyzed within 28 days after collection.

Nitrate in water samples was determined by flow injection analysis according to the colorimetric Cd-reduction method (APHA 1985). Concentrations of Cu, Cd, and Pb were determined by inductively coupled plasma emission spectroscopy (ICP).

Repeated measures analysis of variance was used to compare observed differences in runoff yield, nitrate levels, and trace element concentrations in the runoff water between slope gradients and between treated and control plots. Paired treated and control plots were designated as repeated measures (to incorporate the pairing structure into the analysis) and slope gradient was treated as an analysis of variance factor. A Type I error α = 0.1 was adopted for all analyses.

RESULTS AND DISCUSSION

Runoff Produced by Natural Storms

We recorded runoff from four natural storm events of high intensity during July and August 1991 (Table 1). Storm duration measurements for July are not available because self-activating recording rain gauges had not yet been installed. Quantities of runoff generated from the study plots during the four natural storm events are also shown in Table 1.

Table 1. Natural storm characteristics and runoff yields at the Sevilleta National Wildlife Refuge sludge study area, 1991.

Storm date	July 22	July 25	Aug 2	Aug 10
Storm Characteristics:				
Total Precipitation (mm)	12.7	9.7	18.5	12.7
Storm duration (min)	--	--	120.0	30.0
Storm intensity (mm hr^{-1})	--	--	9.3	25.4
Plot	Runoff yield (mm)			
1L-C	0.09	0.45	0.37	1.12
1L-T	0.00	0.00	0.00	0.00
2L-C	0.00	0.19	0.02	0.93
2L-T	0.00	0.07	0.02	0.03
3L-C	0.04	0.45	0.09	0.43
3L-T	0.00	0.02	0.04	0.04
1H-C	0.02	1.12	0.12	0.71
1H-T	0.00	0.53	0.00	0.00
2H-C	0.00	0.73	0.06	0.48
2H-T	0.00	0.41	0.00	0.05
3H-C	0.08	0.99	0.21	0.80
3H-T	0.01	0.12	0.00	0.00

An analysis of variance comparing runoff yields among plot pairs using slope gradient as the variable found no significant differences ($p \geq 0.1$) based on slope class, except for the July 25 storm (Table 2). However, comparison between treated and control plots clearly shows the sludge's effectiveness in reducing runoff.

Differences in runoff yield among control plots within the two slope gradients were attributed to differences in resistance to surface water flow brought about by microtopographical variation and differences in plant cover. The major factor responsible for the reduced runoff in the sludge-amended plots was apparently an increase in surface roughness. This increased surface roughness greatly reduced surface water flow and likely enhanced infiltration.

Mean runoff yield on control and treated plots for the four natural storm events are plotted in Figure 3. The control and treated plots were significantly different at $p < 0.05$ for all storms except the July 22 event, wherein the large variance among the six control plots reduced the significance level to $p = 0.09$.

Differences in runoff yield among the four natural storms were attributed primarily to variations in storm intensity. Mean runoff yield from the control plots during the August 10 storm was more than five times greater than that produced during the August 2 storm (Fig. 3), yet the August 2 storm was higher in total precipitation (Table 1). The sludge's effectiveness at reducing runoff is evident here in that the difference in mean runoff from the treated plots was only two times greater during the August 10 storm than during the August 2 storm (Fig. 3).

Antecedent soil moisture contents highly influence infiltration and runoff yield, and this factor is likely responsible for the greater quantity of runoff from the treated plots on July 25; this storm was preceded by 27.9 mm of rainfall on July 21 and 12.7 mm precipitation on July 22. Unlike conditions prior to the other three natural storms, the sludge on the treated plots may have been fairly moist upon the onset of the July 25 event; thus, runoff from the sludge-amended plots was appreciably higher during this storm.

Runoff Produced by Rainfall Simulation

Total precipitation inputs and intensities for the rainfall simulation experiments were much

Table 2. Means and variance for the 1991 natural storm runoff yields from the three upper (10%-11% slope) and three lower (6% slope) landscape segments of the sludge application study site.

Storm	Slope Segment	Mean Runoff (mm)	SD	SE
Control plots:				
July 22	Low	0.043a[1]	0.045	0.026
	High	0.033a	0.416	0.024
July 25	Low	0.363a	0.150	0.087
	High	0.947b	0.199	0.115
Aug. 2	Low	0.160a	0.185	0.107
	High	0.130a	0.076	0.044
Aug. 10	Low	0.827a	0.356	0.206
	High	0.663a	0.165	0.095
Sludge-amended plots:				
July 22	Low	0.000a	0.000	0.000
	High	0.003a	0.006	0.003
July 25	Low	0.030a	0.036	0.021
	High	0.353b	0.211	0.122
Aug. 2	Low	0.020a	0.020	0.012
	High	0.000a	0.000	0.000
Aug. 10	Low	0.023a	0.021	0.012
	High	0.017a	0.029	0.017

[1] Paired means followed by same letter are not significantly different at the 0.10 level.

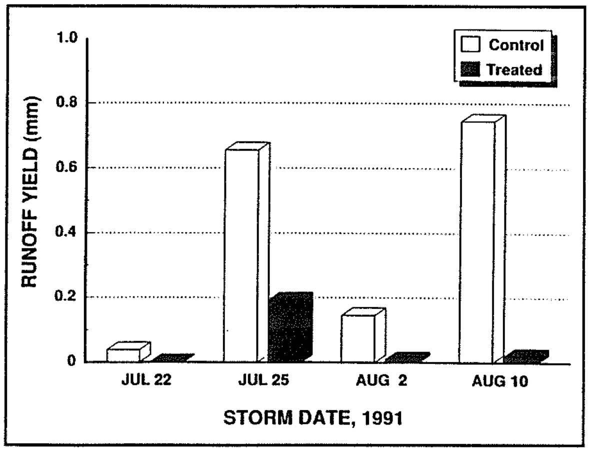

Figure 3. Mean runoff yield from all treated ($n=6$) versus all control plots ($n=6$) during four natural storm events in 1991. (Note: differences in mean runoff between control and treated plots were significant at $p<0.05$ for all storms except the July 22 event, wherein $p=0.09$).

higher than those for the natural storms because we wanted to evaluate the effects of the higher precipitation quantities and intensities that can commonly occur in this region (Table 3). Mechanical pump problems prevented application of similar amounts of rainfall over a 30-minute interval on all plots. Consequently, precipitation on plots 2H-C and 2H-T, though only slightly lower in total amount than that applied to other plots, was interrupted during the 30-minute simulation run. Simulated rainfall on plots 1H-C and 1H-T was terminated after 13 minutes. However, the data from these two rainfall simulation experiments, though not statistically comparable to the remaining trials, provide valuable information on plot response to intermittent rainfall and short-duration rainfall, respectively. Differences in total precipitation

Table 3. Precipitation input (Ppt.), storm duration, and runoff produced by rainfall simulation on sludge-amended (T) and unamended (C) plots in September, 1991. Ratio of runoff quantity (mm) to total precipitation input (mm) standardizes runoff yields among all plots.

Plot No.	Ppt. Input (mm)	Duration (min.)	Runoff (mm)	Runoff/ppt. (mm/mm)	Runoff Yield %
1L-C	43.0	30	9.20	0.214	21.4
1L-T	49.0	30	0.29	0.006	0.6
2L-C	49.0	30	14.00	0.286	28.6
2L-T	50.0	30	0.00	0.000	0.0
3L-C	42.0	30	4.00	0.095	9.5
3L-T	33.0	30	0.20	0.006	0.6
1H-C	13.0	13	0.70	0.054	5.4
1H-T	18.0	13	0.04	0.002	0.3
2H-C	35.0	30	6.40	0.183	18.3
2H-T	39.0	30	0.20	0.005	0.5
3H-C	53.0	30	13.00	0.245	24.5
3H-T	50.0	30	0.40	0.008	0.8

among and within the other paired plots treated with continuous 30-minute simulated rainfall were due to the presence or absence of wind gusts, their prevailing directions, and velocities.

Quantities of runoff generated from control plots during the rainfall simulation runs were generally an order of magnitude greater than the quantities generated during the natural storms. For example, the August 10 storm generated an average of 0.82-mm runoff in 30 minutes for plots 1L-C, 2L-C, 3L-C, and 3H-C (Table 1). Increasing precipitation three to four times (40 mm - 50 mm) over the same time period during the simulation runs resulted in an average of 10.0-mm runoff for these four plots (Table 3), indicating a nonlinear increase in runoff yield in relation to increased precipitation for the control plots.

Quantities of runoff generated during the rainfall simulation runs were divided by the total amount of precipitation input on each plot in order to calculate the quantity of runoff produced per millimeter of rainfall (Table 3). Expression of runoff yield per millimeter of rainfall standardizes runoff yields for comparison between plots (treated vs. control) and among plot pairs within a given slope class or across the entire landscape. A highly significant difference in runoff yield per millimeter of precipitation was observed between the six control and six treated plots (Fig. 4).

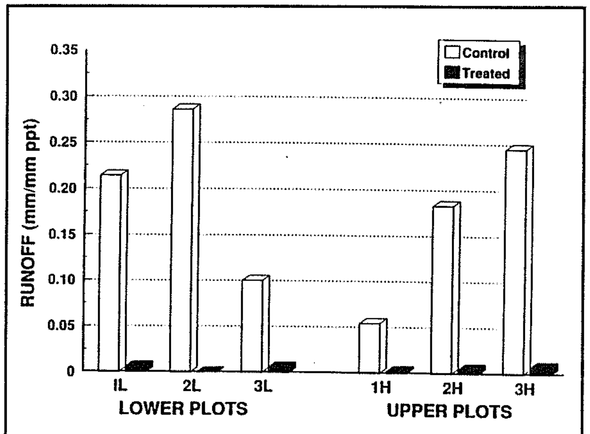

Figure 4. Runoff yield from sludge-amended (treated) and unamended (control) plots during rainfall simulation runs. Experession of runoff yield as runoff (mm) per millimeter of precipitation standardizes the runoff yields for comparison among plots because there were differences in total precipitation input among plot pairs and between paired plots. (Note: difference in runoff yield (mm runoff/mm precipitation) between treated ($n=6$) and control ($n=6$) plots was highly significant at $p=0.005$.)

The proportion of total precipitation input lost as runoff from the control plots ranged from 5.4% for plot 1H-C to 28.6% for plot 2L-C (Table 3). As with natural rainfall, an increasingly higher proportion of runoff per unit quantity of precipitation can be expected from the control plots as precipitation is increased. In contrast, the proportion of the total precipitation input that was lost as runoff on sludge-amended plots remained below 1% for all simulation runs. The sludge appears to have reduced runoff yield to the extent that slight differences observed among the treated plots were independent of total precipitation input or storm duration (Table 3). The small differences in runoff yield (mm/mm ppt) among the treated plots were likely due to differences in microtopography and ground cover (Fig. 4).

Water Absorption by Sludge

Water absorption by sludge (Table 4) was also found to be a contributing factor to the reduced runoff from treated plots. Average increases in percent water in sludge samples were 83% and 105% for plots 1H-C and 1H-T and plots 2H-C and 2H-T, respectively. Using these average increases in

Table 4. Water absorption by sludge during rainfall simulation on plots 1H-C and 1H-T and plots 2H-C and 2H-T. Five samples of sludge at field moisture conditions were collected before (Pre-T) and after (T) the simulated rainfall to determine the percent water absorbed by the sludge.

Sample	Rep.	Weight (g) Oven-dry	Weight (g) Wet	Water(%)
Plots 1H-C and 1H-T (average precipitation for plot pair = 15 mm):				
Pre-T	1	88.90	94.30	6.07
Pre-T	2	107.27	113.79	6.08
Pre-T	3	97.19	103.11	6.09
Pre-T	4	90.85	96.42	6.13
Pre-T	5	85.90	90.40	6.24
			Mean:	**6.12**
T	1	85.22	150.30	76.37
T	2	65.95	122.68	86.02
T	3	75.66	147.09	94.41
T	4	67.81	129.31	90.69
T	5	51.33	102.26	99.22
			Mean:	**89.34**
Plots 2H-C and 2H-T (average precipitation for plot pair = 37.0 mm):				
Pre-T	1	40.75	43.99	7.95
Pre-T	2	76.33	82.22	7.72
Pre-T	3	68.47	73.93	7.97
Pre-T	4	67.92	73.17	7.73
Pre-T	5	95.77	103.34	7.90
			Mean:	**7.86**
T	1	81.72	168.53	106.23[1]
T	2	69.66	147.62	111.92
T	3	77.69	174.46	124.56
T	4	79.31	171.96	116.82
T	5	75.90	155.66	105.09
			Mean:	**112.92**

[1] Sludge water content can exceed 100% because the water is expressed as a percentage of the sludge's oven-dry weight and organic matter can readily hold 2-3 times its dry weight in water.

sludge water content, we estimated the portion of total plot precipitation absorbed by the sludge during the two rainfall simulation trials to be 13% and 25% for plots 2H-T and 1H-T, respectively. These relationships indicate retention of a larger proportion of total precipitation input by sludge during smaller rainfall events.

Nitrate and Heavy Metal Concentrations in Runoff

Nitrate concentrations in runoff water collected from natural storms and the simulated rainfall were consistently well below the recommended standard for groundwater or stream water supplies (Table 5). Current New Mexico standards consider ≥10 mg l^{-1} nitrate discharge as unacceptable (New Mexico Water Quality Control Commission 1991a). The higher nitrate concentrations in runoff collected after rainfall simulation were likely due to external nitrate inputs and may have been associated with litter and/or sediment in the water supply tanks or rainfall simulation equipment such as hoses, standpipes, and sprinklers. No significant differences were found when comparing mean nitrate concentrations in the runoff from treated plots with nitrate concentrations in runoff collected from control plots after natural storms and rainfall simulations. These results indicate that the sewage sludge did not introduce significant nitrate levels to runoff water.

New Mexico standards for groundwater allow ≤ 0.01 mg l^{-1} Cd and ≤ 1.0 mg l^{-1} Cu (New Mexico Water Quality Control Commission 1991a) and ≤ 0.05 mg l^{-1} Cd and ≤ 0.5 mg l^{-1} Cu for livestock and wildlife watering (New Mexico Water Quality Control Commission 1991b). Cd and Cu in runoff were well below these standards, with the exception of the slightly elevated Cd concentration in runoff collected from Plot 1A High (control) after the July 25 storm (Table 6). However, we found no significant differences between mean Cd and Cu concentrations in the six treated versus control plots, indicating that Cd and Cu contamination to surface water runoff from the added sludge is not a concern.

We measured Pb concentrations exceeding current New Mexico standards for groundwater (0.05 mg l^{-1}) and livestock and wildlife watering (0.1 mg l^{-1}), but could not attribute such Pb levels to the sludge (Table 6). We found no significant difference between the Pb concentrations in runoff collected from the sludge-amended plots and the runoff from the control plots for any of the precipitation events, including the rainfall simulation. The elevated Pb levels in the runoff water may either be attributable to elevated Pb in the soils or to Pb solubilization from the galvanized steel runoff collection tanks.

Table 5. Nitrate concentrations (mg l^{-1}) in runoff water collected from sewage sludge-amended (T) versus unamended (C) plots at the Sevilleta National Wildlife Refuge following natural and simulated rainfall events, 1991. Runoff samples were not collected for chemical analysis on July 22.

Plot	July 25	August 2	August 10	Simulation
1L-C	0.018	0.004	0.005	0.295
1L-T	0.046	0.008	0.004	0.396
2L-C	0.026	0.004	0.095	0.620
2L-T	0.026	0.004	0.094	0.552
3L-C	0.019	0.006	0.027	0.284
3L-T	0.023	0.007	0.094	0.209
1H-C	0.062	0.007	0.008	0.343
1H-T	0.023	0.086	0.007	0.595
2H-C	0.002	0.004	0.008	0.383
2H-T	0.006	0.009	0.007	1.037
3H-C	0.072	0.059	0.006	0.000
3H-T	0.018	0.068	0.007	0.253

Table 6. Concentrations (mg l^{-1}) of Cd, Cu, and Pb in runoff collected from sludge-amended (T) and untreated (C) plots at the Sevilleta Wildlife Refuge, 1991. Mean Pb concentrations between treated ($n=6$) and control ($n=6$) plots were not significantly different at $p < 0.10$ for any of the precipitation events, including rainfall simulation.

PLOT	Cd	Cu	Pb	Cd	Cu	Pb
	July 25 Storm			August 2 Storm		
1L-C	<0.005	<0.02	0.31	<0.005	<0.02	0.11
1L-T	<0.005	<0.02	0.36	<0.005	<0.02	0.25
2L-C	0.005	<0.02	0.21	<0.005	<0.02	<0.05
2L-T	<0.005	<0.02	0.26	<0.005	<0.02	<0.05
3L-C	<0.005	<0.02	0.19	<0.005	<0.02	<0.05
3L-T	0.008	<0.02	0.48	<0.005	<0.02	<0.05
1H-C	0.016	0.02	0.47	<0.005	<0.02	0.09
1H-T	<0.005	<0.02	0.23	<0.005	<0.02	0.24
2H-C	<0.005	<0.02	0.66	<0.005	<0.02	0.10
2H-T	<0.005	<0.02	0.82	<0.005	<0.02	<0.05
3H-C	<0.005	<0.02	0.34	<0.005	<0.02	0.07
3H-T	<0.005	<0.02	0.37	<0.005	<0.02	0.25
	August 10 Storm			September Rainfall Simulation		
1L-C	<0.005	<0.02	0.13	<0.005	<0.02	<0.05
1L-T	<0.005	<0.02	0.20	<0.005	<0.02	0.13
2L-C	<0.005	<0.02	<0.21	<0.005	<0.02	0.40
2L-T	<0.005	0.52	2.52	<0.005	<0.02	0.11
3L-C	<0.005	<0.02	0.16	<0.005	<0.02	0.11
3L-T	<0.005	<0.02	0.05	<0.005	<0.02	0.17
1H-C	<0.005	<0.02	0.10	<0.005	<0.02	0.13
1H-T	<0.005	<0.02	0.39	<0.005	<0.02	0.13
2H-C	<0.005	<0.02	0.16	<0.005	<0.02	0.12
2H-T	<0.005	<0.02	0.14	<0.005	<0.02	0.21
3H-C	<0.005	<0.02	0.16	<0.005	<0.02	<0.05
3H-T	<0.005	<0.05	0.46	<0.005	<0.02	<0.05

SUMMARY AND CONCLUSIONS

We conclude that surface application of treated municipal sewage sludge can significantly reduce runoff in semiarid grasslands. The two factors we considered most important for the reduction in runoff yield are increased ground surface roughness and absorption of water by the dry sludge.

Runoff yields were greatest during high-intensity storm events. Runoff rates from the control plots increased progressively with increased precipitation and storm duration. Yet a similar pattern was not observed in the sludge-amended plots, wherein the proportion of total precipitation lost from the plots as runoff remained under 1% of the input regardless of total precipitation and storm duration.

Potential contamination of surface water by constituents in the sludge does not appear to be a limitation for sludge application as a fertilizer and mulch amendment in this environment. Nitrate, Cu, and Cd concentrations in the runoff water were well below established New Mexico groundwater and livestock and wildlife watering standards, and we found no statistical differences in these potentially toxic constituents between sludge-amended and control plots. Although we detected Pb concentrations exceeding current New Mexico standards for groundwater and livestock and wildlife watering after some storms, we found no significant difference between the mean Pb concentrations in runoff from treated and control plots.

ACKNOWLEDGMENTS

This study was funded by the 1991 New Mexico Water Resources Research Institute (WRRI) - Chino Mines Company Grant Fund. We express sincere gratitude to both WRRI and the Chino Mines Company for supporting this research. We also thank the City of Albuquerque for supplying and transporting the sludge to the study area. Gratitude is extended to Theodore Stans, Refuge Manager, Sevilleta National Wildlife Refuge, and the U.S. Fish and Wildlife Service for allowing us to conduct this research at the refuge. We also thank Dr. Timothy Ward and Dr. Susan Bolton, Department of Civil, Agricultural and Geological Engineering, New Mexico State University, for their assistance with the rainfall simulation component of this research.

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