

## Research Article

# Influence of Surface Biosolids Application on Infiltration

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Biosolids from waste water treatment facilities applied to soils not only add plant nutrients, but also increase infiltration and decrease runoff and erosion. Wet biosolids from New York, NY, were surface applied at 0 to 90 Mg ha<sup>-1</sup> dry weight to soils near El Paso, Tex. Simulated rainfall intensities of 16.4 cm hr<sup>-1</sup> for 30 minutes applied to 0.5 m<sup>2</sup> soil plots yielded initial infiltration rates of ~16 cm hr<sup>-1</sup> for all plots. Biosolids applications extended the duration of the initially high infiltration rates. After 30 minutes, infiltration rates for bare soil were 3 cm hr<sup>-1</sup> without and 10 cm hr<sup>-1</sup> with 90 Mg biosolids ha<sup>-1</sup>. Applied biosolids, plant litter, surface gravel, and plant base contributed surface cover, which absorbed raindrop energy and reduced erosion. Biosolids increased cumulative infiltration on the vegetated, wet soils more than for the dry or bare soils. Biosolids increased cumulative infiltration from 2 to 6 cm on a bare gravelly soil and from 9.3 to 10.6 cm on a vegetated soil.

## 1. Introduction

Throughout history, human waste from raw to highly treated waste has been applied to soils by various methods. In the United States, Congress passed the Federal Water Pollution Control Act in 1948, which governed the release of waters and solids into the environment. This act codified raw sewage treatment in publicly owned treatment works (POTWs), where water is removed and residual solids yield sewage sludge. Industrial waste streams are separated from domestic waste to produce much cleaner wastewater solid residuals. The current term for wastewater solid residuals is “biosolids”, which is a term coined by the Water Environment Federation. While biosolids have positive nutrient and hydrologic properties, biosolids were often considered a waste product to be discarded. One method of discarding biosolids was by ocean dumping. The Ocean Dumping Ban Act of 1988 as the name implies, forbid biosolids disposal in the ocean and increased biosolids competition for landfill disposal.

Changing the name from “sewage sludge” to the more benign term “biosolids” eased the way for beneficial land applications of biosolids. Biosolids are composed of water, organic matter, and inorganic matter. Water accounts for 60% to 80% of the mass in dewatered biosolids. The dry solids of anaerobically digested biosolids are about 60% organic matter [1]. The biosolids organic fraction is composed of relatively stable organic compounds that resist oxidation in the anaerobic digestion process. The organic matter in biosolids is a source of slow release nitrogen from the breakdown of amino acids. The clean biosolids produced by POTWs are now being used for beneficial purposes, such as land application for nutrients [2]. Proper biosolids applications can improve soil quality and plant production. With recent increases in biosolids land application, a better understanding of the impact of biosolids on soil physical properties is needed.

Biosolids have been used for years as a soil amendment in mine and disturbed land reclamation and in crop, pasture,

forest, and range production. Biosolids application not only adds nutrients, but also affects hydrology. Soil quality is appreciably improved in a number of land use settings. Mine and disturbed land reclamation pose a significant challenge in transforming spoils into soil. Biosolids have generally improved reclamation efforts across the USA [3]. Meyer et al. [4] reported increased plant cover and less erosion due to biosolids applications after a forest fire.

The hydrologic effects of biosolids on infiltration and erosion have been documented in numerous rangeland settings worldwide. In central Spain, Walter et al. [5] reported favorable soil and vegetation resulted from the decreased erosion and enhanced water relations that resulted from applications of 40 to 80 Mg biosolids ha<sup>-1</sup>. Ojeda et al. [6] reported similar results in north-east Spain using fresh biosolids, composted biosolids, and thermally dried biosolids.

Interception is water absorbed by vegetation or litter (biosolids included), which is subtracted from gross precipitation to give net precipitation. Intercepted water does not infiltrate the soil or run off and the hydrologic importance of interception depends on climatic, soil physical, and vegetative characteristics. Harris-Pierce et al. [7] and Aguilar and Loftin [8, 9] evaluated the relationships between biosolids application rates, infiltration, and erosion in semi-arid grasslands. Harris-Pierce et al. [7] reported that the quantity of runoff was unaffected by biosolids application rate. Aguilar and Loftin [8, 9] evaluated the effects of biosolids on the quantity of runoff water under both natural and simulated conditions. They reported that only one of four natural storms yielded significantly different runoff quantities between slope gradients. Mean runoff, however, was significantly different between biosolids-treated plots and untreated plots for all but one storm. Aguilar and Loftin [9] attributed the reduction in runoff with biosolids application to increased surface roughness. Aguilar and Loftin [8, 9] conducted additional simulated rainfall experiments, and significant differences in runoff were due to differences in soil water content.

The above articles evaluated the relationships between surface applied biosolids and infiltration but do not address infiltration properties and characteristics. Infiltration and surface runoff are the two dominant methods of water loss from precipitation and irrigation. With the use of a rainfall simulator, the excess runoff becomes what is known as "Horton" flow after Horton [10]. This differs from interpedal water flow which occurs within a pedon. The infiltration and redistribution of water takes three stages [11]. These stages are as follows: Stage I in which the soil takes in water as fast as it is applied and is known as "flux-controlled" infiltration [11]. Stage II is known as "profile-controlled" and as the name implies is controlled by the soil profile characteristics. These profile characteristics are determined by soil texture, soil depth, bulk density, and pore size, distribution, and arrangement. The final stage, III, is controlled by the final soil hydraulic conductivity and is a constant-value soil parameter not related to surface conditions.

Infiltration can be modeled using the Green and Ampt [12] equation. This century-old equation relates infiltration

rate to stage III infiltration, hydraulic conductivity, and cumulative infiltration using an arbitrary soil constant. The interactions between infiltration (infiltrability Hillel [11]) parameters can be characterized using the Green and Ampt [12] equation cited by Hillel as follows:

$$i = i_c + \frac{b}{I}, \quad (1)$$

where  $i$  is infiltrability (Hillel's term) or infiltration rate cm hr<sup>-1</sup>,  $i_c$  is the final infiltration rate, cm hr<sup>-1</sup>,  $b$  is an arbitrary constant of infiltration, cm<sup>2</sup> hr<sup>-1</sup>, and  $I$  is the cumulative infiltration, cm.

Using the computed Green and Ampt "b" constant, surface alterations caused by antecedent water content, surface vegetation, or lack of vegetation, and gravel as well as biosolids can be used to compare and contrast the effects of surface application of biosolids on semiarid rangelands.

Extensive studies have evaluated biosolids application and soil physical properties at the Sierra Blanca Ranch [13–16]. All of these studies utilized biosolids transported by rail from New York, NY, to improve rangeland conditions in West Texas.

The overall objective of the research described below was to document the beneficial use of biosolids to improve soil physical properties by enhancing infiltration and, thereby, decrease surface runoff and erosion. Specific objectives were to evaluate the effects of: (1) antecedent soil-water content, (2) vegetative cover, and (3) gravel cover on infiltration and erosion as a function of biosolids application rate.

## 2. Materials and Methods

The study site was located within the northern Chihuahuan Desert in Hudspeth County, Texas. The experiments were conducted on the Sierra Blanca Ranch located 140 km southeast of El Paso, Texas, immediately north of Interstate Highway 10 [16]. The site is a typical northern Chihuahuan desert with grassland vegetation on basin floors and desert scrub on fan piedmonts. The climate of the area is subtropical semiarid with 308 mm annual precipitation, two thirds of which falls during the months of July through September [13]. The regional precipitation exhibits large interannual variations that range from 110 to 430 mm and average 308 mm [13]. Sixty-six percent of the annual precipitation comes as intense, short-duration, convective storms during the summer months. Average air temperatures are 4.9°C in January and 25.3°C in July.

The dominant soil evaluated was the Stellar very fine sandy loam, 1% to 3% slope (fine, mixed, superactive, thermic Ustic Calcicgids). Soil particle size distribution differences between the bare and vegetated Stellar sites are significant in the crust layer and A horizon [13]. Crust layer texture for bare Stellar is loam, but it is within 1% sand of being very fine sandy loam. The particle size class for the crust layer in vegetated treatments and A horizon for both cover condition treatments is very fine sandy loam. Cover treatments differ in distribution of the separates in the crust and A horizon [13]. Erosion and deposition processes likely cause surface sealing that form the crust. The A

horizon below the crust is not as influenced by erosion and deposition. A second soil evaluated was the Chilicotol very fine sandy loam 1 to 3% slope (loamy-skeletal, mixed, superactive thermic Ustic Haplocalcids). The Chilicotol soil horizons differed little with clay content gradually increasing with depth [13]. While the mean particle size increased monotonically from 168 mm in the crust to 125 mm in the Bw1 horizon, all horizons of the Chilicotol soil are very fine sandy loam. The dominate vegetation was a typical desert grassland and was classified as a Loamy Range site with 5% basal cover, 69% bare ground and only 3% gravel cover.

Surface cover includes litter, gravel, plant base, dead plant base, and microphyte. Biosolids application contributes to cover. Surface cover parameters for the Chilicotol site differed from the Stellar site regardless of cover treatment. In the control bare Stellar treatments, 80% of the ground surface was unprotected (data not presented), but in the vegetated Stellar treatments, only 29% of the ground surface was unprotected. The Chilicotol site had little vegetation with ~50% of the ground surface unprotected and with gravel accounting for 48% of the ground cover. The bare Stellar soil had approximately 9% gravel as ground cover compared to the vegetated Stellar soil with 1% gravel surface cover. Litter provided cover for 2% of the ground surface in Chilicotol and 6% in bare Stellar. This level of cover was provided by 142 kg litter ha<sup>-1</sup> in the bare Chilicotol and 100 kg ha<sup>-1</sup> in the bare Stellar. The litter on the Chilicotol soil was generally creosote bush (*Larrea tridentata*) twigs that have a higher density than the grass- and forb-derived litter on the Stellar site. Sixty-three percent of the ground surface was protected by 1560 kg litter ha<sup>-1</sup> in vegetated Stellar treatments and 5% of ground surface cover was from plant bases.

Differences between vegetated and bare treatments may be due also to a physical interaction between biosolids and vegetation. Biosolids may have been suspended by vegetation above the ground surface and held together by the supporting force of adjacent plant stems and leaves. Bare Stellar plots had an average standing crop biomass of 56 kg ha<sup>-1</sup>, while the vegetated plots had 4200 kg ha<sup>-1</sup> standing crop biomass. Chilicotol plots had an average standing crop biomass of 52 kg ha<sup>-1</sup>. Standing crop for bare Stellar and Chilicotol treatments resulted from unwelcome plants at the plot boundaries.

Litter also differed between soils although biosolids application rate had a significant effect on litter and this is likely an artifact of the technique. The vegetated plots without biosolids had 1560 kg litter ha<sup>-1</sup>, whereas the 90 Mg biosolids ha<sup>-1</sup> plots had only 1020 kg litter ha<sup>-1</sup>. The difficulty in separating litter from biosolids may account for this difference. Most of the litter was beneath biosolids in the vegetated treatments. In bare treatments, the control treatments had very minor litter (100 kg litter ha<sup>-1</sup>). For the 90 Mg biosolids ha<sup>-1</sup> plots, the biosolids provided additional wind resistance which facilitated the accumulation of windblown litter. The total quantity of windblown litter, however, was small; it accumulated on top of biosolids, and it was not difficult to separate. Vegetated treatments had an average 59% canopy cover, whereas bare treatments had approximately 1% canopy cover. The canopy cover for the

90 Mg biosolids ha<sup>-1</sup> rate was reduced from 62% to 49% for the control treatments. This was due to partial burial of the plant canopy at this high application rate.

The study plots were not clipped prior to surface application of biosolids or rainfall simulation. Biosolids were applied only once, and the growing-season rainfall during the study was below average. Wet biosolids were surface applied at rates of 0, 7, 18, 34, or 90 Mg biosolids ha<sup>-1</sup> on an equivalent dry-weight basis. Biosolids depth and percent surface area covered by biosolids depended on application rate and increased when the application rate was increased. On average, 90 Mg biosolids ha<sup>-1</sup> provided 69% surface cover at a depth of 20 mm. Specific depth and surface area coverage for this site were presented in Moffet et al. [13].

The simulated rainfall was applied as described by Moffet et al. [13]. Briefly, a portable single-nozzle rainfall simulator was placed 2 m above the soil surface. A tarp was placed around the simulator to protect the simulated rainfall from disturbance by the wind. A nozzle pressure of 20.7 kPa (3 psi) was maintained during simulation to produce a mean rainfall intensity of 16.4 cm hr<sup>-1</sup> on a 0.5 m<sup>2</sup> plot. Median drop size was between 1.2 and 2 mm with the largest drops concentrated in the center of the plot. The water was moderately alkaline with a pH of approximately 8.2, an electrical conductivity of 0.7 dS m<sup>-1</sup>, total dissolved solids of 444 mg L<sup>-1</sup>, and a sodium absorption ratio of 6.7 [13].

A square 0.5-m<sup>2</sup> steel frame was positioned on each plot and driven into the ground, which bounded the plot edges on three sides. The fourth side of the frame, set on the lowest edge of the plot, was flush with the soil surface and was fitted with a runoff collection pan. The runoff collection pan was sheltered from the rain but allowed the plot runoff water to flow to the lowest corner of the pan.

The rainfall simulator was positioned on each plot, and a thirty-minute rainfall was simulated. The simulated rainfall was first applied to ("dry") plots at rates approximating 16 cm hr<sup>-1</sup> and runoff was collected to determine the infiltration rate. The next day, simulated rainfall was again applied to the same plots, and these observations were labeled "wet." For both the dry and wet conditions, surface runoff was collected as a function of time. Runoff water that collected in the lowest corner of the collection pan was transferred through a nylon hose and suction pumped to a graduated cylinder. The volume was then recorded for each period. Runoff was measured and recorded every 2.5 minutes for the first ten minutes and every five minutes for the remaining 20 minutes. The difference in runoff and applied rainfall for each period was the infiltration for that period with infiltration divided by time being the infiltration flux.

The applied rainfall volume was estimated for each plot. At the end of the 30-minute simulation period, a calibration pan with the exact dimensions of the runoff plot was placed over the plot for a period of five minutes. At the end of the 5-minute period, the simulator was shut off, and the volume of water collected in the calibration pan was measured. The values for each plot rained on in a day were averaged, and the average was used as the estimate for all plots measured that day.

The simulated rainfall experiments required between 47 and 66 days to complete for each soil. Both wet and dry (antecedent soil water) conditions were run on 100 Stellar plots for a total of 200 observations. Only 47 days were needed to complete the 60 Chilicotol plots, since there were no antecedent soil water treatments.

Data that address the effects of antecedent soil water contents on infiltration flux, infiltration, and erosion were collected from the Stellar site. The alpha-level degree of certainty for conclusions drawn from  $F$ -tests in an analysis of variance depended on how well the assumptions were met. The assumptions made in an ANOVA generally deal with the shape of the treatment observation distribution about the mean, the dispersion homogeneity among treatments or treatment differences, and, lastly, that the treatment population is representative of the whole population. Tests may be used to determine how well these assumptions are met.

One of the most basic assumptions of parametric  $F$ -tests in an ANOVA is that experimental errors are normally distributed. Although  $F$ -tests are robust with respect to violations of normality, the normality was tested. For serious violations of normality, a log transformation was performed to normalize the data, and normality was tested using the Shapiro and Wilk [17] test.

### 3. Results

**3.1. Infiltration Flux as a Function of Soil Wetness and Surface Cover.** Two of the main factors that influenced infiltration and runoff from surface-applied biosolids sites were antecedent water content and soil surface cover. The following series of figures show the effects of antecedent water contents under bare and vegetated soil conditions on the Stellar very fine sandy loam soil. In the following figures, infiltration flux is plotted versus rainfall simulator run time for plots with different antecedent water contents and vegetation (i.e., bare dry, bare wet, vegetated dry, and vegetated wet). In the figures, applied biosolids range from 0 Mg biosolids  $\text{ha}^{-1}$  to 90 Mg  $\text{ha}^{-1}$ . The first figure (Figure 1) is for a Stellar soil that was bare/vegetated or dry/wet without biosolids. Water was applied using the rainfall simulator described previously.

All plots had application rates and initial infiltration fluxes of approximately  $16 \text{ cm hr}^{-1}$ . This is stage I infiltration, which is the initially high infiltration rate that is controlled by the water application rate. After several minutes, the infiltration flux decreases and stage II infiltration begins. Stage II infiltration is controlled by the soil profile and is the transition from stage I to the lower-flux, stage III infiltration. Stage III infiltration is the steady-state, soil hydraulic conductivity-controlled infiltration rate. The bare-wet infiltration flux decreased less rapidly, because the hydraulic gradient is less than that for the bare-dry soil. Both the wet and dry vegetated soils had longer stage I infiltration times than dry or wet bare soil. The stage I infiltration treatment flux time for vegetated soil was greater than bare soil due to a better pore size distribution. The 30-minute flux rates for bare soils were approximately  $2 \text{ cm hr}^{-1}$  compared

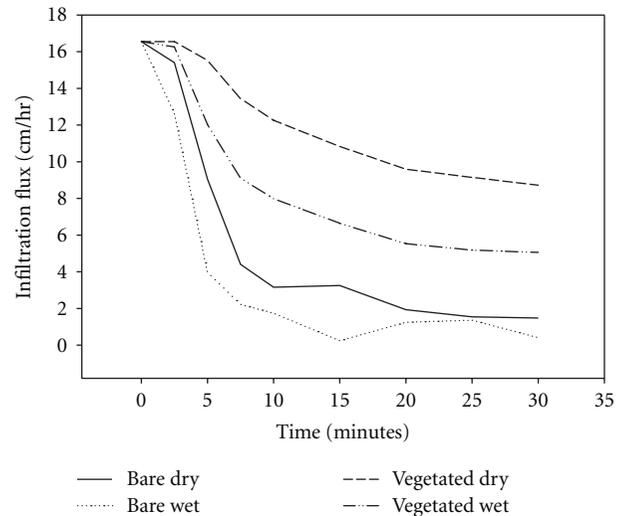


FIGURE 1: Infiltration flux for the Stellar soil under bare dry, bare wet, vegetated dry, or vegetated wet conditions on the Sierra Blanca Ranch.

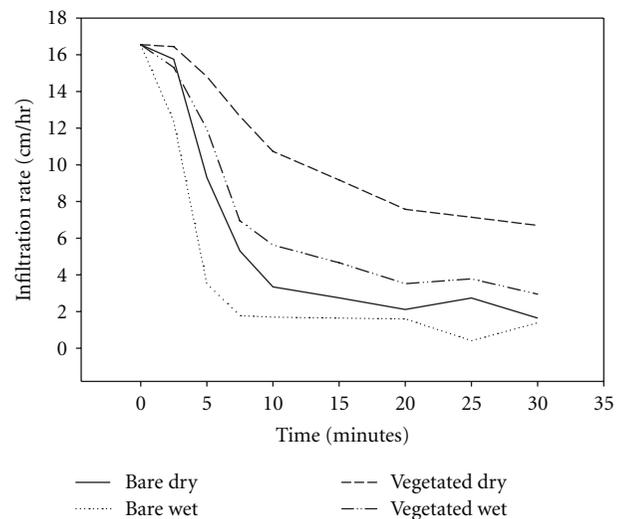


FIGURE 2: Infiltration flux for Stellar soil with 7 Mg biosolids  $\text{ha}^{-1}$  under bare dry, bare wet, vegetated dry, or vegetated wet conditions on the Sierra Blanca Ranch.

to  $9 \text{ cm hr}^{-1}$  for the vegetated soils. The bare soils probably reached stage III infiltration flux, whereas the vegetated soils had not yet reached the stage III infiltration flux. Vegetation enhanced 30-minute infiltration flux by a factor of four or more when no biosolids were applied and delayed the time to stage III infiltration.

The infiltration flux was measured for the Stellar soil with 7 Mg biosolids  $\text{ha}^{-1}$  under bare dry, bare wet, vegetated dry, and vegetated wet conditions and stage I infiltration was approximately  $16 \text{ cm hr}^{-1}$  and the dry-soil stage I infiltration flux time exceeded that of the wet soil (Figure 2). The infiltration fluxes for the 7 Mg biosolids  $\text{ha}^{-1}$  treatments were similar to the soil without biosolids. The initial values were both approximately  $16 \text{ cm hr}^{-1}$  and decreased to  $10 \text{ cm hr}^{-1}$  for the dry soils and  $8 \text{ cm hr}^{-1}$  for the wet soils. The results

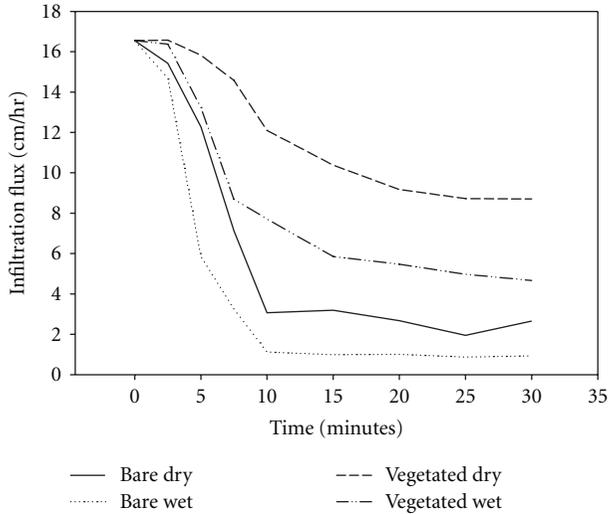


FIGURE 3: Infiltration flux for Stellar soil with 18 Mg biosolids ha<sup>-1</sup> under bare dry, bare wet, vegetated dry, or vegetated wet conditions on the Sierra Blanca Ranch.

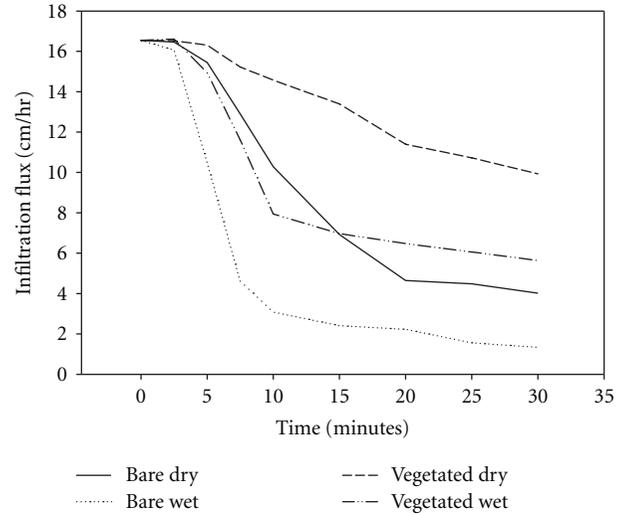


FIGURE 5: Infiltration flux for Stellar soil with 90 Mg biosolids ha<sup>-1</sup> under bare dry, bare wet, vegetated dry, or vegetated wet conditions on the Sierra Blanca Ranch.

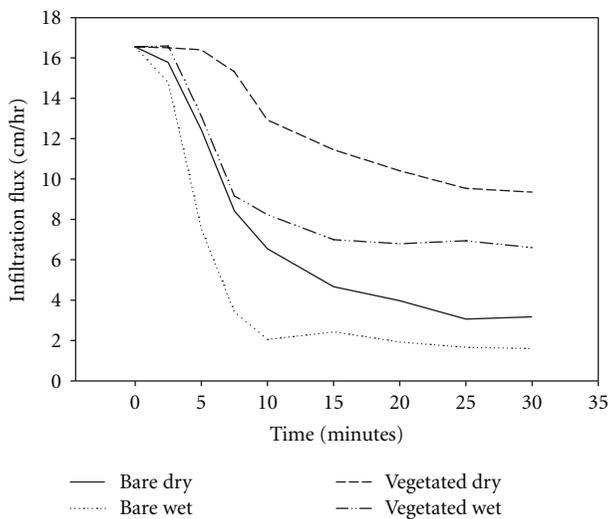


FIGURE 4: Infiltration flux for Stellar soil with 34 Mg biosolids ha<sup>-1</sup> under bare dry, bare wet, vegetated dry, or vegetated wet conditions on the Sierra Blanca Ranch.

were similar for the Stellar soil with 18 Mg biosolids ha<sup>-1</sup> (Figure 3) and 34 Mg biosolids ha<sup>-1</sup> (Figure 4). At greater biosolids application rates, stage I infiltration times increased and the slope of stage II infiltration flux decreased. These differences occurred as added biosolids were increased from 7 Mg ha<sup>-1</sup> through 18 and 34 Mg ha<sup>-1</sup>. Adding 90 Mg biosolids ha<sup>-1</sup> (Figure 5) lengthened the infiltration flux time for the Stellar soil. With the addition of 90 Mg biosolids ha<sup>-1</sup>, only the wet-bare soil achieved a stage III, steady-state infiltration rate of approximately 2 cm hr<sup>-1</sup>. The 90 Mg biosolids ha<sup>-1</sup> bare-treatment stage-I infiltration fluxes were (Figure 5) similar to the vegetated treatments in which no biosolids were applied (Figure 1). Biosolids changed the soil surface properties enough that stage I infiltration flux was enhanced.

Infiltration flux was affected by interactions between biosolids rate, cover, and time (Figures 1–5). The time zero infiltration flux, for comparison, was the mean simulated rainfall intensity for the experiment. In general, wet, bare treatments reached a stage III, steady-state infiltration in less time than vegetated treatments regardless of biosolids rate. Stage III infiltration occurs when the infiltration flux reaches a plateau and does not change appreciably with time. Typically, an infiltration flux plateau formed between five and ten minutes after the initiation of simulated rainfall for the wet, bare treatments. Wet runs reached stage III infiltration within 30 minutes, whereas the comparable dry treatments did not.

Hydraulic conductivity in layered soils changes as the wetted region moves deeper into the soil profile. All soils had a surface crust. In the bare soil treatment, soil hydraulic conductivity was lowest in the crust, increased in the A horizon, and then decreased in the B horizon. Bare treatments had more contrasts in texture between the crust layer and A horizon than vegetated treatments and, therefore, had a short period of transient ponded infiltration (stage II).

The Chilicotai is a very fine, sandy loam soil that is similar in surface texture and slope to the Stellar soil, but is covered with gravel. The Chilicotai soil will be compared to the Stellar soil to evaluate surface gravel content and biosolids addition effects on infiltration flux. Infiltration flux for the Chilicotai soil is plotted versus rainfall simulator run time in Figure 6. The greater surface gravel content slightly reduced the initial infiltration rate to <16 cm hr<sup>-1</sup> for this soil. The Chilicotai has more shrub vegetation and less total surface cover than the more vegetated Stellar soil. This lack of vegetation cover is made up in some way by the increased surface gravel. Infiltration rates for the Chilicotai soil (Figure 6) with added biosolids were similar to the Stellar (Figures 1–5). Stage I infiltration flux time increased as the biosolids application rate was increased. Additionally, the slope of stage II infiltration flux decreased with an increase

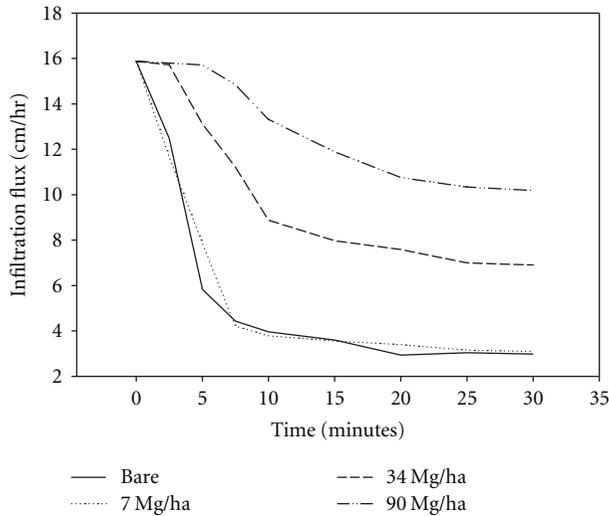


FIGURE 6: Infiltration flux as a function of time and rate of biosolids applied on a Chilicotol soil with a gravelly surface on the Sierra Blanca Ranch.

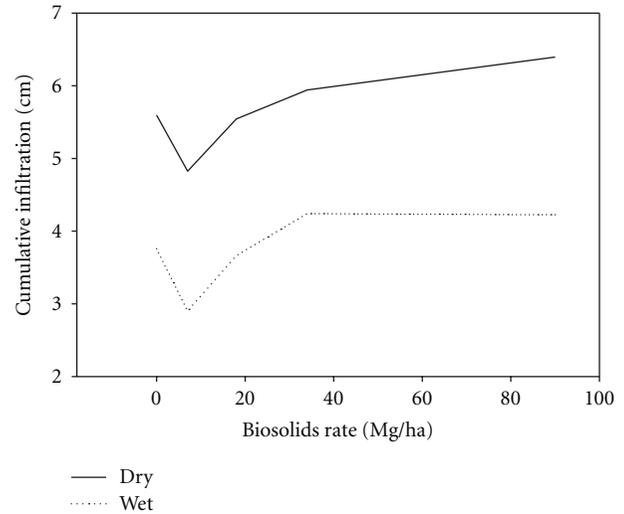


FIGURE 8: Cumulative infiltration for wet or dry conditions in vegetated treatments for the Stellar soil as a function of biosolids rate on the Sierra Blanca Ranch.

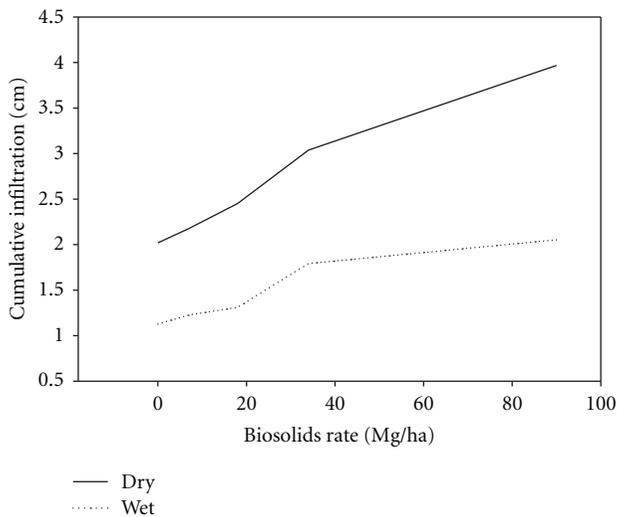


FIGURE 7: Cumulative infiltration for wet or dry conditions in bare treatments for the Stellar soil as a function of biosolids rate on the Sierra Blanca Ranch.

in biosolids application rate. For this gravelly soil, the 0 and 7 Mg biosolids  $\text{ha}^{-1}$  treatments had stage III infiltration fluxes of approximately  $3 \text{ cm hr}^{-1}$ , which are similar to the stage III infiltration of the Stellar soil.

Integrating infiltration flux curves yields cumulative infiltration. Effects of the wet/dry treatments on cumulative infiltration depended on cover and biosolids rate, not on the interaction of cover and rate (Figures 7 and 8). Cumulative infiltration was lower in the wet runs than in the dry runs. Additionally, cumulative infiltration was lower in the bare Stellar soil than in the vegetated Stellar soil.

In the Stellar soil, bulk density and percent clay increased with depth (data not presented). Hydraulic conductivity decreased as density and clay content increased and as structured soils with high clay content swell and close macropores.

In crusted soils, the greatest limitation to infiltration may be the crust layer. After infiltration, soil water is redistributed. In a soil with little water infiltration, the matric potential (attraction of soil for water due to adhesion and cohesion) of the wetted region following a day of redistribution will be more negative than for a similar soil with more water infiltration. The vegetated soil treatment had significant infiltration the first day (dry run), and infiltration for wet run treatments was, thus, significantly reduced. Infiltration was limited in the bare soil treatments by the crust layer, and thus, redistribution had a greater effect on matric potential in vegetated soils. The matric potential in the wet region of bare soils may be more negative than in vegetated soils, because of the effect of redistribution. Therefore, in the bare soil, infiltration in the dry run did not cause as much of a reduction in infiltration as in the wet run.

There was an interaction between biosolids rate and water condition, which suggests absorption of water by the biosolids. Wet treatments with biosolids had 1.37 cm less infiltration than dry treatments without biosolids. Furthermore, wet soils with  $90 \text{ Mg ha}^{-1}$  biosolids applications had 2.05 cm less infiltration than dry treatments. From regression of wet and dry treatment infiltration differences and biosolids rate, it was determined that biosolids do absorb water at a rate of  $0.74 \text{ m}^3 \text{ water Mg}^{-1} \text{ biosolids}$ . This equals 6.7 mm at the  $90 \text{ Mg biosolids ha}^{-1}$  rate and is equivalent to biosolids with 73.5 percent water on a dry weight basis.

Summing the cumulative infiltration for the dry and wet rainfall simulator runs yields the two-day total infiltration. Vegetated soils treated with  $90 \text{ Mg biosolids ha}^{-1}$  infiltrated a total of 10.62 cm (less interception losses). The vegetated control ( $0 \text{ Mg biosolids ha}^{-1}$ ) and vegetated soils treated with  $34 \text{ Mg biosolids ha}^{-1}$  infiltrated 9.36 and 7.72 cm, respectively. Bare soil treated with  $90 \text{ Mg biosolids ha}^{-1}$  infiltrated 6.02 cm and control treatments infiltrated 3.25 cm. The difference between these quantities suggests other mechanisms

in addition to interception losses, since care was taken to minimize evaporation losses between runs. Fresh biosolids with 300% water (dry weight basis) contains 2.7 cm of water ( $90 \text{ Mg ha}^{-1}$ ) [8]. Using their [8] conservative estimate of 100% instead of the measured 50% to 60%, the amount of absorbed water is 0.9 cm.

**3.2. Runoff.** Runoff is influenced by plot characteristics, such as slope, surface roughness, and depression storage volume. The Chilicotol had 0.56 mm of depression storage (data not presented). Although the Stellar vegetated treatments had an average storage volume of 2.2 mm, most of this volume was an artifact of the treatment technique. In the Stellar vegetated treatment, water was trapped between the plot boundary and a region of higher ground at the plot center, but under normal conditions, the water would flow freely away from the plot center. The Stellar bare treatment had 0.90 mm of storage. On the basis of particle size distribution, the Stellar vegetated treatment appeared to be an area of very fine and fine sand accumulation.

**3.3. Hydrologic Response to Biosolids.** Surface-applied biosolids affected hydrologic response. The biosolids provided a protective cover on the soil that reduced erosion by absorbing raindrop energy. Biosolids may also intercept and absorb rainfall, reducing the net precipitation for an event. For small events, this may be an important loss on a percentage basis, but for large events like the simulation events, the loss was insignificant.

Infiltration flux was affected by the interaction of biosolids rate, cover, time, and antecedent soil moisture (Figures 1–5). The time zero infiltration flux, for comparison, is the mean simulated rainfall intensity for the experiment. In general, bare treatments reached stage III infiltration in a shorter time than vegetated treatments regardless of biosolids rate. Wet runs reached Stage III infiltration before companion dry treatments and terminated at a lower infiltration flux.

Hydraulic conductivity in layered soils changes as the wetted region deepens. In the bare soil treatment, soil hydraulic conductivity was lowest in the crust, increased in the A horizon then decreased in the B horizon. Bare treatments were more contrasting in texture between the crust layer and A horizon than vegetated treatments and, therefore, had a short period of transient ponded infiltration (stage II).

Integrating infiltration flux curves yields cumulative infiltration. For the Stellar soil, the effect of wetness condition treatment on cumulative infiltration depended on cover and rate but not on the combination of cover and rate. Cumulative infiltration was lower in the wet run than in the dry; this trend was more evident in vegetated treatments than in bare (Figures 7 and 8). Cumulative infiltration for the Chilicotol soil as a function of biosolids rate is presented in Figure 9.

As a wetting front moves into the soil, the hydraulic gradient term approaches unity. In the Stellar soil, bulk density and percent clay increase with depth. Hydraulic

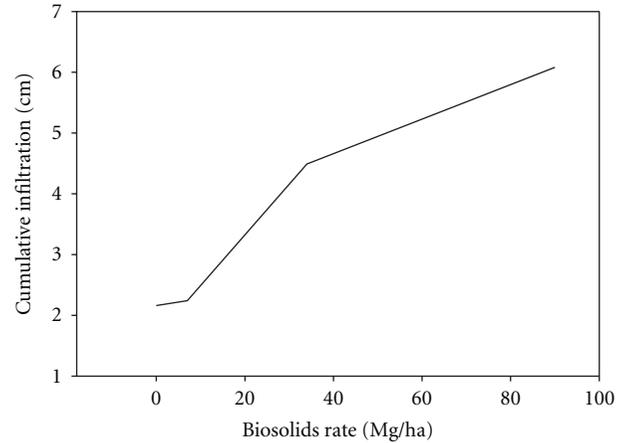


FIGURE 9: Cumulative infiltration for the Chilicotol soil as a function of biosolids rate on the Sierra Blanca Ranch.

conductivity decreases as density and clay content increase and as structured soils with high clay content swell and close macropores. In crusted soils, the greatest limitation to infiltration may be the crust layer. After infiltration, soil water is redistributed. In a soil that has infiltrated little water, the matric potential of the wetted region following a day of redistribution will be more negative than for a similar soil that infiltrated more water. The vegetated soil treatment had significant infiltration the first day (dry run) and infiltration for wet-run treatments was thus significantly reduced. Infiltration was limited in the bare soil treatment by the crust layer, and thus redistribution had more effect on matric potential in vegetated soils. The matric potential in the wet region of bare soils may be more negative than in vegetated soils because of the effect of redistribution. Therefore, in the bare soil, infiltration in the dry run did not cause as much of a reduction in infiltration in the wet run.

The Green and Ampt [12] “*b*” constants of infiltration were computed for the Stellar and Chilicotol soils using their respective infiltration rates, final infiltration rates and cumulative infiltration values. In these calculations, the final infiltration rates were assumed to be indicators of the stage III infiltration rates (Table 1). The final infiltration rate for the Stellar soil was assumed to be  $0.4 \text{ cm hr}^{-1}$  which is the stage III infiltration rate for the bare wet treatment. The final infiltration rate for the Chilicotol soil was assumed to be  $3 \text{ cm hr}^{-1}$  which is the stage III infiltration rate for this soil.

Conceptually, the *b* value is small for infiltration rate rapidly reaching the final infiltration rate,  $i_c$ . For large *b* values, the final infiltration rate is reached over a longer period of time. At the zero biosolids application rate, the bare, wet Stellar *b* values and the Chilicotol soil were both zero. The zero value for *b* indicates that the final infiltration was also the infiltration rate used to determine *b* value. A soil without applied biosolids would be expected to have a smaller *b* value than a soil with large quantities of applied biosolids. This proved to be true for the Stellar bare soils and the Chilicotol soil with low *b* values on soils not receiving biosolids and high *b* values for plots receiving high application rates of biosolids. Similarly, a wet soil would be

TABLE 1: Cumulative infiltration and Green Ampt “*b*” value for the Stellar soil under two wetness conditions and the Chilicotal soil on the Sierra Blanca Ranch.

Soil conditions	Cumulative infiltration, cm “ <i>b</i> ” value	
Stellar soil bare wet biosolids Mg ha <sup>-1</sup>		
0	1.1	0
7	1.2	1.2
34	1.8	2.2
90	2.1	1.9
Stellar soil bare dry biosolids Mg ha <sup>-1</sup>		
0	2	2.2
7	2.2	2.6
34	3	8.4
90	4	14
Stellar soil vegetated wet biosolids Mg ha <sup>-1</sup>		
0	3.8	18
7	2.9	7.3
34	4.2	26
90	4.2	22
Stellar soil vegetated dry biosolids Mg ha <sup>-1</sup>		
0	5.6	46
7	4.8	30
34	5.9	53
90	6.4	61
Chilicotal soil biosolids Mg ha <sup>-1</sup>		
0	2.2	0
7	2.2	0.22
34	4.5	18
90	6.1	44

anticipated to have a smaller *b* value than a dry soil. This was shown in Table 1 for both the Stellar bare and vegetated soils. In general, for all of the soil treatments listed in Table 1, the *b* value increased as the biosolids amounts increased. The *b* values represent soil surface parameters that are altered by the addition of biosolids. The *b* values were larger in the vegetated plots compared to the bare plots, because the vegetation “caught” more of the biosolids and water than did the bare plots.

#### 4. Summary and Conclusions

Biosolids, an end product of publicly owned treatment works, have been used as a soil amendment for years. Biosolids are not only a source of plant macro- and micronutrients, but also physically affect the ecosystem. In this study, biosolids surface-applied to soils were evaluated to reveal their influence on infiltration stage. While the magnitude of stage I infiltration is flux controlled, the length of time

that water infiltrates at the application rate is controlled by surface conditions. Stage II infiltration is altered also by biosolids surface applications in that the water flux slope from stage I to stage III infiltration is more gradual for long stage I infiltration times. In general, soils with long stage I infiltration periods received the highest biosolids surface application rates. Vegetated Stellar soil plots had longer stage I infiltration times than bare Stellar soils and wetted Stellar soils had longer stage I infiltration times than dry Stellar soils. Biosolids lengthened stage I infiltration times most in dry or gravelly soils, which initially had short stage I infiltration times.

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