Production of road born sediment of an agricultural road network in southeast Ohio

Thesis

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By

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Abstract

Unbound gravel roads are thought to be one of the largest anthropogenic sources of fine sediments in the stream channels of small watersheds. Sedimentation can reduce water quality in streams; negatively impacting aquatic habitat as well as being a detriment to municipal drinking water sources. With the expansion of natural gas exploration and subsequent increase of the construction and use of rural roads along with the continued use of these roads for timber extraction and recreation, the relationship between rural gravel roads and surface water quality needs to be addressed. This study sought to quantify the mass of sediment a rural road can produce and identify the forces that drive the erosional losses by measuring the production of sediment from the road surface using controlled precipitation experiments. Rain events were simulated on eight road segments at an agricultural research station in eastern Ohio. The road surface produced an average of 42 g of sediment per m² of road surface with a 30-minute, 1.6 cm precipitation event. Sediment production was shown to be driven by sediment availability but not related to road slope, strength, or drainage characteristics. The production of sediment from the road surface increased with wet traffic use. This study highlights the need to disconnect rural road networks from stream channels in order to prevent negative water quality impacts associated with sedimentation.
Dedication

To Jenny.
Acknowledgments

Thank you Dr. Toman for the opportunity, and the guidance through this unknown experience over the past few years. Your inherent kindness shines through your willingness and ability to answer any question I had with thoughtfulness, and precision no matter what part of left field they may have come from. It has been a sinuous journey, which fulfilled my curiosity and desire to learn about how rivers and streams influence management decisions and shape the landscape that is shared. Thank you for all your help. Thanks to Caitie Sheban and Laura Bond for their help on field visits to EARS and their organizational skills, also thanks to Dr. Williams who cut down all my red tape even though he didn’t ask to.
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Major Field: Environment and Natural Resources
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Chapter 1: Introduction

Unbound gravel roads are ubiquitous in the rural landscape and are becoming more abundant with the expansion of natural gas extraction across the eastern United States. Research on gravel roads has shown that roads can be periodic and episodic sources of sediment through surface erosion of the road prism (including the road surface). Sediment loss from the road network begins during construction of the road and can persist throughout the life of the road. Road construction often removes land cover and disturbs the ground, creating highly erodible bare soil conditions. Once gravel roads are built, the surfacing materials of the road can continue to erode and produce sediment. The rate of sediment production from roads varies and could be influenced by the amount and type of precipitation and road characteristics such as road gradient, road surface area, and vegetative cover. Road use by vehicles may also be a driver of erosion from the road surface with increases in traffic reducing the amount of vegetative cover, increasing the supply of fine sediment through the breakdown and disturbance of the road material, and altering pathways of surface runoff by creating ruts and changing the shape of the road surface.

Streams, especially those that are connected to the road network, may be directly impacted by erosion from gravel roads. Structures of road drainage, such as ditches at stream crossings and gullies from cross drains, may direct fine sediment from the road
surface to the stream network. As road and stream density increase within a watershed the number of locations where the streams and roads are connected may also increase. Increases in sedimentation of streams can reduce stream bed cover quality and change streambed composition, reducing the quality and quantity of habitat for aquatic organisms. Small sediment particles that remain in suspension are thought to be a threat to aquatic environments through the reduction of light levels in the water column that may reduce photosynthesis and limit visibility for hunting. Fine sediment in surface water can also negatively impact anthropogenic systems as they can be a vector for pathogens in drinking water and reduce the effectiveness of water treatment.

The development of shale gas has increased across the United States in recent years including eastern Ohio. As the number of well permits issued by the Ohio Department of Natural Resources has grown greatly in the region, the associated infrastructure has expanded as well. Shale gas infrastructure includes a well pad and access roads (predominately gravel) that are used for construction of the pad and development of the well. Well development is highly dependent on large construction vehicles creating large volumes of traffic in short periods of time. As this increase in road construction and traffic use is seen in areas not historically associated with this type of resource extraction, there is an increased chance for harm to surface water quality as managers may not be versed on best management practices associated with rural road construction and maintenance.
While unbound gravel roads have been studied for decades in forested western landscapes, research on the influx of these roads and their effects into rural areas of the eastern United States is lacking. In addition, much of the existing research on roads is associated with timber harvests and public recreation. Agricultural watersheds in the eastern United States often differ from those in the west in land cover type, land use, basin topography, and climate. These characteristics can contribute to differences between watersheds in sediment sources and production from the road surface. There is a need to address how gravel roads affect different types of watersheds. Associating land cover and land use with surface water quality is a topic of interest in landscape scale planning and the management of watersheds. While rates of sediment production from gravel roads have been well documented, research relating these rates to agricultural watersheds is lacking and is needed to inform land managers of this region.

This research addresses the erosion of sediment from unbound gravel roads in an agricultural watershed in eastern Ohio. The objectives for this research are to: 1. quantify the mass of sediment a rural road can produce in an agricultural watershed during a summer season rain event and 2. identify the road characteristics that influence the production of sediment from rural roads.
Chapter 2: Review of the literature

2.1 Production of suspended sediment from unbound gravel roads and transport to surface waters

2.1.1 Erosion from gravel roads

Fine sediments that are available for transport can originate from the road by different means. Coarse materials in the road surfacing can be broken down by traffic into fine sediments. Fine sediments already exist in the gravel material by design to assist with compaction. Finally, fines are present in the subgrade material and can be transported up to the surface through “subgrade pumping” (Koerner, 1998). This pumping action happens when road surface loads are applied by vehicles and the subgrade is near saturation.

Erosion from rural unbound gravel roads can occur at the different areas or components of the road. The road prism, defined as the area of ground containing the cutslope, fillslope, ditch and the road surface as shown in Figure 2.1, has been shown to be a periodic and episodic source of sediment through surface erosion (Reid & Dunne, 1984; Luce & Black, 1999). Gravel roads have also been shown to increase mass failures of the hillslope through structural failure of the road components, especially at areas of road drainage (Wemple, 1999).
Prior research has found varied results when comparing the rates of erosion from the different surfaces of the road prism. During rainfall simulations over the entire road prism in Spain the cutslope had the greatest erosion rates of 2.15 g/m²/mm, exceeding the fillslope and road surface rates by 16 and 11 times (Arnaez et al., 2004). This was attributed to mass wasting and freeze thaw processes that supplied loose material for transport. However, a yearlong study in Washington found different results. In this
research sediment concentration and hydrograph measurements were taken at culverts and sediment production was quantified from various road segments. The study isolated the contribution of the road surface by comparing the sediment production of paved roads (where only the cutslope and ditch could contribute sediment) to gravel roads and found that the paved sections only had 0.4% of the production that a gravel, highly traveled road surface had (Reid & Dunne, 1984).

The construction of a new road and maintenance activities of an existing gravel road can contribute a large amount of sediment to the stream channel in forested lands due to the removal of vegetation cover, soil disturbance, and removal of armor layers from the road prism and may continue to affect increased erosion for two years before subsiding (Akay, et al., 2008; Luce & Black, 1999). Eventually, the road cuts recover from the initial disturbance as vegetation has time to reestablish leaving only the road surface bare and more likely to produce sediment. Cleaning ditches and the removal of cutslope vegetation can also cause increases in erosion. One study found that unmaintained roads (established roads, 20 years old with a vegetated cutslope and ditch) produced an average of 0.14 g/m²/mm of sediment, while the treated road (road surface graded) produced an average of 0.16 g/m²/mm and the treated cutslope (vegetation removed) and ditch produced 1.06 g/m²/mm (Luce & Black, 1999).
2.1.2 Transport of road sediment to surface waters

Road drainage (locations of stream crossings and connections via cross drains and gullies) is the dominant mechanism of delivery of sediment from roads to streams. Rates of connectivity between the road network and stream network vary in a watershed depending on the types of drainage structures, road maintenance practices, and the stream and road densities within the watershed. Studies beginning in 1984 cite road erosion as an important source of fine-grained sediment in streams and identify road drainage (locations of stream crossings and connections via cross drains and gullies; Figure 2.2) as a mechanism of delivery of sediment to streams (Reid & Dunne, 1984). Roads can act as networks that alter surface flow in the watershed by diverting or extending channels as well as allowing water to interact with terrestrial portions of the watershed such as woody debris or organic layers in the soil profile that would not normally occur (Gucinski, et al., 2001). A study in the western Cascades of Oregon concluded that over 57% of the road network was connected to the stream network by either draining to streams directly or through rutting and gullying below relief culverts and estimated that drainage density increased by 36% to 39% due to the road network in the basins studied (Wemple, et al., 1996). Other studies looking at connectivity of road networks suggest varied rates of connectivity, between 25% and 39% of the road network connected to the stream network (Mills, 1997).
Figure 2.2. Road born sediment entering a stream during a natural rain event. The stream channel is running from the top to bottom of the pictures and the plume of sediment is entering the stream from a road crossing culvert from the left side of the photo and flowing toward the bottom of the photo.
2.1.3 Impacts on aquatic systems due to sedimentation

When sediment that originated from the road reaches the stream network it can have detrimental effects on the aquatic environment. Roads can alter the rate and location of erosion and sedimentation, affecting the hydrology and geomorphology of the stream (Baird, et al., 2012). The increase in sediment deposition can reduce cover quality and change riverbed composition, reducing the quality and quantity of habitat for aquatic organisms in these streams. Smaller particles that remain in suspension are likely to have effects beyond small order streams and are thought to pose the greatest threat to aquatic environments (Ramos-Scharron & MacDonald, 2007). Beyond the effects of sediment deposition, suspended sediment can reduce light levels in the water column reducing photosynthesis rates and triggering additional effects through aquatic trophic levels. These other effects could include: impeding the development of fish eggs, altering the migration of fish, limiting visibility for hunting, and irritating fish gills (Newcombe, 2003). Fine sediments in surface water can negatively impact anthropogenic systems as well as they are shown to be a vector for pathogens in drinking water due to the reduction in the effectiveness of water treatment (Marquis, 2005).

Small order streams are frequently impacted by rural roads due to their proximity to the roads and as the frequency of stream crossings increases with higher road and stream density (Swanson & Jones, 2001). More than 50% of road born sediment can be trapped in small order streams with higher levels of deposition in streams that have increased presence of coarse woody debris (Swanson & Jones, 2001). These small
streams can be impacted directly by engineered stream crossings or by chronic and long term contributions of fine sediments from the road surface (Gucinski, et al., 2001).

2.2 Road characteristics and other attributes that drive sediment production

Results from research on erosion from the surface of gravel roads differ in the amount of sediment produced and the road characteristics that influence sediment production. MacDonald (2001) found rates of sediment production from a road surface of 0.182 to 4.6 grams per square meter of road surface per millimeter of precipitation (g/m²/mm; rates based on total annual estimations) in a forested watershed in St. Johns. Variation in the rate of production was driven by the amount and type of precipitation and road runoff volume, with differing road runoff volumes being attributed to precipitation intensity. Traffic was also noted as a driver of sediment production with increases in traffic reducing the amount of surface cover, increasing the supply of fine sediments, and increasing the possibility of road surface rilling particularly during wet weather (MacDonald et al., 2013). Other research in forested watersheds report erosion rates of 0.85, 0.96, and 2.59 g/m²/mm (Reid & Dunne, 1984; Sheridan & Noske, 2007). Remote sensing studies have estimated much higher rates of sediment production from road surfaces, ranging from 3.7 kg/m² to 19.9 kg/m² from a GIS assisted prediction model that included a precipitation factor as well as erosion rates from the road surface, road age, traffic, and road slope (Akay, et al 2008). A study using a controlled rain event on unbound forest roads in Pennsylvania quantified production rates at 6.25 g/m²/mm (calculated from measured sediment production from single rain events) (Bloser &
Scheetz, 2012). The rates of sediment produced from unbound gravel roads and the road characteristics that were found to influence sediment production from recent research are summarized in Table 2.1.
Table 2.1 Recent research regarding sediment production from gravel roads and the road characteristics that influenced the production of sediment. Sediment rates are reported in grams of sediment per square meter of road per mm of precipitation.

<table>
<thead>
<tr>
<th>Author</th>
<th>Date</th>
<th>Study Area (Land Use/Cover)</th>
<th>Sediment Rate</th>
<th>Driver of Sediment Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reid and Dunne</td>
<td>1984</td>
<td>Washington State (Forested)</td>
<td>0.96 g/m²/mm</td>
<td>Traffic</td>
</tr>
<tr>
<td>MacDona ld et al.</td>
<td>2001</td>
<td>St. Johns (Forested)</td>
<td>0.182 - 4.6 g/m²/mm</td>
<td>Storm rainfall total, storm intensity, and runoff amount</td>
</tr>
<tr>
<td>Arnaez et al.</td>
<td>2004</td>
<td>Spain (Urban, Agricultural)</td>
<td>0.01775 g/m²/mm</td>
<td>Gradient, road surface plant cover, and fine sediment Availability</td>
</tr>
<tr>
<td>Sheridan and Noske</td>
<td>2007</td>
<td>Australia (Forested)</td>
<td>0.85 - 2.59 g/m²/mm</td>
<td>Traffic</td>
</tr>
<tr>
<td>Sharron</td>
<td>2010</td>
<td>Puerto Rico (Urban, Shrub, Agricultural)</td>
<td>0.11 g/m²/mm</td>
<td>Total rainfall, road slope and segment length</td>
</tr>
<tr>
<td>Bloser and Sheetz</td>
<td>2012</td>
<td>Pennsylvania (Forested)</td>
<td>6.25 g/m²/mm</td>
<td>Slope and width combination</td>
</tr>
</tbody>
</table>
Road segment length and slope have been identified as drivers for sediment production with increases in both length and gradient corresponding to increased sediment production. These characteristics are shown to interact with each other; increasing segment length does not increase production levels while the gradient is low but length increase has a large effect on roads with higher gradients (Luce & Black, 1999). The longer road segments contribute to larger sediment loads due to a larger supply of sediment and the ability of the longer segments to concentrate more water that can lead to increased energy and allow for more erosion (Bilby, 1985). Along with the characteristics of surface area, road segment length, and segment slope influencing the production of sediment from a road, traffic use can be a major driver of sediment production. Increases in traffic can reduce the amount of vegetative cover on the road surface as well as stress the road surface leading to a long term source of fine sediments. During a yearlong study on sediment production from unbound gravel roads, researchers compared weekday traffic, which was significantly higher, to weekend traffic and found that sediment production from the roads was 7.5 times higher during the week. The increase in production was shown to decrease to only 0.8% of the high traffic production totals if the road was classified as “light use” for two days beyond the high use and production was shown to decrease further by a factor of 10 if the maintenance and use were completely discontinued (Reid & Dunne, 1984).

Precipitation can influence sediment production from the road surface due to differences in precipitation volume and intensity and raindrop erosivity. The amount and
type of precipitation is thought to be a first order control of sediment production (MacDonald et al., 2013). A study in the U.S. Virgin Islands suggests that there is a minimum threshold volume of precipitation that needs to be met for a road to produce sediment (MacDonald et al., 2001). Sediment production rates from unpaved roads in Southwestern Puerto Rico studied over the span of two years identified precipitation volume as the main driver of mass of sediment produced by the road (Ramos-Scharron, 2010).

Differences in precipitation may also change the connectivity between the road and the stream networks, thus potentially increasing the opportunities for sediment to reach the stream. A study in California found that the proportion of the road network connected to a stream network increases with increases of average precipitation amounts (MacDonald et al. 2013).
Chapter 3: Study Methodology

Methods Overview:

The total mass of road born sediment produced from the road surface with precipitation was quantified using 30-minute simulated rainfall events on eight road segments at a study site in eastern Ohio. Two rainfall events were simulated on each road segment and were separated by an hour long drying period that included passes of a passenger truck. Road surface runoff was measured and collected at the bottom of a road segment during each simulation (Objective 1). The quantity of sediment produced by the road segments during the rainfall simulations was compared to road width, gradient, strength, drainage characteristics, and wet traffic use to identify the road characteristics that influence sediment production (Objective 2).

3.1 Study site

The study location was in Noble County, Ohio, at The Ohio State University’s Ohio Agricultural Research and Development Center’s (OARDC) Eastern Agricultural Research Station (EARS) as shown in Figure 3.1. The 847-hectare (2093 acre) station was established to research forage crops and livestock production to support the region’s large livestock economy (OARDC, 2015). EARS land cover is approximately 53% pasture, 45% forest, less than 1% surface water, and the road network accounts for less than 1% (0.89%, 2.85 hectares, 28,472 m²) of the total land area. The existing road network within the EARS property boundary consists of 7118 meters (23,353 feet) of single-lane road that is used for farm management. This road is constructed with native soil subgrade and surfaced with unbound aggregate (gravel). The road network has an
average road width of 4.0 meters (13 ft) and an average slope of 8.4%. The dominant soil type for the EARS property is the Vandalia-Guernsey silty clay loam that has a colluvium parent material and is well drained with a silty clay texture to a depth of 37 inches (Web Soil Survey, 2015).

Figure 3.1. Eastern Agricultural Research Station (EARS) property boundary and the road network.
3.2 Selection of road segments

Locations on the roads at EARS were randomly selected for rainfall simulation experiments and thought to be representative of the entire road network at EARS. The gradients of the roads at EARS were determined using ArcGIS analysis of aerial imagery and digital elevation model (DEM, 2.5 meter resolution) data files. To ensure that the range of road gradients within EARS was adequately represented by the road segments selected for study, the road network was divided into lengths of similar gradient and the lengths were stratified into grade categories of 0.0-3.0, 3.1-6.0, 6.1-9.0, and > 9.1 percent. The strata were then assembled into linear road segments of 30.5 meters (100 feet) each. A random number generator was used to identify eight, 30.5-meter road segments, two within each strata, for rainfall simulations. This was done twice, with the second set of eight road segments providing an “oversample” that was used for backup segments in the event that a particular road segment was not suitable for the equipment and procedures involved in the rainfall simulations. Reasons that a particular segment was not suitable for rainfall simulation were: no sufficient flat area to place the water storage bladders or no suitable sampling point on the road segment (point at the bottom of a road segment where all the surface runoff could be measured). When neither the original nor the oversample provided a suitable road segment, the top of the latter segment was identified and we moved downslope until a suitable 30.5-meter segment was identified.
3.3 Rainfall simulation on road segments using the RainMaker

3.3.1 Description of the RainMaker and characteristics of the simulated rainfall

Rainfall on the road segments was simulated using the “RainMaker.” The RainMaker is a pressurized sprinkler system that delivers 1.6 cm (0.6 inches) of rainfall in 30 minutes in a highly repeatable event. Eleven sprinkler standpipes are set 3.0 meters (10 feet) apart over a 30.5 meter (100 foot) segment and are pump fed by a 4542-liter (1200 gallon) water bladder.

Figure 3.2 RainMaker and water storage bladders before run 1 at segment B.
The RainMaker was constructed by the Center for Dirt and Gravel Road Studies at The Pennsylvania State University. The rotary nozzles (Rainbird® MPR Rotary Nozzles) deliver consistent precipitation over the entire test segment and produce an average raindrop diameter of 0.84mm. Details of the construction, calibration, and experimental procedure can be found in the Center for Dirt and Gravel Road Studies report titled “Sediment Production from Unpaved Oil Well Access Roads in the Allegheny National Forest” (Bloser & E., 2012). While the RainMaker was designed and tested to mimic the precipitation intensity of a sub annual natural rain event for areas in Pennsylvania, the intensity and duration of the simulated rainfall also falls below the one–year return interval event for the study area (one-year precipitation event in Caldwell, Ohio would have a volume of 2.1 cm with 30-minute storm duration [NOAA, 2015]).

3.3.2 RainMaker runs and protocol

At each of the eight road segments, two rainfall simulation experiments using the RainMaker were run. The rainfall simulations were scheduled for days when the roads were dry and there would be no natural precipitation. The RainMaker was assembled and set up along the entire length of the road segment. At the bottom of the test segment a sampling point was located and barriers were constructed so that all runoff would be accounted for and measured (Figure 3.3). Runoff discharge was measured at the end of each road segment at prescribed intervals by determining the time it took to fill a container of known volume. Samples of runoff were collected in 250 mL glass bottles at the same prescribed time intervals. The total time that the pump was operating and the
total time that the road segment was producing surface runoff were recorded as well as individual run characteristics such as the time taken for the “wetting front” to reach the sample point (Figure A8, Segment C, Appendix A), pressure in the sprinkler system at the terminal end of the system, and local weather characteristics. The RainMaker protocol was determined by The Center for Dirt and Gravel Studies as part of a larger study to identify road characteristics that control sediment production. This prescribed procedure is described below. After the first run of the Rainmaker on each road segment, the road was allowed to dry for 1 hour while a passenger light duty truck (unloaded 1 ton payload, 2330 kilogram curb weight) was driven over the entire test segment for a total of 20 passes in order to simulate traffic and stress the road surface. After the hour break a second simulated rainfall experiment was conducted.
RainMaker set up and run procedure:

1. A flat area was located where the refillable bladders could be placed.

2. A hole at the sample point and a waterbar (trench crossing from one side of the road to the other) were dug to ensure that all the road surface runoff drained to a single point. The hole at the sampling point had to be large enough to fit a 3.5 liter bucket. The upstream side of the sample point was lined with plastic and metal sheeting to aid in
sampling. The waterbar was flushed to remove all sediment created during construction of the waterbar and was tested to make sure no runoff was passing by the sample point.

**Experimental run:**

The pump was turned on and adjusted to 30 psi at the terminal end of the RainMaker. A stopwatch was started and the pump was kept running for a total of 30 minutes.

**Sampling:**

Measurements of runoff discharge and runoff samples were taken at regular timed intervals (Time, T=1, T=5, T=10, T=15, T=20, and T=30) with T=1 occurring one minute after the wetting front reached the sampling point. At each time interval the flow rate of the runoff was determined by timing the amount of time it took to fill a vessel of known volume. A 3.5 liter bucket was used for most of the samples and a smaller flask was used at the end of the run when flow rates were lower. Flow rates were measured after the first minute (T=1), at five minutes (T=5) and at five minute intervals until flow completely stopped. The last runoff sample usually occurred after the pump was shut off due to the delay in the wetting front reaching the sample point.

3.3.3 *Analysis of road sediment*

Runoff samples were placed on ice and transported to Advanced Analytics Laboratory in Columbus, Ohio where they were analyzed for total suspended solids (TSS) following EPA procedure 160.2. Using the measurements of runoff discharge and suspended sediment concentrations, hydrographs of each rainfall simulation experiment
were created. From the hydrographs, estimates of the total volume of runoff and sediment mass were calculated for each road segment and rainfall simulation.

3.4 Measurements of road characteristics

3.4.1 Description and definitions of road characteristics measured at each road segment

Road attributes were measured at each of the eight road segments during the RainMaker experiments and included: road width, length of wheel ruts (Figure 3.5), length of road “gullies” (Figure 3.6), presence or absence of a consistent insloped or outsloped road surface shape, and road segment slope. Road wheel ruts were identified where runoff traveled down the road surface in paths corresponding with vehicle wheel tracks. Absence of these ruts identified a road with consistent outslope or inslope to the road surface shape. Wheel rut length was measured as linear length and thus a segment could have a maximum of 61 meters (200 feet) of ruts. Road slope was measured using a clinometer and identified the slope of the road between the top and the bottom of the 30.5-meter segment. Road gullies (measured in linear feet) were defined as paths of road surface flow that were deeper than the wheel ruts and were made by fluvial erosion of the road surface.
Figure 3.4. Wheel ruts at one road segment. Note the direction of flow of the surface runoff corresponds with the location of vehicle tires during road use.
Figure 3.5. Road gully below one road segment. Note the direction of runoff is not linear and is located outside the path of vehicle tires during road use.

3.4.2 Description and definition of road strength measurements

The mechanical strength of the road surface was measured using a Clegg Impact Soil Tester (Clegg Hammer) with measurements in tens of g-units or Clegg Impact Value (CIV). The Clegg Hammer measures the deceleration of a free falling mass from a set height to determine the hardness of the road surface. Road strength was measured nine times for each segment: once in each of the wheel paths and once in the center of the road.
at the top, middle and bottom of each segment. These nine measurements were then averaged to obtain a single value of road strength for each 30.5-meter segment. The Clegg Hammer measurements were taken for all road segments on the same day instead of during rainfall experiments in order to standardize antecedent moisture conditions across all experimental road segments.

3.4.3 Analysis of road characteristics

The total mass of sediment produced from each segment was compared to identify the road characteristics that were influential to the production of sediment from the road surface. Road characteristics including width, slope, and surface strength were statistically analyzed to identify possible correlations with the production of sediment from each road segment. These characteristics were investigated using pairwise correlation (in R, `pearsons`, with no missing data).
Chapter 4: Results

Results Overview:

The production of sediment from the road surface varied across all rainfall simulation experiments and was shown to increase between the first and second experimental runs at each road segment (Objective 1). The combination of a wet road surface and traffic passes increased sediment production at every road segment; however, other road characteristics of slope, strength did not influence sediment production (Objective 2).

4.1 Road segments selected for RainMaker simulations

Eight, 30.5-meter road segments were selected by randomly for rainfall simulation experiments to estimate sediment production from the road surface. These segments were labeled alphabetically from the east side of the EARS property to the west (Figure 4.1). Road segments were selected within each road gradient category to adequately characterize the range of slopes found at the EARS location (Table 4.1). The road segments that were originally selected (by randomization) for sites A, B, and E were not suitable for the procedures of the RainMaker equipment, therefore these sites required the use of the “oversample.” At site B, the oversample was also not suitable for the Rainmaker equipment; therefore the process of locating a suitable downhill site as described earlier was enacted and resulted in a road segment that fell within the higher slope category.
Figure 4.1. Locations of road segments selected for simulated rainfall experiments on EARS property.
Table 4.1 Slope and slope category for each road segment.

<table>
<thead>
<tr>
<th>Slope Category</th>
<th>Actual Slope (%)</th>
<th>Segment Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-3.0</td>
<td>2.0</td>
<td>G</td>
</tr>
<tr>
<td>0.0-3.0</td>
<td>3.0</td>
<td>H</td>
</tr>
<tr>
<td>3.1-6.0</td>
<td>4.0</td>
<td>A</td>
</tr>
<tr>
<td>3.1-6.0</td>
<td>6.0</td>
<td>E</td>
</tr>
<tr>
<td>6.1-9.0</td>
<td>8.5</td>
<td>D</td>
</tr>
<tr>
<td>9.0+</td>
<td>13.5</td>
<td>B</td>
</tr>
<tr>
<td>9.0+</td>
<td>15.0</td>
<td>F</td>
</tr>
<tr>
<td>9.0+</td>
<td>16.0</td>
<td>C</td>
</tr>
</tbody>
</table>
4.2 Sediment production from the road surface

4.2.1 Volume of runoff from the road surface

The total volume of surface runoff from each road segment was estimated from timed measurements of runoff volume at the collection point at the bottom of each road segment through the rainfall simulations. An example of runoff volume from a road segment is shown in Figure 4.2.

![Graph](image)

Figure 4.2. Example of runoff discharge from road segment G.

The runoff curves for each road segment generally had a steep increase at the beginning of the trial, leveled off and decreased quickly after the RainMaker pump was turned off. At all road segments the wetting front reached the sampling point quicker during the second run compared to the first. At site A, the difference in wetting front times was 1 minute and 30 seconds. The RainMaker applied a consistent amount of
rainfall over the surface of each road segment with each rainfall simulation; however, it was applied to an area that was often wider than the road surface. Applied precipitation was also lost to infiltration into the road surface and evaporation. While approximately 4,700 liters of water was pumped through the RainMaker with each rainfall simulation, only 939 to 2,126 liters were measured at the end of each road segment as surface runoff (Table 4.2).

<table>
<thead>
<tr>
<th>Segment</th>
<th>Total Surface Runoff (l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Run 1</td>
</tr>
<tr>
<td>A</td>
<td>1253</td>
</tr>
<tr>
<td>B</td>
<td>1607</td>
</tr>
<tr>
<td>C</td>
<td>1468</td>
</tr>
<tr>
<td>D</td>
<td>939</td>
</tr>
<tr>
<td>E</td>
<td>1687</td>
</tr>
<tr>
<td>F</td>
<td>1277</td>
</tr>
<tr>
<td>G</td>
<td>1027</td>
</tr>
<tr>
<td>H</td>
<td>1426</td>
</tr>
</tbody>
</table>

Table 4.2. Surface runoff volume (liters) at each road segment with each run of the RainMaker. *Site F had pump problems and total pump time was 18:30 minutes for Run 2.

4.2.2 Concentration of sediment produced from the road surfaces

Runoff samples were collected from each road segment at timed intervals during each rainfall simulation and analyzed for TSS at an offsite laboratory. An example of TSS measured at one road segment with a rainfall simulation is shown in Figure 4.3.
Using the total runoff volume from the road segments and the road segment mass estimates, sediment concentrations were calculated for each RainMaker run across all eight segments. The average concentration of sediment produced at the road segments with rainfall simulation ranged from 1.2 (segment A, run 1) to 8.1 (segment H, run 2) g/l and averaged 3.0 g/l for the first run and 4.9 g/l for the second run across all segments. At all but one road segment (segment B), the concentration of suspended sediment increased between the first and second runs of the RainMaker (Table 4.2).

Figure 4.3. Measured total suspended sediment at timed intervals for segment C.
Table 4.3 Average concentration of sediment produced at the road segments with each run of the RainMaker.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Run 1 (g/l)</th>
<th>Run 2 (g/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.2</td>
<td>2.2</td>
</tr>
<tr>
<td>B</td>
<td>4.8</td>
<td>4.5</td>
</tr>
<tr>
<td>C</td>
<td>3.8</td>
<td>5.7</td>
</tr>
<tr>
<td>D</td>
<td>2.0</td>
<td>2.8</td>
</tr>
<tr>
<td>E</td>
<td>3.2</td>
<td>3.6</td>
</tr>
<tr>
<td>F</td>
<td>3.2</td>
<td>7.2</td>
</tr>
<tr>
<td>G</td>
<td>1.7</td>
<td>5.3</td>
</tr>
<tr>
<td>H</td>
<td>3.8</td>
<td>8.1</td>
</tr>
</tbody>
</table>

4.2.3 Mass of sediment produced from the road surface

The mass of sediment produced from each simulated rainfall experiment was estimated using the concentration of suspended solids from the grab samples and graphs of runoff. Sediment production from the road surface varied from 1,289 g (segment A, run 1) to 11,630 g (segment H, run 2) and averaged 42 g/m² (standard deviation 16 g/m²) as shown in Table 4.4. The graphs of sediment production over time for each road segment show a steep increase in sediment after the wetting front reached the sample point and then declined over the precipitation simulation until surface runoff ceased. The shape displays a “first flush” of sediment where the greatest amount of sediment is mobilized at the beginning of the simulation experiment and declines over time. Segment G had the largest increase between runs and segment H had the highest single run.
productivity (Table 4.4). All road segments saw an increase of nearly double (95 % increase) the sediment production between the first and second runs. This increase typically occurred during the first 20 minutes of the RainMaker simulations (Figure 4.4). Graphs of sediment production for each individual road segment are shown in Appendix A.

Table 4.4 Production of sediment by run, average sediment production over both runs, and increase between runs for each road segment and the overall averages.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Run 1 Sediment (g)</th>
<th>Run 2 Sediment (g)</th>
<th>Two Run Average Sediment (g)</th>
<th>Increase Between Run 1 and 2 (g)</th>
<th>Increase Between Run 1 and 2 (%)</th>
<th>Production (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1290</td>
<td>2790</td>
<td>2040</td>
<td>1501</td>
<td>116</td>
<td>18</td>
</tr>
<tr>
<td>B</td>
<td>7800</td>
<td>8534</td>
<td>8167</td>
<td>734</td>
<td>9</td>
<td>63</td>
</tr>
<tr>
<td>C</td>
<td>5967</td>
<td>9363</td>
<td>7665</td>
<td>3397</td>
<td>57</td>
<td>55</td>
</tr>
<tr>
<td>D</td>
<td>1862</td>
<td>4138</td>
<td>3000</td>
<td>2276</td>
<td>122</td>
<td>25</td>
</tr>
<tr>
<td>E</td>
<td>5998</td>
<td>7415</td>
<td>6707</td>
<td>1416</td>
<td>24</td>
<td>34</td>
</tr>
<tr>
<td>F</td>
<td>3924</td>
<td>4568</td>
<td>4246</td>
<td>643</td>
<td>16</td>
<td>38</td>
</tr>
<tr>
<td>G</td>
<td>1603</td>
<td>6240</td>
<td>3921</td>
<td>4637</td>
<td>289</td>
<td>38</td>
</tr>
<tr>
<td>H</td>
<td>5118</td>
<td>11630</td>
<td>8374</td>
<td>6512</td>
<td>127</td>
<td>64</td>
</tr>
<tr>
<td>Average</td>
<td>4195</td>
<td>6835</td>
<td>5515</td>
<td>2640</td>
<td>95</td>
<td>42</td>
</tr>
<tr>
<td>Std.</td>
<td>2261</td>
<td>2778</td>
<td>2340</td>
<td>1940</td>
<td>87</td>
<td>16</td>
</tr>
</tbody>
</table>

34
Figure 4.4. Average sediment production for all eight road segments. Both runs at each road segment exhibit a “first flush” of sediment. At each segment the second run exhibited higher rates of sediment production.

4.3 Characteristics of the road network

4.3.1 Physical characteristics of the road segments

Although the entire road network at EARS visually appeared to be in a similar condition and had similar vehicle use, the characteristics of width, slope, strength, and surface shape varied between the road segments. The width of the road ranged from 3.4 to 6.0 meters and averaged 4.3 meters (Table 4.4), road slope ranged from 2.0-16.0 % and
averaged 8.5 %, and road surface strength ranged from 7.6-15.6 CIV and averaged 12.3.

All segments except A did not have a functional roadside ditch and had 61 meters of wheel ruts. Segments E, C, and B had gullies present.

Table 4.5 Road segment attributes for the 8 sampled road segments arranged by increasing sediment production.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Average Sediment produced (kg)</th>
<th>Width (m)</th>
<th>Slope (%)</th>
<th>Strength (CIV)</th>
<th>Functional Ditch</th>
<th>Wheel ruts (m)</th>
<th>Gully</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.04</td>
<td>3.7</td>
<td>4.0</td>
<td>12.5</td>
<td>yes</td>
<td>30</td>
<td>no</td>
</tr>
<tr>
<td>D</td>
<td>3.00</td>
<td>4.0</td>
<td>8.5</td>
<td>9.8</td>
<td>no</td>
<td>61</td>
<td>no</td>
</tr>
<tr>
<td>G</td>
<td>3.92</td>
<td>3.4</td>
<td>2.0</td>
<td>15.2</td>
<td>no</td>
<td>61</td>
<td>no</td>
</tr>
<tr>
<td>F</td>
<td>4.25</td>
<td>3.7</td>
<td>15.0</td>
<td>15.6</td>
<td>no</td>
<td>61</td>
<td>no</td>
</tr>
<tr>
<td>E</td>
<td>6.71</td>
<td>6.0</td>
<td>6.0</td>
<td>12.1</td>
<td>no</td>
<td>61</td>
<td>yes</td>
</tr>
<tr>
<td>C</td>
<td>7.67</td>
<td>4.6</td>
<td>16.0</td>
<td>11.0</td>
<td>no</td>
<td>61</td>
<td>yes</td>
</tr>
<tr>
<td>B</td>
<td>8.16</td>
<td>4.3</td>
<td>13.5</td>
<td>7.6</td>
<td>no</td>
<td>61</td>
<td>yes</td>
</tr>
<tr>
<td>H</td>
<td>8.37</td>
<td>4.3</td>
<td>3.0</td>
<td>14.4</td>
<td>no</td>
<td>61</td>
<td>no</td>
</tr>
<tr>
<td>Average</td>
<td>5.52</td>
<td>4.3</td>
<td>8.5</td>
<td>12.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>2.50</td>
<td>0.8</td>
<td>5.6</td>
<td>2.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3.2 Road characteristics that influence sediment production

Pairwise correlation matrices were used along with linear models to identify road characteristics that influenced the production of sediment. The production of sediment from the road surface was strongly correlated with width of the road segments but showed no correlation with slope and strength.
The results from the pairwise correlation (in R, pearsons, no missing data) between the production of sediment from the road surface, “production,” and the road characteristics are shown in Table 4.5. Road width had the highest correlation at $p=0.50$. The average sediment production per segment and road segment width data showed no concerns of non-normality for production ($w=0.8949, p=0.2599$; Shapiro-Wilks with null hypothesis of a normally distributed population) while width showed signs of non-normality ($w=0.8066, p=0.03371$). The production data did not show signs of skewness ($\alpha=0.05$) while the distribution of width had some skew (production: skew $=-0.1010, z=-0.1122, p=0.9107$, width: skew $=1.5132, z=1.6269, p=0.1038$). A natural log transformation (ln) improved the distribution of the variable in terms of normality but increased the skewness (normality, $w=0.8974, p=0.2737$, Skew=$-0.4779, z=-0.529, p=0.5968$) and was used for model fitting. These tests and transformation allow the data to meet assumptions needed for the data to be investigated using a linear model.

Table 4.6. Pairwise correlation matrix for the dependent variable (production) and three independent variables (width, slope, and strength).

<table>
<thead>
<tr>
<th></th>
<th>Production</th>
<th>Width</th>
<th>Slope</th>
<th>Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production</strong></td>
<td>1.00</td>
<td>0.20</td>
<td>0.29</td>
<td>-0.26</td>
</tr>
<tr>
<td><strong>Width</strong></td>
<td>0.50</td>
<td>1.00</td>
<td>0.04</td>
<td>-0.26</td>
</tr>
<tr>
<td><strong>Slope</strong></td>
<td>0.29</td>
<td>0.04</td>
<td>1.00</td>
<td>-0.39</td>
</tr>
<tr>
<td><strong>Strength</strong></td>
<td>-0.26</td>
<td>-0.26</td>
<td>-0.38</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Road width (ln transformation, Pearsons pairwise correlation=0.9844) was investigated using a linear model and was found to be a significant predictor of sediment production from the road surface from the eight road segments (lnWidth coefficient=10.353, p=9.35e-06, y=10.353x-12.577, $r^2=0.97$). While slope and strength did not have a significant correlation with the production of sediment from the road surface, the strong relationship between road sediment production from the road segments and road width indicated that individual segment width was driving sediment production due to increase in road surface area. Road sediment production was calculated on a unit area basis (grams per square meter or pounds per square foot) instead of a linear unit basis to account for the correlation.
Chapter 5: Discussion

5.1 Selection of road segments

Although the selection of road segments was randomized, not all of the segments that were initially selected were suitable for the procedures of the RainMaker simulations. The method used to determine a suitable road segment possibly introduced bias into the sample. This bias leaned toward roads that had more linear feet of wheel ruts. One of the main factors contributing to the unsuitability of a segment is if a sample point at the bottom of the segment could not be identified. The lack of a suitable sample point was more probable for roads that had a crown shape or drained to more than one point. Roads with a crown shape tend to shed water off the road surface rather than down the road in wheel ruts or gullies. However, most of the roads at EARS were not in this condition and the most frequent reason that a site was not suitable was because there were no flat areas sufficient to place the portable water bladders. Even when a site was discounted due to lack of a single sample point, the actual road condition was visually observed to be similar to those road segments that fit the sampling criteria.

5.2 Limitations of the RanMaker protocol

The Rainmaker procedures in this study were modeled after the protocol established by The Pennsylvania State University so that the results from this research could be used as part of a larger study. However, there are some limitations to using this protocol including: lack of a traffic only treatment on the road segments, short road segments (30.5 m), and a lengthy process to complete one pair of experimental simulations, limiting the total number of segments that could be tested. The requirement
of no antecedent moisture on the road surface also limited rainfall simulations to the summer months where regional climate patterns are typically drier for the area of study. The results may not be representative of sediment production during other seasons where antecedent moisture conditions are less likely to be dry.

5.3 Rates of sediment from the road surface

5.3.1 Sediment availability

The RainMaker simulations were all conducted on a standardized length (30.5 m) of road, however road width, and therefore surface area, of the test segments varied. The strong relationship between road width and sediment production suggests that sediment production from the road surface is a function of road surface area. Intuitively this is appropriate as a wider road provides more surface for erosional forces to act on. The production of road sediment has been attributed to the availability of fine sediment at the surface of the road and the generation of runoff from the road surface (MacDonald & Coe, 2008). Considering this, future research, including those using sediment models, should consider sediment production from road area rather than road length. Results of the RainMaker simulations support sediment availability as a primary driver for production by the presence of a “first flush” during the rainfall simulations and an increase in production due to wet conditions with traffic that may disturb the road surfacing and make additional sediments available for runoff.

5.3.2 Wet road use and sediment production

The combination of a wet road surface and 20 vehicle passes between RainMaker runs at each road segment increased the total mass of sediment produced from the road
surface from 9.4% to 289.3% with an average of 95.2%. A pre-saturated road surface reduced the lag time between the start of the simulated rain event and when the wetting front reached the sample point. This increased the volume of surface flow in the first few minutes of the rainfall simulations and may have also contributed to the increase in sediment production during the first flush. Further, the light truck passes likely detached more sediment making it available for transport and contributing to the large increase in sediment production from the first to second runs of the RainMaker. The average increase in sediment production with vehicle traffic and wet road conditions falls within the range of increases as noted by other studies (2 to 1000 times) and also supports the hypothesis that sediment availability can be a driver of the production of sediment from forest roads (MacDonald & Coe, 2008; Ramos-Scharron & MacDonald, 2007; Reid & Dunne, 1984). Traffic can increase the erosion rates of the road surface through multiple ways including the decrease of infiltration of the road surface, reduction of vegetative cover on the road surface, and the increase on fine material availability (MacDonald & Coe, 2008). The increase of fine materials and decrease of infiltration rates are attributed to vehicle wheel loading that compacts the road structure as well as accelerates the breakdown of larger materials into size classes suitable for transport.

The road segment with the largest relative increase (G) and the segment with the largest absolute increase (H) were also the segments with the most shallow slopes. Sediment from lower gradient roads may be produced by the breakdown of particles due to traffic over time but is not mobilized from small rain events and is therefore stored until a sufficient rain event occurs mobilizing large amounts of sediment. Although the
road surface material was not analyzed during the study, the segment that was least
effected by traffic passes over a wet surface was segment B; a segment with a higher
gradient and where it was noted that the surface flow paths were in areas of the road
surface with large materials present and an absence of small fines (Figure 5.1). The
armoring of these flow paths allows for a reduction in fine sediment production during
the stresses of vehicle passes. Road segment G had the highest relative increase in
sediment production between RainMaker runs and the lowest slope of 2%. Segment G
had large amounts of small fine material that were disturbed during the traffic passes
becoming easily available for detachment and movement (Figure 5.2).

Figure 5.1. Surface flow path of road segment B. It was observed that this segment had a
greater proportion of large road material (rock) in the flowpath. This segment had the
smallest increase in sediment production between RainMaker runs.
5.3.3 Sediment production and segment slope

Given the role slope plays in hydraulic power, the ability of a fluid to detach and transport material, slope could be a strong driver of sediment production on a road segment basis. Indeed, slope is referred to as a primary driver of road sediment production in the literature (MacDonald, et al., 1997). The volume and velocity of overland flow drives the erosive force and thus road surface erosion is thought to be based on the interaction between the flowpath length, and slope (Luce & Black, 1999). However, in this research slope did not influence the production of sediment from the road surface. Given the relatively short length of the test segments, the contribution of the slope of the road segment may be understated. The ability of the road surface runoff to detach and transport road surface sediment may be underestimated with the current sampling protocol and segment length due to the inability of the road surface runoff to increase in velocity before being measured at our sampling location. Thus, the sediment
production rates may be underestimated across the trials, and further more on the
segments with steeper slopes. This is supported through theories of open channel flow
where flow is driven by the acceleration due to gravity and, as such, flow velocity
increases with increased length down a continuous channel. Velocity of flow is the main
driver for sediment entrainment and this may account for slope not influencing sediment
production in our study. Surface flow was not able to reach a velocity necessary for
additional sediment entrainment before reaching the sample point. The interaction
between segment length and slope was identified by Luce and Black (1999) who suggest
that these road characteristics are more influential on sediment production together than
individually. Segment slope may also limit sediment availability over time with steeper
segments being eroded down to larger particles or subsurface non-erodible parent
material (bed rock). An interesting finding in this study is that the shallow sloped
segments had both the highest and lowest sediment production rates (Site H at 3% slope
produced 64.38 g/m2, and Site A at 4 % slope produced 18.30 g/m2). The low
production rate for Site A might be attributed to the confounding presence of a functional
vegetated roadside ditch and it being the only segment that did not have 61 m of wheel
ruts, having only 30.5 m, therefore a shorter flowpath on the road surface. The passage of
surface flow through a vegetated ditch is likely to reduce the sediment production from
the segment due to the increased roughness provided by the vegetation, reducing flow
velocity and allowing an opportunity for sediments to fall out of suspension.
5.4 Comparison of sediment production rates between this study and previous work

The average rate of sediment production from road surfaces in this agricultural watershed (2.625 g/m²/mm) was lower than the rates determined by a similar study using the RainMaker in forested roads in Pennsylvania. However, the rates of sediment production for this study were significantly higher than rates published from five other recent studies in forested landscapes (Table 2.1). Road born sediment rates in Reid and Dunne’s 1984 study in a forested watershed sediment rates were highly influenced by traffic with high traffic loads being defined by four fully loaded trucks per day. With this traffic load sediment production increased 7.5 times, and decreases to 0.8% of that value when traffic is restricted to occasional light truck passes. While our study did not isolate traffic only, the combination of wet road surfaces and traffic production rates nearly doubled. This is lower than the increase reported by Reid and Dunne, but our increase in production may have been much higher if our truck passes were fully loaded log trucks as studied by Reid and Dunne. In another forested watershed in St. Johns (MacDonald et al., 2001) natural rain events were used to quantify sediment production and rates were shown to be correlated with the intensity of the rain events. The wide range of rates reported (Table 2.1, high end of range with greater production rates than our study) could be attributed to the high amounts of sediment produced by large storms (hurricane scale) that took place on the island during the study’s monitoring period. A study in a forested watershed in Australia on heavily used gravel logging roads had rates of sediment production similar to this research and their estimate was generated using simulated rainfall with similar rainfall characteristics to the RainMaker on small (1.5m by 2.0 m) plots over various road surface types (Sheridan & Noske, 2007). The low production
rates from their study were produced by gravel roads that were restricted to 2 wheel-drive traffic only suggesting traffic type as a driver of sediment production. Their study also measured sediment production from both gravel and native soil road surfaces and found that production rates from the native soil surfaced roads contributed higher amounts than the gravel (except for the very heavily used gravel road). The two studies with the lowest production rates came from watersheds that were characterized by mixed urban and agricultural land cover/use (Arnaez, et al, 2004; Scharron, 2010). Rainfall simulations in the Arnaez study produced similar results to our study with a significant increase in sediment concentration at the beginning of the simulations quickly tapering off as sediment availability decreases. The authors note that low road sediment production is likely due to surface compaction armoring the road from particle detachment due to raindrop splash. The authors also note the limitation of rills being formed due to the small plot size (1385 cm$^2$) limiting sediment production. Sediment production measured over nearly two years of natural precipitation by Scharron et al. (2010) showed little correlation between sediment production and rainfall amounts but showed significant correlation between production and slope. The authors note that production rates declined over time due to the first half of the study having higher rainfall intensities than the second half and increased surface cover during the second half of the study. Sediment production rates in our agricultural setting and agricultural settings in general may be low due to the relatively low traffic rates associated with agricultural use, particularly during wet weather/seasons, and periods of no traffic use at all. The topography in an agricultural setting is likely to be more flat than some forested areas dominated by timber production; this may also limit sediment production.
Chapter 6: Conclusions

The results of this study met the research objectives by quantifying the rates of sediment production from the road surface. The production of sediment from the road surface increased with conditions of a wet road surface coupled with traffic use. This study did not identify physical road characteristics that significantly influenced sediment production but suggested that sediment availability strongly influences sediment production rates.

Road managers may reduce opportunities for road born sediment to enter the stream channel with practices such as proper road shape that promotes surface flow draining off the road instead of down the road and road maintenance and construction practices that reduce sediment availability. Practices should focus on road sections that have been identified as producing large quantities of sediment and road sections near stream crossings.

Rural roads are ubiquitous on the landscape and are required by natural resource managers, land owners and recreationists to access the landscape. These roads are likely to see increases in the use and construction due to the expansion of natural resource extraction such as shale gas and oil. Given these considerations, the proper steps need to be taken in order to protect surface water resources from increased sedimentation.
References


Appendix A: Pictures of the eight road segments during the RainMaker simulations and description of the weather conditions during the RainMaker runs.

Segment A: Sun with no wind. Road still slightly damp from overnight rain.

Figure A1 Segment A before run 1 looking up slope from near runoff sample point.
Figure A2 Road surface material of segment A.
Figure A3 Segment A runoff sample point, notice runoff also entering sample point from vegetated roadside ditch
Segment B: Slight wind, direction across the road surface toward the sprinklers, sunny.

Figure A4 Segment B looking from the top of the test segment.
Figure A5 Segment B during RainMaker run.
Figure A6 Segment B surface material (left side) and road gully.
Segment C: No wind, sunny

Figure A7 Segment C before RainMaker runs.
Figure A8 Segment C during beginning of run 2.
Segment D: Sunny with wind gusts during run 2

Figure A9 Segment D before RainMaker runs. Notice sample point on left side of photo.
Figure A10 Segment D road surface material.
Figure A11 Segment D during RainMaker run.
Segment E: Sunny with no wind

Figure A12 Segment E before runs, sample point above pump on right side of photo.
Figure A13 Segment E sample point.
Segment F: Sunny with no wind

Figure A14 Segment F before RainMaker runs.
Figure A15 Segment F sampling point and road surface material before runs.
Figure A16 Segment F during RainMaker Run.
Segment G: Sunny with no wind

Figure A17 Segment G sample point.
Figure A18 Segment G during RainMaker run.
Segment H: Little wind and overcast clouds

Figure A19 Segment H at beginning of RainMaker run
Figure A20 Segment H during RainMaker run.
Appendix B: Sediment produced from the road surface (grams) with rainfall simulations for each road segment.

Segment A
Segment B

![Graph showing Grams vs Minute for Site B Run 1 and Site B Run 2]

Segment C

![Graph showing Grams vs Minute for Site C Run 1 and Site C Run 2]
Segment H

![Graph showing data for Site H Run 1 and Site H Run 2 over minutes 1 to 30. The y-axis represents grams, ranging from 0 to 1400. The x-axis represents minute intervals.]