ASSESSMENT OF SEDIMENT RUNOFF FROM NATURAL GAS WELL DEVELOPMENT SITES

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Storm water sediment runoff from disturbed landscapes has the potential to impair aquatic environments. Small construction sites of 1-5 acres in the United States are currently regulated by the United States Environmental Protection Agency to minimize storm water runoff damages to the environment. Gas well construction sites are similar to other construction sites in how the landscape is altered, but are not similarly regulated. This study identified sediment runoff from gas well development sites by collecting it in traps and weirs, and by measuring sediment debris lobes. Sediment primarily consisted of silt and clay sized particles. Sediments from two gas well sites formed five debris lobes that ranged in size from 325 to 3,290 square feet. Sediment loadings estimated from the debris lobes averaged 57.1 tons per year/acre. Future studies should focus on further quantification of sediment movement off of gas well sites and identify effective erosion control methods.

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1. INTRODUCTION

Maintaining and improving waters within the United States has been one of the main objectives of the United States Environmental Protection Agency (USEPA) since its creation in 1970. To meet water quality goals, the USEPA regulates and encourages the study, monitoring, and improvement of watersheds, streams, rivers, and other receiving water bodies by city, county, and state governments. In March 2005 the City of Denton, Texas, as part of a 104b3 Water Quality grant, entered into Cooperative Agreement CP-83207101-1 with the USEPA to determine, through monitoring programs, if gas well construction activities differ from normal construction activities in how they affect water quality (USEPS, 2006b). Unlike construction sites, oil and gas well production sites in Texas are not regulated and have not been extensively studied for storm water runoff effects. The knowledge gained from this cooperative agreement should improve the ability of the USEPA, as well as local governments, to design appropriate regulations regarding storm water runoff from oil and gas production activities.

Recent advances in the science of natural gas recovery, specifically fracturing techniques and horizontal drilling employed in the Barnett Shale (Durham, 2005), have dramatically increased exploration and recovery of natural gas in the North Central Texas region. Thousands of gas wells have been drilled in the area (Devon, 2004) and numerous opportunities for gas well storm water runoff studies exist. The focus of any storm water runoff study of natural gas exploration and production activities should be on the areas affected by the construction and maintenance of gas well sites, roads and buried pipelines. Generally, gas well extraction sites have two distinct parts: an inner gravel covered area where drilling, extraction and equipment maintenance occurs, and an outer disturbed area that is altered during the initial construction and exploration phase of a gas well, often to spread excess dirt or drilling mud to dry, and allowed to re-vegetate once a well is producing gas and requires only maintenance operations. As of 2005, hundreds of sites were already located within the City of Denton (Figure 1) and its extra-territorial jurisdiction (ETJ). And, in the coming years, as many as 650 more sites are expected to be constructed in the Denton area (QAPP, 2005).

Unlike private and public construction sites, storm water runoff from gas well sites that are less than five acres is not currently regulated by the USEPA. Research has shown that storm water runoff from construction sites can contain sediments and other materials related to construction activities, such as solid and sanitary wastes, oil, grease, and fertilizers (USEPA, 2000), which have the potential to seriously impair streams and receiving waters (Schuelor, 1997; Nelson and Booth, 2002). Petroleum exploration and recovery representatives, however, contend that unlike runoff from regulated construction sites, the construction and operation of gas well sites does not significantly contribute to watershed degradation (QAPP, 2005). The intent of Cooperative Agreement CP-83207101-1 is to provide data to the USEPA that will be useful in determining if oil and gas well activities on small acreage sites should be regulated for storm water runoff effects (GAO, 2005).

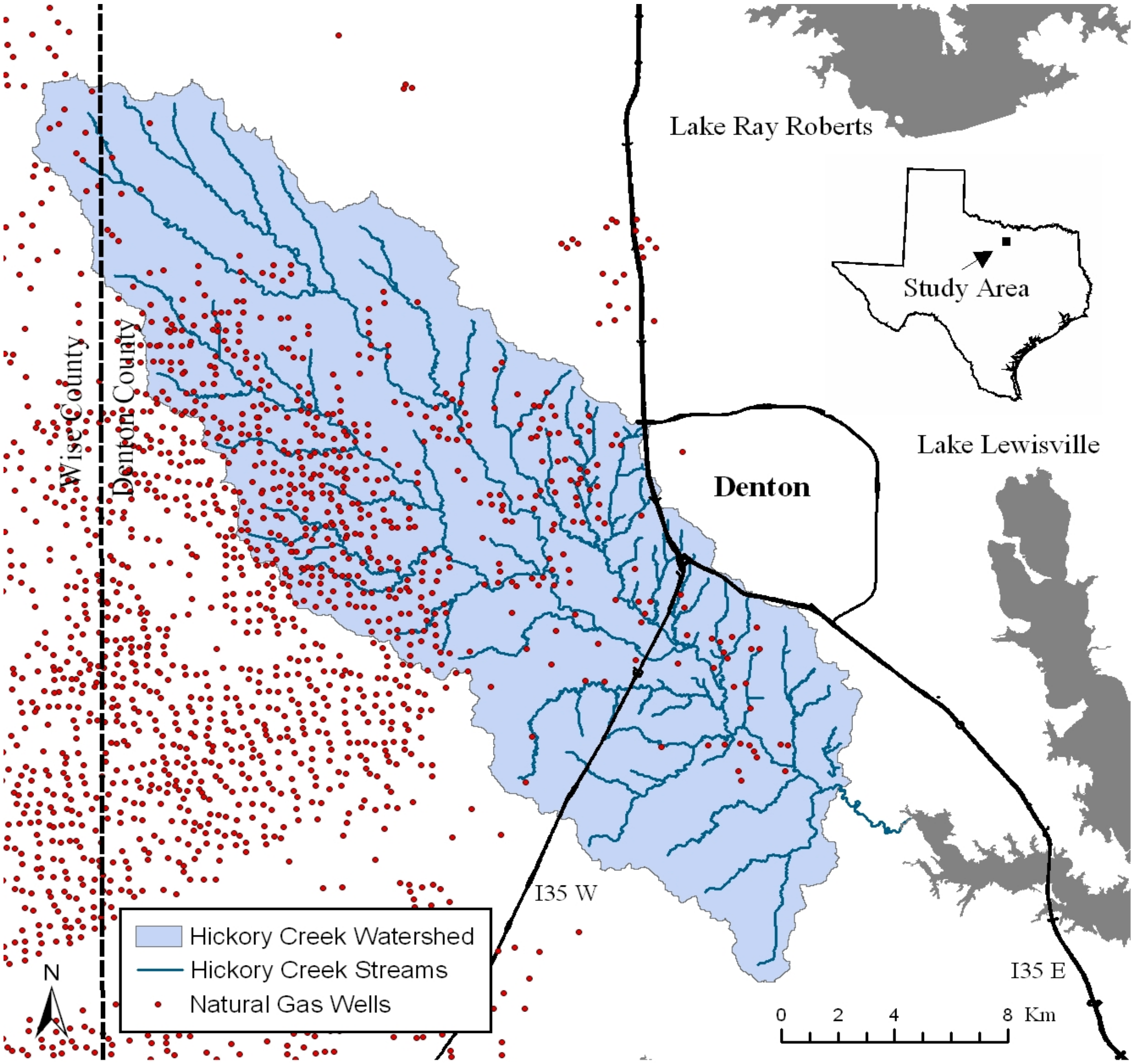

Figure 1. Natural gas well sites in western Denton County,(Wachal, Banks, and Hunter, 2005).

To fulfill research goals, the City of Denton is evaluating storm water runoff for constituents such as alkalinity, pH, total dissolved and total suspended solids, and petroleum hydrocarbons, by collecting and analyzing storm water runoff from or near gas well sites. Initially five sites were selected to fulfill the objectives of the city's research goals. Three of the sites were gas well extraction areas, while two were at sites near to gas wells, but in areas that remained in natural, relatively undisturbed conditions. The undisturbed sites will act as controls on the study and storm water runoff from them will reflect the type of runoff that would naturally occur in the vicinity of the study sites.

At all of the sites, storm water runoff will be collected with weirs and automated sampling devices. Weirs are constructed devices with calibrated openings that enable the relatively easy measurement of gas well site runoff volumes. Automated samplers, triggered by either storm water or by rain gauges situated at each site, collect periodic water samples from the weirs. When storm water runoff occurs, substances are carried by flowing water either in solution, suspension, or as bedload. Under the terms of the cooperative agreement, all of the parameters examined by the City of Denton will only be from substances either dissolved in solution or suspended by the flow of storm water. The study of other sediment runoff, such as bedload collecting in the weirs, sediment (bedload and suspended) transported downslope from disturbed areas or down local stream channels, is not included in the cooperative agreement, even though all these additional sources of sedimentation may be active.

The intent of this study is to: (1) determine the extent of sediment eroding from gas well sites; (2) characterize by particle size the sediment moving off of gas well sites; (3) determine if sediment is traveling beyond the perimeters of gas well sites, such as into local stream channels and water bodies; and (4) identify factors that contribute to sediment runoff from the gas well sites such as the slope, size of drainage area, permeability of gas well sites, and rainfall volume and intensity. Samples of storm water sediment runoff from the gas well sites will also be compared to samples from the control watersheds to determine if significant differences in sediment magnitude and character exist between the disturbed and natural sites.

Results of this research should benefit local, state, and federal policy makers in determining if storm water runoff regulations, similar to those currently applied to small construction sites, should be applied to small acreage gas well extraction activities.

2. LITERATURE REVIEW

Based on the objectives of this research, a review of literature covers the following subjects: (1) problems associated with sedimentation; (2) methods of collecting and characterizing runoff sediment; (3) sediment movement from storm water runoff; (4) sediment loadings from construction sites; and (5) oil and gas industry erosion control methods.

2.1. Problems Associated with Sedimentation

Sedimentation, from both bedload and suspended load is normal in most watersheds but can have considerable effects when it increases beyond what is typical for a water body (Pitt, 2004). Channel morphology for instance can change considerably when the sediment load increases (Simons and Senturk, 1977) and cause frequent and intense flooding, as streams, rivers, flood control structures, and reservoirs fill with sediment. Heavy sedimentation can also affect aquatic life. Fish have trouble spawning and some plants cannot grow when a streambed becomes covered in deep sediments. Other problems associated with sediments include: decreased water transparency, diminish channel depths in navigable water ways, decreased recreational use of water bodies when they become aesthetically undesirable (Thornton, et. al., 1999; Holmes, 1988; Novotny and Chesters, 1981), and eutrophication of aquatic systems when nutrients, such as nitrogen and phosphorus, are carried by sediments into water bodies (Wetzel, 2001). In a study completed by the United State Environmental Protection Agency (USEPA) in 2004, sedimentation was found to be one of the major contributors to poor stream health amongst small US streams (USEPA, 2006a).

Excessive sedimentation is often caused by anthropogenic activities that increase storm water runoff, such as removing natural vegetation, increasing slopes, or increasing the imperviousness of surfaces. Urban structures (pavements, buildings and parking lots) generally are much more impervious than natural surfaces. Heavy rain runoff that would normally be slowed by vegetation, which allows water to soak into the ground and then slowly percolate out, instead rushes over impervious surfaces and floods streams past their natural limits. Flooding is not unnatural but with urbanization, the intensity and frequency of floods increases over pre-urban conditions. A flood can scour and erode a steam channel, but then leave large sediment deposits once rushing waters slow down. Initial constructions of urban structures often have higher runoff and erosion rates than the urban structures being built. Sediment runoff from construction sites is estimated by the USEPA to be 10 to 20 times higher then sediment runoff from agricultural lands and 1,000 to 2,000 times worse than sediment runoff from forested lands (USEPA, 2000).

Because erosion from construction sites can be very high, federal, state, and most local governments within the United States regulate the control of runoff. Storm water Pollution Prevention Plans (SWPPPs) are often required before construction begins at a site (CASQA, 2003), and generally include the use of best management practices (BMPs) to control erosion. Manuals on selecting and using BMPs are plentiful and easy to obtain (EPA Region 10 website lists over 56 state level construction BMP guides (USEPA, 2004)). Examples of a few BMPs listed by the California Storm water Quality Association (CASQA) include the use of silt fencing, sediment basins and sediment traps, check dams, gravel bag berms, earthen dikes, and general site cleanliness (CASQA, 2003). For longer term erosion control more extensive BMPs are listed by the American Society of Civil Engineers, and include the use of ponds, baffle boxes, media filters and constructed wetlands (ASCE, 2001). No shortage of guidance for controlling construction site runoff exists for organizations that desire or are required to use them.

The imperviousness and degree of storm water runoff and sediment movement from gas well sites is unknown. If gas wells pads are like most anthropogenic surfaces, and are less pervious than the surfaces they replaced, then higher than natural storm water runoff and sediment movement will likely occur from them and the use of BMPs might be needed.

2.2. Collecting Sediment

Collection of sediment moving off of the gas well sites must include methods to collect bedload because it is expected to be a significant component of sediment runoff. Because bedload is not suspended within the flow of water, capturing it requires methods of intercepting it as it moves along the bed of a stream. For small streams, a bedload trap can be used. Bedload traps are essentially a container (or multiple abutted containers) placed perpendicular to the stream flow and across the entire bed of a stream. As bedload materials roll, slide, or saltate down a streambed they fall into the container and become trapped (Church, 2005).

Figure 2. Sediment trap. Keys shown for reference.

Typically bedload traps are open containers, but in cases where the collection of material of a specific size is desired, or where flow velocity might change quickly, such as from the rush of storm water, slotted bedload traps might be used (Figure 2). In constant flow situations, slotted traps are designed to capture all particles (which will all be similar in size) that roll or saltate along the channel bottom. If flow changes rapidly, such as from a thunderstorm, then the sizes of particles that become captured will change. During heavy flow, large sand particles (1-2 millimeters) and pebbles (larger than 2 millimeters) might move as bedload and become trapped, while smaller sands, silts, and clays might flow over a trap as suspended load. Once flow decreases, smaller, previously suspended particles settle down and move as bedload. These particles then become captured in the trap. For storm water runoff, a slotted trap is not useful in discriminating particle sizes in relation to flow, but the slot does help protect samples from being washed out if flow increases dramatically.

A second method to capture sediment is to have the runoff flow into a natural, or man-made catchment, such as a weir or storm water retention pond. Once a stream enters an open catchment it loses velocity and sediment deposits in the bottom of the catchment. Later, the material can potentially be related to flow volumes and velocities, either by removing and measuring it or by measuring the change in depth of the material in the catchment (Church, 2005). If a catchment, such as a pond, is able to capture the entire flow from a watershed during a precipitation event, then the sediment captured can be related to the total precipitation that the watershed received for the event. Sediments captured will represent materials that moved as both bedload and suspended sediment.

2.3. Sediment from Storm Water Runoff

Sediment movement often occurs from precipitation related to storm water surface runoff. Runoff is determined by five factors: rainfall of sufficient amount and intensity, permeability of watershed surfaces, slope of land, prominence and density of vegetation, and the moisture content of watershed surfaces before rainfall begins (Hudak, 2006). Activities normally associated with construction, such as creating roads, cutting and grading slopes (to steepen), and removing vegetation, generally increases surface runoff intensity beyond that found naturally in a watershed, while decreasing runoff duration. Runoff duration decreases because water that would normally be slowed by vegetation, or would soak into and later be released slowly from soil, instead quickly runs down slopes and over impervious surfaces.

In storm water runoff, especially where a watershed has been altered, extreme velocity changes often occur. Rapid changes in water velocity, and variation in stream morphology, enable small particles to easily switch from being suspended to moving as bedload, which often makes separating the two load types for measurement difficult (Summerfield, 1991; Haan et al. 1994). Continuous, or multiple simultaneous measurements of suspended sediments and bedload from a storm water runoff event, as well as water volume and flow measurements, would be needed to fully understand how much of each material was being moved wholly at any given time throughout the course of an event. Studies to measure bedload continuously however can be substantially more expensive then those that measure bedload for a whole event. Whereas bedload generated from a whole storm event can be captured in a simple inexpensive trap or catchment (at least for a small stream), a continuous bedload sampler must be more complex and able to collect, measure, and discard bedload at regular intervals. When cost prevents the use of continuous bedload collecting equipment, and where bedload and suspended sediments are difficult to differentiate, the two are often combined as one measurement referred to as the total non-dissolved or sediment load of a runoff event.

2.4. Sediment from Construction Sites

Compared to other land types, such as farm, ranch, and forest, construction sites produce tremendous amounts of erosion and sediments (USEPA, 2002; Canning, 1988; Wolman and

Schick, 1967). Per acre, small construction sites produce considerably more sediments than large sites, generally because large sites have higher proportions of land within the construction area not under actual construction (Wolman and Schick, 1967). For most studies, construction sediment loadings are calculated by relating the size of a site to the amount of runoff and sediments that occur during a runoff event. Sediments are usually measured by multiplying the total suspended solids (TSS) from a small representative runoff sample (generally a liter), by the volume of total storm water that runs off a site (USGS, 2000; Daniels, et. al, 1979; USEPA, 1979; & Wolman, 1967). Estimated annual erosion from a site is usually expressed as sediment loading, or the weight of sediment per unit area, per year. Area units normally are expressed in acres, hectares, square miles, or square kilometers. Loadings for small construction sites are the highest of all land uses and typical per acre loadings range from 7.5 to 500 tons per year according to the USEPA (2002), whereas loadings for forest and rangelands typically per acre are less than half a ton per year (Franklin County, Florida, 1987 in USEPA, 2002). Sediment loadings from oil and gas well sites are relatively unknown, but potentially similar to small construction sites.

2.5. Oil and Gas Industry Erosion Control

Whether for aesthetic, economic, or regulatory reasons, different segments of the oil and gas industry provide guidance to oil and gas construction and recovery operations to decrease storm water runoff and erosion from oil and gas exploration and recovery sites. An example of a manual compiled by the Independent Petroleum Association of America (IPAA), whose members according to the IPAA web site drill 90 percent of United States oil and natural gas wells, is Reasonable and Prudent Practices For Stabilization (RAPPS) (IPAA, 2005). RAPPS is designed to help oil and gas well operators choose methods of storm water runoff and erosion control based primarily on the vegetation coverage and the distance of a site from any EPA regulated water body. The document is not highly technical and gives generalized descriptions of how and why erosion occurs from oil and gas development site. RAPPS states that oil and gas operators are expected to be reasonable and prudent when deciding to use sediment control practices.

RAPPS classifies all areas of the United States according to six general categories based primarily on the slope and vegetation density. Denton, and most of the eastern United States, minus coastal and mountainous regions, falls in an area classified as the Mesic Plains. Other RAPPS regions in the United States include: Coastal Plains, Xeric Plains, Deserts, Xeric Mountains, and Mesic Mountains. RAPPS defines the Mesic Plains as having maximum slopes of less than 40%, soils that erode moderately, vegetation that is highly varied, and annual precipitation that is regular and moderate (IPAA, 2005). For oil and gas organizations operating in the Mesic Plains, RAPPS should be employed when a site is either within 250 feet of an EPA regulated water body, or when a site is within 100 feet of a regulated water body and vegetation coverage between the site and the water body is less than 75 percent. RAPPS suggests that site operators should contact an attorney or environmental professional to determine if a water body is EPA regulated, but no suggestions are made to contact professionals to determine slope and vegetation coverage. Rather, RAPPS explains that slope can be calculated by dividing any distance by the change in elevation across the distance. Examples of vegetation coverage are shown in RAPPS by several very simple drawings. Mesic Plains' soils are not explained in RAPPS other than that they might include clays and loams. Precipitation is not quantified in any way. Implications of potential landscape changes brought on by oil or gas well construction activities, such as modified slopes, removal of vegetation, or increased permeability, are not discussed in RAPPS.

To determine which erosion control methods to use, oil and gas operators follow a decision tree for each RAPPS region. Fifteen potential erosion control methods are listed and include the use of brush piles, diversion dikes, geotextiles, mulch, berms, straw bales, silt fences, and sediment traps. Preventative measures to stop erosion, such as by preserving native vegetation when possible, or keeping the slopes of excavated areas to a minimum, are not options listed on any of the decision trees. For any given erosion control method listed on a RAPPS decision tree, operators are instructed that other options to control erosion, not listed in RAPPS, may be available. Finally, if control methods utilized on a site are not working to control erosion the site operator is expected to find other control methods. RAPPS does not discuss how to quantify the effectiveness of any erosion control methods.

3. STUDY AREA

The study area includes five gas well sites located southwest of the City of Denton, in Denton County, Texas (Figure 3). Three of the sites are gas well drilling pads while two sites are undisturbed natural sites, designed as “controls” for the study. Control sites are located in undisturbed watersheds that are near, and in the same physiographic regions, as the gas well sites.

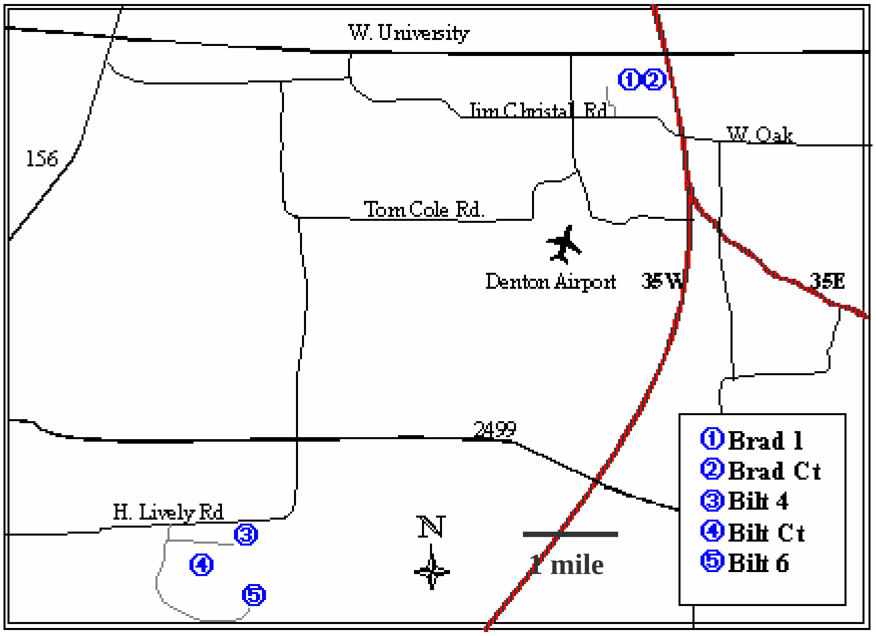

Figure 3. Map of study area.

Many of the wells being drilled or planned for future recovery activities lie within the Hickory Creek watershed, which drains into Lake Lewisville. Soils of two major physiographic areas exist within this watershed: black heavily organic, clay soils of the Grand Prairie physiographic region, and sandier well drained soils typical of the Eastern Cross Timbers physiographic area. The five sites chosen for this study lie primarily on Grand Prairie soils on lands currently used as mixed rangeland. Clay, clay loam, and stony clay soils predominate the study area (Ford and Pauls, 1978). Underlying bedrock at all the sites is an undifferentiated mixture of limestones, marls, sandstones, ironstone concretions, shales, and calcareous clay (Barnes, 1991). Abundant beige marl and limestone rocks, and small amounts of ironstones, are visible on the surface at the Biltmore sites, while the Bradford sites yields few stones. For all sites, materials eroded presumably will reflect local soil and be composed heavily of clay.

One gas well site and one control site are located off of Jim Crystal road, a mile or so west of the UNT campus, and are named after the property owner Jim Bradford, and designated Bradford One (Brad1) and Bradford Control (BradCt). The other two pad sites and control site are located off of C. Lively road on ranch land owned by Robson Ranch, an integrated housing development south of the property. The gas well sites though retain the name of the previous property owners and are called Biltmore Four (Bilt4), Biltmore Six (Bilt6), and Biltmore Control (BiltCt). All of the Biltmore properties are approximately five miles west of Interstate I-35W and county road 2499, and located on relatively treeless *Bothriochloa saccharoides* (Bluestem) (TPWD, 1984) rolling prairie with well developed stream networks. Contrastingly, the Bradford sites are on relatively flat prairie land heavily vegetated with *Prosopis juliflora* (Mesquite) and *Gleditsia triacanthos* (Honey locust). The Natural Resources Conservation Services database shows that the soils between the Bradford and Biltmore sites do not differ significantly.

A key difference between the Bradford and Biltmore sites (gas wells and controls), that is expected to strongly influence degrees of erosion, is the slope of the land surrounding each gas well site. Natural slopes, and those created through gas well construction, approach 15% in some areas around the Biltmore sites, whereas the land around the Bradford sites has slopes of about 1%. Gas well pads in general, where drilling, extraction and maintenance activities occur, are not significantly sloped. They are designed with slopes gentle enough to promote drainage, but not hinder use and essentially appear flat. Gas well pads are also relatively homogeneous in that most are less than four acres, covered in crushed limestone gravel, and designed to last the life of the well, potentially twenty or more years. Surrounding each pad is a disturbed area where drilling pit mud is usually dried and, if the pad is cut into a hill, excess dirt is added or removed. Pads built into hillsides are likely more prone to erosion than those on more level ground (See Figure 4 and Figure 5). In order to create a flat area for a gas well pad, a hill must be cut out. Dirt from an upslope area of the hill is moved to the downslope area to build the height at the downslope area. Both areas upslope and downslope from the gas well pad end up much steeper then the natural hill after construction is completed. Once the pad is constructed disturbed areas are smoothed out by tractors and generally left to re-vegetate naturally. Figure 6 shows a typical completed gas well pad and disturbed area.

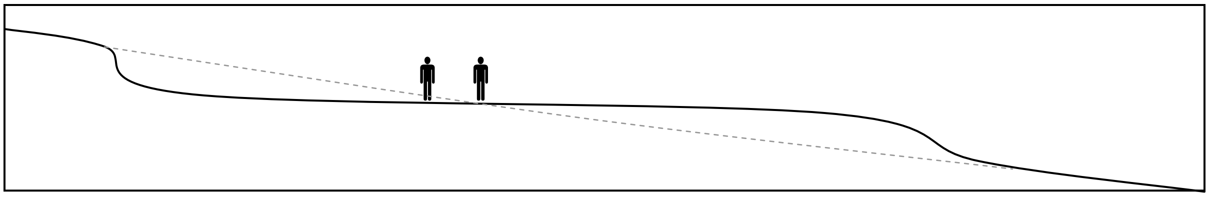

Figure 4. Profile of a gas well pad. The dashed line represents the original hill slope and the solid line represents the contour of the hill after a gas well has been constructed. The flat area where the two figures are standing is the pad. Areas immediately up and down hill from the pad are steeper and likely more prone to erosion than before the pad was built.

Figure 5. Gas well pad cut into hillside. Original hill slope slants from left to right behind the car and, where the car is parked, has been cut away by six or more feet to create the flat pad area.

Figure 6. Typical gas well site. A filter berm was used to prevent erosion and can be seen as the thin black line running through the grass along the edge of the disturbed area.

Some RAPPS listed erosion control methods were used at the sites, including mulch berms created around the perimeters of the disturbed areas during the early extraction phase of each site (required by city ordinance), and a diversion berm used on the south upslope edge of the Bilt6 pad that directed runoff into the Bilt6 disturbed area. Figure 6 shows a site (not one used for the study) that has a filter berm surrounding parts of its disturbed area. Roadside ditches and minimum road slopes were also used in various places at the gas well sites and access roads.

Climate in northeast Texas is general classified as subtropical and is humid during warm months and dry during cooler months (Taft and Godbey, 1975; NOAA, 1974). Summers are typically hot and have multiple 100° F+ days, although the average July high temperature is 96° F. Winters are mostly mild and cool with occasional sub-freezing days, and an average low January temperature of 34° F (Taft and Godbey, 1975). Denton generally receives 31.5 inches of precipitation in an average year, but precipitation can also vary widely and has ranged from less than 20 inches to over 50 inches in past years. Precipitation per month can also vary widely and it is not uncommon for a month to receive all of its precipitation in one or two heavy showers, or to receive almost no rain during some years (NOAA, 1974). April and May are normally the wettest months and July and August the driest. Extreme weather conditions occasionally occur and it is not unheard of for rain in excess of 5 inches per hour to fall or for hailstones and tornadoes to strike the area (Taft and Godbey, 1975). Because precipitation can vary to a great degree periodic flooding and droughts can occur depending on the frequency and intensity of precipitation.

4. METHODS AND MATERIALS

Methodology for the study revolved around three areas: 1) the use of methods and equipment, such as global positioning system (GPS) equipment, a geographic information system (GIS), and traditional mapping methods, to accurately map the study sites and disturbances within each site; 2) developing methods and devices, such as weirs, and using automated water samplers, to gather storm water runoff and sediment data; and 3) using procedures and equipment to characterize sediment samples.

4.1. Site Mapping

Features relevant to the study, such as the locations of weirs, gaswell pad perimeters, and the perimeters of disturbed areas were recorded using GPS equipment. The use of GPS equipment has become the standard in many industries and situations where the quick recording of generally precise locational data is needed. Once recorded, GPS data was differentially corrected and imported into GIS for analysis and to facilitate the recording of future changes to the sites.

GPS coordinates for the study were taken with a Trimble™ Pro X-RS model backpack unit. The accuracy of the Pro X-RS unit is potentially less than 3 feet of error once the data has been corrected. At less than 3 feet the accuracy of the GPS was deemed adequate for most location measurements of this study, such as the perimeters of the gaswell pads and disturbed areas. For parts of the study though, accuracy greater than 3 feet was needed. Debris lobes for instance, which are discussed later, were measured for this study, but could not accurately be mapped using GPS. Lobe growth from one runoff event to the next was sometimes less than a foot, or lobes developed long fingers of material one or two feet wide that stretched for yards.

GPS errors of up to 3 feet would not have accurately measured the small features of some debris lobes. To take accurate measurements of lobes, traditional measuring techniques were used including: a level transit, tape measures, and triangulation from known landmarks.

Site mapping also included recording relative elevation differences between different areas. GPS is not generally effective at recording precise elevation measurements and errors of a dozen feet or more are common. Elevation differences on the gas well pads, disturbed areas, and along stream channels were calculated using a level transit or datum and transit.

4.2. Weir Construction and Automated Samplers

90° v-notch weirs were used at each gaswell pad and control study site to allow for automated samplers to catch storm water samples (Figure 7).

Figure 7. Weir design.
A 90° v-notch weir with barrier fencing, a gray ISCO™ sampler, ground plastic, and sand bags to stop undercutting. Equipment is enclosed in barbed wire fencing to prevent cattle disturbances.

Made from plywood, the weirs were three sided measuring 48” wide by 48” long, and 24” tall, with the front side completely open to incoming flow. Inside each weir, the plywood surfaces were protected from weathering by 1/8” thick sheets of ultraviolet resistant pvc sheeting, attached with construction adhesive, and sealed at the joints with silicone caulk. In the faceplate of each weir, a 90° "v" was cut so that its axis was two inches above the weir bottom and centered between each side. By knowing the size and angle of the v-notch, and the depth and speed of water moving through a weir, the amount of storm water flowing at any particular time could be calculated.

Although relatively flat, all pad sites were constructed with a gentle slope to encourage water drainage. Transits and observations of runoff into disturbed areas were used to determine the predominate direction of drainage off each site (Figure 8). Once the prevailing drainage of a site was known, a weir was placed at the edge of the pad to intercept runoff. Since the weirs have a slight damming effect, non-permeable fencing was installed to direct runoff into the weir. The ends of the non-permeable barriers were attached to the sides of the openings of each weir, (Figure 9), and the bottom edge of the fencing was buried six inches below grade to prevent undercutting. Additionally, sandbags were used for reinforcement to help prevent water from washing under the fencing. Heavy grade pond lining material was attached to the front entrance of each weir to control undercutting. The leading edge of the material was buried approximately six inches into the ground to prevent water from flowing under it.

Figure 8. Erosion of disturbed area.
These large rills leading down from a gas well pad were several feet wide and were the result of heavy erosion. Where the rills originate at the top of this hill, a weir was later placed.

Figure 9. Weir setup.
A slotted sediment trap is installed a few feet in front of this weir. Plywood pieces were later attached to the weir to make a channel directing water over the trap. Erosion between the weir and trap was prevented by lining the channel with heavy plastic.

To collect water samples and measure storm water flow and precipitation, automated ISCO™ brand samplers were used at each site (Figure 10). Signaled by flow meters and rain gauges, the automated samplers had the capacity to collect up to twenty-four 1,000 ml water samples. Precipitation from the rain gauges and water levels within the weirs were generally recorded at one-minute intervals. Total and peak precipitation, and total and peak flow volumes were recorded or derived from data collected by the samplers.

Figure 10. ISCO™ automated sampler with collection bottles stored in the bottom.

4.3. Collection of Runoff Sediment

Weirs and sediment traps were used to collect sediment from each site. Because water had to exit two inches above the weir floors through the v-notches, the weirs acted like small catchments. To test if runoff sediment was carried past each weir, bedload traps were placed in the ground approximately 6 feet downstream from each weir (Figure 8). Most of the traps were constructed from 2”x 6” lumber and had 27”x 12” aluminum covers with 1” x 24” slots (Figure 2). Plastic removable liners facilitated emptying of the traps. Heavy plastic placed on the ground between each weir and its corresponding sediment trap prevented erosion. Under heavy flow, some runoff sediment did escape but for the most part, the weirs acted as effective catchments and retained all the runoff sediment.

Sediment was collected from each weir or trap at the end of each storm event. In most cases, sediment was allowed to dry in the weirs, especially in the summer months, before being collected. In a few cases, multiple storms occurred before weirs could drain and sediment was removed while it was still wet. Before wet material was collected from each weir or trap, standing water was drained, or allowed to naturally evaporate. Weirs and sediment traps were cleaned of all materials between each storm event.

Once removed from a weir or trap, sediment was transported to the lab in five-gallon buckets lined with heavy gauge trash bags. Each bag was labeled with the date of the runoff event, and site location. In the lab, moisture was removed from samples by drying each for at least twenty-four hours in metal pans, at a minimum of one hundred-four degrees Celsius. Once dried, each sample was disaggregated, weighed, and then characterized by particle sizes using a wet sieving process.

4.4. Sediment Characterization

Finding the particle size distribution (PSD) of each sediment sample required several steps. First, large samples were divided into small representative samples using a soil splitter. Typically, each sample was split into approximately 40-gram sub-samples. Sub-samples were then stirred into a distilled water-detergent mixture to break apart clay materials and allowed to sit overnight. Detergent was added to prevent clay particles from binding together once separated by agitation. After sitting overnight, each sub-sample was washed through a standard set of six sieves ranging from 2mm (#10) mesh openings down to 63µm (#230) (Table 1). The set of sieves used are designed to capture small gravel and sand sized particles ranging from 63µm - 2mm. Material caught in the first, #10 sieve were larger than 2mm and considered gravel, while material that passed through the final #230 sieve at the bottom of the set was either silt or clay. The water/detergent mixture only partially broke apart the sub-samples, and large amounts of water and agitation were needed to fully wash through all silt and clay particles.

Table 1. Sieve sizes.

Sieve	Mesh opening
#10	2mm
#18	1mm
#35	500 µm
#60	250µm
#120	125 µm
#230	.063 µm

.

Generally it took ten to fifteen minutes of washing to completely sieve each sub-sample. Considering the volume of water needed, it was impractical to collect clays and silt smaller than 63µm, and they were allowed to wash away.

Once a sub-sample was thoroughly washed, the material in each sieve was carefully rinsed onto pre-weighed paper towels and allowed to air dry for twenty-four hours. Subtracting the weight of each paper towel from the total weight of sieved material enabled the proportion of material removed from a sieve to be calculated. Finding the sum of the weights of the materials caught in the screens, and subtracting it from the pre-sieved weight of the sub-sample effectively calculated the weight of clay and silt that was washed away.

4.5. Measuring Debris Lobes

Preliminary examination of several well sites before the study was initiated indicated that changes in the landscape caused by gas well construction activities, such as increases of slope and the removal of vegetation, would likely encourage debris lobe formations from storm water runoff. Debris lobes would likely flow onto undisturbed areas around the gas well development site and possibly enter local stream channels (Figure 11). Besides slope and vegetation changes, other alterations that would likely contribute to debris lobe formation included the use of crushed limestone gravel, which has large amounts of infiltration-inhibiting clay, to cover gas well pads, and the loosening or disturbance of top soil which would likely contribute to sediment loads. All of these factors decrease the intensity and/or amount of precipitation needed to cause sediment movement and debris lobe formation. Debris lobes that formed were mapped using a combination of GPS instruments and traditional surveying.

Triangulations and tape measures were primarily used to measure debris lobes that developed at the edge of disturbed areas from storm water runoff. GPS was used to identify landmarks near to, or associated with lobes, but not to map them because most of the lobes were either too small or had features too small to accurately measure with GPS. Instead of using GPS, lobes were drawn to scale on graph paper from a grid system created over each lobe.

Large rectangular grids, constructed of t-posts and rope, were created around each debris lobe to aid in drawing lobe shapes on graph paper. Grids made from rope and t-posts were created by first establishing large right triangle around each lobe. To construct a right triangle, the hypotenuse side of the triangle, made with a 50-foot segment of rope, was marked along one side of a lobe, with each rope end anchored by a t-post. Next, to each anchor t-post a second rope section was attached. To one of the t-post a 30-foot rope section was attached, and to the other t-post a 40-foot rope section was attached. Once pulled tight, until they met at a common point, the 30 and 40-foot sections, along with the hypotenuse, became the remaining sides of a right triangle. According to the Pythagorean theorem, a right triangle is formed when the three sides of a triangle have the ration of 3:4:5, or where the squares of two sides of a triangle add up to the square of the third side. A triangle with sides measuring 30, 40, and 50 feet is a right triangle. Once a right-angled triangle was created, a second equal sized right angle triangle was formed that shared its hypotenuse with that of the first triangle, and together they formed a rectangle with 90º angles. The rectangle formed the outline of the grid system. On two perpendicular sides of the rectangle, five-foot intervals were marked and then used to form a coordinate system. Representing the lines on a sheet of graph paper, the grid enabled the shape of each lobe to accurately be drawn.

In addition to being used to record the shape of each lobe, grids were also used to systematically measure lobe depths. Lobes generally formed on top of field grasses and hard, undisturbed ground. Depth measurements were taken by either digging down with a trowel and measuring the depth to preexisting field grass, or by inserting a wide ruler into lobe material until hard ground was reached. Using the afore-mentioned grid patterns, multiple depth measurements across each lobe were measured and later used to estimate the overall volume of each lobe.

The locations of the t-posts used to create the lobe grids were measured either with a GPS unit or by being triangulated to previously mapped land marks and reference points, such as the weirs, piles of boulders, or large trees. To accurately place lobes on GIS maps, at least four t-posts or landmarks were measured using a GPS. The known reference points and landmarks were used to align digitized drawings of the lobes onto GIS maps.

Figure 11. Lobe formation. Field grass covered by debris material. Area photographed is approximately 5 feet across.

A second method considered for determining sediment movement in the study, especially if the movement was associated with sheetflow, was to paint transects across existing lobes, or other areas where sediment movement was expected to occur. Soil movement would result in warped lines after a runoff occurred. This method however, proved only marginally useful. Rain splatter from the heavy rains disturbed painted lines to the point that they were often not visible after an event.

4.6. Rill and Stream Channel Sediment

A final estimate of sediment erosion off gas well sites was made by collecting sediment from large rills formed in disturbed areas from gas well pad runoff, and from natural stream or creek channels near gas well areas. In both circumstances, sediment was collected with traps placed across the entire width of each rill or creek channel. Sediment from the traps was handled, weighed, and characterized in the same manner as pad site sediment collected from the weirs, as described above in Sections 4.3 and 4.4. Two traps each were placed in a prominent Bilt4 disturbed area rill and in a natural stream that flows along the edge of the Bilt4 disturbed area (Figure 23).

The first rill trap was placed approximately 40’ down slope from the Bilt4 weir in a large eroded rill that had formed from the gas well pad runoff. The second weir was placed approximately 220 feet down slope from the first trap within a rill that received the same runoff as the first rill. The grade decreases from approximately 15% at the first trap to around 6% at the second. PSD is expected to differ between the two traps.

The two creek traps were placed approximately 420’ apart in a perennial stream south of the Bilt4 weir (Figure 23). Originating northwest of Bilt4, the stream flows south through an area where the Bilt4 access road was created, and then turns east along the edge of the Bilt4 disturbed area. Eventually it enters a pond about 1100’ from the road. Creek Trap 1 was placed within the steam bed approximately 340’ downstream from where the stream flows under the road through a drainage pipe. Much of the area between the road and Creek Trap 1was heavily disturbed during the construction of Bilt4 and parts of the creek (within approximately 100 feet of Creek Trap 1) flowed directly through disturbed soil. High sediment loads were expected at Creek Trap 1 compared to Creek Trap 2 which was placed in the creek channel about 420’ downstream from the first trap. The creek bed between the two traps was not disturbed during construction of Bilt4, and had heavy native plant growth (mostly grasses) lining its channel. It was expected that the native creek bottom plants would capture and filter sediments and Creek Trap 2 would receive less sediment than Creek Trap 1.

RESULTS

Sedimentation was identified in weirs, in traps placed in rills and creek channels, and in debris lobes. Observations made prior to this study indicated that streams within watersheds receiving runoff from the pad sites and access roads, where the land had been altered, filled quickly with turbid water from most storm events. Streams in undisturbed watersheds that did not receive runoff from gas well sites and roads, had almost no runoff except during large storm events. At all of the gas well pads and the control sites, sediments were captured in weirs during most storm events. Sediment was also captured in traps in rills formed in the disturbed area of Bilt4 and in stream channels near Bilt4 that received runoff from the Bilt4 disturbed area. Large debris lobes covering hundreds of square feet of area and traveling up to 124 feet formed at the edges of the Bilt4 and Bilt6 disturbed areas but not at Brad1 or any of the control sites. Some small debris lobes covering less than 10 square feet also formed around Bilt4 and were not included in the study because of the limited area they covered. Area, volume, and the distance traveled by sediment were measured for each debris lobe.

5.1. Sediment from Weirs and Traps

Sediment from weirs and bedload traps was collected following storm events between March 2005 and May 2006. Not all measurement sites received sediment from every storm because some were established after March 2005 and some storms did not generate runoff at every site. The number of runoff events in which sediment was collected at each site is shown Table 2.

Table 2. Number of sediment runoff events per site.

Site	Number of Events
Bilt4 Creek1	4
Bilt4 Creek2	4
Bilt4 Rill1	6
Bilt4 Rill2	5
Bilt4 Pad Weir	9
Bilt6 Pad Weir	8
Brad1 Pad Weir	6
Brad Ct	0
Bilt Ct	1

The Bradford and Biltmore pad and control sites were established in January and February 2005. The first sediment sample was collected in late March 2005 from Brad1 and late April from Bilt4 and Bilt6. Rill and creek traps at Bilt4, established in early February 2006, first collected sediment in late February 2006.

Besides the date of establishment of collecting sites, the variation in the number of sediment samples collected at each site depended on localized precipitation characteristics. All of the pad sites had similar slope and infiltration characteristics, but the amount of precipitation from site to site varied occasionally to some degree. For instance, a storm event in June 2005 produced 0.83 inches of precipitation at Bilt6 and 1.17 inches of precipitation at Brad1, or just over a third of an inch difference. Precipitation totals recorded by ISCO™ samplers are shown in Table 3. Most sites though received similar amounts of precipitation for any given storm event. Precipitation data from some of the sites was either not available at the time of this study or was not recorded by an ISCO™. Precipitation data from the Denton Municipal Airport weather station was used when a site lacked data (See Figure 3 for airport location relative to study sites).

Table 3. Dates in which at least one site received runoff. Total inches of precipitation by site as collected by ISCO™ samplers and recorded at Denton Municipal Airport.

Date	Brad 1	Brad Ct	Bilt4	Bilt6	BiltCt	Denton Airport
03/26/2005	*	---	---	---	---	2.00
04/28/2005	---	---	*	*	---	**
06/01/2005	1.17	---	*	.83	----	0.97
10/31/2005	*	---	*	*	---	0.52
01/22/2006	*	---	1.28	1.13	----	1.27
02/25/2006	---	---	1.98	1.91	----	2.04
03/19/2006	---	---	3.06	2.82	2.94	3.05
04/20/2006	---	---	*	---	---	1.00
04/28/2006	*	---	*	*	---	1.60
05/05/2006	---	---	.75	.85	----	0.85

--- sites that did not receive sediment runoff.
* sites that received sediment runoff but ISCO™ did not record precipitation.
** no precipitation recorded.

Disturbances to the sites or equipment affected the availability of sediment samples at some of the sites. Cattle had a negative affect on equipment and occasionally tore down weir fencing, knocked over rain gauges, or dislodged ISCO™ data and power wires. Of the different cattle disturbances, only knocking over fencing affected sediment samples with some amount of runoff from a few storms leaking through damaged fencing, which resulting in less flow and sediment collecting in respective weirs; however the effect of these disturbances on results was considered negligible. Disturbed rain gauges, data wires, and power supplies did not affect sediment movement but did affect the collection of rain and flow data. As noted, Denton Municipal Airport weather station data was used when needed to supplement missing ISCO™ precipitation data.

Storm water runoff varied greatly between the gas well pad and the control sites. Brad Ct had no recorded runoff during the study and BiltCt had only one runoff (and sediment) event recorded. In contrast to the control sites, the pad sites had numerous runoff events (See Table 2).

5.2. Sediment Characterization

As explained in section 4.4. weir trap samples were sieved to determine the distribution of sand particles and the overall percentage of combined silt and clay for each sample. Nearly every weir sample contained relatively large percentages of silt and clay with the average being 69% (Table 4). Rill traps averaged 80.5% silt and clay, and creek traps averaged 63%. The smallest average percentage of silt and clay was from Bilt4 Creek2 (48%) and the largest average percentage was from BiltCt (85%). Only one 50-gram sample was collected from BiltCt and it was the smallest sample collected for all the weirs during the study. Most weir and trap samples were much larger than the BiltCt sample, with the average sample weighing 20.95 kg.

Table 4. Percentage of silt and clay collected in weirs and traps.

Site	Average Percentage of clay/silt
Bilt4 Creek1	78
Bilt4 Creek2	48
Bilt4 Rill1	79
Bilt4 Rill2	82
Bilt4 Pad Weir	78
Bilt6 Pad Weir	63
Brad1 Pad Weir	65
Brad Ct	N/A
BiltCt	85

5.3. Creek Sediment Traps

Sediment samples were deposited in the creek traps during three storm events. For each event, the sediment weight and percentage of clay and silt contained in each sample was significantly less for Creek Trap 2 than for Creek Trap 1 (Table 5). No debris lobes flowed from the disturbed area towards the creek containing the traps, so the sediments collected in both creek traps likely came from the section of creek bed between the road and the first creek trap that had been heavily disturbed during construction of Bilt6 and the access road leading to Bilt6.

Sediments in Creek Trap 2 were likely from the disturbed creek bed, which means the sediments would have traveled approximately 500 feet, the distance from the disturbed creek bed to Creek Trap 2.

Table 5. Creek traps sample weights and silt/clay content.

	Creek 1	Creek 2	Creek 1	Creek 2
Date	Sample Weight (g)	Sample Weight (g)	Clay/Silt %	Clay/Silt %
February 2006	94	52	78	45
March 2006	452	374	61	55
May 2006	157	30	93	58

The effect of the total precipitation received by each creek trap on the amount of clay and silt captured was compared using simple trend lines and graphs. Creek Trap 1 showed a strong relationship between decreasing clay content and increasing total rain. For Creek Trap 2, the percentage of clay and silt varied between 35% and 58% and did not seem dependent on the total amount of precipitation that fell during a storm (Figure 12).

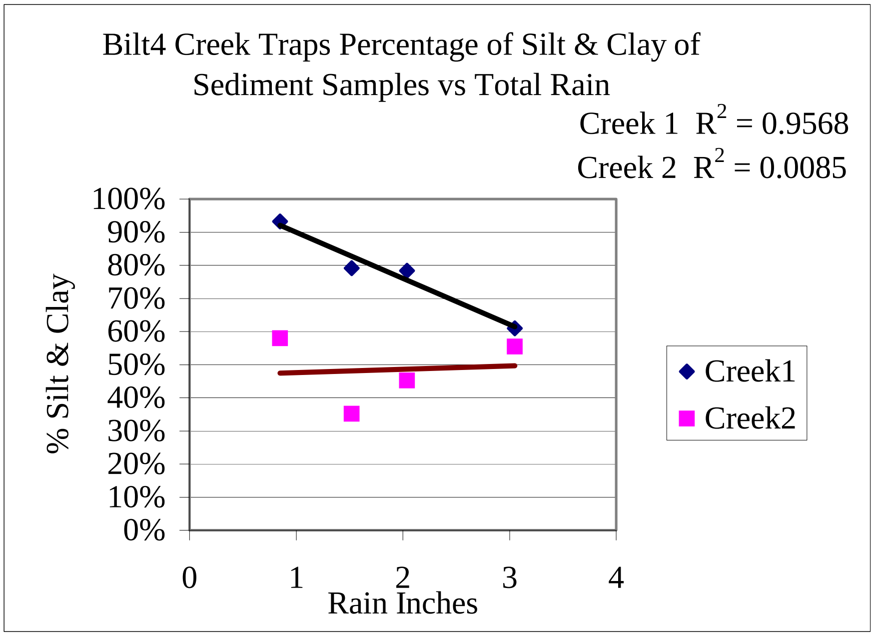

Figure 12. Silt and clay in creek traps vs. rain total.

The weight of sediment collected in each creek trap with respect to total rainfall amounts and 1hour peak rain intensity (the highest amount of rain that fell during any one hour period for a storm) was also compared using trend analysis (Figure 13 and Figure 14). The total weight of sediment collected in each trap appears to be positively correlated to total and peak rainfall. Creek 2 shows a stronger relationship of sediment weight to total rain than Creek 1. The opposite is true for peak rain with Creek 1 showing a stronger relationship of increased sediment weight to increased peak rain values. In both comparisons, Creek Trap 1 collected more sediment than Creek Trap 2.

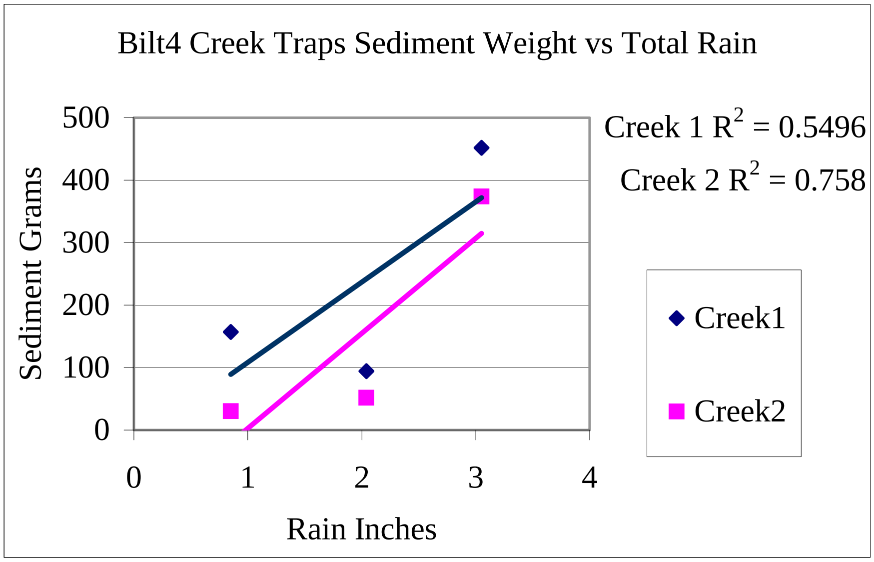

Figure 13. Sediment weight in creek traps vs. total rain.

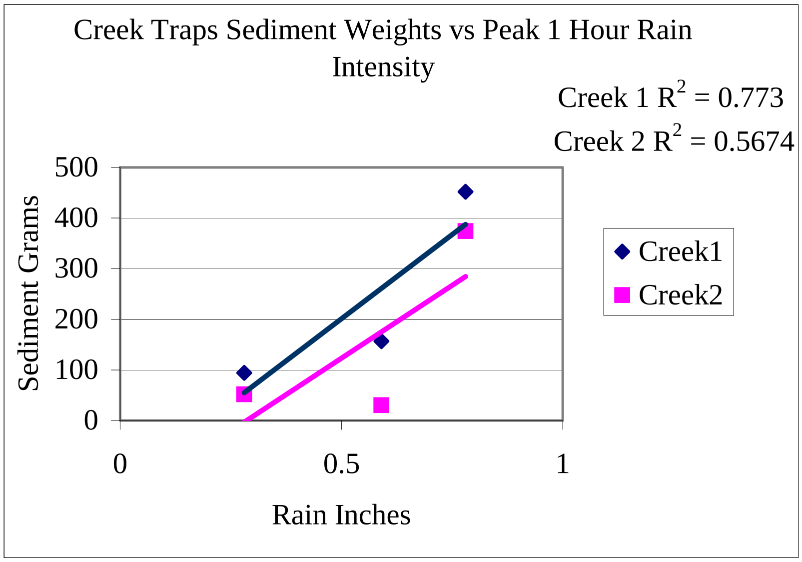

Figure 14. Sediment weight in creek traps vs. rain intensity.

5.4. Rill Sediment Traps

Both rill traps were located in the Bilt4 disturbed area. Rill Trap 1 was located at the base of a 15% slope; Rill Trap 2 was located at the base of a 6% slope. The rill traps showed very similar percentages of silt and clay for every event for which both traps collected sediment (Figure 15), but neither showed a strong relationship of total rain to the silt and clay percentage.

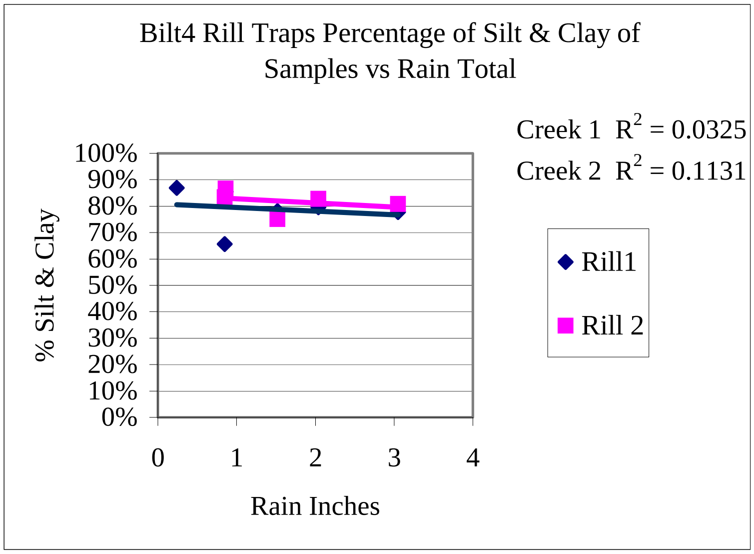

Figure 15. Rill trap silt and clay percentage vs. total rain.

Sediment accumulations in the rill traps were compared to total rain fall and 1-hour peak rain intensity (Figure 16 and Figure 17). Unfortunately, both traps filled to capacity during most rain events. Rill Trap 2 filled during every event while Rill Trap 1 filled whenever total rain was above 2 inches or peak 1-hour rain was above about 0.25 inches. The dry weight of sediment that each rill trap was capable of capturing was 11 kg for Rill Trap 1 and 8.4 kg for Rill Trap 2. Rill Trap 1 was larger due to variation in construction. Since Rill Trap 2 filled with sediments during every event, the sediment amount cannot be compared to total or peak rain. However the results show that Rill Trap 2 collected a minimum of 8.4 kg of sediment whenever about an inch or more of rain fell, or when peak 1-hour rain intensity was at least 0.25 inches. The weight of sediment collected in Rill Trap 1 showed relatively strong positive relationship to total rain, but only a mild positive relationship for peak rainfall (Figure 16 and Figure 17).

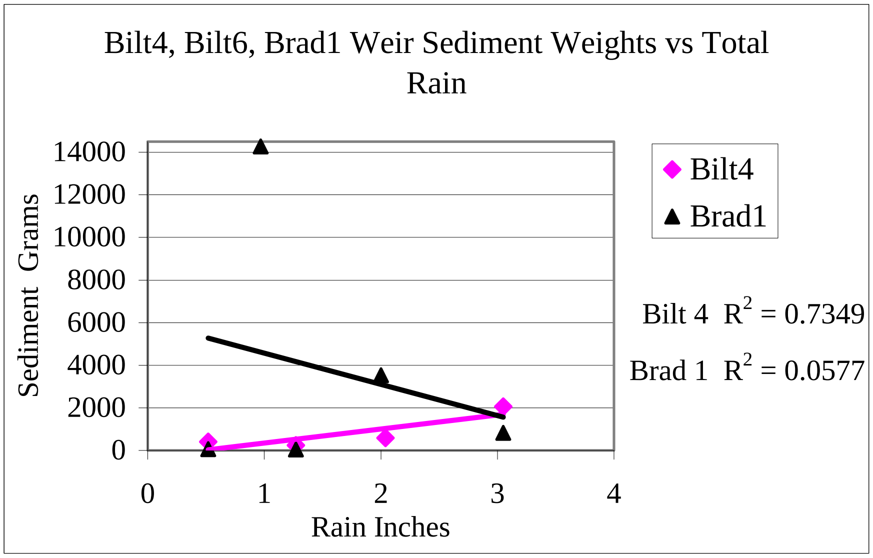

Figure 16. Rill trap sediment vs. total rain.

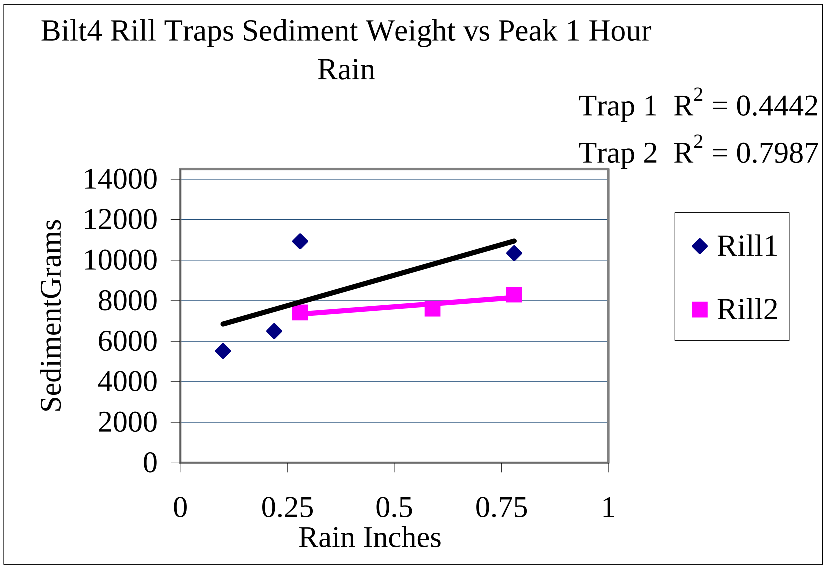

Figure 17. Rill trap sediment weight vs. peak 1-hour rain.

5.5. Weir Sediment Measurements

Gas well pad weir sediment was analyzed in several ways but did not include sediment measurements from either control weir since only one sample was collected from them. Silt and clay percentage of weir sediment samples was compared to total rainfall per event for each gas well site (Figures 18, 19, and 20). Silt and clay content of sediment samples collected from Bilt6 and Brad1 increased steadily as total rain increased. Sediment samples from Bilt4 had relatively high silt and clay content for almost all rain amounts and a positive correlation to total rain is not indicated.

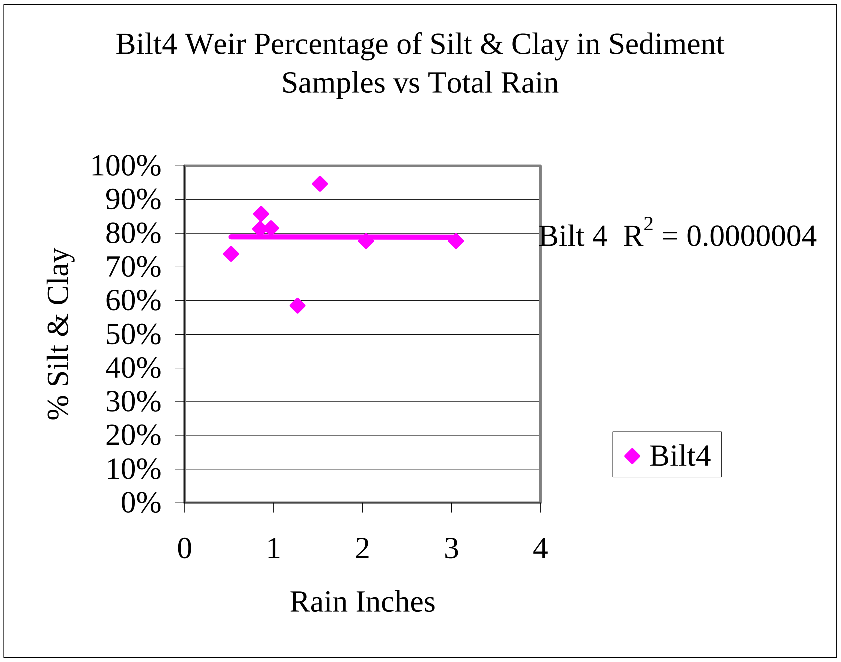

Figure 18. Weir percentage of silt and clay in sediment vs. total rain for Bilt4.

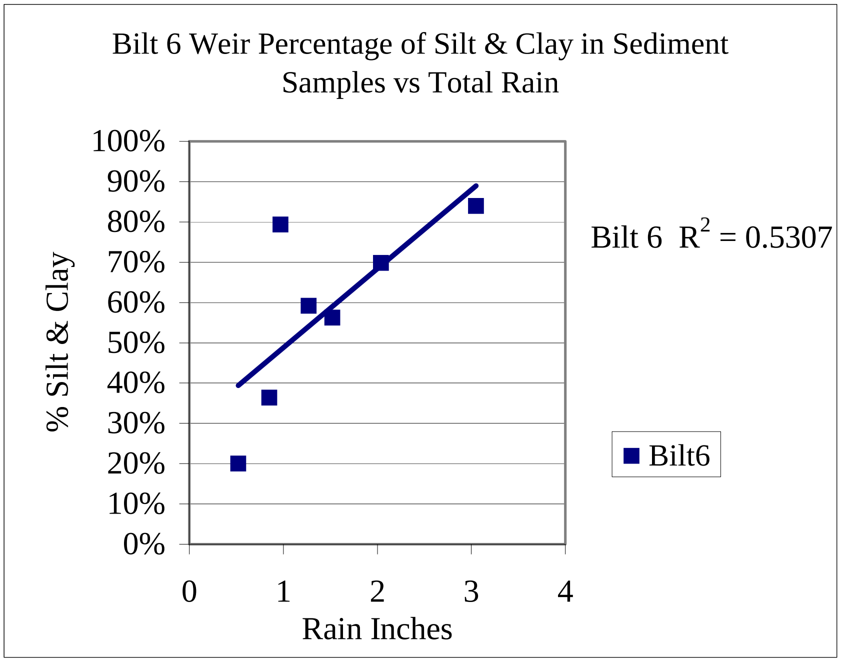

Figure 19. Weir percentage of clay in sediment vs. total rain for Bilt6.

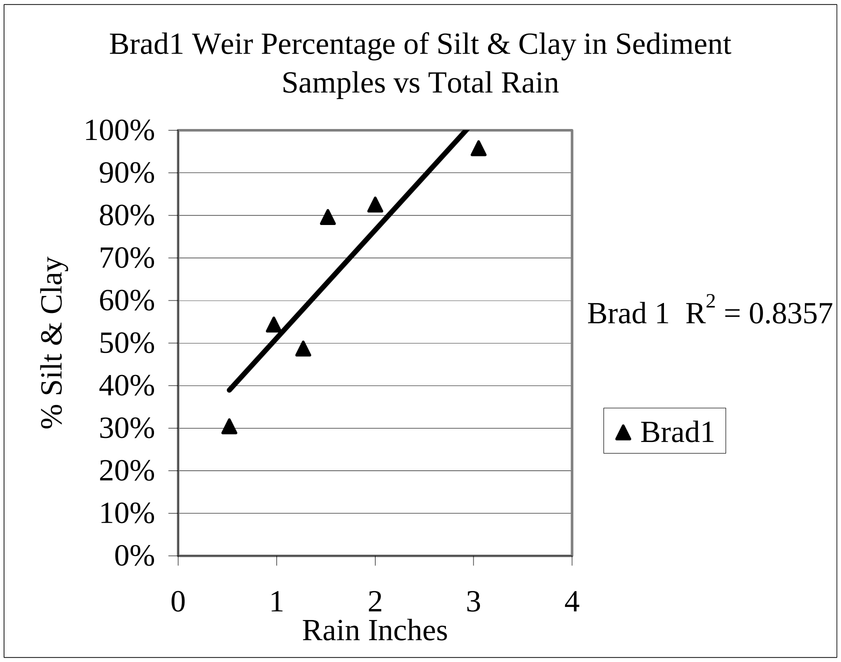

Figure 20. Weir percentage of clay in sediment vs. total rain for Brad1.

The weight of sediment collected from each weir for each storm event was also compared to total rainfall amounts (Figure 21 and Figure 22). Sediment weight in both Bilt4 and Bilt6 are nearly identical for different total precipitation amounts. For both, a good correlation exists that sediment increases as total precipitation increases. Brad1 did not show the same positive relationship, apparently because of an unusually large amount of sediment (about 14 kg.) generated by an intense 1-hour rain event. Brad1's weir was set up slightly different from the other sites and was not directly located off the pad. Brad 1 was located about twenty feet away from the pad in the disturbed area. The1-hour event was chronologically the first event to occur after the weir was installed and the huge sediment deposit was likely just the first flush of sediment washing out of the twenty foot area in front of the weir.

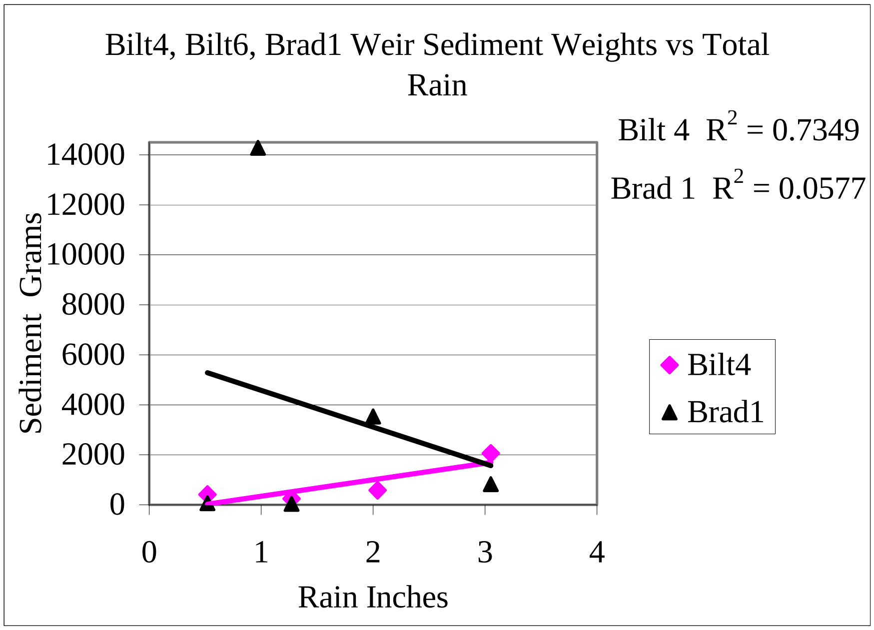

Figure 21. Weir sediment weights vs. total rain at Bilt4 and Brad1.

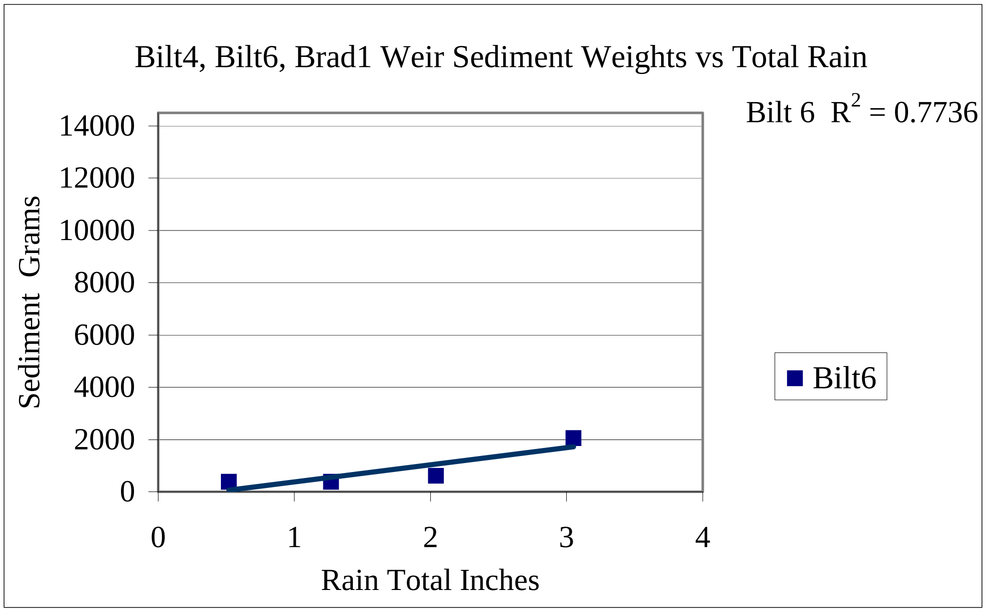

Figure 22. Weir sediment weights vs. total rain at Bilt6.

Weir sediment weight was also compared to peak 1-hour rain intensity. All three weirs showed a positive correlation of the amount of sediment to the intensity of rain (Figure 23 and Figure 24).

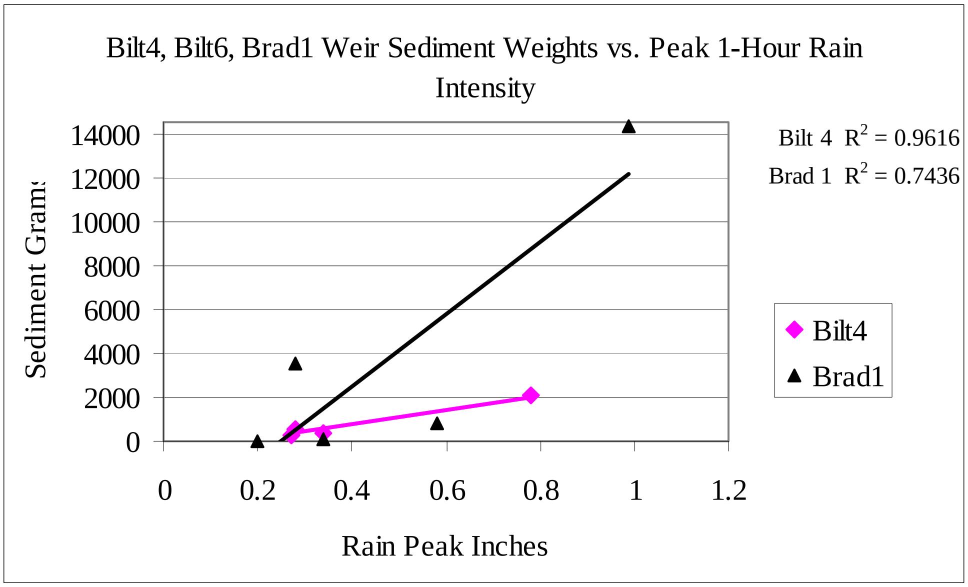

Figure 23. Weir sediment weights vs. peak 1-hour rain intensity for Bilt4 and Brad1.

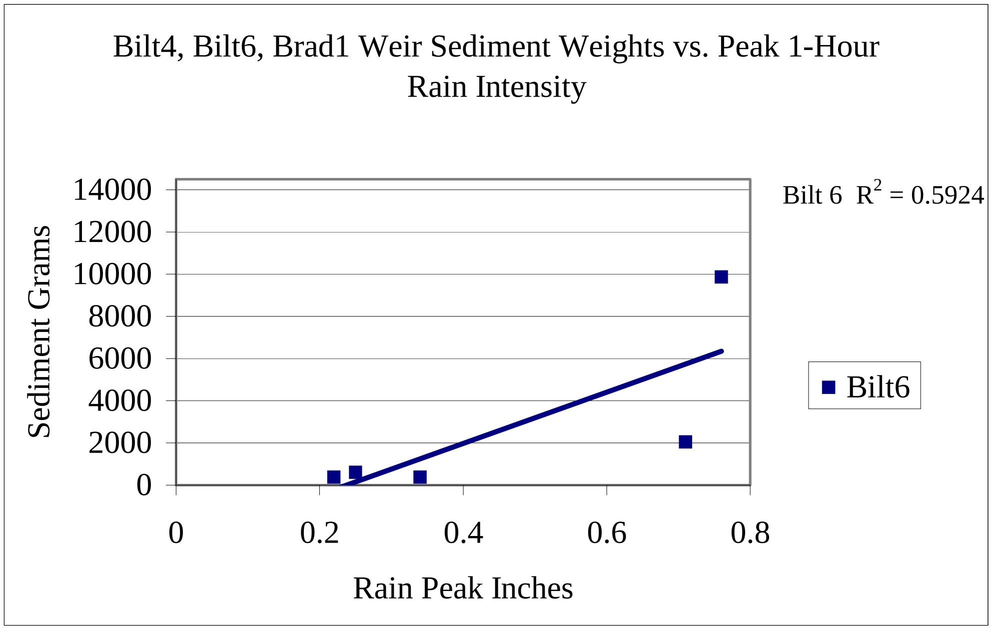

Figure 24. Weir sediment weights vs. peak 1-hour rain intensity for Bilt6.

5.6. Debris Lobes

Large debris lobes formed past the disturbed areas at the Bilt4 and Bilt6 gas well sites, but not at Brad1 or the control sites. Bilt4 and Bilt6 had relatively steep slopes (~10%-15%) from their pads down through their disturbed areas that probably contributed to lobe development (Figure 25 and Figure 26), whereas the slope at Brad1 was about 1% and presumably not steep enough to encourage debris lobe growth, and the control sites had heavy undisturbed vegetation and permeable surfaces. A few lobes were not measured for the study because they were deemed too small (generally less than 10 square feet). Lobes were measured longitudinally from the edge of each disturbed area associated with each lobe along a line roughly perpendicular to the disturbed area from where a lobe developed. Four lobes formed at Bilt4 and one lobe formed at Bilt6. The four Bilt4 lobes were designated as Lobes A, B, C, and D, and the Bilt 6 lobe was designated Lobe E. Some of the designated lobes were actually combinations of multiple small lobes that had formed in close proximity. All of the lobes formed from the runoff of storm events between August 2005 and March 2006. After March 2006, no further lobe growth occurred even though events occurred with similar precipitation totals to those that had previously produced debris lobe growth.

Depth measurements of all the lobes were taken in early and late March 2006 (Figure 27). Measurements taken in early March represent all the accumulation of sediment debris material that had occurred before the March 19, 2006 precipitation event. Measurements after the March 19 event were taken at points where lobes had spread into new areas, and from points where lobes had previously formed. Measurements for the March 19 event, made where lobes had previously deposited materials, were made to determine if new deposits had occurred on top of old deposits. The difference in depth between old and new deposits was used to calculate the amount of new sediment deposited on top of previously deposited lobe material. From depth and area measurements, the volume of material added to each lobe during specific events or groups of events was calculated using a GIS.

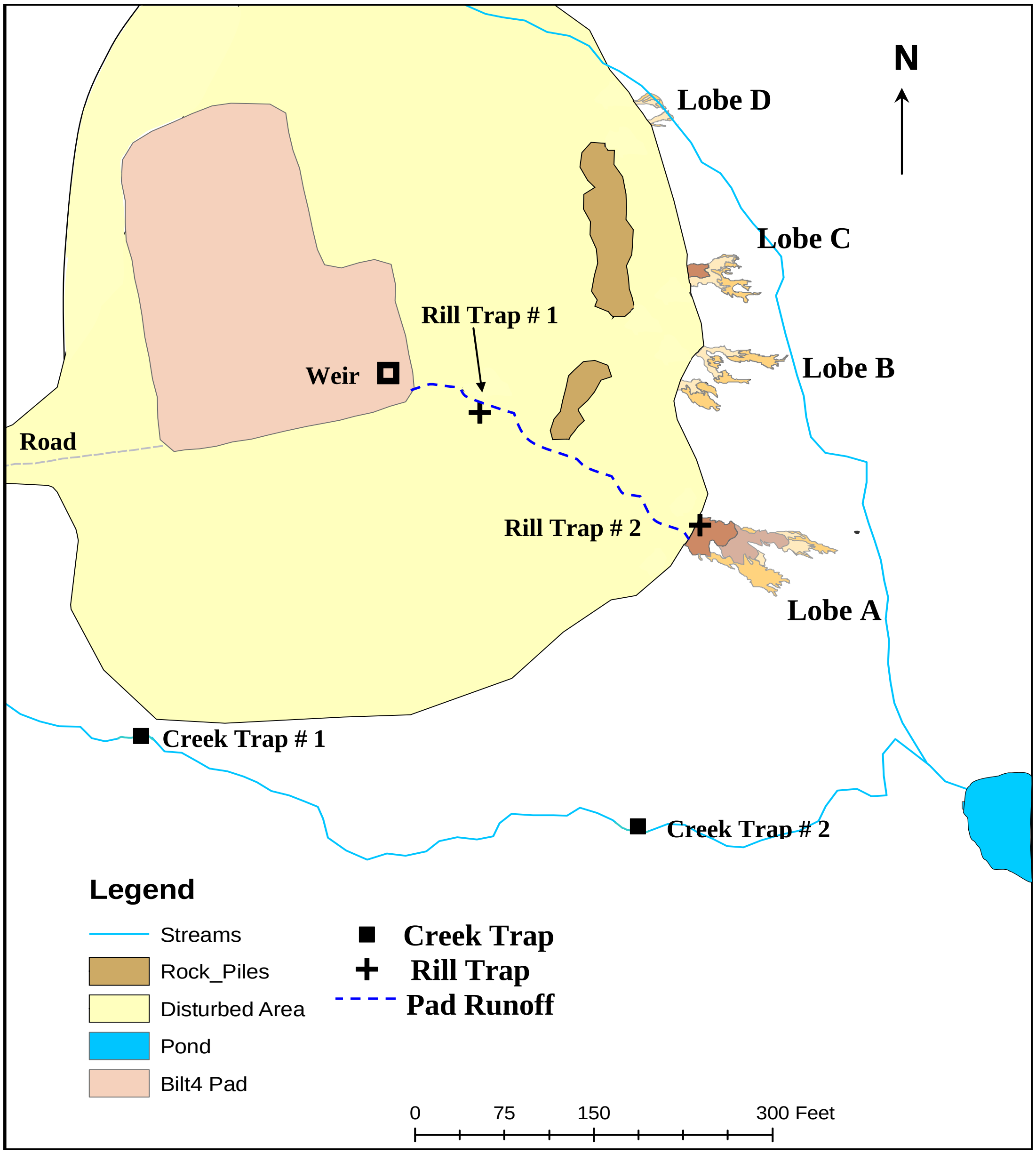

Figure 25. Bilt4 debris lobes and trap locations March 2006.

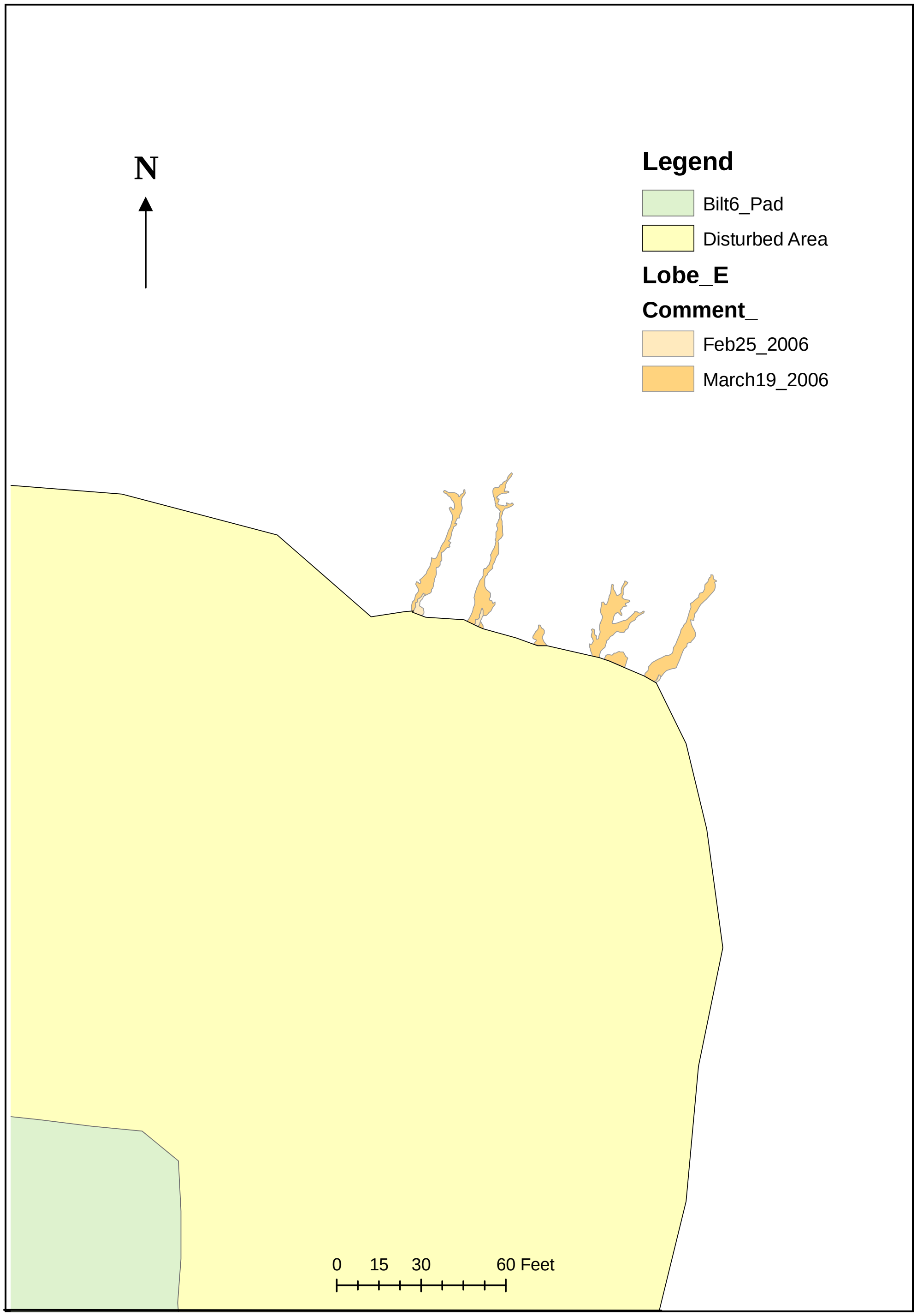

Figure 26. Bilt6 debris Lobe E March 2006.

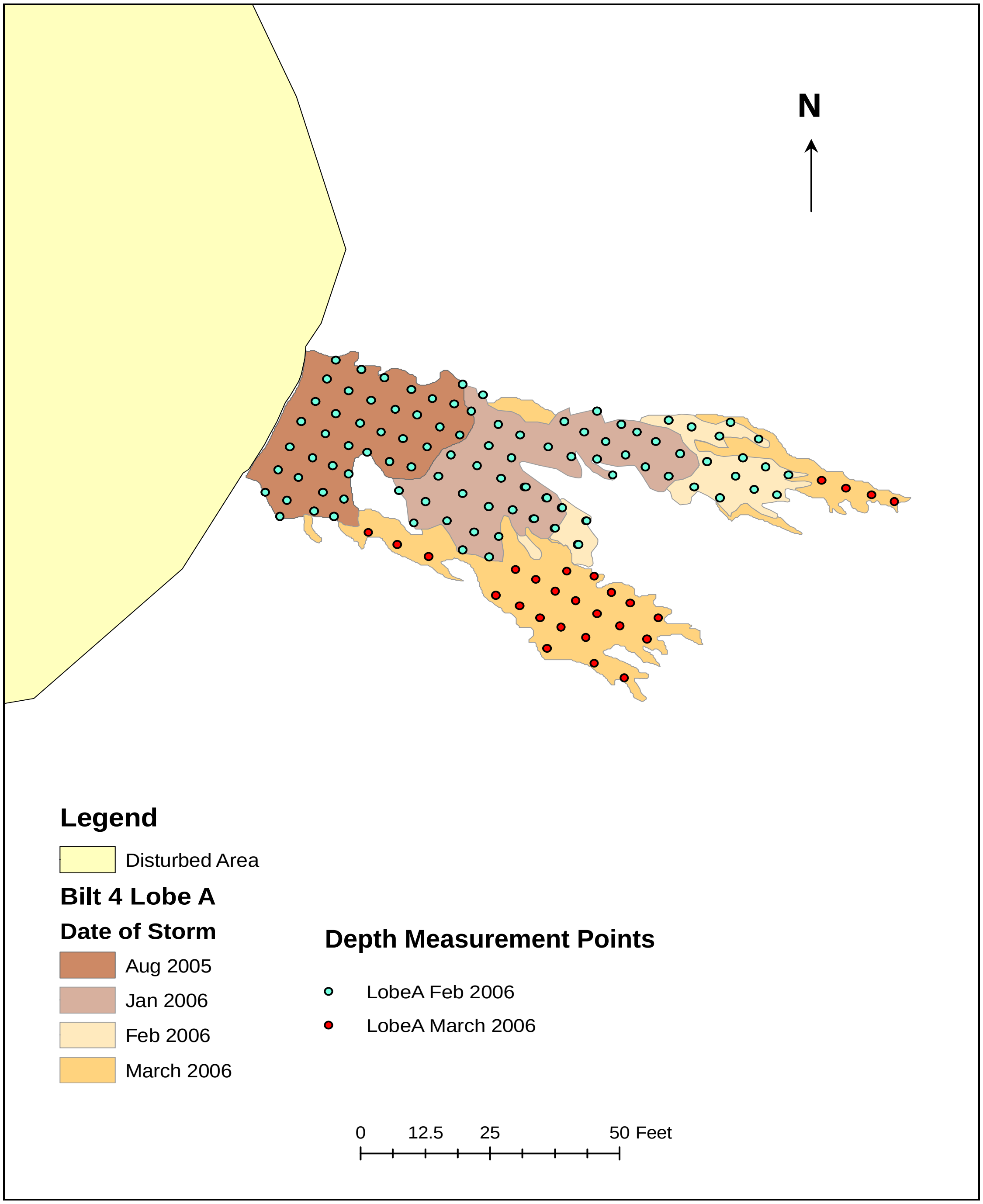

Figure 27. Lobe A storm events and depth measurement points.

Of all the lobes, the most extensive growth was Lobe A at Bilt4 (Figure 25 and Figure 27). It formed from four storm events that occurred August 15-16, 2005, January 22, 2006, February 25, 2006, and March 19, 2006, covered approximately 3,290 square feet of area, and traveled 124 feet from the Bilt4 disturbed area. A few small events occurred between the August 15-16, 2005 and January 22, 2006 events but none were large enough to cause runoff or contribute more to the area or distance traveled by Lobe A. During the six-month period between the August 2005 and January 2006, barely an inch of cumulative rain was recorded at the sites.

Lobes B, C, D, and E all formed from the February 2006 and March 2006 storm events, with the exception of some Lobe C development from the August 2005 event. A GIS was used to calculate the areas and volumes of the lobes and furthest the distance traveled by sediment from disturbed areas for each lobe. Depth measurements needed to calculate volume were recorded only for the February and March 2006 storm events (Table 6 and Table 7).

A perennial creek flows south, along the east side of Bilt4, and two of the debris lobes came near or entered into the creek channel. Lobe B came within a few feet of the creek during the March 2006 event and Lobe D settled into the creek bottom during both the February and March 2006 runoff events. During each event though, the creek was dry and significant runoff was only occurring from the gas well pads. Debris material did not flow down the creek.

Table 6. Area covered and distance traveled by sediment lobe materials.

Lobe Area	Lobe A	Lobe B	Lobe C	Lobe D	Lobe E
	ft^2	ft^2	ft^2	ft^2	ft^2
Aug 2005	929.7	----	195.0	----	----
01/22/2006	929.8	----	----	----	----
02/25/2006	375.4	502.8	422.3	181.0	25.3
03/19/2006	1054.6	909.7	427.6	144.2	628.7
Feet	124	77	63	28	59

---- No sediment movement occurred.

Table 7. Sediment volume added to lobes.

Lobe Volumes	Lobe A	Lobe B	Lobe C	Lobe D	Lobe E
	ft^3	ft^3	ft^3	ft^3	ft^3
Prior to 03/19/2006	450.8	134.0	92.9	25.8	14.1
03/19/2006	341.7	131.1	102.3	49.0	132.8

Material in the debris lobes was composed of sediments that moved as bedload and as suspended load. Although it is possible that some clay and silt particles were carried past the debris lobes in suspension, there is no field evidence that significant sediment accumulations occurred beyond the debris lobe boundaries. Therefore, it is assumed that a high proportion of runoff sediment settled in the debris lobes and that a reasonable approximation of sediment loadings can be based on debris lobe volumes.

Sediment loadings from construction sites are typically estimated from TSS measured in storm water runoff. TSS measurements were not taken for this study, but an estimate of sediment loadings can be made from debris lobes volume. For Bilt4, sediment loadings were estimated from the volume of materials measured for all the lobes formed during two time periods: Period one includes all the events that occurred before March 19, 2006, and period two includes only the March 19, 2006 event.

Bilt4 pad and disturbed area cover approximately 3.5 to 4 acres. For all the storm events that occurred before March 19, 2006, 703.5 cubic feet, or roughly 29.2 tons of material was deposited in the debris lobes. For the March 19, 2006 storm event 624.1 cubic feet, or roughly 25.9 tons of material was deposited in the Bilt4 debris lobes. Lobe sediment weight was calculated by multiplying the sediment volume from each event by the average weight (83 pounds) of a cubic foot of dried lobe sediment.

Total precipitation for all lobe development events that occurred before March 19, 2006 (August 2005 to February 2006) was 4.83 inches, to which 29.2 tons of lobe sediment can be attributed. For 29.2 tons, the rate of sediment deposited per inch of rain would be 6.04 tons. If a 4-acre estimate is used for Bilt4, then the sediment loading for one inch of rain per acre would be 1.5 tons. Annual sediment loading for Bilt4, based on a 31.5-inch average precipitation for Denton, Texas, would be 47.3 tons per acre.

For March 19, 2006 the total precipitation was 3.05 inches and 25.9 tons of lobe sediment was deposited. Per one inch of rain, the average deposit of sediment would be 8.5 tons. Again, if a 4-acre estimate is used for Bilt4 then the sediment loading for one inch of rain per acre would be 2.1 tons. And, at 31.5 average inches of precipitation for Denton, the annual sediment loading for Bilt4 would be 66.9 tons. If the annual sediment loading calculated from the March 19 event and the period before March 19 are averaged, the Bilt4 annual loading would be 57.1 tons per acre.

Lobes A and C were produced from three rain events each. Lobes B, D, and E were produced from only two rain events. The areal growth of debris lobes was compared to the total rain and peak 1-hour precipitation recorded for those events. Except for Lobes A and D, the growth in area of each debris lobe increased as total rain and peak 1-hour rain increased (Figures

28, 29, 30 and 31). The amount of area added to Lobe A, during different events, is not explained by the total rain that fell per event, and is only weakly explained by rain intensity. Lobe D actually had less areal growth as total rain and peak 1-hour rain increased.

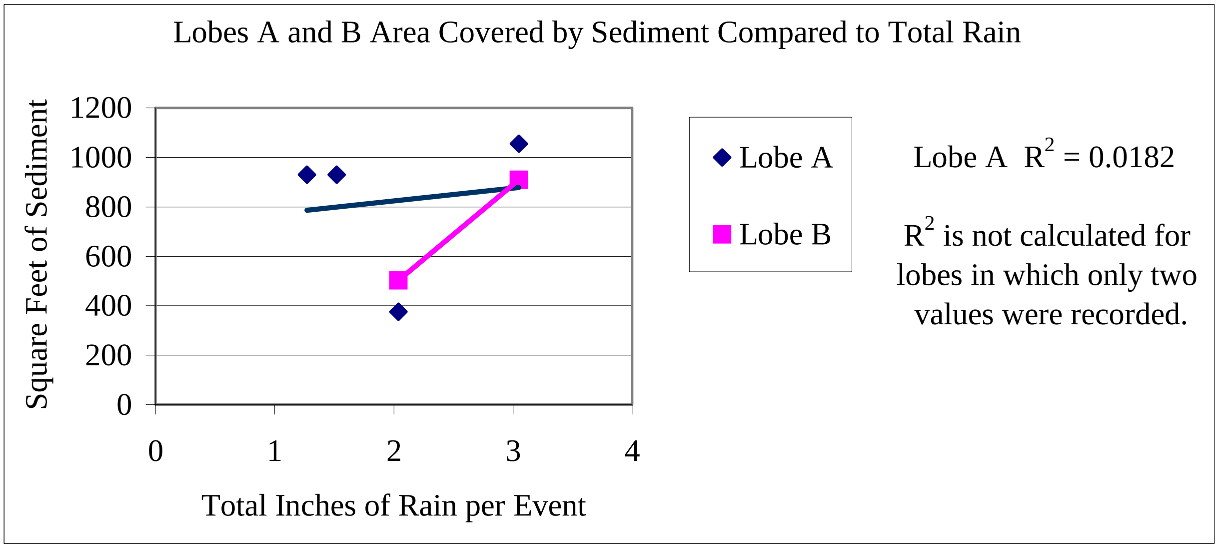

Figure 28. Lobes A and B sediment area vs. total rain.

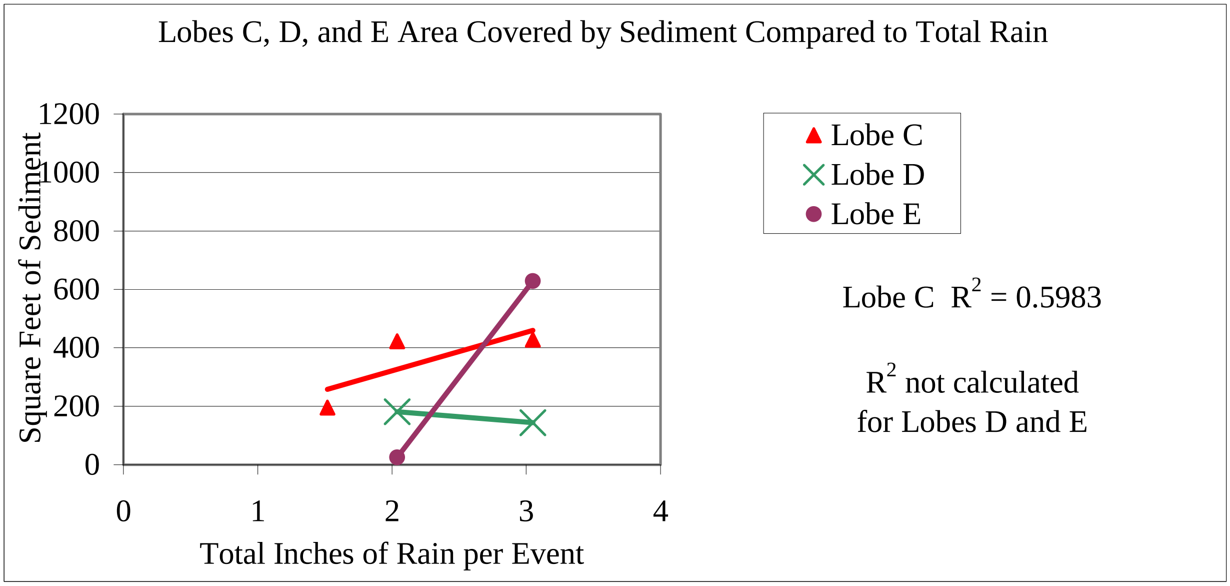

Figure 29. Lobes C, D, and E sediment area vs. total rain.

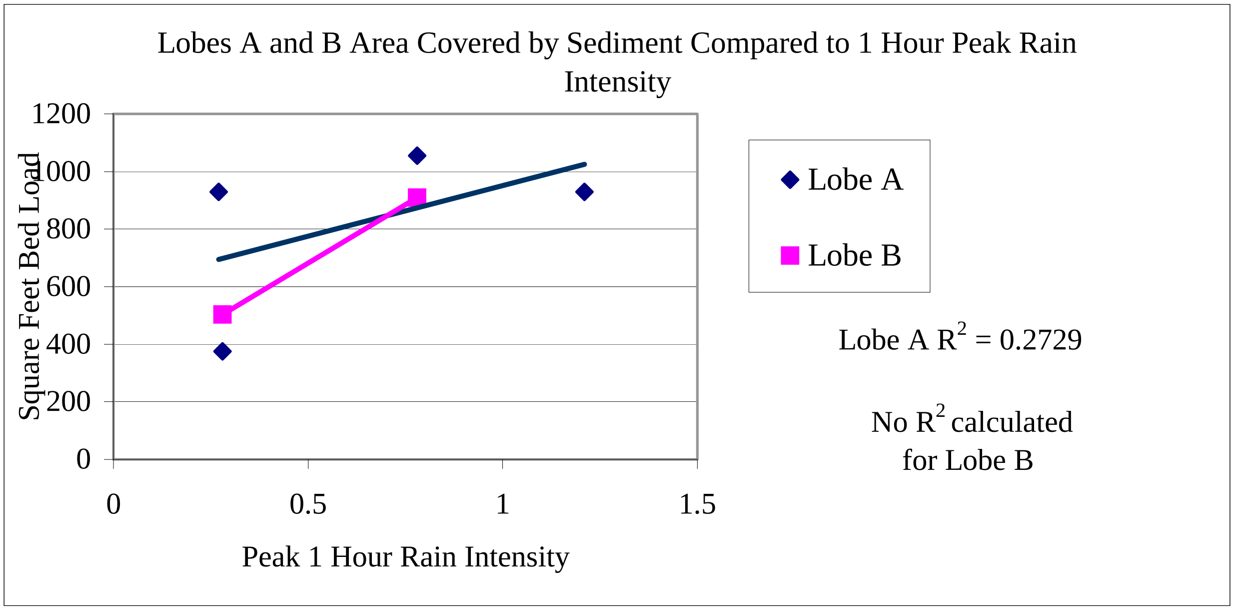

Figure 30. Lobes A and B sediment area vs. 1-hour peak rain intensity.

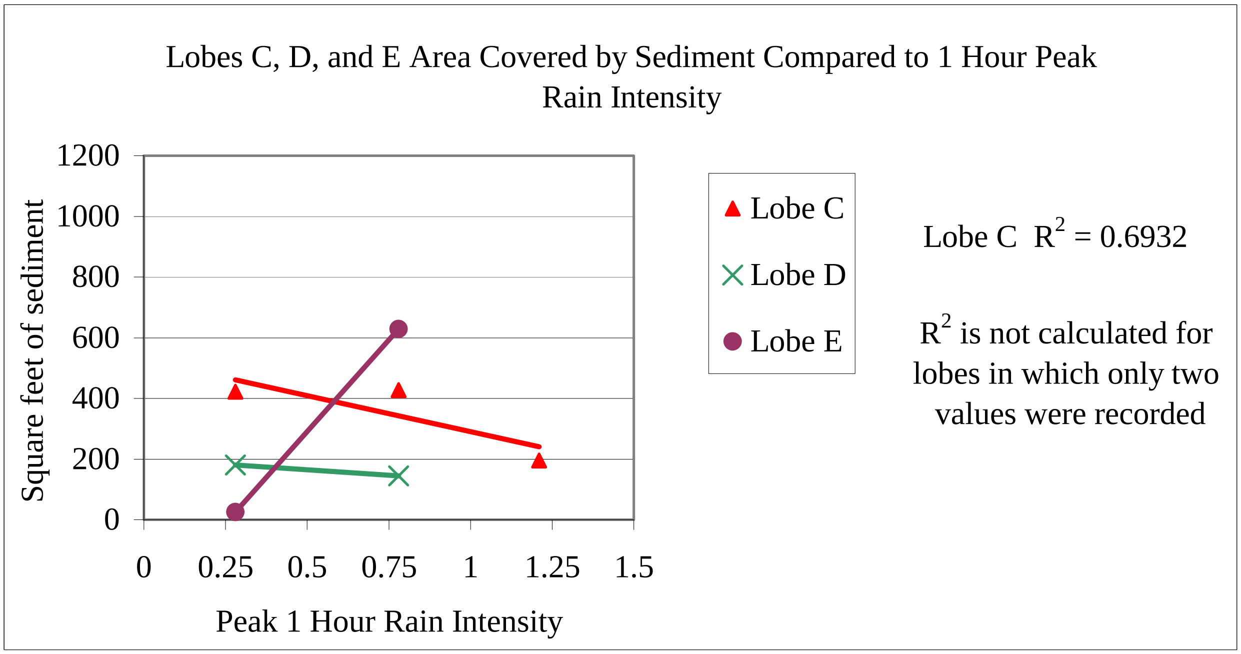

Figure 31. Lobes C, D, and E sediment area vs. 1-hour peak rain intensity.

The volume of sediment added to each lobe from the February and March 2006 storm events, is compared in Figure 32. Lobes A and B had less material added for a 3 inch precipitation event then for a 2 inch event. Accumulations of material for Lobes C, D, and E however increased as total rain went from 2 inches to 3 inch. Compared to total rain, peak rain intensity does not seem to be as strong of a predictor of lobe volume.

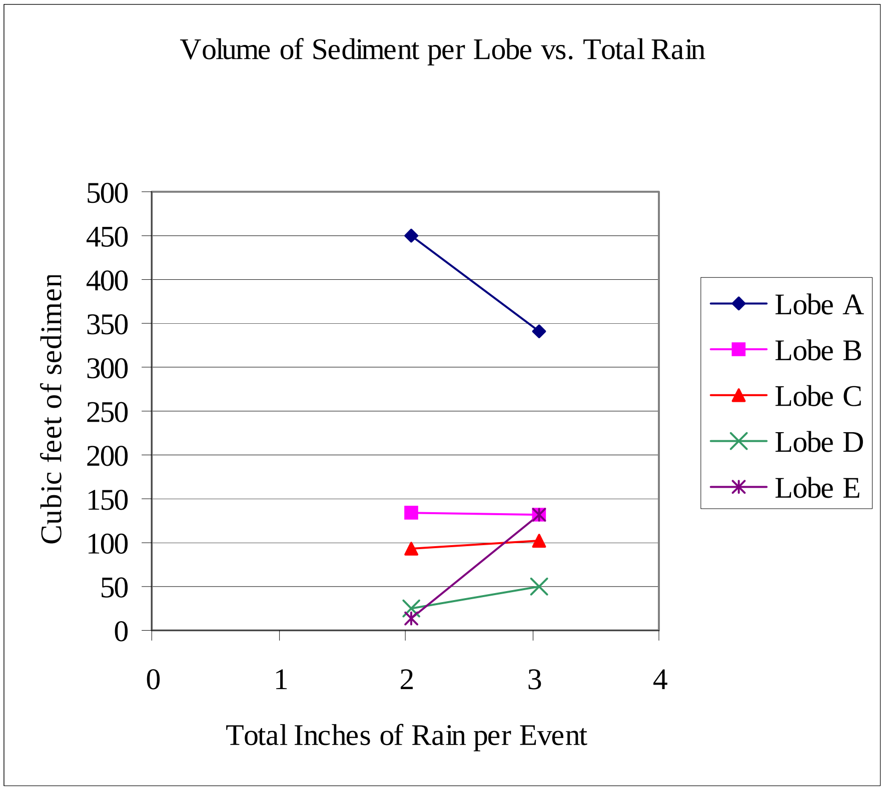

Figure 32. Lobe volume accumulations vs. total rain.

6. DISCUSSION

The main goals of this research was to determine the extent of sediment movement off of gas well sites, identify conditions that might contribute to sediment movement, and characterize the types of materials that are moving as sediment. The results show that sediments are eroding from the gas well sites examined in this study. Observations made during the study include: the amount of runoff and erosion from the gas well sites appears to be greater than that from non-disturbed areas around the sites; the slope of the land where a gas well is built affects erosion; the total rain per event and rain intensity affects erosion in most cases; eroded materials may enter local stream channels from gas well site construction; and vegetation (including revegetation of disturbed areas) appears to effectively slow storm water runoff and decrease the potential for erosion.

6.1. Storm Water Runoff and Erosion from Gas Well Sites

Storm water sediment runoff from the gas well pads and gravel access roads appears to be greater than from undisturbed areas. This statement is supported in that the same storms hit all the sites in most cases, but only one storm generated flow and sediment at the BiltCt weir, whereas flow and sediment were generated by almost every storms at the gas well sites. The difference in runoff is likely due to the ability of surfaces at each type of site to absorb precipitation. The natural fields where the controls were located had high permeability compared to the gravel covered gas well pad sites. Heavy precipitation, which easily runs off the pads and access roads, is presumably absorbed by natural undisturbed land.

Infiltration tests performed in July and August 2005 (when the soil was very dry) at the Biltmore and Bradford sites indicated that the natural field soils could sustain infiltration rates ranging from 0.26 inches to 0.44 inches per minute, while the gravel gas well pads could only sustain infiltration rates ranging from 0.008 inches to 0.05 inches per minute. Large amounts of silt and clay in the crushed limestone gravel of the gas well pads decreased permeability, even when the soil was very dry. Besides decreased permeability, land located along access roads and around the gas well pads is typically disturbed (graded and scraped of vegetation) by gas well site construction. Reduced vegetation enables runoff to occur more readily than from undisturbed areas.

6.2. Effect of Slope on Erosion

Slope appears to play an important part in encouraging erosion at the gas well sites especially when combined with other changes at the sites that increase runoff, such as vegetation being removed from the disturbed areas and the pads being made less permeability. All of the weirs at the three gas well sites and the two control sites received similar amounts of precipitation but only the Biltmore pad sites, where the slopes of the disturbed areas were significantly greater than that of the Bradford site, had debris lobe growth. BiltCt had similar slopes to Bilt4 and Bilt6, but vegetation and permeability were not altered around that site, and runoff and sedimentation did not occur.

6.3. Total Rain and Rain Intensity Effect on Erosion

Erosion, the ability of runoff to carry sediments, was compared to total rainfall amounts and peak 1-hour rain intensities for all the weirs and sediment traps. The total rain and the peak 1-hour rain both showed positive relationships to the total weight of sediments collected in most of the traps and weirs (refer to Figures 13, 14, 16, 21, and 22). As total rain and peak rain increases, so does the amount of sediment eroded. Both creek traps, Rill Trap 1, Bilt4, and Bilt6 showed increased sediment weight as total rain and 1-hour rain intensity increased. Rill Trap 2 was not considered because the trap filled with sediment during all events. Sediment weight in Brad1 decreased as total rain increased, but then increased as 1-hour peak rain increased. The results at Brad1 may have been due to a variation in the overall intensity of the different rain events that occurred at Brad1. For example, a 3” total rain event spread over 12 hours may not produce as high intensity of flow as a 2” inch total event spread over two hours.

6.4. Gas Well Site Erosion into Stream Channels

Eroded gas well site sediment entering stream channels was evident where Lobe D flowed into the stream channel east of Bilt4 (Figure 22). Lobe D developed from two storm events and deposited material into a local creek channel during both events. Compared to the other lobes, Lobe D did not increase in area as total rain increased (Figure 29). Lobe D’s absence of growth is explained because the lobe had flowed into the creek channel. Regardless of how much rain fell, the lobe could not spread out further except perhaps down the creek. Rather than spreading out, Lobe D filled in the bottom of the creek channel a little with each runoff event. Eventually, once the creek had been filled, Lobe D probably would have increased in area by flowing down the creek bed.

The two creek traps located in the stream that flowed along the west and south side of Bilt4 received gas well construction runoff. A large section of the access road leading to Bilt4 drains into the stream, and a portion of the stream leading up to Creek Trap 1 had been heavily disturbed and graded by tractors. About 50’ of the stream channel actually runs through tractor tire ruts. Creek Trap 1 received more sediment than Creek Trap 2 under all conditions (Figure

13 and 14). Creek Trap 2's lower sediment loads were possibly due to the amount of vegetation leading up to each trap. Whereas the area leading to Creek Trap 1 was heavily disturbed by construction, the area leading up to Creek Trap 2 was undisturbed. Heavy grass and plant growth in the creek bottom likely slowed sediment movement and resulted in the lower sediment measurements for Creek Trap 2.

Silt and clay percentage in Creek Trap 1 samples decreased as total rain increased, but did not vary much for Creek Trap 2. Difference in the percentages may be due to the ability of flowing water at different magnitudes to entrain particles from disturbed landscapes. The area around Creek Trap 1 was highly disturbed. With no plants to hold soil in place, low intensity rain events might produce enough flow to entrain small clay particles but not sand and gravel. Higher flows from heavier rains probably dislodged more clay, while also dislodging sand and gravel, so the ratio of silt and clay to sand and gravel would decrease with increased runoff.

The differences in sediment weights between the two creek traps is likely due to the amount of vegetation within the creek bed leading up to each trap. Heavy runoff from short intense bursts of rain likely dislodged the loose non-vegetated soil leading up to Creek Trap 1 faster than the vegetated soil leading to Creek Trap 2. Intense runoff was likely slowed and prevented from eroding sediments by the grass and plant roots leading to Creek Trap 2.

6.5. Vegetation and Erosion

The ability of vegetation to filter sediments was apparent in the differences in silt and clay content and total sediment weight between the two creek traps (Figures 12, 13, and 14). Plants play an important role in stabilizing and filtering sediments and the regrowth of plants in the disturbed areas likely played a role in the cessation of debris lobe formation after the March

19, 2006 storm event. By the end of March 2006, field grasses had grown in at most of the unvegetated gas well disturbed areas. Coverage was far from total, and large areas of bare ground were still exposed, but apparently enough vegetation had grown in to prevent further sediment movement and debris lobe growth. Precipitation and runoff events similar in magnitude to those that had caused debris lobe formation occurred after March 2006 but none produced new debris lobe growth. Cessation of debris lobe growth after March 2006 may have also been due to an exhausted sediment supply. Rills, that had carried eroded sediment to the lobes, reached a hard sub layer of soil after eroding down the top 18 inches or so of the disturbed area.

Compared to the range of annual construction sediment loads listed by the USEPA (7.2 to 500 tons per acre, per year) and calculated in other studies, those estimated for this study (47.3 to 66.9, or 57.1 average tons per acre, per year) are within the range of typical construction sites, and much greater than the half ton per acre sediment loads normally associated with rangelands. It is possible that the debris lobes may represent the initial “first flush” of sediments from disturbed area and that sedimentation will naturally decline as the site becomes more vegetated and the readily available sediment supply diminishes. If sediment supply was exhausted after March 19, 2006 the entire annual load per acre may have been the average 57.1 tons of sediment that eroded during the seven months from August 2005 to March 2006.

7. CONCLUSIONS

Natural gas exploration sites of less than 5 acres are not currently subject to the same regulations as similar sized construction sites. The USEPA currently does not require erosion control for small oil and gas well construction sites, but regulations may someday be initiated if research indicates higher than natural erosion is occurring from those sites. This research has shown that the design and construction practices used to create gas well sites have the potential to increase erosion beyond what would occur in undisturbed settings. Changes to the landscape appear to enable storm water runoff to flow in greater volume and intensity than what would naturally occur in the watersheds containing gas well construction sites. Sediment movement is occurring at higher than natural rates from the gas well pads and disturbed areas.

The potential of sediment to enter local water bodies seems evident by sediments captured in the creek traps, by the distance lobes traveled off of the gas well disturbed areas, up to 124 feet, and by Lobe D which flowed into a local creek channel during two different storm events. All sediment debris lobes stopped forming after disturbed areas around the gas well sites naturally became partially revegetated after March 2006. However, sediments, especially silts and clays were still collecting in the rill and creek traps at the time of this writing, so erosion appears to continue in some form even after partially revegetation.

Based on the debris lobe growth and sediments found in creek traps, gas well constructions in hilly terrain or built near streams may require erosion control methods to keep sediments out of local water bodies. Some erosion control was used at the sites, such as mulch piles around disturbed areas and a diversion berm at Bilt6, but they were likely employed to preserve the functionality of the pad sites, to keep mud off of the pads, or in the case of the mulch berms, required by The City of Denton erosion control regulations. To effectively control sediment movement, more extensively maintained erosion control would be needed. Erosion control methods used at the study sites were not maintained. Mulch piles used in early construction of the sites were spread out when final excavation occurred at each site, and the diversion berm at Bilt6 was eroded through in some areas.

If oil and gas industry operators choose to control erosion, or are required to control erosion, the RAPPS document lists a variety of methods that could be employed at gas well sites. Potential choices of erosion control listed in RAPPS include: straw bales, silt fences, rock berms, drainage dips, turnouts, construction mats, cross-drain culverts, geotextiles, and sediment traps.

This research was limited by time and resources and could be improved in future studies. For example, erosion effects from cattle trails across creek channels and through the gas well disturbed areas were not examined. Future studies might account for cattle disturbances, or to insure that they do not affect erosion, exclude them from the area being studied. A second area that should be examined in future studies was the conditions or occurrences of erosion before gas well sites were built. Rates of erosion are unknown from the sites before the gas wells were constructed since all of the gas well sites studied were under construction when this research started. Control sites were used to compare undisturbed areas to the gas wells, but direct comparisons of the same site before and after a gas well was constructed would probably yield the most accurate measurement of change. Other areas of potential research might include: when and how RAPPS should be used at oil and gas sites, and if RAPPS controls are effective; the use of models such as the Universal Soil Loss Equation to estimate sediment loadings; and studying the nature and rate of vegetation re-growth at gas well site disturbed areas. Such research studies would help in understanding if gas well construction sites have similar erosion characteristics as regular construction sites, and if gas well sites should be regulated similarly as construction sites.

APPENDIX

SEDIMENT CHARACTERISTICS

Appendix

Sediment By Site Clay and Silt

Site	Date	Airport Rain Fall	Weir Rain Fall	Weir Rain Peak	Weir Peak	Weight	Sieved Weight	Mesh #10	#18	#35	#60	#120	#230	clay & silt
		total	total	inches	cfs	grams		2000	1000	500	250	125	63	%
				per hour										
Bilt Ct weir	3/19/06	3.05	2.94	0.71	0.42	50	40	0.305	0.071	0.109	0.132	2.483	2.901	85
Bilt4 Creek1	2/25/06	2.04	1.98	0.28		94.3	40	0.7	0.88	1.177	2.04	1.178	2.69	78
Bilt4 Creek1	3/19/06	3.05	3.06	0.78		452	40	7.033	3.096	1.408	0.83	1.561	1.68	61
Bilt4 Creek1	4/28/06	1.52	1.52				40	4.077	1.171	0.48	0.581	0.919	1.115	79
Bilt4 Creek1	5/5/06	0.85	0.75	0.59		156.93	40	0.329	0.576	0.467	0.407	0.391	0.525	93
Bilt4 Creek2	2/25/06	2.04	1.98	0.28		52	40	13.26	4.326	1.998	1.377	0.585	0.369	45
Bilt4 Creek2	3/19/06	3.05	3.06	0.78		374	40	7.615	3.688	2.458	1.707	1.394	0.939	55
Bilt4 Creek2	4/28/06	1.52	1.52				40	17.09	4.942	2.096	0.89	0.482	0.434	35
Bilt4 Creek2	5/5/06	0.85	0.75	0.59		30.271	30	8.227	2.079	1.004	0.591	0.388	0.314	58
Bilt4 Rill1	2/25/06	2.04	1.98	0.28	0.11	10934	40	0.991	1.3595	2.076	1.808	1.078	0.821	80
Bilt4 Rill1	3/19/06	3.05	3.06	0.78	0.46	10347	40	0.836	1.703	1.745	1.757	1.984	0.847	78
Bilt4 Rill1	4/20/06	0.86	0.86			6503.4	40	1.75	1.282	0.945	0.707	0.523	0.605	85
Bilt4 Rill1	4/21/06	0.24	0.24			5526.5	40	1.216	0.925	0.904	0.813	0.837	0.564	87
Bilt4 Rill1	4/28/06	1.52	1.52				40	3.599	1.556	1.156	0.888	0.909	0.607	78
Bilt4 Rill1	5/5/06	0.85	0.75	0.59	0.53		40	8.862	1.814	1.287	0.84	0.549	0.397	66
Bilt4 Rill2	2/25/06	2.04	1.98	0.28	0.11	7421	40	0.643	1.336	1.069	1.32	1.334	1.177	83
Bilt4 Rill2	3/19/06	3.05	3.06	0.78	0.46	8301	40	0.685	0.794	1.302	0.963	2.419	1.53	81
Bilt4 Rill2	4/20/06	0.86	0.86				40	1.33	1.049	0.773	0.602	0.606	0.992	87
Bilt4 Rill2	4/28/06	1.52	1.52				40	7.517	0.498	0.349	0.342	0.396	0.831	75
Bilt4 Rill2	5/5/06	0.85	0.85	0.59	0.53	7602	40	5.084	0.119	0.161	0.255	0.31	0.725	83
Bilt4 Trap	4/28/05	0	0			2043.5	40	0.344	1.018	1.03	1.206	0.88	0.585	87
Bilt4 Trap	6/1/05	0.97	0.97			9686	40	0.788	1.67	2.043	2.224	3.999	5.194	60
Bilt4 Weir	4/28/05	0	0			239500	40	7.802	1.04	0.678	0.621	0.513	0.396	72
Bilt4 Weir	6/1/05	0.97	0.97			331600	40	3.909	1.027	0.685	0.665	0.652	0.464	81
Bilt4 Weir	10/31/05	0.52	0.52			405	40	1.089	0.515	0.731	2.081	4.196	1.819	74

Bilt4 Weir	1/22/06	1.27	1.28	0.27		238.7	40	0.598	1.106	2.019	2.723	5.332	4.809	59
Bilt4 Weir	2/25/06	2.04	1.98	0.28	0.11	579	40	0.325	1.022	0.329	2.173	2.023	3.073	78
Bilt4 Weir	3/19/06	3.05	3.06	0.78	0.88	2054	40	0.475	0.857	1.607	2.147	0.949	2.901	78
Bilt4 Weir	4/20/06	0.86	0.86				40	1.32	0.96	0.718	0.766	0.896	1.049	86
Bilt4 Weir	4/28/06	1.52	1.52				40	0.115	0.296	0.315	0.375	0.315	0.715	95
Bilt4 Weir	5/5/06	0.85	0.75	0.59	0.53		40	2.004	1.188	0.85	1.025	0.853	1.577	81
Bilt6 weir	4/28/05	0	0			2029	40	0	0.011	0.04	0.243	0.521	0.823	96
Bilt6 weir	6/1/05	0.97	0.83			9857	40	0	0.017	0.057	0.053	4.966	3.178	79
Bilt6 weir	10/31/05	0.52	0.52			376	40	15.6	4.0775	3.349	3.5	3.275	2.199	20
Bilt6 weir	1/22/06	1.27	1.23	0.22	0.28	375	40	3.801	1.776	2.091	2.412	3.507	2.739	59
Bilt6 weir	2/25/06	2.04	1.91	0.25	0.49	609	40	0.302	1.171	3.021	1.782	4.379	1.418	70
Bilt6 weir	3/19/06	3.05	2.82	0.71	0.88	2051	40	0.507	0.408	0.448	0.963	2.079	2.026	84
Bilt6 weir	4/28/06	1.52	1.52				40	6.521	2.747	2.914	2.371	1.849	1.096	56
Bilt6 weir	5/5/06	0.85	0.85	0.67	1.91		40	17.5	2.755	1.851	1.46	1.161	0.716	36
Brad1 weir	3/26/05	2	2			3528.9	40	0.014	0.093	0.052	0.974	1.434	4.424	83
Brad1 weir	6/1/05	0.97	1.17	0.99		14278	40	0.374	0.343	0.652	3.461	6.693	6.724	54
Brad1 weir	10/31/05	0.52	0.52			65	40	0.296	0.786	2.674	7.891	10.01	6.172	30
Brad1 weir	1/22/06	1.27	1.27			43.9	40	0.467	1.358	4.175	6.662	4.882	2.964	49
Brad1 weir	3/19/06	3.05	3.05		0.78	820	40	0	0	0.076	0.096	0.187	1.334	96
Brad1 weir	4/28/06	1.52	1.52				40	0.072	0.095	0.094	0.294	3.054	4.536	80

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