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ORIGINAL ARTICLE

Field-based monitoring of sediment runoff from natural gas well sites in Denton County, Texas, USA

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Abstract This study evaluates sediment runoff from gas well development sites in Denton County, Texas. The magnitude of sediment runoff was investigated by intercepting sediment in traps and weirs at the periphery of each gas well site and by measuring the growth of debris lobes that formed down slope from two sites. Four debris lobes formed at one gas well site and one formed at a second site. Debris lobes ranged in size from 30 to 306 square meters. Sediment from one site entered local creek channels, either as a component of storm water runoff or, in one case, as a debris lobe that flowed into a channel. The study findings suggest that sediment movement is significantly diminished once areas disturbed by gas well construction become naturally re-vegetated. Based on estimates of debris lobe volumes, sediment loading rates of about 54 metric tonnes per hectare per year were calculated for one site. It is concluded that gas well development sites in areas similar to those studied, especially where vegetation has been removed and terrain has relatively steep slopes (greater than 6%), generate sediment runoff comparable to small construction sites and should therefore be considered for regulations requiring erosion and sediment control measures.

Keywords Gas well · Land disturbance · Storm runoff · Erosion · Sediment

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. Numerous studies have documented sediment impacts on aquatic habitats from construction sites. Construction activities can raise soil erosion rates up to 40,000 times greater than pre-construction levels (Harbor 1999) and resulting sediment runoff can alter the morphology of nearby channels (Wolman and Schick 1967; Simons and Senturk 1992; Schueler 1997; Nelson and Booth 2002). Increased sedimentation can also affect aquatic life. Sediment pollution has numerous detrimental impacts on fish populations (Newcombe and Jensen 1996) and aquatic plants (Brookes 1986; Wood and Armitage 1997). Other problems associated with sediments include decreased water transparency, diminished channel depths in navigable water ways, decreased recreational use of water bodies when they become aesthetically undesirable (Ryding and Thornton 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

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United State Environmental Protection Agency (USEPA) in 2004, sedimentation was found to be one of the major contributors to poor stream health amongst small U.S. streams (USEPA 2006). Excessive sedimentation is commonly caused by anthropogenic activities that increase storm water runoff, such as removing natural vegetation, increasing slopes, or decreasing permeability of surfaces.

Currently, small construction sites (larger than 0.4 ha) are subject to USEPA regulations designed to minimize sediment movement from disturbed areas into nearby water bodies (USEPA 2005). Unlike construction sites, oil, and gas well development sites in Texas are not regulated and have not been extensively studied for storm water runoff effects. Recent advances in natural gas recovery, specifically fracturing and horizontal drilling techniques (Durham 2005), have dramatically increased exploration and recovery of natural gas in the North Central Texas region and thousands of gas wells have been drilled in the past decade (Devon Energy 2004) (Fig. 1).

Because relatively little is known about storm water runoff from gas well sites, this study is designed to answer some basic questions about sediment runoff from these sites. The questions the study attempts to answer are: (1) How much sediment is eroded from gas well sites? (2) Where and how does sediment runoff occur? (3) How frequently does sediment runoff occur in response to storms? (4) How far does sediment travel beyond the perimeters of gas well sites (in short time frames)? (5) Is sediment transported into local stream channels? (6) Is there a relationship between slope, rainfall volume and intensity, and erosion? 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 construction sites should also be applied to gas well development sites.

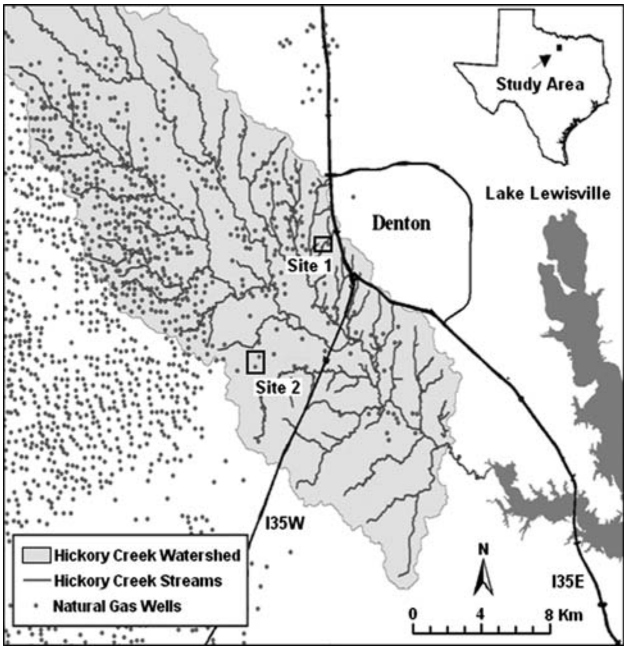

Fig. 1 Location map showing sites 1 and 2 used in the study, the Hickory Creek watershed and natural gas well sites in western Denton County (Modified from Wachal et al. 2005)

Study area

The study area includes three gas well sites and two undisturbed reference sites located southwest of the City of Denton, in Denton County, Texas (Fig. 1). Reference sites are in undisturbed areas located close to the gas well sites and within the same physiographic region. Many of the wells being drilled or planned for future recovery activities lie within the Hickory Creek watershed, which drains into Lake Lewisville (Fig. 1). 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 used for this study are located in the Grand Prairie physiographic region, on lands currently used as mixed rangeland. Clay, clay loam, and stony clay soils predominate in the study area (Ford and Pauls 1980). Underlying bedrock at all sites is an undifferentiated mixture of limestones, marls, ironstone concretions, shales, and calcareous clay (Barnes 1991). Topography in this region is generally flat to gently rolling, with slopes ranging up to about 15%.

One gas well site and one reference site are located approximately 1 km west of Interstate 35W and are designated Site 1 (Site 1) and Site 1 Reference (Site1Ref). The other two pad sites and one reference site are located approximately 5 km west of Interstate 35W and are designated Site 2A (Site2A), Site 2B (Site2B), and Site 2 Reference (Site2Ref). Site 1 sites are on relatively flat prairie land heavily vegetated with *Prosopis juliflora* (Mesquite) and *Gleditsia triacanthos* (Honey locus). Contrastingly, all of the Site 2 sites are located on relatively treeless Bluestem (*Bothriochloa saccharoids;* Texas Parks and Wildlife Division 1984) rolling prairie with well-developed stream networks. An important difference between the Site 1 and Site 2 sites (gas wells and reference sites) is that they have contrasting slopes. The land around the Site 1 sites is relatively flat with slopes of about 1%, whereas natural slopes approach 15% in some areas around the Site 2 sites.

Generally, gas well development sites have two distinct parts: an inner gravel-covered pad where drilling, extraction and equipment maintenance occurs, and an outer disturbed area that is altered during the initial construction

Fig. 2 A typical gas well site consisting of an inner gravel-covered pad and surrounding disturbed area. A mulch filter berm, required by city ordinance and designed to prevent runoff, can be seen at the edge of the disturbed area

and exploration phase of gas well development. Disturbed areas typically extend about 50–100 m from the pad site perimeter. Once the pad is constructed, disturbed areas are smoothed out and left to re-vegetate naturally. Gas well pads are generally constructed with a gentle slope to promote drainage toward one corner of the pad (Fig. 2).

Although not regulated by the EPA, gas well sites can be subject to city ordinances when they are located within a city's corporate boundary or extra-territorial jurisdiction; for example, all three gas well sites used in the study had mulch berms around the perimeters of the disturbed areas, which were required by city ordinance (Fig. 2).

Climate in northeast Texas is classified as subtropical (Taft and Godbey 1975). Summers are typically hot and dry, while winters are mostly mild and cool with occasional sub-freezing days. The City of Denton receives approximately 99 cm of precipitation in an average year. May is usually the wettest month (13.7 cm average) and August the driest month (5.7 cm average). Spring thunderstorms are common and can generate intense rainfall in excess of 12.5 cm/h (National Climatic Data Center 2007a; Taft and Godbey 1975).

Methods

A combination of different techniques was employed to measure sediment runoff from the gas well pads, the undisturbed reference sites, and, for one site, the surrounding disturbed area and within natural stream channels nearby. Assessment of sediment runoff from gas well sites should include methods to collect bed load (coarser sediment that maintains contact with the surface as it is moved by flowing water), because it may be a significant component of sediment runoff during storm flow conditions. Because bed load is not suspended within the flow of water, capturing it requires methods of intercepting it as it moves along a channel or down the surface of a slope. Bed load traps and catchments can both be used to capture bed load, and both were used in this study. A bed load trap is a slotted container installed in the bed of a channel that traps sediment (including bed load) that falls into it. A catchment is a barrier to flow, such as a weir, which causes storm runoff to pond, allowing sediment (including bed load) to settle out.

In storm water runoff, especially where a watershed has been altered, it is often difficult to separate bed load from suspended load (finer sediment suspended in the flow), because large velocity changes frequently occur, enabling small particles to easily switch from being suspended to moving as bed load (Haan et al. 1994). In this study no attempt was made to separate bed load and suspended load and estimated erosion rates include all sediment, without regard to the mode of sediment transport.

In a concurrent study conducted by the City of Denton, V-notch weirs were installed immediately down slope from the lowest corner of the pads and in hill slope concavities at the two reference sites (Fig. 3a). The weirs were fitted with automated sampling devices to measure storm flow volumes and to sample storm flow. Automated recording rain gauges were also installed near each weir.

For the purposes of this study, the weirs provided some insight into sediment runoff, in that they acted as partial sediment catchments. Storm runoff from the pad sites and from the reference sites was funneled into the weirs by fences constructed of plastic sheeting. Storm runoff ponded on the floor of the weir, which was several cm below the notch (Fig. 3a). Sediment settled out on the floor of the weir and was collected after each storm event. Sediment

Fig. 3 **a** A V-notch weir installed at the Site 2 reference site. Plastic sheeting funnels runoff through the weir. The floor of the weir, several cm below the notch, acts as a partial sediment trap capturing bed load and some suspended load sediment. **b** Bed load trap. A plastic-lined, plywood box with a slotted metal cover is buried in the bed of a channel. Sediment is trapped when it falls through the slot (keys for scale). **c** Confluence of two rills running through the disturbed area down slope from the Site 2A pad site. Bed load traps were placed in the larger rill to the right. **d** Edge of debris lobe at Site 2A. Sediment washed from the disturbed area is encroaching onto the grassy undisturbed area (width of view is about 2 m)

collected from the floor of the weirs was assumed to contain bed load and some suspended sediment that settled out in the ponded water. Undoubtedly, some suspended sediment would have been carried over the weir by storm flow and the quantity of this component of sediment runoff is unknown. However, sediment collected from the weirs does at least provide a minimum estimate for sediment eroded from pad sites during storms, as well as an indication of how frequently sediment runoff occurs and changes in the magnitude of sediment runoff over time.

Field observations made during the study indicated that large rills were being eroded by storm runoff in the disturbed areas at the Site 2 gas well sites. At Site 2A, two bed load traps were installed in the bed of one rill, at distances of approximately 25 and 100 m from the edge of the pad site (Figs. 3b, c). Two bed load traps were also installed in a nearby intermittent stream channel that flowed through a culvert under the pad site access road and passed within a few meters of the disturbed area. The traps were placed in the bed of the channel approximately 100 and 250 m down slope from the access road. The creek drains to a stock pond at the base of the slope (Fig. 4).

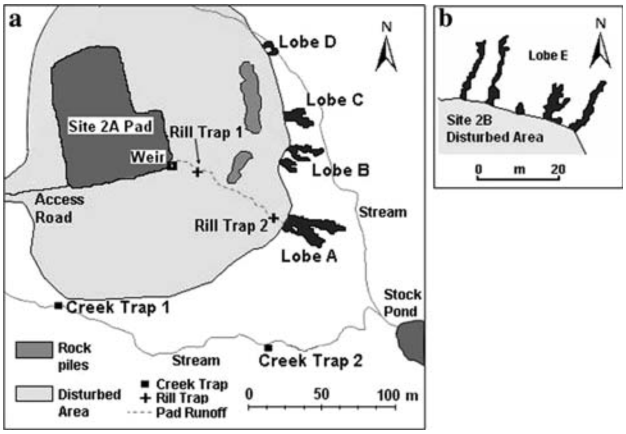

Fig. 4 **a** Map of Site 2A, showing the pad, disturbed area, rill bed load traps, creek bed load traps and debris lobes A–D. **b** Debris lobe E at Site 2B

Sediment from weirs and bed load 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 sediment was transported to the lab and dried for 24 h in metal pans, at a temperature of 104°C. The dried samples were weighed and then a sub-sample was subjected to particle size analysis using a wet sieving process. Like the weirs, the rill and creek traps only provide a minimum estimate of the magnitude and frequency of sediment movement, because it is unlikely that they capture all of the suspended sediment in the storm flow.

At Sites 2A and 2B, debris lobes were observed to be forming at the edge of the disturbed areas, where sediment was being carried by surface runoff into adjoining undisturbed areas (Fig. 3d). At Site 2A, three smaller lobe complexes (combined lobes), designated lobes B, C, and D, formed at the northeast margin of the disturbed area and a larger lobe complex, designated lobe A, formed at the southeast margin, in the area of greatest slope and where the largest rills had formed (Fig. 4a). At Site 2B, a debris lobe complex (several closely-spaced debris lobes), designated lobe E, formed at the northeast margin of the disturbed area (Fig. 4b). Mulch berms were breached and/or overtopped by the debris lobes and appear ineffective, at these relatively steeply-sloping sites at least, at preventing sediment runoff from disturbed areas.

To facilitate mapping of the debris lobes, a regular grid of 1.5 m spacing was constructed over the lobes using metal posts and rope (the ropes were removed after each measurement). After each storm event, the grids were used to transfer the perimeters of the lobes to graph paper. The grids were also used to systematically measure the depth of sediment in the debris lobes at the intersection of every grid line. Debris lobes formed on top of grassy, relatively hard, undisturbed ground. Depth measurements were taken by either digging down with a trowel to find the depth to the buried pre-existing surface or by pushing a probe into the relatively soft debris lobe sediment until hard ground was reached. A Global Positioning System (GPS, ±1 m accuracy) was used to map the metal posts forming the borders of the grids, enabling them to be added to GIS maps. The GPS could not be used to map the debris lobes themselves, because growth of a debris lobe following a storm event was sometimes less than 1 m and some features, such as long narrow fingers of sediment, were smaller than 1 m in width.

Results

Sediment from weirs and bed load traps

Table 1 shows total rainfall in cm, peak rainfall in cm/h, dry weight of sediment runoff in kg, sediment runoff in kg per 1 cm of total rainfall, sediment runoff in kg per 1 cm of peak rainfall and the percentage silt and clay of the sediment. Rainfall data is from rain gauges located at each site, except where noted. Sites that did not receive any sediment runoff (e.g. Site 1 Reference) are not listed in the table. The results show that sediment runoff occurs more frequently and at higher rates at gas well sites than at nearby undisturbed reference sites. The Site 1 Reference weir intercepted no sediment runoff during the entire study period, whereas the Site 2 Reference weir intercepted sediment on only one occasion (it is assumed that even if sediment runoff was entirely in the form of suspended load, some sediment would still had settled out on the floors of weirs). In comparison, forty three incidences of sediment runoff were recorded by pad site weirs, creek traps, rill traps, and debris lobes in response to ten storm events over the study period (Table 1). The largest single sediment runoff event was 331.6 kg of sediment eroded from the Site 2A pad site and intercepted by the Site 2A weir following a 2.46 cm storm event. In comparison, 0.05 kg of sediment was intercepted by the Site 2 reference weir following a 7.47 cm storm event (Table 1).

Debris lobes

Debris lobes ranged in area from about 30–306 m^2 and in volume from about 2–22 m^3 (Table 1). The most extensive sediment accumulation occurred in Lobe A at Site 2A (Fig. 4a). Lobe A formed from four storm events that occurred August 15–16, 2005, January 22, 2006, February 25, 2006, and March 19, 2006. The lobe covered approximately 306 m^2 and extended 38 m beyond the perimeter of the Site 2A disturbed area. Lobe C formed from the August 15–16, 2005, February 25, 2006 and March 19, 2006 storm events. Lobes B, D, and E formed from the February 25, 2006 and March 19, 2006 storm events. A GIS was used to calculate the areas and volumes of the lobes and the extent of each lobe beyond the perimeter of the disturbed area. Depth measurements used to calculate volumes were recorded only after the February 25 and March 19 2006 storm events (Tables 2, 3).

An intermittent stream flows south along the east side of Site 2A (Fig. 4a). Sediment from lobe D flowed into the stream channel during both the February and March 2006 storms. However, during each storm event, stream flow did not occur and sediment was not transported farther down the stream channel.

Discussion

All three weirs intercepting sediment eroded from pad sites show a substantial decline in sediment runoff over time (Table 1; Fig. 5). This is interpreted as a "site stabilization" effect, meaning that large quantities of readily mobilized sediment were flushed from the pad sites by the storms occurring early in the study period. Possible sources of this sediment include finer material interspersed with the

Table 1 Rainfall and sediment data by storm event

Site	Date of storm	Rain (cm)	Peak rain (cm/h)	Sediment Weight (kg)	Sediment (kg) per 1 cm rain	Sediment (kg) per 1 cm peak rain	Silt and clay%
Site2Refweir	19-Mar-06	7.47	1.80	0.05	0.01	0.03	85
Site2A creek1	25-Feb-06	5.03	0.71	0.09	0.02	0.13	78
Site2A creek1	19-Mar-06	7.77	1.98	0.45	0.06	0.23	61
Site2A creek1	05-May-06	1.91	1.50	0.16	0.08	0.10	93
Site2A creek2	25-Feb-06	5.03	0.71	0.05	0.01	0.07	45
Site2A creek2	19-Mar-06	7.77	1.98	0.37	0.05	0.19	55
Site2A creek2	05-May-06	1.91	1.50	0.03	0.02	0.02	58
Site2A rill1	25-Feb-06	5.03	0.71	10.93	2.17	15.37	80
Site2A rill1	19-Mar-06	7.77	1.98	10.35	1.33	5.22	78
Site2A rill1	20-Apr-06	2.21[a]	0.56[a]	6.50	2.94	11.64	85
Site2A rill1	21-Apr-06	0.61[a]	0.25[a]	5.53	9.07	21.76	87
Site2A rill2	25-Feb-06	5.03	0.71	7.42	1.48	10.43	83
Site2A rill2	19-Mar-06	7.77	1.98	8.30	1.07	4.19	81
Site2A rill2	05-May-06	2.16	1.50	7.60	3.52	5.07	83
Site2A weir	28-Apr-05	0.38	0.36	239.50	628.61	673.51	72
Site2A weir	01-Jun-05	2.46[a]	1.93[a]	331.60	134.59	171.78	81
Site2A weir	31-Oct-05	1.32[a]	0.86[a]	0.41	0.31	0.47	74
Site2A weir	22-Jan-06	3.25	0.69	0.24	0.07	0.35	59
Site2A weir	25-Feb-06	5.03	0.71	0.58	0.12	0.81	78
Site2A weir	19-Mar-06	7.77	1.98	2.05	0.26	1.04	78
Site2B weir	28-Apr-05	0.38	0.36	2.03	5.33	5.71	96
Site2B weir	01-Jun-05	2.97[b]	2.51[b]	9.86	4.00	5.11	79
Site2B weir	31-Oct-05	1.32[a]	0.86[a]	0.38	0.28	0.44	20
Site2B weir	22-Jan-06	3.12	0.56	0.38	0.12	0.67	59
Site2B weir	25-Feb-06	4.85	0.64	0.61	0.13	0.96	70
Site2B weir	19-Mar-06	7.16	1.80	2.05	0.29	1.14	84
Site1 weir	26-Mar-05	5.46	0.71	3.53	0.65	4.96	83
Site1 weir	01-Jun-05	2.97	2.51	14.28	4.80	5.68	54
Site1 weir	31-Oct-05	1.32[a]	0.86[a]	0.07	0.05	0.08	30
Site1 weir	22-Jan-06	3.23[a]	0.51[a]	0.04	0.01	0.09	49
Site1 weir	19-Mar-06	8.00[a]	1.47[a]	0.82	0.10	0.56	96

[a] Rainfall data from Denton Municipal Airport

[b] Rainfall data from Site 1

crushed gravel covering the pad site and material from the fill slopes at the edge of the pad. After this initial flushing of readily available sediment, less sediment was available to be moved by later storm events, even if they were of similar amount and intensity as the earlier storms.

Initial sediment runoff at the Site 2A pad site was greatly enhanced by the formation of a small gully on relatively steeply sloping ground between the corner of the pad site and the location of the weir (a fill slope created during leveling of the pad site). Surface runoff may have been concentrated by fences of plastic sheeting designed to channel storm flow through the weir, although gullying was also observed at other pad sites where fencing was not installed. The gully formed during the rain storms of April 28, 2005 and June 1, 2005, which washed 239.5 and 331.6 kg of sediment, respectively, onto the floor of the weir (Table 1). After these two early storms, the floor of the gully became armored by a lag of coarser rock fragments and sediment runoff in response to later storms was greatly diminished.

A similar pattern of declining sediment runoff over time was not observed for the creek and rill traps (Table 1; Fig. 6). Sediment is supplied to both the creek and the rill from the large disturbed area surrounding the Site 2A pad site (Fig. 4a). These findings suggest that the disturbed area can continue to supply sediment runoff in response to a succession of storm events for a longer period than the pad site. Sources of sediment presumably include sheet wash and the erosive widening and deepening of rills. Unlike the pad site, stabilization of the disturbed area appears to be

Table 2 Storms and cumulative areas of debris lobes

Date	Rain (cm)	Peak rain (cm/h)	Cumulative area of debris lobes (m^2)				
			Lobe A	Lobe B	Lobe C	Lobe D	Lobe E[b]
8/15/05	3.86	3.15	86.4	—	18.1	—	—
1/22/06	3.25	0.69	172.8	—	—	—	—
2/25/06	5.03	0.71	207.7	46.7	57.3	16.8	2.4
3/19/06	7.77	1.98	305.7	131.2	97.0	30.2	60.8
Down slope extent[a] (m)			37.8	23.5	19.2	8.5	18.0

— No growth occurred

[a] Beyond disturbed area

[b] Lobe E formed at Site 2B; lobes A-D formed at Site 2A

Table 3 Cumulative volumes of debris lobes

Date[a]	Cumulative volume (m^3)				
	Lobe A	Lobe B	Lobe C	Lobe D	Lobe E
02/25/06	12.8	3.8	2.6	0.7	0.4
03/19/06	22.4	7.5	5.5	2.1	4.2

[a] Depth measurements were obtained within a few days after the storm event

dependent on re-vegetation of the disturbed ground, rather than on flushing of readily mobilized sediment (see below).

The results show that sediment runoff did reach stream channels near the gas well sites; sediment was intercepted in both Site 2A creek traps in response to three storms occurring in early 2006 and a debris lobe flowed into an intermittent stream channel at the site during both the February and March 2006 storms (Table 1). However, the amount of sediment intercepted by the creek traps was very small (the largest amount was 0.45 kg in response to 7.77 cm of rain) and more than an order of magnitude lower than sediment collected in the rill traps (Table 1). Sediment runoff in the rills is presumably supplied by sheet wash erosion of the disturbed area, as well as erosion of the rill banks and bed: in contrast, the creek channel was mostly vegetated and appeared stable; sediment runoff in the creek probably originated as sheet wash from nearby disturbed areas or the gas well site access road, although it is also possible that sediment came from other unknown sources farther upstream.

Although only limited data is available on the growth of debris lobes (Tables 2, 3), the results indicate that much of the sediment forming the lobes probably originated in the disturbed areas surrounding the pads, rather than from the pad sites themselves. Most of the lobe growth occurred in early 2006, by which time sediment runoff from the pad sites had greatly diminished (Table 1). Sediment in the debris lobes was therefore most likely supplied by sheet wash and rill erosion in the disturbed areas (although it is possible that sediment eroded from the pad sites in early 2005 was deposited in the disturbed areas and then reworked by later storms and may have contributed to the growth of the debris lobes).

Debris lobe growth apparently stopped or slowed considerably after March 2006; three storms occurred in April and May 2006 that were comparable in amount and intensity to storms that caused debris lobe growth (Table 1; storms of April 20, April 21 and May 5, 2006) and yet no further growth of debris lobes was observed. It was noticed that by the end of March 2006, field grasses and weeds had naturally regenerated over most of the disturbed areas and the debris lobes. It may be that this re-vegetation was sufficient to increase sediment cohesion and halt or diminish further erosion.

To assess potential sediment loadings represented by the study results, an estimate was made of the weight of sediment transported beyond the disturbed area and deposited in debris lobes at Site 2A. This site was selected because it had the largest amounts and greatest frequencies of sediment runoff measured in the study, presumably reflecting the greater slope at this location (i.e., no debris lobes formed at the relatively flat Site 1 and debris lobe area and volume were about an order of magnitude smaller at the moderately-sloped Site 2B; Tables 2, 3). Unlike the weirs and bed load traps in the rills and creeks, the debris lobes

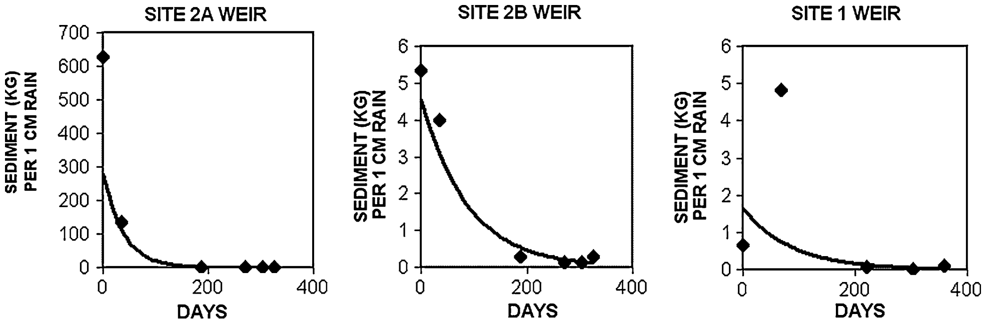

Fig. 5 Exponential declines in sediment runoff from the gas well pad sites intercepted by weirs, interpreted as a "site stabilization" effect. Sediment runoff declines over time as the supply of readily mobilized sediment diminishes. Sediment runoff standardized to kg per 1 cm rain

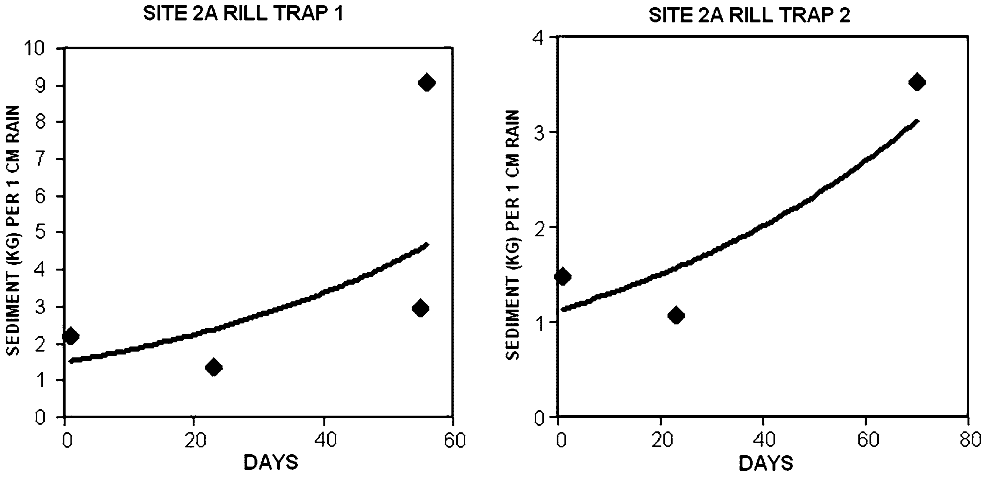

Fig. 6 Sediment runoff intercepted in the bed of a large rill formed in the disturbed area of the Site 2A gas well site (see Fig. 4 for rill trap locations). Sediment runoff standardized to kg per 1 cm rain

appeared to retain all sediment runoff (both bed load and suspended load); it is likely that even fine suspended sediment was deposited in the debris lobes as storm runoff infiltrated into the relatively permeable undisturbed grassy surface beyond the disturbed area.

The four storms of August 15–16, 2005, January 22, 2006, February 25, 2006 and March 19, 2006 generated 37.5 m^3 of sediment runoff (Tables 2, 3). This represents 49,875 kg (about 49.9 t) of sediment or an average of about 12.5 t per storm event, based on the average weight (1,330 kg) of a cubic meter of dried sediment derived from laboratory testing. Many factors probably influence the occurrence and amount of surface runoff in the disturbed areas, including rainfall amount and intensity, and surface conditions. These factors can vary spatially and temporally, complicating sediment runoff estimates. However, for the purposes of approximation, if it is assumed that similar storms to those that generated the debris lobes at site 2A (at least 3.25 cm depth and peak 1-h intensities $\geq$0.69 cm/h) will, on average, produce similar sediment runoff (12.5 t per storm), then an estimate can be made of average annual sediment runoff represented by the debris lobes. In the 7-year period 2000–2006, an average of 6.9 such storms per year was recorded at Denton Municipal Airport (National Climatic Data Center 2007b). This provides an estimated average annual sediment runoff of about 86 t of sediment. The total area of Site 2A (pad and disturbed area) is approximately 1.6 ha; this yields an estimated annual sediment loading of about 54 t/ha/year.

This figure is well within the range of construction site annual sediment loads listed by the USEPA (16–1,121 t/ha/year) and much greater than the 1.1 t/ha/year sediment load typical of undisturbed rangelands (USEPA 2005). The observed stopping or slowing of lobe growth after March 2006 suggests that the debris lobes may represent the initial pulse of erosion from the disturbed area following disturbance and that sedimentation will naturally decline as the site becomes more vegetated, sediment cohesion increases, and the readily available sediment supply diminishes. This means the average annual sediment loading calculated above may only be in effect for a short period—about a year in this study. However, this too would be comparable to small construction sites since most construction projects are completed within fairly short time frames and surrounding disturbed areas are either naturally or artificially re-vegetated.

Summary and conclusions

The study findings show that gas well sites have the potential to increase erosion and sediment runoff well beyond expected levels for undisturbed sites. The estimated annual sediment loading for Site 2A was about 49 times higher than the typical level for undisturbed rangelands based on USEPA data. The study demonstrates that sediment runoff from gas well sites can enter local stream channels, from sheet wash and from debris lobes extending into channels from disturbed areas.

Pad sites exhibit a “site stabilization” effect; an initial pulse of sediment runoff occurs soon after construction, but declines rapidly as the supply of readily mobilized sediment diminishes. Disturbed areas surrounding pad sites appear to supply a greater amount of sediment runoff for a longer period than the pad sites themselves. The disturbed areas represent large sources of readily mobilized sediment subject to prolonged sheet wash and rill erosion.

Sediment runoff from the disturbed areas at the most steeply sloping sites formed large debris lobes extending up to 38 m beyond the perimeter of the gas well sites. The debris lobes accounted for the majority of sediment runoff occurring at the sites and had the potential to transport sediment into local stream channels. Erosion of the disturbed areas and growth of the debris lobes appeared to slow or stop after about a year, apparently because natural re-vegetation increases sediment cohesion and reduces further erosion.

The study results were used to estimate a potential sediment loading of about 54 t/ha/year, which is well within the range of construction site annual sediment loads listed by the USEPA (16–1,121 t/ha/year). This finding suggests that gas well development sites should be subject to similar erosion control regulations as small construction sites.

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References

Barnes VE (1991) Geologic map of Texas: Sherman sheet. The University of Texas at Austin, Bureau of Economic Geology, scale 1:250,000, 1 sheet

Brookes A (1986) Response of aquatic vegetation to sedimentation downstream from river Channelisation works in England and Wales. Biol Conserv 38:351–367

Devon Energy (2004) Feature stories: Barnett Shale. Web site accessed May 2007. Available at: http://www.devonenergy.com/operations/features/corpnews_barnett_shale.aspx?disclaimer=yes

Durham LS (2005) Barnett Shale play going strong. *Explorer*. American Association of Petroleum Geologist (AAPG). Web site accessed May 2007. Available at: http://www.aapg.org/explorer/2005/05may/barnett_shale.cfm

Ford A, Pauls E (1980) Soil survey of Denton County, Texas. US Department of Agriculture, Soil Conservation Service, Washington

Haan CT, Barfield BJ, Hayes JC (1994) Design hydrology and sedimentology for small catchments. Academic, San Diego

Harbor J (1999) Engineering geomorphology at the cutting edge of land disturbance: erosion and sediment control on construction sites. Geomorphology 31:247–263

Holmes TP (1988) The offsite impact of soil erosion on the water treatment industry. Land Econ 64:356–366

National Climatic Data Center (2007a) Climate Data Online, Precipitation Data, Hourly. Web site accessed May 2007. Available at: http://cdo.ncdc.noaa.gov/CDO/cdo

National Climatic Data Center (2007b) Climate Data Online, Precipitation Data, Denton Municipal Airport, Daily Summary. Web site accessed September 2007. Available at: http://cdo.ncdc.noaa.gov/ulcd/ULCD?state=TX&callsign=DTO

Nelson EJ, Booth DB (2002) Sediment sources in an urbanizing, mixed land-use watershed. J Hydrol 264:51–68

Newcombe CP, Jensen JOT (1996) Channel suspended sediment and fisheries: a synthesis for quantitative assessment of risk and impact. North Am J Fish Manag 16:693–727

Novotny V, Chesters G (1981) Handbook of nonpoint pollution—sources and management. Van Nostrand Reinhold, New York

Ryding SO, Thornton JA (1999) Types of aquatic pollutants, impacts on water quality and determination of critical levels. In: Thornton JA, Rast W, Holland MM, Jolankai G, Ryding SO (eds) Assessment and control of nonpoint source pollution of aquatic ecosystems. The Parthenon Publishing Group, Paris, pp 73–112

Schueler T (1997) Impacts of suspended and deposited sediments. Watershed Prot Tech 2:443

Simons DB, Senturk F (1992) Sediment transport technology. Water Resources Publications, Highlands Ranch

Taft H, Godbey R (1975) Texas weather. England and May, Oklahoma City

Texas Parks, Wildlife Division (1984) The vegetation types of Texas. Statewide mapping system. Wildlife Division, Texas Parks and Wildlife, Austin

US Environmental Protection Agency (2005) National management measures to control nonpoint source pollution from urban areas. EPA 841-B-05-004. Washington

US Environmental Protection Agency (2006) Wadeable streams assessment, a collective survey of the nation's streams. EPA 841-B-06-002. Washington

Wachal DJ, Banks KE, Hunter DH (2005) Collecting storm water from overland flow at gas well exploration and production sites. Poster presented at the water environment federation 78th annual conference. Washington, October 29–November 2, 2005

Wetzel RG (2001) Limnology: Lake and River ecosystems, 3rd edn. Academic, San Diego

Wolman MG, Schick AP (1967) Effects of construction on fluvial sediment; urban and suburban areas of Maryland. Water Resour Res 3:451–464

Wood PJ, Armitage PD (1997) Biological effects of fine sediment in the lotic environment. Environ Manage 21:203–217