ESRI 2007 International User Conference – Paper No. UC1038

Integrating GIS and Erosion Modeling: A Tool for Watershed Management

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Introduction

Although erosion is a natural process, its severity is frequently amplified by development activities. Construction sites are responsible for the delivery of over 80 million tons of sediment into receiving waters each year, which on a unit area basis is 10 to 100 times the rate of agricultural land use (Goldman, 1986). Construction activities are by far the leading source of sediment in developing areas with sediment yields ranging from a few tons to over 500 tons per acre per year (USEPA, 2002). Although the United States Environmental Protection Agency (USEPA) has promulgated regulations to minimize sediment yields from construction sites, sediment yields from natural gas sites are not currently regulated by the USEPA. In 2006, almost 30,000 natural gas wells were drilled nationwide (API, 2007). Natural gas exploration and production typically requires the construction of a well site, access roads, and pipelines. Such disturbances have the potential for accelerated soil losses due to land cover modifications, increased slopes, and flow concentration.

Geographic Information Systems (GIS) have emerged as a powerful tool for handling spatial information and interact well with erosion models to provide robust problem solving capabilities useful for effective decision-making (Renschler and Harbor, 2002). Erosion models are helpful for evaluating the impact of land-use practices on soil losses, and are increasingly being used for establishing guidelines and standards for regulation purposes (Croke and Nethery, 2006). Erosion models often require moderate to high amounts of spatial data, which can be effectively handled through GIS.

The Universal Soil Loss Equation (USLE), later Revised (RUSLE), is a relatively simple model that has remained one of the most practical methods for estimating soil erosion potential and the effects of different management practices for over 40 years (Kinnell, 2000). Coupling GIS and USLE/RUSLE has been shown in many cases to be an effective approach for estimating the magnitude of soil loss and identifying spatial locations vulnerable to soil erosion (Fu et al., 2006; Lim et al., 2005).

The objective of this research was to develop a user-friendly GIS-based application that could quickly estimate soil loss from individual gas well sites in North Central Texas through the integration of GIS and erosion modeling. RUSLE was chosen to model erosion due to its simplicity, wide acceptance and use, and manageable data requirements. Also, RUSLE is used for construction site management at the federal level in National Pollutant Discharge Elimination System Phase II permitting (USEPA, 2000) and is often used to calculate soil erosion in construction site erosion control ordinances at the local level (Renschler and Harbor, 2002). The application was designed to assist City of Denton watershed managers, planners, and gas well inspectors in assessing potential soil losses from existing wells, identify future sites for inspection and monitoring, and evaluate erosion and sediment control Best Management Practices (BMP) plans.

Methodology

Study Area

The City of Denton, Texas lies above the Barnett Shale formation, which is an organically rich geologic formation that may contain the largest onshore natural gas formation in the United States (Shirley, 2002). The City of Denton's population recently exceeded 100,000 and is growing at a rate close to 5% per year. In addition to rapid population growth, the number of gas wells in the area has also dramatically increased in recent years. Within the city limits or within the floodplain of Denton's Extraterritorial Jurisdiction (ETJ) (these areas further referred to collectively as Denton's "jurisdictional area"), 130 new well sites have been developed over a five-year period (2000-2005; see Figure 1). In its jurisdictional area, the City of Denton has permitting authority over all gas well drilling operations, which include provisions for sediment and erosion control.

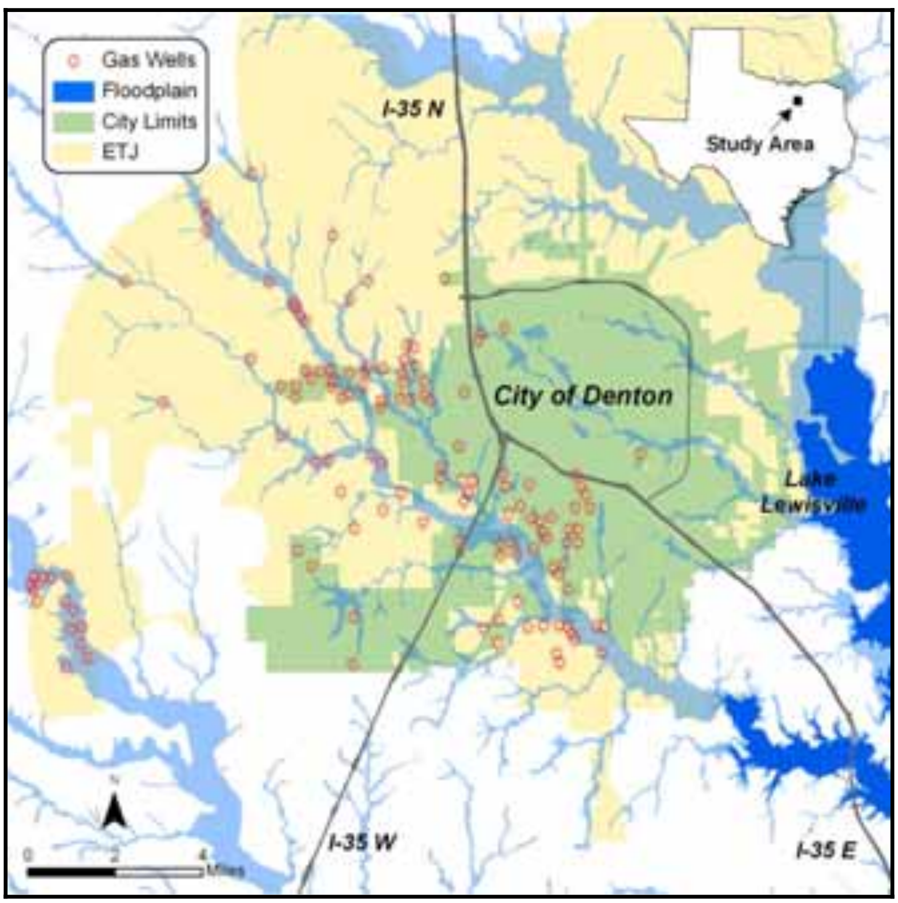

Figure 1. Study Area

Typically, development of a gas well disturbs approximately two or more acres of land. Each site is comprised of a tightly compacted rock base, similar to a gravel road, which is approximately 0.3-meter thick. The rock base, typically referred to as the "pad", has a very slow infiltration rate and is approximately one to two acres in size. The surrounding site area consists of another one to two acres of exposed soil ("disturbed" area; (Figure 2). Runoff from these sites ultimately drains into Lake Lewisville or Lake Grapevine, both of which are major sources of drinking water and recreation for North Central Texas. Gas well development pressures potentially pose a significant threat to the water quality in local streams and reservoirs if proper site planning and management practices are not used to control off-site sediment transport.

Area topography tends to be flat to gently rolling. Soils in the Denton area generally consist of deep clays that are well drained, with very slow permeability. The erosion potential for the majority of soils is moderate, but for a few soils, runoff is rapid and erosion can be severe. Annual normal rainfall for the region is approximately 99 cm, the majority of which normally occurs during the spring months of April and May and the fall months of September and October (Ford and Pauls, 1980). Storms in the area can be severe, intense, and highly erosive.

RUSLE

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) is a field scale empirical model that was developed in 1954 from over 10,000 plot years of natural and simulated rainfall data. A revised version of this model (RUSLE) further enhanced its soil erosion predictive capabilities by incorporating new information made available through more recent research (Renard at al., 1997). The RUSLE model takes the following form:

$$A = R * K * LS * C * P$$

where A is the computed spatial and temporal average soil loss per unit area (commonly expressed as ton per acre per year (t/ac/yr)), R is the rainfall erosivity factor, K is the soil erosion factor, LS is the slope length and steepness factor, C is the surface cover and management factor, and P is the supporting conservation practices (Renard et al., 1997).

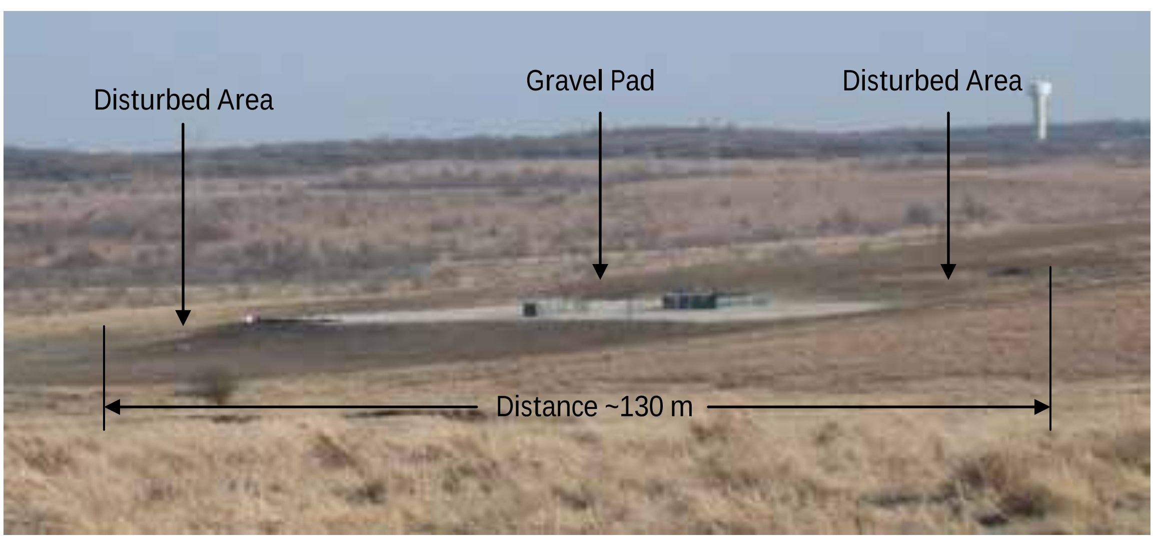

Figure 2. Example of a Natural Gas Well Pad Site

Determining Model Factors

RUSLE was integrated with ESRI's ArcGIS to provide a soil loss estimate for a specific gas well location. Model factors for R, C, and P were set as constant values in the soil loss calculation, as the R factor does not substantially vary over the relatively small study area and C and P are the same for all sites. An R-factor of 275 was chosen for the study area according to an isoerodent map of the Eastern United States (Renard et al., 1997). R factors were calculated by adding individual storm EI30 values (product of total storm energy and maximum 30-min intensity) over a year and averaging annual values over a 22 year period. R values in the Eastern United States range from approximately 10 in the northern Great Plains to 700 in the Gulf Coast.

The C factor is a dimensionless ratio of soil loss from land under various cover and management conditions. Since all gas wells in the area are constructed similarly, the C factor was assumed to be the same for all sites. The C factor for an exposed construction slope ("disturbed" portion of site) is 1.0 and is 0.05 for a slope covered by crushed rock ("pad" portion of site; see Wischmeier and Smith, 1978). Since 30% of the slope consists of exposed soil and 70% consists of crushed rock, the gas well site C-factor was established as 0.363. While the ratio of exposed soil and crushed rock on a gas well surface will vary slightly from site to site, these differences were not expected to affect the soil loss estimate substantially.

The P factor is also dimensionless and is the ratio between soil loss with a support practice, such as a silt fence, seeding, or mulching, to soil loss without a support practice. It was assumed that no supporting practices were applied for soil conservation and therefore the P factor was set at 1.0.

The LS-factor is a function of both slope steepness and slope length. For construction sites, the ratio of rill to interill erosion is high and the soil has a strong tendency to rill resulting in a relatively high LS-factor. The following steps were taken to derive the LS factor for each site: 1) A 30-meter digital elevation model (DEM) (Grid format) for the area was obtained from the United States Geological Survey (USGS) National Elevation Dataset (http://ned.usgs.gov/), 2) the DEM was converted to a Slope Grid using the "Slope" function available in ArcGIS Spatial Analyst, and 3) a look-up table was built containing the LS-factor according to the slope steepness (%) and length provided in Renard et al. (1997). For a particular site, the slope % obtained from the Slope Grid is used to select the LS factor from the look-up table according to a slope length of 400 feet, assumed to be constant for all gas well sites. Slopes in Denton and the surrounding area can generally be classified as "low" to "moderate" and are illustrated in Figure 3.

The K factor is an empirical measure of soil erodibility as affected by intrinsic soil properties such as texture, organic matter, structure, and permeability. K factors have been estimated for all the vertical layers in the soil series surveyed by the Natural Resource Conservation Service (NRCS) and are included in attribute data of soil maps in the Soil Survey Geographic (SSURGO) database (http://soildatamart.nrcs.usda.gov/). K factors are expressed as an annual average and are shown in Figure 4 for soils in study area. Using customized object oriented programming in the ArcMap environment, RUSLE was integrated to automatically calculate a soil loss value for a specific location according to the processes illustrated in Figure 5.

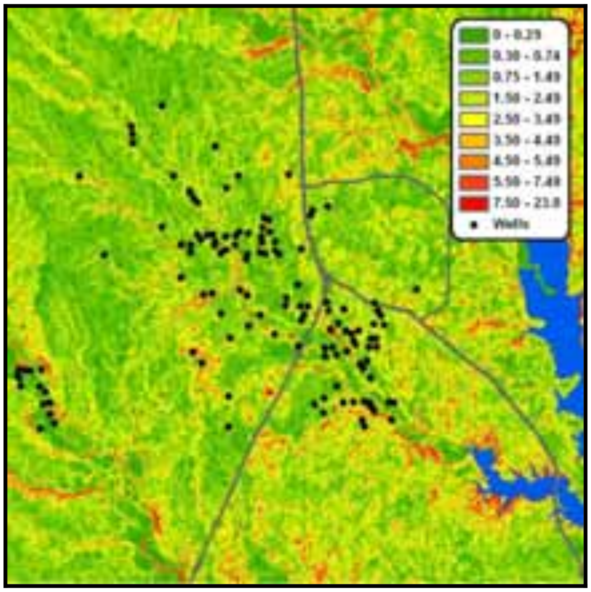

Figure 3. Study Area Slope (%)

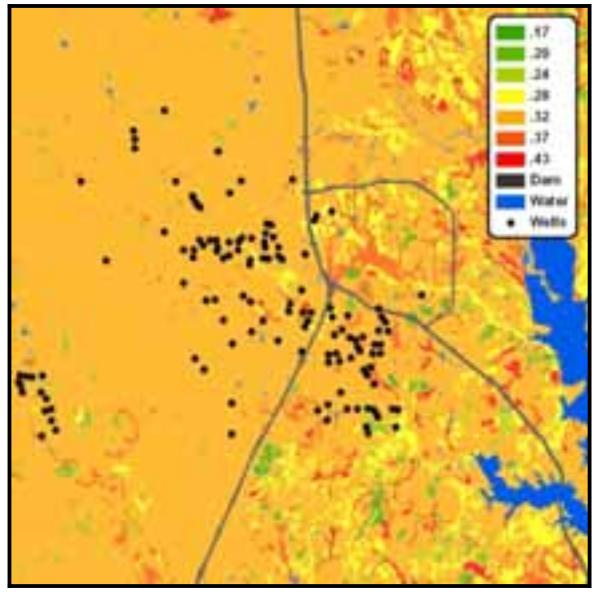

Figure 4. Study Area Soil K factor

Model Application

The Gas Well Planning and Management (GWPM) application was developed for two primary functions: 1) as an evaluation tool (reactive mode) to characterize potential soil loss from existing sites and 2) as a management tool (proactive mode) to be used by watershed managers, planners, and gas well inspectors to identify sites that could potentially negatively impact local surface water resources. As an evaluation tool, the GIS was programmed to import gas well point data and automatically compute a soil loss value for each site using constant values for R, C, and P factors and spatial data layers to obtain LS and K factors. The import function is necessary, since gas well data obtained from the Texas Railroad Commission (http://www.rrc.state.tx.us/) is updated semi-annually. In this capacity, an analyst can quickly provide a multi-site assessment of all existing wells located in Denton's jurisdictional area. Summary information can then be used to prioritize site inspections, target individual watersheds for monitoring, and provide information useful in environmental decision-making.

For use in planning and management, custom tools were developed that allow an analyst to obtain soil loss estimates by a number of methods. The interface also identifies whether or not the future gas well will be in the city limits, ETJ, or is within 100 meters of a water body, which is used to determine whether or not the city has permitting authority over the well and, if so, which permits are necessary. Gas wells located in any area within the city limits require a drilling permit and those located within any floodplain in the jurisdiction of Denton require a watershed protection permit.

Results/Discussion

Table 1 provides a summary of the distribution of LS and K factors for all wells in Denton's jurisdictional area. Across the study area, percent slope ranges from 0 to 23, but most of the

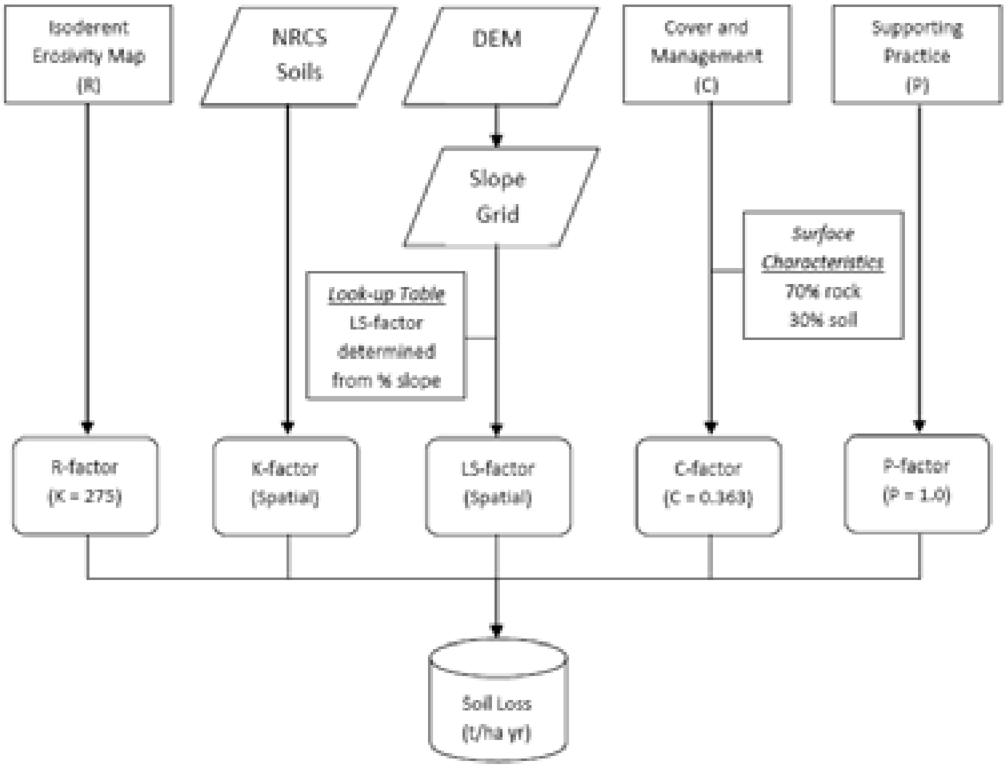

Figure 5. RUSLE/GIS Integration Flowchart

gas wells are located on slopes ranging from 0.03 to 3.49 percent, with steepest slope being 6.18%. K factors in the Denton area range from 0.17 for sandy loam (low erodibility) to 0.43 for silty clay loam (high erodibility). Most of the wells were located on clay loam soils (moderate erodibility) with a K factor of 0.32.

According to calculated soil losses, gas wells were classified into mutually exclusive categories of a "Low" (less than 5 t/ac/yr), "Moderate" (5 to 10 t/ac/yr), or "High" (greater than 10 t/ac/yr) Rating of Concern (ROC, see Table 2). This classification was performed to eliminate the sense of precision conveyed by specific soil loss values when there are likely some data-based errors.

Table 1. Gas Well LS and K factor Summary

Length Slope Factor			Soil Factor	
LS factor	**Slope %**	**# Wells**	**K factor**	**# Wells**
0.06	>0.3	16	0.28	5
0.11	0.30 - 0.74	32	0.32	117
0.22	0.75 - 1.49	35	0.37	7
0.48	1.50 - 2.49	29	0.43	1
0.80	2.50 - 3.49	11		
1.14	3.50 - 4.49	4		
1.51	4.50 - 5.49	1		
1.90	5.50 - 7.50	2		

Table 2. Gas Well Site Rating of Concern

	Low	**Moderate**	**High**
Number of Wells (n)	48	35	47
Soil Loss Range (t/ac)	1.7 - 4.1	6.1 - 9.4	13.4 - 60.7
Mean Soil Loss (t/ac)	3.1	7.1	22.3
Coefficient of Variation (%)	24.7	7.1	50.9
Wells within 100 m of Water	11	7	9

Low (> 5 t/ac/yr); Moderate (5 - 10 t/ac/yr); High (< 10 t/ac/yr)

The classification process also helps minimize potential errors associated with slight variations among site characteristics that are assumed to be the same in the modeling process. Also, as a management tool, relative comparisons among sites can be more important than assessments of absolute soil losses (Millward and Mersey, 2001).

Categories were chosen according to natural breaks in soil loss data and professional judgment based on visual site inspections. Sites with less than 5 t/ac/yr of soil loss generally have only low to moderate rilling and limited sediment movement off-site, whereas sites with 5-10 t/ac/yr have moderate to high amounts of rilling with evidence of small sediment plumes leaving the site. Sites with greater than 10 t/ac/yr of soil loss tend to exhibit high amounts of rilling, and sediment plumes leaving the site tend to be substantial. In some extreme cases, the formation of gullies and slope failures have occurred. Sediment losses also tend to occur over longer periods of time at sites where a high amount of rilling occurs, due in part to the longer amount of time required for natural re-vegetation to occur in the disturbed soils of these sites. Gas wells were fairly uniformly distributed among the “Low”, “Moderate”, and “High” categories with 48, 35, 47 wells, respectively.

Table 2 also shows the range, mean, and coefficient of variation in each ROC category. In a relative sense, the distribution of soil loss values is more disperse among the “High” and “Low” categories compared to the “Moderate” category, as illustrated by the coefficient of variation. Also, there are 27 wells within 100 meters of a receiving water body, 9 of which are categorized as having a “High” ROC. Proximity to a receiving water body is considered a potential concern, regardless of the ROC, due to the limited distance sediment has to travel to enter a stream or lake.

With the integration of RUSLE and ArcGIS, gas well inspectors can prioritize sites for inspection by beginning with those sites that have both a “High” ROC and are within 100 meters of a receiving water body. Watershed managers can also use this information in combination with additional spatial information such as watershed boundaries and environmentally sensitive areas to target streams or sub-watersheds for monitoring. Monitoring downstream from well sites has already been used to demonstrate a few cases of contamination due to breaches of drilling fluid pits and failures of “frac” tanks (temporary storage basins, often holding water very high in chlorides). Information produced by the application may also be useful in future code revision like Denton’s Oil and Gas Well Drilling Ordinance.

A set of customized tools was developed in the ArcMap environment that allows an analyst to quickly obtain a soil loss estimate, ROC, and other information such as whether it is in the city limits or ETJ and if it is within 100 meter of a water body (Figure 6). Information is returned for existing or “future” gas wells by the following options:

1) the analyst selects an existing well location,
2) the analyst enters the latitude and longitude coordinate,
3) the analyst selects an existing latitude and longitude coordinate, or
4) the analyst selects a location on the Map interface

Using the information provided, the analyst can: further assess the ROC by evaluating nearby land use and topography with the use of high resolution aerial photography, review the erosion and sediment control plan for adequacy, and notify the gas well inspector or watershed manager if the site requires inspection during the construction phase. Future revisions to the application could also include the incorporation of a Best Management Practices Assessment Tool (BMPSAT) (Wachal and Banks, 2007a), which identifies the most appropriate BMPs for a gas well site according to specific slope and soil types. The tools can also be used to find a location on a particular gas well lease site that would yield the least amount of soil loss during construction and operation.

The custom application was programmed to provide the user with the ability to change the classification range for the ROC, which provides flexibility when identifying a set of gas wells according to alternative criteria. The user also has the option to change the R and C factors. For the R factor, this option provides transferability of the application to other regions and for the C factor, sites with different surface characteristics could be evaluated.

In its current form, the application has some limitations. First, it was developed for the City of Denton and therefore the R factor was assumed to be the same for the study area. While the application does allow an analyst to change the R factor so that it could be applicable to other regions with different K factors, if the application is used for a larger region (i.e., large watershed, management area, state, or nation) the programming would need to incorporate the ability to select an R factor from a spatial data layer. Second, uniform slopes were assumed for all sites. Slopes at some gas well sites are complex, exhibiting a combination of concave, uniform, and convex slopes. Although algorithms could be added to estimate soil loss according to various complex slopes, comparisons between soil loss estimated with uniform slopes and sediment yields (soil loss and deposition) estimated from complex slope characteristics (Wachal and Banks, 2007b) indicate that the uniform slope estimates are somewhat conservative. Since the application was intended as a tool to compare sites on a relative basis, it could be argued that precise soil loss estimates are not critically important. Finally, the application uses RUSLE to estimate soil losses from a site and not sediment yields to a receiving water body. Evaluating sediment yields could be done through the use of a sediment delivery ratio, which is a ratio of gross soil erosion to soil delivered to a particular point in a watershed. While this may be useful for evaluating watershed scale sediment impacts, construction site erosion and sediment control regulations tend to target the edge of the site, therefore site specific evaluation is appropriate for this application.

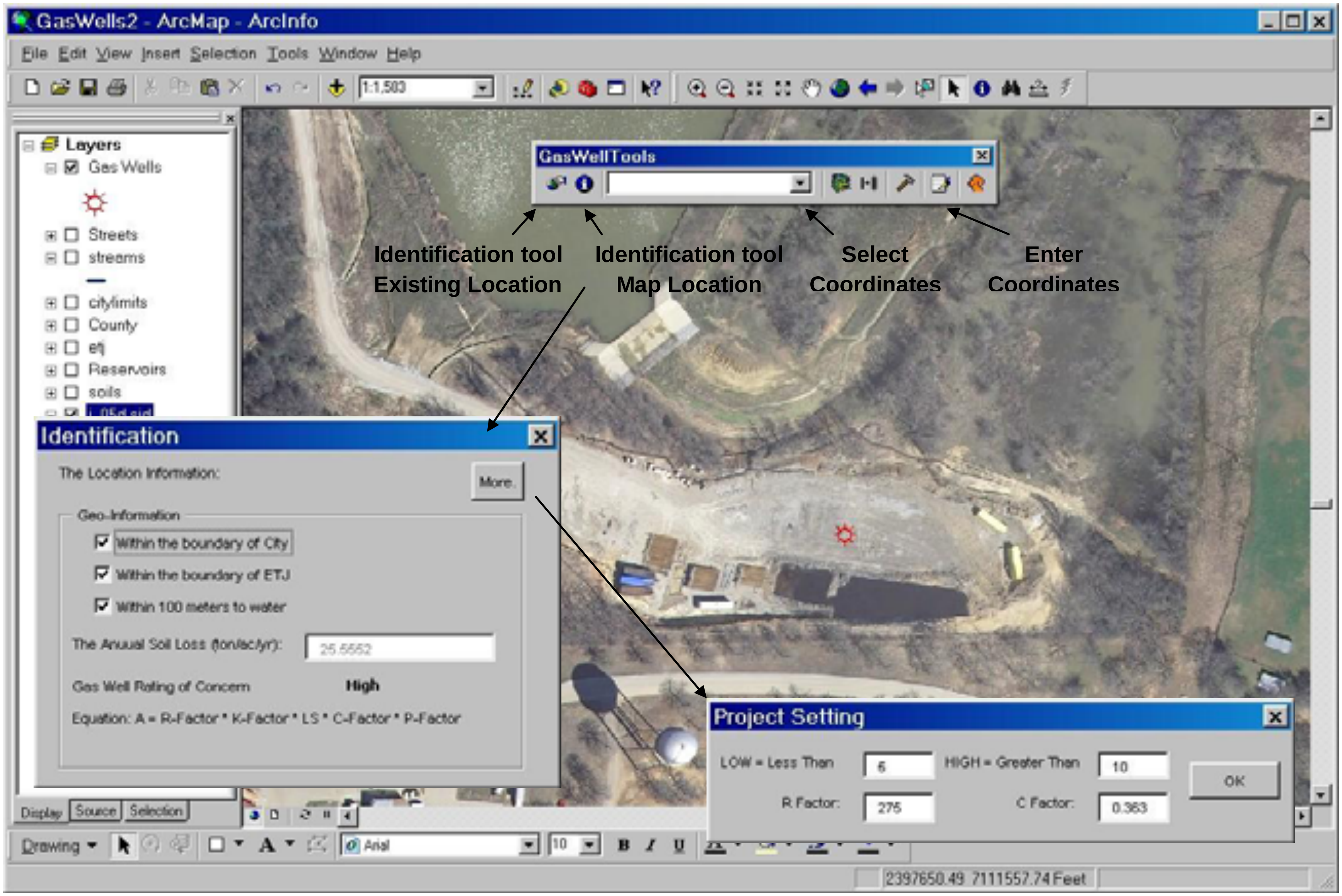

Figure 6. Application Map Document: Gas Well Tools, Identification, and Project Setting

Conclusions

In recent years, rapid development of natural gas wells has been occurring in the City of Denton and surrounding areas. Because gas wells disturb a substantial portion of land surfaces, erosion and sedimentation are a potential concern. In lieu of state or federal storm water regulations, the City of Denton is responsible for protecting the environment within its jurisdiction. A customized GIS application was developed to help support the management of existing and future gas wells. Through the integration of GIS and erosion modeling, existing gas wells were categorized into “Low”, “Moderate”, and “High” Ratings of Concern. Of the 130 gas wells in Denton’s jurisdiction, 47 were categorized with a “High” ROC and 26 were within 100 meters of a water body. This classification provides information that can be used to prioritize site inspections, target watersheds for monitoring, evaluate erosion and sediment control plans, and assist in environmental decision making. Future revisions of the application could provide a spatial determination of the R factor, algorithms to determine the LS factor for complex slopes, and the use of sediment delivery ratios to estimate sediment yields at the outlet of a watershed.

Acknowledgements

This work was partially funded through a Water Quality Cooperative Agreement (104b3 grant) provided to the City of Denton by the United States Environmental Protection Agency (USEPA). Also the authors would like to thank Cai Chen for his work on the application programming.

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