Soil erosion is the process of detachment and subsequent removal of soil particles and small aggregates from land surfaces by wind and/or water in a specified time period (Brooks et al. 1993; Nearing et al. 1994). Soil loss due to erosion processes is a serious problem in many regions of the world.

Considering that it is impossible to estimate and monitor the soil loss effects of weather and land management practices in all ecosystems given financial and equipment commitments, and the difficulty in extrapolating beyond local study areas, an alternative approach is to develop simulation models to achieve these goals. A soil erosion simulation model mathematically describes the process of soil particle detachment, transport, and deposition on land surfaces. This kind of model could be created using a computerized database with geographically referenced systems of soil erosion to account for every parcel of land (Lull et al. 1995).

Thus, we can use erosion models: (1) to estimate current erosion effects for a given area; (2) to predict where and when erosion can occur; (3) to know about the relationship soil loss/soil erosion-crop yield/productivity; and (4) to understand erosion processes and use these experiences for assessing soil erosion planning projects, for soil conservation strategies (the rate of soil loss can be compared with what is considered acceptable), and for regulation (Nearing et al. 1994).

The USDA Soil Conservation Service created the Universal Soil Loss Equation (USLE) in 1965 to predict soil erosion. The USLE is an empirical equation designed to compute long-time average soil losses due to sheet and rill erosion across the land surface. The equation groups the interrelated physical and management parameters which influence erosion into six factors such that erosion is the product of those factors, as follows:

\[ A = R K (LS) C P \]

where

- **A** = computed annual soil loss in tons per unit area
- **R** = a rainfall–runoff erosivity factor
- **K** = a soil erodibility factor, based on soil characteristics such as texture, structure, and permeability
- **LS** = a dimensionless topographic factor combining slope length, L, and slope steepness, S
- **C** = a dimensionless land cover–management factor
- **P** = an erosion control factor, based on soil conservation support practices (Brooks et al. 1993).

Some of these factors may vary spatially within a watershed and are geographic in nature: K, (LS), C, and P. The K factor is related to soil type which is normally mapped. The (LS) factor is a function of the terrain, and can be interpreted from a hypsography map. The C and P factors can be identified from remote sensing data including aerial photographs and satellite images (Potter et al. 1986). Thus, since most of the USLE’s parameters can be represented geographically, it can be combined with remote sensing and GIS techniques to give better results.

Some authors have demonstrated that soil erosion models can generate accurate results when used in combination with geographic information systems (GIS) to estimate erosion in agricultural and natural areas. Lull and Tindall (1995) estimated erodibility risk values for two different watersheds (Howard Creek and Jones Meadow Creek) in western Montana using an erosion simulation model with a GIS. These watersheds differ from each other in their historical management, Jones Meadow Creek having a higher diversity of past land uses and, as a consequence, a higher risk value (2.12 vs. 1.70). They concluded that risk values obtained for these watersheds can be used as a comparative tool, on a relative basis, to evaluate watershed sensitivity to land-use changes and management.
Other soil erosion studies have been accomplished using the USLE in a GIS environment. In 1980, Rasmussen et al. estimated the spatial and total erosion from a surface-mined area. For this study, vegetation, soils, and slope data arrays were developed for mining topsoil conditions. The form of the equation used in this analysis to determine soil loss at any cell location on the area is:

\[
A_{ij} = R * K_{ij} * (LS)_{ij} * C_{ij} * P_{ij}
\]

where \(A\), \(R\), \(K\), \((LS)\), \(C\), and \(P\) represent the parameters for the USLE and \(ij\) represent the coordinates for the parameter values at a given cell in the raster grid.

This way, the output of this computer model can be displayed using different graphic formats such as computer printer maps and perspective plots.

Potter and Gilliland (1986), from the University of Nebraska at Omaha, developed a GIS called RGISM (Raster Geographic Information System for Mapping) to estimate soil loss rates in the Elk-horn River Basin, Nebraska, utilizing the USLE. The system accepts digitally mapped information on soil type, topography, and land use; it calculates slope and slope length; and it relates these characteristics to soils and land-use parameters in order to produce three-dimensional maps of runoff potential, sediment pollution potential, and fecal coliform pollution potential. After calibrating the system and analyzing the results, they concluded that the system has the potential to improve the researcher's ability to allocate mitigation resources efficiently.

Two years later, Oslin et al. (1988) from Halff Associates created STREAMS (Soil, Transport, Rainfall, Erosion, and Mapping System). This program facilitates the transfer of data between computer systems for the purpose of flood plain and watershed management. Soil type and erodibility, topography, slope, rainfall frequency and duration, land use, and vegetation cover are used in conjunction with the universal soil loss equation to compute average annual soil loss and soil erosion classes for a given watershed. Landsat TM and SPOT satellite imagery are used to derive impervious cover information and to determine changes in land use through time. Output from STREAMS maps erodible soil classification, stream erosion and deposition, and flood plain delineations under various rainfall conditions.

By using remote sensing and GIS techniques in conjunction with the USLE, this study illustrates that the Sonoyta River watershed in northwest Sonora, Mexico, may have increased soil erosion in the last two decades due to human activities, basically farming and grazing practices.

**Objective**

The principal objective of this study was to estimate and compare the erosion rates that occurred in 1972 and 1992 in response to land cover and land use changes in a portion of the Sonoyta River watershed, in northwest Sonora, Mexico. The objective was achieved using the USLE linked to a GIS.

**Methods**

The 408,381 acres studied are located in the northwestern part of Sonora, Mexico, just south of the Organ Pipe Cactus National Monument, Arizona (Figure 1). Its climate is dry with a mean annual temperature of 21.4°C, a maximum temperature of 45.1°C, and a minimum temperature of -3.3°C. The mean annual precipitation is 209.7 mm (SARH 1994).

Soil erosion processes are very closely related to land cover and land use occurring in the ecosystems. Changes in land features will be reflected in the soil loss rates for a given area. So, change detection in land cover and land use was determined for the study area following the procedure used by Valdez-Zamudio (1994). Two Landsat MSS images were processed with the remote sensing program ERDAS version 7.5 (ERDAS, Inc.), and the IDRISI for windows GIS program version 1.0 developed by Clark University, Massachusetts. The scenes used in this study were acquired from the EROS data center of the U.S. Geological Survey in Sioux Falls, SD. Those scenes are dated from September of 1972 and October of 1992.

After geometric and atmospheric correction, the 1972 and 1992 images were geographically registered. The identical geographic coordinates of the two images allow overlay operations to compare geographic changes between the two dates of the images.

To define erosion rates in the two images, it was necessary to identify and classify the objects present on those images. The criteria used to distinguish these land cover classes were based principally on topography (slope), reflectance values, the association to other features on the image such as streams, and straight borders on irrigated fields. After two field trips to the site and revising the ancillary data to obtain ground truth data, it was possible to identify training areas for a supervised classification.
When the land-use class maps were created for 1972 and 1992, the next step was to produce corresponding maps for the USLE parameters. Thus, a map layer for the R factor was created using the IDRISI program, based on the average annual values of R calculated for the state of Arizona (USDA, Soil Conservation Service 1976). The R value determined for the study area was 60.

The K or soil erodibility factor map was produced primarily by digitizing five soil-class maps acquired for the study area using the ARC/INFO program. After the digitization was performed, the vector map was then introduced into the IDRISI program to effectively grid the entire study area into a rectangular array of cells. All the cells are of the same size. Given the chemical and physical characteristics of the soils, such as texture, organic matter content, structure, and permeability, the corresponding K values were determined using a special nomograph (soil 1 = 0.20; soil 2 = 0.40; soil 3 = 0.17; soil 4 = 0.34; soil 5 = 0.40). Finally, using the IDRISI program, those values were assigned to each soil type.

In order to create a map layer representing the LS factor, it was necessary to create a slope map using the ARC/INFO program. Thus, a contour-based DEM map was produced by digitizing contour lines from a 1:50,000-scale, 20-m contour interval topographic map. Then, the slope map layer was produced using the IDRISI program. In this study we assumed that the L factor is equal to 1.0. Finally, still inside the IDRISI environment, the S factor map was obtained applying the formula:

\[ S = \frac{(0.43 + 0.3 s + 0.042 s^2)}{6.613} \]

where \( s \) represents the slope gradient values (percent) in the slope map (Brooks et al. 1993).

The potential for erosion without the effect of vegetation or conservation practices was obtained by modifying the USLE to:

\[ EI = R \times K \times L \times S \]

where \( EI \) = erosion potential index (tons per acre).

The estimation of the erosion potential index resulted by overlaying (multiplying) the maps created for the USLE parameters (R, K, and S factors) using the IDRISI program. Since the EI map does not consider vegetation or conservation practices, it can be used indistinctly to compute soil loss for 1972 or 1992.
The C factor maps for 1972 and 1992 were produced by the assignation of different values to the land-cover classes according to their particular management. These values were previously calculated for Arizona by the Soil Conservation Service at Phoenix. The corresponding C values for the different land-cover classes were: croplands = 0.31, vegetation in the bajadas = 0.18, vegetation in the plains = 0.18, riparian areas = 0.01, mesquite woodlands = 0.28, and bare soil areas = 0.45. These maps were created using the IDRISI program.

As with the C factor maps, the P factor maps resulted by assigning values to the land-cover classes on 1972 and 1992 images. These values were also estimated for Arizona by the Soil Conservation Service at Phoenix. All natural areas were given a P value of 1.0, while croplands received a value of 0.37. The resulting maps were created using the IDRISI program.

The soil loss rates for 1972 and 1992 were estimated by overlaying (multiplying) the EI, C, and P factor maps by each other:

\[ A = EI \times C \times P \]

This way, the predicted annual erosion potential (tons per acre) is stored in an output map file which can be analyzed and manipulated for achieving different studies of the area.

Results and Discussion

Five different land-cover classes were created from the image classification for 1972: croplands, bajadas with vegetation, plains with vegetation, riparian vegetation, and bare soil. Due to the amount of rain above the average between 1972 and 1992 (Figure 2), a sixth class (mesquite woodland) resulted for the 1992 image classification.

We can see in Table 1 that croplands, riparian areas, and mesquite woodlands increased in area between 1972 and 1992, while the other classes, those with negative change values, decreased in area. There were two possible factors that caused land-cover changes (positive and negative) in the study area. First, because desert vegetation is soon modified by climatic changes and considering that precipitation in the study area is the only factor of the environment that can cause a rapid change on vegetation (Cloudsley 1977), it is presumed that the amount of rain that accumulated between 1972 and 1992 increased the plant population densities, resulting in an expansion of riparian areas, the formation of mesquite woodland, and the reduction of areas with bare soil. Second, the deforestation practices executed to increase the agricultural activities in the area produced changes in land cover classes, increasing the croplands and decreasing the other classes that contributed to an increase in this class (Figures 3 and 4). These anthropogenic changes occurred as a result of Mexican government policies to generate jobs and improve the regional economy of Sonoyta by financing clearing of natural areas for agriculture and developing new wells to irrigate those new farmlands.

Table 2 shows the resulting values in soil erosion for each category in 1972 and 1992. We can

![Figure 2. Historic precipitation data for study area (SARH 1994).](image-url)
Figure 3. Different percentages of change from each land-cover class to other classes between 1972 and 1992. C = croplands, VB = vegetation in the bajadas, VP = vegetation in the plains, VR = riparian areas, BS = bare soil.
Figure 4. Percentages contribution of classes to change in individual class area between 1972 and 1992. C = croplands, VB = vegetation in the bajadas, VP = vegetation in the plains, VR = riparian areas, BS = bare soil, and MW = mesquite woodland.
see that in 1992, with the exception of riparian areas, all the land-cover classes reveal higher soil erosion rates in comparison to the same categories in 1972. In particular, croplands exhibit these erosion rates due to the tillage activities, and the other categories exhibit higher soil loss rates as a result of the introduction of cattle, sheep, and goats for grazing in densities that exceed the carrying capacity of the ecosystems.

Summary and Conclusions
This study illustrates the potential of remote sensing and GIS for making regional environmental assessments. Differences in soil erosion potential rates between 1972 and 1992 define an evident tendency of soil deterioration in the study area. A soil conservation plan needs to be implemented in this area to control the erosion processes and improve the actual conditions in the ecosystems.

Table 1. Area and percentage estimated for each category on 1972 and 1992 satellite images and percentage of change between 1972 and 1992.

<table>
<thead>
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<td>3567.47</td>
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Table 2. Minimum, maximum, and mean erosion rates for each category in the study area. Total soil loss per category is shown in the ERC column.

<table>
<thead>
<tr>
<th>Category Name</th>
<th>Area (acres)</th>
<th>Mn E R (ton/ac-yr)</th>
<th>Mx E R (ton/ac-yr)</th>
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<td></td>
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<td>192732.31</td>
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<td>1992</td>
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References Cited


