# ASSESSING THE SUCCESS OF WATERSHED REHABILITATION PRACTICES IN THE RIO LAJA BASIN, MEXICO

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In 1998, former officers of the Mexican Audubon Society founded a non-profit organization, known as *Save the Laja,* to address the escalating environmental problems associated with severe soil erosion in the Rio Laja watershed, Guanajuato, Mexico. With the assistance of local organizations and volunteers, they began an ambitious watershed conservation and rehabilitation program in January of 2001. Their primary activity has been the construction of numerous small rock dams designed to catch sediment upstream and slow runoff velocity, in an effort to abate gully erosion during the torrential rains associated with the region's monsoonal climate. This paper describes the spatial methodology developed to assess the effectiveness of these watershed rehabilitation practices, which incorporates a GIS-based soil erosion model at the sub-watershed scale. This geographic analysis serves to review the success of completed restoration work and will facilitate the strategic targeting of future restoration activities.

## INTRODUCTION

One of the most serious problems facing developing countries is long-term environmental degradation. Soil erosion and associated desertification, reduces agricultural productivity and limits the potential for social development in rural areas (Barbier 1997; Reddy et al. 2003). As the topmost layers of soil, rich in organic matter and nutrients, are removed, the long-term productivity of the land is degraded; this can have far-reaching social implications (Brown 1981). Peasant livelihoods are heavily dependant upon the biological productivity of the soil and cannot be improved without responsible land management (Scherr 2000; Reddy et al. 2003). These rural areas are often given low priority by national governments that seek to expand industrial production and export opportunities (Gerritsen 1998). As such, non-governmental organizations (NGOs) are often necessary to provide the impetus for the development of sustainable land management practices at the grassroots level (Pretty and Shah 1997, Warkentin 2001).

Since 2001, *Salvemos el Rio Laja* (*Save the Laja*) has been the central coordinating body for the watershed rehabilitation activities of several NGOs working with rural residents and the underprivileged in central Mexico. These organizations include *Fundación de Apoyo Infantil Guanajuato* (Save the Children), *Centro para los Adolescentes de San Miguel de Allende* (a health care and family planning agency), *Cuerpos de Conservacion Guanajuato* (an environmental conservation group), *Groupo de Desarrollo de Sierra Gorda* (social development in indigenous communities), *Peña Alta* and *Charco de Ingenio* (protected areas) (Salvemos el Rio Laja 2003). By working with existing NGOs that have complementary long-term objectives, *Save the Laja* is able to co-opt previous relationships with individuals and communities for the dissemination of information and recruitment of volunteers. Although community interest in soil conservation and rehabilitation activities is not always enough to produce on-the-ground results, the NGO continues to be generally well received. When community participation is enthusiastic, local needs are often reflected in the type of work being done. For example, stock ponds may be created to provide a permanent source of surface water for livestock and thus reduce grazing pressure surrounding sensitive ephemeral streams. The rehabilitation efforts of local volunteers and partner agencies are considered to operate under the 'umbrella' of *Save the Laja* and are hereafter collectively referred to as *Save the Laja*.

The objectives of this research were to estimate the potential for soil erosion in the Rio Laja watershed and evaluate the success of past rehabilitation efforts. These were accomplished by integrating the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) and Geographic Information System (GIS) technology. ArcView 3.3 and ArcGIS 9.0 were used in this analysis (ESRI 2005a, 2005b).

## STUDY AREA

The Rio Laja watershed is situated in a highland valley in the state of Guanajuato, Mexico (Figure 1). The main branch of the river is approximately 320 km in length. This watershed forms part of the Rio Lerma Basin, which has been designated as "Globally Outstanding" by the World Wildlife Federation for Nature due to its endemic fish and bird populations (Salvemos el Rio Laja 2003; World Wildlife Fund for Nature 2004). The watershed is a predominantly agricultural area and encompasses a total of 9,900 km$^2$. Dominant crops include maize, beans and squash; oats and sorghum are often grown on irrigated land (accounting for less than ⅓ of agricultural land in the study area) (INEGI 1973b; Vázquez-Arista et al. 1995; Tully and Mora 2004). Dominant soil types include medium-textured Haplic and Luvic Phaeozems, Lithosols and Pellic Vertisols (INEGI 1973a; Guanajuato State Government and the Guanajuato Institute of Ecology 2003). The study area of approximately 4,650 km$^2$ includes the middle reaches of the Rio Laja; the vast size of the watershed, the need for data at a moderate-scale resolution and the past fieldwork sites of *Save the Laja* necessitated defining the study area in this manner. Elevation ranges from approximately 1,800m to over 2900m asl with an average slope of 6.8 degrees (7.5%). The climate is semi-arid, as mean annual precipitation is 550mm (ranging from 415mm to 850mm) and the majority (approximately 95%) falls between mid-May and mid-November (IMTA 2000 , SARA 1991). Mean annual temperature is approximately 18 $^{o}$C (INEGI 2005). As noted previously, the watershed possesses abundant social and institutional capital in the form of willing volunteers and various non-governmental organizations.

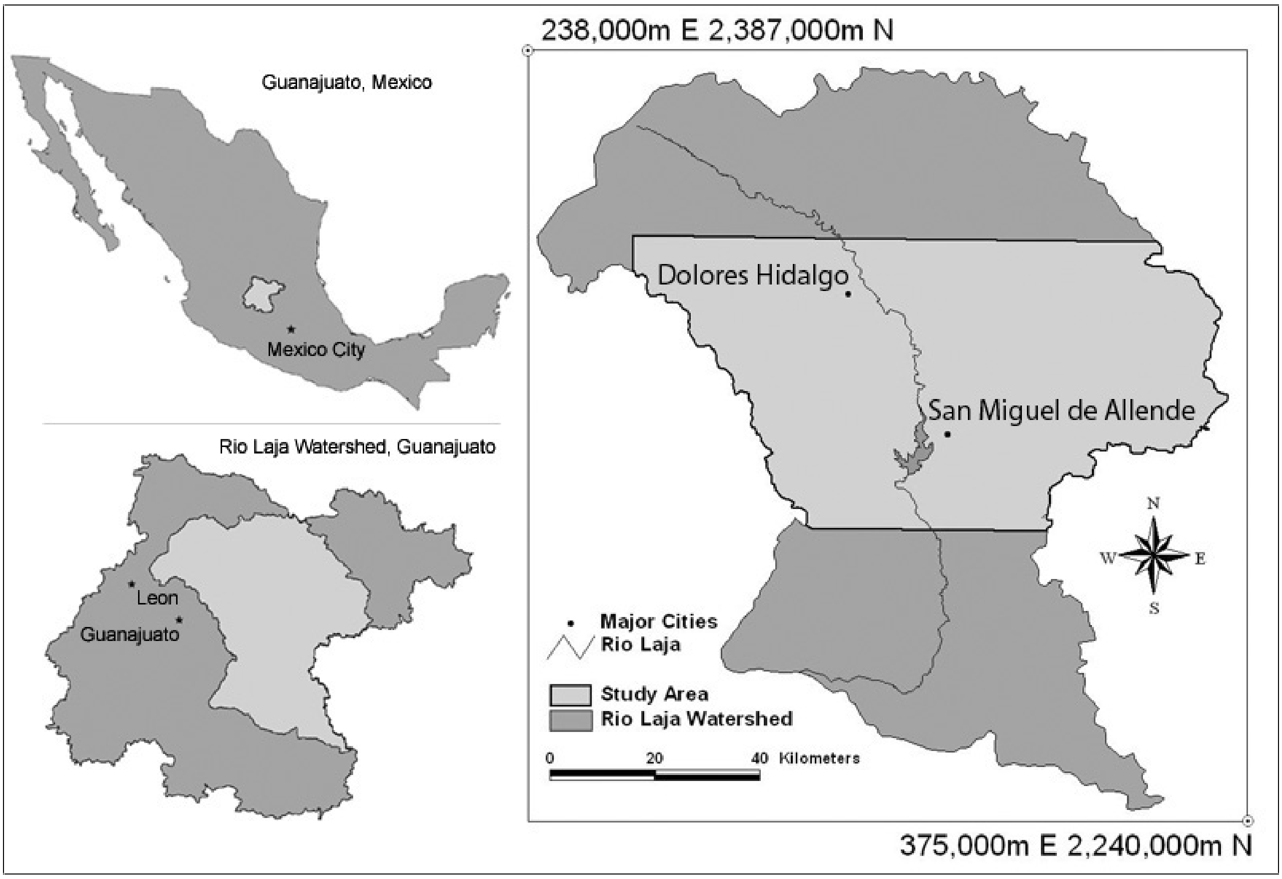

Figure 1. Location of the Study Area within the Rio Laja Watershed, Guanajuato, Mexico.

## METHODOLOGY

The Universal Soil Loss Equation (USLE) was developed by Wischmeier and Smith (1978) to predict soil loss potential on individual farm fields in the continental United States. As a factor-based equation, the USLE considers precipitation, soil erodability, land cover, topography and conservation support practices. Over time, numerous variations and local calibrations of these factors have made this equation the most widely used tool in the prediction of erosion (Fistikoglu and Harmancioglu 2002; Angima et al. 2003; Lee 2004). The advent of geographical information system (GIS) technology has facilitated the use of the equation in a spatially distributed manner; each cell in a raster image comes to represent a field-level unit. Critics argue that the equation is too simplistic and does not provide accurate results (Tiwari et al. 2000; Jetten et al. 2003; Medina 2005). However, when the intended goal is to guide conservation and rehabilitation activities, relative soil loss is more important than finding the absolute quantity of eroded soil (Millward and Mersey 1999; Millward and Mersey 2001). Simple models have limited data requirements and thus can be practical for large watersheds in developing countries, where data may be lacking (Millward and Mersey 1999, Kinnell 2001, Fistikoglu and Harmancioglu 2002, Renschler and Harbor 2002).

The Revised Universal Soil Loss Equation (RUSLE) is an updated version of the original and among other improvements can be used to estimate mean potential soil loss on a seasonal basis (Renard, et al., 1997). The equation is as follows:

$$A = R * K * C * LS * P \quad (1)$$

Where: $A$ = mean annual soil loss potential (tons $ha^{-1}$ $yr^{-1}$)
$R$ = Rainfall Runoff Factor (MJ mm $ha^{-1}$ $h^{-1}$ $yr^{-1}$)
$K$ = Soil Erodability Factor (t ha h $ha^{-1}$ $MJ^{-1}$ $mm^{-1}$)
$C$ = Cover and Management Factor (unitless)
$LS$ = Slope Length and Gradient Factor (unitless)

$P$ = Support Practice Factor (unitless)

By integrating the RUSLE with the capabilities of a GIS, an Erosion Potential Information System (EPIS) was developed for the study area. Each factor grid had a cell size of 100m, although actual resolution (of the lowest resolution data source) is approximately 250 $m^2$. This resampling was done to incorporate the greater precision of the precipitation and topographic interpolations. All layers were projected with UTM Zone 14N using the NAD1927 datum; these correspond to standards used by INEGI (1973a, 1973b). The following methodology was used to generate the factor grids.

## Rainfall Runoff Factor

The $EI_{30}$ index is calculated as the product of storm energy (E) and the maximum 30-minute intensity ($I_{30}$)(Renard et al. 1997). The index characterizes individual storms and reflects how particle detachment relates to the transport capacity of runoff. The RUSLE rainfall runoff factor is the mean annual $EI_{30}$ for a particular location.

Long-term daily precipitation data from 76 rain gauges within and surrounding the Laja watershed were averaged to produce mean annual precipitation quantities for each station. Using ArcView 3.3, various interpolations were tested in the creation of a mean annual precipitation grid (100$m^2$ resolution). A subset of rain gauge stations (N = 9) was removed from the interpolation and was subsequently used to evaluate interpolation accuracy. Neither Pearsons Product Moment ($R^2 > 0.90$ for all tests) nor ANOVA (Significance of 0.996) testing revealed any significant differences between the interpolations or between the subset and any of the interpolations. Based on visual inspection, the Inverse Distance Weighted method at a fixed distance of 50 km with an exponent of 4 appeared the most realistic and thus was selected for further analysis.

Due the sparse distribution of climate stations in Mexico, SARA (1991) created 14 climate regions to characterize areas with similar rainfall conditions. SARA (1991) proposed two regression equations for calculating $EI_{30}$ (the R Factor) that may be applicable to the Rio Laja watershed. Based on the annual distribution of $EI_{30}$ (10-day periods) that was reported by SARA (1991) for each of the climatic regions and for two major cities neighbouring the Rio Laja watershed (Leon and Guanajuato) Region 4 (Equation 2) was deemed most appropriate for calculating the R factor.

$$Y = 2.8959X + 0.002983X^2 \quad (2)$$

Where $Y$ = Mean annual $EI_{30}$ (MJ mm $ha^{-1}$ $hr^{-1}$ $yr^{-1}$)
$X$ = Precipitation (mm $yr^{-1}$)

When using this equation, approximately 92% of the variation in $EI_{30}$ can be explained by mean annual precipitation ($R^2$ = 0.92). SARA (1991) reports that approximately 95.9% of mean annual $EI_{30}$ occurs during the wet season for the study area. Thus to obtain a seasonal distribution, the grid resulting from the above equation was multiplied by 0.959 (wet season) and 0.041 (dry season).

## Soil Erodibility Factor

Soil erodibility refers to the ease with which soil particles are detached per unit of energy from rain splash and surface flow (Renard et al, 1997). Rain splash involves the cumulative impact of raindrops, which transport (eject) fine soil particles away from the point of impact (Morgan 1996). This factor accounts for the influence of soil properties on erosion and considers texture, organic matter content and the density of rock fragments. The RUSLE K-factor is based on measurements taken from standard plots of 22.1 m length, 1.83 m width, on a 9% slope and continuously clean-tilled fallow (up and downslope); K-factor reference tables are often prepared by government agencies and include local soil types (Wischmeier and Smith 1978, SARA 1997).

FAO soil classes from a 1:250,000 vector layer (INEGI 1973a) were assigned K values based on the recommendations of SARA (1991) and using the weighting scheme developed by Millward (1998) for considering the presence of any secondary or tertiary soil types. Where a secondary soil existed, the primary soil type was assigned a weight of 66.7% and the secondary soil received 33.3%. When a tertiary soil was present, the primary soil received a weight of 50%, the secondary soil received a weight of 30% and the tertiary soil received 20%. The K-factor values were subsequently converted to a grid with 100m$^2$ cells; the resolution of this data is approximately 250m$^2$.

## Cover and Management Factor

The RUSLE cover and management factor represents the influence of previous agricultural management decisions, canopy cover, surface cover and the surface roughness of various land use types (Renard et al., 1997). The soil loss ratio (SLR) reflects deviation from soil loss on the standard RUSLE plot under clean-tilled continuous fallow. For agricultural land cover types the SLR is calculated for each phase of crop growth.

Unfortunately, due to the scale of research and financial limitations, it was not feasible to obtain field-level data for individual plots (i.e. management practices) or satellite imagery that would provide greater spatial and temporal resolution. Instead, land cover from 1:250,000 vector data (INEGI 1973b) were assigned C values with reference to SARA (1991) and Millward (1998). Dominant land cover types included rain-fed agriculture (1,420 km$^2$), pasture (1,250 km$^2$), oak forest (880 km$^2$), irrigated agriculture (600 km$^2$) and scrubland (450 km$^2$). Although data were not available for specific crop types in the study area, local knowledge and the available literature suggests that maize is the predominant rain-fed crop in this part of Mexico (Vázquez-Arista et al. 1995; Salinas-Garcia et al. 2001; Tully and Mora 2004). Oats and sorghum are the primary crops of irrigated agriculture (Tully and Mora 2004). These agricultural land uses were assigned seasonal C factor values based on the recommendations of SARA (1991) and Renard et al. (1997); all other cover types were assigned annual values. The estimated C factor values ranged from 0.0005 for Oak forest with secondary shrubs to 0.4229 for irrigated agriculture during the wet season. The C-factor values were subsequently converted to a grid with 100m$^2$ cells; the resolution of this data is approximately 250m$^2$.

## Slope Length and Gradient Factor

The influence of topography on erosion is complex. Local slope gradient (S subfactor) influences flow velocity and thus the rate of erosion. Slope length (L subfactor) is a concept to describe the distance between the origin and termination of interrill processes; termination is either the result of the initiation of depositional processes or the concentration of flow into rills (Wischmeier and Smith, 1978; Renard et al., 1997). In RUSLE, LS factor values are represented by the ratio of soil loss from a given slope length and steepness to that of the standard 22.1 m plot on a 9% slope (where LS = 1.0). Some researchers have argued that upslope drainage area is a better parameter to use when describing the influence of slope length on erosion (Desmet and Govers 1996a). The upslope drainage area for each cell in a DEM can be calculated with various routing algorithms. Single flow algorithms direct all flow entering a cell into a single output cell. Multiple flow algorithms can divide flow between several output cells (Desmet and Govers 1996b). Depressions in the DEM are problematic for most flow routing algorithms and must be eliminated before calculating flow accumulation (Martz and Garbrecht 1998; Rieger 1998). In ArcView, the Hydrology extension uses a single flow routing algorithm and raises the internal cells to remove depressions (Jenson and Domingue 1988, ESRI 2005c).

Digital topographic data were provided by the *Commission Nacional de Agua* (CNA) but a lack of metadata prevents an evaluation of quality (data collection methods, etc.) (Tomlinson 2004). As these data are being used by CNA (a government agency), it is likely to be the best data currently available. A digital elevation model (DEM) was created by first converting the contour lines (10m intervals) into a triangular irregular network (TIN), thus extracting relevant point data. This TIN was subsequently converted into a grid (raster) with a resolution of 25m$^2$. The Spatial Analyst extension of ArcView 3.3 was used to calculate slope for each cell in the study area, based on the DEM grid. The Hydrology extension was used to calculate flow accumulation; as recommended in the literature, accumulation greater than 6 cells (150m) was reclassified to have an accumulation of only 6 cells (Engel 2005). Beyond this threshold, the RUSLE model begins to breakdown as slope length is sufficient for gully erosion to initiate. The LS factor grid was estimated with the following equation proposed by Engel (2005), based on the work of Moore and Burch (1986a, 1986b).

$$LS = ([\text{Flow Accumulation}] * [\text{cell size}] / 22.13)^{0.4} * (\sin [\text{Slope in Radians}] / 0.0896)^{1.3} \quad (3)$$

The $25m^2$ grid was necessary to calculate flow accumulation and apply the upper threshold of 150m; after the LS factor was calculated, this grid was resampled to a $100m^2$ grid using the bilinear technique to remain consistent with the other factor layers (resampled with the GRID PIG extension; USGS 2003).

### Support Practice Factor

Within the RUSLE, the influence of practices that modify the flow pattern, grade or direction of runoff are represented by the P factor. This factor is a ratio that reflects the deviation of soil loss with a particular support practice versus that from a standard plot with upslope and downslope tillage (Renard et al. 1997). Where no support practices are evident, beyond traditional (ubiquitous) conservation methods, the support practice value is assumed to be 1.0. Thus, when calculating an erosion potential grid for baseline conditions, the P factor can be excluded.

## BASELINE SOIL EROSION POTENTIAL

Based on the RUSLE factor grids (Figure 2), mean potential soil loss was found to be 7.8 tons $ha^{-1}$ $yr^{-1}$ within the study area. Total baseline soil erosion across the entire watershed was minimal (approximately 42,600 tons $yr^{-1}$) for the dry season when compared to the wet season (approximately 3,628,600 tons $yr^{-1}$) (USGS 2003). Further discussion refers to erosion potential during the wet season unless otherwise noted; only the wet season soil loss potential is illustrated (Figure 3).

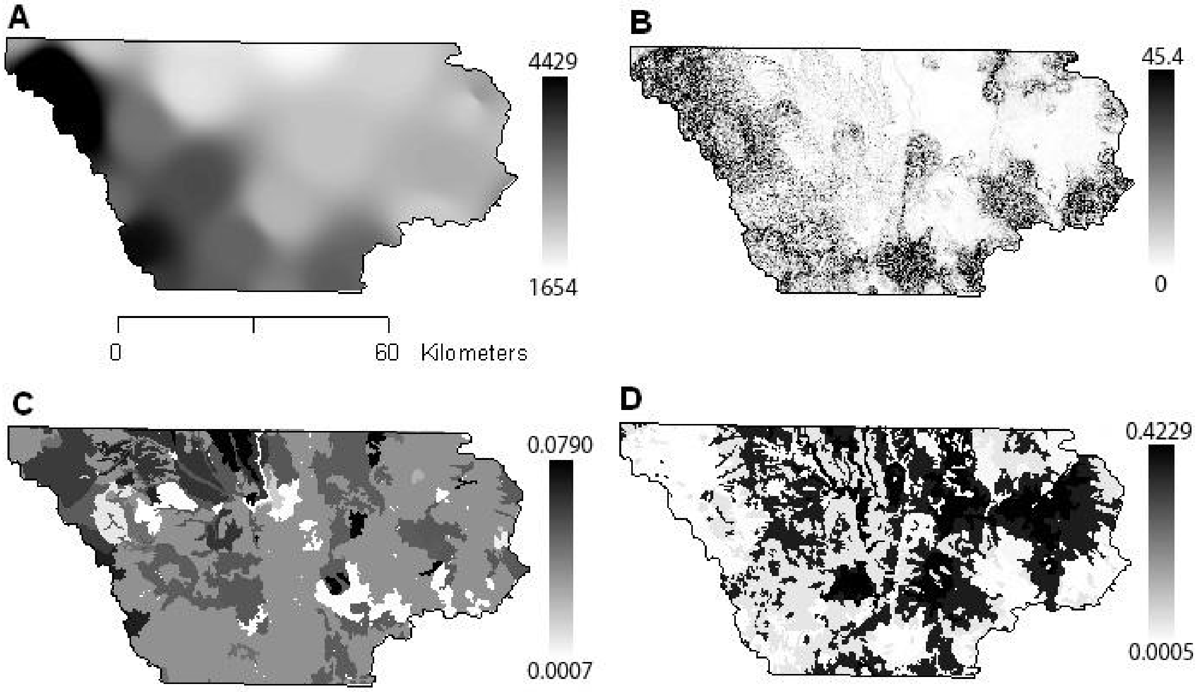

Figure 2. RUSLE Factors: A – wet season Rainfall-Runoff factor grid (MJ mm $ha^{-1}$ $h^{-1}$ $yr^{-1}$),
B – Topographic (LS) factor grid (unitless), C - Soil Erodability factor grid (t ha h $ha^{-1}$ $MJ^{-1}$ $mm^{-1}$),
D – wet season Cover and Management factor grid (unitless).

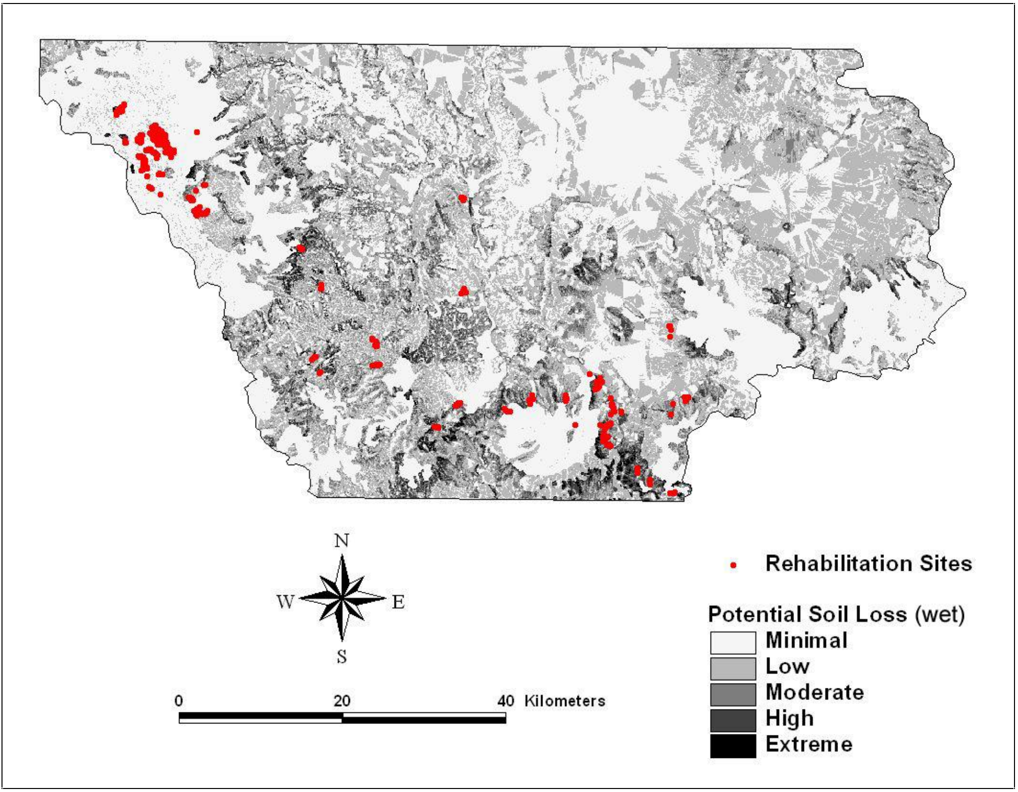

Figure 3: Potential Soil Loss occurring between Mid-May and Mid-November (wet season) with reference to rehabilitation sites.

## ESTIMATING CONSERVATION SUCCESS

The conservation measures evaluated in this research consisted of contour plowing (N = 54) and stone check dams (N = 6,103). These 6,157 sites translated to 453 cells in the support practice grid (100m$^2$ resolution). Other activities including terracing, grazing control and re-vegetation form part of the watershed conservation program, but due data limitations were not considered in this research. Rehabilitation sites located outside of the study area or with apparent errors were eliminated from further study and data from multiple sites located within a single 100m$^2$ cell were amalgamated.

Characteristics of the rehabilitation sites include a mean slope of 11.4 degrees (12.6 %), mean annual precipitation of 726.5mm and mean soil loss potential of 9.9 tons ha$^{-1}$ yr$^{-1}$. Thus sites are generally located in areas of low (1 to 10 tons ha$^{-1}$ yr$^{-1}$) to moderate (10 to 30 tons ha$^{-1}$ yr$^{-1}$) soil erosion potential. The most common soil types were Haplic and Luvic Phaeozems. The most common land cover types were found to be Pasture and Rain-fed Agriculture. Typical stone structures are illustrated in Figures 4a and b.

Cells in the support practice factor grid were modified to reflect the estimated success of each rehabilitation site and thus could be used to generate an overall estimate of success (total soil conserved) for the entire watershed rehabilitation program. With regard to this grassroots conservation program, subsistence plots (~50m$^2$ or ¼ ha) are of greater rehabilitation interest than larger fields used in commercial production; thus for each plot under contour plowing, ¼ of the recommended P value (0.5) was assigned to each rehabilitation site within a 100m$^2$ cell (up to a total of 4 sites)(Renard et al. 1997). Thus for contour plowing, P factor values were 0.875 for cells with only 1 site , 0.75 for 2 sites, 0.625 for 3 sites and 0.5 for cells with 4 or more sites of contour plowing.

Figure 4a. (left) A stone dam after heavy rainfall in Peña Alta, Guanajuato; 4b. (right) Members of FAI participating in a field workshop hosted by *Save the Laja* in Fajardo, Guanajuato.

Recommended P factor values are not available in the literature for most in-channel conservation measures. RUSLE estimates interrill erosion potential, thus P factors for spatially distributed support practices are most appropriate and most easily incorporated into the model. In-channel measures are quite similar to gully control measures and thus are not generally considered in the RUSLE model. Without any in-field data collection, a rough estimate of the support practice value for stone structures was calculated by using terraces as a surrogate.

Terraces and check dams are both labour intensive, structural measures that are intended to reduce flow velocity (by reducing slope length and gradient), increase infiltration and trap sediment (Reese 1966; Morgan 1996; Xiangzhou et al. 2002; Nyssen et al. 2004). Although terraces operate over greater horizontal extents than in-stream structures, and thus can trap greater a volume of sediment; in-stream structures operate where runoff concentrates at a low point in the terrain, thus receiving sediment in concentrations greater than any single point along a terrace (assuming interrill erosion is equal). To account for the shorter horizontal extent of in-stream structures, as well as the greater sediment concentrations received, weights of 0.5, 0.25 and 0.1 were applied to the recommended support practice value of terracing; these weights were intended to represent the sediment trapped by 50m, 25m and 10m horizontal segments of terracing, respectively (cell size is 100m). These weights were used to estimate support practice values for all cells containing dam sites, as described below.

The minimum recommended spacing for stone structures is reported to be 5 to 7 channel widths (Brookes and Shields 1996); the structures were assumed to have a mean width of 2m, thus an interval of 10 to 14m would be ideal. Any structures closer than 10m have no added benefit. Terraces (open-channel, grade of 0.1 to 0.3) have a minimum effective interval of 33.5m and a recommended P value of 0.6; as a value of 1.0 represents no support practice at a particular location, terraces provide a 0.4 support practice credit (1.0 - 0.6)(Renard et al. 1997). Thus based on the minimum recommended intervals, channel reaches of 100m in length with at least 10 structures are considered to be equivalent to Terracing with a 33.5 interval (after weights were assigned). For cells with less than 10 structures per 100m reach, each structure was assigned an equal P credit value respective of the value for ideal terracing and the assigned weight. A total of 86 cells had more than one reach per cell; for each additional reach, up to 10 extra dams were considered effective. The following equation was used to determine the unique P-value for each cell.

$$P_a = 1 - [(w * T_i) / d_i] * d_e \qquad (4)$$

Where:

$P_a$ is the adjusted support practice value for a given cell
$w$ is the weight assigned to account for spatial influence of dams (0.5, 0.25 or 0.1)
$T_i$ is the credit value of ideal terracing (0.4)
$d_i$ is the ideal number of dams per 100m reach (10)
$d_e$ is the number of effective dams ($\leq$ 10 per 100m reach;
cells may contain > 1 reach)

The calculated P-values ranged from 0.0, 0.5 and 0.8 (for weights of 0.5, 0.25 and 0.1 respectively) for a cell with 5 reaches and 76 dams, to 0.980, 0.990 and 0.996 for cells with only 1 reach and 1 dam. Solving the RUSLE with these adjusted P-values and subtracting this from the baseline erosion potential, generated an estimate of total conservation. The total soil conserved was calculated to be 732.6 tons $yr^{-1}$, 406.8 tons $yr^{-1}$, and 211.2 tons $yr^{-1}$ for the 0.5, 0.25 and 0.1 weights respectively. Contour plowing accounts for 76.1 tons $yr^{-1}$ (10.4 %) of total conservation. By dividing the total estimated conservation of the structures (excluding conservation by contour plowing) with the total number of stone structures, the estimate of soil conservation per dam was found to be 0.108 tons $yr^{-1}$ (0.15 $m^3$ $yr^{-1}$, if bulk density is assumed to be 1.4 Mg / $m^3$) for the weight of 0.5. This estimate is consistent with the maximum volume (1 - 2 $m^3$) of a small stone check dam and an accumulation period of several years (Robichaud et al. 2000).

## DISCUSSION AND RECOMMENDATIONS

Based on the comparison above, the weight of 0.5 was deemed to be the most applicable for estimating the support practice value of check dams. This weight however, seems to slightly underestimate the amount of soil conserved. The 656.5 tons $yr^{-1}$ conserved by the 6,103 check dams (weight of 0.5), equates to about 0.15 $m^3$ $yr^{-1}$ of sediment trapped per dam or approximately 1$m^3$ after 6.6 years. As not all rehabilitation sites were considered in this analysis and various other conservation techniques have been employed, the total estimate of ~700 tons $yr^{-1}$ is plausible.

The location of existing rehabilitation sites relative to areas of low to moderate erosion is consistent with the stated objectives of the organization; efforts have been focused in areas where there is a reasonable expectation of success (Tully and Mora 2005). For a non-profit organization with limited resources and dependant upon the goodwill of local volunteers, it would be a risky endeavor to attempt the rehabilitation of extremely eroded areas. This triage philosophy is common throughout the soil conservation literature (Warkentin 2001). The presence of outliers (sites estimated to have extreme erosion) should not diminish the importance of site selection based on field reconnaissance, but simply suggests that great care must be taken. The erosion potential at a particular site may not always be realized; limited experimentation with conservation at sites categorized as having high or extreme erosion potential may lead to alternative solutions and approaches. The structural design of the rock dams in the Rio Laja watershed has followed conservation science guidelines (i.e. gradients of less than 14%)(Lenzi 2002).

Ideally, field investigations would provide validation for assumptions such as accumulation period and the quantities of sediment trapped by particular dams. The documentation of any required structural maintenance activities could also provide site specific data to facilitate cost-benefit estimates and improve estimates of soil conservation (Pretty and Shah 1997; Tomlinson 2004). If future research is to be beneficial, quality control and metadata standards must be improved for the geospatial data currently managed by *Save the Laja.*

## CONCLUSIONS

Approximately 700 tons $ha^{-1}$ $yr^{-1}$ of soil is conserved by the rehabilitation measures considered in this study. Using terracing as a surrogate, a weight of 0.5 generates a plausible estimate of the support practice value of stone dams. Beyond the physical conservation of soil, the activities of *Save the Laja* have provided opportunities for environmental education and local capacity building. Rural communities, often marginalized in the past, have improved their management of land resources and created a brighter future for the next generation. This research suggests that large differences can be made through small increments.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial and logistical support of *Save the Laja* during field research between May and August 2004. All data for this research was provided through this organization. Additional financial support was provided by the Arthur D. Latornell Graduate Travel Grant, the Richard & Sophia Hungerford Graduate Scholarship, the Yeandle Family In-Course Bursary and the University of Guelph.

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