SEDIMENT AND EROSION IN TIJUANA: SOCIOECONOMIC INTERACTIONS WITH SEDIMENT BUDGETS UNDER RAPID URBANIZATION

PROJECT NUMBER: W-08-15

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NARRATIVE SUMMARY

The Tijuana Estuary in San Diego County has been affected by excessive sedimentation. The suspected source of the sediment is erosion caused by rapid urbanization in Tijuana, where persistent soil exposure on steep slopes generates large volumes of sediment that are then routed through the stream network to the estuary. Erosion also poses problems for urban residents in Tijuana, where it damages roads and contributes to slope instability. The sediment problem along the border should be viewed as a combination of socioeconomic and physical processes.

The objectives of this study were to (1) map sediment production potential in Tijuana using a simple model, (2) quantify a sediment budget for a small watershed in Tijuana (Los Laureles Canon, called Goat Canyon in the United States) to determine probable sediment generating mechanisms, and (3) analyze the relationships between socioeconomic status and sediment production. The goal was to quantify the importance and spatial pattern of sediment generation processes, to interpret those patterns as functions of socioeconomic attributes of different communities in Tijuana, and finally to develop a new conceptual model of the socioeconomics of erosion that could be extrapolated to other cities, both on the border and in other regions.

The study documented a new conceptual model of urban erosion, based on a classic model of Latin American city structure. The model highlights the importance of a marginalized periphery in generating sediment due to high and chronic soil exposure and steep topography. The sediment budget pointed to unpaved roads as a dominant source of sediment to the estuary, suggesting that infrastructure improvements in Tijuana may simultaneously benefit both poor residents and coastal ecosystems.

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Introduction

The Tijuana Estuary in San Diego County has been affected by excessive sedimentation. The suspected source of the sediment is erosion caused by rapid urbanization in Tijuana, where persistent soil exposure on steep slopes generates large volumes of sediment that are then routed through the stream network to the estuary. Erosion also poses problems for urban residents in Tijuana, where it damages roads and contributes to slope instability.

The classic Wolman (1964) conceptual model of erosion in urban areas was based on cities in developed countries, but no equivalent exists for developing countries like Tijuana. Therefore, the central goal of this project was to develop a new conceptual model of the socioeconomics and physical geography of erosion that could be extrapolated to other cities, both on the border and in other regions.

The three specific objectives of the project were to (1) map sediment production potential in Tijuana using a simple model, (2) determine the relationship between socioeconomic status and sediment production, and (3) quantify a sediment budget for a small watershed (Los Laureles Canon, called Goat Canyon in the United States) to determine the mechanisms generating sediment. The study resulted in a new conceptual model of urban erosion, based on the Griffin-Ford model of Latin American city structure. The model highlights the importance of a marginalized periphery in generating sediment due to high and chronic soil exposure and steep topography. The sediment budget pointed to unpaved roads as a major source of sediment to the estuary, suggesting that infrastructure improvements in Tijuana may simultaneously benefit both poor residents and coastal ecosystems.

Research Objectives

The objectives of the research were to (1) map the spatial distribution of sediment production potential (SPP) over the city of Tijuana, (2) establish the relationship between SPP and key socioeconomic indicators at the scale of the whole city, and (3) perform a detailed sediment budget of a small watershed on the city's periphery (Los Laureles Canyon Watershed) to identify key processes generating sediment. The overall goal of the project was to develop new conceptual models of the socioeconomic and physical controls on sediment production in Tijuana at two scales: the regional scale of the entire city, and the small watershed scale (~17 km^2). Identification of the key processes generating sediment is vital to developing plans designed to decrease sediment loading to the coast.

The detailed objectives, as stated in the project proposal, were:

- Objective 1. Map sediment production potential over Tijuana. A land cover map, topography data and soils information were used as input to a soil loss model (RUSLE) to identify locations with high susceptibility to sheetwash and rill erosion in Tijuana

- Objective 2. Determine the relationship between socioeconomic status and sediment production potential over Tijuana. A marginality index was developed using data from the Mexican Census, and correlated to the model estimates of sediment production potential from Objective 1

- Objective 3. Establish a sediment budget of Los Laureles Canyon
  - Objective 3a. Estimate the amount of sediment generated by sheetwash, rill erosion, gully development, and channel scour in Los Laureles Canyon using field measurements of rill, gully, and channel cross sections
  - Objective 3b. Compare the sediment budget with measured sedimentation rates at the mouth of Los Laureles Canyon

RESEARCH METHODOLOGY/APPROACHES

The project had three components corresponding to the three major objectives: The sediment production potential modelling, the sediment budget, and the socioeconomic analysis.

Objective 1. Map Sediment Production Potential over Tijuana

Sediment production potential depends on natural factors such as soil type, topography, and climate, and on anthropogenic factors like land cover. These factors have been combined in a simple model called the Revised Universal Soil Loss Equation (RUSLE) (Renard and Ferreira 1993). The RUSLE provides a rough estimate of the sediment production potential of a landscape via sheetwash and rilling. It does not provide accurate estimates for a particular location without significant calibration, but may be used to identify locations with potential for sheetwash and rill erosion (Boysen 1974; Onori, et al. 2006).

The RUSLE requires information on climate (R parameter), soil type (K parameter), topography (LS parameter), and land cover (C parameter). The R value was taken from maps of R for the continental United States. The K value was estimated using a map of the K value for California, taking the value of K of soils immediately across the border. The K value was also estimated using a field survey of erosion on a vacant lot (Appendix B). A digital elevation model with 30m resolution, available at San Diego State University (SDSU) for all Tijuana (Wright 2001), was used to calculate the LS value using the method of Moore and Burch (1986). The C parameters were estimated for each 30 meter cell over Tijuana using land cover maps (Biggs, et al. 2010), which were based on 30 m resolution Landsat TM imagery and quantified the fraction of vegetation, soil, and impervious surfaces (VIS fractions). Multiple endmember spectral mixture analysis (MESMA) was used to estimate the VIS fractions for each 30m cell over Tijuana. The RUSLE was validated using data on sediment accumulation in sediment traps (desarenadores) in Tijuana (Figure 1).

Objective 2. Determine the Relationship between Socioeconomic Status and Sediment Production Potential at the Scale of Tijuana

Landscape properties and sediment production may be related to socioeconomic status and demography (Vanacker, et al. 2003). In Tijuana, it is hypothesized that sediment production potential correlates positively with lower socioeconomic status and negatively with time since urbanization. Poor areas often have limited infrastructure development for controlling soil erosion, and are hypothesized to have a high fraction covered by soil and a greater frequency of earthen (non-concrete) channels compared with areas of higher socioeconomic status. Both of these processes, (landscape susceptibility to erosion and channel type) are hypothesized to correlate with economic status. Time since urbanization was anticipated to correlate with sediment production due to the gradual accumulation of impervious surface following urbanization.

Socioeconomic status was mapped using a Marginality Index derived from the Mexican Census as distributed by the Instituto Nacional de Estadística Geografía e Informatica (INEGI). The index had eight variables related to health, education, and housing, weighted according to the recommendations of the Consejo Nacional de Población (CONAPO) (Table 1). A time series of maps of the urbanized area, starting in 1938, was used to quantify the age of the urban area (Figure 2).

The relationship between marginality, time since urbanization, topography, and sediment production was determined using multiple linear regression, both with and without filtering for spatial autocorrelation.

Objective 3. Establish a Sediment Budget of Los Laureles Canyon

The quantitative predictions of sediment production potential from the RULSE formed the basis for a sediment budget of Los Laureles Canyon (LLC) watershed. The budget identified the major processes generating sediment in the watershed. While complex methods and years of detailed study may be required to refine sediment budget estimates, rapid, reconnaissance-level field techniques may also be used to identify the major controlling processes and their approximate magnitudes (Reid and Dunne 1996). Field visits were made on 12 separate occasions over the period of study. Initial observations included photographs, interviews with local residents, and estimates of channel condition and stability. These observations were used to prioritize collection of channel and gully surveys.

Objective 3a. Rill, Gully and Channel Surveys

Quantification of sediment production from sheetwash, rilling, gullying, and channel erosion is complicated in areas where it is difficult to have data collection from field plots. We used repeat topographic surveys to quantify the importance of rill, gully, and channel erosion for the sediment budget of the LLC. We also installed sediment fences to quantify sheetwash and rill erosion, but they were either vandalized or destroyed by extremely high sediment loads between field visits. As a substitute, we used the RULSE model calibrated to field measurements of erosion in a topographic survey (Appendix B). The original proposal included use of a laser scanner, but the manual topographic surveys proved more rapid, and concerns of security restricted transporting the scanner over the border. More importantly, large gullies were observed in the field, which was not expected and triggered a reconsideration of methods to quantify sediment production. Topographic surveys are the most reliable method to quantify gully formation, and are required where laser scanning would be obstructed by the crenulations of rill and gully topography. The manual field surveys of channel and gully cross sections proved adequate to provide a first-order sediment budget (Appendix B).

Channel surveys, including both cross sectional geometry and length, have been used to quantify the importance of channel erosion for the sediment budget of watersheds in southern California (Trimble 1997). We performed a similar study for the LLC in 2008-2010 (Appendix B). The survey estimated the total volume of sediment generated by channel and gully erosion, and quantified changes over a single year to identify hotspots within the Canyon. The surveys were performed using survey equipment available at San Diego State University Geography Department.

Objective 3b. Sediment Traps at Los Laureles Canyon

The watershed-total sediment load was determined using sediment traps data at the mouth of the canyon where it enters the Tijuana Estuary. Three types of data were used to quantify sediment load from the watershed: (1) the accumulation (tons) of sediment in the LLC traps as quantified by the Tijuana Estuary National Research Reserve, (2) accumulation (tons) of sediment in the LLC traps as quantified by differential topographic analysis collected in 2009, and (3) accumulation of sediment in the Estuary from differential topographic analysis from a report by Phil Williams and Associates (de Temple, et al. 1999) (Appendix C). These data provided a first-order estimate of sediment delivery at the watershed scale. Water flow and the suspended sediment flux at Goat Canyon past the two sediment traps has not been measured. Accordingly, we installed a pressure transducer for discharge measurement and an autosampler for suspended sediment collection at a flume built for road stabilization between the sediment traps, but both the transducer and the autosampler failed during field trials due to high sediment concentrations in the water. Autosamplers often fail in the field, especially under high sediment loads (E. Beighley, personal communication). While supplemental samples of suspended sediment were collected during storm events, insufficient data were available to quantify suspended sediment load past the traps.

PROBLEMS/ISSUES ENCOUNTERED

Significant difficulties were encountered in conducting fieldwork for the sediment budget (Objective 3), due to both security concerns and to damage to field equipment. Security concerns delayed the initiation of the project fieldwork. Our main collaborator at the Colegio de la Frontera Norte (COLEF), Alberto Pombo, moved to San Diego during the study period due to perceived risk of remaining in Tijuana. We therefore established a working relationship with Oscar Romo of the Southwest Wetlands Interpretive Association (SWIA). Romo has long-term experience at a field site in the San Bernardo neighborhood of the LLC, including close connections with the local community. Through Romo, we established working familiarity with community members in San Bernardo, which increased our sense of security and allowed us to participate in SWIA's ongoing research and outreach activities. After gaining familiarity with the watershed in San Bernardo, we expanded our field work to the rest of the watershed.

In Spring 2010, the California State University system banned all travel for sponsored research projects across the U.S.-Mexican border. This severely hampered the ongoing fieldwork. In response, we continued some survey work through our M.A. student from COLEF, Fernando Jagueiri. Fernando continued the surveys and collected soil samples during the remainder of the project.

Security concerns also impacted some of our methods. For example, transport of an expensive laser scanner across the border, as described in the proposal, was deemed too risky. Instead, inexpensive sediment fences were installed to measure sediment production, but they were vandalized or destroyed. More importantly, field observations suggested that gully formation, not sheetwash and rilling that would be quantified by the sediment fences was a major process generating sediment. In response to both the security concerns and the field observations, techniques were developed to rapidly establish the importance of rills, gullies, and stream channels in the field, without leaving field equipment. The revised techniques, which included repeat topographic surveys, proved better than the original laser scanning approach, since we were able to cover larger areas in less time.

RESEARCH FINDINGS

The research findings have been documented in detail in three publications, one published Biggs et al. in 2010, and two in review, one by Biggs et al. and another by Perkins and Biggs. Here are summaries of those results, organized by objective:

Objective 1. Map Sediment Production Potential over Tijuana

Sediment production potential (SPP), and therefore erosional severity, varied widely over Tijuana, from a minimum of zero to a maximum of 21 kg m^{-2} $year^{-1}$ (Figure 3). SPP was highest in areas with steep slopes and persistent bare soil. The bare soil fraction was highest on the periphery of the city, and was high even in areas that had been urbanized up to forty years, suggesting that soil exposure can be persistent and chronic in Tijuana.

The predicted SPP correlated significantly with observed sediment accumulation in the seven sediment traps (Figure 1 and Figure 4), suggesting that the RUSLE provided a useful indicator of erosional severity and sediment production, if not a precise value.

Objective 2. Determine the Relationship between Socioeconomic Status and Sediment Production Potential over Tijuana

The marginality index showed a consistent spatial pattern, with higher marginality (low socioeconomic status) on the periphery and areas recently urbanized, and lower marginality in the city center (Figure 5). A wide range of socioeconomic conditions were present in the tracts. For example, the percentage of households without drainage ranged from 0% to 86%, and the percentage without indoor piped water or with substandard roofing material ranged from 0% to 100%. This suggests that the census tracts were small enough to capture the full range of socioeconomic conditions over Tijuana.

Census tracts with high socioeconomic marginality had higher slope, soil exposure, and sediment production potential than tracts with low marginality. Controlling for time since urbanization, sediment production correlated positively with the marginality index (Table 2 and Figure 6). The results were not highly sensitive to spatial filtering, suggesting that the p-values were not an artifact of spatial autocorrelation.

The main findings may be summarized as: (1) sediment production potential correlates with socioeconomic marginality, controlling for time since urbanization (Figure 6), (2) areas urbanized the longest, located in the interior of the city, were urbanized for more than forty years, and had low socioeconomic marginality and low SPP, due to high amounts of impervious surface, and (3) the highest sediment production occurred in poor areas on the periphery, due to both high soil exposure and steep slopes.

Based on these observations, we proposed a revised model of where and when sediment is produced during urbanization. Our model is an alternative to the classic Wolman model (Wolman 1967), which was based on observations in developed countries. The revised model is based on the Griffin-Ford model of the geography of Latin American cities (Griffin and Ford 1980). The Griffin-Ford model combines three concentric zones of varying socioeconomic status with a rectangular sector containing the central business district (CBD) and elite housing (Figure 7). The first concentric ring of the model is a "zone of maturity," which is the oldest section of middle class housing with relatively high-quality housing stock that has been improved by the residents over decades. The zone of maturity has a range of urban services, including paved roads and sewerage. The second ring, the "zone of in-situ accretion" has similar characteristics as the zone of maturity, though it is more recently urbanized and therefore has more unimproved housing stock undergoing rapid renovation, with fewer urban services. The term “accretion” refers to the gradual accumulation of housing stock and urban services. The third concentric ring contains a recently urbanized periphery with a heterogeneous mix of poor, middle class, and elite neighborhoods.

The marginality index and time since urbanization were used to classify Tijuana's census tracts into the zones described by the Griffin-Ford model (Griffin and Ford 1980) (Figure 7). The original model does not provide threshold values for age and marginality, so these thresholds were based on natural breaks in the plots of age versus fractional cover, and on the spatial contiguity of the resulting zones. Tracts with low marginality (MI < 0.33) and age greater than twenty years were considered to be the "elite core." All other areas with low marginality that were urbanized less than 20 years were classified as the wealthy periphery. The breakpoint between the zone of maturity and the zone of in-situ accretion was taken as forty years. These thresholds resulted in spatially coherent groups of tracts that corresponded to the Griffin-Ford zones (Figure 7). For example, tracts in the "elite core" tended to be spatially contiguous, while the newer elite suburbs were more spatially fragmented and occurred further from the core, as described by the model. Choosing different ages and marginality breaks would alter the size and shape of the resulting zones. Here the purpose of using the Griffin-Ford model was not to make a final map of zones that strictly and uniquely correspond to the zones as originally described by Griffin and Ford (1980), but rather to use the model as a heuristic device for interpreting spatial patterns in land cover and sediment production.

Land cover, slope and sediment production potential differed among the Griffin-Ford zones (Table 3). The elite core, the mature surface, and elite areas on the periphery (MI < 0.33) all had similar land cover and the lowest sediment production and disturbance ratios. The zone of in-situ accretion and peripheral areas with high marginality had higher soil fractions (0.32 and 0.49) and more than twice the sediment production potential of other zones with similar ages. Newly urbanized areas on the poor periphery resembled other mid-marginal areas (0.33 < MI < 0.66) that had been urbanized less than 40 years (zone of in-situ accretion). The poor periphery had the highest soil fraction, slope, SPP and disturbance ratio (DR) of all the zones. The disturbance ratio is the amount of sheetwash and erosion predicted by the RUSLE under observed land cover divided by the amount predicted under pre-disturbance land cover. Pre-disturbance land cover was taken as the land cover fractions in an undisturbed area just south of the city. The DR controls for the effect of slope, and spatial variations in DR are due only to land cover.

Objective 3a. Establish a sediment budget of Los Laureles Canyon: Rill, Gully and Channel Surveys

Construction sites, including vacant lots, ranged from large, active sites to small cleared plots with no activity and covered about 7.2% of the total watershed area. Active construction made up 42% and vacant lots 58% of the construction sites. Based on RUSLE estimates, sheetwash and rill erosion from construction sites contributed between 273 and 1,108 tons year^{-1} (1–2% of the total sediment load) depending on the R and K values used (Table 4). Sediment production potential was highest on high slopes, and in areas with bare soil (Figure 8). Vacant lots contributed the majority of sediment from construction sites with between 184 and 746 tons year^{-1} or approximately 73% of the sediment produced from all construction sites (Table 4).

Los Laureles Canyon watershed had an extensive road network with a total of 158 km of roads (Figure 9). There were a total 1,177 road segments; 67% of the roads were unpaved in June 2008. The roads were on average 8.7 m wide and made up about 1.0 km^2 (9%) of the watershed area. Unpaved roads had an average slope of 15.8°. The majority of unpaved roads experienced extremely high traffic by smaller passenger vehicles (personal observation). Very few unpaved roads had roadcuts, and were graded on the natural surface. Road cuts were confined to the main paved roads in the northern portion of the watershed.

Gullies formed after rainstorms during the winter of 2009 (Figure 10). The gullies measured in spring 2009 ranged from 55 m to 200 m long. Gully width and sediment production increased with distance from the top of the road. The largest gully was up to 256 cm deep, though this depth coincided with a break in a water main about half way down the profile. The road was filled in during regrading in 2009, and a gully of similar size formed in the next rainy season, suggesting that the gully formed largely due to runoff, rather than to the water main break. The road gullies measured in spring 2010 were up to 6 m wide and 1 m deep at the bottom of the hillslope.

The sediment load associated with gully development varied widely but in all cases was significantly larger than the WEPP:Road estimates (Table 4). Gully production varied significantly ($p < 0.001$) by road substrate type. Roads that formed on a substrate with a high percentage (> 50%) of gravel and cobbles had relatively small and intermittent gullies. The sediment flux from roads on gravel and cobble were on average 18 times higher the WEPP:Road estimate while roads on sandy substrates were 46 times higher than the WEPP:Road estimates. Approximately 67% of the unpaved roads in the watershed had some evidence of gully formation in the satellite image from February 2003. Insufficient data were available to determine how gully formation and morphology changed with slope, and the substrate could not be determined from satellite images or after road maintenance, so high and low estimates for road gully production (S_g) were calculated by multiplying S_{rs} for each of the gullied road segments by a S_{rg}:S_{rs} of either 18 (for roads on gravel-cobble conglomerate) or 46 (for roads on sand substrate).

The stream channel length totaled 16.5 km, of which 10.7 km was earth, 4.3 km was concrete, and 1.5 km was considered intermittent or lacking a defined bank (Figure 11). Of the entire channel length, 29% was moderate to severely unstable. Severely unstable channels produced 36–68% of the total sediment from channel erosion while moderately unstable channels produced 19–21%. In total, channels provided 105–195 tons $year^{-1}$ of the sediment (Table 4), which was a very small fraction of the total sediment load (< 1%). The low sediment production from channels was due to channelization of a significant fraction of the network in the canyon. The channel beds and banks were also composed of cobbles, which protected the channel from the extreme incision that has been observed in other locations in southern California (Trimble 1997).

The sediment production from all sources in 2008-2009 ranged from 41,600 tons $year^{-1}$ to 108,200 tons $year^{-1}$ (Table 4), depending on the parameter values used. In all cases, the largest contributor was unpaved roads, which accounted for 36,993 –90,506 tons year^{-1} (84–89%) of the sediment budget depending on the size and frequency of road gully formation and the channel contribution. Construction sites and channel erosion accounted for small fractions of the sediment budget (1–3% and < 1% respectively). Open spaces and built urban surfaces accounted for between 10–15% of the budget. Normalized by area, the entire canyon produced 3,383-–8,798 tons km^{-2} year^{-1}.

Objective 3b. Sediment Traps at Los Laureles Canyon

The total sediment production was compared to several other estimates from the literature and the measurements from the sediment traps (Appendix C). Sedimentation in the Tijuana Estuary at the mouth of Los Laureles Canyon was 3,466 tons year^{-1} from 1986-1992 (average annual rainfall 259 mm) and 68,911 tons year^{-1} from 1992–1998 (average annual rainfall 316 mm) (Phil Williams and Associates Ltd. 1999). The sediment trap had 79,145 tons of sediment measured from the survey done in April 2009 (Appendix C). Rainfall during October 2008–June 2009 was 171 mm, which is below the long term average (250 mm over 1914-2009). The accumulation measured in 1992-1998 (68,911 tons year^{-1}) and 2009 (79,145 tons year^{-1}) was within the range of model estimates (41,608–108,217 tons year^{-1}), and suggests that the model provides reasonable values of sediment delivery by the main erosion processes.

The sediment trap data shows that sheetwash and rill erosion are not sufficient to generate the amount of sediment observed in the estuary, and that gully erosion is likely a dominant component of the sediment budget. In fact, the high estimates of sheetwash and rill erosion account for only 20 thousand tons of sediment, compared with the observed 79 thousand tons that accumulated in the estuary in 2009, suggesting that no combination of model parameters in the RUSLE can produce as much sediment as that observed in the estuary. Therefore, the other erosion processes documented here, in particular gully erosion, must be providing the rest of the sediment not generated by sheetwash and rilling.

Uncertainty in R and K values over the canyon led to a large range of sediment production estimates by sheetwash and rill erosion. The goal in the LLCW was to document the relative importance of erosional processes and land uses. Regardless of the specific combination of parameter values used, the order of importance remains clear, with unpaved roads supplying the majority of the sediment and the stream channel contributing very little.

CONCLUSIONS

The project documented important connections between socioeconomic status and sediment production in Tijuana, and has identified specific physical processes generating sediment in an example small watershed. The main conclusions are: (1) Socioeconomic status and time since urbanization are key determinants of sediment production in Tijuana. Poor areas generate more sediment than rich areas because poor areas are located on steep terrain and have long-term exposure of bare soil. The bare soil occurs on unpaved roads and cleared but undeveloped lots. (2) The pattern of sediment production in Tijuana differed significantly from the patterns observed in the

United States, where a short period of soil exposure during construction is replaced by vegetation and impervious surface during a period of a few years. In Tijuana, by contrast, soil exposure was chronic, lasting decades following urbanization. While a small area of wealthy suburbs on the periphery of Tijuana followed the Wolman model, most of the area was better described by the Griffin-Ford model of Latin American cities, with a poor periphery dominated by steep topography and bare soil exposure. 3) Gully formation on unpaved roads was a dominant process in the sediment budget. Stream channel erosion was minor, because much of the stream network has been channelized, while the rest has a bed of cobble that is relatively resistant to erosion.

In sum, excessive erosion on unpaved roads in areas of low socioeconomic status suggests that infrastructure improvements, especially road paving coupled with channel stabilization, could both reduce erosion and benefit local communities.

Recommendations For Further Research

The research raises several questions about the links between socioeconomics, infrastructure development, and sediment production in Tijuana. Future research could be carried out at two scales: A regional study over Tijuana and other cities on the border, and the small watershed scale, such as carried out in Los Laureles Canyon. At the regional scale, important questions remain about road construction and paving, including why roads remain unpaved for decades, and what combination of policy and management could accelerate sediment control, including paving of roads where gullies develop. What is the connection between socioeconomic status, land tenure, municipal finance, and road paving? At a smaller watershed scale, we recommend quantifying the impact of different management activities, such as road paving, on runoff generation, sediment production, and stream channel erosion in Los Laureles Canyon. These scenarios could be incorporated into a decision support system to allow evaluation of different interventions on sediment delivery to the Tijuana Estuary.

Research Benefits

The research benefits include (1) dissemination of results at public meetings and professional publications, (2) development of key collaborations with non-profits working to address environmental problems on both sides of the border, (3) capacity building of Mexican students at the Colegio de la Frontera Norte (COLEF), and (4) working relationships with community members in Los Laureles Canyon. First, the results of the research have been presented at both academic conferences and in public meetings, including the Association of American Pacific Coast Geographers (September 2009), Border 2012 (October 2009), and a public seminar at the Tijuana Estuary (December 2010). The results have also been published as a series of three articles (one article, Biggs, et al. 2010, was financed in part with another grant). One of these articles has been published and two others are in review as of submission of the report. This documentation is vital to ensure the long-term dissemination of results and to prevent duplication of effort.

Second, the project has resulted in the development of working collaborations between San Diego State University and several governmental and non-profit organizations working for environmental protection on both sides of the border, including the Tijuana Estuary National Research Reserve, the Southwest Wetlands Interpretive Association (SWIA), and the Colegio de la Frontera Norte (COLEF). We look forward to continuing these collaborations in future work on the border.

Third, the research has resulted in capacity building of two Master's students at COLEF. The students assisted in the fieldwork, and one (Fernando Jauregui) is continuing to work independently with local residents of Los Laureles Canyon, which will form the basis of his Master's thesis. Fernando has gained valuable experience in topographic surveys, GPS, census data analysis, and interaction with community members and local non-governmental organizations in the canyon. The work has contributed to his career through both his skill development and professional contacts in environmental management in Tijuana.

Finally, as part of Fernando's work in the community, he has established relationships with community organizations in Los Laureles Canyon by attending focus groups and raising awareness of the research project. While the project did not initially include significant involvement or contact with the community, Fernando has developed a set of working relationships with individuals in the community interested in environmental protection. Future work in Los Laureles Canyon will benefit greatly from this incipient network of community members, non-profit organizations, governmental organizations, and universities in both the United States and Mexico.

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APPENDIX A

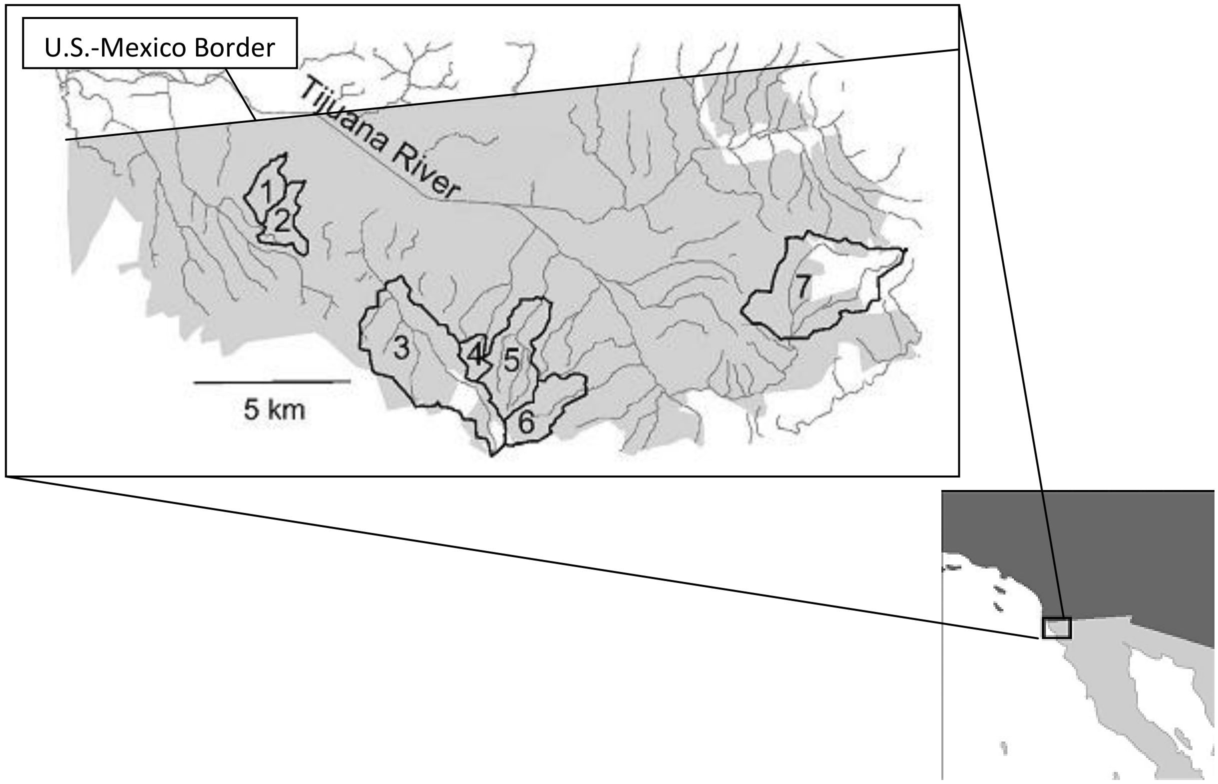

Figure 1. Watershed Boundaries of Sediment Traps in Tijuana

Table 1. Socioeconomic Indicators and Coefficients used to Calculate the Marginality Index

Indicator	Coefficient	Min	Mean	Max
Health				
1. % population ineligible for health services	0.3146	9	40	73
2. % infant mortality (less than 1 year old) to mothers between ages 15 and 49	0.2773	0	4	11
Education				
3. % population between ages 6 and 14 that doesn't attend school	0.2624	0	9	22
4. % population 15 years and older without post-primary education	0.3475	4	37	69
Housing				
5. % dwellings without drainage	0.2968	0	15	86
6. % dwellings without indoor piped water	0.3279	0	28	100
7. % dwellings with roofs made of substandard materials	0.2807	0	58	100
8. % dwellings without a refrigerator	0.3490	0	11	59

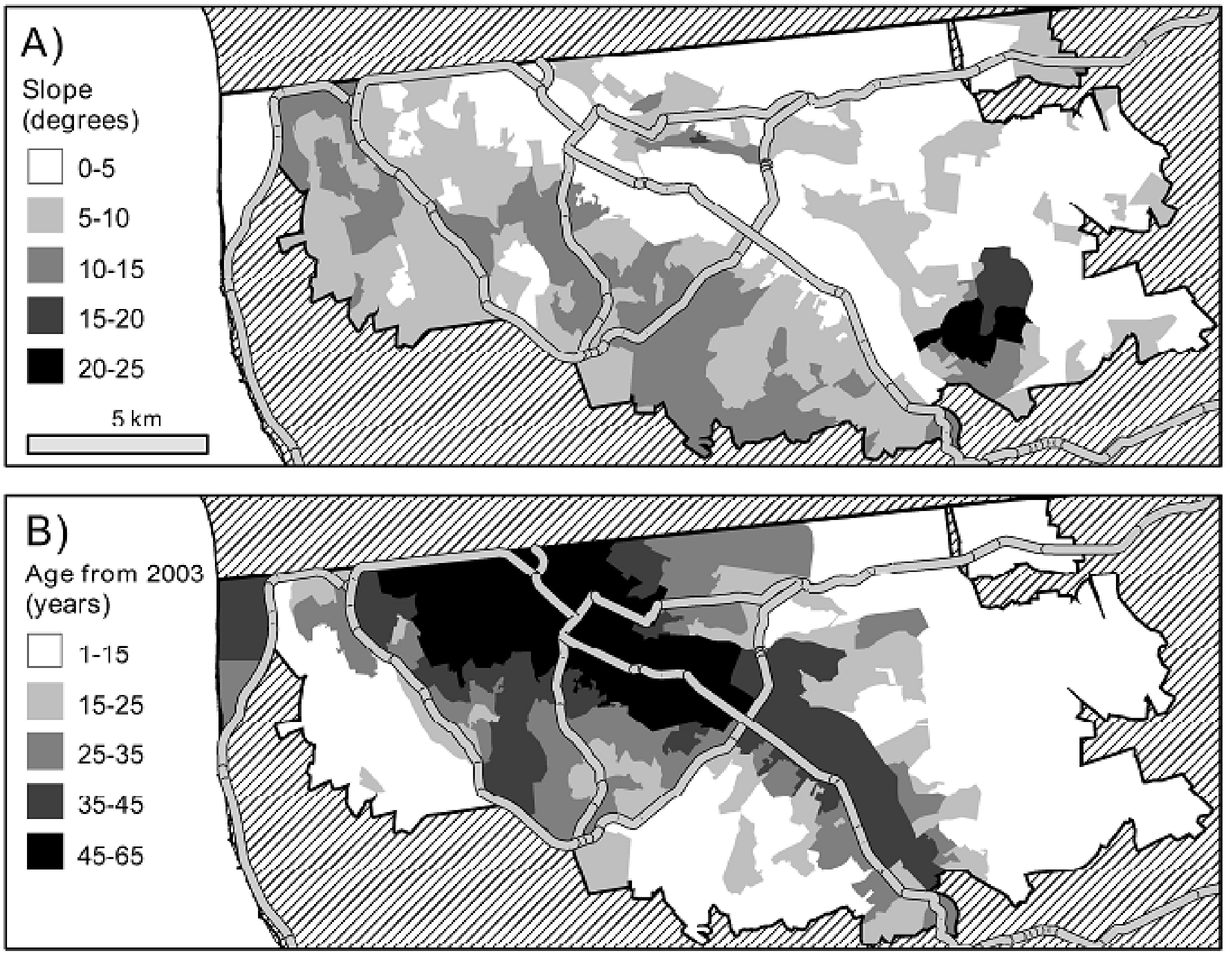

Figure 2. A) Average Slope and B) Average Time since Urbanization by Census Tract

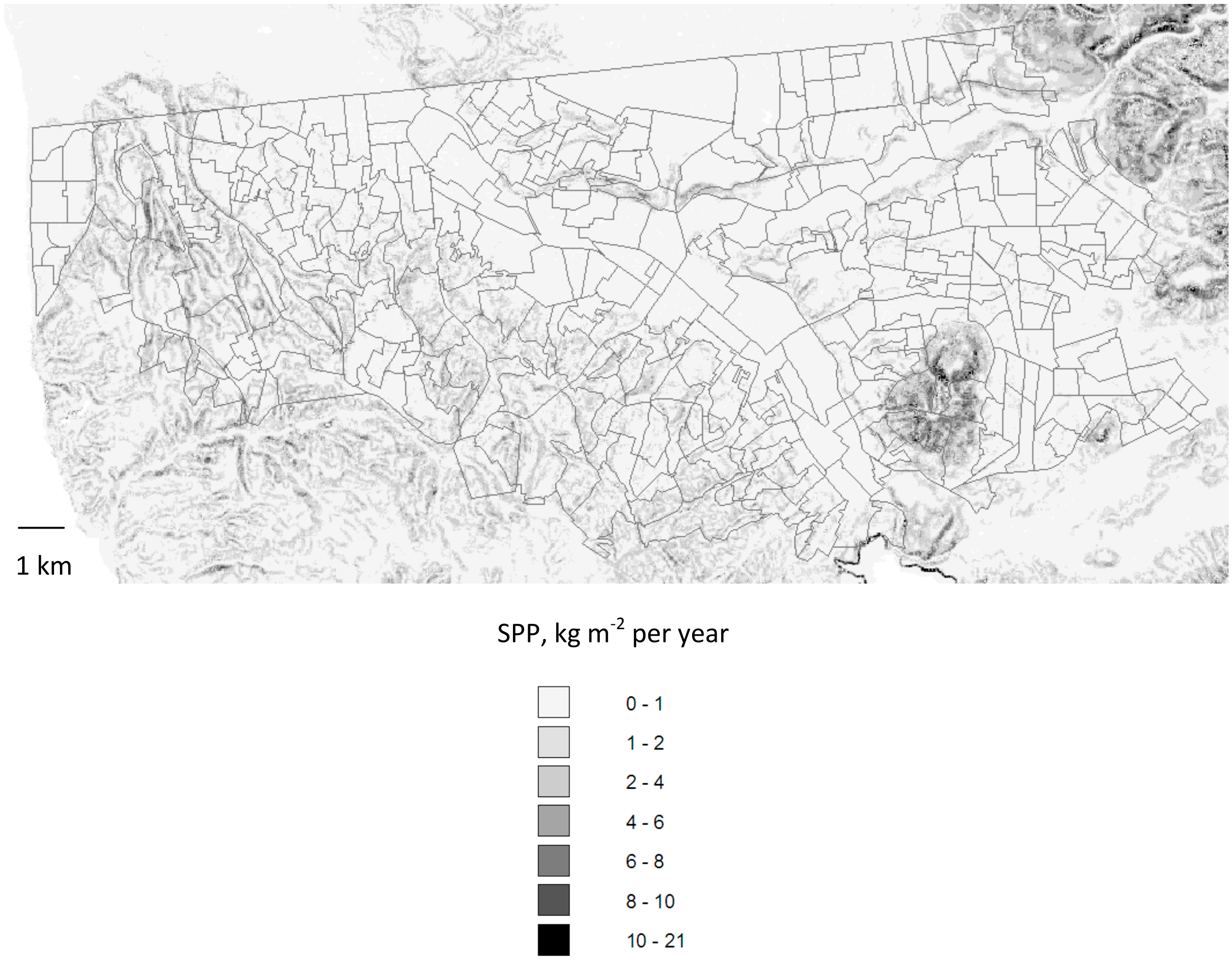

Figure 3. Sediment Production Potential in Tijuana (kg per m^2 per year)

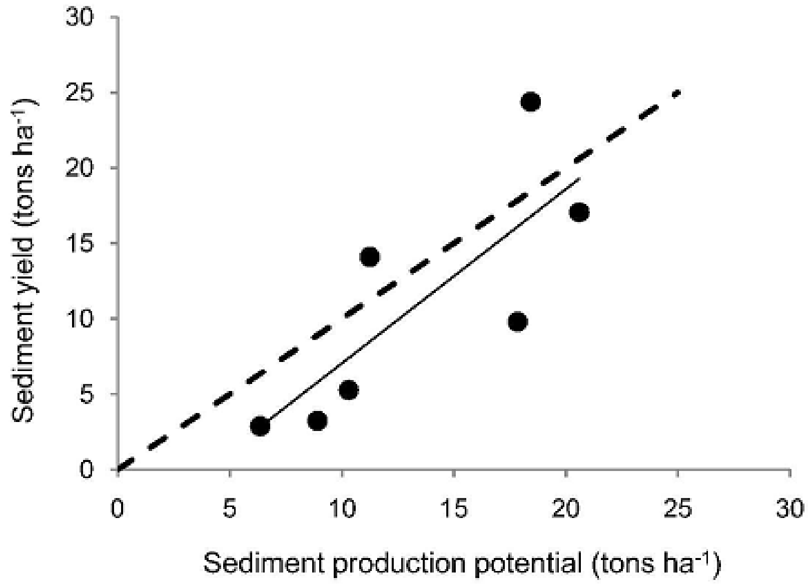

Figure 4. Modeled Sediment Production versus Observed Accumulation in Seven Sediment Traps

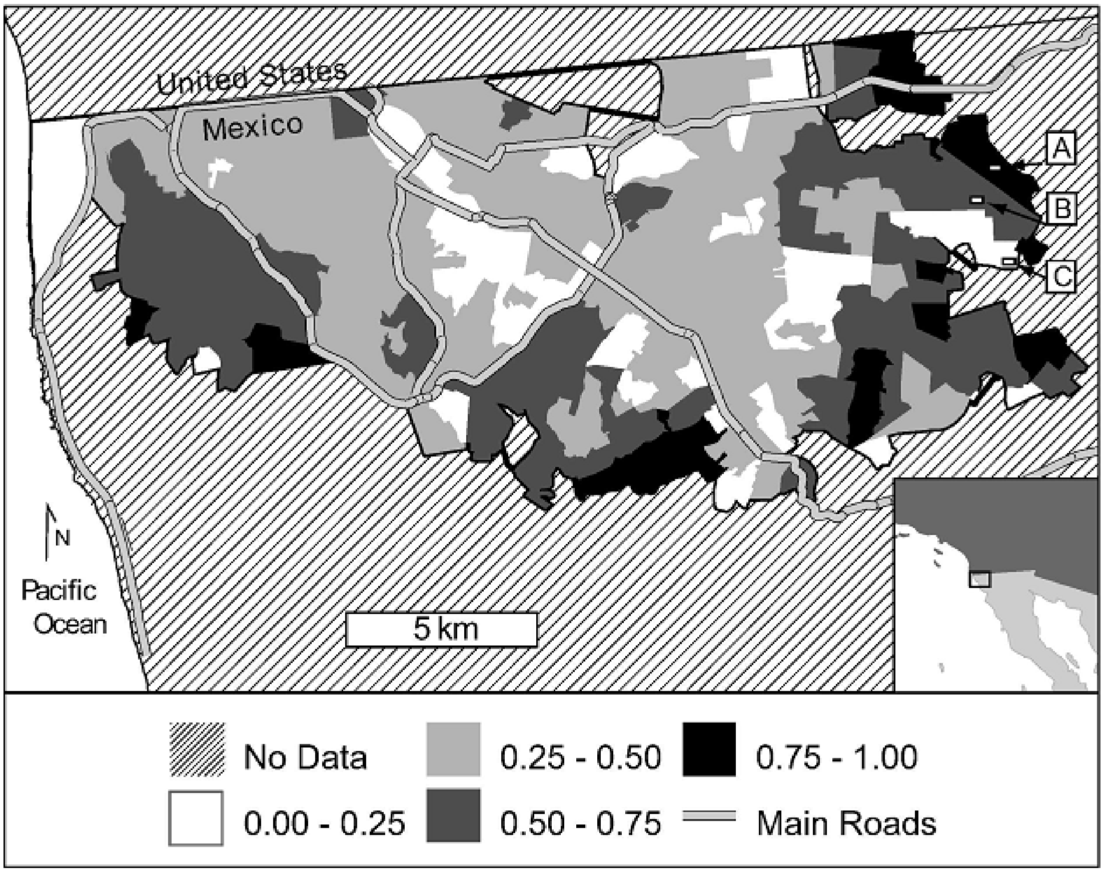

Figure 5. Marginality Index over Tijuana (low=wealthier, high=poor)

Table 2. Regression Parameter Values, with and without Spatial Filtering[a, b]

	MI	Age	Slope	Pop den	Intercept	RMSE	R^2
Vegetation %							
Unfilt	-2[ns]	-0.11	0.96	-0.36	26	5.1	0.46
Filt	3[ns]	-0.04[ns]	0.87	-0.48	24	4.4	0.35
Impervious surf. %							
Unfilt	-21	0.50	-0.85	0.90	36	8.8	0.69
Filt	-20	0.32	-0.81	0.94	40	7.0	0.45
Soil %							
Unfilt	23	-0.39	-0.11[ns]	-0.55	38	8.1	0.59
Filt	10	-0.12	0.41	-0.48	32	5.4	0.26
SPP (tons ha^{-1})							
Unfilt	2.1	-0.04	0.94	-0.04	-0.4[ns]	1.6	0.86
Filt	1.4	-0.04	0.76	-0.06	0.6[ns]	1.0	0.82
Disturbance ratio							
Unfilt	1.2	-0.015	-0.0012[ns]	-0.024	1.6	0.20	0.49
Filt	0.5	-0.004[ns]	0.027	-0.022	1.4	0.12	0.17

a. For the filtered regression, both independent and dependent variables were filtered using the algorithm of Getis and Griffith (2002). The spatial filtering distance (*d*) was different for each variable.
b. All variables were statistically significant at $p<0.01$ except those noted with ns ($p>0.05$).

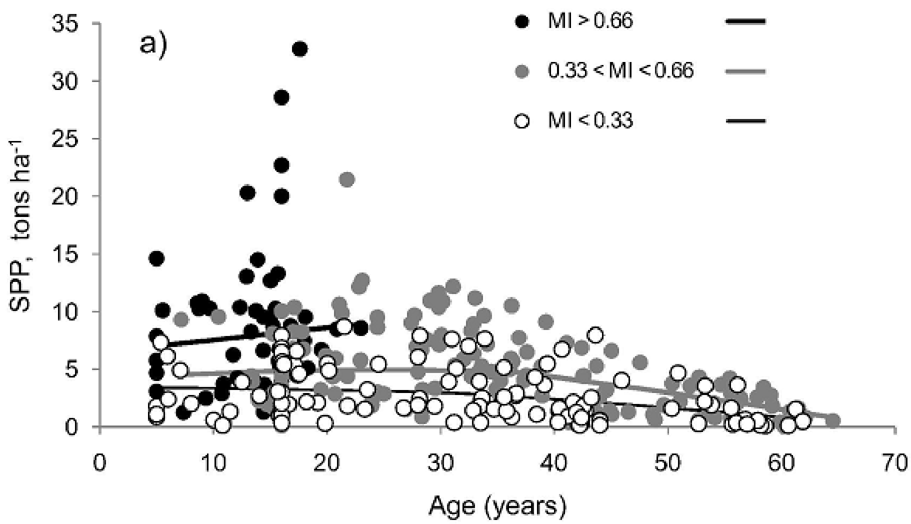

Figure 6. Sediment Production Potential (SPP) versus Time since Urbanization, Grouped by Marginality Index (MI)

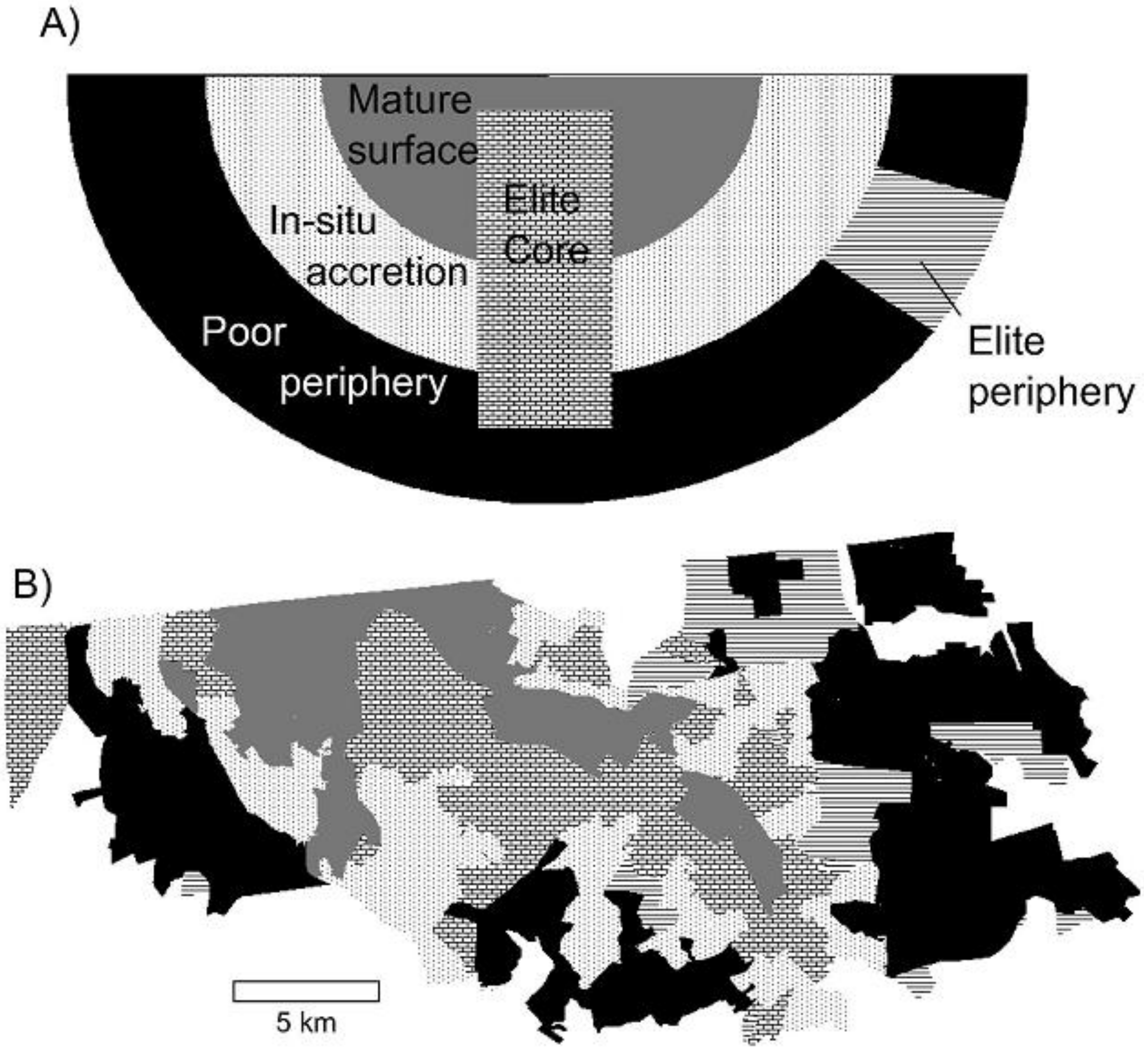

Figure 7. The Griffin-Ford Model of Latin American Cities, including A) General Schematic and B) Application to Tijuana

Table 3. Griffin-Ford Zones of Tijuana and Corresponding Soil Production Potential (*SPP*)

Zone	Marginality index	Age years	Area km^2	Slope	SPP ton ha^{-1}
1. Elite res. and CBD	< 0.33	> 20	45.4	4.9	2.5
2. Maturity	0.33-0.66	> 40	41.7	4.1	2.3
3. In-situ accretion	0.33-0.66	20-40	32.6	8.7	6.7
4. Periphery					
4.1 Low marginality	<0.33	< 20	18.7	4.2	3.1
4.2 Mid marginality	0.33-0.66	< 20	39.4	5.5	3.8
4.3 High marginality	>0.66	< 20	34.2	8.7	8.0

Table 4. Sediment Budget of Los Laureles Canyon Watershed

Land Use		Method	Type of Erosion	Area	Sediment Production (Low[a])	Sediment Production (High[b])
				km^2 (% of total)	tons $year^{-1}$ (% of total)	tons $year^{-1}$ (% of total)
Construction						
	Active	RUSLE	Sheet & rill	0.29 (3.5%)	89 (<1%)	362 (<1%)
	Vacant Lots	RUSLE	Sheet & rill	0.54 (4.7%)	184 (<1%)	746 (1%)
	Total			0.83 (7.2%)	273 (1%)	1,108 (1%)
Open Space		RUSLE	Sheet & rill	2.0 (17%)	1,026 (2.6%)	4,073 (4.0%)
Built		RUSLE	Sheet & rill	7.6 (64%)	2,788 (7.2%)	12,334 (12.3%)
	Total			9.6 (83%)	4,237 (10%)	16,407 (15%)
Roads	Unpaved	WEPP	Sheet & rill	1.0 (8.9%)	2,593 (6.7%)	2,593 (2.6%)
		Profiles	Gully	N/A	31,273 (80%)	79,921 (80%)
	Road Cuts	10% est.	Gully	0.06 (0.52%)	3,127 (8%)	7,992 (8%)
	Total			1.1 (8.6%)	36,993 (89%)	90,506 (84%)
Channel	Very Unstable	Profiles	Channel	0.019 (<1%)	71 (<1%)	71 (<1%)
	Moderate	Profiles	Channel	0.02 (<1%)	21 (<1%)	41 (<1%)
	Slight	Profiles	Channel	0.008 (<1%)	8 (<1%)	32 (<1%)
	Stable	Profiles	Channel	0.028 (<1%)	5 (<1%)	52 (<1%)
	Concrete	Profiles	Channel	0.021 (<1%)	0.0 (0%)	0.0 (0%)
	Total			0.1 (0.86%)	105 (<1%)	196 (<1%)
Landslides	Historical Records and Image Interpretation		Landslides	0.0	0.0	0.0
GRAND TOTAL				11.6	41,608	108,217

[a]Low estimate is calculated with RUSLE variable K= 0.0236, R= 170. Road Gullies are 18 times WEPP estimates.
[b]High estimate is calculated with RUSLE variables K=0.048, R=338. Road Gullies are 46 times WEPP estimates.

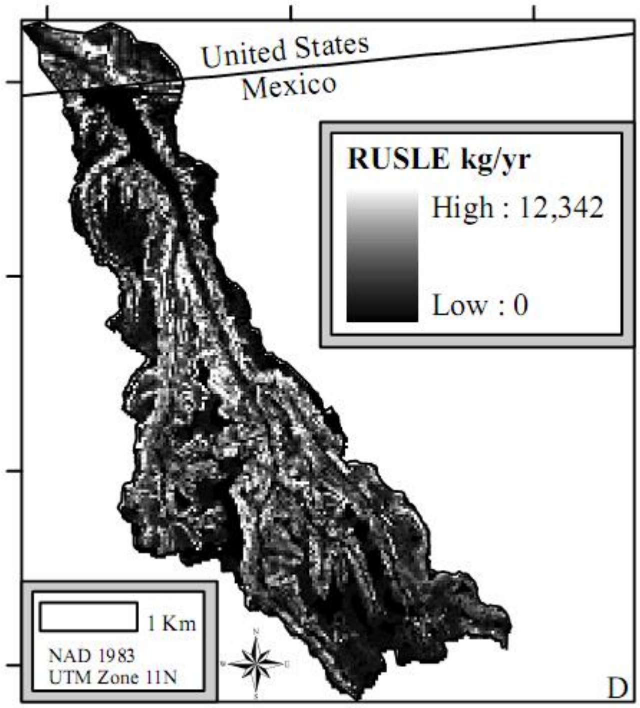

Figure 8. Sediment Production Potential in Los Laureles Canyon, in kg per year in each 30m cell

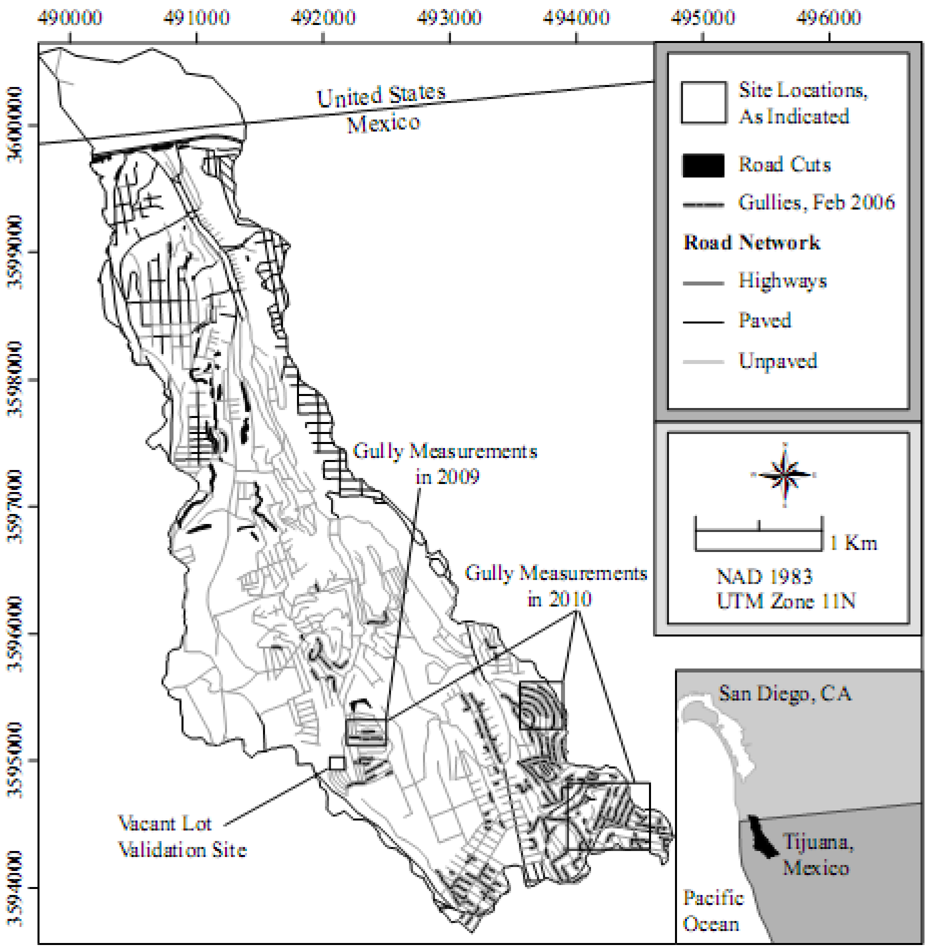

Figure 9. Road Network in Los Laureles Canyon

Figure 10. Gully on an Unpaved Road in Los Laureles Canyon

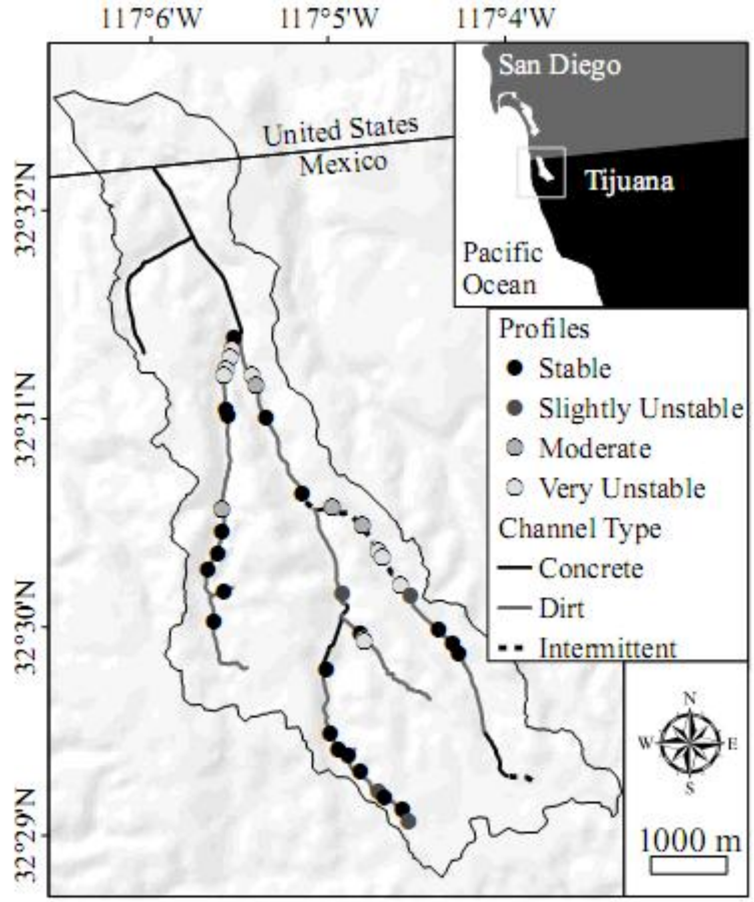

Figure 11. Locations of Channel Survey and Channel Condition.

APPENDIX B

DESCRIPTION OF THE SEDIMENT MODELS AND FIELD TECHNIQUES

Sheetwash and Rilling on Urban Surfaces: Revised Universal Soil Loss Equation

The sediment production potential (SPP) from sheetwash and rilling was calculated for each 30 m grid cell using the Revised Universal Soil Loss Equation (RUSLE) (Renard & Ferreira 1993). The RUSLE and its predecessor (USLE) have been used to model sediment production from watersheds in California (Mertes et al. 1998) and other locations or spatial scales where measurements are not readily available (Nelson and Booth 2002; Winchell, et al. 2008) including construction sites and urban areas (Toy, et al. 1999). While other models of sediment production are available that have more sophisticated process description, such as the Water Erosion Prediction Project (WEPP) (Laflen, et al. 1991), more complex models require significantly more data than was available for Tijuana. Use of a model with more complexity than warranted by available data introduces significant problems with parameter uncertainty and resulting prediction uncertainty (Van Rompaey and Govers 2002). General field observations, which were used to justify certain model assumptions as noted below, were made during several trips to the central and western parts of Tijuana from October 2008 to March 2010.

The RUSLE estimates soil production potential (SPP) from sheetwash and rill erosion as the product of a rainfall erosivity factor (R), a soil erodibility factor (K), a length-slope factor (LS), cover factor (C) and a practice factor (P). The value of R (~15 hundreds of foot-ton inch acre-1 hour-1 year-1) was taken from maps in the RUSLE handbook (Renard et al. 1997) and converted to S.I. units (255 MJ mm ha -1 h-1 year-1) using published units conversion factors (Foster, et al. 1981). R correlates closely with annual precipitation (Renschler, et al. 1999) and with landscape attributes like elevation that serve as surrogates for precipitation (Goovaerts 1999). Mean annual precipitation has low spatial variability over long (decadal) time scales and relatively small geographic areas like Tijuana, so R was assumed constant over Tijuana.

Soil erodibility (K) is a function of texture, organic matter, soil structure, permeability, and depth to a non-permeable layer (Wang, et al. 2001), all of which can vary at multiple spatial scales due to both natural factors and human activity. Soils information in Tijuana was limited to a 1:100,000 scale soils map, which classified most of the soils in the study area as clay Vertisols. A gridded map of the K-factor at 30 m resolution was available for southern California (United States Department of Agriculture 2002), which extends to the border immediately adjacent to Tijuana. The value of K was from the dominant soil group immediately adjacent to the border from the USDA map (0.0236 ton h MJ-1 mm-1). Construction commonly removes the surface horizon, so K could change during urbanization if soil properties differ significantly between the surface and subsurface (Balousek et al. 2000). Insufficient data were available to spatially distribute K, so it was set as a constant over the study area.

A vacant lot showing evidence of sheetwash and deep rill erosion was surveyed in order to compare with RUSLE estimates and calibrate the K-factor. The plot was approximately 12 by 192 m (~2300 m2). Remnant patches of vegetation on the sides of the plot defined the pre-disturbance surface. Five transects were drawn perpendicular to the fall line, each 12 m long, and the depth from the original, pre-disturbance surface to the ground surface was measured every 5 cm. Historical aerial photography was used to establish when the plot was cleared, providing the time since the inception of erosion. Similar methods have been used in other urban areas to quantify long-term erosion rates given a pre-disturbance surface (De Meyer et al, 2011).

The vacant lot surveyed produced a total of 20 tons (87 tons ha-1) of sediment since the disturbance of the initial surface in 2003, an average of 3.3 tons year-1(14 tons ha-1 year-1) were produced from 2003–2008. Since the plot did not have an obvious original surface in many of the transects, this value likely underestimates total sediment delivery from the lot. These plot measurements indicated a K-factor of 0.048 ton h MJ-1 mm-1 (using an R value of 338 MJ mm ha-1 h-1 year-1) compared to a maximum of 0.0236 ton h MJ-1 mm-1 for sandy loams reported in the RUSLE manual (Renard, 1997). A K-factor of 0.0236 ton h MJ-1 mm-1 was used in the “low” estimate and 0.048 ton h MJ-1 mm-1 was used in the “high” estimate (Table B1).

The length-slope (LS) factor was calculated using a method designed for grid cells (Moore & Burch 1986):

$$LS_p = \left(\frac{l}{22.13}\right)^{0.4}\left(\frac{\sin\theta}{0.0896}\right)^{1.3} \quad (1)$$

where l is the length of a DEM cell (30 m), and θ is the slope of the land surface in degrees. The value 22.13 is the length of the reference USLE plot in meters, 0.0896 is the sine of the slope of USLE reference plots (9 degrees), and the exponents 0.4 and 1.3 were derived from stream power theory (Moore & Burch 1986). The validity of the LS values has been tested for slopes up to 84% (Renard et al. 1997), which includes all cells in the study area. Equation (1) does not account for the accumulation of runoff and SPP with distance downslope for hillslope lengths longer than 30 m. While flow accumulation can be calculated with a DEM and incorporated into estimates of sediment production (Mertes et al. 1998), slopes in Tijuana were often interrupted by drainage structures or roads, shortening the hillslope length. Determining the hillslope length for such a complex system of hillslopes and drainage is difficult, so Equation (1) was applied uniformly over Tijuana.

The cover factor (C) for cell i was calculated from the VIS fraction maps and C values for each surface type:

$$C_i = \sum_{j=1}^{3} f_{ij} C_j \quad (2)$$

where fij is the fractional cover of surface type j (V, I or S) in cell i, and Cj is the C value for surface type j. Impervious surface was given a C value of 0 and soil was given a value of 1.0. The C value for vegetation (Cv) varies with canopy cover and groundcover (Dunne and Leopold 1978). The Cv parameter was given a value of 0.038 based on field observations (shrub canopy cover 50% and 60% ground cover). In order to test the sensitivity of SPP to uncertainty in Cv, minimum (Cv = 0.011, corresponds to 95–100% cover of grass and shrubs) and maximum (Cv = 0.14 corresponds to 25% canopy cover, 40% ground cover) values were also used. The practice factor (P), which acc+ounts for reductions of sediment delivery from a plot due to management structures like sediment fences or trenches, was assumed to be 1.0 over the study area due to lack of data.

For a given set of model parameters, spatial variations in the modeled SPP could be due to either slope or land cover. In order to control for the effect of slope, a pre-urban SPP and a disturbance ratio (DR) were calculated for each census tract. The DR was calculated as the SPP under current land cover divided by SPP under pre-urban land cover conditions. Pre-urban land cover conditions were taken as the VIS averages over an undisturbed area of chaparral south of Tijuana. The DR controls for the effect of slope and isolates the effect of land cover on sediment production potential.

The RUSLE models sheetwash and rilling from a given DEM cell. It does not model deposition and storage of sediment on a hillslope, the delivery of sediment to a stream channel, or storage and routing through the drainage network and floodplains (Mertes, et al. 1998; Trimble and Crosson 2000). It also does not include landslides, gullies, or channel erosion, all of which have been observed in Tijuana. There was also significant uncertainty in the model parameters, in particular the values of K and Cj which were assumed constant over the study area due to lack of data. Given these limitations, the goal of using the RUSLE was to quantify the spatial pattern in SPP from small hillslope elements (30 m). The resulting values of SPP should be interpreted as indices of potential erosion by sheetwash and rills from small (~30 m) hillslopes.

Sheetwash and Rilling on Rroads: WEPP:Road

Erosion from sheetwash and rilling on road surfaces (Srs) was estimated using the Water Erosion Prediction Project module for roads (WEPP:Road) (U.S. Forest Service 1999). The predictors included climate, road gradient, road length, road width, soil type, percent of rocks in the soil, ditch type, traffic level, number of years in simulation, and fill and buffer attributes. Climate variables included monthly average precipitation, monthly average maximum daily temperature, monthly average minimum daily temperature, and the annual number of wet days (U.S. Forest Service 1999). A meteorological station in Tijuana provided monthly precipitation and average temperature records for an 18 year period (1972–1989). The average maximum and minimum temperatures were taken from a meteorological station in San Diego with a similar climate to the Tijuana station.

Road length, width, and surface condition (paved or unpaved) were determined from visual interpretation of high-resolution satellite imagery from June 25, 2008. The ditch type for the model was designated as "in-slope bare" for all roads based on field visits.

The traffic level was considered high for all roads and the model was run for a thirty-year period.

WEPP:Road has four soil type options. Sandy Loam was chosen since most of the area was classified as sandy-conglomerate by the Los Laureles Canyon diagnostic report, and detailed soil maps describe the soils on the United States side as sandy loam subsoil (PPMUS Laureles 2006). The percent of rocks in the soil was estimated at 20% based on field visits. Some roads surveyed contained significant amounts of cobble. In the model, increasing the rock fraction increases surface runoff and enhances sheetwash erosion, so in areas where cobble fraction was higher than 20%, sediment from sheetwash on unpaved roads may have been underestimated. The data was input into the batch WEPP:Road web page as a look up table (http://forest.moscowfsl.wsu.edu/fswepp/, accessed August 20, 2010).

Gullies

Gullies were observed on vacant lots, road cuts, and unpaved roads during field visits to Los Laureles watershed between 2008 and 2010. Large gullies up to 2.5 meters deep and 3 –5 meters wide formed on unpaved roads during the rainy season from November to March in both the 2008–2009 and 2009–2010 water years (October to September). In order to estimate the quantity of sediment produced from gully formation, field measurements were taken at select locations in the spring of 2009 and 2010 (February-March). Road gullies for the entire watershed were also mapped using high-resolution imagery from February 27, 2006, and June 25, 2008. In the field, cross sections were taken starting at the beginning of the gully and every 5 to 60 m downslope depending on how rapidly the cross section changed with distance. The substrate of the road was noted, as significant differences in gully size was noted between roads on conglomerate (gravelly loam) and those on sand. A total of 294 cross-sections on 34 roads provided quantitative estimates of road sediment production. These measurements were used to calculate the cross-sectional area and volume of the gullies. The mass of the eroded material was calculated assuming a bulk density of 1.67 Mg m^{-3} (Meek, et al., 1992). The gullies formed yearly and were filled in each spring after the rainy season, according to both local residents and repeat field visits. Some roads, in particular those with high traffic, were re-graded after nearly every storm. In order to provide a conservative estimate of gully sediment production, we assumed that all roads were re-graded only once per year.

The watershed-scale sediment production from gully formation on roads was estimated by calculating the ratio of the measured sediment production from gullies on roads (S_{rg}) to the WEPP:Road estimates of sheetwash and rill erosion on roads (S_{rs}) for each road segment that had gully measurements. Due to the large difference in gully formation by substrate type, a separate ratio was calculated for roads on sand and those on gravel-cobble conglomerate. The S_{rg} was then calculated for all road segments in the watershed using WEPP:Road, and S_g determined as the product of the mean S_g:S_{rs} and the modeled S_{rs} for that segment. While the map of substrate type could be used to assign a different S_g:S_{rs} ratio to each road segment, field surveys suggested that the sand-silt unit, which produced large gullies, was significantly under- represented in the map. In addition, the substrates differed only in the relative mix of sand or silt to gravel and cobble, and sharp boundaries were not observed in the field. Due to the uncertainty in the location and abundance of sand and gravel-cobble substrates, a range of S_g values were calculated using the lowest and highest S_g:S_{rs} ratio observed for each substrate type, applied to all road segments in the watershed.

Road cut location and size were mapped using high resolution imagery from June 2008. Road cuts were relatively uncommon: 8 km of roads had cuts out of 158 km of roads in the watershed, as most roads were graded on the native slope. Due to the relatively low frequency of road cuts, estimates of sediment production from road cuts were a fixed percentage of the sediment production from road surfaces. In similar studies done on St. John Island (Ramos-Scharrón and MacDonald 2007), road cuts were assumed to produce about 10% of the total road sediment. This was used because of the similar road design in Tijuana and St. John Island.

Channel Erosion

Field visits and visual interpretation of satellite imagery were used to map stream channels, the channel material (concrete or sediment), channel condition, and channel morphology. The volume of the bankfull channel was quantified by taking cross-sections at 38 locations on the four main channels in the watershed (Figure 6). A qualitative survey of the channel condition included the material in the bed and on the banks. Local residents indicated water levels during bankfull discharge, the stability of the banks, and locations where the channel was filled in annually.

The amount of sediment generated by channel erosion is commonly measured using sequential cross sections (Trimble 1997). Sequential measurements of channel morphology were not available, so an upper bound estimate of channel sediment production assumed all non-concrete channels formed and was filled in each year. Field observations and interviews with residents suggested that channels were fairly stable, so this was used as the maximum contribution possible from the stream channel. Migrating channels may also produce sediment over an annual cycle while maintaining the same morphology, but the channels in Los Laureles Canyon did not show recent evidence of migration.

A lower-bound estimate of channel erosion assigned different erosion rates to channels by level of geomorphic stability. Each channel reach was classified as stable, slightly unstable, moderately unstable, or extremely unstable based on signs of recent erosion on the bed and banks. Each class was given an erosion ratio, calculated as the amount of erosion expected from the reach divided by the total volume of the channel. Concrete channels were assumed to have a ratio of zero. Extremely unstable channels, which had minimal vegetation and showed evidence of bank erosion, were given a ratio of one since many were re-filled and washed out annually. Stable channels were typically vegetated and showed no evidence of bank erosion. Stable, slightly unstable, and moderately unstable channels were given ratios of 0.1, 0.25, and 0.5 respectively based on field observations and interviews with local residents. While approximate, the calculations provide a range of the possible contribution of stream channel erosion to the overall sediment budget.

Storage of sediment in the channel and on the floodplain was limited due to channelization along many sections of the mainstem, particularly in the more downstream reaches where deposition might be expected. Small patches of sediment accumulated in the concrete channel of the lower portion of the watershed, but the quantity of sediment was small relative to the annual budget.

Table B1. RUSLE Parameters Used in the Sediment Budget

Parameter	Low	High		Units	Source
R	170	338		MJ mm ha^{-1} h^{-1} $year^{-1}$	Renard, et al. 1997
K	0.0236	0.048		ton h MJ^{-1} mm^{-1}	Renard ,et al. 1997 (low) and field measurements (high)
LS[a]	0-12	0-12		unitless	Moore and Burch, 1986
	Impervious	Vegetation	Soil		
CP[a]	0	0.038	1	unitless	Dunne and Lepold, 1978

[a] refers to a variation over space, not multiple runs

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APPENDIX C

Sediment Volume Estimates in Los Laureles Canyon Sediment Traps
Shannon Webber and Dr. Trent Biggs

Abstract

The goal of this study was to estimate the amount of sediment that has filled the Goat Canyon sediment traps after the 2008-2009 winter storm season. This was accomplished by performing GIS analysis with "before" and "after" topographic surveys of the sediment traps.

Approximately 66.7 thousand metric tons of sediment accumulated in the trap system (two traps and diversion structure) in a single year (October 2008 to April 2009). This estimate compared well with the annual sediment accumulation measured from topographic surveys of the estuary over 1992-1998 (68.9 tons) but is significantly higher than estimated loads from 1986-1992 (3,455 tons). The difference over the three time periods may be due to a combination of climate and land use.

Methods

Data Collection

Topographic differencing was used to quantify the amount of sediment that accumulated in the Goat Canyon sediment traps in the winter of 2008-2009. The traps receive sediment from Goat Canyon (Figure C1, Figure C2). The trap system consists of a south trap, north trap, and a diversion structure (Figure C3). Coastal Frontiers conducted two topographic surveys of the Goat Canyon sediment traps in October and November 2008. The sediment traps were cleaned out as part of the Tijuana Estuary Sediment Fate and Transport Study. The October survey took place prior to sediment removal and November survey took place along the base of the traps after the sediment was cleaned out. The post-removal survey was used as the base topographic layer for this study.

For survey control Coastal Frontiers established their own reference marks on the outlet weir, intermediate weir, and diversion structure (Figure C3). A GPS receiver was used to determine the horizontal reference and leveling techniques from a USACE (US Army Core of Engineers) monument was used to determine the elevation. U.S. Coast Guard beacons were used to transmit differential corrections in real-time to improve accuracy (Scott, 2008). The final RMS horizontal accuracy is 3.1 feet and vertical accuracy is ± 0.1 feet.

In April 2009 the sediment traps were surveyed using a Trimble 4800 Real-time Kinematic Survey Grade GPS. The same reference marks Coastal Frontiers established in October were used in order to align the April survey with the Coastal Frontiers survey. Measurements were taken every ten feet. The data was then downloaded to Trimble Geomatics Office software program and converted to a shapefile to be used in ArcGIS 9.3.

To find more reference points were located using the National Geodetic Survey (ngs.noaa.gov). A search radius of 10 miles was used and the stability was at least C or better. If there were a lot of options, points were selected that had a 1 or 2 under the “V” column and a stability of A or B. Besides the X,Y, and Z coordinates and datum, the attribute table of the resulting shapefile linked to the datasheet and the PID (point ID) of each point. The datasheet gives a physical description of the reference point and the last time it was checked by a government agency. However, it was easier to locate these reference points by going to www.geochaching.com. (“find a benchmark”). Information provided when searching by PID includes latitude, longitude, and site photographs.

GIS Analysis

All the analysis was performed in ArcMap in ArcGIS 9.3. The coordinate system used for all data was NAD83State Plane CA Zone 6 in units of feet.

Since the goal was to calculate the volume of sediment in the base of the traps, three polygons were digitized to specify the north trap, south trap, and diversion structure as a mask for the analysis. These three perimeters represent the target area of changes in sediment volume (Figure C3 and C4). After these areas were established only survey points within these areas were manually selected to create three new point shapefiles for both the November and April surveys (Fig C4).

Two methods were used to calculate the volumetric difference between the two survey dates: TIN differencing and raster differencing. Six Triangulated Irregular Networks (TIN) layers were created based on the elevation field in each of the 6 survey shapefiles. The TIN displayed nine equal intervals classes ranging from 18 ft above mean sea level (asl) in the north trap to 50 ft asl in the diversion structure for the November 2008 survey. The April 2009 survey TIN ranged from 26 feet asl in the north trap to 53 feet asl in the diversion structure.

TIN differencing created a shapefile with 3 classes representing areas that either fell above, below, or at the same height as the second surface. The corresponding areas and volumes for each of these three classes are listed in the attribute table of the outcome shapefile. The resulting TIN difference polygon is made up of only areas that occur above the November 2008 TIN. Any negative values fell along the edge or outside the calculation area.

The volumetric difference was also calculated using raster layers. Each tin was converted to a raster. The output cell size was manually set to 5 feet.

The two rasters for each of the three traps were subtracted to calculate the difference in height for each cell. Each cell in the newly created raster represents the elevation differences each of the surveys and spans the extent of the smallest area of the input two rasters (Figure C5).

Accuracy assessment and TIN correction

The accuracy of the survey was assessed using areas with no sediment accumulation (concrete and roads) where the height difference should be zero, and using the posts in the sediment traps that indicate the depth of sediment. In order to arrive at a "best" value, the TIN from April 2009 was corrected by the mean error between the post reading and the uncorrected TIN difference.

Results

The total volume from the uncorrected TIN difference and raster subtraction was 38.8 ac-ft and 38.7 ac-ft, respectively (Table C1). The north and south trap's TIN difference extent covered over 95% of the sediment trap boundary. The raster subtraction calculated a total volume very similar to the TIN difference volume (Table C1). The similarities can be attributed to the raster creation from the TIN. This information is important to note for future studies that may require more complicated raster math analysis that cannot be performed with TINs.

The accuracy assessment using both the posts (Table C2) and concrete areas (Table C3) suggested that the April 2009 survey TIN be corrected by 1.8 feet for the southern trap, and by -0.6 feet for the northern trap (Table C2). Approximately 80% of the points showed the April survey to be approximately 2 feet higher than the November survey. The remaining 20% were within 0.5 ft (Table C4).

Using the corrected April TIN gives a total amount of sediment at 66.7 thousand metric tons, compared to 79.1 thousand metric tons for the uncorrected TIN. There is some uncertainty around these values, but they provide a reasonable range for the quantity of sediment in the traps as of April 2009.

This estimate was compared with previous estimates of sediment yield from Goat Canyon in a report by Phil Williams and Associates (DeTemple, 1999). Sediment yield from Goat Canyon was quantified based on 1- foot contour maps digitized in 1986, 1992, and 1998. The calculation included the entire alluvial fan extending out of Goat Canyon (Figure C6) since their study was prior to construction and installation of the sediment traps (built in 2005). The annual average sediment yield from Goat Canyon between 1986 and 1992 was 3,466 tons and between 1992 and 1998 the yield was 68.9 thousand tons (Table C4). The drastic differences could be explained by the amount and intensity of storms that occurred during these two different time periods (DeTemple, 1999).

The number of tons calculated over one storm season from 2008-2009 was comparable to the PWA average annual sediment yield between 1992 and 1998. The average annual rainfall between 1992 and 1998 was 12.8 inches (DeTemple, 1999) and the total rainfall from November 2008 to April 2009 was 8.1 inches. Although this was an overall drier year compared to the average of previous years in San Diego, two to three intense storms did occur. In fact, a storm in mid-December caused the Tijuana estuary to flood so rapidly and severely that local ranchers had to evacuate all their horses and several residents in Tijuana were evacuated due to mudslides (Krier, 2008).

No reports were available on the effectiveness of the sediment traps, but they do capture a large amount of sediment that would otherwise be deposited in the estuary. This effectiveness can be seen based on the tons calculated by PWA in the area outside the sediment traps (Figure C6). If an average stormy season can yield 70,000 tons prior to construction of the sediment traps, the surveys and analysis in this paper shows that these traps can then hold at least 70,000 tons. The next step in determining a more accurate estimate of the volumes of sediment coming out of Goat Canyon would be researching the amount of suspended sediment leaving the sediment traps. The methodology used in this paper is sufficient for estimating sediment volume changes over a given area; however more studies are needed to determine the fate of the sediment after one or several storm seasons.

Table C3. Volume and mass estimates from A. TIN difference B. raster subtraction and C. Corrected TIN difference based on sediment posts. "C" should be viewed as the best estimate of sediment in the trap system. Mass was calculated using a bulk density of 1.5 g/cm^3.			
A. Maximum Estimate: TIN Difference			
	Volume (thousand ft^3)	Volume (acre-feet)	Mass (thousand metric tons)
Diversion Structure	351	8.1	16.4
South Trap	666	15.3	31.2
North Trap	673	15.5	31.5
Total		**38.8**	**79.1**
B. Maximum Estimate: Raster Subtraction			
Diversion Structure	350	8.0	16.4
South Trap	662	15.2	31.0
North Trap	673	15.5	31.5
Total	1,685	**38.7**	**78.9**
C. Corrected TIN differencing based on post readings and QA points			
Diversion Structure (no posts available)	350	8.0	16.4
South Trap (1.8 feet correction)	327	7.5	15.3
North Trap (0.5 foot correction	749	17.2	35.1
Total (BEST ESTIMATE)	1,426	**32.7**	**66.7**

Table C2. Sediment trap post readings compared to the elevation difference from survey points.			
	Depth of sediment (ft), April 2009	Depth, DEM differencing (ft)	Error (ft)
South Trap 1	**4.2**	**-**	**-**
South Trap 2	**1.8**	**3.6**	**+1.8**
South Trap 3	**2.5**	**4.3**	**+1.8**
North Trap 1	**3**	**2**	**-1.0**
North Trap 2	**4.5**	**4.1**	**-0.4**

Table C3. Twenty QA points selected from cement or roads along the border of the sediment traps.			
	SWIA elevation Nov 08 (ft)	SDSU elevation Apr 09 (ft)	Error (ft)
A	32.2	34.151865	1.951865
B	33.1	35.115074	2.015074
C	33	35.128012	2.128012
D	33	35.083222	2.083222
E	26	27.327538	1.327538
F	26.2	26.179856	-0.020144
G	42	43.961844	1.961844
H	42.2	42.459935	0.259935
I	37.6	39.214265	1.614265
J	35.3	38.266376	2.966376
K	41.6	43.876165	2.276165
L	53.2	55.604453	2.404453
M	55	57.426002	2.426002
N	57.5	59.856004	2.356004
O	58.3	60.53569	2.23569
P	58.8	60.851602	2.051602
Q	59.2	60.184305	0.984305
R	54.7	57.127729	2.427729
S	54.7	57.034704	2.334704
T	53.6	55.727947	2.127947

Table C4. Phillip Williams & Associates average annual sediment yield from a 1999 study.			
Dates	Avg annual sediment yield (ft3)	Avg Annual Sed Yield (ac-ft/yr)	Sed Yield (thousand metric tons/yr)
1986 to 1992	97,200	1.7	**3.5**
1992 to 1998	1,530,000	33.8	**68.9**
2008-2009 survey	-	-	**66.7**

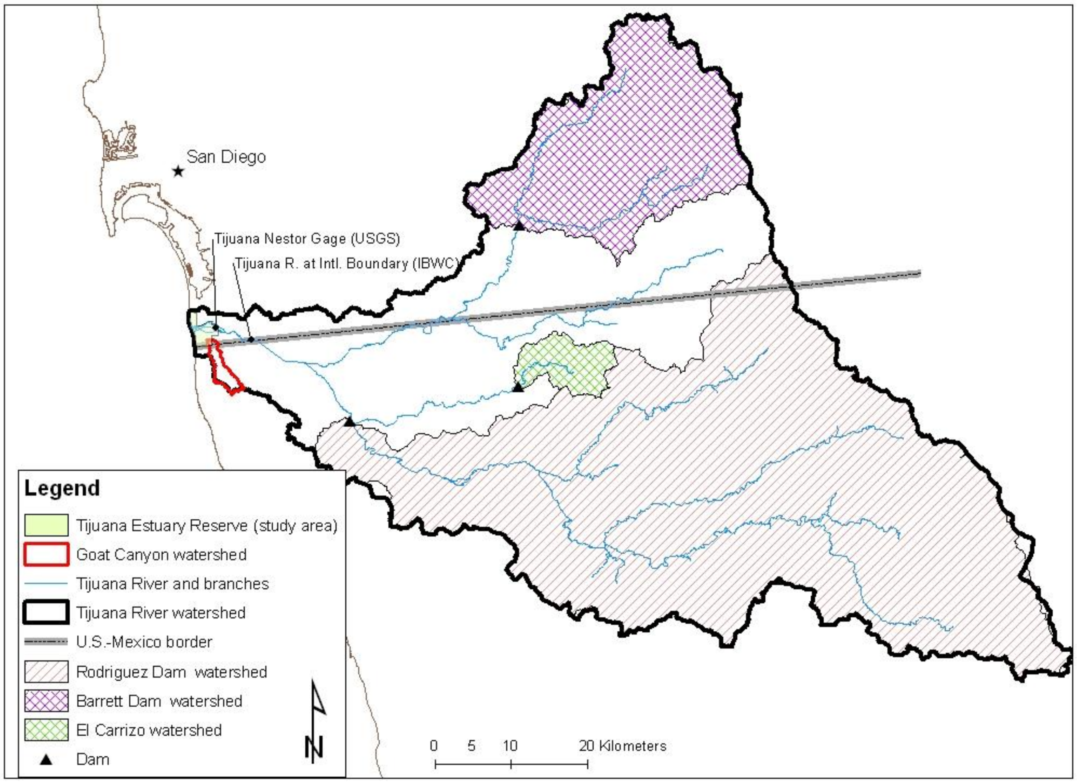

Figure C1. Tijuana River Watershed

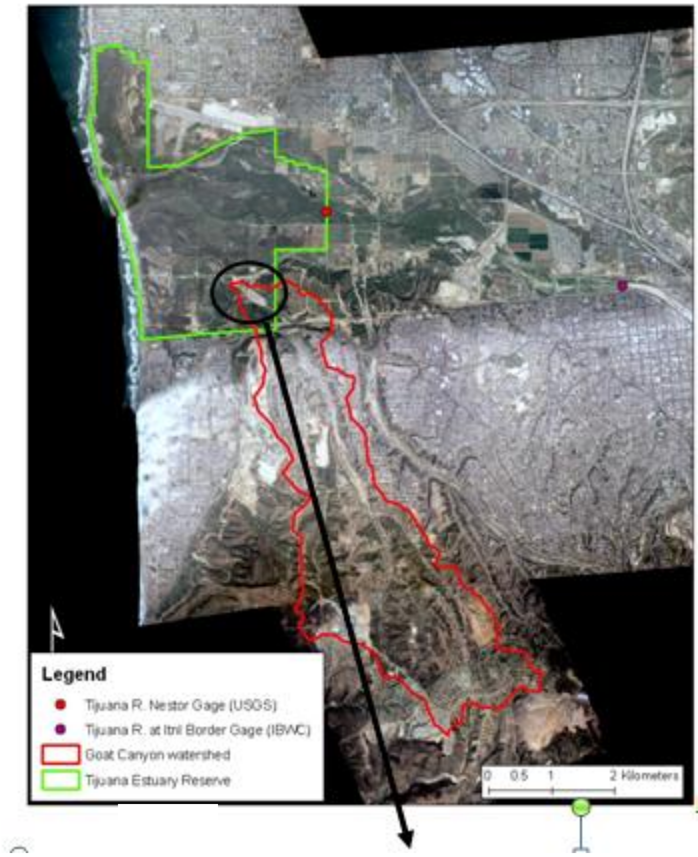

Figure C2. Goat Canyon watershed

Figure C3. Sediment traps at the mouth of Goat Canyon and areas used for analysis (Google Earth).

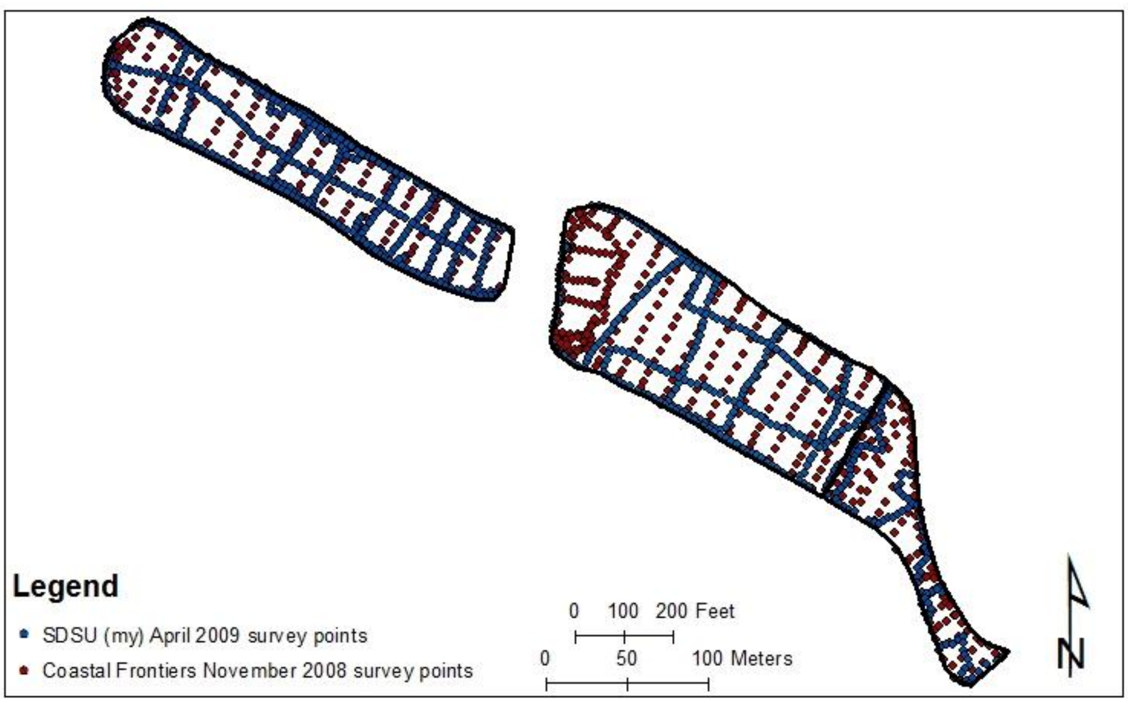

Figure C4. Sediment trap areas and survey points used for analysis.

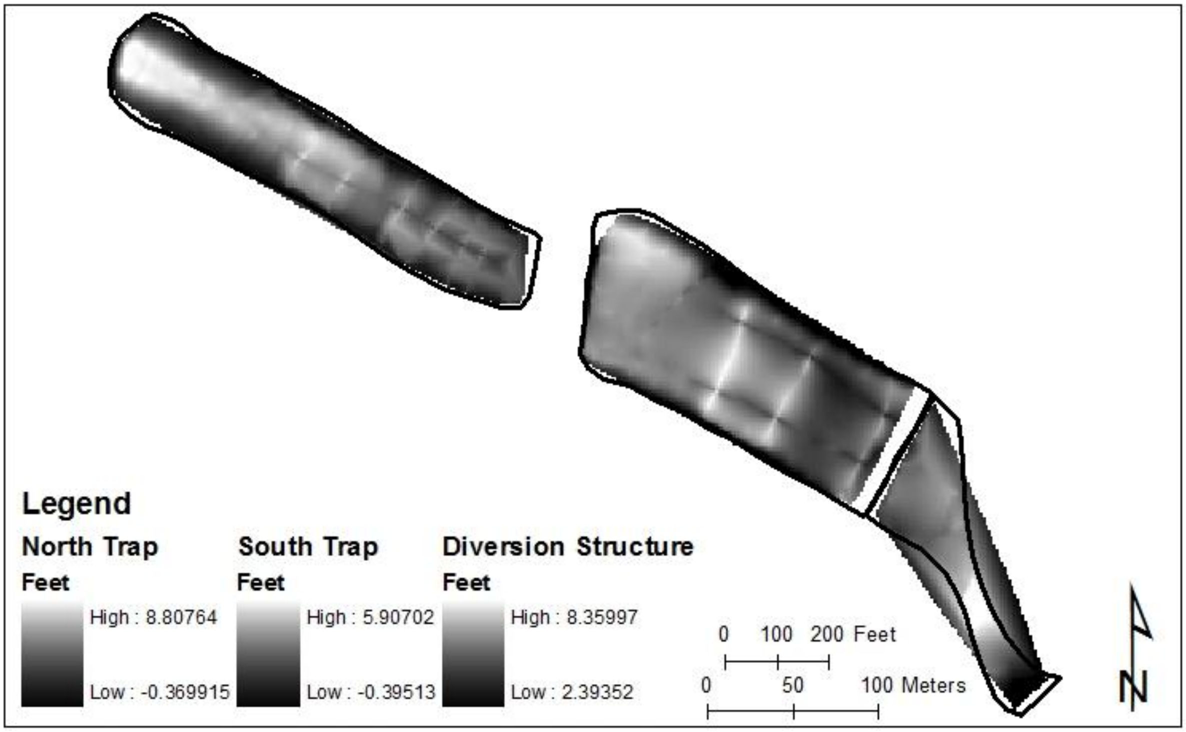

Figure C5. Output from raster subtraction of November 2008 survey from April 2009 survey. Based on the original datum without error correction.

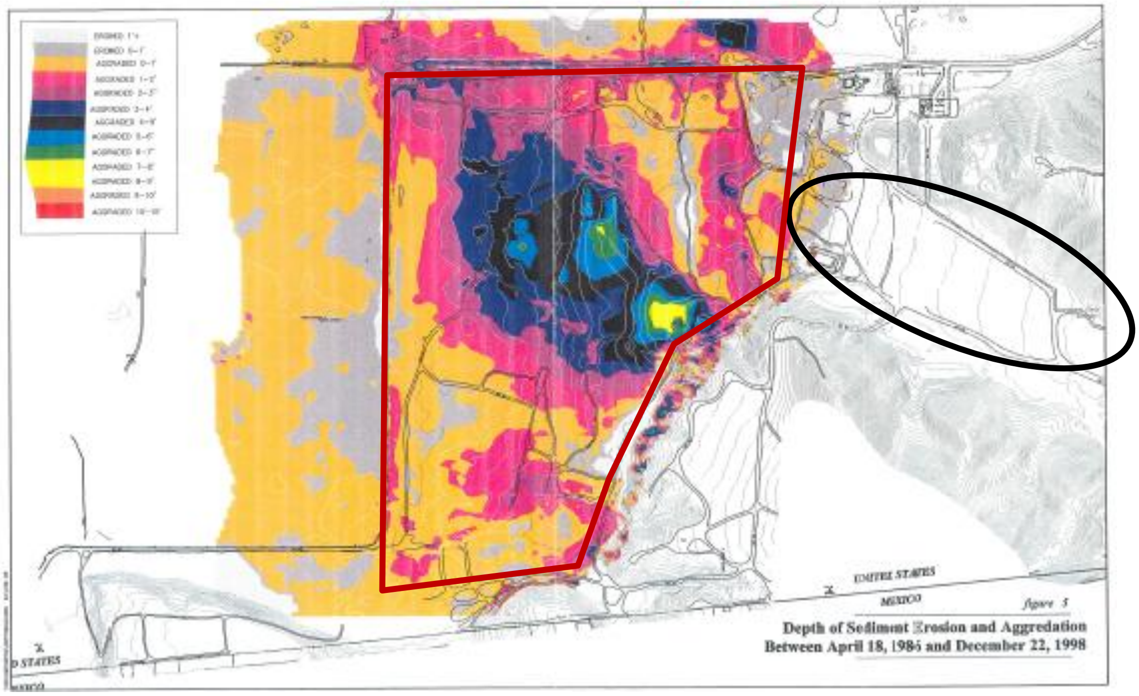

Figure A6. Sediment aggradation map from PWA (1999).

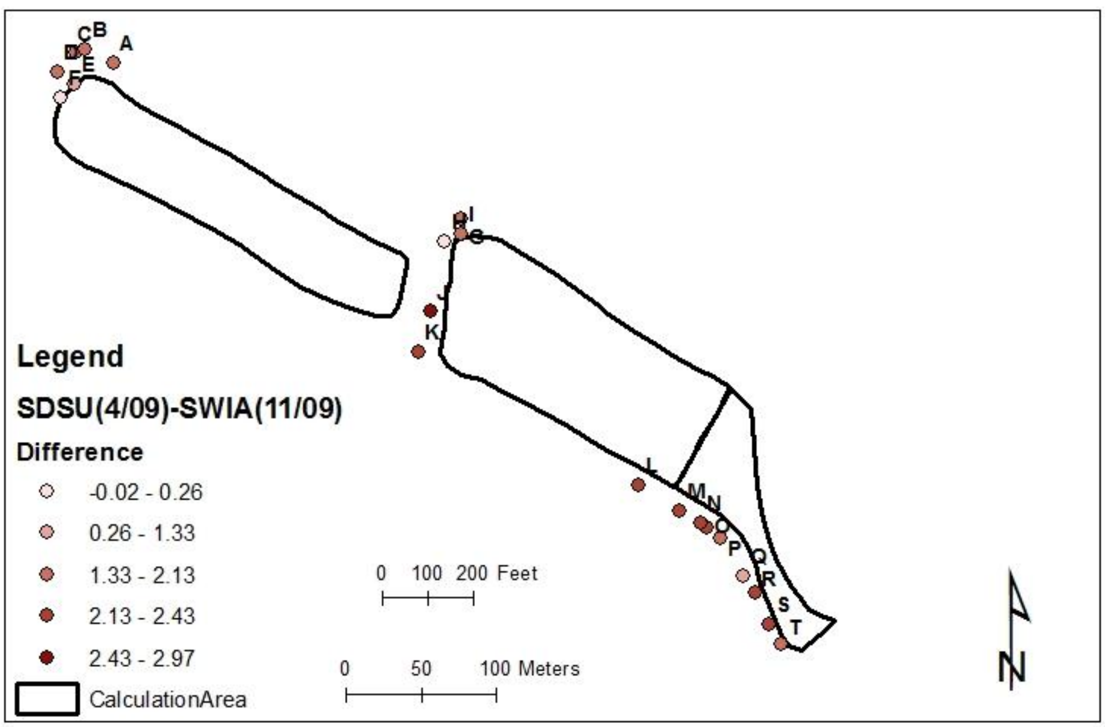

Figure C7. Twenty survey point locations to compare Nov 2008 survey with Apr 2009 survey.

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