DOI: 10.1007/s00267-003-0157-4

Spatial Relations Between Floodplain Environments and Land Use – Land Cover of a Large Lowland Tropical River Valley: Pánuco Basin, México

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ABSTRACT / Large lowland river valleys include a variety of floodplain environments that represent opportunities and constraints for human activities. This study integrates extensive field observations and geomorphic data with analysis of satellite remote sensing data to examine spatial relations between land use/land cover (LULC) and floodplain environments in the lower Pánuco basin of eastern Mexico. The floodplain of the lower Pánuco basin was delineated by combining a digital elevation model with a satellite image of a large flood event. The LULC was classified by combining a hybrid classification strategy with image stratification, applied to 15-m-resolution ASTER data. A geomorphic classification of floodplain environments was performed using a dry-stage image (ASTER data) and a 1993 Landsat image acquired during a large flood event. Accuracy assessment was based on aerial photographs (1:38,000), global positioning satellite ground-truthing, and a Landsat 7ETM^{+} image from 2000, which resulted in an overall accuracy of 82.9% and a KHAT of 79.8% for the LULC classification. The geomorphic classification yielded 83.5% overall accuracy, whereas the KHAT was 81.5%. LULC analysis was performed for the entire floodplain and individually within four valley segments. The analysis indicates that the study area is primarily utilized for grazing and farming. Agriculture is primarily associated with coarse-grained (sandy/silty) natural levee and point bar units close to the river channel, whereas cattle grazing occurs in distal and lower-lying reaches dominated by cohesive fine-grained (clayey) deposits, such as backswamps. In the Pánuco valley, wetlands and lakes occur within backswamp environments, whereas in the Moctezuma segments, wetlands and lakes are associated with relict channels. This study reveals considerable variation in LULC related to spatial differences in floodplain environments and illustrates the importance of considering older anthropogenic influences on the landscape. The research design should be applicable for other large lowland coastal plain river valleys where agriculture is a major component of the floodplain landscape.

Humans utilize floodplains for a multitude of resources and have transformed most of the world's large river valleys into anthropogenic landscapes. In addition to their proximity to riverine resources, floodplains have long represented an ideal setting for agriculture. Prehistoric civilizations settled upon floodplains and were able to maximize agricultural productivity due to knowledge of fundamental differences in the hydrology and stability of floodplain environments (Butzer 1982; Kidder 1996). The transformation of floodplains to highly anthropogenic landscapes accelerated during the 20th century due to an increasing dependence on floodplain agriculture and to engineering modifications for flood management and irrigation (Smith and Winkley 1996; Plate 2002). Throughout the world there are few large river valleys where floodplain environments have not undergone extensive human manipulation.

KEY WORDS: Floodplain geomorphology; Floodplain agriculture; Remote sensing; ASTER; Land use–land cover classification; Moctezuma–Pánuco, Huasteca, Mexico

Published online June 2, 2006.

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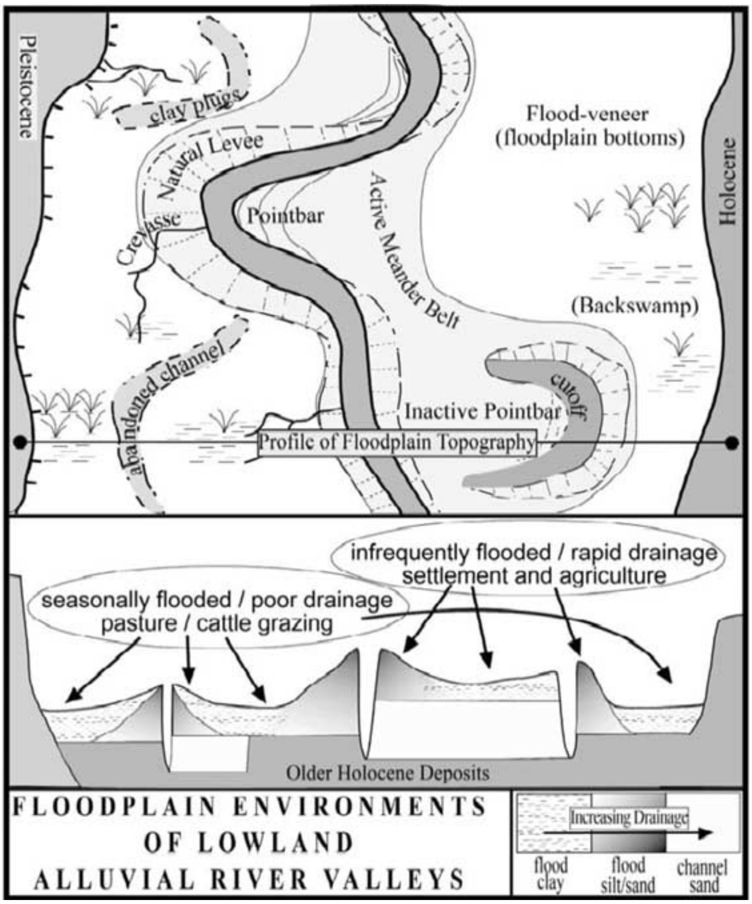

Figure 1. Floodplain environments of a typical large lowland coastal plain river valley. Modified from Hudson and Colditz (2003).

Land-use/land-cover (LULC) analysis of floodplain landscapes requires consideration of geomorphic characteristics of floodplain environments (Walsh and others 2003). Within the context of a floodplain setting, it is important to emphasize that floodplains include a variety of distinct hydrologic surfaces (Wolman and Leopold 1957; Nanson and Croke 1992; Saucier 1994; Mertes and others 1996; Hudson and Colditz 2003) (Figure 1). Although floodplains typically are intensively modified surfaces, the pattern and style of landscape transformation is influenced by differences in floodplain hydrology and sedimentology (Mertes and others 1995; Poole and others 2002). In large coastal plain watersheds, floodplain bottoms, such as backswamps, are composed of clayey deposits that might remain inundated for several months (Table 1). This represents a significant constraint to settlement and agriculture and often relegates these surfaces to being utilized as seasonal pasture and rangeland for cattle. Higher floodplain surfaces, such as natural levees or point bars, are composed of coarser sediments (sand/silt) and rapidly drain after a flood event, making them preferable for settlement or agriculture (Butzer 1982; Kidder 1996; Hudson 2004).

The proportion of individual floodplain environments (Figure 1, Table 1) within a valley segment influences the larger pattern of LULC. In the lower reaches of large watersheds, the dominance of individual floodplain environments varies spatially or longitudinally along the river valley (Mertes and others 1996; Hudson 2002; Hudson and Heitmuller 2003). In large lowland coastal plain river systems, fine-grained (clayey) overbank flood deposits generally increase in thickness downstream, toward the river mouth, where they might form backswamps (Saucier 1994). Spatial changes in floodplain environments along a river valley suggest that there might be concurrent spatial changes in human activities, which has implications to the study of LULC classification.

In many rural settings floodplain surfaces have been significantly modified for agriculture. Thus, floodplain landscapes are formed by a combination of physical and cultural influences that occur over

Table 1. Major floodplain environments having relevance to LULC (see Figure 1)

Major floodplain environments	Sedimentologic/hydrologic characteristics
Flood veneer (backswamps, floodplain bottoms)	Fine-grained (clay); moderately drained where underlain by coarser (sand/silt) channel deposits, poorly drained where characterized as thick backswamps
Point bar	Coarse grained (sandy); well drained
Natural levee	Coarse/medium grained (sandy/silt); well drained near channel, moderately drained where merge with flood-veneer
Relict channel courses (includes abandoned channels, abandoned courses, cutoffs, and clay plugs)	Infilled with clayey deposits; poorly drained in backswamp settings, moderately drained in thin flood-veneer deposits

Source: Modified from Saucier (1994).

varying temporal and spatial scales. Therefore, it is unlikely that the LULC pattern of a large river valley evolved from a single comprehensive plan that takes into account inherent longitudinal changes in floodplain geomorphology, particularly because large river valleys often transcend cultural and political borders. In many instances, modern land uses are superimposed over a floodplain surface that has been altered by older, and even prehistoric, land-use systems (Butzer 1982). In addition to physically modifying the floodplain, such as for drainage, older anthropogenic land-use systems often impart a culturally specific type of land use that persists in contemporary times in spite of political or economic incentives.

This study combines remote sensing and geomorphology to examine spatial relations between floodplain environments and LULC in the lower Pánuco basin of humid tropical eastern Mexico, a region where there has been sparse environmental characterization by researchers or government agencies. The advantages to using remote sensing to examine floodplain landscapes are that it enables large river valleys to be mapped and can be used by agencies for assessment, planning, and developing sound approaches to environmental management. This method is particularly appropriate in developing countries, such as Mexico, which often lack detailed ground-based surveys for rural areas. In addition to being utilized for LULC analysis, remote sensing can be employed for geomorphic mapping at a mesoscale (Avery and Berlin 1989; Walsh and others 1998; Poole and others 2002). We make use of a new data source, the Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) sensor system (Yamaguchi and others 1999; Abrams 2000). ASTER data are appropriate for detailed LULC and geomorphic studies due to high spatial resolution in the visible, near-infrared (15-m), and short-wave infrared (30-m) portions of the electromagnetic spectrum. Although there have been numerous studies of LULC classification within rural settings, because of the subtle topography associated with floodplains few studies have investigated the influence of individual floodplain environments on the pattern of LULC, particularly in tropical environments.

Study Area

The Pánuco basin drains east-central Mexico, which includes the Central Plateau, Sierra Madre Oriental, and the Mexican Gulf Coastal Plain (Figure 2). The basin is located within a seasonally humid tropical climatic regime, with the highest annual precipitation of 2400-mm occurring along the boundary of the Gulf Coastal Plain and Sierra Madre Oriental. The pronounced seasonality (dry winters and wet summers) results in river stage varying ~10-m between winter and summer, which influences groundwater inundation of low-lying floodplain bottomlands. The study area comprises the Moctezuma and Pánuco valleys (Figure 3) within the Mexican Gulf Coastal Plain, which exhibits considerable spatial diversity in floodplain geomorphology (Hudson 2002, 2004; Hudson and Heitmuller 2003). The Rio Moctezuma exits the mountains and flows northerly for 150-km before joining the Rio Tamuín. The Rio Pánuco forms at the confluence of the Moctezuma and Tamuín rivers and flows easterly 185 km before draining into the Gulf of Mexico at Tampico, Tamaulipas (Hudson 2000). Pronounced spatial variability in floodplain geomorphology occurs at the confluence of major tributaries, manifested by differences in river migration rates, valley topography, and floodplain style (Table 2). The active meander belt, defined as the zone of recent meander activity (e.g., Figure 1), increases in width downstream but occupies a smaller proportion of the overall river valley. River migration rates decline downstream from a high of 10 m/year in the upper Moctezuma segment to 1.5 m/year in the lower Pánuco valley (Table 2). In comparison to the upper study area, the lower Pánuco valley has a fine-grained floodplain with high natural levees (Figure 4).

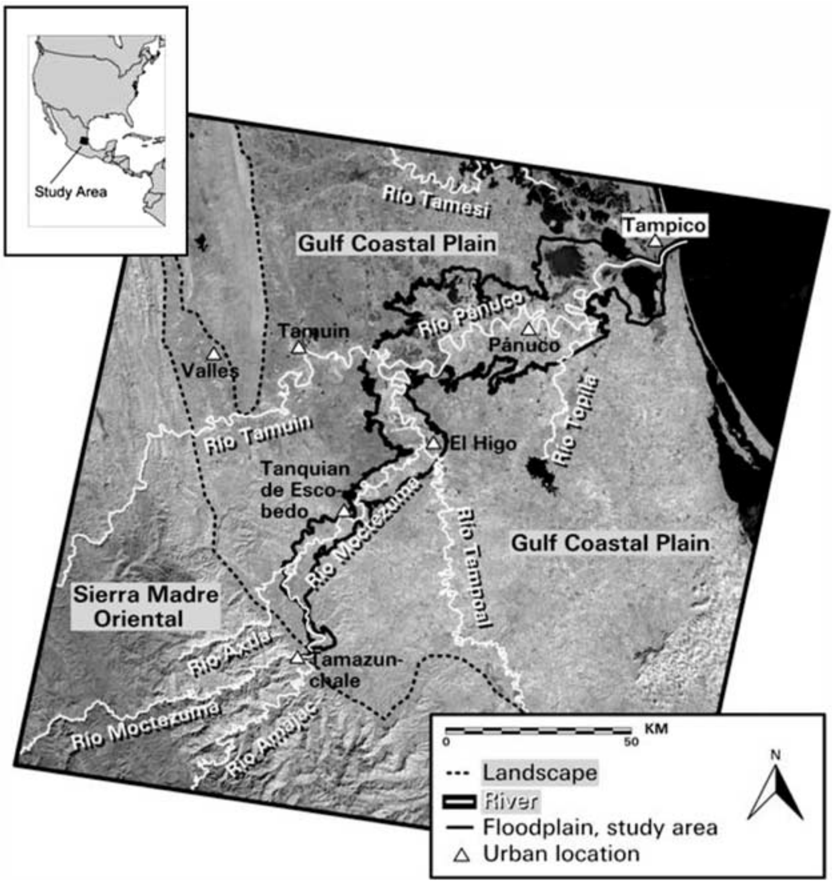

Figure 2. The lower Pánuco basin and study area. Landsat 7ETM^{+} image of December 2000 with band 7 (SWIR2, 2.08–2.35 μm).

The floodplain geomorphology of the lower Pánuco valley contributes to the region's complex environmental history. The Pánuco valley constitutes the core of the Huasteca culture region (Hudson 2004), the northern extent of major prehispanic Mesoamerican society (Ekholm 1944; Coe 2002). Because of the better drainage and lower frequency of flood inundation, prehistoric Huastec settled and farmed on the broad natural levees along the Rio Pánuco (Sanders 1978; Aguilar-Robledo 2003a), and Sanders (1978) suggested that lakes in the lower Pánuco served as an important fishery. The Huastec dispersed upon Spanish arrival, and by the mid-1500s, the region was well established for stock raising, with cattle ranching being the regional hallmark (Aguilar-Robledo 2003b). The Spanish found the extensive grasslands and seasonal wetlands of the lower Pánuco very similar to the Las Marismas (marshes) cattle ranching region within the floodplain environments of southern coastal Spain (Doolittle 1987; Jordan 1989, 1993; Butzer and Butzer 1995; Aguilar-Robledo 2003a).

Data and Methods

Study Area Definition

A hydrologic and geomorphic approach was employed to delineate the study area. Remote sensing data of a large hurricane-generated flood event was combined with a digital elevation model (DEM) of the river valley. The flood scene was a Landsat 5TM image acquired on October 4, 1993 (Hudson and Colditz 2003), several days after the peak of the largest flood event to occur since 1955. The DEM was derived from ERS-SAR tandem data, acquired in December 1995, and has a 28.5-m horizontal and 2.5-m vertical resolution. The flood scene was draped onto the DEM and used to delineate the floodplain boundaries. The DEM was subdivided into 44 valley cross sections oriented tangent to the valley axis. At each cross section, the contact between the floodplain surface and valley margin (Pleistocene or Tertiary surface) was distinguished. Thus, this procedure delineated the floodplain surface, and the boundaries were validated with

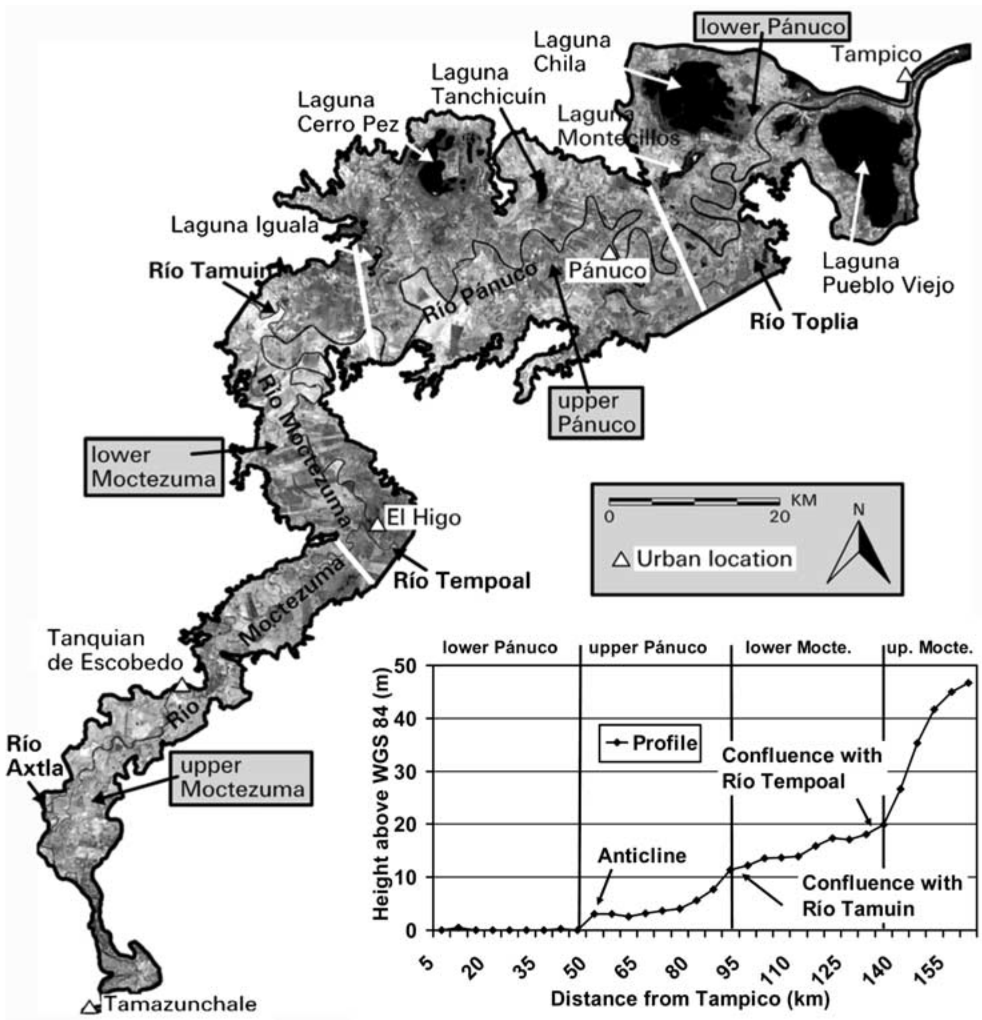

Figure 3. Floodplain of the lower Pánuco basin and valley segments. ASTER image mosaic shown with band 3 (NIR, 0.76–0.86 μm). Inset: Longitudinal valley profile derived from ERS-SAR DEM. Location of hinge points in valley profile correspond with changes in floodplain type described in Table 2.

field mapping that had occurred over several field seasons between 1999 and 2002.

Of central importance to this study are spatial differences in floodplain environments. For this reason, the river valley was segmented where major changes in floodplain geomorphology occur. To segment the river valley, a longitudinal valley profile was created by sampling the floodplain elevation from the DEM at 5-km increments along the valley axis. To ensure that the same geomorphic surface was utilized, the elevation data were obtained by averaging the DEM values of pixels at the channel bank. The valley profile revealed four major valley segments (Figure 3, inset). The boundaries between valley segments occur where there are major changes in the floodplain geomorphology (Table 2), which coincide with changes in valley slope. As expected, changes in valley slope (Figure 3, inset) occur at the location of large tributary confluences along the Moctezuma and a structural control along the Pánuco (e.g., Schumm and others 2000; Bridge 2003). The data in Table 2 show that the floodplain geomorphology changes markedly across these valley segments, manifested by differences in valley width, floodplain topography, and rates of river migration.

LULC Classification

An ASTER image mosaic was the primary dataset utilized for the LULC classification (Figure 3). The ASTER instrument is the ''zoom lens'' of the TERRA satellite platform (Yamaguchi and others 1999; Abrams 2000). Seven images (primarily from March 2002) were obtained from the EOS DATA Gateway. The images

Table 2. Characteristics of floodplain geomorphology of Moctezuma – Pánuco valley

Valley segments	W_v (km)[a]	W_{mb} (km)[b]	Accommodation index (%): W_v/W_{mb}	Migration rates (m/year)	Floodplain type[c]
Upper Moctezuma: Tamazunchale – Rio Tempoál	3.9	3.2	83	10.0	A
Lower Moctezuma: Rio Tempoál – Rio Tamuín	13.3	6.3	47	3.8	B
Upper Pánuco: Rio Tamuín – C. Pánuco	15	8.4	56	4	B–C
Lower Pánuco: C. Pánuco – Rio Tamesí	17.2	5.5	32	1.5	C

[a] W_v = valley width (from Hudson 2002).
[b] W_{mb} = width of meander belt (from Hudson 2004).
[c] Floodplain type: A = coarse floodplain deposits, lateral accretion with active point bar and scroll deposits, limited overbank deposition; B = sandy to cohesive floodplain deposits, paleochannels and oxbow lakes not buried, prominent natural levees, absence of backswamp; C = cohesive floodplain deposits, flood dominated with prominent natural levees and topographically lower backswamp basins, buried paleochannels from older meander belt.

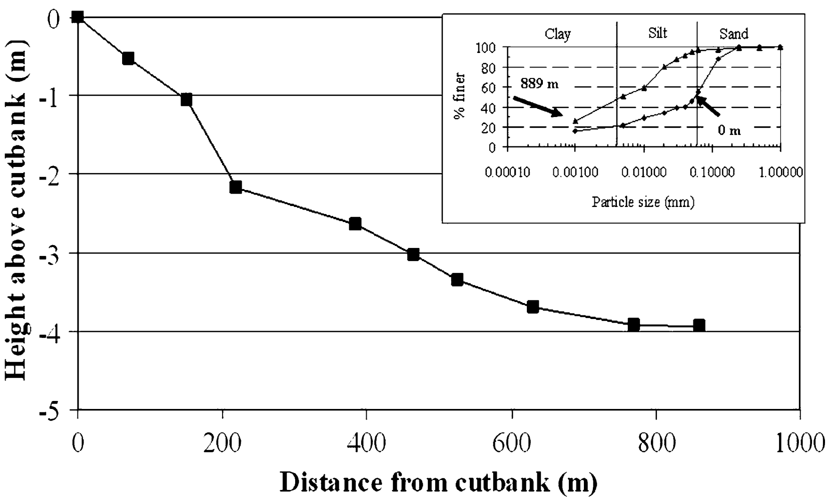

Figure 4. Example of typical natural levee profile, extending from channel cutbank to backswamp environment in the lower Pánuco, downstream of Ciudad Pánuco. Inset: Grain-size curve showing coarser sediments at channel bank (0 m) and fine-grained clayey deposits in backswamp (889 m). Modified from Hudson and Colditz (2003).

were imported to ERDAS IMAGINE and subset to the visible green, red, and near infrared bands (VNIR, with 15-m spatial resolution) and the six short-wave infrared bands (SWIR, with 30-m spatial resolution, resampled to 15-m for computational purposes). Georeferencing was performed using a panchromatic Landsat 7ETM$^+$ master image (15-m spatial resolution), acquired on December 18, 2000. A dark-object subtraction technique (Jensen 1996; Song and others 2001; Tso and Mather 2001) was applied for normalization of atmospheric effects. Finally, the image mosaic was subset to the floodplain surface using the mask derived by the technique described earlier.

The ASTER mosaic was best classified using a hybrid classification method with a stratification technique (Figure 5). The hybrid method for image classification is fairly new and detailed descriptions are provided by Crews-Meyer and others (2004) and Messina and Walsh (2001). The merit of this approach is that it combines the advantages of unsupervised and supervised image classification. Initially, an unsupervised classification (ISODATA algorithm) created 255 spectral clusters (maintaining 8-bit data), using 20 iterations and a convergence threshold (CT) of 0.98. The transform divergence (TD), a statistic for spectral separability, reduced the clusters to 37, utilizing a threshold of 1950. TD is scaled between 0 and 2000, where 2000 means excellent cluster separation. Then, the image was stratified in visually distinctive subregions (e.g., wetlands, urban, and different water surface) to enhance the map accuracy. The 37 clusters were used as statistically derived training data for the Maximum Likelihood Classifier, applied to each stratified subregion. The clusters of the subregions were assigned to classes using an adoption of the Anderson classification scheme (Andersen and others 1976). Clusterbusting (Jensen 1996; Langley and others 2001) was applied to clusters when two or more classes could be assigned using an unsupervised classification with 10 new clusters, 20 iterations, and a CT of 0.98.

Eventually, eight thematic classes were assigned to the statistically derived clusters. River and riparian, a narrow naturally vegetated fringe along the river course (e.g., willows) was extracted during the

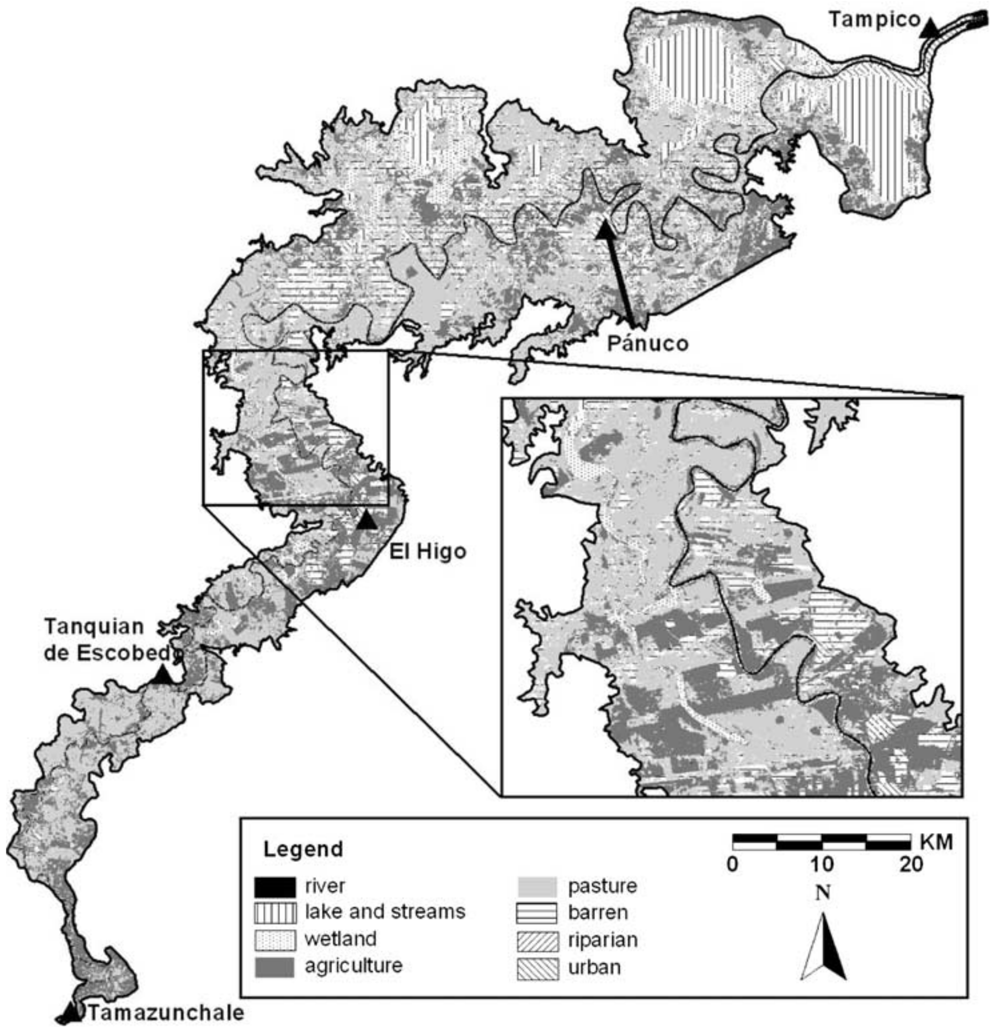

Figure 5. Stratified hybrid LULC classification of the floodplain of the lower Pánuco basin.

stratification approach. Remaining water features and surrounding natural vegetation were assigned to lake and wetland, respectively. Agriculture was defined as dense photosynthetically active vegetation (i.e., a high Normalized Difference Vegetation Index (NDVI) value) and includes sugar cane, papaya, and citrus, whereas pasture was constrained to dried grassland for cattle grazing with a lower NDVI. However, Barren depicted spectral soil signals and indicated burned or fallow plots. Urban areas are frequently difficult to distinguish due to its heterogeneity, but stratification allowed reasonable detection.

Classification of Floodplain Environments and Spatial Relations with LULC

To delineate distinct floodplain environments (e.g., Figure 1), satellite images acquired during the wet and dry season should be utilized (Colditz 2003). The Landsat 5TM image was utilized for wet conditions, whereas dry conditions were depicted with the ASTER mosaic. The flood image revealed subtle variations of relief and was particularly useful for delineating water-filled depressions and dry ridges, whereas the dry-stage image was used to map the extent of "permanent" floodplain water bodies. Image enhancements help to interpret the geomorphic composition and it was found that principal components and the Greenness of the Tasseled Cap transformation provided useful results (Hudson and Colditz 2003). Geomorphic image interpretation using satellite imagery (Figure 6), however, is not a substitute for detailed labor-intensive field mapping. The mapping was verified based on field observations, particle size data from distinct floodplain environments, and topographic data acquired from five field campaigns between 1999 and 2002 (see Hudson 2000, 2002, 2004; Hudson and Heitmuller

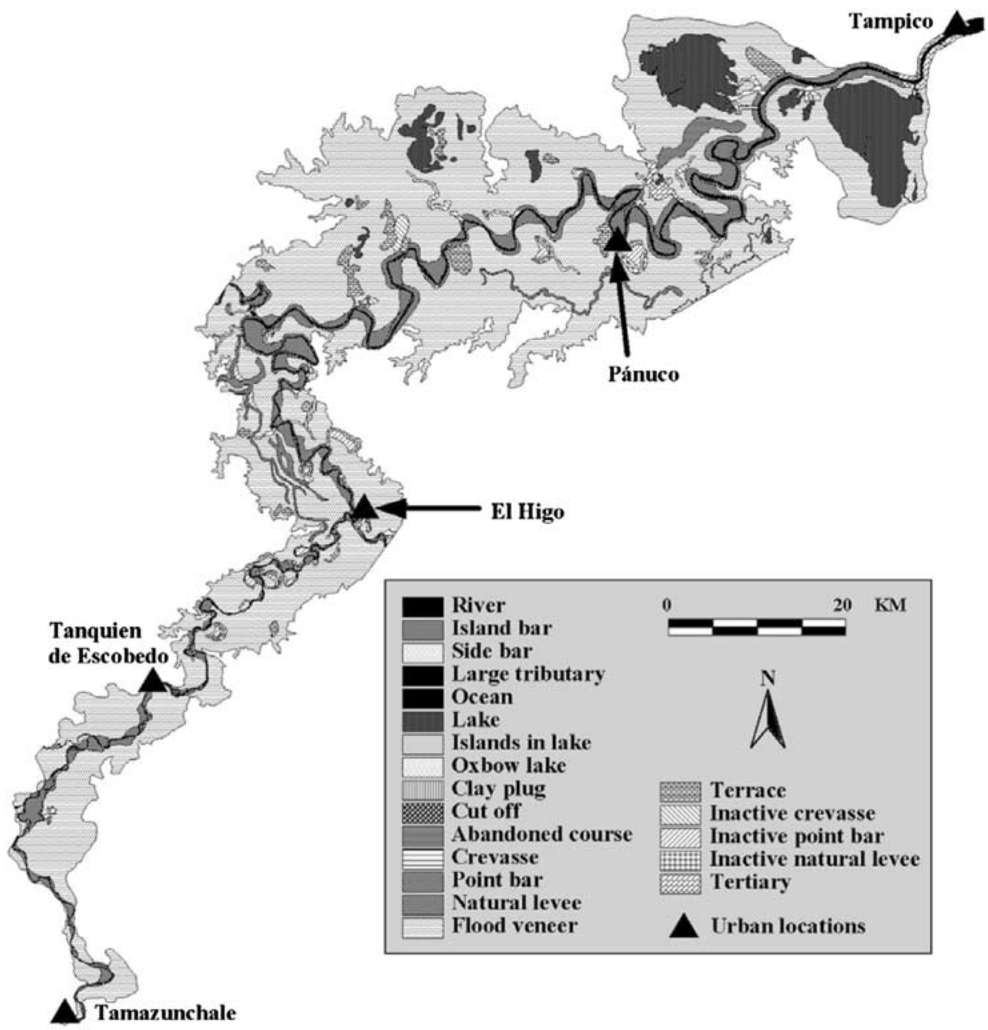

Figure 6. Geomorphic classification of the floodplain of the lower Pánuco basin.

2003). Relationships between LULC and floodplain environments were investigated using geographic information system (GIS) and standard cross-tabulation. The cross-tables were evaluated using statistics for nominal data. Here we employed the contingency coefficient and residuals and proportional area statistics. The residual analysis is based on normally distributed probabilities (Haberman 1973), but only positive probability was considered for interpretation, indicating disproportional spatial co-occurrence. The area proportions provide further normalized indicators for detailed spatial analysis.

Accuracy Assessment

Quantitative accuracy assessment is critical to image classification when a secondary independent dataset is available (Congalton 1991; Congalton and Green 1999; Foody 2002). Numerous sample points were derived from a Landsat 7ETM$^+$ image, aerial photos (1:38,000), and global positioning satellite (GPS) measurements. The LULC classification was tested with 380 samples and the geomorphic classification had 491 test samples. To ensure a minimum of 10 samples for each class, we utilized a random stratified sampling scheme.

The LULC classification has an overall accuracy of 82.9%, with a KHAT of 79.8% (Table 3). The process of quantitatively assessing the accuracy of floodplain geomorphic mapping is similar to LULC assessment. The overall accuracy and the KHAT is high: 83.5% and 81.5%, respectively (Table 3). Minor uncertainty occurs between classes that have large transitional boundaries between floodplain environments, such as between natural levees and flood veneer.

Table 3. Accuracies stratified hybrid LULC classification and geomorphologic mapping

	Overall accuracy	KHAT
Land-cover classification	82.9	79.8
Geomorphological classification	83.5	81.5

Results and Discussion

The results are discussed in several ways. First, the LULC data are presented from the standpoint of its variability within the entire study area, providing a sense of the range of human manipulation and activities that occur throughout the Moctezuma–Pánuco system. Next, correlations between LULC and the floodplain geomorphology are examined. These relations are initially considered for the entire study area, emphasizing the importance of individual geomorphic units to specific types of LULC. This is followed by analysis of the relations between LULC and floodplain geomorphology at the scale of individual valley segments and, in particular, emphasizes the spatial variability in floodplain geomorphology as reviewed earlier in the Study Area section (Table 2).

Overview of Land Use-Land Cover Classification Analysis

The data in Table 4 shows the area of each LULC class as a proportion (%) of the size of the total valley segment. Because the absolute area of each valley segment varies, reporting percentages (%) enable direct comparisons between valley segments, and this is considered a more useful approach for landscape characterization (Oetter and others 2000; Townsend and Walsh 2001).

The data for the entire study area reveal a substantial amount of cattle grazing, as pasture represents 43.4% of the entire floodplain surface (Table 4). Agriculture is the second largest class and represents 24.5% of the floodplain surface, whereas barren represents 11.8% of the floodplam surface. However, because barren represents surfaces that had been burned or tilled shortly before the date of image acquisition, these two classes can be combined, resulting in farmland comprising 36.3% of the floodplain surface. When farming is combined with grazing (pasture), these classes comprise 79.7% of the entire floodplain surface and document that the Moctezuma and Pánuco valleys are extensive anthropogenically modified landscapes. The major classes representing "natural" environments include lakes (8.3%) and wetlands (6.6%). For the entire river valley, urban represent a minor proportion of the floodplain surface.

A closer inspection of LULC variability throughout the valley (Table 4) provides insight into how the LULC classes are related to one another. Because agriculture requires well-drained soils, there is an inverse relationship between lakes and farmland classes (agriculture and barren). Lakes represent a large percentage (26.1%) of the floodplain surface in the lower Pánuco. The larger lakes, Laguna Chila and Laguna Pueblo Viejo (Figure 3), represent an important fishery for the region and serve as habitat for coastal fishes. Lakes represent only 3.4% of the floodplain surface in the upper Pánuco segment and decline to ~1% in the Moctezuma valley segments. Similarly, the lower Pánuco has the largest percentage of wetlands, 12.6%, which usually occur at the margins of shallow lakes (Figure 5). The proportion of wetlands decreases to 7% in the upper Pánuco and to 2.1% and 1.6% for the lower and upper Moctezuma segments, respectively.

Within the floodplain as a whole, the proportion of agriculture is highest in the upper Moctezuma segment, which is intensively utilized for citrus production (primarily oranges). Sugar cane is the dominant form of agriculture in the lower Moctezuma segment and extends across the entire valley due to the absence of backswamps, which would impede agriculture because of poor drainage. Pasture represents 26.1% of the lower Pánuco valley, much lower than other valley segments. Similar to farmland, pasture strongly increases in the upper Pánuco segment, to 49%, and remains at this level for both Moctezuma valley segments (Table 4). This implies that the increase in lake surface within the lower Pánuco is associated with a disproportionate reduction in pasture, in comparison to other LULC classes.

Spatial Relations Between LULC and Floodplain Geomorphology

Study Area Analysis. Because the floodplain geomorphology represents a proxy for soils, hydrology, and topography, a deeper understanding of the floodplain landscape can be obtained by considering spatial relations between LULC and individual geomorphic units (e.g., Figure 1, Table 1).

A first indicator of the correlation between LULC and geomorphic units is Pearson's contingency coefficient (Clark and Hosking 1986). The chi-square test between the observed and estimated occurrences was highly significant for the entire floodplain surface and for each of the individual floodplain segments. The contingency coefficient was between 0.8 and 0.9 for all segments and the entire floodplain, which reveals a strong dependence between datasets. Analysis of residuals can indicate significant disproportional rela-

Table 4. Area proportions (%) of LULC classes for the entire floodplain and the four valley segments, derived from stratified hybrid LULC classification

	Entire floodplain	Lower Pánuco	Upper Pánuco	Lower Moctezuma	Upper Moctezuma
River	2.3	3.1	1.9	1.9	2.5
Lake	8.3	26.1	3.4	0.2	0.0
Wetland	6.6	12.6	7.0	2.1	1.6
Agriculture	24.5	21.0	20.0	27.2	37.3
Barren	11.8	5.7	16.8	17.9	3.4
Pasture	43.4	26.1	49.0	48.4	52.6
Riparian	1.3	1.1	0.8	1.4	2.4
Urban	1.8	4.3	1.1	0.9	0.2

tionships between datasets (Haberman 1973). The analysis focuses solely on positive disproportion shown by unsigned values (i.e., whether there is a statistically strong spatial co-occurrence between LULC and geomorphology). A first approximation of spatial dependence is presented in Table 5. The data reveal a strong coincidence between water surfaces (e.g., LULC classes of lake, oxbows, and water-filled abandoned courses). However, Table 5 also indicates spatial misclassification (e.g., river and riparian), which can be significant when the classes are spatially small. Wetland depicts interesting associations with geomorphic classes (e.g., clay plugs, crevasses, abandoned courses, and flood veneer). This confirms prior assumptions that these low-lying geomorphic units are inundated and swampy. At first appearance, the pattern of humanly modified classes, agriculture, barren, and pasture do not reveal straight forward relations. A closer examination, however, indicates pasture highly corresponds only with floodveneer, whereas both farm classes are highly associated with geomorphic units located closer to the channel (e.g., natural levees, point bars, and other slightly higher units). The urban class shows an association with topographically higher geomorphic surfaces, such as natural levees and terraces. In summary, the statistical analysis of the normally distributed residual probabilities provides insights on the association between LULC and geomorphic units.

Further analysis of associations between LULC and geomorphic classes is based on cross-tabulations expressed in percentages of aerial coverage, with geomorphology as the independent variable (Table 6). The analysis first focuses on the entire floodplain, followed by the floodplain segments. Flood veneer is located beyond the margins of the river channel and is widely covered by pasture (50.6%), but it also contains a substantial amount of farming (27.6% agriculture, 13.3% barren). As a whole, wetlands cover only a small percentage (7.2%) of flood veneer and tend to be located along the valley margins away from the active channel. Agriculture increases markedly near the river channel because of a change in the floodplain geomorphology, principally due to the occurrence of natural levees and point bar deposits. The combination of agriculture and barren (farmland) represents 48.9% of the LULC on point bars and 39.1% on natural levees. This is because these surfaces have well-drained soils composed of coarser fluvial deposits, sands, and silts (Hudson and Heitmuller 2003), and the availability of river water for irrigation.

Somewhat surprising was that relict river channels (clay plugs, oxbows, and abandoned courses) were not predominately classified as wetlands, but, instead, were often utilized for agriculture and grazing (pasture). For the entire river valley, only 26,1% of clay plugs and 29.3% of abandoned courses were classified as wetlands (Table 6). Collectively, grazing (pasture) and farming (agriculture and barren) accounted for over 70% of the land cover associated with clay plugs and over 50% of the land cover associated with abandoned courses. Thus, although relict river courses are frequently depicted as wetland environments (e.g., Saucier 1994; Poole and others 2002; Thoms 2003), they might also be suitable for agriculture. The primary reason for these geomorphic units being utilized for farming is due to the large seasonal fluctuation in river stage in the lower Moctezuma, which varies by as much as 10-m between the dry and wet seasons. During the dry season, which extends from October to May, this results in a large decrease in the height of the water table associated with the floodplain aquifer (e.g., Burt and others 2002) and permits these features to be utilized for agriculture.

Valley Segment Analysis. The results highlighted earlier illustrate clear relationships between the floodplain geomorphology and LULC when the entire study area is analyzed. However, distinct changes in floodplain geomorphology among the four valley segments (Table 2) provides an opportunity to examine local-scale variability in LULC along the river valley (Figure 7), as well as the influence of older anthropogenic influences.

Table 5. Positive significant residuals of contingency coefficient

	River					Lake					Wetland					Agriculture					Pasture					Barren					Riparian					Urban				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
River	X	X	X	X	X																						X				X		X	X	X					
Lake						X	X	X	X	X									X	X										X										
Island bar			X	X												X		X		X											X		X	X	X					
Side bar	X		X	X	X											X		X	X	X											X		X	X	X			X		
Oxbow lake						X		X		X	X				X				X																					
Clay plug										X	X		X	X	X	X		X	X			X																		
Cutoff	X				X											X				X										X	X				X					
Abandoned courses						X	X	X	X		X	X	X	X											X					X										
Crevasse											X	X	X	X				X	X			X			X						X		X	X						
Point bar																X	X	X		X	X	X		X		X	X	X			X	X	X	X	X					
Natural levee																X		X	X	X		X					X				X	X	X	X	X	X	X	X		X
Flood veneer											X	X	X			X	X	X	X		X	X	X	X	X	X	X	X	X	X										X
Terrace																					X	X		X	X	X	X									X	X	X	X	
Inactive crevasse											X		X				X				X	X		X														X		
Inactive point bar											X	X		X	X	X		X	X			X				X			X											
Inactive natural levee											X				X	X	X	X	X		X	X		X	X	X		X		X										
Tertiary																							X					X								X	X			

Note: 1: entire floodplain; 2: lower Pánuco; 3: upper Pánuco; 4: lower Moctezuma; 5: upper Moctezuma; ▢: no co-occurrence between classes, X: significant positive co-occurrence, ■: very significant co-occurrence.
Source: From Haberman (1973).

The association of pasture within the floodplain illustrates the importance of considering the spatial variability in floodplain environments. Pasture on flood veneer (Figure 7a) decreases from the upper to lower Pánuco valley segments, from 53% to 38%, respectively. There is little pasture in the lower Pánuco segment due to the presence of extensive lakes. These lakes are located within large backswamp environments. The floodplain deposits in the lower Pánuco segment are notably fine grained and cohesive and have low rates of river migration (Table 2). The low rates of floodplain reworking (channel migration) have resulted in flooding and vertical accretion becoming the dominant mode of floodplain construction, resulting in an appreciably stable meander belt perched above backswamp that occupies a smaller proportion of the overall river valley (Table 2). In sharp contrast to the lower Pánuco segment, the upper Moctezuma segment contains the largest percentage of pasture on flood veneer. This is because backswamps are absent from this valley segment. The upper Moctezuma segment is dominated by coarser-grained, sand and gravel, channel deposits and has higher rates of lateral migration (Table 2), suggesting that floodplain reworking is much more rapid. Also, the meander belt occupies a larger proportion (83%) of the overall river valley (Table 2).

Although natural levees are less frequently inundated than low-lying portions of the floodplain, Figure 7b depicts less farming along lower Pánuco natural levees and an increase in urban land use. Additionally, many of the smaller urban areas have a prehistoric and historical legacy. These urban areas are situated on sites where large concentrations of prehistoric Huastec resided from the Late Formative through the Post Classic, 2500–500 BP, before Spanish colonization of the Pánuco valley in the early 1500s (Ekholm 1944; Aguilar-Robledo 2003b). Because the river in this portion of the study area has very low rates of migration (Table 2), these sites were preserved along the active meander belt.

More recently, in the 1950s and 1960s, the Mexican federal government initiated a program to convert the cattle grazing lands to agriculture. However, because this program was initiated without consideration of cultural practices or study of the floodplain geomorphology, the program was unsuccessful. The tradition of cattle ranching is heavily entrenched within the inhabitants of the small floodplain communities, which resulted in cultural opposition to this type of land-use change. Thus, the prehistoric and historical history of the Pánuco valley continues to be of relevance to contemporary LULC.

Although pasture is associated with fine-grained deposits, farming requires well-drained soils and is

Table 6. Area proportion (%) of LULC classes within geomorphic units for the entire floodplain

	River	Lake	Wetland	Agriculture	Pasture	Barren	Riparian	Urban
River	92.6	0.0	0.0	0.7	0.1	0.1	6.0	0.5
Lake	0.1	96.7	2.0	0.8	0.1	0.1	0.0	0.1
Island bar	1.9	0.0	0.0	71.4	12.9	0.7	13.0	0.0
Side bar	13.1	0.0	0.0	44.8	6.3	2.5	32.7	0.6
Oxbow lake	0.0	85.2	9.4	4.0	1.2	0.2	0.0	0.0
Clay plug	0.1	0.1	26.1	29.7	37.4	6.3	0.4	0.0
Cutoff	5.8	0.0	0.0	49.1	17.7	7.7	19.7	0.0
Abandoned courses	0.0	15.5	29.3	14.9	36.5	3.8	0.0	0.0
Crevasse	0.2	0.6	29.7	20.6	41.4	4.8	2.3	0.3
Point bar	0.6	0.0	0.2	32.1	44.1	16.8	6.0	0.3
Natural levee	1.4	0.0	1.0	27.5	35.6	11.6	13.1	9.6
Flood veneer	0.0	0.4	7.2	27.6	50.6	13.3	0.2	0.7
Terrace	0.1	0.1	1.4	12.8	46.5	15.8	0.2	23.1
Inactive crevasse	0.0	0.4	23.2	15.7	49.8	9.3	0.0	1.6
Inactive point bar	0.0	0.1	14.5	35.4	33.3	16.7	0.0	0.0
Inactive natural levee	0.0	0.1	8.3	31.4	45.9	14.3	0.0	0.0
Tertiary	1.3	0.0	1.9	6.6	24.9	6.5	1.0	57.8

associated with coarser fluvial deposits. In the lower Pánuco segment, farming is extensive on the large point bar surfaces (Figure 7b). Although point bars are not as topographically high as natural levees and are, therefore, more frequently inundated, point bars are composed of the coarsest floodplain deposits, (sand), and are well drained (Figure 1). Interestingly, in the lower Moctezuma segment, the proportion of farmland on flood-veneer surfaces is greater than point bars. Indeed, agriculture in the lower Moctezuma segment is able to extend across the entire river valley, whereas in the lower Pánuco valley, agriculture is limited by the floodplain hydrology. This is possible because of the absence of thick clayey backswamp units. Instead, the thin overbank flood-veneer deposits overlay coarser point bar deposits (Hudson 2002). Like the Pánuco segments, the lower Moctezuma segment is sufficiently wide and has low rates of migration (Table 2) and therefore preserves these older point bar deposits. Unlike the Pánuco segment, however, the lower Moctezuma segment has not been extensively buried by fine-grained flood deposits, and the flood veneer in this section is at about the same topographic surface as the active meander belt. Indeed, the paleochannels and abandoned courses are more connected to the main-stem channel than in the lower Pánuco, providing a hydrologic network for sediment and water to be transported to distal areas of the valley during high-flow events (Hudson and Colditz 2003). In the upper Moctezuma segment, the data clearly show that farming, predominantly citrus, occurs near the channel. This becomes increasingly apparent when Figures 7a and 7b are compared for the same geomorphic units. Whereas grazing (pasture) occupies only 17% of the natural levee surface, the proportion of natural levees utilized for farming is 53%. Furthermore, it is important to note that the Rio Pánuco natural levees narrow toward the river mouth due to exhaustion of coarser flood sediments (Hudson and Heitmuller 2003). Hence, spatial changes in sedimentology, hydrology, and floodplain topography results in land less suited for agriculture, and simultaneously results in an increase in pasture for grazing.

An unfortunate consequence of the extensive human manipulation of Moctezuma and Pánuco valley floodplain environments is that wetlands have largely been eliminated in most segments, which reflects the tremendous landscape transformation that has occurred throughout the valley. Spatially, the proportion of wetlands increases down-valley, from 1.6% in the upper Moctezuma segment to 12.6% in the lower Pánuco segment (Table 4). Wetlands are primarily located within abandoned channel courses and flood veneer (Figure 7c). Within the flood-veneer class, wetlands increased from less than 1% in the upper Moctezuma to almost 20% in the lower Pánuco. This occurs because the thick backswamps in the lower Pánuco valley impede drainage (Hudson 2002). Additionally, in contrast to the lower Moctezuma (20.5%), wetlands were a much larger proportion (42%) of relict channel courses in the lower Pánuco (Figure 7c). This likely occurs because, in comparison to the Moctezuma segments, the water table of the floodplain aquifer is less variable in the lower Pánuco, resulting in relict courses remaining inundated during the dry season. In both Moctezuma segments, many of the relict channels are intensively used for grazing and farming.

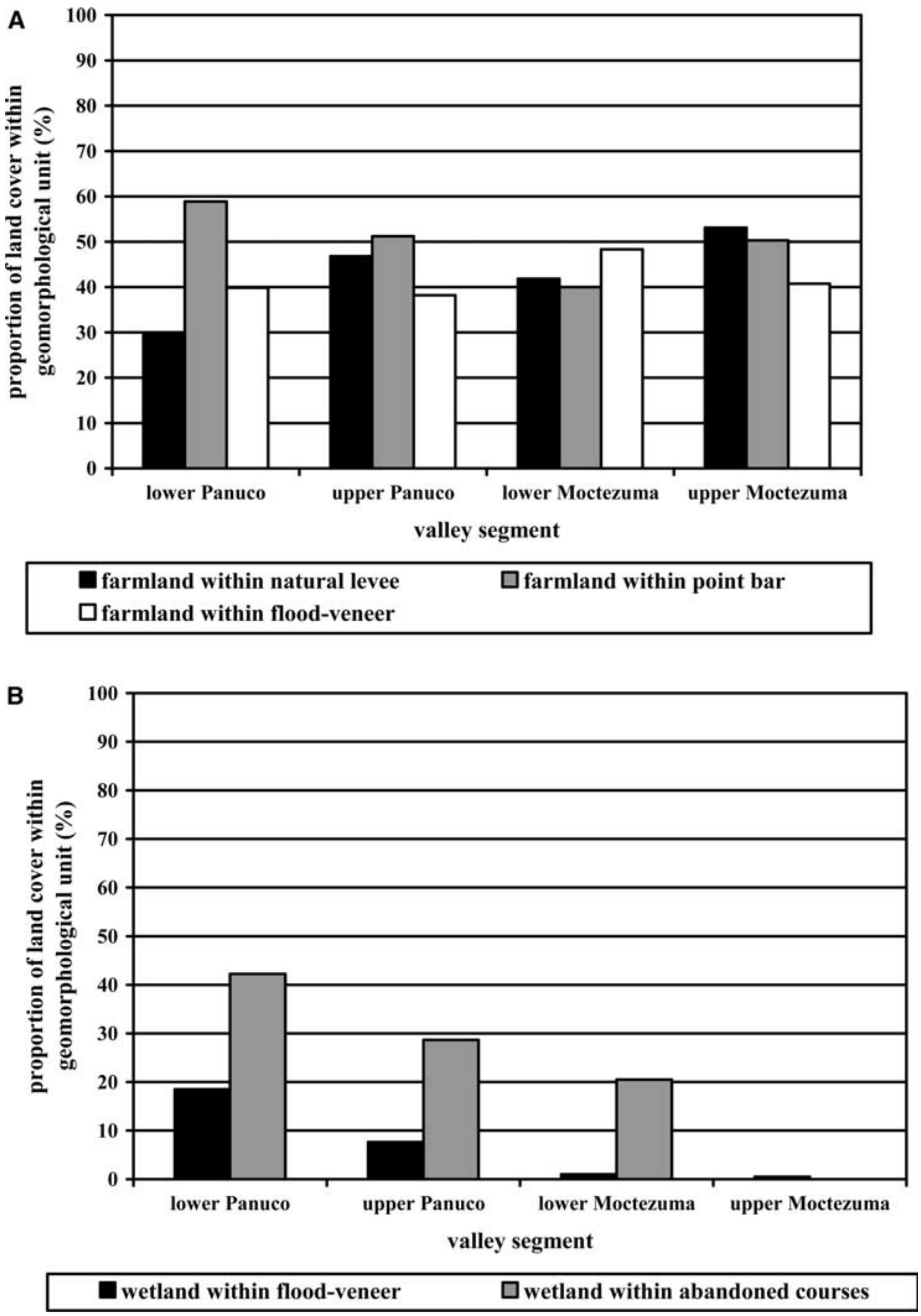

Figure 7. Continued.

Conclusions and Implications

The floodplain surface of the lower Pánuco basin is a significantly humanly modified landscape spatially dependent on the floodplain geomorphology. Findings from this study are relevant from the standpoint of quantitatively characterizing spatial variability in LULC and relations with distinct floodplain environments, offering a methodological framework for future research in humanly altered floodplain landscapes and for increasing our regional environmental knowledge in an area where little research has occurred.

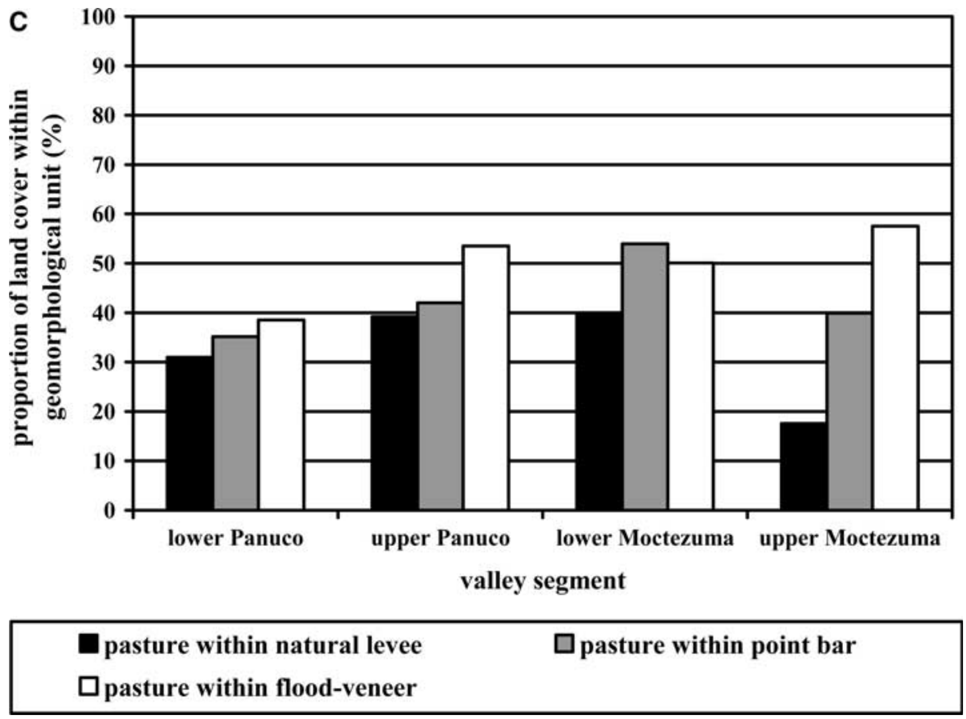

Figure 7. Variation across valley segments for significant LULC-classes related to floodplain environments (geomorphic units). Farmland = agriculture + barren.

An important conclusion of this study is that, from the context of the floodplain geomorphology of large river valleys, subtle differences in sedimentology (clay–sand) and topography (several meters) are associated with major differences in human activities. The association between different types of human activity and floodplain environments was quantitatively investigated by examining relations between LULC and distinct geomorphic units, which change longitudinally along the river valley. The hybrid classification method is suitable for LULC classification, especially when a preliminary stratification technique is applied. Pasture is utilized for cattle grazing and represents a large (43.4%) component of the overall floodplain land use. When considering both grazing and farming, an overwhelming proportion (79.5%) of the floodplain is utilized for agriculture. In the upper valley segments, the entire floodplain is utilized for farming and grazing. However, in the Pánuco valley, farming occurs near the river channel and, in particular, is associated with natural levees and point bar deposits. Within the flood-veneer class, distal portions of the floodplain having clayey and seasonally inundated soils are predominantly used for cattle grazing. Wetlands increase in prominence downstream, which coincides with a change in the floodplain geomorphology. Although these wetlands represent only a smaller percentage of their original extent, they represent an important ecological component of the floodplain, particularly from the standpoint of migratory water fowl. The large spatial extent of this study can be used to inventory wetland types by organizations or researchers and to coordinate management of these resources across state and municipal boundaries.

Segmentation of the floodplain geomorphology provides a useful framework for examining spatial changes in LULC. Indeed, the longitudinal approach used by this study is suitable for researchers working in large river floodplains in other settings, particularly in developing countries lacking high-resolution baseline topographic data or previous geomorphic research. The lower reaches of most large coastal plain river systems exhibit systematic downstream sedimentological and geomorphic variability (Bridge 2003). Although other river valleys are not likely to exhibit the same spatial variability in floodplain geomorphology as the Pánuco system, secondary datasets, such as topographic maps and satellite imagery, can likely be used to appropriately segment the river valley where large tributaries enter the valley.

Land-use/land-cover classification is highly dependent on recent satellite imagery, but this does not preclude consideration of older historical and prehistoric influences. Indeed, this study illustrates the importance of possessing knowledge of the environmental history of a river valley for understanding the modern floodplain surface. Along the Pánuco–Moctezuma valleys in eastern Mexico, prehistoric settlements were converted to urban areas and continue to influence the contemporary LULC. Similarly, cattle ranching, a major LULC class in the lower Pánuco valley, has a historical legacy, but this does not imply that it was independent of the floodplain geomorphology. Indeed, because the meander belt in the lower Pánuco valley undergoes very low rates of lateral migration and is dominated by fine-grained cohesive deposits, the adjacent lower-lying backswamps had extensive wetlands. This floodplain environment represented an ideal setting for establishing an agricultural system similar to what existed within the large lowland coastal plain river valleys of southern Spain. In comparison to Pánuco valley segments, the Moctezuma valley is better suited for farming because of the absence of backswamp environments, which enables sugar cane to be grown across the entire floodplain surface.

By considering relationships between LULC and geomorphology, the results of this study have implications to improving floodplain management, particularly for flood hazards. The backswamp basins in the lower Pánuco valley are ideal for the diversion of floodwaters through construction of spillways. Diverting floodwaters to backswamp basins would reduce the flood peak and protect settlements along the lower Pánuco segment. This would be most appropriate upstream of Ciudad Pánuco, which represents a transition toward larger floodplain basins and cattle ranching, which is less sensitive to inundation. Such an approach is effective in the lower Mississippi Valley, which has long represented a model for the study of engineering modifications to meandering river floodplains (Smith and Winkley 1996). Diversion of floodwaters along the Moctezuma valley could take advantage of existing paleochannels that serve as connections with distal portions of the floodplain. This would also reconnect the channel with the floodplain, which is important to the riparian ecology within the remnants of paleochannels and sloughs (Thoms 2003). However, this would require a valley-scale or watershed management approach because the Pánuco, like many large river valleys, represents the boundary of several political units (municipal and state boundaries).

The approach utilized for this study elucidated relationships between LULC and floodplain geomorphology of a large lowland tropical river valley. The findings provide insights into the pattern and significance of landscape manipulation within a large river valley where previously there had been very little research, and the methodology increases our broader understanding of fundamental relationships between LULC and floodplain environments. Many developing countries within the tropics lack the infrastructure and baseline data necessary for floodplain management. As such, flooding represents a perilous threat to rural populations dependent on seasonal farming. Planning based on sound analysis of the mutual relations between floodplain environments and LULC types might greatly assist floodplain management within these settings.

Acknowledgements

The authors are grateful for the processing of the DEM provided by Melba M. Crawford and Larry Teng (Center for Space Research, University of Texas at Austin), Field and laboratory assistance was also provided by Franklin T. Heitmuller, Sean White, Amy Neuenschwander, and Augustine Avwunudiogba from the Department of Geography and the Environment, University of Texas at Austin, and Humberto Reyes-Hernandez from the Universidad Nacional Autónomica de Mexico (UNAM), Mexico City. We are grateful to the ranchers, farmers, and residents of the Pánuco–Moctezuma valley who during the past several years have provided information on land-use practices and granted permission to access field sites for surveying, sampling floodplain deposits, and ground-truthing satellite imagery. We also would like to thank our reviewers Dr. Leal A. K. Mertes at University of California–Santa Barbara and Stephen E. Walsh at Michigan State University for insightful comments. The ASTER data are distributed by the Land Processes Distributed Active Archive Center (LP DAAC), located at the Earth Resources Observation Systems (EROS) data center. Funding provided by an Interdisciplinary Research Initiative from the Vice President for Research and Provost's office and a Mellon Foundation Award From the Lozano Long Institute of Latin American Studies, University of Texas at Austin.

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