Preliminary United States - Mexico Border Watershed Analysis,

Twin Cities Area Of Nogales, Arizona And Nogales, Sonora

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U. S. DEPARTMENT OF THE INTERIOR
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Abstract

The United States - Mexico border area faces the challenge of integrating aspects of its binational physical boundaries to form a unified or, at least, compatible natural resource management plan. Specified geospatial components such as stream drainages, mineral occurrences, vegetation, wildlife, and land-use can be analyzed in terms of their overlapping impacts upon one another. Watersheds have been utilized as a basic unit in resource analysis because they contain components that are interrelated and can be viewed as a single interactive ecological system. In developing and analyzing critical regional natural resource databases, the Environmental Protection Agency (EPA) and other federal and non-governmental agencies have adopted a "watershed by watershed" approach to dealing with such complicated issues as ecosystem health, natural resource use, urban growth, and pollutant transport within hydrologic systems.

These watersheds can facilitate the delineation of both large scale and locally important hydrologic systems and urban management parameters necessary for sustainable, diversified land-use. The twin border cities area of Nogales, Sonora and Nogales, Arizona, provide the ideal setting to demonstrate the utility and application of a complete, cross-border, geographic information systems (GIS) based, watershed analysis in the characterization of a wide range of natural resource as well as urban features and their interactions. In addition to the delineation of a unified, cross-border watershed, the database contains sewer/water line locations and status, well locations, geology, hydrology, topography, soils, geomorphology, and vegetation data, as well as remotely sensed imagery. This report is preliminary and part of an ongoing project to develop a GIS database that will be widely accessible to the general public, researchers, and the local land management community with a broad range of application and utility.

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Introduction

The twin border cities area of Nogales, Sonora and Nogales, Arizona, provide the ideal setting to demonstrate the utility and application of a complete, cross-border, geographic information system (GIS) based watershed analysis of a wide range of critical natural resource and urban-industrial components and their common interactions. The twin border cities area, referred to as "Ambos Nogales", typifies the condition of a number of border areas with its assortment of water issues, including surface- and groundwater contamination, inadequate water supplies inequitably distributed, flash floods, and endangered riparian habitat (Ingram and others, 1994). Population growth, nearing 250,000 (Sanchez and Lara, 1992), exacerbates already depleted ground water sources. Poor waste containment infrastructures threaten existing and future water resources as well as create health-related concerns based on environmental exposures encompassing physical, chemical, and biological agents. With these and other socio-economic issues occurring across the United States - Mexico border area, the region faces the challenge of integrating aspects of its binational physical and political boundaries to form a unified or, at least, compatible natural resource database upon which to execute a viable international management plan. The objective of this paper is to provide an overview of the newly generated watershed-based framework and key natural resource components, attributed features, and analytical tools database developed for a GIS-platform. In some cases a transnational, compatible data layers needed to be created, e.g. topographical base, hydrological and geological coverages. Each section focuses on issues and solutions associated with the gathering and integrating of transnational geospatial data and preliminary results from the datasets are presented.

The construction of the database is accomplished in three phases: (1) GIS database compilation and development; (2) creation of an integrative platform, available in Arc/Info and ArcView, that provides a means for new input of scientific data and enables integrated watershed management; and (3) presentation of the database as a means of continuing education, and community outreach among decision makers and the general public. This study is the result of an informal data-sharing partnership between the U.S. Geological Survey and the Arizona Department of Environmental Quality (ADEQ). The goals of the partnership are to combine and focus the resources of our investigative teams, thereby to eliminate unnecessary overlap in the execution of this study, and to make the database as widely available as possible through the combined publication and web-accessibility of the government community. Some possible release mechanisms for the data in the future are a deliverable spatial data archive CD-ROM or an interactive data-warehouse Internet site.

The Nogales wash is a tributary of the Upper Santa Cruz River, located in southern Arizona and northern Sonora, Mexico (fig. 1). Major issues in the Nogales wash, including natural resource degradation, technical data acquisition and manipulation, and logistics of publication and presentation, can be addressed with an integrated watershed GIS:

1) Pollution leaks; inefficient water usage and inadequate sewage containment characterize the urban infrastructure of this semi-arid region. Bacteriological contamination, seepage of nitrates, heavy metals and volatile organic compounds (VOCs) from industrial sites into soils and underground water supply have been identified in the waters of both cities (Varady and Mack, 1995). Surface and groundwater hydrological models to determine runoff and sub-surface flow paths could help to pinpoint sources of pollution.

2) Lack of digital data in a unified framework; the data concerning watershed, demographic, environmental, and infrastructure characteristics are not currently available in a contained geospatial database.

3) Current border maps are fragmented; most of the existing digital and analog copy datasets originating in either country terminate at the border, and resource policy decisions are implemented without much regard for impact on adjacent populations. Geospatial inconsistencies occur due to differences in mapping, cartography, resolution and dates of dataset creation. The national, linguistic, and physical barriers increase the challenge of integrating databases in this GIS project (Wright and Winckell, 1999).

4) Lack of communication; transborder data sharing between research and educational facilities and policy makers is lacking. This situation is partly due to the binational/bilingual nature of the region. A graphic digital representation of the factors influencing the transborder watershed could aid in enhancing understanding by sidestepping communication barriers and could be the first step in water quality conflict resolution.

Location of the Study Area

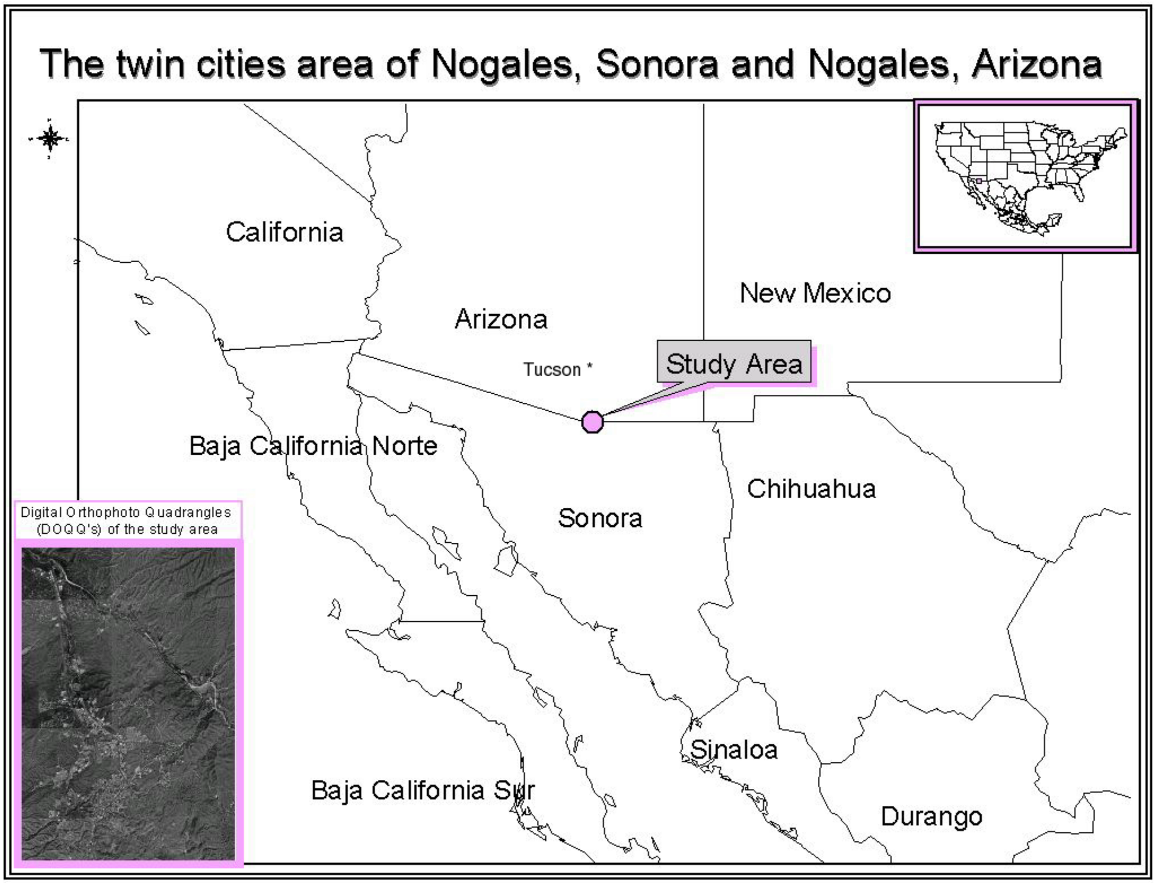

Figure 1: Location map depicting the study area of the twin cities of Nogales, Arizona and Nogales, Sonora.

The twin cities of Nogales lie astride the Arizona-Sonora section of the U.S. – Mexico Border, at Latitude 31.34, Longitude –110.94, approximately 110 km south of the metropolitan area of Tucson, Arizona (fig. 1). The area lies within the Sonoran Desert, locally occurring in a dissected, foothills-like setting that contains the headwaters and main reach of Nogales Wash. Several northeast flowing tributaries, Las Canoas, Mariposa Canyon, Potrero Creek, Alamo Canyon and Pesquiera Canyon flow directly into the main reach of the Nogales Wash system (fig. 3). Within the study area, specified geospatial components such as stream drainage, mineral occurrences, vegetation, wildlife corridors, and land-use can be analyzed.

The average high and low maximum temperature range is 93.9 - 27.4 ^{o} F (34.4 - -2.5 ^{o} C) with an average of 17.66 inches (44.9 centimeters) of annual precipitation, almost half of which occurs in the summer months of July and August (http://www.wrcc.dri.edu/summary/climsmaz.html). These semi-arid conditions indicate a potential water shortage as well as limit pollution dilution potential (Liverman and others, 1999).

GIS Database Development

The purpose of this section is to describe the production of unified, consistent, digital, geographically registered cross-border watershed data that accurately portray the transboundary nature of the selected hydrologic sub-region. The following datasets, or thematic coverages, have been collected or automated within a geospatial database. Binational water resource priorities were identified and systematically mapped to characterize transboundary relationships of natural and anthropogenic factors. Basic geologic and hydrologic data, in digital and analog format, that would be compatible with a GIS were initially researched for the Nogales study area. The physical setting of the region is herein described using a watershed approach to aid in dealing with such complicated issues as ecosystem health, natural resource use, urban growth, and pollutant transport within surface and ground-water hydrologic systems. The procedures for delineating watersheds and creating stream networks are described in the following section, along with descriptions of the created transboundary watershed.

Hypsography

One of the project's preliminary accomplishments has been to generate integrated elevation data from the U.S. and Mexican sources in order to create a watershed-wide topographic surface and derived themes such as slope, aspect, shaded relief, hydrologic features, and hypsographic contours (fig. 2). Due to projection, resolution and contour interval differences among datasets, the integration across the border was difficult. Digital Elevation Models (DEM's) were acquired and concatenated for the areas of interest; resolution of the grids is 90 meters. The USGS National Elevation Data set (NED) (http://edcnts12.cr.usgs.gov/ned/) supplied 30-meter resolution DEM's that were resampled to a 90-meter grid cell size for that portion of the analysis that occurred on the

U.S. side of the border. The Mexico DEM's were purchased through Resource Science, Inc. (http://www.resourcescience.com). These data came packaged in 3-arc-second projection using decimal degree units and were re-projected to Universal Transverse Mercator (UTM) and also resampled to a 90-meter resolution to achieve a uniform projection and grid cell size.

Topographic contour lines were generated within Arc/Info from this newly created DEM, with a 100-meter contour interval to portray elevation (fig. 2). The lowest elevation in the Ambos Nogales is 1,060 meters above sea level, and the highest is 1,710 meters. The mean elevation is approximately 1,278 meters. The topography reveals the typical mountain and intervening valley structure of the Basin and Range Province.

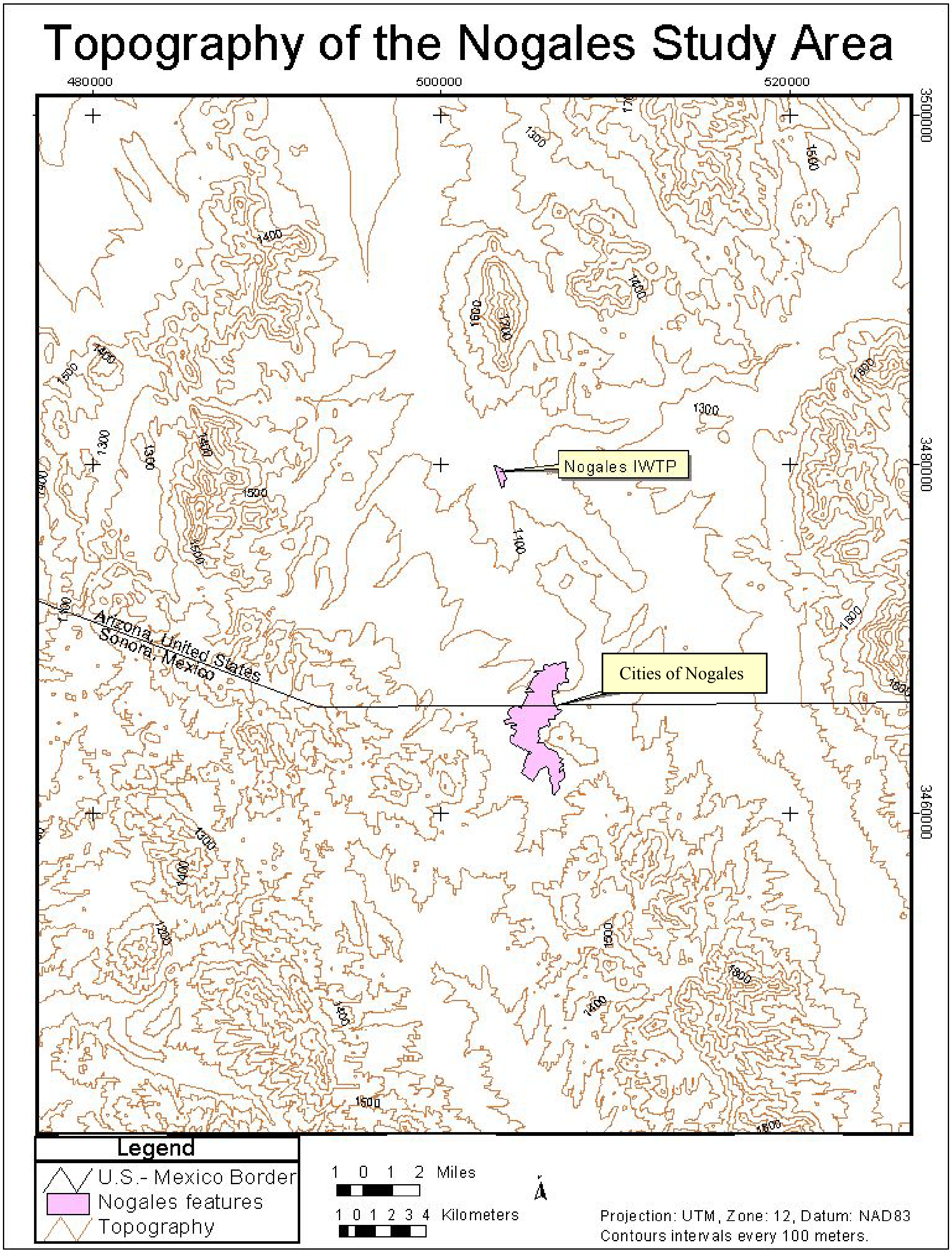

Figure 2: Elevation contours of the Nogales area at a 30-m. resolution. Ambos Nogales and the International Wastewater Treatment Plant (IWTP) also shown.

Watershed Delineation

A watershed is defined as a catchment basin that is delineated topographically and drained by a stream system; it is a hydrological unit used for the planning and management of natural resources (Brooks and others, 1997). Components of a watershed include water, topography, soils, rock, vegetation, wildlife, climate and land-use.

Stream networks were created from the newly generated DEM, using the GRID module of Arc/Info and compared to lower resolution vector datasets in the area. The point at which the Nogales wash enters the Santa Cruz River was determined to be the outlet of the Nogales wash tributary system and that point was used as a pour point in the watershed's delineation. An outlet, or pour point is the point at which water flows out of an area. This was done using a script developed in ArcView (see Appendix), which utilizes the 90- meter resolution DEM and the previously created flow direction and flow accumulation grids to calculate the catchment basin of that specified point. The result of this digital construction of transborder watershed delineation identifies the areas of land within Mexico that are immediately contributing to the pour point or headwaters located in the United States. Figure 3 shows the newly delineated watershed area overlain with generated stream networks and a 1:250,000-scale digital raster graphic (DRG) of the area. The Nogales Wash watershed covers 235 square kilometers, just under half of the area is in Mexico. The topography is the major factor that identifies this basin boundary. The basins have varying amounts of alluvial sediments transected by stream channels. Drainage in the basin is asymmetric and clearly focused along the eastern edge.

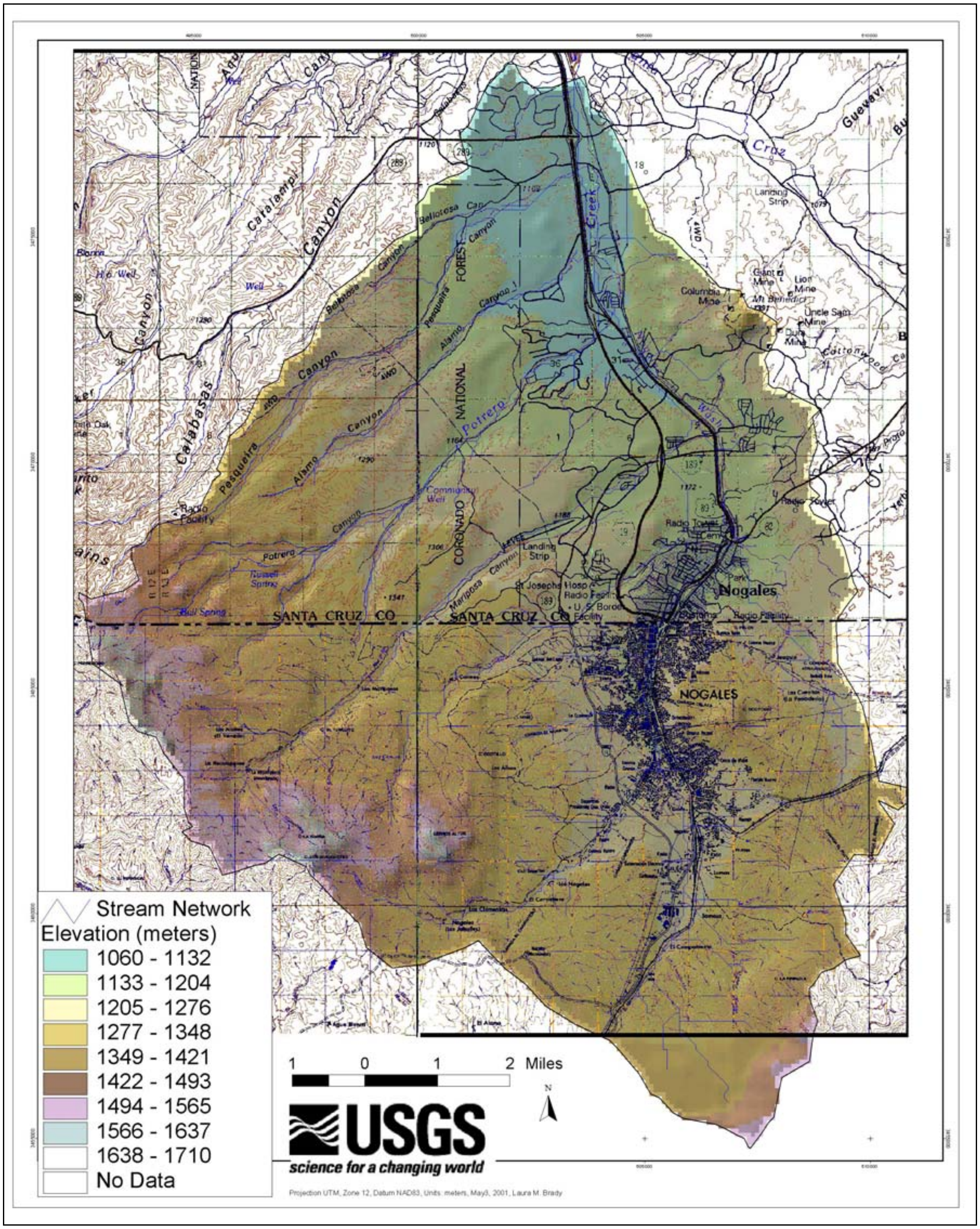

Figure 3: Nogales Wash watershed delineation portrayed by hill shade relief of a DEM.

Hydrography

The stream flow emanating from a watershed is the result of many integrated influences of the watersheds physical composition. The amount of water received though precipitation and how this water is distributed though space and time defines the watershed itself. The Nogales wash is a gaining stream, which receives water from the local groundwater table in addition to discharge from the border area upstream. The Santa Cruz River, which is located in southern Arizona and northern Sonora, Mexico, flows into the Gila River and then into the Lower Colorado River. There are numerous problems associated with the understanding of the Santa Cruz River system's surface flows and groundwater/surface water relationship (US-Environmental Protection Agency, 1996).

The Nogales Wash is a nested tributary within the Santa Cruz River drainage basin and has been identified as major sources of possible contaminant contribution to water in the downstream reach of the Santa Cruz River. Utilizing the predefined Upper Santa Cruz watershed boundary in the United States, identified by the U.S. Environmental Protection Agency in the "Surf Your Watershed" Website (US- Environmental Protection Agency, 2000), pour points were identified and Upper Santa Cruz transborder watershed was created utilizing the Script in ArcView (see Appendix). Figure 4 depicts those stream networks generated within the GRID module of Arc/Info from the newly generated DEM, associated with the Upper Santa Cruz transborder watershed and the placement of the Nogales Wash watershed within.

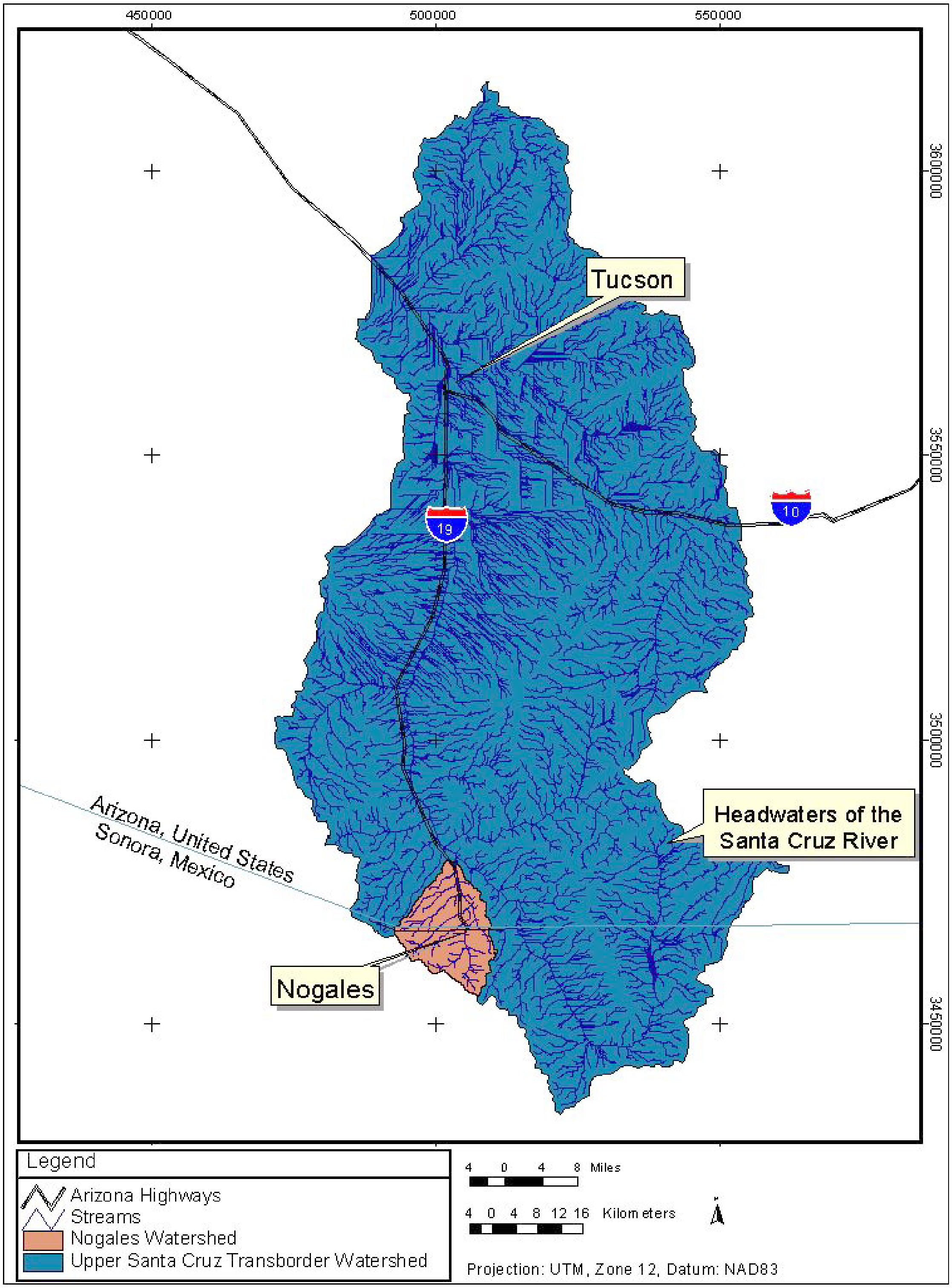

Figure 4: Map showing the relationship of the Nogales Watershed to the Upper Santa Cruz River Transborder Watershed.

A digital elevation model (DEM) was used to model the effects of land topography in the watershed delineation by identifying the streams, flow direction and a catchment perimeter or that portion of the land that effects a given outlet (Maidment, 1993). Surface runoff flow paths are from ridge tops. Runoff flows from watershed boundaries toward the dissecting channels in which the flow accumulates toward the downstream discharge point. The surface runoff from each segment of land surface has its own unique flow path and velocities by which it reaches any designated point. In the Nogales area, during periods of surface runoff, the two sources of stream flow are surface runoff and groundwater discharge. When precipitation stops, the surface runoff rapidly ceases.

A surface runoff flow direction map (fig. 5) was generated in Arc/Info's GRID module, from a 90-meter resolution transborder Digital Elevation Model (DEM), for purposes of study and analysis of water quality. As depicted, surface flow runs predominantly north and northeast.

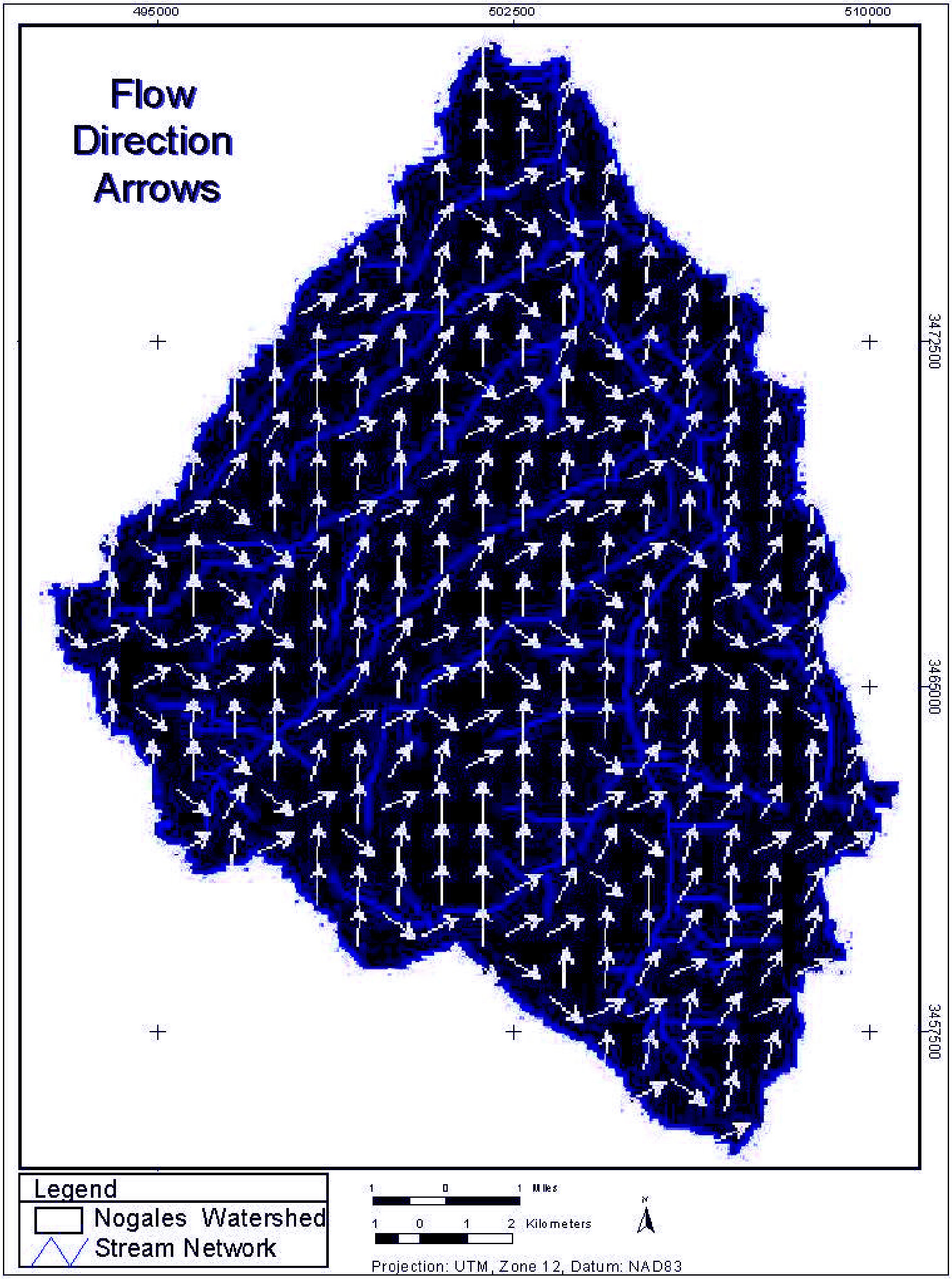

Figure 5: Surface flow direction map of the Nogales Watershed as depicted by a DEM in Arc/ Info's GRID module.

Within the Nogales wash, as mentioned in the site description, are many tributaries. A sub-watershed was delineated at each junction with the Nogales Wash, using the script developed in ArcView (see Appendix) for further investigations of possible contaminant and non-point sources within the area (fig. 6).

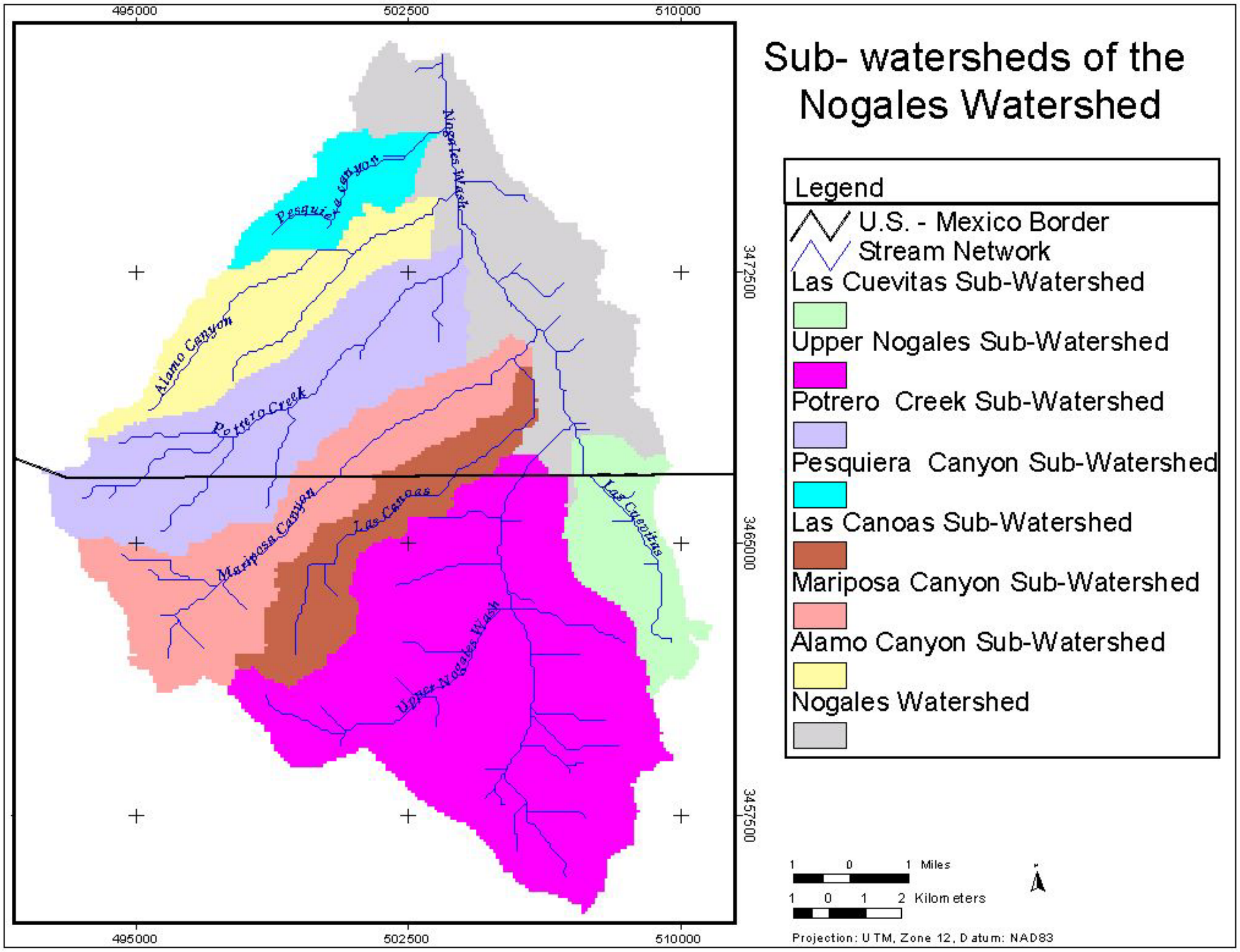

Figure 6: Sub-watersheds of the Nogales Watershed defined by streams and DEM input.

Geologic Setting

Published geologic maps of this portion of the US-Mexico border are country-specific and typically do not include geologic data from the adjacent cross-border area of the frontier. Efforts to merge known geologic databases reveal the problems of scale and nomenclature that are encountered at the international boundary. For a cross-border watershed study of this type, the available published maps at a scale of 1:1,000,000 and 1:2,000,000 are barely adequate for a portrayal of the local geology (fig. 8). A preliminary geologic map derived from larger scale base maps and satellite imagery was prepared for this report (fig. 9). This preliminary cross-border geologic map was created using Thematic Mapper images (Landsat 5), where areas of known geology were examined for color, texture, and slope styles (fig. 15). Extension of those areas was approximated where a level of certainty could be maintained.

The central part of the Nogales Wash-Upper Santa Cruz Valley is composed of basin-fill sediments. In the southern Basin and Range province, these sediments are interpreted as the detritus accumulated in structural basins that had more or less the present configuration observed today (Gettings and Houser, 1997). Generally, two ages of basin fill are defined in most basins in southern Arizona (Houser and others, 1985; Dickinson, 1991). Older basin fill beds are characterized by mild to moderate deformation with dips of 10^{o} to 40^{o}; younger basin fill beds commonly display dips of less than 5^{o}. The older basin fill sediments are typically more consolidated and consequentially denser than the younger basin fill. Locally, on the basis of age, stratigraphic position, and degree of consolidation, rocks in the upper Santa Cruz can be separated into two basin-fill units overlain by surficial deposits as follows: (1) lower basin fill sediments, (2) upper basin fill, and (3) Pleistocene and Holocene age surficial deposits (Houser and others, 1985; Dickinson, 1991). The lower basin fill sediments, locally referred to as Nogales Formation, are lower and middle Miocene age (<17 Ma) sediments, which are widely exposed near the lower slopes of the mountains. The sediments consist of poorly to moderately well consolidated pale red to grayish pink conglomerate with moderate to good bedding displayed in pebbly and sandy intervals. Clasts are composed of predominately prophyritic volcanic rocks with lesser proportions of granitic rocks, Paleozoic sandstone and limestone. The unnamed upper basin fill unit, upper Neogene to lower Pleistocene in age, is composed of unconsolidated to poorly consolidated course to medium gravel and gravelly alluvium from deposits washed down from the adjacent ranges. Pleistocene and Holocene surficial deposits include gravel and coarse, sandy deposits of alluvium in stream channels, flood plains, and terraces; overall they are unconsolidated but are locally well indurated.

The lower slopes of the Atascosa Mountains (fig.7) on the western side of the valley are composed of Tertiary volcanic rocks. The Pajarito (US) and Cerro Pedregoso Mountains (MX), located along the international border west of Nogales, consist of Cretaceous volcanics. The San Cayetano and Patagonia Mountains are on the eastern side of the Nogales Wash and upper Santa Cruz Valley. These mountains are made up of a variety of rocks including igneous, metamorphic, volcanic, and sedimentary rocks ranging in age from Precambrian to Miocene (Drewes, 1980; Simons, 1974). The northern slopes of Cerro El Ocotilloso, lying on the northwestern flanks of Sierra El Pinito, are made up of Cretaceous granitic rocks overlain by a cover of Tertiary sediments equivalent to the Nogales Formation. There is a regional north-northwest structure grain in the area, typical of this portion of southeast Arizona.

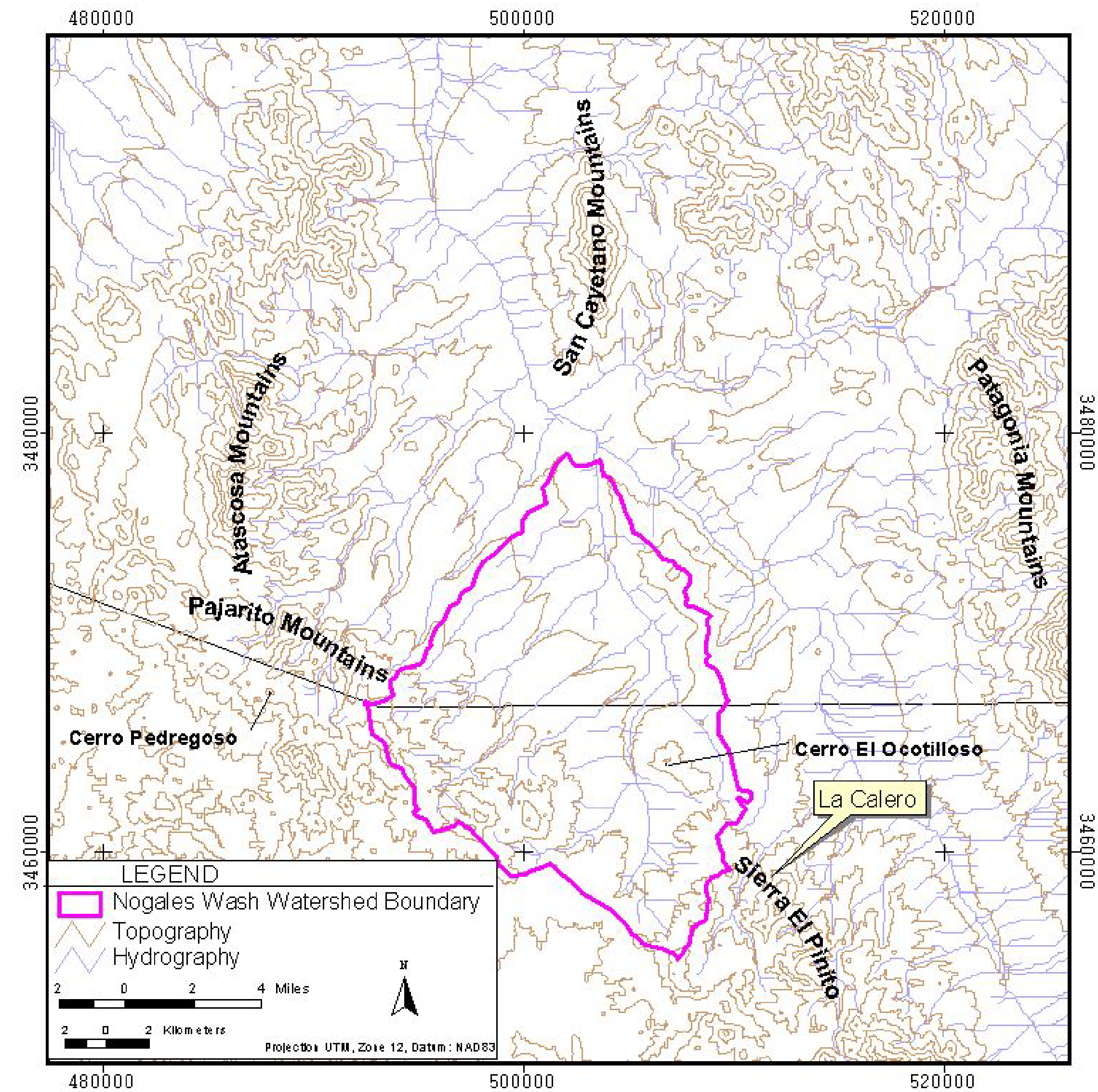

Figure 7: Locality map of the Nogales Wash Watershed in relation to nearby mountain ranges.

Two roughly parallel sub basins are defined in the immediate area of Ambos Nogales by an interpolation of Bouguer gravity data and stratigraphic-structural interpretation: 1) the Nogales subbasin, and 2) the upper Santa Cruz subbasin (Gettings and Houser, 1997) (see fig. 9). The Nogales subbasin forms a northwest-trending approximately 5 km wide trough that begins near Pesquiera Canyon (fig. 6) at its northwest perimeter, narrows through the Nogales urban corridor and terminates in the southeast near La Calera, Sonora (fig. 7). The basin is estimated to reach a depth of about 700 m in the northwest and shallows to some 250 m in its southeastern edge. The upper Santa Cruz subbasin and the course of the river appear to be controlled along the Mt. Benedict fault, depicted just northwest of the mountain itself in Figure 9. The subbasin underlies one of the narrower valleys in southern Arizona (8 to 12 km wide). Because there is a general positive correlation between basin widths, amount of extension, and basin depth, the narrow span of the valley suggests that the basin is shallow. Other indications of a shallow depth to the basin include: (1) weak Bouguer gravity anomalies of the basin (Gettings and Houser, 1997), (2) the absence of lacustrian or playa sediments in the basin fill, suggesting that the basin was never closed, and (3) ubiquitous outcrops of the Nogales Formation in the area, suggesting that basin subsidence stopped after the formation was deposited.

Geophysical data (aeromagnetic and gravity) indicate the possibility of at least two other sub basins within the Ambos Nogales area that may merit further delineation. The Las Canoas sub basin is a northeast-trending anomaly that roughly follows along Las Canoas tributary. The approximately 5 km-wide area is connected to the Nogales subbasin in the northeast and extends to the la Bellotosa -El Pajarito pueblos region to the southwest in Mexico. The southernmost subbasin (El Ocotillosa subbasin) intersects the southern tip of the watershed and is a roughly rectangular feature located due east of Cerro El Ocotilloso. The tributary, La Cason, and Mexico highway 15 dissect area.

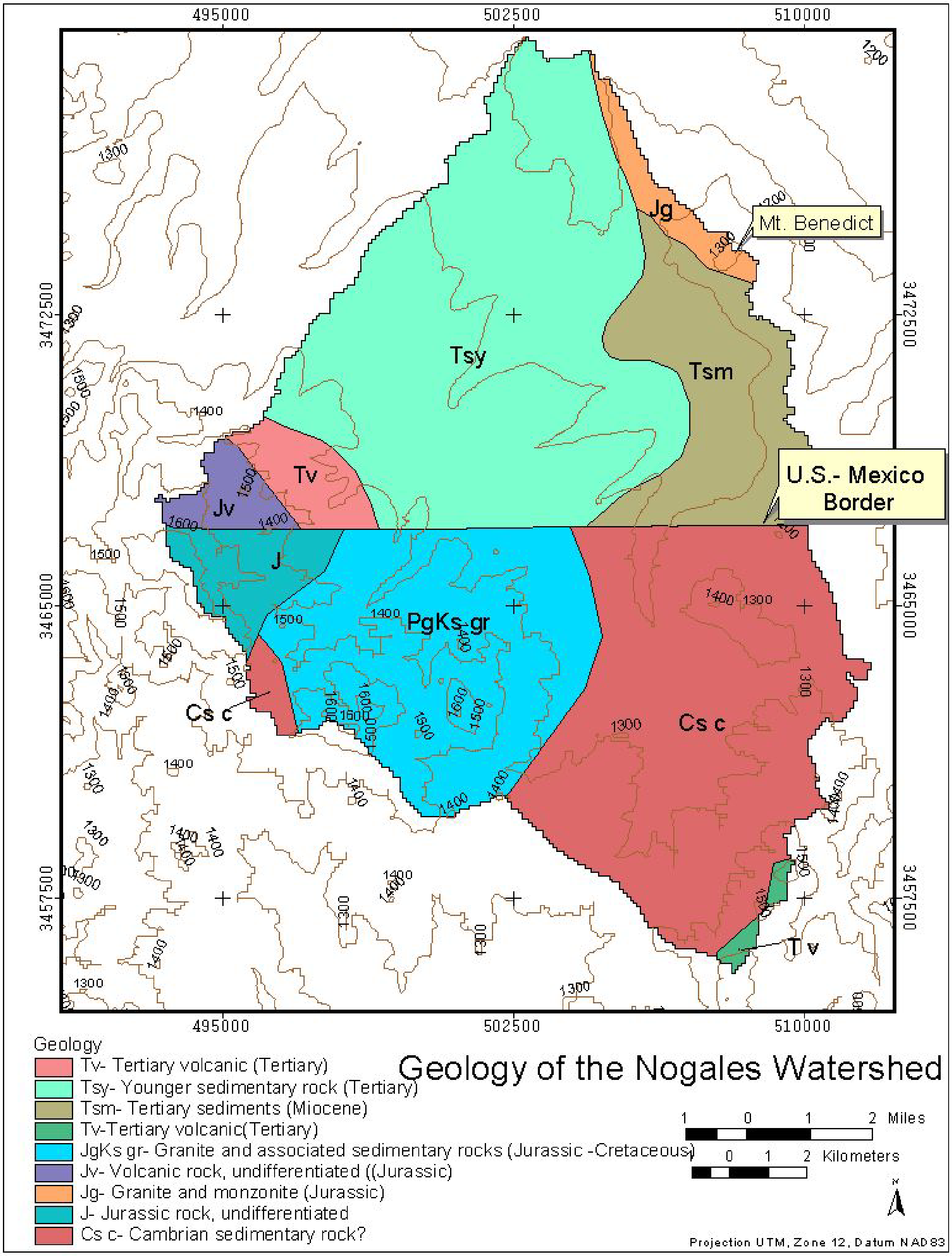

Figure 8: This map depicts the discrepancy in resolution and nomenclature encountered at the international border by combining geologic maps of State of Arizona at 1:1,000,000 (Reynolds, 1988) and the country of Mexico at 1:2,000,000 (Ortega-Gutierrez and others, 1992).

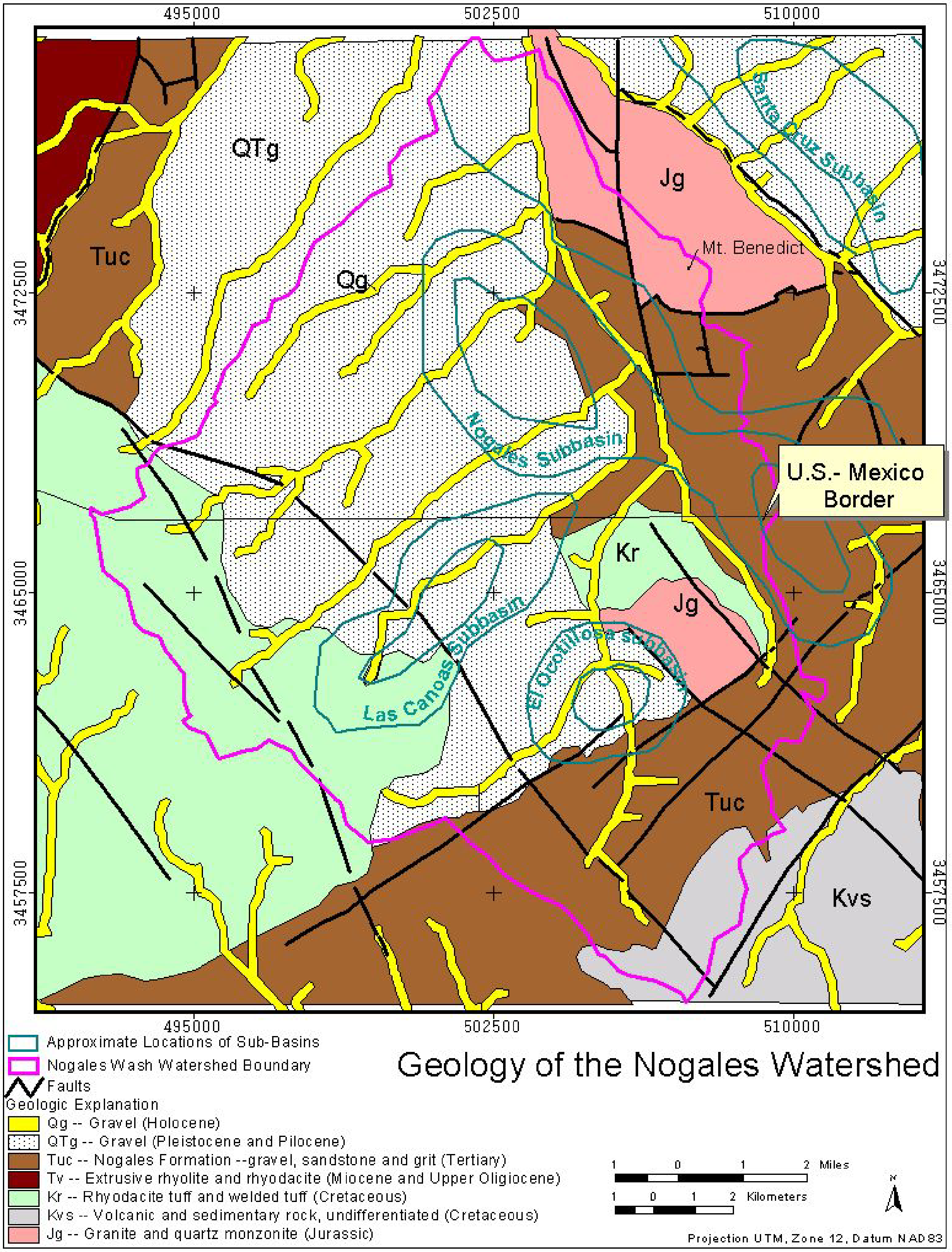

Figure 9: Preliminary geologic map derived from larger–scale base maps (Consejo de Recursos Naturales no Renovables, 1967; Gettings and Houser, 1997) and Landsat 5 TM imagery in the Nogales Wash watershed.

Vegetation

According to the vegetation of North America map (FAO-UNESCO, 1975), the Nogales area lies within the Southwestern Desert Shrubs region and is classified as one of the driest ranges. Sage, creosote bush, sagebrush and greasewood shrubs dominate the area. Short grasses occur with desert cacti and some Juniper and Pinyon Pine exist in the Northern areas. The shrub land/ rangeland is hydrologically very similar to historical accounts although livestock grazing and vegetation removal has increased runoff and erosion.

No geospatial digital vegetation data exist that describe this area yet. However, Arizona Department of Environmental Quality has acquired aerial photographs that are less than 1-meter resolution for vegetation classification and re-vegetation analyses by the Bureau of Applied Research and Anthropology (BARA) group at The University of Arizona (fig. 10). Utilizing remote sensing techniques and GIS software, the classification of vegetation type in these photos will form the vegetation layer in this database.

Figure 10: Aerial photograph taken of the central commercial downtown Ambos Nogales, portraying the border crossing which overlies the tunnel containing the Nogales Wash.

Soils

The point of saturation (POS), which normally occurs as percolation increases in soils, rarely occurs in dry areas like Nogales. The soil mantle in this type of arid environment has the first opportunity to intercept the precipitation and little to no groundwater recharge occurs (Saxton and Shiau, 1990). According to FAO-UNESCO (1975), the Nogales area is located within the characterized 12b soil region and characterized as a hot and dry climate, dominated by plains and alluvial fans with only occasional mountain ranges. Surface runoff is generally limited to local floods caused by intense rain and is often absorbed by drier regions downstream.

No digital soil maps were found for the Mexican portion of the Nogales watershed. The USDA's Natural Resource Conservation Service's (NRCS) State Soil Geographic (STATSGO) Data Base is the only digital soils map that includes Santa Cruz County (USDA-NRCS, 1995). The projection for this data was converted from Albers, NAD27 to UTM, Zone 12, NAD83 (fig.11).

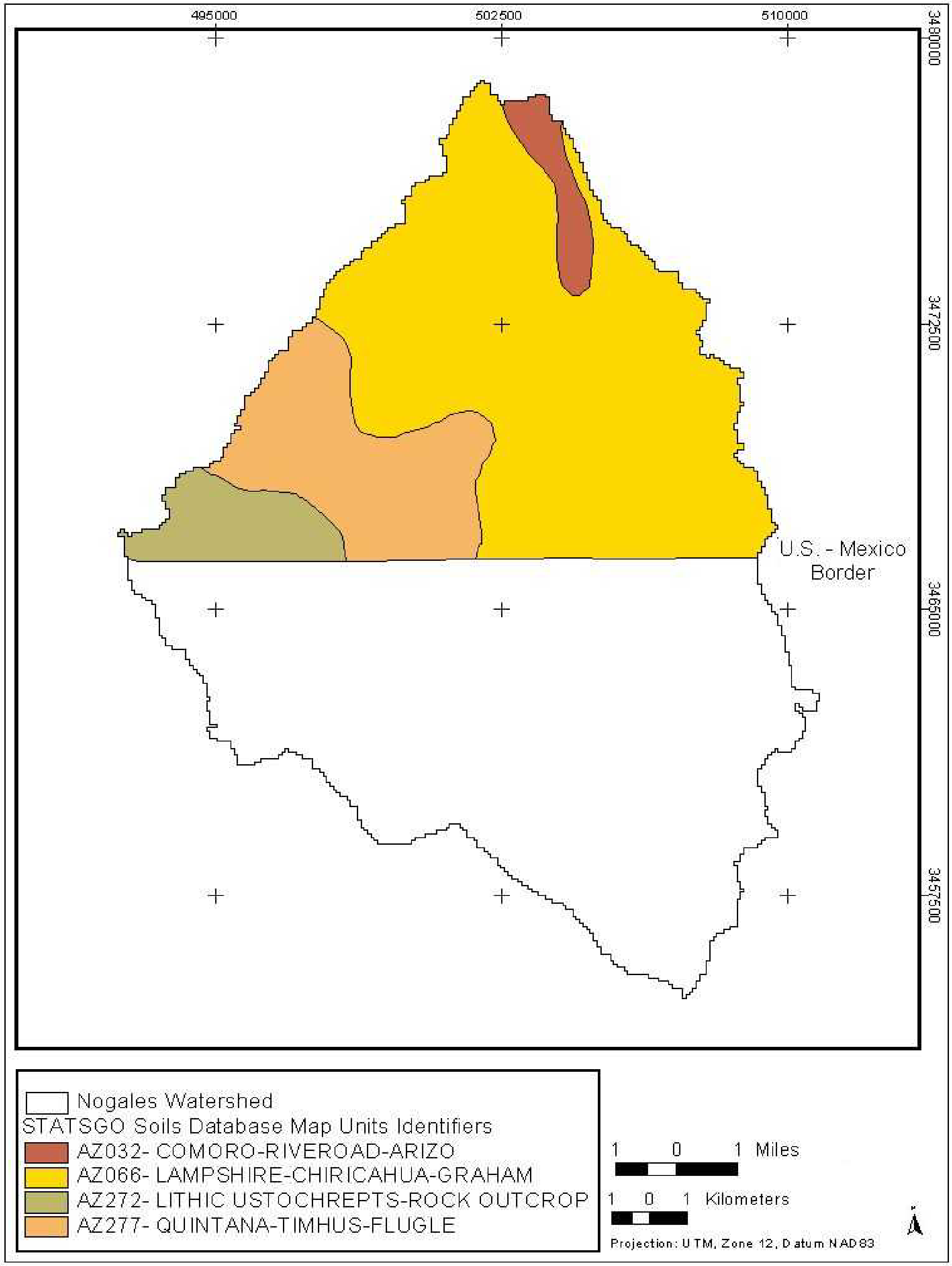

Figure 11: Soil types, called Soil Database Map Unit Identifiers (MUIDS), of the U.S. portion of the Nogales Watershed as defined by STATSGO (USDA-NRCS, 1995).

Basin characteristics

The basin area is approximately 24,435 hectares (60,380 acres). In arid lands, where channels absorb stream flow, runoff decreases with increasing basin size as described in watershed studies in nearby Tombstone, Arizona (Glymph and Horton 1969). Therefore, owing to the 244 square kilometer basin size, Nogales Watershed yields only 8 millimeters mean annual runoff to its outlet from precipitation. Compared to the 448.5 millimeters of precipitation received by the watershed, only 1.7% of what hits the ground ends up in the creek.

Slope of the ground surface is a factor in the overland flow process and very important hydrologically in small basins where it may be the dominant factor in determining hydrograph shape. A hydrograph is a plot of the variation of discharge, stage, velocity, and other characteristics of water with respect to time, generally measuring flow rate trends in the river. The influence of slope is most relevant to indices of peak flow and to hydrograph shape. Average slope in the Nogales Wash watershed is approximately 3 degrees, the standard deviation from the average is approximately 3 while minimum slope = 0 and maximum slope = 29 degrees (fig.12).

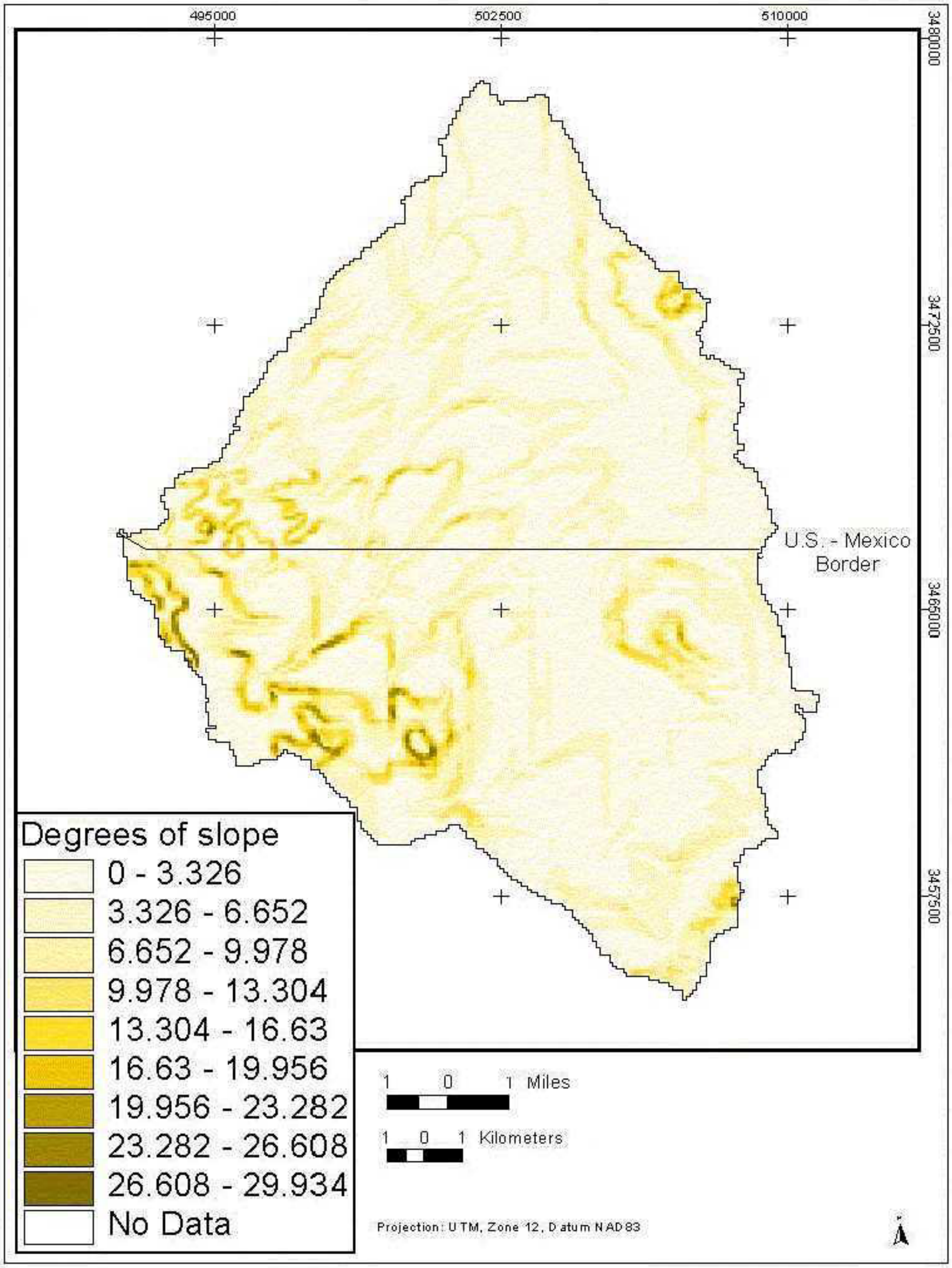

Figure 12: Degrees of slope depicted in the Nogales Watershed.

The shape of the basin also affects the hydrograph characteristics of lag time, the time of rise, and the peak flow rate. Lag time is the time it takes for precipitation to run-off from where it has fallen to get to the river channel. Factors that can affect this include permeability of rocks and interception from vegetation. Given the shape of the watershed, the time of rise in this hydrograph will be later than normal allowing for a longer lag time.

Channel network patterns express the shape of a hydrograph as well. The pattern displayed by the Nogales Wash watershed depicts a slower rise in the hydrograph, but a higher peak compared to a more dispersed network.

As area of watershed increases, so does the order of each watershed according to the Strahler stream ordering method (Strahler, 1957 and 1964). The Strahler stream order number increases where streams of the same order intersect. This is useful when identifying hierarchy within a stream system (fig. 13). Characteristics of streams are inherent under this type of ordering system. For example: first order streams are headwaters, which have no streams running into them. Therefore, these are most susceptible to non-point source pollution problems (Strahler, 1957). Further, 3^{rd} and 5^{th} order streams transport the majority of sediment that they receive because of the inherent steeper gradients and contact with faster moving streams (Naiman and others, 1992).

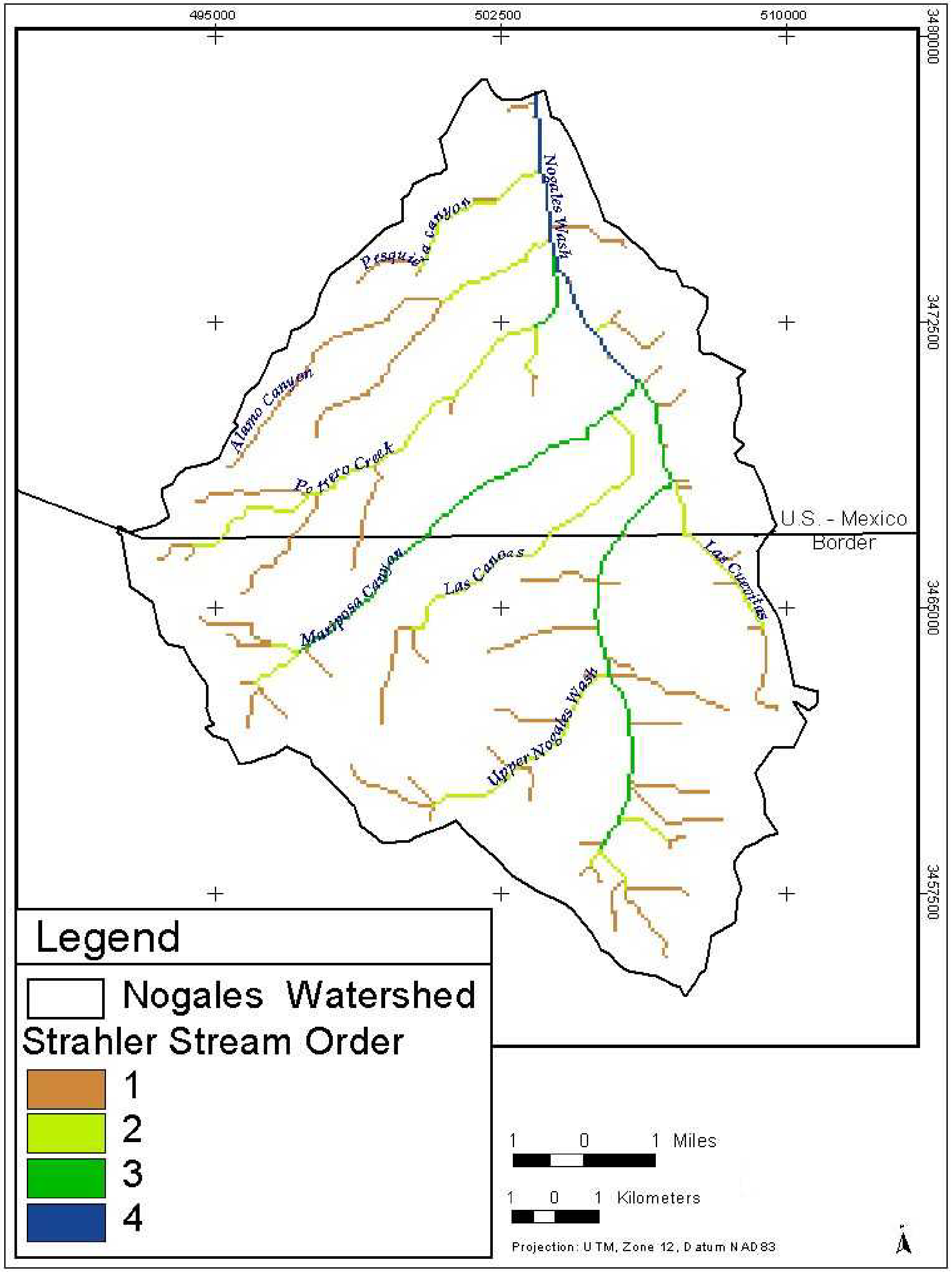

Figure 13: Strahler stream order depicted for the Nogales Watershed.

Drainage density is a measurement of channel length over area of basin. All of the arcs describing stream channels were listed, exported and summed in Microsoft Excel to get a total stream length for all the drainage within the basin. The total length of all streams in the watershed is 173 kilometers, which when divided by the basin area of 244 square kilometers, gives a drainage density of 0.7 km/km^2. Low drainage density occurs where soil materials are resistant to erosion or, conversely, are very permeable and the relief is low. The hydrologic significance of drainage density results from the fact that water and sediment yields are strongly influenced by the length of the watercourses per unit area. The channel networks are developed by long-term hydrology and erosion but, in turn, affect the amount and rate of watershed discharge. Melton (1957) discusses that low runoff rates and low drainage density generally occur together, which is true in the Nogales watershed.

Land Use

Land use is described by the Land-use regions of North America (FAO-UNESCO, 1975) as #6, which contains rapidly developing residential and commercial cities, where water is available. Figure 14 and 15 are satellite images, purchased from USGS-Eros Data Center, Sioux Falls, SD. These images can be used to identify geologic features, such as faults, land use, and vegetation coverage. This data will serve as the basis for creating land use maps in the Nogales watershed area in future studies.

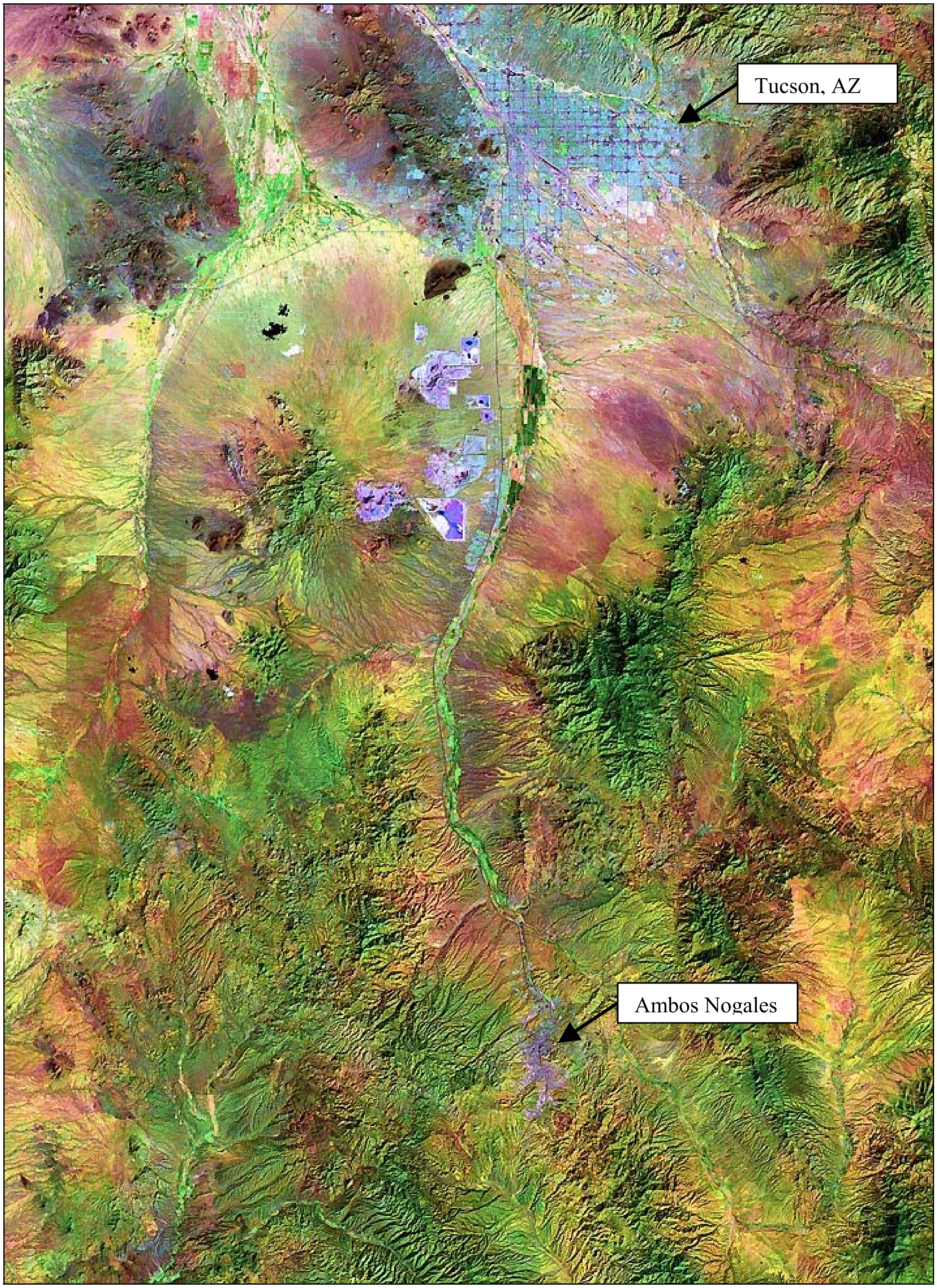

Figure 14:A Landsat TM image digital color composite of middle, near infrared and visible light derived from TM bands 7, 4 and 2 of Tucson, AZ and south to the twin cities of Nogales (Dohrenwend and others, 2001).

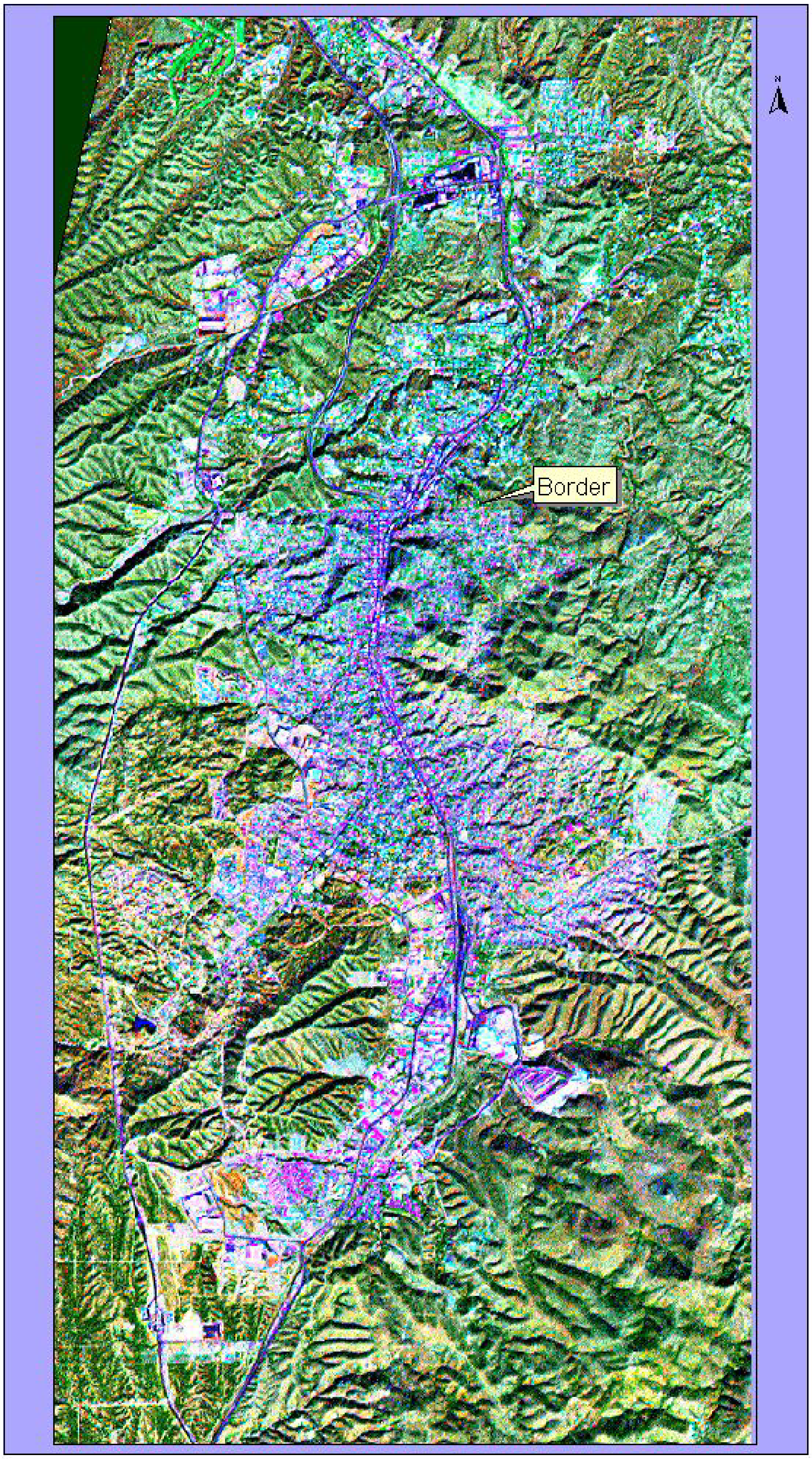

Figure 15:Band 7 (red), Band 4 (green), and Band 2 (blue) color composite of two Landsat 7 scenes (path 35 row 38 and path 35 row 39 both acquired on 13 Nov 1999). Data is UTM projected using NAD83 and the resolution is 30 m pixels. This was combined with Landsat Band 8, 15-m. panchromatic data.

Water Quality

Water delivery lines, well locality, sewer lines, roads and city boundaries maps are examples of infrastructure that describe an area (see Figures 16, 17, & 18). The ADEQ and the Arizona Department of Health Services (ADHS) tested the groundwater and surface water in the 1980's, detecting high levels of perchloroethylene (PCE) and tetrachloraethylene (TCE) in the groundwater (Varady and Mack, 1995). As a result, ADEQ began monitoring water quality in the Nogales area in 1990. They found higher levels of these substances on the Mexican side of the border. They also detected fecal coliform and volatile organic compounds (VOC's). A detailed comparison of water quality data from specific wells with the potential source maps would be useful to guide future monitoring efforts, as attempts are made to link known ground water contamination to specific potential sources of that contaminant (ADEQ, 1997; IBWC, 1998).

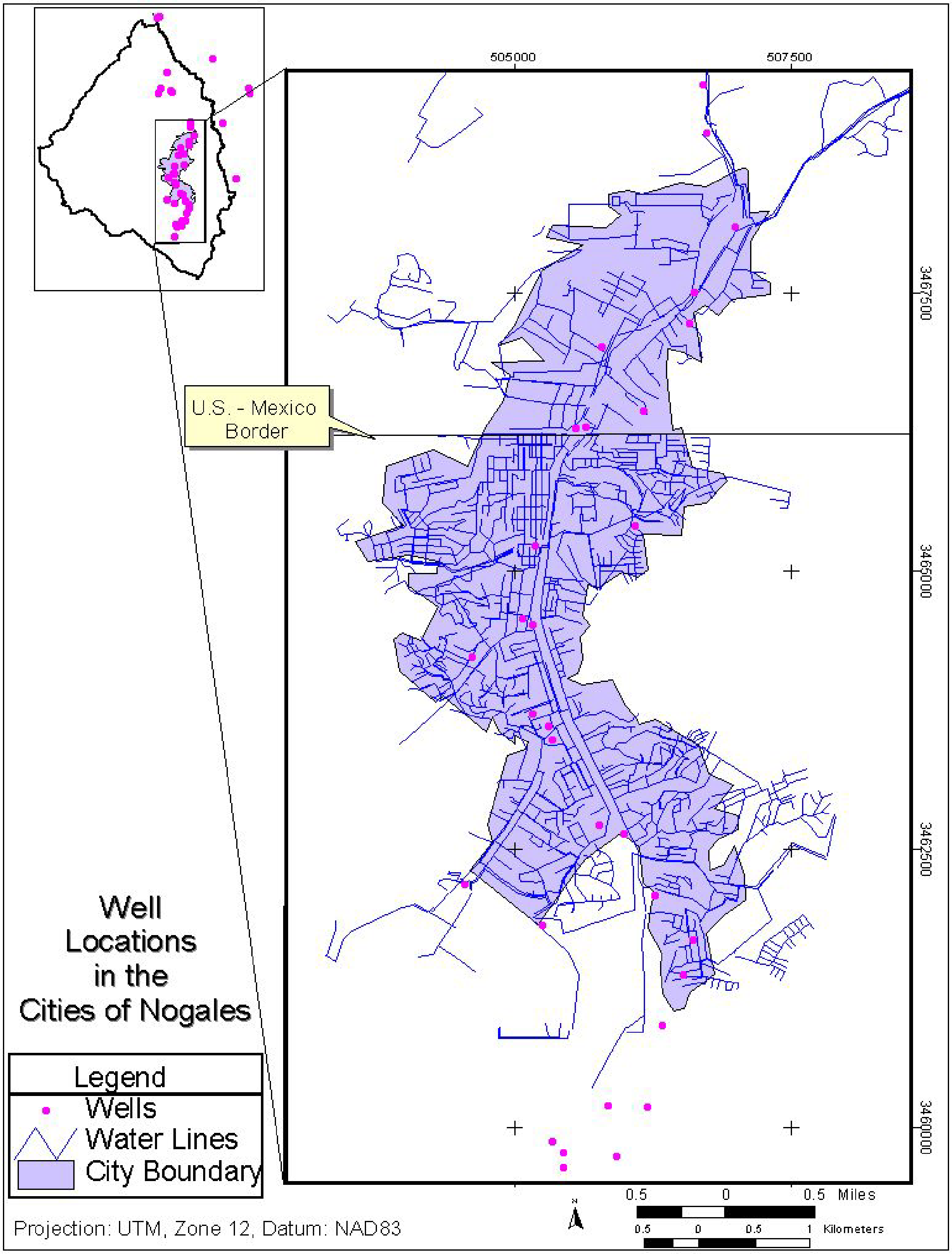

Figure 16: Well locations and water delivery lines within the Nogales watershed (modified after Varady and Mack, 1995).

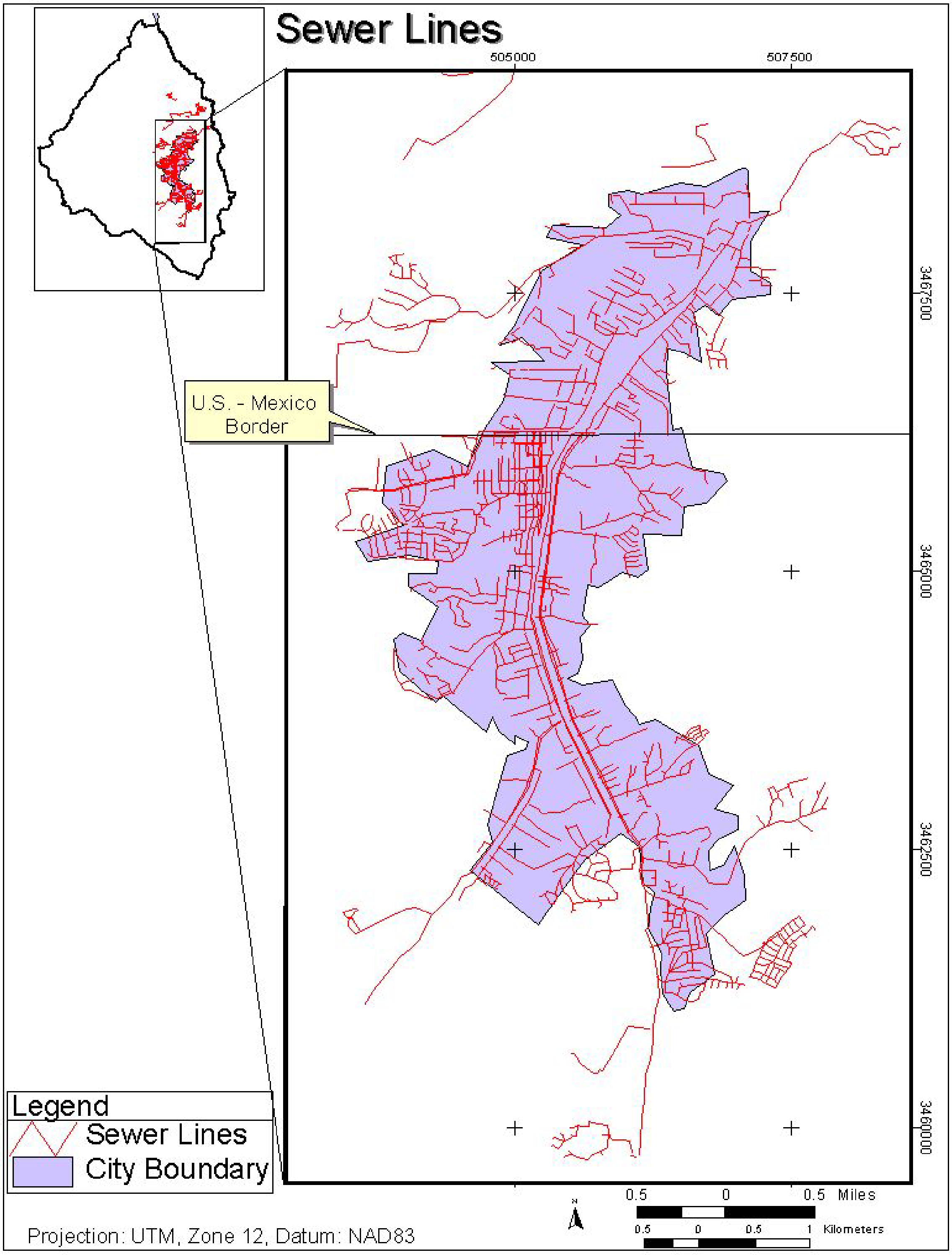

Figure 17: Sewer lines in the cities of Nogales, Arizona and Nogales, Sonora (modified after Varady and Mack, 1995).

Similar to the water delivery lines, sewer lines in the city of Nogales, Sonora are generally restricted to more affluent parts of the city. Colonias are small informal, unstructured settlements that were created to accomodate the high influx of workers who relocated after the NAFTA trade agreement. Some of these colonias are not equipped with water or sewer lines at all (Varady and Mack, 1995, Ingram and others, 1994) (fig.18).

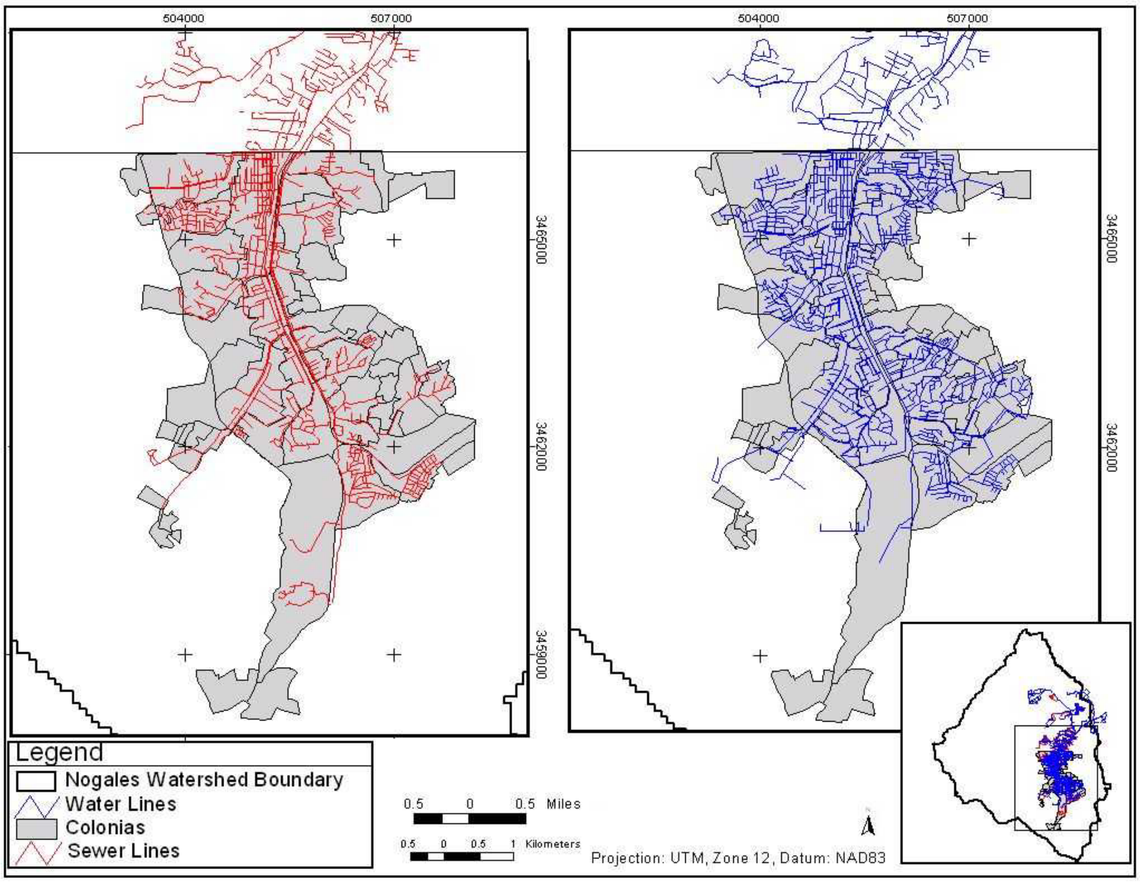

Figure 18: Image depicting those colonias in Nogales, Sonora that have no access to sewer and water delivery lines (modified after Varady and Mack, 1995).

Potential Sources of Contamination

Potential sources of contamination were identified in the Wellhead Protection Area of Valle Verde and were identified by the ADEQ; some sites include industrial and warehouse areas, which handle hazardous materials that could be spilled, automotive service and fueling stations and laundromats (fig. 20). Another area of concern is the Union Pacific Railroad corridor (formerly known as Southern Pacific), which links to the

Mexican National Railroad at the border. This corridor was identified due to its history of spills of unknown substances and the fact that railroad operations and maintenance require use of potentially toxic materials (i.e.: diesel fuel, etc.) (ADEQ, 1997). Broken sewer lines, unmonitored industrial sources, outhouses, storm runoff mixed with street refuse and septic tank fields are sources of untreated sewage and contamination (Varady and others, 1995).

Together with the USGS, students of the Desert View High School in Tucson worked with geographic positioning systems (GPS), to locate possible sites of contamination in the area and took and analyzed water samples (fig. 19). This work combined with numerous sources previously identified by ADEQ provide a layer of data that can be analyzed to see if relationships exist between any of the possible contamination sources and sites of known water contamination (fig. 20).

Figure 19: Michael and Christina, students from Desert View High School, collect water samples in Nogales.

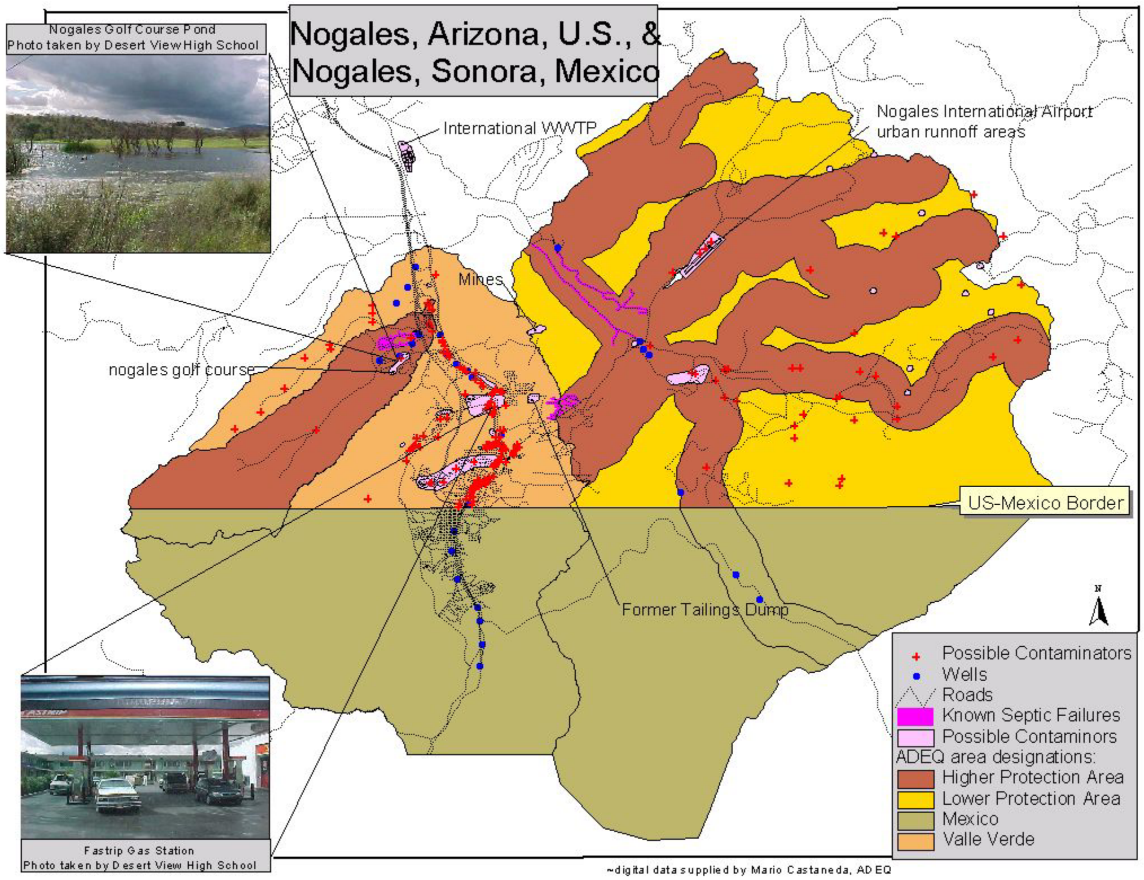

Figure 20: Sites of possible contamination identified by the ADEQ and by Desert View High School.

Surface and Ground Water Quality Evaluation

One of the more significant aspects of the database collection project involves the compilation and generation of water quality information within the Nogales watershed area. This report is preliminary and part of an ongoing project in which initial compilations will summarize existing data from ADEQ and successful cooperative efforts undertaken by the US and Mexico pursuant to the International Boundary and Water Commission (IBWC) Joint Report or Principal Engineers Relative to the Joint Monitoring of the Quality of the Groundwaters in the Ambos Nogales area, dated January 25th, 1996. This cooperative effort serves as a model for successful binational investigations of borderland area (IBWC, 1998). Future cooperative efforts between ADEQ, the USGS, and Mexican partners will continue to investigate aspects of organic and inorganic contaminant chemistry of the area. The geospatial database will be available to GIS software as well as spreadsheet or database software.

Contaminated Plume

A plume is a concentrated ‘pool’ of contaminant in water. It can migrate as a result of direction and velocity of water movement in the aquifer and due to characteristics of the contaminant itself. Trichloroethylene (TCE) had been dumped at the United Musical Instrument factory near Meadow Hills in the 1960’s. Since 1988, there has been a plan to remove a 13-acre TCE plume that was threatening the local wells and a wetlands area (fig. 21). High levels of lead and arsenic have been found in the Potrero Creek surface water but not the groundwater. The people of Nogales fear carcinogens in the plume that may cause lupus and cancer (ADEQ, 1997).

Figure 21: Photo taken by students from Desert View High School of the Nogales wetlands area.

An airborne electromagnetic (EM) survey was conducted in the Upper Santa Cruz River area in an attempt to define the geometry of the basin, the composition of sediments in the basin, and to map conductivity of basin sediments (including faults, water-saturated sediments); detailed descriptions of airborne EM surveys of this type are given in Wynn and Gettings, (1997) and Bultman and others, (1997).

The preliminary interpretation presented here is based on partial data released to the USGS as of 1998. The available data include Conductivity Depth Transforms (“CDTs”), of the 20-channel airborne EM data; a merged aeromagnetic map acquired during the survey; and a graphical representation of the flight line locations. Examples of CDTs can be seen in Figure 22. The color scale indicates relative conductivity. Hotter colors are more conductive and cooler colors are less conductive or more resistive. Crystalline rock with low conductivity (for instance a granite basement rock) will generally be blue to black, while sedimentary rock saturated with slightly saline water typical of southwestern U.S. aquifers will generally show up as red to purple colors (Wynn and Gettings, 1997, Bultman and others, 1997).

Figure 22 depicts the EM interpretation along flight line 504 of the 1998 Santa Cruz EM survey. The red line approximates the flight line. The colored cross section located below the red line is the interpretation of the EM data along flight line 504. The top of the cross section displays the surface topography along the flight line. The maximum depth of the data shown on this cross section is about 700 meters. Figure 22 may display the ground water associated with the Santa Cruz River Valley as the conductive area on the eastern side of the cross section. The water table on the western side of flight line 504 may be displayed as the bright red band near the surface.

According to the electromagnetic maps, an area of high conductivity exists just to the west of an abandoned instrument factory. This area of high conductivity may be associated with known TCE ground water contamination in this area. These are very preliminary interpretations and much more work needs to be done before a definite relationship can be established.

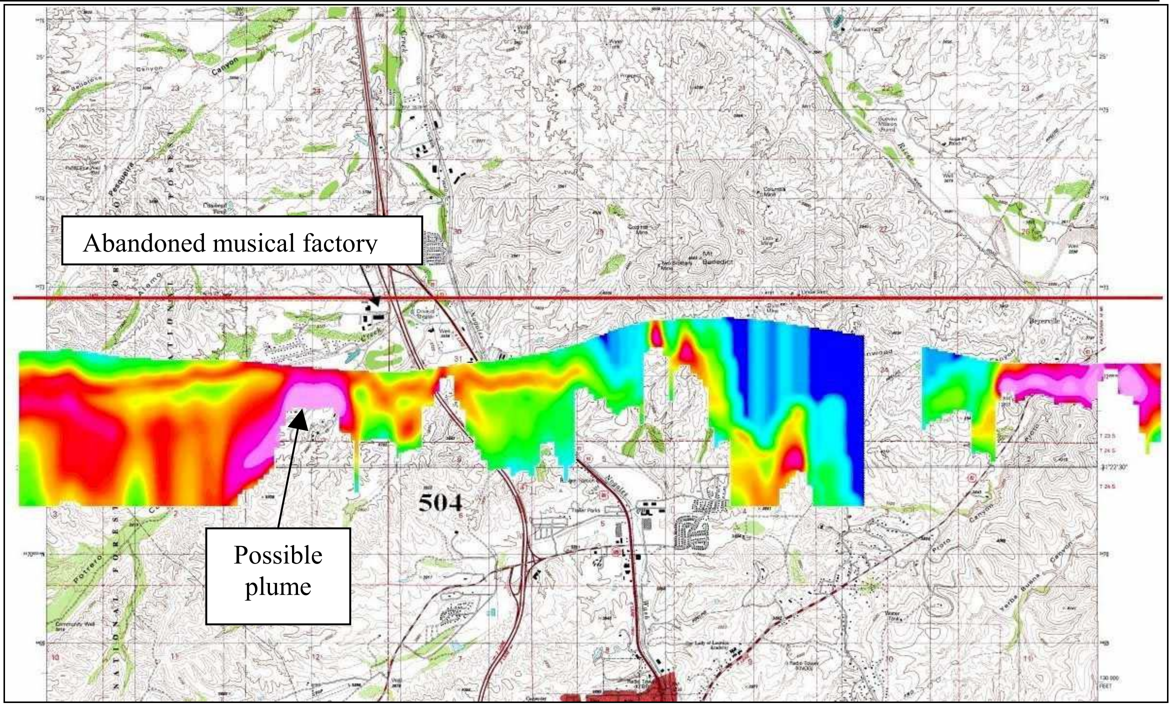

Figure 22: This Digital Raster Graphic (DRG) shows the EM flight line # 504 where hotter colors are more conductive and cooler colors are less conductive.

This dataset contains 20 flight lines in the Nogales, Arizona area. Future work will be concentrated on detailed interpretation of this information in conjunction with well log records, water quality and other stratigraphic details. It would be extremely beneficial if similar flight lines in the Nogales, Sonora area could be acquired.

Conclusions

The Ambos Nogales area, spanning the international border between US and Mexico, can be characterized within a GIS as being physically situated within a 94 square mile sub-watershed of the Upper Santa Cruz River system. Approximately half of this watershed is within Sonora, Mexico. A digitally accurate watershed delineation provides the base unit within to view existing natural resource information and urban infrastructure data in a GIS; as well as form a contextual study area for future data collection. This watershed unit is a tool for analysis and presentation of various datasets that are needed to respond to the water resource situation occurring in Ambos Nogales.

This database, when completed along the guidelines indicated in this text, will enable the modeling of potential environmental changes that can be accurately portrayed and perhaps predicted using an integrative and dynamic GIS system. With the data layers that have been created as part of this project, analysts are better able to study the dynamics of the Nogales Watershed and the effects of its various characteristics on the flow of water and the quality of that water.

This database will be analyzed for the exposure of contaminants in disease demographic context and merged with medical data to look for correlations. The US-Mexico border area is a proposed setting for this type of medical examination and the Nogales Wash watershed geospatial analysis serves as a preliminary investigation. Such studies open the door to development of methodologies that can be used to address similar problems in other watersheds or to better understand how varying factors can change the dynamics within an area.

Future Research

Many new research directions are possible for future efforts. One goal is the incorporation of new soils, vegetation, land-use, economic, and demographic data that are more robust, current, and of higher resolution than what now exists into an ongoing database that can be easily accessed by researchers for a minimal cost. Lines of communication with government agencies, educational institutions, and other interested parties across the border must be opened and improved. A more thorough analysis of all of the electromagnetic data available in the Nogales area may provide a better understanding of the aquifer condition and impacts upon it. Ongoing collection and collaboration are vital to the discovery of the dynamic relationships in the Ambos Nogales area.

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Appendix

ArcView Script for Watershed Delineation developed by Laura M. Brady & Scott Miller

```
theView = av.GetActiveDoc
theDisplay = theView.GetDisplay
theGridTheme = theView.GetActiveThemes.Get(0)
theGrid = theGridTheme.GetGrid
thePoint = theDisplay.ReturnUserPoint
mPoint = MultiPoint.Make({thePoint})
theSrcGrid = theGrid.ExtractByPoints(mPoint,Prj.MakeNull,FALSE)
theFlowDir = theView.FindTheme("Flowdir").GetGrid
theAccum = theView.FindTheme("Flowacc2").GetGrid
theWater = theFlowDir.Watershed(theSrcGrid.SnapPourPoint(theAccum,240))
' create a theme

theGTheme = GTheme.Make(theWater)
' check if output is ok
if (theWater.HasError) then
  return NIL
end
' add theme to the view
theView.AddTheme(theGTheme)
```