Geomorphic Analysis Report for the Lee Moore Wash Basin Management Study in Pima County Arizona

Prepared for and in cooperation with the
Pima County Regional Flood Control District

While under contract and in cooperation with
Stantec Consulting Inc.

August 2008

By Ian P. Sharp, P.E., CFM
JE Fuller Hydrology & Geomorphology Inc.

Registered Professional Engineer (Civil)
CERTIFICATE NO.
43845
IAN PATRICK
SHARP
DATE SIGNED 08/05/08
ARIZONA U.S.A.

Ian P. Sharp
Expires 3/31/2009

Geomorphic Analysis Report for the Lee Moore Wash Basin Management Study in Pima County Arizona

PREPARED FOR:
Pima County Regional Flood Control District
97 East Congress, 3rd floor
Tucson, AZ 85701
Pima County Contract Number 16-59-S-138098-0606, Task D

WHILE UNDER CONTRACT WITH:
Stantec Consulting Inc.
201 North Bonita Avenue, Suite 101
Tucson, AZ 85745

BY:
JE Fuller Hydrology & Geomorphology Inc.
40 East Helen Street
Tucson, Arizona 85705
520-623-3112
http://www.jefuller.com

PRINCIPAL INVESTIGATOR/AUTHOR
Ian P. Sharp, P.E., CFM

SECTIONS

APPENDICES

PLATES

TABLE OF CONTENTS

Abstract

Field reconnaissance and review of external reports and maps support a geomorphic analysis conducted as a part of the Lee Moore Wash Basin Management study, a flood control planning study of over 213 square-miles of land within Pima County, Arizona. This alluvial basin is primarily undeveloped with substantial development likely within the coming decades. The geomorphic analysis documented flow related hazards and provided recommendations to assist floodplain managers, engineers, and development reviewers in planning for future development of roads, infrastructure, and other amenities within the study area. Four geomorphic study zones were delineated based upon similar land forms and drainage characteristics, namely longitudinal slope, cross sectional shape, geologic units, soil units, and geomorphic features. Beginning up-gradient, the zones include the Pediment Zone (Santa Rita Mountains), the Tributary Piedmont Zone, the Distributary Piedmont Zone, and the Incised Zone. The study zones were further divided into sixteen geomorphic risk areas documenting headcutting, lateral erosion, and lateral migration potential. Headcutting and lateral erosion risks are greatest in the northwest and furthest down-gradient parts of the basin while lateral migration and distributary flow are found throughout the lower piedmont. Distributary flow corridors were delineated representing the portion of the flow area which is most important to maintain to minimize disrupting fluvial geomorphic processes.

1 Introduction

1.1 Purpose

The Pima County Regional Flood Control District (PCRFCD) has identified the Lee Moore Wash Basin as a critical area with the potential for extensive future development. To prepare for this development, the Lee Moore Wash Basin Management Study (LMWBMS), a flood control planning study, is being conducted. The LMWBMS includes a geomorphic analysis task to identify one-dimensional and two-dimensional flow corridors as well as to identify and document evidence of scour and bank erosion, sediment deposition, structural failures, and lateral channel migration potential. This report discusses the geomorphic analyses conducted as a part of the LMWBMS.

1.2 Study Area

The Lee Moore Wash Basin is approximately 213 square-miles in area and located entirely within Pima County. The basin covers parts of the incorporated limits of both the Town of Sahuarita and the City of Tucson. Portions of the basin are within the Santa Rita Experimental Range and Wildlife area (administered by the University of Arizona College of Agriculture) to the southwest and Coronado National Forest to the southeast (United States Forest Service). The Lee Moore Wash Basin drains to the Santa Cruz River and is generally bounded by Old Vail Connection Road to the north, Interstate 10 to the northeast, Santa Rita Road to the south, State Route 83 to the east, and the Santa Cruz River to the west. See Figure 1 which shows the study area for further details on project location.

The Lee Moore Wash Basin includes multiple smaller sub-basins and washes. Figure 2 shows the major washes which include the Gunnery Range, Lee Moore, Fagan, Petty Ranch, Flato, Cuprite, and Franco Washes. While the study area is named for the Lee Moore Wash, this wash does not show up throughout most of the basin but is located near the western periphery of the study area. The Franco Wash and its drainage area are included within the overall study area but actually drain into the Santa Cruz River, north and downstream of the inflow point of the Lee Moore Wash, thus separate of the rest of the basin.

Drainage within the basin is generally towards the west and northwest, draining to the Santa Cruz River. The flow patterns vary within the basin; tributary flow occurs in the upper basin, distributary flow within the lower to middle portion of the piedmont, and incised tributary flow near the Santa Cruz River. The vegetation within the majority of the basin is Sonoran Desert Scrub, however grassland areas are found within the higher elevations. Vegetation within the basin is currently in good condition in most of the undeveloped areas.

The majority of the basin is undeveloped and in mostly natural conditions with the exceptions of roads, fences, grazing, stock tanks, and utilities. However, much of the northern and western periphery and some areas within the middle are developed and are continuing to develop, primarily with residential structures. Figure 2 shows the project boundary along with a parcel map and drainage complaints, indications of development density and flow paths. In general, the land use intensity is increasing as development continues to progress.

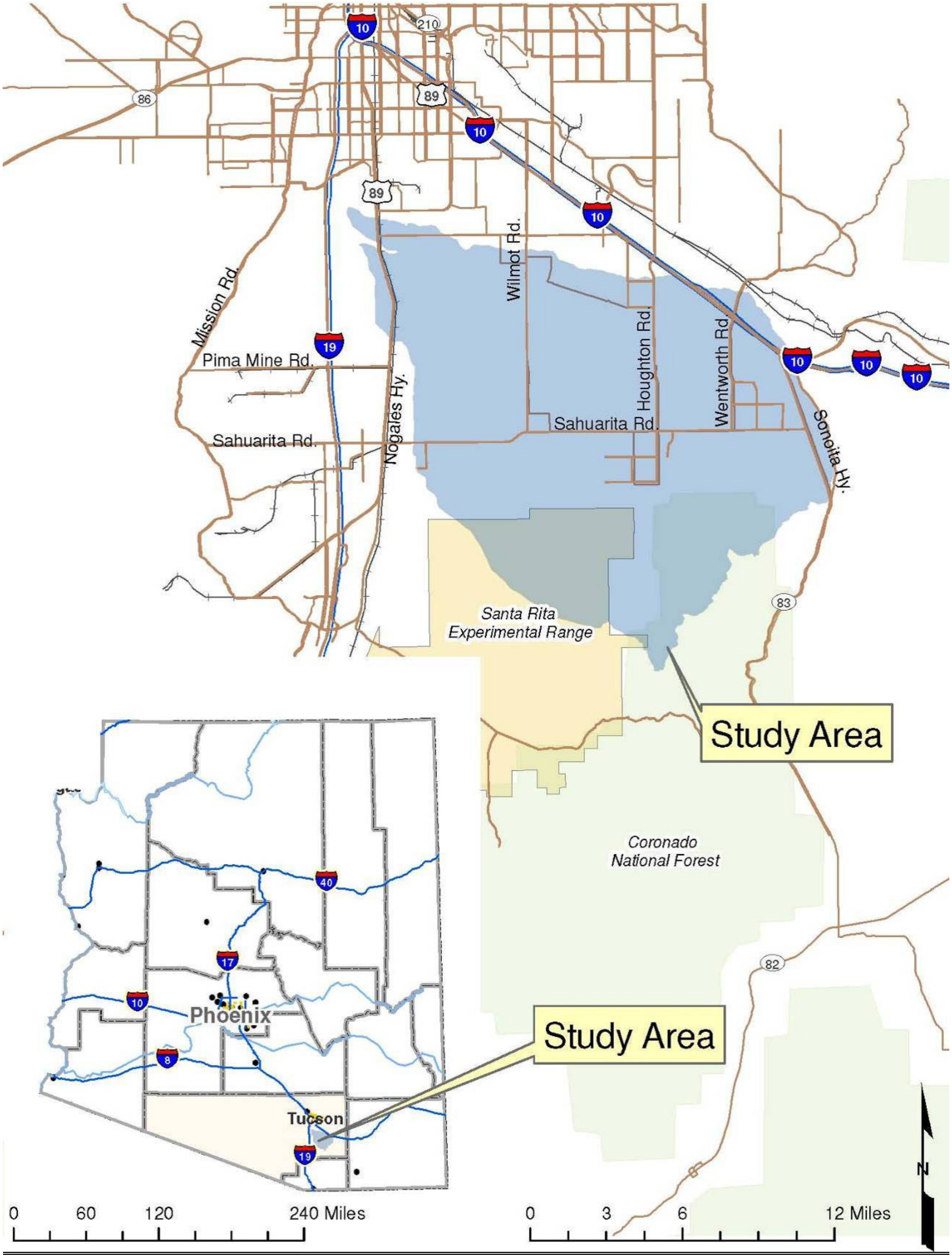


Figure 1 - LMWBMS Project Location Map

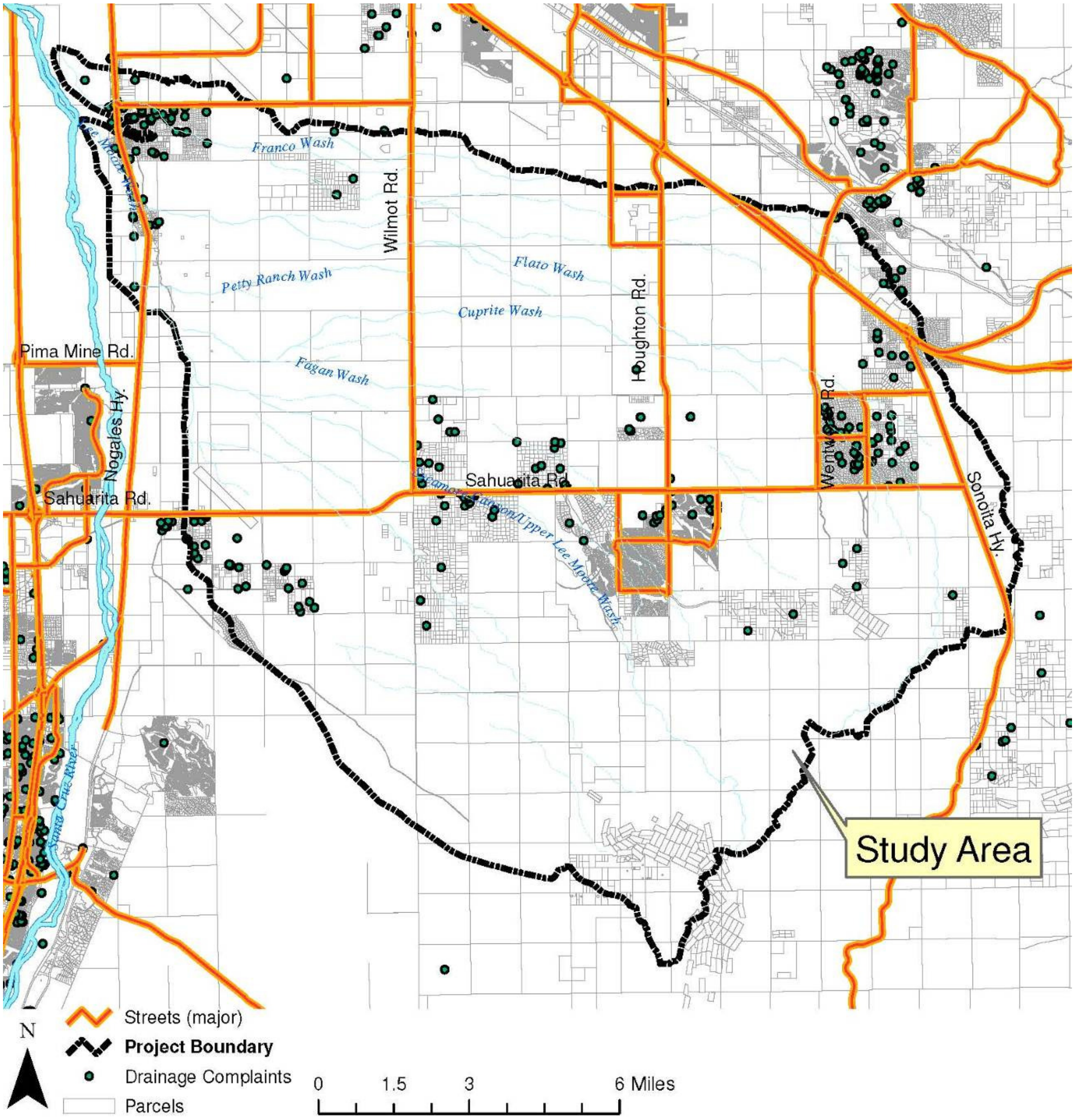


Figure 2 - Map of development and drainage complaints within LMWBMS

1.3 Geomorphic Analysis Scope

JE Fuller Hydrology and Geomorphology, Inc. (JEF) prepared this report while under contract with Stantec Consulting, Inc. (Stantec). This report documents the study and results associated with Task D of Pima County contract number 16-59-S-138098-0606. The fulfillment of the scope is summarized in the following paragraphs.

Task D1 required JEF to delineate one-dimensional and two-dimensional flow areas. This delineation was based upon the analyses described throughout report and primarily based upon identification of flow splits.

- ✓ **Flow splits were identified** on aerial maps and USGS Quadrangle maps. This process is summarized in **Section 2.5.2**
- ✓ Flow splits and the **boundary between probable one-dimensional and two-dimensional** flow are shown on **Plate 1**, **Plate 2**, and **Plate 3** which show the USGS Quadrangle maps, the PAG topography, and aerial maps, respectively.

Task D2 required JEF to "conduct field investigations to identify, inventory and document evidence of existing soil geomorphology, scour problems, bank erosion, sediment deposition and structure failures".

- ✓ **Plate 7** shows the locations of the various field identification points where photographs were obtained along with the areas of observed sediment and erosion problems.
- ✓ Photographs are included digitally in Appendix E.
- ✓ **Representative photographs** from the field investigation are included **throughout this report** along with **documentation of observations**.
- ✓ **Appendix C** provides summary information from the field work.

Task D3 required the investigation into lateral channel migration potential.

- ✓ **Lateral migration** is discussed for each of the geomorphic study zones within **Section 5**.
- ✓ **Hazard risks and maps** are discussed within **Section 6** and shown on **Plate 9**.

Task D4 required JEF to identify the significant flow corridors in sheet flow areas.

- ✓ **Distributary flow corridors** are discussed within **Section 7** and shown on **Plate 8**.

Task D5 included an interpretation of local geomorphic conditions, comparison of the project area landforms to analogous landforms within Arizona, identification of a representative study area, and identification of areas impacted by headcutting.

- ✓ **Local geomorphic conditions** are discussed throughout the report, but are discussed in detail within **Section 5**.
- ✓ A **comparison to analogous landforms** can be found in **Appendix D**.
- ✓ **Section 8** discusses the representative study area.
- ✓ **Headcutting areas** are discussed throughout the report, including **Sections 5 and 6**.
- ✓ **Headcutting areas** identified in the field are found in **Appendix C**. **Plate 9** shows areas at **risk of headcutting**.

Task D6 required JEF to define hydraulic and geomorphic related hazards identifying criteria.

- ✓ **Hazards** are discussed within **Section 6** and documented on **Plate 9**.

2 Investigation and Research Methods

2.1 Section Outline

The geomorphic analysis was based on review of maps and publications prepared by others, new analysis and field reconnaissance by JEF, and review of the hydraulic modeling prepared by Stantec and JEF as a part of this project. This section documents the work prepared previously by others that was used to support this geomorphic assessment. This section also summarizes the new work by JEF.

2.2 Review of Maps

ESRI's ArcMap software was used extensively in this assessment with all maps either obtained digitally or digitized and georeferenced. The maps obtained for this project include;

- United States Geological Survey (USGS) quadrangle maps.
- Arizona Geological Survey (AZGS) geologic maps and reports.
- Pima Association of Governments (PAG) aerial and topographic maps.
- Natural Resources Conservation Service (NRCS) soil surveys.
- Historic aerial photographs from NRCS.

2.2.1 USGS Quad Maps

The USGS 7.5 minute quadrangle maps and USGS DEM data were used as a source of topographic data. These maps were also used to reference vegetation and flow paths, to document stock ponds, and as a source of historic documentation. The study area covers nine maps which have differing contour intervals ranging from 10 to 40-feet. Plate 1 shows the USGS 7.5 minute quadrangles.

The quadrangle maps were obtained from DDS inc. <www.usgsquads.com>.

2.2.2 Surficial Geology Maps

Surficial geology maps were obtained from AZGS. These maps were prepared separately and the geologic map units are not consistent, but are described similarly and have been generalized and associated (by JEF) for the purpose of this study. The geology maps obtained cover the following quadrangle (7.5') maps;

- Tucson Southwest (Jackson, 1989)
- Tucson Southeast (Jackson, 1989)
- Vail (Richard et al, 2002)
- Green Valley and Sahuarita (Pearthree and Youberg, 2000)
- Corona de Tucson (Jackson, 1990)
- Mount Fagan (Ferguson et al, 2002)

The geology maps cover the majority of the basin's geology but omit the southernmost end of the basin which has not been mapped. The maps and accompanying reports were reviewed to aid in the geomorphic analysis.

The surficial geology maps were digitized by JEF (unless provided in digital format by AZGS) and then georeferenced relative to the related quadrangle maps.

2.2.3 *PAG Topographic Maps*

In addition to the quadrangle maps, topographic mapping from PAG was used in this study. This digital DEM and digital terrain model (DTM) data covers the majority of the basin but excludes much of the southern limit. **Plate 2** shows the PAG topography with a 10-foot contour interval. Topographic data was used to assist in the delineation of one-dimensional and two-dimensional flow locations and to assist in the delineation of geomorphic study zones.

PAG topographic data were supplied digitally by Stantec and originally obtained from PAG.

2.2.4 *Aerial Maps*

Aerial maps prepared by PAG were used in the delineation of one-dimensional and two-dimensional flow locations, to compare historic data to recent data, and to assist in the delineation of geomorphic study zones and hazards. Plate 3 shows the aerial maps which cover the project area. Sections within Townships and Ranges (TTRR) 1513, 1514, 1613, 1614, 1615, 1616, 1714, 1715, 1716, and 1717 were flown in 2005. The sections within 1814, 1815, and 1816 were flown in 2002. Additional aerial maps in the form of 2005 digital ortho quarter quads (DOQQs) were used in the analysis to supplement the PAG data.

PAG aerial maps were supplied by Stantec and originally obtained from PAG. DOQQs are available from the following GIS server ;< http://129.219.93.216>.

2.2.5 *Soils Maps and Soil Zones*

The LMWBMS covers an area mapped within three detailed NRCS soil studies; "Parts of Cochise and Pima Counties, Arizona", "Tucson-Avra Valley Area, Arizona", and "Pima County, Arizona, Eastern Part". Two georeferenced sets of soils data maps were obtained from the NRCS.

- Soil Survey Geographic (SSURGO) data base maps. These are the most detailed soils maps and are georeferenced versions of the three detailed soil studies. *SSURGO maps were obtained from NRCS via <http://www.ftw.nrcs.usda.gov/ssur_data.html>.*
- State Soil Geographic (STATSGO) Database maps. These are less detailed and represent a generalization of the SSURGO soil survey maps. The STATGSO mapping is generally good for use in basin-wide studies such as this one. *STATSGO maps were obtained from NRCS via < http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/>.*

2.2.6 *Historic Aerial Images*

Multiple sets of historic aerial photographs are found in the study area with the oldest being a set held by the NRCS dating back to 1936. A mosaic of the 1936 aerial images is found on Plate 6. The historic photographs were compared to more recent photographs to examine for evidence of geomorphic changes such as lateral migration as well as factors which could alter channel positions in the future.

Hard copies of the photographs were obtained from the local NRCS office and then digitized and georeferenced (by JEF) relative to the current aerial maps.

2.3 Review of Reports

Several reports were reviewed for application in this assessment. The various reports associated with the surficial geology maps were reviewed extensively to decipher the geologic map units and to gain further understanding of the geomorphic processes in the study area. Reports reviewed include;

- ‘Flood Hazards of Distributary-Flow Areas in Southwestern Arizona’ and ‘Potential Flood Hazards and Hydraulic Characteristics of Distributary-Flow Areas in Maricopa County’. Both of these reports are USGS publications by Hjalmarson (1991 and 1994, respectively) which give guidance on delineating distributary flow areas and their hazards with local application.
- ‘Rio Verde Area Drainage Master Plan, Geomorphic Analysis Report, Task 3.4 for the Rio Verde ADMP for the Flood Control District of Maricopa County’, JEF (2002) report. This report was referenced in the comparison to analogous landforms as the study area contained similar features to this study area.
- ‘The Climate of the US Southwest’. This 2002 climate research paper by Sheppard et al of the University of Arizona was used to document the hydrologic setting.
- ‘State Standard for Identification of and Development within Sheet Flow Areas’, (1995) Arizona Department of Water Resources report. This often used manual was reviewed to assist in the flow analysis and recommendations.
- ‘Channel Stability Assessment for Flood Control Projects’, (1994) US Army Corps of Engineers publication. This manual was used to assist in the geomorphic assessment.

2.4 Review of Other Maps and Databases

In addition to the above maps and reports, the following maps, websites, and databases were used in this analysis.

- ‘Map of Arizona Showing Selected Alluvial, Structural, And Geomorphic Features’, USGS publication by Cooley (1977). This broad scale geology map was used in the comparison to analogous landforms.
- ‘Santa Rita Experimental Range Digital Database’, USDS and U of A funded digital database for the Santa Rita Experimental Range (SRER). This data was used to obtain historic documentation including historic images. These images are repeat photography ground shots taken over the years of 1902 to 2000 at several locations. Observations from the historic images are made in Section 5.
- < http://www.wrh.noaa.gov/> by the National Weather Service. This website was used to document the hydrologic setting.
- <http://www.wrcc.dri.edu/summary/climsmaz.html>, by the Western Regional Climate Center. This website was used to document the hydrologic setting.

2.5 Original Work by JEF

Original work by JEF for this project includes field reconnaissance, delineation of one-dimensional and two-dimensional flow locations, delineation of broad geomorphic study zones, and delineation of flow related hazards. This work is detailed throughout the remaining sections of this report and summarized in the following sub-sections.

2.5.1 Field Reconnaissance

Detailed field reconnaissance was performed during the course of this study and is summarized in Section 3. Field visits were conducted throughout the project area with over 400 digital photographs obtained at approximately 200 locations to document sedimentation or erosion, structural failure, headcutting, stable locations, landscape or ground views, or other areas of interest. The latitude and longitude were recorded (WGS 84) along with field notes. Field photographs and notes can be found in digital format in Appendix E. Many of the photographs have been included within this document to support the text in subsequent sections

2.5.2 *1D and 2D Flow Locations*

The boundary between one-dimensional and two-dimensional flow modeling divides the basin into areas which will generally have one-dimensional flow, (channelized) flow which can be easily modeled by solving the Energy equation with the standard step method (e.g. HEC-RAS), and areas which will generally have two-dimensional (sheet) flow which must be modeled with a more detailed physical process model (e.g. FLO-2D). This boundary has been delineated based on field reconnaissance and aerial maps which determined locations of flow divergences and confluences. This was followed by review of the topography which was analyzed for contour crenulation and flow path slope. (Contour crenulation refers to the shape of the serrations or waves formed by contour lines). The topography was studied in greater detail where the contour crenulation is minimal. Areas where the crenulations are small and close to each other (minimal crenulation) will tend to have braided drainage networks, distributary flow, and/or flow splits. Large crenulations may indicate contained flow patterns. Flow path slope was analyzed for changes in overall slope from one region to another as well as to determine areas where flow path slope is relatively consistent. Changes in slope indicate a possible change in flow type and sediment transport and production capacity. The aerial maps were also reviewed to identify vegetation and obstructions. This delineation was one of the earliest products of this assessment and was provided to Stantec and PCRFCD in order to determine the limits of FLO-2D modeling by JEF.

2.5.3 *Geomorphic Study Zones*

Division of the study area into smaller, more homogenous areas simplifies the review. Therefore, the study area has been divided into four broad geomorphic zones based on the topographic maps, the surficial geology maps and descriptions, and the delineation of one dimensional and two dimensional flow areas. These study zones contain similar geomorphic features and hazards. The geomorphic zones are the Pediment Zone, Tributary Piedmont Zone, Distributary Piedmont Zone, and the Incised Zone.

2.5.4 *Flow Related Hazards Maps*

Based on the review of all of the above items, flow related hazards maps were prepared which further divide the study area into even more homogenous zones. These zones have similar flow related hazards such as lateral migration, scour potential, lateral erosion, and head cutting.

2.6 Review of Hydraulic Modeling

Hydrologic and hydraulic modeling of the project area was conducted by JEF and Stantec and is documented in separate reports prepared for the LMWBMS. Stantec prepared HEC-HMS hydrologic models and (one-dimensional) HEC-RAS hydraulic models of the tributary areas generally to the north of the Cuprite Wash, including the Flato Wash. The remainder of the study area was analyzed by JEF using (two-dimensional) FLO-2D models which also computed direct runoff. The result of both efforts included floodplain delineations. The floodplain delineations were reviewed as a part of this report to assist in delineation of flow related hazards and distributary flow corridors.

3 Field Reconnaissance

3.1 Section Outline

Field reconnaissance was conducted to identify structural failures, flow splits, geomorphic processes, and to document current conditions at the time of this study. This section summarizes the field reconnaissance conducted to support this study.

3.2 Field Observation Summary

A total of four field reconnaissance visits were performed on the dates of November 11, 2006, November 21, 2006, December 12, 2006, and February 28, 2007. Appendix C provides a listing of all of the photo identification points and a summary of observations. Photographs and notes were taken at several points of interest which have been broadly categorized under the General Description column of Appendix C. The general description recorded in Appendix C lists the principal issue noted. The term ‘stable wash’ indicates that scour and or aggradation were not observed or were not excessive.

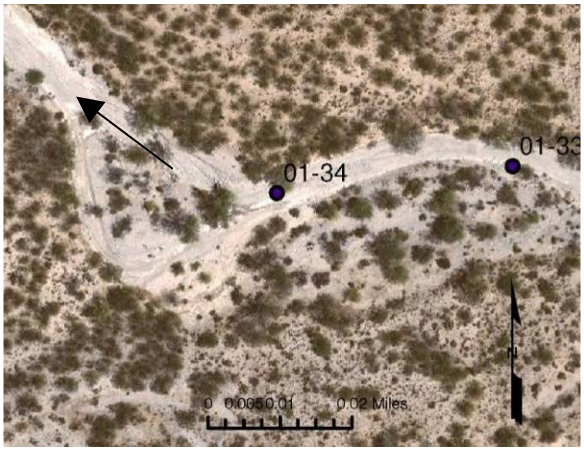
The nomenclature used in indexing the photographs starts with ‘LM’ followed by a field visit number, a location identification number, and location specific photograph number. An example is LM02-43-04. This photograph would have been obtained during field visit 2 at location 43 and would be the fourth photograph at this location. Plate 7 shows the location of the various field photograph identification points. Figure 3 shows a selection of sample photographs of the various general descriptions used in Appendix C.

Landscape view (LM01-02-01) *Ground shot (LM01-14-01)*

Figure 3 - Representative field reconnaissance photographs

Stable wash (LM01-30-01)

Lateral erosion (LM03-50-02)



Avulsion aerial view

Avulsion (LM01-34-04)

Confluence (LM03-09-01)

Braid (LM01-18-01)

Figure 3 - Representative field reconnaissance photographs (continued)

Flow split (Panorama of LM01-43-01 and 02)

Incision (LM03-11-01)

Scour (LM03-23-06)

Figure 3 - Representative field reconnaissance photographs (continued)

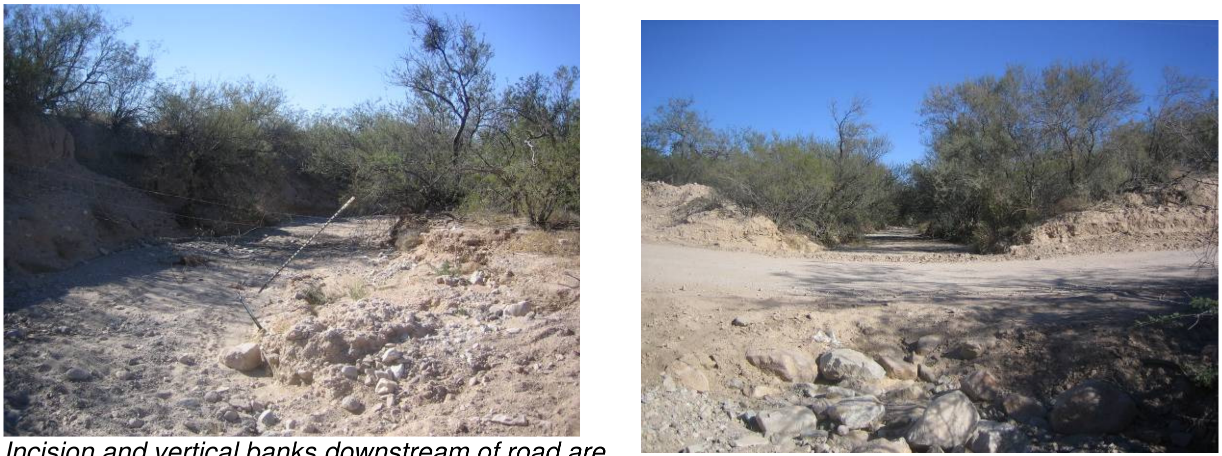
In many cases, more than one geomorphic process was noted, such as vertical scour and lateral erosion. Additionally, the cause of the observed process was not immediately clear in the field and further investigation was required. In many of these areas, an observation of incision is obviously a result of headward erosion (headcutting). This in not often the case where scour and/or incision was noted downstream of a road crossing but not above it. A lack of scour (or deposition) upstream of a road associated with scour downstream could indicate concentrated flow generating a scour hole, could be a result of headcutting eliminated by the road crossing, or a combination of the two. Where incision was found downstream of a road crossing but not above, the term abrupt scour difference has been used in Appendix C to indicate this phenomenon is occurring.

Following are a couple representative locations where scour was greater downstream of a road crossing. The first example (Figure 4) is a case of scour downstream of a road crossing with no significant flow path or scour upstream of the road crossing. The observation occurred in the upper basin, away from the significant headcutting found nearest the Santa Cruz River. The second observation (Figure 5) is of a more significant wash lower in the basin. The banks downstream of the road are vertical while upstream of the road they are sloped and vegetated. The bed material is visibly coarser downstream of the road. This location is close to the Incised Zone where the headcutting is most active and the observation is most likely of a headcut terminated by a road in association with local scour generated by the road crossing.

Scour extends some distance downstream of road (LM01-09-02)

No scour or significant drainage upstream of road (LM01-09-03)

Figure 4 - Representative abrupt scour difference location 1



Incision and vertical banks downstream of road are significant (LM01-49-02)

Well vegetated, sloped banks upstream of road (LM01-49-01)

Figure 5 - Representative abrupt scour difference location 2

Five figures are included to give visual representation of Appendix C. Figure 6 shows the locations of the broadly categorized geomorphic processes, excluding the locations of aggradation or sedimentation as these were limited and generally occurred in areas with other geomorphic processes. This figure also shows the limits of Holocene era or younger deposits (shown as Qy or younger); note the correlation between observed geomorphic activity and the limits of these younger deposits.

Figure 7 shows the locations where headward erosion (this term may be considered synonymous with headcut within this report) and nick points (where a headcut meets a resistant material) were observed. Locations of headward erosion refer to areas where channel incision was observed and the inferred cause was headcutting. Section 6.3.2 provides more explanation of these terms and provides some example photographs of headward erosion.

Figure 8 shows the locations where scour was observed downstream of the point of interest but not upstream, typically at dip road crossings. These locations were labeled ‘abrupt scour difference’ locations.

Figure 9 shows the locations where vertical banks were observed.

Figure 10 shows the locations of naturally occurring and human influenced geomorphic issues. Geomorphic processes which are solely natural are shown as natural. An example of a natural process would be vertical banks on an undisturbed channel in a bend. Examples of human influenced processes include scour caused by diversion of flow or from culvert outflow. The human influenced processes may often include or be accelerated by natural influences. An example would be placing a culvert in a headcutting channel, is the scour at the outlet caused by flow concentration, headcutting, or both? Therefore some amount of conjecture is required when assigning whether a process is natural or human caused. Additionally, the amount of human interference (relative to naturally occurring issues) may be disproportionately shown as observations were made where access is available, primarily along and near roads and development.

Note that the following figures show the geologic zone boundary. This delineation is discussed within Section 5 but is shown on these figures for reference.

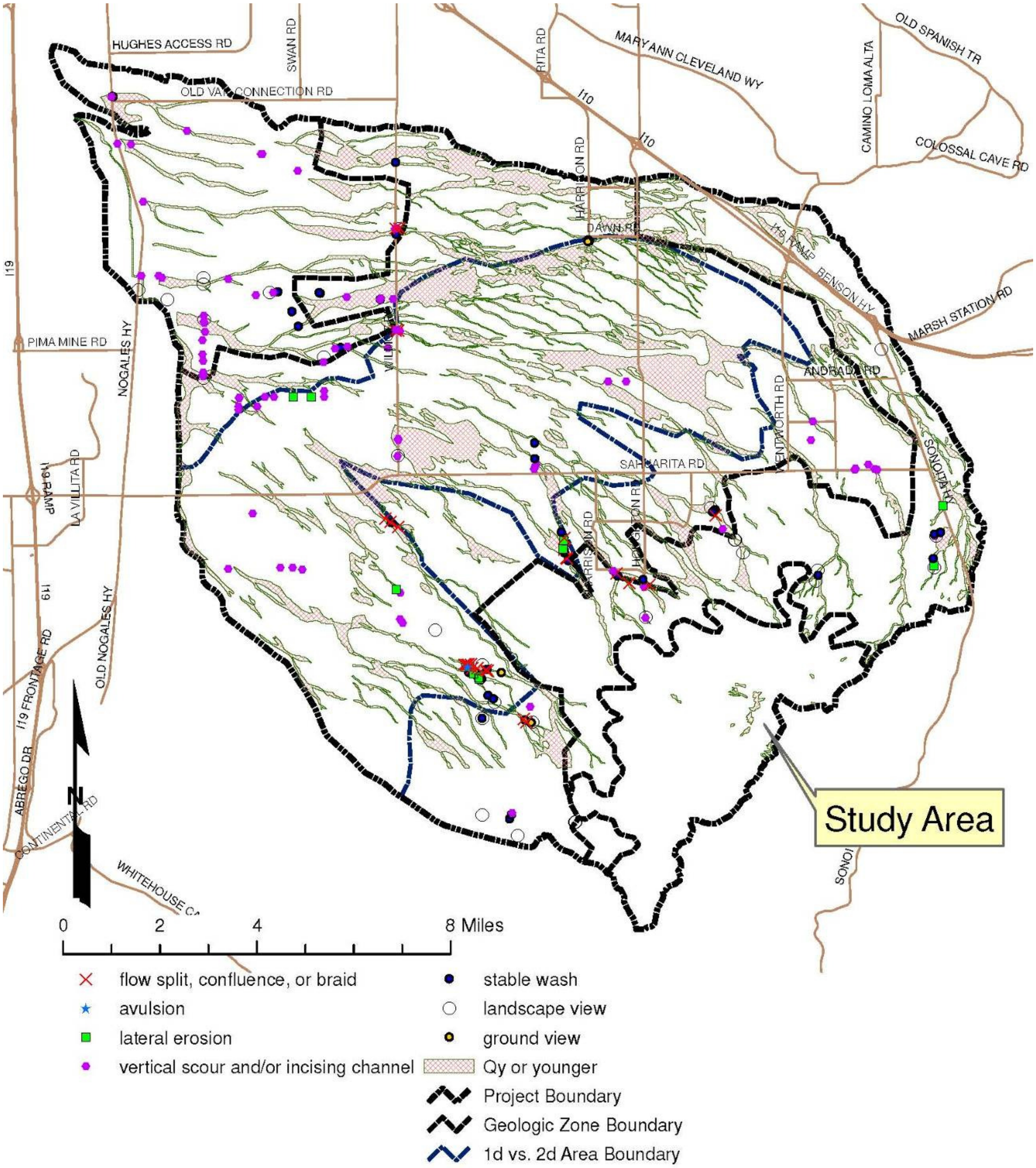
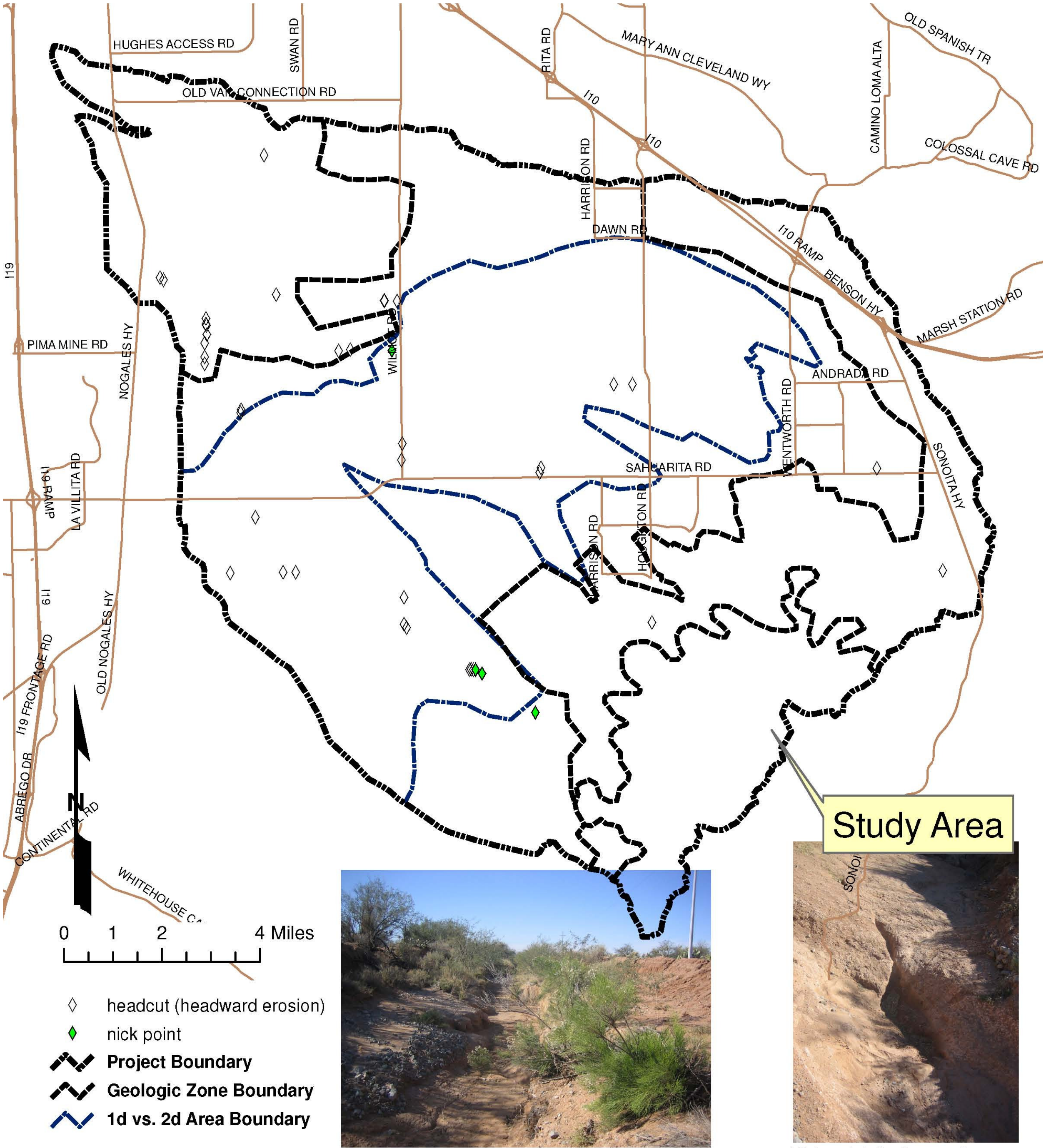


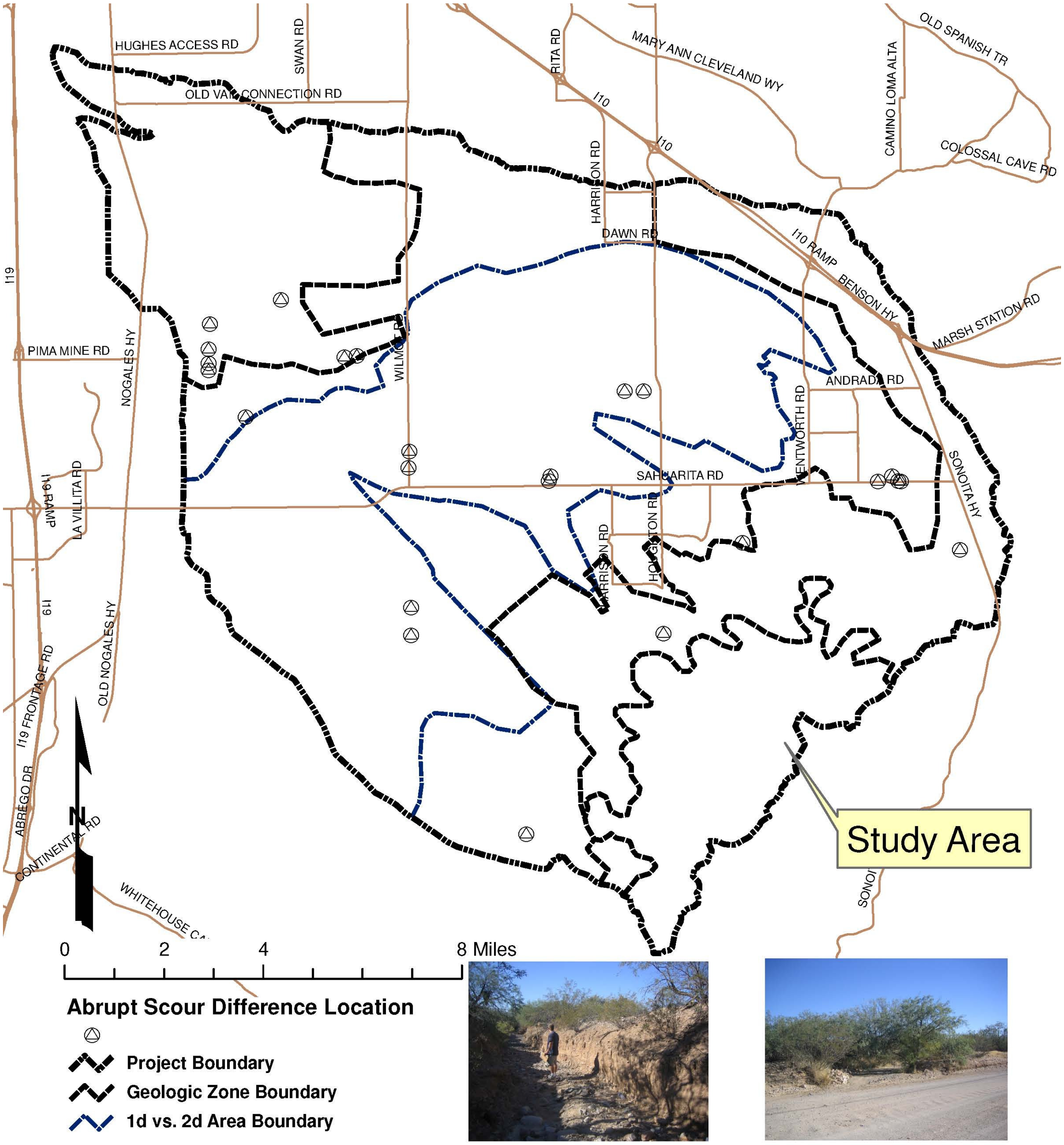
Figure 6 - Generalization of observed geomorphic conditions



Headcut, facing upstream

Nick point, facing upstream

Figure 7 - Observed locations of headward erosion



Incision downstream of road.

Same wash, upstream of road.

Figure 8 - Observed locations of abrupt scour differences

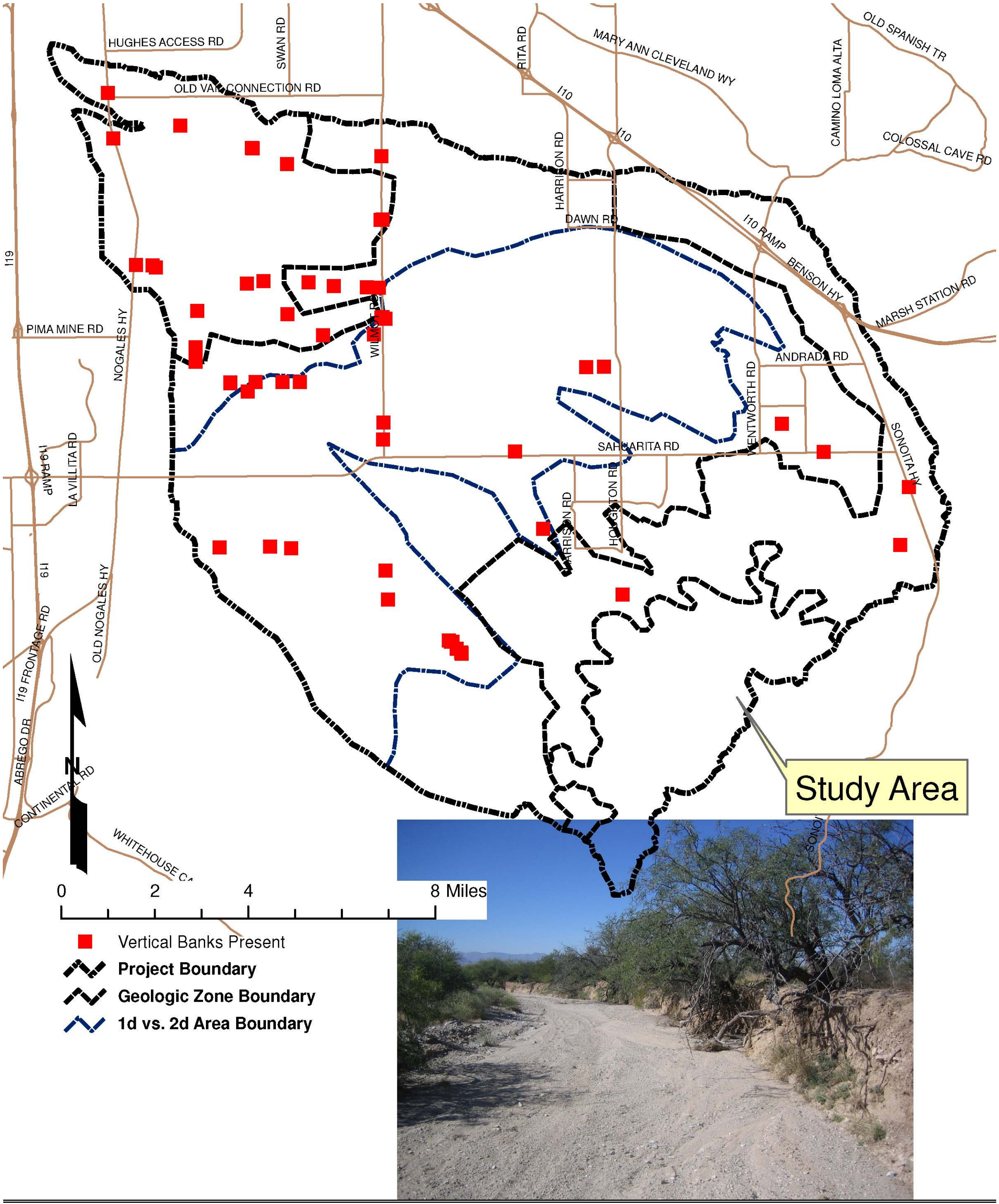


Figure 9 - Observed locations of vertical banks as found in field reconnaissance

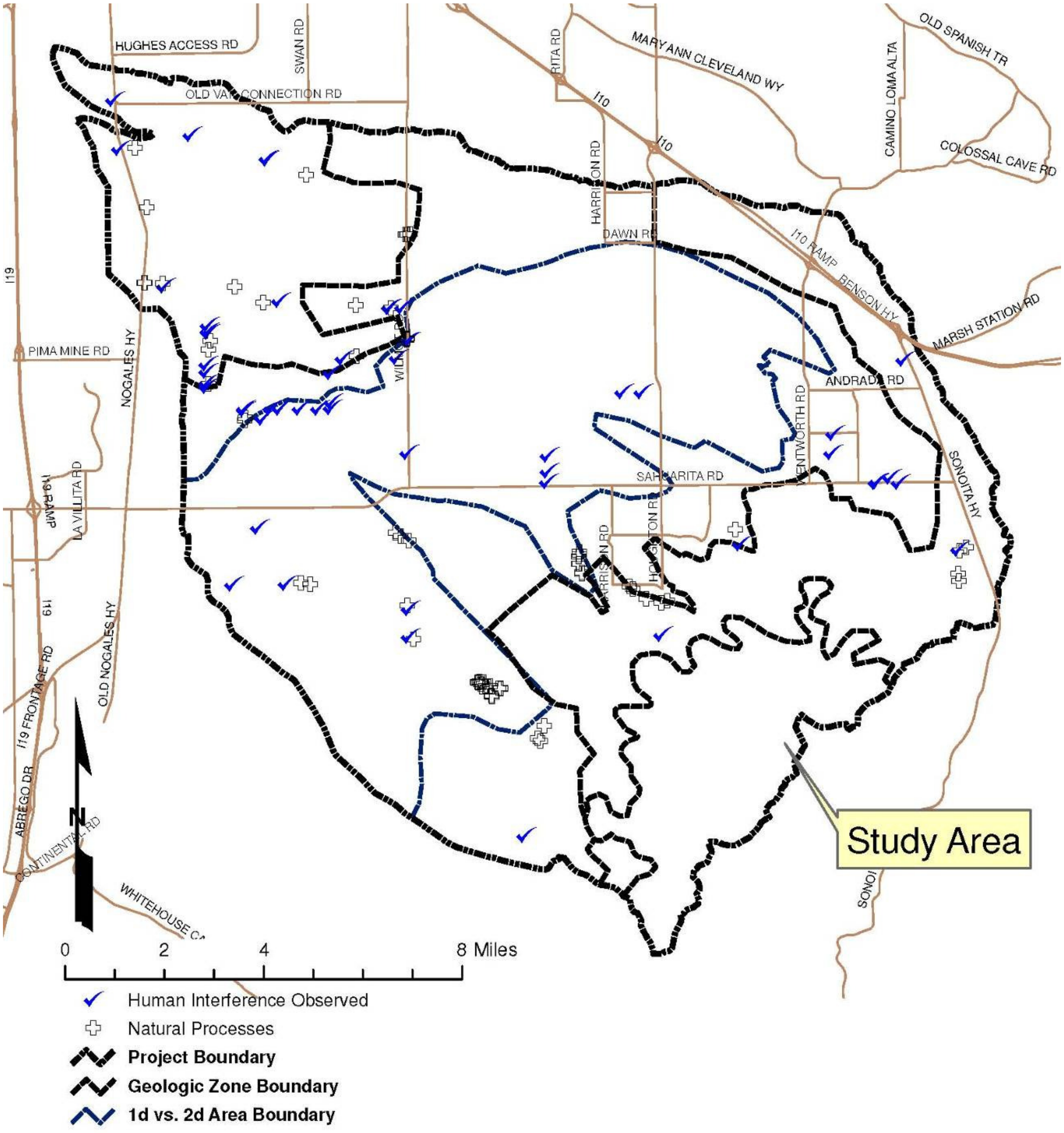


Figure 10 - Observed locations of naturally occurring and human activity influenced geomorphic processes

3.3 Flow Diversion Structures

Many flow diversion structures including stock tanks, borrow pits, flow diversion structures, and water treatment facilities have been identified in the study area by Stantec. The following figure shows an overview of their locations.

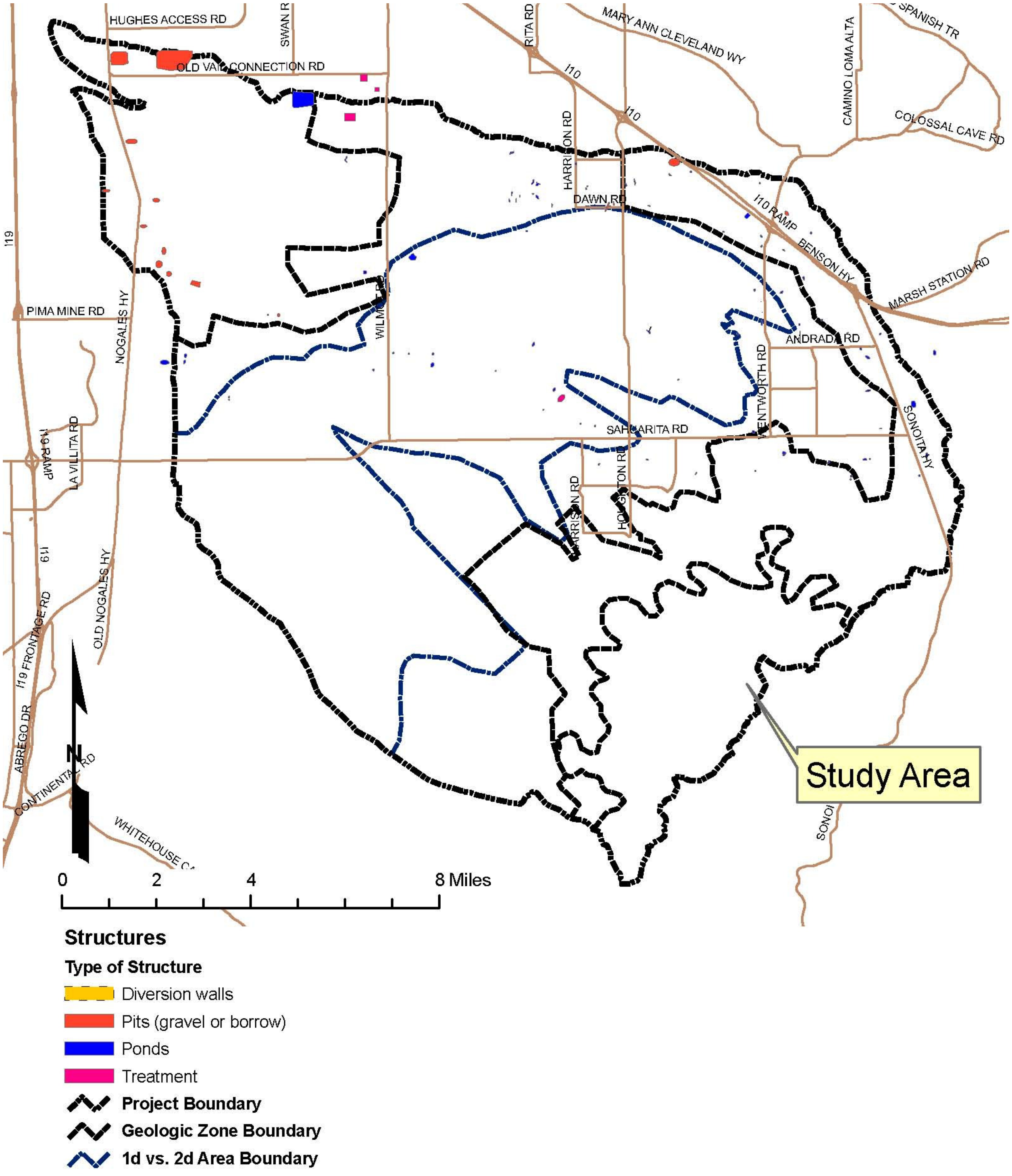


Figure 11 - Identified flow diversion structures and ponds

3.4 Drainage Crossings

Dozens of drainage crossings were observed throughout the course of the field investigations with notable drainage crossings documented within Section 5. The crossings can be generally categorized as underfit culvert crossings, high water crossings, and low water stream crossings (ford or dip crossings). Performance varied for these types of crossings in regards sediment transport and their impacts to the fluvial systems, depending upon the design and maintenance.

Underfit culvert crossings are typically crossings where a relatively small culvert is placed within an embanked road, damming a wash. These crossings did not perform well. High water culvert crossings include culverts and bridges which appear to be capable of handling large runoff events. Large box culverts and bridges were typically found along the major roads and highways within the lower basin and along Highway 83. Smaller culverts were found throughout the remainder of the study area and were typically corrugated metal pipes with no headwall. The larger culvert crossings (i.e. those that were large enough to accommodate runoff of less frequent events) typically performed very well while smaller culverts typically generated extensive scour downstream of the culvert, possibly related to high outlet velocity and greater flow concentration. Low water crossings include vented and unvented ford crossings which appear to be designed to allow the runoff to cross over the road for most events. These crossings occur where the road simply dips down into the channel and were the most common crossings observed. Most of the rural area dip crossings are unpaved roads with no drainage improvements. Concrete ford crossings were found in the larger washes of the incised zone.

Vertical bank erosion was common both upstream and downstream of the culverts within headcutting areas. Other than areas where headcutting has occurred, vertical scour downstream of bridges and large culverts was not typically observed unless a culvert crossing was situated at a channel bend or was skewed to the channel alignment. Limited scour was observed downstream of smaller culverts without erosion control measures. Headwalls and outlet dissipation structures were rarely found in the study area and the resulting erosion which was observed illustrates the need for their use. Severe vertical scour was observed along the large washes nearest the Santa Cruz River.

3.5 Roads Paralleling Flow Paths

Extensive scour and structural failure were found in the general area west of Wilmot Road and north of Sahuarita Road. This area is primarily undeveloped except for access roads and a few other features. The scour and structural failure is significant in areas where roads have been carved which parallel flow paths. These roads have captured historic flow paths and redirected flow patterns. The channels paralleling the roads have incised in response to multiple geomorphic processes including local scour from the roads capturing flows and primarily from system wide scour in the form of headcutting. Discussion of specific observations is included within Section 5.

4 Climate, Hydrology, Geology, and Soils

4.1 Section Outline

Being within the southwest United States, the Sonoran Desert, and the Basin and Range Physiographic Province, the study area is within a unique region with an interesting climate and geomorphic features. This section provides important background information summarized from detailed studies and reports specific to the local and overall region.

4.2 Climate and Hydrologic Setting

The following information was summarized from Sheppard et al (2002), McPhee et al (2004), Richard et al (2002), and literature available online from the NWS and the WRCC.

Annual runoff within the study area is relatively low and typical of the southwest United States. Low annual precipitation is a result of a “subtropical high-pressure ridge” over the region (Sheppard et al, 1). Variation in climate occurs and is primarily due to the position of the region within two atmospheric regimes (Sheppard). Precipitation and runoff vary from year to year and decade to decade. Furthermore, precipitation and runoff vary throughout the year, with 50 percent of the annual rainfall occurring in between July and September. A typical hydrologic year will have two peaks in precipitation with one in the winter and one in the summer. Of importance to the geomorphology is this; as the storm patterns vary with season (and year), so do runoff and sediment transport.

Summer precipitation is generally associated with the North American Monsoon, a shift in statewide wind patterns. The primary direction of wind in Arizona is from the west (from California) and northwest (from Nevada) during the winter. The summer season brings a shift of wind direction with winds coming from the south and southeast, bringing moisture from the Gulfs of California and Mexico. This causes a relatively large shift in statewide moisture conditions. Monsoonal thunderstorms develop in response to this moisture and intense surface heating of the Arizona desert floor. These storms cause severe, localized (flash) floods with high volumes and peak discharges in small basins while large basins can respond with low runoff peak discharges and volumes. Locally, the monsoon season ‘starts’ when the average daily dew point is 54 degrees or greater for 3 consecutive days with July 3rd being the average start date (NWS, <http://www.wrh.noaa.gov/twc/monsoon/monsoon.php>.)

Winter precipitation is generally produced by frontal storms originating in the North Pacific Ocean. Winter storms are typically longer and less intense, allowing for greater infiltration into the soil than intense summer storms. Frontal storms, which tend to develop in winter and early spring, generate slow to moderate rainfall intensities over large (often statewide) areas over long periods (days and weeks). A typical winter storm can continue for several days and is made up of individual frontal storms with or without small breaks between the storms.

Another storm pattern worth mentioning is the cyclonic storm which is caused by dissipating tropical cyclones or hurricanes. These storms are also called tropical remnant storms and usually occur during late August through October. General summer storms within Pima County are often a result of these tropical remnants. These storms produce a significant amount of rainfall and are the least frequent of the three storm types.

4.2.1 Rain Gages

Multiple rain gages have been operated throughout the basin over the past several decades. Figure 12 shows the location of the gages throughout the study area. The largest grouping of gages is in the Santa Rita Experimental Range (SRER) which has operated gages since 1922. Monthly precipitation data sets were obtained from the Santa Rita Experimental Range Digital Database.

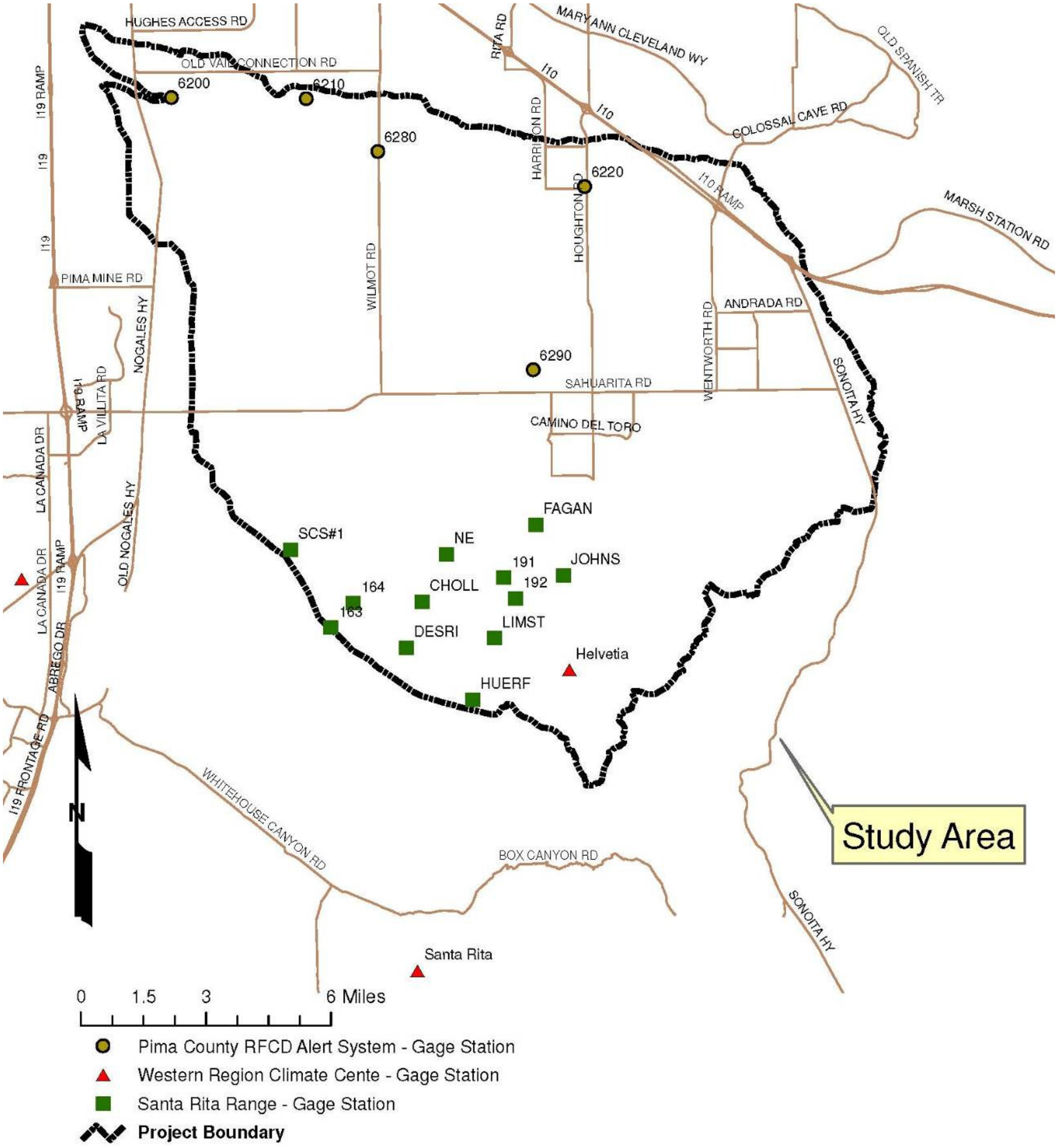


Figure 12 - Location map for precipitation gages

Of the gages shown on Figure 12, 10 of the SRER stations had significant periods of record. Table 1 summarizes the precipitation data for these stations. The maximum monthly rainfall occurred in either the month of July or August for all stations and the minimum occurred in May for all stations.

Table 1 - Summary of Santa Rita Experimental Range Gages

Gage Name	Period of Record*	Minimum Ave. Monthly Rainfall (inches)	Maximum Ave. Monthly Rainfall (inches)	Average Yearly Rainfall ** (inches)
163	7/1939 - 11/1949	0.09	2.83	11.68
Enclosure 164	7/1939 - 12/2006	0.15	2.67	12.02
191	7/1939 - 11/1949	0.04	3.02	12.88
192	7/1939 - 11/1949	0.05	3.08	13.66
Cholla	7/1939 - 8/1950	0.07	2.97	12.31
Desert Rim	7/1939 - 12/2006	0.17	2.64	12.48
Fagan	5/1972 - 12/1982	0.15	2.25	11.72
Huerfano	6/1922 - 12/2006	0.18	3.19	14.77
Limestone	7/1939 - 12/2006	0.19	2.89	13.81
Northeast	6/1922 - 12/2006	0.16	2.80	13.42
All Stations	-	0.12	2.74	12.88

* - Period of record is noncontiguous, some years omitted
** - Sum of the average monthly rainfall depths

The average monthly rainfall depths are represented on Figure 13. The values were calculated based upon the monthly values in the SRER Digital Database. This figure shows the seasonal variation in rainfall depths with the late summer and early fall months contributing the greatest rainfall depths.

The total annual rainfall depths are shown in Figure 14. The period of record extends from 1923 to 2006 and omits the years 1942, 1945, 1953, 1955, and 1992. Total annual rainfall depths represent the average of the sums of the monthly depths for the 10 stations shown in Table 1. Data was ignored if a station did not contain records for the entire year. Figure 14 shows that there is significant yearly variation in rainfall depths and also is evidence of the current drought in the region.

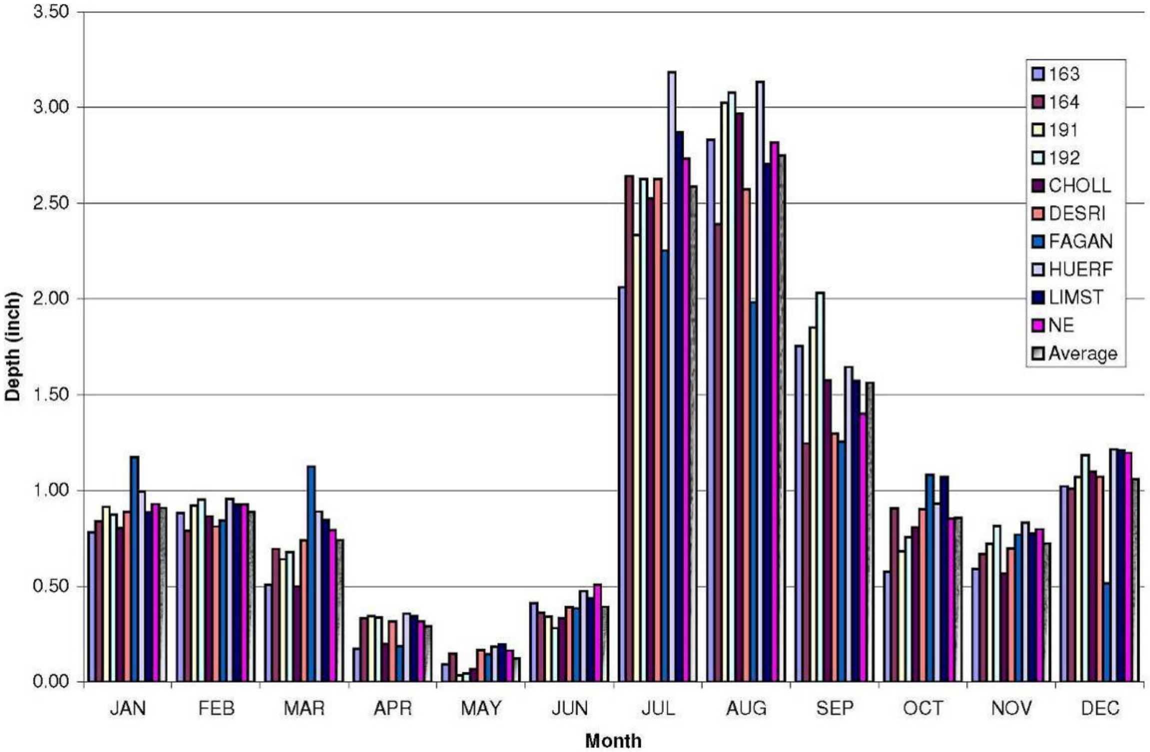


Figure 13 - Average Monthly Rainfall Depths in Santa Rita Experimental Range

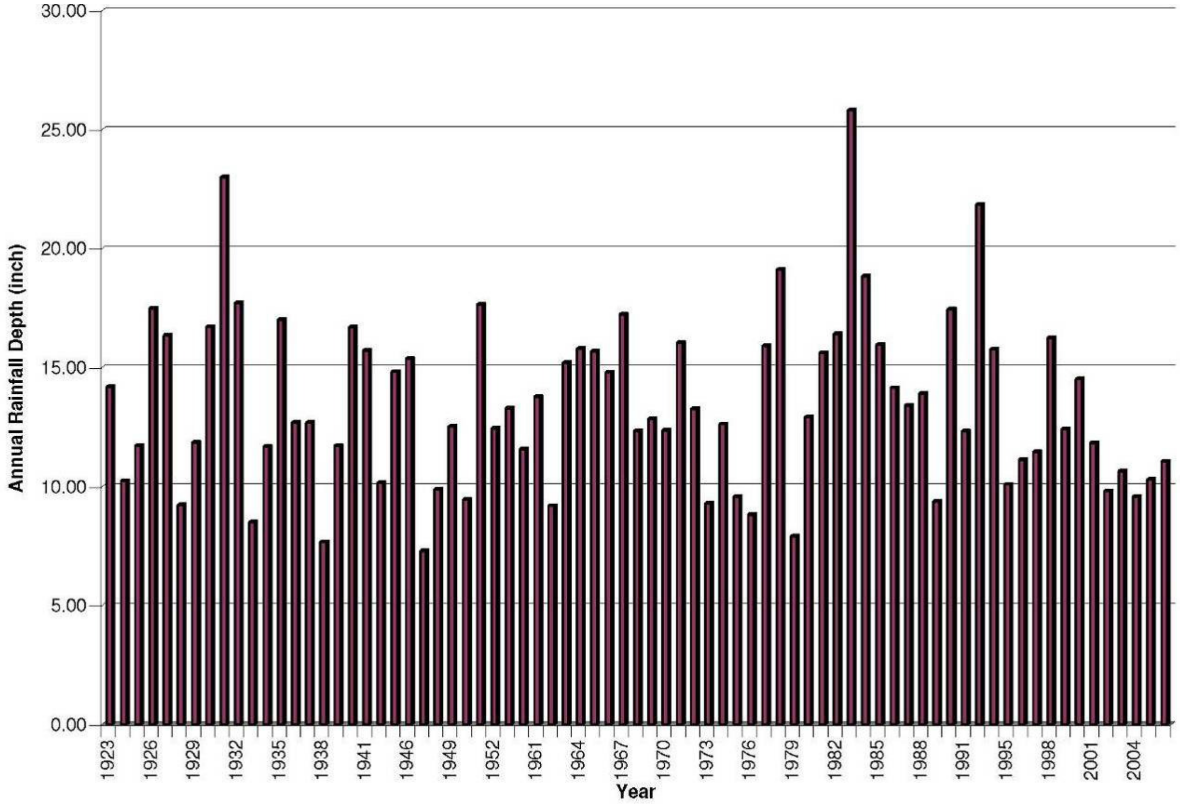
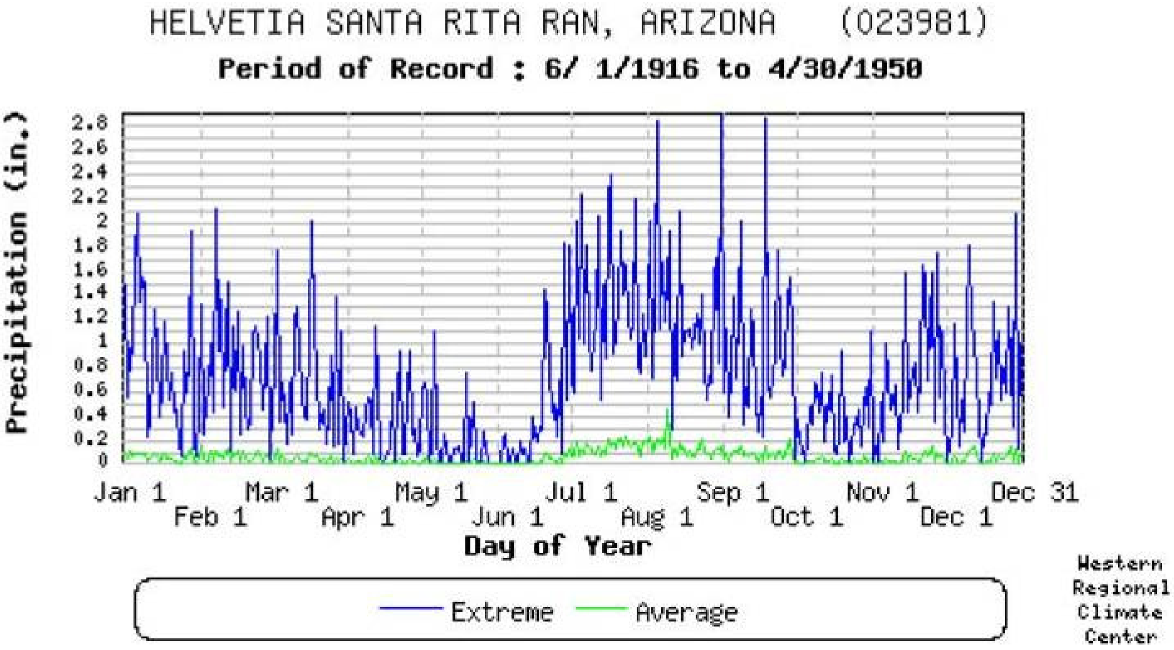


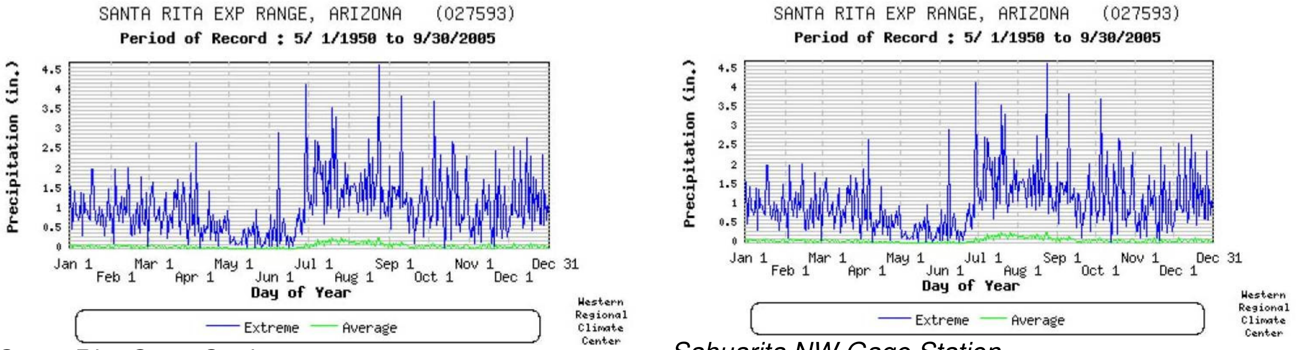
Figure 14 - Total Annual Rainfall Depths for all gages in Santa Rita Experimental Range (averaged)

The extreme and average daily precipitation values for gage stations were reviewed from Western Regional Climate Center data. The three nearest gages are the Helvetia Gage located in the south central end of the study area, the Santa Rita Gage located south of the study area, and the Sahuarita Gage located west of the study area, see Figure 12.

Figure 15 shows the great variation in extreme daily precipitation depths in this region. Review of the average daily rainfall depths indicates that the average depths are relatively consistent and small in magnitude while the extreme depths are relatively large and rare. It is these extreme depths which can have the greatest impact on the fluvial systems because there is often no significant base flow before a large event occurs, limiting the time for fluvial systems to react to the sharp rise in the hydrograph.



Helvetia Gage Station



Santa Rita Gage Station

Sahuarita NW Gage Station

Figure 15 - Extreme daily precipitation depths

There are other sources of gage data throughout the region including PCRFCD alert system gages and USDA Agricultural Research Service gages (rain and runoff data). Data from these gages can be found at the following respective locations:

- http://rfcd.pima.gov/wrd/alertsys/index.htm
- http://www.tucson.ars.ag.gov/DAP/

4.3 Geologic Setting and Soils

The following geologic setting discussion is summarized from the various surficial geologic map reports studied for this project, from Hendricks (1986), and from information available on line at the USGS website.

The Lee Moore Wash Basin is an alluvial basin situated on the western piedmont of the Santa Rita Mountains and east of the Santa Cruz River. The basin is within the Sonoran Desert subprovince of the Basin and Range physiographic province which is made up of mountain ranges separated by intervening valley basins. This province was generally formed by tectonic activity with north-south trending normal faults formed by the extension and stretching of the crust. The tectonic activity which constructed this province has long since ended and has been followed by a period of exposed bedrock weathering, subsequent alluvial fan formation, and filling of the intermontane basins.

The study area piedmont is linked to the Santa Cruz River as downgrading of the river (the axial stream) will have a consequent impact on the tributary streams and adjacent terraces. The Santa Cruz River has experienced substantial downcutting, cutting into its own Quaternary and Tertiary deposits and causing the subsequent downcutting of tributaries and adjacent piedmonts. Formerly active and aggrading fan surfaces became isolated and are currently experiencing degradation. This is further explained by Pearthree and Youberg (2000):

> The Santa Cruz River and its tributaries have downcut substantially into the Quaternary and Tertiary deposits of the Santa Cruz Valley. The high ridges and deep valleys characteristic of the Sierrita piedmont and the high remnant fan surfaces of the Santa Rita piedmont attest to the amount of stream erosion that has occurred since the highest levels of alluvium were deposited. Episodes of downcutting of the Santa Cruz River caused erosion of the toes of alluvial fans on both sides of the valley, and resulted in much of the stream downcutting in the piedmonts east and west of the river. The lower ends of these streams are linked with the river, so if the Santa Cruz downcuts, the slopes of the tributary stream channels steepen and they tend to downcut as well. (11)

Incision which began in the late Pliocene still occurs throughout the Tucson basin. Pearthree and Youberg state that along the Santa Cruz River, “modern channels [with units of around 100 years of age or less] are typically entrenched several meters below adjacent young terraces” (8). Furthermore, the “the ultimate cause of the Santa Cruz River downcutting is not certain” and may be caused as “a delayed response of the integration of the Tucson basin streams into the larger regional drainage system” or from “some broad regional upwarping of southeastern Arizona” (11). Another more modern cause of the downcutting of the Santa Cruz River may be from the large scale pumping of groundwater within the region.

4.3.1 *Surficial Geology Maps*

Surficial geology maps are a key part of this investigation because they give a good indication of historic activity. The relative ages of the various surfaces in the study area can indicate flow patterns and geomorphic hazards. The surfaces tend to be the oldest along the pediment and generally decrease in age westerly along the piedmont. The following is from Pearthree and Youberg's 'Surficial Geologic Maps And Geologic Hazards Of The Green Valley' (2000):

> Surficial geologic mapping provides important information about the extent of floodprone areas on the piedmonts, and it is the best way to delineate areas that may be prone to alluvial fan flooding. Floods leave behind physical evidence of their occurrence in the form of deposits. Therefore, the extent of young deposits on piedmonts is a good indicator of areas that have been flooded in the past few thousand years. These are the areas that are most likely to experience flooding in the future. Following this logic, the extent of potentially flood-prone areas on the piedmont varies with the extent of young deposits (units Qy2, Qy1, Qy, and possibly Qly). Active alluvial fans may be recognized by both distributary (downstream-branching) channel networks and laterally extensive young deposits between channels. (14)

Plate 4 includes a delineation of those deposits described above by Pearthree. These deposits are Holocene deposits and include Qy (Y1, Y2, Qy1, Qy2, ch, Qyc, and Qyd), and Qly (M2). Some interpolation was required when connecting the mapped units between the different studies, but the delineation is reasonably consistent. This delineation of Holocene deposits represents those areas which have flooded most recently (geologic time scale) and which have the greatest potential of flooding in future events.

The following figure (Figure 16) and tables are included to show the locations of the 6 surficial geology maps and to describe the geologic units found in the area. Table 2 includes the individual units found in the study area and their associated name. Table 3 is a generalization (following nomenclature used by Pearthree and Youberg) of the many geologic units found in the study area.

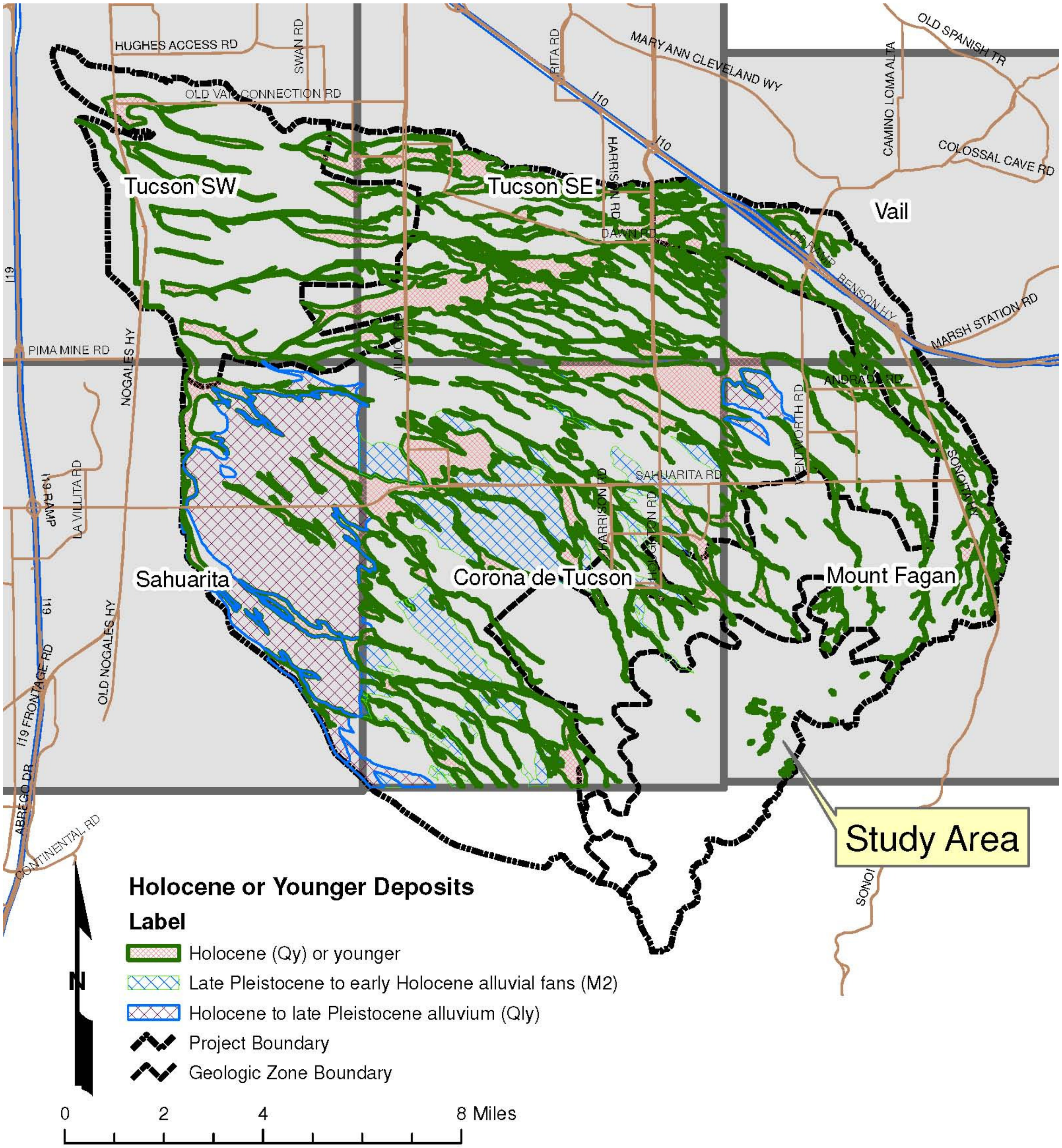


Figure 16 - Index map of applicable surficial geology maps

Table 2 - Summary of Geologic Units in the Study Area

		Map this unit is found in					
Unit	Name	Tucson SW	Tucson SE	Vail	Sahuarita	Corona de Tucson	Mount Fagan
d	Disturbed		yes				
PIEDMONT ALLUVIUM							
M1	Middle to late Pleistocene alluvial fans					yes	
M2	Late Pleistocene to early Holocene alluvial fans	yes				yes	
O	Early to middle Pleistocene alluvial fans					yes	
Qi2	Middle Pleistocene alluvium		yes				
Qi3	Late Pleistocene alluvium		yes				
Ql	Late Pleistocene alluvium			yes			yes
Ql1	Late Pleistocene member						yes
Ql2	Latest Pleistocene member						yes
Qly	Holocene to late Pleistocene alluvium			yes	yes		yes
Qm	Middle Pleistocene alluvium			yes	yes		yes
Qml	Middle to late Pleistocene alluvium						yes
Qmo	Middle to early Pleistocene alluvium						yes
Qmp	Middle Pleistocene alluvium over dissected pediment						yes
Qo	Early Pleistocene alluvium						yes
QTbf	Highly eroded gravelly alluvium	yes					
QTcg	Quaternary to late Tertiary alluvial fan deposits		yes				
QTs	Early Pleistocene to late Miocene alluvium			yes			yes
Qy	Undifferentiated Holocene alluvium		yes	yes	yes		yes
Qy1	Holocene alluvium						
Qy2	Late Holocene alluvium						yes

Table 2 - Summary of Geologic Units in the Study Area

		Map this unit is found in					
Unit	Name	Tucson SW	Tucson SE	Vail	Sahuarita	Corona de Tucson	Mount Fagan
Qyc	Late Holocene channel deposits		yes				
Qyd	Incised Holocene deposits		yes				
T2	Historically abandoned stream terraces on Santa Cruz	yes					
T5	Highest and oldest preserved terrace	yes					
Y	Active and recently active alluvial fans and broad, unincised channels low in the basin	yes					
Y1	Early to middle Holocene alluvial fans					yes	
Y2	Active and recently active alluvial fans and deposits					yes	
AXIAL STREAM DEPOSITS							
ch	Active and historically active, confined streams/deposits	yes				yes	
HILLSLOPE DEPOSITS							
Qc	Holocene and Pleistocene hillslope colluvium						yes
BEDROCK UNITS							
b	Undifferentiated bedrock						yes
Ka	Andesitic lava						yes
Kfc	Fort Crittenden Formation						yes
Kgdy	Corona de Tucson stock, younger phase						yes
Krz	Heterolithic mesobreccia						yes
Tkm	Fine-grained mafic dikes and intrusive bodies						yes
Tq	Quartz porphyry						yes
Xgd	Granodiorite						yes

Table 3 - Generalization of Geologic Units

Unit (Alternative Unit)	General Name	Description
Qy (Y, Tucson SW & Corona de Tucson) (ch, Tucson SW)	Holocene alluvium	**Reported Age:** <10,000 years **Location/setting:** Incised, active drainageways and floodplains in the Piedmont areas and areas at the base of Piedmonts. Included in small areas within the Pediment Zone. **Potential for flooding:** Seasonal flooding in broad channels and less frequent flooding on fans. **Features:** Y1 surfaces are planer while Y2 surfaces vary from smooth channel bottoms to undulating with up to 2 feet of relief. The surface is usually not dissected and has developed into a distributary drainage network. Qy soils are weakly developed. Soil color is brown to dark brown but will show up lighter on aerial maps where gravel is present.
Qly (M2, Tucson SW &Corona de Tucson)	Holocene to late Pleistocene alluvium	**Reported Age:** < 130,000 years **Location/setting:** Alluvial fan surfaces, 3 feet above active channels. **Potential for flooding:** Similar to Ql and Qy. **Features:** The Qly surface is composed of a thin veneer of light brown Qy with reddened Ql (rarely Qm) exposed on ridges, roads, cut banks.
Ql (Qi3, Tucson SE)	Late Pleistocene alluvium	**Reported Age:** 10,000 to 250,000 years **Location/setting:** Alluvial fans with braiding which act as a sediment transport zone in the middle Piedmont and north-central end of basin. **Potential for flooding:** Flooding in broad channels at lower ends of basin. Flooding potential is greater in areas where relief is low and near flow split locations. **Features:** The Ql surface is slightly to moderately dissected by active channels (2-5 feet). The Ql soil is moderately developed and clay-rich. The soil color is yellowish red or orange.
Qm (Qi2, Tucson SE) (M1, Corona de Tucson) (Possibly T5 of Tucson SW)	Middle Pleistocene alluvium	**Reported Age:** 250,000 to 750,000 years **Location/setting:** Isolated, planar surfaces in SW Incised Zone. Moderately dissected alluvial fans found extensively in the middle to upper Piedmont and a small area in the Pediment Zone **Potential for flooding:** Restricted to gullies/entrenched channels. Sheet flow occurs in small local drainage areas. **Features:** Qm surface has experienced rounding of interfluves and is a hummocky surface. Soil development is moderate to mature and the soil color is reddish yellow to reddish brown. Qi2 shows up as pink to red in aerial maps and well-preserved Qm shows up as dark orange on aerials. Well-developed tributary networks are found on this surface.
Qo (O, Corona de Tucson)	Early Pleistocene alluvium	**Reported Age:** 750,000 to 2,000,000 years **Location/setting:** Deeply dissected fans with smooth to rounded surfaces in the upper Piedmont and within the Pediment Zone **Potential for flooding:** Restricted to gullies/entrenched channels. **Features:** Channels which have developed on the fan surface are incised up to 30 feet. The surface is smooth to broadly rounded. The Qo surfaces have the highest recorded levels of aggradation in the Tucson basin. The soil is very well developed and is dark red.

Table 3 - Generalization of Geologic Units

Unit (Alternative Unit)	General Name	Description
Qc	Holocene and Pleistocene Hillslope Colluvium	**Reported Age: <** 1,600,000 years **Location/setting:** Hillslopes and mountains which are moderately steep in the lower Pediment Zone **Potential for flooding:** Restricted to gullies and channels which are entrenched. **Features:** Qc is found in steep environments and is not extensively mapped. Qc deposits are less than a few yards thick. Pleistocene deposits are clay-rich and red and will show up on stable hill slopes. Holocene deposits are found on more active hillslopes.
QT	Early Quaternary to late Tertiary Alluvium	**Reported Age:** 2,000,000 to 10,000,000 years **Location/setting:** Old and deeply dissected/highly eroded alluvial fan deposits with rounded ridges in the eastern Piedmont **Potential for flooding:** Restricted to gullies/entrenched channels. **Features:** This surface is drained by deeply incised tributary channel networks. Ridges are rounded. QT shows up on aerials as gray to white.
Tq	Tertiary Bedrock	**Location:** Pediment Zone
Tkm	Tertiary-Cretaceous Bedrock	**Location:** Pediment Zone
Ka, Kfc, Kgdy, Krz	Upper Cretaceous Bedrock	**Location:** Pediment Zone
Xgd	Proterozoic Bedrock	**Location:** Pediment Zone

Adapted from AZGS DGM-03, AZGS DGM-11, AZGS DGM-12, AZGS DGM-43, AZGS OFR-89-2, AZGS OFR-90-3, and Rio Verde Area Drainage Master Plan, Piedmont Assessment Report, Basis for Delineation of 1-D vs. 2-D Flow Characteristics.

Reported age summarizes the ages of the various units as assumed by the above sources.

4.3.2 Soils Maps

Review of the detailed soil maps for this project indicates there are approximately 100 different mapped soils units in this study area, although many are similar but mapped separately by the three separate studies. The detailed soil delineation is shown on Plate 5. Appendix B provides a summary of each of the detailed soil units found within this study area. From the less detailed NRCS STATSGO soils maps, three noteworthy map unit identifiers (MUID) were found. These are shown as MUID 38, 60, and 66 on Figure 17.

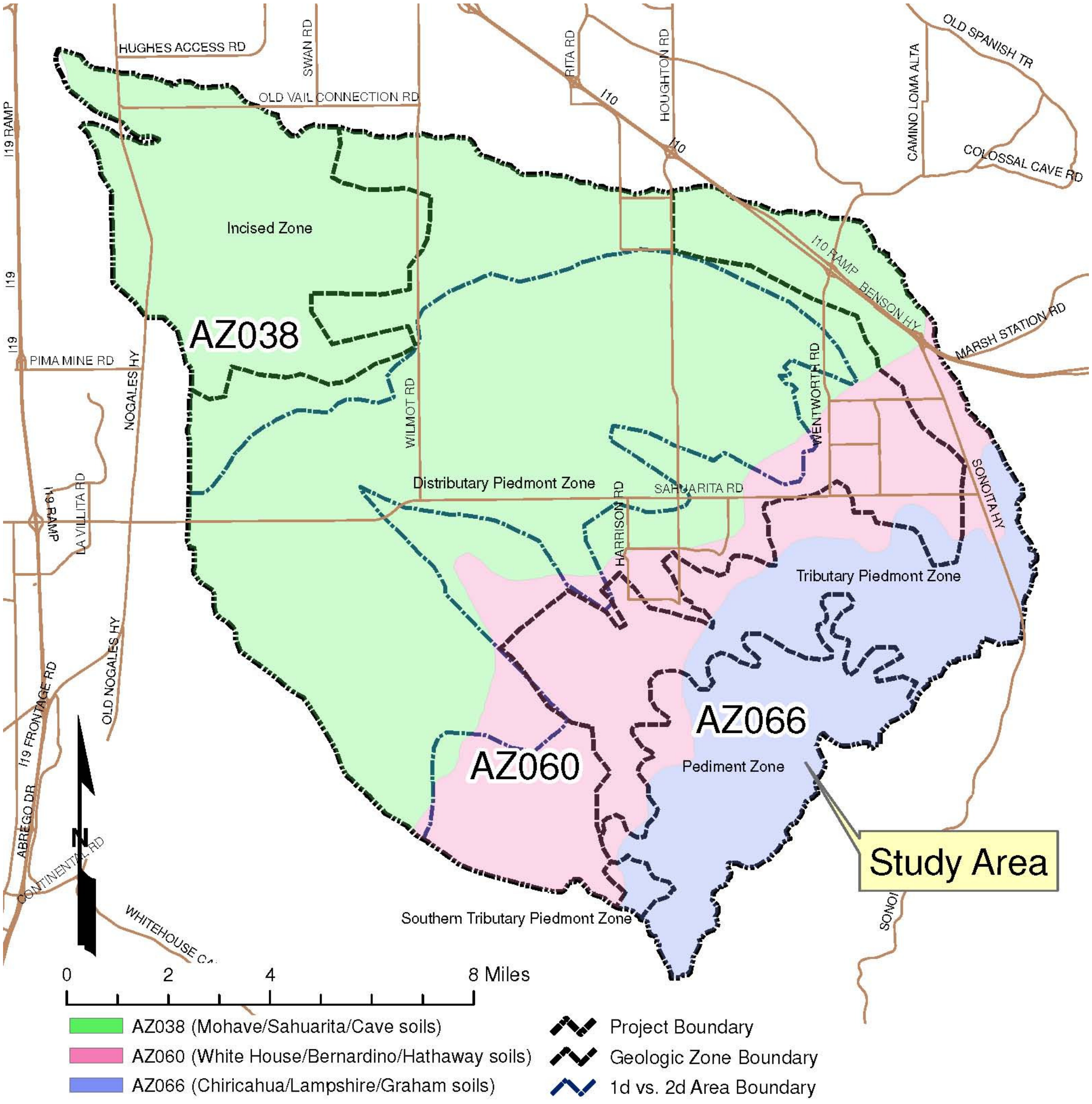


Figure 17 - Project soils map

5 Geomorphic Study Zones

5.1 Section Outline

The overall study area has been divided into separate geomorphic study zones by JEF. These zones are presented because they have unique flooding risks and geomorphic hazard potentials. This section first discusses the methods used to delineate the study zones and then discusses the geomorphology separately for each of the four geomorphic zones.

5.2 Delineation of Geomorphic Study Zones

The geomorphic study zones were delineated based primarily upon topography and geology and supported by review of aerial maps, soils maps, and the delineation of flow splits and one-dimensional and two-dimensional flow areas. Review of the topography and surficial geology maps indicated that the study area could be reasonably divided into two broad regions, the first representing the steep hill slopes and mountain fronts within the upper watershed (Pediment Zone) and the second being the piedmont plain area downstream of this. Further investigation showed that the piedmont plain region contained an area of greatly incised watercourses in the most downstream end of the study area. Finally, the remainder of the piedmont plain, the middle of the study area, could be further delineated into distributary and tributary flow areas. Thus four geomorphic zones were delineated as shown on Figure 18, the downstream three zones being sub-delineations of the piedmont plain. These zones are summarized as follows:

- The **Pediment Zone**. This zone is located in the upper basin near Mount Fagan. This zone includes the pediment, hillslopes, and the mountain areas.
- The **Tributary Piedmont Zone**. This zone is located downhill and to the north of the Pediment Zone. There is an additional, isolated Tributary Piedmont Zone located near the southern limit of the study area.
- The **Distributary Piedmont Zone**. This is the largest zone and is located downhill of the Tributary Piedmont Zone. This zone generally contains younger alluvium than the Tributary Piedmont Zone.
- The **Incised Zone**. This is the most downstream zone, located at the northwest end of the basin, and can be considered part of the piedmont plain.

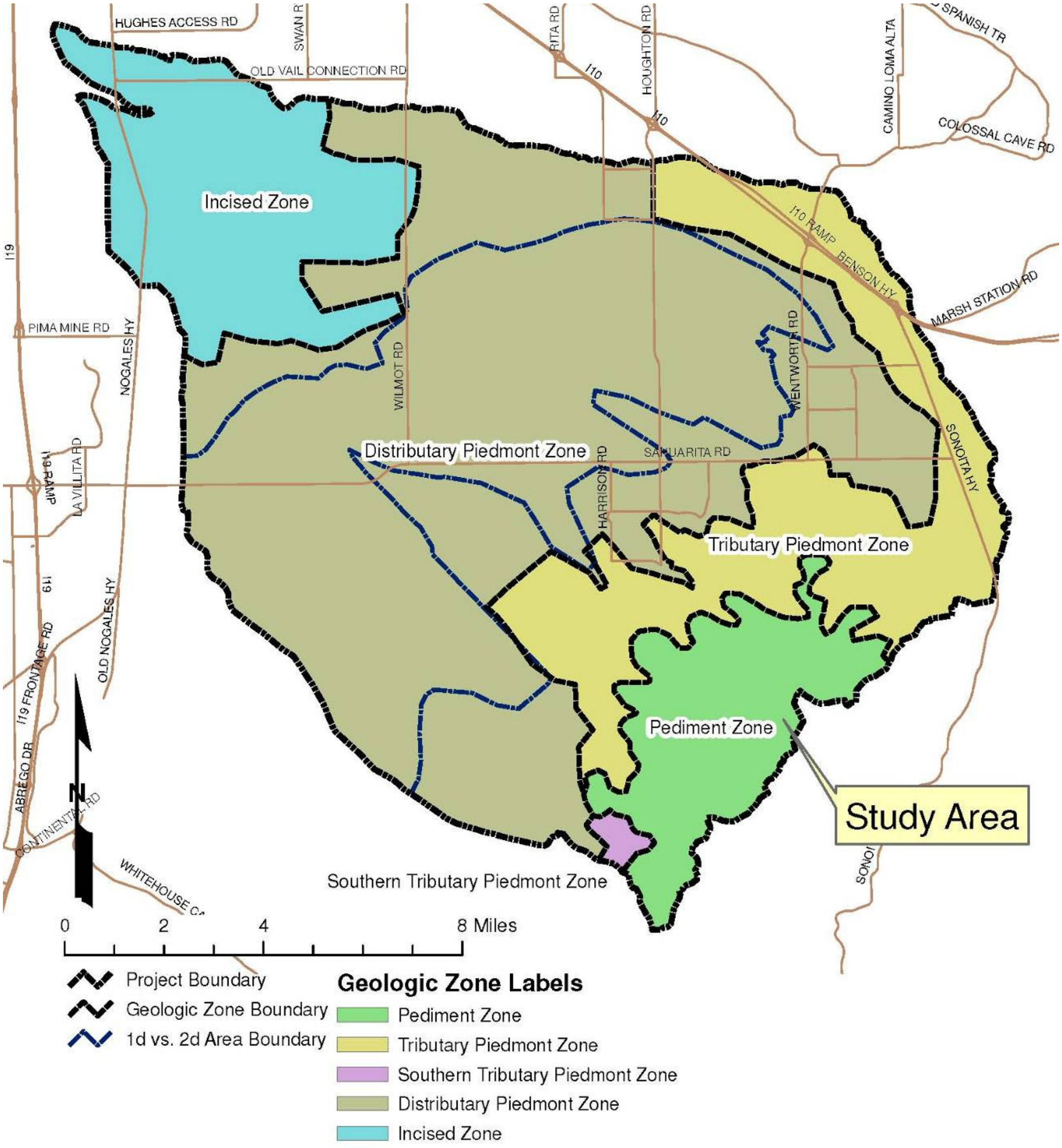


Figure 18 - Geomorphic Zones Location Map

5.2.1 Longitudinal Profiles and Slope Analysis

The slope within the project area is down-gradient to the northwest. The general elevations can be seen in Figure 19 which is a hillshade relief map based on the USGS Digital Elevation Model (DEM). The southeast and upstream end of the basin consists of mountains and inselbergs representing rigid boundaries confining streams topographically. The downstream basin is filled with erodible alluvium with limited rock outcroppings. Streams in the downstream basin area are confined intermittently by relatively shallow interfluves. The piedmont topography is therefore dynamic with respect to geologic time.

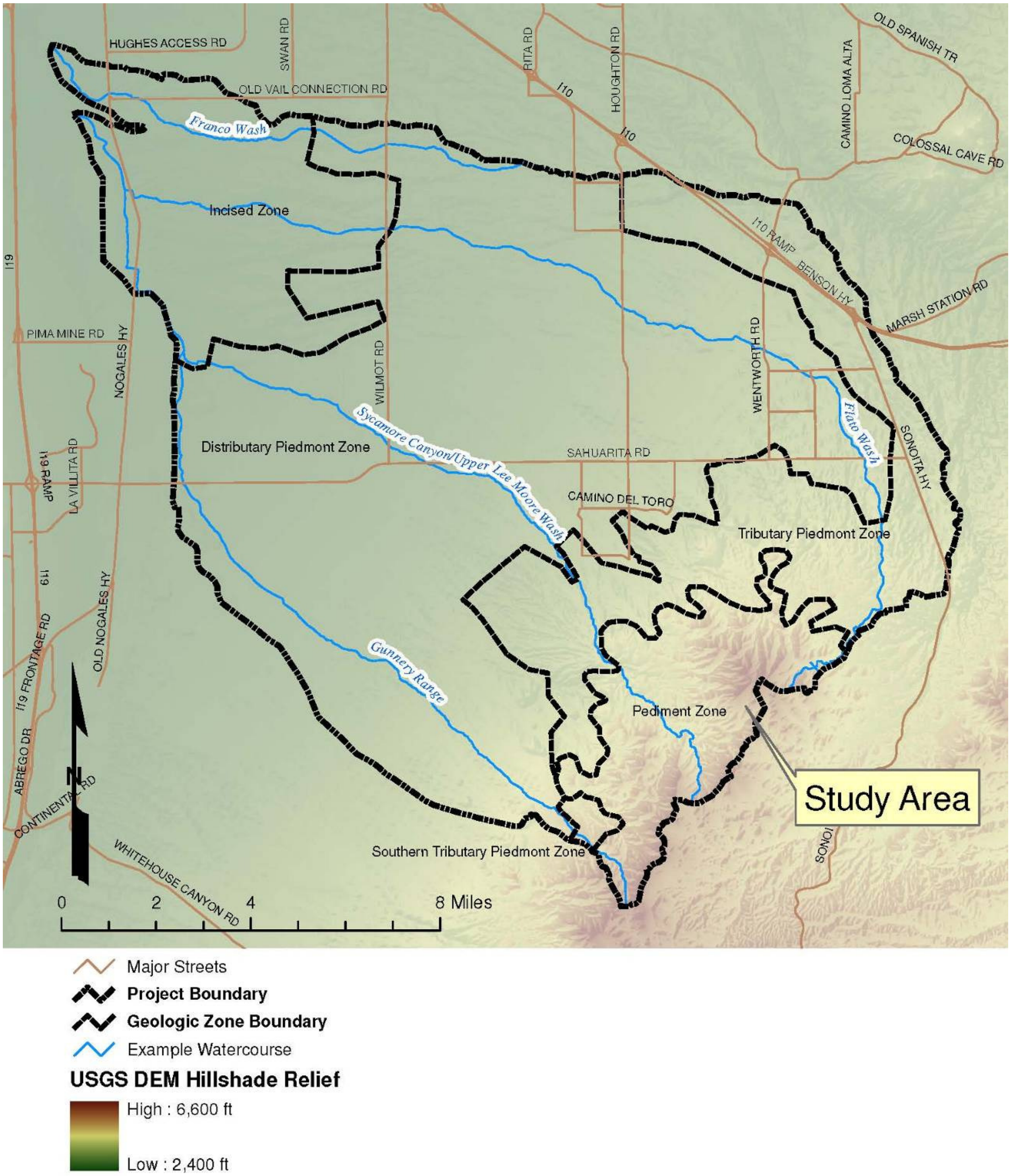


Figure 19 - Hillshade relief map from USGS DEM Data

The topography within the basin varies longitudinally and laterally. Lateral relief is the greatest along the southern hillslopes and the slightest within the middle piedmont. Relief increases again towards the Santa Cruz River. The primary channels and floodplains within the watershed are relatively flat throughout most of the middle and lower piedmont. Slopes across the lower piedmont range from less than 0.003 ft/ft to over 2 percent but are typically less than 1 percent. The hillslopes exceed 50 percent.

To illustrate slope, longitudinal profiles were cut for four sample watercourses; the alignments can be seen on Plate 2. The four sample watercourses include the Franco Wash (Franco Wash and northern Franco Wash Tributary) to the north and three watercourses tributary to the Lee Moore Wash. The southernmost tributary is the Gunnery Range Wash, then north to the Sycamore Canyon Wash/Lee Moore Wash, and then the Flato Wash.

Figure 20 represents the profiles of the four example watercourses. Figure 21 shows the average slope along the profile. Note that the stationing for the Franco Wash (and tributary) begins where the wash crosses the project limit boundary and the stationing for the three southern watercourses begins where the Lee Moore Wash crosses the project limit boundary. The profile represented by the Gunnery Range Wash is the flattest across the lower piedmont areas. Not coincidentally, this is the portion of the basin with the least lateral relief. Conversely the northern portion of the piedmont represented by the Flato and Franco profiles is steeper than the southern watercourses and similarly the lateral relief is greater towards the north.

All of the profiles have similar shapes and average slopes. Excluding the Flato Wash, the slopes are flattest nearest the Santa Cruz River and generally increase (somewhat exponentially) in the upstream direction. The slope of the Flato Wash represents drainage improvements near its confluence with the Lee Moore Wash. Away from the confluence and local drainage improvements, the slope and profile are similar to the other example watercourses.

A few irregularities are noted in the slopes of the example washes. Some are due to the use of PAG topographic data in conjunction with the USGS quad map topography. The irregularity in the slope profiles for Lee Moore Wash, Gunnery Range Wash, and Flato Wash near river mile 15.2, 16.0, and 18.5, respectively, are due to the use of the two topographic sources.

Figure 22 and Figure 23 are included to show how the profile changes across the study zones on two of the example watercourses. These figures divide the profiles into four sections representing the four study zones. The average slopes for the four watercourses are summarized in Table 4. The average slopes within the Incised Zone for the Flato and Franco watercourses exceed those of Lee Moore Wash and Gunnery Range Wash because their direction within this zone is perpendicular to the Santa Cruz River. The southern washes within this zone run parallel to the river and have developed slopes similar to the Santa Cruz River, within the incised zone.

Table 4 - Average Slopes on Example Watercourses

Watercourse	Average Slope (ft/ft)		
	Incised Zone	Dist. Piedmont Zone	Trib. Piedmont Zone
Lee Moore - Sycamore Canyon	0.0032	0.012	0.025
Gunnery Range	0.0053[1]	0.012	0.019
Flato	0.0070[1]	0.012	0.020
Franco	0.0055	0.0086	-

Note 1: Slope in the Incised Zone is measured upstream of the confluence with the Lee Moore Wash.

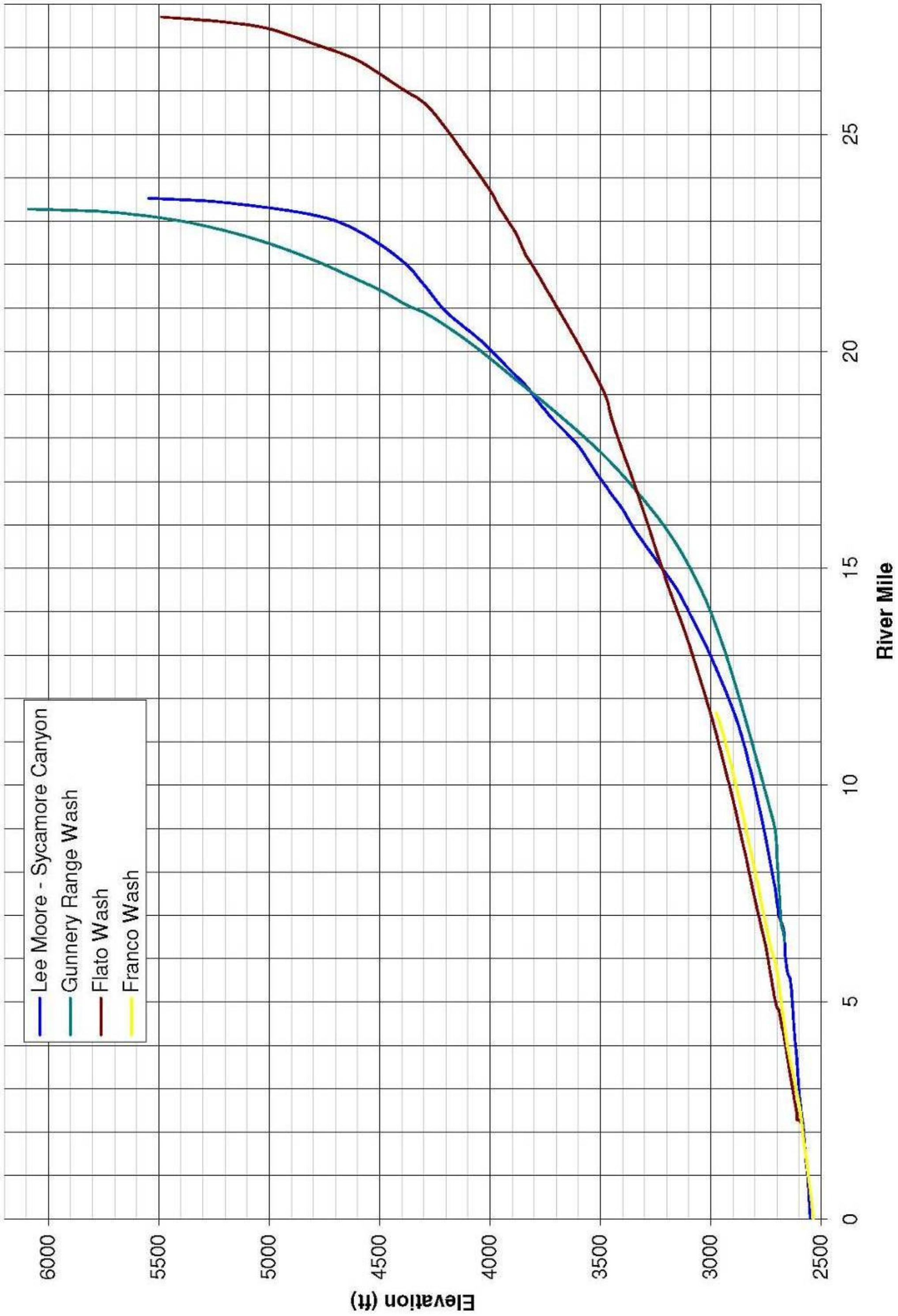


Figure 20 - Profiles for Example Watercourses

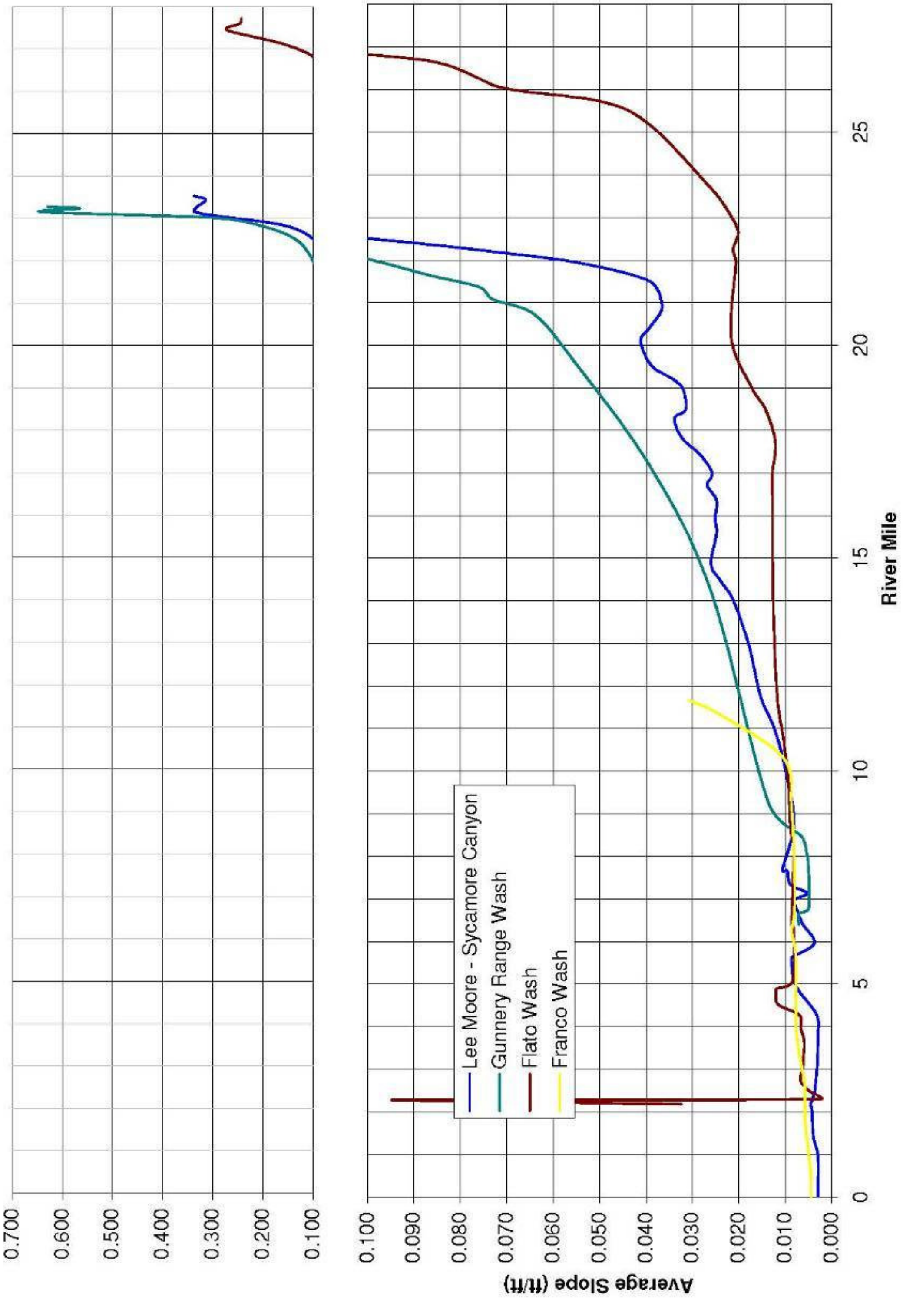


Figure 21 - Running Average Slope for Example Watercourses

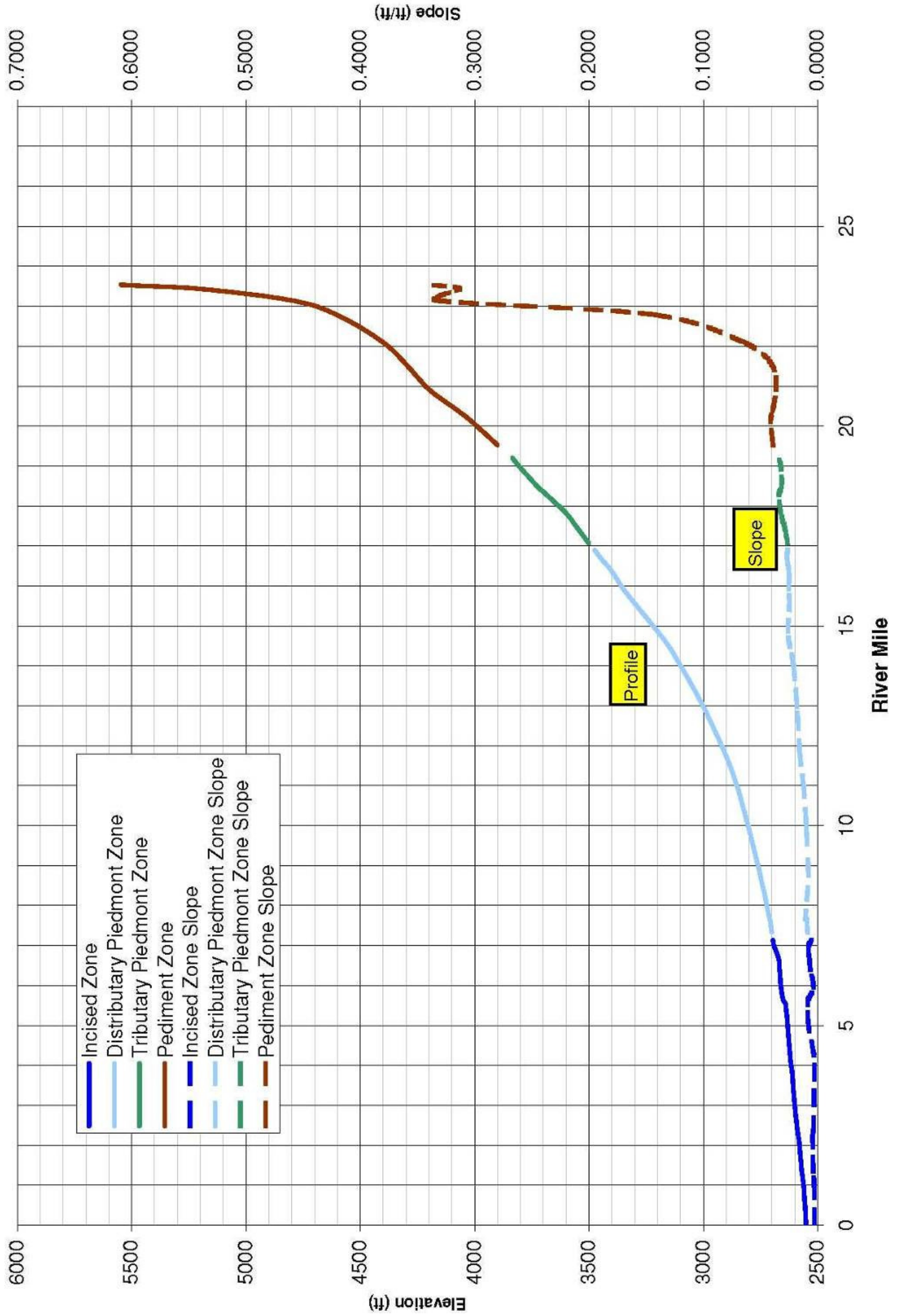


Figure 22 - Profile and Average Slope of Lee Moore Wash & Sycamore Canyon Wash Tributary

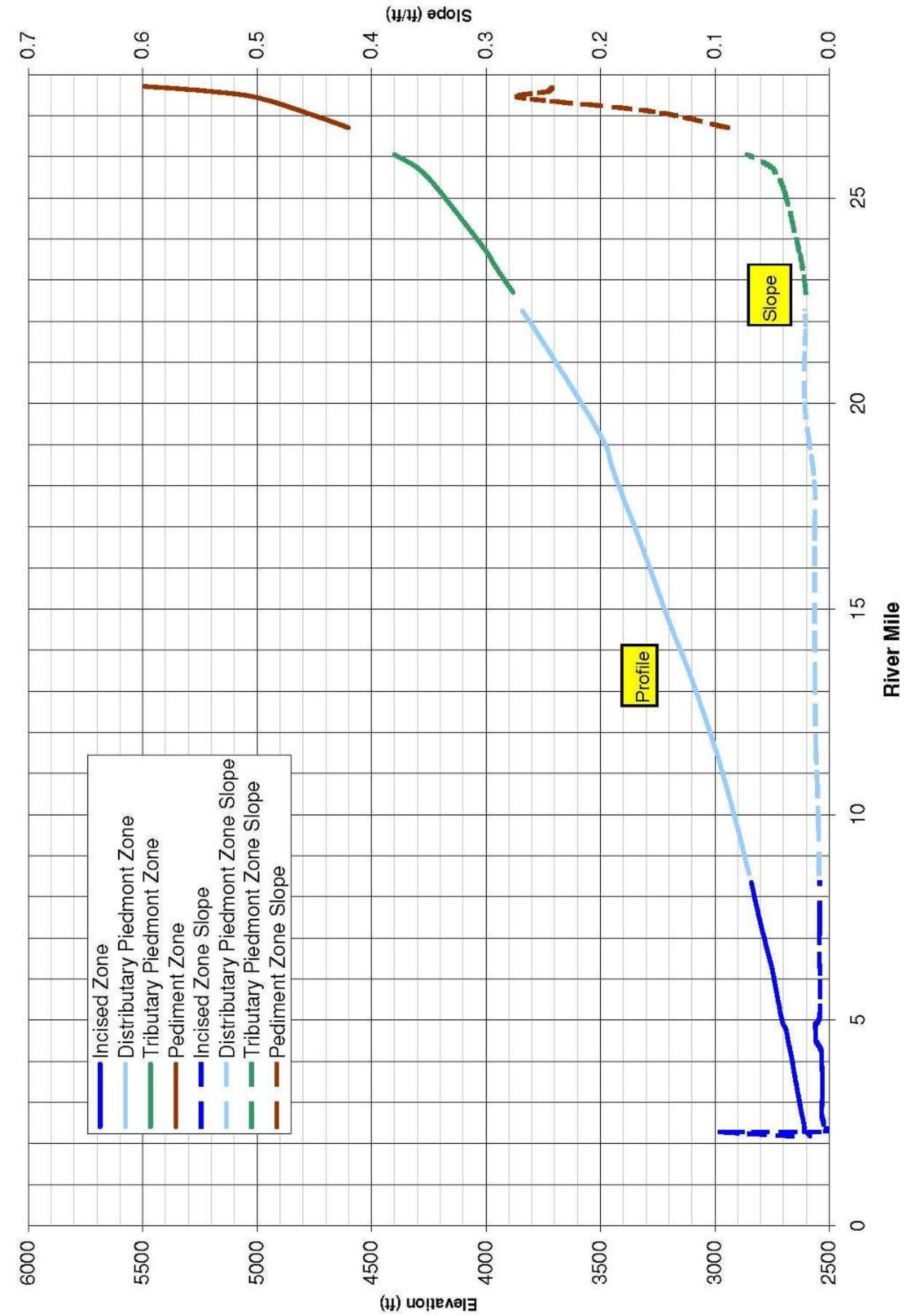


Figure 23- Profile and Average Slope of Flato Wash

5.2.2 *Representative Cross Section Analysis*

Plate 2 and Figure 24 show the locations of where four cross sections were extracted from the USGS topography. The cross sections were drawn at representative locations along the Lee Moore Wash alignment and over predominant geologic units for each of the four study zones. Figure 25 shows the cross sectional view of these sections. These sections show how unique each study zone is in regards to topographic relief across the section. The Pediment cross section clearly exhibits the greatest lateral relief, reflective of the geologic age of the representative units in this section. The two Piedmont Zone cross sections are similar in a few ways. The sections include Holocene alluvium bounded by Pleistocene fan surfaces along with minimal local lateral relief. The differences between the sections are that the adjacent fan surfaces are reportedly older within the Tributary Piedmont Zone and that global relief across the section is greater in the Tributary Piedmont Zone. Therefore lateral migration, avulsion, and split flow activity will be more limited in the Tributary Piedmont Zone than in the Distributary Piedmont Zone. The Incised Zone section shows defined flow paths separated by significant interfluves with some areas having minor lateral relief indicating that one-dimensional flow will dominate. The potential for exchange of flow between watersheds is greatest in the Distributary Piedmont Zone but also exists in the other zones.

A comparison of the contour band widths is shown in Figure 26. The contour band width is the “distance between a tangent to the largest crenulation of a contour that points upstream and a tangent to the largest crenulation of the same contour that points downstream” (Hjalmarson, 1991, pg. VII). Greater band width indicates contained flow corridors and smaller band width can indicate sheet flow. As would be expected, the Distributary Piedmont Zone has the smallest band widths.

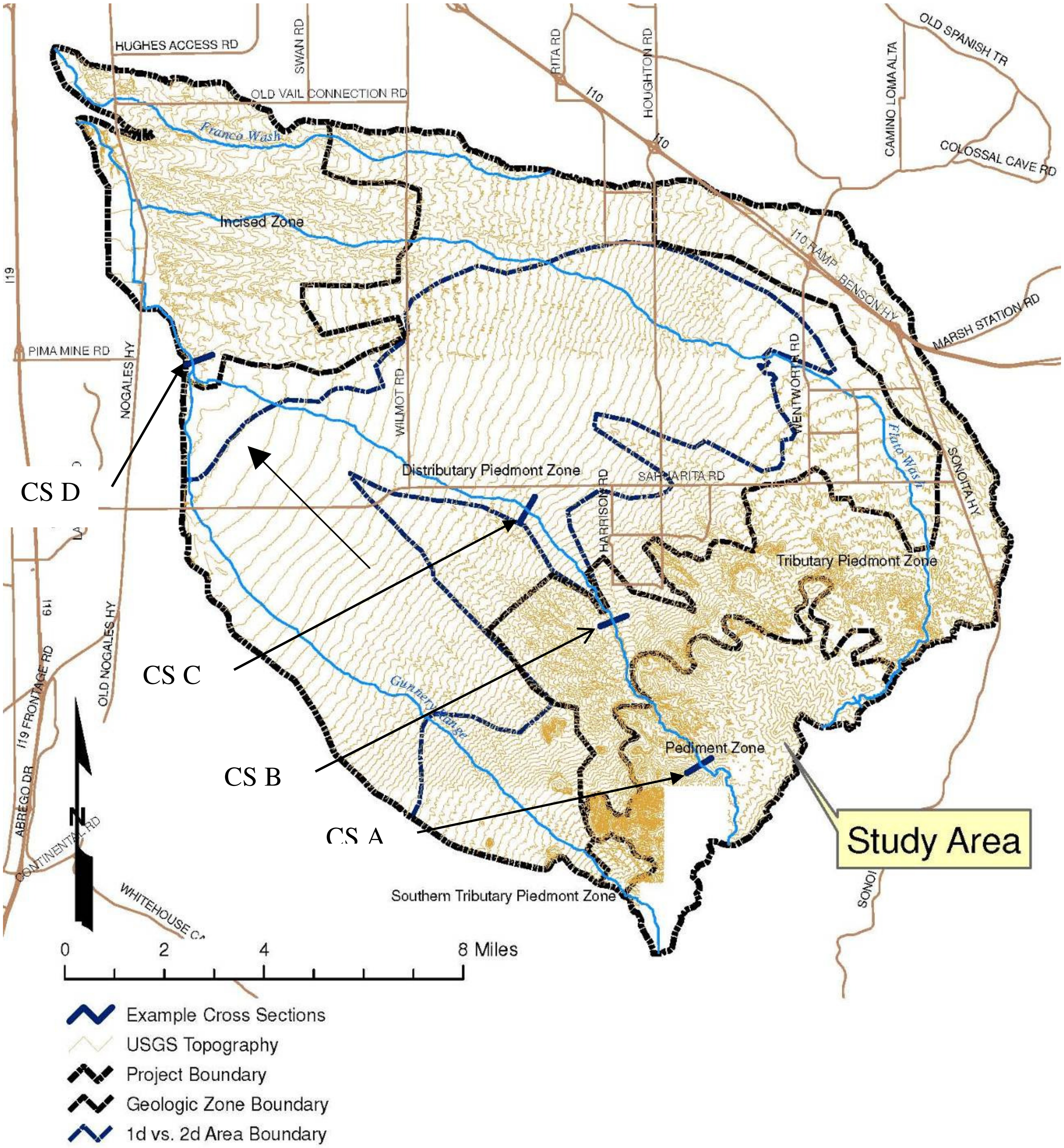


Figure 24 - Typical cross section location map

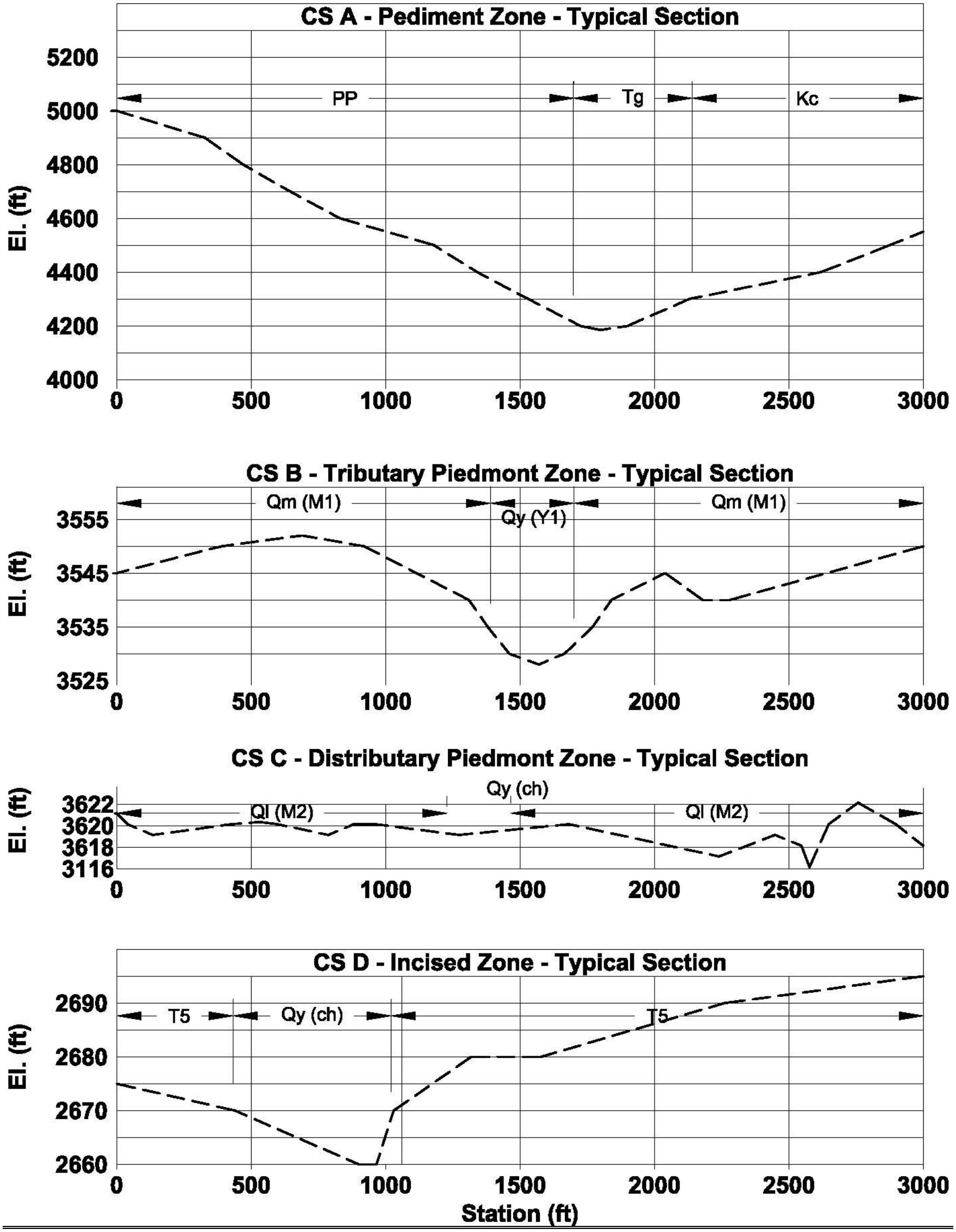


Figure 25 - Geomorphic Zone typical cross sections

(Note: Vertical exaggeration differs while horizontal scale is consistent.)

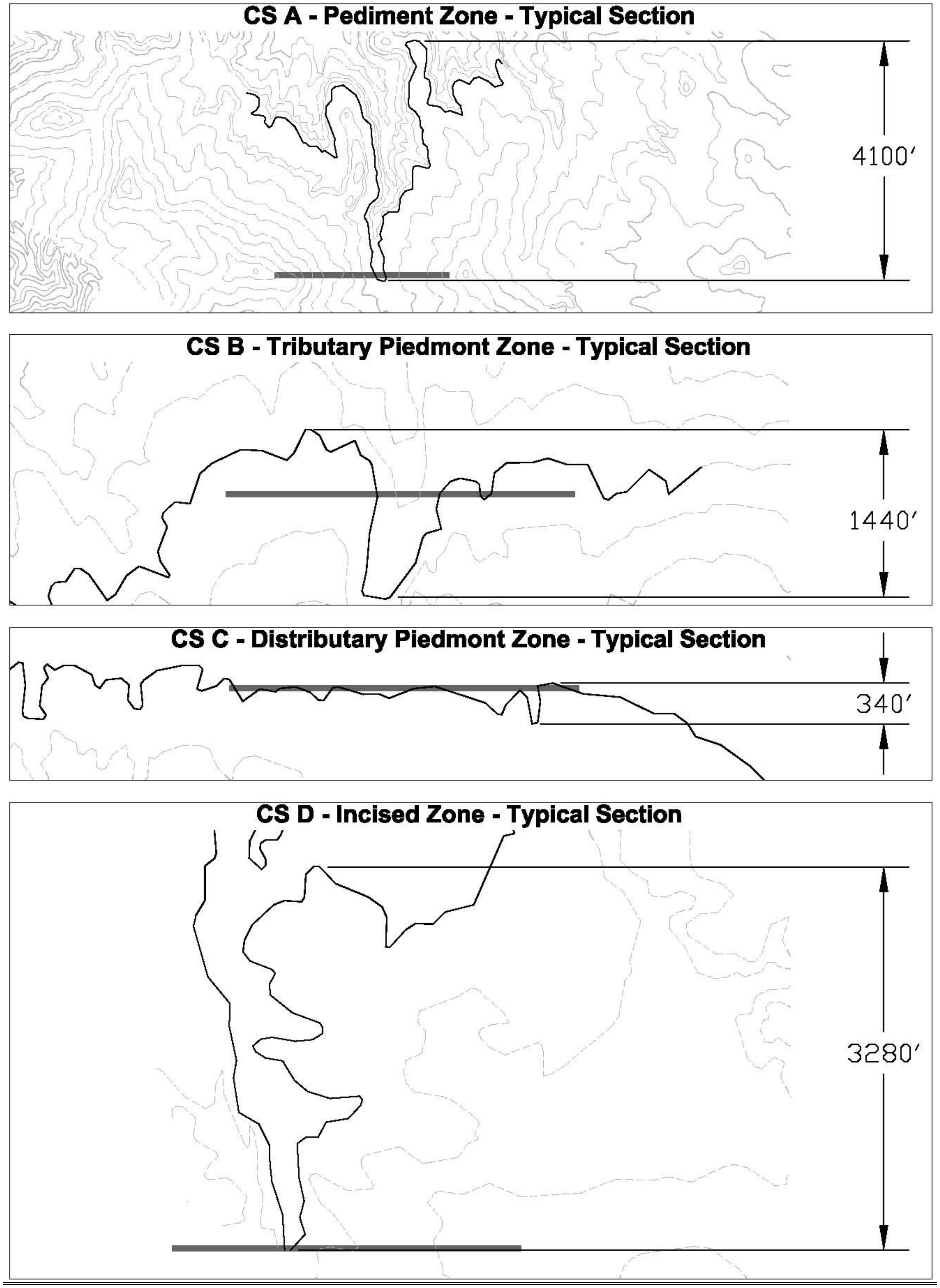


Figure 26 - Geomorphic zone contour band width comparison

5.2.3 Analysis of Soils Maps

For the purposes of this study, the soils have been broadly characterized into groups based on the map unit descriptions and inspection as shown on Plate 5. The soils were generalized into landforms described as:

- **Pediments and Hillslopes**, found within the upper basin. The Pediment Zone is almost entirely composed of these soils. The upper Tributary Piedmont Zone areas are made up of this soil.
- **Drainageways**, found at the lower end of the basin and within the adjacent Santa Cruz River. These soils cover a very limited part of the watershed and signify highly contained channels.
- **Fan Terraces**, found throughout the piedmont. Where the detailed soil study describes a soil as being on an alluvial fan or a fan terrace it was grouped into the Fan Terraces group. Therefore, there is no distinction between relict and active alluvial fans. While a delineation of the two types would be preferable, it was not feasible to provide this delineation considering there are three detailed soils studies with differing descriptions. The Tributary Piedmont Zone contains large areas of this soil.
- **Floodplains**, found throughout the piedmont. Those soils described as being found on floodplains or stream terraces were grouped into the Floodplains group.
- **Mixed**, found throughout the piedmont. The Mixed group includes soils that are described as being found in both Fan terrace and floodplain locations. The majority of the flow splits are found within the Mixed group and within the Distributary Piedmont Zone.

The United States Department of Agriculture (USDA) has defined soil taxonomy with several layers, classifying soils by common properties and parameters. The first layer is the Order, of which there are 12 defined Orders. Soils within an Order will have broadly similar characteristics. There are three Orders present in the study area.

- **Aridisols**, water deficient soils which often have cemented soil horizons, are rich in salts, and poor in organic matter.
- **Entisols**, poorly developed soils that are very similar to their parent material, and lack horizons.
- **Mollisols**, soils with a dark surface layer and are rich in organic matter.

In addition to the landform delineation on Plate 5, three generalized maps of the soils in the study area have been included to give additional visual representations of the soil and landforms in the study area. These maps are delineated based on the descriptions in the detailed soil surveys.

- Figure 27 gives a general depiction of the flooding risk based on the soil descriptions. Soils with a noted flooding risk are found primarily within the Distributary Piedmont and Incised Zones. (Note that the frequency terms defined by NRCS are vague. Based upon the hydraulic models for this project, much of the “not” areas are flood prone.)
- Figure 28 identifies the Order of the soil based on taxonomic description. There is some correlation between Order and geologic zone.
- Figure 29 shows those soils which are listed as being formed of mixed alluvium (in entirety or the predominant soil). Anthony soils and mixed alluvial unit soils are indicative of distributary flow areas (Hjalmarson, 1991). This delineation basically shows the entire piedmont to be mixed alluvial units.

Note that there are some discrepancies between the soil units and generalizations on each of these figures along the soil map boundaries.

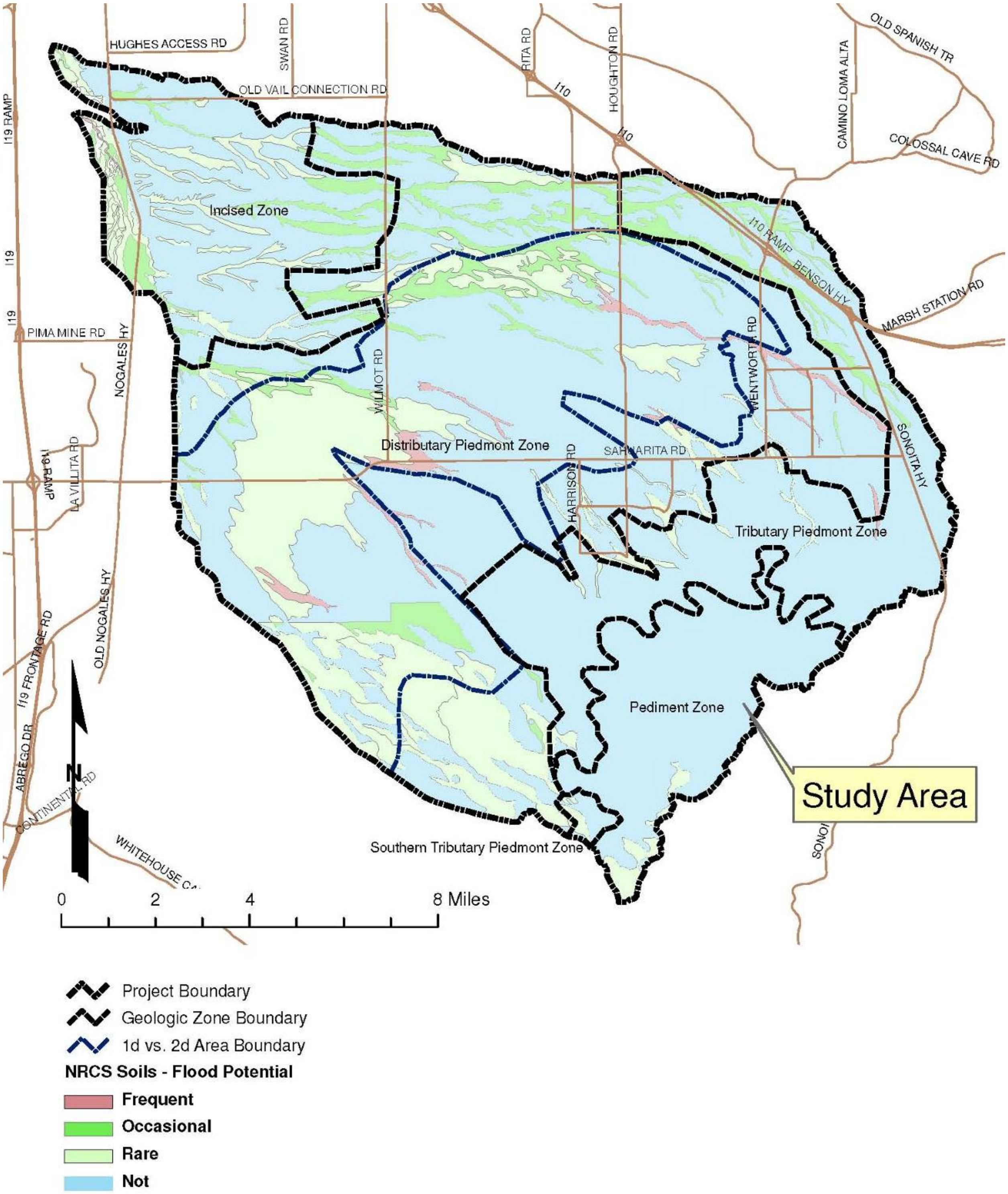


Figure 27 - Flooding Risk Based on NRCS Soils Descriptions

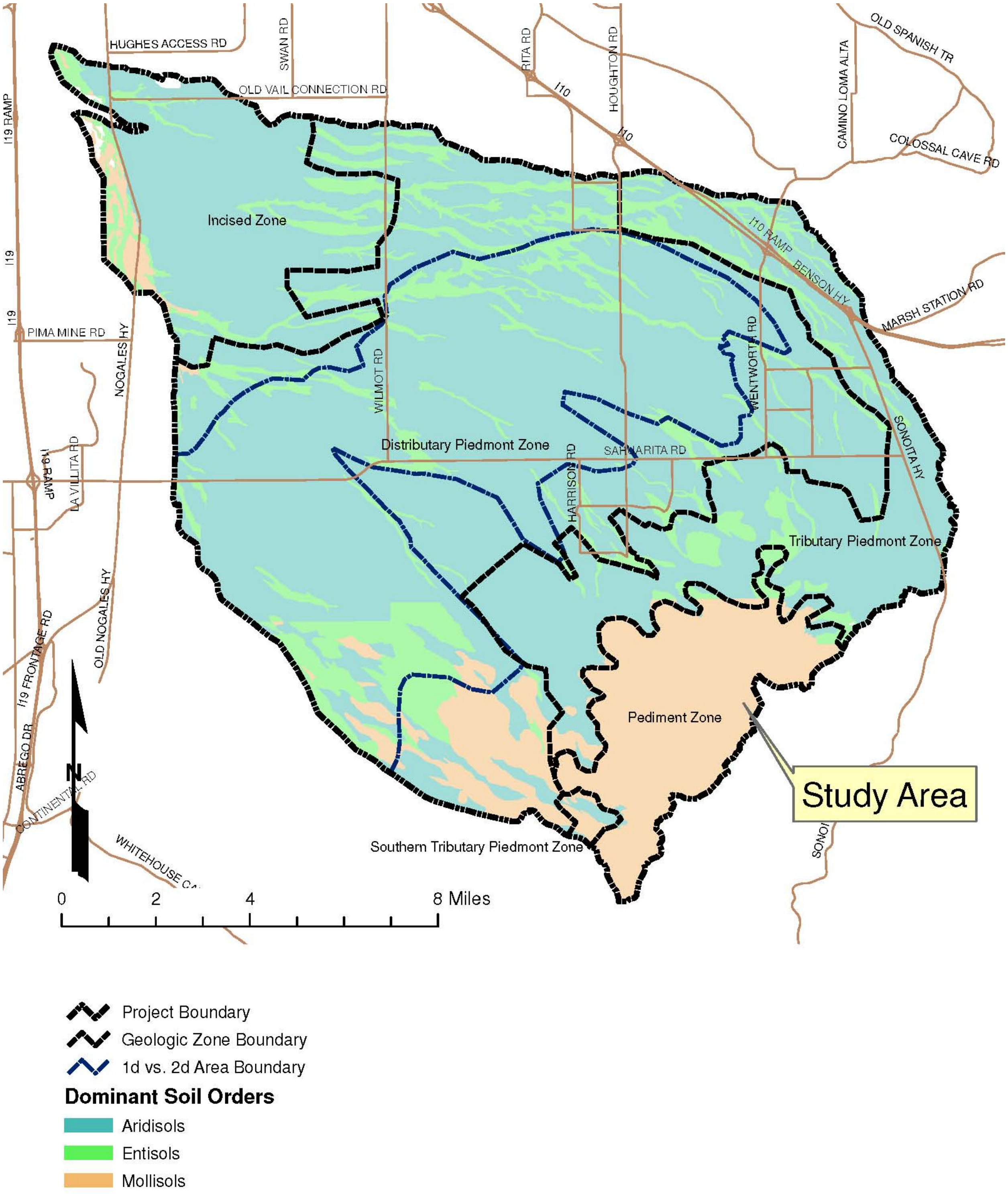


Figure 28 - Soil Order Based on NRCS Soils Descriptions

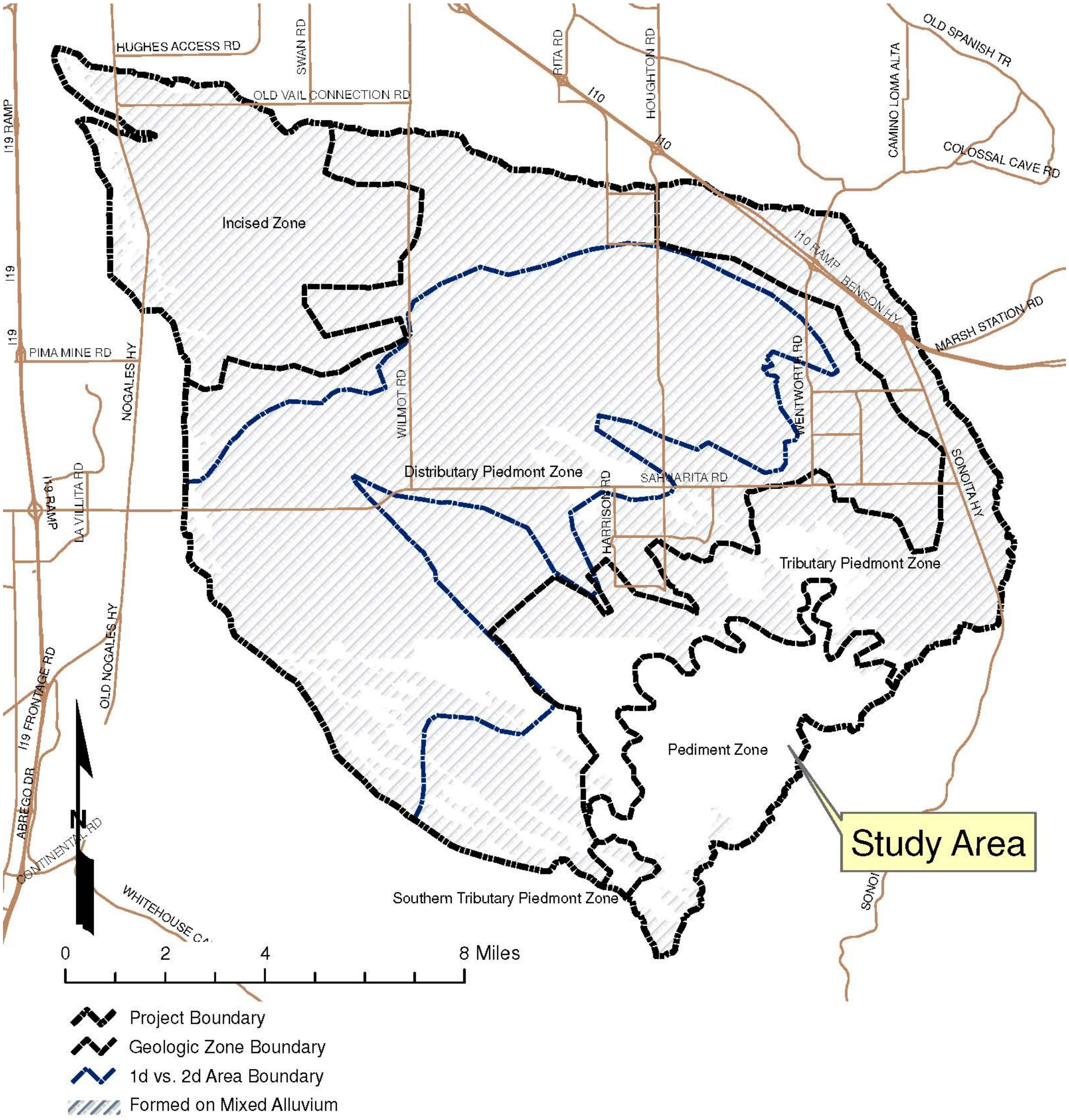


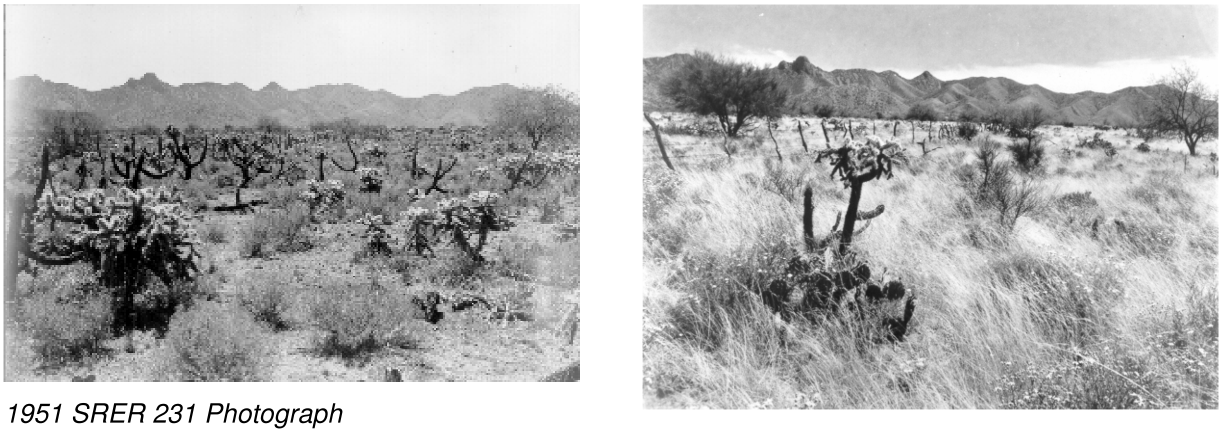
Figure 29 - Mixed Alluvium Soils Based on NRCS Soils Descriptions

5.3 Historic Imagery

A detailed comparison of the modern to historic aerial images is found within the discussions for each of the geomorphic zones. In general, comparison of the 1936 aerial images to the current images does not reveal extensive changes to the overall fluvial systems, but noticeable and sometimes significant changes were observed at specific locations. Vegetation shown on the 1936 aerial photographs appears to be denser along the banks of the major washes and primary channels than the current aerials show. This may be the case as Figure 14 (page 24) shows that 1936 followed a period of average to above average rainfall while the basin is currently in a drought. Review of repeat photography on the SRER from 1902 to 2000 shows noticeable changes in vegetative density over the years. (Note that the changes on the SRER are due in part to rainfall but are also due to grazing and management conditions.) Figure 30 is a series of pictures from SRER Photo Station 231 (see Figure 31) facing east. Figure 31 shows the location of the SRER photograph stations along with the locations of the aerial photograph comparisons.

1905 SRER 231 Photograph

1941 SRER 231 Photograph



1951 SRER 231 Photograph

1962 SRER 231 Photograph

Figure 30 - Santa Rita Experimental Range Historic Photographs

1975 SRER 231 Photograph

1984 SRER 231 Photograph

1990 SRER 231 Photograph

1993 SRER 231 Photograph

1997 SRER 231 Photograph

2003 SRER 231 Photograph

Figure 30 - Santa Rita Experimental Range Historic Photographs *(continued)*

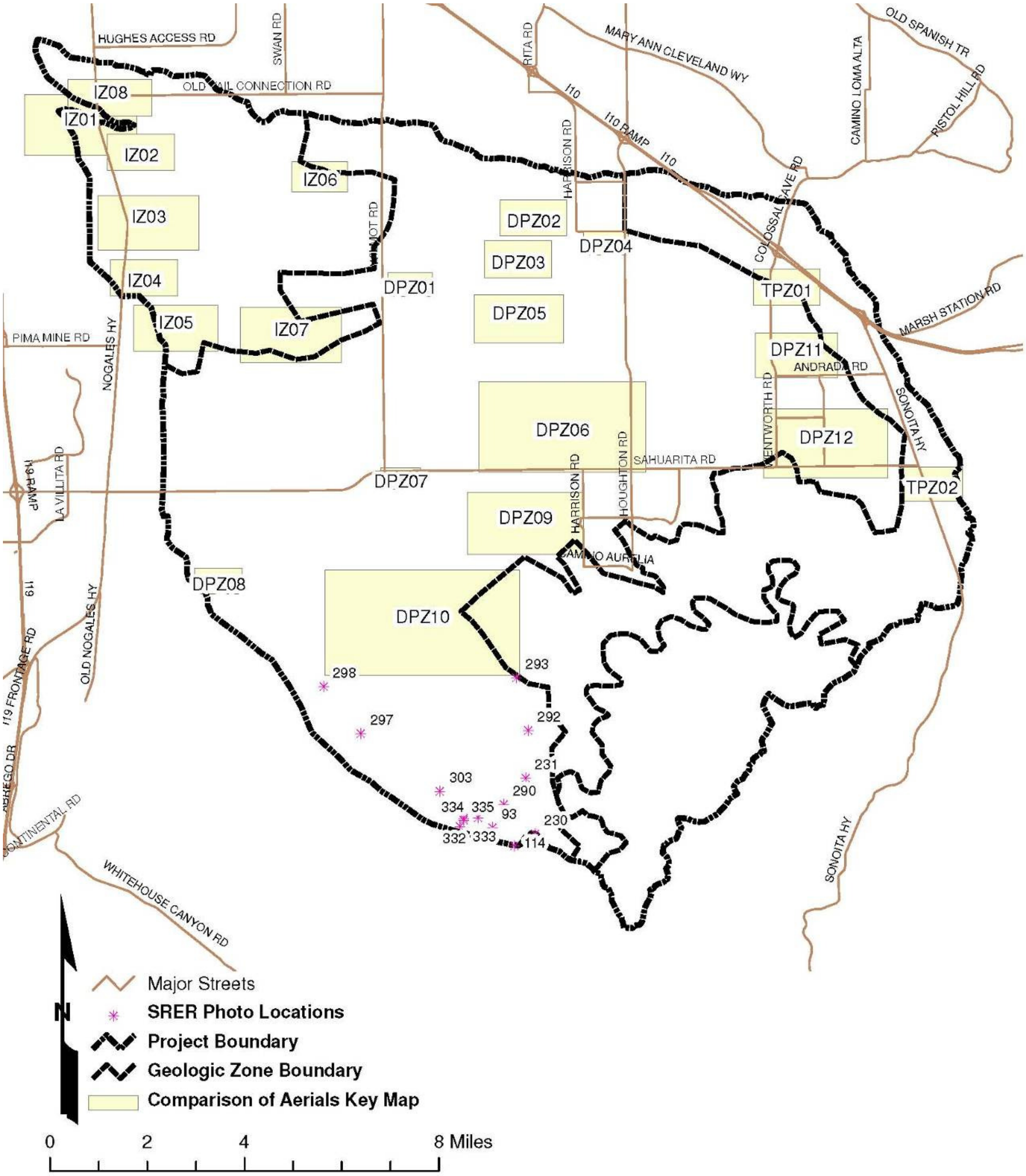


Figure 31 - Key Map for historic photographs

5.4 Pediment Zone

The Pediment Zone is a sediment production zone which is almost entirely composed of weathered bedrock and weathered bedrock covered with a relatively thin alluvium veneer. The hillslopes are typically smooth and rounded. The transition from the Pediment Zone to the Tributary Piedmont Zone is a flat landscape dotted with inselbergs. Drainage within the Pediment Zone is primarily contained within well defined corridors with significant lateral relief. Drainage channel beds are composed of alluvium generated within the upstream hillslopes. Vegetation is scarce on the bedrock hillslopes but is found on highly eroded knobs and where colluvium and alluvium have been deposited at the base of slopes. Development is relatively non-existent. Representative views from this zone are shown within the following figure.

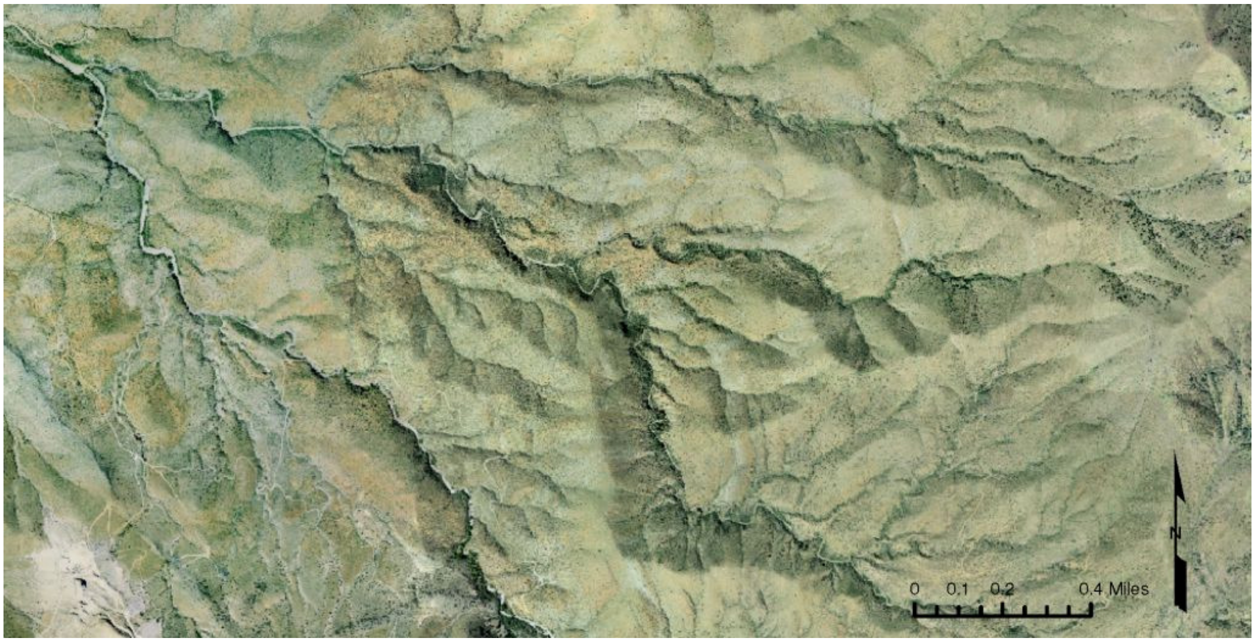
View across Distributary Piedmont onto Pediment hillslopes (panorama of LM01-40-02, 03, 04, and 05)

View of southern Pediment hillslopes from quarry road (panorama of LM01-05-01 and 02)

Figure 32 - Representative views within the Pediment Zone

View of Peach Knob near Helvetia (panorama of LM01-04-01 and 02)

View of Pediment from Houghton Road (panorama of LM-02-10, 11, and 12)



Typical aerial view of tributary flow in Pediment Zone

Figure 32 - Representative views within the Pediment Zone (continued)

5.4.1 *Geomorphic and Topographic Setting*

The Pediment zone consists of the oldest geologic units which make up the pediment on the west side of the Santa Rita Mountains. The geologic units on the pediment are mostly Cretaceous bedrock units of quartz sandstone formations (Ka, Kw, Krw, Kfc, Kgdy, Tq, etc. as mapped on the Mount Fagan map) and limestone bedrock units (P and M as mapped on the Corona de Tucson map). The Mount Fagan bedrock geology is described as "exceptionally complex" (Ferguson et al, 2002) as is evidenced on the associated geologic map.

5.4.2 *Soils*

The soils in this zone are almost entirely dark colored mineral soils (Mollisols). From the STATSGO soil data, the predominant soil in the Pediment Zone is MUID 66. This unit is a composite of Chiricahua, Lampshire, and Graham soils in association with rock outcrops. These soils generate medium to rapid runoff rates and are found on hills, pediments, and mountains. The soils generally form on mixed alluvium and colluvium and the surface is covered by 50-percent or more gravel and cobble. Other soils in this zone (from the SSURGO data) include Mabray in association with rock outcrops.

5.4.3 *Flooding*

Runoff is generally contained in well defined corridors with flooding confined to defined channels and floodplains. The pediment slopes in this area steeply extend 1,500 to 2,000 feet above the adjacent land. Runoff along these slopes is intense but brief. Due to the high runoff potential from the soils within this zone and canyon-like flow paths, the small tributaries may be subject to flash flooding.

5.4.4 *Erosion, Sedimentation, and Lateral Migration*

Because this geomorphic zone is composed of exposed bedrock and thin veneers over bedrock, erosion is greatly limited and confined between bedrock canyon walls and within floodplain corridors. Due to the position within the watershed, deposition is not common in this zone. Furthermore, the degree of bedrock present limits lateral migration within this zone.

5.4.5 *Headward Erosion*

Headward erosion does not generally occur in this zone due to the steep slopes and bedrock soil units.

5.4.6 *Notable Drainage Crossings*

No notable drainage crossings were found within this zone.

5.4.7 *Roads Parallel to Flow Paths*

No notable locations of scour parallel and adjacent to roads were found within this zone.

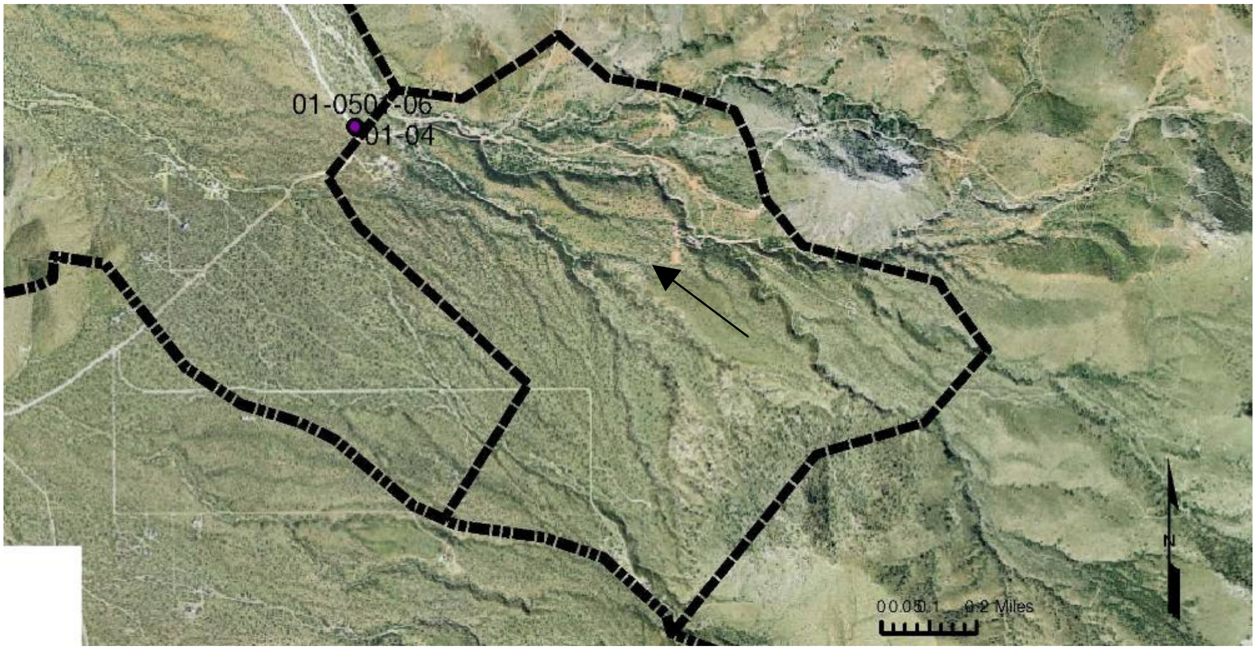
5.4.8 *Aerial Photograph Comparison*

The comparison of aerial images found no observable differences to the fluvial systems within the Pediment Zone.

5.5 Tributary Piedmont Zone

The Tributary Piedmont Zone lies at the base of the Pediment. This zone represents a transition from sediment production to sediment transport. This zone contains limited areas of rock outcrops and inselbergs or knobs. Sediment production occurs in this zone at a greatly reduced scale compared to the Piedmont Zone. The drainage in this zone is predominantly contained in well defined wash corridors. Local lateral relief ranges from 2 to 6 or more feet. Vegetation is well established on the wash overbanks while the wash bottoms are typically sandy with some small cobbles. Washes are easy to traverse as the wash bottoms are fairly well compacted. Vegetation in the washes exists only on islands or between braids. Soil colors range from red and brown on the exposed knobs and adjacent floodplains to sandy and grey in and near the channels.

This zone consists of two sections separated by a small area where there is no competent, tributary channels to transport runoff from the Pediment Zone to the Distributary Piedmont Zone. The southern section is isolated and relatively small, representing a brief transition from the Pediment Zone to the Distributary Piedmont Zone along the western side of the study area. The northern section is much larger in area and in distance from the end of the Pediment Zone to the beginning of the Distributary Piedmont Zone. Along the east side of the study area, this zone extends a sizeable distance towards Houghton Road. Figure 33 shows some representative views from this zone.



Aerial view of Southern Tributary Piedmont Zone

Figure 33 - Representative views within the Tributary Piedmont

View south across southern Tributary Piedmont Zone (LM01-15-01)

View south across southeastern Tributary Piedmont Zone (LM02-40-01)

View of rock outcrop in central Tributary Piedmont Zone (LM02-28-01)

View of development in southeastern Tributary Piedmont Zone(LM02-34-02)

Figure 33 - Representative views within the Tributary Piedmont (continued)

5.5.1 Geomorphic and Topographic Setting

The majority of the zone is made up of dissected relict alluvial fan terraces from the early to middle Pleistocene and includes such alluvium as Qm, O, M1, and Qi2. The uplands in the Tributary Piedmont Zone (near the eastern limit of the study area) consist of mostly Quaternary and some late Tertiary deposits. Older alluvium from the early Pleistocene to late Miocene has been mapped as QTs. Qm and Qo surfaces are situated adjacent to each other with contained Qy surfaces found throughout the zone. The flow in this zone is contained in wash corridors forming a tributary drainage network as shown in Figure 34.

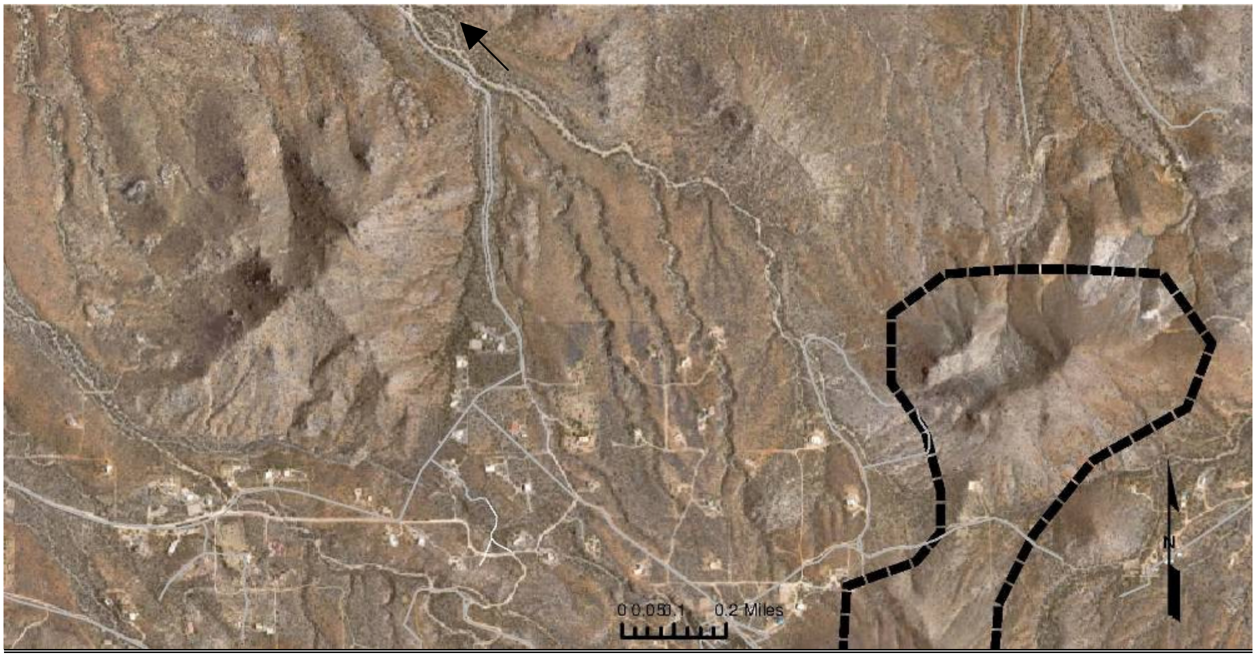


Figure 34 - Tributary watercourses east of Camino Aurelia within Tributary Piedmont Zone

The divide between the Tributary Piedmont Zone and the Distributary Piedmont Zone was generally drawn at the location of the first major flow split (see the primary diffluence discussion in Section 6.3.1) as shown in Figure 35 and Figure 36. The transition from tributary and confined flow to distributary flow along the Flato Wash is seen in Figure 35. Similar transitions are seen for several flow corridors in Figure 36. The Sycamore Canyon Wash is in the middle of the frame (this diffluence is detailed in the Distributary Piedmont discussion). A distinct change in soil color (in the aerial view) is observed at the transition between these two points, especially in Figure 36. The soils appear to be browner in the Tributary Piedmont Zone than those in the Distributary Piedmont Zone which appear to be greyer. Also, there is less apparent vegetation in the Tributary Piedmont Zone.

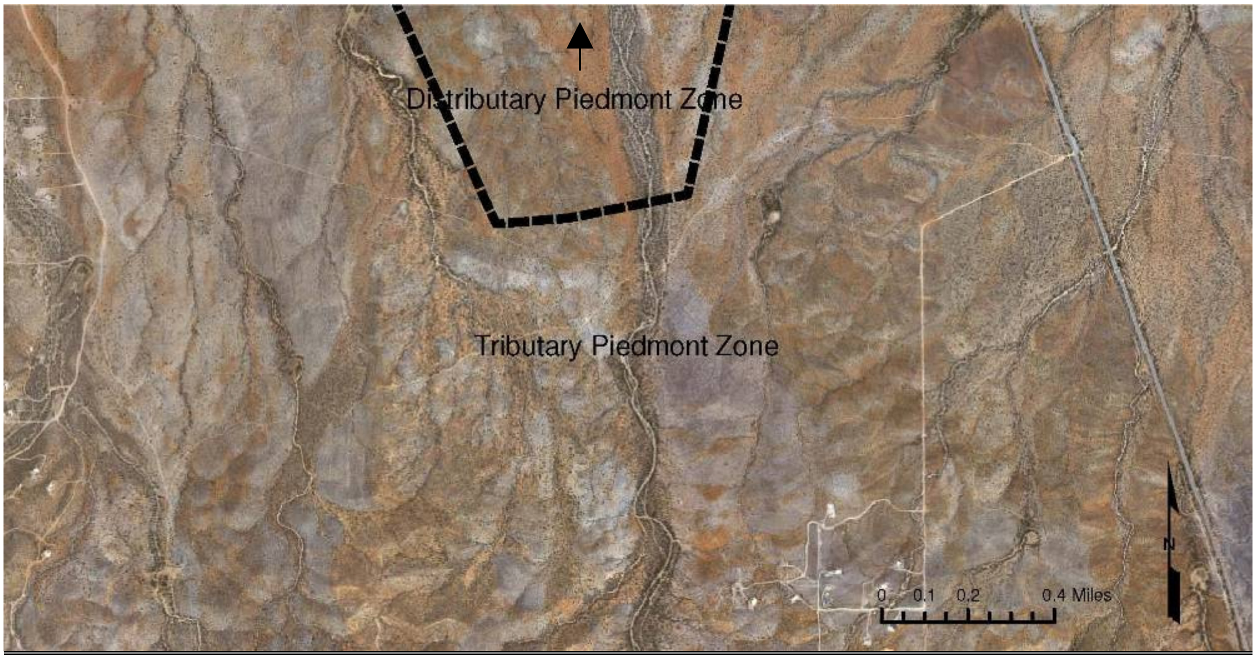


Figure 35 - Flato Wash at the transition from Tributary Piedmont Zone to Distributary Piedmont Zone

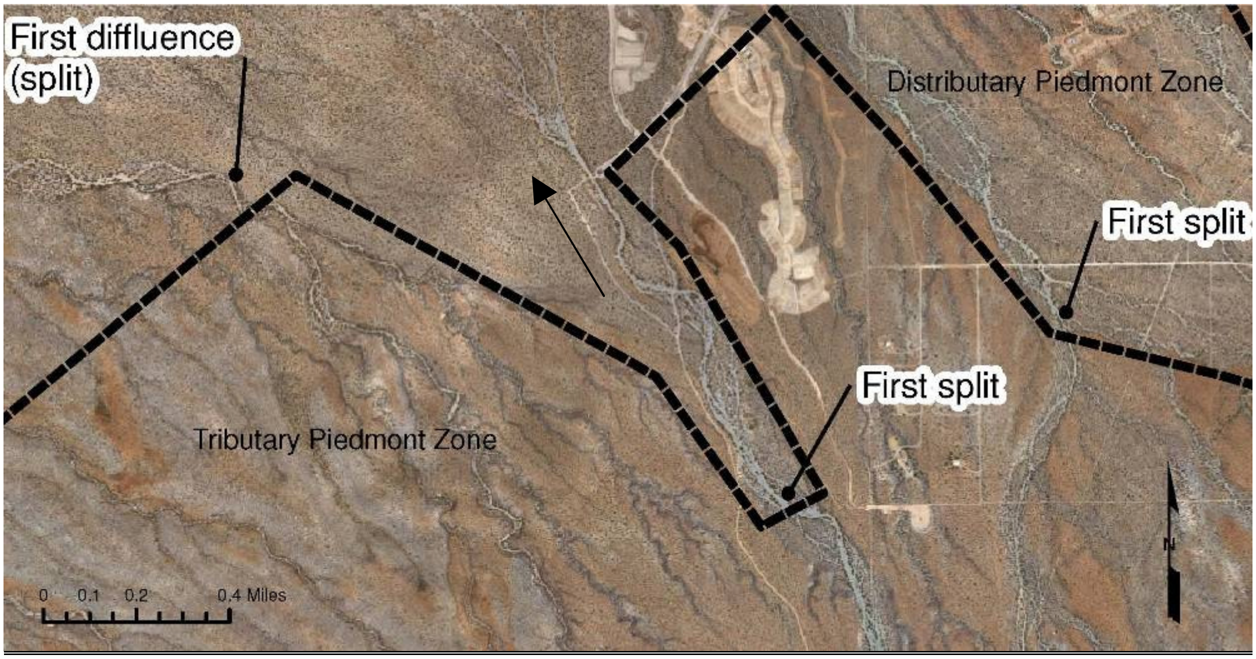


Figure 36 - Sycamore Canyon Wash at the transition from Tributary Piedmont Zone to Distributary Piedmont Zone

The northernmost portion of the Tributary Piedmont Zone has slightly different geomorphology than the uplands and the southern areas of the zone. Tributary flow paths are less apparent but still visible from aerial imagery (Figure 37). This area consists of deeply dissected alluvial deposits from the Quaternary to late Tertiary periods (QTs and QTcg). Younger Pleistocene alluvial deposits (Qm and Ql) are mapped on the Vail surficial geology map in the area to the west of Wentworth road (Figure 38), however the Tucson Southeast map shows isolated Ql surfaces mapped amongst QT surfaces (Figure 39). Within both maps, modern flow paths occupy Qy units bisecting the older terrace units.

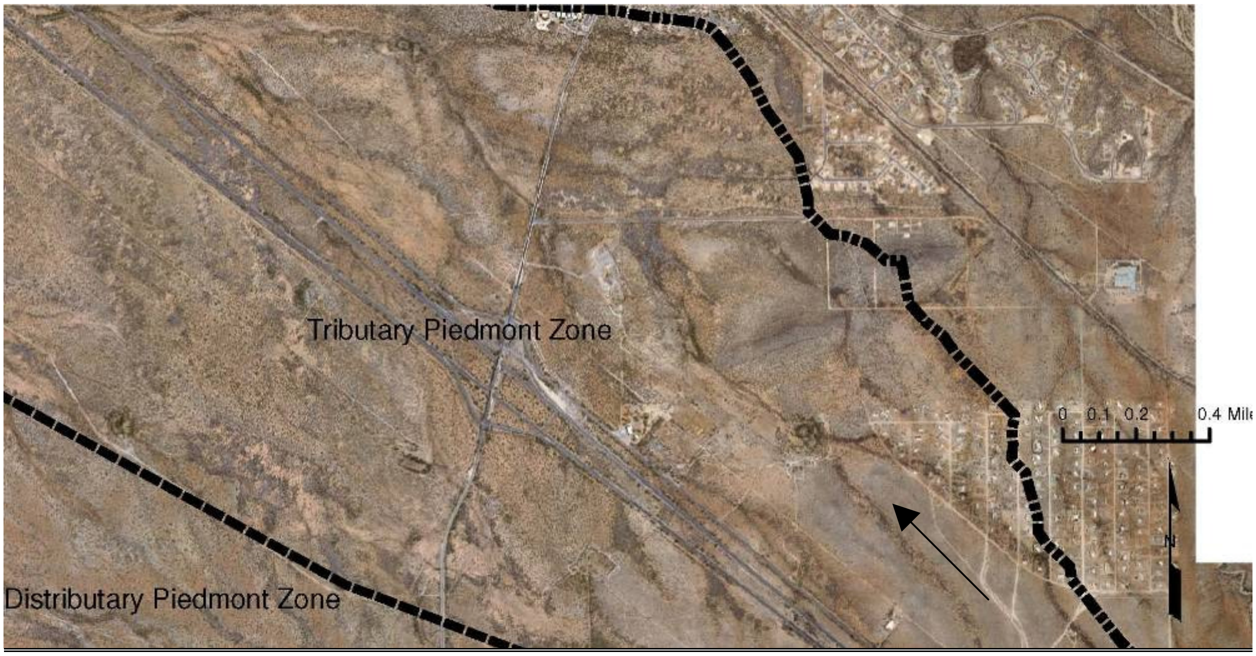


Figure 37 - Aerial view of Tributary Piedmont Zone near Wentworth Road and I-10 intersection

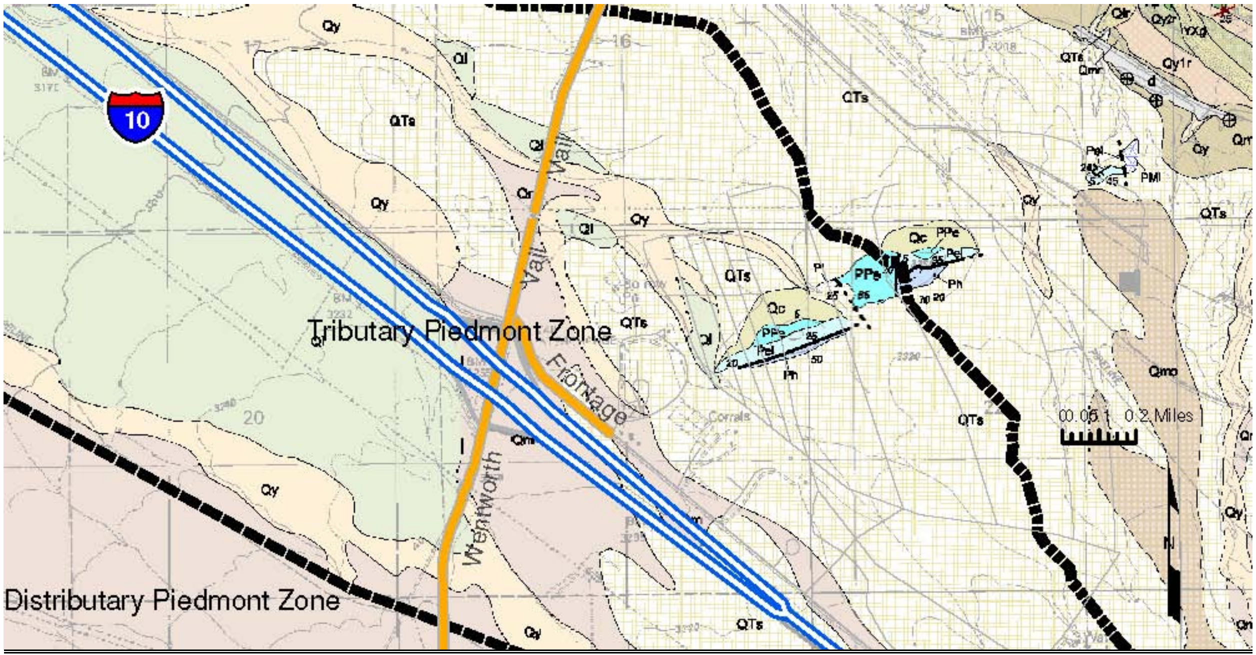


Figure 38 - Surficial geology of Tributary Piedmont Zone near Wentworth Road and I-10 intersection

Figure 39 - Discrepancies in surficial geology units in Tributary Piedmont Zone

Relict alluvial fans consisting of deposits made up through the middle Pleistocene (Qm, M1, Qo, and O in particular) are found within this zone, primarily within the Corona de Tucson surficial geology map. The fans have since been isolated from deposition and are currently eroding. Figure 40 shows the aerial view of two early to middle Pleistocene alluvial fans. The topographic apices are situated at the base of the Pediment. Figure 41 shows the topographic view of these fans.

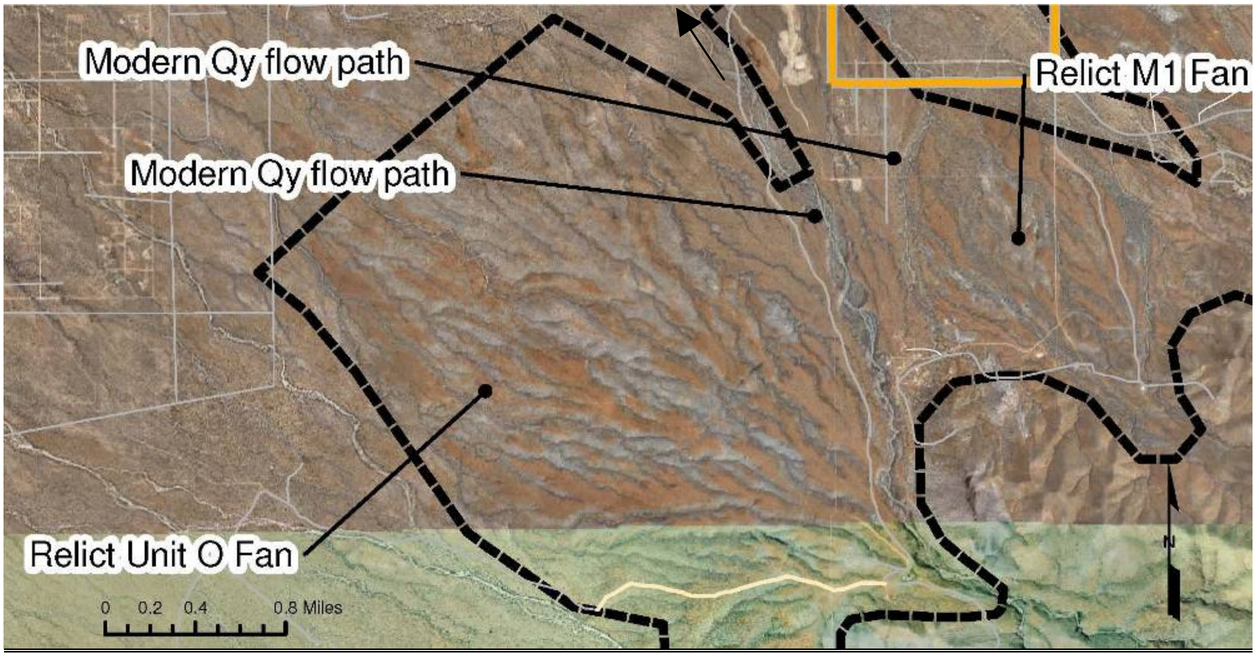


Figure 40 - Relict alluvial fans within Tributary Piedmont Zone

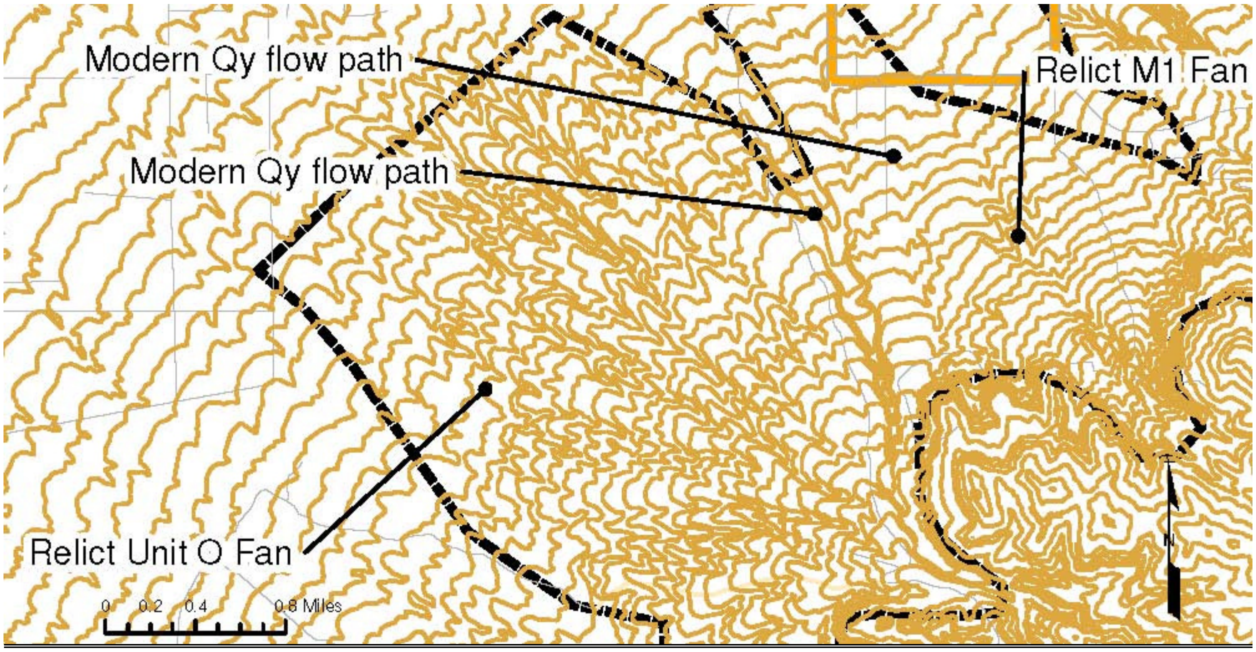


Figure 41 - Topographic map of relict alluvial fans within Tributary Piedmont Zone

5.5.2 *Soils*

The soils in this zone are primarily Aridisols and include calcium carbonate accumulations. Some Mollisols are also found in the Southern Tributary Piedmont Zone. The STATSGO map shows MUID 60 and MUID 66 cover the Tributary Piedmont Zone. MUID 60 is made up of White House, Bernardino, and Hathaway soils. These soils generate medium runoff rates and are found on undulating to rolling fan terraces. The surface is covered by 30-percent gravel and cobble and the soil is formed on mixed alluvium. Recall that MUID 66 is a composite of Chiricahua, Lampshire, and Graham soils in association with rock outcrops.

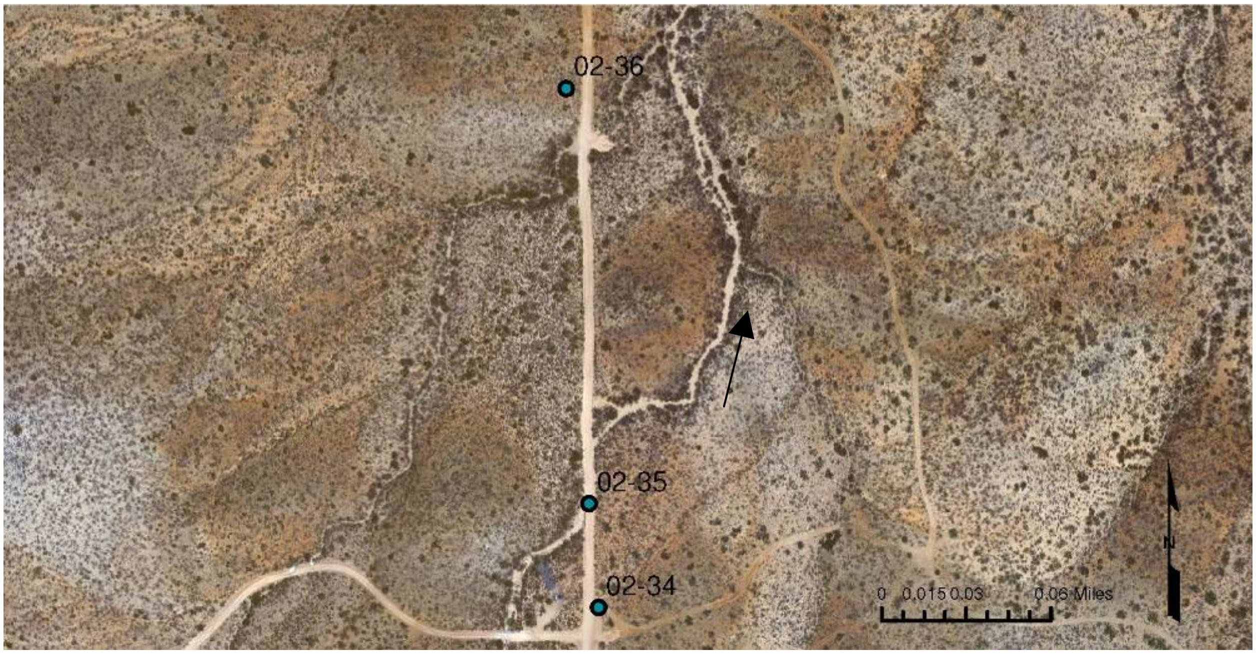
5.5.3 *Flooding*

Flooding risk is typically contained in corridors (usually Qy deposits).

5.5.4 *Erosion, Sedimentation, and Lateral Migration*

Active erosion and sedimentation are generally contained within the flooding corridors. Sedimentation is limited to the wider wash corridors, channel bars and islands, and to areas upstream of underfit drainage crossings. Erosion is occurring on the isolated, relict alluvial fan surfaces. Lateral migration is minimal due to the substantial lateral relief and vegetated bank lines.

The small tributary channels in the Tributary Piedmont Zone uplands (southeastern end of the zone) are bounded by bedrock outcroppings and hillslopes. Access to existing development is typically on dirt roads paralleling and adjacent to the channels, increasing both the risk to the residents and the risk of erosion in and along the channels. Figure 42 shows an aerial view of a wash crossing a road in the uplands, the view upstream from the road crossing, and the west bank of the wash at the crossing. A relatively short vertical bank has developed as a result of the road crossing and minor vertical erosion extends a short distance upstream within the wash bottom.



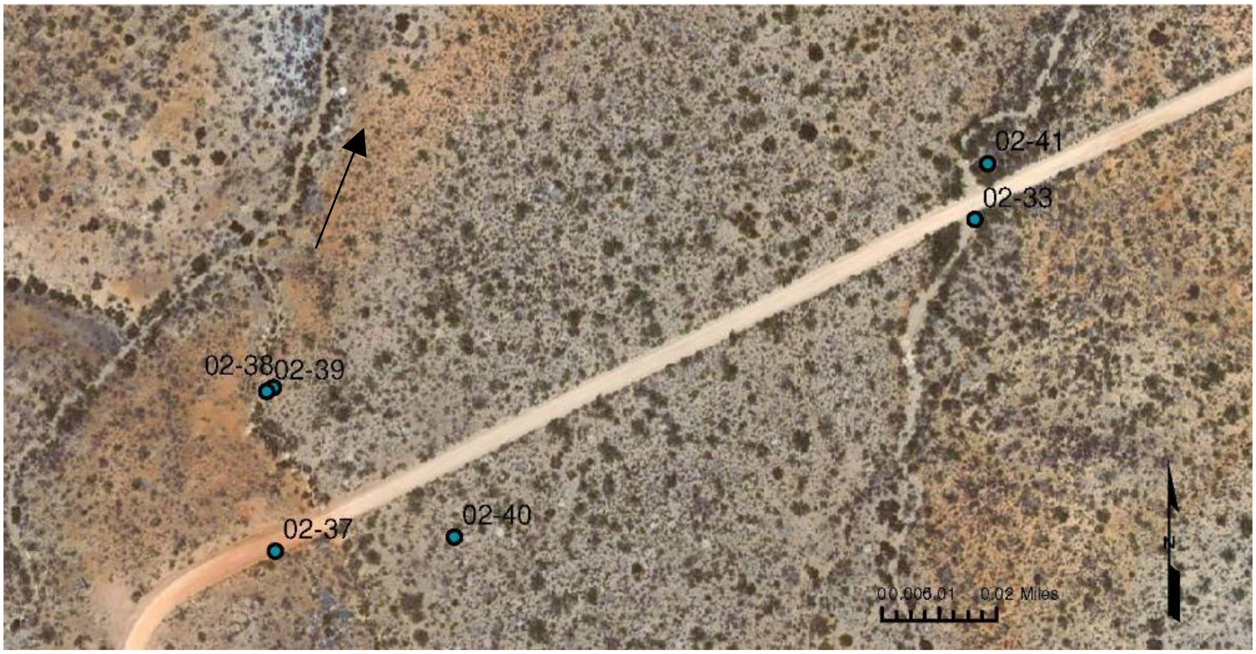
Aerial view of road crossing in Tributary Piedmont Zone uplands

View upstream of wash from along road (LM02-35-02)

Lateral erosion (along west bank) adjacent to road on Qy surface (LM02-35-01)

Figure 42 - Wash crossing road in upper Tributary Piedmont Zone

Figure 43 shows images of two small washes on a Qc surface within the Tributary Piedmont Zone, near Highway 83. The dirt road is not labeled but is accessible from Highway 83 and is within Township 17, Range 16, Sections 23 and 24 at this location. LM02-37-01 is a downstream view of one of the washes crossing the road. The road is elevated above the wash at this location and no culvert was visible although one might exist. LM02-37-03 shows the view of the channel just upstream of the road. The wash is scoured at this location and rock outcrops are visible upstream of the road. LM02-39-01 shows the wash approximately 150 feet downstream of the road. The wash is in a relatively undisturbed condition at this location. The wash bottom is approximately 8 feet below the adjacent terrace. LM02-38-01 shows a ground shot of the adjacent terrace. The soil in the wash and on the adjacent terrace is poorly developed.

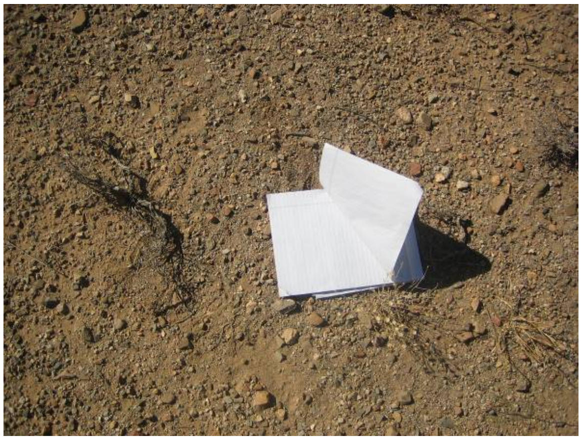


Aerial view of flow paths on Qc surface in Tributary Piedmont Zone uplands

View north from road (LM02-37-01)

Wash north of road (LM02-39-01)

Vertical erosion (LM02-37-03)



Ground shot of Qc surface (LM02-38-01)

Figure 43 - Small washes on Qc surface of Tributary Piedmont Zone

Figure 44 shows another wash crossing on this surface. This wash is less impacted by the road but is also incised with scoured banks.

Downstream view of non impacted wash crossing on Qc surface (LM02-41-01)

Upstream view of non impacted wash crossing on Qc surface (LM02-33-01)

Figure 44 - Another wash on Qc surface of Tributary Piedmont Zone

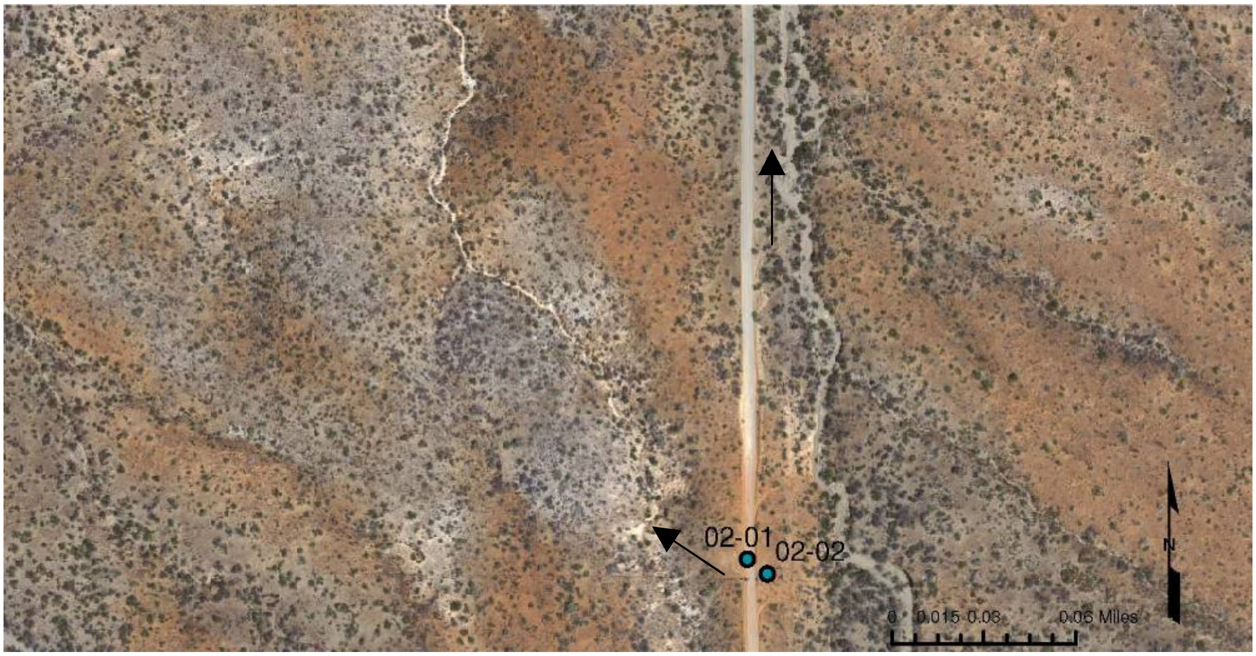
Figure 45 is a view of a wash crossing Highway 83. The banks upstream of the crossing are vertical and the bottom is approximately 10 feet below the adjacent Pleistocene terrace.

Figure 45 - Vertical banks on Qy surface upstream of Highway 83 (LM02-42-01)

5.5.5 Headward Erosion

While the Incised Zone and Distributary Piedmont Zone are significantly impacted by system wide headcutting, the headward erosion emanating from the lowering of the base level of the Santa Cruz River does not appear to impact this zone. Locally induced headcutting can occur and is generally a result of upstream influences and human activity (discharge concentration and/or sediment reduction).

Figure 46 shows the location of a headcut observed along south Houghton Road. The flow direction is to the northwest at this location and flow crosses the road to drain to the wash located west of the road. The wash west of the road is not highly incised and is not impacted by headcutting. However, the wash is at an elevation below the road, and concentrated flow which crosses the road at this location and drains to the wash has caused a headcut to develop from the wash to the road. Only minor scour was noted upstream of the road (LM02-02-01) in association with almost no channel development. LM02-02-02 shows the downstream view where an incised wash has developed with vertical banks. The road has terminated the headcut.



Localized Headcutting along south Houghton Road

View upstream of drainage across south Houghton Road (LM02-02-01)

View downstream of drainage across south Houghton Road, headcutting observed below road (LM02-02-02)

Figure 46 - Headcut observed along south Houghton Road

5.5.6 *Roads Parallel to Flow Paths*

No notable locations of scour parallel and adjacent to roads were found within this zone.

5.5.7 *Notable Drainage Crossings*

No notable drainage crossings were found within this zone.

5.5.8 *Aerial Photograph Comparison*

Very few changes were observed when comparing the aerial images within the Tributary Piedmont Zone. Some evidence of local geomorphic and hydrologic changes due to stock tanks and similar features is found when comparing the two sets of aerial images. Figure 47 shows a diversion near Wentworth Road which has caused aggradation upstream of the diversion and scour downstream of as evidenced by the vegetation patterns. The scour and aggradation are limited to the general area shown in this figure. Figure 48 shows another location with an impoundment, but the impacts to the fluvial system are unclear. Greater vegetative growth appears to have developed downstream of the impoundment and the primary flow path is less visible downstream of the impoundment.

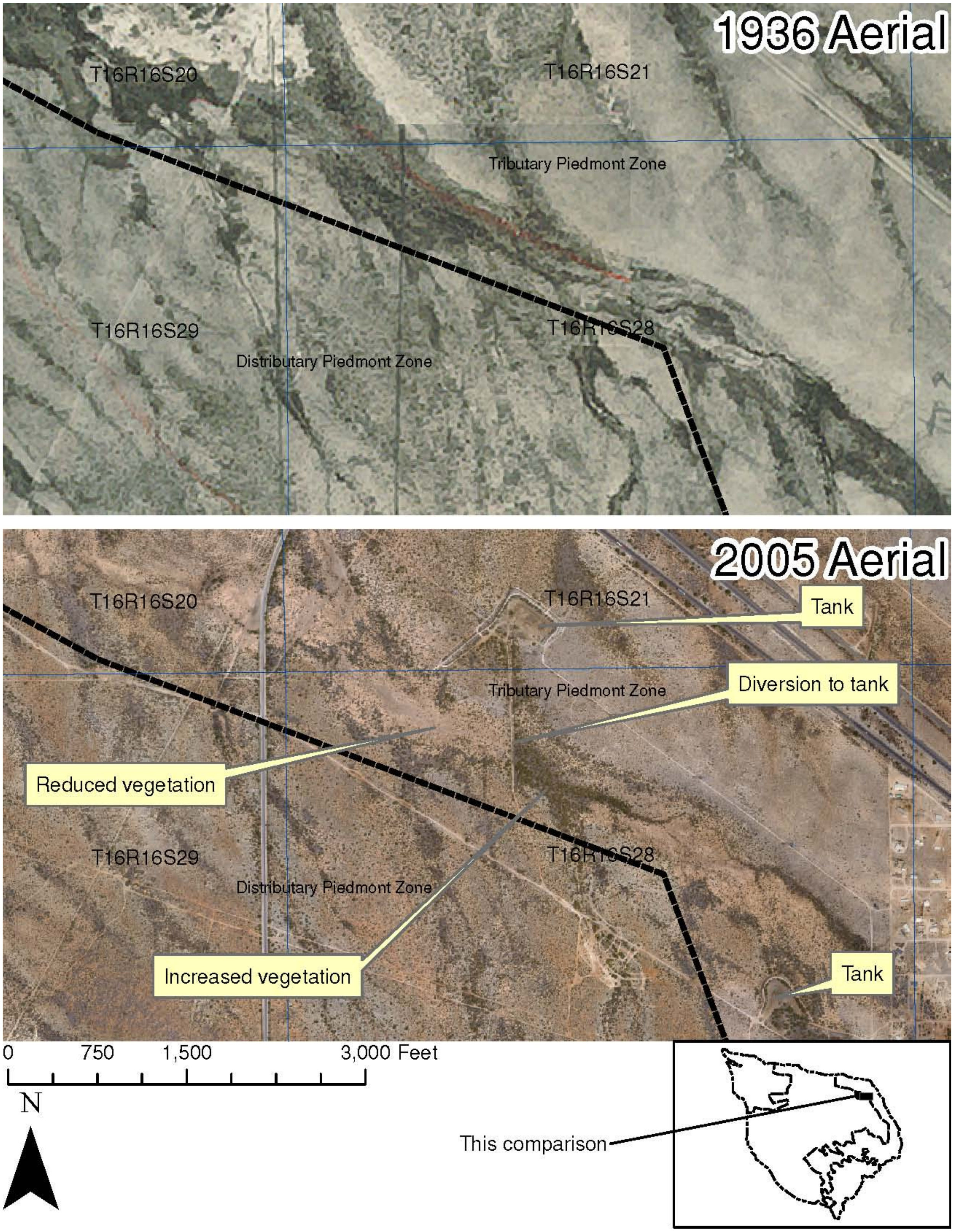


Figure 47 - Comparison of 1936 and current aerial images; station TPZ01

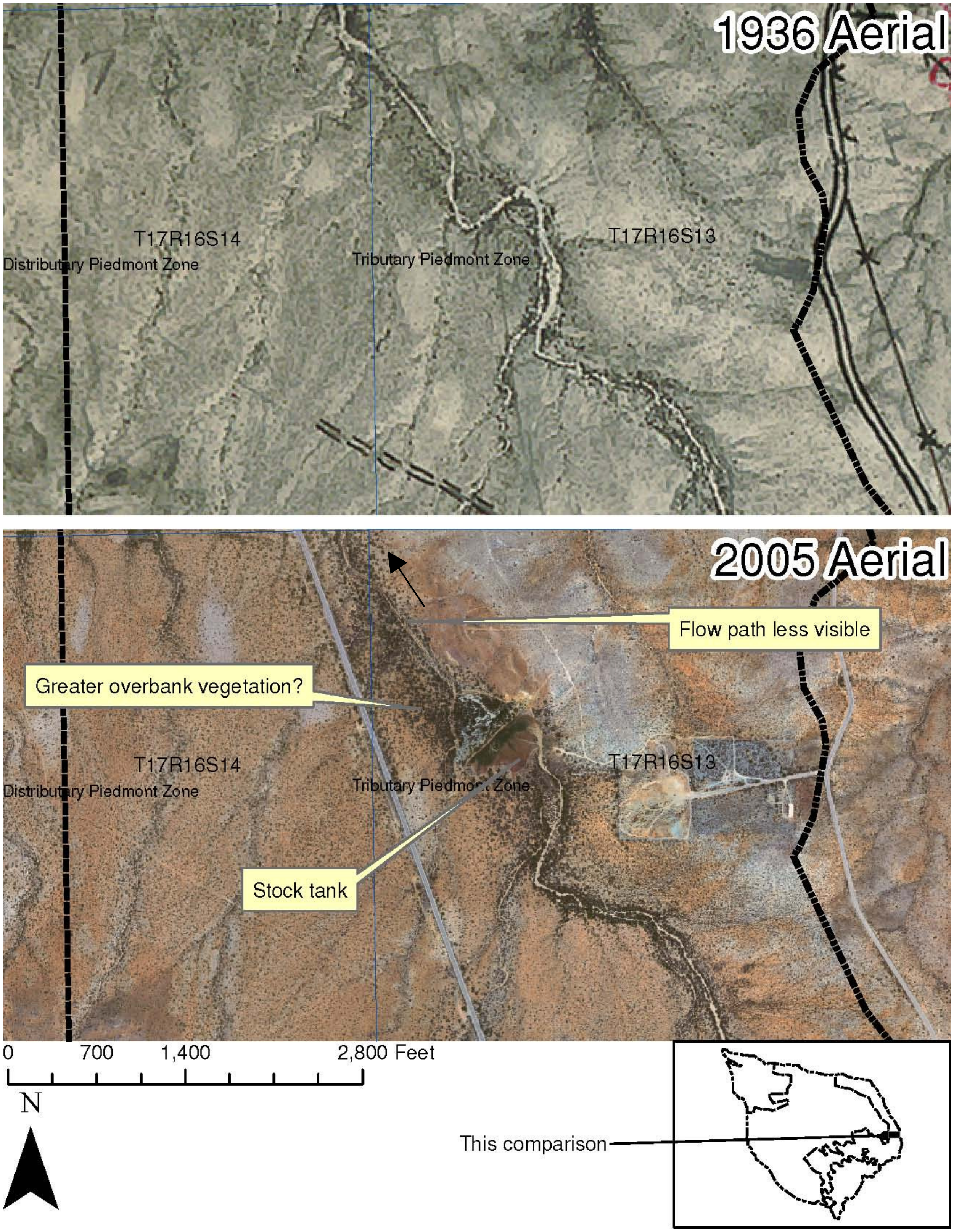
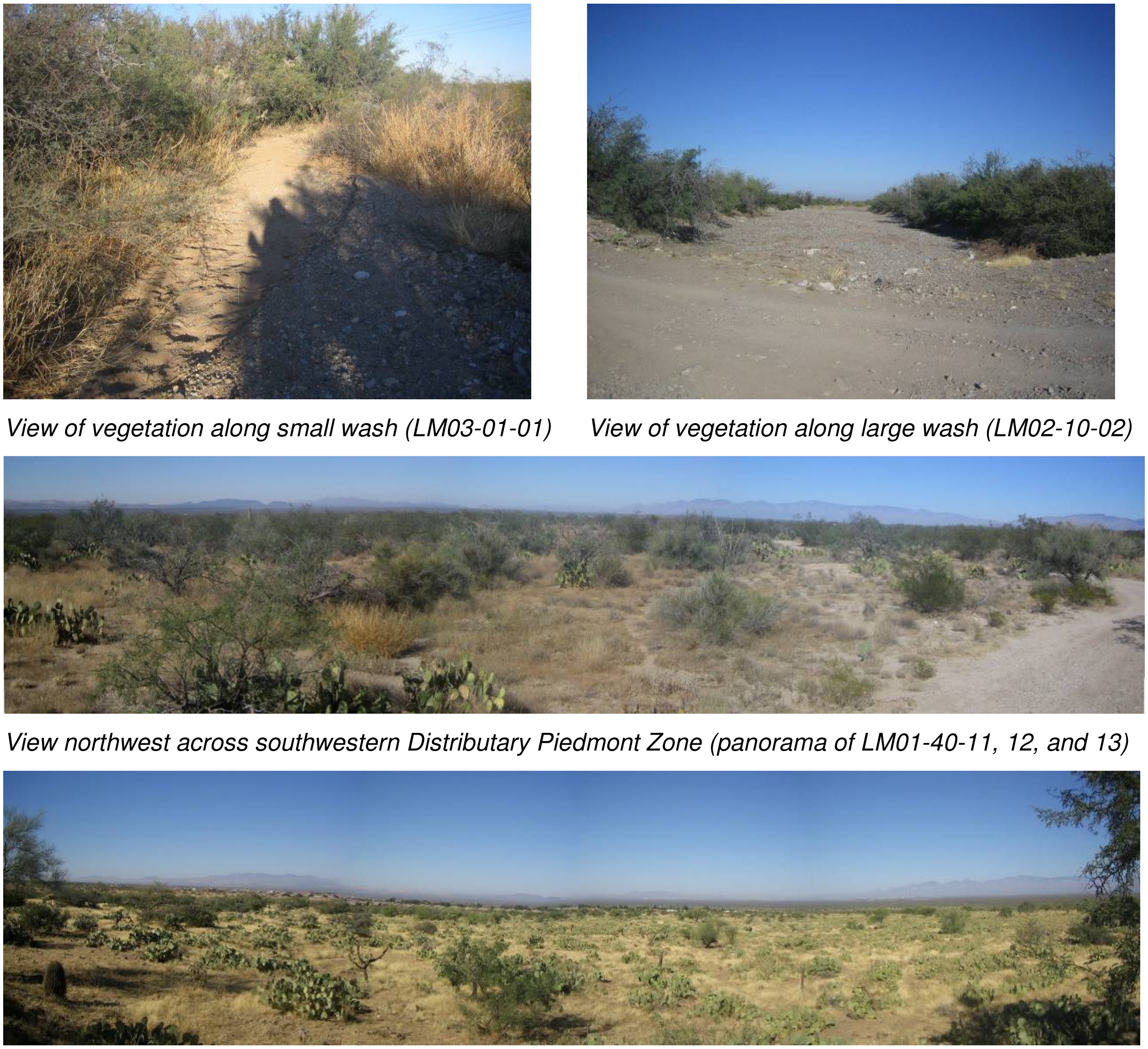


Figure 48 - Comparison of 1936 and current aerial images; station TPZ02

5.6 Distributary Piedmont Zone

The Distributary Piedmont Zone lies downstream of the Tributary Piedmont Zone and is a sediment transport zone although sediment deposition occurs within this zone. This zone is somewhat flatter longitudinally than the Tributary Piedmont Zone as was shown on Figure 20. Greater levels of existing development and human impacts are found in this zone than the Tributary Piedmont Zone. Flow is not only contained in large wash corridors but is also found in smaller swales on the terraces and uncontained on the terraces and floodplains.

Well established vegetation is found in many areas along the wash overbanks and on the terraces, however this zone contains large areas with limited and sparse vegetation. Braided flow patterns dominate in many areas and are obvious on the aerial imagery. Isolated rock outcrops such as Hueferno Butte are found nearest to the Tributary Piedmont Zone. See Figure 49.



View of vegetation along small wash (LM03-01-01)

View of vegetation along large wash (LM02-10-02)

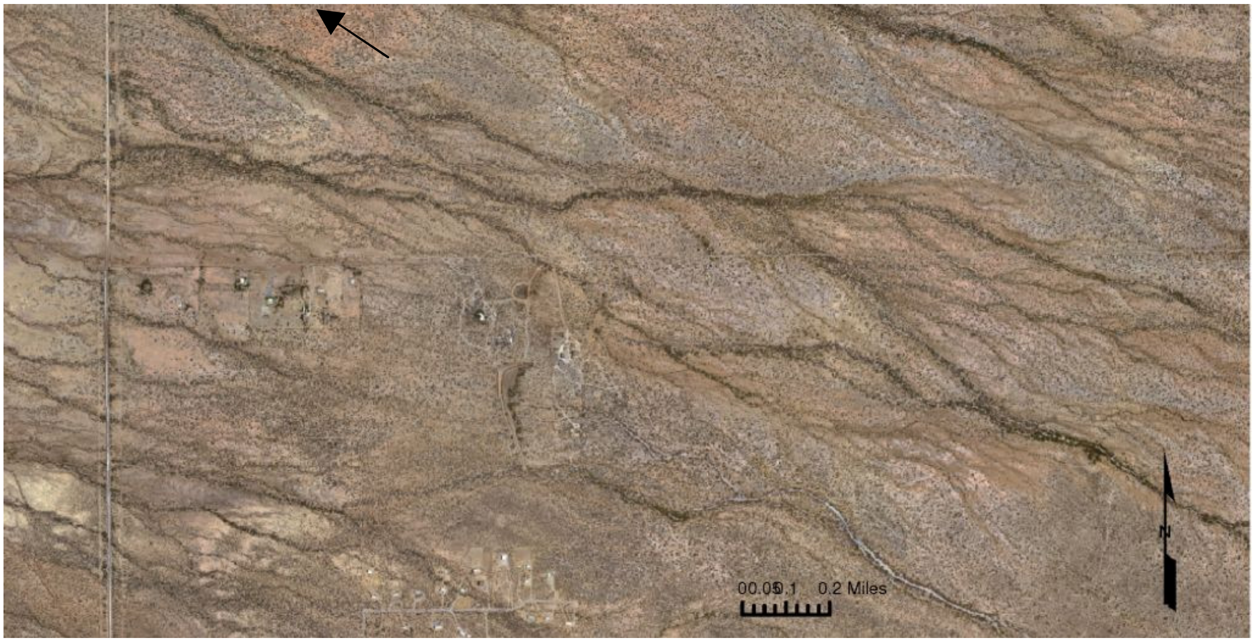
View northwest across southwestern Distributary Piedmont Zone (panorama of LM01-40-11, 12, and 13)

View northwest across Distributary Piedmont Zone (panorama of LM02-21-01, 02, 03, and 04)

Figure 49 - Representative views within the Distributary Piedmont Zone

Sparse vegetation west of Houghton Road, Ql (M2) surface (LM02-57-01)

Huerfano Butte from Santa Rita Rd. (LM01-01-01)



Aerial view of typical braided flow in southwest Distributary Piedmont Zone

Figure 49 - Representative views within the Distributary Piedmont Zone (continued)

5.6.1 Geomorphic and Topographic Setting

The Distributary Piedmont Zone includes Y1, M2, Ql, Qly, Qy, and Qi3 alluvium ranging from the late Pleistocene to the early Holocene. This zone also contains some Quaternary to late Tertiary alluvial fan deposits such as Qm, QTcg, and M1.

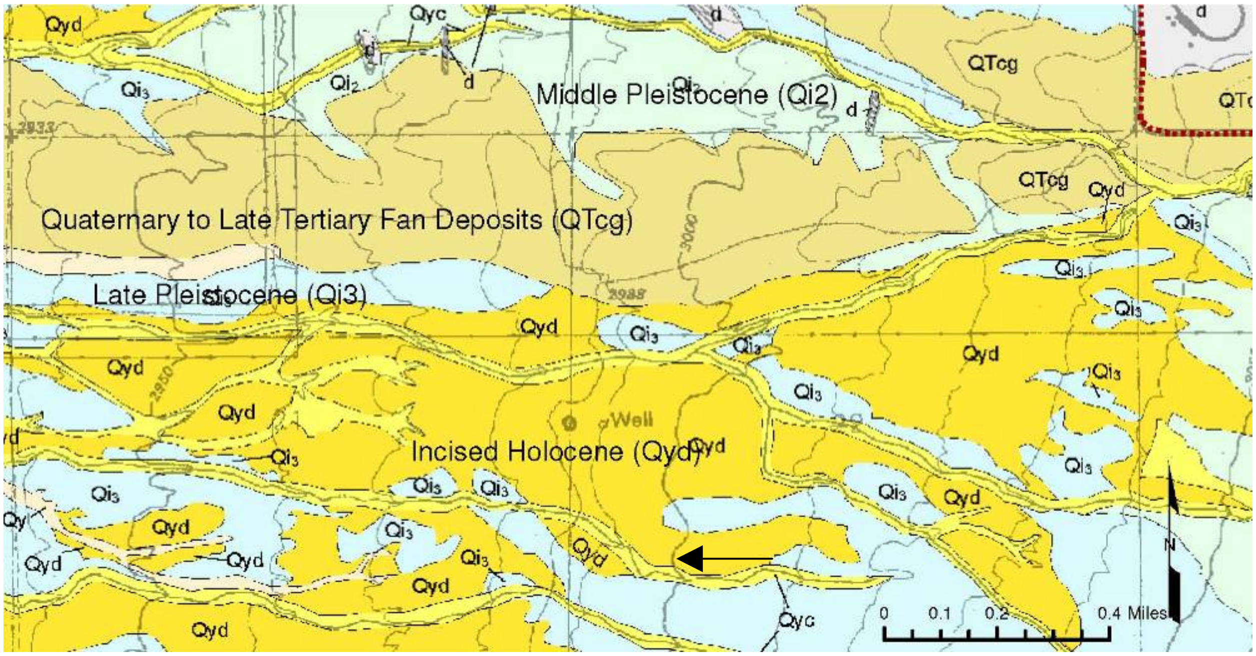
This zone is the most complex of the four zones within the study area from a drainage and fluvial geomorphology perspective. Contour band width is the least within this zone and the majority of the flow splits in the study area are found within the Distributary Piedmont Zone. Washes which were contained and well defined in the upper zones disperse within this zone and disappearing washes occur in this zone. Interfluves are generally below 100-year flood levels within this zone.

Review of the surficial geology maps indicates that adjacent fans are sometimes composed of geologic units of varying ages. Fans of varying ages are found adjacent to each other throughout this zone more so than in the other zones, specifically in the western side of the zone. Within the Corona de Tucson surficial geology map area, Jackson (1990) states that "the piedmont contains a wide variety of ages of fans" and "on the west side of map area, all ages of fans can be found adjacent to each other, with little, if any, vertical separation" (1). The western portion of the Corona de Tucson geologic map is reported by Jackson as transitioning from an alluvial fan regime to a discontinuous ephemeral stream. This interpretation can be applied to the majority of the western Distributary Piedmont Zone. The following is from Jackson's open file report for the Corona de Tucson geologic map (1990):

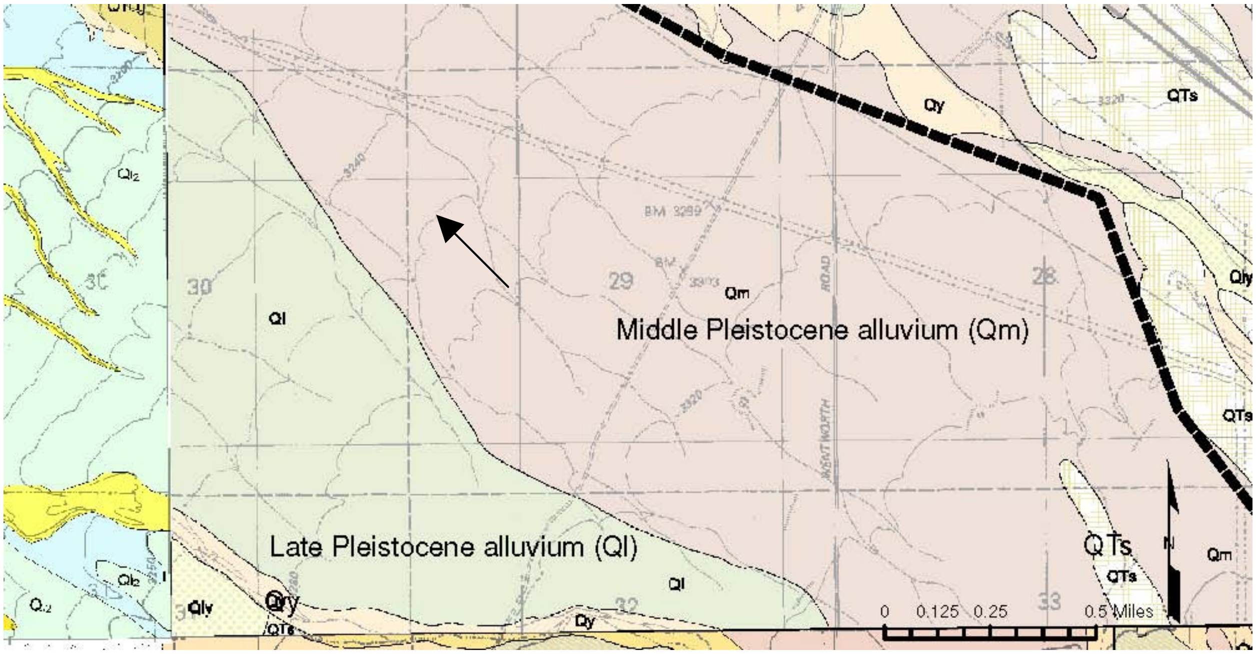
> As the gradient of the piedmont decreases, streamflow becomes unconfined and sediment is deposited. Sheetflow begins to dominate (however, historic arroyo-cutting has channelized much of the flow across the piedmont). With no well-defined drainage divides or channels, loci of deposition (alluvial fans) become increasingly diffuse, and become 'intertwined' with patches of older units on the piedmont. The flow regime then becomes a discontinuous ephemeral stream. In this regime, the drainages experience infrequent flow. During a flow event, parts of the drainage experience sheetflow and deposition, while some parts experience channelized flow and headward erosion. (1)

This zone is covered by multiple maps and Figure 50 shows representative surficial geology for this zone.

- The north/central portion of this zone is mapped on the Tucson SE surficial geology map. This map shows various deposits adjacent to each other and bisected by modern deposits.
- Broad Ql and Qm surfaces (relict alluvial fans and terraces) are found towards the northeast as shown on the Vail surficial geology map.
- The southwest distributary piedmont zone is mapped on the Sahuarita surficial geology map and contains broad areas mapped as Qy and Qly with some Qm surfaces, representing relatively young deposits and signifying large floodprone areas. The Qly surfaces are covered with a thin veneer of Qy Holocene alluvium (Pearthree and Youberg, 2000), an indication of recent alluvial fan activity.
- The central Distributary Piedmont Zone is mapped on the Corona de Tucson surficial geology map. This map includes Y2 units which are active and recently active alluvial fans and deposits.

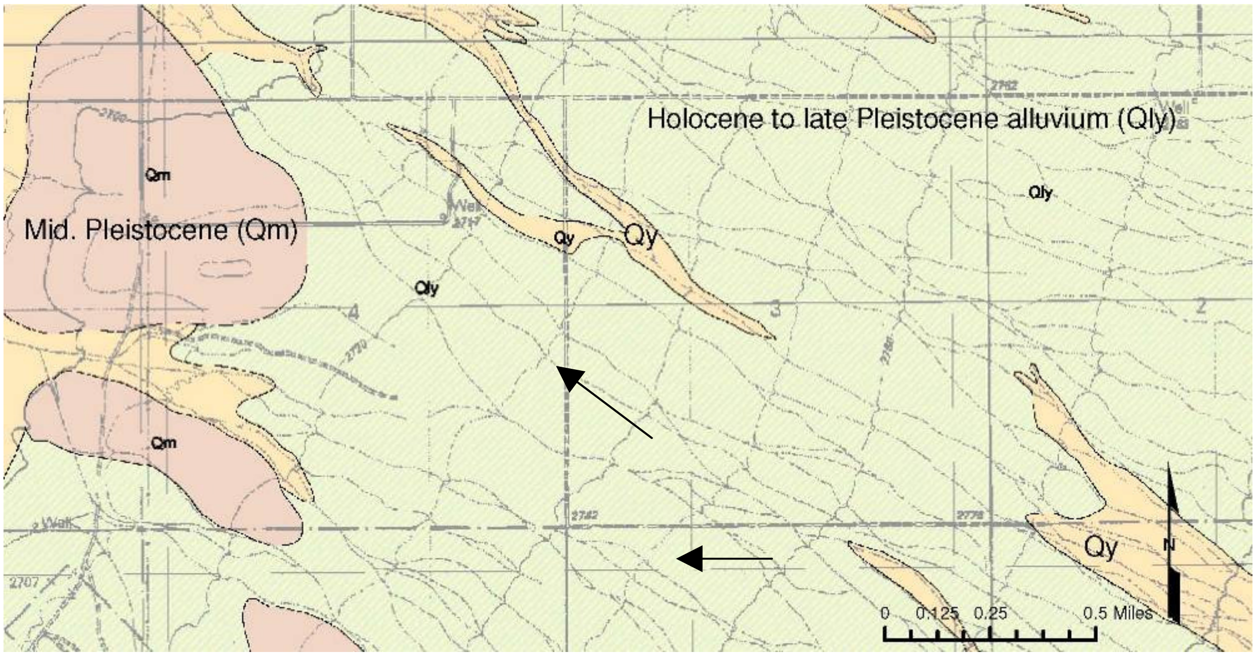


Representative surficial geology in the north/central Distributary Piedmont Zone

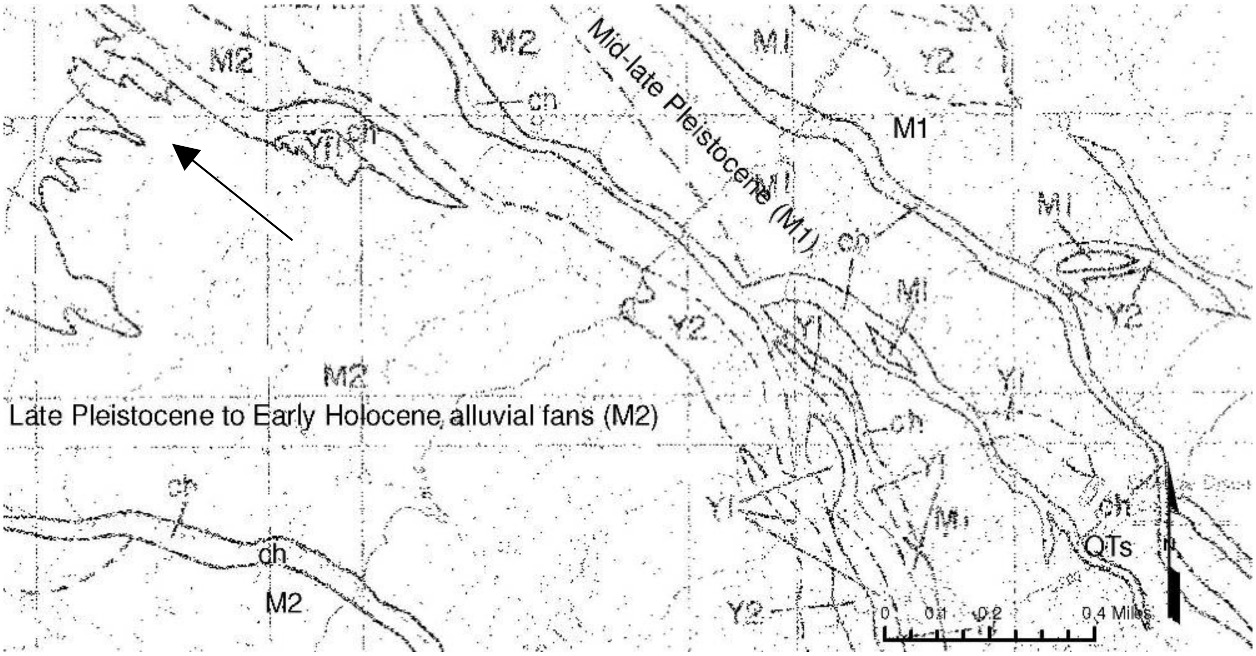


Representative surficial geology in the northeast Distributary Piedmont Zone

Figure 50 - Representative surficial geology for Distributary Piedmont Zone



Representative surficial geology in the southwest Distributary Piedmont Zone



Representative surficial geology in the central Distributary Piedmont Zone

Figure 50 - Representative surficial geology for Distributary Piedmont Zone (continued)

5.6.2 *Soils*

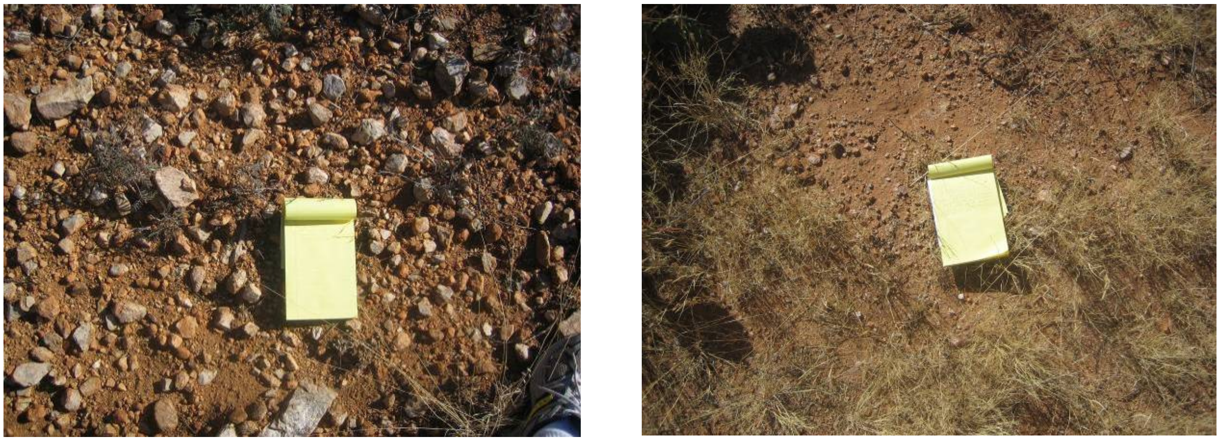
The Distributary Piedmont Zone soils are primarily Aridisols bisected by Entisols. MUID 38 is found towards the lower end of the basin and is made up of Mohave, Sahuarita, and Cave soil units. This unit covers the majority of the Distributary Piedmont Zone. These soils formed on mixed alluvium. The Mohave and Sahuarita soils generate slow to medium runoff while the Cave soils generate more rapid runoff rates. MUID 60 is found in the upstream areas of this zone. Other soils found in this zone include Anthony, Arizo-Riverwash, Bucklebar, Comoro, Hantz, Laveen, Rillito, Sahuarita, Sonoita, Tubac, and Yaqui.

Figure 51 (following) shows ground shots of some of the prominent soils found within this zone.

5.6.3 *Flooding*

This zone has the greatest risk of flooding outside of defined corridors, indicative of sheet flow and distributary flow. Many of the drainage paths in this zone are unconfined with sediment laden flows subject to sheet flooding. The potential for flooding and associated hazards are the greatest where tributary flow paths break down into distributary flow corridors, specifically near the transition from the lower Tributary Piedmont Zone to the upper Distributary Piedmont Zone. Nowhere is this greater than in the southwest Distributary Piedmont Zone.

Braided and anastomozing channels are prevalent in this zone and perched flow where washes parallel one another in this zone will cause an intermingling of flow between watersheds. Contributing flow area to a point is therefore somewhat dependent upon the event and recent conditions. Human interaction within this zone may have a greater impact on redirection of runoff than in the other zones.



Typical bedrock unit soil on knob in Distributary Piedmont Zone (LM01-14-01)

Typical soil in Qm surface floodplain area (LM01-21-01)

Soil within Qy surface channel (LM01-12-01)

Gravelly channel on Qy surface (LM02-14-02)

Desert pavement on Ql surface (LM01-46-04)

Barren Ql surface (LM02-57-02)

Figure 51 - Ground shots of Distributary Piedmont Soils

Qyc surface (LM02-61-03)

QTcg surface (LM03-03-01)

Qyd surface (LM03-18-01)

Visible soil horizons below Ql/Qm surface found on recently eroded bank (LM01-47-01)

Visible soil horizons below Qm surface found on recently eroded bank (LM02-46-03)

Figure 51 - Ground shots of Distributary Piedmont Soils (continued)

5.6.4 Erosion, Sedimentation, and Lateral Migration

This zone includes large areas of isolated relict fan surfaces which are developing internal drainage networks. Active erosion, sedimentation, and avulsion are not limited to the wide wash corridors but are found throughout the zone and are accelerated by human activity. Erosion on the relict terraces is accelerated when vegetation is cleared as new vegetation has a difficult time developing the necessary root structure to withstand future flooding. There is a significant potential for lateral migration and stream piracy within this zone.

Figure 52 (following) is an illustration of how streamflow becomes unconfined as the piedmont gradient decreases. In this example, a contained wash (Sycamore Canyon Wash) with significant lateral relief breaks down into distributary flow. This wash is located along the west side of an area which is currently being developed and will continue to develop within the foreseeable future. Through a series of diffluences, this channel bifurcates into a half-dozen channels which recombine to three distinct channels, occurring over a distance of about 1.6-miles. The upstream tributary channel occupies a Qy surface and the distributary channels occupy both a Qy and an older Ql surface.

Field point LM02-14 is located near river mile 15.75 in reference to the Lee Moore Wash/Sycamore Canyon Wash profile shown in Figure 22. The slope of the wash is decreasing at this location from approximately 2.8% one mile upstream of the beginning of braided flow, to 2.6% at this point of interest, to less than 2 percent 1.6 miles downstream of this location.

LM02-10-01, which faces upstream, shows the contained portion of the wash which is approximately 40-feet wide with a flat, gravelly bottom. The banks are highly vegetated and about 4-feet high with no sign of significant lateral erosion. LM02-11-01 shows the first diffluence, facing downstream. The west branch is lower and much narrower than the east branch and the current flow pattern is clearly to the west.

The breakout washes to the west show signs of lateral and vertical erosion at the flow split while the eastern wash shows signs of aggradation and reduced conveyance. LM02-16-01 shows the eastern bank of one of the western breakout washes. The bank shows signs of lateral erosion heading towards the east and future migration could capture more of the eastern wash. LM02-15-02 shows the aggraded section of channel downstream of the flow split area.

Flow splits along wash west of Sycamore Canyon Estates

Wash upstm. of Sycamore Leaf Rd (LM02-10-01)

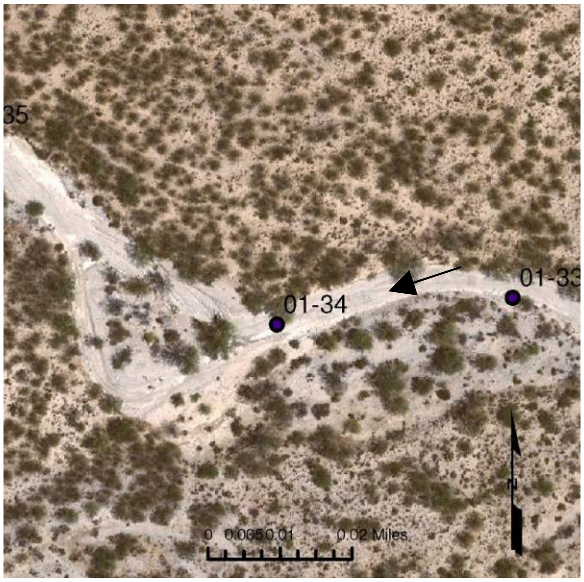
Diffluence dnstm. of Road (LM02-11-01)

Lateral erosion along outside bend of breakout wash (LM02-16-01)

Aggraded channel downstream of flow splits (LM02-15-02)

Figure 52 - Flow splits along Sycamore Canyon Wash

Lateral erosion and avulsion occur within this zone. Figure 53 shows a channel that has cut a path towards the inside of the channel bend. Several instances of vertical banks, specifically along outside bends, were noted. Vertical banks are typically about 4 feet high with exposed roots. Vertical cutbanks exceeding 250 feet in length were found.



Aerial view of avulsion on Qy surface

Ground view of avulsion (LM01-34-02)

Vertical cut bank (LM01-34-01)

Abandoned channel bank (LM01-34-04)

Figure 53 - Lateral erosion and avulsion within Distributary Piedmont Zone

Figure 54 shows an instance of vertical erosion developing downstream of a dirt road crossing. There is no swale upstream of the road; flow is overland at this location.

Vertical erosion at downstream edge of dirt road (LM01-09-01)

Scour formed downstream of dirt road (LM01-09-02)

Figure 54 - Vertical erosion downstream of dirt road crossing within Distributary Piedmont Zone

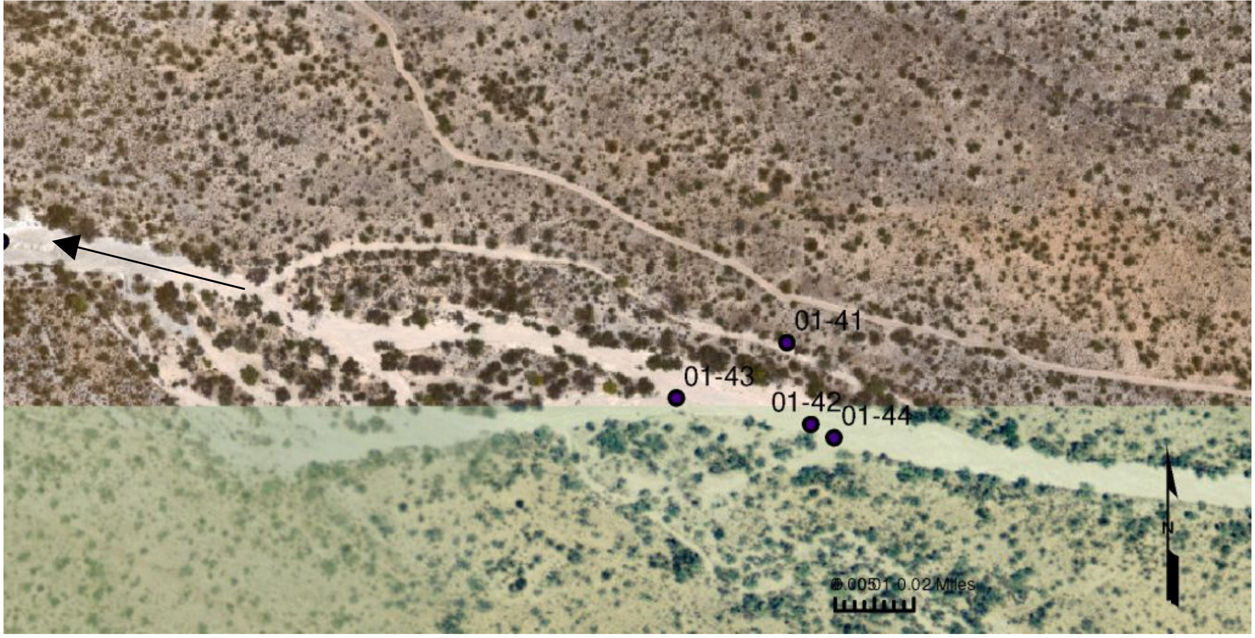
Figure 55 shows erosion downstream of a road at the transitional area from the Tributary Pediment Zone to the Distributary Pediment Zone. The underlying bedrock is exposed revealing how thin the veneer is at this location.

Vertical erosion on Qmo surface exposing underlying bedrock (LM02-29-02)

Vertical erosion downstream of road (LM02-29-01)

Figure 55 - Erosion downstream of road at Piedmont Zone transition

Figure 56 shows a braided channel within the Distributary Piedmont Zone. The main channel is sandy and flat with shallow banks. At this location the breakout channel located to the north of the main channel is actually about 2 feet below the main channel. The breakout channel has a rounded, cobbly bed with well established banks.



Braided channel on Qy surface

(Note that the color discrepancy within the aerial, between the top and bottom of the frame, is a result of the differences in the aerial data at this location.)

Ground view of main channel upstream of braided flow on Qy surface (LM01-42-02)

Ground view of breakout channel (LM01-41-02)

Figure 56 - Braided channel within Distributary Piedmont Zone

Figure 57 shows locations of sedimentation and deposition within wash corridors along with one example of scour on the upstream side of a channel island.

Aggradation upstream of debris in (LM01-50-03)

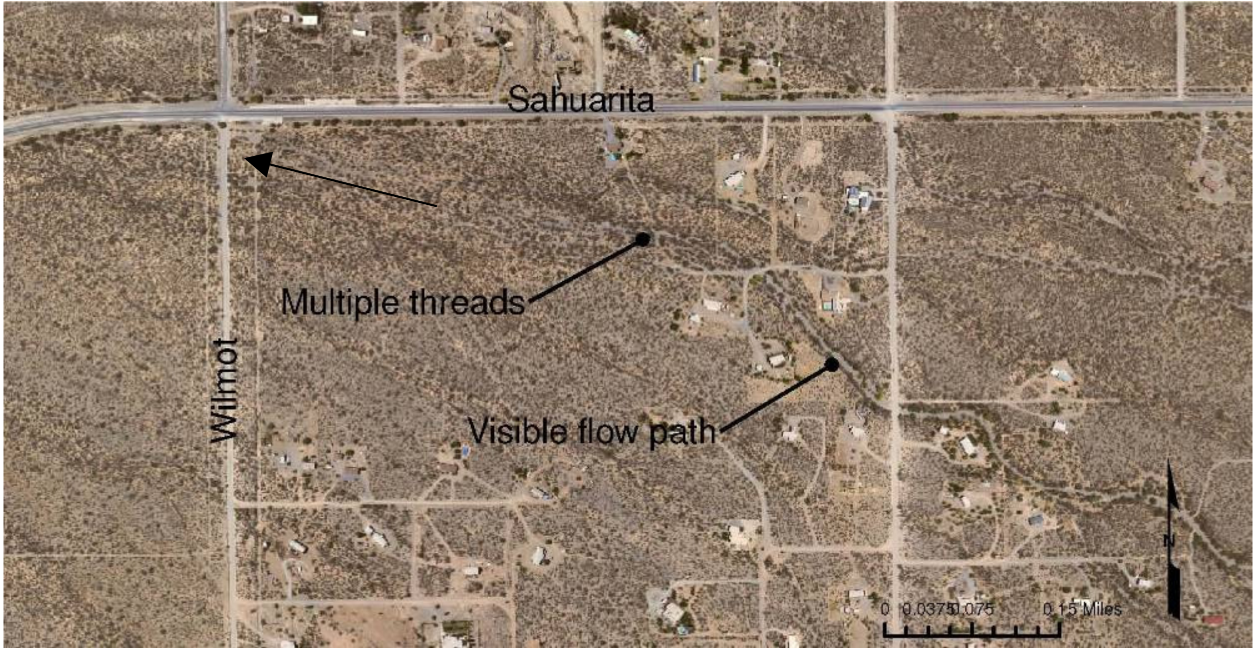
Old deposits along channel bar (LM02-17-01)

Aggraded channel (LM01-24-01)

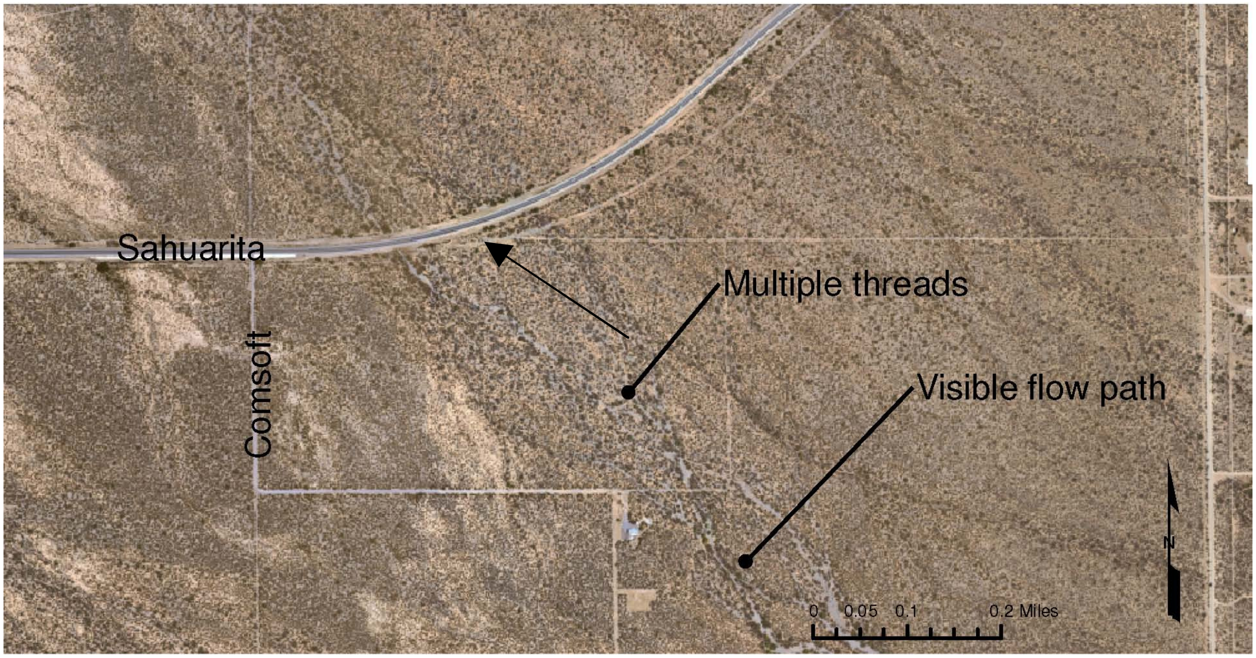
Scour on upstream end of channel island (LM01-51-02)

Figure 57 - Sedimentation and scour in Qy wash corridors within Distributary Piedmont Zone

All of the identified disappearing washes are found within the Distributary Piedmont Zone. The cause of this phenomenon is most likely the deposition of sediment. As the gradient decreases, the energy necessary to convey the sediment within the channel diminishes and sediment is deposited. A transition to sheet flow ultimately occurs as flow is forced out of a main channel into multiple threads. Following are a few example locations of disappearing washes.



Disappearing washes, southeast of Sahuarita Road and Wilmot Road intersection



Disappearing wash, southeast of Sahuarita Road and Comsoft Drive intersection

Figure 58 - Disappearing washes within Distributary Piedmont Zone

Disappearing wash in Section 26 of Township 17S, Range 14E

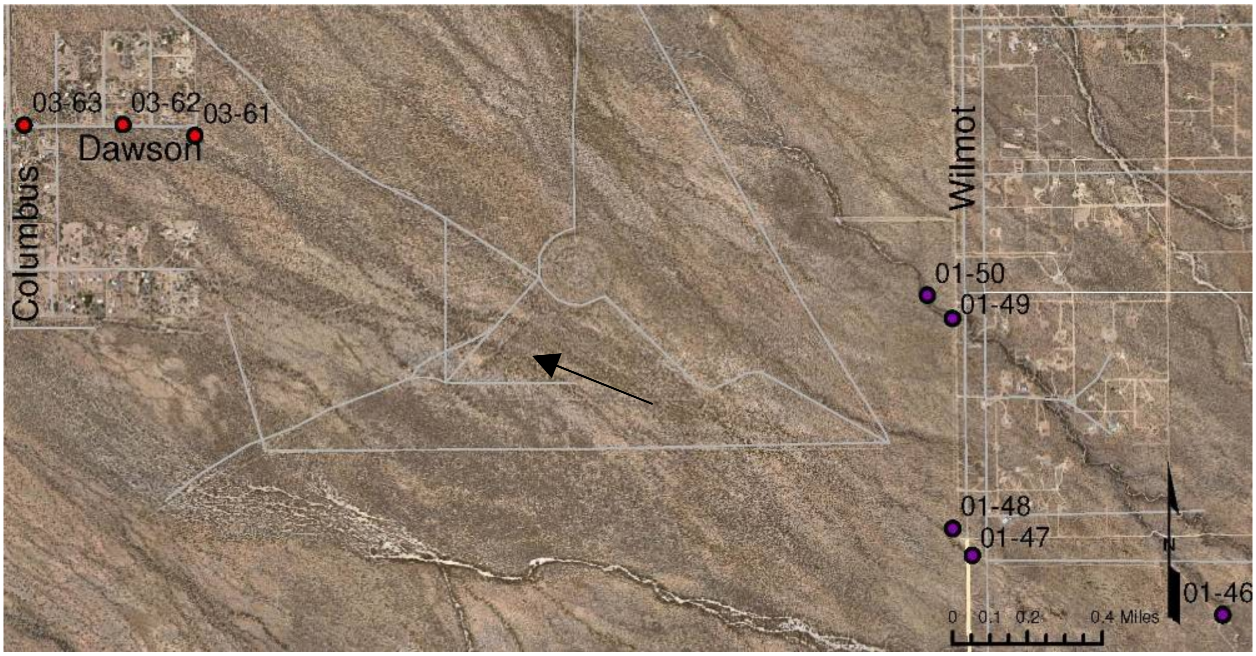
Figure 58 - Disappearing washes (continued)

The disappearing washes are a critical area in regards to planning future development. These areas have naturally exceeded a threshold causing a change in the sediment transport capacity and flow patterns. If development concentrates flow patterns and removes the sheet flow, incision will occur along with increased rates of sediment transport. Impacts will extend both upstream in the form of headcutting and downstream in the form of (temporary) increased sediment supply and resulting aggradation. Furthermore, if development occurs downstream of the disappearing wash, conveyance of sediment will be critical as sedimentation is naturally a problem.

5.6.5 *Headward Erosion*

Headcuts originating within the Incised Zone have migrated a significant distance into the Distributary Piedmont Zone. The top aerial image within Figure 59 shows an example of a headcutting area within the western portion of the Corona de Tucson geologic map in an area mapped as M2/M1. The bottom half of the figure shows the same area and the extension of the flow path 2 miles downstream.

Gully formation in Distributary Piedmont Zone



Drainage from Wilmot Road to Columbus Blvd., two miles downstream of first image

Figure 59 - Aerial view of gully formation

Gullies are forming in several of the flow paths shown in the above aerial images. An example is shown in Figure 60. The gullies are relatively young, narrow, and v-shaped with no gravel or sandy bed material. The primary cause of the gully development is headcutting. The bottom right image (LM03-61-02) within Figure 60 is a view of the same channel network over 2 miles downstream. The channel at this location is incised. In addition to the headcutting which is migrating upstream to this point, local scour has been introduced by the road crossing and is also progressing upstream near photo point 01-47.

Headcutting on M1/M2 surface (panorama of LM01-48-01 and 02)

View upstream of headcutting (LM01-48-05)

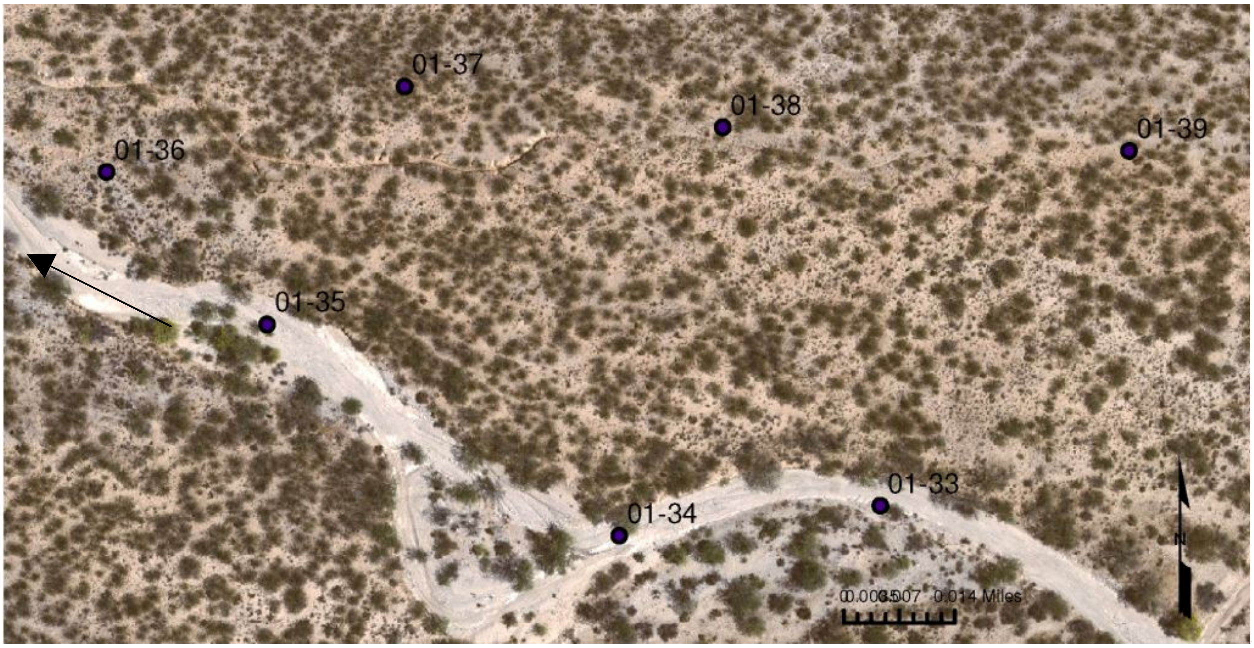
Visible soil horizons below M1/M2 surface (LM01-47-01)

View downstream from Wilmot Road in headcutting channel on M1/M2 surface (LM01-48-04

Incised channel along Dawson Road (LM03-61-02)

Figure 60 - Gully formation near South Wilmot Rd within Distributary Piedmont Zone

Another instance of headcutting and gully formation on a Pleistocene terrace is shown on Figure 61. The main wash (to the south) is mapped as Qy (ch) and the area to the north near photo ID points 1-36, 1-37, 1-38, and 1-39 is mapped as Ql (M2). Breakout from the main channel is apparent. This breakout flow drains to the headcutting area, increasing the flow in the young channel and encouraging future headcutting.



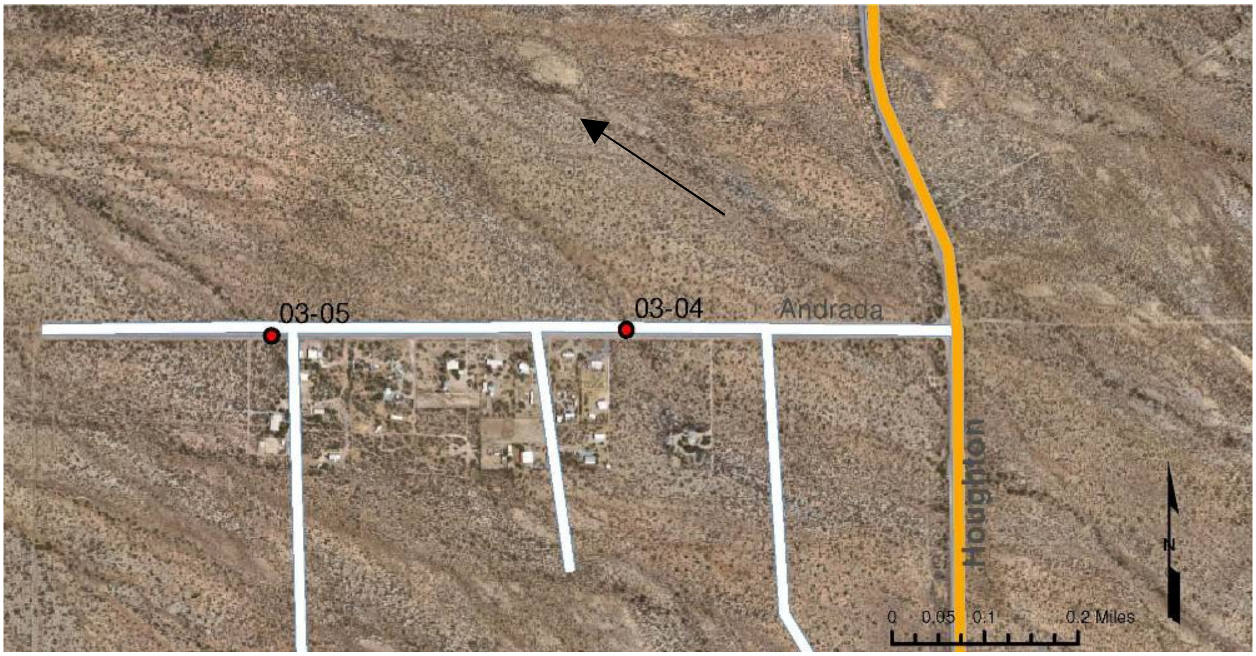
Aerial view of headcut on Ql surface

Ground view of headcut (LM01-36-01)

Confluence of 2 developing washes (LM01-37-01)

Figure 61 - Gully formation at LM01-36 within Distributary Piedmont Zone

In addition to the above examples, larger, older channels within this zone were found to be impacted by headcutting. Figure 62 shows a couple of washes which cross Andrada Road where headcutting was observed. The wash shown on the ground shots is 4 feet deep with vertical banks and a 4 foot wide bottom. The headcut extends up the channel, upstream of Andrada Road, until it terminates at Houghton Road. The area around field point 03-04 is Pleistocene alluvium mapped as M1/M2.



Aerial view

Upstream view of incising wash across Andrada Road (LM03-04-01)

Downstream view of incising wash across Andrada Road (LM03-04-03)

Figure 62 - Incising washes along Andrada Road, West of Houghton Road

Another location of headcutting was found along Salero View Road, north of Sahuarita Road, see Figure 63. The crossing is a simple crossing; the profile of the road does not dip down into a channel. Both ground images were obtained from the same location. The channel is not much lower than the adjacent landscape and it appears that some sediment deposition has occurred upstream of the road with the channel aggrading to the elevation of the road. Vertical scour downstream of the road has cut a significant trench with the channel banks extending up approximately 6-feet. This is a location identified as an abrupt scour difference, and the observed scour downstream of the road is primarily a result of headcutting. A small, local contribution to the scour may be due to concentration of flow at the crossing and scour introduced by weir flow over the road. Headward erosion is mitigated by the placement of a concrete spillway.

Aerial view of headcutting washes crossing Salero View Road

Wash upstream of Salero View Road, draining across road (LM02-52-02)

Wash downstream of Salero View Road (LM02-52-01)

Figure 63 - Incision and sedimentation on Qly surface along Salero View Road

Figure 64 shows two instances of low flow crossings with head cutting scour mitigated by dumped concrete and rock.

Vertical scour downstream of Salero View Road, near Three Kings Road, Qly surface (LM02-53-01)

Rip rap along Salero View Road, north of Toro Bronco, Qy surface (LM02-55-01)

Figure 64 -Observed low flow crossing scour mitigation measures

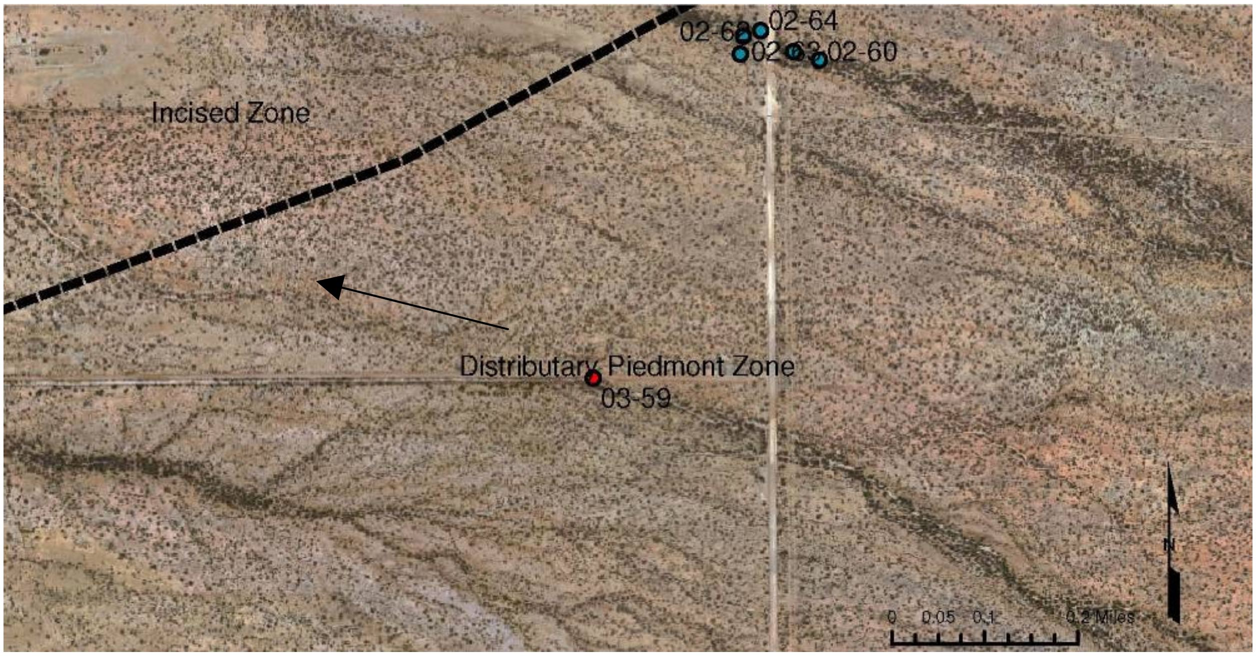
Figure 65 shows two locations where possible nick points were found along minor headcuts. The scour shown in the first photo is also associated with the debris lodged within the channel. The nick point shown in the second photo is along a seemingly abandoned flow path.

Nick point, facing upstream (LM01-13-01)

Nick point on abandoned wash, facing downstream (LM01-32-03)

Figure 65 - Nick points on minor headcuts within Distributary Piedmont Zone

Figure 66 shows a headcutting channel with a headcut which has terminated at a nick point. Headcutting actually extends upstream of the nick point but at a reduced scale.



Nick point location in Distributary Piedmont Zone

Channel upstream of nick point, facing upstream (LM03-59-01)

Headcut downstream of nick point, facing downstream (LM03-59-03)

Nick point in incised wash, facing upstream (LM03-59-02)

Figure 66 - Headcut terminating at a nick point within Distributary Piedmont Zone

5.6.6 *Roads Parallel to Flow Paths*

Figure 67 shows aerial views of flow paths within the Distributary Piedmont Zone that run parallel to roads. Multiple geomorphic processes seem to have caused the observed erosion. Note that in the top photo of Figure 67 the wash at the bottom of the frame is cutting into the floodplain terrace. This wash (LM03-17-01) is not impacted locally by the road, indicating that the roads are not entirely responsible for the scour and that headcutting and system wide scour is occurring. Furthermore, this area is tributary to the Cuprite Wash. A downstream reach of this tributary was observed to be incising as shown on LM03-26-01 (within the upper limit of the Incised Zone). Furthermore, it was observed elsewhere that the Fagan Wash, which Cuprite Wash is tributary to, is incised downstream of this location.

Aerial view of erosion along flow paralleling dirt road

Incised wash at field point 03-17 (LM03-17-01)

Incision on Cuprite Wash Tributary (LM03-26-01)

Figure 67 - Aerial and ground view of flow paths parallel to dirt roads

Another aerial view of a flow path parallel to a road is shown in Figure 68. The observed erosion is similar at this location to that of Figure 67.

Another aerial view of erosion along flow paralleling dirt road

Figure 68 - Aerial view of flow paths parallel to dirt roads

Figure 69 shows a couple of ground shots along flow paths parallel to a road. The vertical banks along the channels within this area range from one to several feet high (LM03-15-04). The scoured washes are generally not vegetated and have neither sand nor gravel present as a bed material. Exposed roots from older trees are common on the vertical banks. The flow paths occupy incised Holocene deposits and Holocene to late Pleistocene alluvial deposits. Flows draining into the washes tend to scour the top of the bank as shown in LM03-15-02.

Vertical bank on Qyd surface beside road (LM03-15-04)

Headward erosion from flow spilling into roadside drainage, Qyd surface (LM03-15-02)

Figure 69 - Scour observed adjacent to road on parallel flow path

Other areas where roads are parallel to flow paths and with similar, yet less severe scour problems were found in areas such as along the south side of Dawson Road within the southwest portion of the Distributary Piedmont Zone (Figure 70) and south of Sahuarita Road, west of Houghton Road. The natural flow paths do not parallel the roads, but the flow paths have been redirected by the roads and therefore parallel the road for some distance.

Flow path altered at Dawson Road, west of Alvernon Road

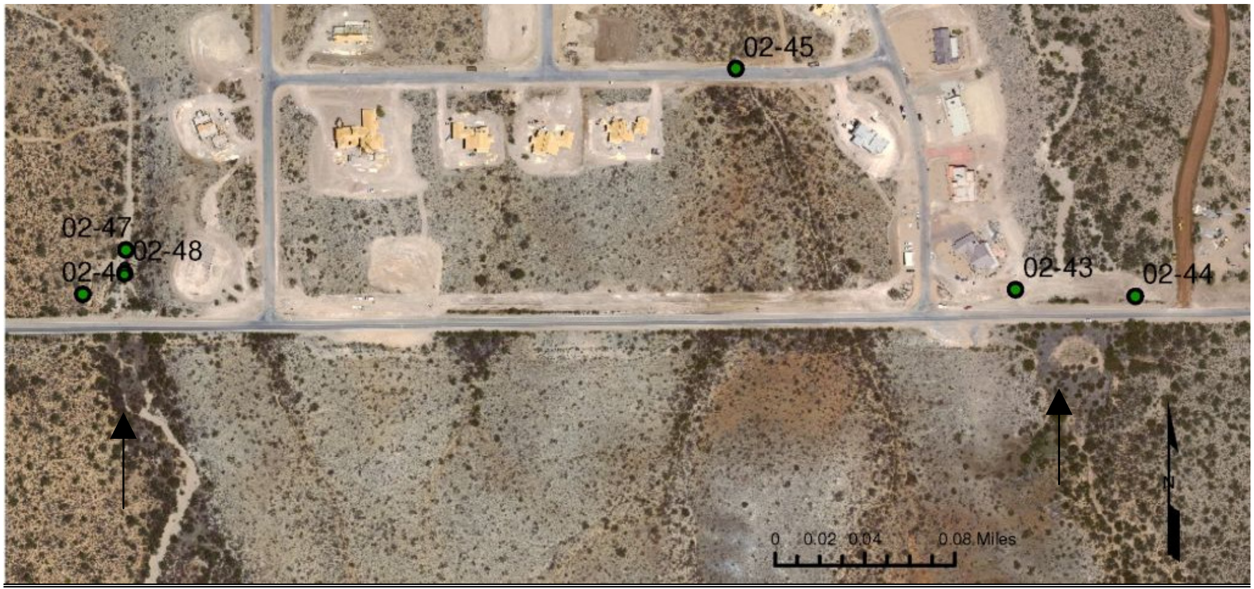
Vertical bank along wash south of Dawson Road (LM03-64-04)

View downstream of roadside drainage south of Dawson Road (LM03-64-05)

Figure 70 - Flow path parallel to Dawson Road

5.6.7 Notable Drainage Crossings

Figure 71 shows the location of two underfit drainage crossings within the Tributary Piedmont Zone along Sahuarita Road.



Aerial view of two underfit drainage crossings

Vertical erosion developing downstream of Road on QTs surface (LM02-43-02), facing east

Vertical erosion downstream of Road, facing road, on QTs surface (LM02-43-05), facing southwest

Wash downstream of vertical erosion (LM02-43-06)

Sediment deposition upstream of Rd (LM02-43-08)

Figure 71 - Underfit drainage crossings along Sahuarita Road

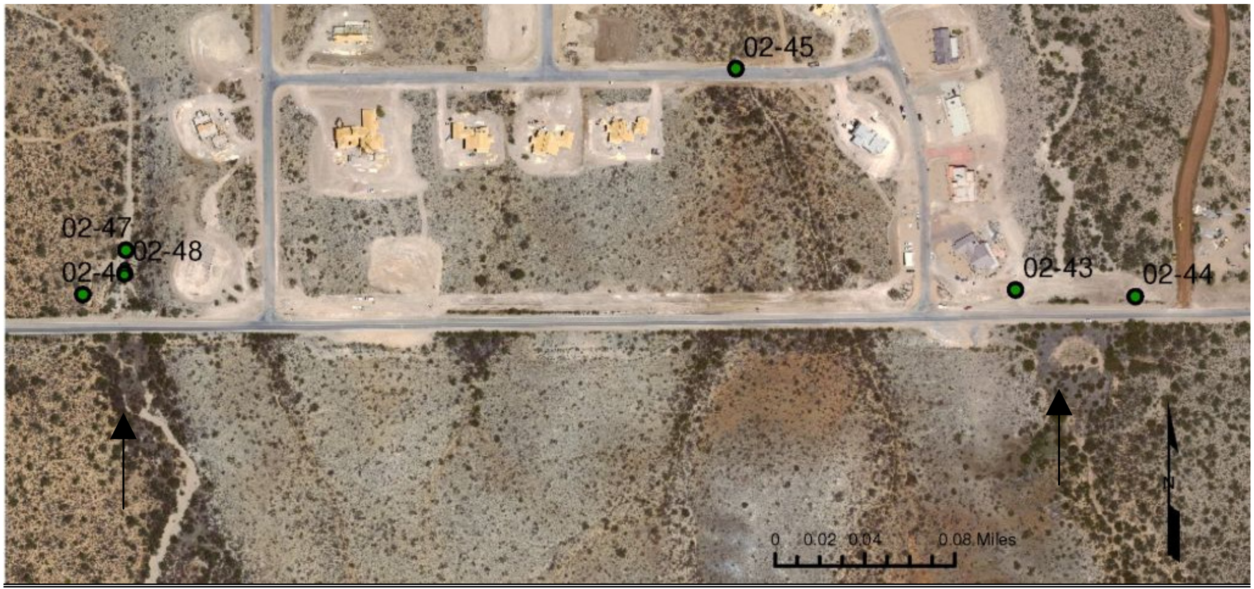
Figure 71 also includes ground shots showing the effects of the east undersized drainage crossing along Sahuarita Road, between Suntan Drive and Atrisco Drive (field point LM02-43). Flow is to the north at this location, crossing Sahuarita Road from the south. Extensive vertical erosion which extends from the Qy wash surface to the adjacent and older QTs surface was observed.

There are several factors influencing the erosion at this location;

- Sediment is deposited upstream of the road yielding clear water scour downstream of the road.
- Runoff from the road flows down the steep embankment, causing scour due to relatively high velocity, clear water flow.
- Flow likely overtops the road on occasion. This overtopping flow will have a hydraulic drop across the steep, downstream embankment, again causing scour due to high velocity flow.
- Headward erosion was observed downstream of this and may also be a contributing factor to the erosion.

While there are many factors influencing the erosion, the underfit culvert which concentrates and accelerates flow is the one which could have been most easily prevented.

The second underfit drainage crossing on Sahuarita road is shown on Figure 72. This crossing is situated between Hilton Drive and Sharon Road. Figure 72 shows vertical erosion downstream of the road at this location which is much more developed than the erosion shown in Figure 71. At this location vertical cut banks exceed 7 feet deep. The erosive activity is primarily occurring outside of the main wash corridor, away from the location of the single CMP. The main wash corridor and the CMP are approximately 40 feet east of (to the right of) the erosion shown in Figure 72. This suggests that the erosion shown in Figure 72 is a result of headcutting with the underfit culvert crossing worsening the condition.



Aerial view of two underfit drainage crossings

Vertical erosion downstream of Rd. (LM02-46-01)

Erosion shown in channel (LM02-46-05)

Erosion in channel, facing Rd. (LM02-46-06)

Undersized CMP east of erosion (LM02-48-01)

Figure 72 - Another underfit drainage crossings along Sahuarita Road

5.6.8 *Aerial Photograph Comparison*

A number of stock tanks and impoundments were found within the Distributary Piedmont zone. Clear evidence of large scale impacts from impoundments onto fluvial systems is not readily found when comparing aerial images. However, conclusions can be made regarding the impacts of these structures to adjacent drainage areas. Figure 73 shows a stock tank which impounds the flow tributary to it, dewatering the land immediately downstream. Overflow from the tank has caused a diversion to occur with water diverted south to an adjacent drainage area. The top half of Figure 75 shows a portion of the Surficial Geologic Map (Tucson SE) covering this area. The two clearly separate primary channels join approximately 2 miles downstream of this point, exemplifying how a stock tank or other similar feature can change the hydrology locally and semi-regionally (i.e. on a scale just beyond the immediate drainage). Note that the 1936 aerial appears to show greater vegetative coverage. It is unclear if this is the case or not as the photograph resolution is low. However, it is likely that the stock tank has reduced the vegetation downstream of the impounded area.

Figure 74 shows an area with multiple impoundments, some of which are visible on the 1936 aerial image. The historic flow paths represented by both the 1936 aerial image and the Surficial Geologic Map (bottom half of Figure 75) are mildly distributary with well defined primary flow paths. The modern flow paths are highly distributary and braided. Dense vegetation is observed upstream of the impoundments while the areas downstream are much less vegetated, suggestive of aggradation upstream of the impoundment and scour downstream. A diversion and stock pond are shown on Figure 85 with no significant changes to the fluvial systems observed at this location.

Figure 76 shows a wash which was found in the 1936 image but is no longer visible. In addition, a stock tank is visible on Figure 76. The wash cutting through the middle of the 1936 portion of Figure 76 cuts through a Qyd (incised Holocene deposits) area, breaking from one Qyc (modern channel deposits) to another Qyc thread. This indicates the potential for wash threads to develop and be abandoned within the dissected Holocene and Pleistocene alluvium deposits. It is unclear what impact the stock tank had on this process, if any.

Evidence of channel realignment due to natural causes and human activity was found in the aerial comparison exercise. Figure 77 shows a small wash thread which has been captured by a dirt access road. The wash thread, mapped as a Qyc area, is much more evident on the 1936 aerial as the wash appears to have since taken the course of the road west to rejoin the primary channel. An instance of channel development is shown on Figure 78 where a flow path has developed since 1936. The cause of this may be in part due to the headcutting within this area and in part due to the section line road at this location. Evidence of flow conveyed along the road is found in the figure, specifically along the north section line of Section 34. Over time, it is likely that a small gully developed which eventually scoured in response to headcutting.

An interesting finding is that much of the upland areas of the Distributary Piedmont Zone show little to no signs of changes to the fluvial systems in the aerial photograph comparison as shown in Figure 79, Figure 84, and Figure 86. Human influence to the systems is minimal in Figure 79 and Figure 84 as development within this area is limited and is low intensity. Greater development density is found near Figure 86, but development has generally preserved the flow corridors. Figure 83 shows the significant diffluence of the Sycamore Canyon Wash, another upland area within this zone. Review of the 1936 aerial indicates that the bifurcations currently observed have changed relatively little since 1936. It should be noted that headcutting and significant local scour were observed in the field within the area shown on Figure 86 while the aerial comparison did not indicate this was happening. This highlights some of the limitation of the aerial comparison as the level of detail and the scale of the comparison preclude finding evidence of no changes to the fluvial systems.

Sedimentation is shown on Figure 80 and Figure 81 which show instances of disappearing washes. The resolution of the 1936 images is grainy and it is not clear if the deposition has increased since 1936. The surficial geology map (top half of Figure 82) shows the disappearing wash of Figure 80, with the defined channel mapped as Unit ch and the depositional area mapped as Y2. The surficial geology map (bottom half of Figure 82) shows the washes of Figure 81 as a Unit Qy and the depositional area as Unit Qly. Note that ch and Qy are similar units as are Y2 and Qly. Logic suggests that this combination of younger channel alluvium followed downstream by slightly older depositional alluvium can be used to identify discontinuous streams and depositional areas.

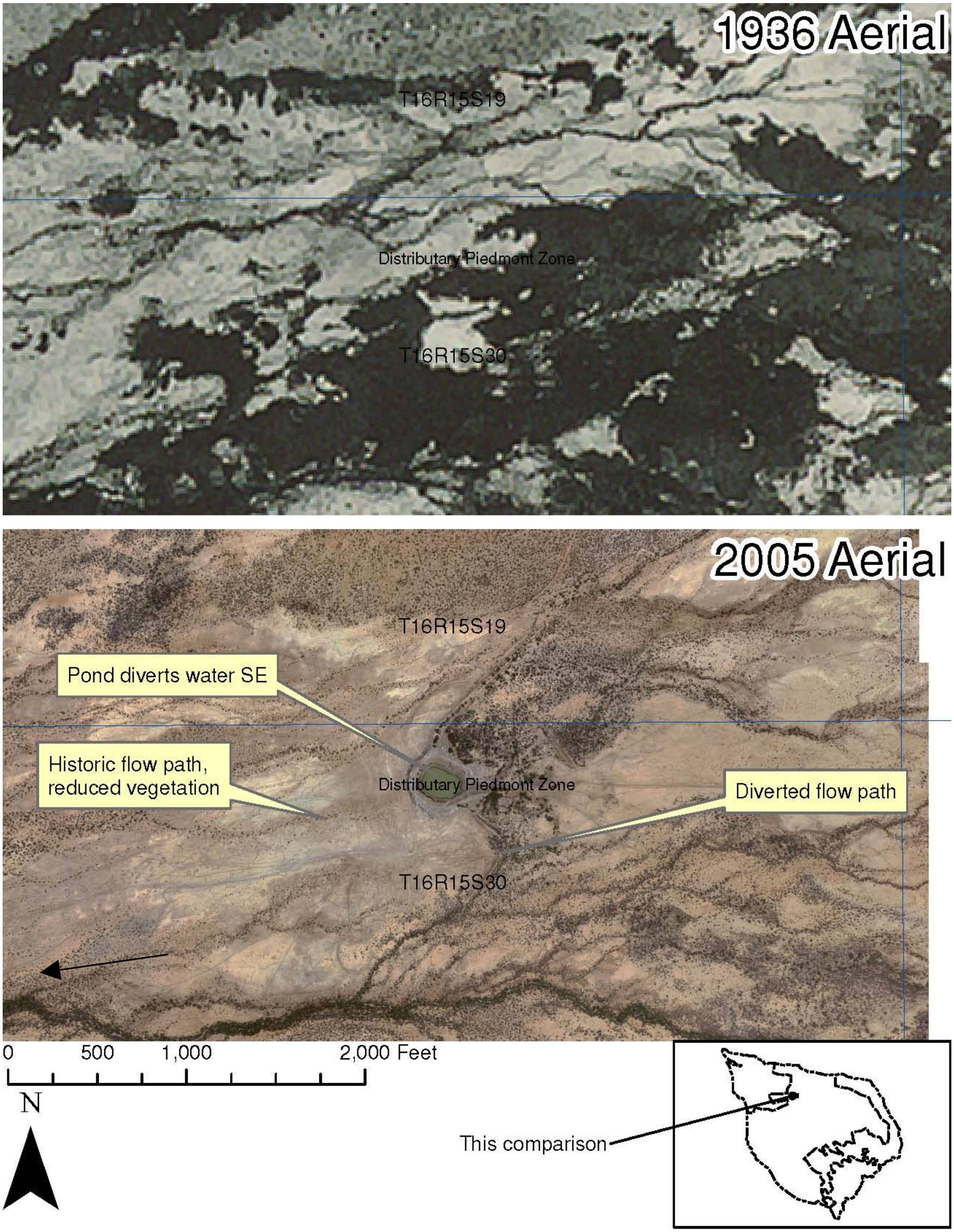


Figure 73 - Comparison of 1936 and current aerial images; station DPZ01

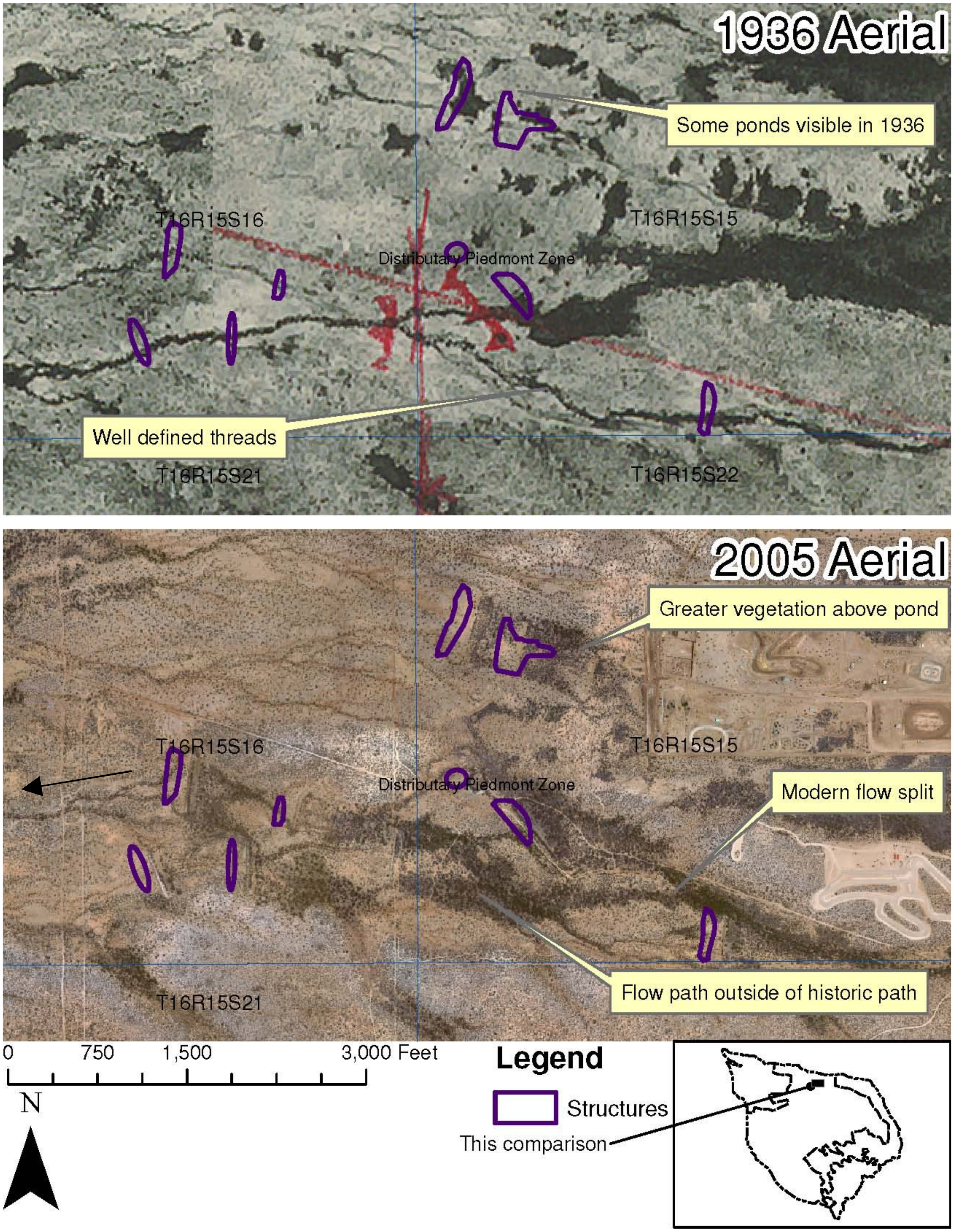


Figure 74 - Comparison of 1936 and current aerial images; station DPZ02

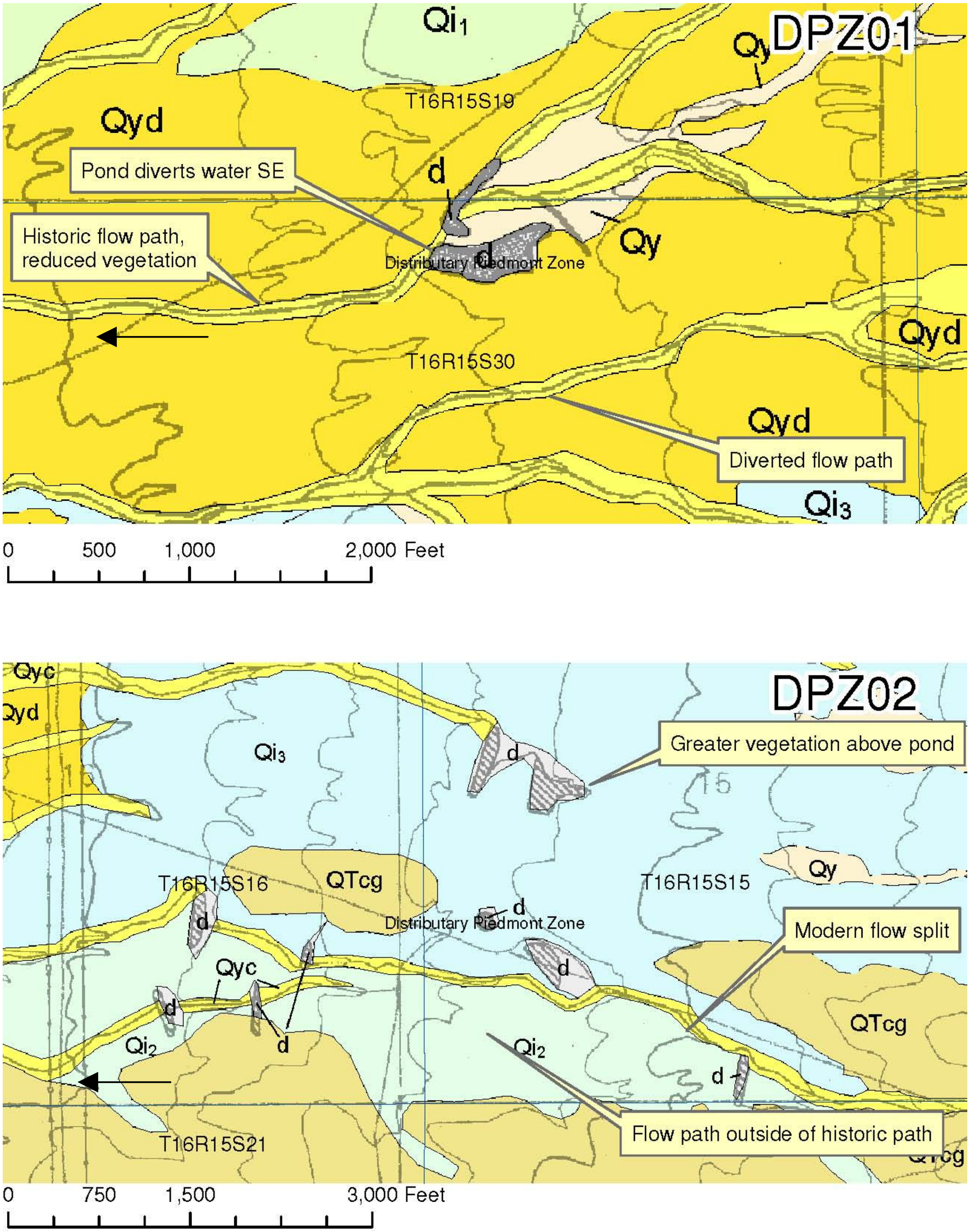


Figure 75 - Portions of surficial geologic maps for stations DPZ01 and DPZ02

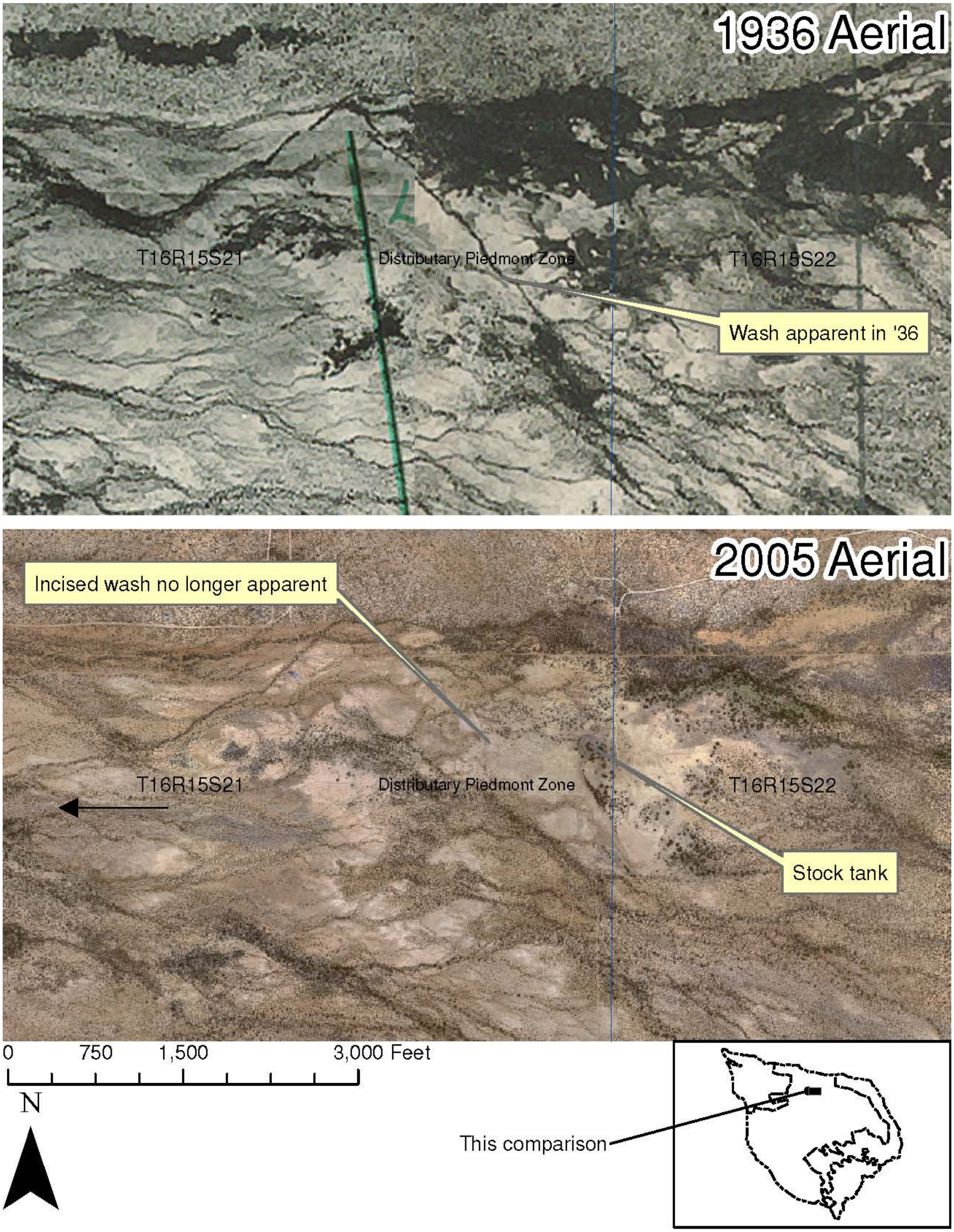


Figure 76 - Comparison of 1936 and current aerial images; station DPZ03

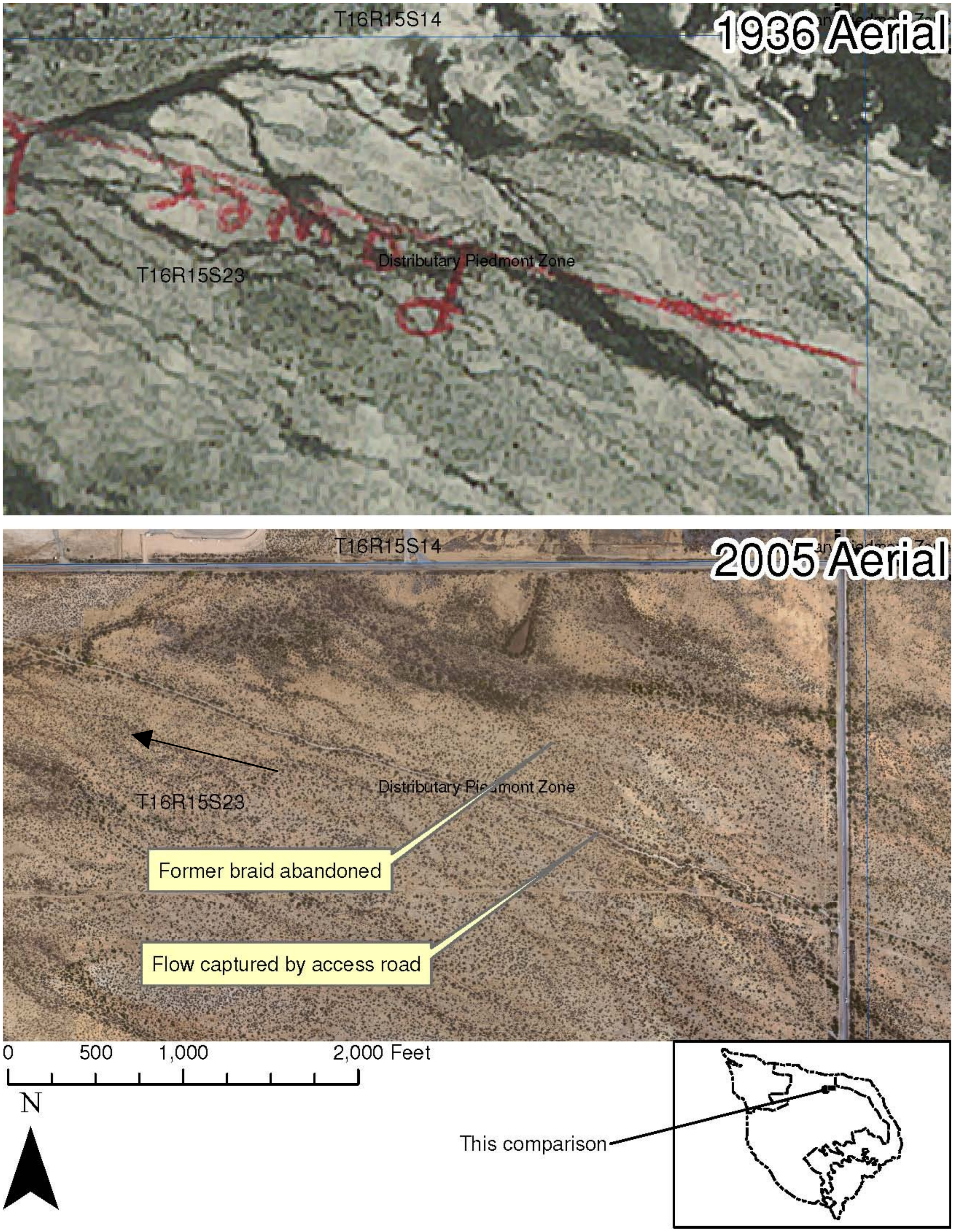
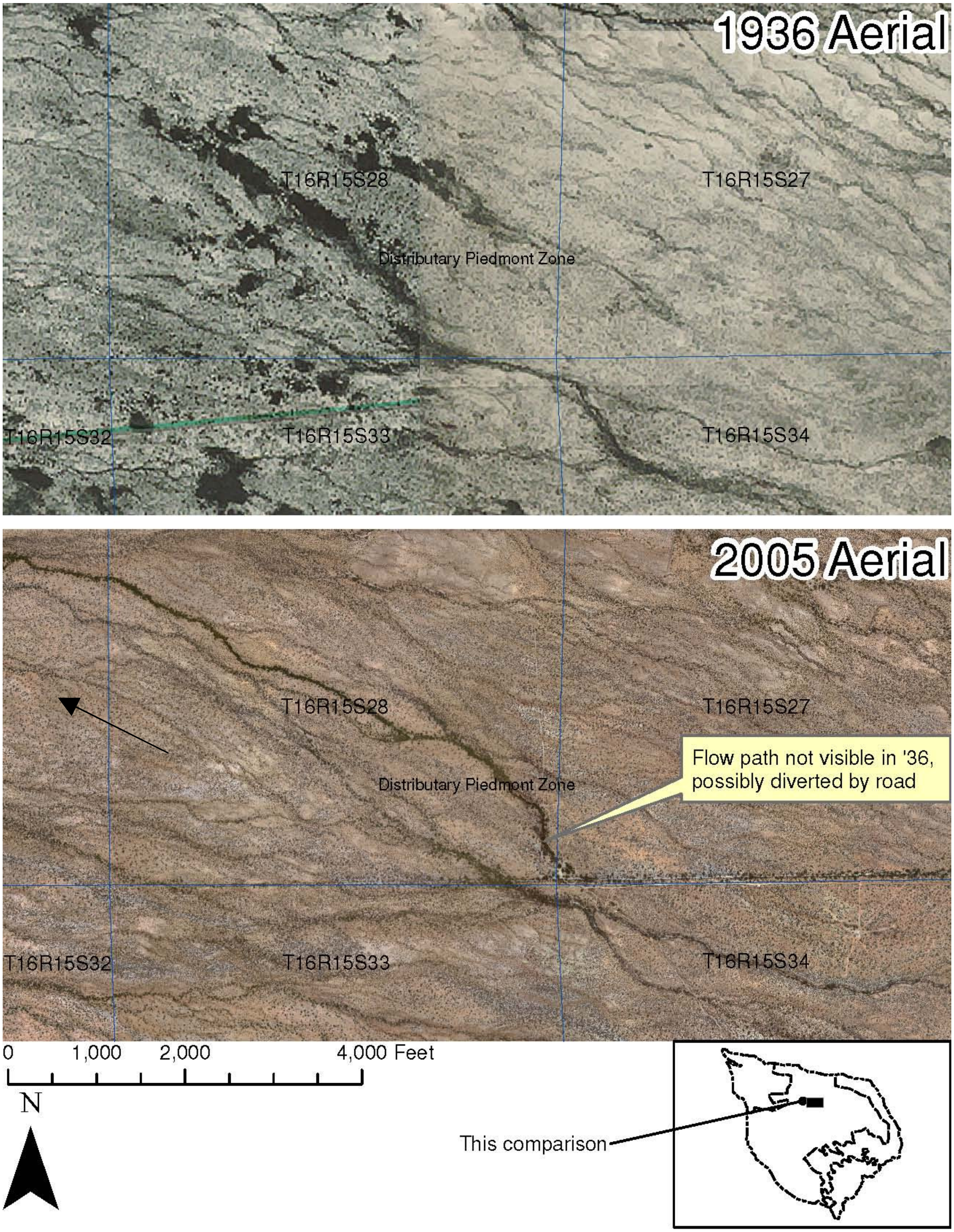
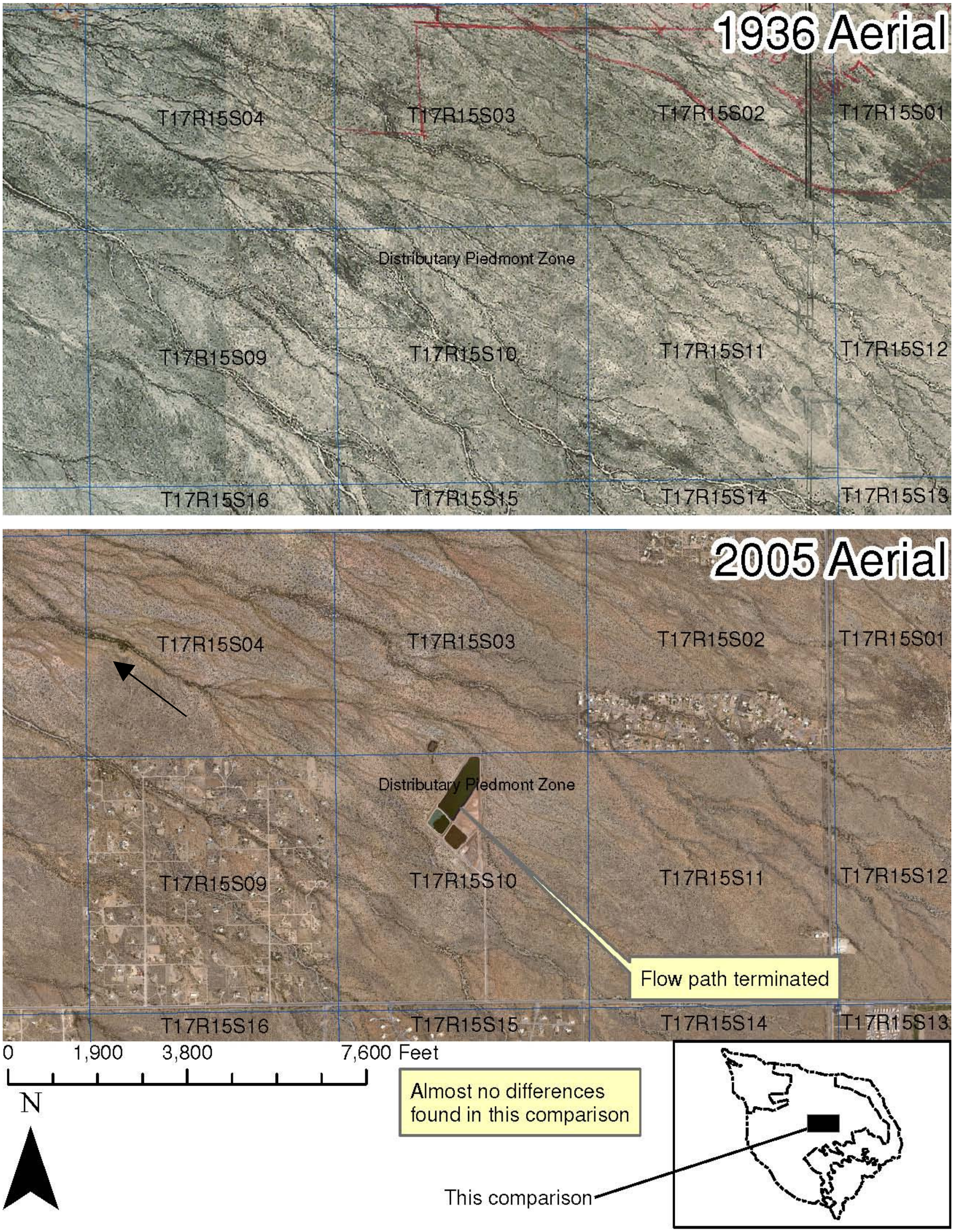


Figure 77 - Comparison of 1936 and current aerial images; station DPZ04



Flow path not visible in '36, possibly diverted by road

Figure 78 - Comparison of 1936 and current aerial images; station DPZ05



Flow path terminated

Almost no differences found in this comparison

This comparison

Figure 79 - Comparison of 1936 and current aerial images; station DPZ06

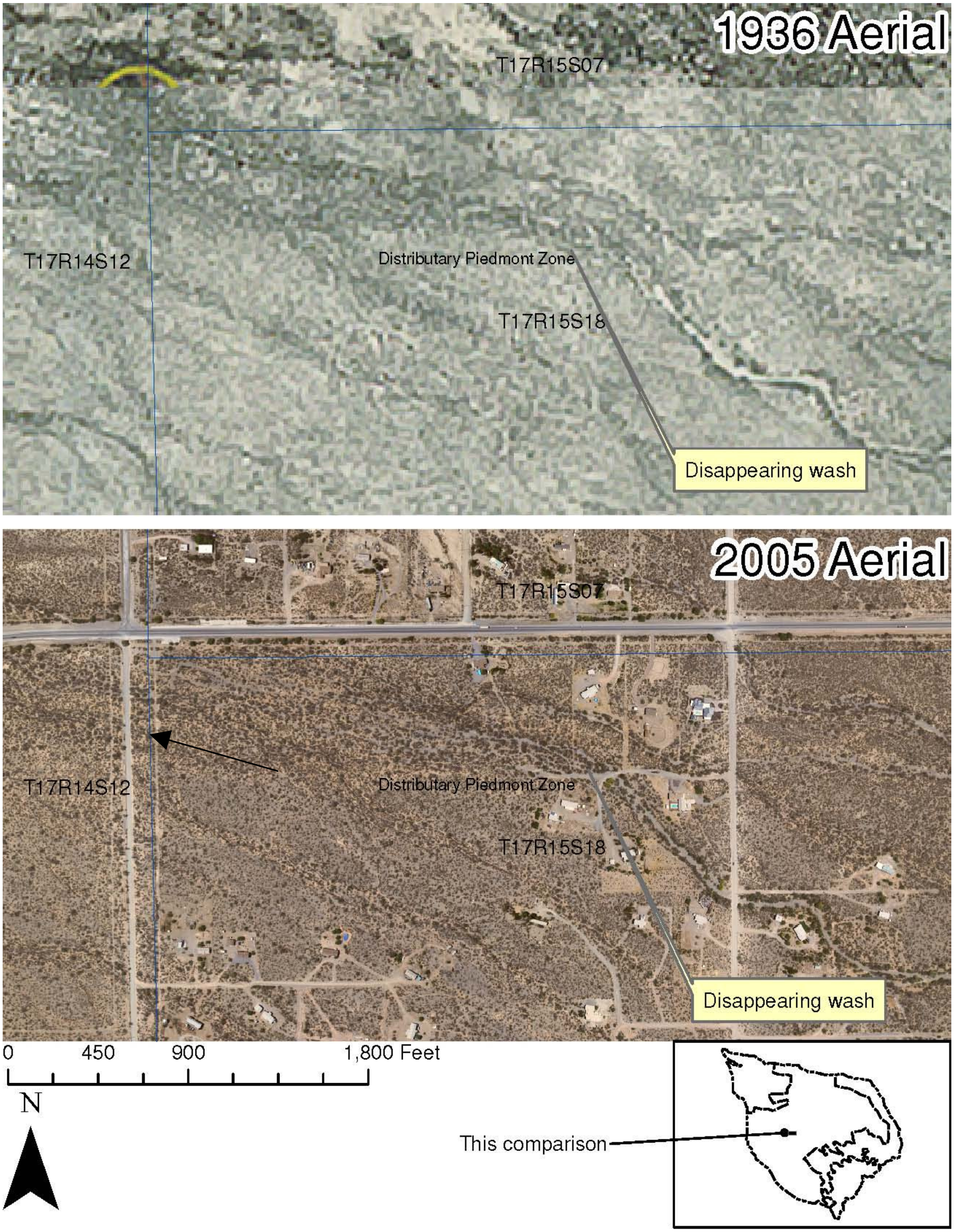


Figure 80 - Comparison of 1936 and current aerial images; station DPZ07

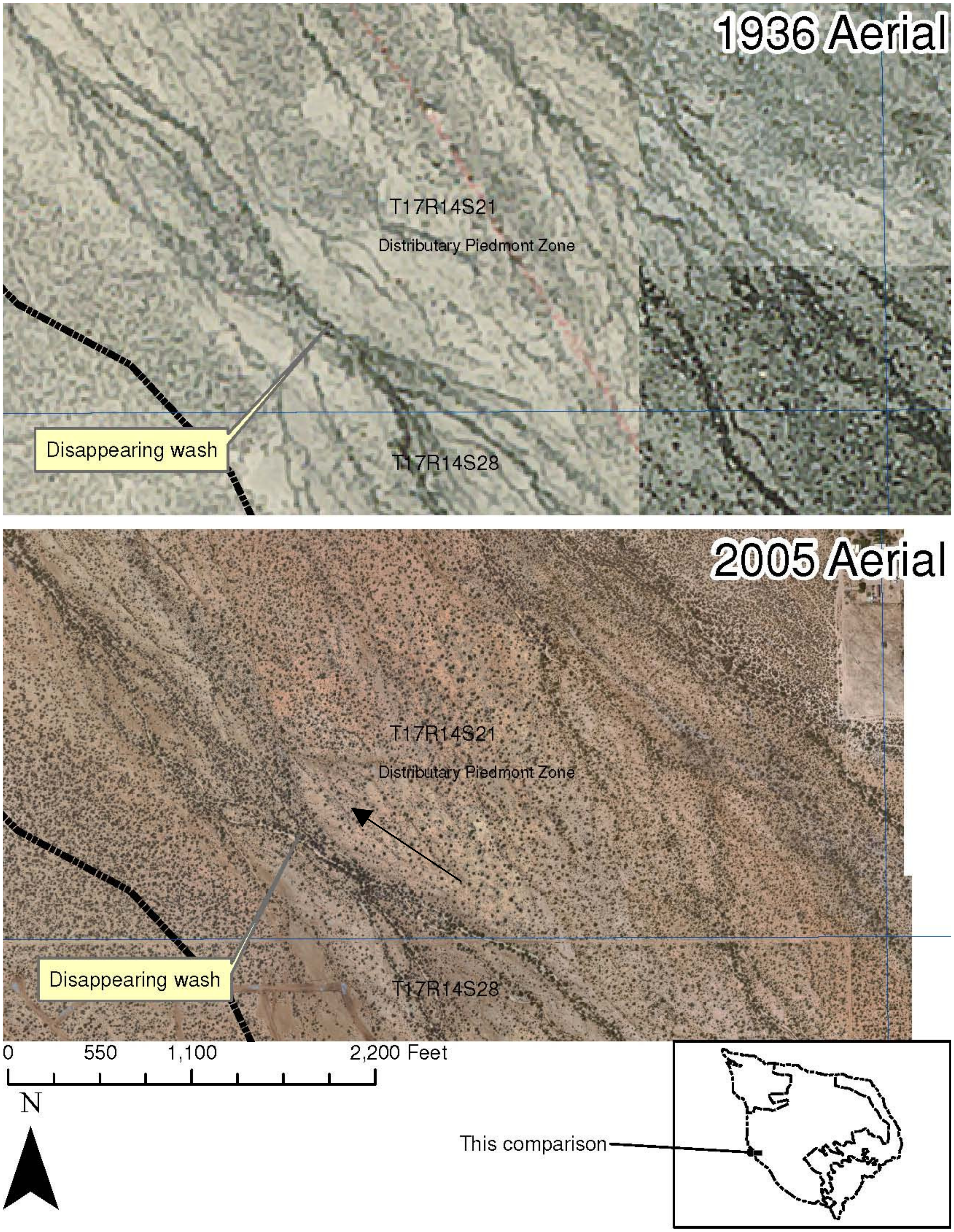
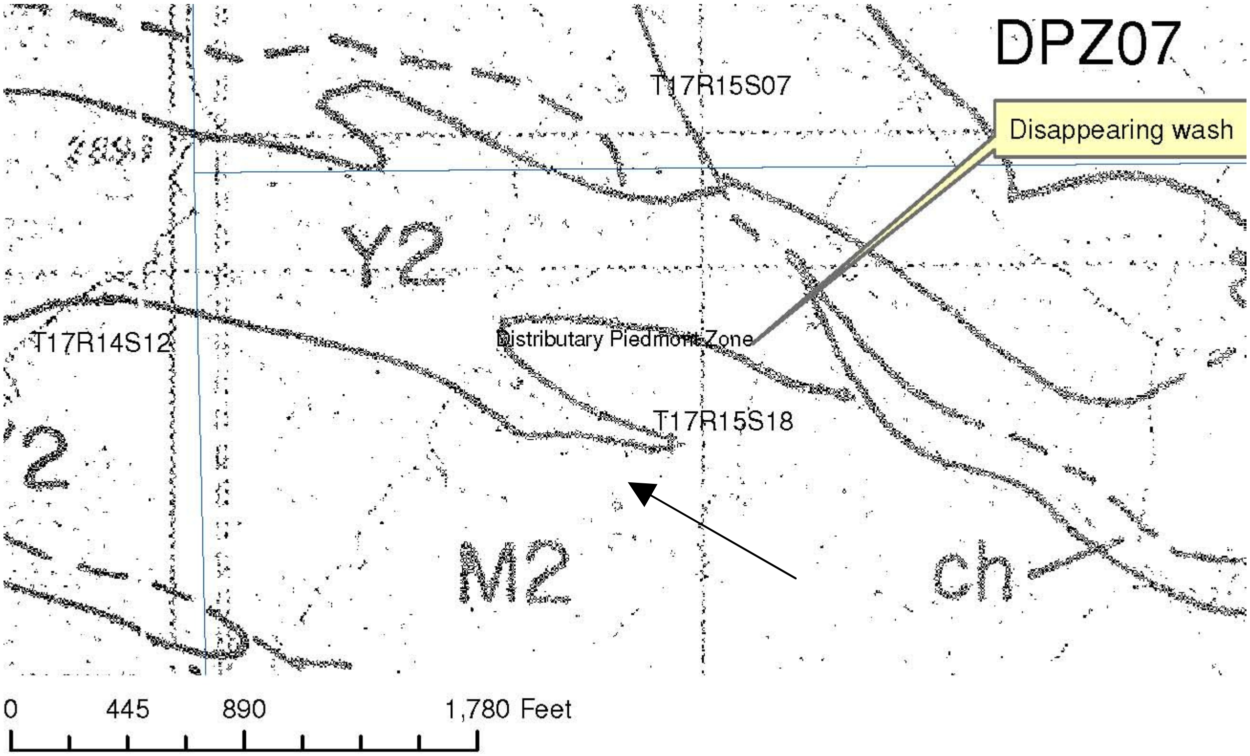


Figure 81 - Comparison of 1936 and current aerial images; station DPZ08



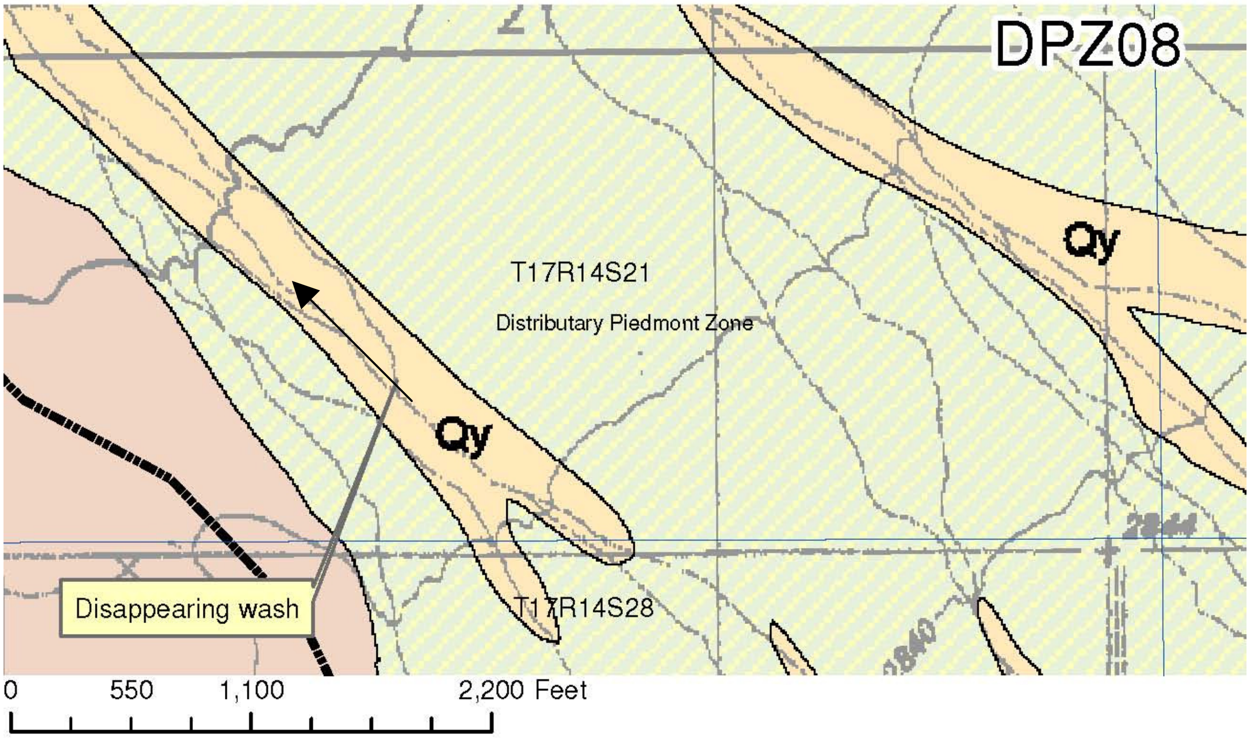
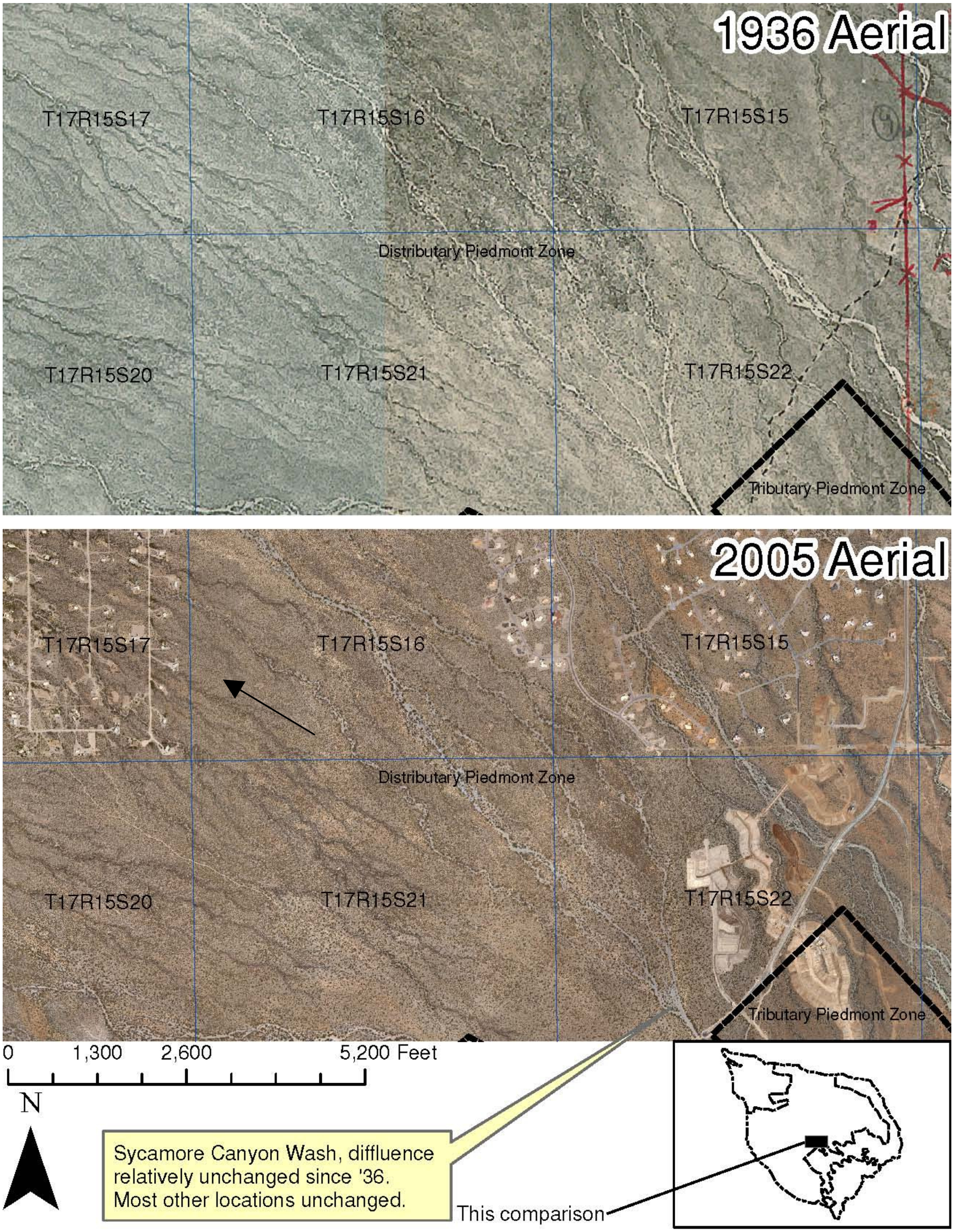


Figure 82 - Portions of surficial geologic maps for stations DPZ07 and DPZ08



Sycamore Canyon Wash, diffluence relatively unchanged since '36. Most other locations unchanged.

This comparison

Figure 83 - Comparison of 1936 and current aerial images; station DPZ09

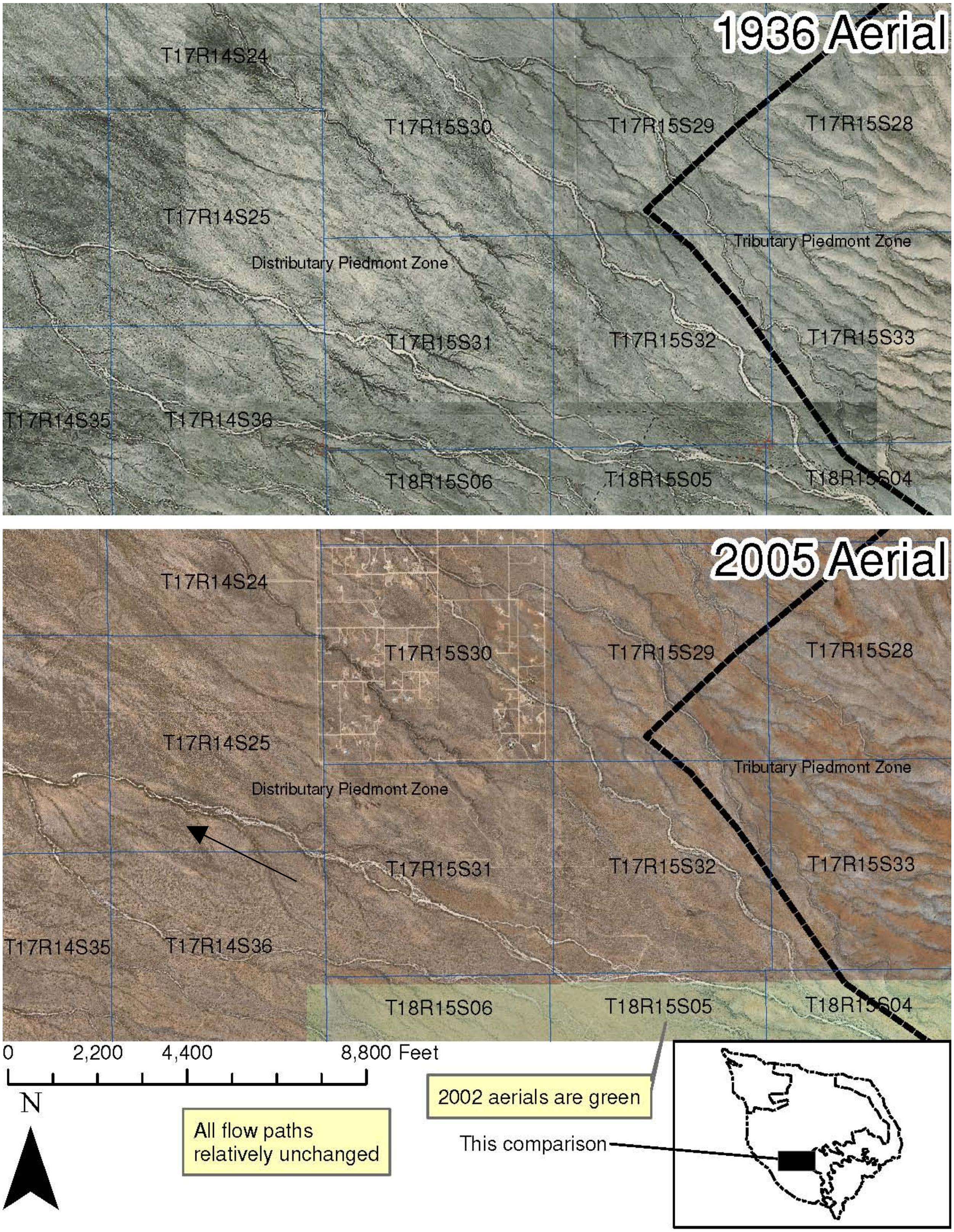


Figure 84 - Comparison of 1936 and current aerial images; station DPZ10

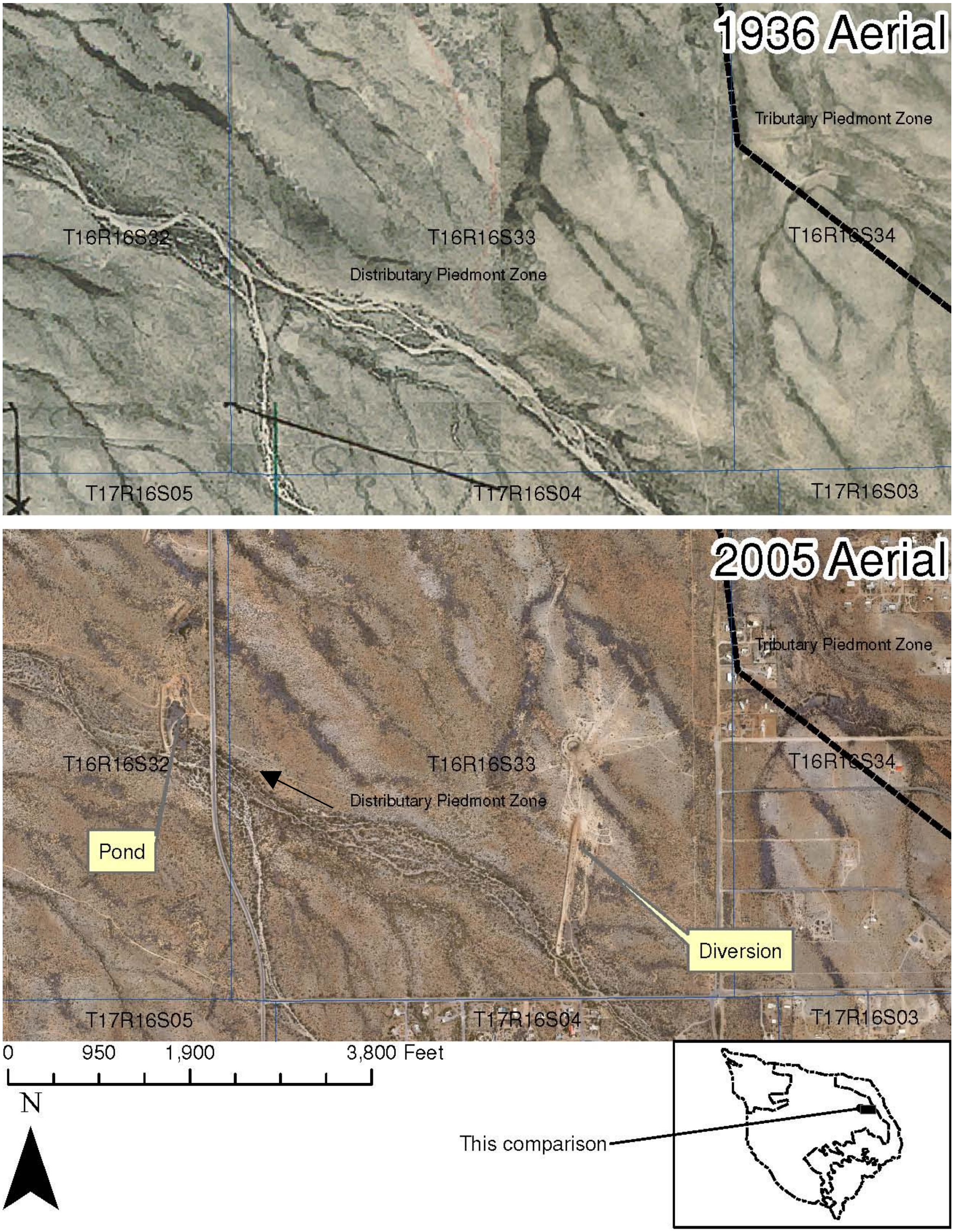
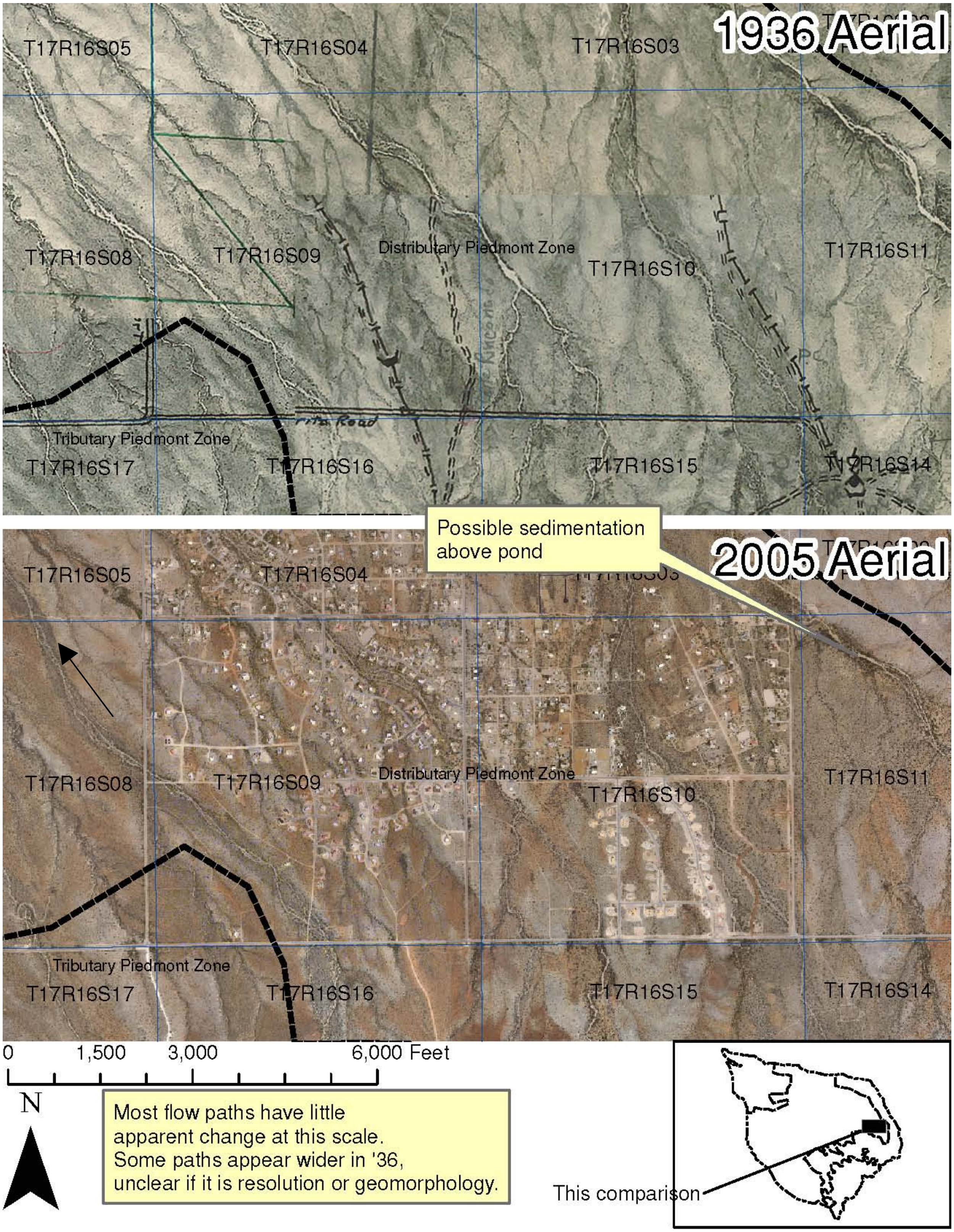


Figure 85 - Comparison of 1936 and current aerial images; station DPZ11



Possible sedimentation above pond

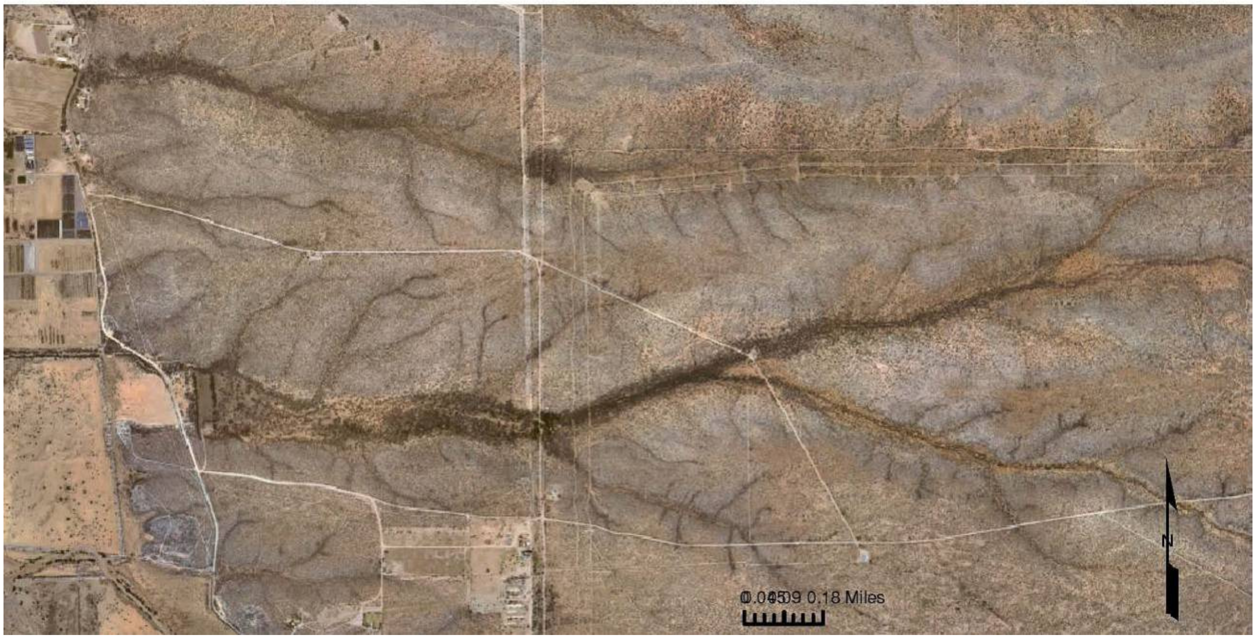
Most flow paths have little apparent change at this scale. Some paths appear wider in '36, unclear if it is resolution or geomorphology.

Figure 86 - Comparison of 1936 and current aerial images; station DPZ12

5.7 Incised Zone

The incised zone is located in the northwest portion of the study area. This zone is a sediment transport zone like the Distributary Piedmont Zone, but is markedly different in that the washes within this zone have developed into significant flow corridors which are linked to the Santa Cruz River. The Santa Cruz River has recently downcut due to headcuts which have moved up the reach (and other processes such as subsidence due to ground water pumping). The local drainages have responded with entrenchment and erosion of alluvial fan toes.

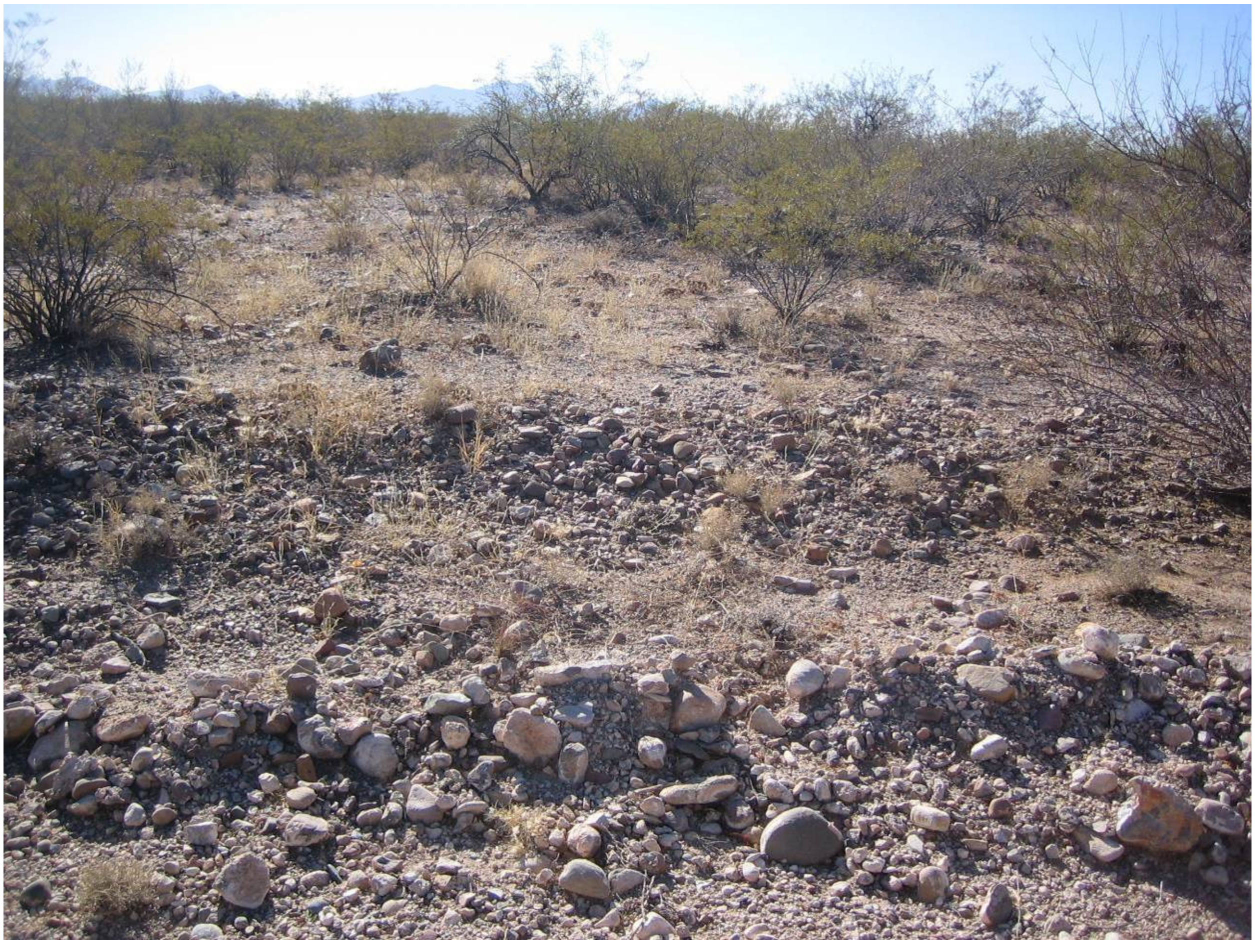
Following are ground and aerial images of various points of interest within this zone. The highly incised washes are visible in the aerial imagery. Vegetation within this zone is well established both within the wash corridors and in the floodplain and terrace areas.



Aerial view of Petty Ranch Wash in Incised Zone

Figure 87 - Representative views within Incised Zone

Aerial view of typical drainage network in Incised Zone



View south across T5 terrace within incised zone (LM03-24-01)

Figure 87 - Representative views within Incised Zone (continued)

View east across Incised Zone (LM03-29-01)

Figure 87 - Representative views within Incised Zone (continued)

5.7.1 *Geomorphic and Topographic Setting*

The Incised Zone contains active to recently active alluvial fans (Y). Older alluvium from the late Tertiary to the early Quaternary is found (QTcg and QTbf) but is highly eroded and poorly preserved. Fluvial paths across these surfaces are often highly eroded and unstable. Well defined and highly incised washes have formed in response to the downcutting of the Santa Cruz River. These washes generally correspond to soils mapped as Qy.

The highly tributary drainage network which has developed within this zone consists of washes and drainage corridors which are confined by older alluvium, limiting lateral erosion hazards and avulsive changes. However, areas mapped as T2 in the Tucson SW and Qyr in the Sahuarita Surficial geologic maps are highly susceptible to lateral erosion. The T2 and Qyr areas represent abandoned terraces along the Santa Cruz River floodplain where near vertical banks are common.

5.7.2 *Soils*

Aridisols make up the majority of the higher terraces in this zone with Entisols found in the wash bottoms and some Mollisols mapped along the Santa Cruz River floodplain. Like the Distributary Piedmont Zone, this zone is made up of MUID 38, a grouping of Mohave, Sahuarita, and Cave soils. Other soils found in this zone include Anthony, Bucklebar, Comoro, Grabe, Hantz, Laveen, Pima, Pinaleno-Stagecoach, Rillito, Sonoita, and Yaqui.

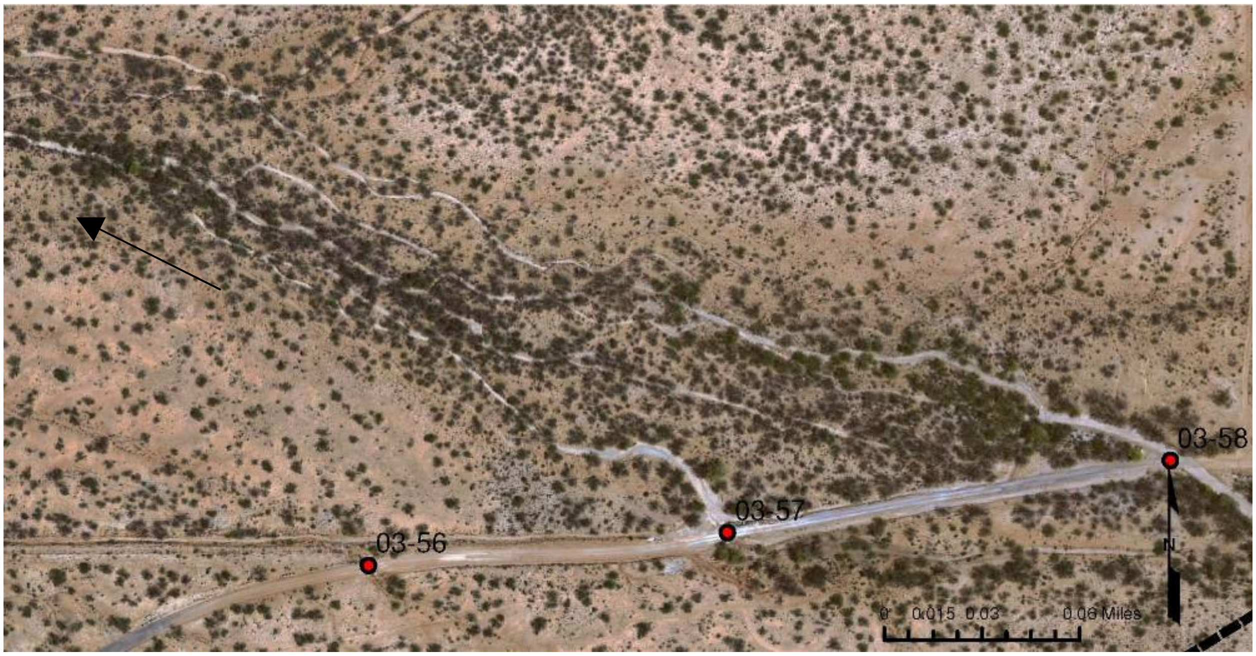
5.7.3 *Flooding*

The risk of flooding is primarily limited to the main drainage corridors while the terraces above the washes are generally free of flooding. Due to the large area tributary to these corridors, and the confined nature, flow depths are deep and velocities may be rapid. One significant risk is that flooding may occur within these channels in response to storms on the upper piedmont while little to no storm activity occurs within this zone.

5.7.4 Erosion, Sedimentation, and Lateral Migration

Erosion, sedimentation, and lateral migration are generally limited to the major wash corridors as flow is confined topographically throughout most of this zone. The risk of these processes may be greatest where the tributaries debouch near their confluence with the Santa Cruz River or other larger streams. Additional erosion and sedimentation risks are present on the older terraces which are susceptible to erosion where human activity has altered drainage patterns or disturbed the soil to a large extent.

During field visits both lateral and vertical erosion were found along the older terraces where roads capture and/or redirect stream flows. Figure 88 shows three locations where flow was found crossing an unimproved road near the transition from the Distributary Piedmont Zone to the Incised Zone (note that some distributary flow patterns are found at this location as it is near the transition into this zone). Field point 03-56 is located on a T5 surface while 03-57 and 58 are on Qy surfaces. LM03-56-01 shows the downstream view of the flow path on the T5 surface; vertical and horizontal erosion are found at this location. LM03-57-01 shows the downstream view of the flow path on the Qy surface; this wash is relatively stable.



Aerial view of flow patterns on Holocene and Pleistocene surfaces

Eroded flow path on T5 surface (LM03-56-01)

Stable flow path on Qy surface (LM03-57-01)

Figure 88 - Vertical and horizontal erosion along road crossing in Incised Zone

Relatively high vertical banks were found on the larger washes west of Nogales Highway. The adjacent floodplain terraces in these areas are typically mapped as T2 surfaces. These vertical banks are a result of substantial headcutting. Examples of vertical banks and areas of highly incised channels on abandoned terrace surfaces are shown on Figure 89. The panorama of LM03-65 shows erosion on a T2 surface just south of where the Lee Moore Wash crosses the Nogales Highway. LM03-67-01 shows the Lee Moore Wash which has the bed mapped as a Qy (ch) surface and the adjacent floodplain terrace mapped as a T2 surface.

Widespread erosion on T2 surface west of Nogales Highway. (Panorama of LM03-65-01, 02, and 03)

View from UPRR Bridge up the Lee Moore Wash, at the Petty Ranch Wash confluence, channel on Qy surface and overbanks on T2 surface (LM03-67-01)

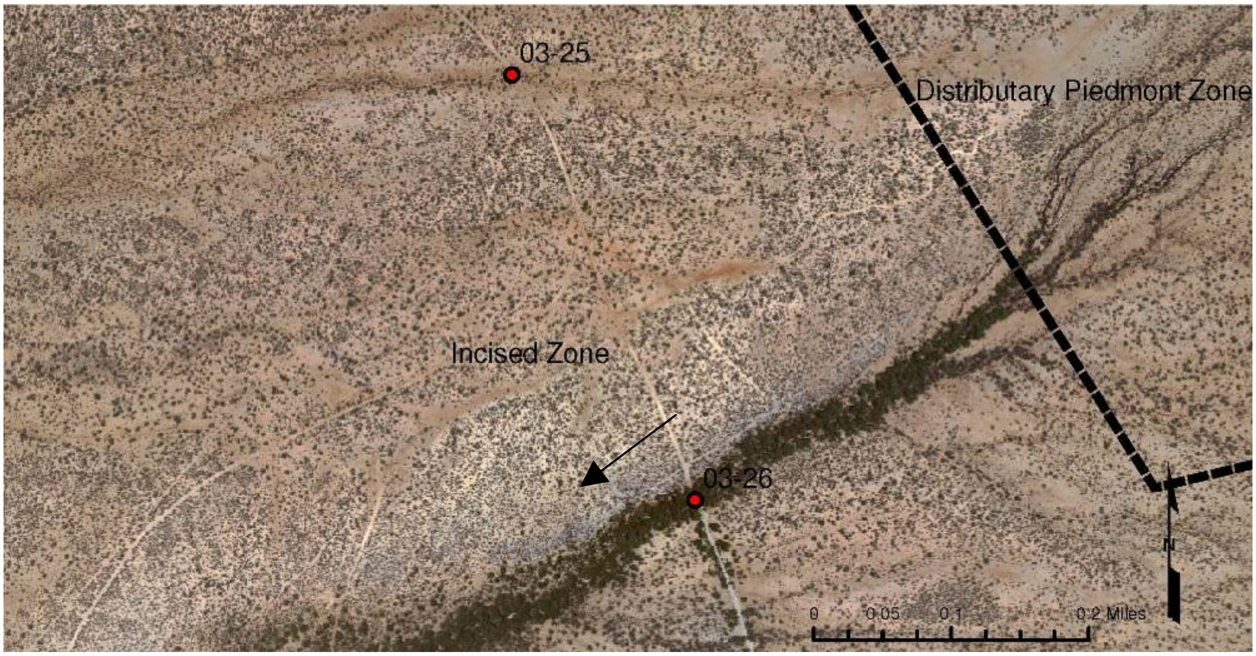
View of the Fagan Wash facing upstream from Country Club Road alignment, T2 surface (LM03-33-01)

Incised braid of Fagan Wash with debris and old cars, T2 surface (LM03-34-01)

View of the Lee Moore Wash facing upstream from Country Club Road alignment, Qy surface and scalloped outer bank (LM03-41-01)

Figure 89 - Highly incised channels on abandoned terraces in Incised Zone

Instances of aggraded washes or washes with extensive sediment supply were generally found in the upper limits of the Incised Zone. Figure 90 shows two locations where such washes were found. LM03-25-01 and LM03-26-02 show the ground views of these washes.



Aerial view of sediment rich washes in upper Incised Zone

Small aggraded wash emanating from Cuprite Wash breakout flow, T5 terrace (LM03-25-01)

Aggraded wash at transition from Distributary Piedmont to Incised Zone on Qy surface (LM03-26-02)

Figure 90 - Sediment rich washes in Incised Zone

The washes in the Incised Zone, more so than in any other zone, have become a place to deposit trash. While smaller items of trash have little impact on geomorphic processes, the larger items such as tires and refrigerators can have alarming impacts when drainage structures become partially or totally blocked. Following are a few representative ground photos of trash accumulation.

Accumulation of debris and trash upstream of Franco Wash crossing of Old Nogales Highway (LM04-07-01)

Trash in incised wash south of Summit Street on Qy surface (LM04-05-01)

Trash and vertical scour on Franco Wash upstream of Summit Street, Qy surface (LM04-06-02)

Figure 91 - Trash and dumped debris accumulation within Incised Zone

5.7.5 Headward Erosion

Headcutting may be the most important process within this geomorphic zone. All of the major flow corridors within the Incised Zone have been impacted and shaped by headcutting which extends beyond this zone and up-gradient into the Distributary Piedmont Zone.

Figure 92 shows the location of an incised wash with extensive vertical scour downstream of a series of culvert structures within the Incised Zone. The wash drains to the Lee Moore Wash just upstream of its confluence with the Santa Cruz River. The panorama of LM03-68-01&02 shows the downstream face of the culvert under Nogales Highway which is on a T2 surface. The wash upstream of the culvert is a Qy surface and a Qy (ch) surface is mapped in the downstream wash. The panorama of LM03-68-04&05 shows the wash downstream of the concrete apron and grade control structure. The wash downstream of the apron is approximately 12 feet below the top of the concrete apron and is deeply incised. The incision within the tributary wash may be primarily caused by downcutting of the Santa Cruz River and the linked effect (refer Section 4.3) on the Lee Moore Wash and its tributaries. It is also likely that the highway and culvert crossing have forced an increase in flow concentration into this channel, further inducing headcutting.

Aerial view of incised tributary to Lee Moore Wash

Culvert under Nogales Highway and grade control structure on unnamed wash (Pan. of LM03-68-01, 02)

Figure 92 -Incised tributary to Lee Moore Wash

Vertical scour downstream of grade control structure on unnamed wash crossing Nogales Highway (Panorama of LM03-68-04 and 05)

Vertical banks on T2 surface downstream of Nogales Highway (LM03-68-05)

Figure 92 -Incised tributary to Lee Moore Wash (continued)

Headcutting and an abrupt scour difference were found along the Petty Ranch Wash ford crossing of the Old Nogales Highway, shown in Figure 93. The wash upstream of the road is highly incised with semi stable banks while the banks are less stable downstream of the road. The channel downstream of the road has scoured right up to the edge of the road which might wash away during a significant event. Reworking of the channel upstream of this location may have reduced sediment supply to this area, further encouraging scour.

Aerial view of Petty Ranch Wash crossing of Old Nogales Highway

Petty Ranch Wash, upstream of Old Nogales Highway, Qy surface (LM04-02-01)

Scour downstream of Old Nogales Highway on Petty Ranch Wash, Qy Surface (LM04-02-02)

Figure 93 - Headcutting and abrupt scour difference along the Petty Ranch Wash

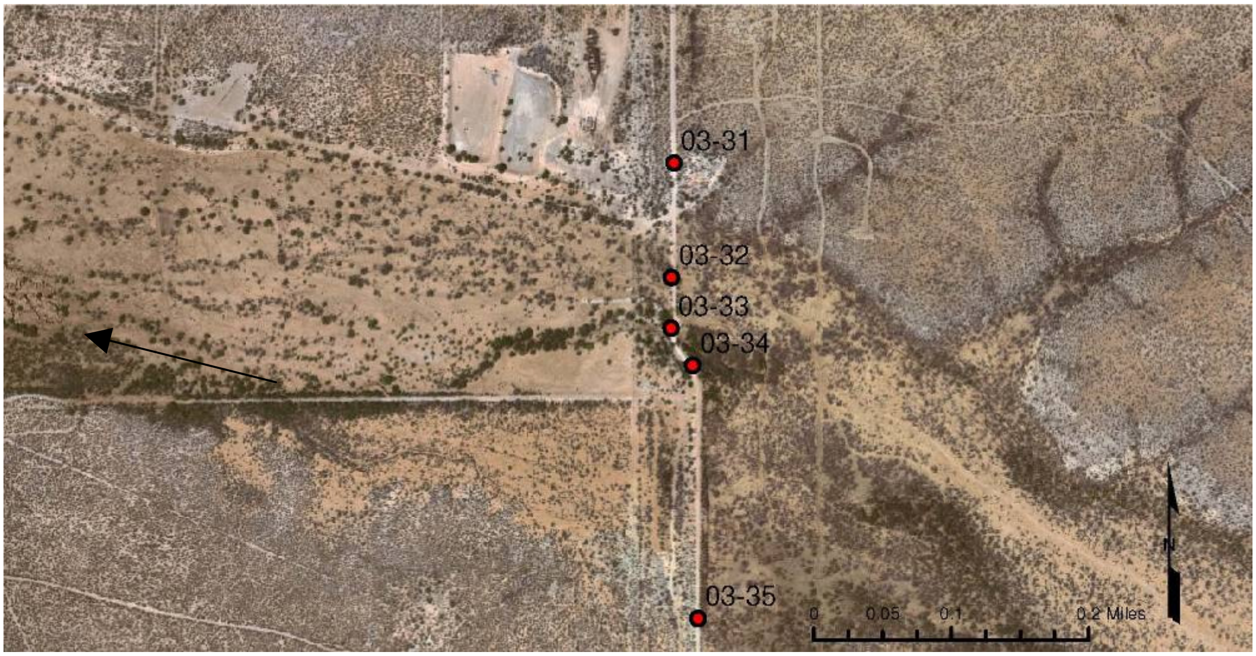
Vertical banks and scour downstream of Old Nogales Highway on Petty Ranch Wash, T2 surface (LM04-02-03)

Vertical banks on Petty Ranch Wash (LM04-03-01)

Vertical banks on Petty Ranch Wash (LM04-03-02)

Figure 93 - Headcutting and abrupt scour difference along the Petty Ranch Wash (continued)

Headcutting along the Fagan Wash was observed along the Country Club Road alignment. The headward erosion extends up minor flow paths such as was observed at field point 03-31; see LM03-31-01. The main channel of the Fagan wash is scarred by headcutting as shown in LM03-33-02. Dumped rip rap has been placed downstream of the road, impounding the water observed in the photograph.



Aerial view

Headward erosion progressing towards Country Club Road along minor flow path (LM03-31-01)

Riprap within Fagan Wash (LM03-33-02)

Figure 94 - Fagan Wash headcutting along Country Club Road alignment

Figure 95 shows a tributary to the Petty Ranch Wash. This wash is incised and shows evidence of impacts due to headcutting with vertical scour shown in LM03-23-06 and LM03-23-02.

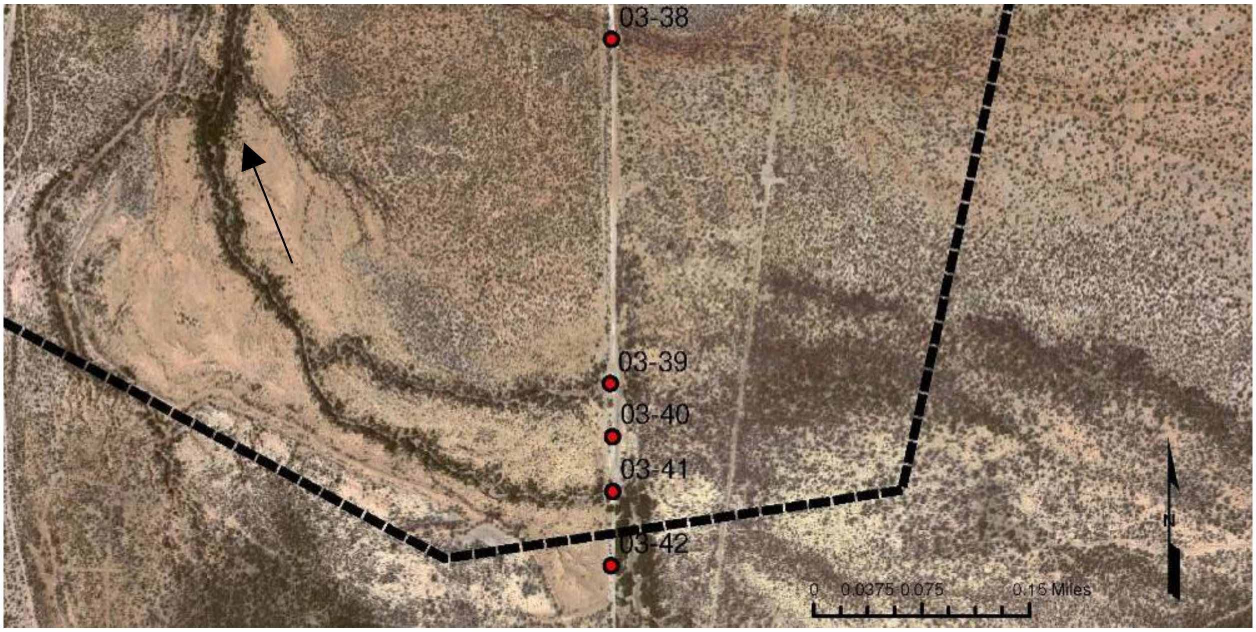
Aerial view

Headcut and scour hole downstream of culvert on T5 surface (LM03-23-06)

Incised wash upstream of culvert on T5 surface (LM03-23-02)

Figure 95 - Incised tributary to Petty Ranch Wash

Figure 96 shows observed headcuts along the Lee Moore Wash and local tributaries.



Aerial view of Lee Moore Wash at Country Club Road alignment

Vert. scour dstrm of rd., Qm surface (LM03-38-01)

View upstrm of Lee Moore Wash trib.(LM03-39-02)

Vertical scour on Qy surface (LM03-40-01)

Lee Moore at Country Club Rd. alignment (LM03-41-01)

Figure 96 - Various observed headcuts along Lee Moore Wash and tributaries

5.7.6 Roads Parallel to Flow Paths

No notable locations of scour parallel and adjacent to roads were found within this zone.

5.7.7 Notable Drainage Crossings

Figure 97 shows a wash tributary to the Franco Wash within the Incised Zone, just down-gradient of the Distributary Piedmont Zone. The picture shows the wash on a QTbf surface, beginning at Swan Road and extending approximately 4,700 feet downstream to Singing Cactus Lane. The wash upstream of Swan Road and downstream of Singing Cactus Lane occupies a Qy surface. The wash crosses Swan Road via a 5-cell, 12' x 8' RCB culvert and crosses Singing Cactus Lane (field point 04-12) via a concrete ford crossing. The RCBC plans for the Swan Road culvert indicate that the 100-year flow will overtop the road at a depth of less than one foot. The wash upstream of Swan Road has some lateral scour with vertical banks, but is generally not highly eroded and the culvert at Swan Road is not filled with sediment. Downstream of Swan Road the wash is stable with well vegetated banks.

Aerial view

View upstream from Swan Road (LM04-10-04)

View downstream from Swan Road, QTbf surface (LM04-10-02)

Figure 97 - Franco Wash tributary crossing of Swan Road, upstream of Singing Cactus Lane

The unvented ford crossing shown in Figure 98 is the Singing Cactus Lane crossing referenced in the plan view of Figure 97. This crossing has steep approaches with no erosion protection for the banks. The wash upstream of Singing Cactus Ln. is moderately stable with vegetated banks and sedimentation upstream of the crossing. It is not clear whether the crossing was placed slightly above the natural channel grade at the time or if it was placed at grade. The wash downstream of Singing Cactus Ln. is highly scoured without any gravel or large sand armoring present. The wash has scoured vertically 3 to 4 feet below the elevation of the road.

Facing south towards concrete ford crossing, (LM04-12-07)

Sedimentation upstream of Singing Cactus Lane, QTbf surface (LM04-12-01)

Extreme scour downstream of road, QTbf surface, facing north (LM04-12-03)

Figure 98 - Scour downstream of Franco Wash tributary crossing of Singing Cactus Lane

Old Nogales Highway crosses several washes by way of low flow crossings. The washes at these locations are highly incised and susceptible to lateral erosion and vertical bank development. Figure 99 shows the aerial view along with upstream and downstream ground views of the Flato Wash crossing within the Incised Zone. The crossing is paved and appears to be constructed above the natural grade of the channel. Deposition of fine grained gravel and sand is present upstream of the crossing while the channel downstream of the crossing is starved of this sediment. The vertical and lateral scour at this location are however limited.

Aerial view

Aggradation upstream of Highway, T2 surface (LM04-04-02)

Degradation downstream of Highway, T2 surface (LM04-04-01)

Figure 99 - Flato Wash crossing of Old Nogales Highway

The cause of the observed impacts at the crossings nearest the Santa Cruz River, especially along Old Nogales Highway, is headcutting. Locally induced scour downstream of the road may be occurring but is overshadowed by the scour generated by headcutting. Similarly, the observed scour downstream of Singing Cactus Lane is due to headcutting with some influence from scour hole development. It is noteworthy that the old Nogales Highway low flow crossings of the Flato Wash, Franco Wash, and Petty Ranch Wash have the effect of grade control, preventing headcutting from migrating upstream of the road crossing.

5.7.8 Aerial Photograph Comparison

Noticeable changes to the alignments of both the Santa Cruz River and the Lee Moore Wash near the Santa Cruz River are evident upon comparison of the aerial images, see Figure 100. In addition to lateral migration, it appears that the main channel of the Lee Moore Wash in this area is narrower, and probably more incised than it was in 1936. (Note that this assertion cannot be quantitatively proven as no topography was obtained related to the 1936 aerial flight.) Further upstream, the portion of the Lee Moore Wash shown in Figure 102 has changed significantly since 1936 as a result of adjacent floodplain development.

Impacts to the fluvial systems within this zone have occurred as a result of the development of homes and construction of stock tanks and impoundments. Figure 101 shows a Qy corridor where homes have been developed, somewhat altering the historic flow path. Figure 105 compares the aerial sets in areas below an impoundment. Figure 105 does not give any clear indication of changes to the main channels as a result of the existence of the impoundment, but it is noteworthy that the majority of the scarred area shown on Figure 105 is mapped as a Qy zone indicating historic flooding and the potential for future flooding around the existing structures.

Headcutting was found in the aerial comparisons. In Figure 103, the Petty Ranch Wash footprint is wider upstream of the road in the modern aerial. Some of this may be attributed to sedimentation upstream of the road crossing, but headcutting was observed in the field and it is also observed in the tributary gullies. Field ID points LM02-02 and LM02-03 showed vertical banks and vertical scour at the road crossing. Review of the modern aerial shows that the gullies draining to the Petty Ranch Wash have extended and additional gullies have developed. Also noteworthy is the erosion shown on Figure 89 which is located toward the top left (northwest) end of Figure 103. This widespread erosion does not appear in the 1936 aerial.

Figure 104 shows a similar indication of a wider vegetated footprint upstream of the concrete low ford crossing (as shown on Figure 94) on the Fagan Wash near the confluence with the Lee Moore Wash. This figure also shows increased incision of the Lee Moore Wash; the channel is less braided and appears to be narrower. Furthermore, multiple incised tributaries have apparently developed since 1936 suggesting that the base level of this wash has been reduced, thus inducing headcutting up the tributaries. The wider footprint of the Fagan and Petty Ranch Washes may be due to expanded flooded widths in response to contractions in the system such as road crossings. Additionally, stagnant water was observed at these locations as a result of road and drainage structures. The local water table may be elevated enough to encourage increased vegetative growth.

Figure 106 shows a series of flow splits and confluences which may have migrated since 1936. The two major confluences appear to have migrated upstream or become wider (possibly as a result of incision). This phenomenon was observed in other locations during the course of this comparison. This figure also shows several locations where breakout flow paths are still visible but less evident and slightly altered since 1936. (The breakout flow occurs from the main Qy channels across T5 terraces.) While avulsion from the main channel appears to be more limited in recent years, this may be in part due to the reduced runoff in the watershed due to the current drought. Therefore, the breakout flow paths may be more visible on the 1936 aerials because the vegetation was healthier at that time and/or overland flow has filled the breakout channels which have not scoured in recent years. Another explanation would be that if the channels have incised and downgraded, avulsion would be less likely to occur. Regardless, Figure 106 shows the potential for abandonment of flow paths which could lead to the carving of additional flow paths, vertical and/or lateral channel changes within the primary channels, and even the reestablishment of abandoned flow paths.

Figure 107 shows the Franco Wash in the vicinity of the Nogales Highway. Obvious changes have occurred downstream of the Highway. The wash in 1936 appears to have terminated at the highway, becoming wide and shallow with substantial vegetative growth. The wash downstream of the highway currently is incised and vegetation on the overbanks is significantly reduced. These observations could be the results of an improved culvert crossing along the highway in conjunction with the downcutting of the Santa Cruz River. An additional observation was made where the wash crosses Old Vail Connection Road; the road has redirected the flow path locally but has not significantly impacted the wash beyond the road alignment.

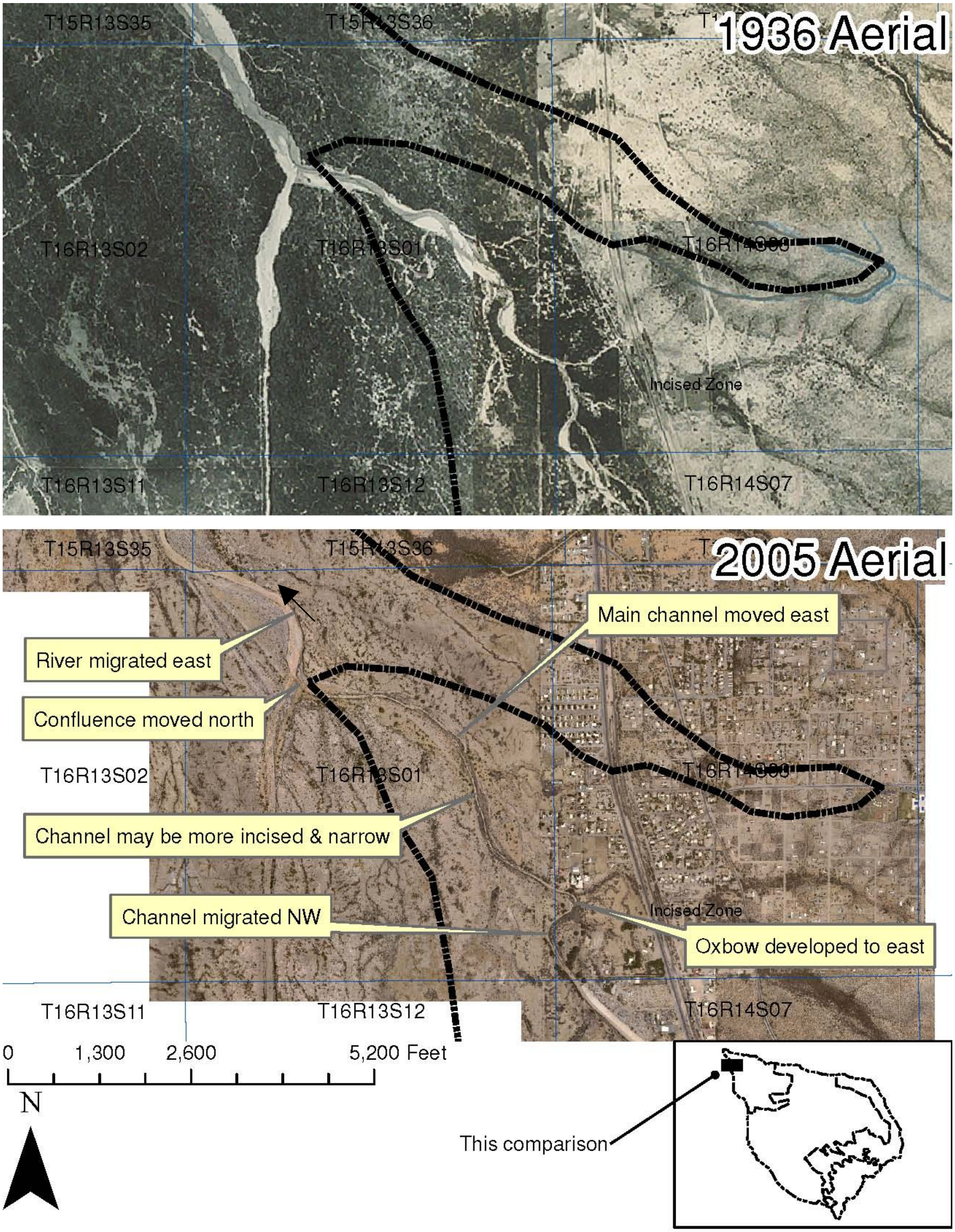


Figure 100 - Comparison of 1936 and current aerial images; station IZ01

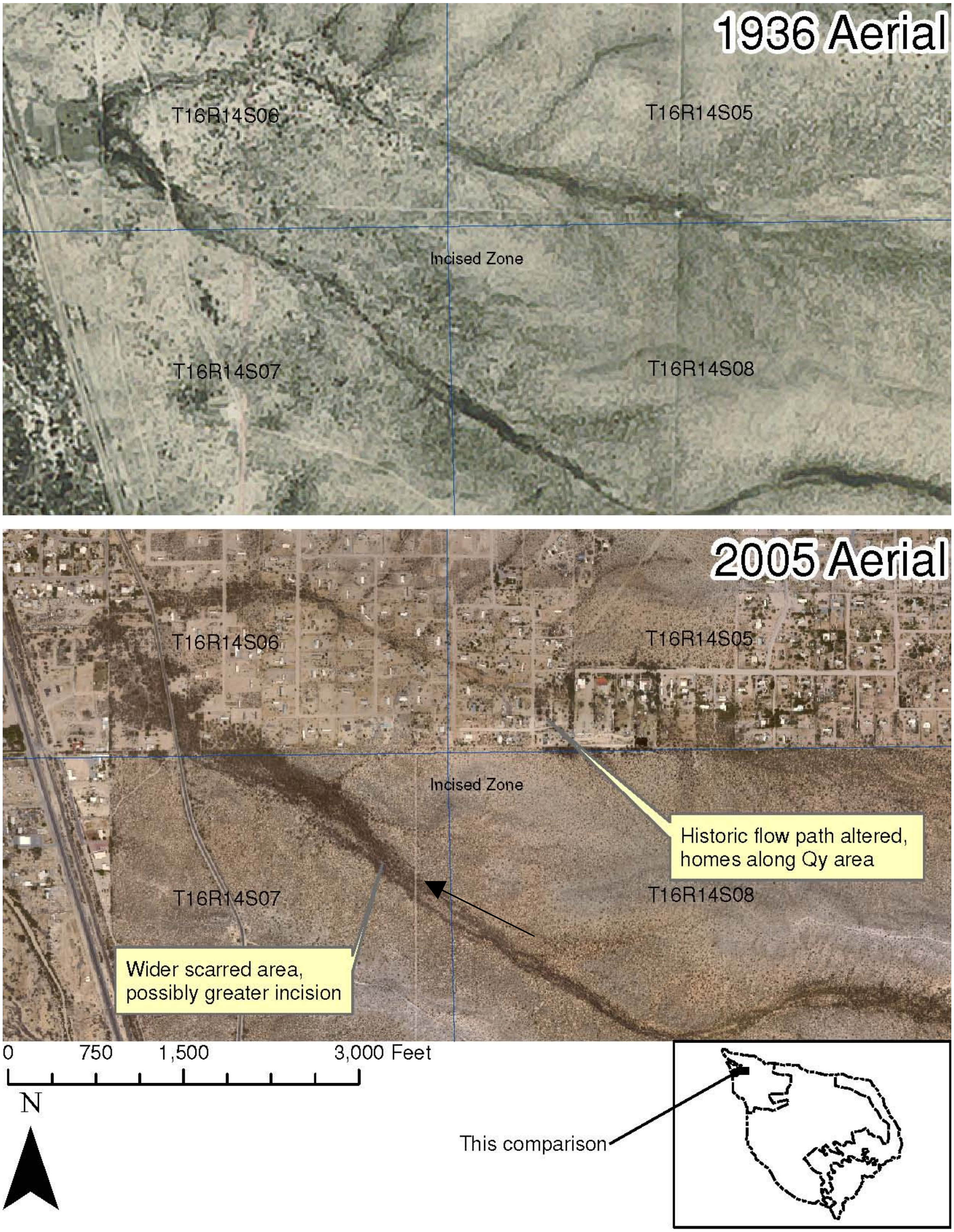


Figure 101 - Comparison of 1936 and current aerial images; station IZ02

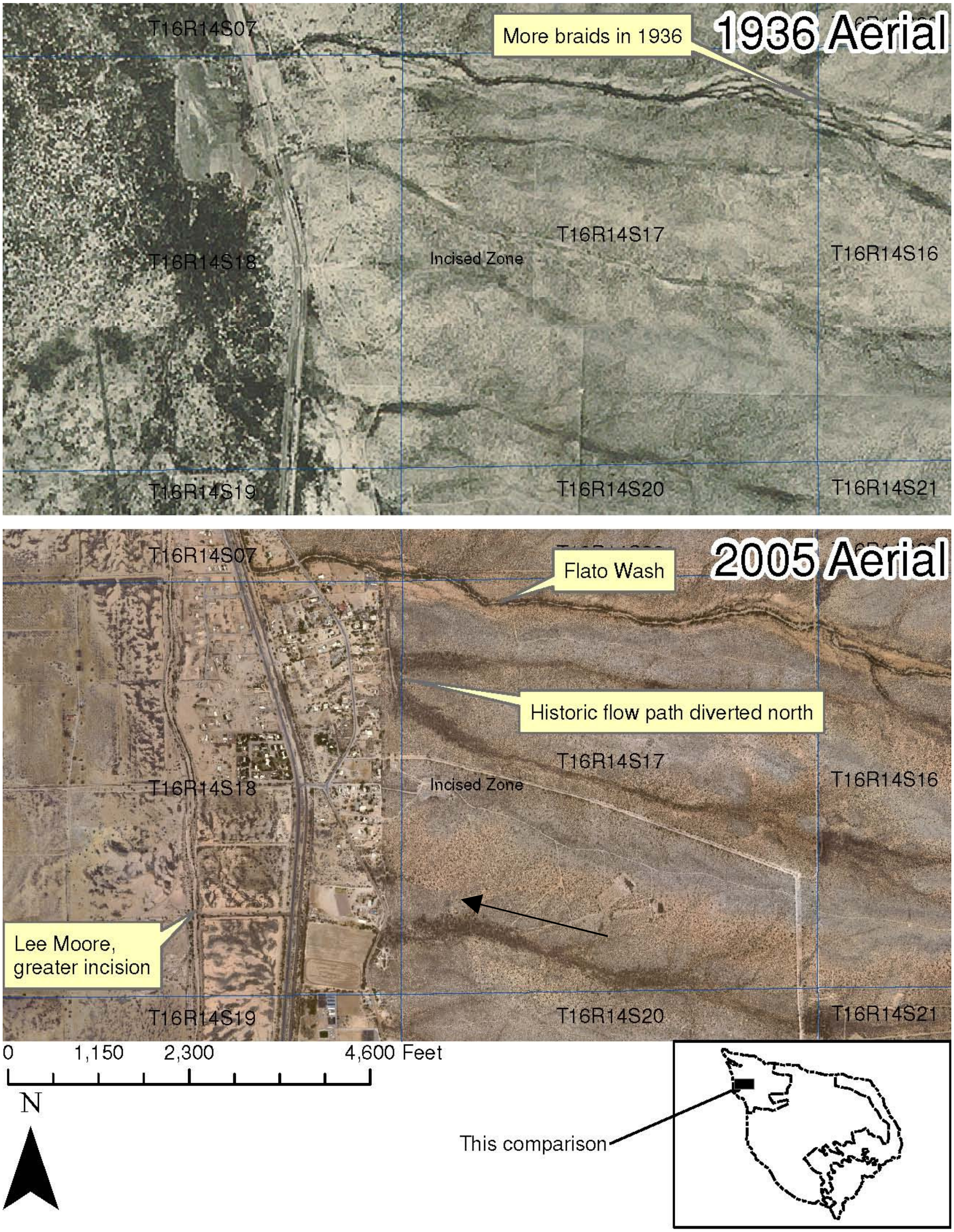


Figure 102 - Comparison of 1936 and current aerial images; station IZ03

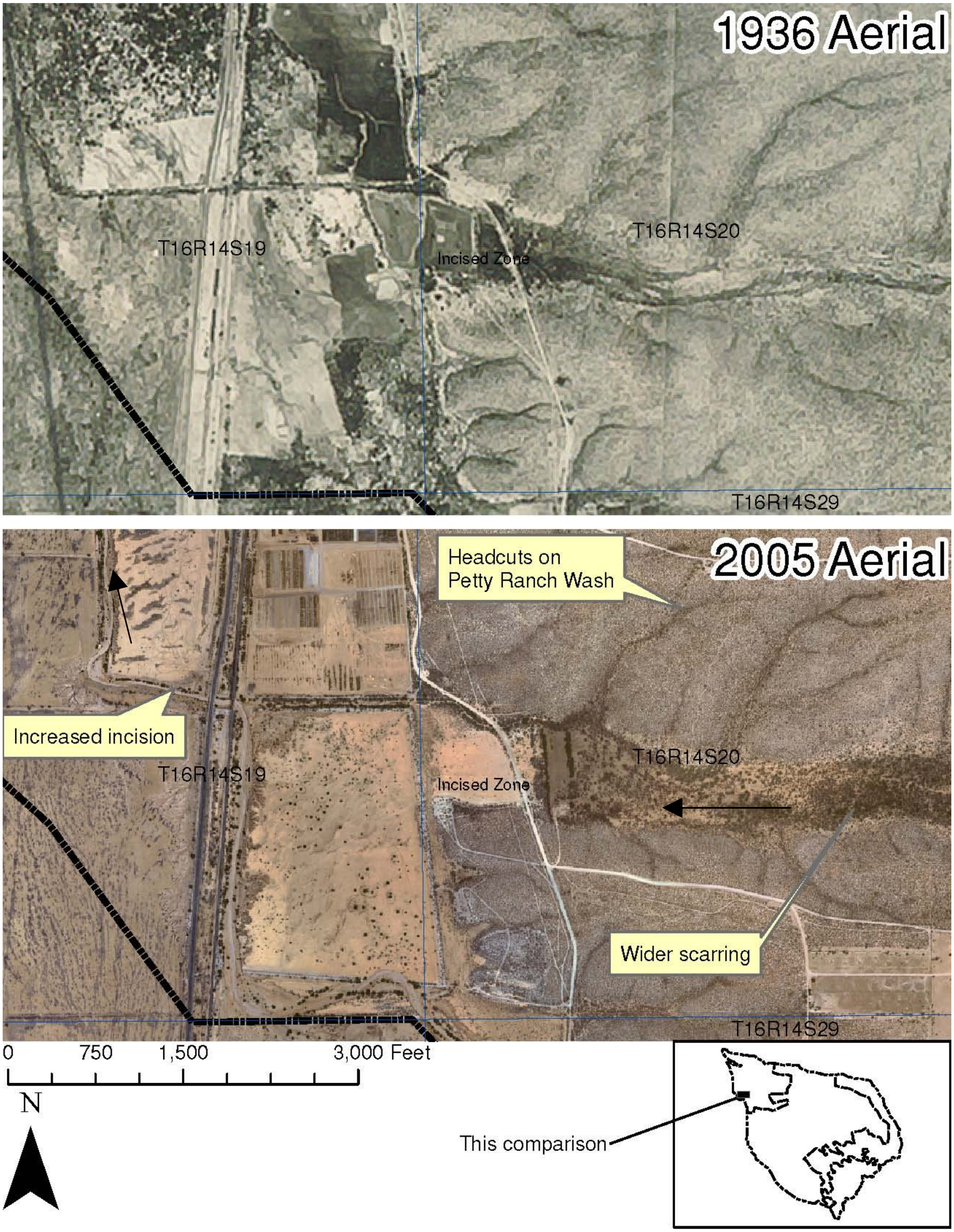


Figure 103 - Comparison of 1936 and current aerial images; station IZ04

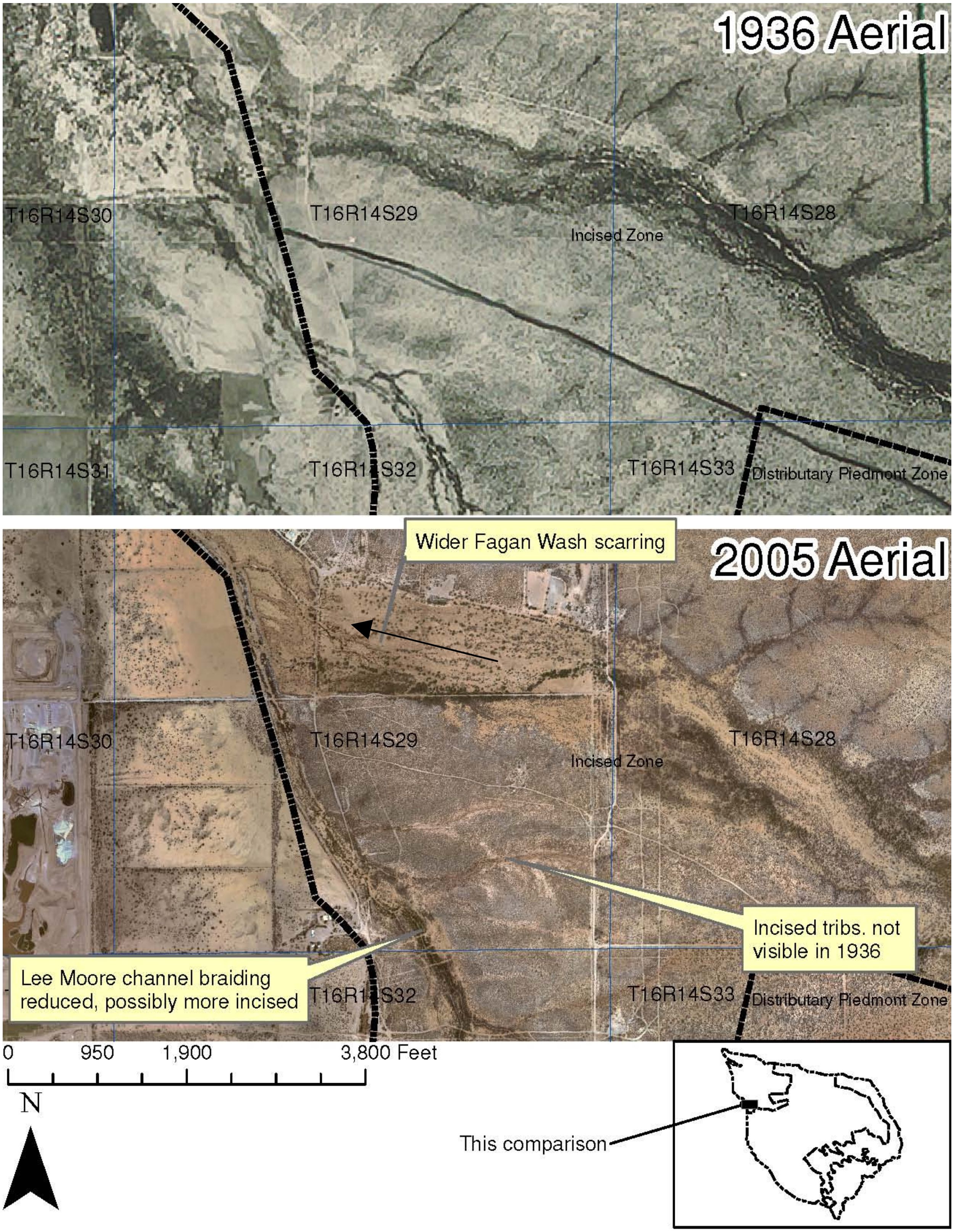


Figure 104 - Comparison of 1936 and current aerial images; station IZ05

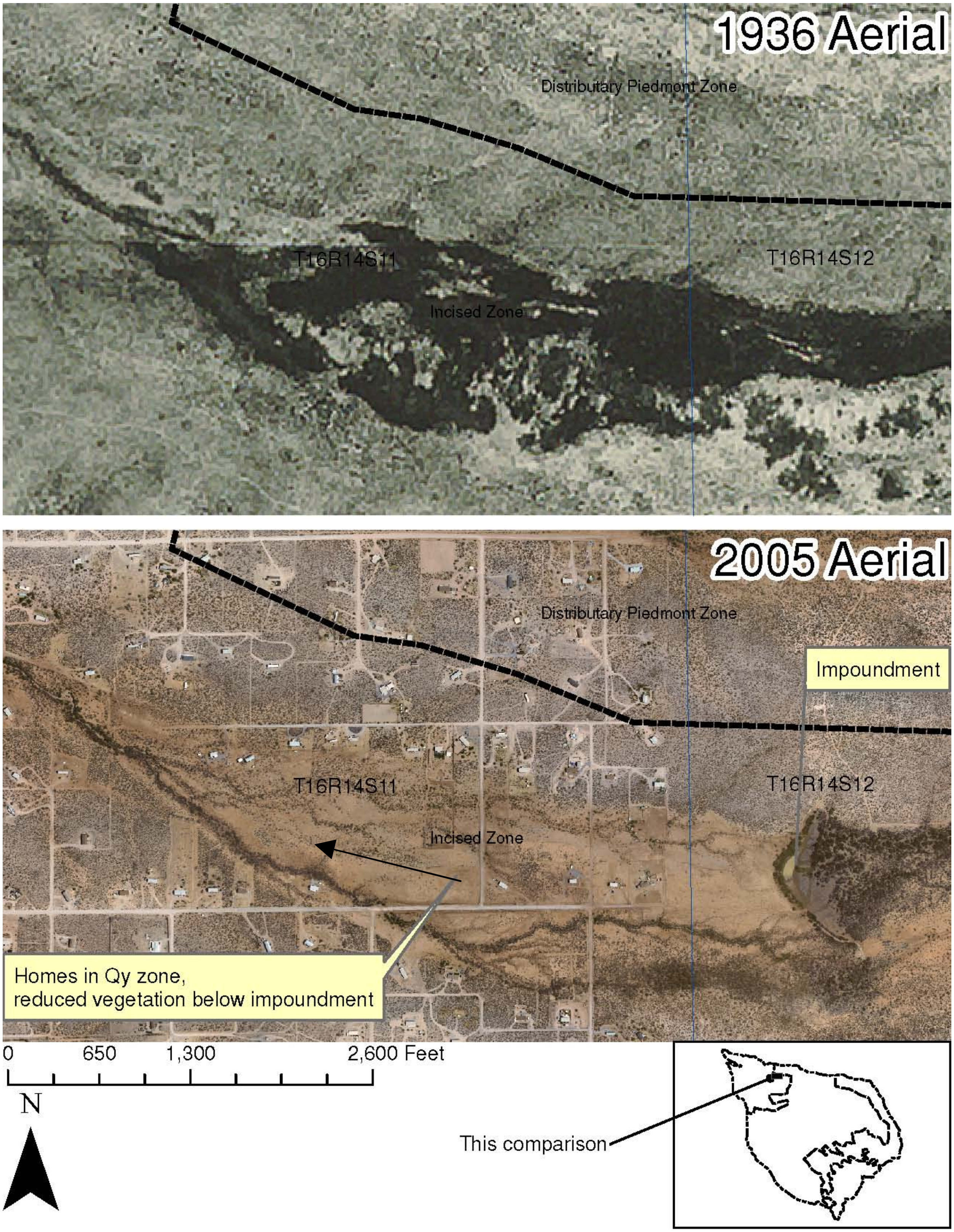


Figure 105 - Comparison of 1936 and current aerial images; station IZ06

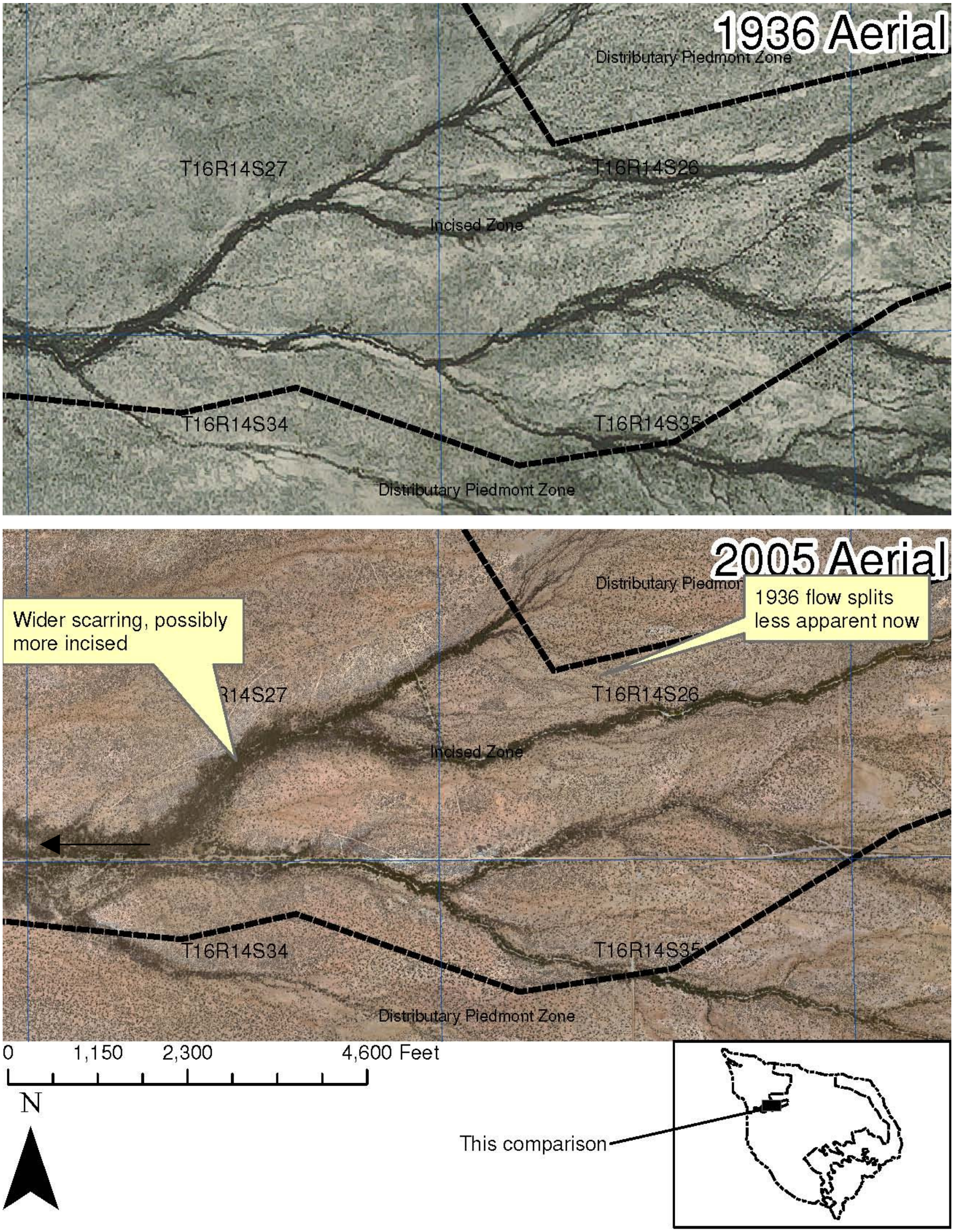


Figure 106 - Comparison of 1936 and current aerial images; station IZ07

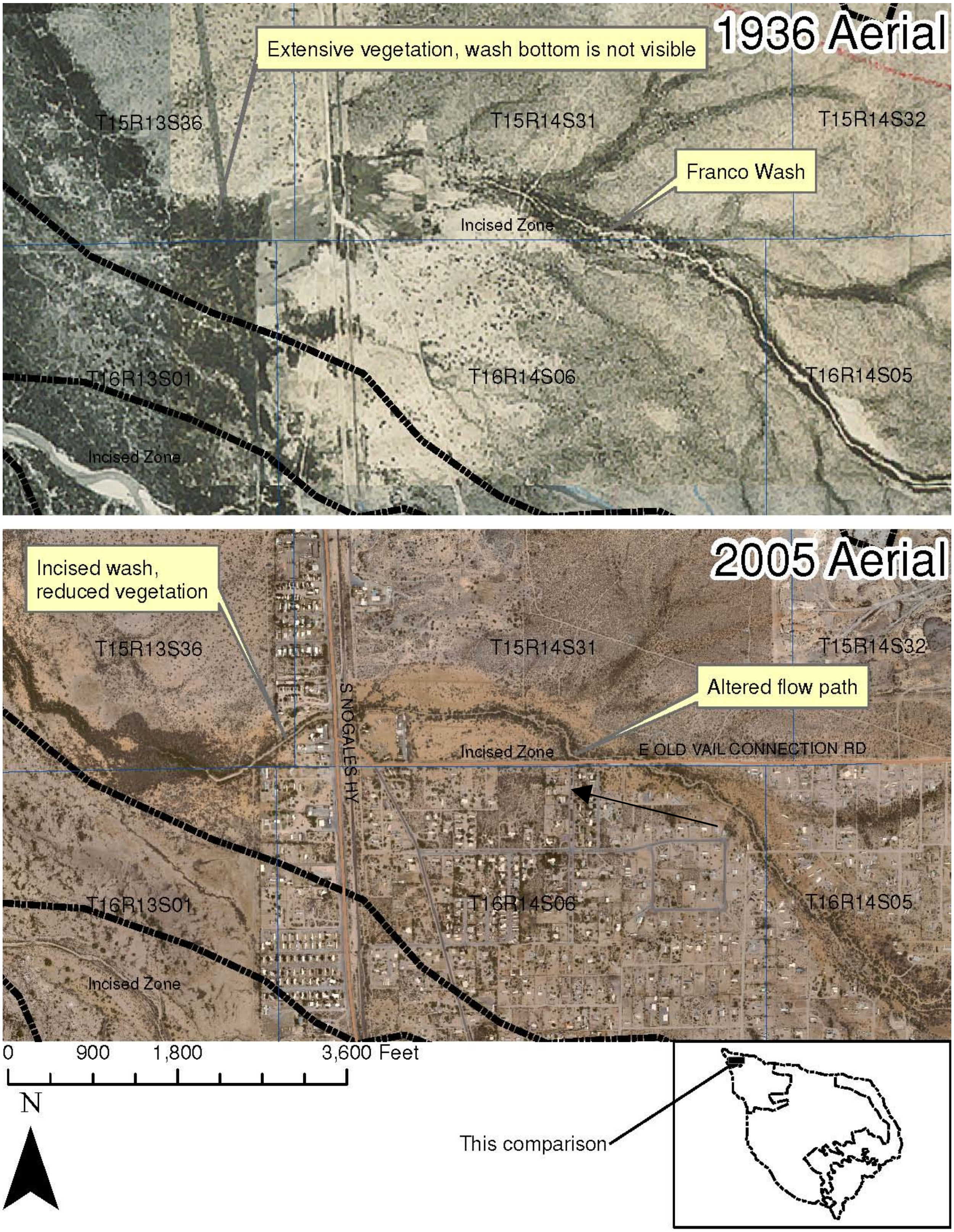


Figure 107 - Comparison of 1936 and current aerial images; station IZ08

6 Flow Related Hazards

6.1 Section Outline

This section provides indicators of flow related hazards by summarizing the findings and criteria discussed throughout the previous sections of this report. This section also documents the delineation of geomorphic risk areas; subdivisions of the four geomorphic study zones based upon homogenous risk levels of headcutting, lateral erosion, and migration. The geomorphic risk areas map is a tool that can be used in the early stages of project progression by counter hydrologists, flood control managers, engineers, and planners. Recommendations for prevention and mitigation of flow related hazards are found in Section 9.

6.2 Correlation of Field Observations to Soils Maps

An analysis was performed to determine which soils were related to the various observed geomorphic processes. The most significant geomorphic processes observed include vertical banks, lateral erosion, vertical scour, headcutting, and channel incision. The intent of the analysis was to determine if there is a significant correlation between erosive activity and the NRCS map units, a correlation which would allow an observer to predict hazards based upon soil type. Some correlations were found, but not of significant usefulness, mostly due to the general nature of the soil descriptions. The observed correlations are shown within Appendix C.

6.3 Flow Related Hazards and their Indicators

There are several geomorphic processes which occur within the study area. The most significant are headcutting, lateral erosion, and lateral migration. These processes are impacted by the effects of distributary flow as well as location within the watershed. The following sub-sections define these terms as used in this report and discuss these hazards.

6.3.1 Distributary Flow Areas

The study area piedmont has typical ephemeral stream patterns and distributary flow corridors. Distributary areas are characterized by sheet flow dominant areas downstream of flow splits followed by (re)development of significant channels and finally convergence into the major channels draining into the Santa Cruz River. Sheet flow areas typically begin with a primary diffluence situated at an alluvial fan apex or other feature and continue downstream with additional minor and major flow divides. Hjalmarson (1991) defines the primary diffluence as the "Diffluence or bifurcation below which flow is distributary and above which the 100-year flood is contained in the channel and flood plain is tributary" (pg. X).

The flow splits which are visible on the aerial photographs have been delineated. These flow splits include simple channel braids, bifurcations, and major flow splits. For this study, major flow splits are defined as the first (most upstream) significant flow split which is discernable from the aerial photographs. These flow splits will divide flow into separate watersheds.

A unique kind of flow split is the disappearing wash which occurs when a wash which is easily delineated on an aerial disperses and is no longer discernable as one wash. These flow splits are important because they represent an area which is likely experiencing deposition. The flow splits, flow type boundary, and disappearing washes are shown on **Plate 2** and **Plate 3**. These locations are included with this report in digital format, both in shape file format for ESRI and .kmz format for use with Google Earth.

Distributary flow areas have many associated flow related hazards including expansive flooded areas, sheet flow flooding, sediment and debris (rare) flow, sedimentation, isolation of dry areas during runoff events, uncertain and alternating flow paths, redirection of flow paths, and arroyo development. Indications of distributary flow areas include;

- **Drainage patterns:** Flow areas with little to no defined drainage network.
- **Flow splits:** Observed on aerial maps.
- **Disappearing washes:** Observed on aerial maps.
- **Slope:** Down valley reduction in longitudinal slope.
- **Relief:** Down valley reduction in lateral relief.
- **Contour patterns:** Down valley reduction in contour band width (distance between a tangent to the largest crenulation of a contour that points upstream and a tangent to the largest crenulation of the same contour that points downstream).
- **Bank height:** Interfluves which do not contain 100-year flood levels.
- **Geology:** Situation of fans of varying age adjacent to each other on surficial geology maps.

Additional information can be found in the State of Arizona Department of Water Resources (ADWR) publication "State Standard for Identification of and Development Within Sheet Flow Areas" which gives guidance on determining if sheet flow is present, what kind of sheet flow is present, and how to protect the fluvial systems.

6.3.2 *Headcutting*

The term headcut, as used in this report, refers to an upstream progressing zone of degradation, a process where degradation migrates upstream (in the headward direction) incising channels in the process. Headcutting can occur when primary flow paths or washes within a study area reduce their base levels in response to axial stream degradation. The degradation of the primary washes will continue to migrate upstream until it reaches a surface that is non-erodible, such as bedrock or a hardened road crossing. A nick point will sometimes develop where the headcut meets a resistant material. Headcutting can also occur due to upstream factors such as when flow is concentrated, if discharge is increased within a channel, or if sediment inflow to a system is reduced. Further complicating this is that the upstream progressing degradation can often be accompanied by downstream progressing aggradation. (This process is discussed within several publications including the U.S.A.C.E. manual "Channel Stability Assessment for Flood Control Projects", pg. 2-9.) Additionally, as a wash scours vertically, the banks tend to erode outward increasing the channel top width. Whereas the delineation of distributary flow locations will not vary over an engineering time scale, the locations of headcutting will change within a relatively short time period.

The risk of headcutting is based upon several factors including proximity to an axial stream, soil characteristics, and potential upstream and downstream influences. Additionally, the major washes within an area have different risks than the smaller washes and the terrace drainage paths. Following are factors which will encourage headcutting to occur;

- **Axial stream degradation:** If the axial stream that an area drains to is degrading (and is not adequately protected by grade control structures), then the tributary streams of the focus area will likely degrade in response.

- **Land use change:** On a region wide level, land use changes will impact headcutting. Increased urbanization will tend to increase runoff and decrease sediment discharge, promoting headcutting.
- **Flow concentration:** More locally, concentration of runoff onto a terrace will generate a headcut between the discharge point and the nearest wash which the area drains to.
- **Flow diversion:** Diversion of flow will encourage headcutting.

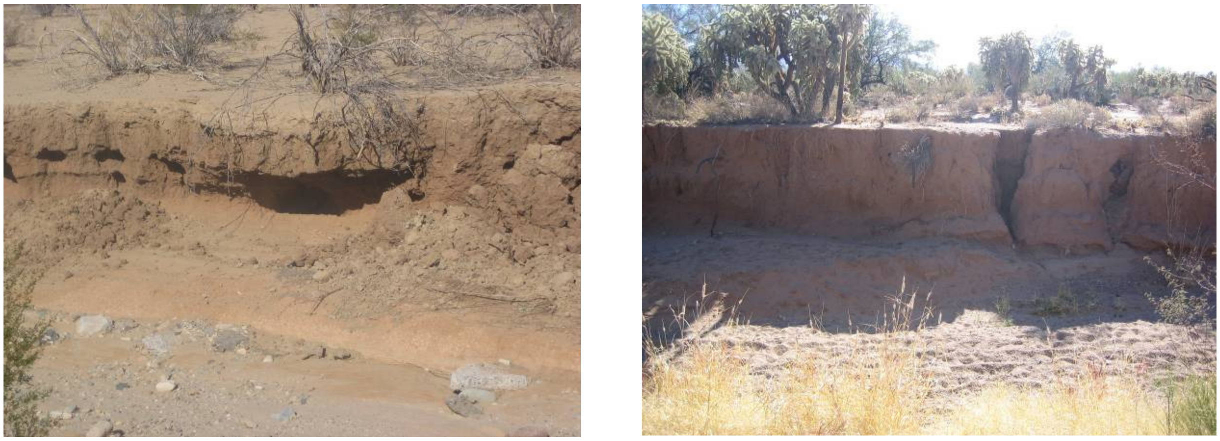
Field reconnaissance is often necessary to determine if headcutting is occurring. Indications of headcutting include;

- **Cross section:** A highly incised channel bottom which is not well armored
- **Arroyo development:** A small v-shaped channel on a terrace
- **Excessive scour**: Scour beyond what would be expected from scour hole development downstream of a hard point such as a dip crossing in association with little to no scour upstream of the hard point.

For reference, a few of the incised channel evolution phases (USACE EM 1110-2-1418, pg. 2-17) are illustrated in Figure 108. The first is incision of the primary channel (A and B). Here the incision extends near vertically below the channel floor. Incision is followed by widening of the channel bottom and undercutting of the adjacent floodplain terrace as shown in C. The channel bottom undermines the terrace vegetation leading to vertical banks (D). In response to the undercutting of the adjacent floodplain terrace, the banks fail causing lateral erosion and generating colluvium (E and F). These channels will likely continue to undermine the vegetation on the adjacent terraces. This will be followed by further cutting into the floodplain terrace and then possibly by aggradation (as colluvium accumulates within the channel) until dynamic equilibrium is achieved within the system. The channel section in dynamic equilibrium will have a wider top width than it currently does with an aggraded channel bottom composed of alluvium and colluvium eroded from upstream banks and terraces.

A - Incised channel bottom (LM03-39-03)

B -Upstream view of headcut, nick point in lower right of frame (LM03-59-01)



C - Widening and undercutting of terrace vegetation (LM03-51-01)

D - Vertical bank development and scouring of banks from inflow (LM03-64-01)

E - Lateral erosion and sloughing (LM03-50-01)

F - Headcut downstream of culvert outlet (LM03-56-01)

Figure 108 - Incised channel evolution phases

6.3.3 *Lateral Erosion*

Lateral erosion risks refer to erosion of channel banks which increases channel widths. The potential for lateral erosion is substantially related to the degree of headcutting present. Therefore many of the indications that lateral erosion will occur are related to headcutting. Furthermore, lateral erosion and lateral migration can be interrelated and lateral erosion and bank migration may occur if a channel bend or meander migrates through a reach. Meander induced lateral erosion is not common within this study area as most of the washes have a relatively straight plan form due to the flat valley slopes. Indications of lateral erosion include;

- **Toe failure:** Failure or erosion of the toe of the bank. (Lateral erosion is generally caused by a failure of the toe of the bank.)
- **Flow concentration:** Concentration of runoff along the top of a channel bank and/or erosion of the bank line where a flow path drains to a channel. Runoff flowing down the bank will scour the bank. This erosion in association with erosion from channel flow can cause lateral erosion and bank failure.
- **Headcutting:** Prediction of future headcutting and incision of the channel.
- **Vertical banks:** Banks which exceed the angle of repose or are steeper than would be expected in a stable reach.
- **Vegetation:** Exposed roots along a channel bank.
- **Shortening of a channel:** A channel will attempt to maintain its length, therefore if a channel is shortened locally (manmade or natural), then the channel will tend to lengthen itself elsewhere by cutting into the banks and lengthening channel bends if possible.
- **Observation of meanders upstream:** Meanders tend to migrate down valley, so if meanders occur upstream, then it is likely that they will migrate downstream. These types of meanders will likely be accompanied by point bars.

6.3.4 *Lateral Migration*

Lateral migration refers to avulsion and migration processes where a channel (wash or other flow path) changes course. Channels and flow paths change course through several processes. The processes of lateral migration within the study area are primarily related to distributary flow patterns where sudden channel shifts occur, primarily at aggraded locations. Stream piracy can occur within the distributary flow locations. When stream piracy occurs, flow volume is increased within a channel, increasing the potential for headcutting and lateral erosion. Avulsion and/or lateral migration can occur within underfit channels with flat longitudinal slopes within both distributary and tributary areas. Lateral migration can also occur at stream confluences.

6.4 Flow Related Hazards versus Geographic Location

Flow related hazards vary with position in the study area. An idealized profile from the mountain front down to the axial stream is shown in Figure 109. This figure is a generalization of the geomorphic components along with flow related hazards (adapted from Figure 2 of Hjalmarson 1991). In general;

- Headcutting risks are greatest at the confluence with the Santa Cruz River and decrease as one heads up the alluvial plain.
- Lateral erosion hazards are greatest in the areas most proximate to the Santa Cruz River and decrease as one heads up the alluvial plain.
- Lateral migration and sheet flow hazards are the greatest and most widespread within distributary flow areas on the piedmont as relief and flow containment are at a minimum.

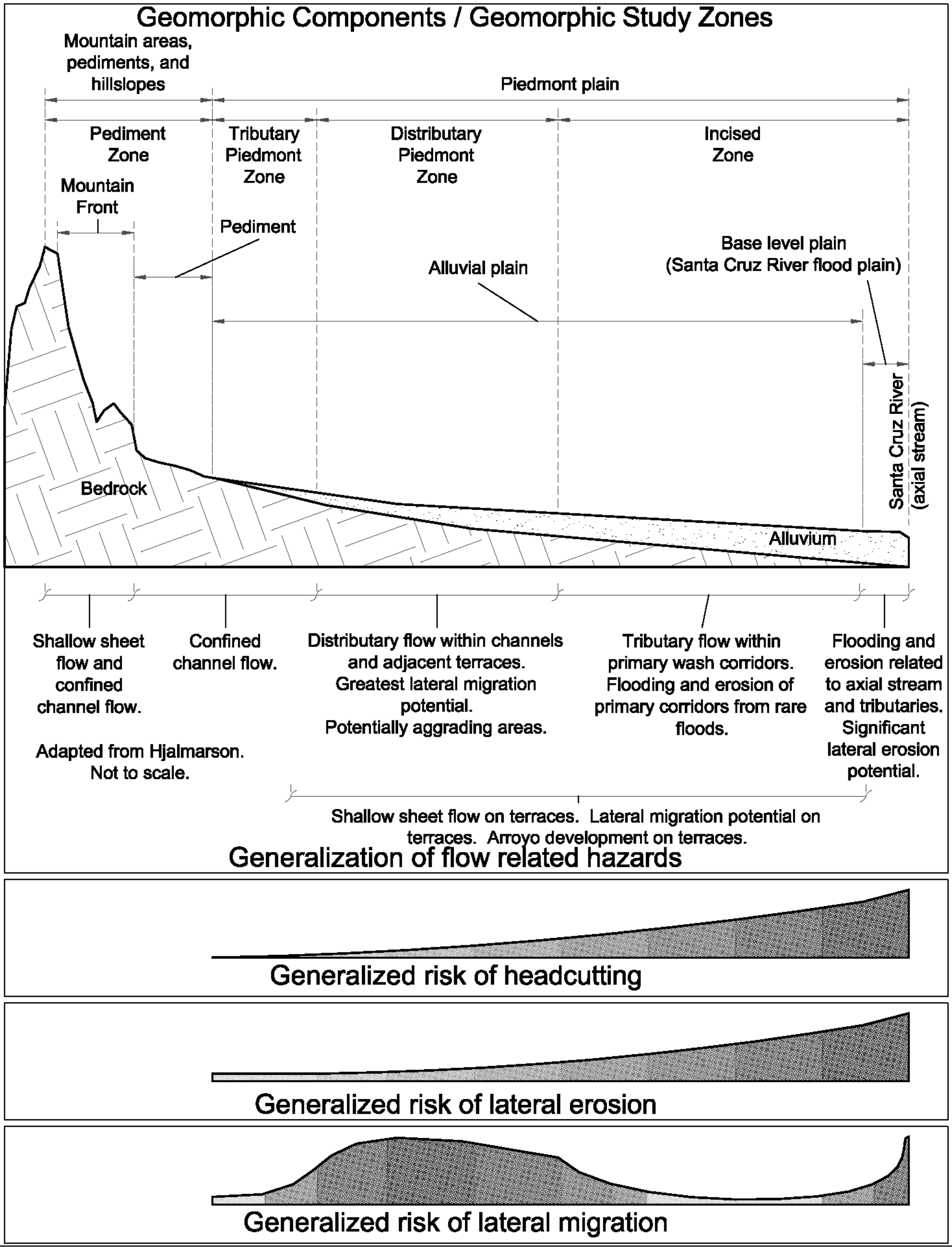


Figure 109 - General profile of study area with flow related hazards and geomorphic components

6.5 Delineation of Geomorphic Risk Areas

Plate 9 is a map of the study area divided into 16 separate geomorphic risk areas, broad geographic areas with relatively homogenous flow related hazards. Along with position within the watershed, the dominant characteristics used to delineate the geomorphic risk areas were distributary versus tributary flow patterns, risk of headcutting, and lateral erosion and migration hazards. An adjective based rating is used for each of the hazard categories as detailed in Table 5 through Table 7. Note that the risk assigned to each zone may be different for headcutting, lateral erosion, and lateral migration. Specific risks for each area are summarized within Table 8.

Table 5 - Headcutting Hazards Rating System

Risk Code	Headcutting
Negligible	Highly unlikely due to bedrock constraints.
Low	Areas where headcutting was not observed. Headcutting is possible if upstream impacts alter water and sediment discharge.
Moderate	Areas where headcutting is rare and mostly a result of flow concentration. Some headcutting reaches were observed. Additional headcutting might occur if water and/or sediment discharge are altered. Incision may be followed by lateral erosion (but lateral erosion was not observed)
High	Areas where headcutting is active but can be mitigated and reversed. Incised washes observed and/or arroyo development observed on the terraces. Headcutting will likely occur as a result of headcuts migrating from a downstream area as well as if water and/or sediment discharge are altered. Lateral erosion was observed and will increase.
Very High	Areas already shaped by headcutting. Greatly incised washes found with scour related headcuts approximately 4 to 6 feet deep and/or vertical banks found on both sides scouring into the adjacent terraces.
Extreme	Areas already shaped and significantly formed by headcutting. Greatly incised washes found with scour related headcuts observed several feet deep (~10 or more) and several feet wide as a result of downcutting of the Santa Cruz River. Major washes have vertical banks on both sides of the channel.

Table 6 - Lateral Erosion Hazards Rating System

Risk Code	Lateral Erosion
Negligible	Highly unlikely due to bedrock constraints.
Low	Areas where vertical banks were not found, but future headcutting is possible which may trigger lateral erosion.
Moderate	Locations where channel deep vertical banks were not observed, but locations of incision of the channel bottom were observed. Lateral erosion may eventually occur. Also includes areas where shallow vertical banks were found without erosion.
High	Vertical banks observed. Lateral erosion is occurring, but was not found in great quantities.
Very High	Vertical banks observed along with extensive erosion into the terraces.
Extreme	Vertical banks greater than 10 feet deep exist. Lateral erosion is a significant danger to existing properties.

Table 7 - Lateral Migration Hazards Rating System

Risk Code	Lateral Migration
Negligible	Highly unlikely due to bedrock constraints
Low	Areas with washes that are highly tributary with interfluves above the 100-year flow and with stable banks observed.
Moderate	Areas where 100-year flow may be above interfluves. Periods of high discharge may cause changes to flow paths. Includes tributary flow areas and distributary flow areas. Also includes areas with highly incised washes with 100-year flow contained (lateral erosion may occur, but migration is unlikely).
High	Areas with washes found to be stable in some locations but will have vertical banks in other areas. Vertical banks typically a result of channel bends were observed. Evidence of avulsion and/or overbank flow evident.
Very High	Areas with highly distributary flow paths. Flow splits are not easily defined. Stream piracy may occur along adjacent and parallel flow paths.
Extreme	Not used.

Table 8 - Headcutting and Lateral Erosion Risk Assessment

Area Label	Risk Levels and Discussion
1 **Incised Zone Risk Area A**	**Flow Pattern:** Tributary, highly incised **Headcutting Risk Level:** Extreme **Headcutting Hazards**: Extreme incision with steep vertical banks already exists. Risks exist to major road crossings and adjacent structures. **Additional Predicted Hazards:** Future incision possible if the Santa Cruz River continues to degrade, failure of grade control and crossings possible. **Controlling Features:** Santa Cruz River controls the vertical grade of washes, Old Nogales Highway limits progression upstream of this area**.** **Lateral Erosion Risk Level:** Very High **Lateral Erosion Issues:** A very high potential for lateral erosion exists along the major washes. Extremely deep and steep vertical banks could slough and/or be undermined and fall back. Development within erosion hazard areas is at risk if banks fail. Some terrace areas have vertical banks due to Santa Cruz River. **Lateral Migration Risk Level:** Very High **Lateral Migration Issues:** While the washes are highly incised, lateral migration is a potential considering the large discharges and the proximity to the Santa Cruz River.
2 **Incised Zone Risk Area B**	**Flow Pattern:** Tributary, highly incised **Headcutting Risk Level**: Extreme **Headcutting Hazards**: Extreme incision with steep vertical banks already exists. Risks exist to major road crossings and adjacent structures. Grade and erosion control structures are found within some of the major wash corridors. **Additional Predicted Hazards:** Future incision possible if the Santa Cruz River continues to degrade, failure of grade control and crossings possible. **Controlling Features:** Santa Cruz River controls the vertical grade of washes, Old Nogales Highway limits progression upstream of this area**.** **Lateral Erosion Risk Level:** Extreme **Lateral Erosion Issues:** The steep vertical banks along the major washes present a very high to extreme risk of lateral erosion. Vertical banks are found which could slough and/or be undermined and fall back. Vertical banks are a safety concern to those standing on banks. Some terrace areas have vertical banks due to Santa Cruz River. **Lateral Migration Risk Level:** Very High **Lateral Migration Issues:** While the washes are highly incised, lateral migration is a potential considering the large discharges and the proximity to the Santa Cruz River.

Table 8 - Headcutting and Lateral Erosion Risk Assessment

Area Label	Risk Levels and Discussion
3 **Incised Zone Risk Area C**	**Flow Pattern:** Tributary, incised **Headcutting Risk Level**: Very High **Headcutting Hazards**: Extreme incision downstream of this area has progressed into this area. Incision abruptly stops at low flow crossings (which act as grade control). This differential may increase and/or undermine crossings. Erosion control structures are found within some of the major wash corridors. Some risks exist to roads/structures. **Additional Predicted Hazards:** Further incision of channels likely, arroyo development possible, and lateral migration possible. Aggradation may eventually occur in currently incised channels. **Controlling Features:** Country Club Road alignment limits progression upstream of this area. **Lateral Erosion Risk Level:** Very High **Lateral Erosion Issues:** The major washes which have vertical banks that may fail and fall back. Flow paths tributary to the primary channels could degrade in response to headcutting triggering vertical banks and lateral erosion of banks. **Lateral Migration Risk Level:** Moderate **Lateral Migration Issues:** The major washes are incised, straight, and generally controlled horizontally upstream and downstream by road crossings and topography, reducing lateral migration potential. However, the large washes have significant discharges which may warrant a significant setback. The risk of lateral migration may be higher on the smaller washes found on the terrace areas or downstream of diverted historic flow paths.
4 **Incised Zone Risk Area D**	**Flow Pattern:** Tributary, incised **Headcutting Risk Level**: Very High **Headcutting Hazards**: Extreme incision downstream of this area has progressed into this area. Some risks exist to roads/structures. **Additional Predicted Hazards:** Further incision of channels likely, arroyo development possible, lateral migration possible, and aggradation may eventually occur in currently incised channels. Design of north-south roads such as Country Club Road will need to address the headcutting issues. **Controlling Features:** Incision intermittently controlled by existing roads. **Lateral Erosion Risk Level:** Very High **Lateral Erosion Issues:** Vertical banks may fail and fall back. Flow and channel development exists on the terraces, with eroding minor washes observed. Several of the terrace drainage paths are in poor condition and will evolve. Channel top widths will likely increase. **Lateral Migration Risk Level:** Moderate **Lateral Migration Issues:** Lateral migration is not a significant risk due to the incised nature of the major washes. Additionally, these washes are controlled horizontally upstream and downstream by road crossings and topography. However, the large washes have significant discharges which may warrant a significant setback. The risk of lateral migration is greater on the smaller washes found on the terrace areas.

Table 8 - Headcutting and Lateral Erosion Risk Assessment

Area Label	Risk Levels and Discussion
5 **Dist. Pied. Zone Risk Area A**	**Flow Pattern:** Distributary **Headcutting Risk Level**: High **Headcutting Hazards**: Very high incision downstream of this area has progressed into this area. Some headcutting observed on the terrace areas. Some risks exist to roads/structures. **Additional Predicted Hazards:** This area is just upstream of the Incised Zone and further incision of channels likely. Arroyo development possible, lateral migration possible, aggradation may eventually occur in currently incised channels. **Controlling Features:** Wilmot Rd & Sahuarita Rd limit progression upstream of this area. **Lateral Erosion Risk Level:** High **Lateral Erosion Issues:** Major washes are intermittently stable, vertical banks were observed. **Lateral Migration Risk Level:** High. **Lateral Migration Issues:** Lateral migration is a potential due to distributary flow. Migration may be minimized by topographic constraints downstream as this area enters the Incised Zone as well as existing road crossings.
6 **Dist. Pied. Zone Risk Area B**	**Flow Pattern:** Distributary **Headcutting Risk Level**: Very High **Headcutting Hazards**: Very high incision downstream of this area has progressed into this area. Incision abruptly stops at low flow crossings. Existing roads running parallel to drainage patterns are at risk as headcuts migrate up onto the roads and/or scour the channels adjacent to roads. Dangerously deep channels are adjacent to existing access roads. **Additional Predicted Hazards:** This area is just upstream of the Incised Zone and further incision of channels likely. Arroyo development possible, lateral migration possible, aggradation may eventually occur in currently incised channels. Road design will need to address the potential for scouring flow paths along roadside swales and the deep channels adjacent to the roads. **Controlling Features:** Wilmot Rd & Sahuarita Rd limit progression upstream of this area. **Lateral Erosion Risk Level:** Very High **Lateral Erosion Issues:** Major washes are intermittently stable, vertical banks were observed. Incised channel evolution may widen channels. Smaller washes on the terraces are not well armored and are currently eroding laterally. Further lateral expansion highly likely. **Lateral Migration Risk Level:** Very High **Lateral Migration Issues:** Unstable distributary flow patterns exist on the terraces with vertical banks observed in several locations. Lateral migration is a significant risk as well as avulsion and stream piracy.

Table 8 - Headcutting and Lateral Erosion Risk Assessment

Area Label	Risk Levels and Discussion
7 **Dist. Pied. Zone Risk Area C**	**Flow Pattern:** Distributary **Headcutting Risk Level**: High **Headcutting Hazards**: Very high incision downstream of this area has progressed into this area, arroyo development found **Additional Predicted Hazards:** Future incision and arroyo development likely, aggradation may eventually occur with wider top widths and lateral erosion. This area will likely experience headcutting as development occurs upstream. Roads paralleling flow paths may have similar issues described currently in Area 6. **Controlling Features:** Houghton & Sahuarita limit progression upstream of this area. **Lateral Erosion Risk Level:** High **Lateral Erosion Issues:** Major washes are intermittently stable, vertical banks were observed. Incised channel evolution may widen channels. **Lateral Migration Risk Level:** Very high **Lateral Migration Issues:** Lateral migration is a risk as unstable distributary flow patterns exist on the terraces and vertical banks were observed in several locations. Avulsion is possible.
8 **Dist. Pied. Zone Risk Area D**	**Flow Pattern:** Distributary **Headcutting Risk Level**: High **Headcutting Hazards**: Very high incision downstream of this area has progressed into this area, arroyo development already occurring. Some risks exist to roads/structures. Some locations of headcutting were observed which were likely induced (or increased) by concentration of flow along roads. **Additional Predicted Hazards:** Future incision and arroyo development likely, aggradation may eventually occur with wider top widths and lateral erosion. Future development may induce headcutting. **Controlling Features:** incision intermittently controlled by existing roads, position and topography may limit progression upstream of this area. **Lateral Erosion Risk Level:** High **Lateral Erosion Issues:** Major washes are intermittently stable, vertical banks observed in several locations, incised channel evolution may widen channels. Smaller washes and swales on the terraces are not highly armored and have a high erosion potential. **Lateral Migration Risk Level:** Very high. **Lateral Migration Issues:** Unstable distributary flow patterns exist on the terraces, avulsion is possible.

Table 8 - Headcutting and Lateral Erosion Risk Assessment

Area Label	Risk Levels and Discussion
9 **Dist. Pied. Zone Risk Area E**	**Flow Pattern:** Distributary **Headcutting Risk Level**: High **Headcutting Hazards**: Incised washes found, upstream influences from development may be spurring headcutting. Some risks exist to roads/structures. Several low flow crossings have greater scour downstream of the road than above. Some areas have been observed where newly constructed roads (such as north-south roads located south of Calle Agassiz) have become flow paths and concentrate flow on terrace areas inducing arroyo development and scour along roads. **Additional Predicted Hazards:** Future incision and arroyo development likely, aggradation may eventually occur with wider top widths and lateral erosion. Development will likely influence headcutting. Roads paralleling flow paths may have similar issues described currently in Area 6. **Controlling Features:** Sahuarita Rd. limits progression upstream of this area, incision intermittently controlled by existing roads. **Lateral Erosion Risk Level:** High **Lateral Erosion Issues:** Major washes are intermittently stable, vertical banks were observed. incised channel evolution may widen channels. **Lateral Migration Risk Level:** Very High **Lateral Migration Issues:** Shallow vertical banks observed in some locations, distributary flow patterns exist on the terraces, avulsion is possible.
10 **Dist. Pied. Zone Risk Area F**	**Flow Pattern:** Distributary **Headcutting Risk Level**: Moderate **Headcutting Hazards**: Incision and arroyo development rarely found. **Additional Predicted Hazards:** Development may spur headcutting. **Controlling Features:** Sahuarita Rd. prevents headcuts from downstream to progress into this area. **Lateral Erosion Risk Level:** Moderate **Lateral Erosion Issues:** Incised channel evolution may widen channels **Lateral Migration Risk Level:** Very High **Lateral Migration Issues:** Significant flow splits found on the major washes, Sycamore Canyon Wash has significant bifurcations. Development may alter current flow splits and present hazards downstream. Lateral migration is a risk. Distributary flow patterns exist on the terraces, shallow vertical banks observed in some locations

Table 8 - Headcutting and Lateral Erosion Risk Assessment

Area Label	Risk Levels and Discussion
11 **Dist. Pied. Zone Risk Area G**	**Flow Pattern:** Distributary **Headcutting Risk Level**: Moderate **Headcutting Hazards**: High incision downstream of this area, almost no issues in this area **Additional Predicted Hazards:** Development may spur headcutting. **Controlling Features:** Sahuarita Rd. limits progression upstream of this area **Lateral Erosion Risk Level:** Moderate **Lateral Erosion Issues:** Washes are generally free of vertical banks and lateral erosion. **Lateral Migration Risk Level:** Moderate **Lateral Migration Issues:** Major washes controlled horizontally by road crossings, vertical banks not observed. Small risks of lateral migration exists. Minimal flow and channel development exists on the terraces.
12 **Dist. Pied. Zone Risk Area H**	**Flow Pattern:** Distributary **Headcutting Risk Level**: Low **Headcutting Hazards**: Incision downstream is high, minor incision found intermittently and rarely in this area, arroyo development rare. **Additional Predicted Hazards:** Incision from downstream area may progress upstream into this area. **Controlling Features:** Few, this area is within the SRER. **Lateral Erosion Risk Level:** Low **Lateral Erosion Issues:** Major washes are relatively stable but distributary. Incised channel evolution may widen channels. **Lateral Migration Risk Level:** Moderate **Lateral Migration Issues:** A small risk of lateral migration exists. Distributary flow patterns exist, vertical banks observed in some locations.
13 **Trib Pied. Zone Risk Area A**	**Flow Pattern:** Tributary **Headcutting Risk Level:** Moderate **Headcutting Hazards:** Minor incision found intermittently in this area, arroyo development rare. **Additional Predicted Hazards:** Development may spur headcutting **Controlling Features:** Position and topography **Lateral Erosion Risk Level:** Moderate **Lateral Erosion Issues:** Few signs of lateral erosion were found. **Lateral Migration Risk Level**: Moderate **Lateral Migration Issues:** Minimal flow and channel development exists on the terraces. Major washes are have tributary patterns but may not entirely contain 100-year flows. Washes typically have stable banks.

Table 8 - Headcutting and Lateral Erosion Risk Assessment

Area Label	Risk Levels and Discussion
14 **Trib Pied. Zone Risk Area B**	**Flow Pattern:** Tributary **Headcutting Risk Level:** Moderate **Headcutting Hazards:** Minor incision found intermittently in this area, arroyo development rare. **Additional Predicted Hazards:** Development may spur headcutting **Controlling Features:** Position and topography **Lateral Erosion Risk Level:** Low **Lateral Erosion Issues:** Few signs of lateral erosion were found. **Lateral Migration Risk Level:** Low **Lateral Migration Issues:** Minimal flow and channel development exists on the terraces. Major washes are have tributary patterns, are well contained, and typically have stable banks. Lateral migration is unlikely.
15 **Trib Pied. Zone Risk Area C**	**Flow Pattern:** Tributary **Headcutting Risk Level:** Low **Headcutting Hazards:** None **Additional Predicted Hazards:** Development may spur headcutting. However, this area is within the SRER. **Controlling Features:** Position and topography **Lateral Erosion Risk Level:** Low **Lateral Erosion Issues:** None. **Lateral Migration Risk Level:** Low **Lateral Migration Issues:** Major washes have tributary patterns, are well contained, and typically have stable banks. Lateral migration is unlikely. Minimal flow and channel development exists on the terraces.
16 **Piedmont Zone Risk Area**	**Flow Pattern:** Tributary **Headcutting Risk Level:** Negligible **Headcutting Hazards:** None **Additional Predicted Hazards:** None **Controlling Features:** Position, topography, bedrock **Lateral Erosion Risk Level:** Negligible **Lateral Erosion Issues:** Bedrock features. **Lateral Migration Risk Level:** Negligible **Lateral Migration Issues:** Bedrock features.

The distributary flow locations delineated within the study area are shown on **Plate 9** and Figure 110.

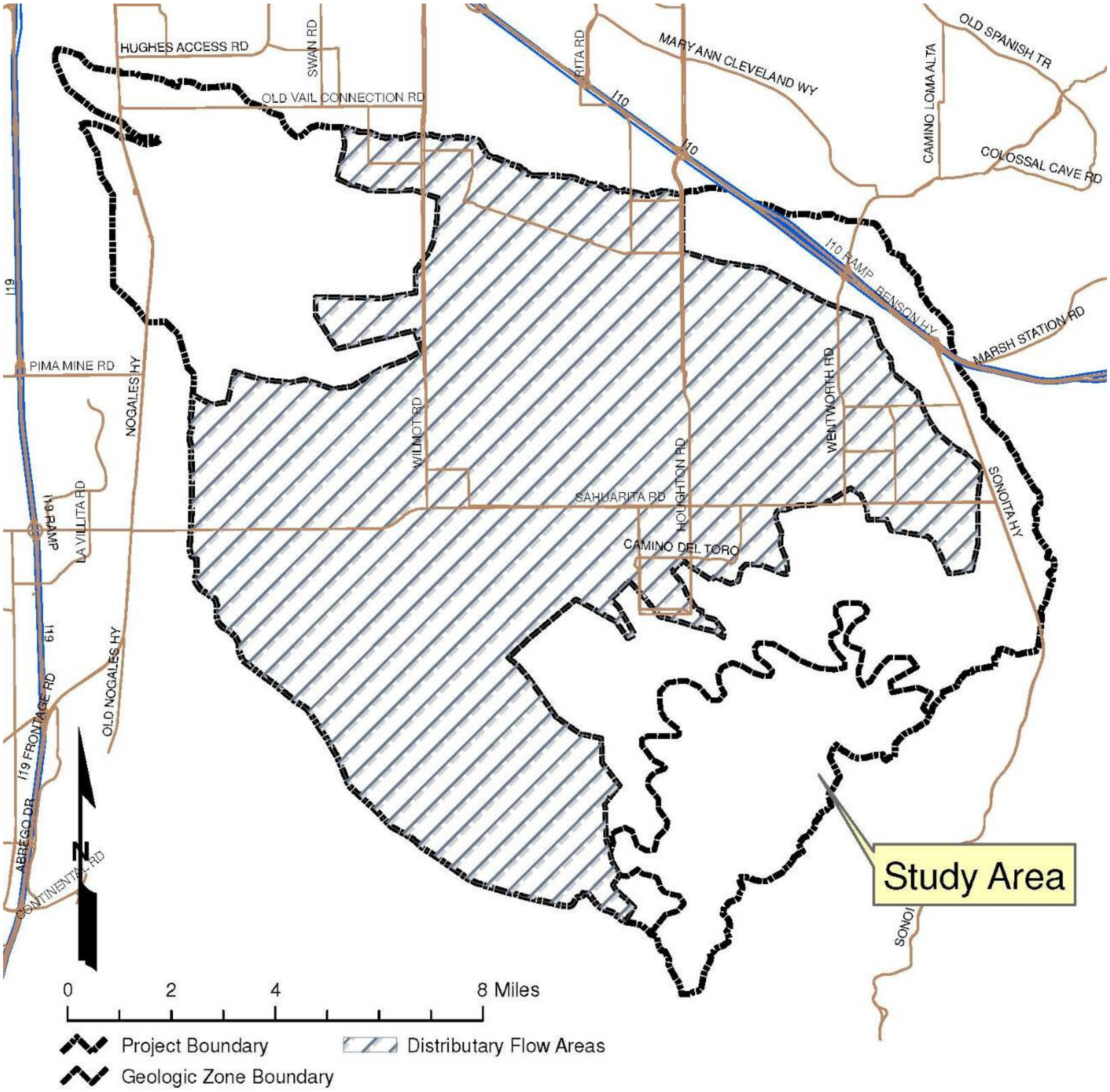


Figure 110 - Distributary flow delineation

Plate 9 and Figure 111 show the individual geomorphic risk areas color coded based upon the assigned risk of headcutting.

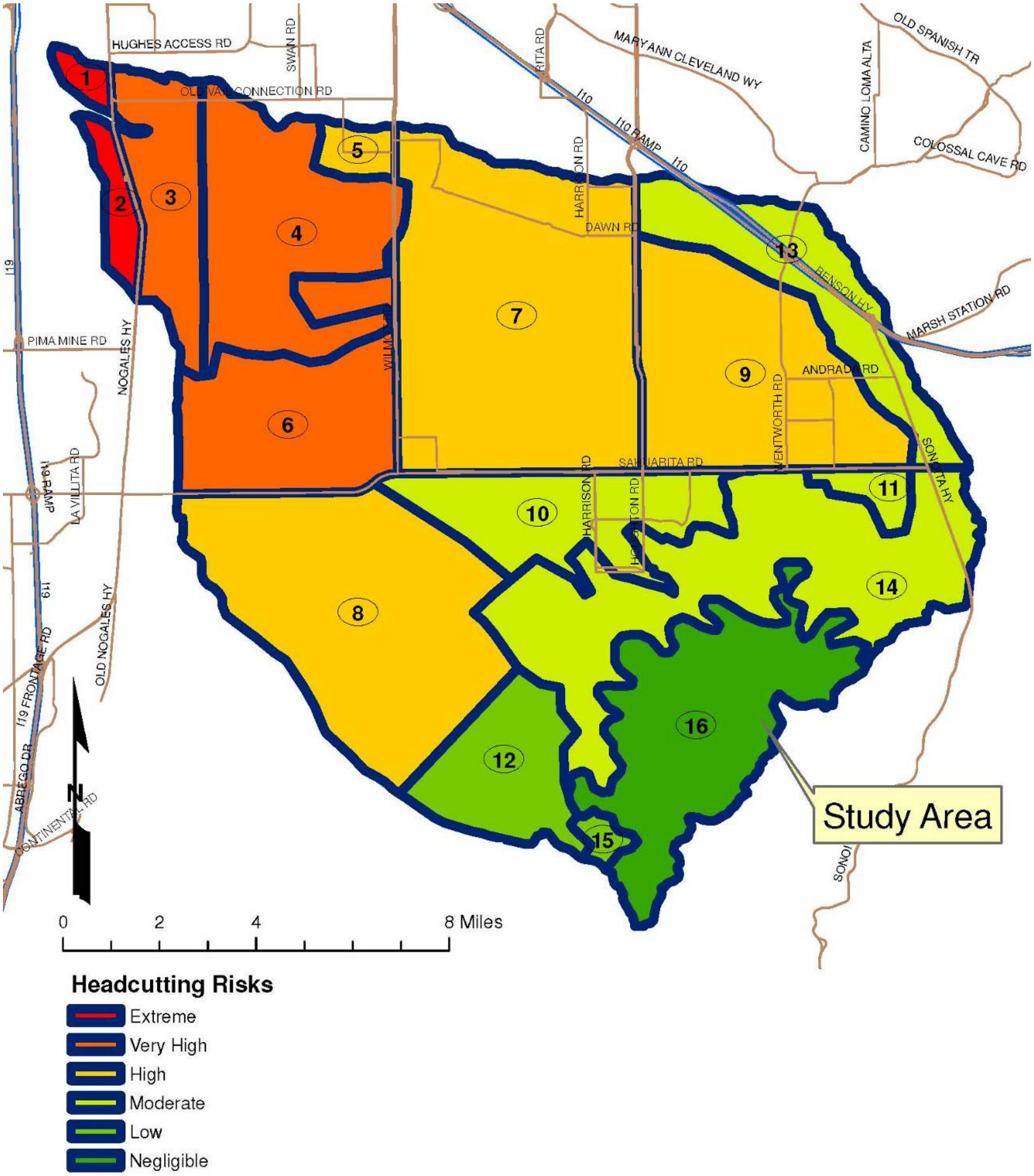


Figure 111 - Headcutting risk assessment delineation

Figure 112 shows the individual geomorphic risk areas color coded based upon the assigned risk of lateral erosion.

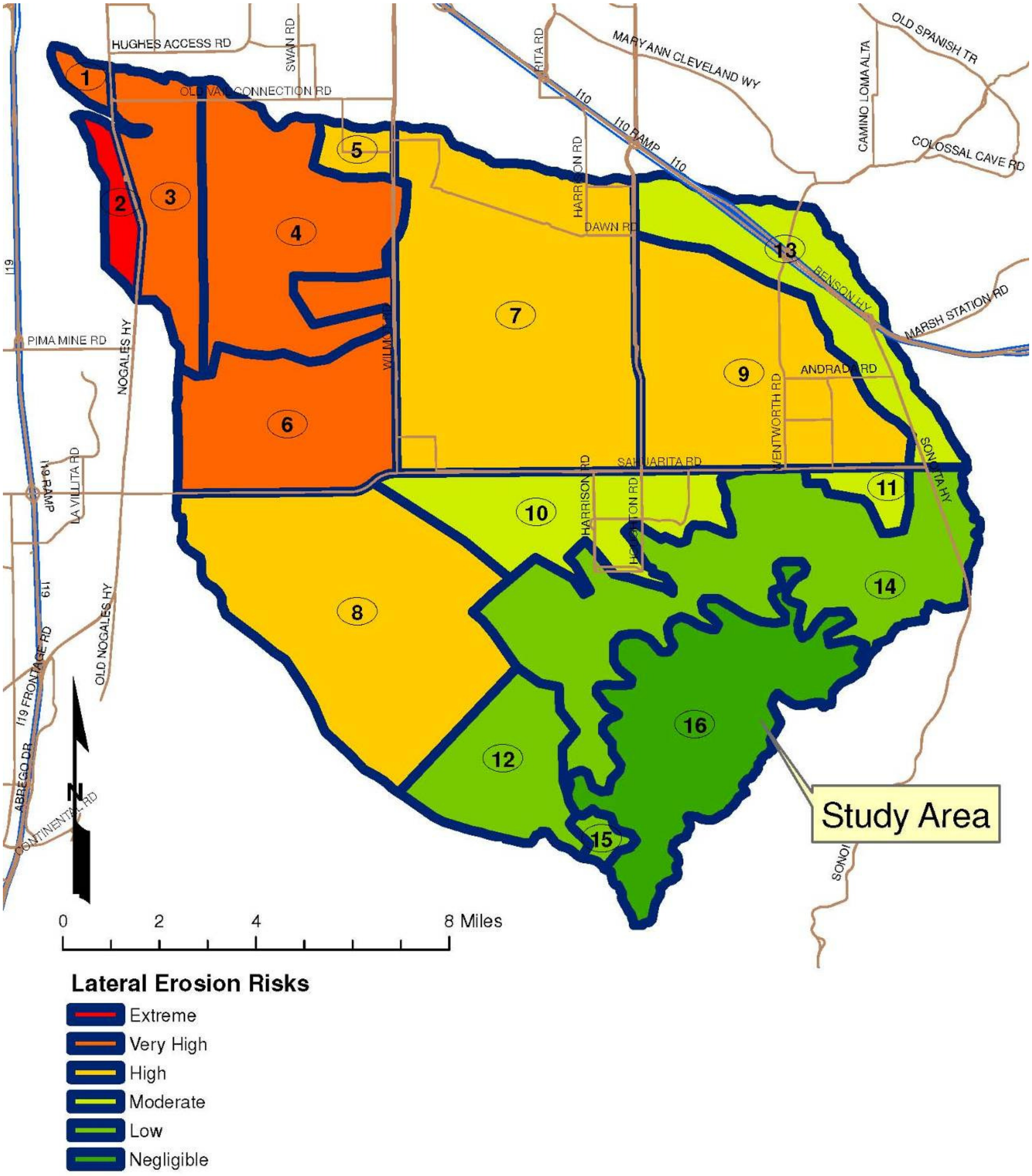


Figure 112 - Lateral erosion risk assessment delineation

Figure 113 shows the individual geomorphic risk areas color coded based upon the assigned risk of lateral migration.

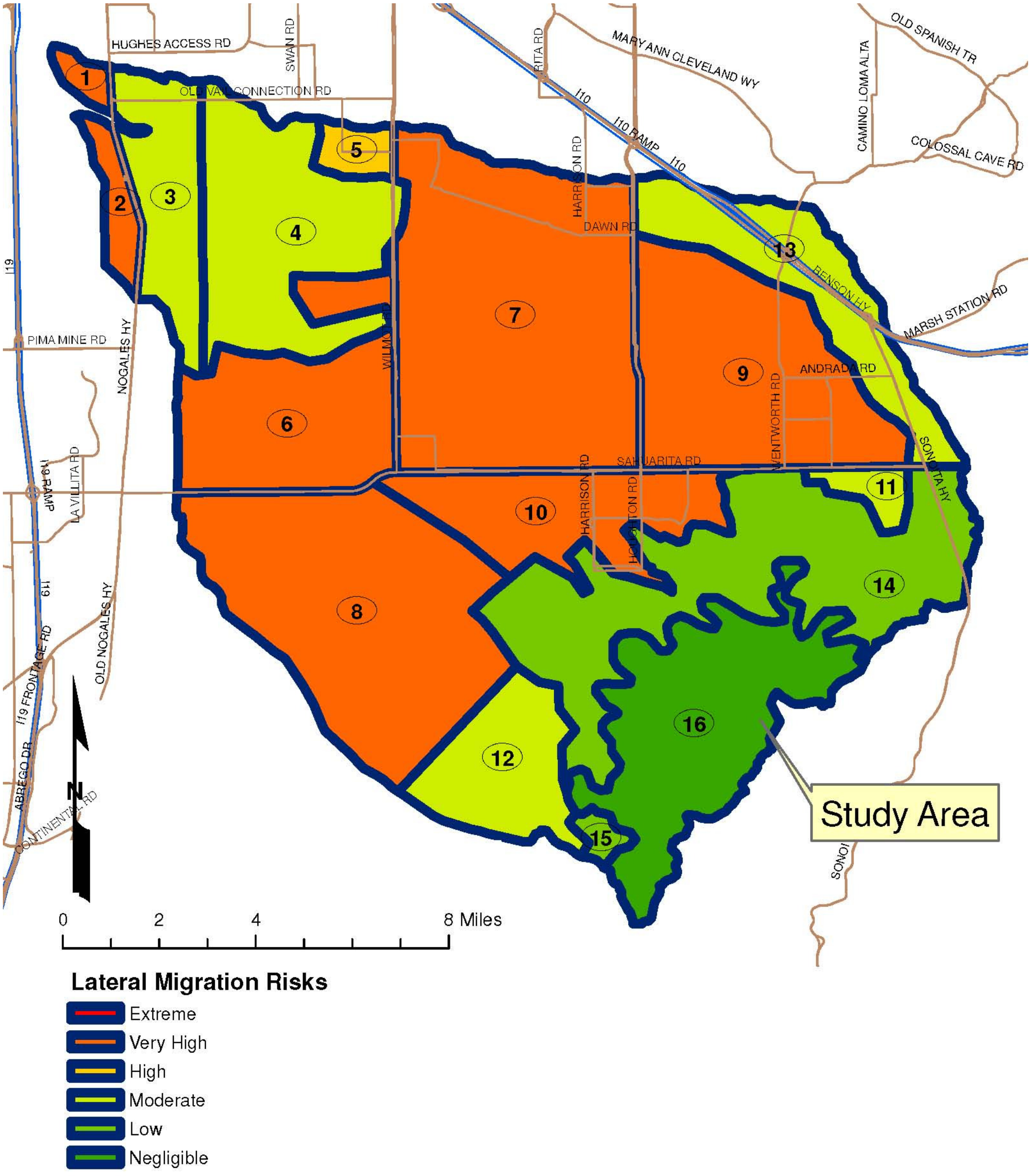


Figure 113 - Lateral migration risk assessment delineation

7 Significant Distributary Flow Corridors

7.1 Section Outline

Flooding and erosion hazard risks are greatest within the washes and the adjacent floodplain areas. This section presents significant flow corridors which were delineated to define those areas most important to conveyance of water and sediment and where erosive activity will be the greatest. The intent of delineating significant distributary flow corridors is to minimize human related impacts on the fluvial systems and reduce the risk of flooding and erosion hazards to adjacent properties.

7.2 Methodology

Flow corridors are shaped by the topography, discharge, and position within the study area. Easily defined corridors can be delineated within the Incised and Tributary Piedmont Zones which are often separated by relatively wide ‘dry’ areas with insignificant flow. The corridors within the Distributary Piedmont Zone are not as easily discernable and are relatively wide compared to the intervening ‘dry’ areas. The delineation significant distributary flow corridors was based upon the results of the FLO-2D analysis prepared by JEF and the HEC-RAS analysis prepared by Stantec as well as review of surficial geology maps and review of drainage complaints within the study area.

In general, if a Qy unit was mapped, then a corridor was mapped in the same location (adjusted to match the aerial and topographic maps and the flood delineations). Where Qly or M2 units were mapped, multiple threads were drawn as corridors, following the primary flow paths observed from the aerial maps. In many areas the Qy, Qly, or M2 delineation fell outside of the mapped floodplains. In these situations the corridors were adjusted and/or clipped to fall within the floodplain.

A few points should be considered.

- ➢ The delineation is only within the Distributary Piedmont Zone and flow corridors were not mapped within the Santa Rita Experimental Range or within the Coronado National Forest.
- ➢ The delineation was based on interpretation; the presented corridors are not based upon a technical analysis similar to a floodway analysis.
- ➢ The delineation is rough due to the scale of the effort. Areas will be found where the delineation should be fine tuned.

Considering these things, leniency may be necessary on a case-by-case basis in regards to encroaching upon these corridors. The results are shown on Plate 8. Recommendations for the use of the corridors are found in Section 9.

8 Representative Study Area

8.1 Section Outline

A representative study area has been identified to support the Rules of Development phase of this project which relies on documentation and recommendations included within this analysis.

8.2 Selected Area

The study area is large and has many geomorphic processes which are found to varying degrees throughout. Identification of a single area which emphasizes all of the observations made in this report is difficult. The one area which seems to best be representative of the study area is roughly Geomorphic Risk Area 6 located north of Sahuarita Road and west of Wilmot Road. An aerial and topographic view of this area is shown on Figure 114. Figure 115 shows this location as RSA 1. RSA 1 represents the distributary flow areas which dominate the study area and contains many of the most extreme headcuts along minor washes and terraces which are found on the lower piedmont. This area also has disappearing washes and many flow splits. The northwest portion of RSA 1 is a transition from distributary to tributary flow.

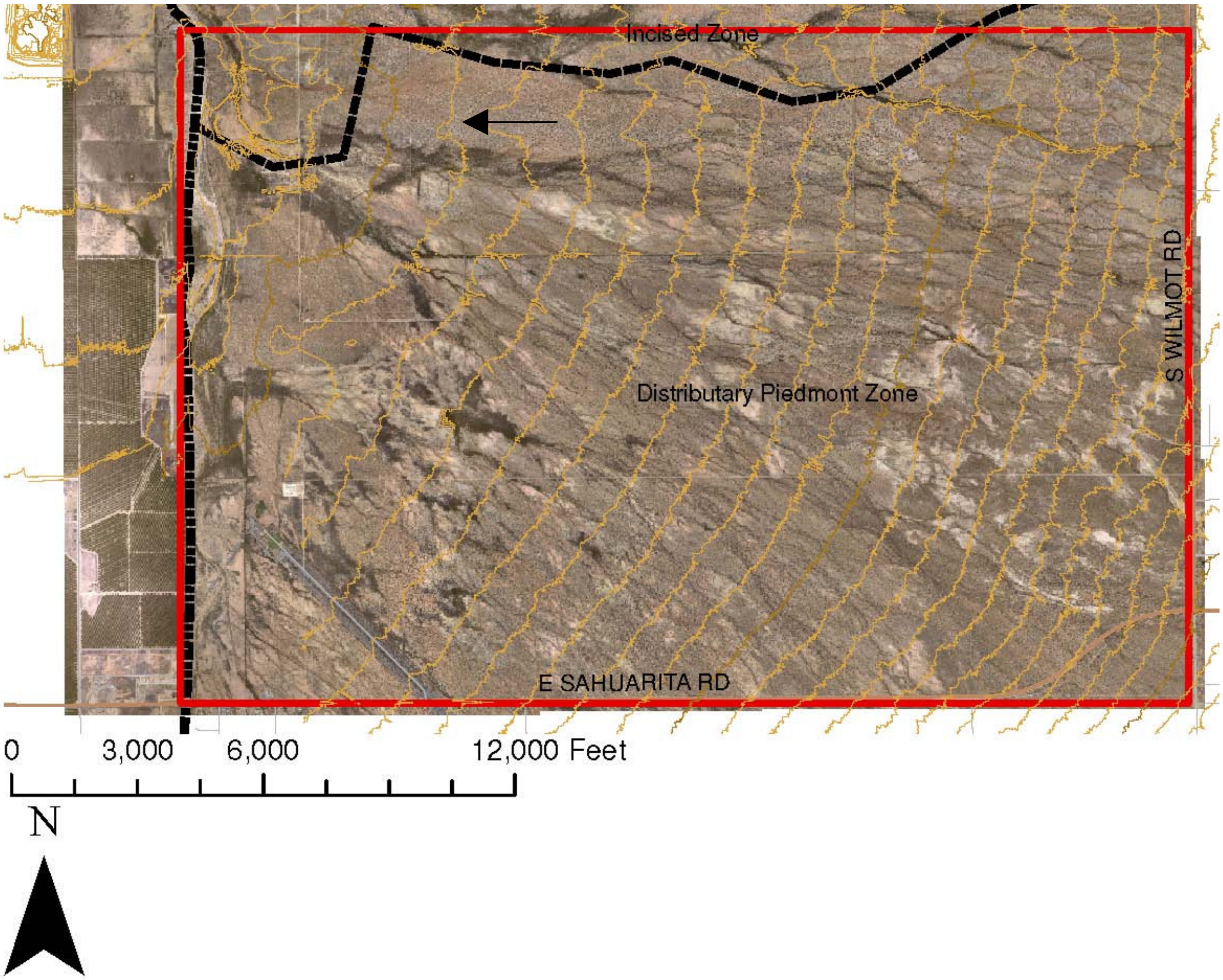


Figure 114 - Aerial view of representative study area

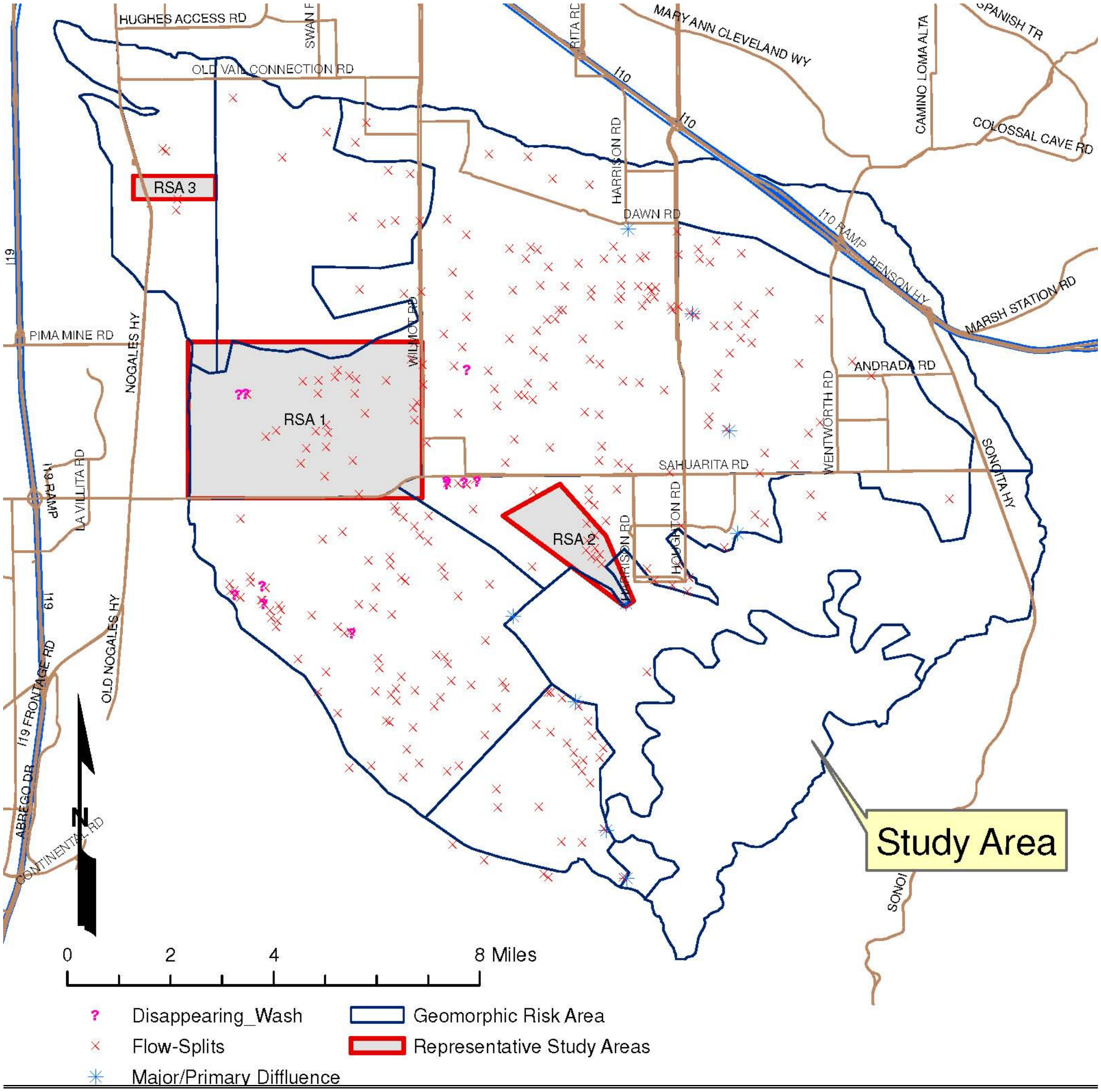


Figure 115 - Location map for representative study areas

8.3 Supplementary Study Areas

Two other areas are suggested which show additional features (contained flow paths, transitions from tributary to distributary flow, greater development) and are labeled as RSA 2 and RSA 3 on Figure 115. RSA 2 is the transition from tributary to distributary flow along the Sycamore Canyon Wash within Geomorphic Risk Area 10. This area is a developing area with uncertain flow paths. A primary diffluence was located within this area along with several flow splits. RSA 3 is the highly incised section of the Flato Wash within Geomorphic Risk Area 3 which is representative of the highly incised flow paths adjacent to old terraces within the northwest portion of the study area.

9 Recommendations

9.1 Section Outline

The Distributary Flow Corridors (Plate 8) and the Geomorphic Hazards Map (Plate 9), discussed previously, should be used in preliminary estimates of the fluvial geomorphology risks associated with an individual parcel or project. Additional project specific hazards will be present and may vary from those presented on Plate 9 due to the broad scale presented. This section provides additional recommendations to be used for developing projects within the study area.

9.2 Floodplain Management within Distributary Flow Areas

The amount of protection required for permitting development within distributary flow areas should be based upon the risks to the structure. In the absence of a project specific, detailed analysis, the floodplain manager needs a method to determine how to regulate each project, specifically for individual floodplain use permit applications. The method suggested here is to:

1) Adopt the Distributary Piedmont Zone and the mapped 100-year flood limits (separate report) as regulatory areas. Review and revise as necessary the distributary flow corridors and adopt them as a regulatory area.
2) Designate the distributary flow areas outside of the flood delineation as within Shaded X or similar regulatory measure.
3) Require minimal protection for all structures within the distributary flow areas but outside of the setbacks defined in 4 and 5. Define minimum finished floor elevations as 18 inches above grade along with a detail to protect pads including a rock lined trench, 12 inches deep.
4) Define a setback buffer to the mapped 100-year floodplain as a fraction of the floodplain width. This might be 10 percent. Permit structures within this buffer with increased finished floor elevations, say 24 inches. Require deeper erosion protection, say 18 inches deep.
5) Allow construction within the 100-year floodplain but outside the standard discharge based setbacks. Finished floor elevations would be 30 inches. This regulation would also apply to areas outside of the floodplain but within this defined setback. Measure setbacks from the primary channel or banks. The pad erosion protection depth should increase, possibly up to 36 inches. An engineer may be required to determine the discharge if it is not known.
6) In the absence of channel banks, use the distributary flow corridors as a regulatory equivalent to "channels", however those presented with this report should be reviewed in detail before use in this capacity.
7) Allow an applicant to dispute the flow corridor delineation with better site specific data. Areas where either velocity or DV^2 (product of depth times the square of velocity) exceed some threshold values, say 3 or 5 respectively, might be considered the regulatory equivalent to channel banks in place of the flow corridors. The setback could therefore be measured from this more rapid flow area. Require the applicant to hire an engineer to determine DV^2 through the project site and for the primary flow path(s) OR delineate the channel banks.
8) Determine whether the commonly accepted discharge based erosion hazard setbacks should be applied to distributary flow areas. Note that their use may be problematic because the "distribution of runoff between channels may vary between storm events due to minor channel changes upstream" (ADWR, 1995, page 13). Furthermore, the assumptions used to define the commonly accepted equations may not translate to sheet flow conditions.

9.3 Single Lot Criteria within Distributary Flow Areas

Many of the recommendation within this section are adapted from 'State Standard for Identification of and Development within Sheet Flow Areas', (1995) by ADWR.

9.3.1 *Level 1*

Level 1 applies to distributary flow areas outside of the floodplains (see separate reports by JEF and Stantec), significant flow corridors, and any applicable setbacks and/or buffer from them.

1) Stay out of the delineated 100-year floodplains and setbacks/buffer.
2) Stay out of the significant flow corridors identified on Plate 8. In addition, stay out of identifiable washes not delineated on Plate 8.
3) Stay out of the Erosion Hazard Setback (EHS).
4) Allow flow to pass around lot.
5) Build up pads on compacted fill (to 95%). Place a rock trench around the foundation with D-50 of at least 6 inches. See Table 9 for elevation and depths.
6) Grade towards flow paths.
7) Roads should cross flow paths close to perpendicular.
8) Buildings placed within the distributary flow areas should be aligned to the flow and walls, fences, and obstructions should be minimized. Limit overall perpendicular flow blockage to 50%.
9) Walls should be built with holes to allow flow to pass through with blockage accounted for. Fences should be elevated above flow areas. Walls openings must span any flow paths with no adverse effect on the water surface profile, if applicable.

9.3.2 *Level 2a and 2b*

Level 2a applies to development outside the 100-year floodplain but within any applicable setback/buffer. Level 2b is development within the 100-year floodplain. Both are out of EHS. 2a also applies to areas where floodplains have not yet been delineated.

1) Stay out of the significant flow corridors identified on Plate 8. In addition, stay out of identifiable washes not delineated on Plate 8.
2) Stay out of the Erosion Hazard Setback (EHS).
3) Flood water must exit the property at the same locations as pre-developed conditions. An encroachment analysis is required within the floodplain. Depths must not change by more than 0.1 feet and velocities must not change by more than the greater of 10 percent OR one foot per second.
4) Allow flow to pass around lot.
5) Build up pads on compacted fill (to 95%). Place a rock trench around the foundation with D-50 of at least 6 inches. See Table 9 for elevation and depths.
6) Grade towards flow paths.
7) Roads should cross flow paths close to perpendicular. Compute and map backwater from roads. Finished floor elevations should be 6 inches above road elevation if backwater is created.
8) Buildings placed within the distributary flow areas should be aligned to the flow and walls, fences, and obstructions should be minimized. Limit overall perpendicular flow blockage to 50%.
9) Walls should be built with holes to allow flow to pass through with blockage accounted for. Fences should be elevated above flow areas. Walls and fences must have no adverse effect on the water surface profile.

9.3.3 *Level 3*

Level 3 applies to development where the applicant hires an engineer to reduce elevation requirements, reduce EHS, or dispute the floodplain delineation.

1) Stay out of the significant flow corridors identified on Plate 8 OR hire an engineer to provide better delineation. In addition, stay out of identifiable washes not delineated on Plate 8.
2) Stay out of Erosion Hazard Setback OR hire an engineer to reduce the setback and/or provide increased scour protection.
3) Hire an engineer to show that the lot will not be inundated, OR design such that the finished floor elevation is 1 foot above the design 100-year flood elevation as determined by the engineer, AND the foundation is protected from scour during that event.
4) If the lot is shown to be within the floodplain, an encroachment analysis is required. Depths must not change by more than 0.1 feet and velocities must not change by more than the greater of 10 percent OR one foot per second.
5) The engineer should design infrastructure including utilities, wells, roads, roadway drainage, wash crossings, etc. so that continuity of sediment and water discharges are maintained to the extent reasonably possible.
6) Stay out of the significant flow corridors (and any applicable setback from them) identified on Plate 8 OR those identified by the engineer and accepted by Pima County review. In addition, stay out of identifiable washes (and any applicable setback from them) not delineated on Plate 8.
7) Reduced setbacks may be allowed with an engineering analysis documenting safe setbacks.
8) Grade towards flow paths.
9) Roads should cross flow paths close to perpendicular. Compute and map backwater from roads.
10) Buildings placed within the distributary flow areas should be aligned to the flow and walls, fences, and obstructions should be minimized. Limit overall perpendicular flow blockage to 50%.
11) Walls should be built with holes to allow flow to pass through with blockage accounted for. Fences should be elevated above flow areas. Walls and fences must have no adverse effect on the water surface profile.

Table 9 - Minimum Finished Floor Elevations and Scour Depths in DFA

Level	Condition	Minimum FFE (inches)	Scour Depth
1	Outside floodplain, flood buffer, and EHS .	18[1]	12”
2a	Outside floodplain, within flood buffer, outside EHS. Also areas where floodplain not delineated	24[1]	18”
2b	Inside floodplain, outside EHS.	30[1]	24”
3	Engineered	12[2]	Per engineer
Note 1: Measured from highest natural grade Note 2: Measured from determined base flood elevation			

9.3.4 Single Lot Criteria Example

Consider the parcel shown in Figure 116. The 100-year floodplain is shown along with the flow corridors. The topography shown indicates that one may be able to delineate a channel bank, but assume that none could be delineated and/or the flow corridor is the best available data. Based upon the discharges shown, a 50 foot erosion hazard setback (EHS) is applicable for the west flow path and a 25 foot EHS applies for the east flow path. The floodplains have been offset by 10 percent of their width, 45 feet for the west flow path and 15 for the east.

- Point A would be Level 1 as it is out of the floodplain, the buffer, and the EHS.
- Point B is out of the floodplain, but in the buffer and would be Level 2a.
- Point C is within the floodplain and out of the EHS. This would be Level 2b.
- Level 3 could be used for all the above locations to reduce the finished floor and erosion requirements. Level 3 would be necessary to permit at Point D.

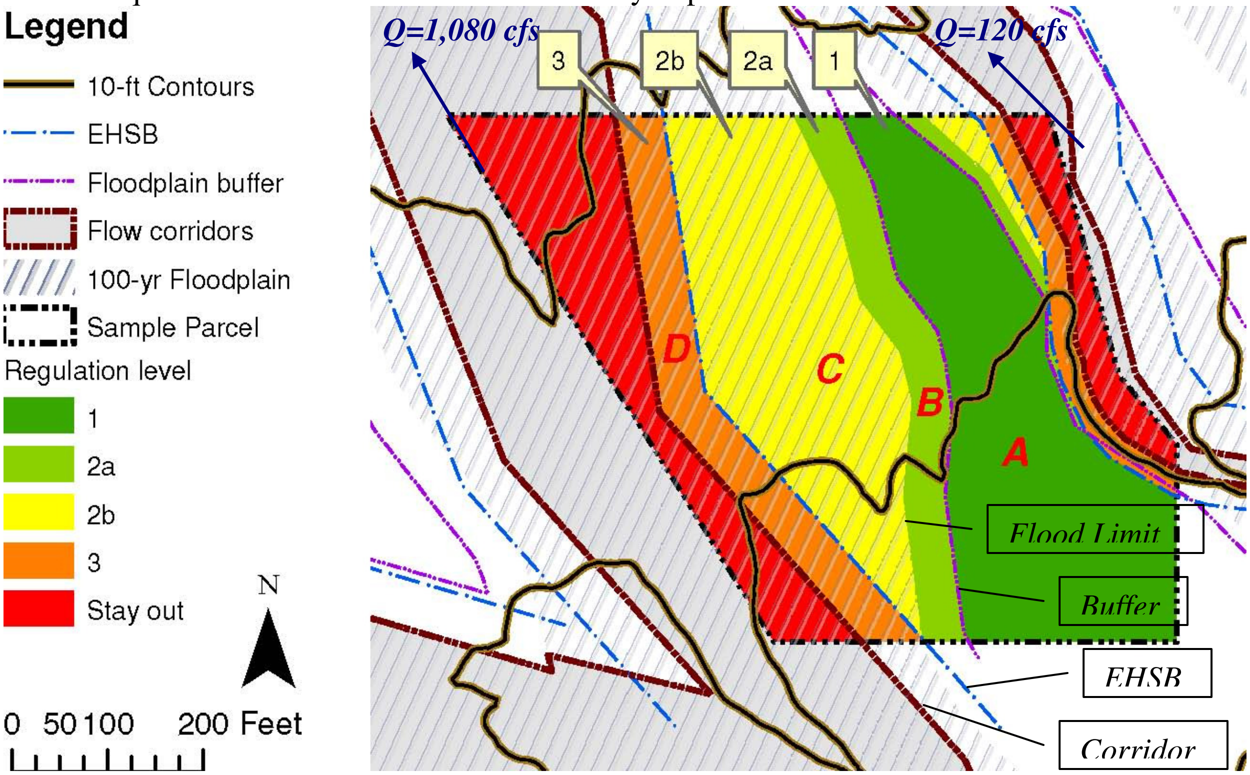


Figure 116 - Single Lot Criteria Example

9.4 Subdivision Criteria within Distributary Flow Areas

Many of the recommendation within this section are adapted from 'State Standard for Identification of and Development within Sheet Flow Areas', (1995) by ADWR. .

9.4.1 *Level 1*

1) Orient lot splits to flow patterns to allow flow to pass around lots, i.e. design lots so they are wide with respect to flow.
2) Limit lot sizes to no less than 1 acre.
3) Build habitable structures and lots according to single lot criteria.

9.4.2 *Level 2*

Densities of greater than one residence per acre are only recommended if a regional approach to development is followed with regional flood control facilities/planning employed. The existing drainage patterns and flow rates rely on shallow sheet flow which retards flood peaks, reduces distal peak discharges, and reduces total runoff volume. Channelization should be minimized while maintaining the existing floodplain storage.

1) Provide an engineered solution to increase development density with a master plan solution for the subdivision.
2) Ensure that continuity is maintained (within reason) upstream and downstream for flood water and sediment transport.
3) The use of collector channels should be minimized (or eliminated) and their length should be minimal due to sedimentation within the channels and headcutting which may be introduced as a result of sediment depletion.

9.5 Floodplain Management within Headcutting and Erosion Risk Areas

The following is most important within areas at greatest risk for headcutting and lateral erosion (Geomorphic Risk Areas 1 through 9, especially 1 through 4 and 6).

1) Consider stream restoration and grade control projects within Geomorphic Risk Areas 1 through 3 as these areas will have the greatest risks associated with headcutting and lateral erosion within the major washes.
2) Existing low flow, dip crossings have stopped headcuts from migrating upstream but may be at risk of failure. Preventative maintenance and/or design are recommended to protect the existing crossings.
3) Address headcut risks to future road crossing improvements.
4) Reduction to the prescribed minimum setback should still be allowed if applicable, but should account for the risks documented within this assessment. Greater caution should be used when granting a reduction to the minimum erosion hazard setback within higher risk areas.

9.6 General Project Considerations

9.6.1 *Sediment Transport*

1) Keep projects out of the significant flow corridors identified on Plate 8 and any other identifiable washes not delineated on Plate 8.
2) Determine both existing and with-project sediment inflow and conveyance. The post-construction sediment conveyance should be reasonably unchanged from the natural or

existing condition. Significant sediment discharge should be expected and accounted for in all geomorphic risk areas.

3) Minimize flow concentration. Flood widths, depths, and velocities must be returned to existing within the project limits.
4) Grade control structures should be placed within the site where flow is concentrated to prevent headcutting.

9.6.2 Hydrologic Analyses

1) Determine the general nature of the flow patterns based upon Plate 9, the flood maps (separate reports), and inspection. For projects within distributary flow areas, the hydrologic analyses will be more complicated and should account for alternative flow split patterns upstream of the site.
2) The FLO-2D, HEC-HMS, and HEC-RAS modeling, under separate covers, are a good starting point for planning and design. However, the limitations of this modeling should be understood (such as storm modeled and limitations of accuracy) and more detailed modeling may be warranted which better considers local topography and rainfall intensity.
3) Identify significant bifurcations upstream of the site. Quantify current conditions flow splits through hydrologic analysis. Determine the stability of the bifurcations and estimate alternative flow split patterns if necessary. The hydrologic analysis should account for the most conservative scenario, within reason. (Note that many flow splits are documented in this study and can be used in future studies).

9.6.3 Headcutting and Lateral Erosion Risk Areas

1) Perform field inspections to document the channel conditions upstream, through the site, and downstream of the site. Consider that the channel section within the site may evolve into a similar channel section observed downstream of the site because headcuts migrate upstream.
2) Armor flow paths between flow release points and existing washes. Minimize flow concentration and release from pavement drainage.

9.6.4 Roads Crossing Flow Paths

1) Determine erosion hazard areas. Adequately protect road from migration and avulsion.
2) Protect flow paths from the road to the washes to prevent scour and headcutting.
3) Minimize concentration of runoff from the road.
4) Minimize diversion of flows.
5) Where roads divert flow paths upstream of the road, the response is for the longitudinal slope to increase where it can, causing scour, or for the channel to widen, causing erosion and migration. Adequately armor a collector channel if placed along a road. The channel may require periodic grade control structures. Sedimentation should be expected and maintained.

9.6.5 Design Recommendations for Culvert Crossings

1) Analyze and minimize the ratio of headwater depth to culvert diameter (HW/D). As HW/D exceeds a value of 1, sediment deposition in the culverts increases.
2) Analyze and design culverts for both low flow and high flow events. Minimize 10-year event backwater to reduce sediment accumulation upstream of the culvert and clear water scour downstream of the culvert.
3) Design culverts so that the width approximates the channel width and the rise approximates the bank height to minimize the negative impact on the fluvial system.
4) Predict outlet scour and design structures to mitigate and/or prevent outlet scour.

5) Limit the concentration of flow by culverts.
6) Install adequate toe-down at the culvert outlet, especially where headcutting is problematic. Determine if grade control structures are necessary downstream of the culvert.
7) The approach channel and the downstream channel should be adequately protected from lateral erosion because vertical banks are so prevalent in this study.
8) Analyze plan geometry of the channel. If there is a channel bend upstream of the crossing, expect the bend to migrate downstream with potential point bar development. Sufficiently armor the channel.
9) Install headwalls to limit scour.

9.6.6 Design Recommendations for Low Water Stream Crossings

1) Minimize the impact from the crossing on flow velocity as velocity has a direct impact on sediment transport and scour.
2) Maintain channel geometry, do not widen or narrow the channel as this can cause an abrupt hydraulic transition and subsequent sediment transport problems. Where channel transition is necessary, the transition should be smooth and adequately long.

10 Summary

This report has documented a geomorphic assessment conducted as a part of the Lee Moore Wash Basin Management Study. Existing mapping and literature were reviewed and analyzed to assess past and current conditions in order to predict future changes to the fluvial systems. This was supplemented with field reconnaissance and hydraulic modeling.

The study area geology and topography can be summarized as follows. The upper end of the basin, towards the southeast, is made up of a steep pediment composed of complex bedrock geology, this pediment being a part of the Santa Rita Mountains. Downslope of this is the piedmont which composes the majority of the study area and can be described as an alluvial basin. This piedmont transitions from rolling topography with contained flow paths in the uplands, to highly distributary and flat areas within the central study area, to highly incised flow corridors near the northwest and downstream end of the study area.

The study area was divided into four geomorphic study zones in order to simplify the discussions. From the upper basin down, the study zones are the Pediment Zone, Tributary Peidmont Zone, the Distributary Peidmont Zone, and the Incised Zone. The geomorphology, geology, soils, topography, historic observations, and field observations were discussed for each zone and vary significantly between the zones.

Geomorphic processes observed within the study area include significant headcutting within the Incised Zone and moderate headcutting within the Distributary Piedmont Zone, significant lateral erosion risk to moderate erosion risk within the Incised Zone and lower Distributary Piedmont Zone, lateral migration and distributary flow hazards within the Distributary Piedmont Zone, and sediment transport functions throughout the study area.

Based upon the above observations and the delineation of the four geomorphic study zones, the study area was further divided into 16 geomorphic hazard areas. These hazard areas contain homogenous flow patterns, headcutting hazards, lateral erosion hazards, and lateral migration hazards and are presented to assist the floodplain manager and reviewer in reviewing proposed projects and planning rules of development.

Significant Distributary Flow Corridors were delineated. The corridors represent the primary flow paths and the areas most important to maintain in order to protect both the fluvial systems and property. Development within these corridors should be avoided.

Recommendations have been provided to be used in planning future development patterns and for use in design of individual lots, subdivisions, culvert crossings, and low flow crossings. Maintenance of existing flow paths and sediment transport functions is strongly encouraged to the extent reasonable when planning rules of development and when designing individual projects.

Finally, a representative study area has been provided which can be used in assigning rules of development. This area is located north of Sahuarita Road and west of Wilmot Road and includes most of the geomorphic risks observed within the study area including headcutting, lateral migration and erosion, distributary flow, and flow convergence.

10.1 Time of Concentration Note

The three longest washes which were documented within the example washes section, namely the Lee Moore/Sycamore Canyon Wash, the Gunnery Range Wash, and the Flato Wash, have very similar lengths and slopes. In addition, the primary watersheds have similar shapes to each other. Compared to typical watersheds within the region which are often long and linear, the Lee Moore Wash Basin is somewhat anomalous in shape. Where other basins often have a single main thread with tributaries joining along the way, the Lee Moore Wash Basin is composed of several large sub-basins which drain mostly independent of each other and do not join until close to terminus of the basin. These unique characteristics should tend to cause the peak flow rates to be relatively higher near the terminus as compared to other watersheds. Therefore, the peak runoff rates for the entire basin should be expected to exceed regional regression estimates.

11 References

Cooley, Maurice E., 1977, Map Of Arizona Showing Selected Alluvial, Structural, And Geomorphic Features, United States Geological Survey Open-File Report 77-343, 29 pages, 1 sheet.

Ferguson, Charles A., et. al., 2002 (revised), Geologic Map Of The Mount Fagan 7.5' Quadrangle, Eastern Pima County, Arizona, Arizona Geological Survey Digital Geologic Map 11, 34 pages, 1 sheet 1:24,000.

Hendricks, David M., 1986, Arizona Soils, University of Arizona College of Agriculture, 244 pages.

Hjalmarson, H.W. and Kemna, S.P., 1991, Flood Hazards Of Distributary-Flow Areas In Southwestern Arizona, United States Geological Survey Water-Resources Investigations Report 91-4171, 58 pages.

Hjalmarson, H.W., 1994, Potential Flood Hazards And Hydraulic Characteristics Of Distributary-Flow Areas in Maricopa County, Arizona, United States Geological Survey Water-Resources Investigations Report 93-4169, 56 pages.

Jackson, Garrett, 1989, Geologic Map Of The Tucson SE 7.5' Quadrangle, Pima County, Arizona, Arizona Geological Survey Digital Geologic Map 43, 1 sheet 1:24,000.

Jackson, Garrett, 1989, Surficial Geologic Maps Of The Northeastern, Southeastern, And Southwestern Portions Of The Tucson Metropolitan Area, Arizona Geological Survey Open File Report 89-2, 6 pages, 1 sheet 1:24,000 (Tucson SW).

Jackson, Garrett, 1990, Quaternary Geologic map Of The Corona de Tucson 7.5' Quadrangle, Arizona, Arizona Geological Survey Open-File Report 90-3, 6 pages, 1 sheet 1:24,000.

JE Fuller/Hydrology & Geomorphology, Inc. (Sealed by Ted Lehman), 2002, Rio Verde Area Drainage Master Plan, Geomorphic Analysis Report, Task 3.4 for the Rio Verde ADMP for the Flood Control District of Maricopa County

McClaran, Mitchel P., Angell, Deborah L., and Wissler, Craig, 2002, Santa Rita Experimental Range Digital Database: User's Guide, USFS Forest Service General Technical Report RMRS-GTR-100, 13 pages.

McClaran, Mitchel P., Angell, Deborah L., and Wissler, Craig, 2002, Santa Rita Experimental Range Digital Database, <http://ag.arizona.edu/SRER> (Funding for the digitization of these data was provided by USDA Forest Service Rocky Mountain Research Station and the University of Arizona).

McPhee, Jenna, Comrie, Andrew, and Garfin, Gregg, 2004, Drought and Climate in Arizona, Top Ten Questions and Answers, University of Arizona, Technology and Research Initiative Fund Water Sustainability Program, 23 pages.

National Weather Service, Western Region, < http://www.wrh.noaa.gov/>.

Pearthree, Philip A. and Youberg, Ann, 2000, Surficial Geologic Maps And Geologic Hazards Of The Green Valley - Sahuarita Area, Pima County, Arizona, Arizona Geological Survey Open-File Report 00-13, 21 pages, 2 sheets 1:24,000.

Pima Association of Governments, Digital Orthographic Aerial Photography, 2002 and 2005 flights.

Pima County, 2005, Floodplain and Erosion Hazard Management Ordinance, Ord. 1999 FC-1 § 1 (part), 1999; Ord. 1988 FC-2 Art. 1, 1988, <http://municipalcodes.lexisnexis.com/codes/pima/_DATA/TITLE16/index.html>

Pima County Department of Transportation, Improvement Plans for Swan Road Extension, South From Nogales-Old Vail Connection, Plan Number R-796

Richard, Stephen M., et. al., 2002 (revised), Geologic Map Of The Southern Part Of The Vail 7.5' Quadrangle, eastern Pima County, Arizona, Arizona Geological Survey Digital Geologic Map 12, 29 pages, 1 sheet 1:24,000.

Sheppard, Paul R., et. al., 2002, The Climate of the US Southwest, Institute For The Study Of Planet Earth, University of Arizona CLIMAS Report Series, 41 pages.

State of Arizona Department of Water Resources Engineering Division, 1995, State Standard for Identification of and Development Within Sheet Flow Areas, SSA 4-95, 28 pages.

State of Arizona Department of Water Resources Engineering Division, 1996, State Standard for Watercourse System Sediment Balance, SSA 4-96, 48 pages.

United States Army Corps of Engineers, 1994, Channel Stability Assessment for Flood Control Projects, EM 1110-2-1418, 86 pages.

United States Department of Agriculture, 1994 (revised) State Soil Geographic (STATSGO) Data Base, U.S. general soil map, Arizona state subset < http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/>.

United States Department of Agriculture, 2006, Soil Survey Geographic (SSURGO) database for Pima County, Arizona, Eastern Part, <http://www.ftw.nrcs.usda.gov/ssur_data.html>.

United States Department of Agriculture, 2006, Soil Survey Geographic (SSURGO) database for Santa Cruz and Parts of Cochise and Pima Counties, Arizona, <http://www.ftw.nrcs.usda.gov/ssur_data.html>.

United States Department of Agriculture, 2006, Soil Survey Geographic (SSURGO) database for Tucson-Avra Valley Area, Arizona, <http://www.ftw.nrcs.usda.gov/ssur_data.html>.

U.S. Geological Survey, 1981, Corona de Tucson, AZ, Digital Orthographic Quadrangle, GeoTIFF format, UTM Zone 12, NAD83 projection, 20 foot contour interval.

U.S. Geological Survey, 1981, Empire Ranch, AZ, Digital Orthographic Quadrangle, GeoTIFF format, UTM Zone 12, NAD83 projection, 40 foot contour interval.

U.S. Geological Survey, 1981, Green Valley, AZ, Digital Orthographic Quadrangle, GeoTIFF format, UTM Zone 12, NAD83 projection, 20 foot contour interval.

U.S. Geological Survey, 1981, Helvetia, AZ, Digital Orthographic Quadrangle, GeoTIFF format, UTM Zone 12, NAD83 projection, 40 foot contour interval.

U.S. Geological Survey, 1981, Mount Fagan, AZ, Digital Orthographic Quadrangle, GeoTIFF format, UTM Zone 12, NAD83 projection, 40 foot contour interval.

U.S. Geological Survey, 1981, Sahuarita, AZ, Digital Orthographic Quadrangle, GeoTIFF format, UTM Zone 12, NAD83 projection, 20 foot contour interval.

U.S. Geological Survey, 1981, Vail, AZ, Digital Orthographic Quadrangle, GeoTIFF format, UTM Zone 12, NAD83 projection, 40 foot contour interval.

U.S. Geological Survey, 1983, Tucson SW, AZ, Digital Orthographic Quadrangle, GeoTIFF format, UTM Zone 12, NAD83 projection, 10 foot contour interval.

U.S. Geological Survey, 1992, Tucson SE, AZ, Digital Orthographic Quadrangle, GeoTIFF format, UTM Zone 12, NAD83 projection, 10 foot contour interval.

Western Regional Climate Center, Arizona Climate Summaries, <http://www.wrcc.dri.edu/summary/climsmaz.html>.

Appendix A - List of Figures and Tables

LIST OF FIGURES

LIST OF TABLES

Appendix B - Summary of Soil Units and Descriptions

Table A - 1- Soil Units and Brief Descriptions on the LMWBMS Piedmont

NRCS Map Unit Symbol	NRCS map unit	Component Series	Setting / Location*	Flooding Potential	Subgroup, Order
AhA	Anthony sandy loam, 0 to 1 percent slopes	Anthony/similar: 100%	alluvial fans, floodplains, mixed alluvium formation	rarely	- Typic Torrifluvents, Entisols
An	Anthony soils	Anthony/similar: 80%	alluvial fans, floodplains, mixed alluvium formation	rarely	- Typic Torrifluvents, Entisols
Ao	Anthony soils, very gravelly variants	Anthony/similar: 100%	alluvial fans, floodplains	occasionally, very brief duration	- Typic Torrifluvents, Entisols
ApB	Anthony soils, 0 to 3 percent slopes	Anthony/similar: 90%	alluvial fans, floodplains, mixed alluvium formation	occasionally, brief duration	- Typic Torrifluvents, Entisols
BgF	Barkerville-Gaddes association, steep	Barkerville/similar: 60% Gaddes/similar:25% Rock Outcrop: 15%	mountains	not	- Udorthentic Haplustolls, Mollisols - Ustollic Haplargids, Aridisols
BhD	Bernardino-Hathaway association, rolling	Bernardino/similar: 55% Hathaway/similar: 25%	alluvial fans, floodplains	not	- Ustollic Haplargids, Aridisols - Aridic Calciustolls, Mollisols

Table A - 1- Soil Units and Brief Descriptions on the LMWBMS Piedmont

NRCS Map Unit Symbol	NRCS map unit	Component Series	Setting / Location*	Flooding Potential	Subgroup, Order
Br	Brazito loamy sand	Brazito/similar: 100%	floodplains, mixed alluvium formation	rarely	- Typic Torripsamments, Entisols
Bt	Brazito sandy loam	Brazito/similar: 100%	floodplains, mixed alluvium formation	rarely	- Typic Torripsamments, Entisols
CgE	Caralampi gravelly sandy loam, 10 to 40 percent slopes	Caralampi/similar: 90%	eroded fan remnant sideslopes, mixed alluvium formation	not	- Ustollic Haplargids, Aridisols
ClC	Cave-rillito complex, 0 to 8 percent slopes	Cave/similar: 60% Rillito/similar: 35%	terraces, mixed alluvium formation	not	- Typic Paleorthids, Aridisols - Typic Calciorthids, Aridisols
Cm	Comoro sandy loam	Comoro/similar: 100%	floodplains	rarely	- Aridic Haplustolls, Mollisols
Cn	Cave gravelly sandy loam	Cave/similar: 95%	alluvial fans	not	- Typic Paleorthids, Aridisols

Table A - 1- Soil Units and Brief Descriptions on the LMWBMS Piedmont

NRCS Map Unit Symbol	NRCS map unit	Component Series	Setting / Location*	Flooding Potential	Subgroup, Order
Co	Comoro loam	Comoro/similar: 100%	alluvial fans, floodplains	rarely	- Aridic Haplustolls, Mollisols
CoE	Chiricahua cobbly sandy loam, 10 to 45 percent slopes	Chiricahua/similar: 90%	mountains, ridges	not	- Ustollic Haplargids, Aridisols
CsC	Comoro sandy loam, 5 to 10 percent slopes	Comoro/similar: 85%	alluvial fans	rarely	- Aridic Haplustolls, Mollisols
CtB	Comoro soils, 0 to 5 percent slopes	Comoro/similar: 100%	floodplains, mixed alluvium formation	rarely	- Aridic Haplustolls, Mollisols
CuC	Continental soils, 1 to 10 percent slopes	Continental/similar: 100%	terraces, alluvial fans	not	- Typic Haplargids, Aridisols
CvB	Cowan-Valencia complex, 0 to 5 percent slopes	Cowan/similar: 65% Valencia/similar: 25%	ridges, mixed alluvium formation	rarely	- Typic Torrifluvents, Entisols - Typic Torrifluvents, Entisols

Table A - 1- Soil Units and Brief Descriptions on the LMWBMS Piedmont

NRCS Map Unit Symbol	NRCS map unit	Component Series	Setting / Location*	Flooding Potential	Subgroup, Order
FrF	Faraway-Rock outcrop complex, 30 to 60 percent slopes	Faraway/similar: 55% Rock outcrop: 30%	hills, mountains, mixed alluvium formation	rarely	- Lithic Haplustolls, Mollisols
Gh	Grabe loam	Grabe/similar: 100%	alluvial fans, floodplains	rarely	- Typic Torrifluvents, Entisols
Gm	Grabe silty clay loam	Grabe/similar: 100%	floodplains	rarely	- Typic Torrifluvents, Entisols
GoB	Grabe soils, 0 to 3 percent slopes	Grabe/similar: 90%	alluvial fans, floodplains	rarely	- Typic Torrifluvents, Entisols
Gu	Gullied Land	Gullied land: 100%	floodplains		
HaF	Hathaway gravelly sandy loam, 20 to 50 percent slopes	Hathaway/similar: 75%	ridges	not	- Aridic Calciustolls, Mollisols

Appendix B - Summary of Soil Units and Descriptions-

Table A - 1- Soil Units and Brief Descriptions on the LMWBMS Piedmont

NRCS Map Unit Symbol	NRCS map unit	Component Series	Setting / Location*	Flooding Potential	Subgroup, Order
LaA	Laveen sandy loam, 0 to 1 percent slopes	Laveen/similar: 100%	alluvial fans, terraces, mixed alluvium formation	not	- Typic Calciorthids, Aridisols
LaB	Laveen sandy loam, 1 to 3 percent slopes	Laveen/similar: 100%	fans, terraces, mixed alluvium formation	not	- Typic Calciorthids, Aridisols
LcF	Lampshire-Chiricahua association, steep	Lampshire/similar: 60% Chiricahua/similar: 25%	mountains, hills	not	- Lithic Haplustolls, Mollisols - Ustollic Haplargids, Aridisols
LeA	Laveen loam, 0 to 1 percent slopes	Laveen/similar:	alluvial fans, mixed alluvium formation	not	- Typic Calciorthids, Aridisols
LeB	Laveen loam, 1 to 3 percent slopes	Laveen/similar: 100%	alluvial fans, mixed alluvium formation	not	- Typic Calciorthids, Aridisols
LgF	Lampshire-Graham-Rock outcrop association, steep	Lampshire/similar: 35% Graham/similar: 30% Rock outcrop: 30% (Note: values as recorded in study =	mountains	not	- Lithic Haplustolls, Mollisols - Lithic Argiustolls, Mollisolls

Table A - 1- Soil Units and Brief Descriptions on the LMWBMS Piedmont

NRCS Map Unit Symbol	NRCS map unit	Component Series	Setting / Location*	Flooding Potential	Subgroup, Order
LrB	Laveen-rillito complex, 0 to 3 percent slopes	Rillito/similar: 35% Laveen/similar: 60%	terraces, mixed alluvium formation	not	- Typic Calciorthids, Aridisols - Typic Calciorthids, Aridisols
LsB	Laveen gravelly sandy loam, heavy variant, 1 to 3 percent slopes	Laveen variant and similar: 100%	alluvial fans, terraces, mixed alluvium formation	not	- Typic Calciorthids, Aridisols
McF	Mabray-Chiricahua-Rock outcrop association, steep	Mabray/similar: 35% Chiricahua/similar: 35% Rock outcrop: 30%	mountains	not	- Lithic Haplustolls, Mollisols - Ustollic Haplargids, Aridisols
MdB	Mohave sandy loam, 1 to 3 percent slopes	Mohave/similar: 100%	terraces	not	- Typic Haplargids, Aridisols
MhA	Mohave loam, 0 to 1 percent slopes	Mohave/similar: 100%	alluvial fans, terraces	not	- Typic Haplargids, Aridisols
MhB	Mohave loam, 1 to 3 percent slopes	Mohave/similar: 100%	terraces, fans	not	- Typic Haplargids, Aridisols

Table A - 1- Soil Units and Brief Descriptions on the LMWBMS Piedmont

NRCS Map Unit Symbol	NRCS map unit	Component Series	Setting / Location*	Flooding Potential	Subgroup, Order
Mo	Mohave clay loam	Mohave/similar: 100%	terraces, alluvial fans	not	- Typic Haplargids, Aridisols
Pm	Pima soils	Pima/similar: 100%	floodplains, mixed alluvium formation	occasionally, brief duration	- Aridic Haplustolls, Mollisols
Pn	Pima clay loam, sandy clay loam subsoil variant	Pima/similar: 90%	floodplains, terraces, mixed alluvium formation	occasionally, brief duration	- Aridic Haplustolls, Mollisols
ReC	Rillito gravelly sandy loam, 0 to 8 percent slopes	Rillito/similar: 100%	alluvial fans, terraces, mixed alluvium formation	not	- Typic Calciorthids, Aridisols
Rn	Rock outcrop-Lithic Haplustolls, Mollisols association	Rock outcrop: 50% Lithic Haplustolls, Mollisols and similar: 30%	hills, mountains	not	- Lithic Haplustolls, Mollisols
Ru	Riverwash	Riverwash: 100%	floodplains, channels	frequently, brief duration	

Table A - 1- Soil Units and Brief Descriptions on the LMWBMS Piedmont

NRCS Map Unit Symbol	NRCS map unit	Component Series	Setting / Location*	Flooding Potential	Subgroup, Order
SmB	Sonoita sandy loam, 1 to 3 percent slopes	Sonoita/similar: 100%	plains, mixed alluvium formation	not	- Typic Haplargids, Aridisols
SoB	Sonoita gravelly sandy loam, 1 to 8 percent slopes	Sonoita/similar: 85%	terraces, alluvial fans	not	- Typic Haplargids, Aridisols
StB	Sonoita-tubac complex, 1 to 3 percent slopes	Sonoita/similar: 50% Tubac/similar: 40%	alluvial fans, mixed alluvium formation	not	- Typic Haplargids, Aridisols - Typic Paleargids, Aridisols
Th	Torrifluvents, Entisols and Haplustolls, Mollisols		fans, drainageways	Torrifluvents, Entisols occasionally, very brief duration	- Torrifluvents, Entisols - Haplustolls, Mollisols
TrF	Tortugas-Rock outcrop complex, 25 to 60 percent slopes	Tortugas/similar: 50% Rock outcrop: 40$	mountains	not	- Lithic Haplustolls, Mollisols
TtA	Tubac sandy loam, 0 to 1 percent slopes	Tubac/similar: 100%	swales on terraces	not	- Typic Paleargids, Aridisols

Table A - 1- Soil Units and Brief Descriptions on the LMWBMS Piedmont

NRCS Map Unit Symbol	NRCS map unit	Component Series	Setting / Location*	Flooding Potential	Subgroup, Order
TtB	Tubac sandy loam, 1 to 3 percent slopes	Tubac/similar: 100%	terraces	not	- Typic Paleargids, Aridisols
TuA	Tubac sandy clay loam, 0 to 1 percent slopes	Tubac/similar: 100%	terraces	not	- Typic Paleargids, Aridisols
TuB	Tubac sandy clay loam, 1 to 3 percent slopes	Tubac/similar: 100%	terraces	not	- Typic Paleargids, Aridisols
VsA	Vinton loamy sand, 0 to 1 percent slopes	Vinton/similar: 100%	floodplains, mixed alluvium formation	rarely	- Typic Torrifluvents, Entisols
Vt	Vinton sandy loam	Vinton/similar: 100	alluvial fans	rarely	- Typic Torrifluvents, Entisols
Vu	Vinton-anthony sandy loams	Vinton/similar: 45% Anthony/similar: 40%	floodplains, mixed alluvium formation	rarely	- Typic Torrifluvents, Entisols

Table A - 1- Soil Units and Brief Descriptions on the LMWBMS Piedmont

NRCS Map Unit Symbol	NRCS map unit	Component Series	Setting / Location*	Flooding Potential	Subgroup, Order
WgC	White House gravelly loam, 0 to 10 percent slopes	White house/similar: 80%	fan piedmonts, mixed alluvium formation	not	- Ustollic Haplargids, Aridisols
1	Altar-sasabe complex, 1 to 8 percent slopes	Altar/similar: 50% Sasabe/similar: 30%	terraces	not	- Ustochreptic Camborthids, Aridisols - Ustalfic Paleargids, Aridisols
3	Anthony fine sandy loam, 0 to 3 percent slopes	Anthony/similar: 85%	floodplains and drainageways, mixed alluvium formation	rarely	- Typic Torrifluvents, Entisols
5	Arizo-riverwash complex, 0 to 3 percent slopes	Arizo/similar: 50% Riverwash: 20%	floodplains, drainageways and channel bottoms, mixed alluvium	frequently, brief duration	- Typic Torriorthents, Entisols
6	Bernardino-tombstone association, 5 to 16 percent slopes	Bernardion/similar: 50% Tombstone/similar: 25%	terraces, mixed alluvium formation	not	- Ustollic Haplargids, Aridisols - Ustollic Calciorthids, Aridisols
8	Bucklebar-sahuarita complex, 0 to 3 percent slopes	Bucklebar/similar: 45% Sahuarita/similar: 30%	terraces, mixed alluvium formation	not	- Typic Haplargids, Aridisols - Typic Camborthids, Aridisols

Table A - 1- Soil Units and Brief Descriptions on the LMWBMS Piedmont

NRCS Map Unit Symbol	NRCS map unit	Component Series	Setting / Location*	Flooding Potential	Subgroup, Order
9	Caralampi very gravelly sandy loam, 5 to 15 percent slopes	Caralampi/similar: 90%	terraces and hills, mixed alluvium formation	not	- Ustollic Haplargids, Aridisols
10	Caralampi extremely gravelly sandy loam, 15 to 45 percent slopes	Caralampi/similar: 85%	terraces and hills, mixed alluvium formation	not	- Ustollic Haplargids, Aridisols
11	Cave soils and urban land, 0 to 8 percent slopes	Cave/similar: 40% Urban land: 40%	terraces, mixed alluvium formation	not	- Typic Petrocalcids, Aridisols
19	Comoro sandy loam, 0 to 2 percent slopes	Comoro/similar: 80%	floodplains, mixed alluvium formation	rarely	- Ustic Torrifluvents, Entisols
23	Deloro-andrada complex, 5 to 35 percent slopes	Deloro/similar: 40% Andrada/similar: 30%	hills, mountains, mixed alluvium formation	not	- Ustollic Haplargids, Aridisols - Ustollic Calciorthids, Aridisols
24	Deloro-rock outcrop complex, 15 to 60 percent slopes	Deloro/similar: 60% Rock outcrop: 15%	hills, mountains, mixed alluvium formation	not	- Ustollic Haplargids, Aridisols

Appendix B - Summary of Soil Units and Descriptions-

Table A - 1- Soil Units and Brief Descriptions on the LMWBMS Piedmont

NRCS Map Unit Symbol	NRCS map unit	Component Series	Setting / Location*	Flooding Potential	Subgroup, Order
27	Diaspar sandy loam, 1 to 5 percent slopes	Diaspar/similar: 75%	terraces	not	- Ustalfic Haplargids, Aridisols
30	Glendale silt loam, 0 to 3 percent slopes	Glendale/similar: 80%	terraces, mixed alluvium formation	rarely	- Typic Torrifluvents, Entisols
33	Guest fine sandy loam, 0 to 1 percent slopes	Guest/similar: 80%	swales, drainageways, floodplains, mixed alluvium formation	occasionally, brief duration	- Ustertic Torrifluvents, Entisols
34	Hantz loam, 0 to 1 percent slopes	Hantz/similar: 80%	alluvial fans, floodplains, mixed alluvium formation	occasionally, brief duration	- Vertic Torrifluvents, Entisols
35	Hayhook sandy loam, 1 to 5 percent slopes	Hayhook/similar: 85%	alluvial fans	not	- Typic Camborthids, Aridisols
36	Hayhook-sahuarita complex, 1 to 5 percent slopes	Hayhook/similar: 35% Sahuarita/similar: 30%	alluvial fans	not	- Typic Camborthids, Aridisols - Typic Camborthids, Aridisols

Table A - 1- Soil Units and Brief Descriptions on the LMWBMS Piedmont

NRCS Map Unit Symbol	NRCS map unit	Component Series	Setting / Location*	Flooding Potential	Subgroup, Order
37	Keysto extremely gravelly fine sandy loam, 2 to 8 percent slopes	Keysto/similar: 80%	terraces, mixed alluvium formation	rarely	- Ustic Torrifluvents, Entisols
42	Mabray-deloro-rock outcrop complex, 20 to 65 percent slopes	Mabray/similar: 35% Deloro/similar: 25% Rock outcrop: 15%	mountains	not	- Lithic Ustic Torriorthents, Entisols - Ustollic Haplargids, Aridisols
47	Mohave soils and urban land, 1 to 8 percent slopes	Mohave/similar: 40% Urban land: 40%	terraces, mixed alluvium formation	not	- Typic Haplargids, Aridisols
51	Nolam-tombstone complex, 8 to 30 percent slopes	Nolam/similar: 45% Tombstone/similar: 40%	terraces, mixed alluvium formation	not	- Ustollic Haplargids, Aridisols - Ustollic Calciorthids, Aridisols
52	Oracle-romero-rock outcrop complex, 5 to 35 percent slopes	Oracle/similar: 30% Romero/similar: 25% Rock outcrop: 20%	hills	not	- Ustollic Haplargids, Aridisols - Ustic Torriorthents, Entisols
59	Pantano-rock outcrop complex, 25 to 60 percent slopes	Pantano/similar: 50% Rock outcrop: 25%	hills, mountains, mixed alluvium formation	not	- Typic Calciorthids, Aridisols

Table A - 1- Soil Units and Brief Descriptions on the LMWBMS Piedmont

NRCS Map Unit Symbol	NRCS map unit	Component Series	Setting / Location*	Flooding Potential	Subgroup, Order
60	Pinaleno-stagecoach complex, 5 to 16 percent slopes	Pinaleno/similar: 40% Stagecoach/similar: 35%	terraces, mixed alluvium formation	not	- Typic Haplargids, Aridisols - Typic Calciorthids, Aridisols
62	Pinaleno very cobbly sandy loam, 1 to 8 percent slopes	Pinaleno/similar: 80%	terraces, mixed alluvium formation	not	- Typic Haplargids, Aridisols
64	Pits, dumps	Pits: 40% Dumps, stony: 20% Dumps, tailings: 15%	terraces (found on terrace next to 72)	not	
68	Riveroad and comoro soils, 0 to 2 percent slopes	Riveroad/similar: 50% Comoro/similar: 50%	floodplains	rarely	- Ustic Torrifluvents, Entisols - Ustic Torrifluvents, Entisols
70	Romero-oracle complex, 25 to 60 percent slopes	Romero/similar: 45% Oracle/similar: 30%	hills, mountains	not	- Ustic Torriorthents, Entisols - Ustollic Haplargids, Aridisols
72	Sahuarita soils, mohave soils and urban land, 1 to 5 percent slopes	Sahuarita/similar: 25% Mohave/similar: 25% Urban land: 25%	terraces, mixed alluvium formation	not	- Typic Camborthids, Aridisols - Typic Haplargids, Aridisols

Table A - 1- Soil Units and Brief Descriptions on the LMWBMS Piedmont

NRCS Map Unit Symbol	NRCS map unit	Component Series	Setting / Location*	Flooding Potential	Subgroup, Order
73	Sasabe-caralampi complex, 1 to 15 percent slopes	Sasabe/similar: 45% Caralampi/similar: 30%	terraces, mixed alluvium formation	not	- Ustalfic Paleargids, Aridisols - Ustollic Haplargids, Aridisols
78	Stagecoach-sahuarita association, 1 to 8 percent slopes	Stagecoach/similar: 50% Sahuarita/similar: 25%	terraces, mixed alluvium formation	not	- Typic Calciorthids, Aridisols - Typic Camborthids, Aridisols
79	Tombstone very gravelly loam, 15 to 50 percent slopes	Tombstone/similar: 85%	terraces, mixed alluvium formation	not	- Ustollic Calciorthids, Aridisols
81	Tubac gravelly loam, 1 to 8 percent slopes	Tubac/similar: 80%	terraces, mixed alluvium formation	not	- Typic Paleargids, Aridisols
82	Tubac sandy loam, 0 to 2 percent slopes	Tubac/similar: 75%	terraces, mixed alluvium formation	not	- Typic Paleargids, Aridisols
84	White house-caralampi complex, 5 to 25 percent slopes	White house/similar: 45% Caralampi/similar: 40%	terraces, mixed alluvium formation	not	- Ustic Haplargids, Aridisols
86	Yaqui fine sandy loam, 1 to 3 percent slopes	Yaqui/similar: 80%	alluvial fans, mixed alluvium formation	rarely	- Fluventic Camborthids, Aridisols

* - mixed alluvium formation signifies those soils which are composed of mixed alluvium
Adapted from the following detailed soils studies;
- Santa Cruz and Parts of Cochise and Pima Counties, Arizona
- Tucson-Avra Valley Area, Arizona
- Pima County, Arizona, Eastern Part

Appendix C - Field Reconnaissance Summary

Table B - 1 - Field Reconnaissance Summary

Point ID	General Description	Abrupt Scour Difference Issues	Headcutting Issues	Vertical Banks Present?	Human Induced Issues
01-01	landscape view				
01-02	landscape view				
01-03	landscape view				
01-04	landscape view				
01-05	landscape view				
01-06	landscape view				
01-07	stable wash				
01-08	stable wash				minor local scour at road crossing
01-09	vertical scour and/or incising channel	scour downstream of road crossing, no scour above			scouring due to dip type road crossing, arroyo developing downstream of road
01-10	stable wash				
01-11	landscape view				
01-12	ground view				
01-13	vertical scour and/or incising channel		nick point		
01-14	ground view				
01-15	landscape view				
01-16	flow split, confluence, or braid				
01-17	flow split, confluence, or braid				

Table B - 2

Table B - 1 - Field Reconnaissance Summary

Point ID	General Description	Abrupt Scour Difference Issues	Headcutting Issues	Vertical Banks Present?	Human Induced Issues
01-18	flow split, confluence, or braid				
01-19	stable wash				
01-20	stable wash				
01-21	landscape view				
01-22	stable wash				
01-23	lateral erosion			yes	
01-24	stable wash				
01-25	lateral erosion			yes	
01-26	lateral erosion			yes	
01-27	stable wash				
01-28	ground view				
01-29	stable wash				
01-30	stable wash				
01-31	flow split, confluence, or braid				
01-32	flow split, confluence, or braid		nick point		
01-33	lateral erosion			yes	
01-34	avulsion			yes	

Table B - 1 - Field Reconnaissance Summary

Point ID	General Description	Abrupt Scour Difference Issues	Headcutting Issues	Vertical Banks Present?	Human Induced Issues
01-18	flow split, confluence, or braid				
01-19	stable wash				
01-20	stable wash				
01-21	landscape view				
01-22	stable wash				
01-23	lateral erosion			yes	
01-24	stable wash				
01-25	lateral erosion			yes	
01-26	lateral erosion			yes	
01-27	stable wash				
01-28	ground view				
01-29	stable wash				
01-30	stable wash				
01-31	flow split, confluence, or braid				
01-32	flow split, confluence, or braid		nick point		
01-33	lateral erosion			yes	
01-34	avulsion			yes	
01-35	lateral erosion			yes	

Table B - 1 - Field Reconnaissance Summary

Point ID	General Description	Abrupt Scour Difference Issues	Headcutting Issues	Vertical Banks Present?	Human Induced Issues
01-36	flow split, confluence, or braid		headcut, wash developing		
01-37	flow split, confluence, or braid		headcut, wash developing		
01-38	flow split, confluence, or braid		headcut, wash developing		
01-39	flow split, confluence, or braid		nick point		
01-40	landscape view				
01-41	stable wash				
01-42	flow split, confluence, or braid				
01-43	flow split, confluence, or braid				
01-44	flow split, confluence, or braid				
01-45	ground view				
01-46	landscape view				
01-47	vertical scour and/or incising channel		headcut above road	yes	
01-48	vertical scour and/or incising channel	scour greater downstream of road than above	headcuts appear present		scouring due to dip type road crossing
01-49	vertical scour and/or incising channel	scour greater downstream of road than above	headcuts appear present	yes	scouring due to dip type road crossing

Table B - 1 - Field Reconnaissance Summary

Point ID	General Description	Abrupt Scour Difference Issues	Headcutting Issues	Vertical Banks Present?	Human Induced Issues
01-50	lateral erosion				
01-51	flow split, confluence, or braid				
01-52	stable wash				
01-53	flow split, confluence, or braid				
01-54	flow split, confluence, or braid				
02-01	landscape view				
02-02	vertical scour and/or incising channel	scour downstream of road crossing, no scour above	wash may be headcutting up to road, does not extend beyond road	yes	scouring due to dip type road crossing
02-03	vertical scour and/or incising channel				
02-04	flow split, confluence, or braid				
02-05	flow split, confluence, or braid				
02-06	stable wash				
02-07	stable wash				
02-08	flow split, confluence, or braid				
02-09	vertical scour and/or incising channel				
02-10	stable wash				

Table B - 1 - Field Reconnaissance Summary

Point ID	General Description	Abrupt Scour Difference Issues	Headcutting Issues	Vertical Banks Present?	Human Induced Issues
02-11	flow split, confluence, or braid				
02-12	flow split, confluence, or braid				
02-13	stable wash				
02-14	stable wash				
02-15	flow split, confluence, or braid				
02-16	lateral erosion			yes	
02-17	vertical scour and/or incising channel				
02-18	lateral erosion				
02-19	flow split, confluence, or braid				
02-20	stable wash				
02-21	landscape view				
02-22	stable wash				
02-23	ground view				
02-24	stable wash				
02-25	flow split, confluence, or braid				
02-26	landscape view				
02-27	landscape view				

Table B - 1 - Field Reconnaissance Summary

Point ID	General Description	Abrupt Scour Difference Issues	Headcutting Issues	Vertical Banks Present?	Human Induced Issues
02-28	landscape view				
02-29	vertical scour and/or incising channel	scour hole downstream of road			scouring due to dip type road crossing
02-30	landscape view				
02-31	stable wash				
02-32	landscape view				
02-33	vertical scour and/or incising channel				
02-34	landscape view				
02-35	lateral erosion		headcut above road	yes	
02-36	stable wash				
02-37	vertical scour and/or incising channel	scour hole downstream of road			scouring due to dip type road crossing
02-38	ground view				
02-39	stable wash				
02-40	landscape view				
02-41	stable wash				
02-42	lateral erosion			yes	possible influence to scouring above culvert
02-43	vertical scour and/or incising channel	scour downstream of road crossing, sedimentation above			scouring downstream of and sedimentation above road crossing and undersized culvert

Table B - 1 - Field Reconnaissance Summary

Point ID	General Description	Abrupt Scour Difference Issues	Headcutting Issues	Vertical Banks Present?	Human Induced Issues
02-44	vertical scour and/or incising channel	scour induced downstream of road crossing			scouring downstream of road crossing and undersized culvert
02-45	vertical scour and/or incising channel	scour greater downstream of road than above	possibly headcutting downstream of road		scouring downstream of and sedimentation above dip type road crossing
02-46	vertical scour and/or incising channel	massive scouring downstream of road		yes	scouring downstream of above road crossing and undersized culvert
02-47	vertical scour and/or incising channel				scouring downstream of above road crossing and undersized culvert
02-48	vertical scour and/or incising channel				scouring downstream of above road crossing and undersized culvert
02-49	vertical scour and/or incising channel			yes	scouring due to dip type road crossing
02-50	vertical scour and/or incising channel				scouring due to dip type road crossing
02-51	landscape view				
02-52	vertical scour and/or incising channel	scour downstream of road, stable above road	headcutting downstream of road likely stopped by road	yes	scouring downstream of and sedimentation above dip type road crossing
02-53	vertical scour and/or incising channel	scour downstream of road, stable above road	headcutting downstream of road likely stopped by road		scouring due to dip type road crossing
02-54	stable wash				

Table B - 1 - Field Reconnaissance Summary

Point ID	General Description	Abrupt Scour Difference Issues	Headcutting Issues	Vertical Banks Present?	Human Induced Issues
02-55	stable wash				
02-56	vertical scour and/or incising channel	scour downstream of road, stable above road	headcutting downstream of road likely stopped by road	yes	possible scouring due to dip type road crossing
02-57	landscape view				
02-58	vertical scour and/or incising channel	scour downstream of road, stable above road	headcutting downstream of road likely stopped by road		scouring due to dip type road crossing
02-59	vertical scour and/or incising channel			yes	scouring due to dip type road crossing
02-60	vertical scour and/or incising channel			yes	
02-61	flow split, confluence, or braid				
02-62	flow split, confluence, or braid				
02-63	vertical scour and/or incising channel			yes	
02-64	vertical scour and/or incising channel			yes	
03-01	stable wash				
03-02	stable wash				
03-03	ground view				

Table B - 1 - Field Reconnaissance Summary

Point ID	General Description	Abrupt Scour Difference Issues	Headcutting Issues	Vertical Banks Present?	Human Induced Issues
03-04	vertical scour and/or incising channel	scour greater downstream of road than above	headcutting downstream of road likely stopped by road	yes	scouring due to dip type road crossing
03-05	vertical scour and/or incising channel	scour downstream of road, stable above road	headcutting downstream of road likely stopped by road	yes	scouring due to dip type road crossing
03-06	stable wash			yes	
03-07	vertical scour and/or incising channel			yes	
03-08	landscape view				
03-09	flow split, confluence, or braid				
03-10	flow split, confluence, or braid				
03-11	vertical scour and/or incising channel			yes	
03-12	stable wash				
03-13	stable wash				
03-14	vertical scour and/or incising channel		headcut up wash, headcut laterally from bank to floodplain	yes	scour along drainage running parallel to flows
03-15	vertical scour and/or incising channel		headcut	yes	scour along drainage running parallel to flows
03-16	vertical scour and/or incising channel		headcut	yes	scour along drainage running parallel to flows

Table B - 1 - Field Reconnaissance Summary

Point ID	General Description	Abrupt Scour Difference Issues	Headcutting Issues	Vertical Banks Present?	Human Induced Issues
03-17	vertical scour and/or incising channel				
03-18	ground view				
03-19	vertical scour and/or incising channel			yes	
03-20	stable wash			yes	
03-21	stable wash				
03-22	stable wash				
03-23	vertical scour and/or incising channel	scour downstream of culvert extends downstream	headcut	yes	scour from culvert crossing
03-24	landscape view				
03-25	stable wash				
03-26	stable wash			yes	
03-27	vertical scour and/or incising channel			yes	
03-28	vertical scour and/or incising channel				
03-29	landscape view				
03-30	landscape view				
03-31	vertical scour and/or incising channel	scour downstream of road	headcutting downstream of road likely stopped by road		scour from roadside drainage
03-32	landscape view				

Table B - 1 - Field Reconnaissance Summary

Point ID	General Description	Abrupt Scour Difference Issues	Headcutting Issues	Vertical Banks Present?	Human Induced Issues
03-33	vertical scour and/or incising channel		headcut		concrete ford crossing and dissipation pool
03-34	vertical scour and/or incising channel		headcut	yes	junk cars placed in incised channel
03-35	vertical scour and/or incising channel		headcut		
03-36	vertical scour and/or incising channel	scour greater downstream of road than above	headcutting downstream of road likely stopped by road		
03-37	vertical scour and/or incising channel	scour greater downstream of road than above	headcutting downstream of road likely stopped by road		scour from culvert crossing
03-38	vertical scour and/or incising channel	scour greater downstream of road than above	headcutting downstream of road likely stopped by road	yes	scouring due to dip type road crossing
03-39	vertical scour and/or incising channel			yes	concrete ford crossing
03-40	vertical scour and/or incising channel				
03-41	vertical scour and/or incising channel			yes	concrete ford crossing
03-42	landscape view				
03-43	vertical scour and/or incising channel		headcut		
03-44	vertical scour and/or incising channel	scour greater downstream of road than above	headcutting downstream of road likely stopped by road		

Table B - 1 - Field Reconnaissance Summary

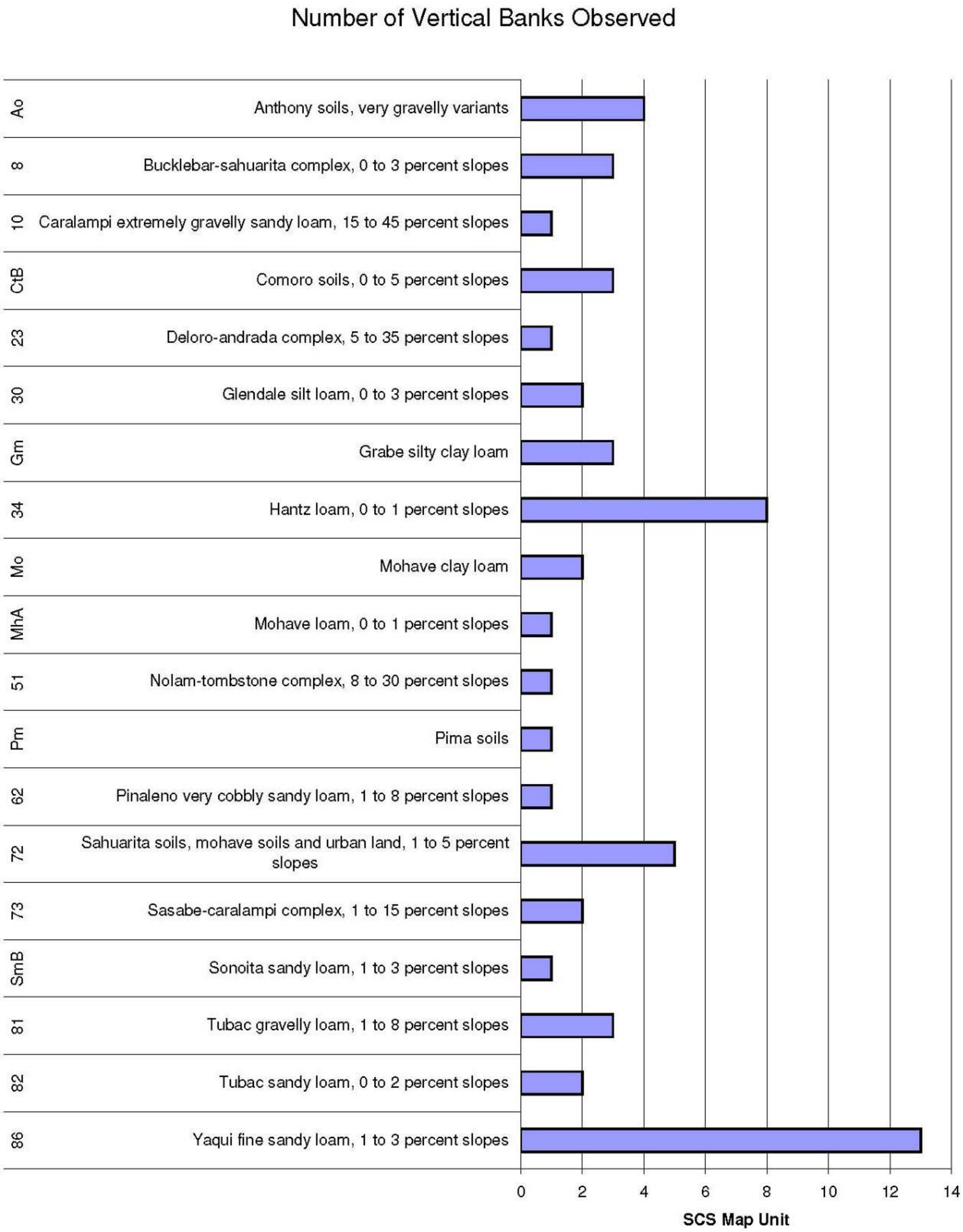
Point ID	General Description	Abrupt Scour Difference Issues	Headcutting Issues	Vertical Banks Present?	Human Induced Issues
03-45	vertical scour and/or incising channel			yes	scour from culvert crossing
03-46	vertical scour and/or incising channel			yes	scour from culvert crossing
03-47	vertical scour and/or incising channel			yes	scour along drainage running parallel to flows
03-48	vertical scour and/or incising channel			yes	scour along drainage running parallel to flows
03-49	vertical scour and/or incising channel				scour along drainage running parallel to flows
03-50	lateral erosion			yes	scour along drainage running parallel to flows
03-51	lateral erosion			yes	scour along drainage running parallel to flows
03-52	vertical scour and/or incising channel				scour along drainage running parallel to flows
03-53	vertical scour and/or incising channel				scouring due to dip type road crossing
03-54	vertical scour and/or incising channel				scouring due to dip type road crossing

Table B - 1 - Field Reconnaissance Summary

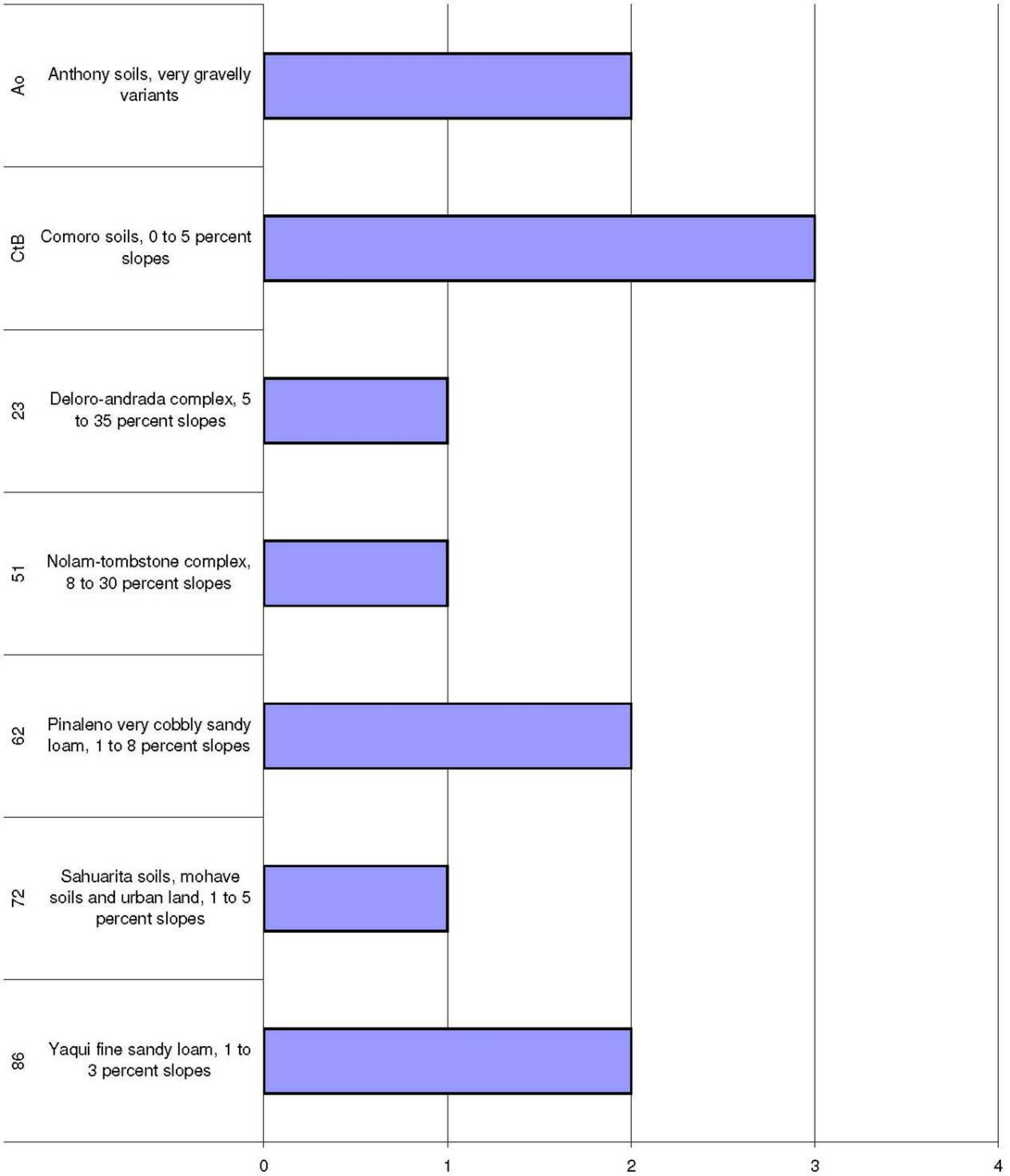
Point ID	General Description	Abrupt Scour Difference Issues	Headcutting Issues	Vertical Banks Present?	Human Induced Issues
03-55	landscape view				
03-56	vertical scour and/or incising channel	scour greater downstream of road than above	headcutting downstream of road likely stopped by road	yes	scour from culvert crossing
03-57	stable wash				
03-58	vertical scour and/or incising channel	scour greater downstream of road than above	headcutting downstream of road likely stopped by road		
03-59	vertical scour and/or incising channel		nick point	yes	scour along drainage running parallel to flows
03-60	vertical scour and/or incising channel		headcut above road		scour from roadside drainage
03-61	vertical scour and/or incising channel			yes	
03-62	vertical scour and/or incising channel		headcut		
03-63	vertical scour and/or incising channel		headcut	yes	scouring due to dip type road crossing
03-64	vertical scour and/or incising channel		headcut	yes	scour along drainage running parallel to flows
03-65	landscape view				
03-66	vertical scour and/or incising channel				

Table B - 1 - Field Reconnaissance Summary

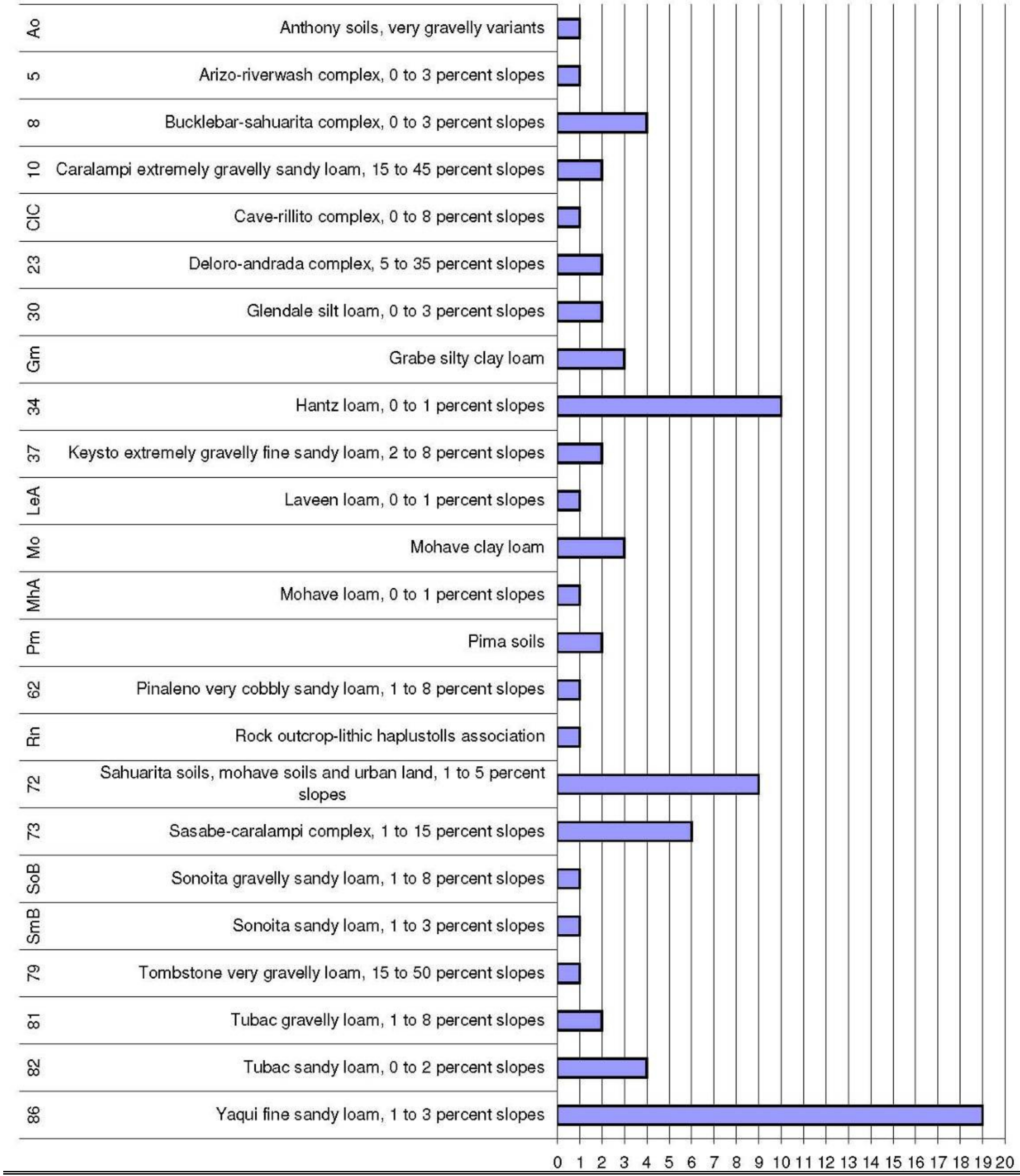
Point ID	General Description	Abrupt Scour Difference Issues	Headcutting Issues	Vertical Banks Present?	Human Induced Issues
03-67	vertical scour and/or incising channel			yes	
03-68	vertical scour and/or incising channel			yes	scour downstream of spillway
04-01	landscape view				
04-02	vertical scour and/or incising channel		headcut	yes	scour from roadside drainage
04-03	vertical scour and/or incising channel		headcut	yes	
03-04	vertical scour and/or incising channel				
04-05	vertical scour and/or incising channel				
04-06	vertical scour and/or incising channel			yes	scour from roadside drainage
04-07	stable wash				
04-08	stable wash				
04-09	vertical scour and/or incising channel			yes	impacted by culvert crossing
03-10	vertical scour and/or incising channel			yes	
04-11	vertical scour and/or incising channel			yes	scour from roadside drainage
04-12	vertical scour and/or incising channel	scour at road inducing scour hole	headcutting downstream of road likely stopped by road	yes	scour downstream of ford crossing, sediment above



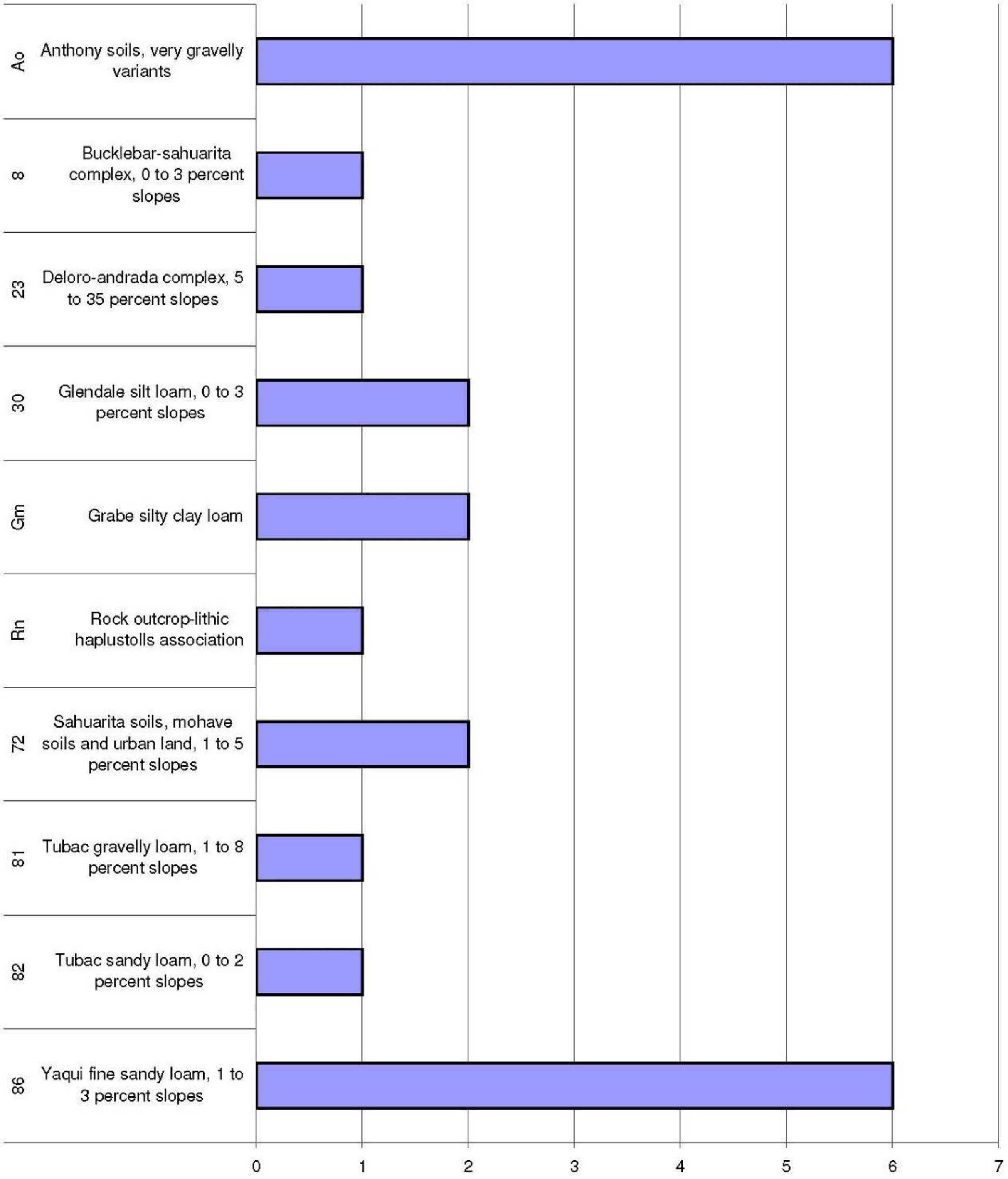
Number of vertical banks observed for each NRCS Map Unit



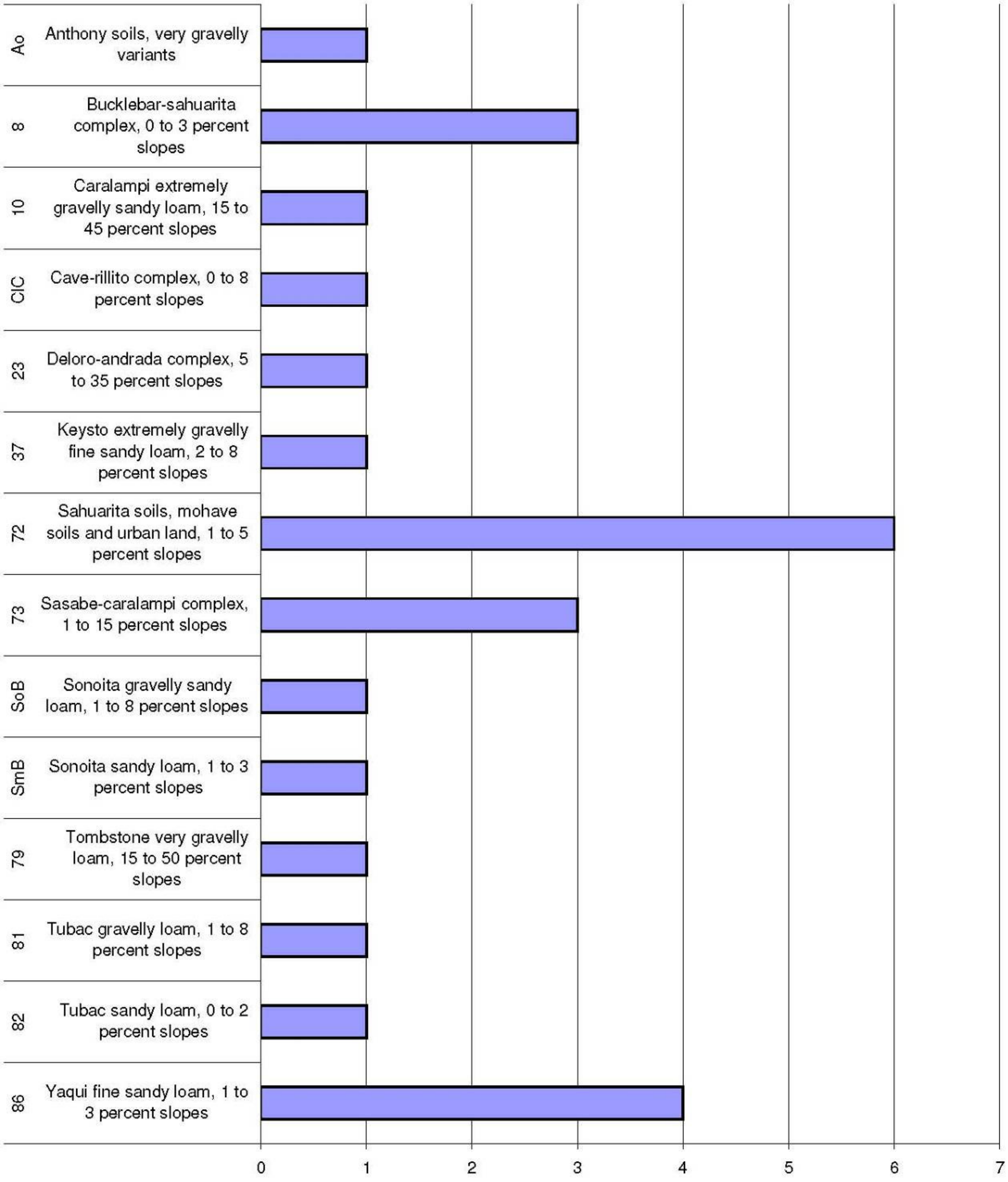
Number lateral erosion areas observed for each NRCS Map Unit



Number of vertical scour and/or incising channel areas observed for each NRCS Map Unit



Number of headcuts observed for each NRCS Map Unit



Number of abrupt scour differences observed for each NRCS Map Unit

Appendix D - Comparison with Analogous Landforms

D COMPARISON WITH ANALOGOUS LANDFORMS

The text within this section is provided to satisfy the project scope and to document similar areas within the region which could be used as a predictor of future geomorphic issues. It is included as an appendix because it is not an integral part of the assessment.

The study area has broad topographic features which are characteristic of the Basin and Range physiographic province. The LMWBMS area consequently has similar features to other alluvial basins throughout the province. In addition, while the landforms of the LMWBMS are analogous to other areas within southern and central Arizona, the historic, current, and future development trends have similarities to the trends within basins with analogous land forms. The LMWBMS is evolving from a rural and ranched basin to a sporadically developed basin, and ultimately to a largely developed basin (assumed). The same thing has happened locally and beyond. Known and studied issues (specifically impacts from development) within similar areas can aid in developing recommendations for future development in the LMWBMS.

D.1 Identification of Analogous Landforms in Arizona

The location of analogous landforms can be found from review of a USGS open file report entitled “Map of Arizona showing selected alluvial, structural, and geomorphic features” (Cooley, 1977). Figure D-1 and Figure D-1 are excerpted from Cooley’s 1977 USGS open file report. The map delineates alluvial deposits throughout the state into broad divisions and shows that the lower Piedmont of this study area is within what Cooley delineates as Division B. These deposits are described as “generally weakly cemented valley-fill deposits of southeastern Arizona” (Cooley 3). This division is found elsewhere in large valleys including areas near Safford, Sierra Vista, and Benson. Similar deposits are mapped nearby as Division C, “generally weakly to firmly cemented valley-fill deposits of southeastern Arizona” (Cooley 4), and elsewhere in western Arizona as Divisions E and H along the Colorado and Gila Rivers, respectively. Much of the Pediment Zone is mapped as Division R which is described as “firmly to well-cemented sedimentary, igneous (excluding volcanic rocks), and metamorphic rocks … that range in age from Precambrian to Tertiary” (Cooley 12). The band of Division H deposits in the Tributary Piedmont Zone is “a heterogeneous assortment of generally weakly consolidated slope-wash deposits, including small areas of virtually undissected alluvial fan deposits, dissected alluvial fan deposits, terrace deposits, flood-plain alluvium, colluvium, and caliche” (Cooley 8). Note that Figure D-2 shows a similar delineation as Figure 17 (page 33).

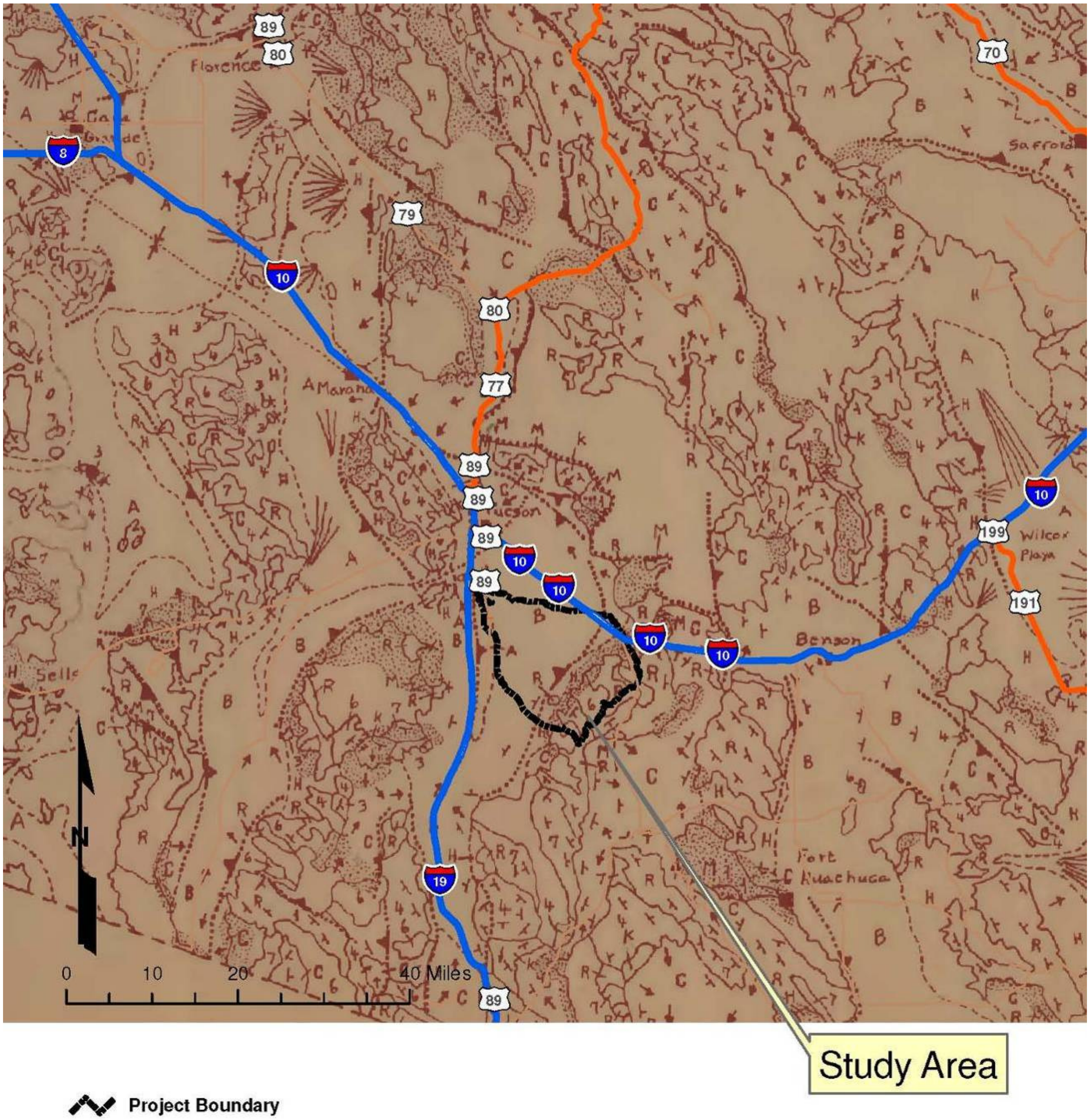


Figure D-1 - Southern Arizona over a portion of USGS "Map of Arizona showing selected alluvial, structural, and geomorphic features"

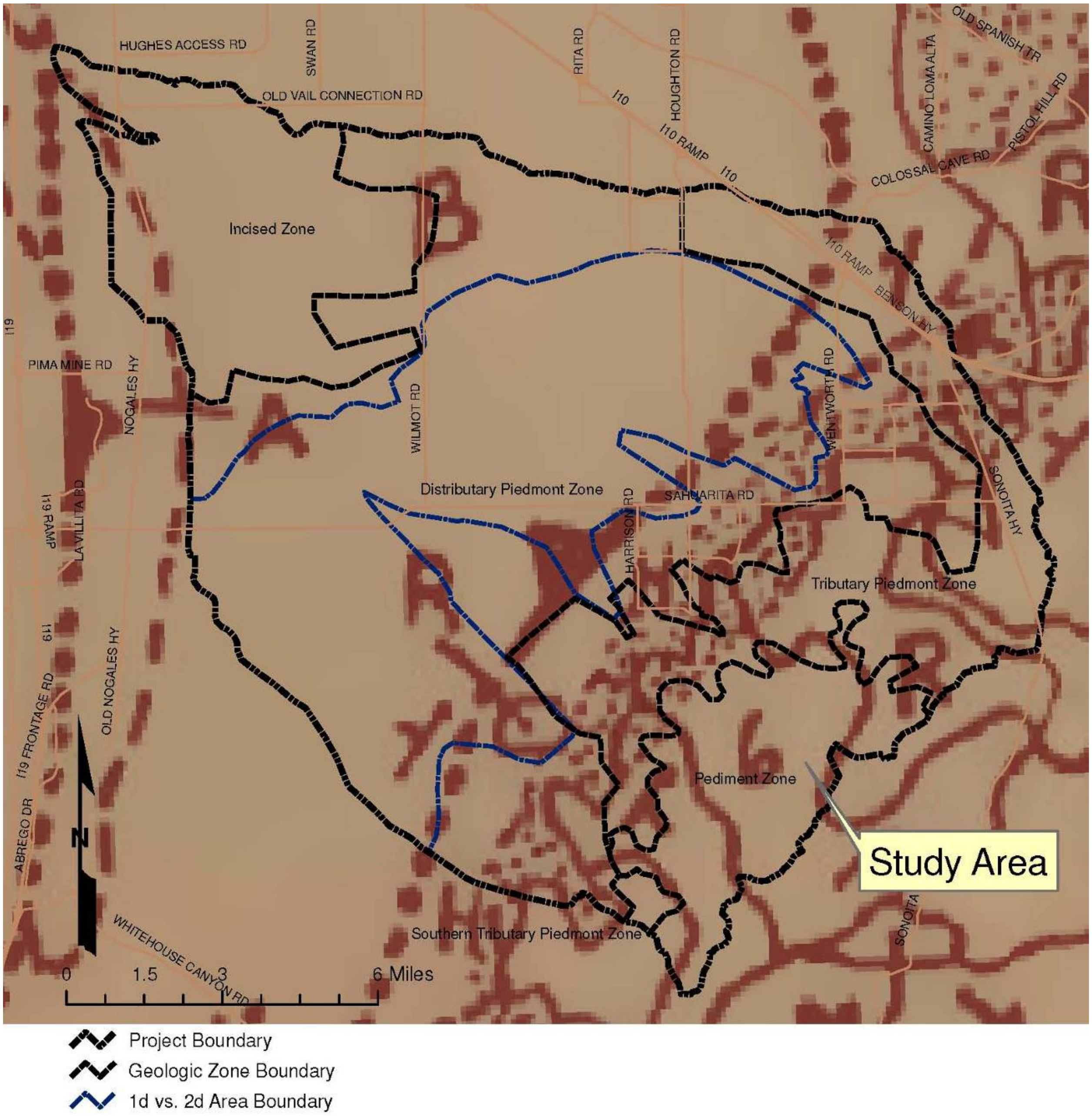


Figure D-2 - Study area over a portion of USGS "Map of Arizona showing selected alluvial, structural, and geomorphic features"

A similar formation of R Division mountain terrain with B Division Piedmont is found around the Sierrita Mountains, directly west of and across the Santa Cruz River from the LMWBMS study area. Much of the low lands and developable areas along the Sierrita Mountains are under less development pressure than the LMWBMS area, but the drainage paths which flow north to cross West Valencia Road, east of Ajo Highway, are under increasing development pressure and represent similar landforms to the LMWBMS. These areas are downstream of long, linear watersheds similar to those in the LMWBMS and are in sheet flow areas similar to the middle

Piedmont of the LMWBMS. It is certain that drainage and sedimentation problems within the West Valencia Road area are to be expected within the LMWBMS.

D.2 Rio Verde ADMP Geomorphic Assessment

Lessons of the impacts from recent development can be found in central Arizona, specifically in Maricopa County. In 2002, JEF (in association with Dibble & Associates) prepared a similar geomorphic assessment (to this assessment of the LMWBMS) as a part of the Rio Verde Area Drainage Master Plan (RVADMP). The RVADMP study area (located northeast of Phoenix) is a watershed of approximately 40 square miles draining the McDowell Mountains east to the Verde River. The similarities between the RVADMP and the LMWBMS include;

- The RVADMP Piedmont covers an area mapped by Cooley as Division C, a similar landform to the LMWBMS area.
- Development type and intensity (in 2002) within the RVADMP is similar to the LMWBMS.
- The RVADMP was divided into four geomorphic study zones with similar features to those within this study.
- Although the surficial geomorphic units within the RVADMP are considerably more homogenous within the study zones, they are similar in age to the units in the LMWBMS; the Hillslopes and Pediments Zone (analogous to the Pediment Zone) was mostly mapped as a Yg (old bedrock) surface, the Piedmont Zone (analogous to the Tributary Piedmont Zone) was mostly mapped as Qm surfaces, the Transport Zone (analogous to the Lower Distributary Zone) was mostly mapped as Ql surfaces, and the Incised Zone was mostly mapped as Ql surfaces.
- Flow splits were greatest within the Transport Zone and also were found in plenitude within the Piedmont Zone.
- The Incised Zone became incised in response to lowering of the Verde River.

One of the primary differences between the studies is longitudinal slope. The primary watercourse longitudinal slopes within the RVADMP are at all locations greater than one percent and typically exceed two percent, significantly greater than the LMWBMS primary watercourse slopes. Also, the slopes are consistent across the watershed and do not shallow near the axial stream and lower Piedmont as the LMWBMS slopes do.

Both natural and man influenced erosion and sedimentation issues occur within the RVADMP. Sedimentation within channels upstream of fallen or impounded trees and shrubs (and scour below) was noted in several locations within the RVADMP. Scour downstream of and sedimentation upstream of roads, residences, underfit culverts and crossings, and stock tanks were common and possibly greater than in this study. This is likely caused by the steep slopes of the RVADMP which develop greater flow velocity and sediment transport than would occur in the LMWBMS. It can be inferred that for the same size of soil material, the shallow slopes of the fluvial systems within the LMWBMS are more forgiving of disruption than the steeper slopes found in the RVADMP.

D.2.1 Rio Verde ADMP Aerial Comparison

A comparison of aerial photographs was included in the RVADMP, with the comparison made between 1953 and 2002. From the geomorphic analysis report:

> Comparison of these photographs showed a number of changes in the watershed over the fifty-year period. Most of the changes appear to be the product of human activity or the combination of human and natural forces. (JEF 25, paragraph 1)
>
> Comparison of channel positions in locations outside the areas disturbed by stock tanks does not reveal any significant changes in the positions of the primary channels. So, while the system is sensitive to changes imposed on it by sediment transport disruptions or diversions of floodwater, evolution of the drainage network is otherwise taking place at smaller scales than those detectable in the aerial photographs, or over longer time scales than 50 years or both. (JEF 25, paragraph 5)

A similar conclusion can be drawn from the aerial comparison within this study. The fluvial systems are in a state of dynamic equilibrium and naturally occurring changes to the systems often occur over periods of time which are greater than photographic periods of record or following significant runoff events.

D.2.2 Rio Verde ADMP Stock Tanks

The stock tanks within the RVADMP diverted flow upstream of the tanks and have caused scouring and arroyo development below the tanks in addition to aggradation within the primary channels upstream of the tanks and diversion structures.

> Diversions … upstream of tanks … have resulted in significant changes in the drainage network. Given the complex drainage network these changes may be resulting in long-term alterations of the downstream areas. … channels immediately downstream of the stock tanks have changed from a broad area of multiple channel braids to a single channel. (JEF 25, paragraph 3)

Development within the RVADMP has already altered and will continue to alter and/or remove these stock tanks.

> The Buckhorn Tank … has been breached by the property owner and is being used as a horse corral. Another tank … has been completely removed. The fate of these tanks is likely to become an important concern for everyone in the area. Meanwhile, the effects of their (temporary) existence will continue to be felt by the drainage systems for some time to come. (JEF 25, paragraph 3)

D.2.3 Rio Verde ADMP Development Impacts

Scour and sedimentation issues caused by development were noted during field visits conducted for the RVADMP. Following a flood on July 14, 2002, "a number of road crossings [dip crossings] were observed to have deposited sediments on the road" and "Erosion from clearwater scour downstream was also observed" (JEF 36). Most of the culverts within the area "were installed only recently and have not experience[d] many significant flows since construction" (JEF 36). However, some impacts were noted, specifically around poorly constructed culvert crossings, such as residential driveways.

Appendix E - Analysis of Singing Cactus Lane Crossing

E FORD CROSSINGS DISCUSSION

This appendix has been included to discuss some of the observations made at the many low flow dip type or ford crossings found throughout the study area,

The ford crossings that were observed to perform most favorably were constructed at the grade of the channel and well maintained. This combination reduces the retardation of flow velocity at the crossing. Many of the unpaved ford crossings may have originally been constructed at the channel grade, but maintenance grading of the road has elevated the road to above the natural channel grade, generating high velocity scour and possibly clear water scour downstream of the road. This is the case for both subcritical and supercritical flow. Subcritical flow will pile up behind the crossing, retarding flow velocity and dropping sediment upstream of the crossing. If supercritical flow exists, a hydraulic jump may occur at the road crossing causing a drop in sediment upstream of and along the road. Both situations will generate increased velocities and clearer water downstream of the crossing which will pick up sediment from the channel bed and banks.

An engineer designing a low water stream crossing in a subcritical flow channel may be tempted to design the road above the channel grade using an unvented, raised ford in order to reduce the flow depth over the road. Based on the above observation of clear water scour downstream of the road, this design should be avoided as it will generate a scour hole downstream of the road and the channel upstream of the crossing will aggrade to a point that the hydraulic drop across the raised ford will no longer occur.

The use of a vented, raised ford may provide a compromise, but sediment accumulation in the culverts will be problematic. This accumulation of sediment upstream of and in the culverts will be accelerated in supercritical flow reaches as a hydraulic jump at the crossing will occur. Furthermore, a vented ford crossing would have headwater depths approximating the culvert height (HW/D near 1) for frequent events such as the 5- or possibly 10-year event, but a larger event would generate headwater above the culverts potentially plugging the culverts. The use of this type of crossing will require maintenance and an understanding of the sediment transport capacity in the design. Unfortunately, maintenance is not always consistent and often cannot keep up with monsoonal runoff.

E.2 Analysis of Singing Cactus Lane Crossing

An idealized HEC-RAS model was developed to model the Singing Cactus Lane ford crossing. A 100-year discharge of 4,600 cfs was modeled based on the plans for the Swan Road RCBC. A cross section geometry and slope were extracted upstream of the culvert and four models were developed. The first is a control model (control-sub) which represents the natural conditions. The slope was measured at less than 0.008 feet per foot and the resulting flow regime is subcritical. The second model represents a raised ford crossing (raised-sub), 1 foot above the channel grade. The third model represents a vented ford with 3-36” corrugated metal pipes. The fourth represents an at-grade ford crossing (AtGrade-sub).

All three crossings exhibited increased water surface elevations at the crossing, see Figure E-1. The at-grade ford crossing increased the water surface elevation the least while the vented crossing increased the water surface elevation the most. Similarly, the at-grade crossing had the least impact on the velocity while the vented crossing retarded flow velocities by almost 40 percent. Both the at-grade and the raised ford crossings provided lower water surface elevations at the crossing. An important observation shown on Figure E-2 is that the velocity profiles do not return to normal within the modeled limits, a distance of 550 feet upstream of the crossing. This provides a considerable distance for the flows to drop out sediment. A similar set of figures, E-3 and E-4, show the flow profile and velocity for the four above situations in a supercritical channel. The results are similar, but the hydraulic jump occurs over the crossing with less upstream influence.

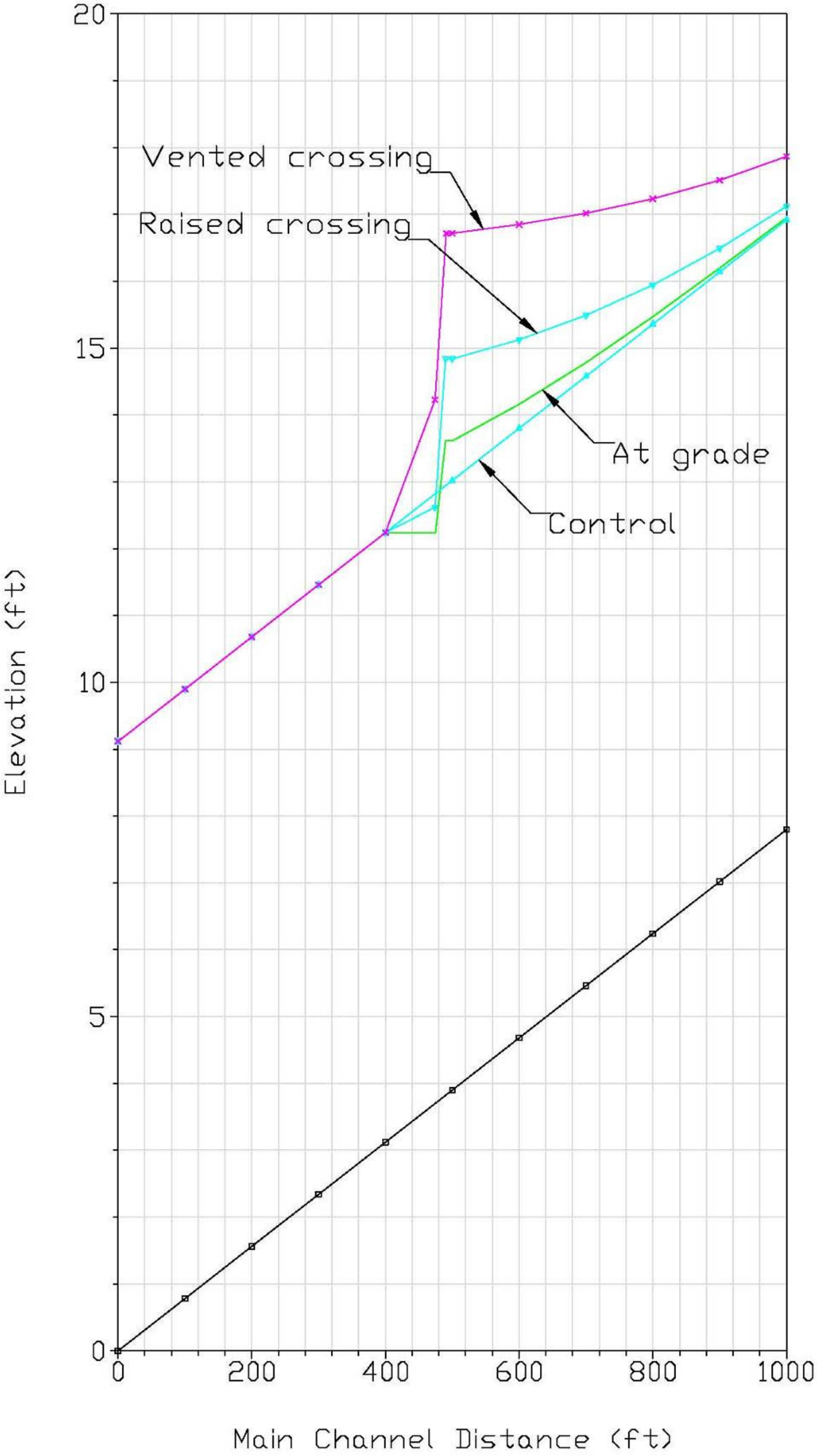


Figure E-1 - Subcritical flow profiles for low water crossing

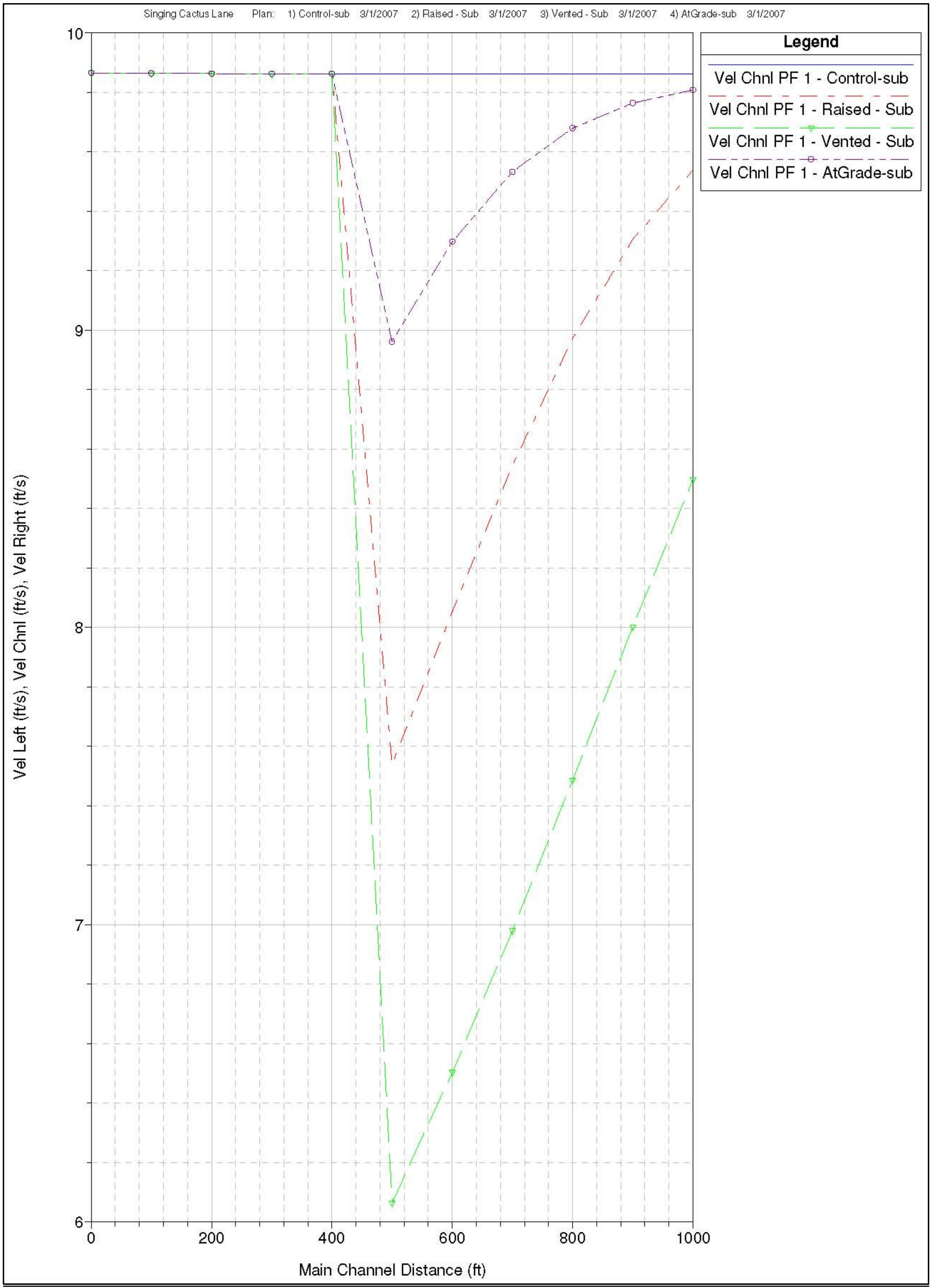


Figure E-2 - Subcritical flow velocities for low water crossing

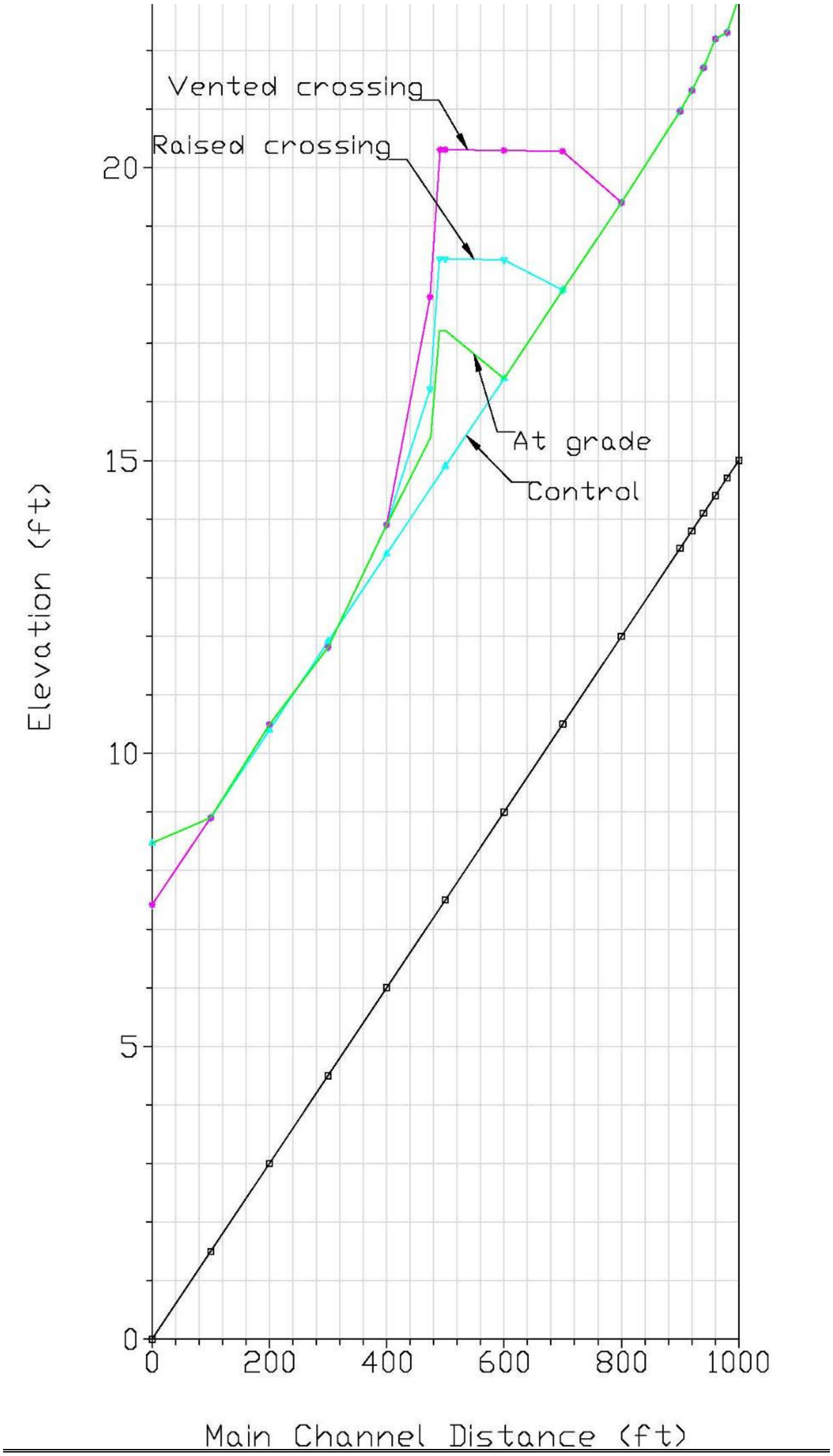


Figure E-3 - Supercritical flow profiles for low water crossing

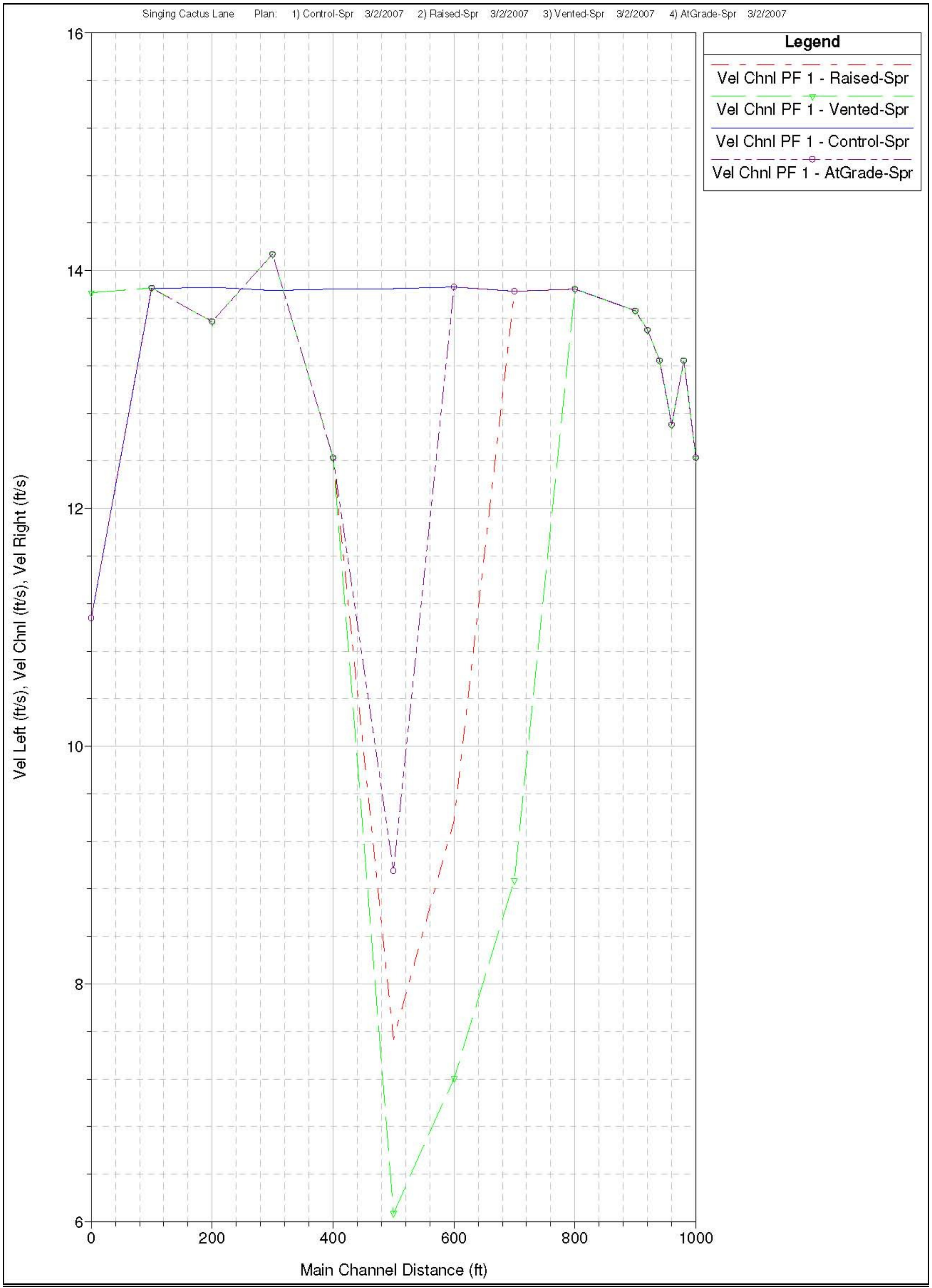


Figure E-4 - Supercritical flow velocities for low water crossing

Appendix F - Field Photographs and Field Notes (digital files)

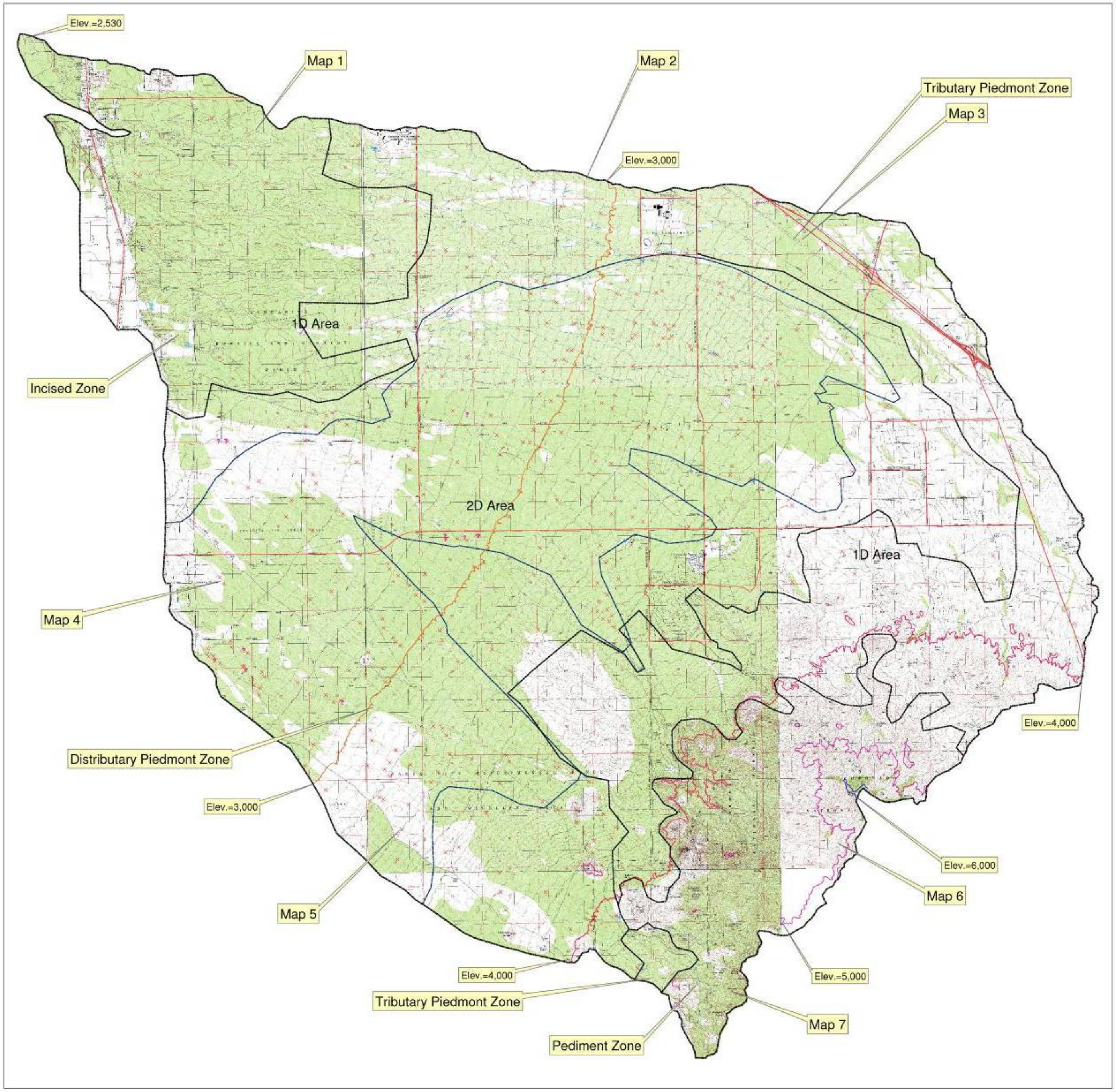
(digital files)

Appendix G - Plates

Plate 1 - USGS Quadrangle Map Composite
Plate 2 - Project Topography
Plate 3 - Aerial Map
Plate 4 - Surficial Geology Map
Plate 5 - NRCS SSURGO Soils Map
Plate 6 - 1936 Aerial Map
Plate 7 - Field Investigation Map
Plate 8 - Significant Distributary Flow Corridors
Plate 9 - Geomorphic Related Hazards

Lee Moore Wash Basin Management Study

Plate 1
USGS Quadrangle Map Composite



N

0 0.375 0.75 1.5
Miles (1" = 3,000')

╱╲╱	Major Streets	**USGS Topography**	
╱╲╱	Project Boundary	**Major Elevations**	
╱╲╱	Geologic Zone Boundary	╱╲╱	3000
╱╲╱	1d vs. 2d Area Boundary	╱╲╱	4000
✳	Major Diffluence	╱╲╱	5000
×	Flow-Splits	╱╲╱	6000
?	Disappearing Wash		

Map 1 - U.S. Geological Survey, 1983
Tucson SW, AZ
10 foot contour interval
032110a8

Map 2 - U.S. Geological Survey, 1983
Tucson SE, AZ
10 foot contour interval
032110a7

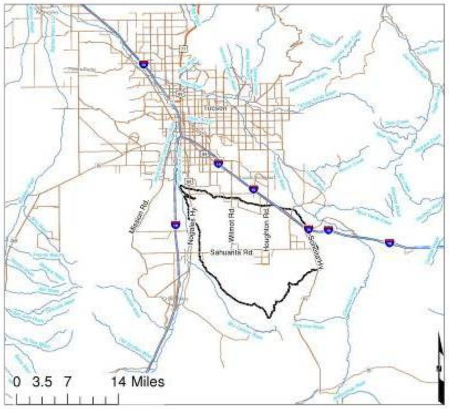
Map 3 - U.S. Geological Survey, 1981
Vail, AZ
40 foot contour interval
032110a6

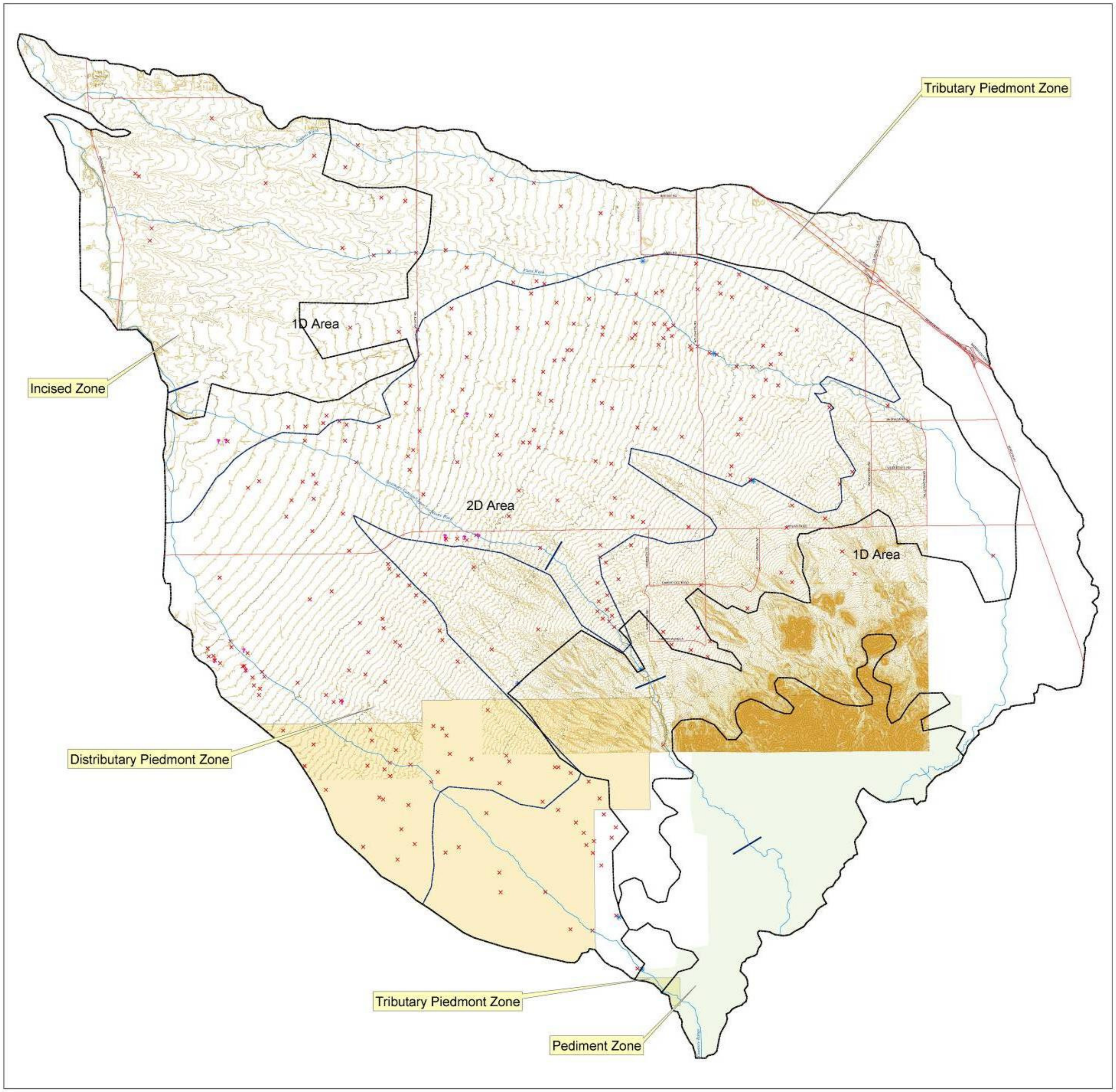
Map 4 - U.S. Geological Survey, 1981
Sahuarita, AZ
20 foot contour interval
031110h8

Map 5 - U.S. Geological Survey, 1981
Corona de Tucson, AZ
20 foot contour interval
031110h7

Map 6 - U.S. Geological Survey, 1981
Mount Fagan, AZ
40 foot contour interval
031110h6

Map 7 - U.S. Geological Survey, 1981
Helvetia, AZ
40 foot contour interval
031110g7





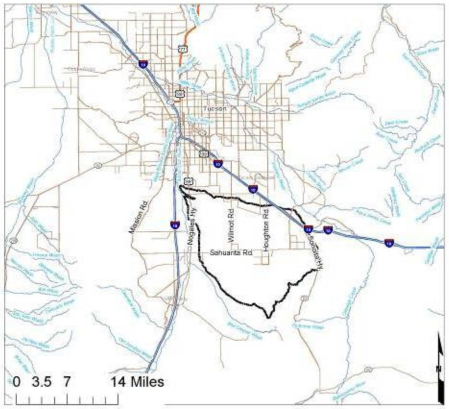
Lee Moore Wash Basin Management Study

Plate 2
Project Topography

N

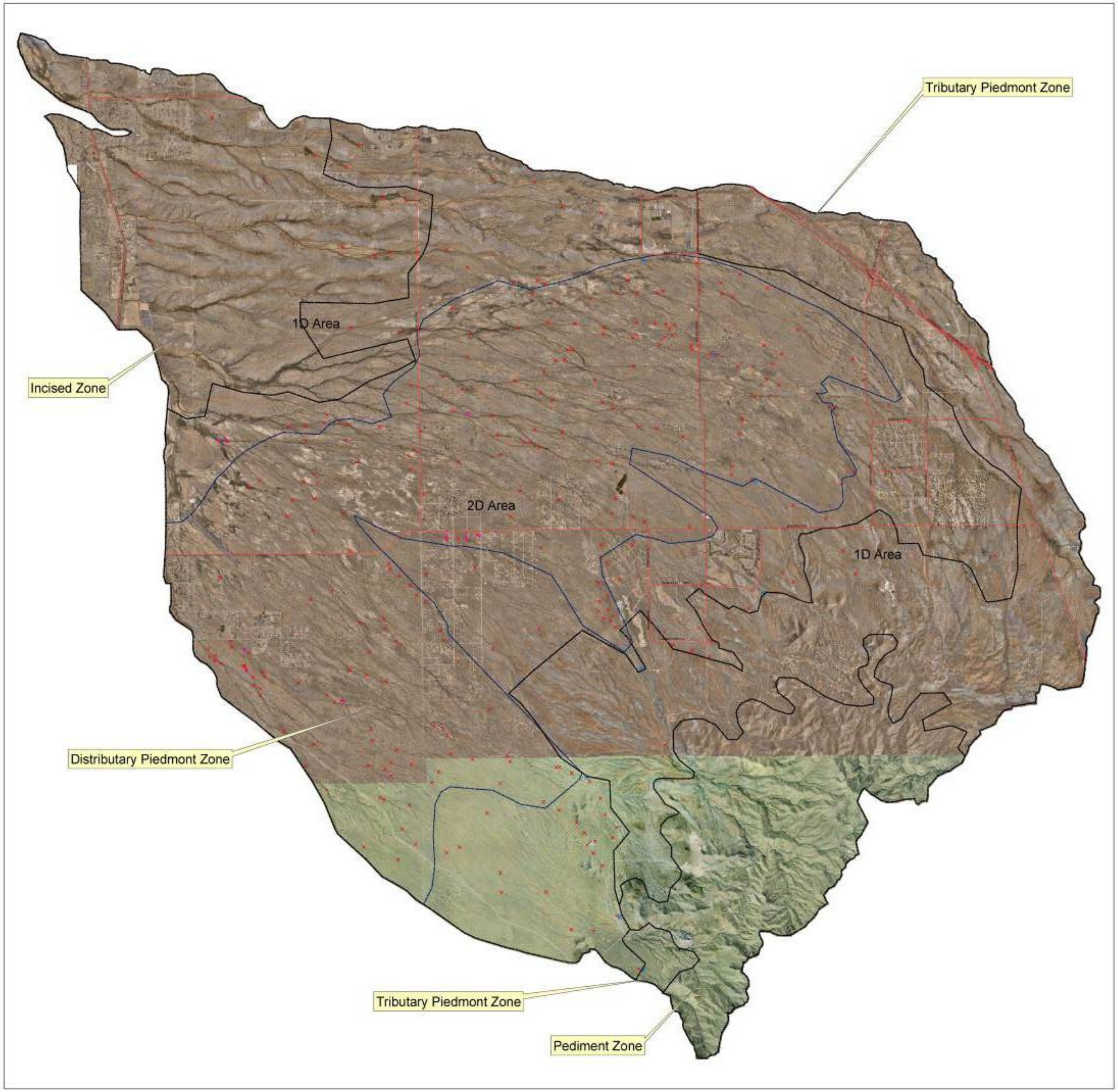
0 0.5 1 2
Miles (1" = 3,000')

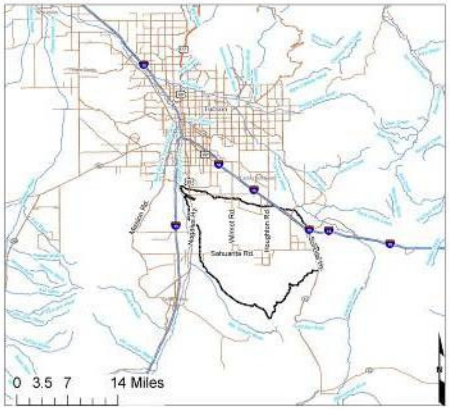
Major Streets
Project Boundary
Geologic Zone Boundary
1d vs. 2d Area Boundary
Example Watercourse
Typical Cross Section Location
✱ Major Diffluence
× Flow Splits
Disappearing Wash
100ft Interval Topography, PAG, NAVD 88
10ft Interval Topography
▨ Santa Rita Experimental Range
🟩 National Forests

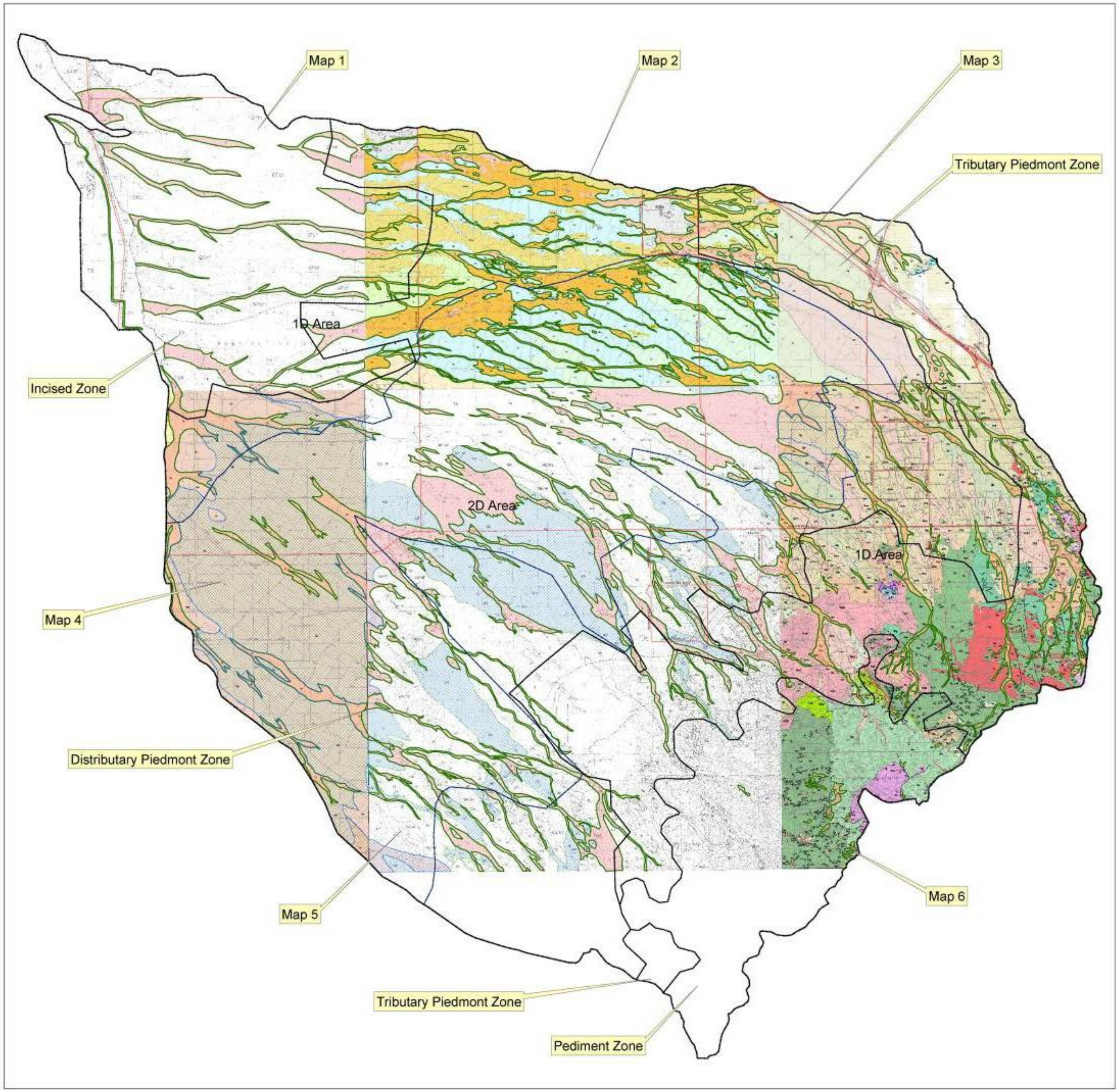


Lee Moore Wash
Basin Management Study

Plate 3
Aerial Map (PAG 2002 & 2005)







Lee Moore Wash Basin Management Study

Plate 4
Surficial Geologic Maps

Major Streets
Project Boundary
Geologic Zone Boundary
1d vs. 2d Area Boundary

Holocene or Younger Deposits

Label

▨ Holocene (Qy) or younger
▨ Late Pleistocene to early Holocene alluvial fans (Ql)
▨ Holocene to late Pleistocene alluvium (Qly)

Map 1 - Jackson, Garrett, 1989.
Surficial Geologic Maps Of The Southwestern Portions Of The Tucson Metropolitan Area, AZGS OFR 89-2 (digitized and georectified by JEF)

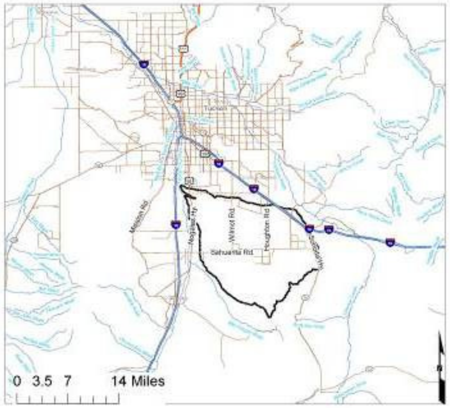
Map 2 - Jackson, Garrett, 1989.
Geologic Map Of The Tucson SE 7.5' Quadrangle, Pima County, Arizona, AZGS Digital Geologic Map 40

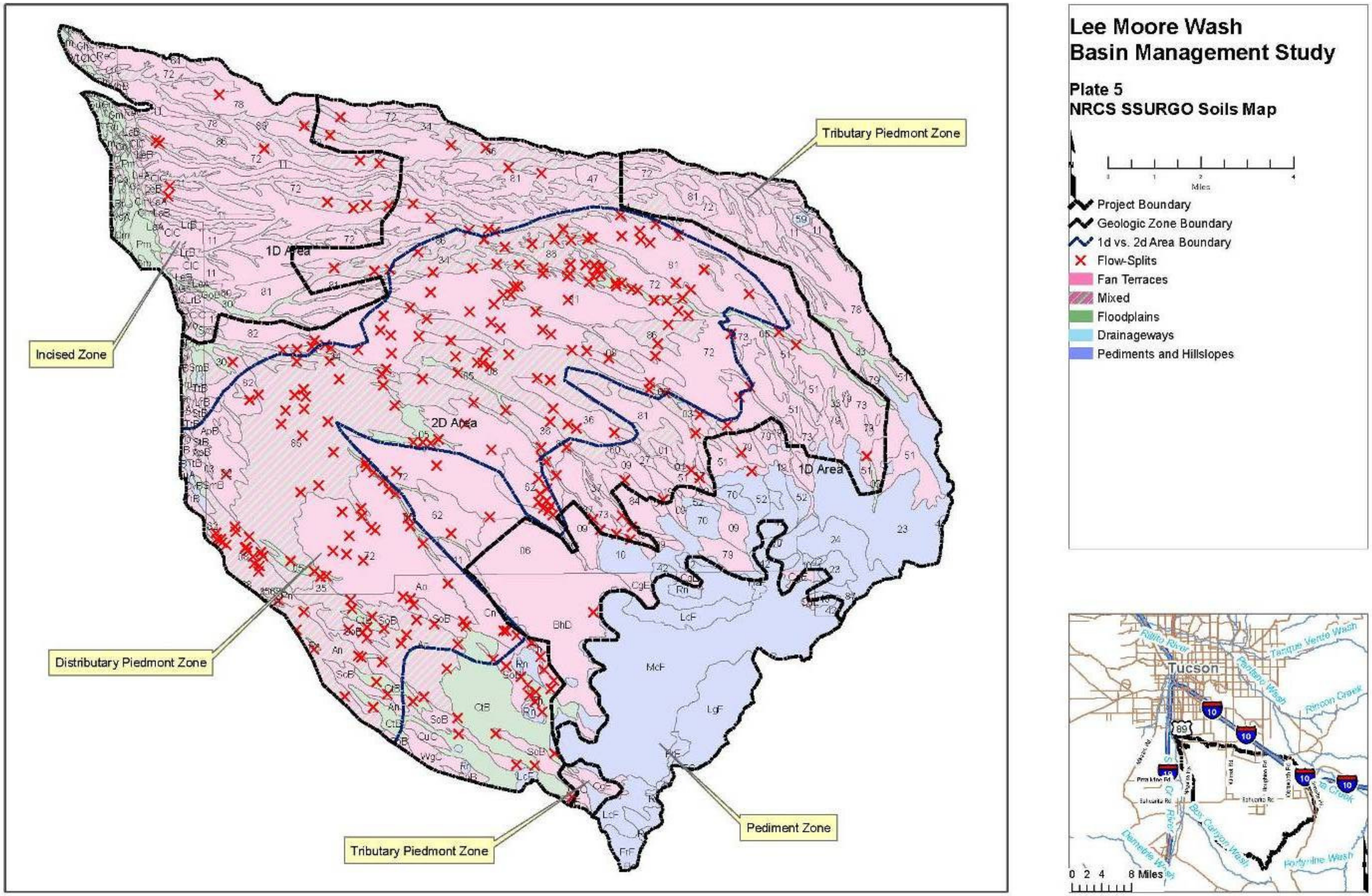
Map 3 - Richard, Stephen M., et. al., 2002 (revised),
Geologic Map Of The Southern Part Of The Vail 7.5' Quadrangle, Eastern Pima County, Arizona, AZGS Digital Geologic Map 12

Map 4 - Pearthree, Philip A. and Youberg, Ann, 2000,
Surficial Geologic Maps And Geologic Hazards Of The Green Valley - Sahuarita Area, Pima County, Arizona, AZGS OFR 00-13

Map 5 - Jackson, Garrett, 1990,
Quaternary Geologic map Of The Corona de Tucson 7.5' Quadrangle, Arizona, AZGS OFR 90-3 (digitized and georectified by JEF)

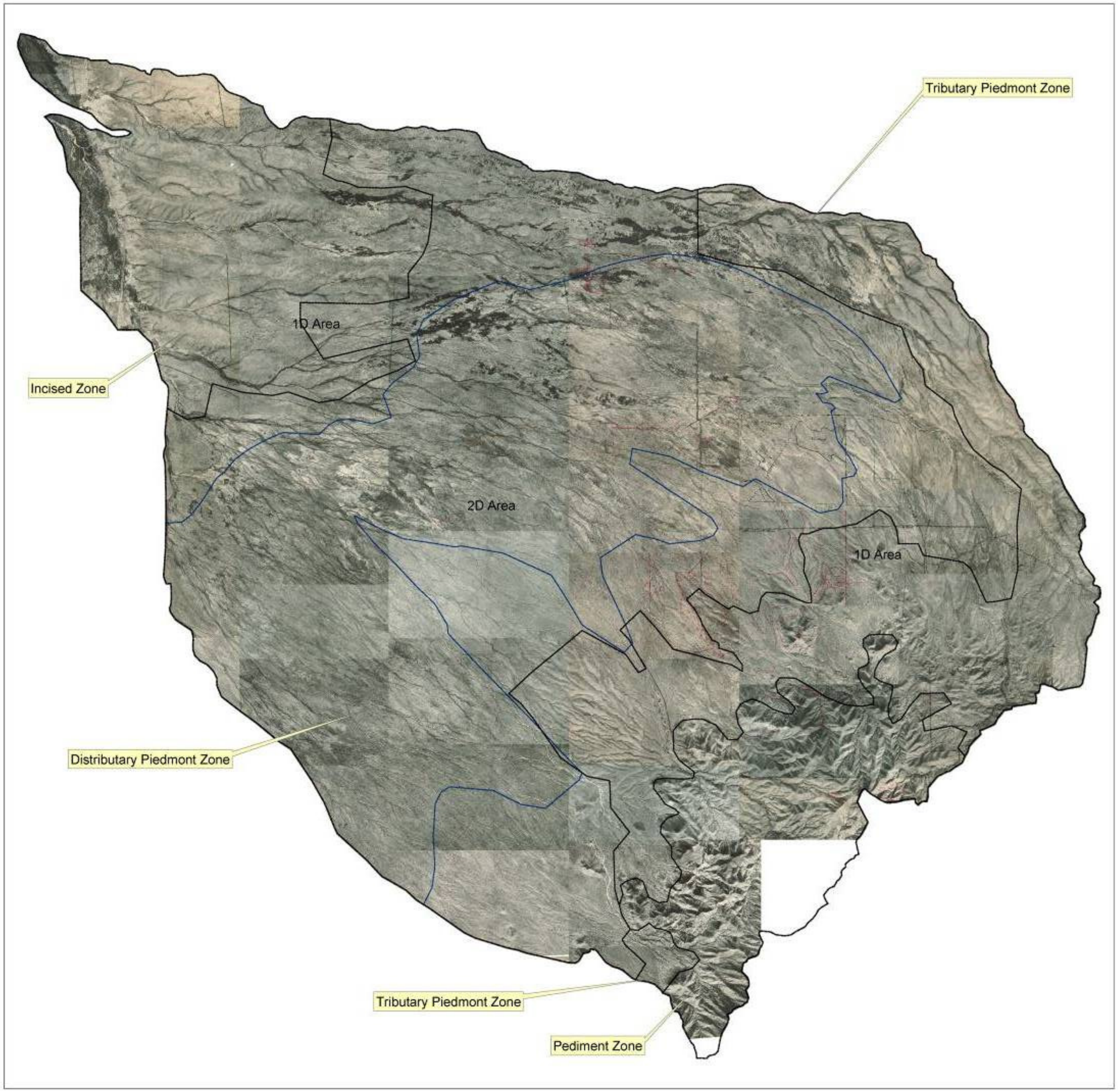
Map 6 - Ferguson, Charles A., et. al., 2002 (revised),
Geologic Map Of The Mount Fagan 7.5' Quadrangle, Eastern Pima County, Arizona, AZGS Digital Geologic Map 11





Lee Moore Wash Basin Management Study

Plate 5
NRCS SSURGO Soils Map

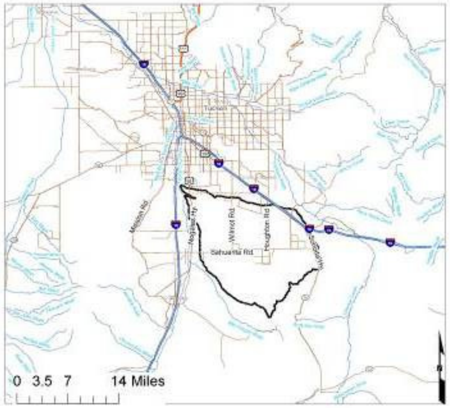


Lee Moore Wash
Basin Management Study

Plate 6
1936 Aerial Map

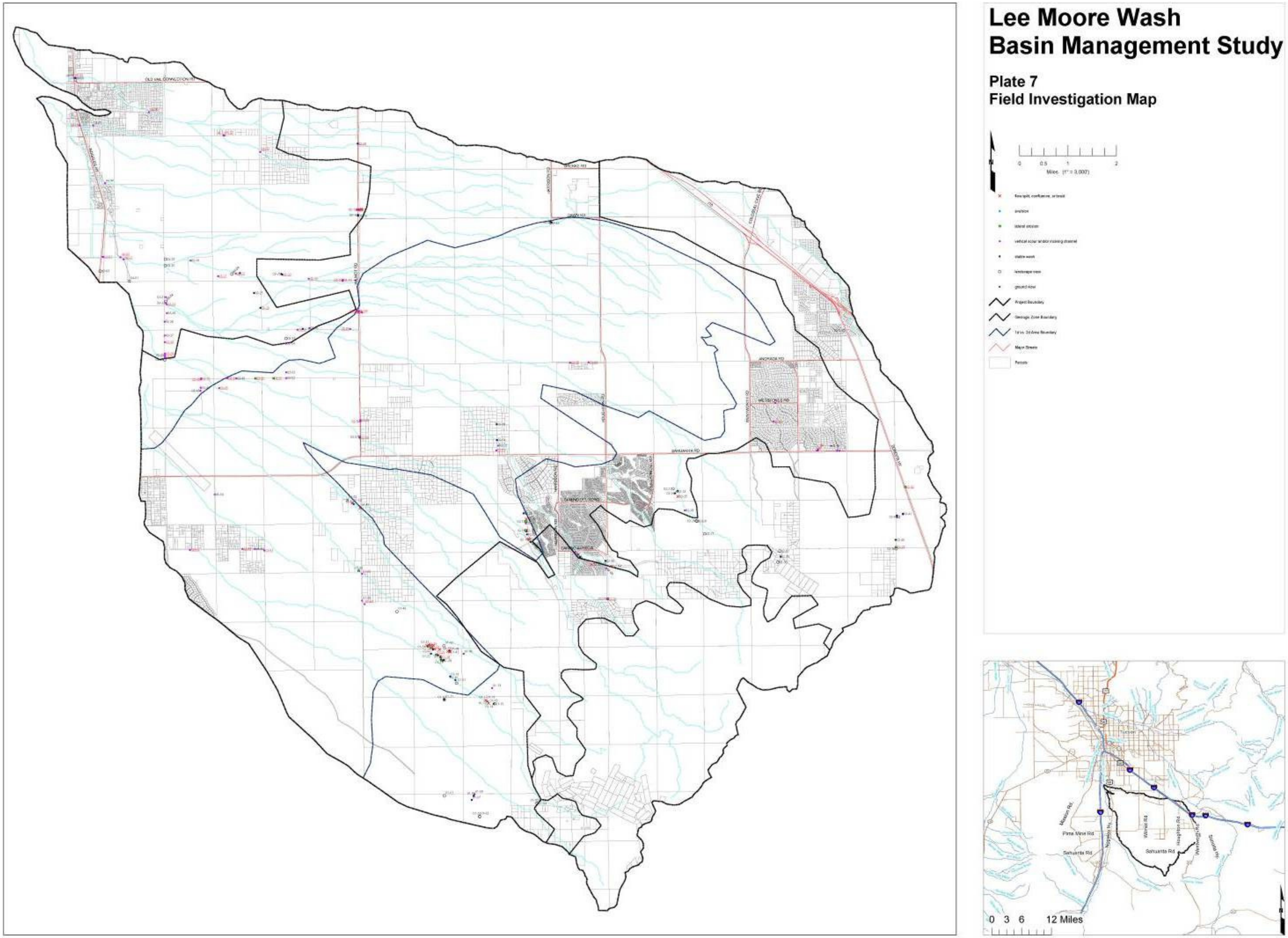
N
0 0.5 1 2
Miles (1" = 3,000')

Project Boundary
Geologic Zone Boundary
1d vs. 2d Area Boundary



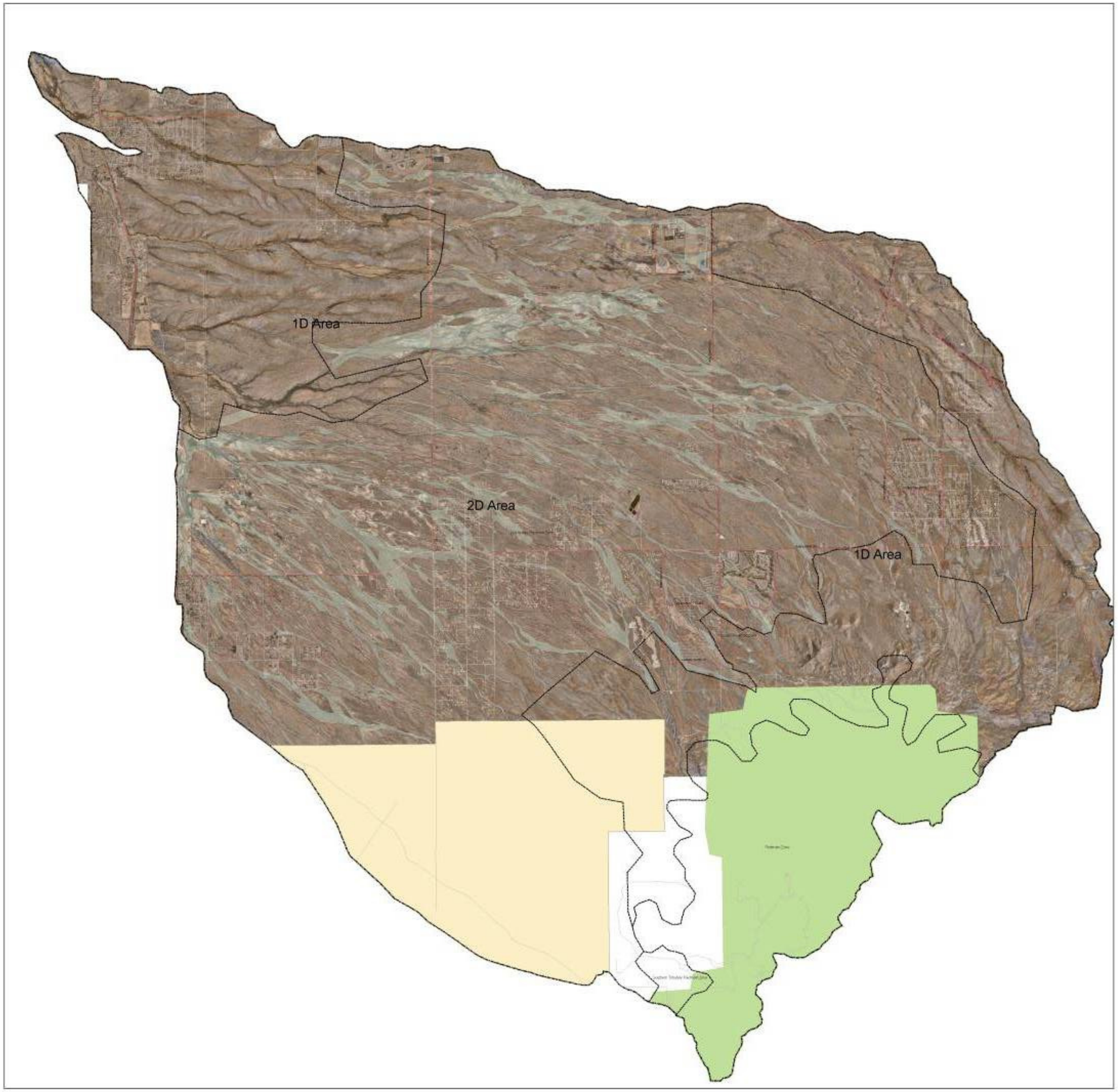
Lee Moore Wash
Basin Management Study

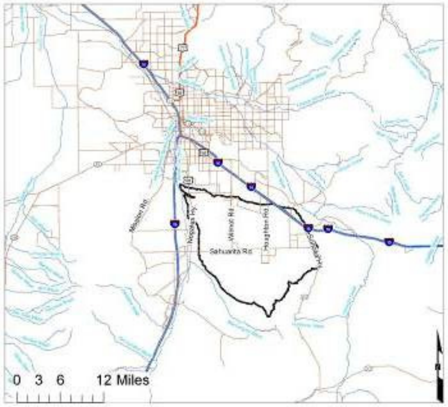
Plate 7
Field Investigation Map



Lee Moore Wash Basin Management Study

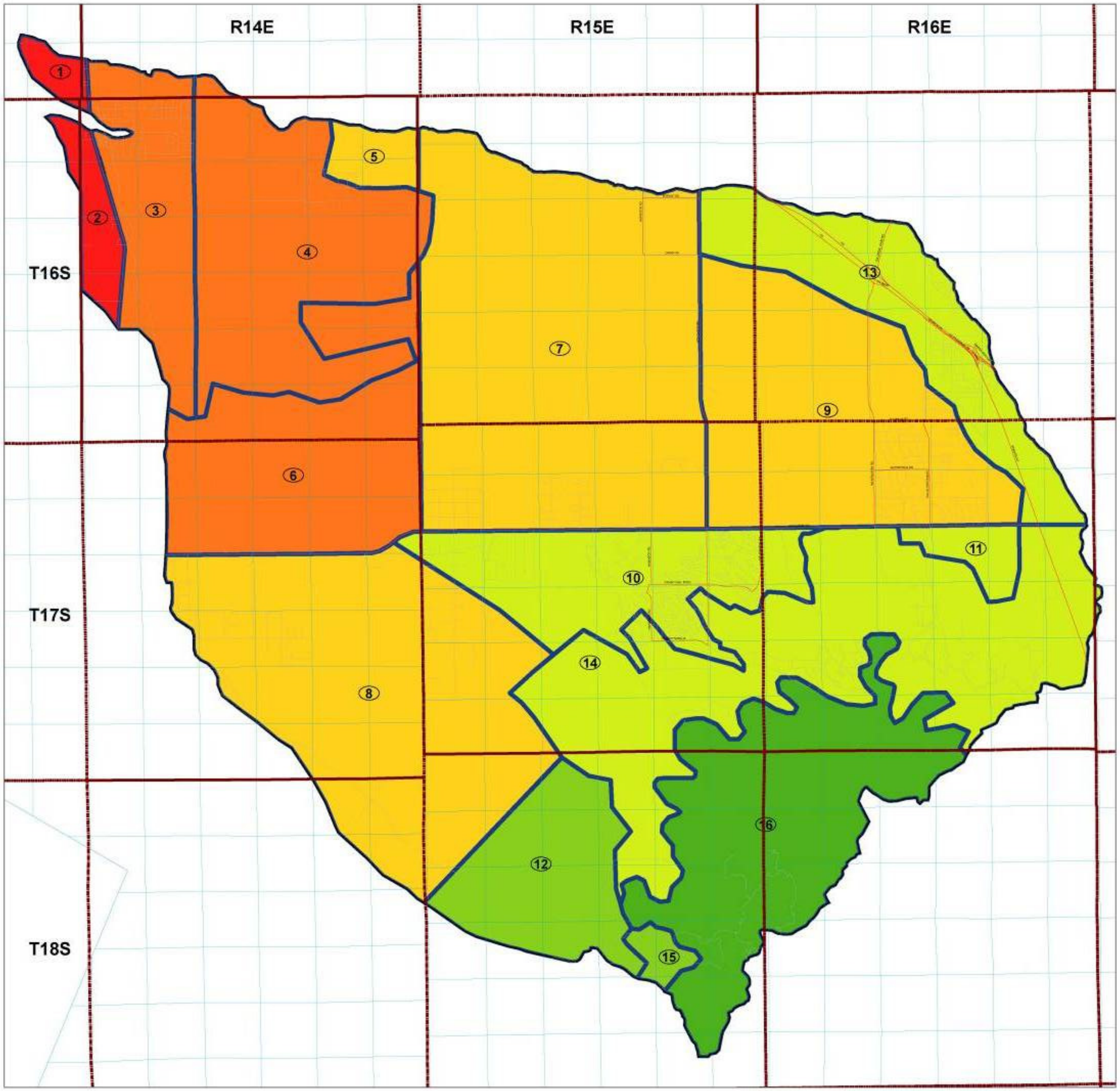
Plate 8
Flow Corridors





Lee Moore Wash
Basin Management Study

Plate 9
Geomorphic Related Hazards Map
Headcutting Hazards



Geomorphic Hazards Assessment			
Area Label	Headcut Assessment	Lateral Erosion Assessment	Lateral Migration Assessment
1 - Incised Zone Risk Area A	Extreme	Very High	Very High
2 - Incised Zone Risk Area B	Extreme	Extreme	Very High
3 - Incised Zone Risk Area C	Very High	Very High	Moderate
4 - Incised Zone Risk Area D	Very High	Very High	Moderate
5 - Dist. Pied. Zone Risk Area A	High	High	High
6 - Dist. Pied. Zone Risk Area B	Very High	Very High	Very High
7 - Dist. Pied. Zone Risk Area C	High	High	Very High
8 - Dist. Pied. Zone Risk Area D	High	High	Very High
9 - Dist. Pied. Zone Risk Area E	High	High	Very High
10 - Dist. Pied. Zone Risk Area F	Moderate	Moderate	Very High
11 - Dist. Pied. Zone Risk Area G	Moderate	Moderate	Moderate
12 - Dist. Pied. Zone Risk Area H	Low	Low	Moderate
13 - Trib. Pied. Zone Risk Area A	Moderate	Moderate	Moderate
14 - Trib. Pied. Zone Risk Area B	Moderate	Low	Low
15 - Trib. Pied. Zone Risk Area C	Low	Low	Low
16 - Piedmont Zone Risk Area	Negligible	Negligible	Negligible