# Vulnerability of Borderland Water Resources: Developing Indicators for Selected Watersheds on the U.S. Mexico Border – The Paso del Norte Region

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### Introduction

By the very nature of the physical and human geography of the U.S.-Mexico border region, urban areas and the natural environment in the border region exist under a condition of water stress. Water is often not available in the quantities and quality to meet a wide range of ecosystem and human development needs. This situation has been recognized in a wide range of governmental reports and applied research efforts investigating border water resources (Brown et al. 2002; GNEB 2000; and Turner, Hamlyn, and Ibanez 2002), and other research has focused specifically on water quality issues within the Rio Grande/Rio Bravo Basin (Texas Natural Resource and Conservation Commission 1996).

Due to its rapidly increasing population, extremely arid nature, and economic importance to the US-Mexico border region, the Paso del Norte region is especially worthy of investigation. This sub-region of the Rio Grande Basin is defined by its position at the conjunction of three states and an international boundary, limited rainfall, and scarce water resources. The Paso del Norte region sits at the intersection of New Mexico, Texas and Chihuahua, where the Rio Grande – Rio Bravo shifts from being a transboundary to a boundary river. Like many other twin city areas, it is characterized by burgeoning growth, vast expanses of land, limited economic resources, and isolation from other population centers.   When defined by water issues, the Paso del Norte begins at Elephant Butte Dam in New Mexico and ends at the twin towns of Ft. Quitman, Texas and Cajoncitos, Chihuahua.  See Figure 1 for additional locational data (Paso del Norte Water Task Force 2001).

The region's geography is determined by a series of isolated mountain ranges -the Franklin Mountains in Texas, the Organ Mountains in New Mexico and the Sierra de Juárez in Mexico-and a wide basin through which the Rio Grande flows.  The area is semi-arid, receives on average 8.5 inches of rainfall annually, has approximately 64 inches of net annual evaporation, and is at the northernmost end of the Chihuahua Desert ecosystem. Regional elevation is approximately 4,000 feet above sea level, and temperatures can range from 117$^{o}$F on summer days to below freezing on winter nights.

The most dramatic temperature changes are found in the winter, where daytime and nighttime temperatures can shift as much as 40°F, causing inversions that dramatically affect air quality (Paso del Norte Water Task Force 2001).

The principal cities are Las Cruces, New Mexico, El Paso, Texas, and Ciudad Juárez, Chihuahua; the combined population of these cities and their outlying urban areas was 2,210,459 as of 2000 (Paso del Norte Water Task Force 2001). Although the combined population of the San Diego-Tijuana region is greater, the international urban area formed by El Paso-Juárez is the largest community directly on the United States-Mexico border. That population is generally young, predominately Hispanic and relatively poor. The region has experienced rapid population growth since the 1950's, and at current rates of growth -approximately three percent per year- the regional population will double in just over 20 years. All of these factors contribute to regional water stress and also pose a range of vulnerabilities to regional water resources and underlying environmental quality (Paso del Norte Water Task Force 2001).

In this project funded by the Southwest Consortium for Environmental Research and Policy (SCERP), researchers examine the vulnerability of the Paso del Norte region of the Rio Grande/Rio Bravo watershed, specifically the vulnerability of watersheds with respect to water quality, ecosystem viability, and socio/economic development activities. Although this project report specifically discusses this work in the Paso del Norte region, the project team coordinated this research with colleagues at San Diego State University (SDSU) who conducted a companion project in the Tijuana River Watershed. In this project, a framework developed previously by Hurd and others to examine the vulnerability of watersheds in a national context (Hurd et al. 1998 and 1999) was employed. This earlier work by Hurd that employed this framework was highly successful at the national level employing four digit United States Geologic Survey (USGS) hydrologic unit classification (HUC) watersheds. These project efforts sought to sharpen the spatial scale of analysis to be consistent with the six or eight digit USGS HUC watersheds in both U.S. and Mexican border watersheds, allowing a finer spatial resolution to be advanced.

## RESEARCH OBJECTIVES

An indicator of water resource or watershed vulnerability is a metric by which the condition or health of a watershed or drainage catchment and its underlying elements may be gauged (United States Environmental Protection Agency [USEPA] 1997). The overall objective of this project is to develop a methodology for assessing the vulnerability of the Paso del Norte region of the Rio Grande Basin. Existing measures, for example, the USEPA Index of Watershed Indicators (USEPA 1997) and those found in Hurd (1999), are the starting point of this work and are reviewed and examined for applicability and appropriateness to the border situation in general, and the project study area in particular. Upon this foundation, the project team then developed region specific indicators of watershed vulnerability based on the analysis of appropriate geo-spatial data within a geographic information system (GIS) analytical framework.

The research team sought to identify three related components of watershed vulnerability indicators, namely underlying sources of vulnerability (i.e. groundwater overdraft), a specific indicator by which this could be measured (i.e. change in aquifer storage), and the underlying geo-spatial data on which the indicator could be built (i.e change in depth to water over time). Through this approach, a common geo-spatial dataset is developed that supports further applied water quality and related policy research in border watersheds.

The assessment of vulnerability in the PDN region highlights regions and subjects of critical concern and lays the primary information foundation necessary for subsequent policy action. The client for this project is the Paso del Norte Watershed Council, a group whose mission and mandate it is to "to explore how water-related resources can best be balanced to benefit the Rio Grande ecosystem and the interests of all watershed stakeholders" (PDNWC 2002). This project is highly consistent with and supportive of the Council's efforts and mission. For example, a current area of investigation of the Council is the development of a 'biological assessment and management plan.' To insure that our efforts are consistent with the Watershed Council's work in this area, Christopher Brown, Project Principal Investigator and member of the PDNWC Executive Committee serves as project coordinator to the Watershed Council. The results of the project will be served through the Council's webpage as a vehicle to disseminate these findings, with a special interest in sharing the GIS output of the project with regional stakeholders and interested parties.

A major goal of the project is to develop a consistent, cross-border geo-spatial framework and database, inventory of available resources, and measures of the current condition of water resources. Each of these elements is necessary for the development and implementation of a comprehensive and forward-looking border water management plan in this region, which is consistent with the mission of the Watershed Council. This methodology may also be instrumental in helping advance the larger scope of indicators supporting Border 2012. The degree to which this proposed work achieves its goals will be determined by how well the project supports the work of the PDNWC in its biological assessment, and by how useful the outcomes are to related work in other border basins.

## RESEARCH METHODOLOGIES/APPROACHES

As noted above, the work conducted in this project builds on the earlier work of Hurd et al. (1999), and this research also expands on the work of Brady, Wright et al. that was conducted under the Transboundary Watersheds Research Program (TWRP -SCERP 2002). The TWRP sought to "… investigate the interdependencies and feedback mechanisms among ecological, economic, social, and political factors influencing land use." Although the approach of TWRP was highly valid in employing a watershed perspective in this work, the results indicated that modeling tools developed in humid regions of the U.S. did not perform well in the arid Southwest. This project seeks to build on this result by ensuring that the indicators being used are relevant and appropriate to working in arid watersheds. The specific steps of the project that involve the quality, consistency, and availability of data are noted below.

*Subtask 1. Literature Review and Assessment*

Initial work in the project focused on a review and assessment of the scientific literature on indicators, including USEPA (1997), Hurd et al. (1999), Rogers (1997), and Lane (1999). The intent of this literature review is to inventory the work to date on indicators of vulnerability, provide a foundation for more detailed examination, and begin to explore how to develop indicators more appropriate for arid border watersheds. A secondary outcome of this early work was to develop a "reading list" of select literature that was provided to scientists from the U.S. and Mexico in preparation of the binational Experts Panel to be discussed below.

*Subtask 2. Identify and Convene a Panel of Experts*

Following the initial screening of indicators from Subtask 1, a two-day workshop was convened to examine the suitability and appropriateness of indicators uncovered in Subtask 1, as well as to search for possible additional indicators. The workshop, convened in Las Cruces, New Mexico, brought together twenty water resource experts from the United States and Mexico across a variety of disciplines to consider indicator selection criteria, data availability, geographic resolution, and commensurability of possible indicators across both sides of the border. Christopher Brown and Janet Greenlee at NMSU, and Richard Wright at SDSU worked together to identify, invite, and "deliver" experts from the U.S., and Alfredo Granados worked to identify, invite, and "deliver" experts from Mexico.[1] A roster of the workshop attendees is provided as Table 1 in this report.

The specific charge given to the panel was to "develop a set of indicators characterizing and representative of the vulnerability, sensitivity, variability, and adaptive capacity of the watershed's water resources that are transparent and readily applied from existing and available data." The project team specifically posed the following trigger questions to the experts attending:

- What are the key sources of water resource vulnerability in arid border watersheds?
- What are potential indicators of these key sources of vulnerability?
- What data sources should be employed in constructing such indicators?
- Specifically, what is meant by the concept of vulnerability with respect to water resources? (This last question was not one of the original questions posed to conference attendees; rather, it arose in subsequent discussion).

[1] The successful identification and recruitment of the Mexican scientists that attended the conference was a very important element to this project, as it helped to insure the project had legitimate binational participation and a Mexican perspective to the underlying research. Dr. Granados' work in this area was critical and deserves considerable recognition.

Out of this discussion, several tables were developed that detailed the sources of water resource vulnerability, indicators by which these sources could be studied, and the geo-spatial data that would be required to build these indicators. The experts that attended the workshop then reviewed these tables, and a final set of working tables was compiled which guided project work. This work was conducted both in the Paso del Norte region within which the NMSU/UACJ team is working and the Tijuana River Watershed within which the SDSU/el Colegio de la Frontera Norte team is working. Copies of these data tables are included as Tables 2 and 3 in this document. Table 2 details the responses to the trigger questions, and Table 3 details the "Omissions, Biases, and Uncertainties (OBU)" that came from the Experts Panel discussion. These latter issues did not fit into the context of specific indicators as detailed in Table 1, but the research team deemed these issues important enough to be noted in project documentation.

A specific effort was made to include members of the SDSU team, allowing both proposed projects that seek to examine vulnerability indicators to benefit from this Expert Panel. The panel provided guidance for this initial phase and also served as a quality assurance check through the peer-review of analysis and reporting; a special effort was made to examine the overall issue of quality control/quality assurance for the project. To initiate the workshop, each expert was invited to give a brief presentation on their perspective on possible indicators and data sources appropriate to borderland water issues. The importance of this Subtask is underscored by the experience reported in Hurd (1998) in which several of the indicators "that emerged after the panel discussions were significantly different than those originally identified." The crosscutting expertise of the panel is designed to be an effective guard against unreasonable or unattainable objectives. Through discussions and interactions, the expert panel helped bridge gaps between what is desirable from a theoretical basis and what is reasonable and feasible.

*Subtask 3. Identify Criteria for Selecting Indicators*

During the workshop, selection criteria for target indicators were discussed. Discussion began with the USEPA Index of Watershed Indicators as a starting point; these indicators were then refined to be more appropriate for arid border watersheds. This process borrowed from Hurd at al. (1998), who identified the following selection criteria that may serve as an initial starting point for guiding the indicator selection process:

- Appropriateness and relevance to the underlying sensitivities and vulnerabilities - does a given indicator accurately measure sensitivity and vulnerability?

- Transparency of the structure and content - is the indicator readily understandable by users?

- Feasibility of compiling the indicator based on data availability and timeframe - can the data be collected and indicators developed for each region within a reasonable time period?

- The degree to which indicators can be closely linked to specific policy recommendations – can changes in policy be gauged to see how effective they may be by examining how the indicator in question behaves after the policy change?

*Subtask 4. Prepare Interim Report on Proposed Indicators and Criteria*

Following the workshop and the above-referenced work on selecting relevant indicators and the data needed to build them, an interim report in the form of Tables 2 and 3 mentioned previously was prepared to summarize the workshop outcomes, including the selection of indicators and criteria for evaluating potential vulnerability. The project team solicited input from participants in the workshop, and their input was incorporated, yielding the final versions of the tables included in this final project report.

*Subtask 5. Design GIS Framework, Assemble Data, and Develop Indicators*

Based on the input from the Expert Panel members, work in this Subtask addressed the collection and assembly of the underlying data, design of the geographic information system (GIS) framework, and the development of the indicators and application of the vulnerability criteria. One of the major challenges facing all who pursue GIS analysis in a cross-border or transborder context is the difficulty in identifying and obtaining comparable datasets on both sides of international borders (Wright and Winckell 1998 and Wright et al. 2000). Accordingly, a very important element of GIS analysis in the project is that of data integration across the border, specifically concerning how the spatial scale of six or eight digit USGS HUC watersheds would be implemented across the border. Researchers at SDSU (Richard Wright), NMSU (Christopher Brown and Janet Greenlee), and UACJ (Alfredo Granados) with extensive experience conducting cross border GIS data compilation and GIS analysis took the lead on this particularly important subtask, and research staff at UACJ and NMSU (Marguerite Hendrie and Nori Koehler at NMSU, Hugo Luis Rojas and Nora Reyes Villegas at UACJ) conducted the actual data mining, compilation and analysis work involved.

Considerable effort was spent on “fine tuning” the actual area of investigation from a hydrologic perspective. The Paso del Norte region is very well known as a socio-economic region within which the urban areas of interest are located, and this region is also reasonably well defined topographically as was discussed earlier in this document. However, “the box” that is defined in Figure 1 is not well defined from a hydrologic perspective; put simply, hydrologic sub-regions (HUCs, watersheds, or sub-basins) are not defined in commonly used maps of the region. Accordingly, project staff spent a good deal of time conducting a literature review of GIS-based tools to delineate hydrologic regions and working to implement various routines in commonly available GIS tools.

The major pieces of research examined included Omernik (1987, 1997, and 2003), Verdin and Verdin (1999), and Figurski and Maidment (2001), and staff worked with numerous variations of digital elevation model (DEM) data and related topographically based GIS analyses in attempting to generate a hydrologically-based sub-regionalization of the study area. In this work, staff encountered a range of problems including software routines errorring out due to massive data sets and processing limitations, data compatibility problems, and some very interesting complications arising from the Tularosa Basin being a closed hydrological basin. After much discussion with experts on the regional hydrology, project staff decided on a hydro-regionalization developed by Kennedy and Hawley (2003) that is based on USGS HUCs in the US and 1:250,000 surface hydrology maps compiled by el Institute Nacional de Estadistica Geografía y Informatica (INEGI) for Mexico. This became the "target basins" frame of reference used for the balance of the project, as detailed in Figure 2.

With the target basins area clearly delineated in a GIS framework, the next step in the GIS analysis was the compilation of relevant data sets in the US and Mexican parts of the study area at the appropriate scale that each indicator required. This effort involved project PIs and research staff at both NMSU and UACJ, and staff spent several weeks combing Internet GIS data sources and government publications at a range of research institutions in the US and Mexico and contacting numerous people at regional, state, and national data providers. This effort was driven by the indicators detailed in Tables 2 and 3, and the goal of this data mining and compilation efforts was to "fill in the blanks" in these tables and identify and compile the actual GIS data layers that would drive the development of the relevant indicators of watershed vulnerability.

Concurrent with the data compilation effort, project staff also conducted a literature review into the basic GIS processing that would be needed to develop the indicators that are detailed in Tables 2 and 3, and this literature review supported extensive discussions among project staff at NMSU and UACJ as to how the specific indicators could be developed in a GIS framework. These discussions were tempered by the realities of data availability; in some cases, indicators that were noted as important and desirable to develop were dropped from the analysis due to problems obtaining needed cross-border geo-spatial data at the appropriate scale. Once the target indicators were finalized and the basic processing steps identified, the actual GIS processing workload was parceled out to the project teams working at UACJ and NMSU. Details of the indicators and processing steps involved are provided in the results section of this document.

*Subtask 6. Report and Documentation*

At various stages of the project, results and findings have been documented through a series of presentations at SCERP-related meetings and in other professional outlets as determined appropriate. These presentations are detailed in the research findings section below. Findings will additionally be reported in research articles to be submitted to appropriate scientific journals. At the time of the completion of this final project report, two such articles are in the process of being completed, one on the results of the hydroregionalization work that was done in the early stages of the GIS analysis, and a second article discussing the mapping of specific indicators in a GIS framework. The project team is also working with Dr. Alfredo Granados at UACJ to submit Spanish language versions of these publications to journals in Mexico.

Related to this sharing of results, we are also undertaking outreach activities with our client, the Paso del Norte Watershed Council, and we will also work to develop a relationship with similar outreach organizations in the Ciudad Juárez region to share as widely as possible the results of our research. Linked to this outreach is ongoing work to post the results of this project at an NMSU/SCERP GIS Data Node that is related to another SCERP Project, "Assessment, Inventory, and Strategy for a Coordinated United States – Mexico Border Region Water Resource Geographic Information System" (Project # EIR-05-03). The URL for this Data Node is http://mapper.nmsu.edu/SCERP, and project staff will be posting results of this project as part of the research activities of this more recent SCERP project.

## PROBLEMS AND ISSUES ENCOUNTERED

This project has presented considerable challenges, some of which were noted in the Experts Panel meeting held in Las Cruces, and others that were not anticipated. The majority of these relate to the availability of data needed to construct the indicators that project staff sought to develop and a realization that the work we sought to complete was of a much larger scope and scale than the level of funding that was granted to the project team.

The overarching challenge that the project faced was obtaining geo-spatial data at the appropriate scale and resolution that covered the US and Mexican parts of the study area. As indicated in Figure 1, the study area spans two countries, the US and Mexico, and three states, Texas, New Mexico, and Chihuahua. Geo-spatial data are collected by many different agencies at the federal, state, and regional level across the study area, and each of these agencies executes this data collection and compilation to meet **their own internal needs**. Little if any coordination is evident in this effort, and the end result is that various data layers are complied at different spatial scale and resolution, include different topical variables, and employ different classification systems. Related to this are spatial gaps where comparable data for specific variables are simply not available, a fact that leads to the "blank part" of cross-border maps. This latter concern was especially evident in the rural areas of the Mexican part of the study area.

The project team also experienced difficulty in obtaining adequate and appropriate data at the sub-basin level, a concern that was discussed at some length in the Experts Panel meeting. The initial intent of the project was to "borrow the method" successfully employed by Hurd et al. (1998 and 1999) who examined water resource vulnerability at the four digit HUC scale, specifically employing a wide range of data readily available via US governmental agencies for these 204 sub-basins in the coterminous US. Despite extensive efforts at identifying and obtaining needed data in the study area, project staff often found data at a much coarser resolution that lacked the spatial variability that was needed to map vulnerability at the sub-basin level depicted in Figure 2. These challenges are related directly to the criteria discussed in the Experts Panel as noted on page six of this report; namely, are data available at the proper scale, and does adequate spatial variability exist on the landscape to support analysis at the scale of the sub-basins in our study area? Based on the experience of the project, the answer to these related questions is "not for the entire study area and not for all the variables involved."

As noted earlier, project staff also spent a good deal of time exploring GIS-based techniques to delineate an "anthropogenic hydrosphere," a series of sub-basins that would allow the analysis of indicators of "natural environmental dynamics" and human-induced impacts on the viability of watersheds and related ecosystem health. Due to the problems discussed above concerning software routines errorring out due to massive data sets and processing limitations, data compatibility problems, and some very interesting complications arising from the Tularosa Basin being a closed hydrological basin, these efforts were unsuccessful in generating the sub-basins that we sought to delineate. However, this was a particularly interesting area of investigation that certain members of the project team may examine in future work.

## RESEARCH FINDINGS

### *General findings*

As noted above in the discussion of problems encountered, data availability issues were a considerable impediment to achieving the goals of this project, and a particular issue related to this is that of data fusion, the compiling and integration of disparate geo-spatial data across political, administrative, and institutional boundaries, and across scale and resolution. The project outcome that is of notable importance to SCERP and border researchers that seek to do cross-border GIS analysis is that **much more work needs to be done to tackle these data fusion challenges than has been done in the past**. Based on the experience of the project team, **successful efforts at cross-border data integration and fusion on the U.S.-Mexico border will require a multi-institutional effort over a series of years and a commitment of financial resources orders of magnitude greater than have been previously committed by interested agencies**. This finding reinforces the value of the "roadmap concept" that SCERP has funded in the project discussed previously, "Assessment, Inventory, and Strategy for a Coordinated United States – Mexico Border Region Water Resource Geographic Information System" (Project # EIR-05-03).

Related to this general issue of data fusion are the questions posed above concerning the role of scale and resolution; are data available at the proper scale, and does adequate spatial variability exist on the landscape to support analysis at the scale of the sub-basins in our study area? Based on the experience of the project, the answer to these related questions is "not for the entire study area and not for all the variables involved." Although this is not the finding one would hope to come from a project like this, it is nonetheless an important finding to share with the larger research community.

The above notwithstanding, the project team did generate important positive outcomes, and these outcomes were due in large part to the commitment of a capable binational and multi-institutional team consisting of staff and faculty at SDSU, NMSU, and UACJ. It is the authors' firm conviction that the model that SCERP has advanced of assembling and funding interdisciplinary and binational research teams to advance important applied environmental research is critical to the success of such efforts.

*GIS Mapping and Analysis Products*

The driving intent of this project was to compile and analyze a range of geo-spatial data towards the development of indicators of watershed and water resource vulnerability and to then map the spatial variability of these indicators. An important early step in this work is the compilation and management of these geo-spatial data, and project staff have done this important step and also made these data available through the Internet at http://mapper.nmsu.edu/SCERP, as introduced previously. Through ongoing efforts of the project, "Assessment, Inventory, and Strategy for a Coordinated United States – Mexico Border Region Water Resource Geographic Information System" (Project # EIR-05-03), additional GIS data and map products will be posted to this site in the future.

The end results of the GIS work conducted in this project are a series of map products that display the spatial variability of the relevant indicators examined. The data and processes involved in these map products are discussed below, and the actual map products are included as figures in this report, as noted below:

**Evapotranspiration –** Evapotranspiration (ET) is the combined process by which plants transpire water and surface water evaporates into the atmosphere. As such, this process can be seen as a measure of the relative dryness of the regional climate. ET maps describe areas where water is likely to be a limiting factor in agricultural production, ecosystems, and in some domestic uses such as lawns and gardens, and where evaporation losses are highest. ET is sensitive to changes in both temperature and precipitation and can be interpreted as a direct physical measure of a region's vulnerability to changes in climate and related water stress (Hurd et al. 1999).

To map ET, the project team downloaded ASCII GRID ET data from the Food and Agriculture Organization website. Team members then ran an area weighted average algorithm on the GRID data and the target basin boundaries to examine how the underlying statistical support of the GRID data would be distributed across the sub-basins in the study area. The product of this analysis is found in Figure 3.

**Groundwater potential –** Much of the urban water supply in the study area is derived from groundwater resources, and agriculture also relies heavily on this resource, especially during times of surface water drought. In general, derivation of this indicator requires a thorough knowledge of groundwater hydrology and geomorphology and is best-accomplished using complex spatial analysis involving the modeling of several variables. Relevant parameters include lithology, geomorphic units, frequency of lineaments, drainage density, slope (as derived from DEM), land use and land cover, and other subsurface information such as depth to water. This level of analysis was beyond the scope of the project, and project staff were also limited to the spatial extent for which select source data were available, namely the Mexican part of the basin.

To map groundwater availability, an INEGI dataset depicting groundwater potential in a polygon map was used as the input dataset, as indicated in Figure 4. This dataset was converted into a GRID, and zonal statistics were then run, using the target basins file for Mexico as the input feature dataset and the statistics type as mean. The resulting raster dataset is then converted back to a polygon dataset and displayed with three classes to represent low, medium, and high potential for groundwater, as depicted in Figure 5. The lack of data on the US side of the border highlights the data access issues noted above in the problems encountered section of this report.

**Groundwater salinity –** As noted above, groundwater resources are especially important as a regional water supply, both for municipal/industrial and agricultural uses. However, salinity above 1000 ppm poses risks to agriculture and urban uses, and this makes for a reasonable threshold for a groundwater quality analysis. Due to the broad study area and the few points of data located on the zone of interest, contours of concentration for TDS were created based on minimum data and extrapolated to a considerable region without taking into consideration the geomorphology or the sedimentation processes of the watersheds. Hence, the resulting layers of concentration are questionable since these are extrapolated regions under a GIS spatial analysis considering only the points that had TDS data within the complete study area, without taking into consideration the potential natural subsurface barriers or geological structures within the watersheds of analysis.

Data were selected from groundwater sampling years 1982 till 1985 from a US dataset, and these data were merged with data for the same period of time from a database created by INEGI. This generated a common groundwater quality layer, and two classes were assigned to the data in which levels <1000 parts per million (ppm) were considered a low concentration and levels >1000 ppm were considered a high concentration. A zonal statistics routine was then run on the shallow and deep groundwater quality layers to distribute the underlying statistical support across the area of the sub-basins. These processes were completed for shallow alluvial groundwater near the river and also for deep groundwater located in the majority of the study area. These products where finally converted to shape files which represented the contours of concentration for TDS for both shallow alluvial groundwater and deeper groundwater, as detailed in Figures 6 and 7.The authors are comfortable with the end result of this analysis for the shallow aquifers in Figure 6, but Figure 7 raises some questions due to the underlying statistical support not extending throughout the entire study area.

**Population change** – As was recognized at the Experts Panel meeting, population growth in arid watersheds like those on the U.S.-Mexico border is a driving factor for many sources of vulnerability of regional water resources (i.e. groundwater overdraft, over allocation of surface water resources, and negative impacts on groundwater and surface water quality). Accordingly, project staff compiled US Census and INEGI population data for the study area for the years 1990 and 2000 and mapped the population change across the target basins. Source data were input as polygon files and converted to the GRID data format, at which point zonal statistics were run on these population data and the target basins, with the statistics type as mean. The final product of this analysis is noted as Figure 8. Examination of this map indicates that the major growth was in the urban areas; by overlaying an urban mask on the resulting map, this influence can be visualized. Given that the reporting units employed are the sub-basins and that the zonal statistics method employs mean values for the sub-basin, the final map for this indicator does show that by far the largest growth occurs in the PdN region.

**Salinity** – Given the potential for salinity impacts on agricultural soils and activity, project staff examined a range of data from the Natural Resource Conservation Service (NRCSS) Soil Survey Geographic (SSURGO) Database in an effort to map the potential risk to row crops and tree crops, both as regards soil salinity (expressed as electrical conductivity (EC) of soil as saturated paste) and sodicity (expressed as the Sodium Absorption Ration (SAR) for soil layer or horizon). Again, project staff were faced with data limitation problems; these data are not available for the Mexican part of the study area, and only tabular data lacking a geo-spatial dimension were available for Socorro County, NM and Hudspeth County, TX.

To generate soil salinity and sodicity maps for these counties, source polygon data were extracted from the NRCS SSURGO database and converted to the GRID data format. These data were then reclassified based on low, medium and high potential risk to the relevant crops, based on reference data provided by the Natural Resource Service and the Colorado State University Cooperation Service. Output GRIDS were then converted back to polygon data formats, and the final map products are noted as Figures 9, 10, 11, and 12. Examination of these maps indicates that both row and tree crops in the sub-basins mapped see very low risk from sodic soils, but higher risk and much greater variability in risk results from saline soils. In particular, saline soils pose a greater risk to tree crops, especially in the eastern most part of the study area in which the Tularosa Basin is located.

**Standardized Precipitation Index (SPI) as a measure of drought** – The Standardized Precipitation Index (SPI) is a tool that was developed primarily for defining and monitoring drought. It allows an analyst to determine the rarity of a drought at a given time scale (temporal resolution) of interest for any rainfall station with historic data. It can also be used to determine periods of anomalously wet events, but the SPI is not a drought or precipitation prediction tool. The recognition that shortfalls of precipitation relative to regional water demand negatively impact groundwater, reservoir storage, soil moisture, snowpack, and streamflow drove the development of the Standardized Precipitation Index (McKee, Doesken, and Kleist 1993). Positive SPI values indicate greater than median precipitation, and negative values indicate less than median precipitation. Because the SPI is normalized, wetter and drier climates can be represented in the same way, and wet periods can also be monitored using the SPI.

To produce the SPI map for the study area, project staff downloaded SPI data for the US side of the study area from the Spatial Climate Analysis Service at Oregon State University (http://www.ocs.orst.edu/prism). SPI data for the Mexican portion of the Study area were obtained from UACJ as a point file for eight stations (although three of those stations share the same latitude/longitude values). Average values were computed for the Mexican dataset for a 72-month period that was consistent with that for the gridded US dataset. The datasets were then merged, and zonal statistics were run to distribute the mean values of SPI over the target basins, with the final product being the map depicted in Figure 14. However analysis of the Mexican SPI data poses some questions as detailed below.

The point file for the Mexican data consists of eight records for eight named stations, but three of the stations share the exact same location (latitude/longitude). In addition, the remaining five stations are all located outside the range of the target basins, so it is not clear how these data values contribute to the interpolated SPI surface in the Mexican target sub-basins.  Figure 13 depicts the unusual nature of the interpolated surface in the Mexican part of the study area, especially the influence of points outside of the study area on the surface. In Figure 14, the zonal statistics function fits these data into the sub-basin framework, but the authors still have questions on the degree to which this output can be defended. This is another example of the data challenges introduced earlier in this report, clearly arguing for further discussion and analysis to determine the correct way to analyze and present these datasets.

**Surface water quality (biochemical oxygen demand (BOD) and fecal coliforms)** – As urban areas in the region turn to surface water as a raw water source, surface water quality becomes increasingly important as a variable contributing to the vulnerability of regional water resources. Based on discussions with regional water experts and past research in border watersheds (Brown, Placchi, and Gersberg 1998 and Gersberg et al. 2000), biochemical oxygen demand (BOD) and fecal coliform concentrations were selected as water quality variables to analyze.

Project staff compiled surface water quality data for these two constituents for the time period of 1 January 2004 to 1 July 2005 from the National Pollution Discharge Elimination System permit databases and the Texas Clean Rivers Program datasets maintained by the International Boundary and Water Commission (http://www.ibwc.state.gov/CRP/Welcome.htm). These point data served as inputs into an interpolation routine that was linked with a dynamic segmentation tool to generate a polygon dataset showing the spatial variability of water quality in various reaches of the main stem of the Rio Grande. These polygonal data were then converted into a GRID dataset, and a zonal statistics function was then run on these gridded data to determine the spatial variability of how different sub-basins are contributing to surface water quality. The final map products of this analysis are noted as Figures 15 and 16. Examination of these maps indicates that the lower reaches of the main stem of the river see poorer water quality on both measures, and the lower sub-basins in the watershed are contributing to this poorer water quality in the river.

**Surface water quality due to wastewater discharges** (**BOD) and fecal coliforms**) – Similar analyses were conducted with the addition of water quality sampling points related to wastewater treatment plants that are discharging treated effluent into the Rio Grande. The same basic processes as those detailed above were run on these data, and the final products of this analysis are noted as Figures 17 and 18. As was the case with the surface water quality indicators previously discussed, examination of these maps indicates that the lower reaches of the main stem of the river see poorer water quality on both measures, and the lower sub-basins in the watershed are contributing to this poorer water quality in the river.

*Project Reporting and Documentation*

As was discussed in the research methods section above, project staff have been active in disseminating results of the project at various stages of work through presentations at research conferences and meetings, and these activities are detailed below:

- Brown, C., A. Granados, J. Greenlee, and B. Hurd. 2005. “Usos de las Sistemas de Información Geográfica para Examinar la Vulnerabilidad de los Recursos Hídricos Regioinales en la Frontéra de México y los Estados Unidos,” a paper presented at the **XVII Semana Internacional de Agronomía**, la Universidad Juárez del Estado del Durango, Facultad de Agronomía y Zootecnia, Gomez Palacio, Mexico. 9 September 2005.

- Brown, C. A. Granados, J. Greenlee, and B. Hurd. 2005. “An Analysis of Water Resource Vulnerability in the Paso del Norte Region of the Rio Grande Watershed,” a project update report presented at the International Conference on Environment and Human Health, 30 March 2005, El Paso, Texas.

- Brown, C., A. Granados, J. Greenlee, M. Hendrie, and B. Hurd. 2004. “Developing Indicators of Water Resource Vulnerability in the Paso del Norte Region.” Paper presented at the 2004 Annual Meeting of the Universities Council on Water Resources. 19 July 2004. Portland, OR.

- Granados, A., C. Brown, and Juan Martínez-Ríos. 2004. “Mapping Ecohydrological Regions with GIS and Remote Sensing for Vulnerability Assessment in the Mexico-US Transboundary Paso del Norte.” Paper presented at the 2004 Annual Meeting of the American Society of Photogrammetry and Remote Sensing, May 2004. Denver, CO.

- Brown, C., A. Granados, J. Greenlee, M. Hendrie, and B. Hurd. 2004. "Preliminary Results of a Study of Water Resource Vulnerability in the Paso del Norte." Paper presented at the 2004 Annual Meeting of the Association for Borderland Studies, 22 April 2004. Salt Lake City, Utah.

- Brown, C., Granados, J. Greenlee, M. Hendrie, B. Hurd, and J. Kennedy. 2004. "A GIS Analysis of Water Resource Vulnerability in the Paso del Norte." Invited paper presented at the New Mexico Tech Hydrology Seminar. 12 April 2004. Socorro, NM.

- Brown, C., A. Granados, J. Greenlee, M. Hendrie, B. Hurd, H. Johnson, and R. Wright. 2004. "An Appropriate Regionalization for Studying Water Resource Vulnerability: The Case of the Paso del Norte." Paper presented at the 2004 Centennial Meeting of the Association of American Geographers, 18 March 2004. Philadelphia, PA.

- Brown, C. 2004. "Water Resources and Watershed Vulnerability in the Paso del Norte." Invited paper presented at ***El Taller de Evaluación Ecohidrológica en Cuencas Transfronterizas en la Frontera México-Estados Unidos***, an international workshop hosted by *la Universidad Autonoma de Ciudad Juarez* on 3 February 2004.

- Brown, C. 2003. "The Hydroregionalization of an Anthropogenic Hydrosphere." Invited paper presented at the Southwestern Region Geospatial Workshop and Seminar held at the New Mexico Farm and Ranch Museum, 23-24 October 2003.

## CONCLUSIONS

Several major points can be made based on the experience of the project team and the specific research findings discussed above. First, research into indicators of water resource and watershed vulnerability in a trans-boundary context like the U.S.-Mexico borderlands is a complex and demanding exercise, due primarily to limitations in adequate and appropriate cross-boundary datasets needed to construct these indicators. Issues of data compatibility, adequate data coverage, and scale and resolution pose considerable challenges to this work. These difficulties comprise a data fusion challenge that must be met if similar work is to be successfully conducted in this and other border regions. This finding further highlights the importance of research in this area, work that is currently being conducted in the SCERP-funded project, "Assessment, Inventory, and Strategy for a Coordinated United States – Mexico Border Region Water Resource Geographic Information System" (Project # EIR-05-03).

Second, the project team generated an increased understanding into the role of spatial scale in a study like this. Questions that were examined include, are data available at the proper scale, and does adequate spatial variability exist on the landscape to support analysis at the scale of the sub-basins in our study area? The outcomes of the project partially answer these related questions …. "not for the entire study area and not for all the variables involved." As noted earlier in this document, the project team also uncovered challenges in watershed delineation related to large basins similar to the study area. Many of the "off the shelf tools" available via commercial vendors and the Internet showed much promise for delineating sub-basins of interest, but these tools encountered a range of difficulties that were impediments to their successful use, yet also likely areas of future work.

Despite these challenges, the project team was able to successfully employ GIS tools in a collaborative binational and cross border research effort and produce a limited, yet useful set of GIS products that map the spatial variability of select indicators of watershed vulnerability. These GIS products in turn contribute to an understanding of how human activities and agency, as well as natural processes and variables, drive the vulnerability of water resources in the study area. This work has also uncovered areas for future work that are discussed in detail below.

## RECOMMENDATIONS FOR FURTHER RESEARCH

Several areas of future work have been uncovered in this research. Perhaps the most important of these is the need to meet the data fusion challenges detailed above. If future applied environmental research along the border is to be successful, progress must be made in generating and gathering comprehensive cross-border geo-spatial datasets concerning the environmental variables of interest. The "white spaces" depicted on some of the GIS products included in this report are clear evidence of this need, as are some of the anomalous datasets that this research produced.

Project staff worked with some very interesting tools that failed to yield the useful products that were desired, but did raise some interesting questions. At the suggestion of William Kepner, a research ecologist with the USEPA National Exposure Research Laboratory in Las Vegas, Nevada, project teams at SDSU, NMSU, and UACJ underwent a training workshop for the Automated Geospatial Watershed Assessment (AGWA) watershed modeling software in the summer of 2004.[2] This workshop was given by Dr. Darius Semmons, a research scientist with the USEPA National Exposure Research Laboratory in Las Vegas, and hosted by Richard Wright at SDSU. Participants were excited about the prospects of using this software in the latter stages of the project work, but researchers at all three institutions encountered data access

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**2** The USDA-ARS Southwest Watershed Research Center, in cooperation with the U.S. EPA Office of Research and Development, has developed a GIS tool to facilitate watershed modeling in a GIS environment. AGWA is an ArcView extension that provides the framework within which spatially distributed data are collected and used to prepare model input files and evaluate model results. AGWA uses widely available standardized spatial datasets that can be obtained via the Internet. The data are used to develop input parameter files for two watershed runoff and erosion models: KINEROS and SWAT (USDA-ARS 2004).

and processing issues related to large basins that prevented successful deployment of this tool. A future release of the software may prove helpful in overcoming these challenges, and the overall research team has expressed interest in pursuing the use of this tool in the future. The project team had similar experience in the use of "off the shelf tools" available via commercial vendors and the Internet for delineating sub-basins of interest. Various members of the research team have expressed interest in further exploration of these in future work.

## RESEARCH BENEFITS

The project team sees several benefits accruing to the larger research community with an interest in border environmental work and vulnerability research. The data fusion challenges noted in this document highlight areas where future work can make an important contribution to the development of comprehensive geo-spatial data holdings along the U.S.-Mexico border. An awareness of these challenges also will guide future researchers in the scoping and scaling of projects to be consistent with the level of resources available, something that is very clear to the research team on this project. Such awareness also reinforces the value of developing the "roadmap for development of a borderwide GIS capability that the currently funded SCERP project, "Assessment, Inventory, and Strategy for a Coordinated United States – Mexico Border Region Water Resource Geographic Information System" (Project # EIR-05-03), seeks to advance.

The GIS maps that are noted in this report have perhaps the most direct benefit to the research community. In addition to providing a partially successful "proof of concept" that this type of GIS work can be competed, these GIS products in turn contribute to an improved understanding of how human activities and agency, as well as natural processes and variables, drive the vulnerability of water resources in the study area. This understanding is an important ingredient to researchers and policy and decision makers in the border region whose responsibility it is to examine the underlying causes of resource vulnerability and craft potential solutions to the problems that are involved.

The last benefit to be discussed is perhaps one of the most intangible benefits, yet one that may also be the most important and lasting outcome, namely the long-term value of the interdisciplinary, binational, and collaborative research team involved. The lead author of this document has extensive experience in conducting applied environmental science and policy research in the U.S.-Mexico borderlands, and the drafting of this final project report has reminded him of how critical it is to have a quality, binational team involved, and the long-term value of such a team. The trust and relationships built in such and effort have been extremely important to the successes achieved, and it is highly likely that many future research efforts will see similar successes as the researchers involved continue their collaboration.

## ACKNOWLEDGEMENTS

This work was sponsored by the Southwest Consortium for Environmental Research and Policy (SCERP) through a cooperative agreement with the U.S. Environmental

Protection Agency. SCERP can be contacted for further information through www.scerp.org and scerp@mail.sdsu.edu.

The lead author would also like to acknowledge and thank numerous people, without whose assistance and support, this project would not have been possible. The individuals listed in Table 1 traveled to Las Cruces and made significant contributions to the Experts Panel held on October of 2003, and the insight and guidance that came from this workshop were very important to the project. Marguerite Hendrie and Nori Koehler at New Mexico State University and Hugo Luis Rojas and Nora Reyes Villegas at la Universidad Autonoma de Ciudad Juarez worked diligently on the compilation, management, analysis, and display of geo-spatial data. Richard Wright and Harry Johnson at San Diego State University conducted similar research in the Tijuana River Watershed and provided important support and input.

Lastly, the lead author wishes to thank and acknowledge his co-authors and collaborators on this project. Brian Hurd conducted the research on which the project is based and provided important guidance at many steps in the work. Janet Greenlee provided a very important technical lead for GIS work conducted at NMSU and also produced most of the final map graphics in this report. Alfredo Granados was key in providing Mexican participation at the Experts Panel, delivering key data for Mexico, and completing needed GIS analysis in a timely manner. Gracias a todos!

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## FIGURES

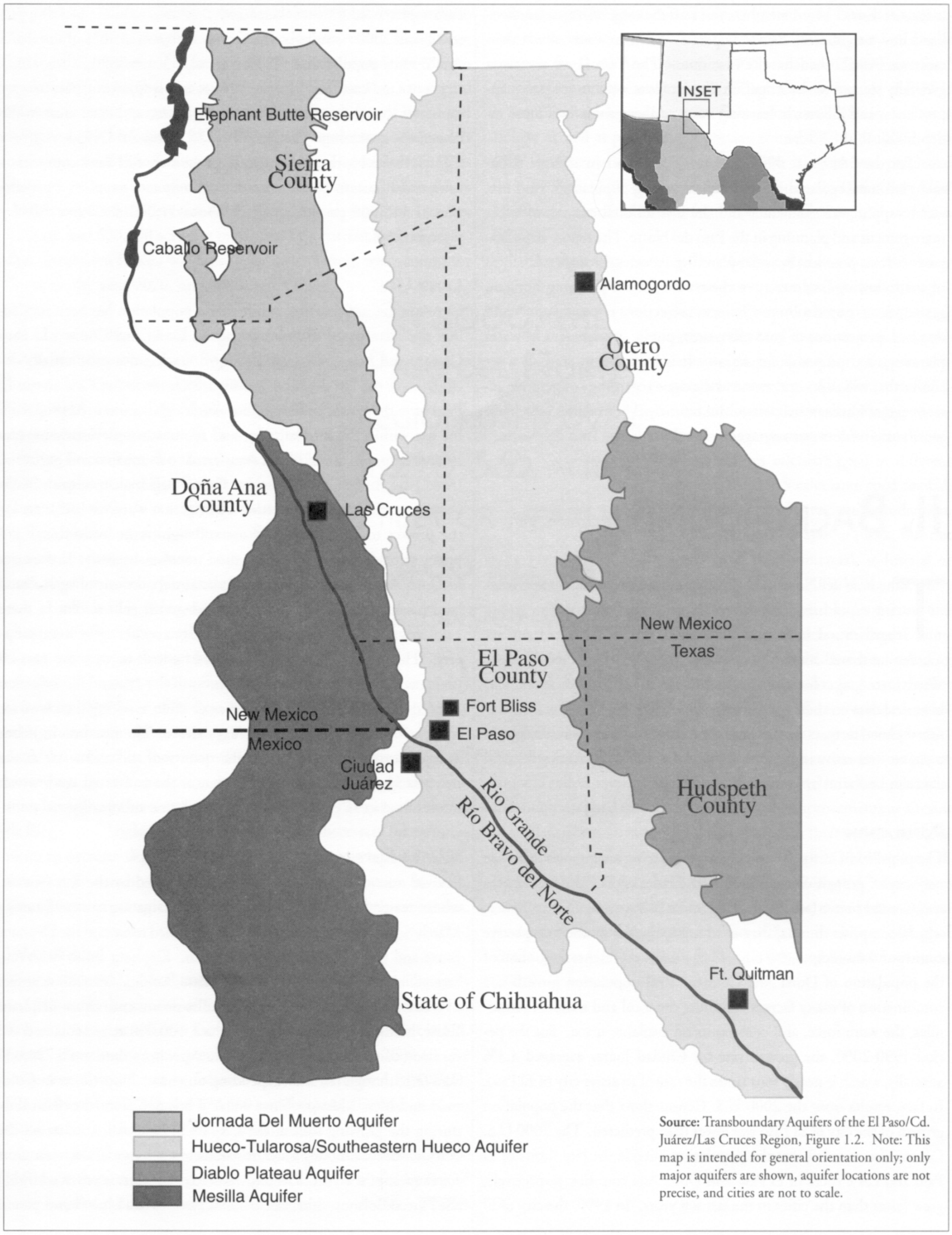


Figure 1. The Paso del Norte regioN

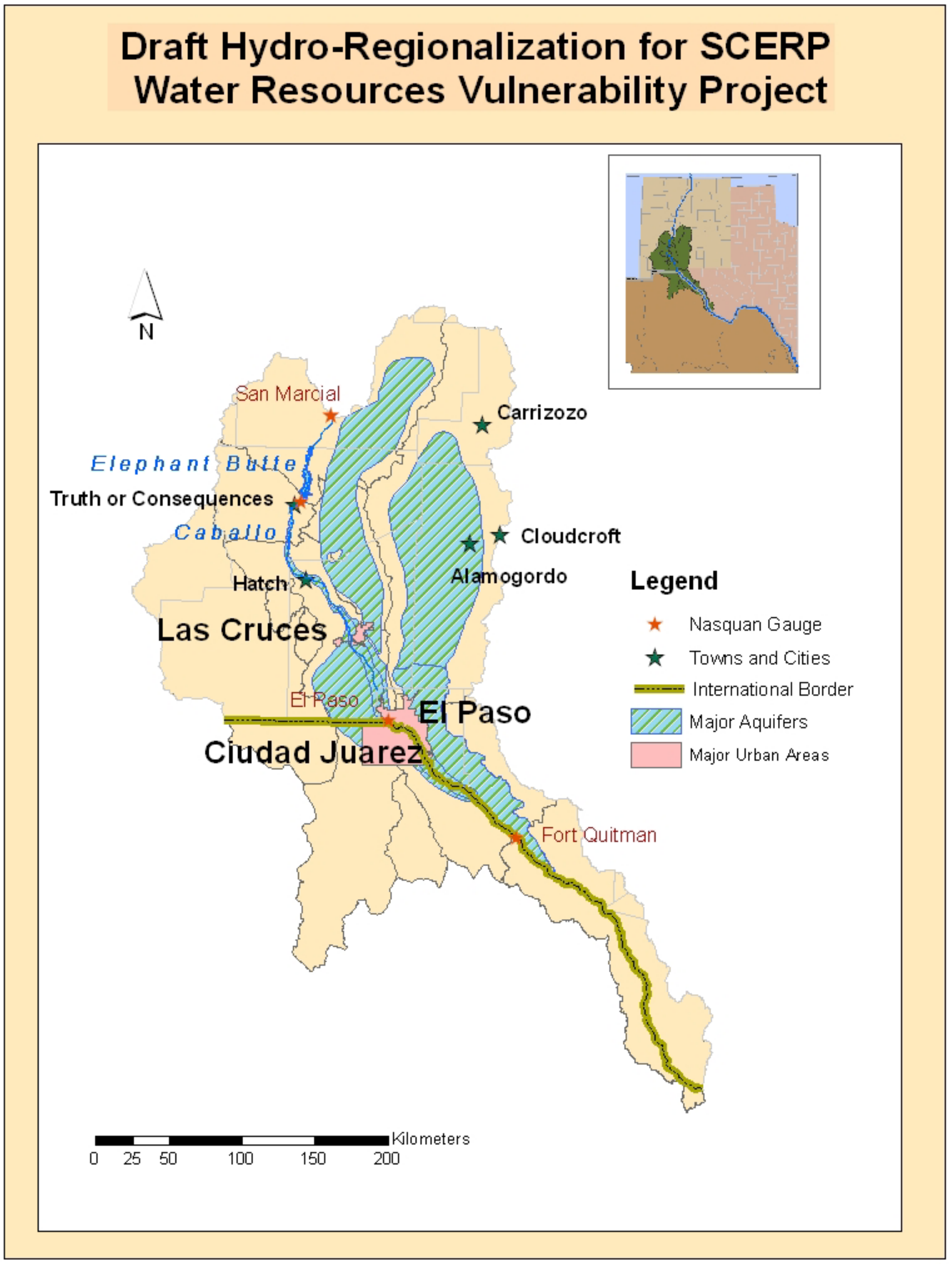


Figure 2. Hydro-regionalization of the study area (GIS data are from TWDB and NMWRRI 1997 and Kennedy and Hawley 2003)

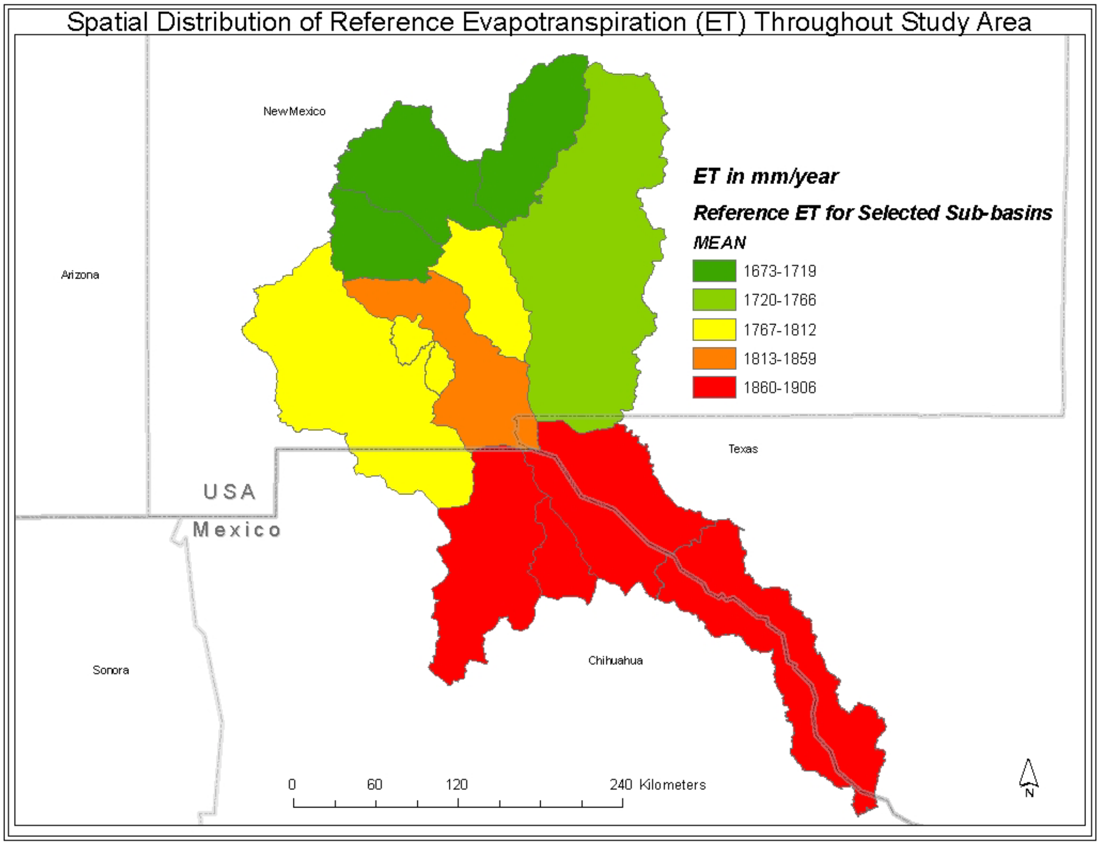


Figure 3. Reference Evapotranspiration of the study area

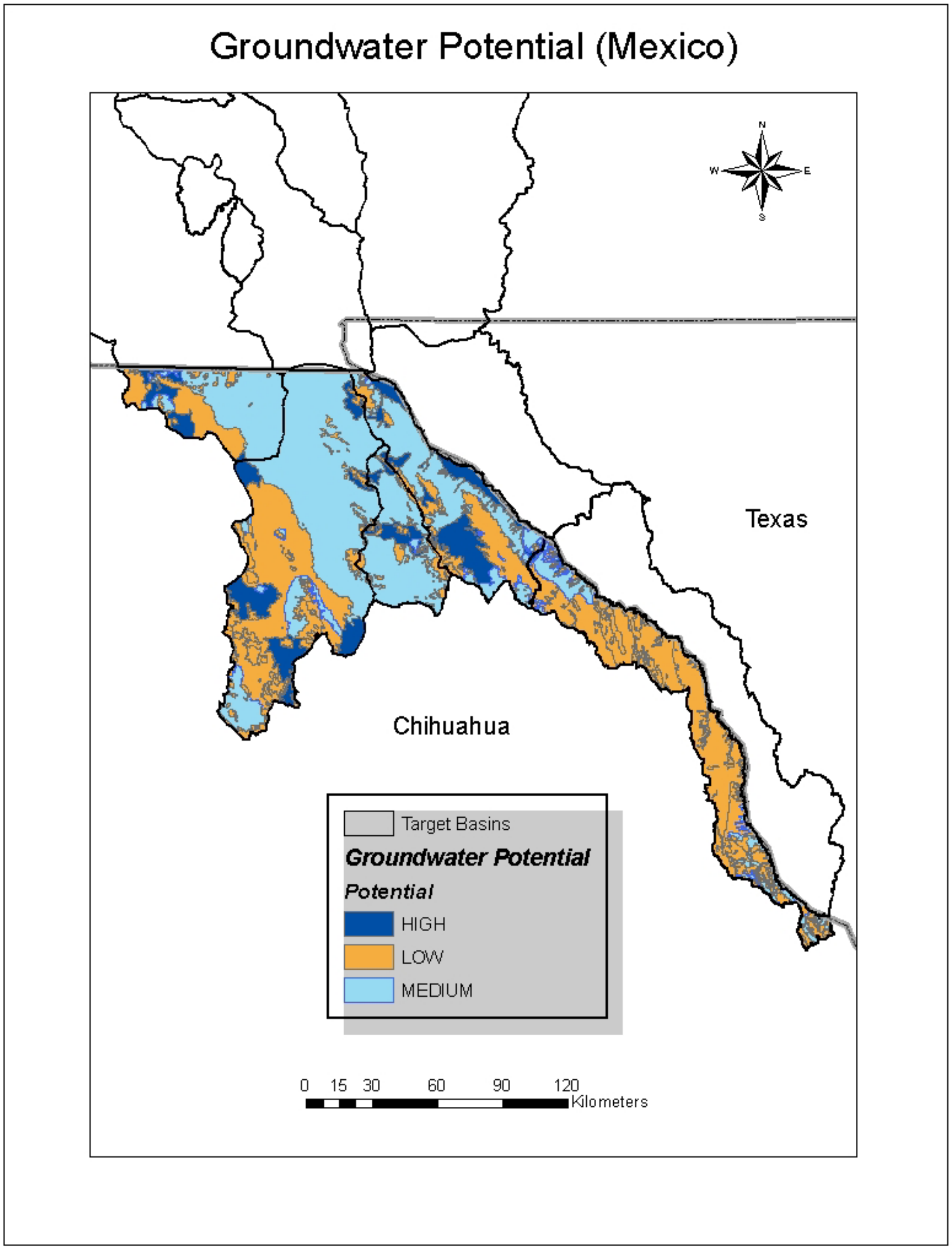


Figure 4. Raw INEGI input data for groundwater potential

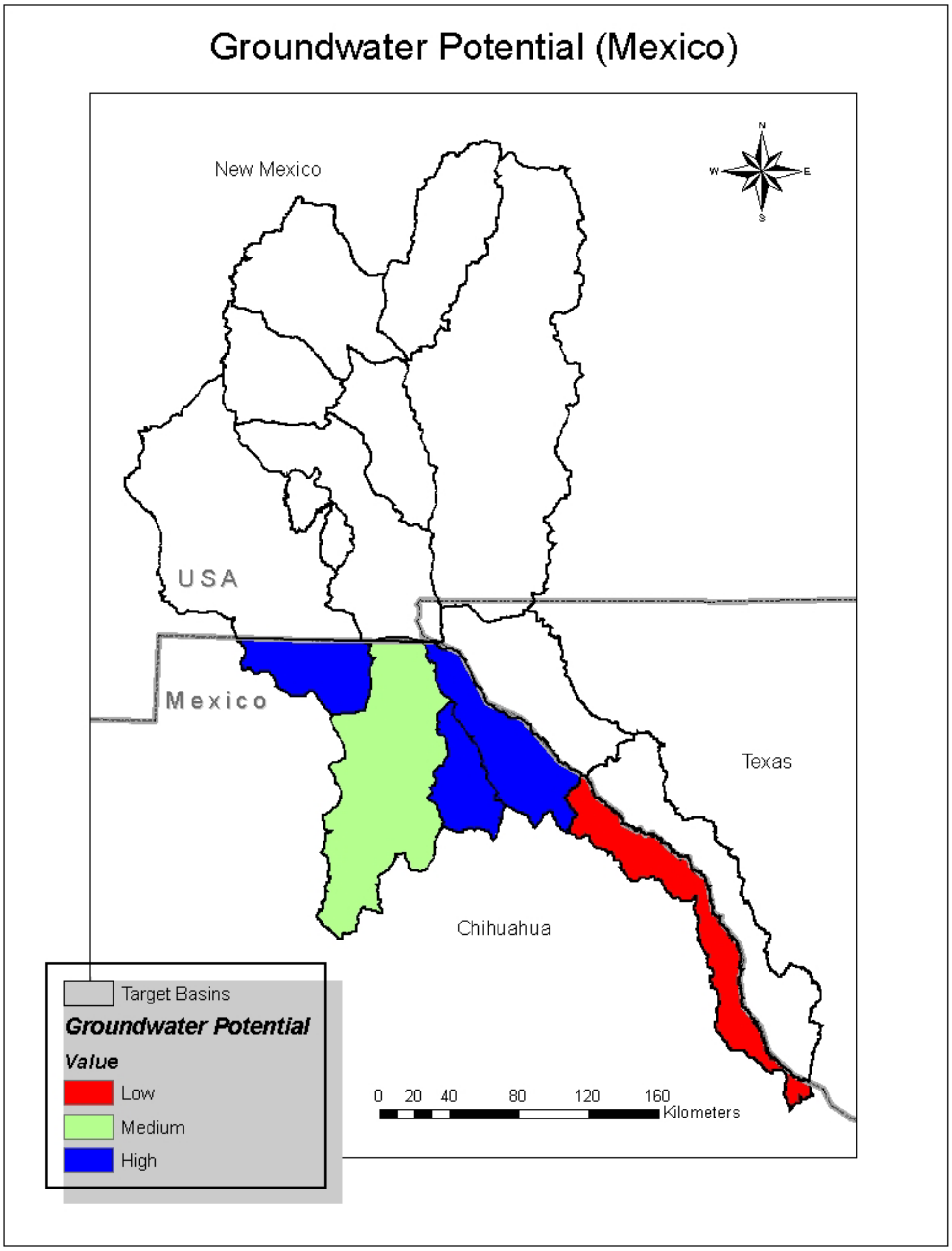


Figure 5. Final output map for groundwater potential

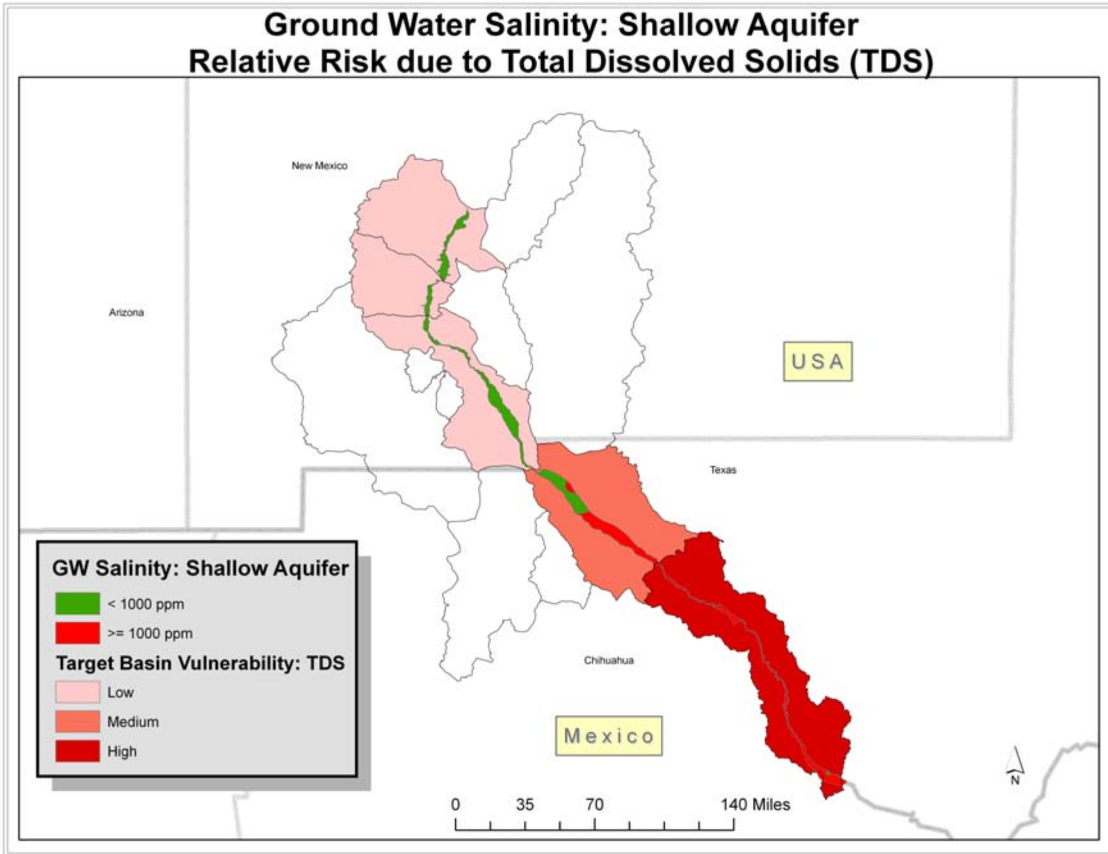


Figure 6. Groundwater salinity map for shallow alluvial groundwater

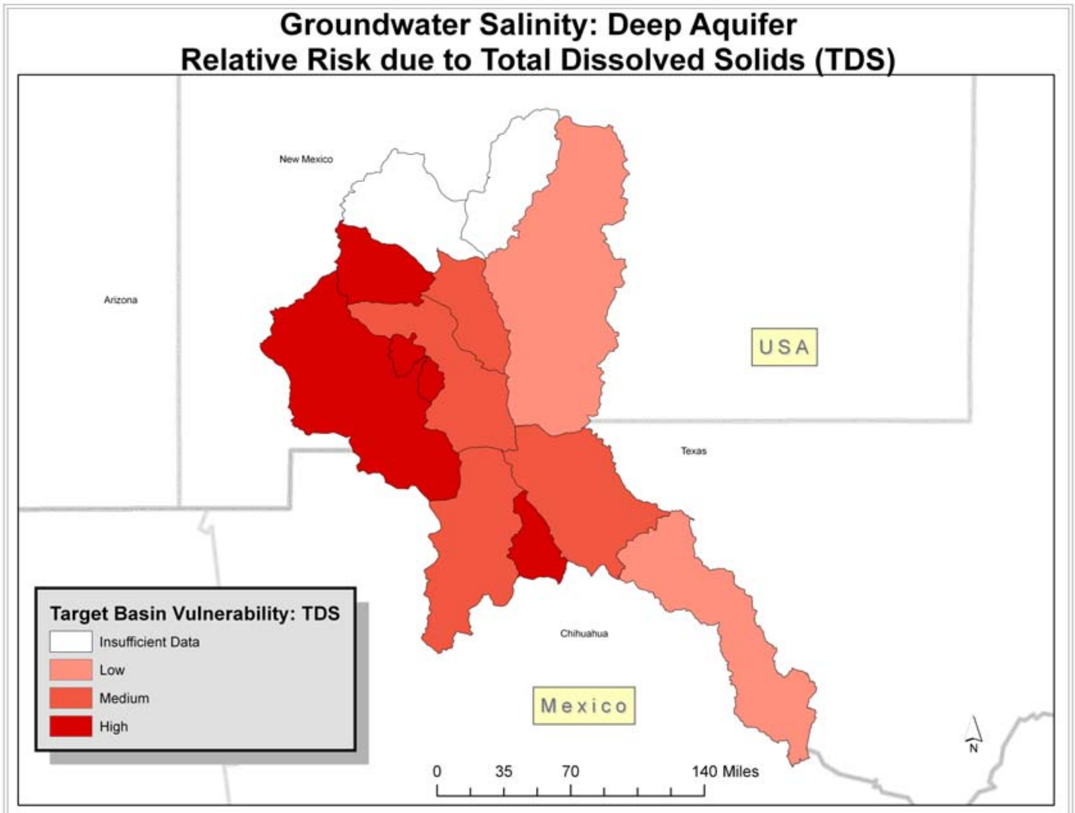


Figure 7. Groundwater salinity map for deep groundwater

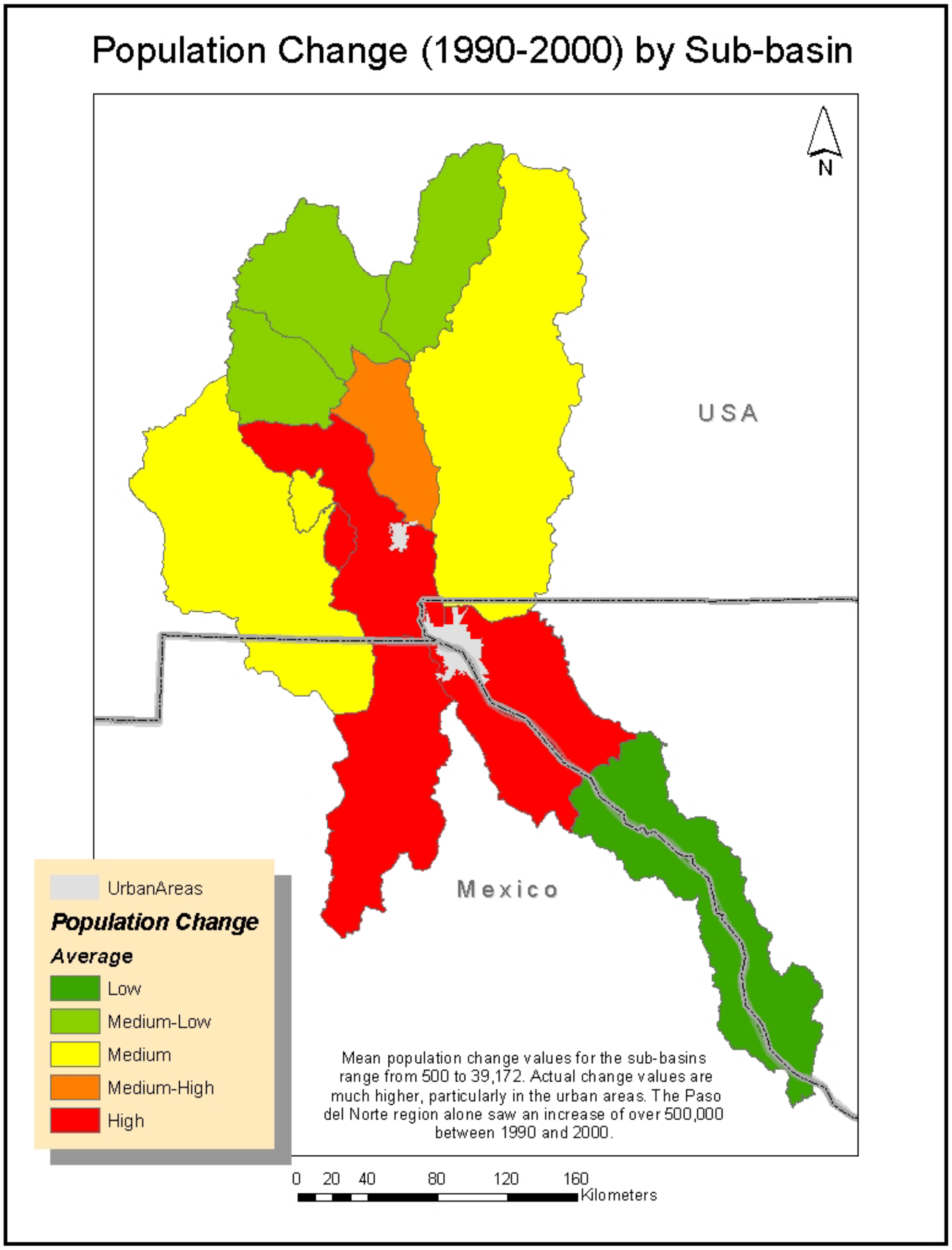


Figure 8. Population change (1990-2000) across target basins

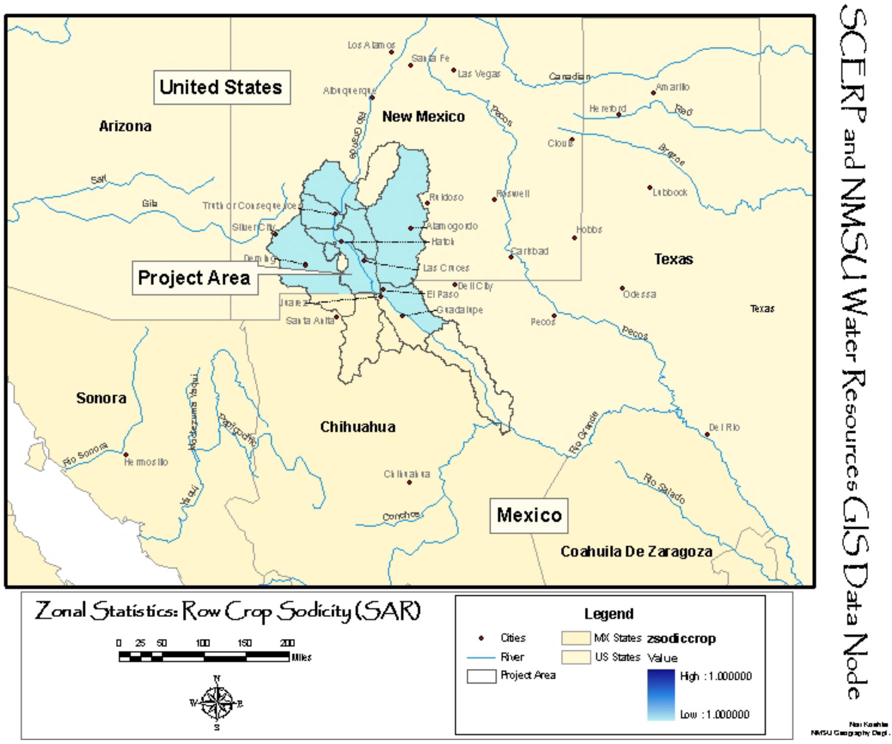


Figure 9. Map of sodicity risk to row crops in the study area

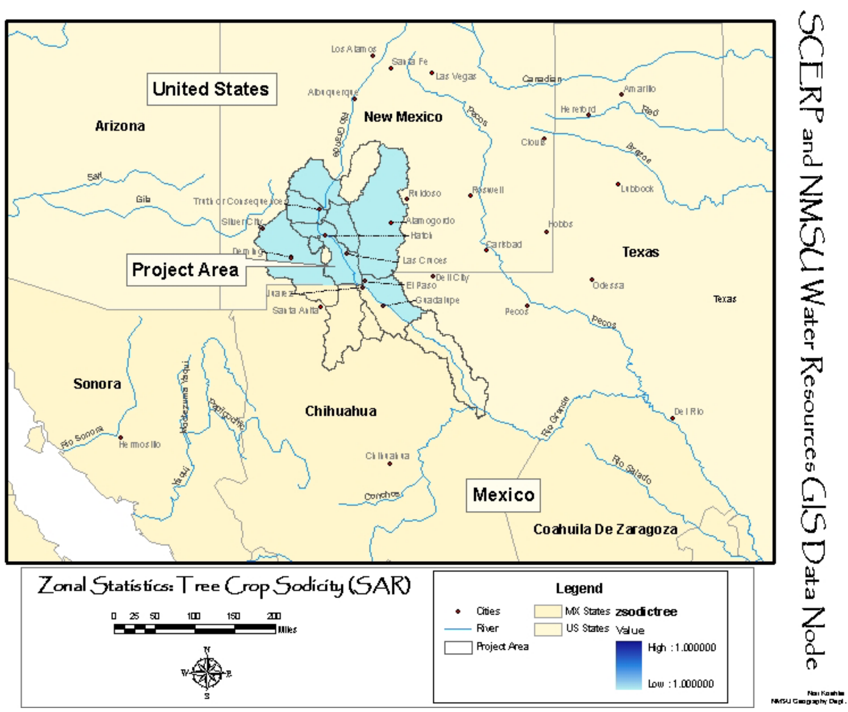


Figure 10. Map of sodicity risk to tree crops in the study area

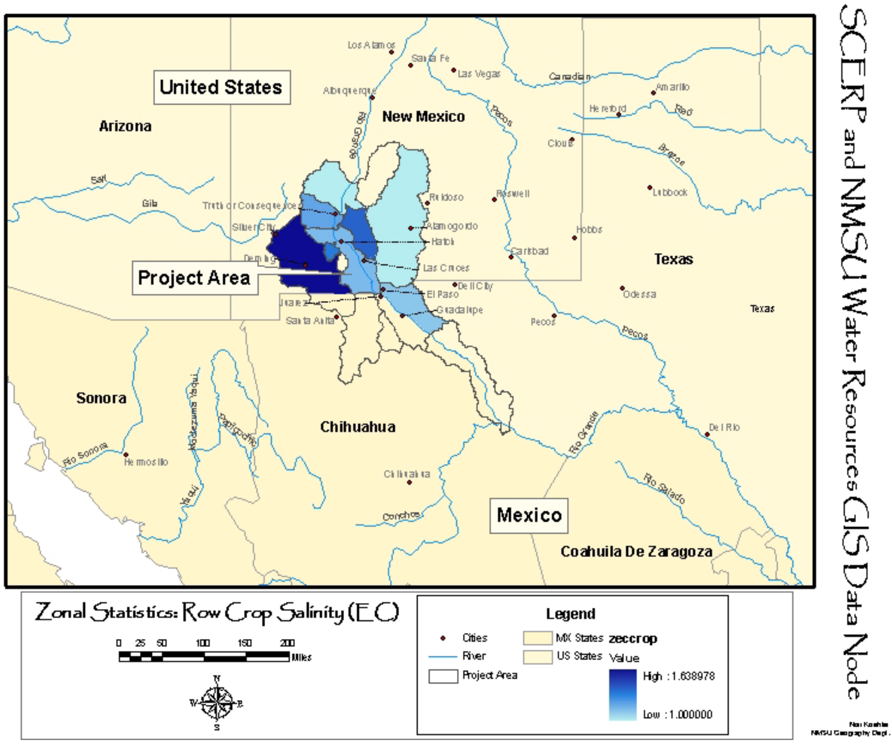


Figure 11. Map of salinity risk to row crops in the study area

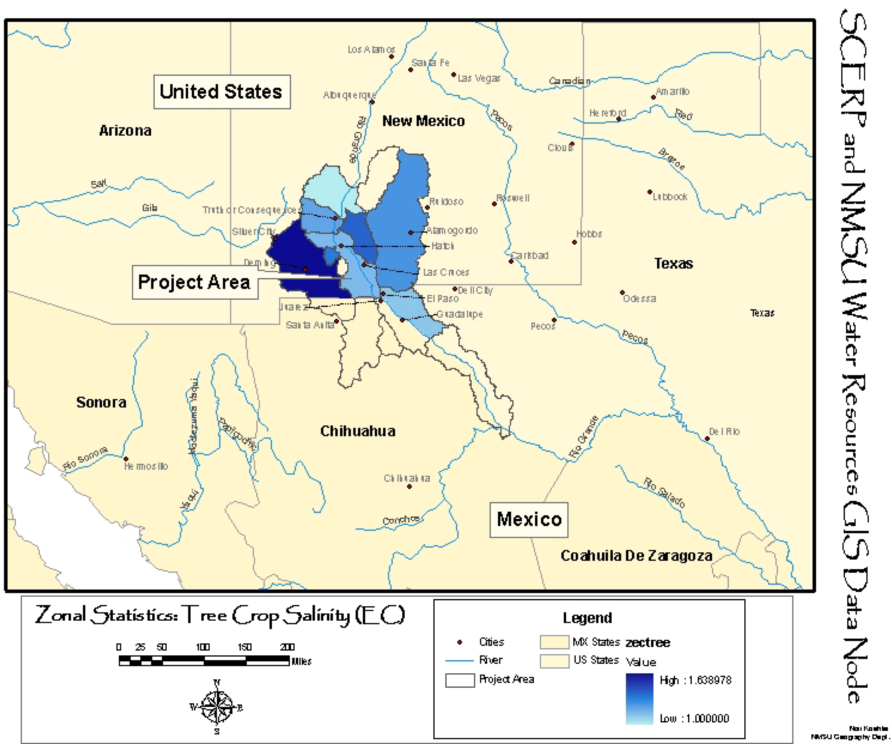


Figure 12. Map of sodicity risk to tree crops in the study area

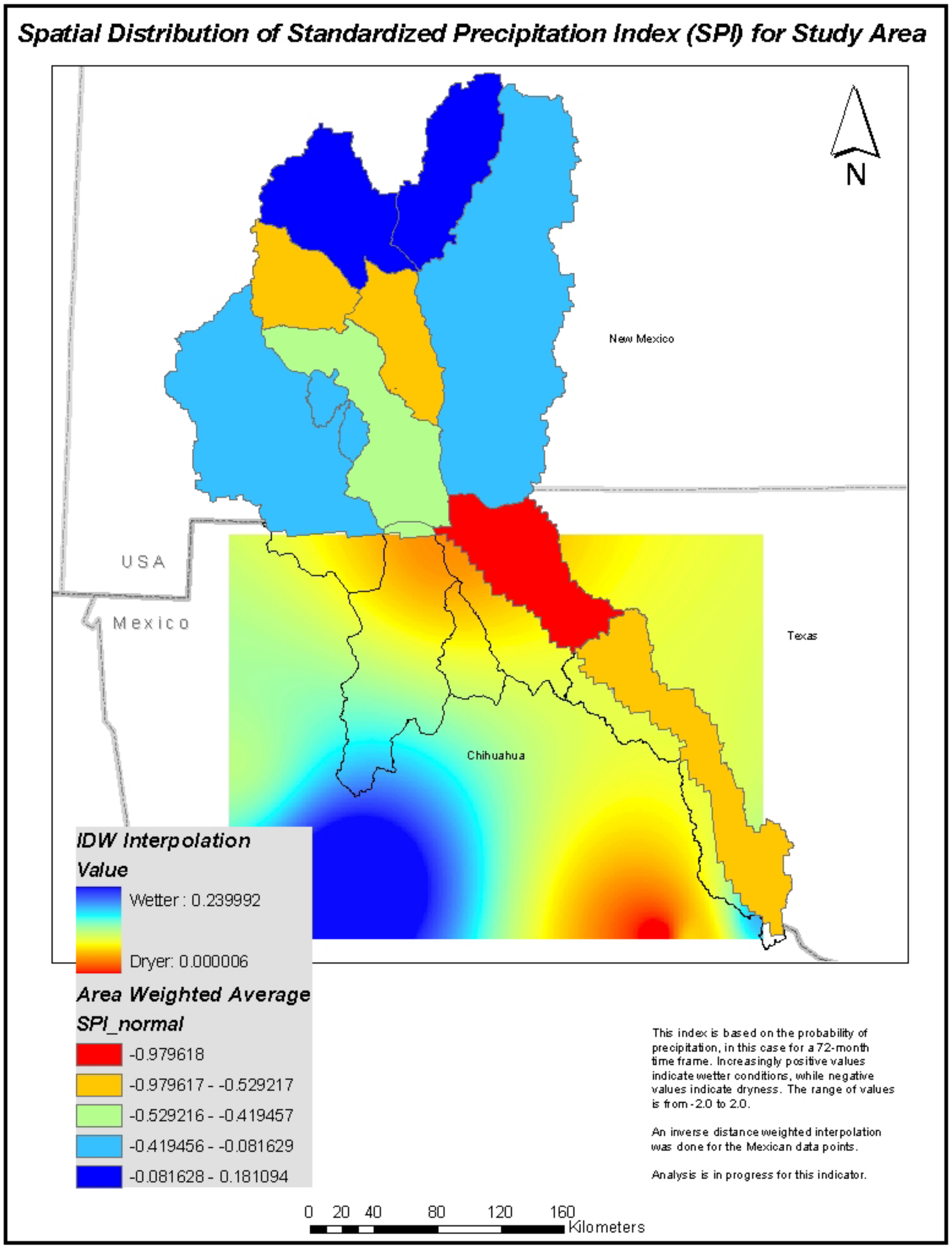


Figure 13. Map of Standardized Precipitation Index data for study area, showing raw interpolated surface values in the Mexican part of the basin

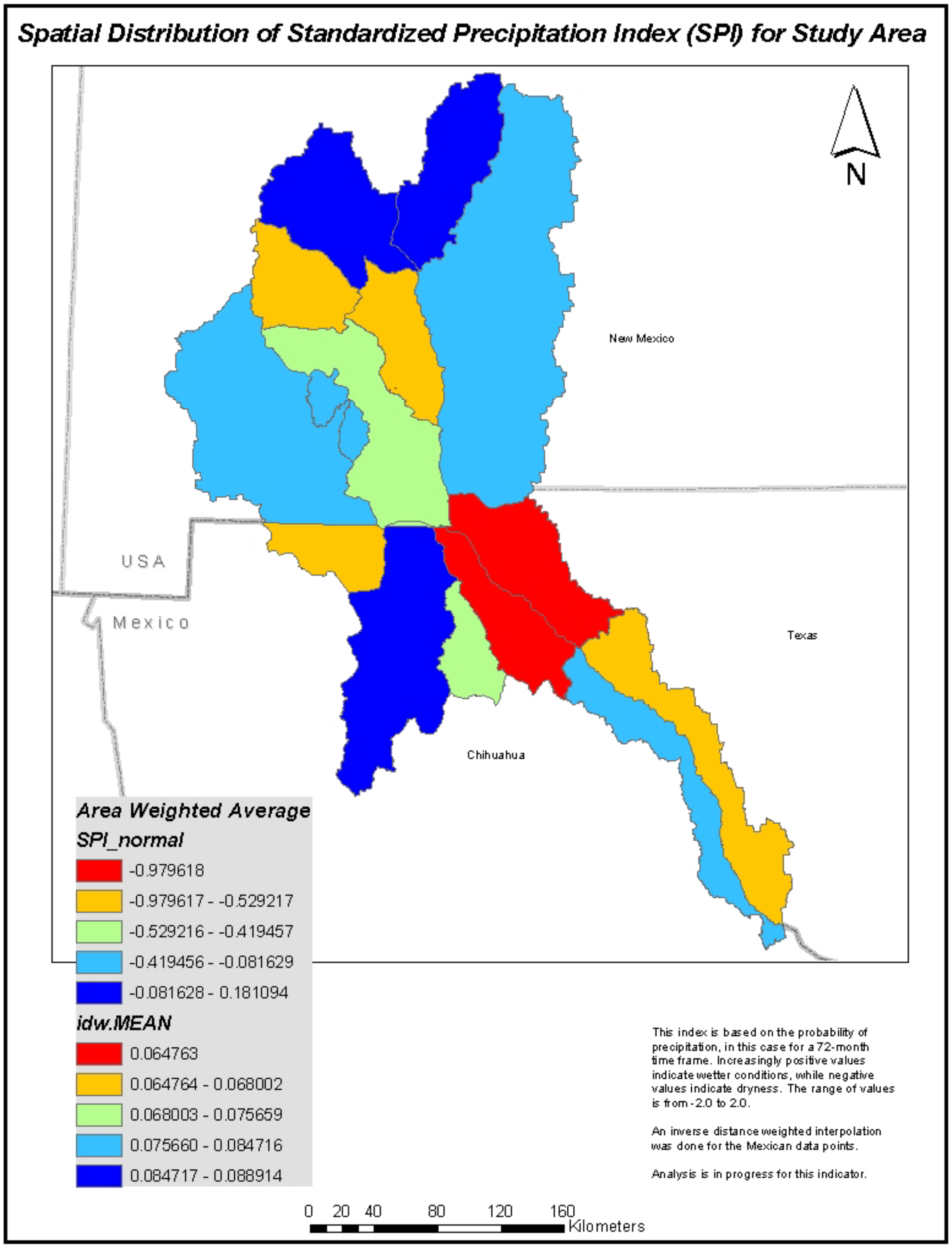


Figure 14. Map of Standardized Precipitation Index data for study area, with the zonal statistics function run in Mexico.

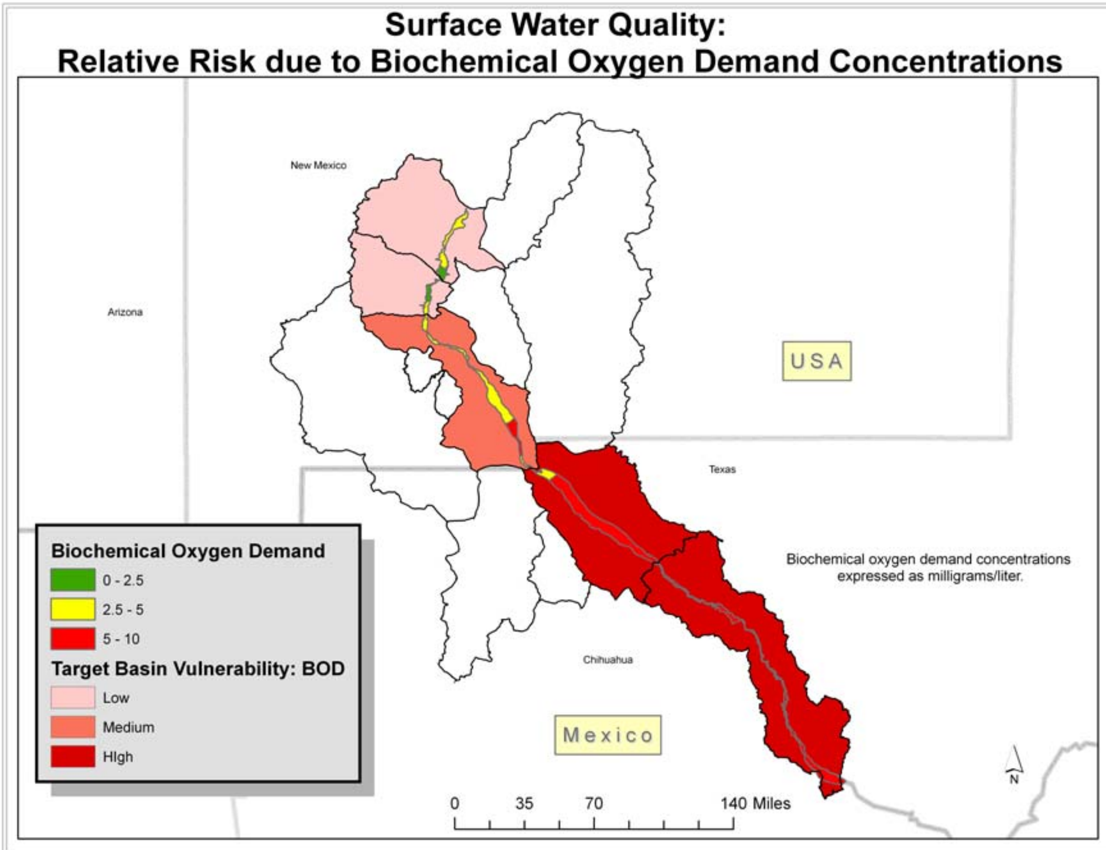


Figure 15. Map of surface water quality in the main stem of the Rio Grande, specifically biochemical oxygen demand (BOD)

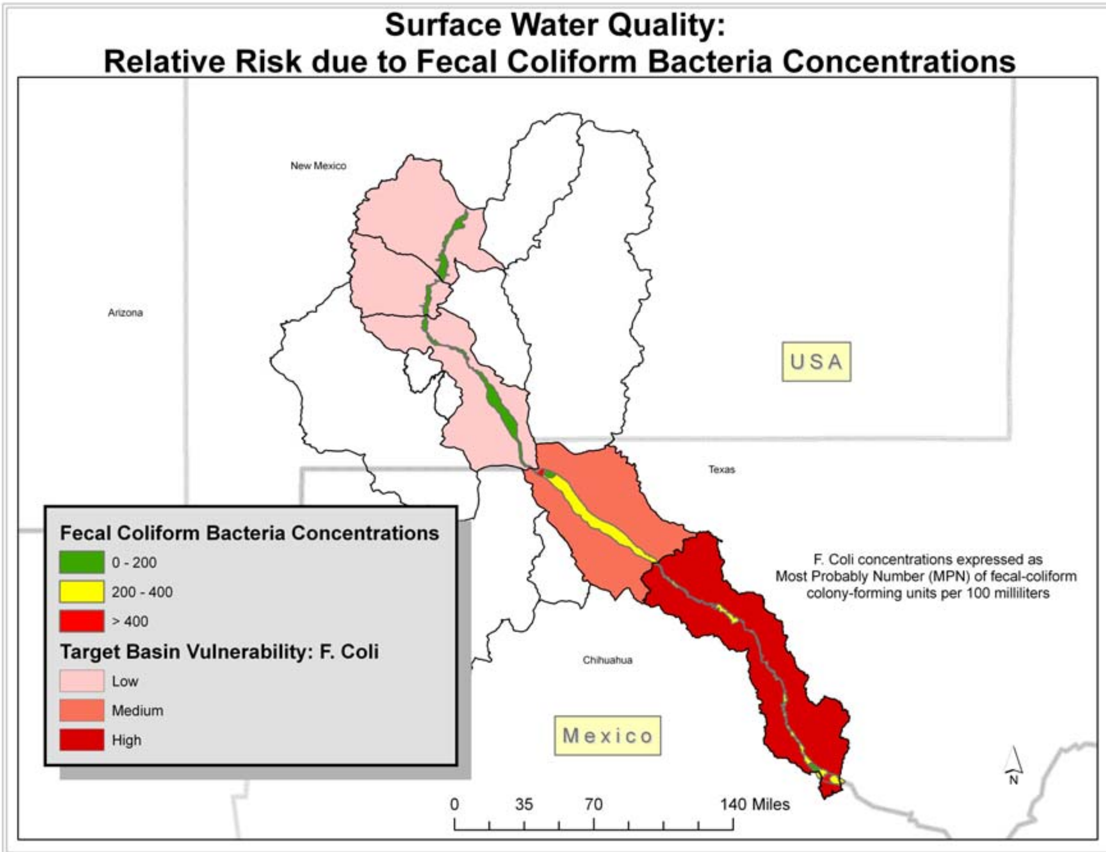


Figure 16. Map of surface water quality in the main stem of the Rio Grande, specifically fecal coliform concentrations

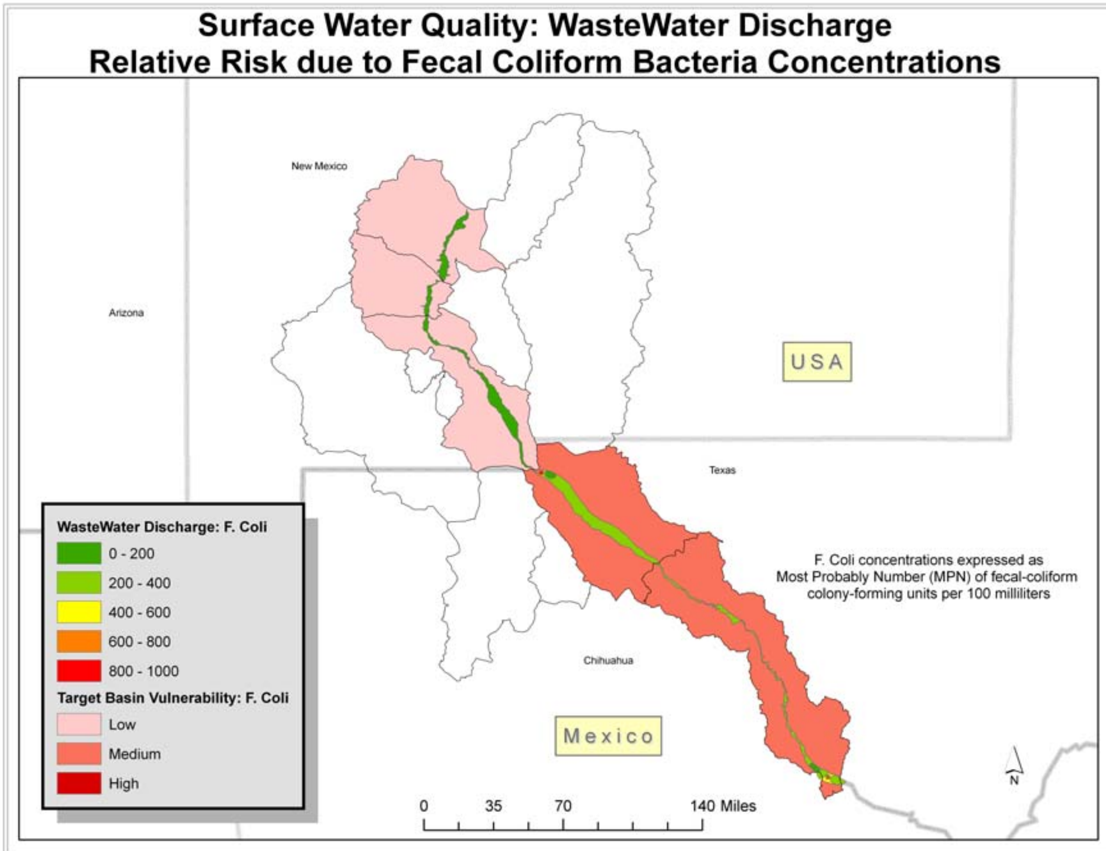


Figure 17. Map of fecal coliform concentrations in the main stem of the Rio Grande, specifically related to wastewater treatment plants

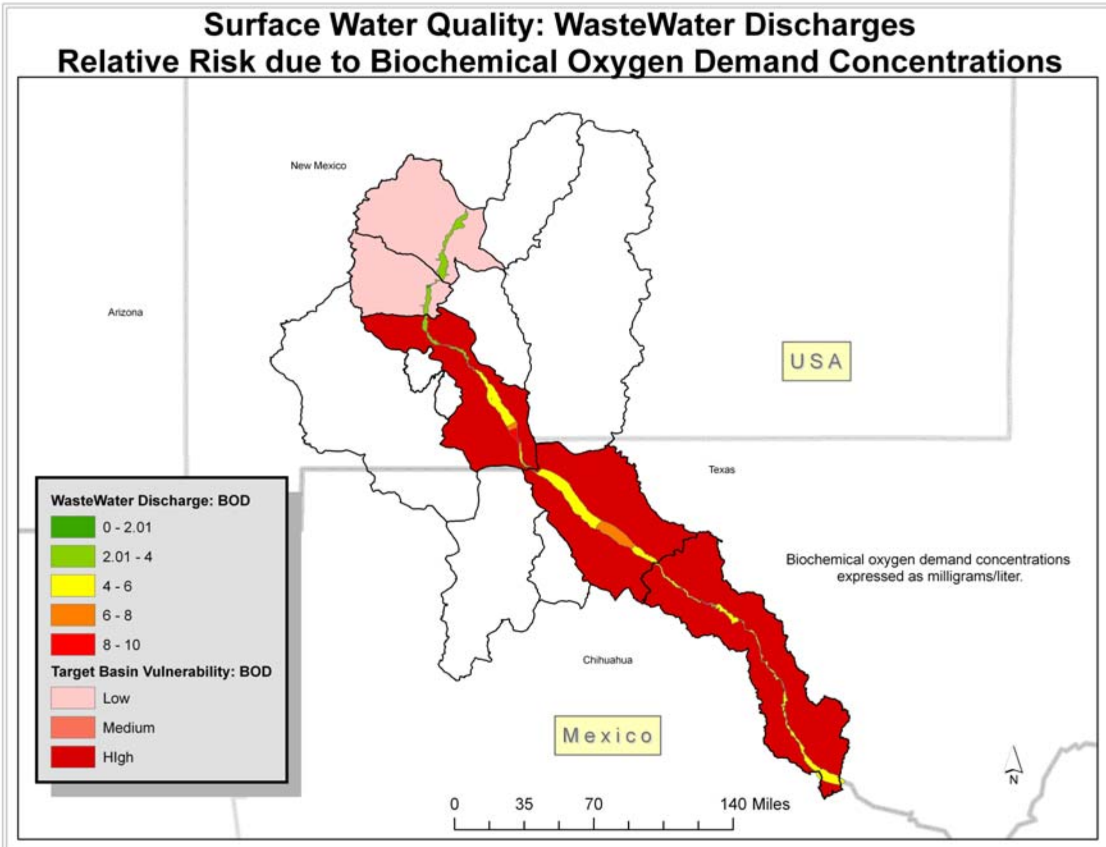


Figure 18. Map of biochemical oxygen demand concentrations in the main stem of the Rio Grande, specifically related to wastewater treatment plants

**TABLES**

Table 1. List of attendees at the SCERP Experts Panel
Convened 23-24 October 2003, Las Cruces, New Mexico

| | |
|---|---|
| Dr. Christopher Brown<br>New Mexico State University | Dr. Jose Luis Castro<br>El Colegio de la Frontera Norte |
| Mr. Michael Cohen<br>The Pacific Institute | Dr. Rene Franco<br>Franco y Asociados |
| Dr. Alfredo Granados<br>La Universidad Autonoma de Ciudad Juarez | Ms. Janet Greenlee<br>New Mexico State University |
| Ing. Alberto Guitron de los Reyes<br>Instituto Mexicano de Technologia del Agua | Ms. Marguerite Hendrie<br>New Mexico State University |
| Mtra. Del Consuelo Hori<br>Tec de Monterrey | Dr. Brian Hurd<br>New Mexico State University |
| Mr. Harry Johnson<br>San Diego State University | Mr. William Kepner<br>U.S. Environmental Protection Agency |
| Dr. Fabian Lozano<br>Tec de Monterrey | Ing. Ramiro Lujan<br>Comision Internacional de Limites y Aguas |
| Dr. Eugenia McNaugton<br>U.S. Environmental Protection Agency | Dr. Kristina Mena<br>University of Texas at Houston |
| Mr. Howard Passell<br>Sandia National Laboratories | Dr. Richard Vogel<br>Tufts University |
| Lloyd Woosley, P.E.<br>United States Geological Survey | Dr. Richard Wright<br>San Diego State University |

Table 2. Vulnerability indicators chart developed from Expert's Panel Workshop

| Vulnerability Source | Indicator | Data Source | Comments/Additions |
|---|---|---|---|
| ***Related to Human Population, Consumption, and Land Use Practice*** | | | |
| Population growth | Demographics/Change in growth | INEGI-Mexico<br>U.S. Census | |
| Population water stress | Deficit of potable water supply | (1+g/1+r) pop. growth/water<br>g= population growth<br>r=supply growth<br>(must include ground water storage, and surface water interaction/input) | [1] |
| Consumptive use | Per capita water use + allocation/acre consumptive use | Municipal Utilities<br>Irrigation districts EBID, EP#1<br>satellite (Mexico)<br>current landuse map | Satellite imagery =relative<br>Per capita consumption for municipal use and per acre use for ag.<br>Data from irrigation by different crops? (Min = trees versus crops) |
| Ground Water overdraft | Change in aquifer storage<br>(rate of change) | Change in depth to water over time. Well attribute data (WRRI),<br>Attempt to attain volume estimates (USGS,WRRI, UTEP, A&M, UACJ). | Perhaps consider summer and winter statistical surface. We won't have resources for modeling GW-SW interaction for this study. |
| Degree of over-allocation | amount of groundwater pumped to meet demand<br>Ag, M & I | Compact, NMOSE Water Rights, EBID, EP#1, EPWU | [2] This indicator ignores instream rights. |

| Vulnerability Source | Indicator | Data Source | Comments/Additions |
|---|---|---|---|
| Economic sensitivity to water availability | Water use by industrial sector and revenue generated per use | Las Cruces—MVDA, LRGWUO<br>El Paso—Ari M.<br>Juarez—Lucinda Vargas, Rene Franco | |
| | ***Water Quality-Related/Human Health*** | | |
| Impairments to water quality | salinity | NM Environment Department<br>El Paso—TCEQ, EPWU<br>Mexico—Is there a law?, INEGI, Mexican Universities<br>NAWQUA, NASQUON | |
| | DO | | |
| | Fecal coliforms | | |
| | Non-point ag contaminants (CAFO) | Land cover, crop type, and pesticide intensity, EPA data on feedlot and # of animals | Bob Gilliam model USGS salinity v. important |
| Water pollution (public health- environmental health) | Sewage hook-ups, potable water supply, health measure | TCEQ, NMED, Dona Ana County, CESPT, Junta Municipal | |
| | Sewage discharge/river discharge<br>Nitrogen load | | |
| Specific biological contaminants | Disease, enteroviruses, fecal coliforms, cyclosporidium | No systematic testing | Problem is linking disease with water quality |

| Vulnerability Source | Indicator | Data Source | Comments/Additions |
| --- | --- | --- | --- |
| ***Natural Events (Although effects are influenced by anthropogenic disturbance)*** | | | |
| Flood Risk | % class of stream that is channelized | Aerial/Digital RS Satellite<br>Aerial photo project along border?<br>Tijuana-San Diego flood control project w/ COLEF, SDSU, and others | |
| | Impervious surface-precipitation | Land cover/ satellite-DEM's<br>Tijuana-San Diego flood control project w/ COLEF, SDSU, and others | |
| | Population in Floodplain | FEMA, map of urbanization | |
| Drought Severity | # of times in past X years that Drought severity index has exceeded threshold value (rangeland communities) | CAN/NOAA /Prism (OSU) | [3], [4] |
| | Coefficient of variation of streamflow | FBOR, USGS, IBWC, CAN, | |
| ***Ecological Concerns*** | | | |
| Reduction in Riparian Ecosystem Extent/Composition | Series of landscape metrices from field counts, remote sensing data, | Remote Sensing Surveys, SWREGAP, Literature, Universities SEMARNAT-Mex//State Fed.//NGO<br>INE, search Frt. Bliss | Use of macroinvertebrates—more diverse. |
| | Diversity Indicators<br>changes in # of species at risk<br># of Extirpated Species | Literature, Universities, NGOs, Fed | |
| | Degree of protected-ness | SWREGAP | |

| Vulnerability Source | Indicator | Data Source | Comments/Additions |
|---|---|---|---|
| Threat to biodiversity<br>(Not just riparian) | Quant changes in habitats<br>Series of landscape metrics from field counts, remote sensing data, | NA models/GAP data<br>Remote Sensing<br>Surveys, SWREGAP, SEMARNAT-Mex/State Fed.//NGO<br>INE, search Frt. Bliss | Imperviousness also tied to ecological integrity |
| | Diversity Indicators<br># species prospect<br>changes in # of species at risk<br># of Extirpated Species | Literature, Universities<br>SEMARNAT-Mex/State Fed./NGO<br>INE, search Frt. Bliss | |
| Urbanization | Extent/Connectivity- Landscape metrics | Land Use (*)<br>"Atilla" | |
| | Hydrological response- sediment yield, surface runoff, percolation, change in land use | DEM's- soils cover-NALC-USGS (soils –differences between Mex-US)-SWAT<br>NRCS | |
| ***Issues related to infrastructure and Water delivery*** | | | |
| Infrastructure quality performance | Age of Network/Condition<br>Transmission/conveyance and billing efficiencies<br>Ag efficiency | Municipal utilities<br>Irrigation districts? | |
| Infrastructure "brittleness" | Distance to water supply<br>Redundancy of water supply<br>Contingency Plan | Sewer and water coverages from municipal utilities possibly census data | |

| Vulnerability Source | Indicator | Data Source | Comments/Additions |
| --- | --- | --- | --- |
| Lack of Adaptive Capacity | Per capita consumptive water use in M & I. | Municipal utility data | |
| | % of total ag in permanent crops (ex pecan, vineyards). | Acreage data from irrigation districts | |
| | Consumptive use over total extraction by sector | EPWU—Municipal utility | |
| | Institutional Potential for transfers and maturity of water markets | Potential for trans—ordinal ranking using institutional research literature CAN-pronagua | transaction costs, import demand ratio, spending power, legal flexibility |
| | Presence/absence, effectiveness, and comprehensiveness of water plan | Water plans themselves Critical literature that reviews them | Performance measures |
| | Conjunctive management of surface and ground water resources | Regional Water plans, groundwater and surface water codes | |
| Financial capacity of water institutions (# and nature to be determined) | Bond rating | S+P and Moody's /Rosters-Scorecard | |

[1] We recognize that some issues are not going to show variability at a sub-basin level, but they are important issues and should be included in any analysis of vulnerability

[2] see above

[3] see above

[4] H. Passell—magnitude and duration of annual extreme conditions? and 90-day means, or magnitude of monthly water conditions, or timing of annual extreme water conditions, or frequency and duration of high and low pulses, or rate and frequency of water condition changes.

Table 3. Omissions, Biases, and Concerns from SCERP Expert Panel Workshop

| Item | Issue | Explanations |
| --- | --- | --- |
| Groundwater-surface water interactions | Not enough time and resources to investigate this issue | Given the broad scope of this work and the complexities of groundwater-surface water interactions in this region, we do not feel that we will be able to model this interaction. We do, however, recognize its importance. |
| Aquifer levels | Aquifers have different numbers and extents of impervious layers. | Sometimes depth to groundwater will not reflect this difference. The quality and rate of recharge for each layer will be different. |
| Service vs. Manufacturing | Estimating economic return per unit of water use for service industries such as universities. | |
| Value of effluent re-use for industries | In terms of amount of return per unit of water use, the potential for effluent re-use was mentioned. | Parts of the border region are not ready to deal with this issue yet, as extensive water re-use facilities have yet to be developed. This issue may be best examined at the local, rather than regional level, owing to ongoing local initiatives. |
| Lack of periodic inventory and assessment | How do we measure this? What is the indicator? | We agree that this is an important source of vulnerability for water sources, but it was hard for us to develop a suitable indicator. |
| Non-point source pollution | Complex agricultural areas | In homogeneous agricultural areas, we will map chemical output in terms of high, medium and low intensity of chemicals per type of crop. This will be a difficult process in areas of heterogeneous crop types. This analysis would be based on analysis of aerial photography and satellite imagery, supported by ancillary data. |
| Trend analysis | Time consuming for every issue | We recognize the importance of projecting into the future, but we feel that this a difficult process, perhaps limited to a select few indicators. Historical data will need to be readily available. |

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| Flood risk | Ecological role of floods | It was brought to the attention of the panel that while flooding might be an anthropogenic vulnerability, the lack of flooding is a source of vulnerability for riparian ecosystems. We hope our ecological indicators can balance out this important paradox. |
| Human health | Is morbidity too late? | Although there was much discussion on the importance of water-borne disease and pathogens, we were never able to satisfactorily answer the question of an indicator to tie human health with water quality. |
| Drought | Water dependence in this area is not tied to local rainfall, but rather to snowfall in the Colorado Rockies | Local drought has an impact on ranchers, ecosystems, and potential groundwater recharge in this area, but the major concern is amount of water that comes from snow pack in Colorado. Below Elephant Butte, the water flow is more like a faucet than a natural streamflow. An additional question is whether the current drought is a factor of long term climate change which may not be applicable at the sub-basin level. |
| Biodiversity | High or low vulnerability? | Some issues relate to ranking some of the ecological indicators. Is an area with high biodiversity more or less vulnerable? If a region is diverse because it is in a unique position on the landscape that has escaped development, it could be considered vulnerable. However, an area that has already lost most of the native species is vulnerable due to the inability to adapt. |
| Lack of knowledge of the minimum amount of water required to sustain a population | What is the indicator? | Certainly, ignorance is a source of vulnerability, but we do not have an adequate indicator of this. Due to the binational extent of the research, “an adequate amount of water” will be difficult to define since “standards of living” vary spatially along and across the border. |

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|---|---|---|
| Binational opaqueness | Sub-regionalization? Who is more vulnerable? | Other than U.S. vs. Mexico differences, a problem of mapping exists. Also, is an open institution that operates more "loosely" than a more authoritarian or centralized regime, more or less vulnerable? |
| Maturity of water allocation | Maturity of allocation mechanism vs. age of rights. Is this an adjudication issue? | |
| Quality of water plans | How to measure? | We feel that rating city and municipal water plans would provide a good indicator of vulnerability, but as of now, we do not know of such a system or set of criteria for this. |
| Potential loss of agricultural value | Quality of life issue? | This source of vulnerability is tied to land use change. It was hard for us to definitively tie this to water resource vulnerability, yet given the value of regional agriculture, we wanted to examine this. |
| Public values and policy changes over time | How to map/measure, what is the vulnerability exactly? | This issue is consistent with the question of "water for fishes or families." This will be hard to map and harder to quantify. |