THE TRANSBORDER WATERSHED RESEARCH PROGRAM

A Proposal Submitted to the
Management Committee of the
Southwest Center for Environmental Research and policy

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ABSTRACT

The Tijuana and San Pedro watersheds span the international border between the United States and Mexico. Both watersheds have been studied extensively, both watersheds are undergoing explosive population growth, and water resource issues are critical factors influencing sustainability in these ecologically-fragile, semiarid ecosystems. From an ecological perspective, these watersheds form meaningful landscape units for study and management because of the shared functional relationships that exist within their boundaries. However, very different social, political, and economic influences occur on the two sides of this international border. One result for these transboundary watersheds is that a significant gap exists between the watershed as an ecological unit and the watershed as a planning and administrative unit. The overall objective of the Transboundary Watershed Research Program is to initiate for the Tijuana and San Pedro basins an integrative program of research which explores this gap and identifies barriers to¾ and opportunities for¾ bridging this gap. While two watersheds are being studied, one goal of our study is to integrate these studies in a cooperative analysis through the use of common models.

Integrative approaches to watershed research combine ecological, economic, political, and social factors in the study of watershed processes. Land uses are influenced by these factors and, in turn, impact ecosystem dynamics through events that can be identified and monitored. The principal objective of our research is to investigate the dynamic interrelationships between human and natural factors as reflected by land use patterns in the Tijuana and San Pedro watersheds. Our central research question therefore is: What economic, social, political, and ecological processes interact to generate land use patterns in the Tijuana and San Pedro watersheds, and how do these patterns and processes influence environmental conditions in the two basins?

Our research approach will focus on characterizing the distribution and intensity of land use in each watershed and developing models which describe the interrelationships between land use patterns and ecological and human factors. Patterns of land use will be documented using maps, planning documents, aerial photographs, and satellite imagery to generate a GIS-based record of recent land use change.

Numerous studies are being conducted on both watersheds. Consequently, a sizable amount of data currently exists (collected by government agencies, private organizations, and university researchers). However, these data vary greatly in thematic content, geographical coverage, and scale and resolution. In the Tijuana Watershed our research and data needs will focus on the land use-ecological relationships (especially among land use, urban runoff, non-point source pollution, and the estuarine ecosystem). To insure a comparative analysis of the two watersheds, we intend to take a similar approach in the Upper San Pedro. Numerous studies are currently being conducted in the Upper San Pedro that emphasize ecological and landscape processes. We have been in contact with these researchers and intend to build upon and complement their

studies and work cooperatively to avoid duplication. Specifically, we intend to look at land use as the ecological process which characterizes human influences and resource demands on the landscape. For both watersheds, our goal is to integrate existing information into a larger land use model which will investigate the interdependencies and feedback among ecological, economic, social, and political factors influencing land use. In particular, our models will explicitly consider the impact of the border on watershed properties and dynamics.

Several types of modeling activities will be undertaken. For the San Pedro Watershed, we will develop a hierarchically structured, patch dynamic, watershed model. This watershed model will be spatially explicit and will use grid-based, remotely sensed data as well as integrated ecological and socio-economic data. Of particular interest will be socio-economic and institutional factors influencing patch development and patch influences on water resources and the riparian ecosystem components of the watershed. For the Tijuana Watershed, we will develop a similar GIS-linked model, that, when coupled to an empirically-based runoff model, will serve to both manage the spatial and temporal datasets and predict pollutant loading to the estuarine ecosystem. For both watersheds, land use characteristics which will be described for each patch type will include 1) social and economic factors, 2) surface and subsurface water flow, 3) point-source and non-source pollution, 4) biodiversity, and 5) other activities such as fuel combustion that give rise to air pollution which in turn impacts water quality.

As part of our efforts to characterize environmental conditions in these two semi-arid, transborder watersheds we will also evaluate applications of existing approaches including EPA's Index of Watershed Indicators, the PLAnning for Community Energy Economic and Environmental Sustainability (PLACE^{3}S) model, and EPA's BASINS software package. Indices for the Index of Watershed Indicators have not been computed for the Mexico portions of the watersheds, thus providing an incomplete characterization of the total area of each basin. This deficiency will be overcome by our cross-border program perspective.

The overall goal of the transborder watershed program is to provide information for decision makers that will aid in policy formation and adaptive management aimed at sustainable ecological and human health in the two basins. Our research will assist in meeting the need for 1) reasonably sophisticated and accurate integrated transborder watershed models which can be used to support watershed management and restoration decisions and for 2) education and public outreach to help local citizens and other stakeholders recognize the importance of a watershed-wide perspective. One tool for communicating results of our research will be a web site which will portray the physical, social, economic, and political characteristics of the watersheds as well as the results of the modeling efforts. This easily accessible medium should be an invaluable aid in helping stakeholders visualize and understand spatial patterns and relationships over the watersheds. For the Tijuana watershed, another major product of the program will be press-ready negatives for a folio-size multi-color atlas that will contain the same information in hard copy form. (In the second year of the project, development of an atlas for the San Pedro watershed will also begin in collaboration with the SALSA project). In addition, our research will: 1) increase understanding of relationships between anthropogenic factors and physical/biological processes; 2) improve knowledge of baseline conditions in the watershed; 3) increase collaboration among scientists from SCERP institutions; 4) improve

cooperation between researchers, community groups and government agencies having interests in the watersheds; 5) increase understanding of the influence of cross-border asymmetries on watershed processes through cooperative analysis of the San Pedro and Tijuana Watersheds; 6) identify stressors and high risk areas; 7) identify data gaps; and 8) develop improved methodologies for addressing environmental problems in transborder watersheds, taking into account new methodologies and guidelines recommended by NAS/NRC and EPA.

OBJECTIVES AND RESEARCH CONTEXT[1]

The Tijuana and San Pedro watersheds span the international border between the United States and Mexico. Both watersheds have been studied extensively, both watersheds are undergoing explosive population growth, and water resource issues are critical factors influencing sustainability in these ecologically-fragile, semiarid ecosystems. From an ecological perspective, these watersheds form meaningful landscape units for study and management because of the shared functional relationships that exist within their boundaries. However, very different social, political, and economic influences occur on the two sides of this international border. One feature of these transboundary watersheds is that a significant gap exists between the watershed as an ecological unit and the watershed as a planning and administrative unit. The overall objective of the Transboundary Watershed Research Program is to initiate for the Tijuana and San Pedro basins an integrative program of research that explores this gap and identifies barriers to—and opportunities for—bridging this gap. While two watersheds are being studied, one goal of our study is to integrate these studies in a cooperative analysis through the use of common models.

Integrative approaches to watershed research combine ecological, economic, political, and social factors in the study of watershed processes. Land uses are influenced by these factors and, in turn, impact ecosystem dynamics through events that can be identified and monitored. Land uses can be studied in terms of type of use (e.g., urban, residential, and rangeland), spatial distribution of land use, and change over time. The principal objective of our research is to investigate the dynamic interrelationships between human and natural factors as reflected by land use patterns in the Tijuana and San Pedro watersheds. Our central research question, therefore, is:

What economic, social, political, and ecological processes interact to generate land use patterns in the Tijuana and San Pedro watersheds, and how do these patterns and processes influence environmental conditions in the two basins?

Specific research questions can then be organized under this question into several categories. For example, what factors have influenced the spatial and temporal distribution of land use? How does land use impact the quality and quantity of water? What are the ecological

[1] This proposal reflects a collaborative process. The process began when the SCERP research team met with Dr. Will Graf, member of the National Research Council Watershed Management Committee. Based on our discussion with him we began to refine our plans for an integrative watershed study. Our team then developed the basic framework and content of the proposal and released it for review. The reviewers included were Wendy Laird-Benner (EPA, Region 9), Beau McClure (BLM, Arizona), Hector M. Arias (CIDESON), Bruce Goff (SALSA/ARS), William Kepner (EPA, Las Vegas), and Susan Liberman (DOI). We have carefully considered their input and revised the proposal to reflect their comments.

consequences of water resource degradation? How does the international border influence the factors that guide land use decisions? These and other questions are described in more detail later in this proposal.

APPROACH

Our research approach will focus on characterizing the distribution and intensity of land use in each watershed and developing models that describe the interrelationships between land use patterns and ecological and human factors. Patterns of land use will be documented using maps, planning documents, aerial photographs, and satellite imagery to generate a GIS-based record of recent land use change.

Numerous studies are being conducted on both watersheds. Consequently, a sizable amount of data currently exists (collected by government agencies, private organizations, and university researchers). However, these data vary greatly in thematic content, geographical coverage, and scale and resolution. In the Tijuana Watershed our research and data needs will focus on the land use-ecological relationships (especially among land use, urban runoff, non-point source pollution, and the estuarine ecosystem). To insure a comparative analysis of the two watersheds, we intend to take a similar approach in the Upper San Pedro. Numerous studies are currently being conducted in the Upper San Pedro that emphasize ecological and landscape processes. We have been in contact with these researchers and intend to build upon and complement their studies and work cooperatively to avoid duplication. Specifically, we intend to look at land use as the ecological process which characterizes human influences and resource demands on the landscape. For both watersheds, our goal is to integrate existing information into a larger land use model that will investigate the interdependencies and feedback among ecological, economic, social, and political factors influencing land use. In particular, our models will explicitly consider the impact of the border on watershed properties and dynamics. A considerable effort will be expended in identifying, unifying, and filtering existing data for incorporation into our GIS models. One expected outcome of our modeling effort is the identification of data gaps. While our research is designed to make extensive use of existing data, where data do not exist, effort will be directed toward collecting new data needed for model completion as budgets allow.

Several types of modeling activities will be undertaken. For the San Pedro Watershed, we will develop a hierarchically structured, patch dynamic, watershed model. This watershed model will be spatially explicit and will use grid-based, remotely sensed data as well as integrated ecological and socio-economic data. GIS software will be used to store, manipulate, and analyze spatial data and to facilitate the modeling process. Of particular interest will be socio-economic and institutional factors influencing patch development and patch influences on water resources and the riparian ecosystem components of the watershed. For the Tijuana Watershed, we will develop a similar GIS-linked model, that, when coupled to an empirically-based run-off model, will serve to both manage the spatial and temporal datasets and predict pollutant loading to the watershed and particularly to the estuarine ecosystem of the critical Tijuana Natural Estuarine Research Reserve. For both watersheds land use characteristics that will be described for each patch type will include 1) social and economic factors, 2) surface and subsurface water flow, 3)

point-source and non-source pollution, 4) biodiversity, and 5) other activities such as fuel combustion that give rise to air pollution which in turn impacts water quality.

As part of our efforts in characterizing environmental conditions of these two semi-arid, transborder watersheds we will also evaluate applications of existing approaches including EPA's Index of Watershed Indicators, the PLAnning for Community Energy Economic and Environmental Sustainability ($PLACE^3S$) model, and EPA's BASINS software package. Indices for the Index of Watershed Indicators have not been computed for the Mexico portions of the watersheds, thus providing an incomplete characterization of the total area of each basin. This deficiency will be overcome by our cross-border program perspective. The $PLACE^3S$ model relates land use to water and air pollution and energy use. Finally, BASINS provides a variety of analytical and modeling tools of potential use to this project.

OVERALL EXPECTED RESULTS OR BENEFITS

The overall goal of the transborder watershed program is to provide information for decision makers that will aid in policy formation and adaptive management aimed at sustainable ecological and human health in the two basins. Our research will assist in meeting the need for 1) reasonably sophisticated and accurate integrated transborder watershed models that can be used to support watershed management and restoration decisions and for 2) education and public outreach to help local citizens and other stakeholders recognize the importance of a watershed-wide perspective. One tool for communicating results of our research will be a web site that will portray the physical, social, economic, and political characteristics of the watersheds as well as the results of the modeling efforts. This easily accessible medium should be an invaluable aid in helping stakeholders visualize and understand spatial patterns and relationships over the watersheds. For the Tijuana watershed, another major product of the program will be negatives for a folio-size, multi-color atlas that will contain the same information in hard copy form. (In the second year of the project, development of an atlas for the San Pedro watershed will also begin in collaboration with the SALSA project). In addition, our research will:

1) increase understanding of relationships between anthropogenic factors and physical/biological processes;
2) improve knowledge of baseline conditions in the watersheds;
3) increase collaboration among scientists from SCERP institutions;
4) improve cooperation between researchers, community groups and government agencies having interests in the watersheds;
5) increase understanding of the influence of cross-border asymmetries on watershed processes through cooperative analysis of the San Pedro and Tijuana Watersheds;
6) identify stressors and high risk areas;
7) identify data gaps; and
8) develop improved methodologies for addressing environmental problems in transborder watersheds, taking into account new methodologies and guidelines recommended by NAS/NRC and EPA.

THE TIJUANA RIVER WATERSHED

Objectives of the Proposed Research

The proposed research in the Tijuana River Watershed (TRW) has several specific objectives. They are to:

1) Identify through a GIS-based mass loading model significant sources of lead found in sensitive areas in the TRW.

2) Directly measure the mass emission of selected anthropogenic pollutants (cadmium, chromium, copper, lead, nickel, zinc, and conventional contaminants (nitrate, ammonia, phosphate, suspended solids) into the Tijuana Estuary using an ISCO autosampler to calibrate the model in 1) above.

3) Analyze the surface water runoff and non-point source pollution characteristics of the watershed utilizing the BASINS 2.0 software.

4) Characterize the condition and vulnerability of the watershed by applying the EPA Index of Watershed Indicators (IWI) framework.

5) Estimate the impact of alternative urban designs and land use strategies on air and surface water quality using the Planning for Community Environmental, Energy and Economic Sustainability (PLACE^{3}S/INDEX) Model.

6) Provide user friendly products to assist community groups and decision makers in obtaining an improved understanding of geographic relationships in the watershed.

Context of the Proposed Research

The Tijuana River Watershed (TRW) is a 4,500 square kilometer basin that lies astride the California-Baja California section of the United States-Mexico border. Two-thirds of the basin is in Mexico. For decades raw sewage from human settlements, principally from the cities of Tijuana and Tecate, has flowed into the Tijuana River and across the international border into the Tijuana Estuary. This problem has worsened in recent years with substantial population growth, along with intensive industrial development associated with the maquiladora (in-bond manufacturing and assembly plants) program in Mexico. Indeed, the Tijuana River Watershed is the single greatest source of lead (and other anthropogenic pollutants) loading to the coastal ocean of southern California and Baja California (known as the Bight of the Californias). Many of the water quality problems in the watershed are due to diffuse, non-point sources of pollution, and can be addressed most effectively along watershed lines.

In 1994, the presidents of San Diego State University (SDSU) and El Colegio de la Frontera Norte (COLEF), a Mexican think tank and graduate training institution, signed a

memorandum of understanding (MOU) that obligated the two institutions to work together in addressing environmental problems in the TRW through a watershed approach. The MOU provided a framework for transborder for cooperation in four complimentary areas: GIS database development, education and community outreach, scientific studies, and watershed management. Concurrent with the MOU signing, the National Oceanic and Atmospheric Administration (NOAA) granted start up monies to the partners to support the cost of obtaining aerial photography and satellite imagery, the creation of basic layers in the GIS, and the initiation of SCERP funded scientific studies such as the use of the World Bank's Industrial Pollution Projection System which has been employed for modeling industrial air pollutant emissions in the TRW. Chief among the educational products already generated from the GIS is a 36 inch by 46 inch multi-color print in two languages, Spanish and English. This print is unique in that it was the first time that the watershed had been visualized as a complete entity, extending across the international border. The popularity and use of this map to date further reinforces our belief that additional cartographic products will prove invaluable for informing decision makers and other stakeholders about the watershed's characteristics.

Methods, Approaches, and Techniques

The objectives of this research will be accomplished through a combination of data collection in the field, GIS database development, the development and application of a suite of water and air pollution models, and the creation of the digital files for a major atlas.

Data Collection

An ISCO autosampler will be deployed in the lower Tijuana River Watershed in the Tijuana River (near the Hollister Street Bridge). This sampler will gather flow-weighted composite samples of the river before it enters the estuary. Four storm events will be sampled during each year, that when coupled with hydrographs of the river flow, will allow estimation of the annual mass emission of the measured anthropogenic pollutants. In addition, we will perform sampling of the flow-weighted concentrations of these same pollutants under dry-weather (base flow) conditions. These data will allow us to directly calculate the annual mass loading of pollutants to the estuary, and also allow us to calibrate our GIS-based model for lead. Chemical analyses of the water samples will include measurements of levels of nitrate, ammonia, phosphate, total suspended solids, and the following heavy metals: cadmium, chromium, copper, lead, nickel, zinc. The metal analyses will be carried out using graphite furnace atomic absorption spectrophotometry using a Perkin-Elmer SIMAA 6000 atomic absorption unit with Zeeman correction. Nutrient analyses will follow Standard Methods using colorimetric analyses. Suspended solids will be determined gravimetrically.

Database Development

The data collected from the autosampler will be added to the existing GIS database and used to calibrate the GIS-based model described below. The digital database will also be enhanced through the addition of data from three principal sources: demographic and housing censuses,

Mexican agencies that collect data on water and sewage, and the results of modeling conducted during this project.

Environmental Pollution Modeling

Several pollution models will be applied to the watershed in order to compare the two watersheds and address border impacts on the watersheds. The models to be examined are:

1) a GIS-based mass loading model to identify sources of lead,
2) the BASINS software package,
3) the Index of Watershed Indicators, and
4) the PLACE^{3}S/INDEX

1) GIS-Based Mass Loading Model

A significant source of many harmful pollutants (including lead) to the watershed is atmospheric deposition. Ambient air quality data are now being collected on an hourly basis from monitoring stations located in Tijuana and southern San Diego County to determine the level of pollutants in the atmosphere. These monitors are operated and maintained by the Air Pollution Control District of San Diego, the California Air Resources Board, and the Mexican environmental agency, SEMARNAP. All data are QA/QS by the Air Resources Board to meet USEPA requirements for inclusion into the National Aeromatic Information Retrieval Systems (AIRS).

Although the air monitoring stations measure a number of pollutants, we will concentrate on lead, which is known to have harmful effects on human health and aquatic ecosystems. Large quantities of lead have been found to enter the Tijuana Estuary and the coastal ocean via storm water runoff from the Tijuana River. The source of this lead is at present unknown, but it is possible that lead deposition from the atmosphere could be a significant source. Preliminary data from monitors in Tijuana show relatively high levels of lead in the atmosphere, presumably resulting from the use of leaded gasoline in Mexico. Although the use of leaded gasoline in Tijuana has declined in recent years, it is still in use.

A GIS-based mass loading model for lead will be generated taking into account the quantitative significance of land use, transportation, and combustion sources which deliver lead to the watershed via wet and dry deposition from the air. In this way, significant sources of lead will be identified, and sensitive areas within the watershed can be accurately located. Moreover, the sub-basins with the largest contributions of this pollutant will be identified and prioritized for targeting more intensive monitoring and for applying best management practices (BMP's), infrastructure improvement, or industrial pretreatment. This approach also will allow managers to evaluate impacts of various BMP's under given hypothetical conditions, and offers a predictive capability to estimate mass loading of lead to the Estuary under a variety of border development scenarios.

2) The BASINS Software Package

BASINS, developed for EPA, provides a variety of analytical and modeling systems applicable to this project. ASSESS is for single watershed analysis, limited watershed studies, and for more specific sites. DATA MINING is used to dynamically link maps and data for different sources. The Non-point Source Model (NPSM) is combined with EPA's hydrologic simulation program and ArcView to model land use data with source loadings for specific pollutants in a watershed. Some other modeling capabilities of BASINS that are germane to the binational watershed are: TOXIROUTE—a stream routing model that can include non-point source pollution data and perform dilution/decay analysis, and Post Processing—to assist in analysis and evaluation for management and decision making purposes. BASIN 2.0 is run with ArcView 3.0a and therefore will operate with all ArcView compatible datasets. This will insure the communication of project results to both sides of the border.

Since BASINS was developed for the United States, several substantial issues of data compatibility exist for a binational watershed analysis. In the initial year, the team will undertake the acquisition and adaptation of datasets to conform to BASINS specifications. Data for the US side of the border are available from EPA, USGS, and other sources. Some of the applicable data include: land use/land cover, urbanized areas, soils, hypsography, major roads, USGS hydrological unit boundaries, and water quality monitoring station summaries. Mexican data will be acquired from SEMARNAP, INEGI, and other federal, state, and local agencies in Mexico. The team will rely on the existing detailed land cover/use database for the Tijuana region developed by SDSU. These data will be supplemented by fieldwork and the use of aerial photographic and satellite imagery data sources to acquire necessary data or to update existing databases for the Mexican portion of the watershed.

3) Index of Watershed Indicators

As part of the effort of the USEPA to move towards a watershed-based approach to integrated environmental protection, the ``Index of Watershed Indicators" (IWI) approach was promulgated in order to create an index of water quality on a watershed basis. The four primary objectives of the IWI are:

a) to characterize the condition and vulnerability to pollution of the watersheds of the United States,
b) to serve as a baseline to measure progress towards the goal that all watersheds be healthy and productive places,
c) to provide the basis for dialogue between stakeholders and water quality managers in the watershed, and
d) to empower the public to learn more about their watershed, and to work to protect it.

Fifteen data layers of the IWI cover two categories of information on the Condition and Vulnerability of a given watershed. The Condition data layers are designed to denote existing water quality and the Vulnerability data layers are designed to indicate where discharges or other stressors impact the watershed and could cause future problems. Since the IWI is still in its first

stage of development there is still much need to improve the datasets to support watershed characterization. More importantly, coverage of the IWI does not extend beyond the United States border. For example, the Cottonwood-Tijuana Watershed (USGS Cataloguing Unit 18070305) is characterized by the existing IWI database, but this characterization is wholly based on only the United States portion of the watershed. Since the Mexican section encompasses about 2/3 of the total area, there is an obvious gap in the IWI rating. Indeed, the present IWI gives the Cottonwood-Tijuana Watershed an overall score of 1, the highest score denoting better water quality and low vulnerability, even though most of the lower river and the estuary are impaired due to sewage contamination. Moreover, even the existing IWI dataset for the US portion of the watershed needs to be expanded and made more consistent.

The IWI datasets will be extended to include existing data in the Mexican portion of the watershed and gather new data (via the autosampler) on ambient water quality and total loading for toxic and conventional pollutants. We also propose here to update datasets for the indices on contaminated sediments, wetland loss index, aquatic species at risk, and the estuarine pollution susceptibility index for the watershed. This effort to improve, extend, and update the IWI dataset for the TRW, and will afford interested agencies and organizations an expanded capacity to communicate with other stakeholders, review and comment on the data and its significance, and disseminate information to interested parties and the public.

4) The PLACE^{3}S/INDEX Model

The PLACE^{3}S/INDEX Model has been used for energy and air quality planning in the San Diego region as well as in community-level applications. We propose to apply the model to regions in the Tijuana Basin to determine the likely outcome that different land use strategies will have on air pollution and water quality. A powerful element of the package is that it incorporates a GIS database thereby allowing results of different scenarios to be displayed in an easily understood geographical format. An important element of the PLACE^{3}S/INDEX tool is that it works best when local decision makers and stakeholders are incorporated into the decisions that make up the assumptions of the models. This will be the first time such a stakeholder-based approach has been used in a transborder region.

The PLACE^{3}S portion of the model is designed to provide qualitative and judgmental input from stakeholders. This gives stakeholders an organized way to participate in any planning process right from the beginning, rather than being presented with a set of scenarios at a later date in which they have had no input or participation. The INDEX part of the model is the actual analytical tool (software) and GIS database that will be used by the research team to quantify the qualitative inputs from the stakeholders. Taken together the PLACE^{3}S approach and the INDEX software allow an interactive, participatory, analytical process to evaluate land use planning scenarios and their impact on the two watersheds under study.

Atlas Development

As indicated previously, a principal product of this project is press-ready negatives for a folio-size map book that will be approximately 100 pages in length. Six major sections are

envisioned. The first four will allow the reader to explore the environmental, infrastructural, political, and socio-economic characteristics of the Tijuana Watershed. Following these will be two more sections that explore (1) the spatial relationships of these characteristics through the use of maps, graphs, and illustrations and (2) the results of spatial modeling activities generated from the broader project. A gazetteer will also be included in the atlas. The atlas that will ultimately be produced will be a full-color rendition, with explanatory text in both Spanish and English since the region is shared by both the United States and Mexico.

Data for this project will come primarily from the GIS database developed by San Diego State University (SDSU) and El Colegio de la Frontera Norte (COLEF). Where data are not available, new data (in the forms of maps, planning documents, aerial photography, and satellite imagery) will be collected to supplement the existing data sets. The resulting digital data sets will then be used to create the required maps, graphs, illustrations, and models for the atlas. Initial data manipulation and graphics for the atlas will be produced using ESRI's ArcInfo software. Data files will then be ported to a variety of other software, such as ESRI's ArcView and Macromedia's Freehand illustration software, for final map design and layout. Final graphics files will be produced on a Macintosh 8600 computer system, and rough color proofs will be produced using a Laserjet 5M color printer. The final versions of the digital graphic files will be ported into a page layout program, such as Quark Express, where they will be merged with the text developed for the atlas. These files will then be sent to a service bureau for more accurate proofing and for the negatives required by the printer to complete the press run for the atlas.

The atlas project will be carried out in several overlapping steps. At the beginning a work flow chart will be prepared. Existing data will be inventoried and cataloged. Preliminary atlas design will begin by identifying major atlas themes. Responsibility for the design, layout, and production of graphics and text will be identified. Thumbnail sketches showing the rough layout of elements for all graphics and text will be prepared. Data gaps will be filled and the results from water and air quality modeling will be integrated into the atlas project. Initial text will be drafted for each graphic. Work will proceed by sections of the atlas. As one section is completed, it will be passed to the next stage, allowing some overlap to occur in the flow of work. Next, a period of time will be devoted to establishing a cohesive ``look" for the atlas. Color schemes will be set, methods of data representation chosen, layouts revisited and revised as necessary, and text will be revised. Next, individual sections of the atlas will be proofed, edited, and finalized. Formal color proofs will then be made to determine adjustments of ink percentages, text, and map symbology. Final page layouts will be made, resulting in digital files to be delivered to the service bureau. Proofing of the files will be done, corrections made, and negatives will be generated. Note: Additional funding will be sought from other sources to cover the costs of printing the atlas.

THE UPPER SAN PEDRO BASIN

Objectives of the Proposed Research

The proposed research on the Upper San Pedro watershed has several specific objectives (generally similar to those discussed for the Tijuana portion of the project). They are:

1) Describe land use patterns for the Upper San Pedro Basin (USPB) including trend analysis and patch dynamics (patterns of land use patches and interactions among land use patches on the landscape).
2) Describe socio-economic and institutional factors that are driving land use decisions and develop GIS linked models relating these factors to changes in land use pattern.
3) Describe and model the linkages between land use and environmental indicators (with particular emphasis on water quality and quantity). Potential tools that may be used in this modeling effort are the BASINS 2.0 software, the EPA Index of Watershed Indicators (IWI) framework, and the PLACE^{3}S model.
4) Conduct a field study that will provide data on important linkages between land use and environmental indicators. The study will describe the relationship between the integrity (ecosystem health) of two of the dominant plant communities of the San Pedro River floodplain (cottonwood-willow forest and sacaton grasslands) and groundwater and surface flow regimes.
6) Provide user friendly products to assist community groups and decision makers in obtaining an improved understanding of geographic relationships in the watershed.

Context of the Proposed Research

The Nature Conservancy, in cooperation with over 100 private and public partners, has declared the Upper San Pedro Basin to be one of 12 "Last Great Places of the Western Hemisphere" in terms of ecological diversity and importance. One rationale for this designation was the very high faunal diversity of the watershed (for instance, over 300 bird species occur on the San Pedro riparian corridor alone). In addition, the San Pedro is among the few rivers in the Southwest that has unregulated flow. The San Pedro Riparian National Conservation Area is a 23,000 hectare natural area that was established 1988. The Nature Conservancy also operates an internationally known bird sanctuary known as the Ramsey Canyon Preserve in the Huachuca Mountains and the National Audubon Society manages a unique research station (the Appleton-Whittell Research Ranch Sanctuary) on the watershed's grasslands.

The San Pedro River flows north into the United States from its headwaters near Cananea, Sonora. The division between the upper and lower San Pedro Basins occurs in an area known as the "narrows" approximately 12 miles north of Benson, Arizona. The upper basin has a total area of about 6,500 square kilometers with about 72 percent of the area occurring in the United States. Elevations range from 1,100 to 2,900 meters while annual rainfall varies from about 300 millimeters to 750 millimeters. Within this relatively small watershed an extraordinary diversity of ecosystems exists including Chihuahuan Desertscrub, Plains Grasslands, Semidesert Grassland, Rocky Mountain Montane Grassland, Rocky Mountain Riparian Deciduous Forest, Madrean Montane Riparian Deciduous Forest, Interior Southwest Riparian Deciduous Forest and Woodland, Southwest Interior Chaparral, Madrean Evergreen Forest and Woodland, Madrean Montane Conifer Forest, Petran Montane Conifer Forest.

Significant growth management problems now face the Upper San Pedro Basin. In the United States portion of the watershed, rapid suburbanization, expansion of Ft. Huachuca, and a

growth in tourism have exacerbated water quantity and quality issues. The projected expansion of the copper mining operation near the headwaters of the San Pedro in Cananea, Sonora, increases the potential of serious water quality problems along the entire river. The conversion of ranches and farmlands to new subdivisions has resulted in a loss of open space, a decline in visual quality, and increased fragmentation and destruction of habitats for numerous species.

The ecologically rich and significant Upper San Pedro Basin has attracted significant research attention. Of particular note is the SALSA (Semi-Arid Land-Surface Atmosphere) program that was organized to understand, model, and predict the consequences of natural and human induced change on the basin-wide water balance and ecological diversity of semiarid regions at event, seasonal, interannual, and decadal time scales. Current research and measurement efforts are focused on the San Pedro River basin. Participants in SALSA include scientists from federal agencies and universities from several countries including the United States and Mexico. Our research is planned to be done in cooperation with other SALSA participants. In addition, a new study funded by a DOD Legacy Grant, entitled "Alternative Futures for the Upper San Pedro River Basin," will be conducted by the United States Army Corps of Engineers-CERL, EPA, and Harvard University. The objective of this project is to provide optional scenarios for regional land use planning similar to that done for the Camp Pendleton, California project. Our research has a narrower focus on land use as an ecological process (integrating socioeconomic and environmental factors). However, we anticipate cooperation with this project and expect that our results will be of value in their scenario generation framework.

Methods, Approaches, and Techniques

Land-use Characterization and Modeling

Land use represents the interface between humans and the landscape; therefore, development of a land use coverage for the San Pedro Basin using remotely sensed imagery is a core effort of the proposed study. Development of this coverage will first require definition of appropriate land use categories (for both sides of the international border) and the relationship of land use categories to land cover classifications. Initial systems to be considered include the U.S. Geological Survey Land Use/Land Cover Classification System (which is a resource oriented classification system designed to be driven by the interpretation of remote sensor data) and the Standard Land Use Coding Manual (which is land use activity oriented). The classification system used in this study will be such that comparisons with the Tijuana Watershed will be possible.

Other topics that initial efforts must address will be identification of the most suitable remotely sensed imagery in terms of spatial, spectral, and temporal resolution. Images will be selected from both the present and several dates in the past for analysis. Standard image processing methodology will be used to extract thematic information including use of both hard classification algorithms (using both supervised and unsupervised approaches) and soft classification algorithms (using fuzzy set classification logic). Training sites will be identified from a combination of field work, analysis of aerial photography, and existing land cover classification

data. Past states of land use will be reconstructed from archived land use maps and planning documents.

Error evaluation of the land use classification maps will be conducted to insure the usefulness of the product. Two sources of information will be used in the classification accuracy assessment: (1) the remotely-sensed-derived classification map and (2) reference test information not used in the classification process. Error will be reported in terms of overall accuracy (a nonsite-specific accuracy assessment), producer's accuracy (the probability of a reference pixel being correctly classified), and user's accuracy (the probability that a pixel classified on the map actually represents that category on the ground). Lineage documentation of the remote sensing product will also be maintained.

The product of this work will be a time series of land use classifications which can be analyzed for both spatial and temporal change which will aid in identification of resources at risk (using environmental indicators) and agents of change (socio-economic and institutional drivers). Change detection will be conducted using standard algorithms. Land use patterns will be analyzed using landscape metrics to identify the land use patch composition (number of patch types and their relative abundance) and configuration (including such metrics as size distribution, dispersion, adjacency, and connectedness). For both temporal and spatial analysis the influence of scale on patterns of change will be considered.

Socio-Economic and Institutional Driver Characterization

Socio-economic and institutional factors will be represented by multiple data layers in our modeling. Two general questions will guide our studies. First, what processes drive the generation of land use patterns? Second, how do consequences of land use feed back on future land use decisions?

The processes that drive the generation of land use patterns will be modeled using rule-based transition probabilities. Rules which control land use transition probabilities themselves reflect a semi-Markovian process where current land use is a function of past and "adjacent" land uses (influenced by land use scale, and patterns of land use which reflect factors such as locations of population centers and transportation corridors. Other processes that drive land use can be grouped into the categories of bio-physical factors, and institutional and socioeconomic factors. Biophysical factors include characteristics of the physical watershed such as soils, slope, drainage, site contamination, water availability, and plant and animal community characteristics. Institutional and socioeconomic factors, in contrast, are influenced by characteristics of both the physical watershed and the larger "shadow watershed" that surrounds the physical watershed. These variables would include population and employment, the demographic profile of the population, individual and community values, perceived quality of life, and land use policy for both the watershed and regions adjacent to the watershed.

Land use will also be modeled using logistical regression since the dependent variable (land use) takes the form of a discrete variable. Such logistical (both binomial and multinomial) models of land use change have been used for a variety of previous studies such as the influence

of distance from city boundaries on land use changes in Ann Arbor, Michigan, conversion of farm land to urban uses, the share of business land uses in Dallas, Texas, as a function of industrial and employment character of the area, and the impact of transit and highway proximity on land use change.

Because land use is a semi-Markovian process, the consequences of land use feed back directly on future land use.

Environmental Indicators Model Development

Environmental indicators will also be represented by multiple data layers in our modeling. The general question which will guide our studies is how are environmental indicators associated with the range of current land uses? The modeling approach for examining relationships between land use and environmental indicators will be the development of a GIS-based hierarchical patch-dynamics model. Several existing modeling approaches which may be of utility in development of this model will be examined for their suitability and incorporated when appropriate. The existing modeling approaches which will be examined are the same as those employed for the TRW section of the project (the BASINS software package, the Index of Watershed Indicators, and the PLACE^{3}S models).

1) GIS-Based Hierarchical Patch Dynamics Model

The hierarchical patch-dynamic modeling approach will address the relationships between land use and environmental indicators at several scales. At the local scale, homogeneous patch models will relate land use to environmental indicators (e.g. surface and subsurface water flows, point and non-point pollution variables, and biodiversity). These models will apply to simple patch types such as residential areas, industrial areas, or grazing land. These models may be as simple as statistical relationships, may be input-output models, or may incorporate results from existing models. Initial modeling efforts will be based on existing data collected by government agencies, private organizations, and university researchers. Data gaps, as they appear, will be identified and efforts will be made to collect necessary data as budgets allow. Landscape scale models will be built for distinctive landscapes consisting of multiple patch types. At the watershed scale, a spatially explicit model will be built to integrate watershed characteristics across all patches. Models will be written in C or C++. They will not only relate land use patches to environmental indicators, but will also provide spatial and temporal output suitable for importing into GIS layers for subsequent display, analysis, and evaluation.

2) The BASINS Software Package

The BASINS software package has been described above (see the Methods, Approaches, and Techniques section for the Tijuana River Watershed). Since BASINS was developed for the United States, substantial issues of data compatibility exist for the San Pedro watershed as well as for the Tijuana watershed. In the initial year, the San Pedro team will evaluate the applicability of

BASINS to research objective on the San Pedro and if appropriate will undertake the acquisition and adaptation of datasets to conform to BASINS specifications.

3) Index of Watershed Indicators

The Index of Watershed Indicators (IWI) has been described above (see the Methods, Approaches, and Techniques section for the Tijuana River Watershed). Since it is still in the early stages of development, there is still need to improve the datasets to support watershed characterization. The Upper San Pedro watershed (USGS Cataloguing Unit 15050202) is characterized by the existing IWI database, but unfortunately this characterization, like that of the Tijuana River watershed, is wholly based only on the United States portion of the watershed. Since the Mexican portion for the watershed encompasses about 28% of the total area and major potential watershed stressors exist in the Mexican portion, there is an obvious gap in the IWI rating. The present IWI gives the Upper San Pedro an overall score of 3, indicating less serious water quality problems and low vulnerability to stressors such as pollutant loadings.

Application of the IWI requires that datasets be extended to include existing data in the Mexican portion of the watershed. This effort to improve, extend, and update the IWI dataset for the Upper San Pedro will afford interested agencies and organizations an expanded capacity to communicate with other stakeholders, review and comment on the data and its significance, and disseminate information to interested parties and the public.

4) The PLACE^{3}S/INDEX Model

The PLACE^{3}S model has been described above (see the Methods, Approaches, and Techniques section for the Tijuana River Watershed). As indicated previously, this model has been used for energy and air quality planning in the San Diego region as well as in community-level applications. The suitability of the model for addressing the relevant research questions will also be considered for the Upper San Pedro Basin.

Riparian Community Studies

Study sites will be established along the San Pedro River and other rivers in southern or central Arizona (e.g. Sonoita Creek, Turkey/O'Donnell Creeks, Hassayampa River). Ten sites will be in areas that support sacaton grasslands and ten in areas that support cottonwood forests. About half of the sites will be along the San Pedro River. Inclusion of sites at other rivers will allow us to span a broader range of site conditions, and encompass the range of variation within sacaton and cottonwood communities. Some of the study sites have been established as part of an ongoing project on sacaton ecology. At each site, transect lines will be established perpendicular to the stream, spanning the riparian corridor. Study plots will be established along transect lines in areas supporting sacaton or cottonwood stands. Study plots and sites will be selected so as to minimize influence of non-hydrologic factors (e.g., recently burned sacaton sites will be excluded).

Two monitoring wells will be installed per site and monitored monthly during the growing season for depth to groundwater. Topography of the floodplain surface (including elevation above the stream thalweg) will be determined using standard survey equipment. The survey data in conjunction with the monitoring well data will be used to estimate depth to groundwater at each study plot. Stream discharge will be measured monthly, or data will be obtained from the USGS for nearby stream gauging stations. Stage-discharge relations will be developed using the cross-sectional surveys; and stream flow data and XS-PRO software will be used to calculate inundation frequencies at the study plots. Soil moisture will be monitored through the use of gypsum blocks. Soil texture, macronutrient content, and soil moisture holding capacity data will be determined at each site, using standard methods.

Biotic integrity of the sacaton and cottonwood-salt cedar stands will be assessed by measuring physiological data, population data, and community data. For sacaton plots, measurements will be taken twice per year (pre- and post-summer rains) on water potential (a measure of internal water stress), height, cover, and total vegetation volume (vertical line intercept method) of sacaton plants. At the end of the growing season, reproductive output of sacaton plants will be measured. Data will be collected on weight per seed, number of seeds per inflorescence, number of inflorescence per plant, and total seed number and weight per plant and per meter square of land. For cottonwood plots, measurements will be taken twice per year on plant water potential and leaf size and weight. Annual branch growth rate will be measured once during the study, as will vegetation volume and woody plant density and basal area. Herbaceous cover, by species, will be measured twice per year.

Indices of integrity for sacaton stands will be developed that reflect values for reproductive productivity, vegetative productivity, and water stress of sacaton; and diversity and composition of the plant community. Indices of integrity for cottonwood stands will be developed that reflect values for productivity, water stress, and community composition. The biotic integrity indices, and individual parameters used to develop the indices, will be statistically analyzed in relation to hydrologic and soil parameters. If the abiotic variables are found to be sharply discontinuous among sites, the data will be analyzed with analysis of variance; otherwise, they will be analyzed with single or multiple regression analysis.

GIS Based Educational/Decision Support Tools

A major goal of the proposed research is to educate stakeholders about watershed characteristics and the interrelationships between ecological, socio-economic, and institutional (particularly the binational character of the watershed) factors. To enable completion of this goal, all team members will coordinate work to insure that their results can be integrated on a common GIS platform. This integrated GIS application will then be used both for the visualization of GIS coverages on the watershed and for simulation of different land use change scenarios. Development of a bilingual atlas for the USPB is also proposed to begin in year two to further educational goals.

RESULTS AND BENEFITS

The results and benefits of the proposed project in the two basins are as follows:

First, the study will provide a detailed description of land use patterns and dynamics in the watersheds on both sides of the border. Socio-economic and institutional driver studies will help to understand past land use change and provide guidance for future land use decisions. The environmental indicator studies will summarize existing knowledge regarding relationships between land use and environmental quality and will also serve as a guide for future land use planning. Integration of these factors will enhance our understanding of land use as an ecological process. Development of GIS applications which integrate these components will allow scenario generation and visual display of spatial modeling exercises. Simulation models which project possible consequences of hypothesized scenarios will provide information concerning future threats to region sustainability.

Second, the Index of Watershed Indicator framework will serve as a baseline to measure progress in the future, and provide the basis for dialogue between stakeholders and water quality managers in the watersheds.

Third, the evaluation and potential use of existing watershed models (including the Index of Watershed Indicators, BASINS, and PLACE^{3}S) will allow consistency in comparison of the Tijuana and San Pedro transborder watersheds as well as assessing the impacts of the border on environmental conditions. Integrating of these analytical tools into GIS-based models of the land use planning process, we will be able to evaluate the impacts of a spectrum of land use scenarios on water quality in the two watersheds. It will be possible to display these impacts in a vivid, colorful geographical format, which will be of assistance to policy makers and local decision makers.

Fourth, as a result of the proposed project, significant sources of anthropogenic pollutants such as lead will be identified, and sensitive areas within the Tijuana Watershed can be accurately located. Moreover, the sub-basins with the largest contributions of each pollutant will be identified and prioritized for targeting more intensive monitoring and for applying best management practices (BMPs), infrastructure improvement, or industrial pretreatment. This approach also allows managers to evaluate impacts of various BMPs under given hypothetical conditions, and offers a predictive capability to estimate mass loading of pollutants to the Estuary under a variety of border development scenarios. By examining the quantity of lead in the atmosphere in the Tijuana Watershed, we will be able to determine, for the first time, the relation between atmospheric lead concentrations and the high levels of lead found in the Tijuana estuary. This will lead to developing mitigation strategies to reduce lead loading to the estuary.

Fifth, field studies will add to our knowledge of ecological processes and relationships in the San Pedro Watershed. Specific results of the riparian study include: (1) identification of degraded and high-quality cottonwood and sacaton stands; (2) elucidation of techniques for discriminating between degraded and high-quality stands; (3) elucidation of hydrologic requirements (surface flows and ground water levels) needed to restore degraded stands and to

maintain stands that have high functional value. Biohydrology studies explore the linkage between hydrologic site conditions and biological components of the ecosystem. As such, they allow one to predict and assess consequences of hydrologic change on ecosystems. Such studies are of particular importance in watersheds such as the San Pedro, where hydrologic factors are primary ecological stressors. Groundwater and surface water decline from agricultural, municipal, and industrial (mine) activities constitute primary threats to riparian ecosystems in the San Pedro Watershed.

Sixth, an important product of this project will be a WEB site complete with maps and text as well as the negatives for the TRW atlas and a preliminary design for the USPB atlas. The WEB site and atlas will be comprised of distinct sections. One section will allow the reader to explore the environmental (e.g., soils and vegetation), infrastructural (e.g., roads and sewer lines), political (e.g., cities and water districts), and socio-economic (e.g., population density and income) characteristics of the watersheds. Another will include illustrations that portray spatial relationships in the basins, e.g., the correlation between vegetation types and characteristics of the terrain. The third section will display through maps and graphs the results of previous modeling activities as well as those generated from this project. A gazetteer and appropriate explanatory text in both Spanish and English will also be included.

Potential beneficiaries of the WEB site fall into three broad categories: government officials, persons engaged in public and K-12 outreach, and university researchers and educators. The watersheds are under the jurisdiction of many different government agencies. Elected officials and employees of these organizations will find the GIS, WEB site, and hardcopy products to be excellent regional planning tools. Organizations such as the San Diego Natural History Museum, the Tijuana River National Estuarine Research Reserve, The Nature Conservancy, and the National Audubon Society (The Research Ranch) have significant water and watershed education programs for the general public and K-12 students. The project products can be used to educate students about the characteristics of the watersheds and to help them visualize relationships between water quality and characteristics of the landscape such as land use and water flow. Academics, particularly at SDSU, ASU, COLEF, UABC, and the University of Sonora will employ the digital and analog products as visualization tools for research and education. Students will be able to use these materials to study the characteristics of semi-arid streams, model surface water runoff of intermittent stream courses, and understand the influence of the border on watershed ecology.

SPECIAL FACILITIES AND PERSONNEL

This project will be supported by the facilities and technical personnel of several centers and laboratories.

At SDSU a key organization is the Center for Earth Systems Analysis Research (CESAR), an internationally recognized research and instruction facility administered by the SDSU Department of Geography. The Center specializes in applying state-of-the-art technology in image processing, remote sensing, geographic information systems, automated cartography and

numerical modeling to problems with a spatial dimension. Research conducted by CESAR is directed at both applied and fundamental problems in fields ranging from biophysical remote sensing to urban planning. This research includes computerised map and image data processing and spatial simulation modeling, as well as field experimentation. All analyses of the heavy metals, including lead, and the conventional pollutants (nutrients plus total suspended solids) will be carried out in the laboratories of the Graduate School of Public Health (GSPH). The GSPH labs are equipped with several major instruments suitable for environmental analyses. The labs contain instruments needed to do aquatic chemistry analyses. Instrumentation includes balances, ion/pH meters, miscellaneous incubators, water baths and shaker baths, spectrophotometers (UV and visible), benches centrifuges, chemical fume hoods, deionized water, and a Barnstead Easypure system for ultrahigh-purity water. The facilities used for running the PLACE^{3}S/INDEX models will be the Environmental Modeling Laboratory at the Center for Energy Studies. In addition, the model will be loaded on a laptop which can be taken to stakeholders meetings so that inputs provided by stakeholders can be evaluated immediately in an interactive manner. All data analysis for atmospheric lead concentrations will be performed at the Environmental Modeling Laboratory based on QA/QS data obtained from EPA approved ambient air monitoring stations.

At ASU this project will be supported by the facilities of the Center for Environmental Studies and the Salt River Project Geographic Information Systems Laboratory. State-of-the-art technology is available in these organizations for image processing, remote sensing, geographic information systems, and spatial modeling. Research conducted at both the Center for Environmental Studies and the Salt River Project GIS Laboratory is directed at applied and theoretical problems in fields ranging from ecological remote sensing to land use analysis. This research includes computer-based analysis, image processing, simulation modeling, as well as field experimentation.

Technical support will also be provided by the substantial GIS and remote sensing center at the University of Utah. This facility is operated under the supervision of Dr. George Hepner who will be directing the BASINS modeling effort.

ADVISORY COMMITTEE

An advisory committee comprised of representatives from significant stakeholder organizations will be formed before the project's initiation. Invitations to serve on the committee will be extended to individuals from both sites of the border and from a) non-government groups, b) Indian reservations, c) the private sector, and d) local, regional, state, and federal agencies.