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A Composite Spatial Model Incorporating Groundwater Vulnerability and Environmental Disturbance to Guide Land Management

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by

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DEDICATION

I dedicate this work to my father, Lynn P. Kovarik (1943 – 2013).

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ABSTRACT

Research has long recognized and studied the dynamics of groundwater processes. More recently, groundwater dependent ecosystems (GDEs) are being recognized for their diversity and vulnerability to anthropogenic impact. Groundwater in karst landscapes presents a distinctive situation where flow through the subsurface often moves rapidly on the scale of days and weeks as opposed to years or millennia in other systems. This distinctive situation of karst systems and their vulnerability to human impacts necessitate an integrated and multifaceted approach for the management of these important resources. However, development of such an approach is complicated by the difficulty of obtaining detailed data about the ecosystem, especially in remote areas of developing countries. Additionally, management difficulties related to political boundaries, jurisdictions, and land ownership can result in ineffective and inconsistent policies and practices across a single catchment. In order to address these issues, this dissertation creates a new composite model for groundwater dependent ecosystem (GDE) management in areas of karst development. Within this new composite model, the combination of the KDI and the GVM recognizes both human disturbance and how the physical nature of the karst will enhance this impact. These studies bridge the gap between science and management by connecting the final model to management strategies for a sub-catchment of the Rio la Venta watershed, the majority of which is within the Reserva de la Biosfera Selva el Ocote. This composite model serves as an adaptable spatial tool for management planning and protection for all components of the karst environment.

CHAPTER ONE

INTRODUCTION

Research has long recognized and studied the dynamics of groundwater processes. More recently, groundwater dependent ecosystems (GDEs) are being recognized for their diversity and vulnerability to anthropogenic impact. Groundwater is defined as subsurface water in unconsolidated deposits and rock and these zones contain the majority of the world's freshwater resources (Freeze and Cherry, 1977). Ecosystems dependent on groundwater are reliant on both its quantity and quality. Groundwater in karst landscapes presents a distinctive situation where flow through the subsurface often moves rapidly on the scale of days and weeks as opposed to years or millennia as in other systems. Karst forms through dissolution of soluble bedrock, and well-developed karst landscapes can contain sinkholes, karren, sinking streams, springs, and caves. GDEs in karst areas are home to a wide variety of fauna from salamanders to microbes. The stability of GDEs, particularly caves, has an influence over biota in the subsurface as well as other resources than can be found within them (Gilbert et al., 1994). Humans and fauna have used caves for millennia, leaving behind artifacts preserved in these protected environments (Moyes, 2012). Caves also are resources for studying the past, particularly paleoclimates using speleothems that form in this constant environment along with a wealth of other mineral resources (Hill and Forti, 1997).

Unsustainable extraction and subsequent impacts such as salinization, surface collapse, and desertification are a few of the main anthropogenic effects on groundwater and GDEs. Over pumping of groundwater also impacts karst; due to the high permeability and rapid recharge in karst aquifers groundwater contamination concentrations and consequently the pollution of springs and wells happens more frequently. In karst environments, the growing body of knowledge related to the processes at work within the system has enabled a wide range of studies concerning human disturbance on the surface and subsurface karst environment (Drew and Hotzl, 1999; Urich, 2002; Parise and Gunn, 2007). The decrease and contamination of groundwater within the karst environment can negatively impact other resources in the subsurface, damaging artifacts, reducing or destroying habitat for endemic biota, and dissolving speleothems (Harding and Ford, 1993; Gunn et al., 2000; Langer, 2001; Boulton et al. 2003; Jiang et al. 2008; Chen et al., 2009; Hienz, 2009; Castillo et al., 2013). Quarrying and mining destroys entire caves or portions of caves which permanently alters hydrologic flow pathways (Clements et al., 2006; Parise and Pascali, 2003; Auler et al., 2015). Finally, tourism in caves can result in introduction of non-endemic biota through creation of artificial environments with lights and manmade entrances, condensation corrosion through increased $CO_{2,}$ and destruction of speleothems (Fong 2011).

Based on these impacts and their causal mechanisms, land managers have worked to create best practices for mitigation. However, these efforts are stymied by a lack of knowledge of the ecosystem necessary to target areas where best practices would most effectively be implemented. Additionally, management difficulties related to political boundaries, jurisdictions, and land ownership result in ineffective mitigation. Water resource planning frequently occurs within political instead of hydrologic boundaries resulting in managers have no control over outside contributing areas to their portion of a watershed (Barham, 2001). Compounding this problem is the difficulty of delineating groundwater basins in karst areas where flow pathways often do not follow drainage divides and can change seasonally (Ford and Williams 2007).

These above issues illustrate the need for adaptive tools based on scientific understanding that aggregate threats to the watershed and susceptibilities of the ecosystem while allowing for easy modification as more quantitative data become available. With advances in technology, geographic information systems (GIS) and remotely sensed techniques have aided the development of tools such as groundwater vulnerability mapping and environmental indices. These tools should be couched within the appropriate framework in light of the scale and type of data available in order to guide the conclusions based on the results and project future work. The United State Environmental Protection Agency (U.S. EPA) has developed a three-tiered framework for environmental assessments. Level one is a landscape-scale assessment using GIS and remote sensing, level two is a rapid assessment adding simple field data, and level three produces quantitative data for an intensive site assessment at a smaller site based on the level one and two assessments (Fennessy et al., 2004). The models developed within this dissertation provide tools for level one and level two assessments, and guide selection of sites where level three assessments are necessary based on the U.S. EPA framework.

Vulnerability of groundwater to natural and anthropogenic processes can be mapped using intrinsic and. specific vulnerability. Intrinsic vulnerability is defined as the inherent vulnerability of the watershed as characterized by its natural processes independent of the nature of contaminants, while specific vulnerability is generally mapped as the vulnerability of a source or well to a particular contaminant (COST 620, Daly et al. 2002). The environmental index approach as described by Hammond (1995) is comprised of indicators based on empirical data to help quantify and abridge information of environmental processes and effectiveness of environmental policies. Environmental indicators provide information about phenomena that are regarded as typical or critical to environmental quality, however they do not include data related to the intrinsic vulnerability of the ecosystem (Smeets and Weterings 1999). While GVM sometimes include information concerning surface land use through risk and hazard mapping, these data only represent threats to groundwater quality. With the composite model developed in this dissertation, human activities resulting in deterioration of the entire karst environment will be referenced spatially with physical features of the area. This will result in the delineation of areas of concern for enhanced protective measures where disturbance is occurring and areas to target for protection where undisturbed land still exists.

On Biosfera de la Reserva Selva el Ocote (el Ocote) in Chiapas, the karst ecosystem in the Rio La Venta watershed is threatened by habitat degradation and destruction through impacts from development, agriculture, grazing, iguana hunting (which includes the use of fires), and introduction of non-native species (CONANP 2000). Currently, the staff of el Ocote lack the necessary tools for managing and protecting the groundwater and its dependent ecosystem within the reserve and contributing watershed. International exploration groups have accomplished a great deal of work including archaeological surveys and cave mapping. However, quantitative data characterizing the aquifer such as hydraulic conductivity measurements are difficult to obtain for this remote area. Topography, fauna, and vegetation are prohibitive to fieldwork such as installment of data logging equipment. In addition, the reserve does not have the funds or personnel necessary to conduct projects requiring expensive equipment and extensive fieldwork. Finally, currently available data representing the understanding of the reserve’s karst system have yet to be aggregated into a useful format for local leaders and resource managers.

The overall goal of this study is to develop management strategies for the protection, conservation, and sustainable development of the Rio la Venta watershed. This dissertation will provide tools for el Ocote land managers to justify decisions made to local stakeholders related to development within the reserve boundaries, and to make recommendations for private land owners within the watershed to protect their water quality and GDEs. Currently, no cave and karst resource management tools exist for their reserve. Urich states that there is a "gap between the science of karst and the practice of karst management" (2002). His statement still applies today. It is anticipated that this dissertation will help bridge the gap between karst science and the needs of land managers furthering the understanding of the complex and fragile relationships between surface and subsurface tropical karst ecosystems thereby creating useful tools for managers on the ground.

The overarching research questions of this dissertation:

1. Where are the areas of concern for the health of the karst ecosystem under current land use practices?
2. What management strategies can be applied on the Reserva de la Biosfera Selva El Ocote to address those areas of concern?

To address these above questions, a number of more specific questions will be answered:

1. What is the state of the catchment and degree of human disturbance and where is this disturbance the highest as measured by the karst disturbance index?
2. What are the most vulnerable areas to groundwater contamination within the study area?

3. What management strategies can the Selva El Ocote adopt within the framework of an adaptive management plan in order to manage their karst resources and where should these management strategies be focused?

Research Objectives

The following research objectives will be addressed for the study area by:

1. Creating and implementing a spatially explicit formulation of the KDI
2. Generating a validated GVM
3. Combining the KDI and GVM to create a composite model to aid the creation of management strategies for the watershed based on that model

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CHAPTER TWO

APPLICATION OF THE KARST DISTURBANCE INDEX AS A RASTER-BASED MODEL IN A DEVELOPING COUNTRY

Abstract

Karst landscapes provide important services such as sources of water, hosting rare and endangered biota, and sites of significant human historical artifacts. The complex hydrology of karst systems and their vulnerability to human impacts necessitate a multifaceted approach to the management of these economically important resources. Evaluating and mitigating human impact, or human-caused disturbance of the environment, is a key component of land management planning and is best accomplished through adaptive management. This paper specifically addresses disturbance to the karst environment caused through anthropogenic activities using a karst-specific adaptive environmental index, the Karst Disturbance Index (KDI). This study develops a spatially-explicit formulation of the KDI in a geographic information system (GIS) for application to a sub-catchment of the Biosfera de la Reserva Selva el Ocote in Chiapas, Mexico. The advancement in the KDI using a GIS reduces subjectivity and increases the spatial accuracy compared to previous applications. This particular project demonstrates that the KDI can be successfully applied in a remote location of a developing country.

Introduction

Karst landscapes are important assets that provide a source of water, host rare and endangered biota, and serve as sites of significant human historical artifacts. People utilize caves within karst landscapes for a variety of purposes from recreational to religious. Additionally, 20 to 25 percent of the world's population use karst aquifers for their water needs (Ford and Williams, 2007). However, high hydraulic conductivity and points of rapid infiltration such as sinking streams, enlarged dissolution fissures, and sinkholes make karstic aquifers particularly vulnerable to exploitation and pollution. Ongoing studies worldwide are examining the impacts of human activities on karst from activities such as deforestation, irrigation, agricultural pollutants, as well as from industrial and urban impacts such as mining, tourism, and karst water exploitation (Harding and Ford, 1993; Drew and Hotzl, 1999; Gunn et al., 2000; Langer, 2001; Urich, 2002; Chen et al., 2009; Hienz, 2009). Human population growth can decrease both the water quality and quantity through urban pollution and increased demand for water, and these issues can result in declines on potable water sources in karst landscapes through contamination and increased groundwater pumping. Forestry can increase sedimentation within caves and agriculture practices raise concentration levels of NH+4, NO3-, and NO2 which can then exceed drinking water standards in wells and springs (Boulton et al., 2003; Jiang et al., 2008; Castillo et al., 2013). Additional negative impacts to the karst environment include surface collapse, dissolution of speleothems, and destruction of cultural artifacts (Gutierrez et al., 2014; He et al., 2014; Mulec, 2014; Parise et al., 2015). Human visitation in caves impacts the ecosystem and biota through changes to the cave environment such as new entrances, artificial lighting, destruction of speleothems, and increased waste (Fong, 2011). Finally, mining and quarrying can result in destruction of karst landscapes on the surface as well as changes to cave formations and habitat in the subsurface (Clements et al., 2006; Parise and Pascali, 2003; Auler et al., 2015).

The complex hydrology of karst systems and the easily impacted nature of its subsurface resources necessitate a multifaceted approach to management. Van Beynen (2011) provides a detailed review of different issues related to managing and conserving karst environments, as well as dealing with hazards unique to karst lands. Evaluating and mitigating human impact or human-caused disturbance of the environment is a key component of land management planning and is best accomplished through adaptive management. This paper specifically addresses disturbance to the karst environment caused through human actions using the Karst Disturbance Index (KDI), which is a karst-specific adaptive environmental index (van Beynen and Townsend, 2005). The KDI has roots in the work of pressure-state-response (PSR) frameworks or indicator systems, as well as the work of the U.S. Environmental Protection Agency (U.S. EPA) and Millennium Ecosystem Assessment (OECD, 1993; Hasaan et al., 2005; EPA, 2008). It is comprised of indicators based on empirical data to help quantify and summarize information regarding human impact on the karst system. This quantification and summary is conducted in order to evaluate the degree of impact and the effectiveness of current and past environmental policies in mitigating and preventing disturbance.

Researchers and land managers have applied the index to various karst areas globally to assess levels of disturbance. (Calo and Parise, 2006; van Beynen et al., 2007; De Waele, 2008; North et al., 2009; Bauer and Kellerer-Pirklbauer, 2010; Day et al., 2011). A study in the Waitomo area of New Zealand (van Beynen and Bialkowska-Jelinska, 2012) demonstrated the applicability of the KDI at the watershed scale. In its original formulation, van Beynen and Townsend (2005) designed the KDI to be applied in the field at a single site using a mix of qualitative assessment and quantitative field data. Recent studies have improved the approach by using GIS to map the KDI values for different watersheds over political boundaries (Anguloet al., 2013). However, to date the KDI has not been fully implemented in a GIS. Calculating the KDI in a GIS will give land managers the ability to generate a continuous surface of KDI values that allows exploration of variability within watersheds or other study areas. Additionally, the spatially-distributed KDI will allow managers to target certain areas where disturbance is more severe for mitigation plans, as well as comparison of areas of disturbance with locations of sensitive resources.

The first goal of this study is to develop a spatially explicit formulation of the KDI that can be applied using GIS. The second goal of the study is to calculate the KDI for the project area utilizing the methodology of van Beynen and Townsend (2005), and compare the results with the KDI in a GIS. Finally, this study works within the Biosfera de la Reserva Selve el Ocote in Chiapas, Mexico to evaluate the application of the KDI in a remote area of a developing country where minimal data is available and the landscape is difficult to access.

The Karst Disturbance Index

The KDI evaluates 31 indicators that are outlined in detail by van Beynen and Townsend (2005) (Table 2.1). Disturbances are scored with a value from zero to three, based on the degree of disturbance – zero indicates no human impacts, one indicates localized disturbance, two corresponds with a higher degree of disturbance occurring across the study area, and a score of three indicates severe, widespread disturbance. To calculate the final KDI score, all applicable indicators scores are tallied and then divided by the total possible score. The final KDI score is then compared with the related ranks for disturbance (Table 2.2).

Where assessors were either not able to measure some indicators within the scope of the project or the indicators simply were not present, these indicators were given a lack of data (LD) designation. The number of LD scores was used to calculate a degree of confidence for the work with a value between zero and one. The greater the values of the LD score, the lower the confidence in final KDI score. A score with a value of less than 0.1 denotes a high degree of certainty, where as a score of greater than 0.4 suggests that more information is necessary before the KDI can be applied to the study area (van Beynen and Townsend, 2005).

Application to the Study Area

Study Area

Contained within Chiapas is the area of the Reserva de la Biosfera Selva el Ocote (el Ocote) (Fig. 2.1) that is located near the Isthmus of Tehuantepec (16°57’50” North - 93°38’21” west) and as of 2014 covers approximately 1013 km^2 (101,300 ha). El Ocote and its area of influence consist of three main sub- catchments of the Cuenca Rio Grijalva –Tuxtla Gutierrez, which is part of the Grijalva-Usumacinta hydrologic region. The sub-catchment of the Rio la Venta covers the southern portion of the reserve and consists primarily of carbonate rock. The Rio la Venta (Fig. 2.1) flows northwest through el Ocote at approximately 2,000 m.a.s.l. in the Sierra Madre de Chiapas to the reservoir of Nezahualcoyotl (Malpaso) (Badino et al.,1999). Within the borders of the reserve, the river meanders 97 km from Aguacero, in the southeast corner to el Encajonado at the western boundary, incised in some places over 400 m deep into carbonate rock.

Table 2.1 - The Karst Disturbance Index

Category	**Attribute**	**Scale**	**Indicator**	**3**	**2**	**1**	**0**
Geomorphology	Surface landforms	Macro	Quarrying/Mining	Large open cast mines	Small working mines	Small scale removal of pavement	None
		Macro/ meso	Flooding (human built surface structure indirect effect)	Total flooding of valley for hydroelectric dams	Flooding of fields for irrigation	Small scale reservoirs built for farming	Natural precipitation-induced flooding
		Meso	Stormwater drainage (% of total stormwater funneled into sinkholes)	>66%	34-66 %	1-34%	None
		Meso	Infilling (% of infilled caves and sinkholes)	>66%	34-66 %	1-34%	None
		Micro	Dumping (% of sinkholes affected)	>66%	34-66 %	1-34%	None
	Soils	Macro	Erosion	Severe	High	Moderate	Natural rate
		Micro	Compaction due to livestock or humans	Widespread and high levels	Widespread but low levels	Few isolated concentrated areas	None
	Subsurface Karst	Macro	Flooding (human induced cave flooding due to surface alteration	Permanent cave inundation	Increased intermittent flooding & > 50% filling	Increased intermittent flooding & < 50% filling	Only natural flooding due to high rainfall
		Micro	Decoration removal – vandalism	Widespread destruction	~ 50 % of speleothem removed	Some isolated spots of removal	Pristine
		“	Mineral - sediment removal	Most of material removed	~ 50% of cave affected	Some isolated spots	Pristine
		“	Floor sediment compaction- destruction	Most of floor sediments – decorations affected	~ 50 % of floor sediments – decorations affected	Small trail through cave	Almost pristine, mostly rock surface

Table 2.1, con.

Category	**Attribute**	**Scale**	**Indicator**	**3**	**2**	**1**	**0**
Atmosphere	Air quality	Macro	Desiccation	Widespread and high levels	Widespread but low levels	Isolated and very low levels	Pristine
		Micro	Human-induced condensation corrosion	Widespread and high levels	Widespread but low levels	Isolated and very low levels	Pristine
Hydrology	Water quality i) Surfaces	Meso	Pesticides and herbicides	Leakage of concentrated chemicals into aquifer	Heavy spraying of crops/weeds on surface	Little use of chemicals	None used
	Practices	Micro	Industrial and petroleum spills or dumping	>20 Brownfields	10-19 Brownfields	1-9 Brownfields	No Brownfields
	Water quality ii) Springs	At all Scales	Occurrences of algal blooms	Only aquatic life is algal growth	Occasional or seasonal short-term blooms	Nutrients concentrations just above background levels in water	Pristine water
		Macro	Changes in water table (decline in meters)	> 35	15	<5	Only natural variability
	Water quantity	Micro	Changes in cave drip waters	Total cessation	Long dry spells (not seasonally related)	Slight reduction	No change
Biota	Vegetation disturbance	At all Scales	Vegetation removal (% of total)	>66%	34-66 %	1-34%	0
	Subsurface biota - cave	Micro	Species richness (% decline)	50-75	20-49	1-19	0
		“	Population density (% decline)	50-75	20-49	1-19	0

Table 2.1, con.

Biota (cont'd)	Subsurface biota –ground water	Micro	Species richness (% decline)	50-75	20-49	1-19	0 or increase in numbers
		"	Population density (% decline)	50-75	20-49	1-19	0 or increase in numbers
Cultural	Human artifacts	At all scales	Destruction/removal of historical artifacts (% taken)	>50	20-49	1-19	0
	Stewardship of Karst region	At all scales	Regulatory protection	No regulation	A few weak regulations	Statutes in place but with loopholes	Region fully protected
		"	Enforcement of regulations	Widespread destruction, no enforcement	No policing, but little damage done	Some infrequent enforcement	Strong enforcement
		"	Public education	None, public hostility	None, public indifference	Attempts through NGOs	Well funded government programs
	Building infrastructure	Macro	Building of roads	Major highways	Some two lane roads	Some country lanes	Minor trails
		Meso	Building over karst features	Large cities	Towns	Small rural settlements	No development
		Micro	Construction within caves	Major modification	Major tourist cave	Cave trail marked	Pristine

Table 2.2 - Classification of disturbance

Score (tally/total possible tally)	**Degree of disturbance**
0.8-1.0	Highly disturbed
0.6-0.79	Moderately disturbed
0.4-0.59	Disturbed
0.2-0.39	Little disturbance
0-0.19	Pristine

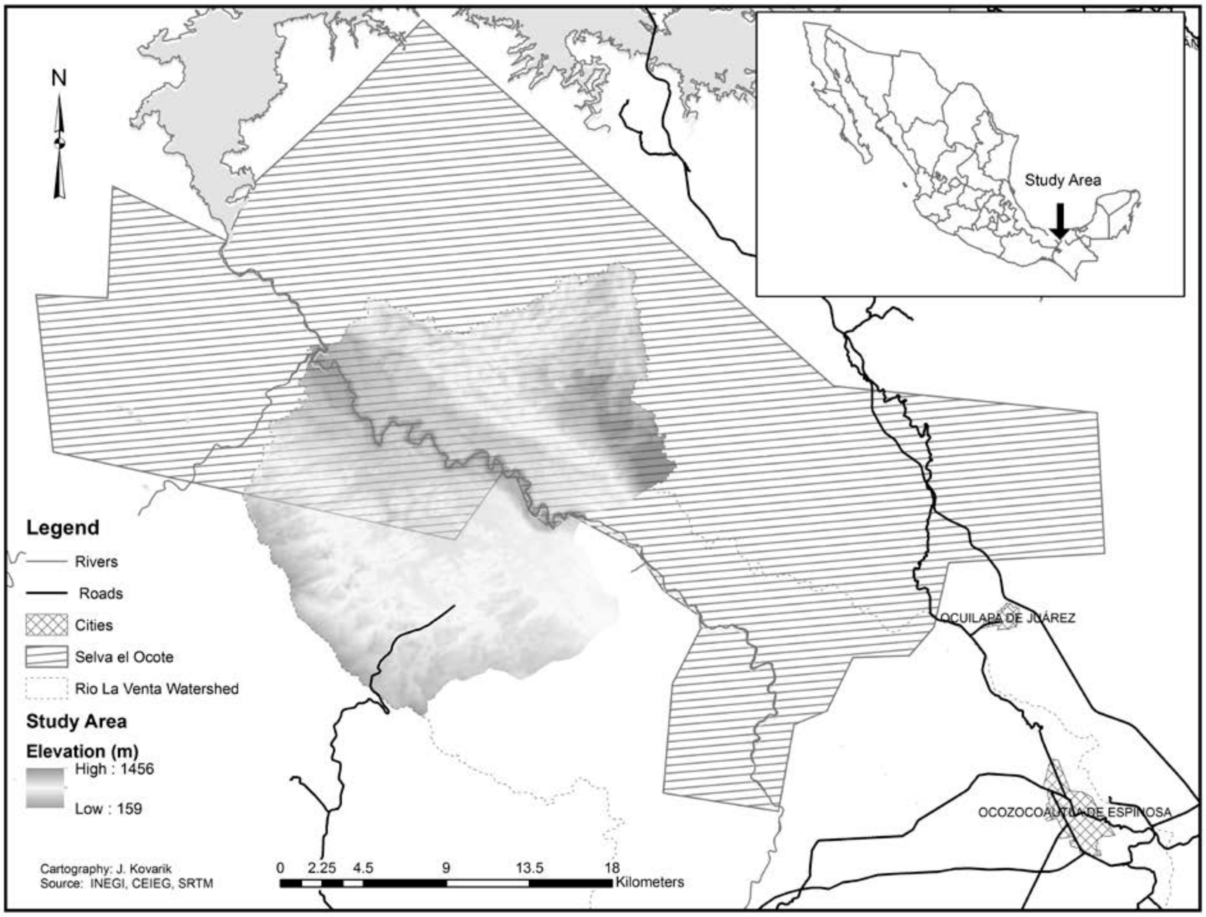

Figure 2.1 - The study area, el Ocote, and greater Rio la Venta Watershed

Because surface water is scarce in el Ocote due to karstification, the canyon and river provide important habitat to the riparian vegetation and many of the rare and endangered fauna. Three main native forest types can be found within the reserve, including the tall perennial forest, the tall sub-perennial forest, and the intermediate sub-perennial and sub-deciduous forest. A typical five hectare block in the reserve contains 286 species of flora while the entire Ocote is home to approximately 50 percent of all known species in Mexico (Badino et al., 1999). The reserve also contains a great diversity of wildlife including the jaguar (Panthera onca), Howler monkeys (Allouata geoffrogy), and the highly poisonous royal nauyaca (Bothrops asper).

The study area is a sub-catchment of the Rio la Venta which is 368 km^2 (36,800 ha) that is bounded to the southwest by the Uxpanapa Fault, the northwest by the Rio Negro, and the northeast by the Sierra Monterrey. Middle to upper Cretaceous carbonates comprise the majority of the study watershed with the exception of the higher elevations along the Uxpanapa Fault in the southwest where uplifted Jurassic-aged siltstone and sandstones outcrop.

The La Venta Group has mapped over 147 caves in the project area, and the longest mapped cave in the catchment is the Cueva del Rio la Venta with 13 km of passageway (Bernabei et al., 2013). The climate of this region is wet-warm and humid-warm depending on elevation, with the maximum annual average temperatures between 30 to 33 ºC, with areas lower in elevation near the canyon reaching on average 33 to 34.5 ºC. Rainfall exceeds 1500 mm per year in portions of the catchment with the wet season occurring May to September and the dry season October to April. The vegetation consists of primary and secondary tropical forest within the reserve, and second-growth tropical forest and slash-and-burn agriculture outside of the reserve boundary.

In the project area there are six main settlements, including Rabasa to the northeast of the Rio laVenta, and Emiliano Zapata, Venustiano Carranza, General Cardenas, Unidad Modelo, and the largest of these, Adolfo Lopez Mateo to the southwest. There are many smaller settlements connected to each other with dirt roads, and the southwestern portion of the catchment is comprised of several small ranches. The major economic activities within the area are agriculture and animal husbandry.

Data

To score and map these specific disturbances in a GIS, numerous sources of data were required. These included the staff of el Ocote, U.S. Forest Service and U.S. Fish and Wildlife Service, Instituto Nacional de Estadística y Geografía (INEGI), Comité Estatal de Información Estadistica y Geográfica de Chiapas (CEIEG), the La Venta Group, and local residents and officials. Academic journals, university repositories, websites, and field surveys of the study areas were also used (Table 2.3). Data collection occurred from 2010 – 2014. Fieldwork and ground-truthing within the study area were utilized to assess the validity of information remotely collected. Many of the available data collected were maps, however, not all data were in digital format, or a digital format readily usable in a GIS. Data collected such as paper maps were digitized, georeferenced, and cataloged in GIS and the field surveys and interviews were given spatial reference using Global Positioning Satellites (GPS) then converted into GIS layers.

Application

The scoring of the KDI in this study is conducted using the original methodology of van Beynen and Townsend (2005) as well through raster creation and calculation in a GIS. For the GIS process, ESRI's ArcGIS software was used to process all data and calculate the final KDI score. In the GIS calculation, vector layers (polygon, point, line) were converted to raster (grid) utilizing ArcToolbox. All rasters were resampled to 30-meter cell size and snapped to the project area. Each cell of the raster layer that contained the disturbance indicator was reclassified to reflect the score; cells not containing the indicator were reclassified to zero. Once all indicators were scored in individual rasters, the final layers were then combined through raster calculator to create an overall disturbance score for each cell.

Table 2.3 - Data Sources for the Karst Disturbance Index of the Study Area

Indicator	Data Source
Quarrying/ Mining	Remote sensing data, field surveys, communication with el Ocote staff
Flooding (due to human-built structures)	Remote sensing data, field surveys, communication with el Ocote staff
Stormwater drainage	Remote sensing data, field surveys, CEIEG
Infilling of sinkholes	Field visits, communications with el Ocote staff
Dumping into sinkholes	Field visits, communications with el Ocote staff
Soil Erosion	Remote sensing data, field surveys, communication with el Ocote staff, CEIEG
Soil Compaction	Remote sensing data, field surveys
Decoration Removal and Vandalism	Field surveys, communication with local cavers
Mineral / Sediment Removal	Field surveys, communication with local cavers
Sediment Compaction	Field surveys, communication with local cavers
Desiccation	Field surveys, communication with local cavers
Condensation Corrosion	Field surveys, communication with local cavers
Pesticide/ Herbicide Use	Remote sensing data, field surveys, communication with el Ocote staff
Industrial Spills/ Dumping	Field surveys, communication with el Ocote staff
Water Quality in karst springs/ streams	Field surveys
Gasoline Stations	Field surveys, communication with el Ocote staff
Changes in Water Table	Field surveys, communication with el Ocote staff
Cave Drip Waters	Field surveys, communication with el Ocote staff
Vegetation Removal	Remote sensing data, field surveys
Cave Biota Species Richness	No data
Cave Biota Population Density	No data
Groundwater Species Richness	No data
Groundwater Population Density	No data
Destruction of Artifacts	Communication with local cavers and el Ocote staff, journal articles
Regulatory Protection	Communication with el Ocote staff
Regulation Enforcement	Communication with el Ocote staff
Public Education	Communication el Ocote staff, INEGI
Building of Roads	Remote sensing data, field visits, CEIEG
Building over Karst	Remote sensing data, field visits, CEIEG
Cave Construction	Field visits, communication with local cavers and el Ocote staff

The overall disturbance raster was then divided by the total possible score to create the final KDI raster. The final KDI raster is then compared with the KDI score calculated through the original methodology. The LD indicators and the LD score were calculated in keeping with van Beynen and Townsend (2005).

Results

Geomorphology

Within the study area there are two gravel pits/ quarries (Fig. 2.2). The first is located along the main road into Adolfo Lopez Mateo, and the second on the road from Lorenzo Cardenas to La Unesco. These gravel quarries are approximately 0.5 km^2 (500 ha) and mine into the carbonate hills, or cerros. The indicator quarrying/ mining is scored as one due to the limited scope of quarrying within the area (Fig. 2.6). Human-induced flooding does not occur in the study site. As typical in karst areas, natural flooding during the wet season from precipitation exceeds the drainage capacity of the karst system. The impact from stormwater drainage in the area is not of major concern within the study area due to minimal urban development.

Dumping of trash into sinkholes and other karst features is prevalent in areas near roadways and settlements. Trash can also be found in subsurface conduits and in the canyon itself. While most refuse disposal in the area is through backyard burning, other larger and/or non-burnable items such as batteries are often disposed of in the forest and karst features. Larger batteries such as car batteries are not disposed of in this manner, however smaller batteries are discarded this way.

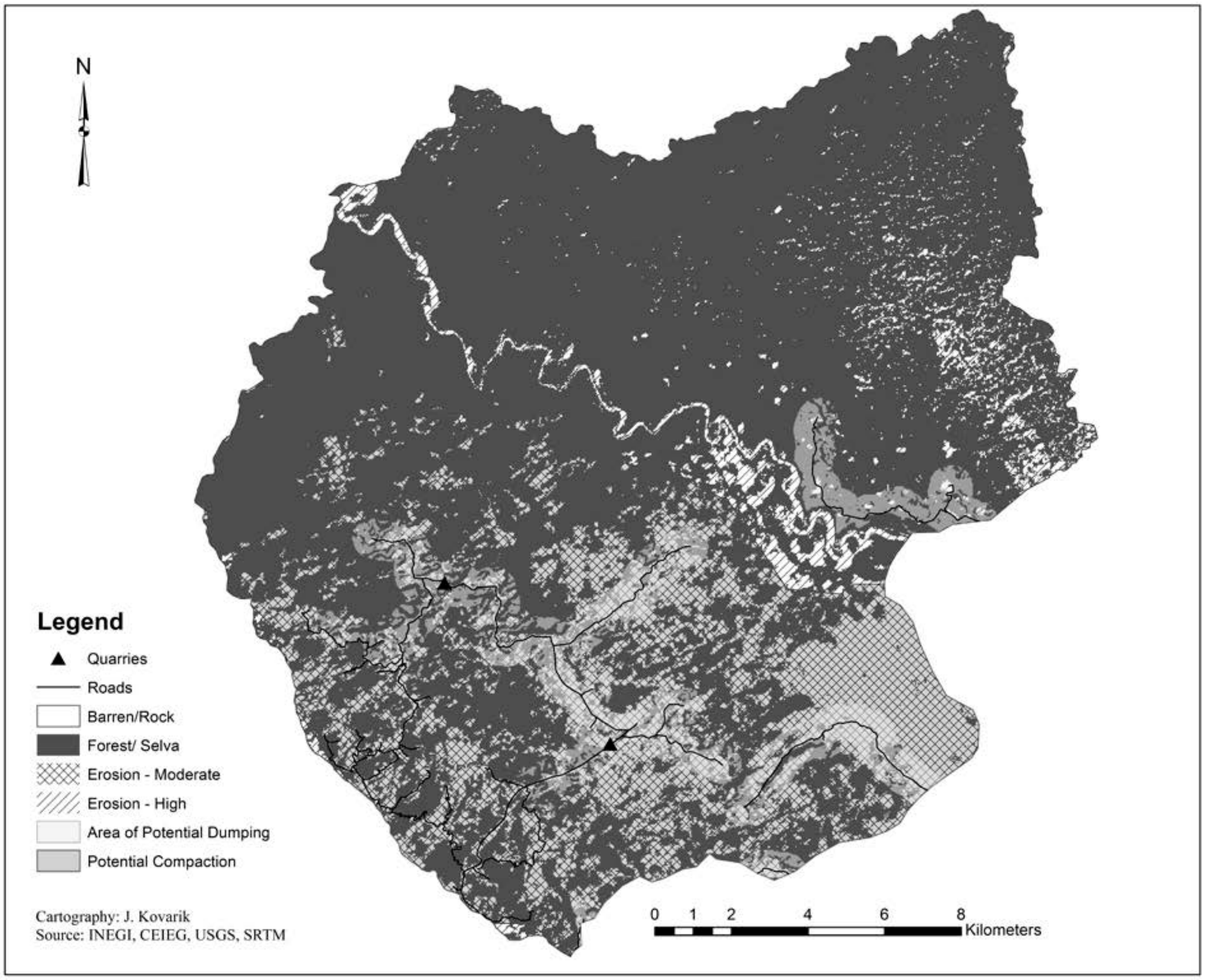

Figure 2.2 - Geomorphology indicators within the study area.

As the total number of sinkholes for the project area was not available, this indicator was scored one based on the assumption that dumping would occur in sinkholes most easily accessed from the road system (those found approximately 0.5 km from any type of road, the estimated distance trash might be hand carried, packed, or thrown), and calculated based on the percent of the total available area where sinkholes were likely to form (Fig. 2.2).

Erosion has been documented as predominantly laminar with medium and high intensity in the study area (Fig. 2.2). Where deforestation has occurred on steeper slopes, the already thin soils are quickly lost resulting in exposed epikarst. This indicator is scored at one for areas of medium intensity and two for areas of high intensity within the GIS (Fig. 2.6), while the traditional KDI is scored with a value of 2 (Table 2.4). Soil compaction is present and is quantified in the index using the assumption it occurs where forest has been converted to agricultural use or development (Fig.2.2). Compaction is scored at a value of two for both calculations, as it occurs over a broad area within the study area, but at low levels.

Certain indicators were all scored as zero for this indicator group; therefore no layer was created for calculation in GIS. These included human-induced hydrologic change, stormwater drainage, infilling, subsurface flooding, cave decoration removal/vandalism, subsurface minerals/ sediment removal, and subsurface floor sediment compaction/ destruction.

Atmosphere

Only two to four caves in the project area near the settlement of Lopez Mateo are used for ecotourism and average visitation per year is estimated at less than 50 people. Currently, locals have not modified any of the caves in ways which would cause desiccation, altered air flow, or increased humidity. Highest visitation to the caves within the watershed occurs approximately twice year when an outside caving group visits the area with 10 or more people. Local cavers from Tuxtla Gutierrez are infrequent visitors. The current level of visitation per trip and per year is insufficient at this time to impact cave atmosphere composition compared to impacts seen at commercial show caves where visitation often exceeds thousands of tourists per month. The indicators for air quality, desiccation and human-induced condensation corrosion, both score zero, or pristine for the study area.

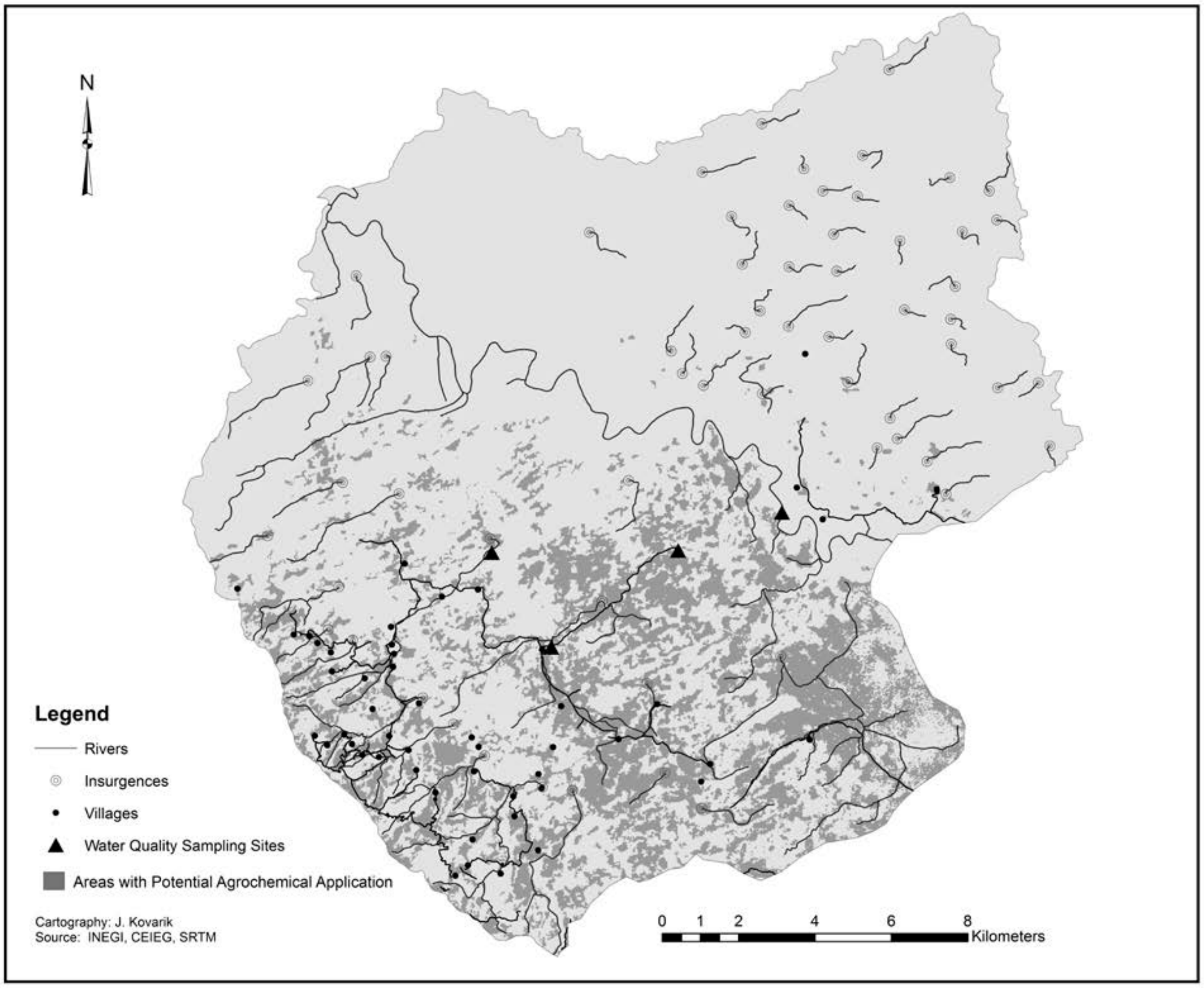

Figure 2.3 - Hydrology indicators within the study area.

Hydrology

Good water quality is a necessity for both the health of people utilizing water from the reserve and its aquatic biota. Additionally, the degradation of water quality can result in destruction of mineralogical, archaeological, and paleontological resources in caves. For this study, it is assumed that agrochemicals are or have been utilized in all areas mapped as agricultural or cleared, amounting to approximately 63 km^2 (6300 ha) (Fig. 2.3). Currently used agrochemicals include Glyphosate, Paraquat, Furadan and Semevin.

In the rural areas of Chiapas, farmers often do not handle agrochemicals or dispose of materials associated with those chemicals precisely as recommended in health and safety protocol. In 2003, Mexico enacted the Law for the Prevention and Integral Management of Waste to control disposal and cleanup of contaminated materials. However, while Mexico signed the Rotterdam and Stockholm Conventions in 2005 as an effort at adopting controls on toxic substances used in the environment, little controls exist on application of agrochemicals (Satoh and Gupta 2011). Consequently, the water quality indicator is scored as two for the study area (Fig. 2.6; Table 2.4).

Water quality studies in 2013 and 2014 undertaken by the U.S Forest Service and el Ocote personnel were the first to comprehensively sample within the study area for 15 different parameters at 15 locations, 4 of which were within study area (Fig. 2.3). Levels of lead, turbidity, total coliform, and Escherichia coli (E. coli) were of primary concern in 2013, however, lead levels declined in 2014. Levels of total coliform and E. coli were highest during the wet season in August 2013. No studies to date have measured the amount of agrochemicals in water resources within the study area. There are no gasoline stations or industrial activity in the area therefore chemical spills or leaking of subsurface gasoline storage tanks resulting in a score of 0 for these indicators. Finally, no large-scale groundwater pumping occurs within the study area, so any variability in the water table is natural also resulting in a score of zero.

Biota

Approximately 82 percent (303 km^2 or 30,300 ha) of the watershed is forest (primary and secondary) and 65 km^2 (6500 ha) are classified as open area – recent land clearing, early regrowth, developed, or agriculture (grazing and crops) (Fig. 2.4). In 1998, 144 km^2 (14,400 ha) or 39 percent of the study watershed was burnt with an additional 6 km^2 (60 ha) in 2003.

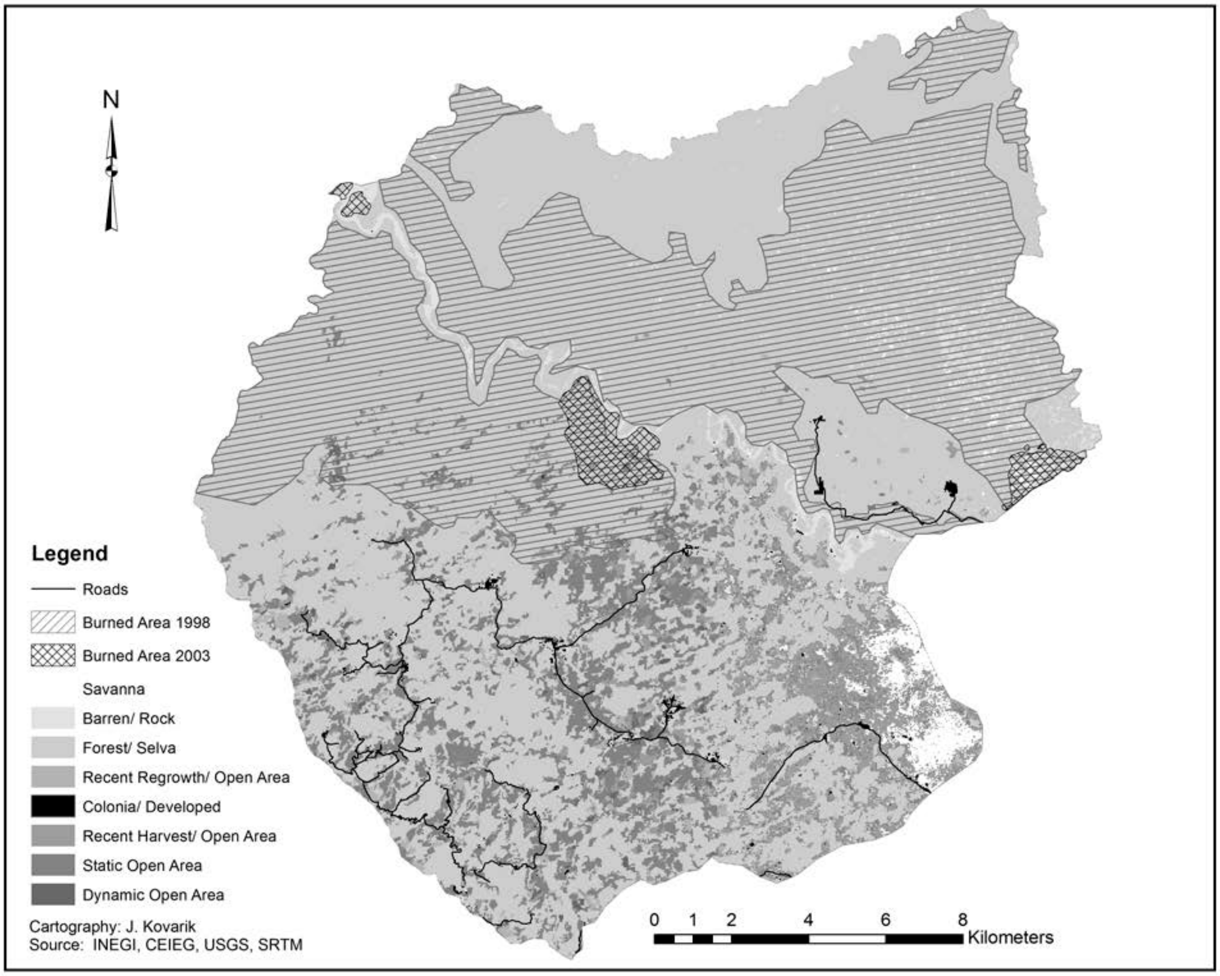

Figure 2.4 - Biota indicators within the study area.

Within the reserve, the primary forest remains, however slash-and-burn agriculture, harvest for timber, as well as clearing areas for ecotourism trails has reduced forest coverage, resulting in a score of one for the area where clearing has occurred. Minimal research has been done on the biota and habitats of the project area. Unpublished studies have documented rare and unique cave-adapted biota but not enough data is available to score this indicator. Cave biota species richness, population density, and groundwater species richness and population density are all considered LD.

Cultural

Human artifacts. The area of el Ocote has been continually occupied for thousands of years. Before the Spanish conquest and the Maya, the major groups of people inhabiting the area were the Zoque, and even today people living in el Ocote and surrounding area speak one of the mixe-zoque families of languages (Villanueva, 1998). The first archaeological reports of the caves of the Rio La Venta area containing Zoque artifacts were written in the 1940s. Artifacts were collected and returned to the United States for evaluation from the 1940s to the 1960s. This began a trend that has continued through the present day with the majority of the archaeological research conducted in the area by cavers and European explorers. While early efforts were partnered with local researchers, later works were carried out independent of local and governmental entities. The majority of the archaeological research has been accomplished by Italian speleologists and explorers with assistance from Italian archaeologists and universities. To date, over 100 archaeological caves and sites have been located and documented and the main use is theorized to be ritual or religious in significance (Villanueva, 1998; Domenici, 2001).

The types of artifacts found are of organic origin including human remains as well as fibrous objects which can be easily damaged or destroyed if handled improperly (Villanueva 1998). A history of looting and damage of artifacts and sites is evident although not prevalent. Villanueva (2002) suggests that efforts need to be made to ensure 1) archaeological studies within the area have a scientific and not commercial focus, 2) that projects are regulated by Mexican authorities and monitored by competent archaeologists and 3) that those interested in exploring the caves in the area follow a set of guidelines and are aware of Mexican Federal Laws relating to Monuments and Archaeological Areas, Artistic and Historic.

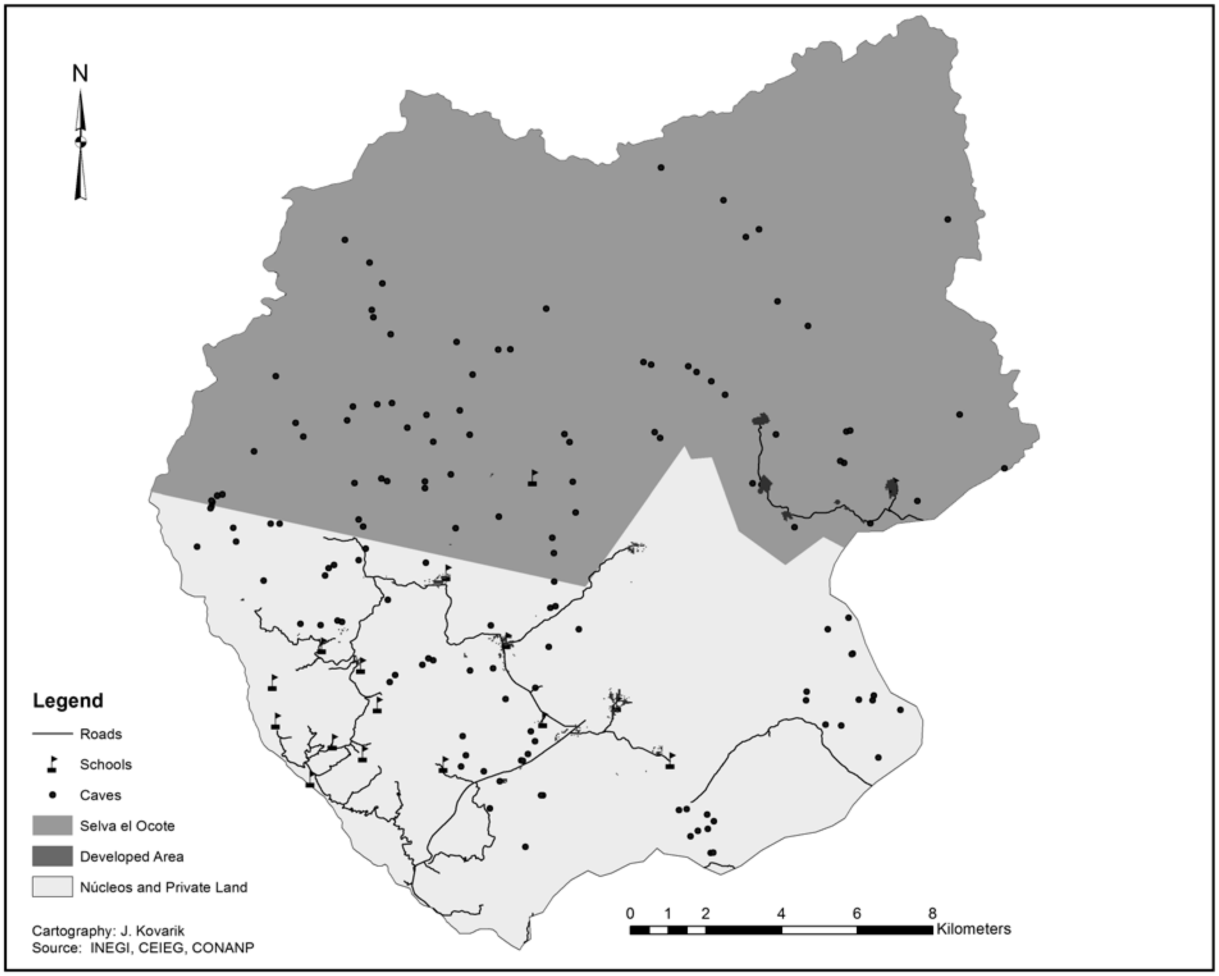

Figure 2.5 - Cultural indicators within the study area.

The indicator destruction/removal of historical artifacts is given a value of one, which is applied to cells containing cave entrance data and based on information from discussions with the reserve personnel and journal articles (Fig. 2.5). This is instead of calculating the percent taken as in order to know the percent of artifacts taken, one must know the total amount of artifacts in an area – which is difficult if not impossible to determine.

Stewardship of the karst region. Currently, no federal laws or policies in Mexico protect cave and karst resources with the exception of groundwater. Current Mexican water policy is managed comprehensively by the Comisión Nacional del Agua (Conagua or CNA) and is based upon not only the two laws outlined above, but also the 2008 Registro Público de Derechos de Agua (REPDA) (Public Register of Water Rights). Today, CNA is part of the Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT) (Ministry of Environment and Natural Resources). Within this arm of the Mexican government exists the environmental enforcement branches including the Subsecretaría de Gestión para la Protección Ambiental (Undersecretary of Public Works and Environmental Regulation) and the Procuraduría Federal de Protección al Ambiente (PROFEPA) (Federal Attorney of Environmental Protection). Also, under the umbrella of SEMARNAT is the Comisión Nacional de Áreas Naturales Protegidas (CONANP) (in English, National Commission of Natural Protected Area), which manages protected areas such as el Ocote. Under these agencies and laws, groundwater is considered to be waters of the state of Mexico and access to this resource is regulated through titling of wells to specific owners under REPDA. While public, urban, and industrial users are required to pay for groundwater rights, agricultural users do not (Scott et al., 2010). As such, a rural farmer can dig a well independently or in a group with other local farmers to irrigate farmland. The only regulations on agriculture include the stipulation that a well owner(s) must formalize the endeavor with a title, report the volume of water pumped (a gauge must be placed on the well), and ensure that no damage occurs to third parties (Scott et al. 2010). However, within the reserve regulations exist to prohibit deforestation and development. The portion of the study area that is within the reserve was scored zero within the GIS and the portion outside the reserve was scored three – in the classical scoring of the KDI the entire area was scored three.

Sixty percent of the study area is currently part of el Ocote, while the rest of the study area is private land and núcleos (Figure 2.5). Enforcement efforts by reserve staff of the environmental protection laws regarding illegal timber harvest and similar issues resulted in lawsuits brought by the local population who suggested that these enforcement efforts were illegal under natural area laws. Consequently, reserve workers now document illegal activities with photos and notation in the hope that they will be addressed in the future – however, enforcement of citations has a backup of approximately seven years. Compliance with archaeological laws has more promise. Federal natural area employees and researchers cite the need for cooperation with civic leaders and local nucleo authorities for surveillance and protection. With ecotourism on the rise, local landowners and leaders are more interested in policing caves and looking for non-local visitors. They generally require that visitors have a local guide and permission of the landowner to enter the cave, both of which could potentially ensure the safety and proper ethics of visitors. Due to these issues, the entire study area is scored three for both the GIS and classical calculation.

In the study area, there are 16 communities with school groups, the majority of these falling into the preschool or primary education category (Fig. 2.5). General education does not include any environmental content. However, after the wildfires of 1998 and 2003, el Ocote launched a major informal environmental education campaign. The focus of this campaign was to educate residents in the area about the negative impacts of wildfire to the ecosystem. This campaign was largely successful and documented wildfires have been reduced in the area each year subsequent to this campaign. Currently, foreign speleological groups occasionally provide training to local residents from some of the larger local villages in vertical and horizontal caving techniques. They also give informal talks about speleology and the group's caving projects in other countries. Because of this work, the study area is scored at two for the indicator education of the public about karst. However, none of these efforts can be considered a substitute for environmental education materials adapted for the local area.

Building infrastructure. Approximately 88 km of roadways exist within the study area of which 80 km are dirt and gravel while the remaining 8 km was paved within the past ten years (Figure 2.5). Dirt roads were scored as one in the GIS and paved roads were scored as two. For the first scoring of the index outside the GIS, the building of roads indicator is scored as two. In the villages, sewage is collected in septic tanks. During the dry season, septic tanks function properly, however, during the wet season the water table can rise within a meter or so of the surface resulting in leakage of the sewage into the water sources. Within the study area, approximately 0.3 percent (1 km^2 or 100 ha) is classified as developed which includes structures and roadways (Fig. 2.5).

Final Scoring of the KDI

For the final KDI calculation, over half the indicators score as zero, this is equivalent to no or very minor disturbance for the project area (Table 2.4). This is most noticeable in the category for atmosphere, and the geomorphological attribute subsurface karst, in which all indicators were scored as zero. Indicators scoring the highest values for disturbance were related to regulatory protection and enforcement of regulations, followed by indicators related to education, development, and agriculture. The final KDI GIS reveals that areas located outside of the reserve boundary show the highest disturbance values, and areas within the reserve show the lowest values. Highest values for disturbance occur where settlements and roads are located (Fig. 2.6). Overall, indicators related to deforestation and agriculture have the broadest geographic impact and the most influence on the final map.

Table 2.4 - Indicator and disturbance scores for the study area

Indicator	Score
Quarrying/Mining	1
Human-induced hydrologic change	0
Stormwater drainage	0
Infilling	0
Dumping	1
Erosion	2
Compaction due to livestock or humans	2
Flooding (Human-induced flooding due to surface alteration)	0
Decoration removal/ vandalism	0
Mineral/ sediment removal	0
Floor sediment compaction/ destruction	0
Desiccation	0
Human-induced condensation corrosion	0
Pesticides and herbicides	2
Industrial and petroleum spills or dumping	0
Concentration of harmful chemical constituents in groundwater	0
Potential of leakage from underground petroleum storage tanks	0
Changes in water table (decline in meters)	0
Changes in cave drip waters	0
Vegetation removal (% of total)	1
Species richness of cave biota	LD
Population density of cave biota	LD
Species richness of groundwater biota	LD
Population density of groundwater biota	LD
Destruction/ removal of historic artifacts (% taken)	1
Regulatory protection	3
Enforcement of regulations	3
Education of public about karst	2
Building of roads	2
Building over karst features	1
Construction within caves	0
Total	***21***
Total Possible	***81***
Final KDI Score	***0.26***
LD Score	***0.14***

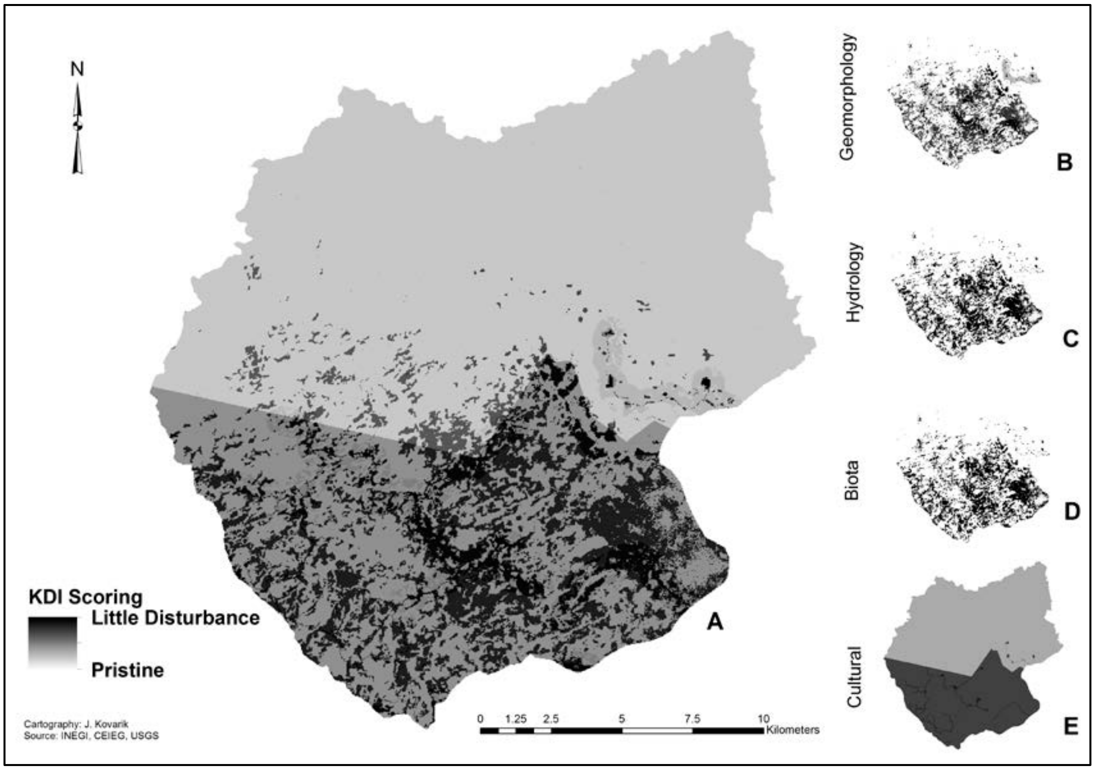

Figure 2.6a,b,c,d, and e - Final KDI scoring in GIS (a), with individual category maps (b-e).

The score for the total study area using the original index is 0.26 while the highest value for the GIS calculated KDI is slightly lower at 0.22 (Fig. 2.6, Table 2.4). This difference is due to indicators that must be aggregated for the entire area in the original KDI application, where in the GIS only the area where the indicator is applicable is given a particular score. An example of these indicators/ layers would be laws and regulations for different areas of land ownership and areas with different impact from erosion. These two indicators received two different scores in the GIS, but only one in the original scoring method. This demonstrates there could be potential for over or underestimation of the amount of disturbance for the portion of the study area that does not fall within the majority area in the original application of the KDI. The confidence level for the application of the KDI in both methods is 0.14, demonstrating that the index had sufficient information to be scored.

Discussion

Calculation of the KDI as a Raster-Based Model in GIS

Applying the KDI within a raster-based model in a GIS requires more time and technology than simply calculating the index by hand; however the benefits to distributing the disturbance indicators across a particular area are many. Individual maps of discrete groupings of indicators as well as the overall KDI map provide different layers of information to guide development or protection depending on proposed activities. Putting all the indicator information into a GIS not only provides a cohesive digital catalog of information, but also creates a benchmark for future comparisons which can be conducted and analyzed in a GIS. The KDI could also potentially be calculated for previous time periods utilizing remotely sensed data to begin to analyze disturbance trends over time immediately as well as in the future.

In creating a raster model in GIS, any vector-based layers must be converted to raster, and all raster layers must be the same resolution. It is important when calculating a spatial model in GIS to evaluate the data input into the model for accuracy and to take into account fluctuations in temporal scales of data collected such as remote sensing data. The resolution chosen for the final project area is based on the lowest resolution layer as it is not possible to down sample these particular layers to match those with a higher resolution. For certain indicators such as enforcement or stewardship, one assigned value was applied to the whole area as appropriate. However, for those indicators which only partially covered the study area or were linear in nature, adjusting the cell size for the final calculation results in the modifiable unit area problem (MAUP) and commission. MAUP is an issue of scale and aggregation problems with datasets. In particular, MAUP refers to error within a cell related to cells that have a mixture of features but must be represented as a single value in the raster dataset. For example, converting the layer with roads from vector to raster and re-sampling at the 30 m cell size results in larger cells classified with the disturbance value for road when the road is not 30 m wide.

While recognizing that no road in the study area is 30 m wide, any road does in fact have boundary effects that exceed its actual width. Therefore, this commission of land around the road being labeled as disturbed we deem is justifiable.

Another issue highlighted by the application of the KDI in a GIS is the relationship between types of indicators and the quantitative vs. qualitative differences in scoring. In van Beynen and Townsend (2005), "The allocation of scores for individual indicators required either quantitative analysis or qualitative evaluation; therefore not every indicator has the same quantitative, incremental divisions between the scores." While not identified in previous applications of the index, this problem of relationships between indicators and subjectivity of indicator scoring is addressed in studies critiquing other overlay and index methods such as groundwater vulnerability mapping (Elçi 2012). Future work might refine the index to take on continuous values (rather than ordinal ranks) to better quantify disturbance.

Application of the KDI in a Remote Setting of a Developing Country

As Mexico is a developing country, it is difficult for land management agencies as well as universities to acquire continual funding, support, and manpower for the empirical studies necessary to model natural processes and assess trends in environmental resource quality. Without that information, it is difficult to ascertain the changing needs for the mitigation of human impacts for a karst environment and its resources. With greater accessibility to remotely sensed data, more information for karst areas such as el Ocote is now available at higher temporal, spatial, and spectral scales. As such, agencies and management groups with low budgets can acquire and similarly manipulate these data as in this study.

While remote sensing data has many benefits, it isn't as accurate as direct observations of the karst environment. Assumptions were necessary to apply the KDI in this setting, which reduced the accuracy of the final raster model in terms of spatial distribution of the indicators across the study area. For example, as it was not possible to map every sinkhole in the study area, a sinkhole potential map was created based on a combination of elevation data measured using remote sensing, field survey data, and information from INEGI such as local geology. The two field-verified assumptions were that sinkholes are highly unlikely to develop on steep slopes and carbonate bedrock had to be present. As a result, a polygon was created that includes slope and the geology for the watershed, which yielded a GIS layer of high potential for sinkhole formation. A GIS-based application of the KDI should be viewed as an adaptive management tool – as more detailed information becomes available, the GIS layers can be updated and the KDI recalculated. This is particularly true for remote and rural areas as development encroaches and more environmental data is able to be collected.

Utility of the KDI in Best Practice Development

With ecotourism in Chiapas being seen as an economic driver, karst areas of el Ocote are becoming the focus of advertisements and media exposure. Along with the clearing of forests and application of agrochemicals, increased tourist activity constitutes the major concern for the study area. With the little disturbance of the karst environment in the study watershed, measuring disturbance indicators is key to maintaining this low level of impact. Best management practices include measuring baseline disturbance values and monitoring key indicators such as water quality as well as beginning to characterize the karst aquifer in the catchment. Also important is increasing the overall education and awareness of importance of karst resources, and the challenges that living in a karst environment present. An additional benefit of the application of the index within a GIS is the potential to create maps highlighting where disturbance is most intense, which can then be cross-referenced with locations of important karst resources such as caves. This will allow the creation of target areas for protection in pristine areas or for mitigation in disturbed areas with significant caves or well-developed karst.

Conclusions

The KDI calculation in a GIS raster model reduces subjectivity and has greater spatial accuracy through scoring all indicators at a greater spatial resolution, at the micro scale instead of macro or meso. Instead of applying one score for each indicator across the entire watershed or application region, discrete areas of disturbance are calculated at 30 m cell size based on the spatial occurrence of an individual indicator as well as changes in the scoring within that area of occurrence. Issues of scale related to the resolution of the data should be carefully considered and the results of the KDI application not construed at an improper scale. This study demonstrates that remote protected areas with limited environmental data can be analyzed using a GIS-based KDI at the sub-catchment level at a high confidence level based mainly on remote sensing data.

The data from this application of the KDI shows that while the study area is still relatively undisturbed, the lack of environmental regulation in areas adjacent to the reserve and the lack of enforcement within the reserve could result in higher overall disturbance in coming years. Indicators related to agriculture such as forest removal and pesticide and herbicide application are issues within the study area that could be addressed through increased enforcement of existing regulation. The lack of data highlights the need for intensification of monitoring and inventory of biota and water quality on the surface as well as underground.

With the GIS-based KDI, managers can quickly see areas where deforestation and other impacts are most intense and cross-reference those disturbances with areas where development is most prevalent. This method gives land managers a tool to spatially evaluate the most suitable locations for focusing limited resources in terms of best practice implementation and limit development. The GIS-based KDI can be easily cross-referenced with other planning tools such as groundwater vulnerability assessments to improve land management decisions. Finally, a GIS-based KDI creates a digital database of disturbance indicators for land managers, as well as a benchmark with which to compare past and future disturbance. Future work on el Ocote should focus on applying this method to the other two sub-catchments of the Rio la Venta watershed and to assess the vulnerability of groundwater, and subsequently the Rio la Venta, within the catchments to disturbance.

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CHAPTER THREE

GROUNDWATER VULNERABILITY MAPPING FOR A SUBCATCHMENT OF THE RIO LA VENTA WATERSHED, CHIAPAS, MEXICO

Abstract

Karst systems are particularly vulnerable to overexploitation and pollution due to their high hydraulic conductivity and points of rapid infiltration that allow rapid influx of runoff and pollutants into the aquifer. The sustainability of clean groundwater in these systems is imperative for both humans and groundwater dependent ecosystems (GDEs). An important practice in managing groundwater sustainability involves assessing aquifer vulnerability. This study creates the first groundwater vulnerability map (GVM) for a sub-catchment of the Rio La Venta watershed in Chiapas, Mexico, using the COP method and conducts the first tracer study in the Rio la Venta watershed to establish connectivity between the catchment and the Rio La Venta Canyon. Results of the GVM clearly demarcate areas of very high, high, moderate, and low vulnerability within the study area. The delineation of the various vulnerability categories was successfully validated through tracing two locations within the study area to the Rio la Venta canyon with fairly rapid flow velocities. Based on these results, the GVM is a useful tool for land managers requiring information on where the most vulnerable areas to groundwater contamination within the study area are located.

Introduction

Access to clean water has been recognized as a basic human right by the United Nations General Assembly (2010). However, many countries are unable to supply their populations with this essential resource. Mexico currently has more than 100 groundwater aquifers that are overexploited and threatened by pollution from urban and agricultural expansion (CAN, 2010). While the majority of Mexico is arid with limited water resources, the southern state of Chiapas has a humid climate with abundant water resources. Many of these resources are contained in karst aquifers. Karst is formed by the dissolution of soluble bedrock such as limestone and dolostone. Common karst features include sinking streams, solutionally enlarged fissures, and sinkholes. Karst systems are particularly vulnerable to overexploitation and pollution due to their high hydraulic conductivity and points of rapid infiltration that allow rapid influx of runoff and pollutants into the aquifer. Additionally, the physical nature of the karst aquifer allows for easy groundwater extraction that potentially results in falling water tables (Ford and Williams, 2007). The sustainability of clean groundwater in these systems is imperative for both humans and groundwater dependent ecosystems, as approximately 20 to 25 percent of the world's population utilizes the water emanating from karst systems (Ford and Williams, 2007).

An important practice in managing groundwater sustainability involves assessing aquifer vulnerability. The vulnerability of groundwater to natural processes and anthropogenic activities can be assessed using intrinsic and specific vulnerability. Intrinsic vulnerability is defined as the inherent vulnerability of the watershed as characterized by its natural processes independent of the nature of contaminants, while specific vulnerability is the vulnerability of an aquifer to a particular contaminant (Daly et al., 2002; Zwahlen, 2004). In recognition of this vulnerability, groundwater vulnerability maps (GVM) can delineate areas for protection of a particular source such as springs, wells, or protection of the saturated zone. The appropriateness of a method utilized for addressing groundwater vulnerability hinges on the availability of data, characteristics of the aquifer and the ultimate use of the map. Index and overlay methods are the most widely used for intrinsic GVM for creating resource protection zones (Vrba and Civita, 1994; Gogu and Dassargues, 2000). Today, many GVMs include factors to specifically address karst aquifers. Examples of these mapping methods include EPIK, RISKE, RISKE 2, KARSTIC, GLA, the European Method, PaPRIKa, and DRISTPI (Doerfliger et al., 1999; Daly et al., 2002; Kattaa et al., 2010; Kavouri et al., 2011; Jimenez-Madrid, 2013). The European method has been adapted in continued work in the form of the COP method and the Slovenian Approach in various parts of Europe and evaluated in comparison with other methods such as EPIK, AVI, GOD, and DRASTIC over the course of the past fifteen years (Goldscheider et al., 2005; Kiros and Zhou, 2006; Vias et al., 2006; Ducci, 2007; Ravbar and Kranjc, 2007; Dimitriou et al., 2008; Leyland, 2008; Plan et al, 2009; Vias et al., 2010; Marin et al., 2012; Guastaldi et al., 2014; Zhang, 2014).

While there is no standard technique for validating GVMs, various approaches include artificial tracer tests, water quality testing, hydrograph and chemograph analysis, and water balance calculations (Daly et al., 2002; Goldscheider, 2001; Perrin et al., 2004; Andreo et al., 2006; Neukum et al., 2008; van Beynen et al., 2012). In order to understand impacts of upstream contaminates, studies have often utilized tracer techniques to delineate karst watersheds, identify subsurface flow paths, and measure flow times from insurgence points to resurgences (Mull et al., 1988; Quinlan, 1989; Connair and Murray, 2002; Prussian and Baichtal, 2003; Moss, 2013).

For example, Ravbar and Goldscheider (2009) built upon the work of Goldscheider et al. (2001) and outlined the use of tracer tests for validation where high normalized tracer recovery and short transit time to initial dye detection indicate areas of high vulnerability where tracers are first injected and vice versa.

This research develops and validates a GVM in a karst system within a protected area in Mexico. The first goal of this study is to create the first GVM for a sub-catchment of the Rio La Venta watershed in Chiapas, Mexico. This is accomplished using the European Approach, specifically the COP method (Vias et al., 2006) with modifications from the Slovene Approach (Ravbar and Kranjc, 2007). The COP method was selected because it is karst-specific and accurately captures the hydrogeologic behavior of several karst aquifers while not requiring complex, detailed data sets (Yildrim and Topkaya, 2007; Ravbar and Goldscheider, 2009; Jimenez-Madrid et al., 2011; Marin et al., 2012; Guastaldi et al., 2014). Modifications from the Slovene Approach were incorporated in order to improve the accuracy of the COP method.

The second goal is to conduct the first tracer study in the Rio la Venta watershed to establish connectivity between the catchment and the Rio La Venta Canyon and to validate of the proposed vulnerability mapping. Tracer tests were selected as the validation method as done by many studies (Ravbar and Goldscheider, 2009). The creation of vulnerability zones and an understanding of flow timing and pathways within the watershed will provide information and tools for resource managers. This will allow for educated land management decisions concerning the watershed for the protection of groundwater, subsurface resources, and ultimately the health of the ecosystem.

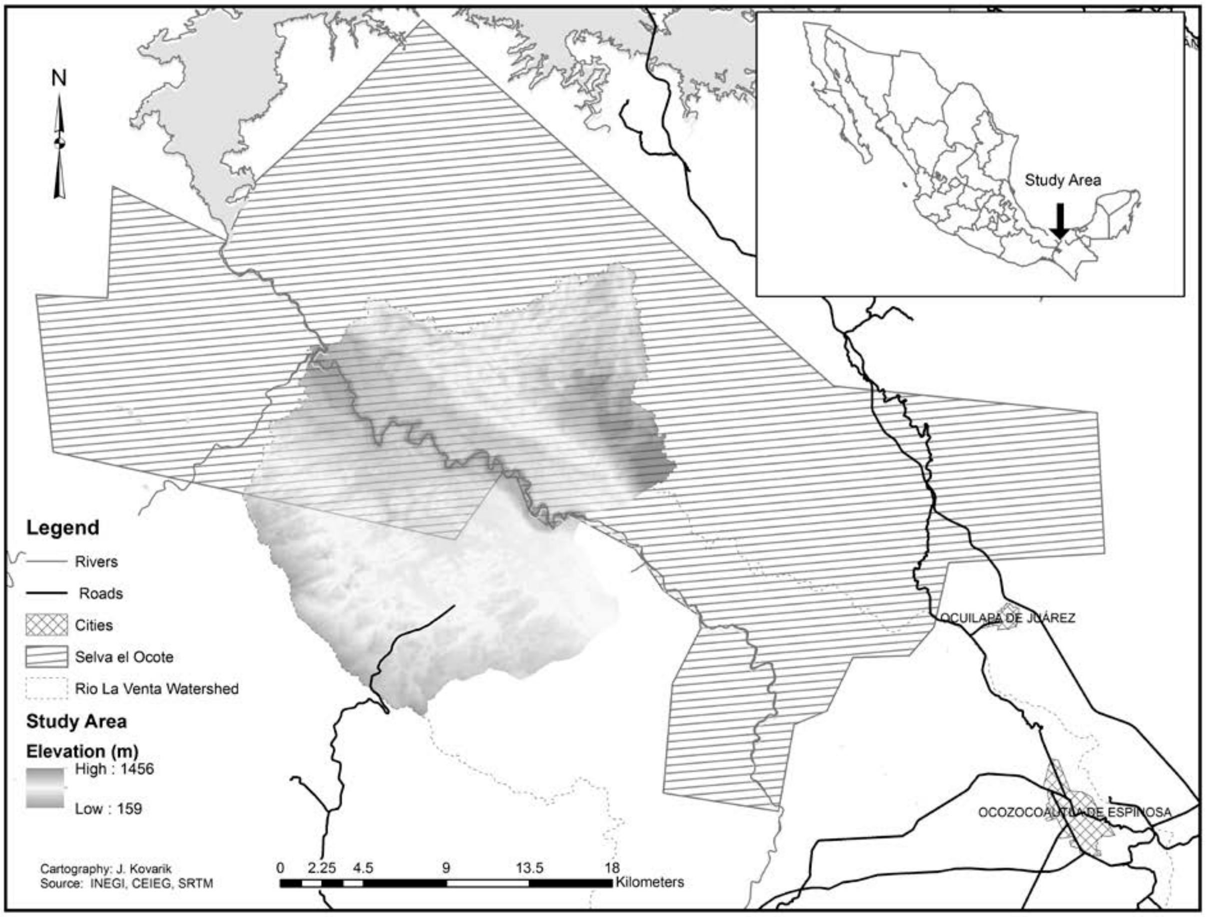

Figure 3.1 – The study area, el Ocote, and greater Rio la Venta Watershed

Study Area

Reserva de la Biosfera Selva el Ocote (el Ocote) Chiapas, Mexico (16°57’50” North – 93°38’21” West) covers approximately 1,013 km^2 (101,300 ha). El Ocote consists of three main sub-catchments of the Cuenca Rio Grijalva –Tuxtla Gutierrez, within the Grijalva-Usumacinta hydrologic region. The Rio la Venta flows northwest through el Ocote at approximately 2,000 m.a.s.l. in the Sierra Madre de Chiapas terminating at the reservoir of Nezahualcoyotl (Malpaso). Within the Rio la Venta watershed, the river meanders 97 km northwest from Aguacero near the beginning of the Canyon del Rio la Venta, to el Encajonado.

The study area is a sub-catchment of the Rio la Venta which is 368 km^2 (36,800 ha) that is bounded to the southwest by the Uxpanapa Fault, the northwest by the Rio Negro, and the northeast by ridgelines of the Sierra Monterrey and the Sierra Veinte Casas (Fig. 3.1). Sixty percent of the study area is currently part of el Ocote, while the rest of the study area is private land and núcleos.

Middle to upper Cretaceous Cintalapa limestone and Cantelha dolostone of the Sierra Madre formation comprise the majority of the study watershed. Higher elevations along the Uxpanapa Fault in the southwest consist of uplifted siltstone and sandstones of the Campanian-Maastrichtian Ocozocoautla Formations (Cros et al. 1998) (Fig. 3.2). The Sierra Madre formation is karstified into cone and cockpit karst, with the most extreme development in the northeast portion of the watershed where shafts up to 520 m deep have formed (Concha 2009). Caves, sinking streams, and springs are present in all parts of the catchment (Fig. 3.2). It is suggested that karst springs in the northeastern area drain primarily into the Rio La Venta, however, it is possible that a portion of the system also drains into the Rio Grijalva to the north of the reserve. The La Venta Group has mapped over 147 caves within the study area; with the Cueva del Rio la Venta the longest at 13 km of passageway (Bernabei et al., 2012).Sixty-four percent of soils in the study area are Luvisols, which contain high amounts of clay. Luvisols can be used for agriculture but tend to erode (Krasilnikov et al,. 2013). The remaining 46 percent is comprised of Litosols (Redzines or Leptosols) which are characteristically rocky thin soils with high carbonate content.

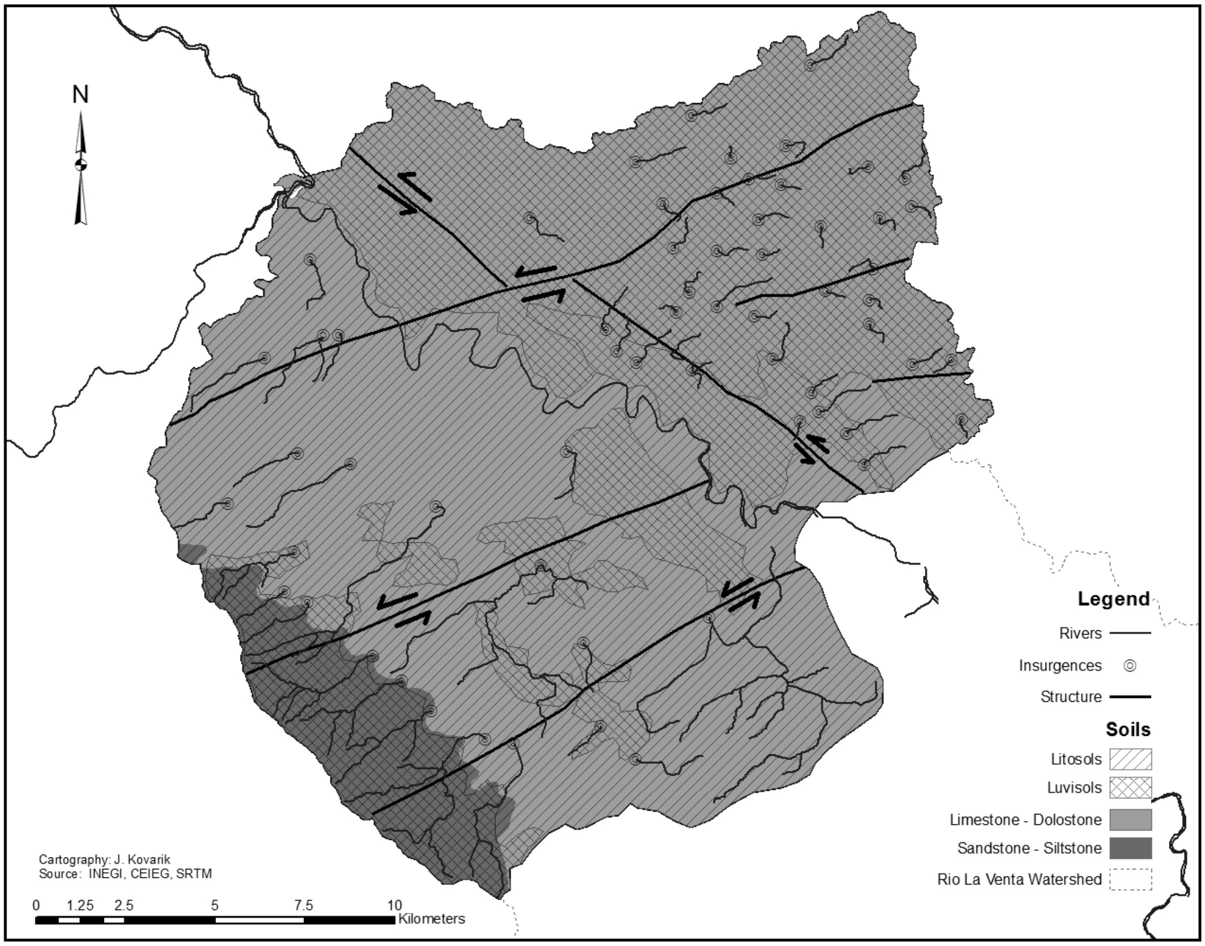

Figure 3.2 – The geology, soils, and general hydrology of the study area.

The climate of this region is wet-warm and humid-warm depending on elevation with the maximum temperature approximately 34 ºC. Rainfall ranges between 1100 to 2000 mm per year depending on elevation (CONANP, 2000). The wet season generally occurs May to September and the dry season October to April. Vegetation consists of primary and secondary tropical forest within the reserve and second-growth tropical forest and slash-and-burn agriculture outside of the reserve boundary. In the study area there are seven main settlements, the largest of these is Adolfo Lopez Mateo. Many smaller settlements and ranches are scattered throughout the catchment, and major economic activities are agriculture and animal husbandry.

Methodology

Adaptation of the COP Method to the Study Area

COP is a parametric system method based on the European Approach for mapping groundwater vulnerability (Vias et al., 2006). The COP method is comprised of three distinct elements that investigate the degrees of openness to the phreatic zone and likelihood of direct vs. diffuse recharge to create an intrinsic GVM (Vias et al., 2006). These include 1) properties of the unsaturated or vadose zone in the overlying layers (soils, geology) (O); 2) protective cover and concentration of flow (vegetation, slope) I; and 3) precipitation (P) (Figure 3.3). All are assigned a value and combined in a Geographic Information System (GIS) to create the resource vulnerability layer.

The OL sub-factor quantifies and categorizes the type, depth, and structure of the lithology present in the unsaturated zone including confinement situation that is used for weighting purposes. The OS sub-factor addresses the thickness, texture, and grain size of soils of the study area. These two sub-factors are combined to create the final O score – a higher score of each sub-factor signifies greater depth of the overlying layers and more protective soil and lithology type.

The C and P factors modify the O factor and describe the degree to which recharge can bypass the overlying layers and the degree of temporal and hydrologic intensity. The C factor is divided into two scenarios. The first is where allogenic and autogenic recharge bypasses the unsaturated zone through direct insurgence into a karst feature. Here parameters include the distance to swallow hole and sinking streams (dh and ds sub-factors), and the protective properties or lack thereof related to vegetation and slope (s and v sub-factors). The second

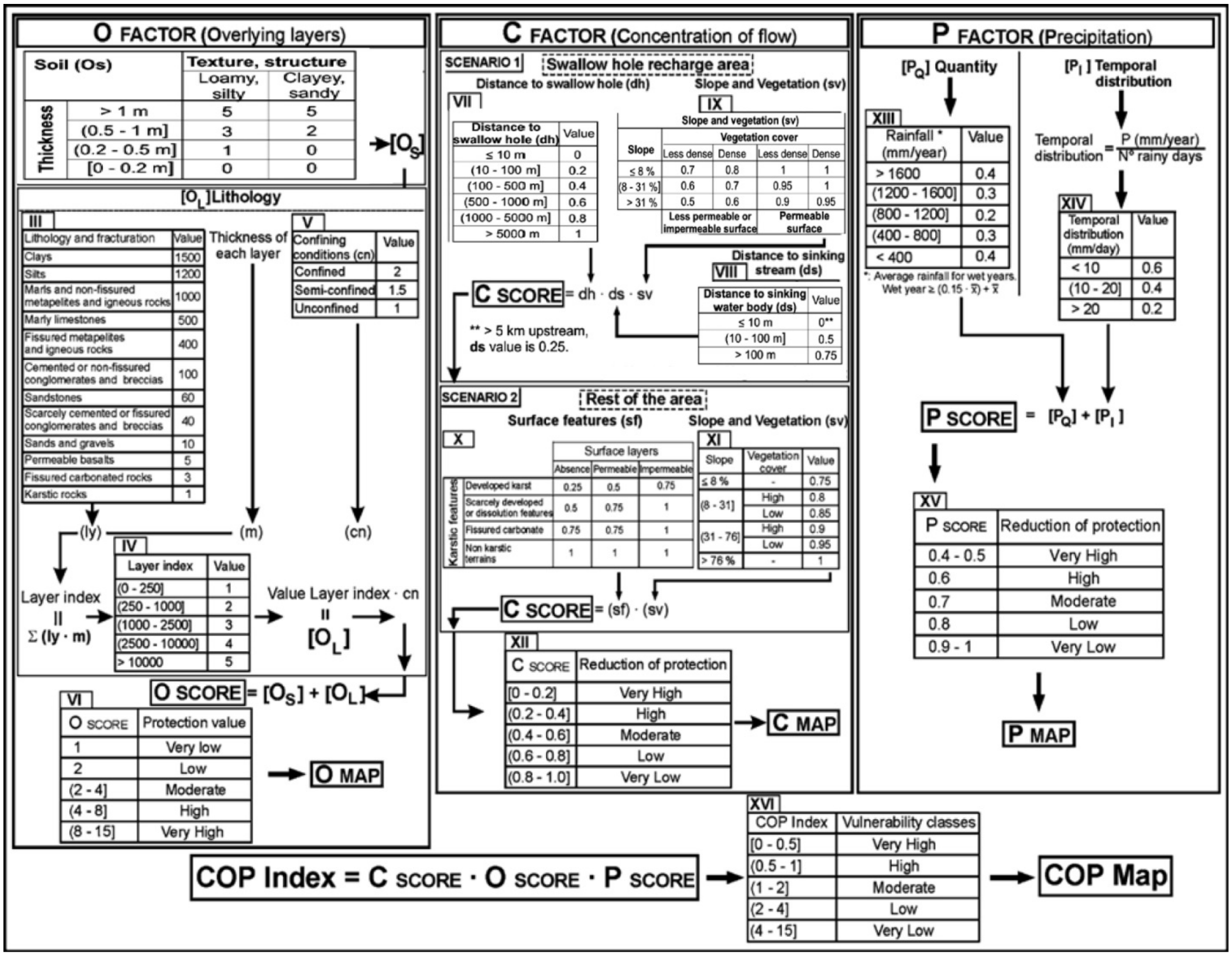

Figure 3.3 – The GVM methodology as applied to the study area (Vias et al., 2006)

scenario applies to diffuse autogenic recharge and addresses permeability of surface features (sf sub-factor) as well as slope and vegetation (s and v sub-factors). The P factor categorizes the amount of precipitation within an area (PQ sub-factor) that is modified by the timing and intensity of events (PI sub-factor). The overall C, O, and P scores are multiplied for a result between 0 and 15, with lower scores indicating higher vulnerability (Vias et al., 2006). This study adopts two alterations of the COP method developed in the Slovene Approach by Ravbar and Kranjc (2007).

Modifications for the O factor, as adapted in the Slovene Approach, simplifies the soil sub-factor (Os) by taking into account the effective field capacity of soils (eFC) enabling the approach to combine the COP method's four soil texture classifications into two categories, loamy/silty and clayey/sandy (Ravbar and Kranjc, 2007). Additionally, the Slovene Approach separates the shallowest class of soil thickness to include a 0 – 0.2 m depth class, and calls for evaluation of effective soil thickness as depths can be variable in karst due to epikarst development. Second, for the C factor, the Slovene Approach simplifies the slope classes into three instead of the original four and changes the vegetation classification from "high vs. low" to "dense vs. less dense". Prior studies have found that the number of parameters incorporated into a GVM have little impact on the overall vulnerability rating of a system. For example, more simplistic GVMs such as AVI produced similar results to the more complex methods such as GOD and DRASTIC (Gogu and Dassargues, 2000; Vias et al., 2005). Taking these findings, we feel confident that the simplification of the Os sub-factor and the slope classes are applicable to the study area based on data available for these factors. All other factors and sub-factors were analyzed as described in the original COP methodology. The adapted COP approach applied to the study area is illustrated in Figure 3.3.

Table 3.1 – Data sources for the GVM

Factor	**Data Source**
Soils	INEGI, field surveys
Lithology / Geology	INEGI, field surveys
Karst features, karst development (swallow holes, sinking streams)	INEGI, La Venta Group, field surveys
Vegetation Cover	USGS, field surveys
Slopes	USGS, field surveys
Precipitation	INEGI, SMN, field surveys

Data Collection and Geographic Information System

Data were collected between 2010 and 2014: some maps required conversion into digital format so that they could be incorporated in the GIS. Data sources included Instituto Nacional de Estadística y Geografía (INEGI), Servicio Meteorológico Nacional (SMN), United States Geological Survey (USGS), and the La Venta Group (Table 3.1). Karst features were investigated during field surveys, and soil depth and texture were assessed at 14 different sites of varying slope and vegetation cover. Data collected in the field were given spatial reference with a Global Positioning Satellites (GPS) and transferred into GIS layers. In order to calculate the GVM for this study, vector layers were converted into raster (grid) format. Each cell within the raster is assigned a value based on the original data of the study area relative to the rating scheme of the vulnerability assessment. Twelve rasters were created and combined to create the three intermediate raster maps and one final map to score resource vulnerability with a resolution of 30 m x 30 m in UTM NAD 83 Zone 15 North.

Tracer Tests

Tracer tests are often utilized to delineate subsurface flow pathways and establish travel time of contaminants from diffuse or discrete recharge sites to the groundwater table or a particular well. A particular tracer is selected, whether naturally occurring or artificial, and sampling is conducted at locations such as springs or wells in order to detect background levels of the tracer prior to injection. Following injection of the tracer, sampling can be continuous through data loggers with optical probes or automated water samplers, or manual through the placement and collection of activated charcoal packets.

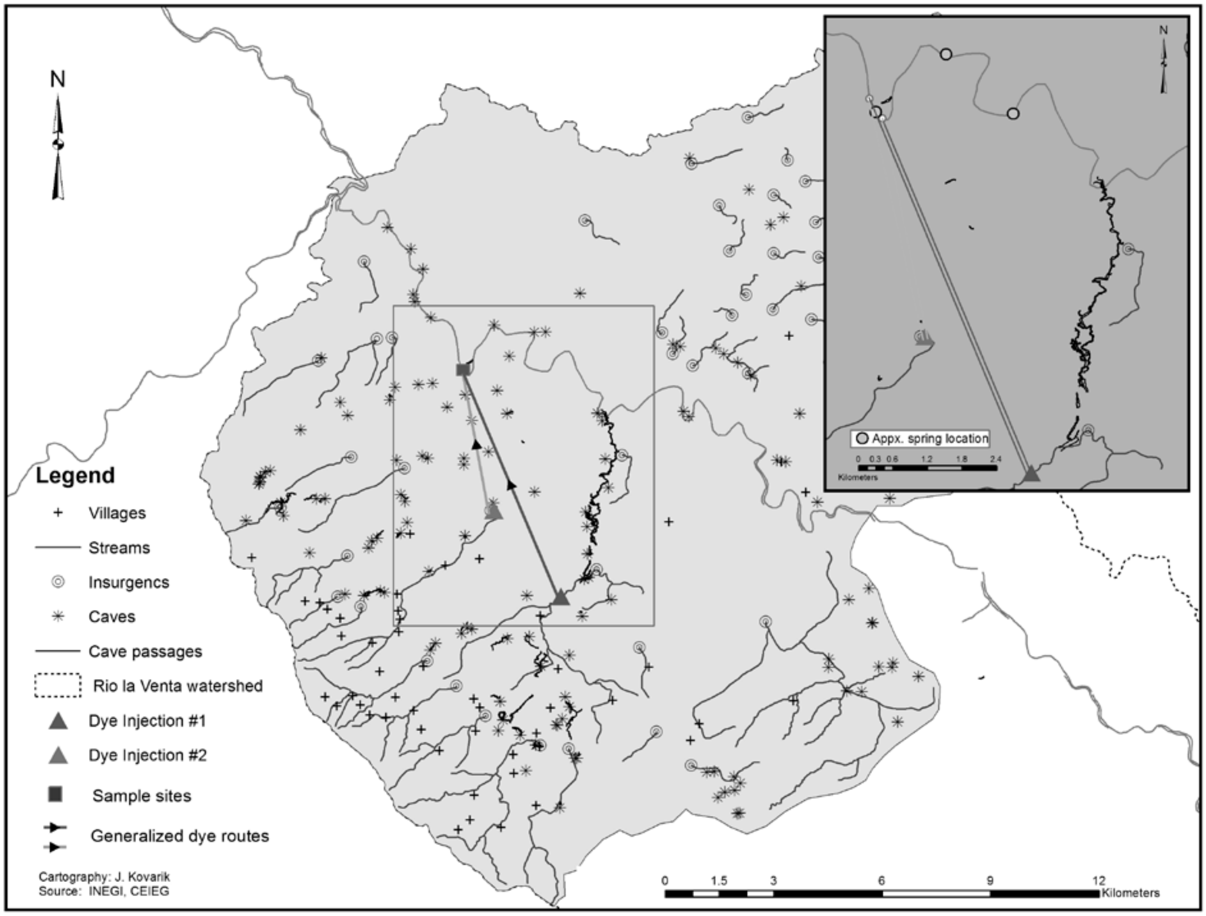

Figure 3.4 – Dye trace study and the project area.

For this study, two discrete injection sites were selected in locations mapped as very high vulnerability by the GVM (Fig. 3.4). Sampling sites for placing charcoal receptors were chosen in the canyon based on reconnaissance trips documenting discrete spring locations in the canyon and cave surveys mapped with topographic data showing the connection between the Cueva del Rio la Venta and the Canyon del Rio la Venta. Locations mapped as very high vulnerability were chosen for the trace because those areas are of highest concern in terms of vulnerability of the aquifer to contamination. Two pounds each of Fluorescein and Eosine were pre-mixed with water from the catchment offsite using proper procedures to prevent contamination of the trace (Aley and Fletcher 1976, Mull et al. 1988).

One background packet was placed and one background water sample was collected at the Arco del Tiempo on April 20 2014. Background water samples were taken and charcoal packets were placed in the Rio la Venta below Unidad Modelo, and above the confluence of the Cueva del Rio la Venta. Two pounds of uranine (fluorescein) dye were injected and sank immediately in an insurgence below the colonia of Cardenas on April 21 2014 (Fig. 3.4). Two pounds of eosine dye were injected and sank immediately in an insurgence below the colonia of Unidad Modelo on April 21 2014 (Fig. 3.4). Charcoal packets and water samples were taken manually approximately every two hours during daylight hours at two sampling sites near the Arco del Tiempo downriver from the confluence with the Cueva del Rio La Venta from April 22 2014 to April 24 2014 (Fig. 3.4). Standard protective gear and precautions were taken to prevent dye cross-contamination between injection sites and at sample retrieval locations (Aley, 1976; Mull et al., 1988; Quinlan, 1989).

Results

The C map illustrates high vulnerability where streams descend into the subsurface and where higher gradient slopes on less permeable surface direct water into sinking streams and sinks. However, there is no clear influence by dense vs. less dense vegetation (Fig. 3.5). The O map classifies areas of steep slopes on the carbonate portions of the study area as very high vulnerability (Fig. 3.5). Here, the rock type has more influence on the final map than the soil type. However, the effect of soil depth can be seen in the classification of high gradient slopes as very high as soils are thinner. The amount of annual precipitation and intensity within the study area are not enough to be considered a major stress factor, and consequently the P map has little influence on the final GVM.

The final groundwater vulnerability map values range from 0 to 3.36, falling into vulnerability classes of low to very high (Fig. 3.5 and 3.6). The majority of the catchment falls into the moderate or low vulnerability classes with approximately 22 percent (82 km^2 or 8,200 hectares) moderate and 72 percent (266 km^2 or 26,600 hectares) low vulnerability (Fig. 3.5 and 3.6). Moderate vulnerability areas mainly occur within 1,000 m buffer zones for insurgences with slope values less than 31 percent, and 100 m buffer zones for sinking streams. Less than one percent of the area (0.7 km^2 or 700 hectares) is mapped as very high vulnerability. These locations consist of sinking streams and insurgences.

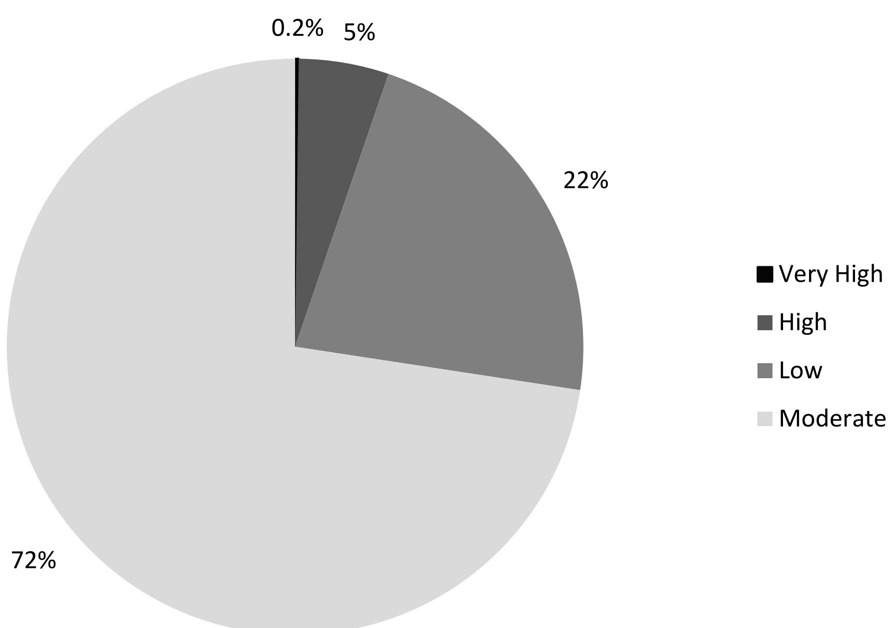

Figure 3.6 – Vulnerability rating as percent of study area.

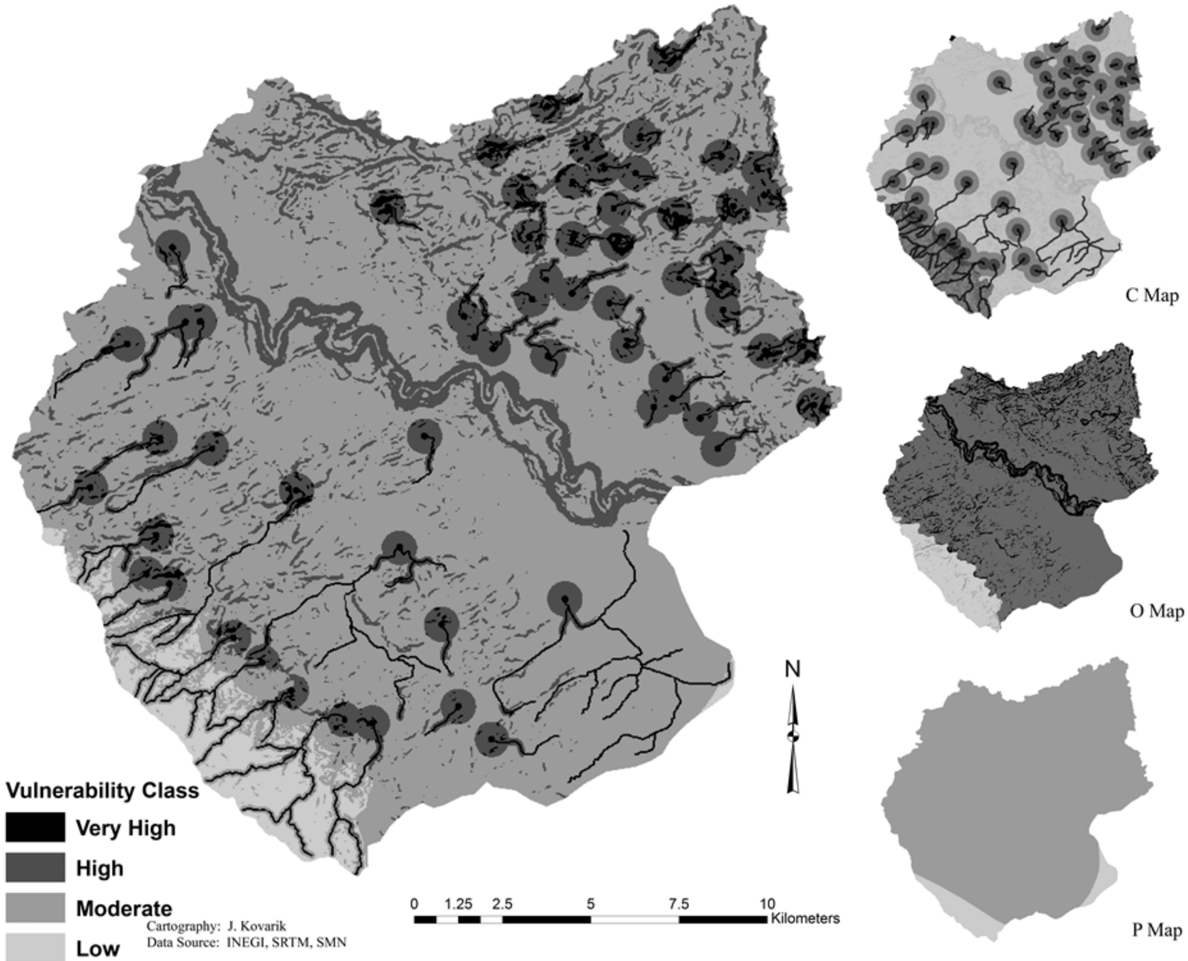

Figure 3.5 – The adapted COP GVM with the individual C, O, and P maps.

The remaining five percent (20 km2 or 20,000 hectares) of high vulnerability mainly corresponds to areas where slope values are greater than 31 percent across the study area, within the 500 m buffer zone for insurgences and the 100 m buffer zone for sinking streams with slope values over 31 percent. Additional areas mapped as high vulnerability occur where those two buffer zones intersect on lower slope values.

The tracer test was positive with dye from both injection locations being recovered at sample locations within the Rio la Venta canyon (Appendix A). Both the eosine and fluorescein dyes were recovered in amounts higher than background at both sampling locations in the Rio la

Venta canyon beginning on April 23 2014. The time to leading edge (or time to dye concentration elevation above background value) following injection was approximately 48 – 52 hours for each individual dye/ location, and a time to peak of approximately 67 hours (Fig. 3.4). The time to trailing edge was not recoverable due to timing and logistical complications related to personnel and travel to and from the study sites. Flow velocities were calculated to be approximately 70 – 130 m/h from the injection points to the sample sites.

Discussion and Conclusions

Results of the GVM clearly demarcate areas of very high, high, moderate, and low vulnerability within the study area. Positive tracer tests and the calculated high flow velocities to the Rio la Venta confirm the GVM very high vulnerability demarcations. The C and O maps are the main contributors to the final COP GVM map, with little influence from the P map. The P score for the area shows moderate to low reduction of protection due to high rainfall quantity (dilution of contaminants) and moderate intensity (lack of increased transportation). No areas were classified as very low vulnerability by the GVM that is appropriate in a well-developed karst area with steep slopes. The less permeable non-carbonate areas in the southwestern portion of the study area would normally be considered very low vulnerability even though possessing steep slopes. However, these steep slopes channel surface flow directly to sinking streams that sink on the contact with the Sierra Madre formation (Fig. 3.4). Because contaminants could reach these streams with little infiltration and then move rapidly underground, this portion of the study area is appropriately classified as low vulnerability instead of very low vulnerability.

In terms of the dye traces, sampling locations were downstream from the connection of the Cueva del Rio la Venta by approximately 10 river kilometers, the largest mapped conduit in the area with a connection to the Rio la Venta, (Fig. 3.4). When mapping resource vulnerability, the time of flow from the surface to the top of the phreatic zone is the main concern, but for this study sampling either at the top of the saturated zone or at the confluence with the Rio la Venta was not possible. However, the rapid flow velocity measured by the tracer tests indicate that the flow times during the dry season from local settlements to the phreatic zone (on route to the resurgences) must be less than the measured 48 to 52 hours (Fig. 3.4).

The GVM created in this study can be compared with readily accessible spatial information in a GIS such as roads, settlements, and land use. The location of settlements and roads near high or very high vulnerability zones such as streams on the surface which eventually sink would suggest that contaminants from these areas would move quickly subsurface based on the dye trace results. This will assist land managers with deciding where monitoring and mitigation of current land use practices should take place. The GVM could also be utilized to create protection zones around high and very high vulnerability features through continuous weighting of values, as opposed to the current sharply demarcated vulnerability classifications. Protection zones that are more continuous in nature could be created in a GIS based on the GVM, and would be more realistic than the current cutoff values between classes. Ultimately, comparison with a spatial environmental index showing current disturbance in the catchment would allow resource managers to target locations where high vulnerability areas are impacted by disturbance. This would be useful to plan monitoring and mitigation, and to also target areas for prohibiting development that are undisturbed yet high vulnerability.

The GVM does not include information related to current anthropogenic hazards to groundwater or disturbance of the overall karst environment, nor does it assess the resulting risk from those potentially damaging practices. Additionally, it should be noted that this study does not quantitatively characterize the aquifer, which will be necessary for assessing specific vulnerability to particular sources such as wells and ultimately to the Rio la Venta. Quantitative hydrologic monitoring and modeling to calculate recharge rates, depth to saturated zone and groundwater flow within the aquifer during the dry and wet season will be necessary in the future to continue to improve the GVM into a process-based model and apply it to smaller areas within the catchment.

This study applied an adapted version of the COP GVM to a remote area with limited data sets. Its delineation of the various vulnerability categories was successfully validated through tracing two locations within the study area to the Rio la Venta canyon with fairly rapid flow velocities during the dry season. Based on these results, the GVM is a useful tool for land managers requiring information on where the most vulnerable areas to groundwater contamination within the study area are located. The adapted COP method requires data that is generally available or easily acquired in remote areas and the application in GIS is not a complicated process. The final GVM is useful in guiding decisions at the regional scale by 1) showing where development projects can occur based on their vulnerability classification and 2) defining locations requiring careful environmental monitoring due to their high vulnerability classification. To improve on the limited nature of the validation tests, future work should focus on additional discrete and diffuse traces in the dry and wet season with higher temporal and spatial scale resolution of dye retrieval in the Rio la Venta. In addition, implementing monitoring work with hydrologic data loggers to characterize flow within the karst aquifer and properly delineate the catchment. These data would also help researchers investigating the dynamics of contamination and pollutant transport from settlements to the groundwater, and ultimately to the Rio la Venta canyon.

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CHAPTER FOUR

A KARST-SPECIFIC COMPOSITE MODEL FOR INFORMED RESOURCE MANAGEMENT DECISIONS ON THE BIOSFERA DE LA RESERVA SELVA EL OCOTE, CHIAPAS, MEXICO

Abstract

Karst environments are important sources of water, function as significant carbon sinks, and provide habitat for a great diversity of biota. High permeability and rapid recharge in karst aquifers result in groundwater contamination and pollution of springs and wells due to poor agricultural practices, deforestation, and other human land use. Additionally, humans have used caves over the millennia for recreational to religious purposes which can negatively impact subsurface environments. No one model for karst systems exists that evaluates both current disturbance and its susceptibility to human impacts as a whole. This study addresses the above problems by incorporating a groundwater vulnerability map (GVM) with a holistic environmental disturbance index (KDI) as an adaptable spatial tool for management planning and protection for all components of the karst environment. The composite model is successfully calculated and applied, creating zones of least, moderate, and highest concern for the study area. These zones are used to evaluate which locations within the sub-catchment of the Rio la Venta are appropriate for development or require management action in relation to karst ecosystem health. Finally, possible integrative management strategies are discussed.

Introduction

Karst formation is the result of the dissolution of soluble rock that produces rapid subsurface hydrologic flow and characteristic features such as springs, sinking streams, caves and sinkholes. The distinctive nature of the subsurface hydrologic system of European karst was recognized during the early part of the 20^{th} century (Grund, 1903; Katzer, 1909; Cvijić, 1918). By the later part of the century it was found that karst areas cover approximately 12 percent of the earth's surface and serve as important sources of water and carbon sinks (Ford and Williams, 2007; Liu et al., 2008; Zhang, 2011). Caves which form within karst preserve archaeological and paleontological artifacts, provide habitat for rare and endangered biota and hold formations which record past climate conditions. High permeability and rapid recharge of karst aquifers lead to high groundwater contamination potential and impaired springs and wells fostered by poor agricultural practices, deforestation, and other detrimental human land use. Additionally, humans have used caves over the millennia for recreational to religious purposes which can negatively impact these subsurface environments.

Increased understanding of the natural processes operating within karst landscapes has led to the investigation of environmental issues such as the overexploitation and pollution of water resources, sinkhole collapse and desertification due to vegetation removal (Stringfield and LeGrand, 1969; LaMoreaux, 1991). Various studies examine these fragile landscapes, human impacts and possible approaches of adaptive and holistic management to reduce negative human activities (Drew and Hötzl, 1999; Parise and Gunn, 2007; Van Beynen, 2011). Advances in technology such as computer-based geographic information systems (GIS) have aided the development of management tools to assist prevention and mitigation of human impacts through best management practice development. Many studies have created GIS-based groundwater vulnerability maps (GVM) to designate zones of vulnerability for aquifers or delineate protection areas for a particular source such as a spring or well (Daly et al., 2002; Zwahlen, 2004; Goldscheider et al., 2005; Vias et al., 2006; Kattaa et al., 2010; Kavouri et al., 2011; Jimenez-Madrid, 2013). Risk and hazard maps measure the potential vulnerability of a particular area to contamination, but as with GVM development, these mapping techniques focus do not holistically address impacts to the karst ecosystem as a whole (Ravbar and Kranjc, 2007; Bonacci et al., 2009; Goldscheider, 2012).

Resource managers have used the Environmental Impact Statement (EIS) process in the United States to evaluate potential impact to karst systems; however, as with the GVM approach, they do not account for the complexity of karst ecosystems (Veni, 1999). In recent years, investigators applied environmental indices to assist managers with identifying environmental problems, deciding which problems require immediate attention and to provide a framework for effectiveness monitoring (Smeets and Weterings, 1999). Van Beynen and Townsend (2005) developed the karst disturbance index (KDI), however this index scores impacts to the environment without consideration of the intrinsic susceptibility of the particular karst system (Calo and Parise, 2006; van Beynen et al., 2007; De Waele, 2009; North et al., 2009; Bauer and Kellerer-Pirklbauer, 2010; Day et al., 2011). Harley et al. (2011) and Van Aken et al. (2014) have created a method for modeling and predicting cave disturbance, however, their approach assumes that only non-submerged cave entrances are associated with disturbance and not the spatial component of impacts caused by surface disturbance.

This study addresses the shortcomings of the above problems by incorporating a GVM with a holistic environmental disturbance index (KDI) as an adaptable spatial tool for management planning and protection for all components of the karst environment. Within this new composite model, the combination of the KDI and the GVM recognizes both human disturbance and how the physical nature of the karst will enhance this impact. The composite model creates the most comprehensive approach available today allowing resource managers to quickly identify areas of highest concern and implementation of adaptive holistic management strategies to mitigate these problems. The location for applying this model is a sub-catchment of the Rio la Venta watershed, a portion of which is incorporated by the Reserva de la Biosfera Selva el Ocote. The first goal of the study is to calculate the factors of the GVM and the KDI and combine them into a GIS. Second, this study will use the composite model to delineate zones of concern which require protective measures through evaluating final scores of the composite model. Finally, management strategies will be discussed based on the above results.

Study Area

Reserva de la Biosfera Selva el Ocote (el Ocote) is located within the Highlands of Chiapas, Mexico at approximately 16°57’50” North – 93°38’21” West (Fig. 4.1). El Ocote is part of the Grijalva-Usumacinta hydrologic region, which consists of three main sub catchments, including the Rio la Venta subcatchment. The Rio la Venta watershed consists mainly of Middle to upper Cretaceous Cintalapa limestone and Cantelha dolostone of the Sierra Madre formation where karstification has produced cockpit karst, large sinkholes, caves, sinking streams, and springs. The longest mapped cave system in the area is the Cueve del Rio la Venta at 13 km (Concha, 2009). Within el Ocote, the Rio la Venta flows through a 400 m deep canyon incised within Sierra Madre formation and travels approximately 97 km from Aguacero at the southeastern corner of el Ocote to el Encajonado in the west.

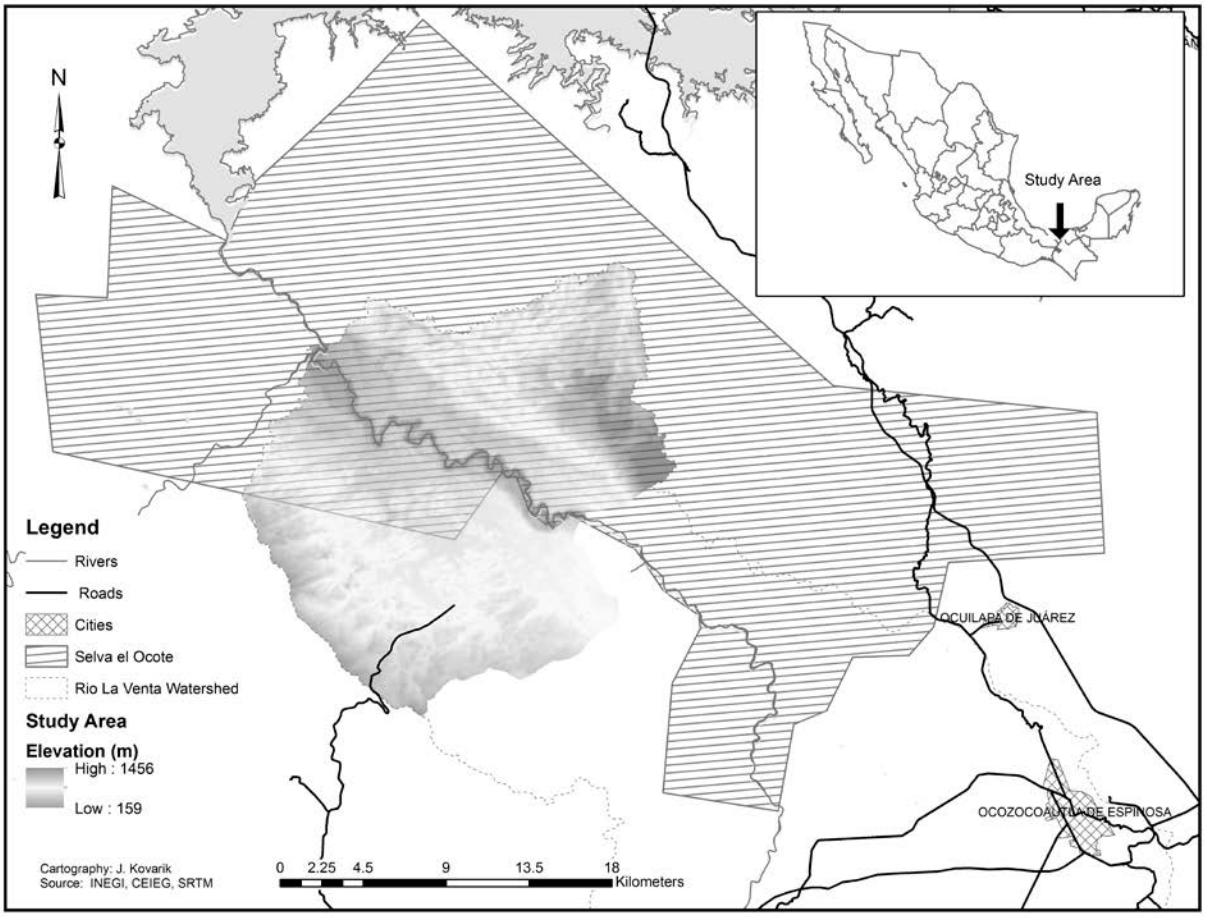

Figure 4.1 – The study area, el Ocote, and the greater Rio la Venta Watershed.

The study area is a 368 km^2 (36,800 ha) portion of the larger Rio la Venta watershed of which 60 percent is el Ocote lands and the remaining 40 percent núcleos or private land. The NE-SW trending Sierra Monterrey and the Sierra Veinte Casas form the boundary to the north, and the Uxpanapa fault forms the southern boundary (Fig 4.1). Vegetation within the area consists of over 286 species of flora, and is 82 percent primary and second-growth forest of tall perennial, sub-perennial, or intermediate sub-perennial and sub-deciduous forest depending on elevation with the remaining areas slash-and-burn agriculture. El Ocote contains a broad diversity of fauna, including the jaguar (Panthera onca), howler monkeys (Allouata geoffrogy), and a poisonous snake, the royal nauyaca (Bothrops asper). Precipitation amounts annually average 1500 mm and fall during the wet season from May to September. Temperatures reflect the humid-warm climate reaching annual maximums of 30 to 34.5 ºC depending on location within the study area. There are 16 communities, smaller settlements, and ranches including six main villages. The major economic activities within and around Rabasa, Emiliano Zapata, Venustiano Carranza, General Cardenas, Unidad Modelo, and Adolfo Lopez Mateo are agriculture and animal husbandry.

Methdology

KDI and GVM Development

Two previous studies using GIS calculated a spatially explicit map of the KDI (Kovarik and van Beynen, 2015a) and a validated GVM (Kovarik and van Beynen, 2015b) for this study area. The KDI was based on the methodology of van Beynen and Townsend (2005) (Fig. 4.2a) while the GVM used the European Approach, specifically the COP method (Vias et al 2006) with modifications from the Slovene Approach (Ravbar and Kranjc 2007) (Fig. 4.2b). In order to produce both maps, vector layers were converted into raster (grid) format using ESRI's ArcGIS software.

Each cell within the raster was assigned a value based on the original data of the study area relative to the rating scheme of the disturbance index or vulnerability assessment. The rasters for each indicator or sub-factor were then combined for each respective map to produce the final GVM and KDI in GIS. Twelve rasters (one for each indicator with a score greater than

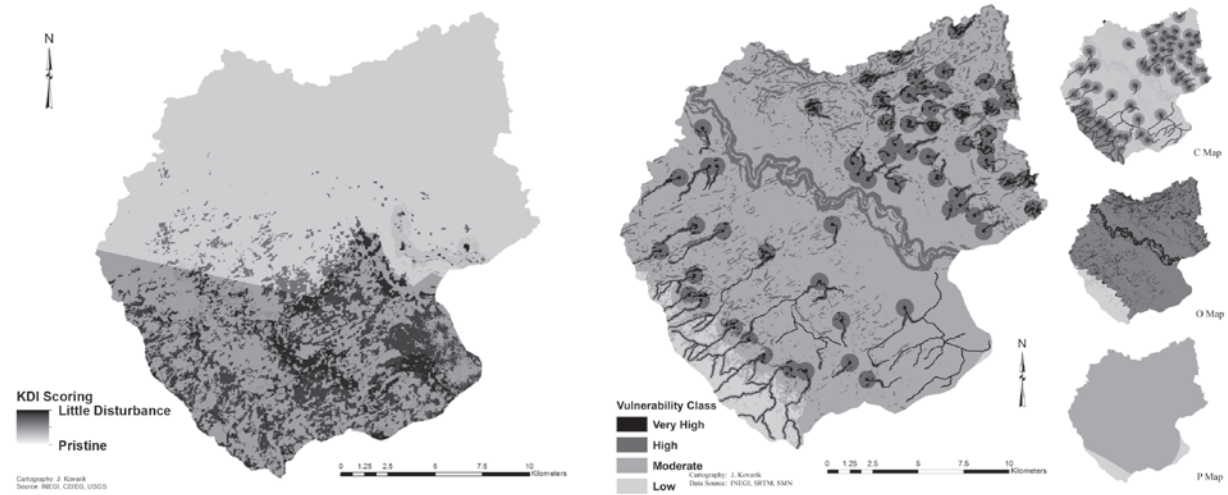

Figure 4.2a – The KDI map for the study area and **4.2b –** The GVM for the study area.

Zero) were created and combined to score the final KDI map and twelve rasters were created and combined to create three intermediate rasters and one final map to score resource vulnerability (Fig. 4.2a-b). All rasters and the final maps for both have a resolution of 30 m x 30 m in UTM NAD 83 Zone 15 North. Final values for the KDI ranged from 0 to 0.22, or *pristine* to *little disturbance* and the GVM values ranged from 0 to 14.28, or from *very high vulnerability* to *low vulnerability*. No areas were found to be *disturbed*, *highly disturbed*, or *severely disturbed* and areas of *very low vulnerability* were not classified in the study area for the GVM.

The Composite Model

Incorporating caves. Caves are an important part of karst environments that are particularly sensitive to disturbance and once disturbed cannot be restored to their pristine state (Elliot, 2004). For this particular project, if disturbance occurs within a cave, then the KDI incorporates cave locations and subsurface development in the spatial model for disturbance.

Table 4.1 – Reclassified KDI and GVM scores

KDI			**COP GVM**		
Disturbance	Original Class Values	Adjusted Class Values	Vulnerability	Original Class Values	Adjusted Class Values
Severely	0.8-10	5	Very High	0-0.5	5
Highly	0.6-0.79	4	High	0.5-1	4
Disturbed	0.4-0.59	3	Moderate	1.0-2.0	3
Little	0.2-0.39	2	Low	2.0-4.0	2
Pristine	0-0.19	1	Very Low	4.0-15.0	1

Table 4. 2 – Aggregate Values

				Disturbance		
Vulnerability		Pristine	Little	Disturbed	Highly	Severely
Very Low	1	2	3	4	5	6
Low	2	3	4	5	6	7
Moderate	3	4	5	6	7	8
High	4	5	6	7	8	9
Very High	5	6	7	8	9	10

Least
Moderate
Highest Concern

Conduit development is considered through the O factor in the GVM, which includes with subsurface cave passage development. However, the GVM does not include cave entrances unless they are also insurgences. In order to ensure that this major component of the karst environment is incorporated into the composite model, the final GVM scores are altered to incorporate cave locations. A raster is created based on cave locations, where each cell containing the location of a cave is given a value of zero, and all other cells a value of one. The value of zero is considered by this study to be appropriate, due to their sensitivity to disturbance. This raster is then multiplied by the final GVM, so that each cell containing a cave entrance is given the highest vulnerability rating in the final raster.

Aggregating values. In order to create the composite model, the final GVM including cave values and the KDI created for the study area are reclassified, using ESRI's ArcGIS, based on the scores and values of disturbance and vulnerability, respectively (Table 4.1). These two rasters are added together in ArcGIS to obtain the final values for the study area (Table 4.2). Values in the final raster between seven and ten indicate areas of the highest concern. Seven was chosen as the cutoff value as any disturbance on very high vulnerability areas could result in serious impact to the karst ecosystem. Values between five and six indicate areas of moderate concern, as areas of high and very high vulnerability karst should be monitored even when lacking disturbance, and values between one and four indicate areas of least concern (Table 4.2).

Results and Discussion

Creation of Management Zones Based on the Composite Model

With the pristine or little disturbed nature of the study area, the final map reflects more the GVM than the KDI. The majority of the cells score three and four capture the low to moderate vulnerability and pristine state and little disturbance of the study area (Figure 4.3a). Seventy-two percent of the study area (265 km^2) is classified as area of least concern in terms of management, with 60 percent of this area (146 km^2) within el Ocote. Consequently, while there are concerns regarding the vulnerability of the karst ecosystem, the lack of development and the natural protection of the ecosystem, the immediate need for remedial action by the area's managers is currently minimal. Seventy-nine percent of the area of the zone classified as least

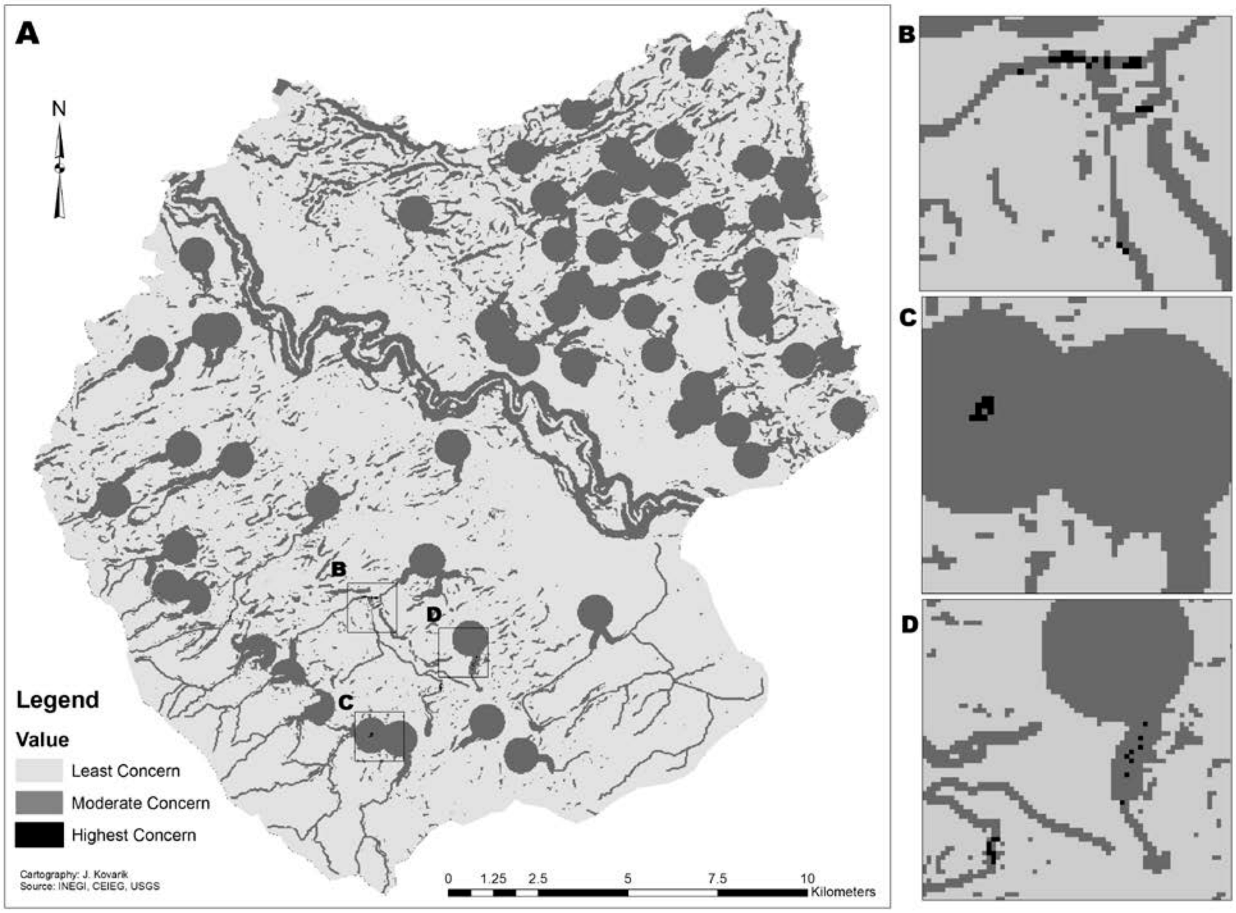

Figure 4.3a,b,c, and d – Management zone mapping within the study area.

Concern falls within natural area such as forest or savanna. These are areas on non-carbonate rock, or with slope values of less than 31 % on carbonate bedrock. Twenty percent of this zone is cleared land, again in areas on predominantly non-carbonate rock, or with slopes of less than 31 % on carbonate. The remaining one percent is developed, containing either settlements or roads on areas of non-carbonate or less steep slopes on carbonate. Where the zone of least concern falls within el Ocote, further development or land clearing should be discouraged or prevented where possible. However, the area outside of el Ocote is suitable for development and agriculture as current disturbance is minimal and the vulnerability of the ecosystem is lower in these areas.

Approximately 27 percent of the study area (102 km^2) is of moderate concern of which 34 percent (75 km^2) is within el Ocote. This reflects the moderate and high vulnerability areas where a little disturbance does occur, and the high- and very high vulnerability areas which are still classified as pristine. Eighty-nine percent (91 km^2) of the moderate concern is natural area, 10 percent (10 km^2) is cleared land, and approximately one percent (1 km^2) is developed. This classification covers sites which are within the outer buffer zones for insurgences (500 – 1,000 m) and streams (100 m) which sink directly into the subsurface, cave entrance areas, and slopes over 31 percent in areas of carbonate rock. Areas of moderate concern indicate zones where some development is possible but requires some guidance. Deforestation and agricultural practices on slopes greater than 31 percent and within stream buffers should be avoided, due to thin soils and increased risk of movement of contaminants into the subsurface. Quarrying should not occur, and any future road and settlement construction should be located to areas of least concern, or should utilize mitigation strategies to avoid impacting karst features for already developed areas.

Areas of highest concern exist in the study area where settlements and roads correspond to areas of very high vulnerability, less than one percent of the sub-catchment (Figure 4.3b,c,d). No areas of this zone occur within the reserve. Only values of seven were scored which fall within the lowest end of the highest concern category for the study area which indicates that disturbance may not be permanent as scores of ten are possible for this category. To ensure these areas will improve, it is imperative that local residents and natural resource managers work to create a plan for mitigation, involving best practices for agriculture, septic tanks, and trash disposal.

Management Strategies

In developed countries, the management and protection of karst landscapes have only been implemented within the past 30 years generally through the use of inadequate policy-based strategies (Fleury, 2009). Federal and state agencies have created best management practices (BMPs), standards and guidelines for management, ordinances, and comprehensive plans to mitigate or prevent impacts from human actions to the natural environment. BMPs can be defined as methods or practices either structural, nonstructural, and/ or land use planning (Evans and Corradini, 2001). Such management strategies for karst environments would need to incorporate specific regulations and BMPs concerning roads built over well-developed karst, cattle exclusions from sinkholes, stream ways, and springs; buffer zones around both urban and rural karst including installation of buffer strips; and transition of land from agriculture to forest through conservation reserves. BMPs and strategies for caves and karst areas are well-documented worldwide (Clarke, 1997; Watson et al., 1997; Eberhard, 1998; Stokes and Griffiths, 2000; BC Forestry, 2003; Jones et al., 2003; Zhou, 2005; Werker and Werker, 2006; USDA, 2008; Williams, 2008; van Beynen, 2011; Burt et al. 2013).

Generally, management strategies are most successful on federal or state government lands where there is a structured process for addressing resistance to implementation and associated costs. Conversely, on private land, participation and implementation of such management strategies are uncommon. Additionally, federal and state lands do not always encompass the entire hydrologic or ecologic unit and so practices from non-managed lands will impact the protected areas. In developing countries, policy and practice are forced on local populations through a top-down approach as the land status on which they subsist changes to that of protected area (Urich 2001). Many BMPs represent a significant change to the current practices of local farmers and can elevate costs of farming or result in the loss of workable land (Urich et al., 2001). Finally, local residents frequently have limited understanding of natural karst-related processes or the larger picture of what BMPs are meant to accomplish.

The health of the overall karst ecosystem is reliant on the participation of all concerned parties within a watershed. Case studies have demonstrated that environmental education and resource monitoring projects involving local residents greatly improve understanding of environmental problems as well as the relation between environmental issues and everyday life (Elke et al. 2007). Environmental education can also provide information of simple measures that individual property owners can employ to help alleviate or prevent negatively impacting karst ecosystems thereby improving community health without the onerous pressure of restrictive government policy. Federal, state and non-governmental organizations (NGOs) in the U.S. have created informational booklets and websites to share with private landowners, containing tips and information regarding the susceptibility of karst landscapes. BMPs are outlined that inform landowners on how they can be applied to ensure good water quality and maintain soil productivity (Zokaites, 1997; Duchene et al., 2001).

In many areas, a top-down approach is attempted for managing natural resources with the implementation of policy and BMPs. In the study area, 60 percent of the land is currently part of el Ocote, however, the remaining portion within the sub-catchment is private land and ejidos. With the lack of enforcement on reserve property and incorporation of private land within the greater watershed, a top-down approach will most likely be ineffective. Through working to educate the local people concerning the natural processes within karst environments and the impact of their actions on ecosystem health, hopefully a cooperative environment will be created where local residents will begin to mitigate their own actions. Based on the management zones created in this study, much of the sub-catchment is within the zones of least or moderate concern, where disturbance has not occurred. This presents an opportunity to prevent any major human impact to vulnerable areas and the ecosystem as a whole.

Within the study area a water quality monitoring project and an environmental education program were started in areas of highest concern. Water quality sampling was initially conducted by U.S. Forest Service International Programs workers and el Ocote personnel and then the sampling was continued by a local university. Karst curricula were adapted to the local region and translated into Spanish. Settlements within the study area in an area of highest concern as well as larger communities with easy access to the reserve were selected for the pilot project. Workshops introducing karst curriculum to teachers and reserve workers occurred first in order to evaluate the usefulness of the materials and gather information to alter the curricula specifically for the study area. These curricula will be incorporated into classroom learning in the region over the next two years. BMPs for local landowners regarding cave visitation and tours were translated into Spanish and provided to el Ocote to share with local landowners. Finally, BMPs such as sinkhole management, environmentally considerate septic tank practices, and pesticide management targeted at land owners for agriculture, forestry and development in rural karst areas have been translated into Spanish. They are currently being adapted into a booklet in cooperation with el Ocote that can be shared with local residents and industry incorporating the composite model along with information concerning the natural processes at work within the Rio la Venta watershed.

Conclusions

This study successfully calculated and applied a composite model based on the KDI and a GVM creating zones of least, moderate, and highest concern for the study area. These zones are used to evaluate which locations within the sub-catchment of the Rio la Venta are of highest concern to land managers and local residents in relation to karst ecosystem health and where management strategies should be focused. The composite model can also guide development and provide a simple, easy-to-understand representation that can be included in educational materials for local residents and industry. Top-down approaches to natural resource management such as requiring BMPs through policy and regulatory control would most likely be ineffective in the study area due to lack of enforcement and understanding of the environment. Due to these issues, karst-specific environmental education and water quality monitoring were the first management tools applied within the study area within areas of highest concern. While the composite model was applied in a rural, remote area of a developing country, it is anticipated that it is also very applicable to other locations and would benefit planners and managers in developed countries.

Future work within the study area should focus on continued characterization of the natural hydrologic processes of the watershed and inventory of biota and karst features to incorporate into the model. This information can be utilized to further refine the composite model and to adapt site-specific management strategies where needed within zones of highest concern. It is hoped that through educating local residents about their karst environment and the impacts of their actions on various facets of the ecosystem will result in a reduced need for future mitigation.

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CHAPTER FIVE

CONCLUSION

The purpose of this research was to create a new model for groundwater dependent ecosystem (GDE) conservation and protection in areas of karst development and to bridge the gap between science and management by connecting the model to management strategies for the study area. Not only was a novel model created, but this dissertation also built a new spatial expression of an environmental index. This contributes towards making environmental indices more meaningful and useful to leaders, managers, and residents within an ecosystem. This work was conducted within the theoretical framework of the United States Environmental Protection Agency's three tiered assessment approach, with the developed models creating level one and level two assessments for the study area. The research undertaken in this dissertation provides the first in-depth look at a portion of the Rio la Venta watershed, including the first tracer tests to hydrologically connect karst features within the study area to the Rio la Venta canyon. Finally, these studies expounded on previous work with the KDI as well as the COP model, successfully applying each to a remote area of a developing country.

In chapter two, data were gathered as to the human-induced disturbances within the study area and a karst-specific environmental index, the KDI, was calculated based on these data. Previous studies had not applied the KDI in the remote area of a developing country, nor implemented it spatially (van Beynen and Townsend, 2005; North et al., 2009; Bauer and Kellerer-Pirklbauer, 2010; van Beynen and Bialkowska-Jelinska, 2012; Anguloet al., 2013). This study used remote sensing data as well as other sources, finding the spatial implementation to be less subjective and more accurate overall. The spatial implementation of the KDI for the study area was able to illustrate that this sub-catchment of the Rio la

Venta watershed is still relatively pristine. It also characterizes the principle disturbances within the ecosystem as those related to agriculture such as forest removal and agrochemical application. Main areas of concern for the health of the sub-catchment are outside the reserve boundary on private land and núcleos, however areas within the reserve around the settlement of Rabasa are beginning to show impacts. It is thought based on the KDI classifications that continued development and agricultural work without a detailed management plan in place will greatly accelerate the future degradation of the karst ecosystem.

In chapter three, the European Approach to groundwater vulnerability mapping in the form of an adaption of the COP method was applied to the study area. This is the first application of groundwater vulnerability mapping within the Rio la Venta watershed and within the Grijalva-Usumacinta hydrologic region. The final map illustrates that the study area ranges from low vulnerability where noncarbonated rocks outcrop in the southwest to very high where areas are characterized by carbonate rock with slopes greater than 31 percent, thin soils, and in zones within 500 m of insurgences and 100 m of sinking streams. In order to validate the map, two insurgences within areas of very high vulnerability were successfully traced to the Rio la Venta canyon, completing the first dye trace within the watershed and establishing the hydrologic connection between the settlements within the study area and the Rio la Venta. This work contributes to knowledge concerning the timing of subsurface flow pathways within the watershed.

Finally, in chapter four, cave data were combined with the GVM, and then this final product was aggregated with the KDI in ArcGIS. This created a composite model integrating spatial locations of all categories of anthropogenic disturbance with locations of the most vulnerable areas on the landscape. The resulting classification created a gradation of zones of concern which can be used to focus actions for conservation and preservation of the karst ecosystem. Other studies have begun to highlight the need for more comprehensive karst ecosystem models, not just those assessing groundwater quality and quantity (Stokes and Griffths, 200; Goldscheider, 2012). However, this is the first creation and application of such a model. Based on the information from the first two studies, and the history of land conflict and management within the area as well as within protected areas worldwide, it is thought that a top-down management strategy will not work in this area (Simonian, 1995; Benjamin, 1996; Phillips, 1998; Urich, 2001). Instead, a recommended strategy of providing information to local leaders and residents, and working with them to monitor their ecosystem and develop protocol and best practices will be most effective. This is being accomplished through an environmental education program and the development of an information booklet integrating the maps from this dissertation.

Beyond el Ocote and Mexico, future work with this study can be applied to other types of watersheds with GDEs in developed as well as developing countries. The COP method contains adaptations for all types of aquifers not just karst and could easily be applied in other areas. Additionally, many other applications of GVMs exist for a wide range of situations. While the KDI is karst-specific, it could be easily adapted to other areas with GDEs, such as areas with volcanokast or piping. These areas may face similar contamination and disturbance issues to traditional karst (Parker et al. 1990; Kiernen, 2003).

The maps created in this dissertation provide a solid foundation and a beginning for adaptive management within the Rio la Venta catchment, and a model for providing a foundation for management in other developing karst areas. The GIS provides a database benchmarking the current state of disturbance within the environment and a library of information for local leaders and land managers to reference for justifying decisions and developing best management practices. Maps illustrating past levels of disturbance can be created using this foundation in order to begin to assess rates of disturbance and where and at what rate disturbance is becoming more severe. As part of a larger adaptive management framework and the U.S. EPA three-tiered approach, this model should continue to be updated and include more detail as more information becomes available. Disturbance should be remapped every five years in order to assess continuing rates of change and as a method of effectiveness monitoring of management strategies. Perhaps more importantly, quantitative characterization of the aquifer should occur within the framework of a level three assessement. It is hoped that in the future a detailed groundwater model for the Rio la Venta watershed can inform future adaptations of the GVM. It is hoped that the efforts outlined above will lead to the reduction of future disturbance, and the sustainable management of the Rio la Venta watershed in future years.

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APPENDIX A:

STUDY DATA

Geographic Information System (GIS) data is located on the Karst Information Portal (http://www.karstportal.org/) or housed with the respective agency or group from which it was collected. Original dye trace results are reported below.

CRAWFORD HYDROLOGY LAB

Hydrogeologists, Geologists, Environmental Scientists

*Karst Groundwater Investigations * Fluorescent Dye Analysis*

LABORATORY REPORT SHEET

FLUORIMETRIC ANALYSIS RESULTS

Reserva de la Biosfera Selva el Ocote

Analysis requested by:

Johanna Kovarik - USFS

	FLUORESCEIN	EOSINE
Color Index:		Acid Red 87
Dye Receptor:	Activated Charcoal	Activated Charcoal
Analysis by:	Spectrofluorophotometer	Spectrofluorophotometer

WATER SAMPLE AND CHARCOAL RECEPTOR RESULTS

	FLUORESCEIN	EOSINE
PQL in Eluent	0.005 ppb	0.005 ppb
PQL in Water	0.010 ppb	0.010 ppb
λ in Eluent	515.8 nm	540.2 nm
λ in Water	509.9 nm	534.5 nm

Lab ID	Event	Date Collected	Feature Name	TIME COLLECTED	Peakfit	Fluorescein Results	Fluorescein Conc in ppb	Fluorescein Peak Center (nm)	Eosine Results	Eosine Conc in ppb	Eosine Peak Center (nm)	Comments
WL-001-0	BG1	04/21/14	#1	1700		ND			ND			
EL-001-1	02	04/22/14	#1	845		ND			ND			
WL-002-0	BG1	04/21/14	#2	1700		ND			ND			1900 RECORDED ON SAMPLE BAG
EL-002-1	02	04/22/14	#2	845		ND			ND			
WL-004-0	BG1	04/22/14	#4 IN SPRING	840		ND			ND			
WL-006-0	BG1	04/22/14	#6 BELOW SPRING IN CANYON	920		ND			ND			
WL-007-0	BG1	04/20/14	#7 ABOVE	1300		ND			ND			
EL-007-1	02	04/22/14	#7 ABOVE	1700		ND			ND			
EL-007-2	03	04/22/14	#7 ABOVE	1900		ND			ND			
EL-007-3	04	04/22/14	#7 ABOVE	2100		ND			ND			
EL-007-4	05	04/23/14	#7 ABOVE	730		ND			ND			
EL-007-5	06	04/23/14	#7 ABOVE	1000		ND			+	0.268	540.4	
EL-007-6	07	04/23/14	#7 ABOVE	1230		ND			++	4.139	541.0	
EL-007-7	08	04/23/14	#7 ABOVE	1600		ND			++	2.881	541.0	FL SHOULDER COULD NOT BE QUANTIFIED
EH-007-8	09	04/23/14	#7 ABOVE	1900		++	1.108	515.4	++	2.133	540.6	
EH-007-9	10	04/23/14	#7 ABOVE	2100		++	3.692	515.6	++	4.810	540.4	
EH-007-10-D	11	04/24/14	#7 ABOVE	730	x	+++	88.700	515.3	+++	58.500	539.0	PEAKFIT RESULTS
EH-007-11	12	04/24/14	#7 ABOVE	930	x	+++	27.725	515.3	+++	12.781	538.3	PEAKFIT RESULTS
WL-008-0	BG1	04/20/14	#8 BELOW	1300		ND			ND			
EL-008-1	02	04/22/14	#8 BELOW	1650		ND			ND			
EL-008-2	03	04/22/14	#8 BELOW	1900		ND			ND			
EL-008-3	04	04/22/14	#8 BELOW	2100		ND			ND			
EL-008-4	05	04/23/14	#8 BELOW	730		ND			ND			
EL-008-5	06	04/23/14	#8 BELOW	1000		ND			+	0.408	540.4	
EH-008-6	07	04/23/14	#8 BELOW	1300		ND			+++	5.549	541.0	
EH-008-7	08	04/23/14	#8 BELOW	1600	x	+	0.712	514.6	+++	7.241	540.9	PEAKFIT RESULTS
EH-008-8	09	04/23/14	#8 BELOW	1900		++	1.374	515.6	++	3.496	540.8	
EL-008-9	10	04/23/14	#8 BELOW	2100		+	0.435	515.2	++	0.656	540.6	
EH-008-10	11	04/24/14	#8 BELOW	720	x	+++	57.272	515.4	+++	45.141	539.7	PEAKFIT RESULTS
EH-008-11	12	04/24/14	#8 BELOW	930	x	+++	9.908	515.3	++	4.496	538.7	PEAKFIT RESULTS

Approved by: L. Bledsoe on 05/07/14

Comments:

DUP = Field Duplicate	NS = No Sample Recovered	Q = Lab Duplicate
B = Background	GS = Grab Sample	+ = Positive
ND = No Detection	NPI = No Peak Identified	?+ = Questionable Positive
IB = Initial Background	POR = Peak Out of Range	Peakfit Utilized