A Systems Approach to Environmental Sensitivity Index (ESI) Mapping for Oil Spill Contingency Planning and Response

John R. Jensen, Joanne N. Halls, and Jacqueline Michel

Abstract

Oil spills can devastate ecosystems and severely impact water quality. The Environmental Sensitivity Index (ESI) was developed to reduce the environmental consequences of a spill and help prioritize the placement and allocation of resources during cleanup efforts. The successful use of analog and digital geographic information system versions of the ESI concept during the past ten years has led to improvements and refinements, including (1) the development of tidal inlet protection strategy maps produced before a spill that specify the type of response (e.g., boom, skimmer) and where and how to place it, (2) new large format seasonal summary maps, (3) geographic expansion of the ESI concept inland to classify the sensitivity of rivers using a river Reach Sensitivity Index (RSI), (4) regional watershed analysis to identify hazards and potential spill consequences, and (5) the identification of unusually sensitive areas *to environmental damage if there is a hazardous liquid pipeline accident.*

Introduction

One of the primary objectives of oil spill planning and response, after protecting human life, is to reduce the environmental consequences of the spill and cleanup efforts. This objective is best achieved if the location of sensitive resources are identified in advance, so that protection priorities can be established and cleanup strategies selected. With only a few hours to respond, there is no time for responders to contact all of the different resource managers for information on what areas are the most important to protect. For sensitive area mapping to be effective, it must be an integral component of an overall planning activity. A key requirement of the Oil Pollution Act of 1990 was the establishment of Area Committees who prepare Area Plans identifying sensitive areas, protection priorities, and protection methods. Area Committees are comprised of representatives of local, state, and federal agencies with regulatory authority and resource management responsibilities, as well as industry representatives who also must prepare facility and vessel response plans. These committees pre-plan how to implement an effective response during spill emergencies.

The most widely used approach to sensitive area mapping, in both coastal and inland areas throughout the world, is known as the Environmental Sensitivity Index (ESI), an original concept which was first applied in 1979, when prototype ESI maps were prepared days in advance of the arrival of an oil slick into Texas waters from the *Ixtoc I* well blowout in the Gulf of Mexico. The ESI is a spatial information system which is composed of three main components: a shoreline ranking system which ranks shoreline types on a scale of 1 to 10; oil-sensitive biological resources; and human-use resources of commercial, recreational, or subsistence value. Significant effort has been expended developing sensitivity mapping components of oil spill contingency plans around the world. Over the last 20 years, 61 ESI atlases (2,756 map sheets) have been prepared for the United States' coastline, including Alaska and the Great Lakes (Table 1). This approach has been implemented in other countries such as Canada, United Arab Emirates, Israel, Jordan, El Salvador, Germany, South Africa, Mauritius, and New Zealand. Baker *et al.* (1995) reviewed the range of mapping methods used internationally, all of which evolved from the basic ESI concept.

In the last few years, sensitivity mapping has moved from a static product of limited distribution focused only on coastal oil spills, to a more versatile and valuable tool for a wide range of natural resource management applications. In many areas, an ESI project becomes the impetus for compiling, synthesizing, and automating extensive data which have never been available in digital formats. This article describes coastal oil spill ESI mapping and how the digital ESI concept has evolved to (1) develop tidal inlet protection strategy databases, (2) include season summary information, (3) conduct risk assessments of entire watersheds and regions, (4) monitor inland regions using a river reach sensitivity index (RSI), and (5) model unusually sensitive areas (USAs).

Environment Sensitivity Index (ESI) Logic and Use

In the United States, spill planning and response is organized under a tiered structure of national, regional, and area teams. The U.S. Coast Guard (USCG) is responsible for managing spills in navigable waters, and the U.S. Environmental Protection Agency (USEPA) is responsible for inland spills. These agencies chair the various contingency planning organizations and become the Federal On-Scene Coordinator during spill emergencies. Spill planning and response is a multiagency and multidisciplinary process, involving stakeholders with often very different objectives, mandates, skills, and responsibilities. Yet, during a spill emergency, a group of people who seldom if ever work together have to quickly become a team with common understanding and goals on

J.R. Jensen is with the Department of Geography, University of South Carolina, Columbia, SC 29208 (johnj@garnet.cla.sc.edu).

J.N. Halls and J. Michel are with Research Planning, Inc., Columbia, SC 29201.

Photogrammetric Engineering & Remote Sensing, Vol. 64, No. 10, October 1998, pp. 1003–1014.

0099-1112/98/6410–1003$3.00/0

Table 1. Environmental Sensitivity Index Atlases Compiled for the United States

Atlas	Year Published	No. of Maps	Digital Available
Alabama	1996	26	Y
Alaska (6 atlases)	1982–86	371	N
Alaska (Southeast)	1992	98	Y
California (3 coastal atlases)	1994–95	131	Y
California (San Francisco Bay) (currently being updated)	1999	27	Y
Connecticut	1984	17	N
Delaware/New Jersey/Pennsylvania	1996	64	Y
Florida (Apalachicola River System)	1984	19	N
Florida (5 coastal atlases)	1995–96	265	Y
Florida (St. John's River)	1997	31	Y
Georgia	1997	39	Y
Guam	1994	15	N
Hawaii	1986	86	N
Lake Erie System	1985	66	N
Lake Huron	1994	69	Y
Lake Michigan (Eastern Shore)	1986	23	N
Lake Michigan (3 atlases)	1993–94	135	Y
Lake Ontario	1993	34	Y
Lake Superior (3 volumes)	1994	133	Y
Louisiana	1989	98	N
Maine/New Hampshire (3 atlases)	1983–85	102	N
Maryland (2 volumes)	1983	118	N
Massachusetts (currently being updated)	1997	51	Y
Mississippi	1995	29	Y
Mississippi, Leaf River	1996	9	Y
New York (2 atlases)	1985	78	N
North Carolina (3 volumes)	1996	135	Y
Oregon/Washington (Outer Coast)	1986	55	N
Oregon/Washington (Columbia River)	1991	26	Y
Puerto Rico	1984	35	N
Rhode Island and Massachusetts	1983	18	N
South Carolina	1996	63	Y
St. Lawrence River	1985	17	N
St. Marys River	1986	15	N
Texas (South)	1980	15	N
Texas (Upper Coast)	1995	51	Y
U.S. Virgin Islands	1986	8	N
Virginia (2 volumes)	1983	104	N
Washington (2 Puget Sound atlases)	1984–85	80	Y
United States ESI Total: (61 atlases)	—	2756	—

how to deploy limited resources to contain and recover the oil, protect sensitive resources, and clean up contaminated areas.

Because protecting natural resources is the primary goal of spill response, spatial and temporal information on the most sensitive resources is critical to the entire planning and response strategy. The concept of an environmental atlas which depicted all of the oil-sensitive resources in an area evolved during the 1970s as the United States started developing contingency plans and response teams as required under the Clean Water Act. ESI atlases have become an integral component of oil-spill contingency planning. Within the National Contingency Plan, the National Oceanic and Atmospheric Administration (NOAA) Hazardous Materials Response and Assessment Division provides scientific support to the U.S. Coast Guard. NOAA has a national team of experts on 24-hour call in all the scientific aspects of spill response, and they respond to 50 to 100 spills a year. The first question asked of NOAA is for a trajectory analysis of where the spilled material will go; the second question asked is what are the resources at risk for the spill conditions (oil type, weathering conditions, time of year, environmental setting, etc.). To assist NOAA and other agencies in determining the resources at risk, NOAA published the traditional, hardcopy ESI atlases during the 1980s for most of the U.S. shoreline, through cooperative efforts with federal agencies, state governments, and private industry. Since 1989, NOAA has taken the lead in developing standards and publishing digital ESI atlases.

The shoreline habitats are classified using a ranking system based on extensive studies conducted during spills and was first applied to the shoreline of lower Cook Inlet, Alaska (Michel *et al.*, 1978). Through the years, the classification scheme has been validated at numerous spills and is now the basis for a wide range of spill planning activities. For example, the ESI shoreline ranking is used in matrices prepared by Area Committees and in spill response manuals to identify which shoreline cleanup techniques are approved for use (NOAA and API, 1994). The scheme is standardized and incorporates codes that encompass a range of environmental settings, including estuarine, lacustrine, and riverine environments (Table 2). The higher the ESI code, the more sensitive the habitat to oil or other contaminants. For example, wetlands are the most sensitive shoreline habitat while exposed rocky shores are the least sensitive.

ESI maps and databases are used in several modes. Planning teams use the data to predetermine protection priorities. The maps provide a single, consistent source of information on which to base very complex decisions. They are also valuable for training and drills, as response teams test their ability to implement the plans. During spill emergencies, they are most valuable to the response organization, which often includes regional or national experts who are not familiar with the local resources. In the very early stages of a spill, one of the first questions asked is "What are the resources at risk?" The ESI maps can be quickly consulted to identify those resources which are present now, at the time of the spill, which ones have special protection status, and when the most sensitive life stages might be present. Later in the spill, the maps can be used to identify areas where cleanup operations should be restricted (e.g., no fly zones around eagle nests) or when cleanup operations should be terminated to prevent disturbing animals (e.g., cleanup of a seal pupping haulout must be completed by the date pupping is expected to begin).

Historically, the ESI products were analog, hardcopy map atlases, with only five to ten copies produced. Since 1989, digital ESI atlases have been prepared using geographic information system (GIS) and remote sensing technology. With the power of a GIS, sensitivity mapping has moved from a hardcopy map of limited distribution to a tool available on demand in various formats, including (1) digital maps that can be viewed on personal computers, (2) a World Wide Web browser interface, and (3) a complex GIS relational data structure that contains important spill-response information.

Environmental Sensitivity Index (ESI) Geographic Information System Design

NOAA has devoted considerable resources developing standards and guidelines for sensitivity mapping products (Michel and Dahlin, 1993; Halls *et al.*, 1997) so that appropriate data are presented in consistent formats. Many response organizations are national or regional; thus, users from different geographic areas and disciplines should immediately recognize and understand the mapped information for a specific spill site. GIS applications based on a consistent data structure can be readily shared among response teams.

Because ESI maps form the basis for establishing protection priorities, it is critical that state and federal resource

Table 2. Expanded and Standardized Environmental Sensitivity Index Classification Scheme

ESI Code	Estuarine	Lacustrine	Riverine
1A	Exposed rocky shores	Exposed rocky shores	Exposed rocky banks
1B	Exposed, solid man-made structures	Exposed, solid man-made structures	Exposed, solid man-made structures
2A	Exposed wave-cut platforms in bedrock, mud, or clay	Shelving bedrock shores	Rocky shoals; bedrock ledges
2B	Exposed scarps and steep slopes in clay		
3A	Fine to medium-grain sand beaches	Eroding scarps in unconsolidated sediments	Exposed, eroding banks in unconsolidated sediments
3B	Scarps and steep slopes in sand		
4	Coarse-grained sand beaches	Sand beaches	Sandy bars and gently sloping banks
5	Mixed sand and gravel beaches	Mixed sand and gravel beaches	Mixed sand and gravel bars and gently sloping banks
6A	Gravel beaches	Gravel beaches	Gravel bars and gently sloping banks
6B	Riprap	Riprap	Riprap
7	Exposed tidal flats	Exposed tidal flats	
8A	Sheltered rocky shores and sheltered scarps in bedrock, mud, or clay	Sheltered scarps in bedrock, mud, or clay	
8B	Sheltered, solid man-made structures	Sheltered, solid man-made structures	Sheltered, solid man-made structures
8C	Sheltered riprap	Sheltered riprap	Sheltered riprap
8D	Vegetated, steeply-sloping riverine bluffs		Vegetated, steeply-sloping bluffs
9A	Sheltered tidal flats	Sheltered sand/mud flats	
9B	Vegetated low riverine banks	Sheltered vegetated low banks	Vegetated low banks
10A	Salt- and brackish-water marshes		
10B	Freshwater marshes	Freshwater marshes	Freshwater marshes
10C	Swamps	Swamps	Swamps
10D	Scrub-shrub wetlands	Scrub-shrub wetlands	Scrub-shrub wetlands

managers participate in all stages of data collection and agree with the information as presented. The methodology for creating a digital ESI atlas using GIS technology involves

- meeting with local and regional resource experts;
- documenting the location of biological, human use, and environmental resources;
- compiling the information onto maps and into tables;
- digitizing spatial data and attribute information into specified digital formats;
- performing initial classification of shoreline environmental sensitivity;
- producing initial ESI maps and attribute tables for review;
- incorporating edits from local resource experts;
- producing final ESI atlas and tabular products; and
- releasing digital products (including metadata) for dissemination.

The following digital files (layers) are contained in the digital ESI atlas (Figure 1):

- ESI — Shoreline habitats (arcs, polygons) classified according to environmental sensitivity
- HYDRO — Water polygons and linear rivers/streams
- INDEX — U.S. Geological Survey 7.5-minute quadrangle boundary polygons
- MGT — Managed land
- SOCECON — Socioeconomic resource information including points (e.g., water intake facilities and desalinization plants) and linear features (e.g., recreational beaches)
- HABITATS — Regions of habitats and rare plant species
- INVERT — Regions for mollusk and crustacean species (invertebrates)
- T_MAMMAL — Regions for terrestrial mammal species
- M_MAMMAL — Regions for marine mammal species
- BIRDS — Regions for bird species
- NESTS — Points for bird nesting colonies
- FISH — Regions for fish species
- REPTILES — Regions for reptile species

The human-use and biology data are linked using a relational database management system. During the data entry process, attribute data are stored in Oracle® data tables and views. The final ESI information are stored in ARC/INFO® attribute tables and coverages.

Base Map Data Layers

During an oil spill event, scientists and resource managers must orient themselves rapidly, often in unfamiliar territory. To expedite orientation, an ESI map usually contains the planimetric detail of a black-and-white scanned 7.5-minute quadrangle or a black-and-white orthophotoquad of the region of interest. Relatively high spatial resolution satellite data may also be used for the planimetric detail (RPI International, 1989; Jensen *et al.*, 1990; Jensen *et al.*, 1993; Jensen *et*

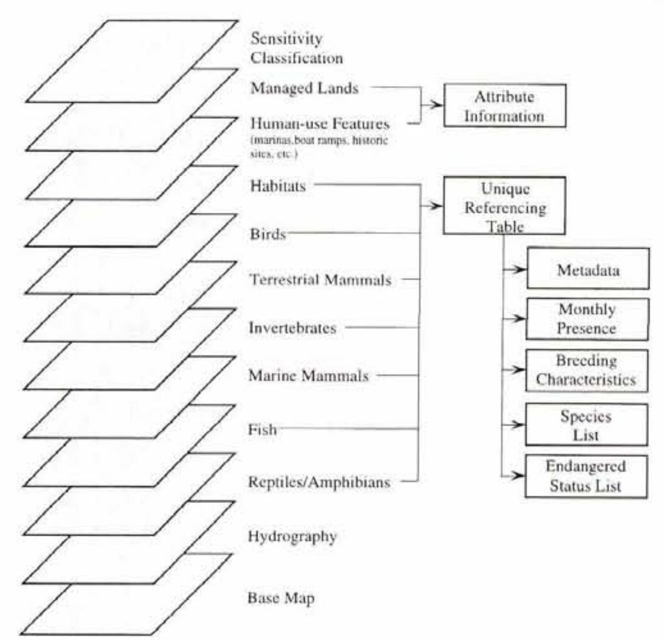

Figure 1. The Environmental Sensitivity Index (ESI) data structure.

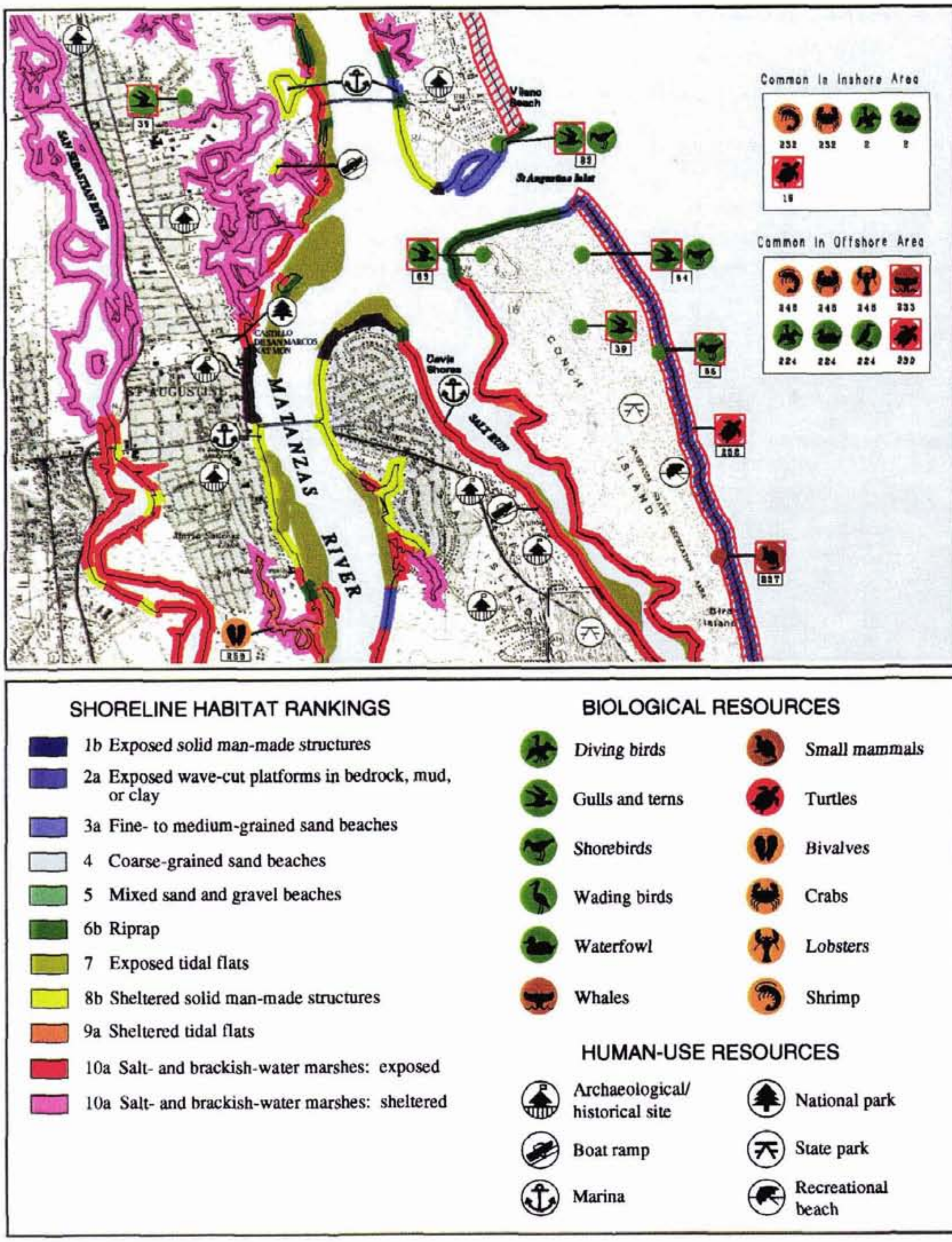

Plate 1. An ESI map for St. Augustine, Florida. Refer to Table 5 for a summary of the biological attributes.

al., 1996; Narumalani *et al.*, 1993). An ESI digital map sheet for St. Augustine, Florida is found in Plate 1 (Research Planning, 1996b). In this example, the resource sensitivity information is draped over a scanned 7.5-minute orthophoto.

The HYDRO data layer contains polygonal water features as well as all tidally influenced linear stream features that are superimposed on the 7.5-minute quadrangle. The file also includes the names of water bodies and land features for spill planning, response, and navigation. The INDEX layer contains polygons for all 7.5-minute quadrangles in the atlas and attribute information on the name, revision date, map angle, and scale.

ESI Shoreline Sensitivity

This ESI data file contains information on the linear shoreline geomorphology and polygonal habitats that are adjacent to navigable waterbodies. Each line and polygon feature is classified according to its sensitivity to oil. The shoreline sensitivity ranking is controlled by several parameters, including relative exposure to wave and tidal energy, slope, substrate

TABLE 3. ENVIRONMENTAL SENSITIVITY INDEX HUMAN-USE FEATURES

Data Element	Sub-Element	Mapped Areas
Recreation/Access	Access	Vehicular access to the shoreline
	Beach	High-use recreational beaches
	Boat Ramp	
	Diving Site	High-use recreational areas
	Marina	
	Recreational Fishing	High-use recreational areas
Management Area	Indian Reservation	
	Marine Sanctuary	
	National Park	
	Park	State and regional parks
	Special Management Areas	Usually water-associated
	Wildlife Refuge, Preserve, Reserve	
Resource Extraction	Aquaculture Site	Hatcheries, ponds, pens, etc.
	Commercial Fishery	
	Log Storage Area	
	Mining	Intertidal/subtidal mining leases
	Subsistence	Designated harvest sites
	Water Intake	Industrial; drinking water; cooling water
Cultural Resources	Archaeological Site	Water, coastal, or wetland-associated
	Historical Site	Water, coastal, or wetland-associated

type (grain size, mobility, penetration, trafficability), and biological productivity and sensitivity.

The classification of shoreline sensitivity is based on site-specific conditions using combinations of the standard classification codes. For example, the bright red shoreline of St. Augustine, Florida in Plate 1 is salt and brackish-water marsh, one of the most oil-sensitive habitats (code 10A). If the marsh is fronted by an exposed tidal flat, the composite code would be 10A/7 (refer to Table 2). During digitization, every shoreline feature is assigned a code that is documented in the metadata.

Human-Use Data

The human-use resources included in ESI atlases include (Table 3) recreational/access sites (e.g., public beaches, marinas), managed lands (e.g., marine sanctuaries), resource extraction locations (e.g., water intakes), and cultural resources (e.g., archaeological sites). These resources can be impacted economically in the event of closures during a spill to protect human health, or have special protection and regulatory status that can complicate oil removal strategies. Cultural resource sites pose additional problems because often it is necessary to protect the actual location of the site to prevent unauthorized access. Numerous marinas, boat ramps, and archaeological/historical site icons are found in the St. Augustine, Florida study area (Plate 1).

The human-use data are stored in both the MGT data layer that contains managed land and the SOCECON data layer that contains point and line features. Each feature in the human-use data layers contains a unique identifier (HUNUM) that links to an associated SOC_DATA relational table that stores items such as facility name, and site-specific comments such as the number of boat slips at a marina. Critical information that changes often, such as contact person and phone number, are included in planning manuals and phone lists that can be updated without having to republish maps.

Biological Data

The biological resources include species found on federal or state threatened or endangered lists, as well as other species of commercial, recreational, or ecological importance, such as fish nursery areas and bird nesting sites. The major biological elements included in the ESI database, include (Table 4) marine mammals, terrestrial mammals, birds, reptiles and amphibians, fish, shellfish and insects, and rare habitats or plant species distribution. Each of the elements is mapped at the species level for both spatial extent and monthly temporal presence and absence. To set protection strategies and mitigate environmental damage, the goal of the biological mapping is to emphasize the locations and areas of highest concentrations, the most sensitive life stages or activities, and the *most vulnerable species*. The icons used to represent sensitive biological resources are shown in Plate 1 with a number below the icon. This number is referred to as a Resource-at-Risk (RAR). The Resource-at-Risk table associated with Plate 1 is found in Table 5 and includes a detailed list of sensitive species, their statistics as threatened (T) or endangered (E) on state (S) and Federal (F) lists, their concentrations (Concen), months when the species are present, and the time of sensitive life stages (e.g., nesting, laying, hatching). The presence and life-stage information is indispensable for all aspects of spill planning and response. For example, on turtle-nesting beaches, it would be necessary to restrict equipment use during the nesting period to prevent destruction of eggs in the nests, but unnecessary after the hatchlings have emerged. No-fly zones are often established around bald eagle nests during the nesting seasons. A higher degree of cleanup may be required when sensitive resources are present and likely to be exposed, such as areas near seabird nesting colonies.

One of the unique characteristics of the biological symbolization is the concept of *common throughout* which removes the larger polygons from the map and summarizes the data as symbols with the associated resource numbers in inset boxes (Plate 1). This symbolization reduces the number of polygons and symbols that would make the map overly complex and difficult to read, yet still makes the information available on one map.

If a spill of diesel oil occurred offshore of St. Augustine Inlet in June and was predicted to come ashore, the map in Plate 1 and Table 5 could be used to assess the resources at risk. Diesel oil is a light, refined product that spreads into a thin film and evaporates usually within a few days, so shoreline contamination is expected to be light for a small to medium sized spill. But, diesel has a high concentration of the most toxic fractions in oil, which are also the most water soluble, so those resources which use the water surface and are in shallow water are at greatest risk. Of the birds potentially in the area, diving birds such as pelican and cormorants are present in high concentrations, but not breeding. These birds

TABLE 4. ENVIRONMENTAL SENSITIVITY INDEX BIOLOGY ELEMENTS, SUB-ELEMENTS, AND AREAS THAT ARE MAPPED

Data Element	Sub-Element	Mapped Areas
Marine Mammal	Dolphin	Concentration areas
	Manatee	Concentration areas, cold weather refuge
	Pinniped	Haulouts, concentrations areas
	Polar Bear	Concentration areas
	Sea Otter	Concentration areas
	Whale	Migratory or other concentration areas
Terrestrial Mammal	Bear	Intertidal feeding or aquatic/wetland concentrations, hazards to spill responders
	Canine	Threatened/endangered or rare species
	Deer	Intertidal feeding or aquatic/wetland concentrations
	Feline	Threatened/endangered or rare species
	Pig	Hazards to spill responders
	Small Mammal	Aquatic fur-bearer concentrations, threatened/endangered, rare occurrences
Bird	Alcid	Rookeries; wintering concentration areas
	Diving Bird	Rookeries; forage/wintering areas; roosting concentrations
	Gull/Tern	Nesting sites; other concentration areas
	Passerine	Threatened/endangered or rare occurrences, especially nesting
	Pelagic	Rookeries, roosting, and other concentrations
	Raptor Nesting sites;	Migratory/feeding concentrations
	Shorebird	Nesting sites; migratory, wintering, roosting concentrations
	Wading Bird	Rookeries; feeding and roosting concentrations
	Waterfowl	Wintering and migration concentrations, nesting sites
Reptile/Amphibian	Alligator/Crocodile	Concentration areas, especially nesting
	Other Reptiles/Amphibians	Threatened/endangered or rare occurrences, especially aquatic/ wetland concentrations
	Turtle	Nesting beaches; concentration areas
Fish	Diadromous Fish	Spawning, nursery, threatened/endangered or rare occurrences
	Estuarine Nursery Fish	Spawning, nursery, and other concentration areas
	Estuarine Resident Fish	Spawning concentration areas; threatened/endangered or rare occurrences
	Freshwater Fish	Spawning and nursery areas; threatened/endangered or rare occurrences
	Marine Benthic Fish	Spawning and nursery areas; reef, kelp bed, or other concentrations
	Marine Pelagic Fish	Spawning or other concentration areas
Shellfish/Insect	Bivalve	Harvest areas; abundant beds; threatened/ endangered or rare occurrences
	Cephalopod	Harvest areas; high concentrations
	Crab	Nursery areas; high concentrations
	Echinoderm	Harvest areas
	Gastropod	Harvest areas; high concentrations, threatened/endangered, rare occurrences
	Lobster/Crayfish	Nursery spawning and harvest areas; threatened/endangered or rare occurrences
	Shrimp	Nursery areas; high concentrations
	Insect	Threatened/endangered or rare occurrences
Habitat/Rare Plant	Coral Reef	
	Floating Aquatic Vegetation	
	Hardbottom Reef	
	Kelp Bed	
	Rare Plant	Threatened/endangered or rare species or communities
	SAV	Submerged aquatic vegetation; seagrass beds
	Worm Bed	

spend much of their time resting on the water surface and diving for prey; thus, they are likely to become contaminated. Terns and plovers are present, some are nesting, and some are listed on either the state and/or Federal lists as threatened. Listed species are always of special concern. Some of the nesting sites are very close to shore, and the adults feed aggressively in nearshore waters.

Although there is a very important calving area offshore for the highly endangered northern right whale, whales are not present at this time, and thus not of concern for a non-persistent oil. Sea turtles nest on all the outer beaches, though only the leatherback sea turtle is present in high concentrations. Hatchlings should be emerging from nests at this time, and would be highly susceptible to oiling. Also, care would be required to prevent disturbance of active nests during deployment of equipment and workers. All sea turtles are listed species.

Shellfish abound in the area (crabs, shrimp, lobsters, oysters), and many are spawning. But, there are no special concentration areas, and significant impacts are expected only in the vicinity of the initial release because of the rapid weathering of this type of oil. There is an endangered beach mouse location on Conch Island, and thus crews would be alerted to avoid the site in the event of work in this area.

The outer beaches are both fine- and coarse-grained sand, and specific cleanup methods would be allowed if the oil stranded and required removal. Inside the inlet are extensive tidal flats and marshes, which are highly sensitive. Fig-

TABLE 5. RESOURCE-AT-RISK (RAR) BIOLOGICAL ATTRIBUTES FOR ST. AUGUSTINE, FLORIDA, ESI MAP (REFER TO PLATE 1)

Bird: RAR#	Species	S/F	T/E	Concen	J	F	M	A	M	J	J	A	S	O	N	D	Nesting	Laying	Hatching
2	Brown pelican			HIGH	X	X	X	X	X	X	X	X	X	X	X	X	—	—	—
	Bufflehead			LOW	X	X										X	—	—	—
	Common loon			LOW	X	X	X	X							X	X	—	—	—
	Double-crested cormorant			HIGH	X	X	X	X	X	X	X	X	X	X	X	X	—	—	—
	Lesser scaup			MED	X	X	X	X						X	X	X	—	—	—
	Red-breasted merganser			LOW	X	X	X	X						X	X	X	—	—	—
	Redhead			LOW	X	X	X								X	X	—	—	—
39	Least tern	S	T				X	X	X	X	X	X	X				APR–AUG	—	—
82	Least tern	S	T	148			X	X	X	X	X	X	X				APR–AUG	—	—
	Wilson's plover			9	X	X	X	X	X	X	X	X	X	X	X	X	APR–JUL	—	—
83	Least tern	S	T	50			X	X	X	X	X	X	X				APR–AUG	—	—
85	Piping plover	S/F	T/T	1	X	X	X	X	X			X	X	X	X	X	—	—	—
224	Brown pelican			HIGH	X	X	X	X	X	X	X	X	X	X	X	X	—	—	—
	Bufflehead			LOW	X	X										X	—	—	—
	Common loon			LOW	X	X	X	X							X	X	—	—	—
	Double-crested cormorant			HIGH	X	X	X	X	X	X	X	X	X	X	X	X	—	—	—
	Lesser scaup			MED	X	X	X	X						X	X	X	—	—	—
	Northern gannet			LOW	X	X	X	X								X	—	—	—
	Red-breasted merganser			LOW	X	X	X	X						X	X	X	—	—	—
	Redhead			LOW	X	X	X								X	X	—	—	—

M_MAMMAL: RAR#	Species	S/F	T/E	Concen	J	F	M	A	M	J	J	A	S	O	N	D	Mating	Calving	Pupping
233	Humpback whale	S/F	E/E	HIGH	X	X	X								X	X	—	—	—
	Northern right whale	S/F	E/E	HIGH	X	X	X								X	X	—	NOV–MAR	—

REPTILE: RAR#	Species	S/F	T/E	Concen	J	F	M	A	M	J	J	A	S	O	N	D	Nesting	Hatching	Inter-nesting
19	Green sea turtle	S/F	E/E		X	X	X	X	X	X	X	X	X	X	X	X	—	—	—
	Loggerhead sea turtle	S/F	T/T		X	X	X	X	X	X	X	X	X	X	X	X	—	—	—
230	Leatherback sea turtle	S/F	E/E	HIGH	X	X	X										—	—	—
252	Green sea turtle	S/F	E/E	LOW				X	X	X	X	X	X	X	X	X	APR–OCT	MAY–NOV	MAR–OCT
	Leatherback sea turtle	S/F	E/E	LOW	X	X	X	X	X	X	X	X	X				FEB–AUG	MAR–SEP	JAN–AUG
	Loggerhead sea turtle	S/F	T/T	LOW			X	X	X	X	X	X	X	X	X		APR–OCT	MAY–NOV	MAR–OCT

SHELLFISH: RAR#	Species	S/F	T/E	Concen	J	F	M	A	M	J	J	A	S	O	N	D	Spawning	Larvae/Juv	Mating
232	Blue crab			HIGH	X	X	X	X	X	X	X	X	X	X	X	X	—	JAN–DEC	MAR–DEC
	Brown shrimp			MED	X	X	X	X	X	X	X	X	X	X	X	X	—	JAN–DEC	—
	Pink shrimp			LOW	X	X	X	X	X	X	X	X	X	X	X	X	—	JAN–DEC	—
	Stone crab			LOW	X	X	X	X	X	X	X	X	X	X	X	X	—	JAN–DEC	SEP–NOV
	White shrimp			MED	X	X	X	X	X	X	X	X	X	X	X	X	APR–OCT	JAN–DEC	—
248	Blue crab			LOW	X	X	X	X	X	X	X	X	X	X	X	X	JAN–DEC	JAN–DEC	—
	Brown shrimp			HIGH	X	X	X	X	X	X	X	X	X	X	X	X	JAN–DEC	—	—
	Pink shrimp			LOW	X	X	X	X	X	X	X	X	X	X	X	X	MAR–NOV	—	—
	Spiny lobster			LOW	X	X	X	X	X	X	X	X	X	X	X	X	—	—	—
	Stone crab			LOW	X	X	X	X	X	X	X	X	X	X	X	X	MAR–OCT	JAN–DEC	—
	White shrimp			HIGH	X	X	X	X	X	X	X	X	X	X	X	X	APR–OCT	—	—
258	American oyster (eastern)			MED	X	X	X	X	X	X	X	X	X	X	X	X	APR–NOV	—	—

T_MAMMAL: RAR#	Species	S/F	T/E	Concen	J	F	M	A	M	J	J	A	S	O	N	D	Spawning	Larvae/Juv	Mating
237	Anastasia Island beach mouse	S/F	E/E		X	X	X	X	X	X	X	X	X	X	X	X			

ure 2 shows the protection strategy in the contingency plan, which would be modified as needed for the spill-specific conditions of waves, winds, and tides. The strategy consists of primary and backup deflection booms and collection areas, with the primary objective of keeping the oil out of the marshes and tidal flats. Not all of the booms shown would be deployed simultaneously.

Analog and Digital ESI Atlases

An *analog ESI atlas* is composed of hardcopy maps, data tables, a foldout legend, introductory pages, and a title page showing the location of all maps in the atlas. Introductory pages contain a description of the ESI components, including shoreline habitat classification methods; biological and human-use types, locations, temporal characteristics, and response actions; acknowledgment of data providers and experts; a species list by element, sub-element, common name, and scientific name; ESI habitat photographs with accompanying descriptions; predicted oil behavior; and response considerations. A *digital ESI atlas* is composed of digital versions of the above-mentioned components, seasonality data tables, ARC/INFO® export files of all NOAA-structured GIS data, ARC/INFO® map compositions, and metadata.

New ESI Tools and Applications

The successful use of both analog and digital versions of the Environmental Sensitivity Index concept during the past ten years has led to improvements and refinements, including

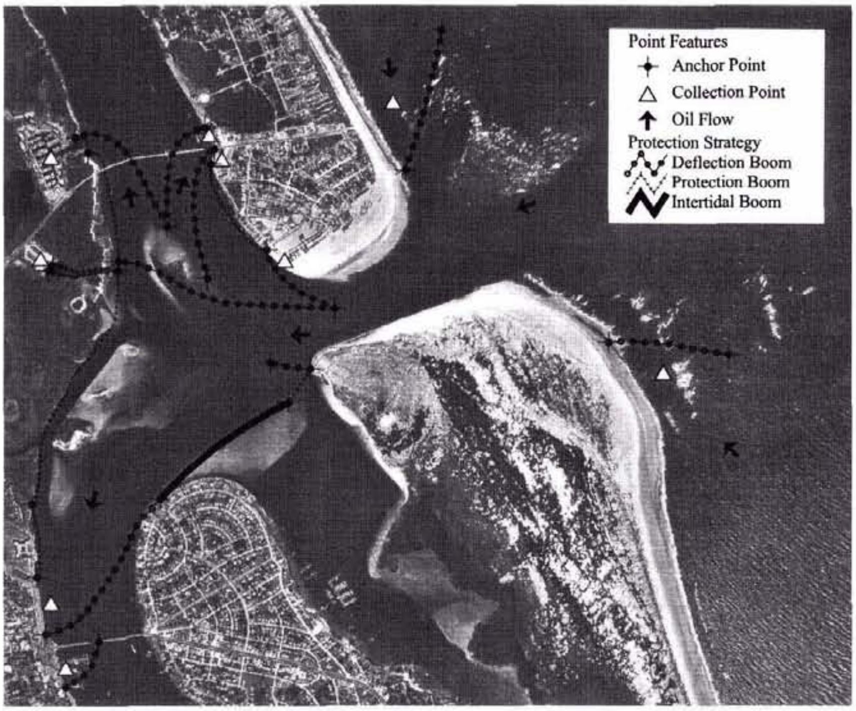

Figure 2. The tidal inlet protection strategy for St. Augustine, Florida, depicts anticipated oil flow directions, boom anchor points, collection points, and boom placement strategies. The information is overlaid on rectified black-and-white vertical orthophotography.

- tidal inlet protection strategy ESI maps produced before a spill that specify the type of response (e.g., boom, skimmer) and exactly where and how to place it,
- new cartographic products such as large format seasonal summary maps,
- geographic expansion of the ESI concept inland to classify the sensitivity of large rivers and reaches of smaller rivers,
- regional watershed analysis to identify hazards and potential spill consequences,
- the design and classification of Unusually Sensitive Areas in the United States, and
- development of federally compliant ESI metadata and the establishment of a clearinghouse node to disseminate ESI information.

Tidal Inlet Protection Strategies

The most productive and sensitive coastal resources such as salt marshes and fish nursery areas often are concentrated within tidally influenced estuaries located landward of tidal inlets. Therefore, a protection strategy that can prevent oil spilled in the open ocean from passing through the inlets during flood tides would effectively protect these resources. Most protection strategies consist of the deployment of floating booms which deflect the oil to collection areas. The specific deployment configuration is primarily a function of the current speeds; booms placed directly perpendicular to the flow will fail when currents exceed 0.36 m/sec. To develop successful inlet protection strategies, local and national experts analyze the physical processes in the inlet, probable oil movement, habitat and human-use protection priorities, potential boom positioning and deflection angles, and probable oil collection points.

Strategies are evaluated in the field and may include a test of boom placement, deflection, and containment. An example of the inlet protection strategy for St. Augustine Inlet, Florida is shown in Figure 2 (Hayes and Montello, 1994). Tidal inlet protection strategies are developed and tested *before* an oil spill. This is pro-active planning rather than reactive oil spill response. Uses of the digital data include the ability to rapidly modify the protection strategy to reflect spill-specific conditions, and ready calculation of the length of boom needed to protect the areas threatened by a slick, either manually or by overlay with the output from trajectory analyses. Joint preparation and sharing of the inlet protection strategies among government and industry increases the likelihood of successful deployment because everyone has agreed on the strategy and planned for its implementation.

ESI Seasonal Summary Maps

Spills often impact large areas; thus, planning and response efforts benefit when a more regional perspective on sensitive areas is provided. To meet this need, *seasonal* summary maps (because sensitive areas can change dramatically with the season) of contiguous regions have been prepared, at scales ranging from 1:250,000 to 1:500,000. The months which comprise winter, spring, summer, and fall seasons are different for each area. Unlike the ESI maps that have related tables for each map, the summary maps are purely cartographic and uniquely portray important habitat sensitivities, biological concentrations, and cultural resources. Summary maps have been produced for the Chesapeake Bay, Puget Sound, Prince William Sound, Cook Inlet/Kenai Peninsula, and the Kodiak Island/Shelikof Straits. The maps are printed in large numbers, increasing the user community and value. The Prince William Sound seasonal summary maps were printed just months before the Exxon Valdez spilled 10.9 million gallons of oil into the Sound in 1989. The oil spread throughout the western part of the Sound. Whereas there were only five copies of the ESI atlas, every organization had

Table 6. River Reach Sensitivity Index (RSI) Classification Scheme

RSI Code	Description
1	Quiet water pools with low, sensitive banks
2	Small, non-navigable channel with moderate currents and low, sensitive banks
3	Navigable channel with moderate currents and low, sensitive banks
4	Small, non-navigable channel with rapids over bedrock
5	Navigable channel with rapids over bedrock
6A	Small, non-navigable channel with associated low-vulnerability upper bottomland hardwoods
6B	Navigable channel with associated low-vulnerability upper bottomland hardwoods
7	Navigable. Low gradient and variable currents (usually < 1.5 knots). Wide and low floodplain. Stream hugs old valley wall with steep banks composed of muddy sediments or bedrock against the wall. Other side of channel has leakage of waters into an associated wide cypress-tupelo swamp
8	Navigable. Low gradient and variable currents (usually < 1.5 knots) with flow mostly confined to relatively straight channel with well-defined low banks. Wide and low floodplain. Associated wide cypress-tupelo swamp
9A	Small, non-navigable meandering channel with abundant leakage points into associated cypress-tupelo swamps and ox-bows
9B	Navigable meandering channel with abundant leakage points into associated cypress-tupelo swamps and ox-bow lakes
10A	Small, non-navigable anastomosing channel with abundant leakage poins into adjacent cypress-tupelo swamps
10B	Navigable anastomosing channel with abundant leakage points into associated cypress-tupelo swamps

copies of the summary maps in their command posts and frequently referred to the maps during planning meetings, press briefings, and orientations with the constantly changing response teams.

River Reach Sensitivity Index (RSI)

The river Reach Sensitivity Index (RSI) was developed as a component of the Inland Sensitivity Mapping Project for the USEPA Region 4 (Michel *et al.*, 1995; NOAA, 1996). USEPA is the Federal On-Scene Coordinator for inland spills, and it has similar responsibilities for mapping and prioritizing of sensitive areas. However, instead of having to prepare Area Plans for the 46 mostly coastal USCG zones, USEPA has to prepare Area Plans for 12 multi-state Regions which cover very large land areas. There has been no national initiative or standard for inland mapping for oil spill applications, and there was no ESI mapping scheme for classifying the shoreline sensitivity of smaller rivers and streams. A regional assessment of the rivers and streams of the southeastern United States was performed to evaluate existing riverine classification schemes, define the geomorphic and hydrologic characteristics of the watersheds, and identify existing national and state databases that may be useful (Hayes *et al.*, 1997). The RSI classification scheme (Table 6) was tested on the Leaf River watershed in Mississippi (Research Planning, 1996a). The primary criteria for defining the reach sensitivity were (1) the degree of difficulty anticipated for the containment and recovery of oil and (2) the sensitivity and vulnerability of the associated wetlands.

The RSI mapping is similar to the ESI in that river reaches, biological resources, and human-use resources are included and structured in a comparable and standardized manner. However, the classification of river reaches is different from the traditional ESI classification because the river is subdivided into segments, or *reaches*, where each designated reach has similar spill-response modes and potential ecological and human-use impacts. An example of a Reach Sensitivity Index map of Leaf River, Mississippi is shown in Plate 2. Bottomland hardwood ecosystems such as *cypress-tupelo swamp* (code 10B) are the most vulnerable and sensitive wetlands present along the river reaches of the southeastern United States as opposed to scrub-shrub wetland that are the most sensitive habitat found in the traditional ESI scheme (Table 2). The least sensitive reaches are quiet water pools (code 1). The biological and human-use resources shown on RSI maps are similar to the ESI, but with more issues associated with protection of drinking water sources, access for deployment of response equipment, and how changes in water level can change the resources at risk. Rapid notification of downstream water users is often the highest priority. The RSI is currently being used for sensitivity mapping in several areas, including Texas and Puerto Rico. In Puerto Rico, ESI and RSI mapping are being conducted concurrently so that there is an integrated map and database tool for responders.

Watershed Vulnerability Index (WVI) Modeling

The Reach Sensitivity Index demonstrated the inland expansion of ESI mapping to smaller rivers and streams and prompted another focus for spill response and planning: the analysis of watershed vulnerability at the regional scale. In 1997, USEPA Region 4 used a GIS and sensitivity concepts to identify and rank entire watersheds according to their oil spill risk and the sensitivity of natural and cultural resources (Hall, 1997). The purpose of the watershed risk analysis was to identify those watersheds of highest priority for sensitive area mapping and planning. The USEPA Regions are too large to map completely, within current resources, and a scheme was needed to set priorities.

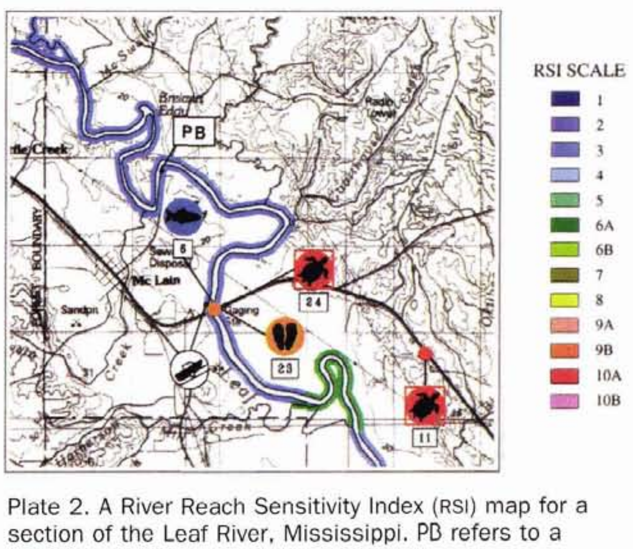

Plate 2. A River Reach Sensitivity Index (RSI) map for a section of the Leaf River, Mississippi. PB refers to a point bar which is an ideal oil collection location. The numbers beneath the icons represent resources-at-risk summarized in the database (refer to Table 5 for an example).

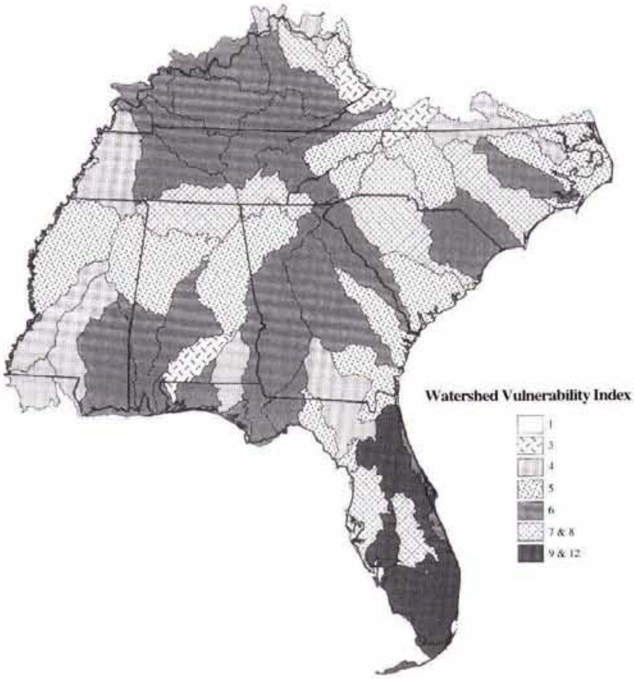

Figure 3. Watershed Vulnerability Index (WVI) for southeastern U.S. hydrologic units. The rankings range from 1 to 12 and are based on the co-occurrence of hazards and consequences.

The Watershed Vulnerability Index (WVI) stochastic modeling for USEPA Region 4 was based on two spill *hazard* indicators (length of pipelines and location of oil facilities) and four *consequence* indicators (surface drinking water intakes, area of wetlands, occurrence of species and communities of conservation concern, and locations of managed lands). These spill risk and consequence indicators were modeled in a GIS to visualize and rank the level of vulnerability (Figure 3). The vulnerability model is the result of integrating, standardizing, and normalizing existing data from various national programs and is based on 1:250,000-scale USGS Hydrologic Units (Table 7). Watershed vulnerability ranged from a low of 1 to a high of 12. The Watershed Vulnerability Index has focused the efforts of Area Committees and helped them prioritize sub-areas for more detailed mapping efforts.

Gulf-Wide Information System

The U.S. Minerals Management Service developed the Gulf-Wide Information System (GWIS) for use in coastal zone management, environmental assessments, and oil spill planning and emergency response. The GWIS data structure is based on ESI mapping concepts but includes other layers such as pipelines, demographic data, and a detailed transportation network. The distributions of the biological and human-use resources are extended to their natural boundaries, instead of the edge of the base map, as was done in previous ESI datasets. The GWIS design focuses on the highly variable nature of both the spatial and temporal dimensions and has been developed in close cooperation with universities, government agencies, and private companies. Results of this project are included in a Database Specifications Manual (LSU *et al.*, 1996).

GWIS is a cooperative effort between government and the regulated industry. The goal is to jointly generate a regional database that meets multiple objectives and regulatory requirements in an area where offshore oil and gas leasing will continue to accelerate and move into deep water. Previously, there was little agreement among government and industry on the accuracy and resolution of information used in conducting oil spill risk assessments and planning. Now, there will be a common, mutually agreed upon dataset for the entire Gulf of Mexico.

Unusually Sensitive Areas

The Research and Special Programs Administration of the Office of Pipeline Safety, U.S. Department of Transportation, must identify areas that are *unusually sensitive* to environmental damage if there is a hazardous liquid pipeline accident. Once identified, pipeline operators must determine if a release from their pipeline could impact these areas. If so, then they must undertake a range of actions to *prevent* such accidents, in addition to the traditional actions to protect such areas during emergency responses. Identification of Unusually Sensitive Areas (USAs) is being carried out for drinking water resources, ecological resources, and possibly cultural/Indian tribal concerns. A map showing drinking-water unusually sensitive areas in Iowa is shown in Figure 4. Through an open process with public and private sector participation, criteria for identifying drinking-water USAs have been determined. In preparation for the nation-wide assessment of USAs, a digital catalog of existing data has been compiled for all drinking-water resources. It is the goal of the Office of Pipeline Safety to map USAs for the entire United States, where possible with existing data sources. Although this database is being developed for a specific regulatory requirement for the pipeline industry, it will also be valuable for spill response organizations nationwide, and the Office of Pipeline Safety has closely coordinated its efforts with other federal agencies.

ESI Metadata and Clearinghouse Node

In 1996, the Federal Geographic Data Committee funded a project to convert existing ESI analog documents into digital metadata that comply with federal standards and to establish

TABLE 7. DATA SOURCES FOR PERFORMING WATERSHED VULNERABILITY INDEX (WVI) MAPPING

Data Layer	Source	Purpose
Facilities	EPA	Potential oil spill sources
Historic Spills	EPA	Susceptibility of an area to spills
Pipelines	FEMA	Miles of pipelines by county
Hydrology	River Reach Files (RF3) from USGS	Identify the density of hydrology by County and Hydrologic Unit
Counties	ESRI	Geocode the county statistics
Hydrologic Units	USGS	Watershed geography
Drinking Water Intakes	EPA	Water withdrawal sites for human consumption
Managed Lands	Geographic Names Information System (USGS National Mapping Division)	Names, types, and locations of managed lands
Wetlands	USGS	Land Use/Land Cover
Species/Communities	State Natural Heritage Programs	Frequency of species and communities by county

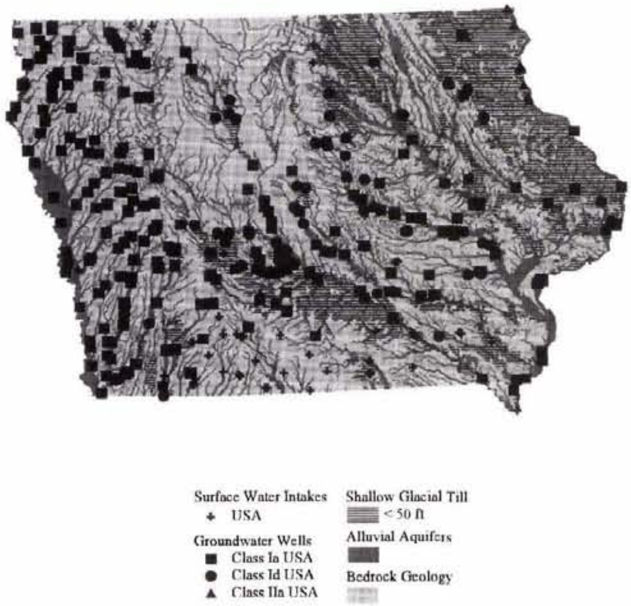

Figure 4. Drinking-water Unusually Sensitive Areas (USAs) in Iowa derived from surface water intakes, groundwater wells, glacial till thickness, aquifer sources, and surficial geology. The USAs are grouped into several categories based on groundwater vulnerability rules developed by the US EPA (Pettyjohn *et al.*, 1991). The classification scheme includes Ia: unconsolidated aquifers, Id: covered aquifers with < 50 feet of glacial till, and IIa: high yield bedrock aquifers.

a clearinghouse node for disseminating the metadata. The project involved networking various platforms, installing E-mail, and developing a WWW site. The server software was compiled and installed on a UNIX workstation, the metadata were converted from word processing documents to Metadata Parser compliant files, and the metadata database was tested as a clearinghouse node (**http://130.11.52.178/gateways.html**). Thus far, 141 ESI documents have been converted.

Future Directions

The Environmental Sensitivity Index is a mature, robust system used to plan for and mitigate the effects of oil spills. In addition, it has been expanded in concept and scope to (1) develop tidal inlet protection strategy databases, (2) include season summary information, (3) conduct risk assessments of entire watersheds and regions, (4) protect important river reaches using a river reach sensitivity index (RSI), and (5) model unusually sensitive areas (USAs). NOAA is in the process of publishing all of the ESI datasets in various formats which allow free exchange among different software and hardware systems. The NOAA web site provides information on the status and availability of the datasets (**http://response.restoration.noaa.gov**). Several refinements would enhance the ESI concept.

The nationwide ESI species list should be compared with the National Biological Service's National Biological Information Infrastructure, NOAA's NODC Interagency Taxonomic Information System, the Nature Conservancy's Natural Heritage Program Biological Conservation Database, the National Marine Fisheries Service and U.S. Fish and Wildlife Service threatened and endangered species list, and the TRITON zoological index to standardize and link species nomenclatures.

Resources-at-risk reports should be generated automatically during a spill event. Work on such a tool has been initiated by the Florida Marine Research Institute based on existing ESI databases and the use of a friendly graphical user interface. Future research will likely incorporate heuristic rules from NOAA manuals and be implemented using an expert system or neural network.

Applications should be developed for other natural resource management needs, such as permit reviews and environmental impact assessments. The ESI is a national, standard dataset and thus applications could be shared among state and federal resource managers.

References

Baker, J.M., M. Spaulding, and J. Moore, 1995. Sensitivity Mapping Worldwide Harmonization and the Needs of Different User Groups, *Proceedings, International Oil Spill Conference*, American Petroleum Institute Publication No. 4620, Washington, D.C., pp. 77–81.

Halls, J., 1997. *EPA Region 4 Watershed Vulnerability Assessment*, NOAA Hazardous Materials Response and Assessment Division, Seattle, Washington, 21 p.

Halls, J., J. Michel, S. Zengel, J. Dahlin, and J. Petersen, 1997. *Environmental Sensitivity Index Guidelines, Version 2.0*, NOAA Hazardous Materials Response and Assessment Division, Technical Memorandum NOS ORCA 115, Seattle, Washington, 79 p.

Hayes, M.O., and T. M. Montello, 1994. *Tidal Inlet Protection Strategies for Oil Spill Response: Volume 1, East Coast of Florida*, Marine Spill Response Corporation and Florida Marine Research Institute, Tampa, Florida, 23 p.

Hayes, M.O., J. Michel, and T.M. Montello, 1997. The Reach Sensitivity Index (RSI) for Mapping Rivers and Streams, *Proceedings, International Oil Spill Conference*, American Petroleum Institute Publication No. 4651, Washington, D.C., pp. 343–350.

Jensen, J.R., 1996. *Introductory Digital Image Processing: A Remote Sensing Perspective*, Prentice-Hall, Inc., Saddle River, New Jersey, 318 p.

Jensen, J.R., E.W. Ramsey, J.M. Holmes, J.E. Michel, B. Savitsky, and B.A. Davis, 1990. Environmental Sensitivity Index (ESI) Mapping for Oil Spills Using Remote Sensing and Geographic Information System Technology, *International Journal of Geographical Information Systems*, 4(2):181–201.

Jensen, J.R., S. Narumalani, O. Weatherbee, M. Murday, W.J. Sexton, and C.J. Green, 1993. Coastal Environmental Sensitivity Mapping for Oil Spills in the United Arab Emirates Using Remote Sensing and GIS Technology, *Geocarto International*, 2:5–13.

Jensen, J.R., K. He, J.D. Althausen, and M. Hayes, 1996. The Environmental Sensitivity of Oil Impacted Habitat, *Sistema Terra: Remote Sensing and the Earth*, 5(1):39–42.

Louisiana State University, U.S. Minerals Management Service, Research Planning, Inc., and Environmental Systems Research Institute, 1996. *Gulf-Wide Information System (G-WIS) Database Specifications*, Center for Coastal, Energy, and Environmental Resources, Baton Rouge, Louisiana, 72 p.

Michel, J., and J. Dahlin, 1993. *Guidelines for Development of Digital Environmental Sensitivity Index Atlases and Databases*, NOAA Hazardous Materials Response and Assessment Division, Washington, D.C., 43 p.

Michel, J., M. Hayes, and P. Brown, 1978. Application of an Oil Spill Vulnerability Index to the Shoreline of Lower Cook Inlet, Alaska, *Environmental Geology*, 2(2):107–117.

Michel, J., M. Hayes, J. Dahlin, and K. Barton, 1995. *Sensitivity Mapping of Inland Areas: Technical Support to the Inland Areas Planning Committee Working Group*, HAZMAT Report 95–4, NOAA Hazardous Materials Response and Assessment Div., Washington, D.C., 54 p.

Narumalani, S., J. Jensen, M. Hayes, J. Michel, T. Montello, and J. Robinson, 1993. Gulf War Legacy: Using Remote Sensing to Assess Habitat in the Saudi Arabian Gulf Before the Gulf War Oil Spill, *Geo Info Systems*, 3(6):32–41.

NOAA and American Petroleum Institute, 1994. *Options for Mini-*

mizing Environmental Impacts of Freshwater Spill Response, NOAA Hazardous Materials Response and Assessment Division, Seattle, Washington, 126 p.

NOAA, 1996. *A Strategy for Mapping Sensitive Resources of Rivers and Streams in EPA Region 4*, HAZMAT Report 96–11, NOAA Hazardous Materials Response and Assessment Division, Seattle, Washington, 36 p.

Pettyjohn, W., M. Savoca, and D. Self, 1991. *Regional Assessment of Aquifer Vulnerability and Sensitivity in the Conterminous United States*, Robert Kerr Environmental Research Lab, USEPA, 600/2-91/043, Oklahoma, 49 p.

Research Planning, Inc., 1996a. *Sensitivity of Riverine Environments and Wildlife to Spilled Oil: Leaf River, Mississippi*, NOAA Hazardous Materials Response and Assessment Division, Seattle, Washington, 42 p.

———, 1996b. *Sensitivity of Coastal Environments and Wildlife to Spilled Oil: East Florida*, Florida Marine Research Institute, Tallahassee, Florida, 140 p.

RPI International, Inc., 1989. *Sensitivity of Coastal Environments and Wildlife to Spilled Oil: Louisiana, An Atlas of Coastal Resources*, NOAA Hazardous Materials Response and Assessment, Seattle, Washington, 292 p.