POTENTIAL EFFECTS OF HYPOXIA ON SHRIMPERS & IMPLICATIONS FOR RED SNAPPER BYCATCH IN THE NORTHWESTERN GULF OF MEXICO

by

Jennifer M. Macal

Date: ____________

Approved:

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Dr. Michael K. Orbach, Advisor

____
Dr. William H. Schlesinger, Dean

Masters project submitted in partial fulfillment of the
requirements for the Master of Environmental Management degree in
the Nicholas School of the Environment and Earth Sciences of
Duke University

2002

Abstract

Red snapper (*Lutjanus campechanus*) is a valuable commercial and recreational fishery on the Gulf of Mexico continental shelf. In recent years red snapper stocks have drastically declined presumably due to a combination of directed overfishing on adults and high mortality of juveniles taken as bycatch in the shrimp trawl fishery. The presence of large-scale hypoxia (15-20,000 km^2) on the Louisiana shelf that results from nutrient inputs from the Mississippi River system may modify vital rates (growth and mortality) of red snapper via direct effects of low dissolved oxygen or indirect effects mediated by shifts in spatial distribution. This study addresses the hypothesis that hypoxia modifies the distribution of red snapper and their association with shrimpers on the Louisiana continental shelf. Depending on the direction (inshore vs. offshore) and magnitude of shifts in spatial distribution, overlap between snapper and shrimpers and thus, the potential for bycatch interactions, may increase, decrease, or remain the same.

The primary objectives of this study were to examine: (1) annual variation in the spatial distribution of shrimping effort on the Louisiana shelf during the period of most severe hypoxia (July), (2) the spatial distribution of red snapper during the same time period, and (3) annual variation in overlap of shrimping effort and red snapper. I used spatial and statistical ArcView/Info Geographic Information System (GIS) mapping and analysis techniques to address the above three objectives. The first dataset that I used for these objectives comes from long-term SEAMAP (Southeast Area Monitoring and Assessment Program) groundfish surveys in the northwestern Gulf of Mexico. Secondly, I used spatial distribution of shrimping effort on a monthly time scale throughout the Gulf to address objective (1) and (3).

Shrimping effort on the Louisiana shelf shifted offshore during periods of extensive hypoxia, and this shift offshore was greater for the western than eastern Louisiana shelf. Red snapper were distributed primarily offshore during periods of extensive hypoxia and appeared more abundant on the western than eastern Louisiana shelf. The greatest overlap of shrimping effort and juvenile red snapper occurred primarily on the western Louisiana shelf between depths of 15-25 fathoms. I interpret these results in terms of their utility to fishery managers formulating fishery management plans (FMPs) for the Gulf of Mexico red snapper and shrimp fisheries.

Problem Identification and General Background

Coastal ecosystems dominated by major river systems are recognized as important regions of fishery production. Large rivers act as conduits for substantial amounts of land-based nutrients to enter marine food webs. This increase in nutrients, most often nitrogen, supports additional primary production that, in turn, leads to increased secondary production and eventually to increased fishery yields. Several aquatic ecosystems show a positive correlation between nutrient conditions and fishery yields, supporting this "bottom up" effect (Caddy 1993). Recently, however, evidence has mounted indicating that anthropogenic activities in coastal watersheds are causing nutrient over-enrichment of aquatic ecosystems (Bricker *et al* 1999).

Nutrient over-enrichment has a wide range of detrimental effects including increased prevalence and severity of toxic algal blooms, disease, and bottom water hypoxia and anoxia (Rabalais *et al* 1996). Evidence suggests that hypoxia (dissolved oxygen <2.0 mg/l) is becoming more frequent and widespread in shallow coastal and estuarine systems (Bricker *et al* 1999). However, the effects of nutrient over-enrichment and associated bottom water hypoxia on fish and fisheries are not well understood. Some evidence suggests that fishery yields have declined or been eliminated in association with the secondary effects of nutrient over-enrichment, though causal links to hypoxia are uncertain.

While much attention has been devoted to understanding the relationship between nutrient-loading and water quality characteristics such as hypoxia (Rabalais *et al* 1996), little is known about how variation in water quality affects fish and mobile invertebrates in upper trophic levels. Hypoxia may have direct effects on populations of mobile species, as shown by fish kills (Paerl *et al* 1998), yet the sublethal and often chronic effects of low dissolved oxygen—such as habitat loss, declines in food availability and growth, physiological stress, and increased exposure to predators—are more likely to have population-level consequences (Craig *et al* 2001).

What is Hypoxia?

Hypoxia refers to a depressed concentration of dissolved oxygen in water. Within the marine environment, hypoxia occurs whenever dissolved oxygen levels fall below 2-3 mg/liter. The normal concentration of dissolved oxygen in nearshore marine waters ranges between 5 and 8 mg/l, and many fish species begin having respiratory problems at concentrations below 5 mg/l. I operationally define hypoxia as dissolved oxygen $\leq$ 2.0 mg/l. In environments of extremely low dissolved oxygen, less tolerant marine species cannot survive and either leave the area or die. For sedentary species, mortality is especially likely. In addition, lack of oxygen can affect spawning areas and other essential habitat. If these conditions persist, a "dead zone" may develop in which little to no marine life exists (Dandelski and Buck 1998).

Hypoxic zones frequently occur along coastlines where rivers enter the ocean. Nutrient-rich fresh water is less dense than saltwater and typically flows across the top of the seawater. The fresh surface water effectively "caps" the more dense, saline bottom waters, retarding mixing with the atmosphere and creating a two-layer system, promoting development of hypoxia in the lower, more saline waters (Dandelski and Buck 1998).

Decreased concentrations of dissolved oxygen result in part from natural eutrophication when nutrients (i.e., nitrogen and phosphorus) and sunlight stimulate algal growth, increasing the amount of organic matter in the aquatic ecosystem. In stratified systems, planktonic organisms die and sink below the pycnocline (middle zone of the ocean in which density increases rapidly with depth (Garrison 1996)), where they are consumed (decomposed) by oxygen-dependent bacteria, thus depleting the isolated bottom-water of oxygen. When algal production is high and stratification persistent, bottom waters may become hypoxic, or even anoxic (no dissolved oxygen), while surface waters remain normoxic. Rising bottom-water temperatures stimulate bacterial decomposition, which leads to the seasonal development of bottom-water hypoxia (Dandelski and Buck 1998).

The process of eutrophication occurs naturally when offshore winds or surface currents cause cold, nutrient-rich, deep marine waters to rise near coasts, resulting in algal blooms and natural hypoxic events. However, eutrophication can increase in intensity or frequency by anthropogenic nutrient-loading from non-point sources (i.e., runoff from lawns and agricultural activities including fertilizer use and livestock feedlots), from point source discharges such as sewage plants, and from emissions given off by vehicles, power plants, and other industrial sources (Dandelski and Buck 1998).

Hypoxia in the Northwestern Gulf of Mexico

Physical and biological processes in the northwestern Gulf of Mexico are strongly influenced by the Mississippi River system. The eighth largest river in the world, the Mississippi drains about 40% of the continental United States and is the major conduit for sediment, nutrients, and freshwater entering the continental shelf in the Gulf of Mexico (Rabalais *et al* 1996). Spring (March-May) freshwater outflow from the Mississippi results in salinity stratification and high nutrient concentrations in the upper water column of the adjacent continental shelf. Weak winds and solar warming maintain stratification throughout most of the summer months (June – August) (Craig 2001). Because this salinity stratification isolates bottom waters from wind mixing, biological processes deplete available oxygen supplies resulting in large areas of hypoxic or anoxic (<1.0 mg/l oxygen) bottom water. Hypoxia is a seasonally dominant feature on the Louisiana continental shelf where the Mississippi enters the Gulf, although sometimes extending to Texas waters. Wind reversals during late summer maintain hypoxic waters on the continental shelf until strong winds and storms break down stratification in the fall (Craig 2001). This feature is most intense from June to August, but has been detected as early as February and as late as October.

Since monitoring began in 1985 the extent of the hypoxic zone has varied from about 40 km^2 to as high as 20,000 km^2 (Rabalais *et al* 1998). Nutrient inputs from the Mississippi-Atchafalaya River system that drive the formation of the Gulf hypoxic zone have increased since the 1950's, and are correlated with increases in fertilizer use in the midwestern United States (CENR 2000).

The continental shelf of the northwestern Gulf of Mexico is historically an area of high fishery productivity, with annual landings greater than one billion pounds, which is about 15-

20% of U.S. domestic landings and total dollar value (Condrey and Fuller 1992). These highly productive fisheries are a direct result of nutrients from the Mississippi River watershed, making Louisiana second only to Alaska in landings and ex-vessel value. These regions of high fisheries productivity, however, are in the same area as those that are currently hypoxic during much of the summer, rendering some of the most productive shelf habitat in U.S. coastal waters unavailable to animals including shrimp, fish, sea turtles and marine mammals (Craig 2001).

While hypoxia on the scale observed in the Gulf can clearly decrease the productivity of lower trophic levels on the shelf, few studies have addressed effects on upper trophic levels. Published studies, however, indicate that, (1) the abundance of mobile fish and invertebrates decreases in areas of the Gulf where dissolved oxygen levels are low (< 2.0 mg/l), (2) decreases in abundance are most likely due to horizontal displacement, although direct mortality, horizontal movement, and vertical movement are often confounded, and (3) in locations where hypoxia is an aperiodic (not chronic) event, mobile species are able to re-occupy previously hypoxic areas quite rapidly (days-weeks) (Craig *et al* 2001).

Additional effects of hypoxia on Gulf fisheries are also likely. Some evidence suggests that the "dead zone" may force fish and shrimp further offshore as well as into shallow nearshore areas that are less desirable habitat. Furthermore, hypoxia increases stress on aquatic ecosystems and may decrease biological diversity in areas with repeated and severe hypoxia. Crowding of marine life into restricted habitat also may lead to indirect consequences through altered competition and predation interactions. Hypoxia may delay or impede the offshore migration of older, larger shrimp, thus preventing shrimp trawlers from targeting larger shrimp for harvest.

The occurrence of any hypoxic zone may also force fishers to change their normal fishing patterns, possibly expending more time and fuel. In addition, crowding of different fishing groups (e.g., shrimp trawlers and red snapper fishermen) could result in conflicts among fishermen. Other potential effects on fisheries include: “concentration of fishing effort in other areas, resulting in localized fishing; damage to essential habitat, and possible decreased future production; localized mortality of finfish in shoreline areas; and decreased growth due to reduced food resources in the sediments and water column” (Dandelski and Buck 1998).

Hypoxia and Red Snapper in the Gulf of Mexico

Within the Gulf of Mexico, red snapper is a valuable commercial and recreational fishery. Yet, in recent decades, red snapper stocks have drastically declined and can no longer be commercially fished at sustainable levels. Two factors have been identified as potentially deterring the recovery of red snapper: (1) directed overfishing and (2) the high mortality of juvenile snapper in shrimp trawl bycatch. In addition, it is hypothesized that the presence of hypoxic areas on the continental shelf exacerbates the problem.

For mobile, demersal species such as shrimp and snapper what are the implications of large-scale habitat loss and subsequent shifts in distribution due to hypoxia? One potential effect is increased snapper mortality and subsequently decreased snapper recruitment. As the extent of the hypoxic zone increases, juvenile red snapper and shrimp shift to a smaller area (outside of the hypoxic zone), causing a potentially greater overlap of shrimp and juvenile snapper. Shrimp trawlers are then trawling in areas that contain large numbers of shrimp, their real target, and juvenile red snapper taken as bycatch.

Red Snapper Life History

Red snapper are a shelf-resident species distributed from Massachusetts to Brazil, with large concentrations of the Gulf red snapper (*Lutjanus campechanus*) off the Yucatan Peninsula and the Texas and Louisiana coasts (Klima 1976). Red snapper usually show partial sexual maturity when 1 year old (attaining a length of 110-130 mm) and show full maturity at about 2 years old (length 200-230 mm); thus some red snappers do not spawn their first year (Moseley 1966; Holt and Arnold 1982; Moran 1988). Red snapper spawn mainly from June to mid-September in the northern Gulf of Mexico (Moseley 1966; Gallaway *et al* 1999) with one peak spawning period in Florida waters (summer) and two peaks (summer and fall) in Texas waters. Individual fish often spawn several times during the spawning season (Moran 1988). Red snapper spawn primarily away from reefs over firm sand bottoms with little relief. Their early life history comprises a planktonic egg stage, a larval stage, and a benthic juvenile stage that occurs after the larvae undergo metamorphosis and settle near the bottom (Gallaway *et al* 1999). Juvenile snapper inhabit open bottom along with penaeid shrimp, primarily brown shrimp, only moving to the secure reef habitat when they reach 150 to 200 mm at approximately 1 year of age.

Red snapper are first taken as bycatch in the shrimp trawl fishery when they are about 50 mm total length (TL). However, they do not appear fully vulnerable to shrimp trawls used in the fishery until fall when they are 100 mm TL or longer (Gallaway *et al* 1999). Benthic juveniles (approximately 90 mm TL in January of their first year) are broadly distributed over soft bottoms and other trawlable bottoms of low relief. They occupy these habitats from the time of settlement in the summer of their first year through the following summer and fall, when they have reached 180-200 mm TL. At these sizes, they begin to move offshore to deeper water and recruit to high profile reefs; they are fully recruited to high-relief habitats by their second winter at ages of about 18 months (Bradley and Bryan 1976; Gallaway *et al* 1999).

Mark-recapture and sonic tracking experiments suggest that postlarval stages (i.e., juveniles, subadults, and adults) of red snapper are relatively sedentary, nonmigratory, and usually associated with specific substrates or structures (Gold *et al* 1997). Juvenile red snapper exhibit highest abundance in microhabitats of low relief (sandy or muddy bottoms) that range from silted-over patches of rubble to individual items of trash or debris. An important feature is that large predators (like adult red snapper) are not densely aggregated in the same areas with juveniles. Most of the habitats where juveniles occur can be sampled by trawling (Gallaway *et al* 1999). In contrast, reef habitats occupied by subadult and adult red snapper are not trawlable given their vertical relief. These habitats range from boulder-sized blocks of carbonate to coral reefs and man-made structures such as petroleum platforms and sunken ships (Gallaway *et al* 1999).

Based on field experiments, red snapper have temperature preferences between 14°C and 30°C, a lower lethal temperature limit of about 13°C, an upper lethal limit of 33.5°C, and an optimal activity temperature of 18°C (Moran 1988; Gallaway *et al* 1999). The highest adult red snapper abundances occur in water temperatures of 24.4°C, lowest abundances at 16.7°C, and intermediate abundances at temperatures averaging 20.6°C. Researchers have also observed maximum abundance of juvenile red snapper off the Alabama coast in July at a temperature of 23.4°C. Thus, the optimum temperature for juvenile red snapper appears to lie between 24°C and 26°C (Moran 1988; Gallaway *et al* 1999). In addition, the distribution of juvenile red snapper reflects a marine affinity, and high abundances appear to be commonly associated with salinities of 34-35‰ (Moran 1988; Gallaway *et al* 1999).

Red snapper are abundant at depths of about 40-110 m and have been caught at 7-146 m depth (Moran 1988). The relationship between fish size and depth occurrence indicates that juveniles and younger fish occupy shallow waters whereas larger adults occupy deeper waters (Rivas 1970). Observations by Gallaway *et al* (1999) suggest that juvenile red snapper habitat lies between 18 and 64 m depth and that peak abundance occurs at 37 m depth.

Gallaway *et al* (1999) further observed that the abundance of juvenile red snapper during summer was typically low in areas having mean dissolved oxygen concentrations between 0 and 4 mg/l, especially areas where hypoxic conditions (< 2.0 mg/l) were evident. This suggests that juvenile red snapper prefer dissolved oxygen levels of 5 mg/l and greater, and that they may be adversely affected by levels below 5 mg/l.

Juvenile and adult red snapper are carnivorous, feeding over sand, shell, or mud bottoms next to reefs or other rocky bottoms. Juveniles consume shrimp throughout the year, although crabs and other crustaceans are important as well (Bradley and Bryan 1976; Moran 1988). Adults primarily consume other fish, although during the fall and winter a higher proportion of the diet is composed of crabs and other crustaceans (Bradley and Bryan 1976; Moran 1988). Both juveniles and adults, however, are polyphagous, eating the most available food (Moseley 1966; Bradley and Bryan 1976).

Red Snapper Management

Red snapper appears to be the most overfished species in the Gulf of Mexico (Shipp 1999). This fishery is now under restrictive regulations because of declining stocks and historically high fishing effort. Recent reports show that the red snapper spawning potential ratio (SPR) is drastically low (<2%); overfishing is defined as an SPR of less than 20%. One of the main factors deterring recovery of the snapper stocks is the high mortality of zero and 1-year age-classes in shrimp trawl bycatch. Although red snapper are only a small fraction of the shrimp trawl bycatch, this bycatch represents a large percentage of the red snapper landings allowed under the Gulf of Mexico Fishery Management Council's management criteria (Condrey and Fuller 1992).

In 1976, the Magnuson Stevens Fishery Conservation and Management Act (Magnuson Act) created eight regional fishery management councils with the authority to formulate and implement management plans for fishery stocks under their jurisdiction. Although the councils make these plans, the federal government has final authority regarding their approval (Christie and Hildreth 1999; Cicin-Sain and Knecht 1998). Fishery management plans (FMPs) are developed based on ten national standards set out in the Magnuson Act. These national standards require FMPs to establish conservation and management measures based on the best scientific information to prevent overfishing and assure optimum yield.

The Gulf of Mexico Fishery Management Council (Gulf Council) prepares fishery management plans (FMPs) for species in federal waters of the Gulf of Mexico (excluding highly migratory species that are managed directly by NMFS). The Gulf Council consists of 17 voting members as follows: NMFS Southeast Regional Director, the directors of the five Gulf state marine resource management agencies, and 11 members who are nominated by state governors and appointed by the Secretary of Commerce for 3-year terms. In addition, four nonvoting members represent the U.S. Coast Guard, U.S. Fish and Wildlife Service, U.S. Department of State, and the Gulf States Marine Fisheries Commission. In the course of developing FMPs, the Gulf Council relies on advice from experts from other state and federal agencies, universities, and the public who serve on advisory panels and committees established for each fishery (Kemmerer, Cranmore and Mager 1999; Gulf Council 2001). Once the Council proposes rule changes to specific FMPs, they are submitted to NMFS for further review and approval before implementation. These fishery management plans are then enforced through regulations of the Department of Commerce.

The Gulf of Mexico red snapper fishery is the fourth most valuable fishery in the region and represents more than 95% of total U.S. red snapper landings (Brown *et al* 1999; Gillig *et al* 2001). Despite its significance, the red snapper fishery is facing a serious problem of declining stocks, which are estimated to have fallen 90% since the 1970s (Gillig *et al* 2001). This decline can be attributed to both severe overharvesting of adult red snapper by the commercial and recreational fisheries and discard of juvenile red snapper bycatch in shrimp trawls.

In an effort to rebuild red snapper stocks, the National Marine Fisheries Service (NMFS) and the Gulf of Mexico Fishery Management Council (Gulf Council) have imposed a series of regulatory efforts aimed at restricting both the direct harvesting of adult red snapper and the indirect harvesting of juveniles (Gillig *et al* 2001). Regulations on the red snapper fishery were first implemented in November 1984 under the Reef Fish Fishery Management Plan (FMP) which established a minimum size limit for red snapper of 13 inches total length (TL) (GMFMC 2000; Gillig *et al* 2001). Management of the red snapper resource has required the division of fishing mortality between two competing fisheries: the directed fishery, further composed of commercial and recreational sectors, and the non-directed shrimp fishery. The first amendment to the FMP, implemented in 1990, set a total allowable catch (TAC) for red snapper caught commercially (3.1 million pound commercial quota) and placed a bag limit (7 fish per fisher) on red snapper caught recreationally. (The TAC is the level of fishing intended to obtain optimum yield (OY) and to prevent overfishing, or to follow a recovery plan when a stock is overfished (GMFMC 2000).) The TAC was later applied to the recreational sector as well (Gillig *et al* 2001). Of the TAC, 51% is allocated to the commercial sector and 49% to the recreational sector. The catch of both the commercial and recreational sector is monitored within the year and each of the fisheries is closed upon reaching their respective allocation of the TAC (Schirripa 1999). In addition, a minimum size limit was imposed on both the commercial and recreational sectors. In 1998, a bycatch reduction device (BRD) was required on shrimp trawls operating in statistical zones 8-21 of federal waters in the Gulf of Mexico (extending from the Florida panhandle to the Texas-Mexico border) (see Appendix I Figure 2 for map depicting statistical zones).

Although the TAC policy successfully limited annual commercial red snapper harvests, it motivated commercial fishermen to race for the fish, thus creating a "derby" fishery. The derby caused large quantities of red snapper to be placed on the market in a short period of time, which thus led to a decline in the price of the fish (Gillig *et al* 2001). In an effort to spread commercial red snapper landings over a longer period of time and keep prices from falling, four other policies were developed: (1) splitting the commercial red snapper TAC into two seasons, (2) closing the last portion of each month to commercial red snapper fishing, (3) restricting commercial vessels to a limit of 2,000 lb per trip, and (4) capping the total number of licenses (Gillig *et al* 2001).

Currently, the Reef Fish FMP requires that overfished stocks be restored to a level of 20 percent spawning potential ratio (SPR) (i.e., maintain egg output from the stock at 20% of the level from an unexploited stock) within one and a half generation times (average time it would take a year class in an unfished population to replace itself). Consequently, the objective of the red snapper recovery program is to restore the stock to 20 percent SPR by 2019 (GMFMC 2000).

Recent changes in the language of the Magnuson-Stevens Fishery Conservation and Management Act (Sustainable Fisheries Act of 1996), however, require that the overfished threshold be based on the spawning stock size that would support maximum sustainable yield (MSY). New target and recovery time frame parameters to comply with the changes are still in the process of being revised and have not yet been implemented. Research by Schirripa (1999) suggests that it is highly unlikely that the red snapper fishery resource can be simultaneously fished at MSY and maintain a 20% SPR unless bycatch mortality of red snapper in the shrimp fishery can be reduced by approximately 90% or more.

Management of issues concerning water quality (including the problems of hypoxia) and the overfishing of red snapper are currently treated separately. While the Gulf of Mexico Fishery Management Council has the primary responsibility for managing regional fisheries, the management efforts of several agencies have focused efforts on hypoxia in the Gulf. The majority of water quality issues are managed under the auspices of the 1972 Clean Water Act, which is overseen by the Environmental Protection Agency (EPA). The EPA, in turn, delegates authority to individual state and local water quality agencies. This has important implications, as over 40% of the continental United States has waters flowing into the Gulf of Mexico. Each of these agencies has an extremely difficult task in regulating water quality; this is because specific levels of decreased anthropogenic change do not guarantee positive changes in water quality such as decreased hypoxic area. Thus, an adaptive, precautionary management approach is needed to address the interaction of water quality and fishing on red snapper populations. This management approach would be structured to take into account the effects of hypoxia on Gulf fisheries when formulating fishery management plans (FMPs) as required by the Magnuson-Stevens Fishery Conservation and Management Act.

Objective

Habitat loss due to large-scale hypoxia in the northwestern Gulf of Mexico may result in associated costs to demersal species such as shrimp and fish. Many of those potential costs, such as changes in feeding, growth, and fishery interactions are likely mediated by shifts in spatial distribution. Hence, my approach focused on the analysis of existing long-term, large-scale survey data. Efforts focused on shrimping effort and red snapper given their predominance in the demersal community and importance as nontarget species of the commercial shrimp fishery. The overall objective of this study was **to assess annual changes in the spatial distribution and overlap of shrimping effort and red snapper associated with variation in the spatial extent and location of hypoxia in the northwestern Gulf of Mexico**. I hypothesized that hypoxia modifies the distribution of red snapper and their association with shrimpers on the Louisiana continental shelf. Depending on the direction (inshore vs. offshore) and magnitude of shifts in spatial distribution, overlap between red snapper and shrimpers, and thus, the potential for bycatch interactions, may increase, decrease, or remain the same. Below I describe particular hypotheses, data sources, and analyses relevant to this objective. In addition, preliminary information regarding red snapper commercial fishermen's perspective on water quality within the Gulf was attained to identify potential effects of hypoxia on fishing behavior.

Methods

Shrimping Effort in Relation to Hypoxia

The first objective of this study was to examine the distribution of shrimp fishing effort in the Gulf of Mexico. I hypothesized that the amount and/or distribution of shrimping effort would change in response to hypoxia on the Louisiana shelf.

Data sources that I used for this approach included the spatial distribution of shrimping effort and landings on a monthly time scale (Zimmerman and Nance 2001). The National Marine Fisheries Service (NMFS) Galveston Lab collected the spatial distribution of shrimping effort as part of the shrimp statistics database. Data collected consists of monthly estimates of days shrimped, by statistical areas and by depth bins, throughout the Gulf of Mexico. The procedure used to calculate effort is largely based on port agent interviews with commercial fishermen and census of landings.

I first characterized the seasonal patterns in the distribution of shrimping effort and then tested three specific hypotheses regarding effects of hypoxia. To delineate seasonal patterns I calculated the proportion of total offshore shrimping effort (0-50 fathoms) versus month, from 1990-99 on the Louisiana shelf (stat zones 13-17). Proportion of total offshore shrimping effort was subdivided into five 10-fathom depth increments (i.e., 0-10, 10-20, ... 40-50).

Hypothesis #1

I hypothesized that total shrimping effort on the Louisiana shelf decreases as the spatial extent of hypoxia increases. This result could occur if hypoxia results in extensive habitat degradation, thus resulting in decreased recruitment and growth for shrimp and, hence, less shrimping effort. To test this hypothesis, total shrimping effort (days fished) during July was compared between Texas (statistical zones 18-21) and Louisiana (statistical zones 13-17) for the years 1990-99. The Texas shelf does not experience hypoxia, and thus serves as a partial control for effects of hypoxia off Louisiana. I predicted that if hypoxia results in decreased shrimp production and declines in shrimping effort then during years of extensive hypoxia total shrimping effort would decline off Louisiana but not off Texas.

Hypothesis #2

I also developed an alternative hypothesis that total shrimping effort off Louisiana (stat zones 13-17) may remain the same during years of extensive hypoxia, but shifts in the distribution of effort would occur in response to hypoxia. To test this hypothesis, the proportion of total shrimping effort (0-50 fathoms) versus month was examined for Louisiana (stat zones 13-17) for the years 1990-99. Proportion of total offshore shrimping effort was subdivided into five 10-fathom depth increments (i.e., 0-10, 10-20, ... 40-50). In addition, the proportion of total "inshore" shrimping effort (0-5 fathoms) off Louisiana (stat zones 13-17) versus the area of the hypoxic zone was examined. This was done for the month of July during the years 1990-99. The proportion of total "offshore" shrimping effort (10-50 fathoms) off Louisiana (stat zones 13-17) versus the area of the hypoxic zone was also examined. Once again, this was done for the month of July during the years 1990-99. Effort would likely shift either inshore or offshore depending on the extent of the hypoxic zone; the greater the extent, the more likely that habitat loss will occur, thus forcing shrimp (and subsequently shrimpers) further inshore or offshore of the hypoxic zone.

Hypothesis #3

Finally, I hypothesized that shifts in distribution of shrimping effort vary for the different regions of the Louisiana shelf (eastern vs. western Louisiana). The eastern Louisiana shelf experiences chronic hypoxia, while the western Louisiana shelf only experiences aperiodic hypoxic events (largely when the extent of the hypoxic zone is great). Statistical zones 13-15 represent eastern Louisiana while statistical zones 16-17 represent western Louisiana. To test this hypothesis, I examined the proportion of total shrimping effort by depth (0-50 fathoms) versus month for 1990-99 separately for the eastern and western Louisiana shelf. Proportion of total offshore shrimping effort was subdivided into four depth-range increments (0-5, 5-10, 10-20, and 20-50 fathoms).

I also examined the relationship between the distribution of shrimping effort and the area of the hypoxic zone. July "offshore" shrimping effort (10-50 fathoms) versus hypoxic area (square kilometers) was examined for eastern (stat zones 13-15) and western (stat zones 16-17) Louisiana. In addition, July "inshore" shrimping effort (0-5 fathoms) versus hypoxic area (square kilometers) was examined for eastern (stat zones 13-15) and western (stat zones 16-17) Louisiana. I would expect that shrimping effort would increase offshore and decrease inshore as the area of the hypoxic zone increases. This result would be consistent with increased inshore habitat loss, and thus the need for shrimp and shrimpers to move outside of the hypoxic area. Because most hypoxic events occur inshore (Craig 2001), shrimp, and hence shrimping effort, would move offshore during years of extensive hypoxia.

Red Snapper Distribution in Relation to Hypoxia

The second objective of this study was to examine the distribution of red snapper in relation to bottom-water hypoxia to determine if there is a correlation between low oxygen and snapper distribution.

Data that I used for this objective comes from long-term SEAMAP (Southeast Area Monitoring and Assessment Program) groundfish surveys in the northwestern Gulf of Mexico.

The survey is a stratified random design (based on depth and geographic location) that samples approximately 250-300 stations on the northwestern Gulf continental shelf (Alabama-Texas/Mexico border, 4-110 m depth) (Eldridge 1988). The shelf-wide survey takes place semi-annually in both June-July (since 1982) and October-November (since 1987) and is ongoing. Cooperating state agencies participate in the shelf-wide survey as well as conduct year-round, seasonal sampling on a more limited spatial scale. Standard information collected during these surveys includes counts, weight, species composition, and size distribution from bottom trawls and environmental information (dissolved oxygen, temperature, salinity, chlorophyll) from CTD (conductivity, temperature, depth) casts. The datasets that I used for this study encompass all summer (July-August) fishery-independent data collection activities in the northwestern Gulf, including those pursued by state and federal agencies for 1990-2000.

To delineate red snapper distribution within the Gulf of Mexico, I conducted spatial analyses using ESRI Geographic Information Systems (GIS) ArcView/Info software. Red snapper survey catches (obtained from SEAMAP data) from 1990-2000, in the northwestern Gulf of Mexico were plotted spatially using GIS. A GIS coverage identifying statistical zones (labeled 13-21) and further subdivided into 5 fathom bin intervals was used for all spatial analyses. The area referred to as "Louisiana" is composed of statistical zones 13-17, while the area referred to as "Texas" is composed of statistical zones 18-21.

Survey catch rates of red snapper were log-transformed and graphed spatially using GIS. Red snapper point patterns were interpolated to a surface area using universal kriging (12 neighbors, 75 km search radius). After log transformation, stations were ranked in order of increasing red snapper catch per unit effort (CPUE). Those stations containing the highest 25%, 50%, 75%, and 95% of snapper catches were taken from the cumulative distribution and mapped in GIS, where percentiles are inclusive (e.g., stations within the 25th percentile are included in those within the 50th percentile, etc.). I examined red snapper distribution on the Louisiana shelf for the years 1990-2000.

There are a number of reasons why I chose to examine snapper distribution only on the Louisiana shelf and not on the Texas shelf. The Shrimp Fishery Management Plan (FMP) regulates fishing for brown shrimp in the Exclusive Economic Zone (EEZ) off the coast of Texas. Provisions in the Shrimp FMP prohibit brown shrimp fishing off the coastline to 200 miles off Texas during Mid-May to early-July. These closures are meant to prevent fishing of small, juvenile shrimp and allow them time to grow and migrate offshore. Thus, during the Texas closures little to no shrimping effort takes place. In addition, the SEAMAP survey often trawls in Texas waters during the Texas closure, making comparisons between fished (Louisiana) and un-fished (Texas) waters difficult. Furthermore, the extent of the hypoxic zone occurs largely within Louisiana shelf waters and, thus, any relation between snapper distribution and hypoxia would likely be seen only within Louisiana shelf waters.

I also examined the distribution of red snapper with respect to depth. This analysis was performed to determine the differences in red snapper distribution between the eastern (stat zones 13-15) and western (stat zones 16-17) Louisiana shelf. I expected that red snapper distribution would be greatest within the western Louisiana shelf as hypoxia is only an aperiodic event in this region as compared to the eastern shelf, which experiences chronic hypoxia. In addition, I expected that red snapper distribution would be further offshore during years of extensive hypoxia due to severe habitat loss inshore. The log-transformed number of red snapper per tow (as described earlier) versus depth was examined for eastern and western

Louisiana from 1990-2000. The depth was further subdivided into eight depth bins (0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-35, and 35-50 fathoms).

Relationship Between Red Snapper Distribution and Shrimping Effort

The third objective to this study was to quantify the overlap between red snapper and shrimping effort to determine if the shifts in shrimping effort previously described result in increased overlap between shrimpers and red snapper during years of extensive hypoxia. Snapper are generally an offshore species and so if effort shifts offshore during years of extensive hypoxia I would expect that: (1) high densities of red snapper occur in areas where there is a high density of shrimp fishing effort, (2) the number of high areas of overlap (off Louisiana) has increased in years of extensive hypoxia, and (3) the location of high areas of overlap has shifted offshore (in years of extensive hypoxia).

Using GIS, I mapped the log-transformed number of red snapper and the log transformed shrimp fishing effort for the northwestern Gulf of Mexico for the month of July during the years 1990-2000. Shrimp fishing effort data were interpolated as previously described for red snapper data. Survey catches of the log-transformed number of snapper (with larger circles representing the highest percentage (25th percentile) and smallest circles representing the lowest percentage (95th percentile)) were overlaid with the shrimping effort data using GIS. The area of the hypoxic zone was mapped as well for comparison with red snapper distribution and effort during the years 1990-98, and 2000. The year 1999 was not graphed, as there was no map of the hypoxic area for that year.

In addition, the Louisiana shelf was examined during the month of July during the years 1990-2000 to determine if a greater overlap of red snapper and shrimping effort (depicted graphically as described above) occurs during years of extensive hypoxia as compared to years of low hypoxia. Years of extensive hypoxia include 1993-1997 (Figure 1). I compared the log transformed shrimping effort and the log-transformed number of red snapper to determine areas where the greatest overlap of effort and red snapper occur. Effort and snapper abundance were ranked by depth bins (0-5, 5-10, ... , and 45-50 fathoms). First, the highest 50th percentile of effort and the presence of any red snapper were compared and regions where overlap occurred identified and labeled as "Overlap 1." Second, the highest 50th percentile of red snapper and the highest 50th percentile of effort were compared and regions where overlap occurred identified and labeled as "Overlap 2." These regions thus contain the highest percent of red snapper and the highest percent of shrimping effort in any given year.

Preliminary Survey of Fishermen's Perceptions of Water Quality

The final objective of this study was to obtain red snapper commercial fishermen's perspective on current water quality in the Gulf of Mexico. I conducted a "key informant" interview process. The subject population consisted of individuals holding a Class 1 Red Snapper license (2,000-pound trip limit) for the Gulf of Mexico. Individuals were identified through a list obtained from the Gulf of Mexico Fishery Management Council. Five participants were contacted initially by mail (see attached cover letter—Appendix I) to advise them of my interest in calling them at a later date for an interview. Participants were then called and the 17 question survey was conducted via telephone (see attached survey questionnaire—Appendix I).

Results

Distribution of Shrimping Effort Data

Seasonal patterns of shrimping effort appear consistent with the migratory patterns of the major shrimp species, brown shrimp and white shrimp. Effort generally increased during April-May in nearshore waters (0-10 fathoms), consistent with the period of peak immigration of brown shrimp to the shelf (Figure 2(a-j). Effort in waters <10 fathoms remained high throughout the summer months and into the fall, consistent with the period of peak immigration of white shrimp (Figure 2(a-j)). In addition, for most years (1990-2000) the greatest proportion of shrimping effort was found shallower than 20 fathoms (approximately 70-90% of the effort for each year) (Figure 2(a-j)).

Hypothesis #1

To test the hypothesis that total shrimping effort decreases due to habitat loss from hypoxia, I compared total shrimping effort off Texas (control) and Louisiana (treatment) (Figure 3). Effort on the Louisiana shelf was fairly constant from 1990-1996, and increased slightly from 1997-1999. In contrast, effort on the Texas shelf was fairly constant from 1990-1994 and then decreased through the late 90s. The pattern off Louisiana is opposite of that predicted due to effects of hypoxia, with effort remaining stable or increasing during the high hypoxia period of 1993-97 and 1999.

Hypothesis #2

To test the hypothesis that the spatial distribution of shrimping effort off Louisiana would shift during years of extensive hypoxia, I examined the distribution of effort by depth on the Louisiana shelf. In 5 of 8 years, 75-80% of effort off Louisiana during July was from 0-10 fathoms (zones 13-17) (Figure 2(a-j); Figure 4). The years 1995 through 1997 were an exception to this pattern, with effort in waters <10 fathoms ranging from ~50-65% and effort from 10-20 fathoms increasing to ~80-90% (Figure 2(f,g,h); Figure 4). These were years of (1) extensive hypoxia and (2) hypoxia distributed relatively close to shore. This result supports my second hypothesis that shrimping effort shifts offshore during periods of extensive hypoxia, but only when hypoxia is distributed relatively close to shore and little inshore habitat is available. In contrast, 1993-1994 were also years of extensive hypoxia but effort did not shift offshore, likely because hypoxia during these years was distributed further offshore.

Supporting a shift in effort offshore during years of extensive hypoxia, there appears to be a significant negative relationship between effort inshore (0-5 fathoms) (zones 13-17) and area of bottom-water hypoxia (r^2=0.280, p=0.043, n=15) (Figure 5). Furthermore, there appears to be a positive relationship, although marginally insignificant, between effort offshore (10-50 fathoms) (zones 13-17) and area of bottom-water hypoxia (r^2=0.203, p=0.092, n=15) (Figure 6). These relationships are driven largely by the years 1995-1997.

Hypothesis #3

To test the hypothesis that shifts in the distribution of shrimping effort vary for different regions of the Louisiana shelf (eastern vs. western Louisiana), I compared the proportion of total shrimping effort by depth versus month for 1990-1999. From 1990-1999, effort off the eastern Louisiana shelf (zones 13-15) was very consistent. Effort increased inshore (0-5 fathoms) beginning in April/May and stayed high through summer and early fall (Figure 7(a-j). Most effort (nearly always >50%) was found inshore of 5 fathoms (Figure 7(a-j)). Shrimping effort by depth off the western Louisiana shelf (zones 16-17) showed a very different temporal pattern (Figure 8(a-j)). The highest effort was found early in the season (April/May, sometimes June) generally from 0-10 fathoms. Later in the season, effort became highly variable, with effort from 10-20 fathoms becoming increasingly important (Figure 8(a-j)).

I also examined the proportion of total shrimping effort versus the area of the hypoxic zone. A positive relationship between hypoxic area and offshore effort (10-50 fathoms) exists for both eastern and western regions of Louisiana (Figure 9(a,b)). This positive relationship between offshore effort and hypoxia is significant, and thus much stronger, in western Louisiana (zones 16-17) (r^2=0.257, p=0.054, n=15) than eastern Louisiana (zones 13-15), where the relationship is not significant (r^2=0.007, p=0.763, n=15). This result seems reasonable and is consistent with my hypothesis that the distribution of shrimping effort varies for the different regions of the Louisiana shelf. Because the western Louisiana shelf experiences aperiodic hypoxia and because there is increased offshore habitat, a greater shift can be expected for this region.

In addition, a negative relationship between hypoxic area and inshore effort exists for both eastern and western regions of Louisiana (Figure 10(a,b)). Once again, this relationship (here negative) is significant, and hence stronger, off western Louisiana (r^2=0.457, p=0.006, n=15) than eastern Louisiana, where the relationship is not significant (r^2=0.042, p=0.464, n=15). Because hypoxia is chronic on the eastern Louisiana shelf (zones 13-15) and there is less available habitat offshore, this result is consistent with greater shifts in the distribution of effort in the western versus eastern shelf.

Red Snapper Distribution Data

I examined the distribution of red snapper along the Louisiana shelf of the Gulf of Mexico. From 1990-2000, the majority of red snapper were found offshore (>10 fathoms) in the western region (stat zones 16-17) of the Louisiana shelf (Figure 11(a-k) Note: darker areas indicate higher abundances of red snapper.) In addition, stat zone 14 (eastern Louisiana) also contains red snapper, although in smaller abundances, during the years 1990, 92, 94, 96, 97, and 2000.

To determine the differences in red snapper distribution/abundance between the eastern and western regions of Louisiana, I examined the log number of snapper/tow versus depth for 1990-2000. Red snapper abundance was greater off the western Louisiana shelf (stat zones 16-17) than the eastern Louisiana shelf (stat zones 13-15) for all years 1990-2000 (Figure 12(a-k)). For most years (1990-2000), western Louisiana red snapper abundance was distributed over a broad range from 5-35 fathoms. In contrast, eastern Louisiana snapper abundance was not distributed over such a wide range of depths for any given year. In most years, the greatest amounts of red snapper occurred at 15-20 and 20-25 fathoms within both regions of Louisiana. Thus, red snapper appears to be primarily offshore and more prevalent in the western than eastern Louisiana shelf.

Red Snapper Distribution and Shrimping Effort Data Comparisons

The log transformation of red snapper and the log transformation of shrimping effort were graphed spatially using GIS for the years 1990-2000. Figures 13(a-k) show the graphical relationship between the distribution of red snapper, shrimping effort, and the area of the hypoxic zone. Circles, with the larger circles representing the greatest abundances of red snapper (the

25th percentile), are the log-transformed number of red snapper. Shrimping effort can be identified by color, with the darkest color representing the greatest percentage of effort (25th percentile). The hypoxic zone is indicated by black outlined area coverages.

I also examined where the greatest overlap of red snapper and shrimping effort occur and their relation to the hypoxic zone. To quantify the relationship between shrimping effort and red snapper distribution, I calculated two measures of overlap. "Overlap 1" is defined as the highest 50th percentile of shrimping effort and the presence of red snapper, while "Overlap 2" is defined as the highest 50th percentile of shrimping effort and the highest 50th percentile of red snapper distribution. In all but one year (1994), overlap of red snapper and shrimping effort occurred within western Louisiana (stat zones 16-17) (Figure 14(a-j)). "Overlap 1" between the 50th percentile of effort and presence of any snapper, occurred for all years (1990-98, 2000). This overlap occurred from 5-10 fathoms up to 20-25 fathoms within stat zones 16-17 (Figure 14(a-j)). "Overlap 2" between the 50th percentile of shrimping effort and the 50th percentile of red snapper occurred only during 1991, 1995, 1996, 1997, 1998, and 2000 (Figure 14(b,f,g,h,i,j)). In all but 2 years, (1997,1998) "Overlap 2" was the offshore set of bins depicted in "Overlap 1." Thus, the greatest amount of overlap between shrimping effort and red snapper, and the greatest potential for red snapper bycatch, occurs offshore on the western Louisiana shelf.

Preliminary Survey of Fishermen's Perceptions of Water Quality

Gulf of Mexico red snapper commercial fishermen were interviewed to obtain their perceptions about water quality issues in the Gulf and how it affects the red snapper fishery (see Appendix I Figure 3 for sample survey questionnaire). Four of five contacted participants were interviewed, resulting in an 80% response rate. All four fishermen are based in the Florida panhandle. Demographic questions were asked to help characterize the red snapper fishermen. Fishermen were first asked how many years they had been commercial fishermen; the average number of years the respondents had been commercial fishermen was 30 years. Respondents were also asked how long they had been fishing for red snapper; the average number of years the respondents had been fishing for red snapper was 30 years. For all but one individual, respondents had been fishing for red snapper their entire commercial fishing career. Respondents were also asked, "What other fisheries do you engage in besides red snapper?" All four respondents fish for king mackerel in addition to red snapper. Other fisheries that respondents participate in include yellow-fin tuna, amberjack, and other reef fish (i.e., grouper).

Respondents were also asked questions to characterize when and where they fish. The fishermen were asked, "What months do you fish for red snapper?" Red snapper fishermen fish the first ten days of each month from February to May (and sometimes in June if there is any remaining quota left over) and then again, from September to November; their season is established each year by NMFS. Fishermen were also asked what NMFS statistical zones they fish in most often for red snapper. Zones 9, 12, 13, 14, 15, 16, and 17 were all mentioned. Zone 13 was fished in by three of the four respondents. Zones 15, 16, and 17 were only fished by one respondent, as was zone 9.

Fishermen were then asked questions about water quality, specifically hypoxia, in the Gulf of Mexico. Respondents were first asked if they had heard of the "hypoxic" or "dead zone." Three of the four fishermen interviewed had heard of the hypoxic zone. Fishermen were then asked if they had ever noticed the hypoxic zone while fishing; two of the four respondents had seen the hypoxic zone while fishing. One respondent had seen the hypoxic zone in stat zones 16-17 at 0-10 fathoms depth. The other respondent had observed hypoxia in the shallow waters of zone 13. Those respondents who had noticed the hypoxic zone while fishing were then asked, “What are the signs of the hypoxic zone that you notice?” Both fishermen responded that there were no fish in the hypoxic area, “Everything just disappears,” one respondent replied.

Respondents were then asked questions about how hypoxia affects fishing behavior. When asked, “Has the hypoxic zone affected your fishing for red snapper?” two respondents answered “no,” one respondent answered “don’t know,” and one respondent answered “yes.” The one respondent whose fishing had been affected felt that he had to fish further offshore and out of certain areas that he was used to fishing in—what once was only a couple mile run, was now a 5-10 mile run. Respondents were also asked whether the hypoxic zone affects other fisheries besides red snapper. Two of the four respondents felt that the hypoxic zone did affect other fisheries; they felt that king mackerel and other reef fish fisheries were affected.

Questions about the general consequences of hypoxia were then asked. First, respondents were asked if fishermen have been forced to fish further inshore or offshore due to the effects of hypoxia. Two of the four respondents felt that fishermen have been forced to fish further offshore. Fishermen were also asked if hypoxia has caused decreased catches of red snapper. All four fishermen felt that decreased catches of red snapper did not result. In fact, one fisherman responded that the red snapper fishery has been doing better than ever. Fishermen were also asked if hypoxia has caused crowding of vessels; all four respondents answered “no” to this question. Finally, fishermen were asked, “In your opinion, is hypoxia a significant threat to the red snapper fishery?” None of the respondents felt that hypoxia was a threat to the red snapper fishery.

Discussion

Distribution of Shrimping Effort in Relation to Hypoxia

Seasonal patterns of shrimping effort appear consistent with the migratory patterns of Gulf shrimp species—with brown shrimp migrating to the shelf in spring/early summer and white shrimp migrating late summer/early fall. Thus, the shrimping effort data, although possibly having some bias as it comes from interviews with commercial fishermen, seems reliable for this analysis. It is important to note that from 1990-2000, most shrimping effort was found shallower than 20 fathoms. Because the hypoxic zone is largely found in many of these same inshore areas, implications for effects of hypoxia on shrimp, and subsequently shrimping effort, do exist.

Hypothesis #1

The hypothesis that total shrimping effort off Louisiana decreases due to habitat loss from hypoxia and presumably decreases in shrimp production or accessibility to shrimpers was rejected. Contrary to the original prediction, shrimping effort on the Louisiana shelf remained stable or increased during the high hypoxia years of 1993-97 and 1999. This result may have been due to shrimp having the ability to move outside of the hypoxic zone with little direct mortality effect from low oxygen. It is possible that growth and condition of shrimp were adversely affected, but not to the extent that large decreases in shrimping effort occurred.

Overall, levels of shrimping effort were probably maintained and possibly increased by high densities of shrimp inshore and offshore of the hypoxic region (Craig 2001) allowing adequate catch per unit effort (CPUE) to be attained by commercial fishermen. The maintenance of temporal patterns of shrimping effort despite large shifts in the distribution of shrimp has important management implications. For example, if shrimp are concentrated into smaller areas then commercial catch rates can remain high even though population abundance is declining. This suggests temporal trends in commercial CPUE may not adequately represent the status of the stock.

Hypothesis #2

The distribution of shrimping effort in relation to depth on the Louisiana shelf supports the hypothesis that shrimping effort shifts off Louisiana during years of extensive hypoxia. Historically, Louisiana is an inshore shrimping industry with most effort occurring within 20 fathoms depth. From 1995-97 shrimping effort shifted offshore from <10 fathoms out to 10-20 fathoms. These were years of extensive hypoxia (14,900 km^2 – 16,400 km^2) that was distributed relatively close to shore. In contrast, 1993-1994 were also years of extensive hypoxia (13,300 km^2 – 17,000 km^2) but effort did not shift offshore, likely because hypoxia during these years was distributed further offshore.

The landward and seaward edges of the hypoxic zone were closer to shore and further west in 1995-1997 compared to 1993-1994 (Craig 2001). Craig (2001) estimated the proportion of available habitat inshore of 10 fathoms by subtracting the area of bottom water hypoxia from the total area from 0-10 fathoms for each year 1983-2000. He found that about 35% more habitat was available inshore of 10 fathoms from 1993-1994 than during 1995-1997. This result supports the hypothesis that shrimping effort shifts offshore during periods of extensive hypoxia, but only when the hypoxic zone is distributed close to shore and little inshore habitat is available.

A significant positive relationship between the amount of effort offshore and the area of bottom-water hypoxia also supported a shift offshore during years of extensive hypoxia. In addition, there was a negative relationship between the amount of inshore effort and the area of bottom-water hypoxia. The positive relationship with offshore effort and negative relationship with inshore effort suggests this pattern is the result of a shift in effort from inshore to offshore rather than independent changes in effort in the two regions (inshore, offshore).

Hypothesis #3

The hypothesis that shifts in the distribution of shrimping effort vary for different regions of the Louisiana shelf (eastern and western) was also supported. Effort off eastern Louisiana was consistently high inshore (0-5 fathoms) throughout the summer and into early fall. In contrast, the highest effort off western Louisiana earlier in the season was from 0-10 fathoms, and then later in the season highest effort occurred further offshore (10-20 fathoms). This suggests the shift in effort offshore on the Louisiana shelf during years of extensive hypoxia was driven largely by patterns on the western shelf. Hypoxia is chronic on the eastern Louisiana shelf, with large areas of the eastern shelf annually subject to low oxygen. Thus, we would not expect to see strong shifts in the distribution of shrimping effort for the eastern region. In contrast, the western region of the Louisiana shelf is much broader and only experiences low oxygen when hypoxia is extensive. This combination of more available habitat and more variable hypoxia results in stronger shifts in shrimping effort on the western than eastern shelf.

The relationship between the depth distribution of shrimping effort and the area of the hypoxic zone also supported the hypothesis of offshore shifts in effort, mainly on the western shelf, when hypoxia is extensive. A positive relationship exists between the area of hypoxia and the proportion of offshore effort; this relationship is stronger on the western compared to eastern Louisiana shelf. Also, a negative relationship between the area of hypoxia and proportion of inshore effort was observed for both the eastern and western Louisiana shelf. The relationship was significant and stronger on the western than eastern Louisiana shelf—again suggesting that variation in both the area of available shrimping habitat and the annual extent of low oxygen have important effects on where shrimpers shrimp.

Red Snapper Distribution

Red snapper appear to be more abundant and broadly distributed on the western (zones 16-17) compared to eastern (zones 13-15) Louisiana shelf. Red snapper is known to be an offshore species (Bradley and Bryan 1976; Gallaway *et al* 1999), and such a distribution (>10 fathoms) was evident for the years 1990-2000. Although red snapper were largely found outside of the hypoxic zone (1990-2000), it does not appear that snapper are strongly displaced due to hypoxia. In some years (e.g.1998) snapper distribution shifted far inshore (i.e., to 5 fathoms). Still in other years (e.g. 1991, 1995, 1997) there was some evidence the distribution of red snapper was split inshore and offshore of the hypoxic zone, suggesting snapper on the western shelf may be displaced from preferred habitat. Overall, however, it appears that their normal habitat is offshore, which for most years occurred outside of the hypoxic zone.

There were some years (1990, 1994, 1996, 1997), however, that red snapper were distributed along the edge of the hypoxic zone—this edge effect was most consistent off the eastern Louisiana shelf. Thus, any direct effects of hypoxia on red snapper would likely be seen on the eastern Louisiana shelf. This seems reasonable as the eastern shelf annually experiences low oxygen and there is less available inshore habitat. Similarly, the eastern shelf is narrower and drops off into a deep canyon (Mississippi Canyon) that may be unsuitable habitat for red snapper. Possible direct effects of hypoxia on red snapper may include decreased food availability and unsuitable temperatures, resulting in decreased growth and condition, and subsequently increased fishery or natural mortality.

Relationship Between Red Snapper Distribution and Shrimping Effort

In nine of ten years, overlap between the presence of any red snapper and the highest 50th percentile of shrimping effort was highest on the western Louisiana shelf (zones 16-17) from 5-10 fathoms up to 20-25 fathoms depth. In 1994, however, overlap between red snapper and shrimping effort was highest on the eastern Louisiana shelf (zones 13-15) from 5-10 fathoms depth. In four of six years (1991, 1995, 1996, 2000) that experienced overlap between the highest 50th percentile of red snapper and the highest 50th percentile of shrimping effort, overlap was higher offshore. Except for the year 2000, this pattern occurred when hypoxia was extensive. In most years, high overlap occurred just offshore of the hypoxic zone on the western shelf, suggesting that hypoxia forced shrimp (and shrimpers) and red snapper further offshore. These results were especially evident on the western Louisiana shelf (zones 16-17) and suggest that the potential for increases in juvenile red snapper bycatch in the shrimp trawl fishery is greatest on the western shelf (stat zones 16-17) from 5-25 fathoms depth with a "core area" of interaction from 15-25 fathoms depth. These high overlap areas thus represent potential regions for shrimp trawl closures, with the goal of preventing juvenile red snapper bycatch.

Preliminary Survey of Fishermen's Perspectives of Water Quality

Based on the survey results, it appears that red snapper commercial fishermen understand what hypoxia is and how it affects their fishing behavior. Hypoxia generally seems to affect fisheries by causing fishermen to fish further offshore. This effect, however, does not lead to decreases in red snapper catch and thus it does not appear to be a significant threat to the red snapper fishery. It is important to note that red snapper fishermen do not fish during the height of the hypoxic season (late June-August) and thus they may not be directly experiencing any "effects" of hypoxia while fishing. Furthermore, because fishermen only fish the first 10 days of each month, and hypoxia is a variable feature, any effects of hypoxia on red snapper may not be noticeable to fishermen. This survey only sampled four red snapper commercial fishermen. Further interviewing work needs to be conducted to get a clearer picture of the effects of hypoxia, if any, on the red snapper fishery.

Management Implications & Conclusions

Red snapper constitute an important commercial fishery in the Gulf of Mexico. Now is the time for it to return to a state where sustainability (rate of harvest does not exceed rate of regeneration) is attained. The current management system used by the Gulf Council cannot ensure sustainability in the presence of scientific uncertainty regarding effects on fisheries due to hypoxia. Although current fishery management plans (FMPs) exist for both red snapper and Gulf of Mexico shrimp, neither takes into consideration the effects of hypoxia on the shrimping industry and the subsequent implications for red snapper bycatch. The results from my study offer evidence concerning the effects of hypoxia on fisheries within the northwestern Gulf of Mexico.

A greater awareness of water quality issues would aid the Gulf of Mexico Fishery Management Council in their development of future FMPs. The above observations lead me to conclude that by implementing a precautionary management approach, fisheries managers can begin to manage the shrimp and red snapper fisheries so that they may avoid future deleterious effects of hypoxia.

One potential option for Gulf fisheries managers would be to enact seasonal and/or area closures for the shrimp trawl fishery. Fishery managers could sample areas occupied by red snapper. If a large percentage of juvenile red snapper is caught in the sample, then shrimpers could be prevented from trawling in that area. Also, if a determination can be made (as in this study) as to when and where hypoxic conditions cause more intense overlap of juvenile red snapper and shrimp, fisheries managers can close either areas or seasons, thereby reducing the potential for red snapper caught as bycatch.

Based on the results from this study, I would suggest that area closures for the shrimp fishing industry occur within the western Louisiana shelf (statistical zones 16-17). During July, a large amount of red snapper overlaps with shrimping effort within these areas, thus increasing the potential for red snapper bycatch. This overlap usually occurs from about 5-25 fathoms depth. Because the shrimp fishery is largely an inshore fishery, closures from 5-10 fathoms may not be supported and hence difficult to enforce. But because the majority of the overlap occurs further offshore, I suggest that the closures take place from 15-25 fathoms depth within zones 16-17. These closures would target areas that experience the greatest abundance and distribution of red snapper over the entire Louisiana shelf. In addition, the closures would target areas where shrimping effort is generally low; thus, there would perhaps be less of an economic impact on the shrimp fishery. These closures would help to reduce red snapper bycatch, and thus increase the potential for red snapper growth and recruitment.

Before any suggested shrimping area closures can occur, however, a number of factors need to be evaluated. First, managers should attempt to determine the socioeconomic costs to individual shrimpers and the shrimping industry. Second, the actual benefits to the red snapper population and the red snapper fishery need to be quantified. For example, if we decreased the bycatch of red snapper by X%, what increase in the proportion of red snapper reaching sexual maturity and reproducing would be achieved? Finally, managers would need to work with all stakeholders to devise other innovate bycatch reduction strategies—such as gear modifications—for the shrimping industry.

One problem with this system of management (i.e., closures) is that it tends to be reactive rather than proactive. Fisheries managers may have a tendency to wait until conditions are bad (i.e., intense overlapping spatial distributions of shrimp-trawl effort and juvenile red snapper) to enact area or seasonal closures. Instead, managers should rely on the precautionary approach and close areas/seasons early, based on SEAMAP data from prior years, instead of waiting for sub-optimal conditions. In addition, by decreasing the total allowable catch for the directed red snapper fishery, managers would be factoring in the effects of hypoxia on shrimping effort, and thus, bycatch mortality on the red snapper resource. In this way, fisheries managers would be acting in a precautionary manner.

For this management approach, I am not suggesting that a new regime be established. Rather, it is important to use the existing Gulf Council framework in order to maintain the rapport already established between the Gulf Council and the fishermen. Fisheries managers should be using—and be able to rely upon—current scientific information concerning hypoxia and its effects on fisheries. This study serves as one step toward understanding the effects of hypoxia on fisheries in the northwestern Gulf of Mexico. Further research on the indirect impacts of low dissolved oxygen on fish populations is still needed. Although it is possible to hypothesize the potential effects of hypoxia on fisheries, almost nothing is really known of how hypoxia affects fishery productivity and fish health. Given that fishery resources in the Gulf of Mexico are highly valuable, and that great uncertainty exists in our understanding of the effects of hypoxia on this ecosystem, a precautionary management approach seems critical for the future of this system.

Acknowledgements

I thank the NMFS Pascagoula Lab for collecting and providing the data from the SEAMAP research cruises and the NMFS Galveston Lab for collecting and providing the shrimp effort data. I would like to thank my primary advisor, Dr. Mike Orbach, for his continued support and encouragement throughout the entire Master's Project process. I would also like to thank my secondary advisor, Dr. Larry Crowder, who generously allowed me to work in his lab and has provided me with valuable advice and insight throughout my graduate studies. Special thanks go to Dr. Kevin Craig who helped me develop the concept for my MP and who spent endless amounts of time answering my questions and editing my work. Finally, I must thank all my MEM friends and my family whose support provided encouragement throughout the entire process.

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FIGURES

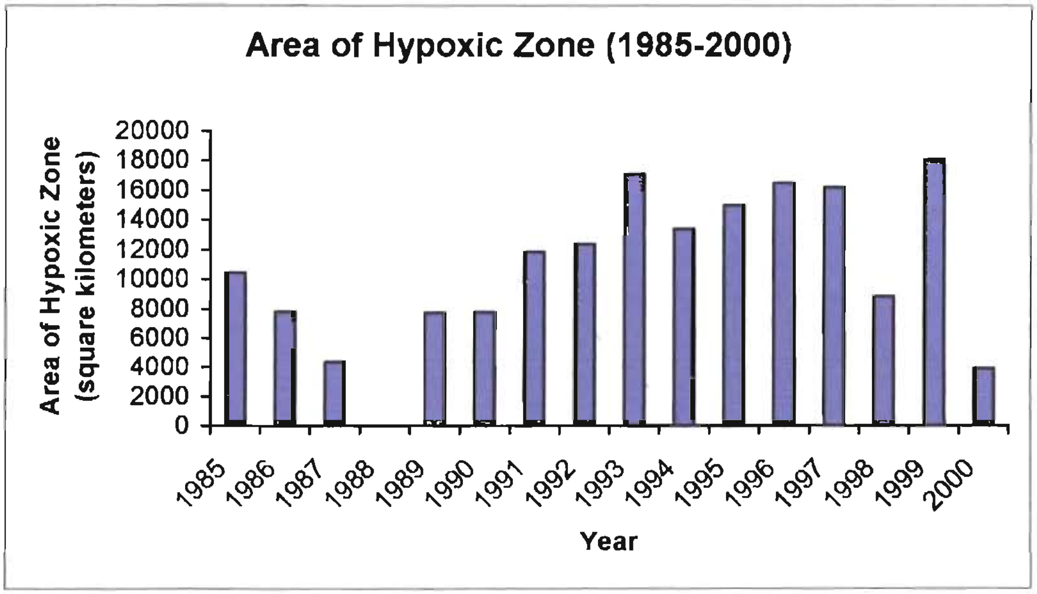


Figure 1. Area of bottom water hypoxia (dissolved oxygen ≤ 2.0mg/l) from 1985-2000. Areas interpolated from SEAMAP for all years except 1999 (Craig 2001). Extensive hypoxic years include 1993-1997 and 1999.

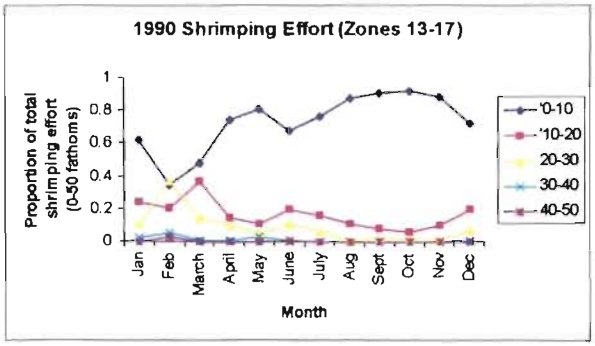


Figure 2a. 1990 shrimping effort by depth (0-50 fathoms) for Louisiana (zones 13-17).

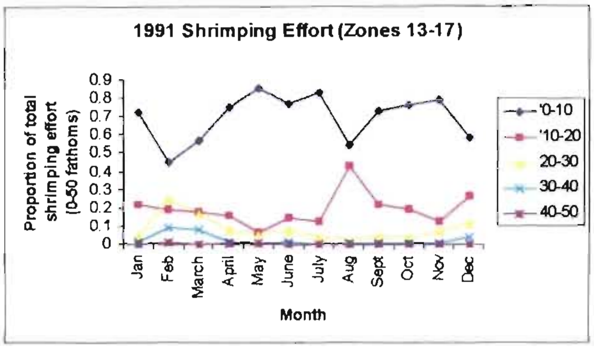


Figure 2b. 1991 shrimping effort by depth (0-50 fathoms) for Louisiana (zones 13-17).

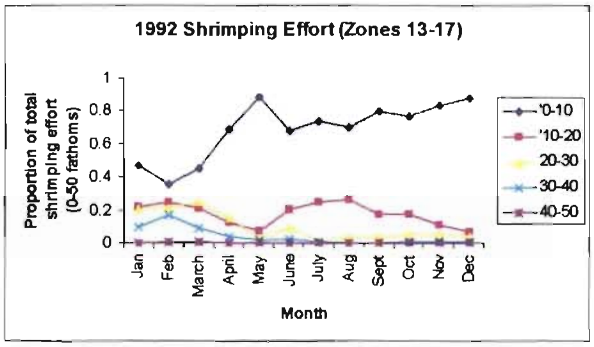


Figure 2c. 1992 shrimping effort by depth (0-50 fathoms) for Louisiana (zones 13-17).

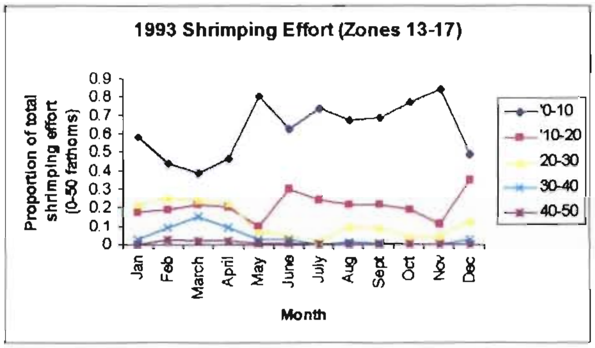


Figure 2d. 1993 shrimping effort by depth (0-50 fathoms) for Louisiana (zones 13-17).

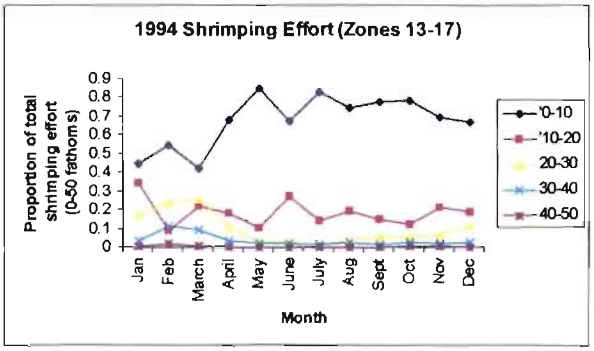


Figure 2e. 1994 shrimping effort by depth (0-50 fathoms) for Louisiana (zones 13-17).

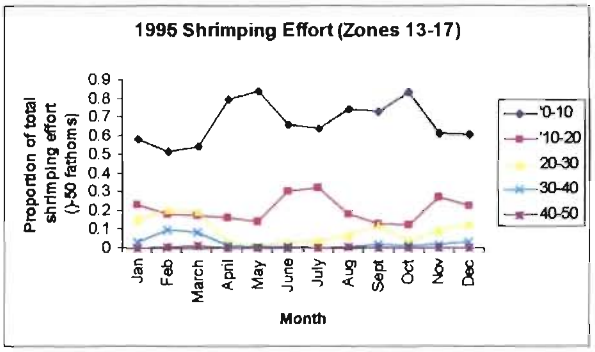


Figure 2f. 1995 shrimping effort by depth (0-50 fathoms) for Louisiana (zones 13-17).

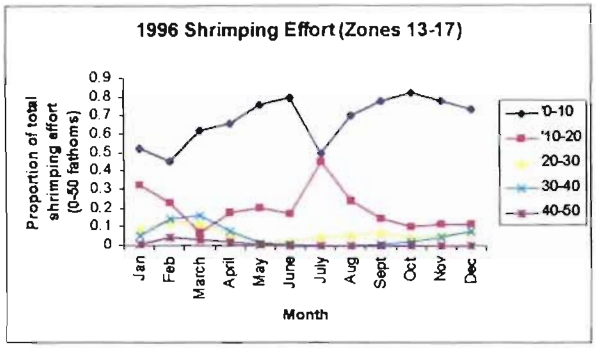


Figure 2g. 1996 shrimping effort by depth (0-50 fathoms) for Louisiana (zones 13-17).

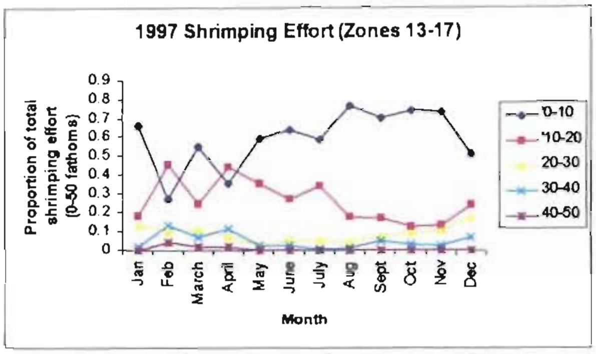


Figure 2h. 1997 shrimping effort by depth (0-50 fathoms) for Louisiana (zones 13-17).

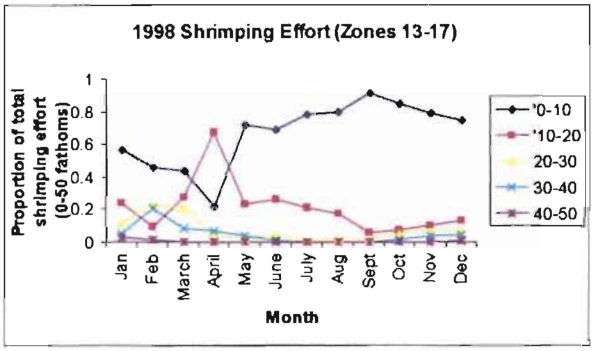


Figure 2i. 1998 shrimping effort by depth (0-50 fathoms) for Louisiana (zones 13-17).

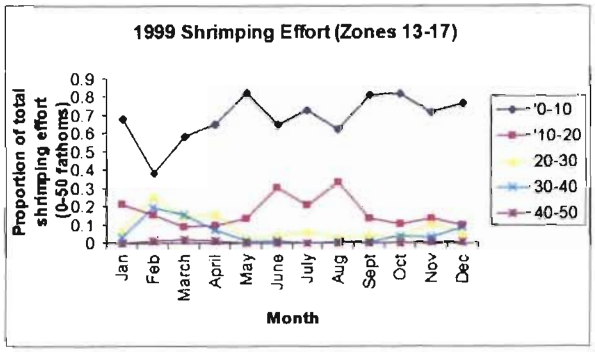


Figure 2j. 1999 shrimping effort by depth (0-50 fathoms) for Louisiana (zones 13-17).

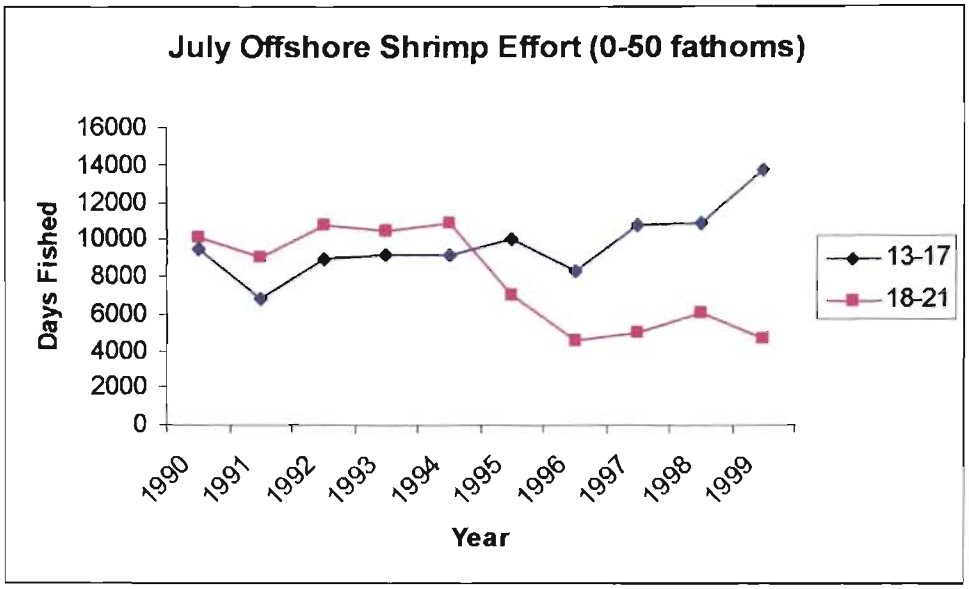


Figure 3. July offshore shrimping effort for 1990 through 1999. Shrimping effort (days fished) off Louisiana (zones 13-17) is compared with Texas effort (zones 18-21).

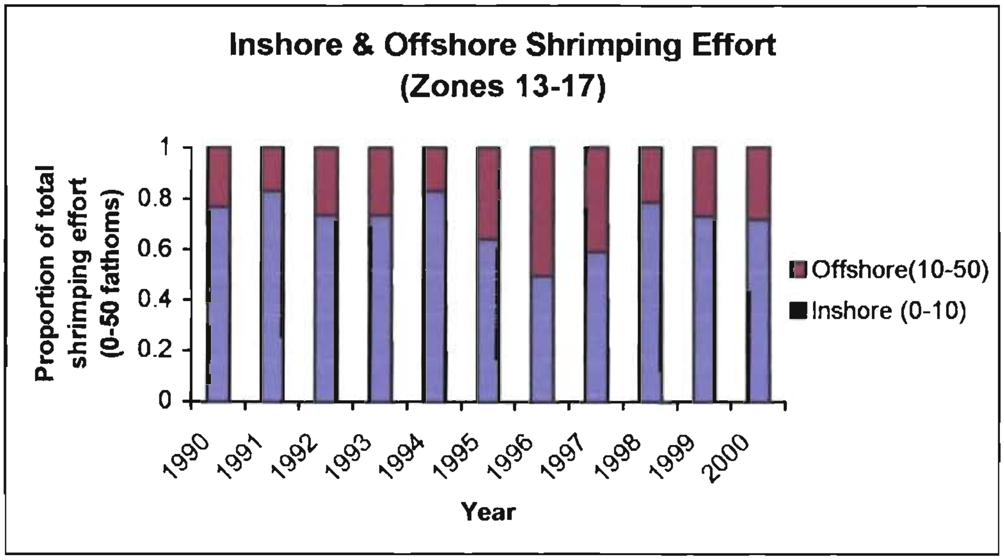


Figure 4. Inshore (0-10 fathoms) and offshore (10-50 fathoms) shrimping effort off the Louisiana shelf (zones 13-17) for 1990-2000. Notice the increase in offshore shrimping effort for 1995-1997.

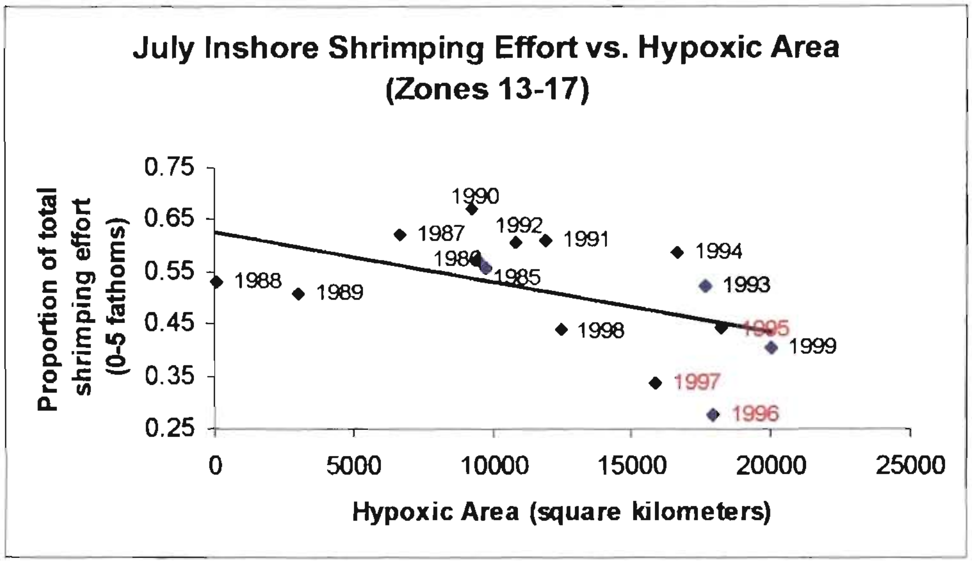


Figure 5. July inshore (0-5 fathoms) shrimping effort off Louisiana (zones 13-17) vs. area of hypoxic zone (square kilometers) (r^2=0.280, p=0.043, n=15). Years indicated in red experienced extensive hypoxia distributed inshore.

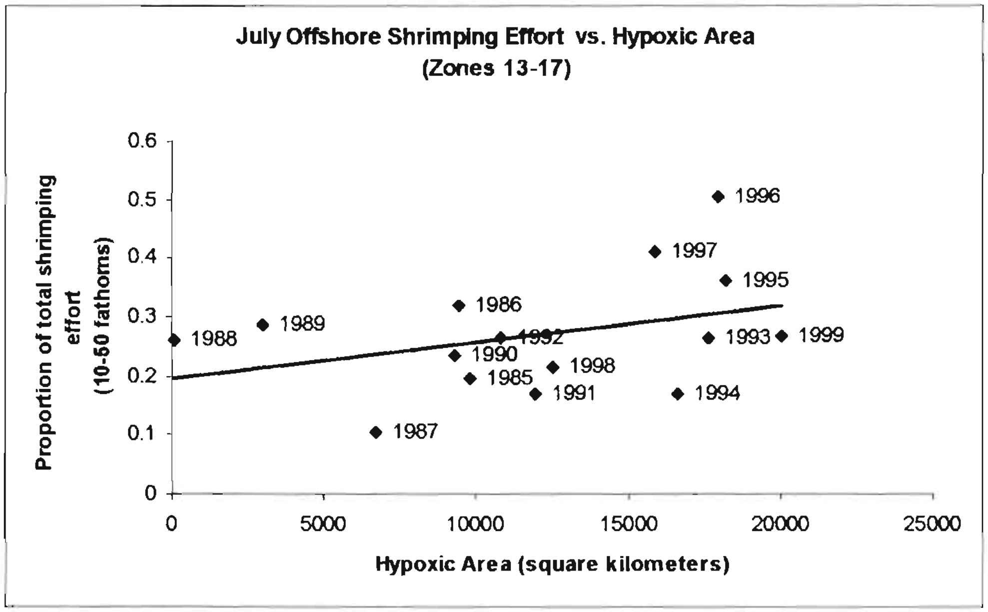


Figure 6. July offshore (10-50 fathoms) shrimping effort off Louisiana (zones 13-17) vs. area of hypoxic zone (square kilometers) (r^2=0.203, p=0.092, n=15).

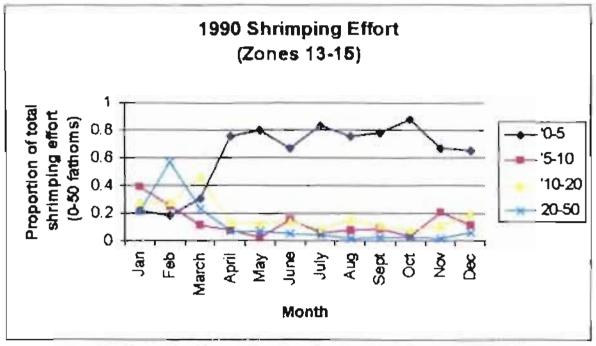


Figure 7a. 1990 shrimping effort by depth (0-50 fathoms) off Eastern Louisiana (zones 13-15).

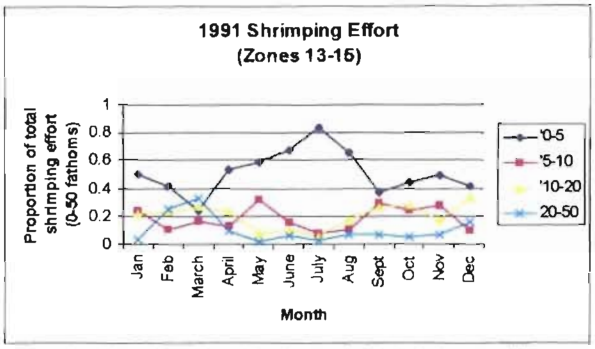


Figure 7b. 1991 shrimping effort by depth (0-50 fathoms) off Eastern Louisiana (zones 13-15).

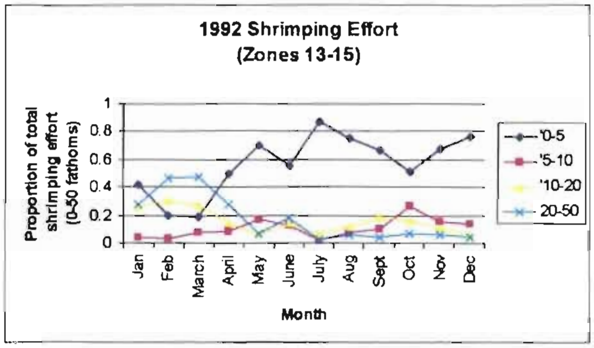


Figure 7c. 1992 shrimping effort by depth (0-50 fathoms) off Eastern Louisiana (zones 13-15).

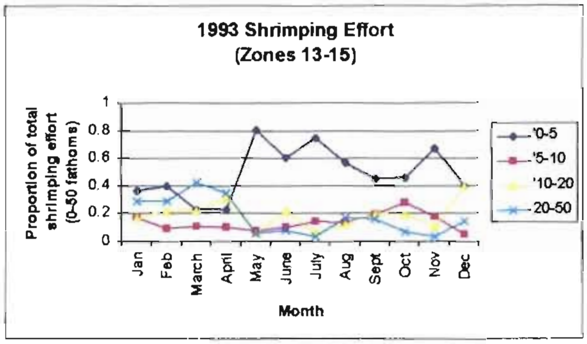


Figure 7d. 1993 shrimping effort by depth (0-50 fathoms) off Eastern Louisiana (zones 13-15).

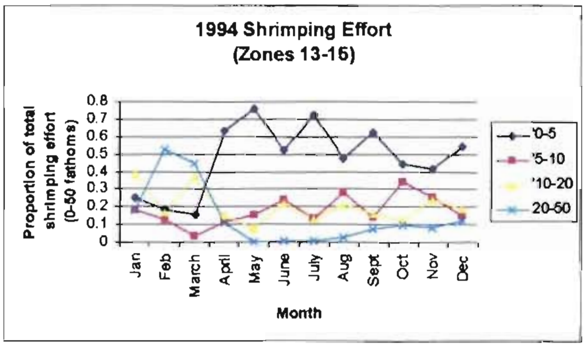


Figure 7e. 1994 shrimping effort by depth (0-50 fathoms) off Eastern Louisiana (zones 13-15).

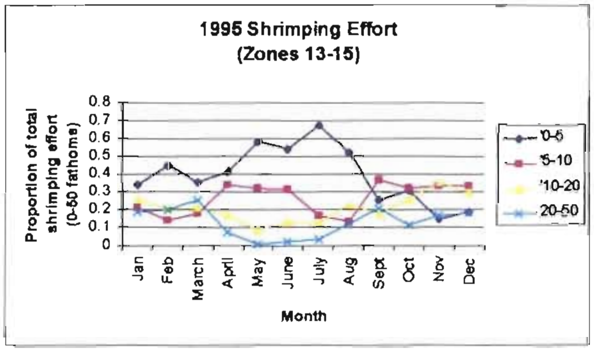


Figure 7f. 1995 shrimping effort by depth (0-50 fathoms) off Eastern Louisiana (zones 13-15).

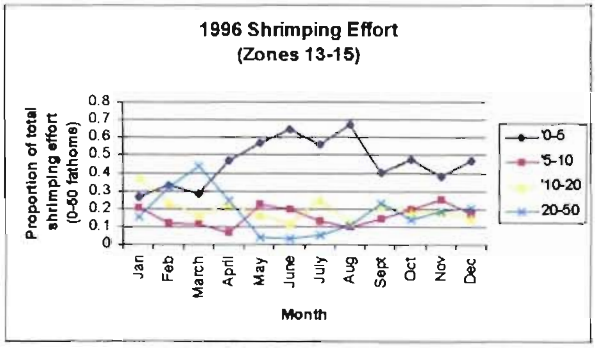


Figure 7g. 1996 shrimping effort by depth (0-50 fathoms) off Eastern Louisiana (zones 13-15).

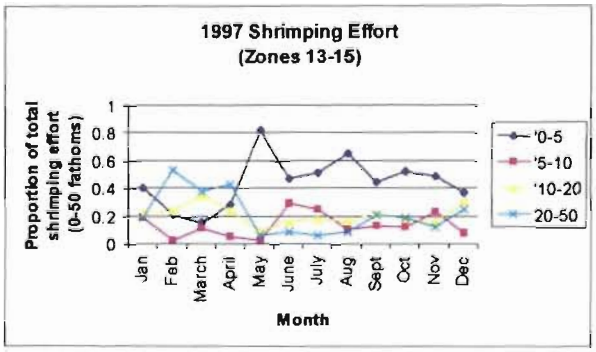


Figure 7h. 1997 shrimping effort by depth (0-50 fathoms) off Eastern Louisiana (zones 13-15).

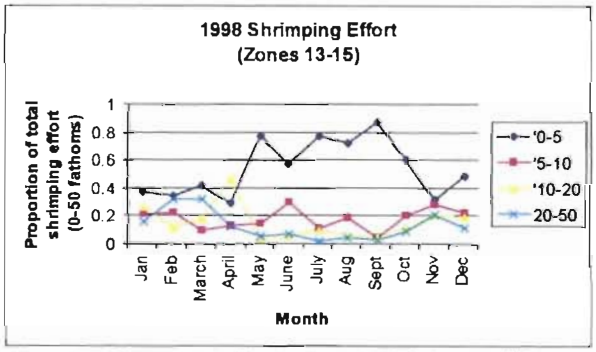


Figure 7i. 1998 shrimping effort by depth (0-50 fathoms) off Eastern Louisiana (zones 13-15).

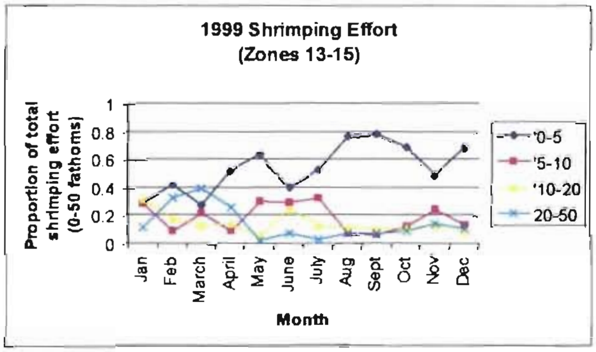


Figure 7j. 1999 shrimping effort by depth (0-50 fathoms) off Eastern Louisiana (zones 13-15).

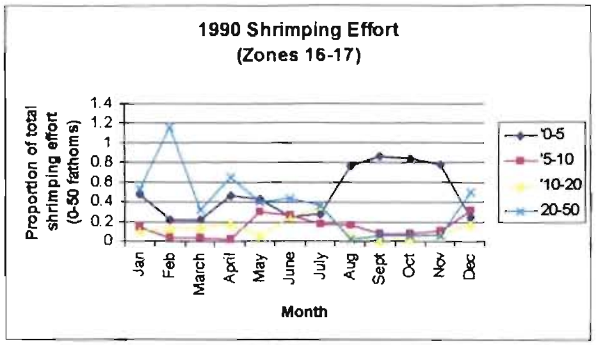


Figure 8a. 1990 shrimping effort by depth (0-50 fathoms) off Western Louisiana (zones 16-17).

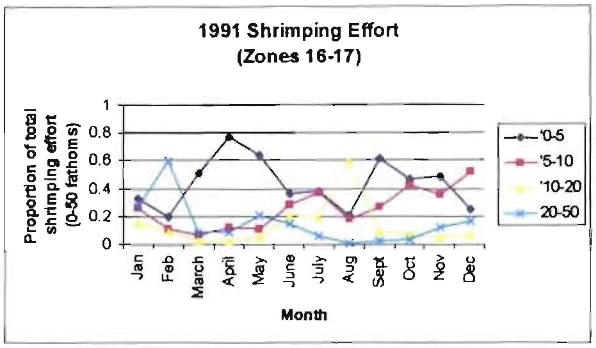


Figure 8b. 1991 shrimping effort by depth (0-50 fathoms) off Western Louisiana (zones 16-17).

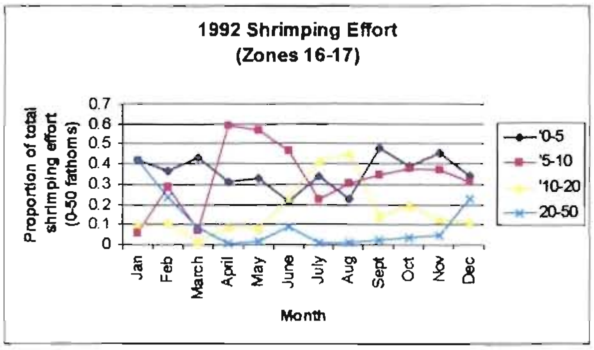


Figure 8c. 1992 shrimping effort by depth (0-50 fathoms) off Western Louisiana (zones 16-17).

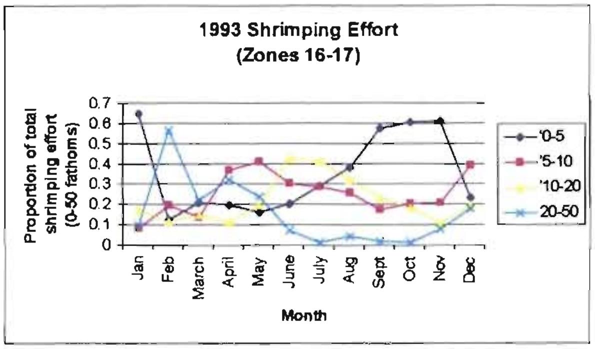


Figure 8d. 1993 shrimping effort by depth (0-50 fathoms) off Western Louisiana (zones 16-17).

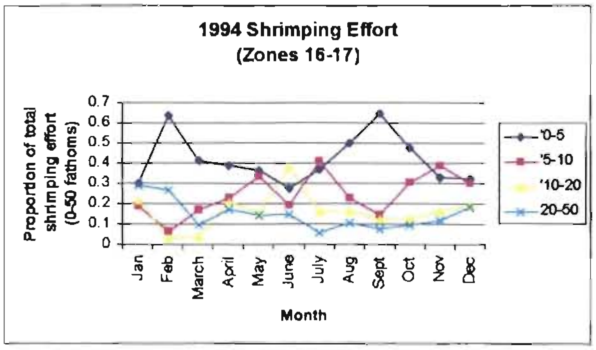


Figure 8e. 1994 shrimping effort by depth (0-50 fathoms) off Western Louisiana (zones 16-17).

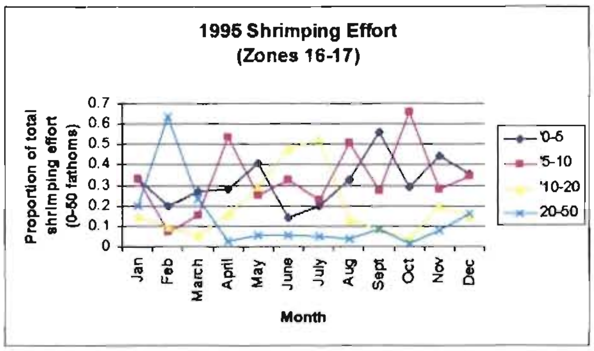


Figure 8f. 1995 shrimping effort by depth (0-50 fathoms) off Western Louisiana (zones 16-17).

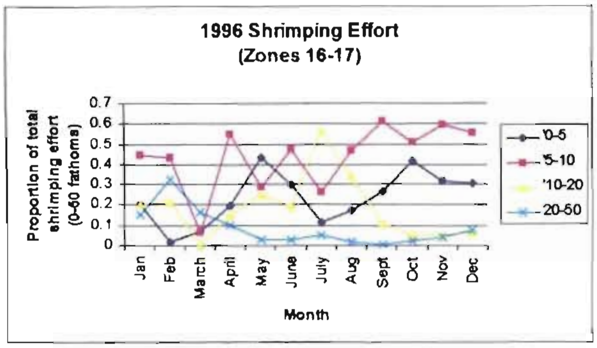


Figure 8g. 1996 shrimping effort by depth (0-50 fathoms) off Western Louisiana (zones 16-17).

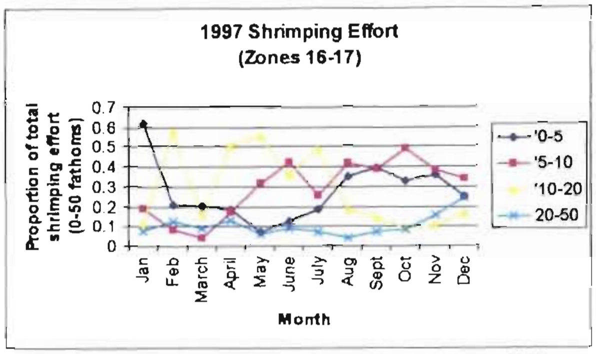


Figure 8h. 1997 shrimping effort by depth (0-50 fathoms) off Western Louisiana (zones 16-17).

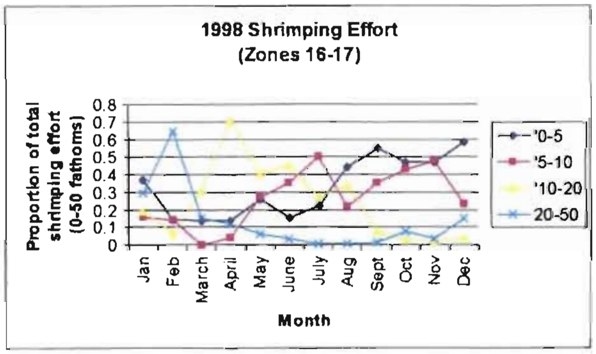


Figure 8i. 1998 shrimping effort by depth (0-50 fathoms) off Western Louisiana (zones 16-17).

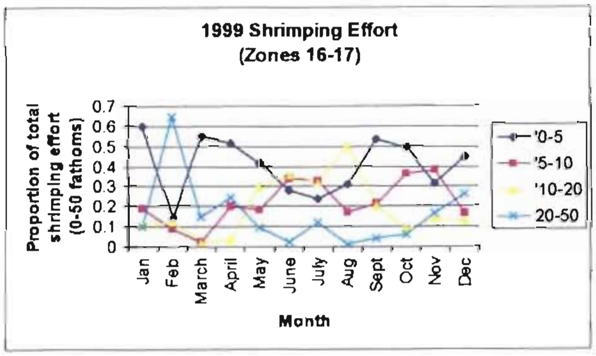


Figure 8j. 1999 shrimping effort by depth (0-50 fathoms) off Western Louisiana (zones 16-17).

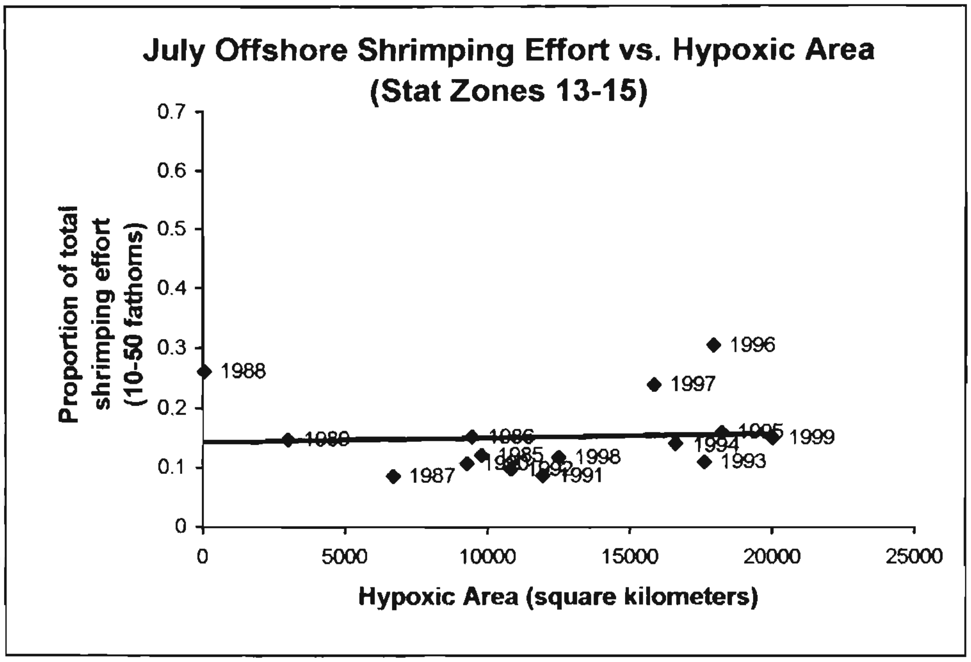


Figure 9a. July offshore shrimping effort (10-50 fathoms) vs. hypoxic area (square kilometers) off Eastern Louisiana (zones 13-15) (r^2=0.007, p=0.763, n=15).

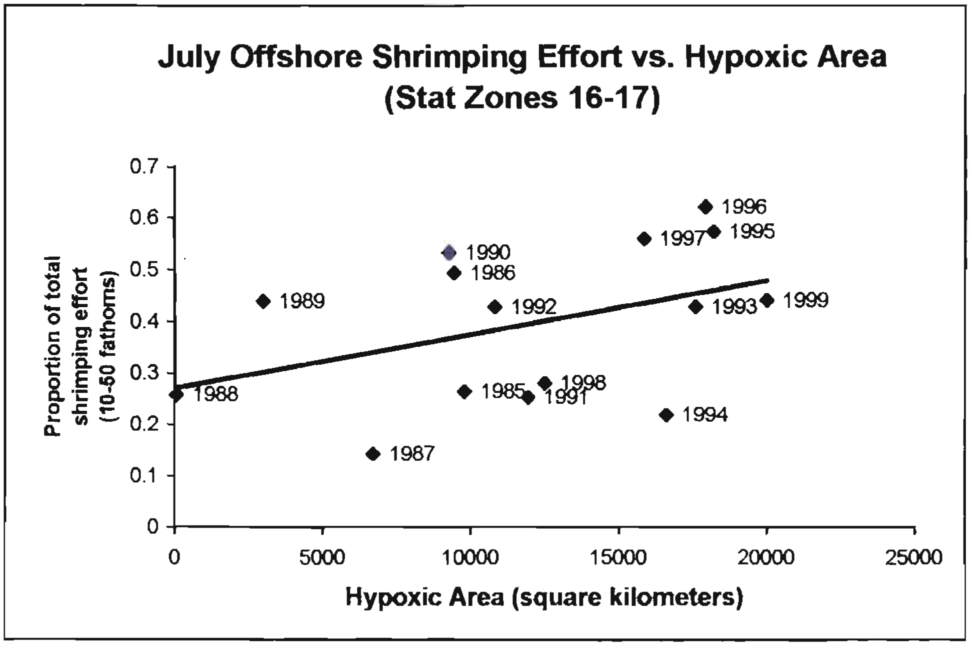


Figure 9b. July offshore shrimping effort (10-50 fathoms) vs. hypoxic area (square kilometers) off Western Louisiana (zones 16-17) (r^2=0.257, 0.054, n=15).

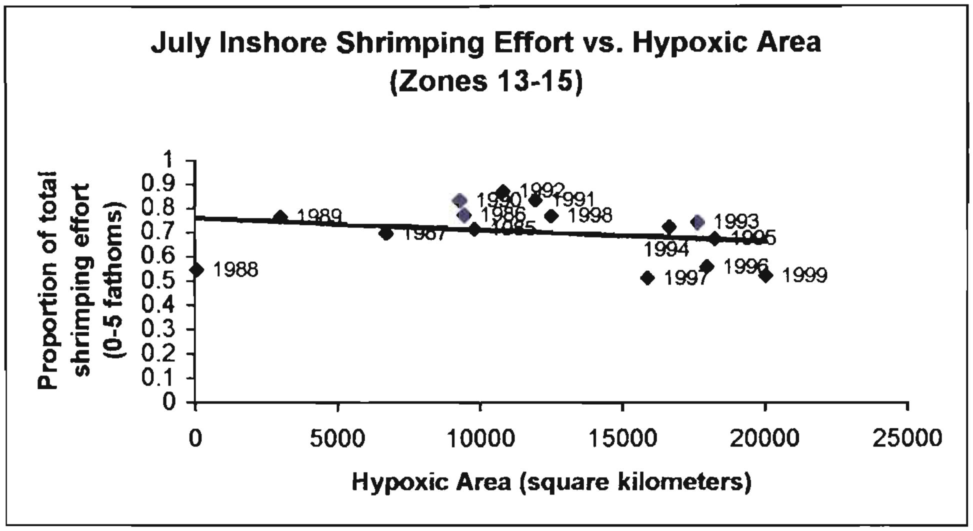


Figure 10a. July inshore shrimping effort (0-5 fathoms) vs. hypoxic area (square kilometers) off Eastern Louisiana (zones 13-15) (r^2=0.042, p=0.464, n=15).

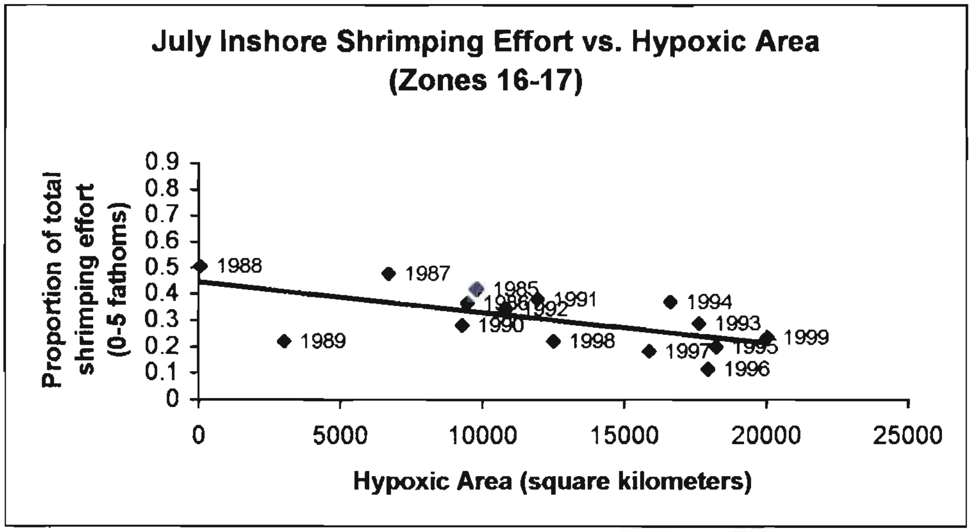


Figure 10b. July inshore shrimping effort (0-5 fathoms) vs. hypoxic area (square kilometers) off Western Louisiana (zones 16-17) (r^2=0.457, p=0.006, n=15).

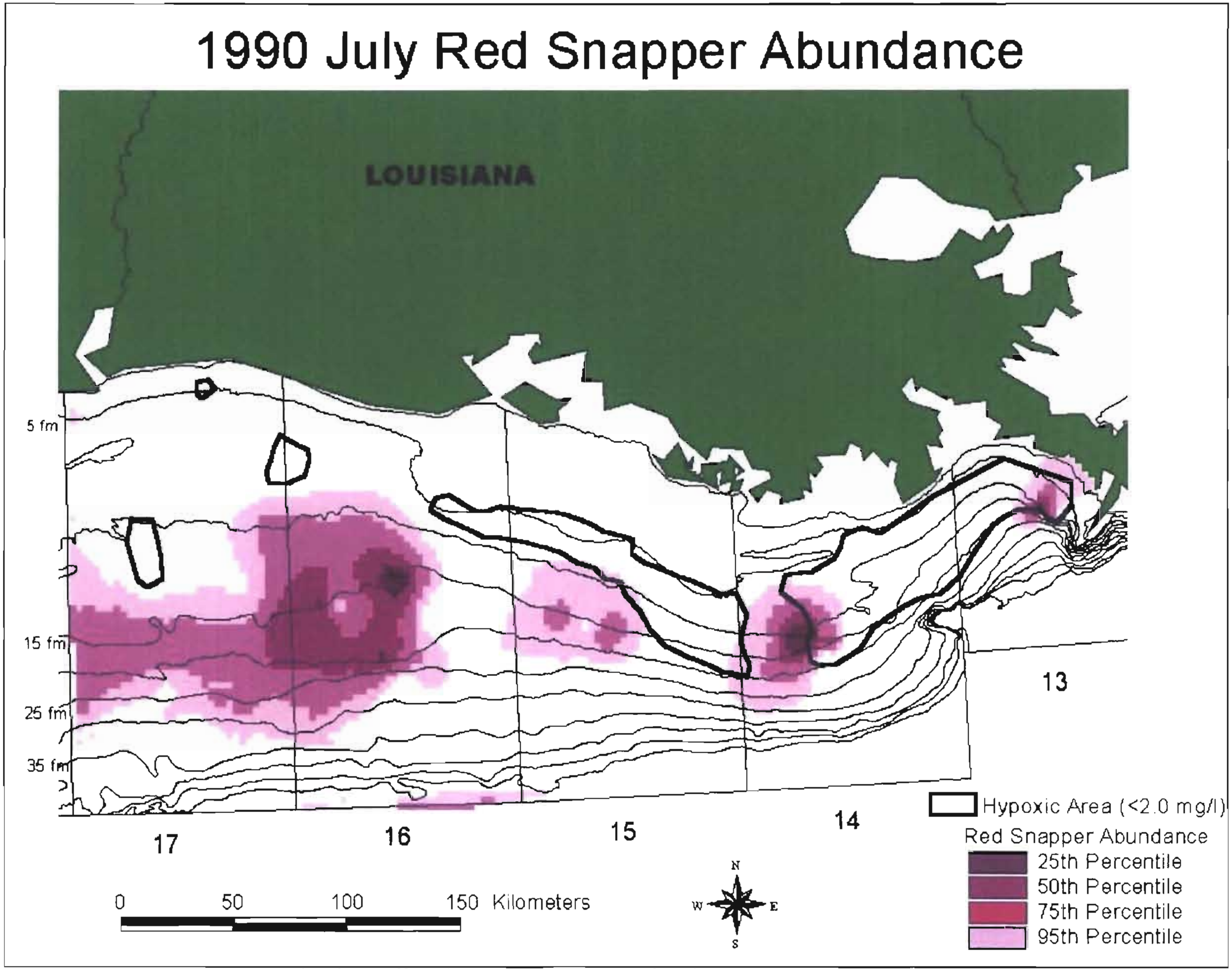


Figure 11a. 1990 July red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Darker purple areas represent greater red snapper abundance.

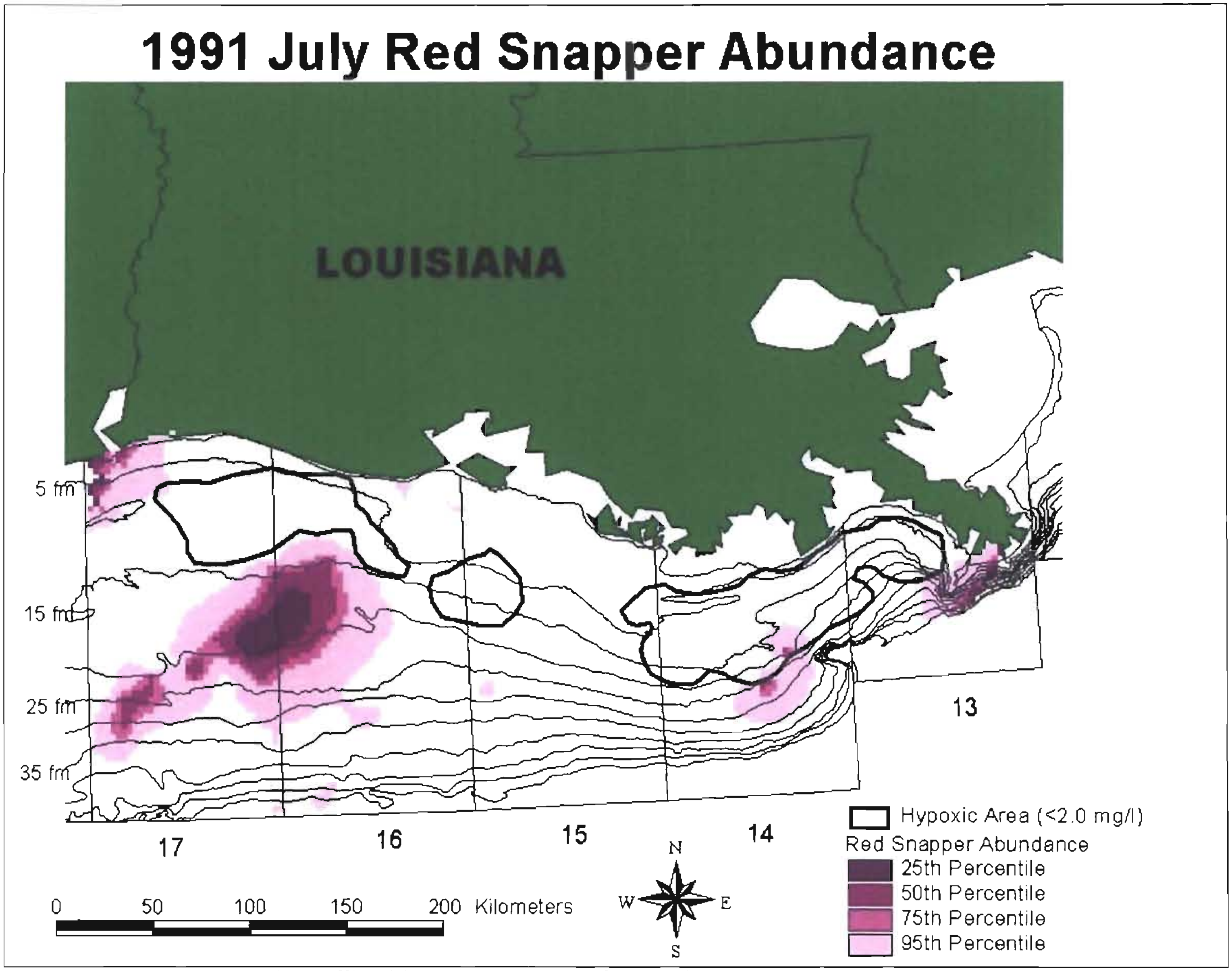


Figure 11b. 1991 July red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Darker purple areas represent greater red snapper abundance.

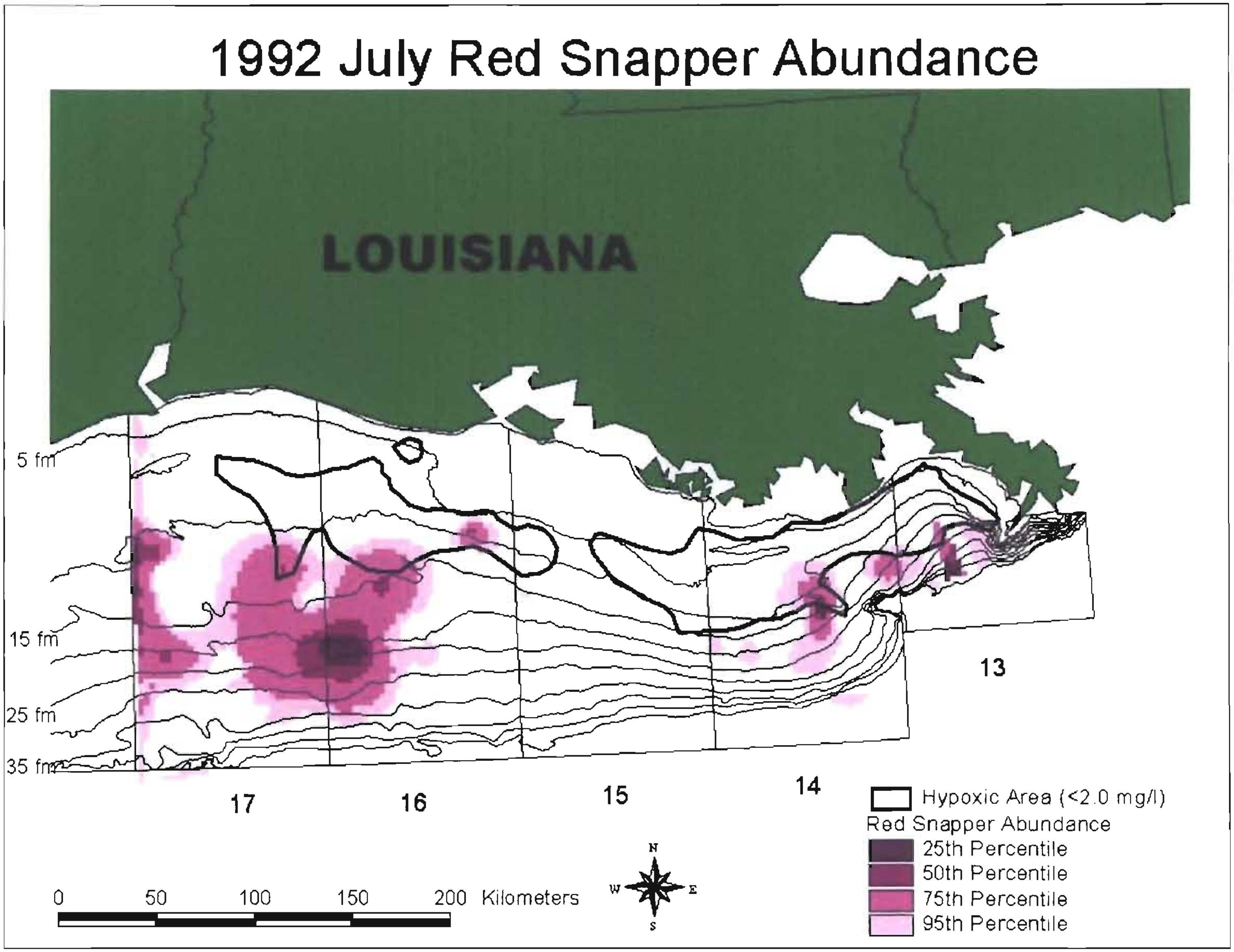


Figure 11c. 1992 July red snapper abundance off Louisiana (zones 13-17, from Patella 1975). Darker purple areas represent greater red snapper abundance.

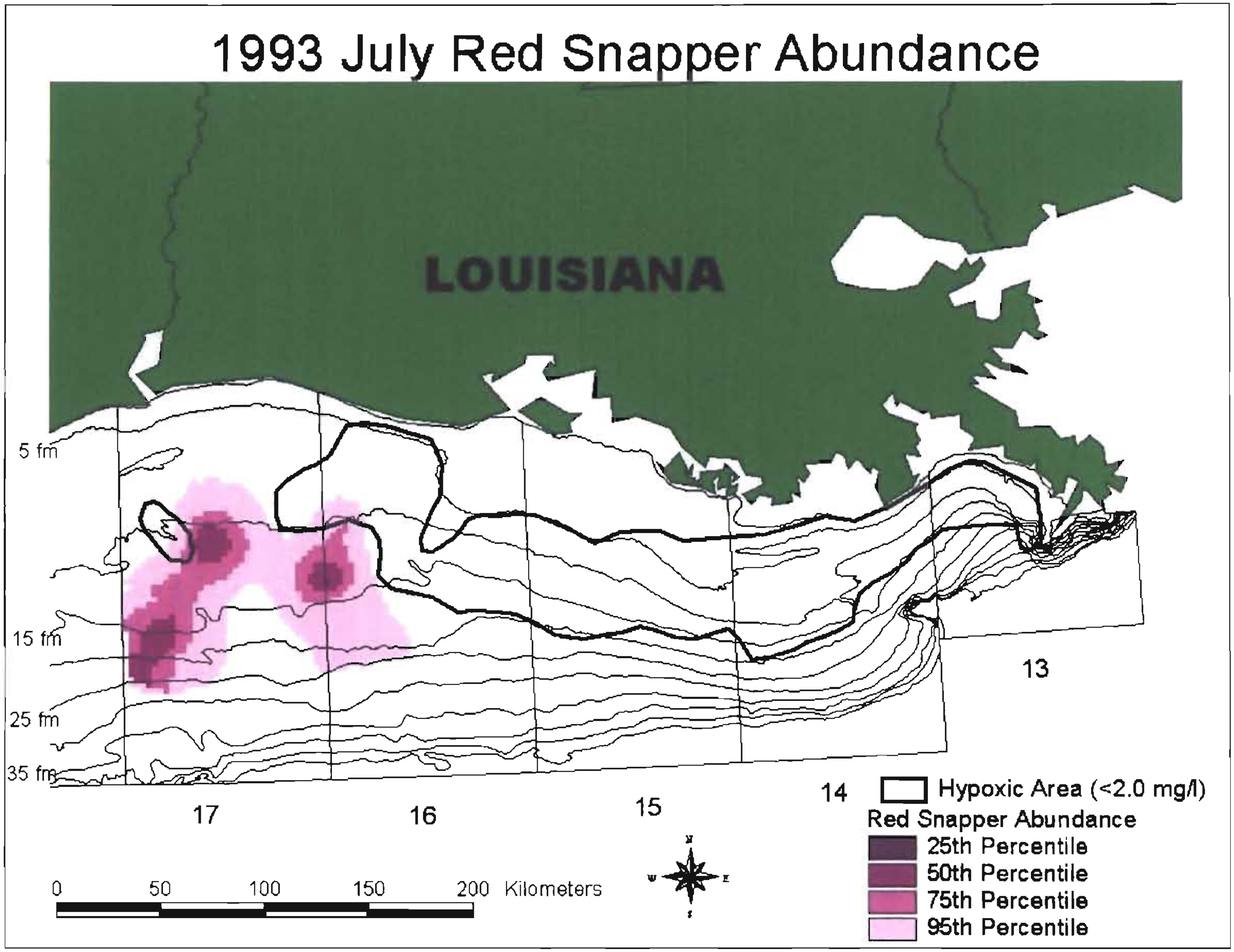


Figure 11d. 1993 July red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Darker purple areas represent greater red snapper abundance.

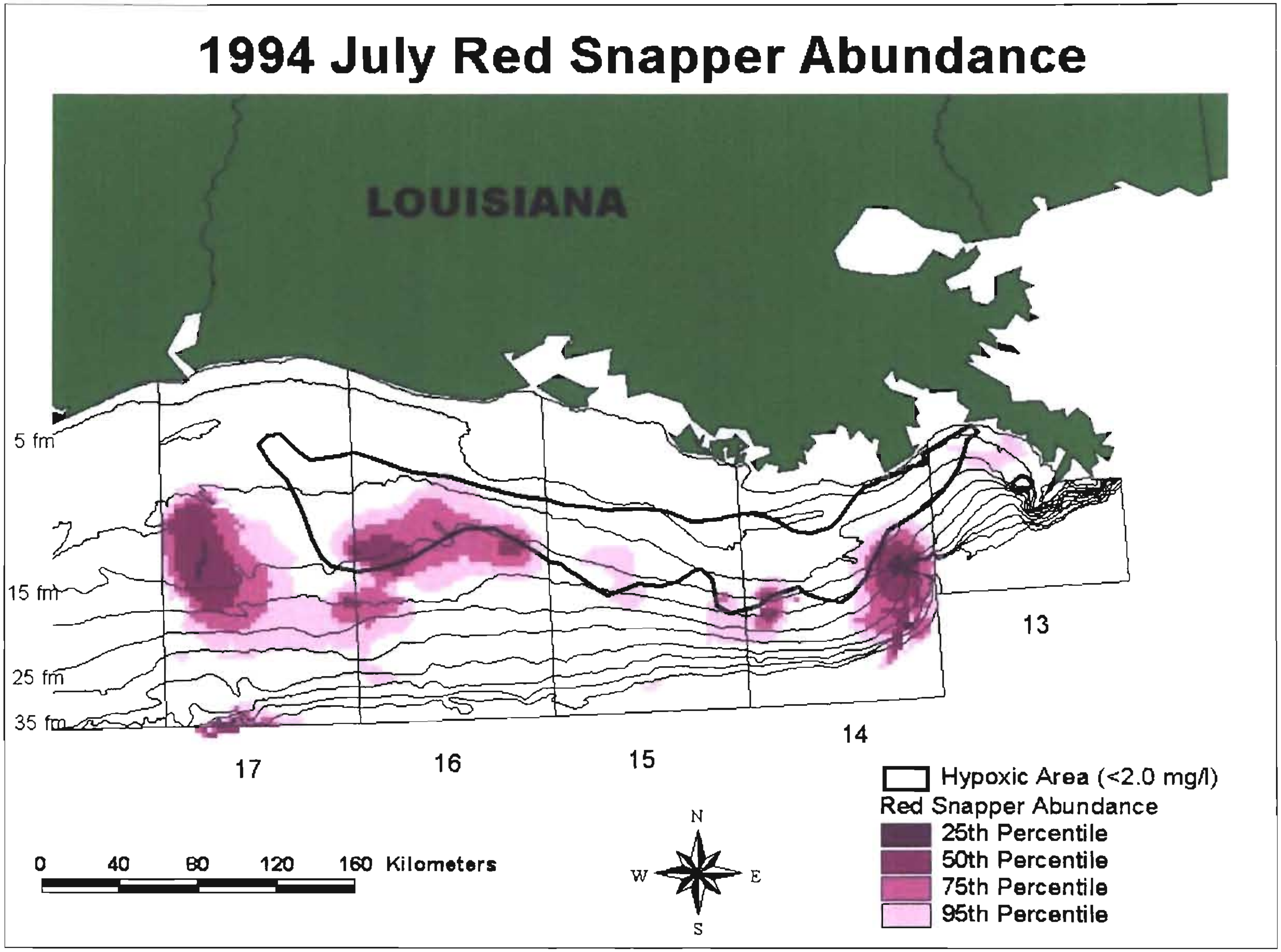


Figure 11e. 1994 July red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Darker purple areas represent greater red snapper abundance.

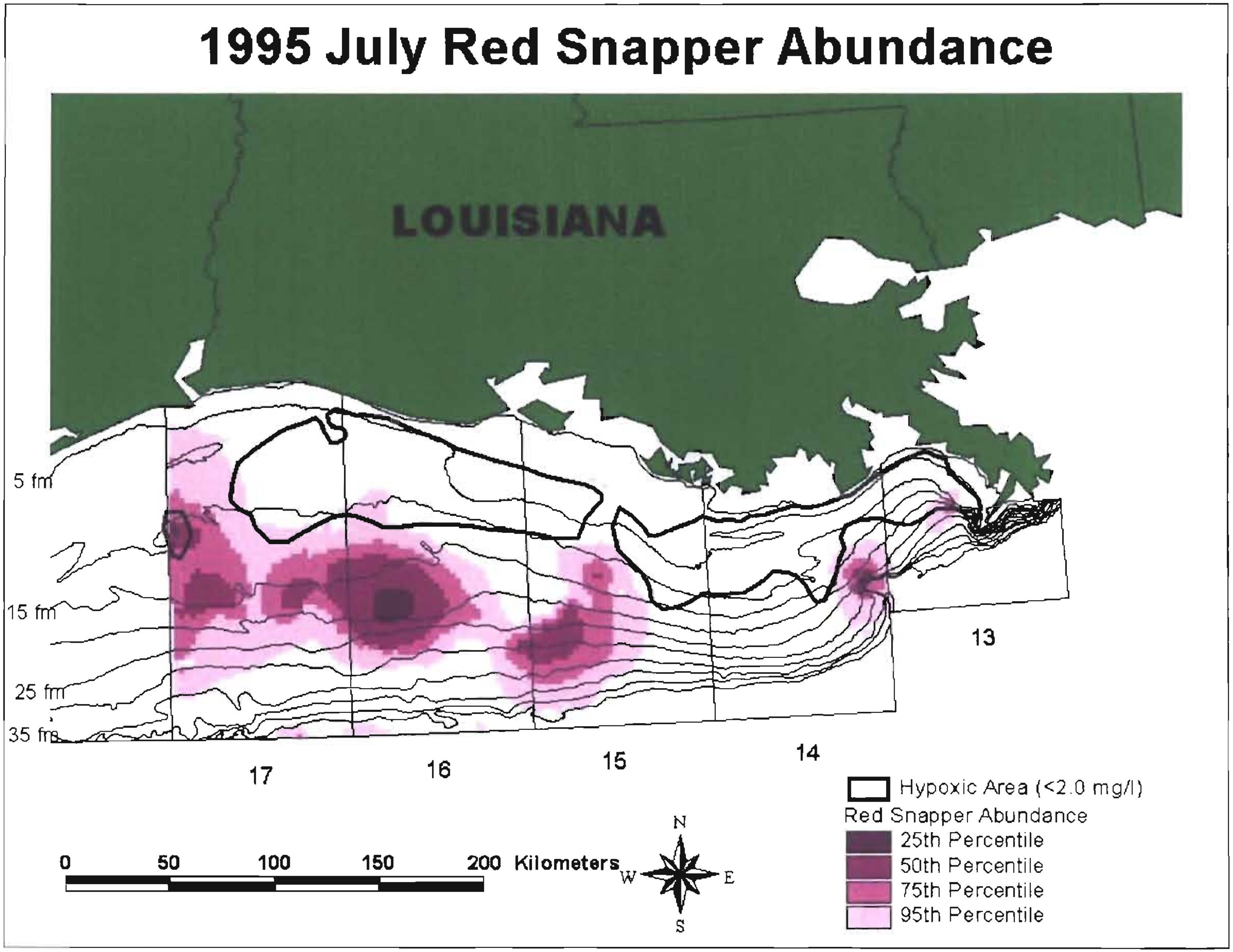


Figure 11f. 1995 July red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Darker purple areas represent greater red snapper abundance.

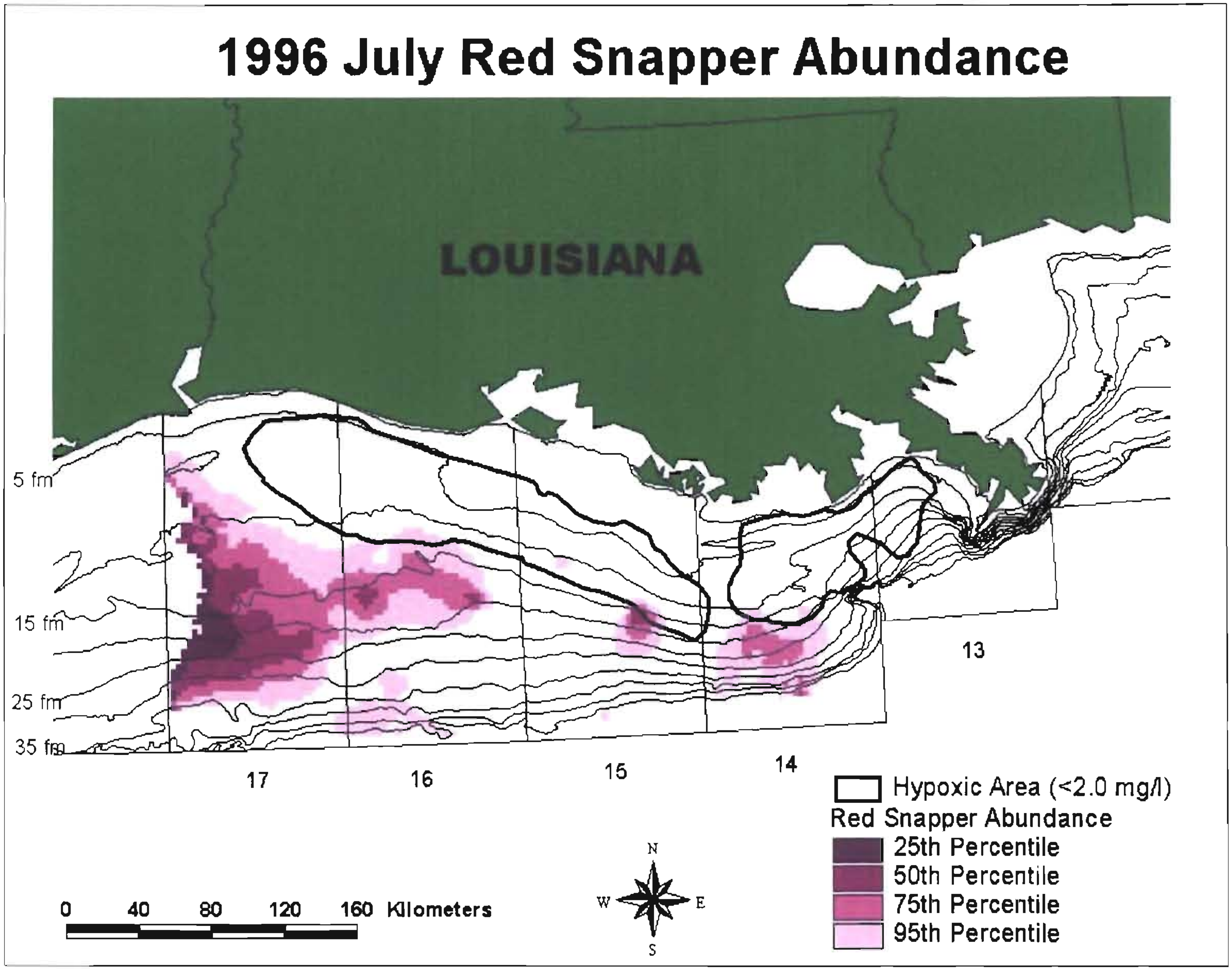


Figure 11g. 1996 July red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Darker purple areas represent greater red snapper abundance.

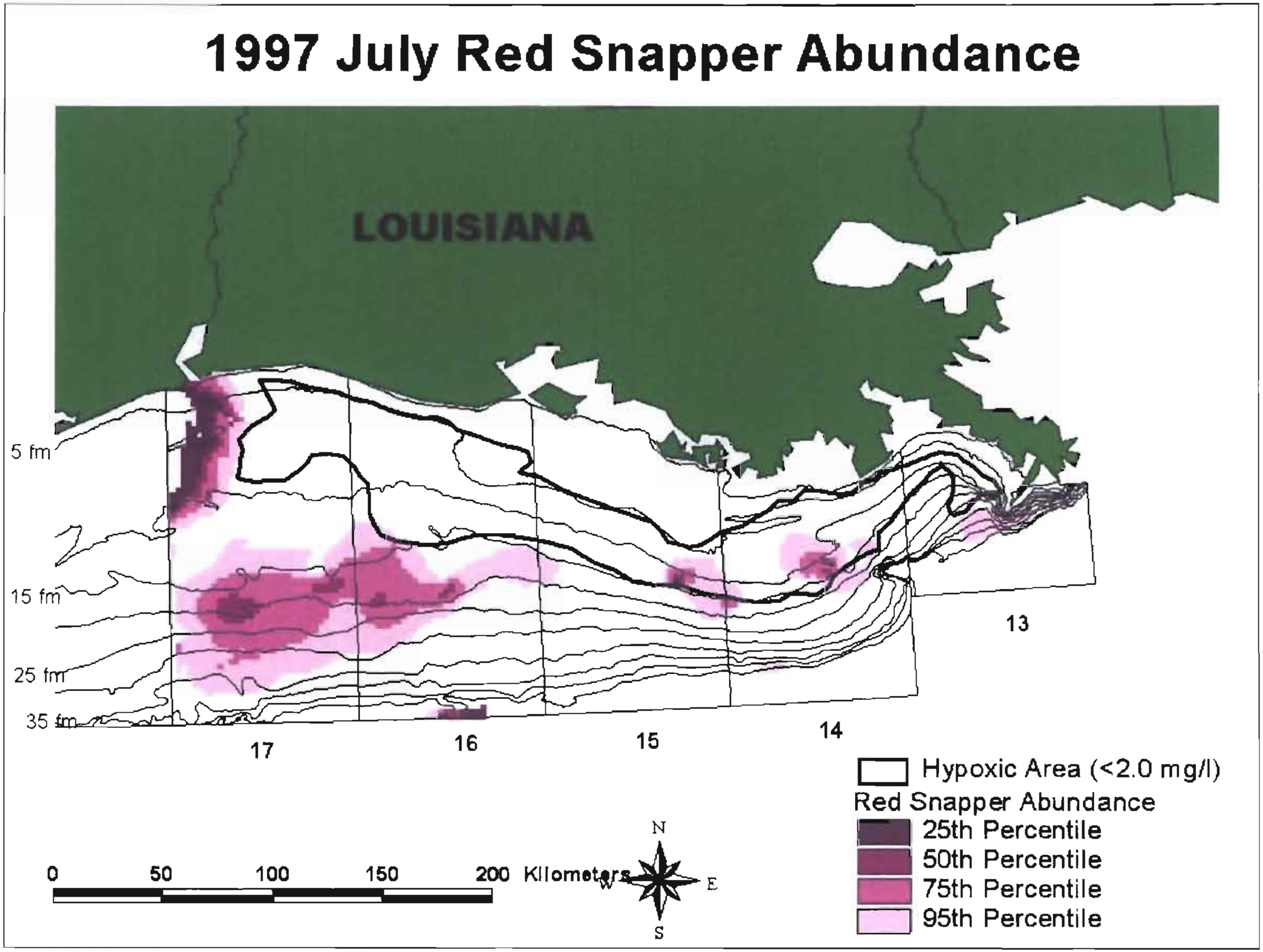


Figure 11h. 1997 July red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Darker purple areas represent greater red snapper abundance.

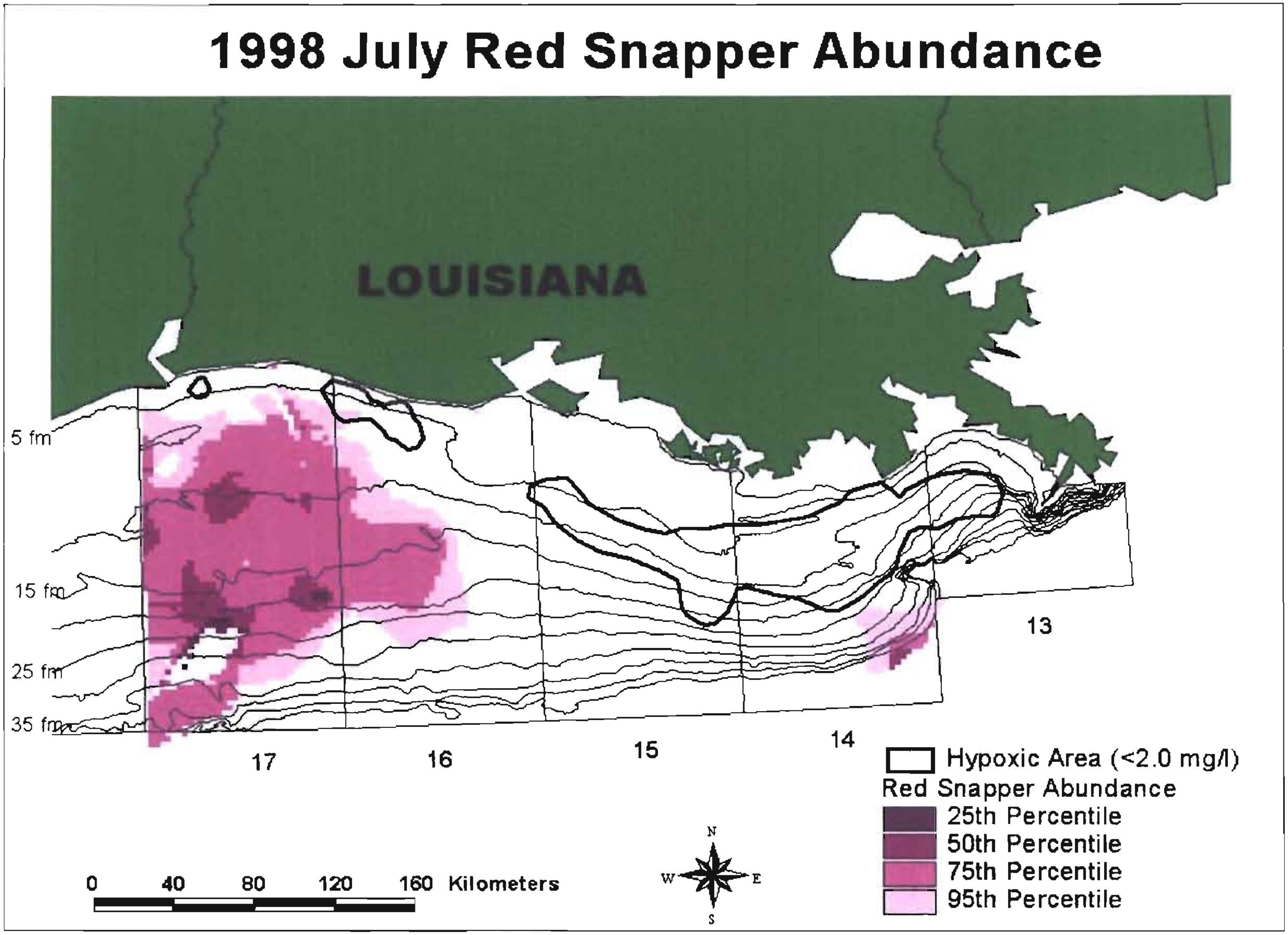


Figure 11i. 1998 July red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Darker purple areas represent greater red snapper abundance.

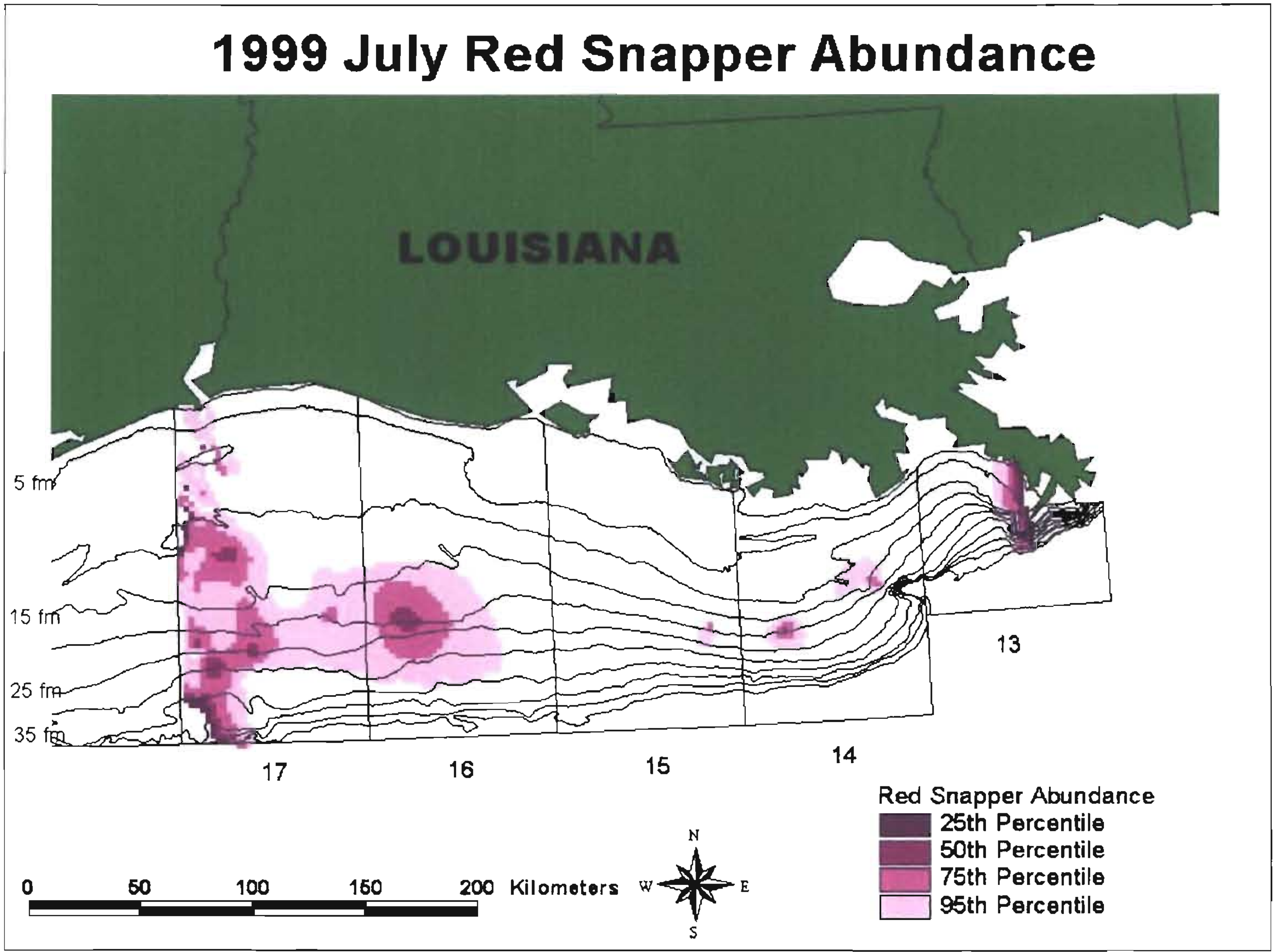


Figure 11j. 1999 July red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Darker purple areas represent greater red snapper abundance.

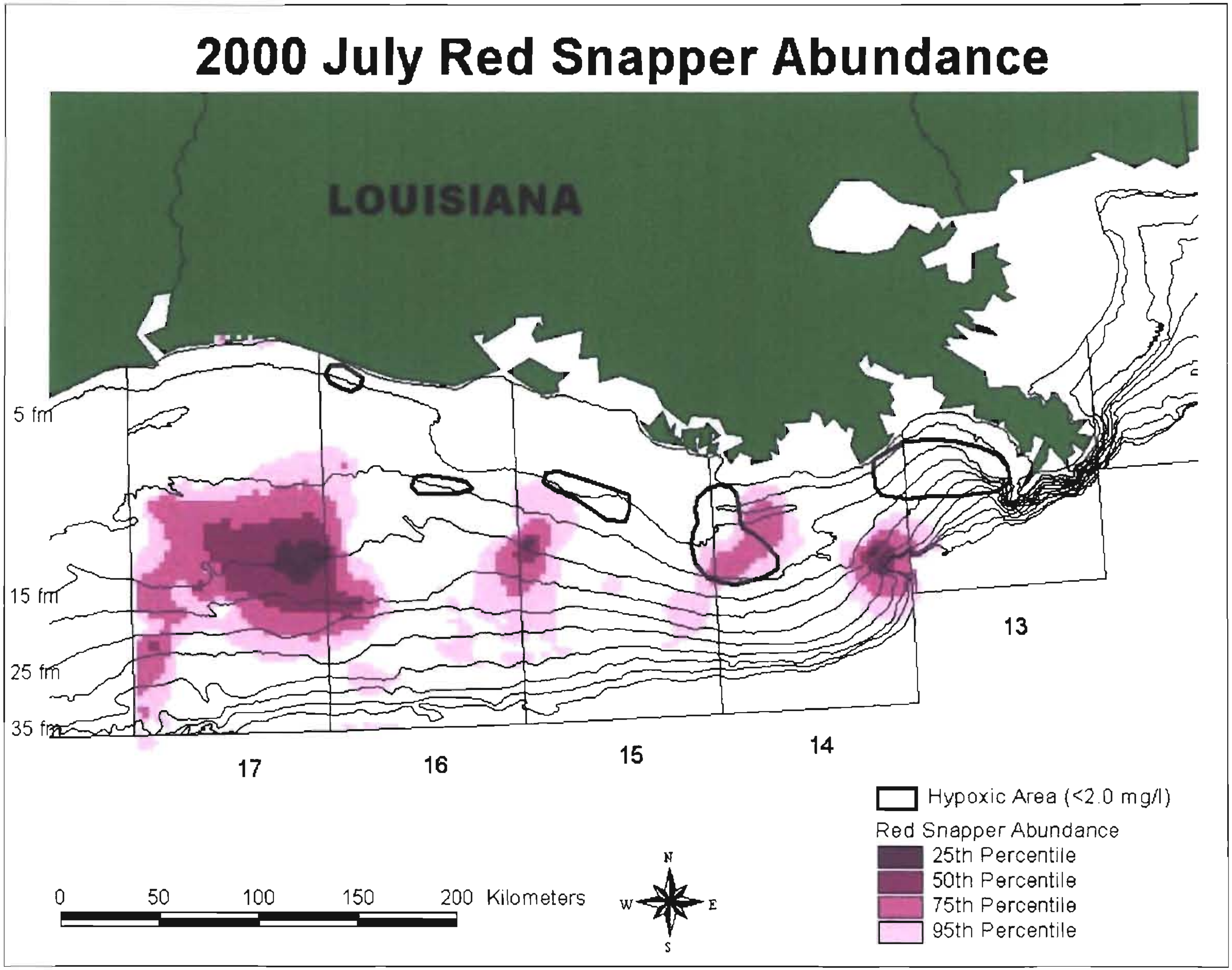


Figure 11k. 2000 July red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Darker purple areas represent greater red snapper abundance.

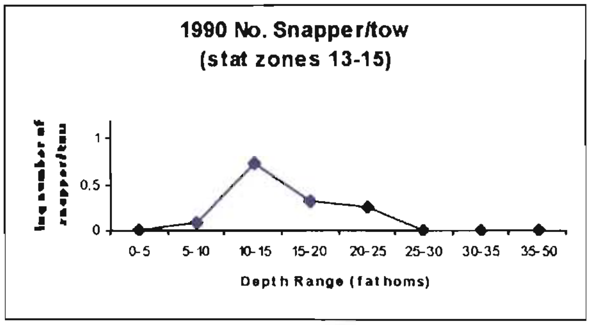


Figure 12a. 1990 log number of red snapper/tow versus depth for Eastern Louisiana (stat zones 13-15).

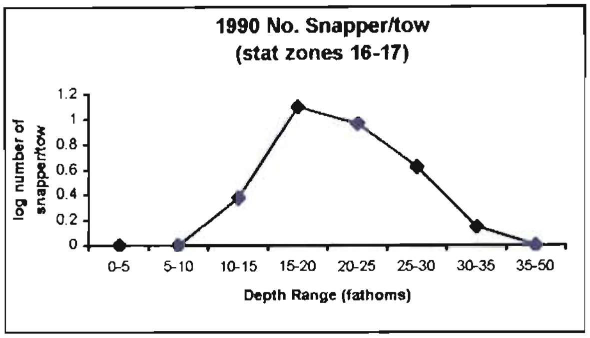


Figure 12a. 1990 log number of red snapper/tow versus depth for Western Louisiana (stat zones 13-15).

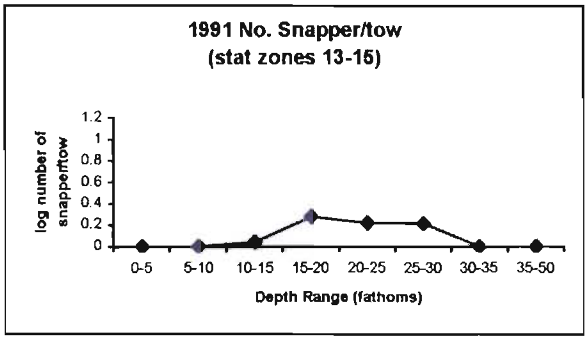


Figure 12b. 1991 log number of red snapper/tow versus depth for Eastern Louisiana (stat zones 13-15).

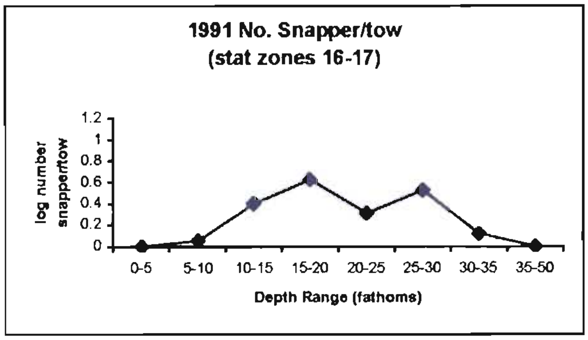


Figure 12b. 1991 log number of red snapper/tow versus depth for Western Louisiana (stat zones 13-15).

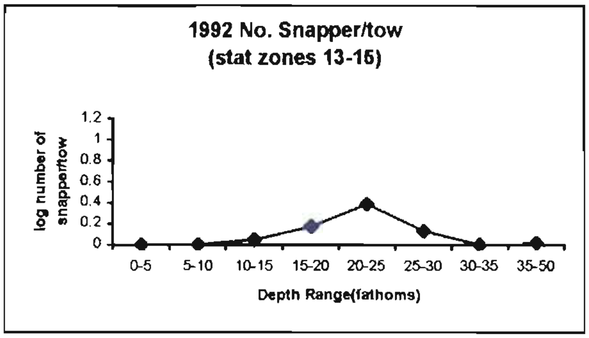


Figure 12c. 1992 log number of red snapper/tow versus depth for Eastern Louisiana (stat zones 13-15).

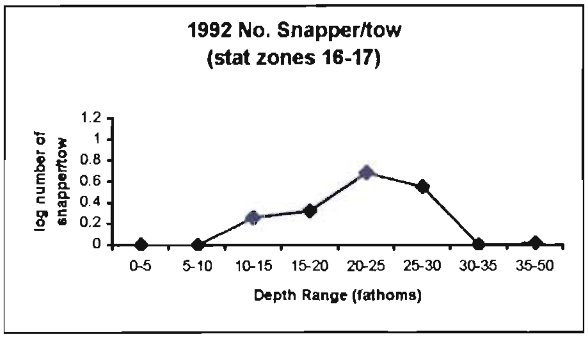


Figure 12c. 1992 log number of red snapper/tow versus depth for Western Louisiana (stat zones 16-17).

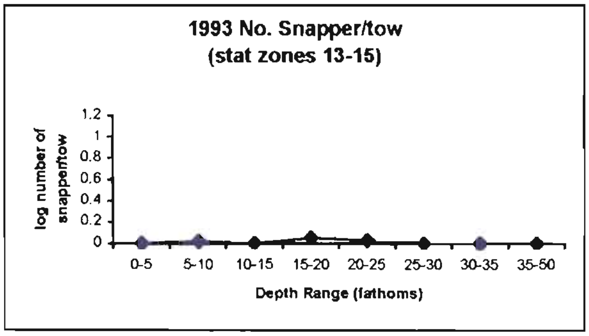


Figure 12d. 1993 log number of red snapper/tow versus depth for Eastern Louisiana (stat zones 13-15).

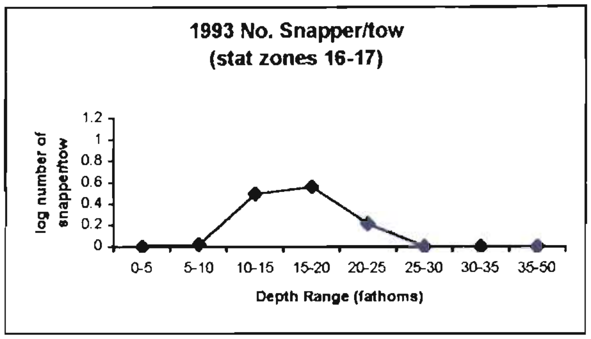


Figure 12d. 1993 log number of red snapper/tow versus depth for Western Louisiana (stat zones 16-17).

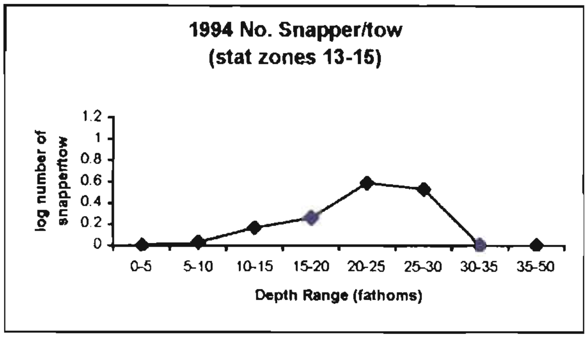


Figure 12e. 1994 log number of red snapper/tow versus depth for Eastern Louisiana (stat zones 13-15).

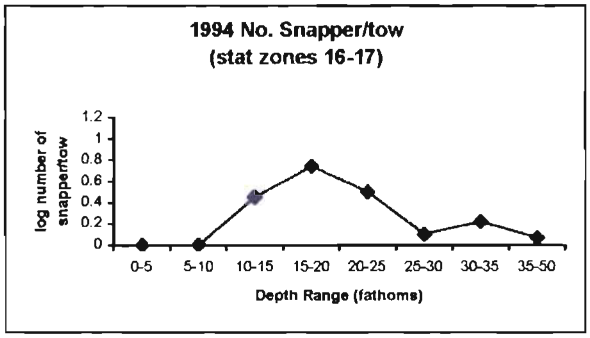


Figure 12e. 1994 log number of red snapper/tow versus depth for Western Louisiana (stat zones 16-17).

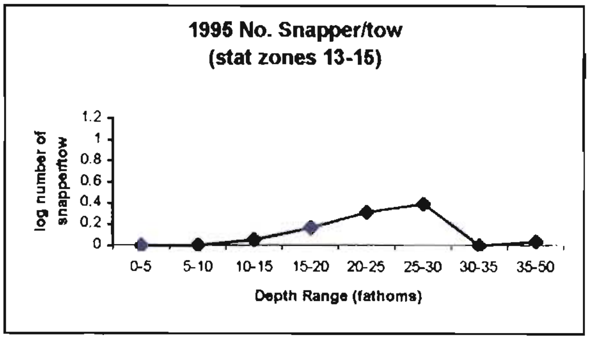


Figure 12f. 1995 log number of red snapper/tow versus depth for Eastern Louisiana (stat zones 13-15).

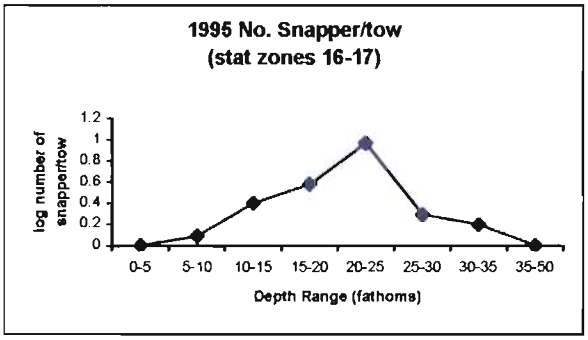


Figure 12f. 1995 log number of red snapper/tow versus depth for Western Louisiana (stat zones 16-17).

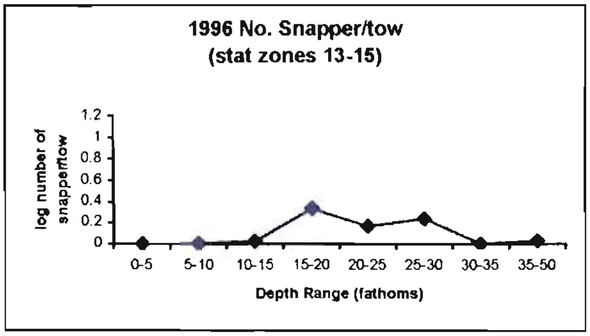


Figure 12g. 1996 log number of red snapper/tow versus depth for Eastern Louisiana (stat zones 13-15).

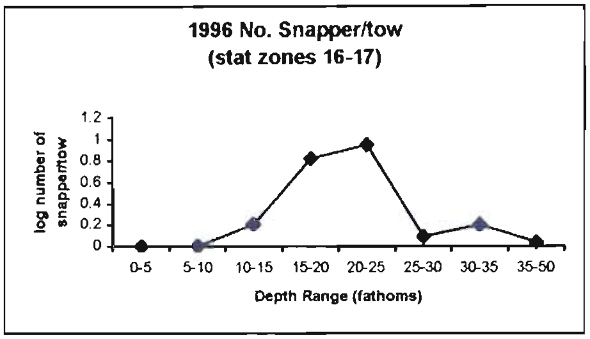


Figure 12g. 1996 log number of red snapper/tow versus depth for Western Louisiana (stat zones 16-17).

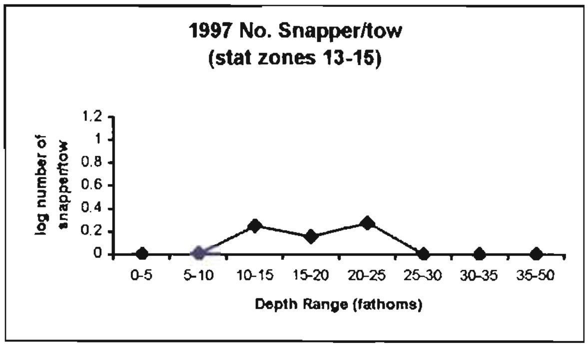


Figure 12h. 1997 log number of red snapper/tow versus depth for Eastern Louisiana (stat zones 13-15).

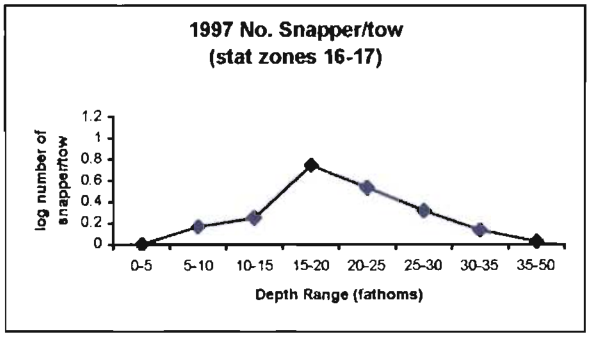


Figure 12h. 1997 log number of red snapper/tow versus depth for Western Louisiana (stat zones 16-17).

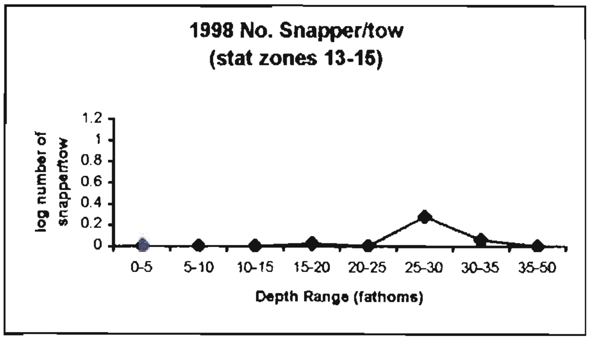


Figure 12i. 1998 log number of red snapper/tow versus depth for Eastern Louisiana (stat zones 13-15).

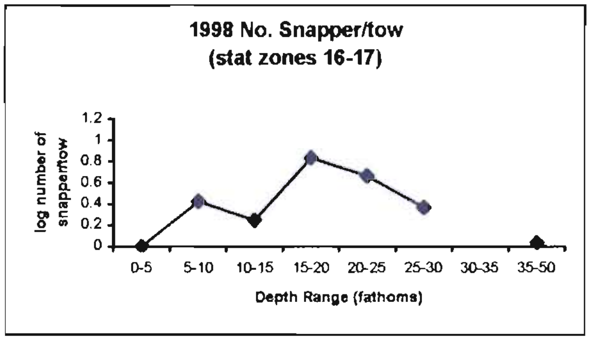


Figure 12i. 1998 log number of red snapper/tow versus depth for Western Louisiana (stat zones 16-17).

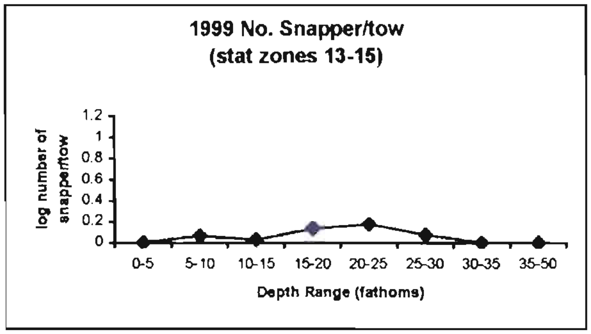


Figure 12j. 1999 log number of red snapper/tow versus depth for Eastern Louisiana (stat zones 13-15).

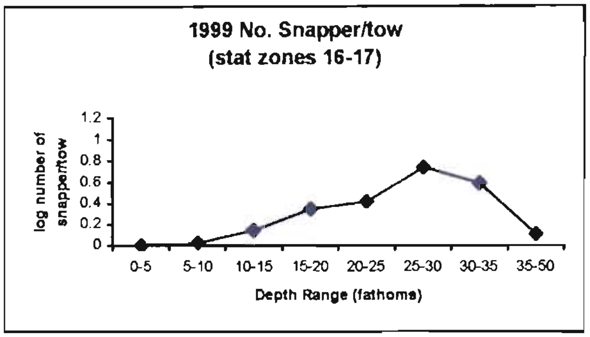


Figure 12j. 1999 log number of red snapper/tow versus depth for Western Louisiana (stat zones 16-17).

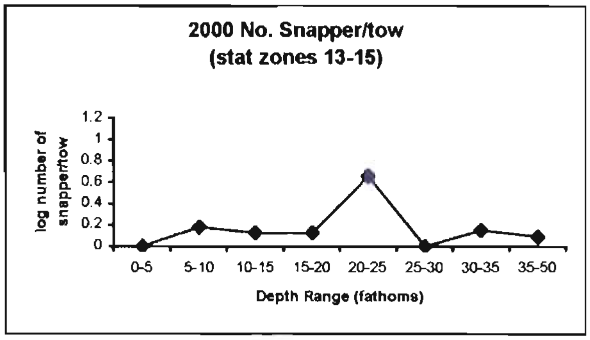


Figure 12k. 2000 log number of red snapper/tow versus depth for Eastern Louisiana (stat zones 13-15).

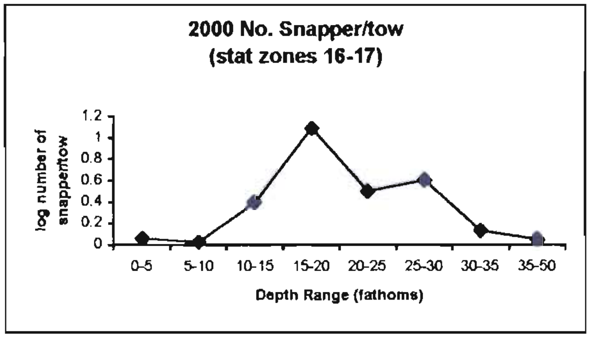


Figure 12k. 2000 log number of red snapper/tow versus depth for Western Louisiana (stat zones 16-17).

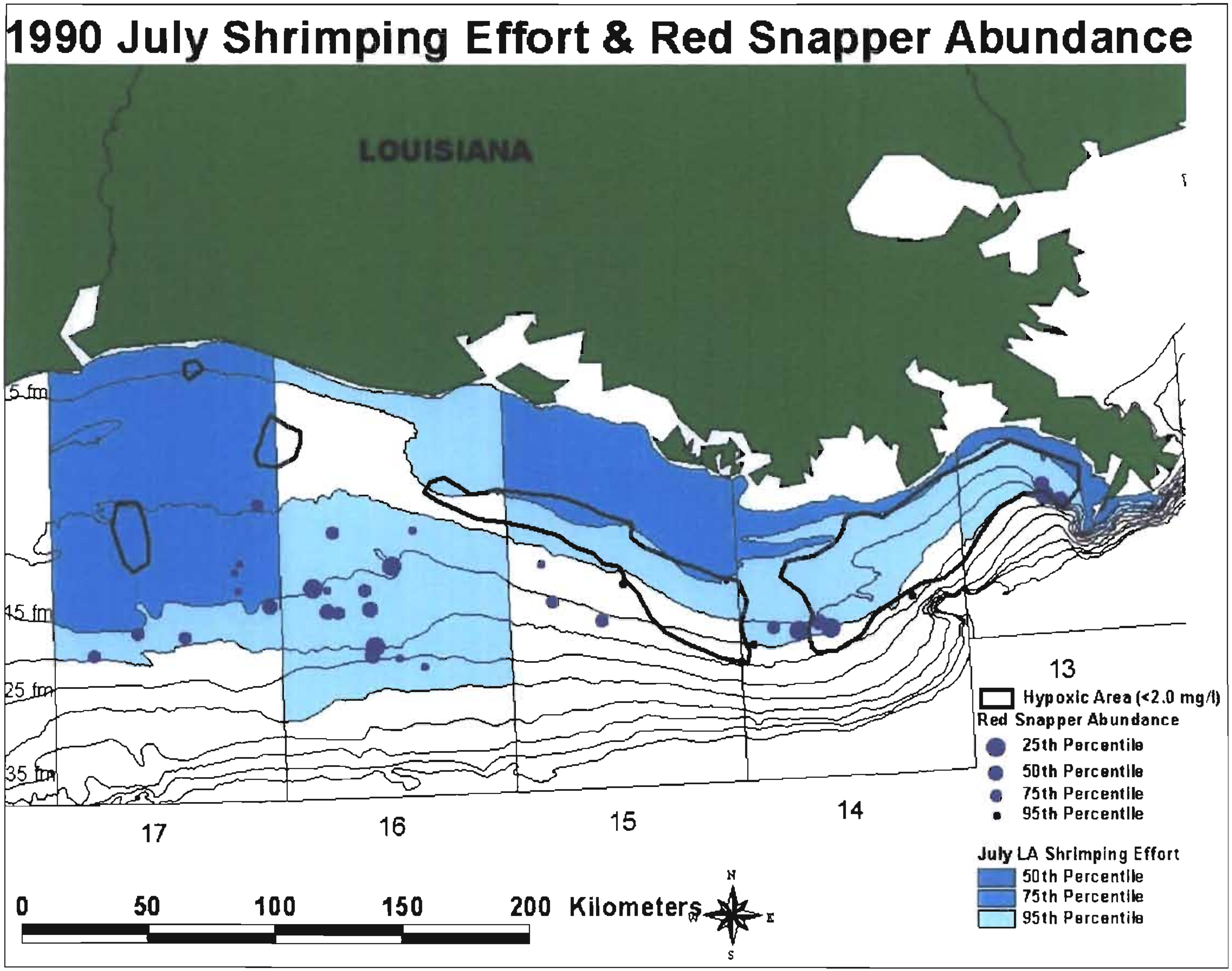


Figure 13a. July 1990 shrimping effort and red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Larger circles indicate greater red snapper abundance while darker aqua indicates greater shrimping effort.

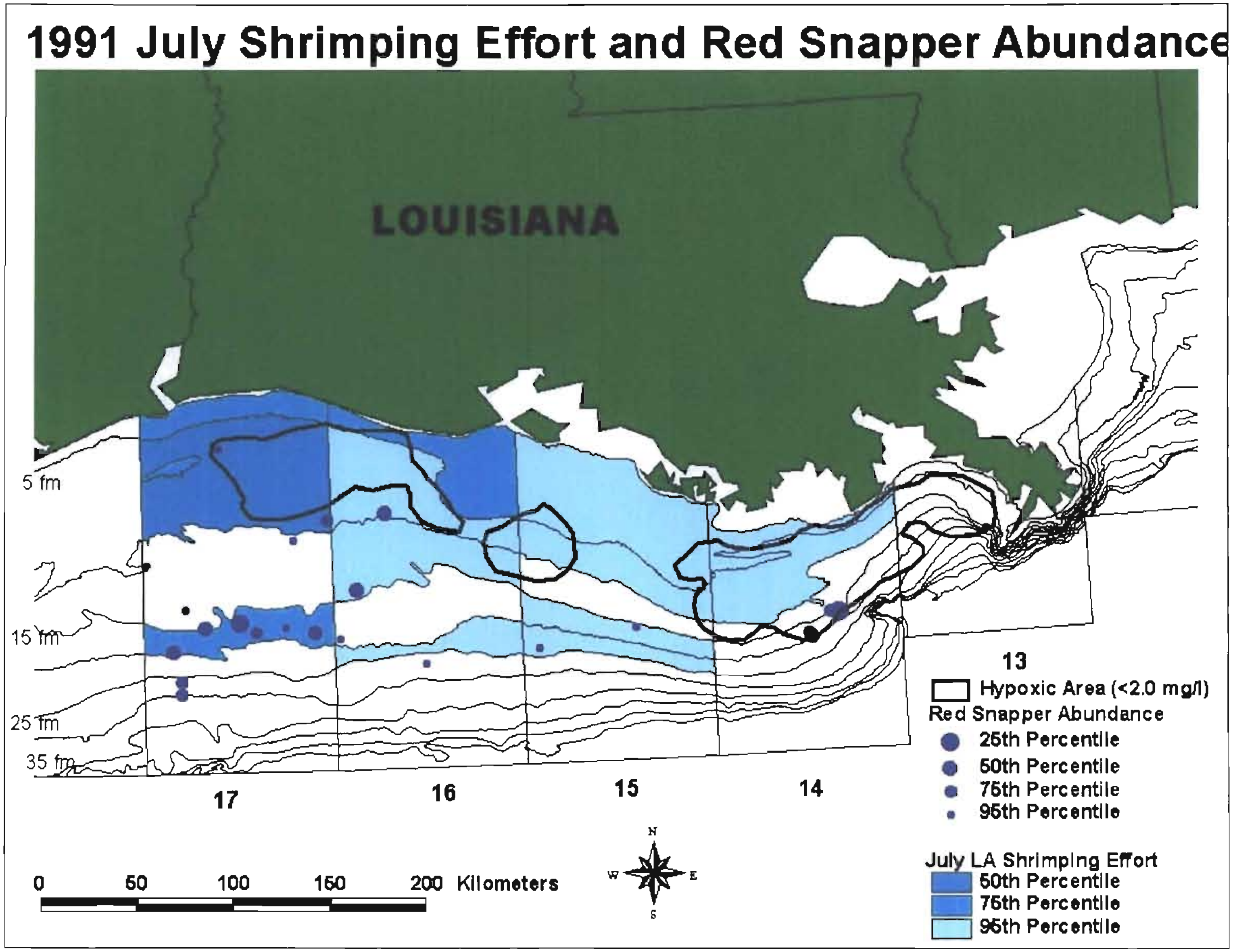


Figure 13b. July 1991 shrimping effort and red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Larger circles indicate greater red snapper abundance while darker aqua indicates greater shrimping effort.

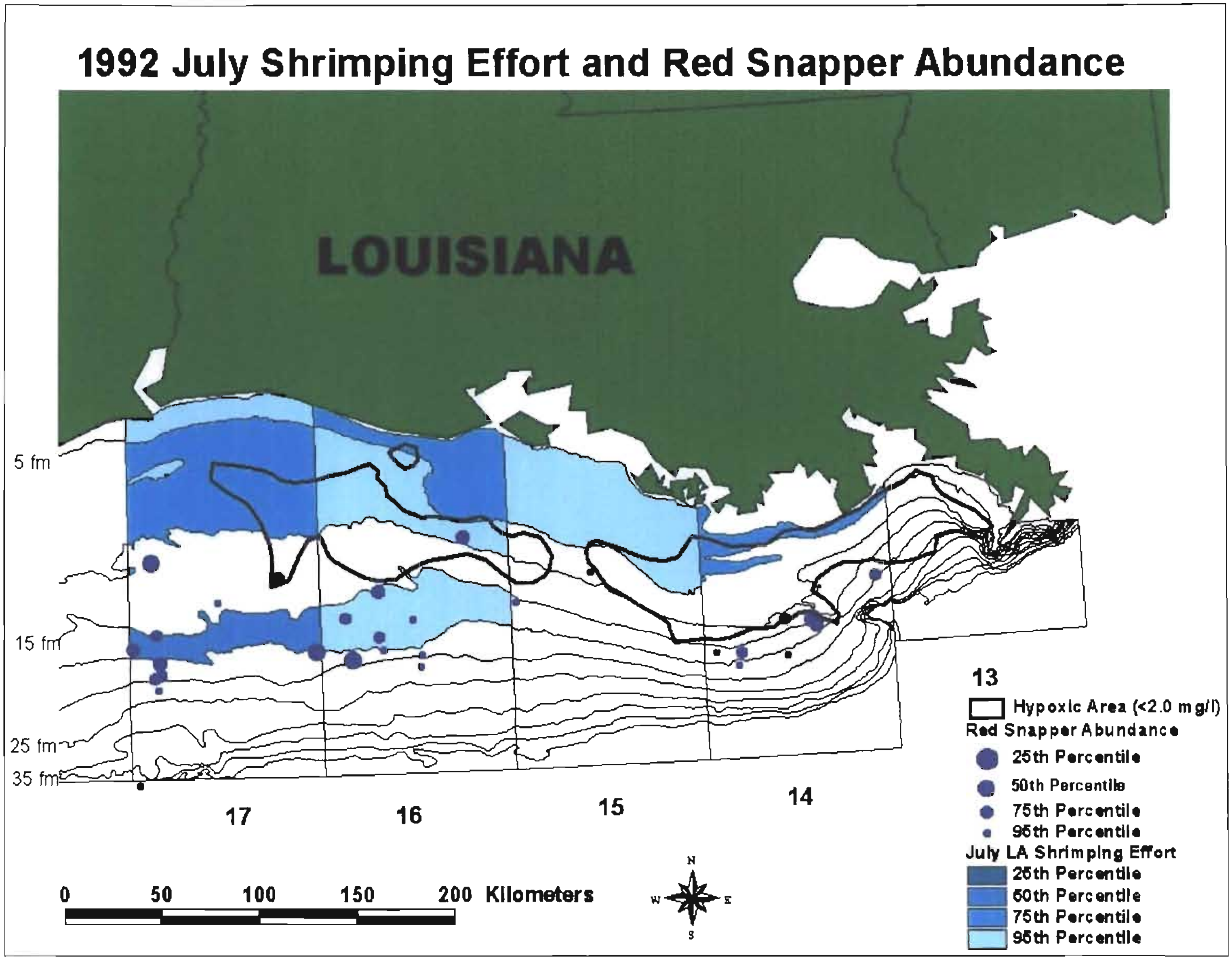


Figure 13c. July 1992 shrimping effort and red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Larger circles indicate greater red snapper abundance while darker aqua indicates greater shrimping effort.

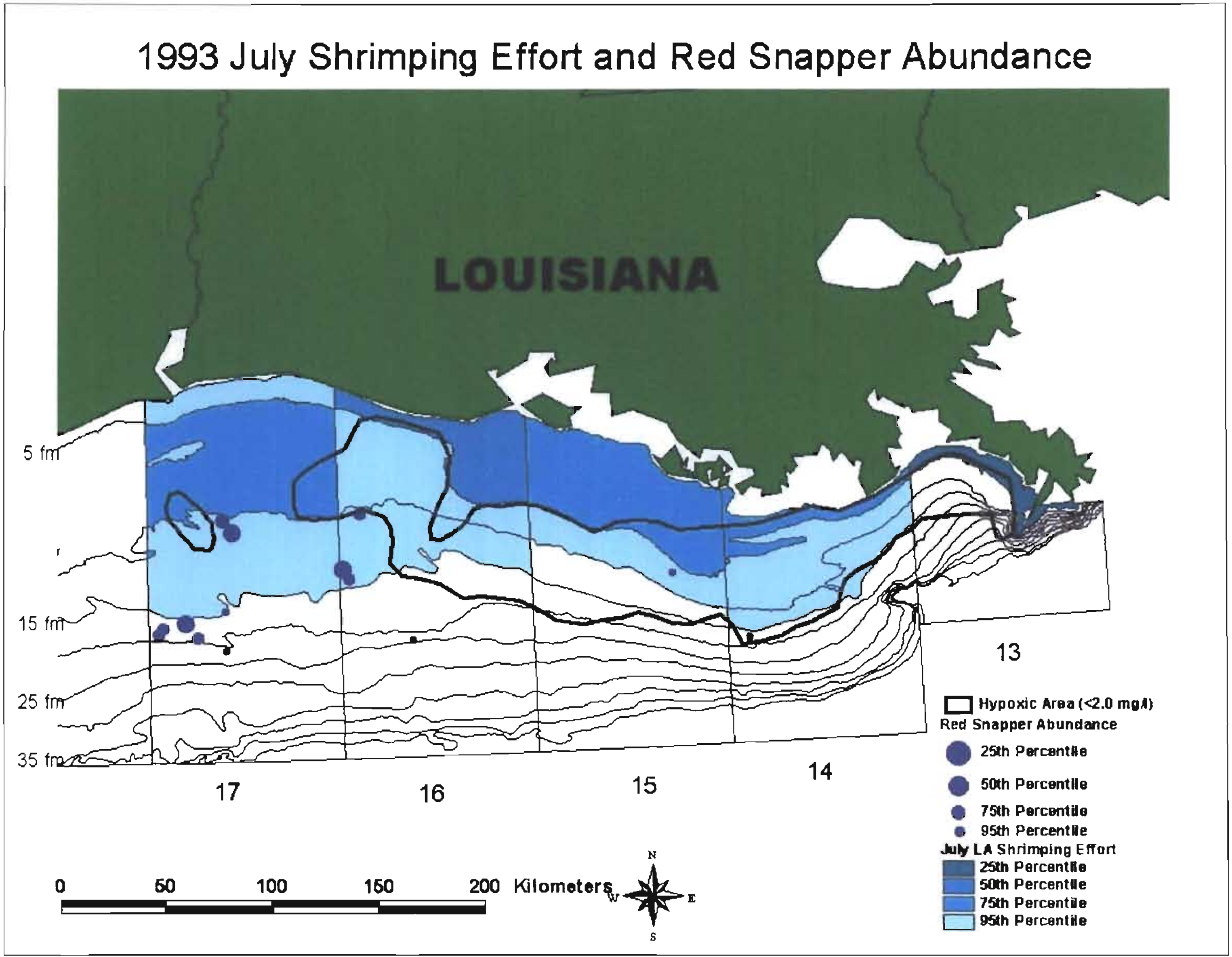


Figure 13d. July 1993 shrimping effort and red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Larger circles indicate greater red snapper abundance while darker aqua indicates greater shrimping effort.

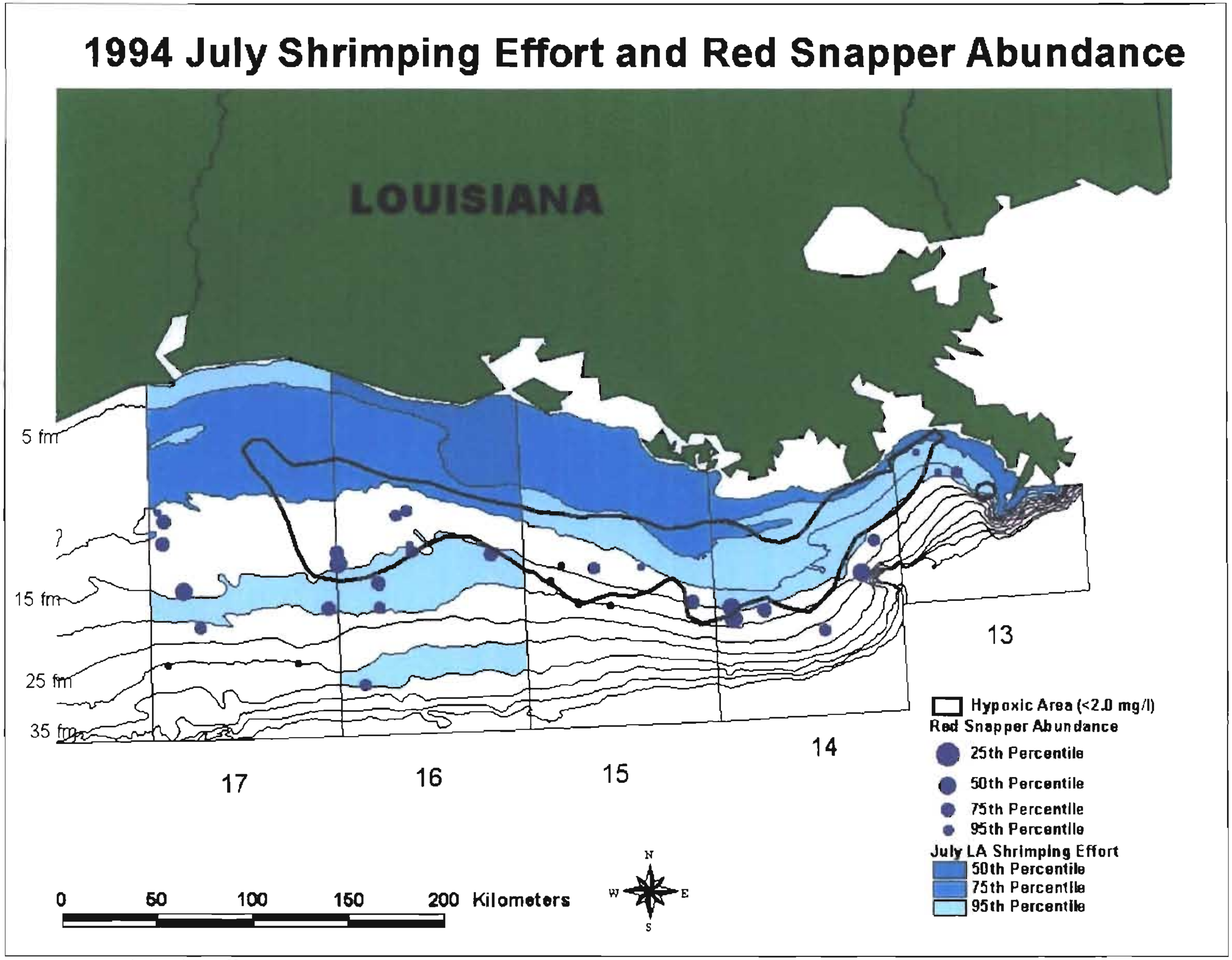


Figure 13e. July 1994 shrimping effort and red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Larger circles indicate greater red snapper abundance while darker aqua indicates greater shrimping effort.

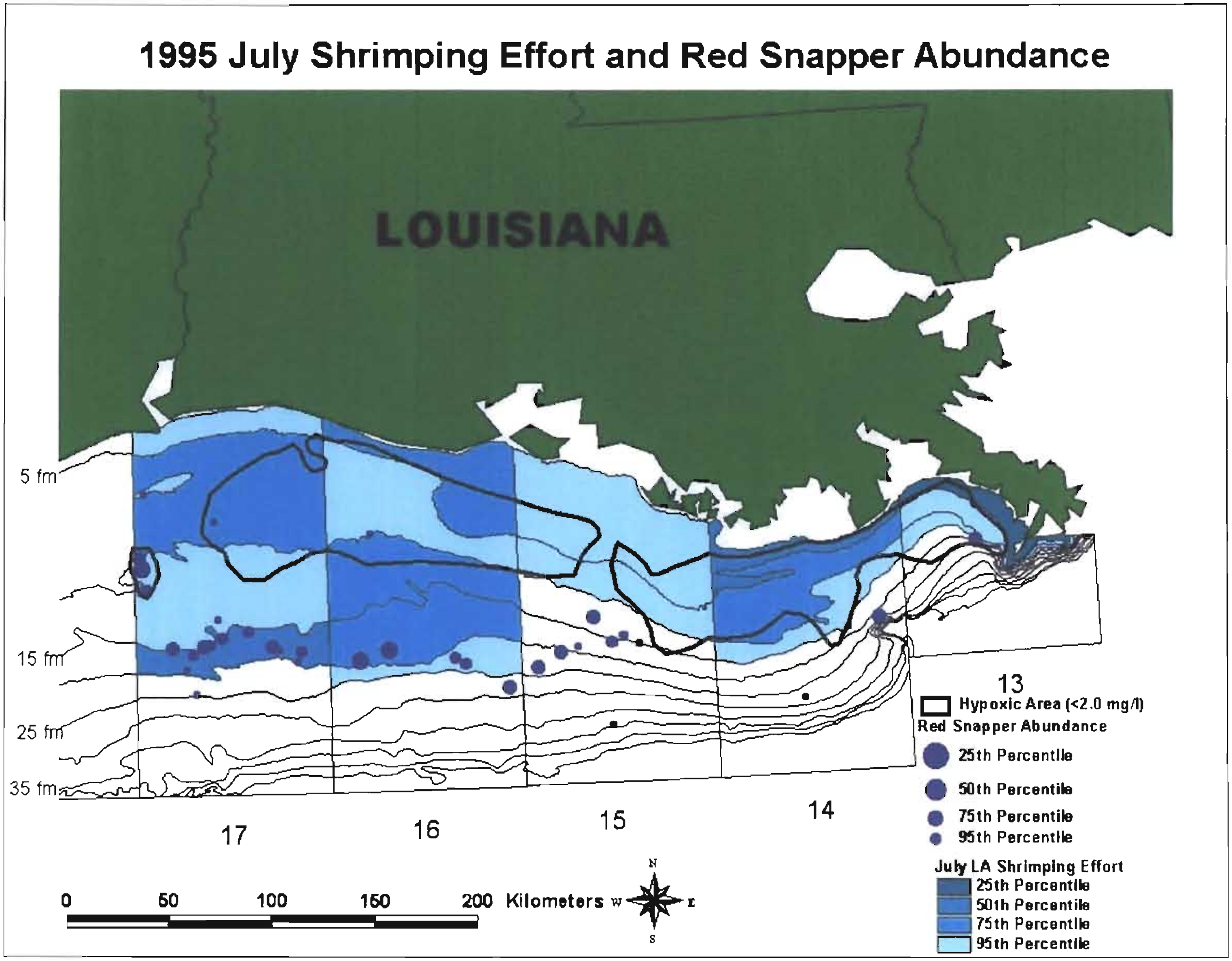


Figure 13f. July 1995 shrimping effort and red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Larger circles indicate greater red snapper abundance while darker aqua indicates greater shrimping effort.

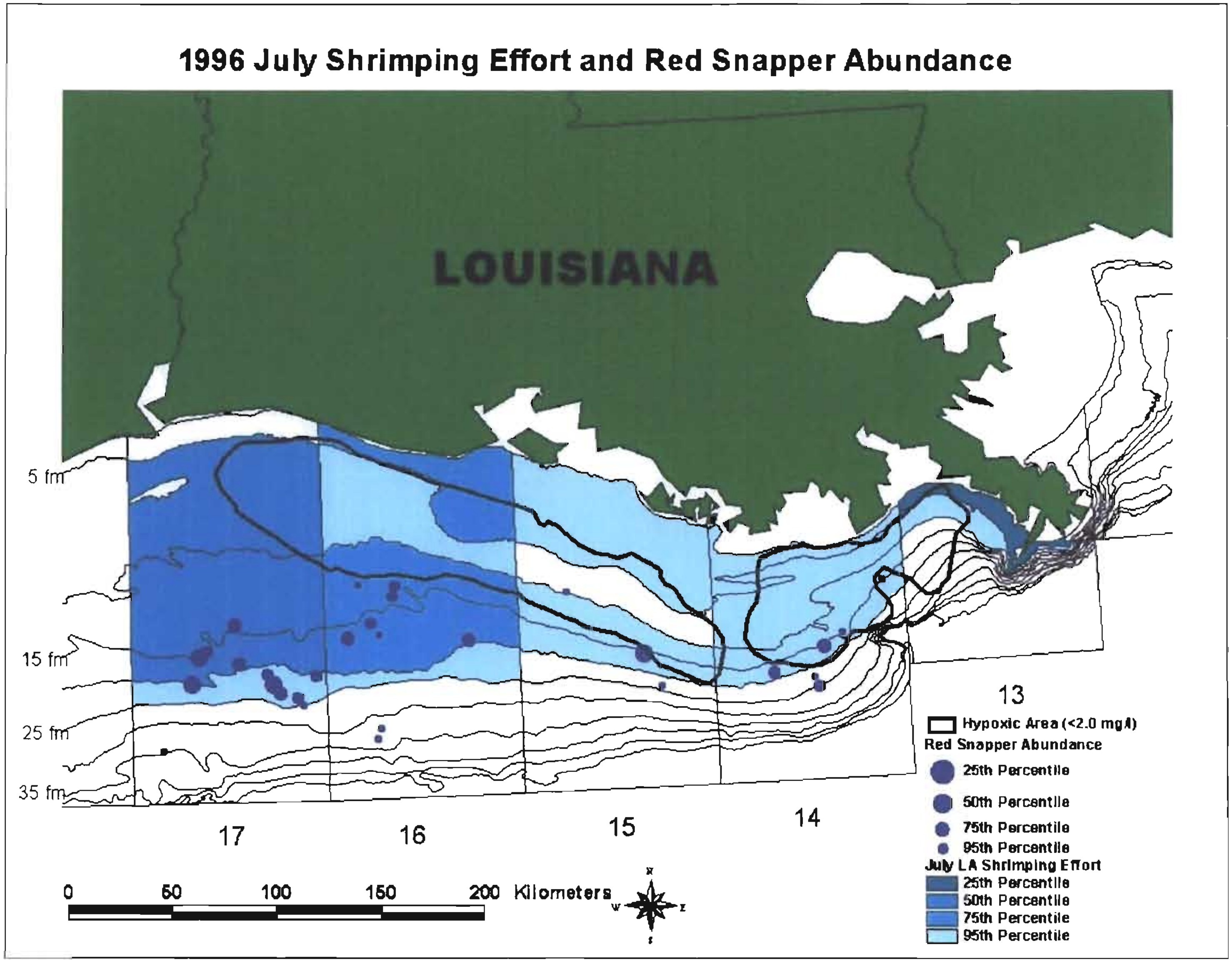


Figure 13g. July 1996 shrimping effort and red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Larger circles indicate greater red snapper abundance while darker aqua indicates greater shrimping effort.

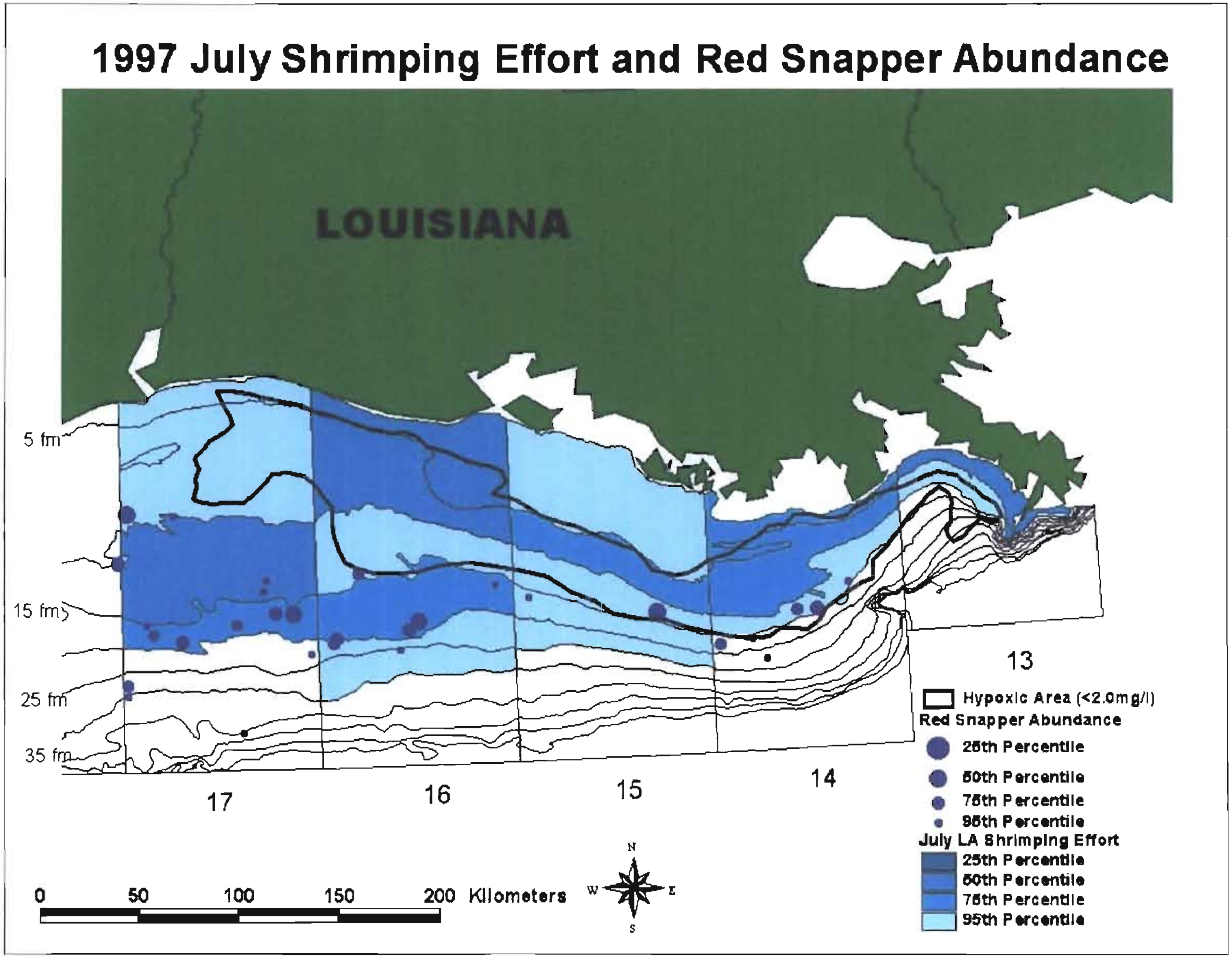


Figure 13h. July 1997 shrimping effort and red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Larger circles indicate greater red snapper abundance while darker aqua indicates greater shrimping effort.

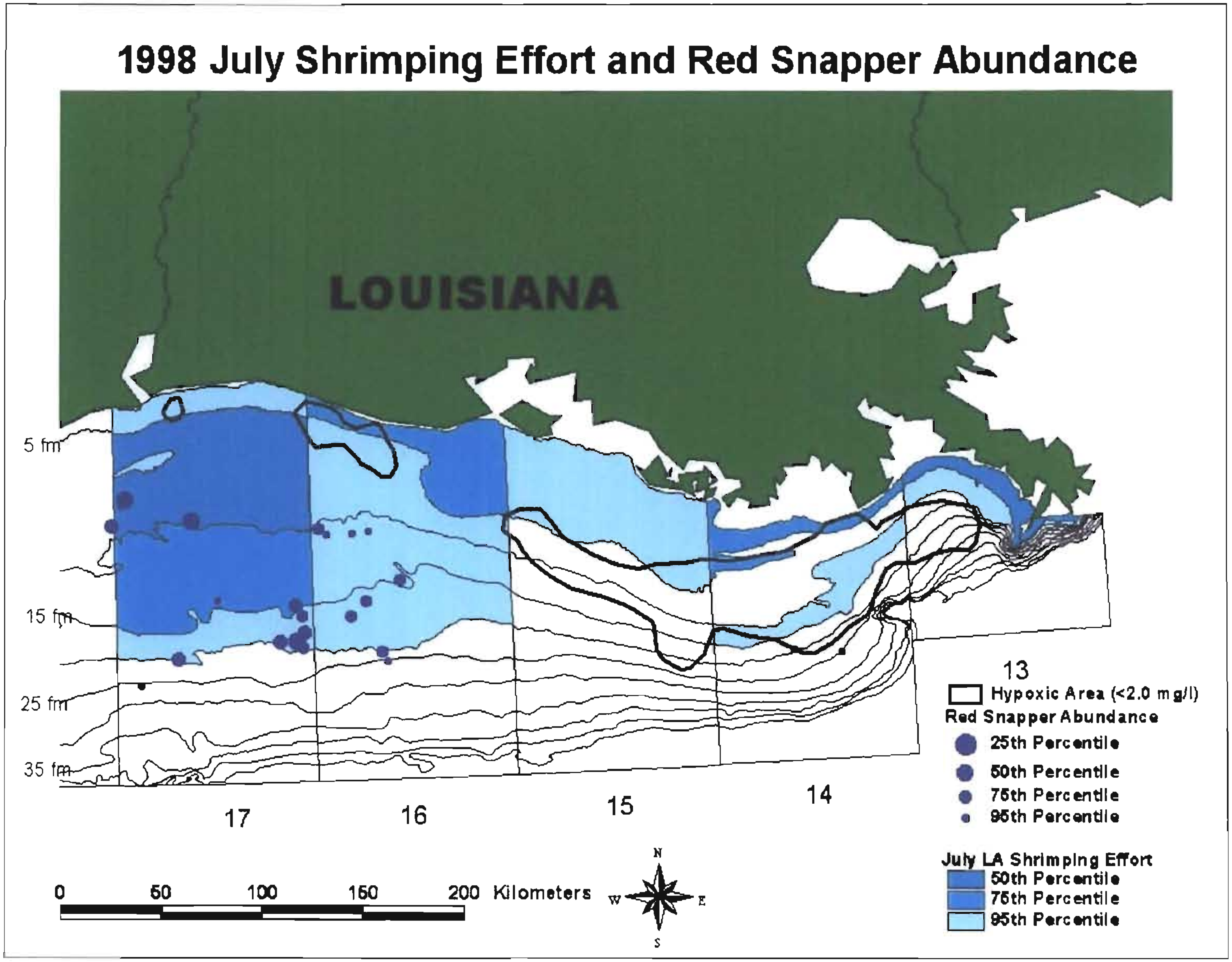


Figure 13i. July 1998 shrimping effort and red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Larger circles indicate greater red snapper abundance while darker aqua indicates greater shrimping effort.

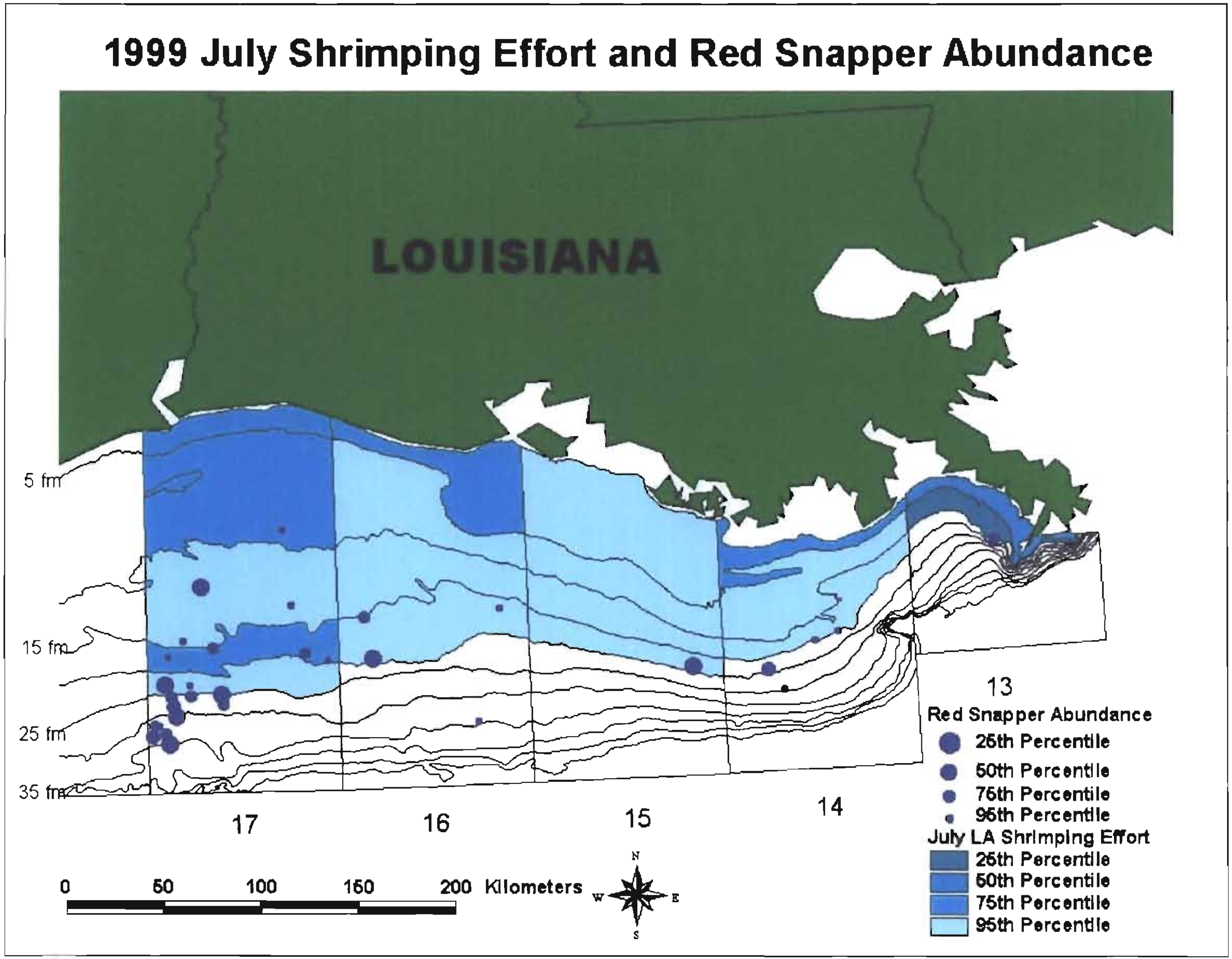


Figure 13j. July 1999 shrimping effort and red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Larger circles indicate greater red snapper abundance while darker aqua indicates greater shrimping effort.

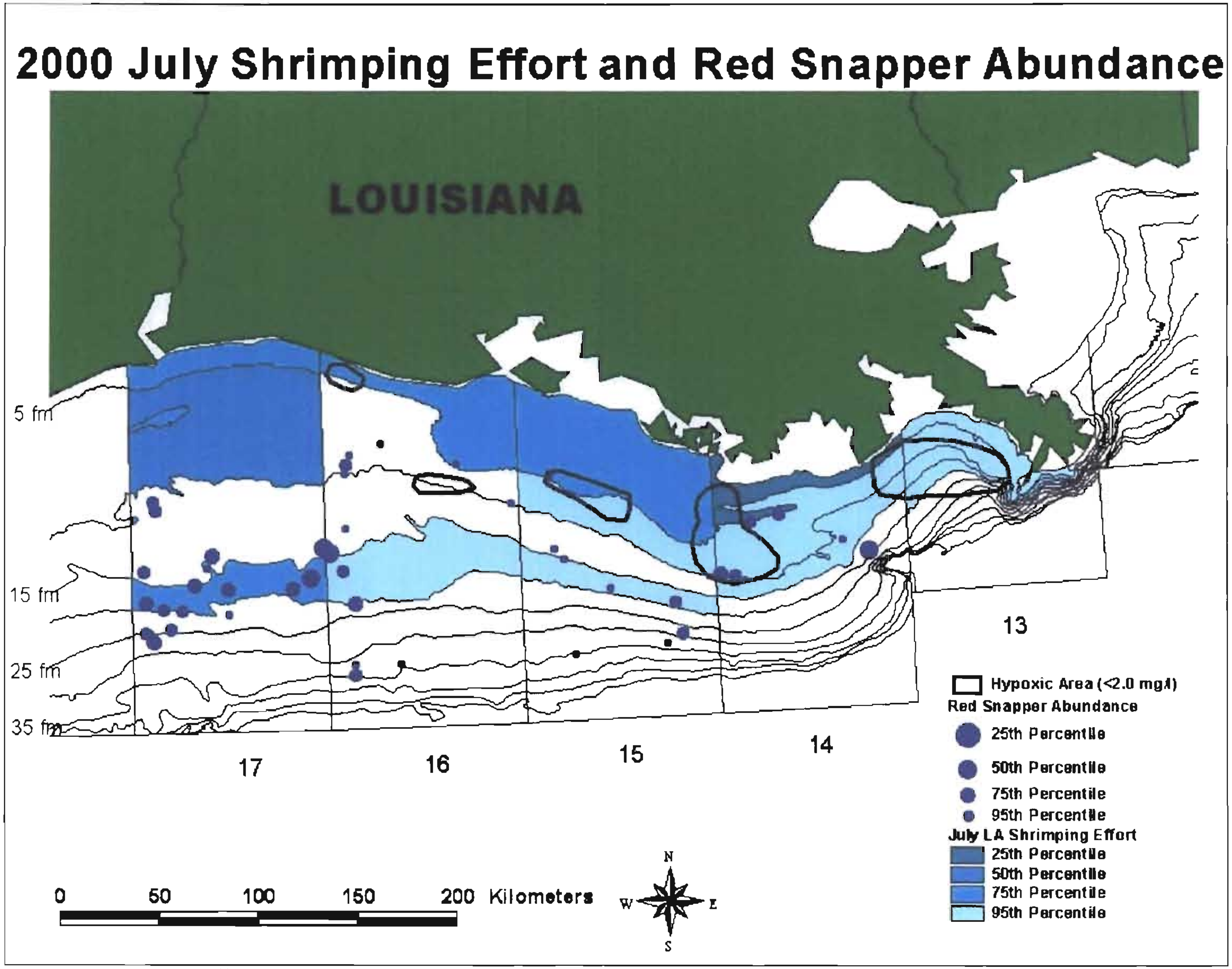


Figure 13k. July 2000 shrimping effort and red snapper abundance off Louisiana (stat zones 13-17, from Patella 1975). Larger circles indicate greater red snapper abundance while darker aqua indicates greater shrimping effort.

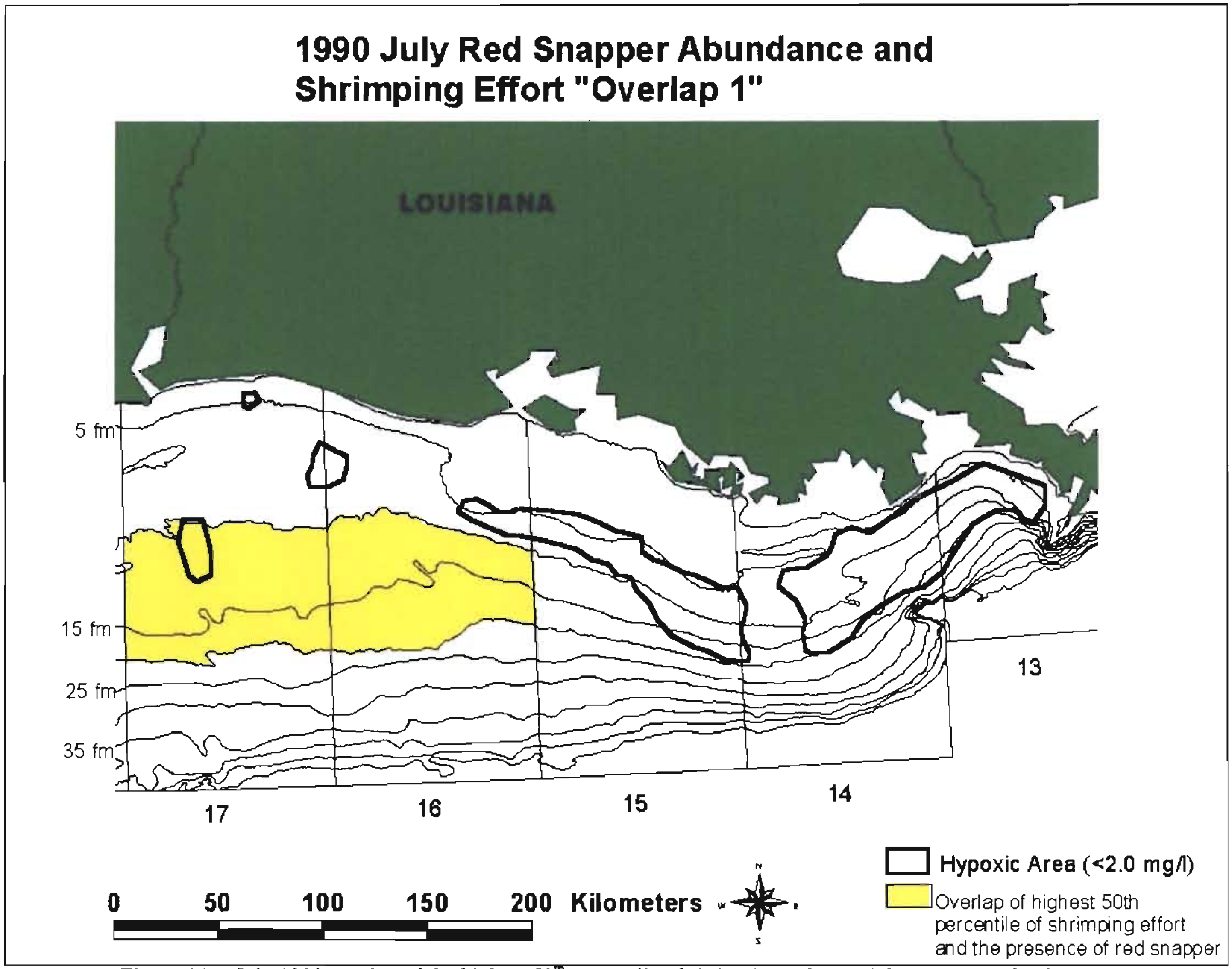
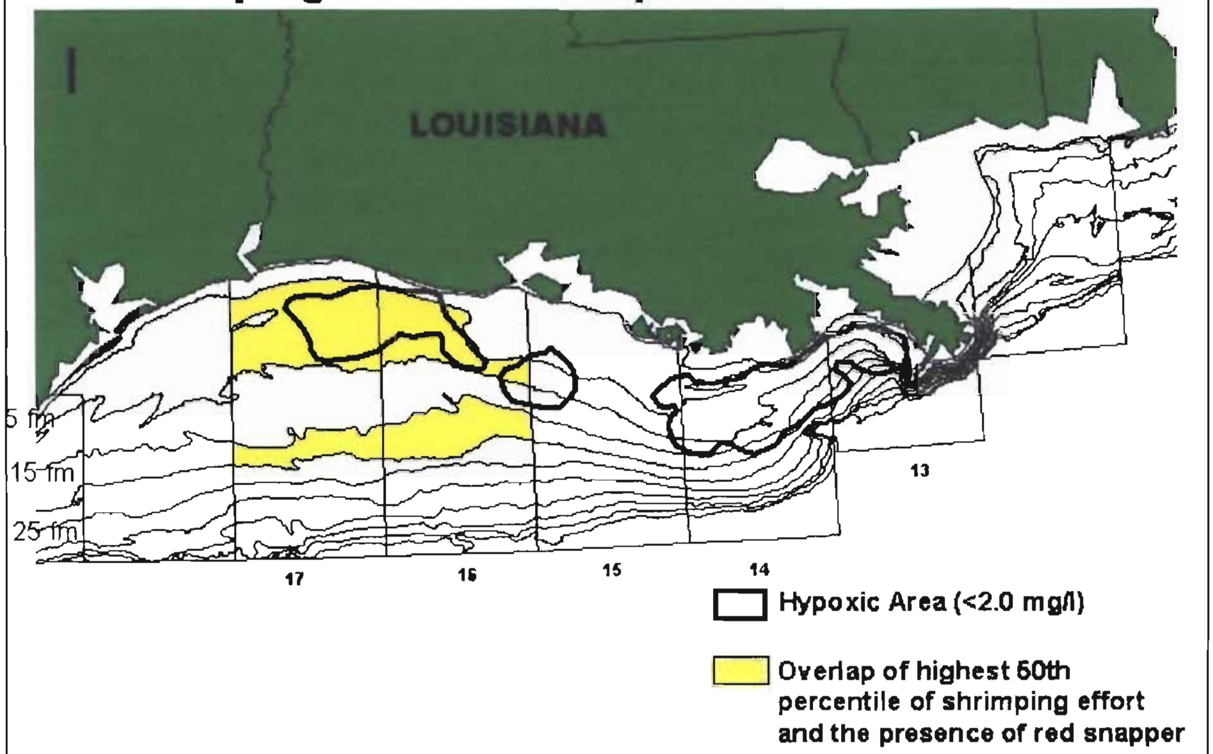


Figure 14a. July 1990 overlap of the highest 50th percentile of shrimping effort and the presence of red snapper.

1991 July Red Snapper Abundance and Shrimping Effort "Overlap 1"



1991 July Red Snapper Abundance and Shrimping Effort "Overlap 2"

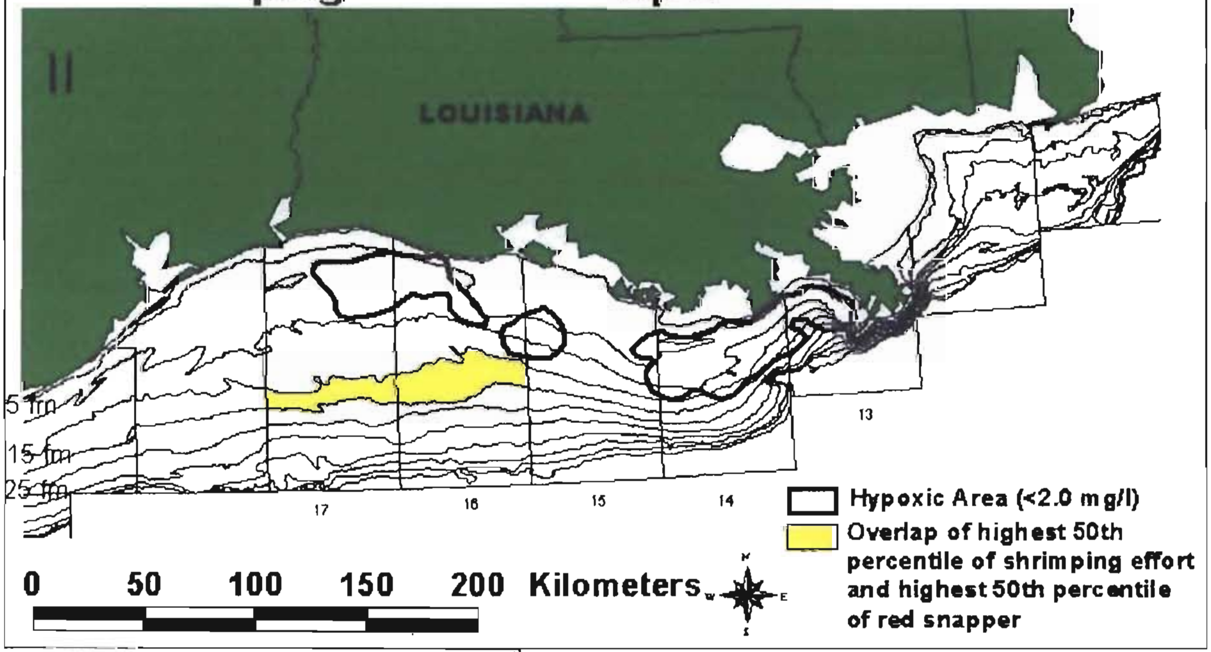


Figure 14b. I-July 1991 overlap of the highest 50th percentile of shrimping effort and presence of red snapper. II-July 1991 overlap of the highest 50th percentile of shrimping effort and the highest 50th percentile of red snapper.

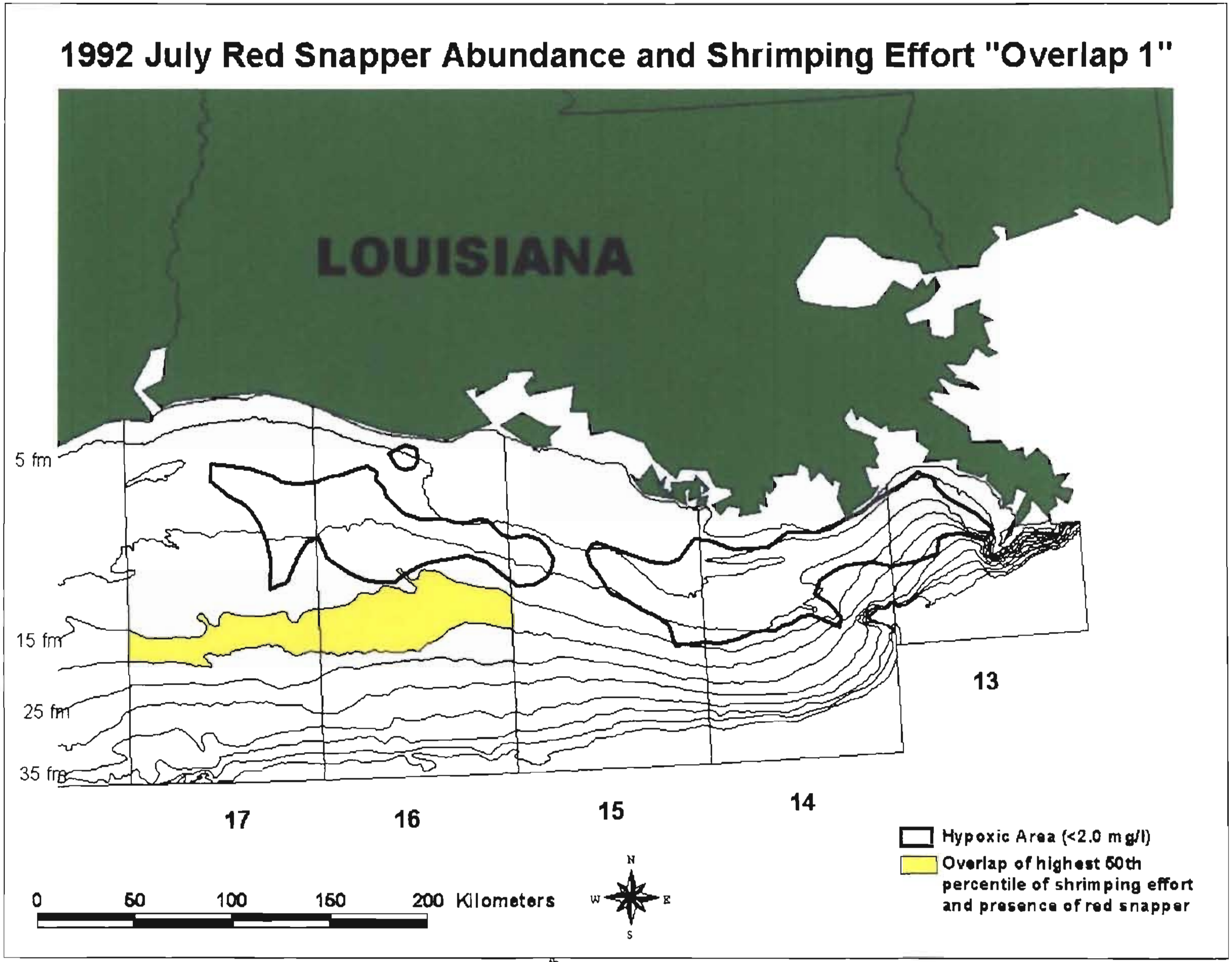

1992 July Red Snapper Abundance and Shrimping Effort "Overlap 1"

Figure 14c. July 1992 overlap of the highest 50th percentile of shrimping effort and the presence of red snapper.

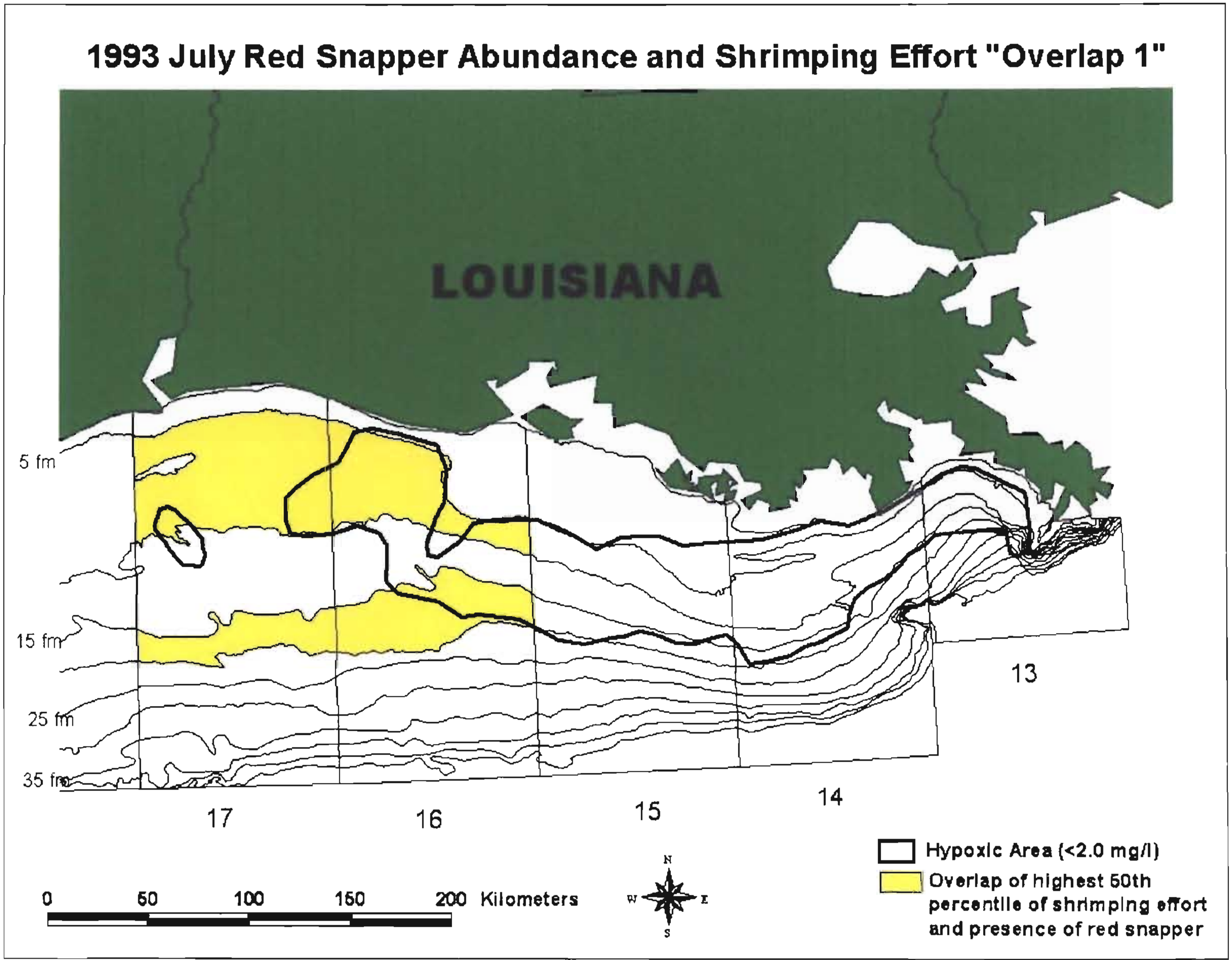


Figure 14d. July 1993 overlap of the highest 50^{th} percentile of shrimping effort and presence of red snapper.

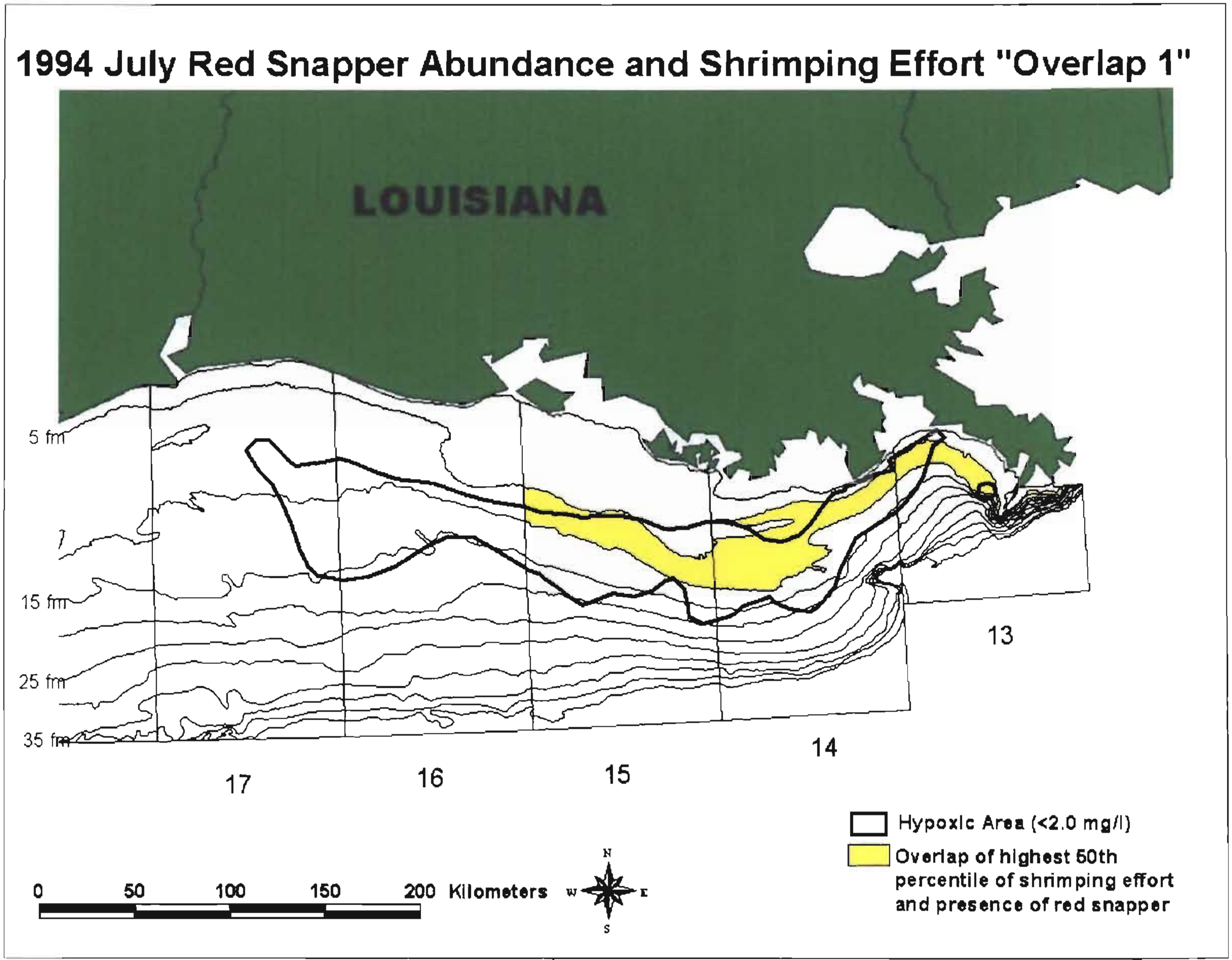


Figure 14e. July 1994 overlap of the highest 50th percentile of shrimping effort and the presence of red snapper.

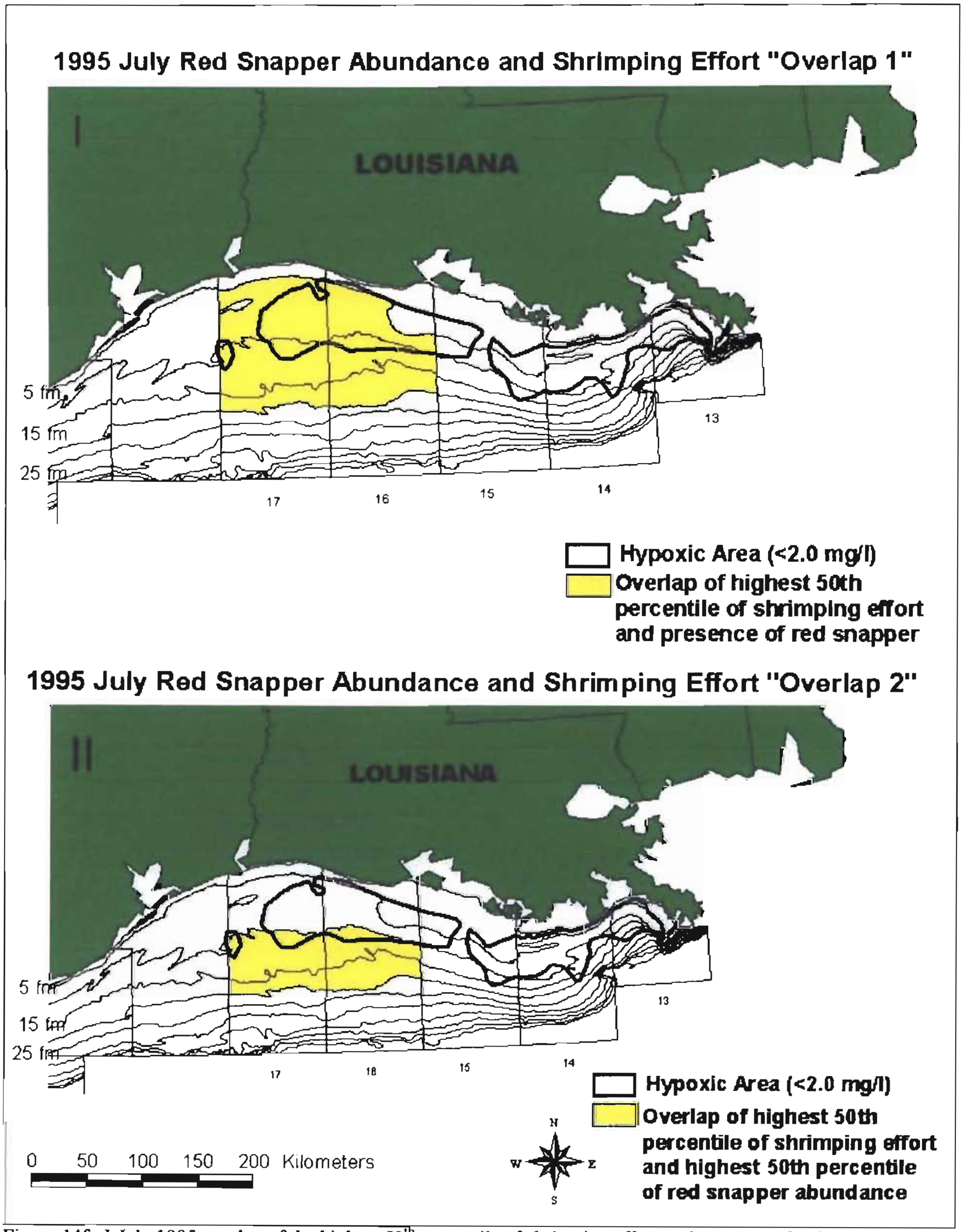
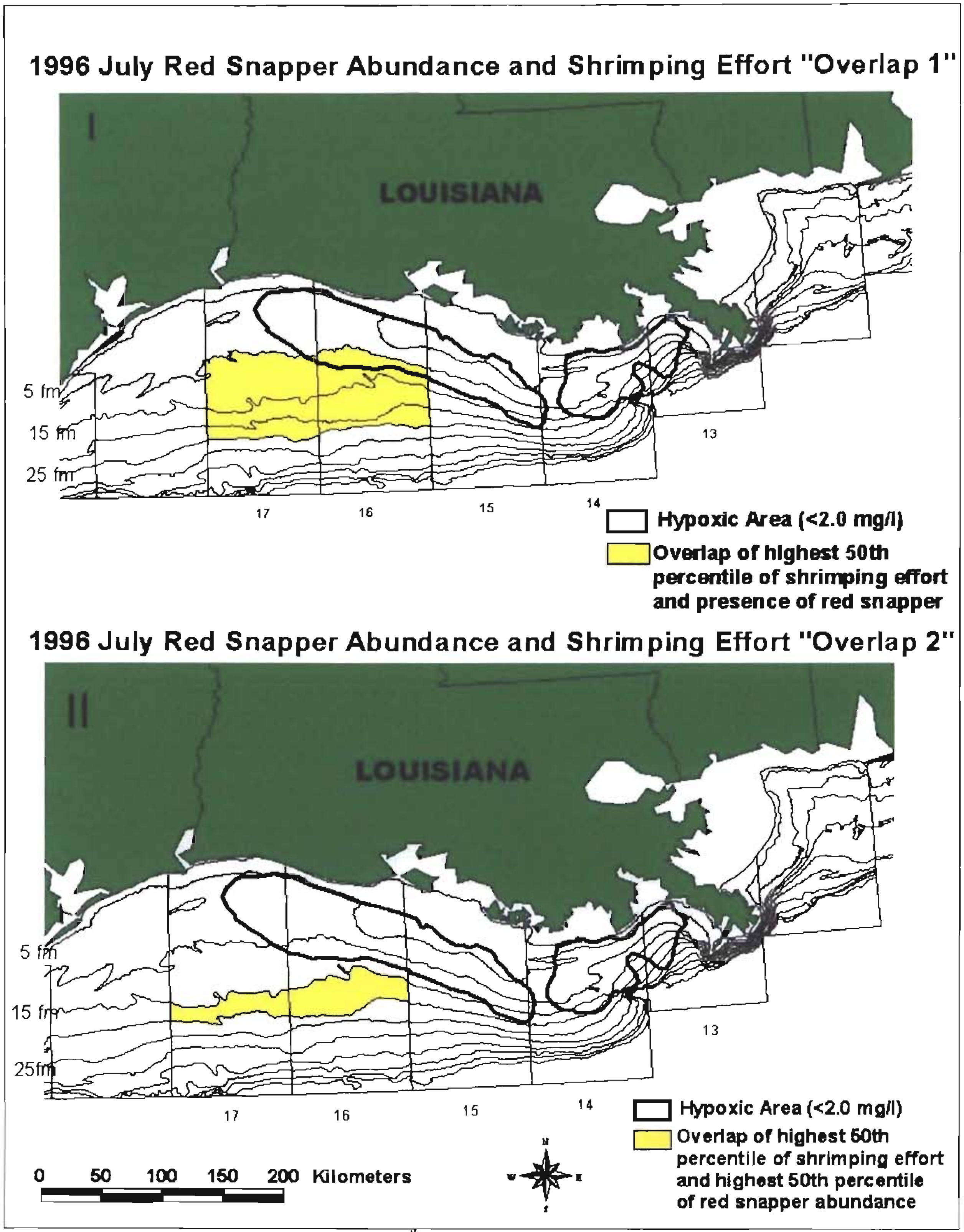


Figure 14f. I-July 1995 overlap of the highest 50th percentile of shrimping effort and presence of red snapper.
II-July 1995 overlap of the highest 50th percentile of shrimping effort and the highest 50th percentile of red snapper.


1996 July Red Snapper Abundance and Shrimping Effort "Overlap 1"

1996 July Red Snapper Abundance and Shrimping Effort "Overlap 2"

Figure 14g. I-July 1996 overlap of the highest 50th percentile of shrimping effort and presence of red snapper.
II-July 1996 overlap of the highest 50th percentile of shrimping effort and the highest 50th percentile of red snapper.

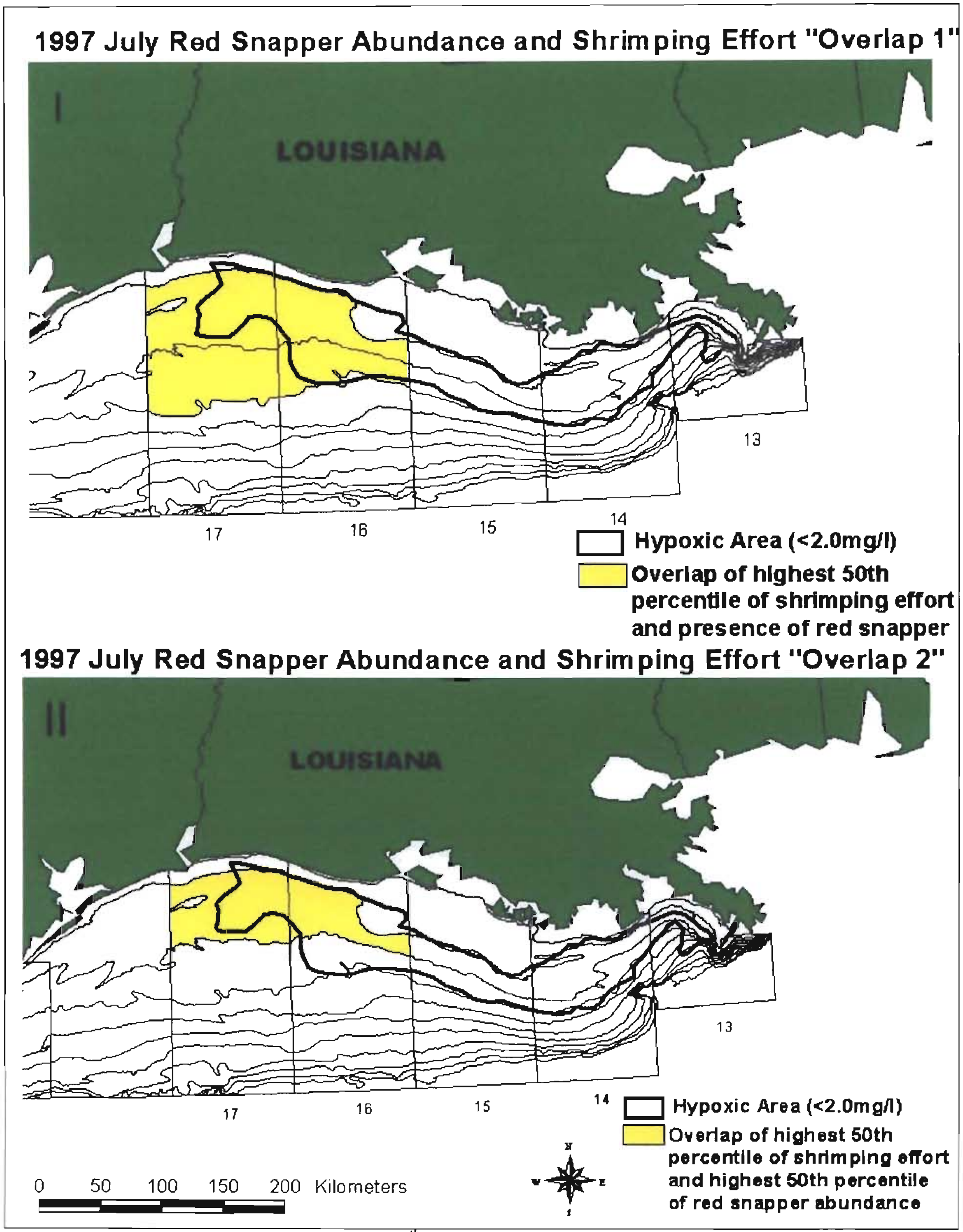
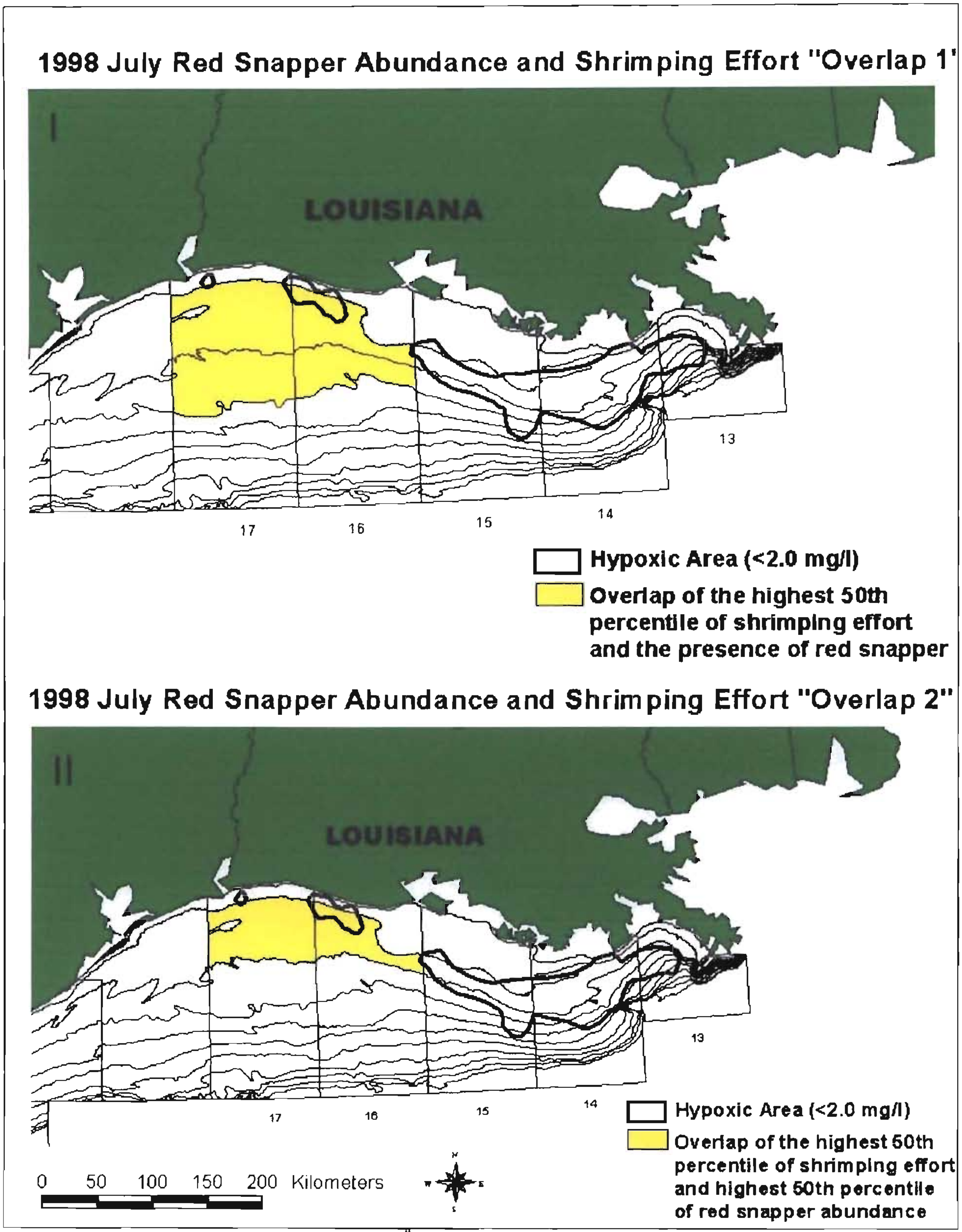


Figure 14h. I-July 1997 overlap of the highest 50th percentile of shrimping effort and presence of red snapper. II-July 1997 overlap of the highest 50th percentile of shrimping effort and the highest 50th percentile of red snapper.



1998 July Red Snapper Abundance and Shrimping Effort "Overlap 1"

1998 July Red Snapper Abundance and Shrimping Effort "Overlap 2"

Figure 14i. I-July 1998 overlap of the highest 50th percentile of shrimping effort and presence of red snapper. II-July 1998 overlap of the highest 50th percentile of shrimping effort and the highest 50th percentile of red snapper.

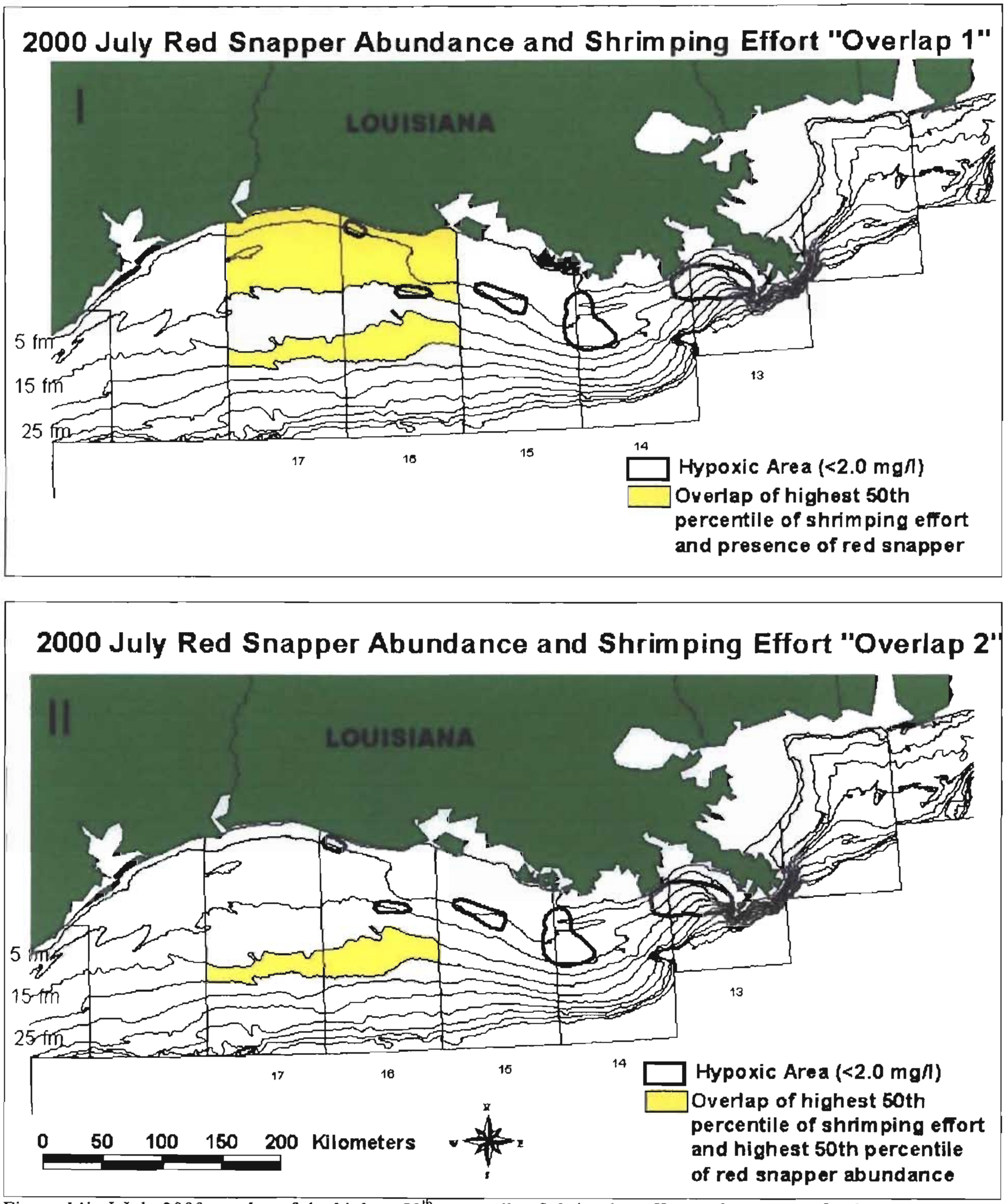
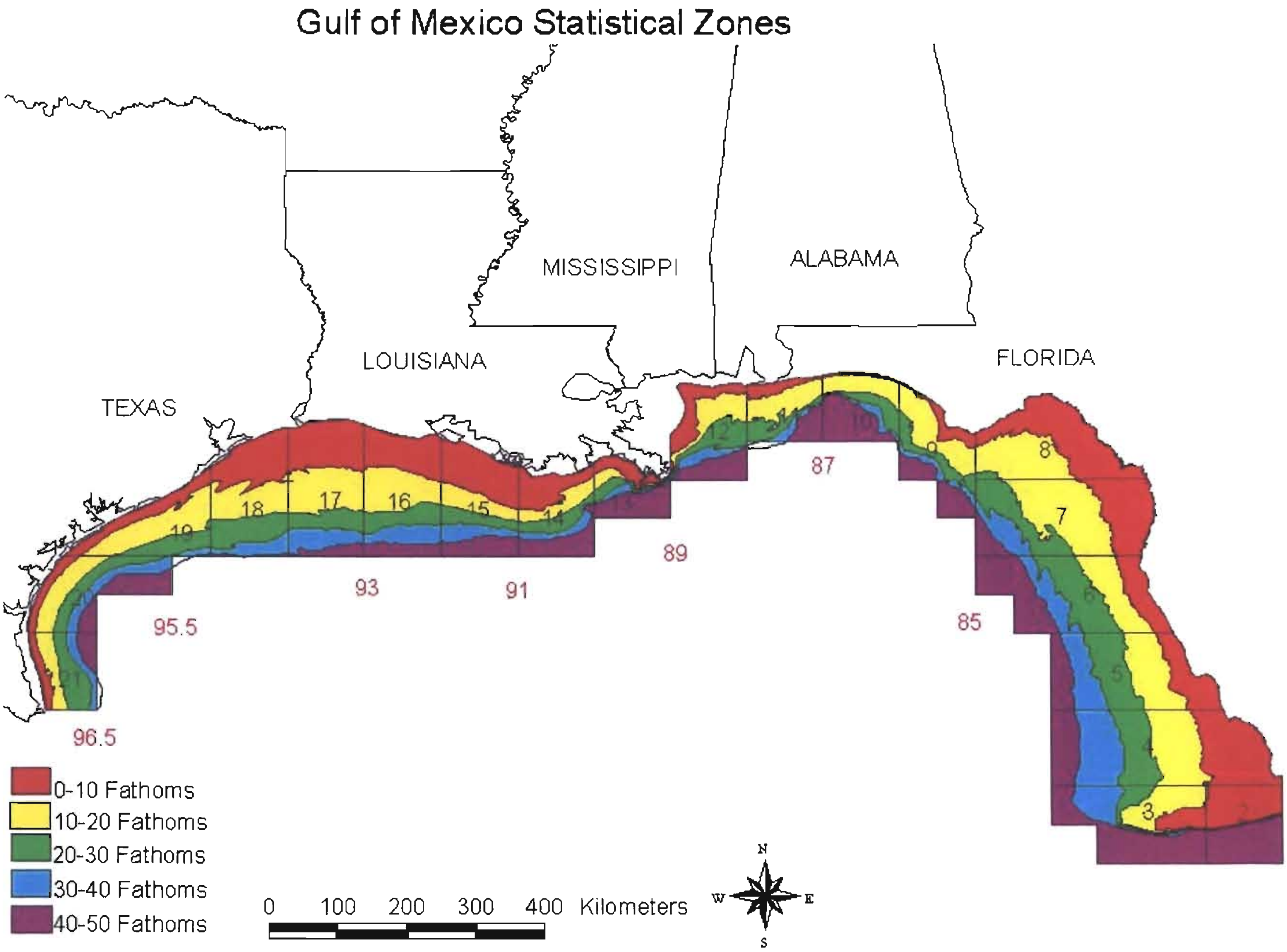


Figure 14j. I-July 2000 overlap of the highest 50th percentile of shrimping effort and presence of red snapper. II-July 2000 overlap of the highest 50th percentile of shrimping effort and the highest 50th percentile of red snapper.



Appendix I. Figure 2. Map depicting the Gulf of Mexico Statistical Zones 2-21 (from Patella 1975). Stat zones are further subdivided into 10 fathom depth increments. Red numbers denote degrees longitude.

Appendix I. Figure 1. Sample Survey Coverletter

Jennifer Macal
Duke University
135 Duke Marine Lab Road
Beaufort, NC 28516
(252) 504-7636
DATE

Address Line 1
Address Line 2

Dear Mr./Ms. (last name),

Hello! My name is Jennifer Macal and I am a Duke University graduate student conducting a survey of commercial red snapper fishermen in the Gulf of Mexico. I am very interested to learn how water quality impacts you and the red snapper fishery. During December I will be calling you to ask you some questions concerning water quality and its effects on the red snapper fishery. Attached you will find a copy of the survey questions that I will be asking you and a map depicting the Gulf of Mexico statistical fishing zones and depth ranges. I will refer to the map of the Gulf of Mexico during the survey, so please keep this diagram available for reference when I call you.

I look forward to speaking with you soon and gaining valuable knowledge from you concerning the red snapper fishery. Thank you.

Sincerely,

Jennifer M Macal

Appendix I. Figure 3. Sample Survey Questionairre

Good evening (afternoon/morning), is Mr./Ms. ____________ there? Hello. My name is Jennifer and I am a Duke University graduate student conducting a survey of Red Snapper Commercial Fishermen in the Gulf of Mexico. I received your name from the Gulf of Mexico Fishery Management Council and I would like to ask you a few questions about some water quality issues in the Gulf that may affect you and the red snapper fishery. Would you mind taking about 10 minutes of your time to answer some questions for me? There are no correct or incorrect responses, so feel free to express your opinions. You are also free to skip any questions. I guarantee that the answers you give me will be confidential and in no way will the information you provide be connected with your name.

1. I sent you a map depicting different fishing zones of the Gulf of Mexico. Did you receive this map and do you have it available to look at now?
   - ☐ Yes
   - ☐ No

2. Could you please tell me the top **three** zones and the corresponding color for depth that you commercially fish in most often for red snapper?

   ____

   ____

   ____

3. What other fisheries do you engage in besides red snapper?

   ____

   ____

4. How long have you been a commercial fisherman?

   ____________ Years

5. How long have you fished for red snapper?

   ____________ Years

6. What months do you fish for red snapper?

01 January
02 February
03 March
04 April
05 May
06 June
07 July
08 August
09 September
10 October
11 November
12 December

7. Have you heard of the "hypoxic" or "dead zone"?
   - ☐ Yes
   - ☐ No (read statement below)
   - ☐ Don't Know

   The hypoxic zone is defined as an area of low dissolved oxygen (<2 mg/l), often so low that fish and other organisms cannot live in this area.

8. Have you noticed the hypoxic zone while fishing?
   - ☐ Yes
   - ☐ No
   - ☐ Don't Know

9. In which areas? (please refer to the map if possible (stat zone and color (= depth))

____

____

10. What are the "signs" of the hypoxic zone that you notice?

____

____

11. Has the hypoxic zone affected your fishing for red snapper?
    - ☐ Yes
    - ☐ No (If no, skip to question 14)
    - ☐ Don't Know

12. In what way?

____

____

13. Does the hypoxic zone affect other fisheries besides red snapper?
    - ☐ Yes
    - ☐ No (If no, skip to question 16)
    - ☐ Don't Know

14. Which ones?

____

____

15. In what way?

____

____

16. Do you think there have been general consequences of the hypoxic condition? For example,
    - A. Have fishermen been forced to fish further inshore or offshore? (circle one)
        - ☐ Yes
        - ☐ No
        - ☐ Don't Know
    - B. Has there been decreased catch of red snapper?
        - ☐ Yes
        - ☐ No
        - ☐ Don't Know
    - C. Has there been crowding of vessels?
        - ☐ Yes (If yes, go to question 16D)
        - ☐ No
        - ☐ Don't Know
    - D. Is this crowding just among red snapper vessels?
        - ☐ Yes
        - ☐ No
        - ☐ Don't Know
    - E. Is it between red snapper fishermen and shrimpers?
        - ☐ Yes
        - ☐ No
        - ☐ Don't Know
        - ☐ Other

____

17. In your opinion, is hypoxia a significant threat to the red snapper fishery?
    - ☐ Yes
    - ☐ No
    - ☐ Don't Know

This is the end of the survey. I want to take this opportunity and thank you for your time.