Coastal Protection and Restoration Authority
150 Terrace Avenue, Baton Rouge, LA 70802 | coastal@la.gov | www.coastal.la.gov

2017 Coastal Master Plan

Attachment C3-19: Crayfish, *Procambarus clarkii and P. zonangulus*, Habitat Suitability Index Model

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Prepared By: Robert P. Romaire (Louisiana State University Agricultural Center))

Coastal Protection and Restoration Authority

This document was prepared in support of the 2017 Coastal Master Plan being prepared by the Coastal Protection and Restoration Authority (CPRA). CPRA was established by the Louisiana Legislature in response to Hurricanes Katrina and Rita through Act 8 of the First Extraordinary Session of 2005. Act 8 of the First Extraordinary Session of 2005 expanded the membership, duties, and responsibilities of CPRA and charged the new authority to develop and implement a comprehensive coastal protection plan, consisting of a master plan (revised every five years) and annual plans. CPRA's mandate is to develop, implement, and enforce a comprehensive coastal protection and restoration master plan.

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Executive Summary

The 2012 Coastal Master Plan utilized Habitat Suitability Indices (HSIs) to evaluate potential project effects on wildlife species. Even though HSIs quantify habitat condition, which may not directly correlate to species abundance, they remain a practical and tractable way to assess changes in habitat quality from various restoration actions. As part of the legislatively mandated 5-year update to the 2012 plan, the wildlife habitat suitability indices were updated and revised using literature and existing field data where available. The outcome of these efforts resulted in improved, or in some cases entirely new suitability indices. This report describes the development of the habitat suitability indices for the red swamp and white river crayfishes, *Procambarus clarkii* and *Procambarus zonangulus*, respectively.

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List of Abbreviations

CI	Component Index
CPRA	Coastal Protection and Restoration Authority
HSI	Habitat Suitability Index
ICM	Integrated Compartment Model
LDWF	Louisiana Department of Wildlife and Fisheries
ppt	Parts per thousand
SI	Suitability Index
SSURGO	USDA-NRC Soil Survey Geographic Database
USFWS	United State Fish and Wildlife Service

1.0 Species Profile

The red swamp crayfish *Procambarus clarkii* is an ecologically important and commercial valuable freshwater species in coastal Louisiana. Red swamp and white river crayfishes are "temperate" species, capable of tolerating winter conditions as far north as the Midwestern USA, but both species thrive in warm climates. The species natural range extends from northwestern Mexico, through southern and central Texas, eastward to the Florida panhandle (Walls, 2009). The red swamp crayfish is distributed throughout Louisiana, but is found in highest abundance in the freshwater coastal wetlands and riverine floodplains of south-central and southwest Louisiana. The sympatric southern white river crayfish *Procambarus zonangulus* (formerly *Procambarus acutus acutus*) has a nearly identical state wide distribution but is usually found in lower abundance than red swamp crayfish. Juveniles and adults of both species are ecologically important food resource for numerous species of freshwater fishes (e.g., largemouth bass), reptiles (e.g., alligators), and avian species (e.g., yellow-crowned night herons), and mammals (raccoons) (Pollard, 1983; Huner & Barr, 1991; Walls, 2009; Huner & Jeske, 2010).

Of the 39 known species of freshwater crayfishes in Louisiana, the red swamp and southern white river crayfishes comprise nearly all of the commercial and recreational harvest (Huner & Konikoff, 2009; Walls, 2009), and red swamp crayfish are estimated to comprise 85 to 90% of the annual harvest of the two species (Huner, 2002). Commercial harvest of red swamp and southern white river crayfishes from natural (non-aquaculture) habitats have averaged nearly 17 million pounds since 1990, ranging from a low of nearly 400,000 pounds in 2000 to 50 million pounds in 1993 (Issacs & Lavergne, 2010). Most of the commercial harvest of "wild" crayfish populations occurs in Louisiana's coastal zone south of Interstate-10 (I-10), and 85 to 90% of the commercial wild harvest occurs within the Atchafalaya River Basin (Louisiana Department of Wildlife and Fisheries, Annual Trip Ticket Reports, 1999 through 2013).

1.1 Reproduction

In Louisiana, both species are short-lived (2 years or less), have high juvenile survival and can alternate between reproductively active and inactive forms (Huner & Barr, 1991). The red swamp crayfish is capable of reproducing year-round in Louisiana, but spawning of white river crayfishes is usually restricted to fall through winter (Romaire & Lutz, 1989; Figure 1). Peak production of juveniles for both species occurs in fall and early winter (primary recruitment), though minor pulses (or "waves") of red swamp crayfish reproduction occur in late winter through spring (secondary and tertiary recruitment) (Konikoff, 1977; Figure 1). The extended reproductive period and differential growth among age classes typically results in populations of mixed sizes.

Mature crayfishes mate in open water and sperm is stored by the female, after which the female constructs a sub-surface burrow in the sediment or retreats to an existing burrow to spawn.

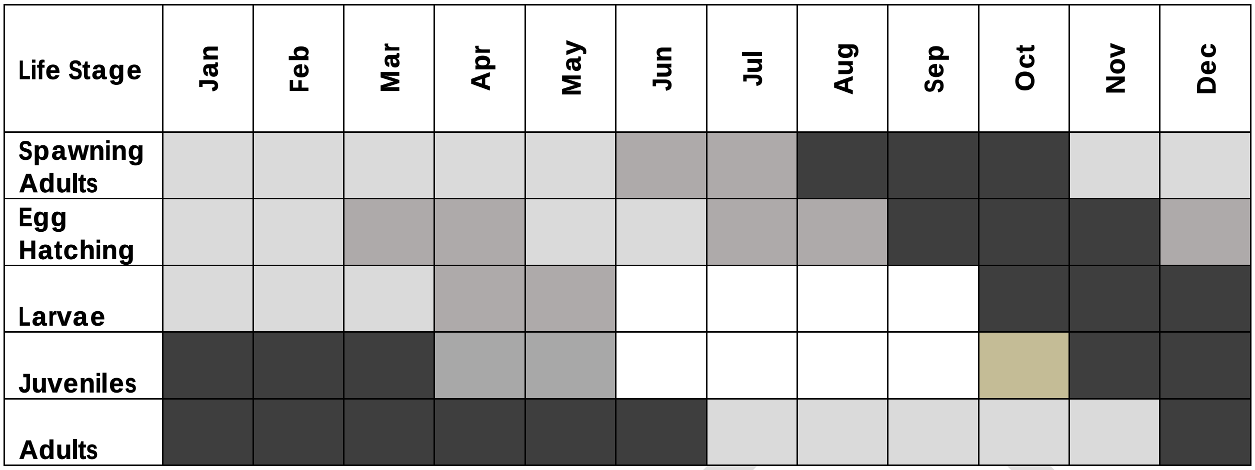

Figure 1: Space-Time Plot by Life Stage for Red Swamp and White River Crayfishes. White cells indicate the life stage is seldom present in open water, light gray cells indicate the life stage is likely present but in low abundance, moderately gray cells indicate the life stage in present in moderate abundance and dark gray cells indicate the life stage is present in high abundance.

No known hybridization occurs between the two species. In Louisiana, mating and burrowing can occur in any month in flooded habitats but is most prevalent in late spring/early summer (Penn, 1943; Konikoff, 1977; O'Brien, 1977). Burrows are simple or multi-branched, and although depth of the burrows varies widely, most are usually 1 to 3 ft deep. Although burrows are used primarily for reproduction by adults, crayfish of all ages, sizes, sexes and maturity, will construct burrows, or retreat to existing burrows, to survive periods when surface waters recede or environmental conditions become acutely adverse (e.g., high water temperatures) (Huner & Barr, 1991). Burrows are excavated at the sediment-water interface, and must be constructed in water-saturated soils with a sufficient clay (low sand content) to maintain burrow integrity and to prevent desiccation when occupied (Penn, 1943, Burras et al., 1995; Burras et al., 1999; McClain & Romaire, 2004) (Table 1). The top of occupied burrows are sealed with a sediment plug, and oviposition (spawning/egg laying) occurs inside the burrow. Eggs will not hatch without water being present in the terminal chamber of the burrow. Crayfish seal the burrow and manipulate the interior surface to retain water, particularly if the water table depth recedes below the bottom of the burrow (Jaspers & Avault, 1969). Healthy adult crayfish are reported to survive in sealed burrows 6 to 9 months.

Ovarian (egg) development in mature females is temperature dependent, with development beginning prior to burrowing and oviposition (egg laying) occurring in the burrow. Developing eggs increase in size, and change from a light color to dark as they mature (Penn, 1943; Jaspers & Avault, 1969). The number of eggs varies with female size (Penn, 1943), but on average mature female red swamp or white river crayfish will produce 220 to 250 hatchlings (10 to 14 hatchlings per gram of female body weight) (Romaire, McClain, and Huner, unpublished data). Once laid, eggs hatch in as little as 3 weeks at 21 to 24°C (70 to 75°F) and 4 to 5 months at 10 to 15.6°C (50 to 60°F) (Huner & Barr, 1991).

Table 1: Habitat Requirements for Red Swamp and White River Crayfishes.

Life Stage	Salinity		Temperature		Water Depth		Sediment Substrate
	Range[1]	Optimum[2]	Range[2,3]	Optimum[2,3]	Range[2,4]	Optimum[2]	Optimum[5]
Spawning Adults	< 30 ppt for one week	< 1.5 ppt	0 to 36°C	22 to 30°C	46 to 274 cm fall, winter, spring; bare ground to 15 cm in summer	46 to 91 cm fall, winter, spring; bare ground in summer	Clay or Silty Clay Loam to Depth of 3 feet)[5] Sandy soil or excessively high organic soil is not suitable burrowing/ reproductive habitat
Egg Hatching	Not Known	< 1.5 ppt	0 to 36°C	22 to 30°C	Same as Spawning Adults	Same as Spawning Adults	Same as Spawning Adults
Hatchlings	0-8 ppt	< 1.5 ppt	0 to 36°C	22 to 30°C	Same as Spawning Adults	Same as Spawning Adults	Same as Spawning Adults
Juvenile	< 15 ppt	< 1.5 ppt	0 to 36°C	22 to 30°C	Same as Spawning Adults	Same as Spawning Adults	Same as Spawning Adults
Adults	< 30 ppt for one week	< 1.5 ppt	0 to 36°C	22 to 30°C	Same as Spawning Adults	Same as Spawning Adults	Same as Spawning Adults

[1] Loyacano, 1967a,b; [2] Romaire, 2012; [3] Huner, 1987; [4] Konifoff, 1977; [5] Burras et al., 1995

Newly hatched crayfish are attached to pleopods (swimmerets) on the female's abdomen through two molts or about 30-35 days (Huner & Barr, 1991). Hatchlings remain with the female for several weeks after their second molt although they are no longer attached. Although hatchlings can survive 1 to 3 months in burrows, it is critical that the female and her young leave the burrow within a reasonable time after hatching because food resources are usually deficient (Jaspers & Avault, 1969). When environmental conditions (e.g., lack of water to inundate and soften burrow plugs) force the crayfish to remain in the burrow, increased mortality from starvation and cannibalism can occur (Jaspers & Avault, 1969; Konikoff, 1977). Adults and hatchlings exit the burrows and colonize flooded habitats when rains soften the burrow plug or increasing water depth in floodplain habitats inundate the burrows.

1.2 Food Habits

Crayfish are polytrophic benthic omnivores (Momot, 1995), that consume a variety of microbial, vegetative and animal matter. Crayfish ingest living and decomposing plant matter, seeds, algae, periphyton, microorganisms and an assortment of larger invertebrates such as insects, aquatic worms, and snails (Sanguanruang, 1988). These food sources vary seasonably in the quantity and quality in aquatic habitats. Living plants and starchy seeds, though consumed in great quantities, contribute little to the direct nourishment of crayfish (Sanguanruang, 1988; Momot, 1995). Decomposing plants, with its associated microorganisms (collectively referred to as detritus) is consumed in significant amounts but has limited food value beyond general metabolic maintenance. However, mollusks (e.g., snails), insects, aquatic worms, small crustaceans and juvenile vertebrates depend on detritus as an energy resource, and, when consumed by crayfish, these animals furnish high-quality nutrition. For crayfish to grow at their maximum rate, they must feed to a greater extent on high-protein, energy rich animal food sources (Sanguanruang, 1988; Momot 1995).

1.3 Growth

Crayfish must molt or shed its hard exoskeleton to increase in size. Molting interval and growth rate is affected by a number of variables, including water temperature, population density, water quality, and food quality and quantity (Huner, 1987; McClain, 2010; Romaire & Villigran, 2010). Harvest size for commercial markets is usually attained 3 to 5 months after hatching for fall and winter recruits, but in as little as 2 to 3 months under optimum environmental conditions (warm water temperatures and low population densities). Molt intervals for crayfish range from 6 days to 30 days depending on water temperature and age.

Under ideal conditions of 22 to 30°C (75 to 86°F), crayfish can mature in 3 months, but under the normal temperature regimes in southern Louisiana, assuming emergence of hatchlings in the fall, it takes 5 to 6 months for crayfish to mature. A minimum of 11 molts are necessary for hatchlings to grow to sexual maturity (Huner & Barr, 1991). When males and females mature, growth ceases (Penn, 1943). Size at maturity is directly dependent on environmental conditions with density being the most important factor (Romaire & Villagran, 2010). Sexually mature individuals of both species exhibit distinct characteristics, including darker coloration, enlarged claws, and hardened sexual structures. Mature males develop prominent hooks at the base of the third and fourth pair of periopods (walking legs). Mature crayfish in the population increase in abundance as water temperatures increase during late spring. Females will mate (often several times) after molting to a mature form and then begin the process of constructing burrows for reproduction.

1.4 Habitat Preferences

The red swamp and southern white river crayfishes thrive in wetland habitats that flood and dry seasonally (e.g., overflow floodplain habitats of river systems), but they are also found in lesser abundance in permanently flooded habitats (Huner & Konikoff, 2009; Walls, 2009). Ideal crayfish habitats in natural (non-aquaculture) systems include backwater, slow-moving, cypress-tupelo gum, hyacinth swamps, or natural bayous (Sheppard, 1974; Konikoff, 1977; O'Brien, 1977; Shenoi, 1996). Wild crayfish production in the Atchafalaya River Basin is positively correlated with increasing river stage in the Atchafalaya River Basin floodplain (Dellenbarger & Lazur, 1988; Huner & Konikoff, 2009; Bonvillain, 2012; Alford & Walker, 2013).

Red swamp and white river crayfishes are found in highest abundance in shallow waters of 46 to 91 cm (1.5 to 3 ft) depth (Table 1). Deeper waters, particularly during summer, can adversely affect crayfish abundance because of fish predation and a reduction in the area of edge-substrate (water-land interface area) required for crayfish burrowing, an essential requirement for reproduction (Bonvillain, 2012; Alford & Walker, 2013). Wetland habitats are important to crayfish distribution with crayfish most widely found in swamp and freshwater marsh habitats that exhibit high annual fluctuations in water depth. Water level and depth fluctuations are important hydrological variables that affect crayfish reproduction and habitat quality. Shallow water in summer-early fall increases the area of reproductive burrowing habitat and mitigates fish predation on reproductively-active females.

Deeper waters in late-fall-winter-spring expands aquatic habitat for crayfish, particularly in overflow lowland floodplains. Rising river and stream water levels in late winter and spring, and its subsequent movement into overflow floodplains generally improves water quality for crayfishes by displacement and dilution of stagnant, hypoxic (low oxygen of less than or equal to 2 mg/L) waters (Kaller et al., 2011). Hypoxic waters are detrimental to crayfish in Louisiana's riverine habitats (Bonvillain et al., 2009; Kaller et al., 2011; Bonvillain, 2012). Melacon and Avault (1977) and Huner (1987) reported that red swamp crayfish exposed to dissolved oxygen concentration of 1 mg/L or lower for several days is highly detrimental to the survival of hatchlings and juveniles. More recently, Bonvillain (2012) demonstrated that dissolved oxygen levels exceeding 2 mg/L (normoxic) were not stressful to red swamp crayfish, but sustained exposure to dissolved oxygen concentrations between 1 and 2 mg/L (hypoxia), resulted in significant physiological stress, which could affect long-term growth and survival.

Despite the similarities of the two species and the overlapping use of habitats, red swamp crayfish are typically associated with "swamp" habitats and the southern white river crayfish are associated with "riverine" habitats (Sheppard, 1974; Konikoff, 1977; O'Brien, 1977; Paille, 1980; Pollard et al., 1983; Shenoi, 1996). Frequency of occurrence (%) for red swamp and white river crayfishes in various wetland habitat types are summarized in Table 2.

Table 2: Frequency of Occurrence of Red Swamp and White River Crayfishes by Habitat Type (Huner & Konikoff, 2009).

Habitat Type	Red Swamp Crayfish (% frequency of occurrence)	White River Crayfish (% frequency of occurrence)
Marshes and Marsh Pools	35	0
Swamps and Swamp Forests	30	9
Ponds and Borrow Pits	14	27
Ditches (mostly roadside)	12	27
Bayous	8	0
Pineland Sloughs and Springs	1	10
Creeks and Rivers	0	25
Other	0	2

Both species thrive in areas that are periodically flooded and dry (bare ground). The majority of wild crayfish commercially harvested in Louisiana are from the floodplain swamp habitats of the Atchafalaya River Basin with lesser quantities captured in freshwater marsh habitats throughout coastal Louisiana (Louisiana Department of Wildlife and Fisheries trip ticket data base, 2009-2013). Permanent open water habitats which are not subject to annual flooding and drying, and which have resident populations of fishes, usually support populations of crayfish in low abundance because of potentially heavy fish predation and reduced water-sediment interface habitat for reproductive burrowing.

Red swamp and white river crayfishes have a relatively high tolerance to dissolved mineral content (salinity) in water (Loyacano, 1967a; Loyacano, 1967b; Perry & LaCaze, 1969; Chaney, 1971; Sharfsetein & Chafin, 1979; Green et al., 2011) (Table 1). Tolerance to salinity is directly proportional to crayfish size. Newly hatched young die at 15 parts per thousand (ppt), and juveniles die at 30 ppt after one week. Salinity affects crayfish reproduction at much lower concentrations (Perry & LaCaze, 1969), and the effect of continuous exposure to low salinity on crayfish reproduction is not fully known. Although physiologically crayfish are reasonably tolerant to salt water exposure, areas subject to saltwater intrusion are not conducive to crayfish production. Coastal areas with low salinity water usually have highly organic soils that are marginal for burrow construction. Although crayfish can tolerate slightly brackish water, the vegetative food resources on which crayfish depend likely have a much lower tolerance to saline water.

1.5 Hydrology and Crayfish Ecology

The hydrologic cycle in southern Louisiana that is optimal for reproduction of red swamp and southern white river crayfishes consists of a low water depth or dry (bare ground) conditions during a 3 to 4 month period during the summer and early fall, followed by deeper water conditions during fall, winter and spring (Konikoff, 1977; Pollard et al., 1983; Dellenbarger & Luzar, 1988; Huner & Konikoff, 2009; Bonvillain, 2012; Alford & Walker, 2013). Red swamp and southern white river crayfishes thrive in areas that are periodically flooded and dry (bare ground, no water).

The annual hydrological cycle in which water is confined to the deep main channel of a river at a certain time of the year (e.g., summer and early fall), and then overflows it banks into an adjacent floodplain at another time (e.g., late winter and spring) is referred to as a "flood pulse." Low (shallow) water depth or bare ground during summer and early fall: 1) significantly increases the amount of reproductive burrowing habitat, 2) permits the growth of terrestrial and semi-aquatic emergent vegetation that serves as the base of the food web for the crayfishes when the area floods in late fall/winter, and 3) reduces the predatory pressure of fishes on mature (reproductively active) crayfish populations (Huner & Konikoff, 2009; Bonvillain, 2012; Alford & Walker, 2013). As water depth increases in overflow habitats in late fall and winter in response to rising river levels in the lower Mississippi River watershed, adult female crayfish and hatchlings are flushed from burrows and dispersed into habitats replete with forage, protective vegetative cover and generally oxygen-rich water. Deeper, flowing water in floodplain habitats in fall, winter, and spring is generally conducive to high crayfish production (Konikoff, 1977; Huner & Konikoff, 2009; Alford & Walker, 2013).

Pollard et al. (1983) reported procambarid crayfishes were most abundant in areas of the Atchafalaya River Basin where water depth was less than 91 cm (3 ft). Shallow water of less than 31 cm (1 ft) in depth can reduce crayfish growth in winter because shallow water cools more rapidly. Crayfish growth in early summer can be reduced from high water temperature as water recedes in riverine floodplains. High water temperatures associated with receding waters are an important environmental cue that stimulates mating and subsequent burrowing of adult crayfish. Crayfish predation from wading birds and mammals are likely higher when water is shallow (Huner & Barr, 1991; Huner & Konikoff, 2009). Because crayfish are benthic and often reside on sediment substrates, deep, non-flowing water is also not conducive to optimal crayfish growth and survival. In deep water, crayfish are more likely to be subjected to hypoxia during warmer months when hydrological conditions do not favor water flow (flushing action) through floodplain habitats (Konikoff, 1977; Shenoi, 1996; Bonvillain et al., 2011; Kaller et al., 2011). Furthermore, in deeper water, juvenile and adult crayfishes are likely more vulnerable to predation by freshwater fishes (Perret et al., 2009; Huner & Konikoff, 2009).

2.0 Approach

Habitat suitability indices (HSIs) are used to assess the suitability (potential quality) of habitat for a species but it does not predict either numbers or biomass of the species within the area that is modeled. Habitat suitability indices have a history of development and use in the management of aquatic resources in the U.S. Development of the 2017 crayfish HSI model follows assumptions and recommended procedures as set forth by the United State Fish and Wildlife Service (USFWS) in the publication "Standards for the Development of Habitat Suitability Index Model" (USFWS, 1981).

The crayfish habitat suitability index model for the 2017 Coastal Master Plan is an update of the crayfish HSI model developed for the 2012 Coastal Master Plan (Romaire, 2012). Procambarid crayfish habitat suitability variables were selected from literature reviews and the author's knowledge of procambarid crayfish biology and ecology. Salinity and vegetative habitat class variables, both present in the 2012 crayfish HSI model, are retained for use in the 2017 model, but the suitability index equations/functions for these two variables are updated to include new scientific information.

The 2017 crayfish HSI model includes three new habitat suitability variables not present in the 2012 HSI model –"water depth, October through June," "water depth, July through September" and "percentage of sand in soil substrate." The habitat suitability variables "water temperature" and "water level fluctuation," present in the 2012 model are excluded in the 2017 model. Water temperature extremes in coastal Louisiana are not likely to affect habitat suitability for procambarid crayfishes. High temperature that could be deleterious to the survival of procambarid crayfishes occurs when crayfish are sequestered to subterranean burrows that buffer high-end temperature extremes. Additionally, temperatures do not get sufficiently cold in winter to be deleterious to procambarid crayfish survival. Water level fluctuation was excluded because differential water level fluctuations (maximum water depth minus minimum water depth) from "December through May" and "June through November" had limitations in effectively defining hydrological regimes important to environmental and reproductive crayfish habitat suitability in Louisiana's coastal rivers, lakes, and floodplains.

In the 2017 crayfish model water level fluctuation variables are replaced with the variables "water depth from October through June," and "water depth from July through September." A new variable "percentage of sand in soil substrate" is included in the 2017 model to classify habitats where soils/sediments do not have sufficient water retention capacity required for crayfish reproduction in burrows.

In summary, salinity and vegetative habitat variables in the 2012 model are retained, but the suitability function equations are updated for the 2017 model. Water temperature is excluded in the 2017 model. Water level fluctuation from December through May, and water level fluctuation from June through November from the 2012 model are replaced with water depth from October through June, and water depth from July through September. The percentage of sand in the soil substrate is added as a new suitability index variable for the 2017 model.

The conceptual crayfish HSI model for the 2017 Coastal Master Plan is depicted as follows:

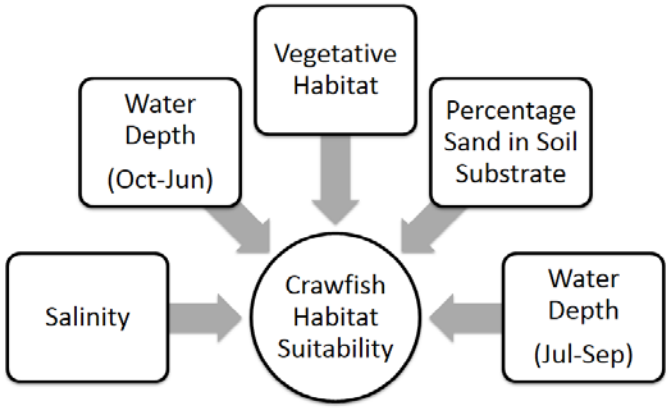

Figure 2: Conceptual Crayfish Habitat Suitability Model.

3.0 Habitat Suitability Index Model for Crayfish

The crayfish HSI is calculated from the un-weighted geometric mean of three component index (CI) equations that define "water suitability", "habitat quality", and "crayfish reproduction." The three components collectively describe the suitability of an aquatic habitat to support freshwater procambarid crayfishes.

Each of the five habitat variables (V_1, V_2, V_3, V_4, V_5) in the 2017 crayfish HSI model is assigned a dimensionless suitability index (SI) value which ranges from 0 (unsuitable habitat incapable of supporting sustainable populations of crayfish) to 1.0 (optimal habitat). The crayfish HSI is calculated as a geometric mean of the SI values, and has an overall value that ranges from 1 to 0. If any SI of the five habitat variables is equal to 0 (unsuitable habitat) then the calculated HSI will also be 0.

$$\text{Crayfish HSI} = (\text{CI}_{\text{water suitability}} \text{ x } \text{CI}_{\text{habitat}} \text{ x } \text{CI}_{\text{reproduction}})^{1/3}$$

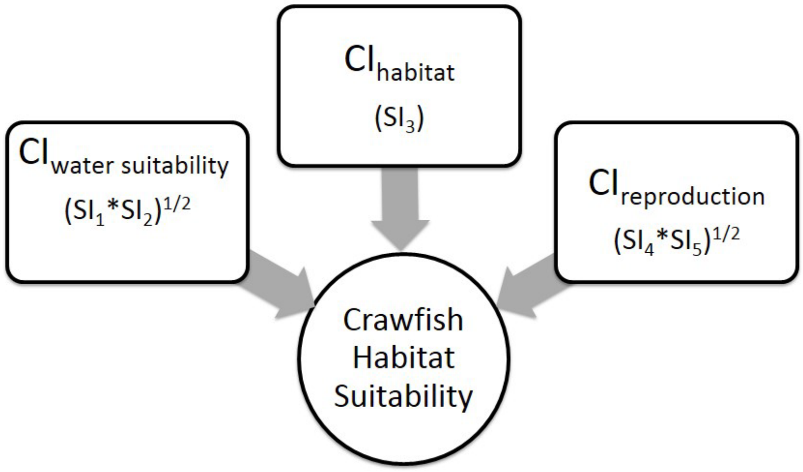

Figure 3: Component Index Equations (CI) and Suitability Indices (SI) Comprising Crayfish Habitat Suitability Model.

The component index equation for water suitability ($CI_{water\ suitability}$) is determined from the suitability index (SI) values for the two variables, water salinity (SI_1) and average water depth from October through June (SI_2)

$$CI_{water\ suitability} = (SI_1 \text{ x } SI_{2\ Oct\ through\ Jun})^{1/2}$$

The component index equation for habitat ($CI_{habitat}$) represents the single variable “vegetative habitat type” (SI_3), and thus the quality of food resources for crayfish and protective cover for crayfish from predators

$$CI_{habitat} = (SI_3)$$

The component index equation for crayfish reproduction ($CI_{reproduction}$) is determined from SI values for the two variables, percentage of sand in the soil substrate (SI_4) and average water depth (SI_5) from July through September.

$$CI_{reproduction} = (SI_4 \text{ x } SI_{5\ Jul\ through\ Sep})^{1/2}$$

Alternatively, the crayfish HSI model can be expressed in SI units for the five SI variables as follows:

$$\text{Crayfish HSI} = (SI_1 \text{ x } SI_{2\ Oct\ through\ Jun})^{1/6} \text{ x } (SI_3)^{1/3} \text{ x } (SI_4 \text{ x } SI_{5\ Jul\ through\ Sep})^{1/6}$$

3.1 Applicability of the Model

The 2017 crayfish habitat suitability model is applicable to all life stages (hatchlings, juveniles, adults) of procambarid crayfishes for the Louisiana coastal zone. The 2017 model is capable of calculating monthly and aggregate annual HSI values per cell for crayfish habitat, as was calculated for the 2012 model.

3.2 Response and Input Variables

V_1: Salinity

Variable 1 (V_1) is water salinity reported in parts per thousand, ppt or equivalent g/L. The value applied is the mean monthly water salinity for each habitat cell where water is present. Optimal crayfish production is best determined by habitats in which the tolerance of vegetation to salinity is less than or equal to 1.5 ppt according to the function below.

$SI_1 =$	1	for $V_1 \leq 1.5$
	$1.5 – 0.333*V_1$	for $1.5 < V_1 \leq 3.0$
	$1.0 – 0.167*V_1$	for $3.0 < V_1 \leq 6.0$
	0	for $V_1 > 6.0$

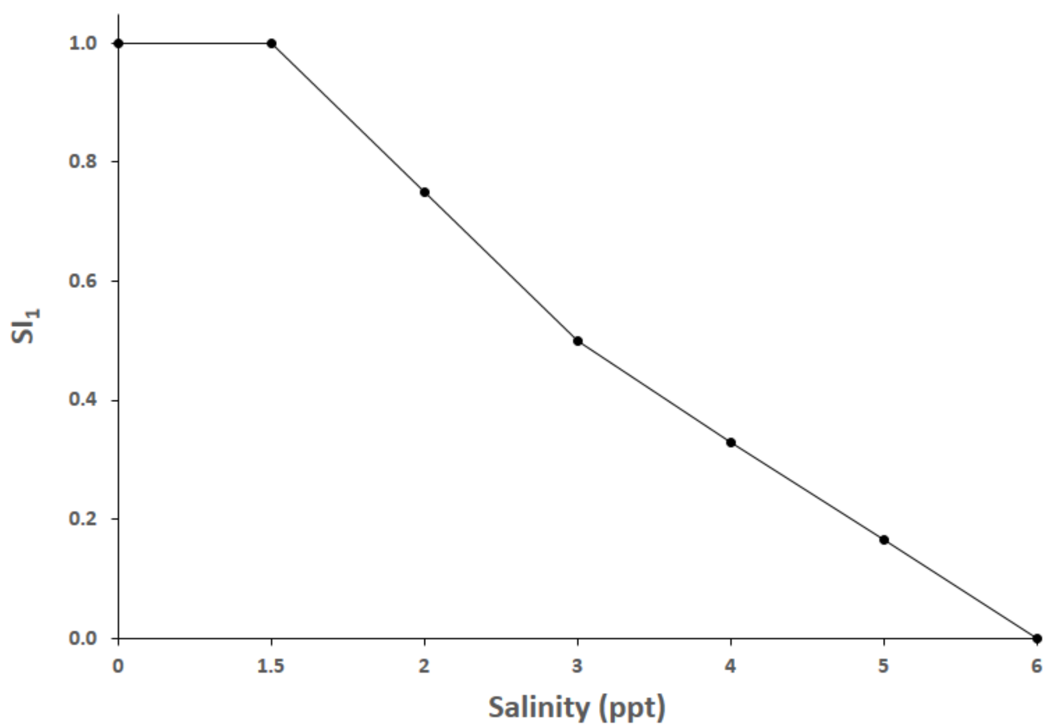

Figure 4: Relationship between Salinity (ppt) and the Suitability of Salinity as Environmental Habitat for Procambarid Crayfishes.

Rationale: Crayfish are freshwater aquatic invertebrates that have a relatively high tolerance to short-term exposure to dissolved mineral content (salinity) in water (Loyacano, 1967a; Loyacano, 1967b; Perry & LaCaze, 1969; Chaney, 1971; Sharfstein & Chafin, 1979; Green et al., 2011). Long-term exposure to salinity impairs reproduction at concentrations as low 6 to 8 ppt (Perry & LaCaze, 1969). Field observations show that crayfish are routinely found in high abundance at salinities up to 1.5 ppt, but favored sources of vegetative habitat (potential food resources and protective cover) can be negatively impacted by long-term exposure to higher salinities. Romaire (unpublished data 2011-2013) showed that physiological stress from long-term (6 months) exposure to salinities of 3 ppt to 6 ppt significantly reduced crayfish production at a proportionally higher rate than long-term exposure at 1.5 to 3 ppt. Therefore, two suitability index function equations (equation 1 for salinities ranging from 1.5 to 3.0 ppt, and equation 2 for salinities ranging from 3.0 to 6.0 ppt) were developed to account for the difference in habitat suitability for the two ranges of salinity.

Although crayfish can survive concentrations of saline water exceeding 6 ppt for extended periods, reproduction is impaired. Thus, flooded habitats subject to continuous saltwater intrusion or exposure to salinities exceeding 6 ppt are considered to be unsuitable crayfish habitat in this model.

V_2: Water Depth from October through June

Variable 2 (V_2) is water depth in the assigned cell from October through the following June. The value applied is the mean monthly water depth for each cell where water is present. The suitability index for mean water depth (cm) in fall, winter, spring (October through June) is assigned as follows:

$SI_2 =$	0	for $V_2 = 0$ or > 274
	$0.02174*V_2$	for $0 < V_2 \leq 46$
	1	for $46 < V_2 \leq 91$
	$1.5 - 0.00547*V_2$	for $91 < V_2 \leq 274$

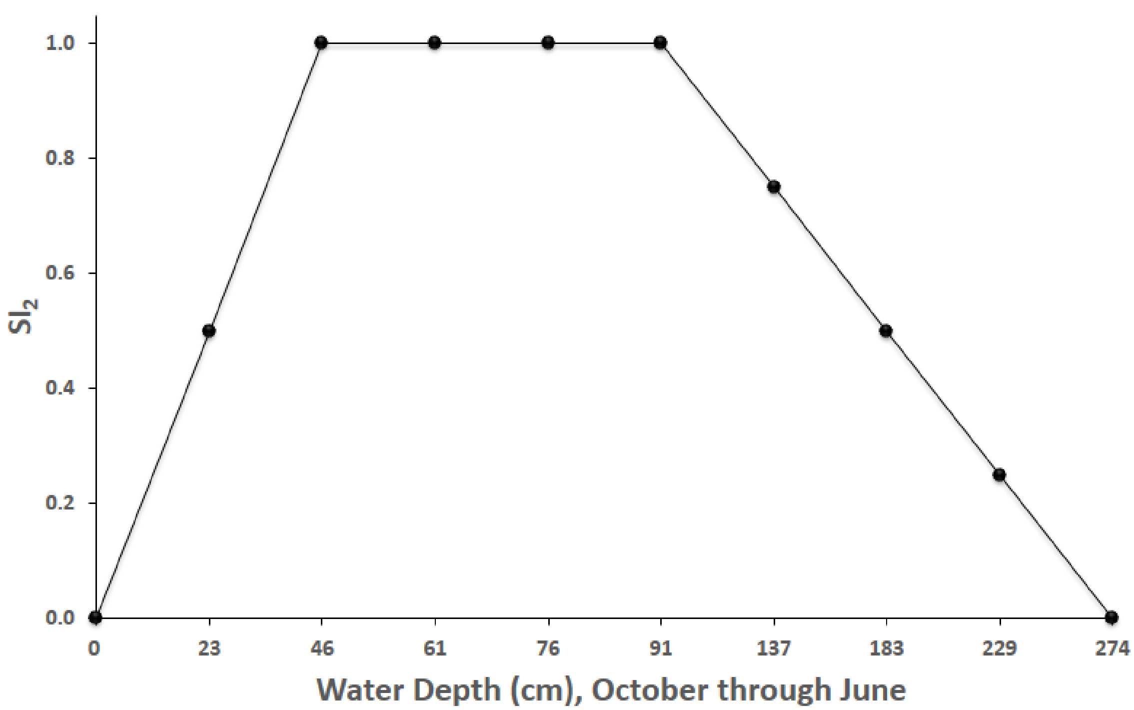

Figure 5: Relationship between Water Depth (cm) from October through the Following June, and the Suitability for Fall, Winter, Spring Water Depth as Environmental Habitat for Procambarid Crayfishes.

Rationale: Optimal crayfish production occurs at water depths from 46 to 91 cm (1.5 to 3.0 ft). Water depths of 0 (dry or bare land) and exceeding 274 cm (9 ft) are defined in the model as unsuitable habitat. As water depth increases in overflow riverine habitats in late fall and winter in response to rising river levels in coastal Louisiana, adult and juvenile crayfish are flushed from burrows and dispersed into habitats replete with food, protective vegetative cover and generally oxygen-rich water. Water depths of 46 to 91 cm (1.5 to 3 ft) from fall through spring are conducive crayfish habitat (Konikoff, 1977; Huner & Barr, 1991; Huner & Konikoff, 2009), but sustained shallow water depths less than 46 cm (1.5 ft) during the same period can expose crayfish to high levels of predation by mammals and birds. Additionally, hypoxia is more severe in shallow water from elevated water temperature and high biological oxygen demand associated with decaying organic matter that concentrates in shallow water. Bottom waters at depths exceeding 274 cm (9 ft) are more likely to be hypoxic during spring and early summer (April through June) if environmental conditions do not favor sufficient water flow (flushing action) through wetland habitats (Konikoff, 1977; Shenoi, 1996; Kaller et al., 2011). The impact of shallow water, 0 to 46 cm (0 to 1.5 ft) on crayfish habitat suitability is likely to be more acute than in deeper water (91 to 274 cm; 3 to 9 ft); therefore, two suitability index function equations were developed to describe the relationship between water depth and habitat suitability from 0 to 46 cm (0 to 1.5 ft), and from 91 to 274 cm (3 to 9 ft), respectively. Water exceeding 274 cm (9 ft) in depth from October through June is considered to be non-suitable habit for crayfishes of all sizes because of high levels of predation by fishes and from potential hypoxia in the hypolimnion (bottom waters) during periods of low water flow.

V_3: Vegetative Habitat Class

Variable 3 (V_3) is vegetative habitat class for each cell. The suitability index for vegetative habitat is as follows:

SI_4 = 1.00 for V_{3a} = Swamp Forest
0.85 for V_{3b} = Fresh Marsh
0.75 for V_{3c} = Open Water
0.60 for V_{3d} = Intermediate Marsh
0.20 for V_{3e} = Brackish Marsh
0.00 for V_{3f} = Saline Marsh
0.00 for V_{3g} = Bare Ground (restricts crayfish to semi-permanent or permanent aquatic habitats by excluding terrestrial habitats)

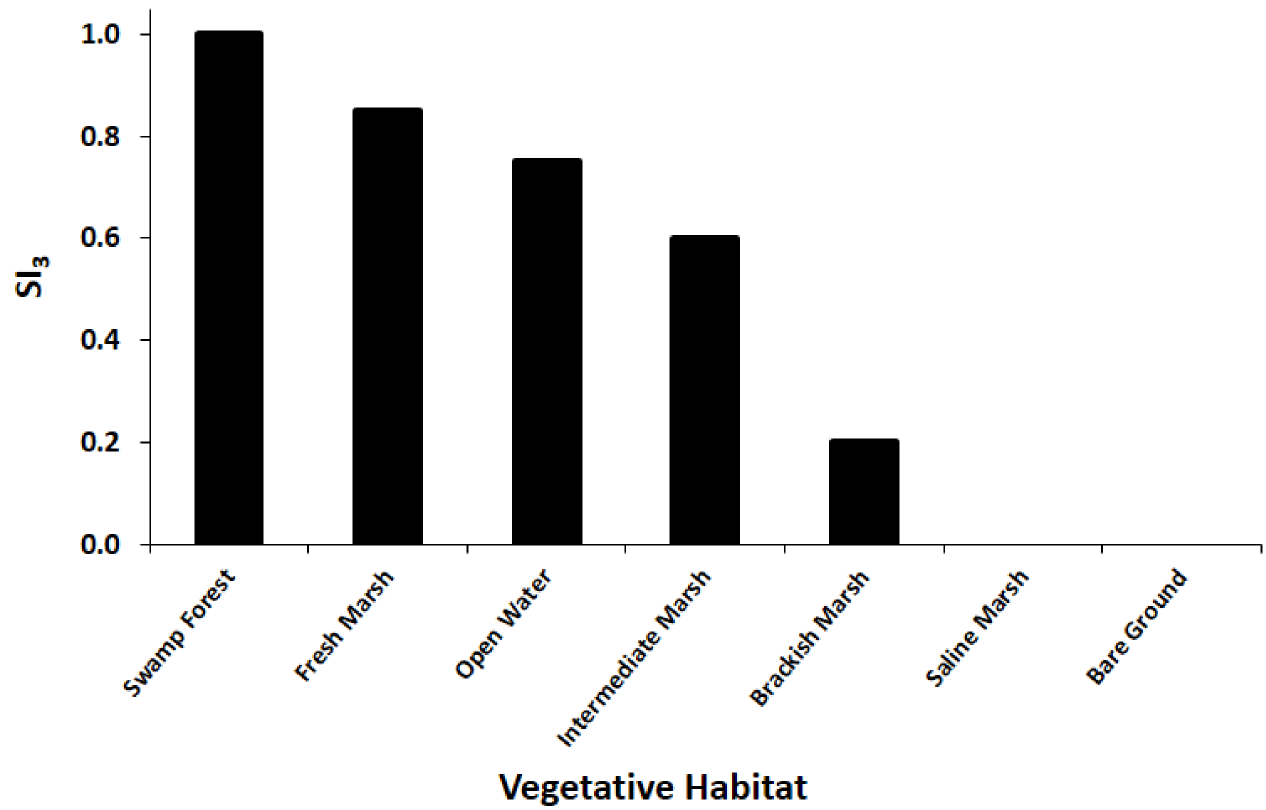

Figure 6: Relationship between Vegetative Habitat and the Suitability of the Wetland Habitat Type for Procambarid Crayfishes.

Because each habitat cell can potentially have multiple vegetative habitat types, the following equation weights vegetative habitat suitability for a mixture of vegetative habitats within an individual cell:

$$SI_3 = [(1.0 \text{ x } V_{3a}) + (0.85 \text{ x } V_{3b}) + (0.75 \text{ x } V_{3c}) + (0.6 \text{ x } V_{3d}) + (0.2 \text{ x } V_{3e}) + (0.0 \text{ x } V_{3f}) + (0.0 \text{ x } V_{3g})]$$

Rationale: Optimal habitats for procambarid crayfishes are swamp forests and freshwater marshes. Open water habitats can provide moderately suitable habitat if water is present from October through June, and if water depth during the summer (July through September) is at or near zero (bare ground). Intermediate, brackish and saline marshes are sub-optimal habitats because of saline conditions, and permanent (year round) bare ground habitats cannot support procambarid crayfishes. Red swamp crayfishes are most widely associated with lentic, swamp/ marsh-type habitats (Penn, 1943) and southern white river crayfishes are largely associated with more permanent, flowing (lotic) aquatic habitats (Huner, 1995), although either species can be found in abundance in both lentic and lotic habitats (Sheppard, 1974; Konikoff, 1977; O'Brien, 1977; Paille, 1980; Pollard et al., 1983; Shenoi, 1996; Bonvillain, 2012).

Both species thrive in floodplain (forested swamp and freshwater marsh) habitats that are flooded in the fall-winter-spring and dry (bare ground) in the summer-early fall. Open water habitats subject to annual fall-winter-spring flooding and summer drying episodes are suitable, but not optimal habitats, because of a paucity of protective cover from predators (particularly fishes) and potential limitations in food resources. Brackish water and saltwater marsh habitats are not suitable habitats for procambarid crayfishes because of long-term salinity exposure. Crayfish are excluded from year-round terrestrial (bare ground) habitats.

V_4: Percentage of Sand in Soil Substrate

Variable 4 (V_4) is the percentage of sand, relative to the percentage of clay and silt, in the sediment for each cell. The suitability index for the percentage of sand (relative to the percentage of clay and silt) in the sediment substrate is assigned as follows:

$SI_4 =$	0	for $V_4 \geq 90$
	$2.25 - 0.025*V_4$	for $50 < V_4 \leq 90$
	1	for $V_4 \leq 50$

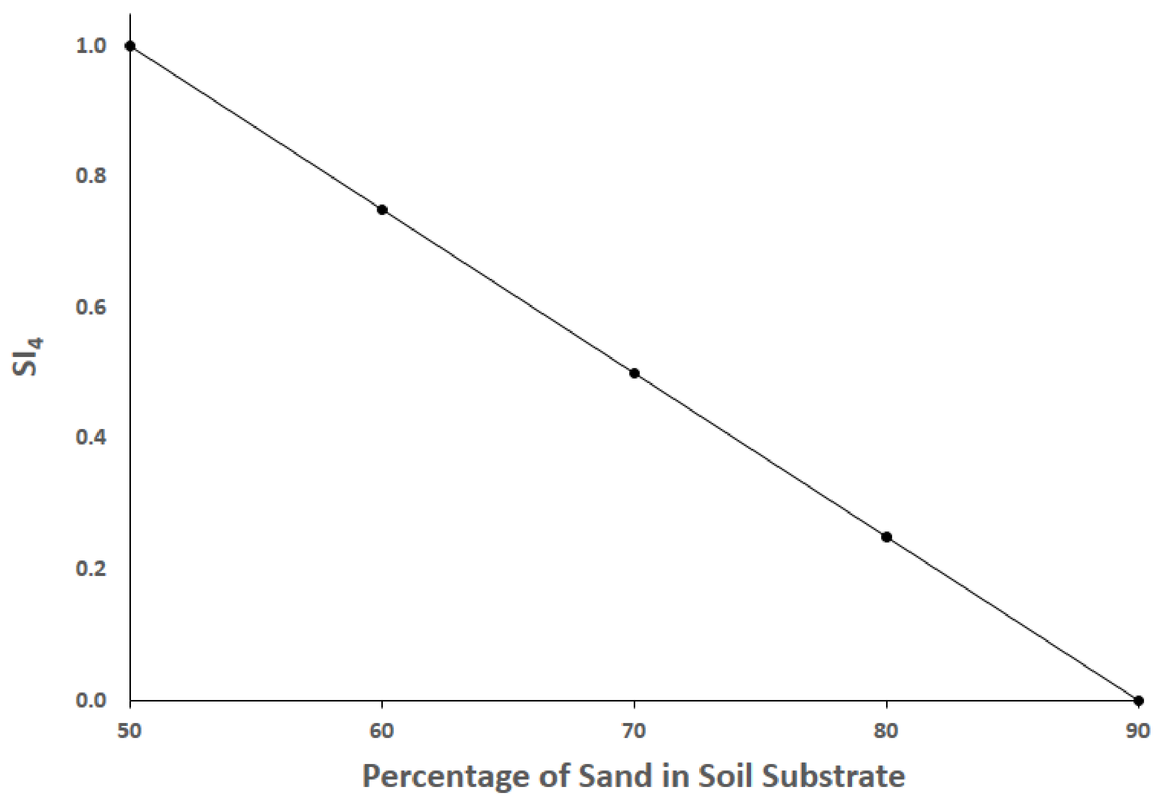

Figure 7: Relationship between the Percentage of Sand in Soil Substrate and the Suitability of Soil as Reproductive Habitat for Procambarid Crayfishes.

Rationale: Burrows are excavated by crayfish at the sediment-water interface, usually when water recedes, water temperatures increase to physiologically stressful levels, and/or females mature, mate and eggs begin to develop in the ovaries. Soil must have sufficient clay and silt (low amount of sand and low porosity) to sustain burrow integrity (prevent burrow collapse) and retain some perched water in the terminal burrow chamber. Eggs will not hatch without water being present in the terminal chamber of the burrow (McClain & Romaire, 2004). A high percentage of sand in the soil substrate (high soil porosity) reduces water retention in the burrow, and when the sand content of the soil is high, burrows can collapse during or following construction, impairing reproduction.

Although burrows are used primarily for reproduction by adults, crayfish of all ages and sizes will construct burrows or retreat to existing burrows to survive periods when surface waters recede or environmental conditions become severely adverse (e.g., high water temperatures and exposure to hypoxia) (Huner & Barr, 1991; Huner, 1995). Burrows excavated at the sediment-water interface must be constructed in water-saturated soils with a sufficient clay and silt (ideally with sand content less than or equal to 50% of soil composition) to maintain burrow integrity and to prevent desiccation in the burrow when occupied (Penn, 1943, Burras et al., 1995; Burras et al., 1999; McClain & Romaire, 2004).

Both research and anecdotal observations from procambarid crayfish aquaculture in southern Louisiana indicate that soil textures classified as sandy loam (50-70% sand), loamy sand (70-90% sand) and sand (>90% sand) are marginal or non-suitable habitat because reproduction may be impaired, presumably from death loss of reproductively active females in burrows that do not retain perched water, or from failure of eggs to hatch if perched water is not present in the terminal chamber of the burrow. The model assumes that suitability of crayfish habitat based on soil substrate texture composition decreases linearly as the percentage of sand comprising the soil increases from 50 to 90%. Soils with sand exceeding 90%, most common in coastal areas, are considered unsuitable burrowing habitat for procambarid crayfishes.

V_5: Water Depth from July through September

Variable 5 (V_5) is water depth (cm) in a habitat cell from July through September. The suitability index function for water depth in cm from July through September is as follows:

$$SI_5 = \begin{cases} 0 & \text{for } V_5 > 15 \\ 1.0 - 0.06667 * V_5 & \text{for } V_5 \leq 15 \\ 1 & \text{for } V_5 = 0 \end{cases}$$

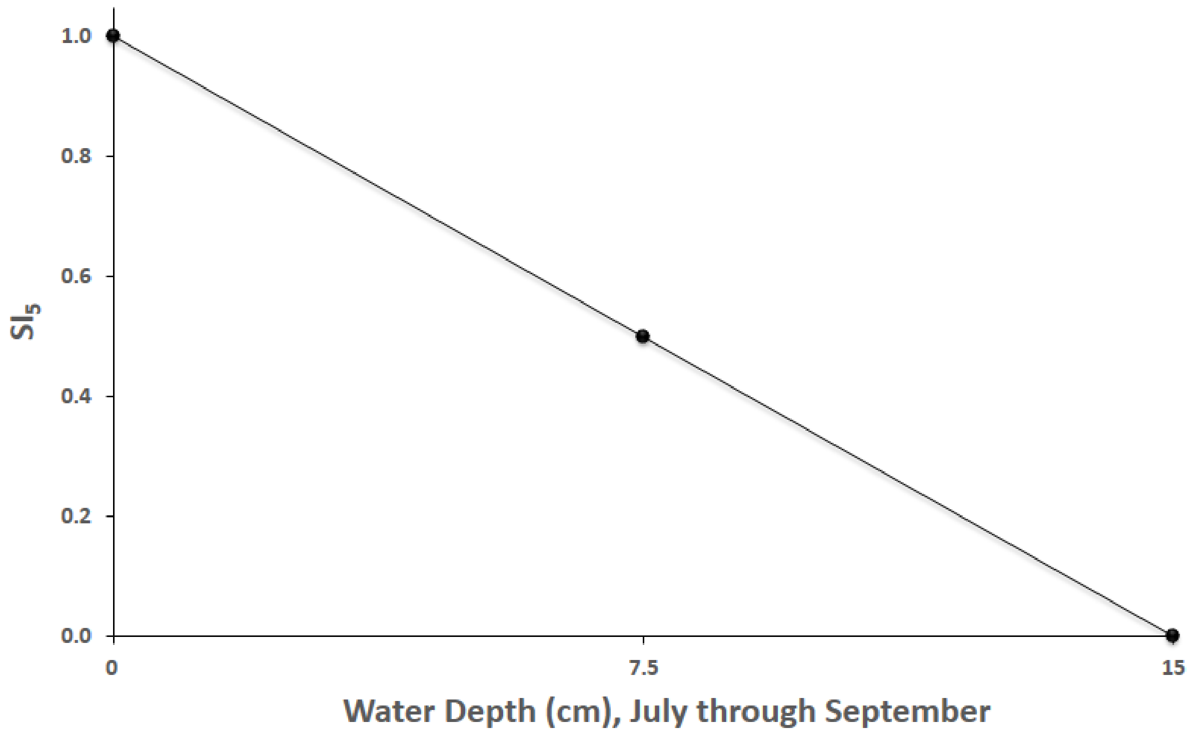

Figure 8: Relationship between Water Depth (cm) from July through September, and the Suitability of Summer Water Depth as Reproductive Habitat for Procambarid Crayfishes.

Rationale: The model assumes a linear reduction in habitat suitability as water depth during July through September increases from 0 cm (bare ground) to 15 cm (0.5 ft). A dry or nearly dry habitat in summer-early fall that induces burrowing by crayfish for reproduction is optimal. Shallow water of less than 15 cm (0.5 ft) in depth in summer has moderate suitability as habitat provided high spots/ridges project above the water's surface that will enable crayfish to burrow at the sediment-water interface. Continuously flooded habitat during the summer, in which crayfish have no access to bare ground for burrowing, is unsuitable because reproduction will be impaired.

The hydrologic cycle in southern Louisiana that is optimal for reproduction of procambarid crayfishes requires exceedingly shallow water or dry (bare ground) during summer/early fall when adult females are sequestered to subterranean burrows and eggs are laid and hatched (Konikoff, 1977; Pollard et al., 1983; Huner & Konikoff, 2009). As water recedes in depth to bare ground conditions, the area of habitat available for crayfish to burrow increases, and the biomass of terrestrial and semi-aquatic emergent vegetation that serves as the base of a food web for crayfish is increased. Shallow water and/or bare ground during the summer reduce predation by fishes that cannot survive in shallow water or bare ground habitats (Penn, 1943; Konikoff, 1977; Huner & Konikoff, 2009).

4.0 Model Verification and Future Improvements

A crayfish HSI model verification exercise was conducted to validate the distribution and suitability of habitats for red swamp and white river crayfishes in the Louisiana coastal zone. The HSI models were run using calibrated and validated ICM spin-up data to produce a single value per ICM grid cell. At present, the Integrated Compartment Model (ICM) spin-up data produced by the coast wide model may not reflect 'real-world' conditions in all areas of the coast. For example, some areas known to have wetland vegetation were classified in model output as non-wetland habitat, and as result generated low HSI scores when high scores would otherwise be expected. In these instances, no improvements could be made to the HSI values calculated for crayfish as these issues reside in other ICM subroutines of the overall coastal model (i.e., vegetation). Consequently, the accuracy of the verification exercise is contingent on these inconsistencies.

Moderately high HSI scores were observed in swamp and fresh marsh habitats known to be suitable habitat for red swamp and white river crayfishes. Highest HSI scores were observed in the lower Atchafalaya River Basin watershed, the area of highest commercial crayfish harvest in coastal Louisiana. Moderately high HSI scores for crayfish were found in numerous scattered habitat cells throughout the Vermillion-Teche and Mermentau River basins, two basins that support limited and scattered commercial crayfish harvest in the coastal zone.

Calculated HSI scores in the lower Atchafalaya River basin were concentrated further east in the lower Atchafalaya River basin watershed than expected based on commercial harvest sites. The reason for this anomaly will be further investigated in quality assurance/quality control (QA/QC) exercises to be conducted later, and corrected/adjusted as necessary. Optimal habitat as defined by HSI scores between 0.8 to 1 were not observed in any cells and this is might be associated by using of average annual water depth input data in model calculations rather than monthly water depth values to calculate monthly HSI values, that can then be averaged on annual basis.

The crayfish HSI model can be limited by the quality of the modeled data that is used as input variables. For example, errors in the model used to predict salinity or mean winter-spring water depth and spring-fall water depth will be transmitted through this model and influence the predicted habitat quality for crayfish. An additional limitation of the present model is the inability to assess the weighted importance of the five suitability index variables in determining habitat suitability for procambarid crayfishes in coastal Louisiana. As in the 2012 crayfish HSI model, the 2017 crayfish HSI model provides equal weight to each of the five SI variables to assess the suitability of crayfish habitat. Based on model calibration and validation runs, it is possible that model output can be improved by providing a higher weight to specific SI variables.

Historical wild crayfish harvest (landing) data from LDWF have been provided for each major water basin in coastal Louisiana. These harvest data will assist in calibrating the crayfish HSI model output during future QA/QC exercises. Additional limitations or weaknesses in the crayfish HSI model may be identified at that time but if so, habitat suitability index functions should be able to be modified (re-calibrated) to improve the model.

Future projects in the Louisiana coastal zone that alter river and wetlands hydrology have the potential to degrade crayfish habitat in some areas while expanding suitable crayfish habitat in other areas.

The 2017 crayfish HSI model addresses recommendations of Romaire (2012) to improve the 2012 crayfish HSI model, by including a sediment substrate suitability index variable. The current version of the 2017 model utilizes percentage sand in the sediment substrate as a surrogate to assess the likelihood of a burrow to retain sufficient amount of perched water in the terminal chamber, a requirement for successful oviposition (egg laying) and hatching. Further investigations should consider substitution of categorical soil classification types in the USDA-NRC Soil Survey Geographic Database (SSURGO) for the variable percentage sand in the sediment substrate. The SSURGO database is more robust and should be easily integrated for potential use the crayfish HSI model by model programmers. However, a limitation of the SSURGO database is coastal restoration projects might alter soil type classification, projecting decades into the future.

Biologically, increases in water depth in the fall, winter and spring, followed by dewatered conditions (bare ground) during the summer in swamp forests and freshwater marsh floodplain habitats are conducive to crayfish production and is well documented in the scientific literature. However, the specific time frame selected for use in the 2017 model, mean monthly water depth from October 1 through June 30 (suitability index variable V_2), and mean monthly water depth from July 1 through September 30 (suitability index variable V_5), although largely based on observations of historical commercial crayfish catches, the scientific literature, and professional judgment might require adjustments during future QA/QC exercises. For example, adjusting the fall, winter, and spring water depth (V_2) SI function to start in September, or alternatively in November, rather than October, might be required to determine if HSI model output identifying optimal crayfish habitat more closely aligns with areas of historical commercial crayfish landings.

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