APPENDIX F-8: AQUATIC RESOURCES

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APPENDIX M – AQUATICS

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Abstract

Aquatic impacts and mitigation requirements previously reported in the 2007 Yazoo Backwater Area Reformulation study were reexamined using updated information. EnviroFish was used to quantify changes in flooded acres, and associated Habitat Units (HUs) for spawning and rearing fish. The 2020 Proposed Plan resulted in a reduction of 2,838 and 3,232 HUs for spawning and rearing, equivalent to a reduction of 2,404 and 3,861 Average Daily Flooded Acres (ADFAs), respectively. Total acres of reforested agricultural lands in the 2-year floodplain required to offset impacts are 3,998 and 4,553 for spawning and rearing, respectively. Although reforestation was the primary method of mitigating impacted floodplain habitat in 2007, monitoring studies (see Water Quality Appendix N) have documented extensive hypoxia (< 3.0 mg/l dissolved oxygen) in the Yazoo Study Area during inundation, questioning the value of reforestation to address aquatic impacts. Furthermore, long term trends in fish species composition indicate little change in diversity despite repeated flooding events and prior reforestation. Periodic fish collections in the Yazoo Study Area over the past 20 years document a rapid decrease in abundance below 2 - 3 mg/l of dissolved oxygen for all life stages. The effects of hypoxia on spawning and rearing were considered by calculating a Relative Value Index (RVI = 0.6) to weight the difference in the functional value of hypoxic and normoxic water in the floodplain. With this updated relative value index applied, mitigation reforestation requirements were decreased to 2,399 and 2,732 acres for spawning and rearing, respectively indicating that reforestation efforts have limited benefits to fish reproductive success. Hypoxia and other long- term environmental disturbances in the Yazoo Study Area during the latter half of the 1900's reduced fish species diversity, and today, the assemblage is dominated by species tolerant of poor habitat conditions. Extreme low flows during the fall season in the Big Sunflower-Steele Bayou drainage was identified as a major impairment impacting the overall fish community. Therefore, a combination of reforestation (in-kind) and establishment of environmental flows (out-of-kind) was considered as a more effective mitigation approach. Re-establishing perennial flows in the Big Sunflower-Steele Bayou drainage, including the project area, with supplemental low flow groundwater wells may offset high mortality of larvae and juvenile fish in the spring from hypoxia, improve survival of juveniles and adults during autumn, and compensate for a reduction in reforestation requirements. Elevated flows will also benefit mussels, including listed species, by preventing stranding and desiccation. This approach addresses the overall aquatic community during all life stages. A total of 9,321 acres of streams will be improved by environmental flows from the groundwater wells benefiting fish, mussels, and other ecological attributes of the Yazoo Study Area.

Purpose and Objectives

This aquatic appendix will update the 2007 Final Supplement No. 1 to the 1982 Yazoo Area Pump Project Final Environmental Impact Statement (FSEIS), hereinafter referred to as the 2007 FSEIS. The U.S. Army Corps of Engineers (USACE) is evaluating new information on ecological effects of the project. This appendix is divided into five major parts each with their own objective, but together, describe the ecological status of the mussel and fish communities in the Yazoo Study Area as well as potential mitigation strategies to improve biotic diversity.

1. EnviroFish - A re-analysis of existing floodplain habitat was completed for spawning and rearing fishes that includes more recent hydrologic data (1978 - 2019) and improved elevation mapping data (10-meter versus 30-meter resolution) compared to the 2007 FSEIS. ADFAs were calculated using EnviroFish 1.0 for the No Action Alternative and the Proposed Plan. Reforestation requirements to offset impacts are presented.
2. Dissolved Oxygen –Statistical relationships are presented between hypoxia and fish species abundance, including larvae, juvenile, and adult life stages, using a long-term dataset collected in the Big Sunflower-Steele Bayou drainage over 30 years.
3. Fish Species Trend Analysis – The status and trends of the Big Sunflower fish assemblage over the past 50 years is described. Drainage-wide impairments to the aquatic environment are identified.
4. Alternative Mitigation – The aquatic benefits of out-of-kind mitigation that addresses low flows using supplemental groundwater wells are quantified.
5. Entrainment and Impingement – Potential risk of fish entrained or impinged during pumping operations is evaluated.

Part 1: EnviroFish

Background

EnviroFish is a certified, hydraulic model coupled to a spreadsheet that estimates acres of floodplain habitat suitable for fish reproduction under a given set of hydrologic conditions (Killgore et al. 2012). Utilizing the results of the hydrologic model (*i.e.,* daily elevations), EnviroFish integrates the daily flood elevations, floodplain land use, and Habitat Suitability Indices (HSI) to calculate a response variable. The response variable is in the form of a Habitat Unit annualized over the project life (AAHU) so the Habitat Evaluation Procedure can be used to complete the analysis of the alternatives. EnviroFish was used to compare the impacts and mitigation requirements in the 2007 FSEIS to the 2020 Proposed Plan for spawning and rearing fishes. Environmentally conservative changes were made in this analysis compared to the 2007 report including increased HSI score for flooded bottomland hardwoods (BLH) and evaluating impacts to BLH up to the five-year frequency flood.

Objective

The objectives of this analysis were to calculate average daily flooded area (ADFA) for the No Action Alternative and the Proposed Plan, calculate impacts, determine floodplain reforestation acres necessary to offset impacts, and consider the effect of hypoxia on reforestation benefits to fish spawning and rearing.

Approach

Average Daily Flooded Acres (ADFA) are an area equivalent to one acre that is inundated on average every day of a defined season for a specified number of years. The ADFAs were calculated using the elevation data and hydrologically modeled water surface elevation. A new dataset was used to calculate Average Daily Flooded Acres that included hydrologic data up to 2019 (1978 - 2019) and improved elevation mapping data (10-meter versus 30-meter resolution) compared to the 2007 FSEIS report. The acreage analysis area was constrained to lands within the 2-year flood frequency and the spawning and rearing season was defined as 1 March – 30 June. The aerial measure of inundation (ADFAs) is multiplied by the appropriate Habitat Suitability Index (HSI) value in EnviroFish to output HUs with which to compare alternatives and annualized over the 50-year project life.

Seasonally flooded habitat types were delineated from satellite imagery and verified with ground-truthing to characterize the majority of floodplain landuse in the Yazoo Study Area. The actual acres of each habitat type by stage elevation (i.e., stage-area curves) were entered into the EnviroFish software to calculate ADFAs. Habitat types are defined as follows:

1. Agriculture – all areas in which an agricultural product was grown including developed and pasture lands.
2. Fallow – agricultural lands that have been abandoned where there is a prevalence of herbaceous, non-woody cover.
3. Bottomland hardwoods – all forested areas.

For this application, only agriculture, fallow, and bottomland hardwood cover types within the 2-year flood frequency were considered. The percentages of each land use in the Yazoo Study Area were based on 2019 Landsat imagery (Table 1). Bottomland hardwoods represented the highest landuse percentage, followed by agricultural and fallow fields. An increase in bottomland hardwoods in the 2-year floodplain was largely due to reforestation.

EnviroFish calculates ADFAs for spawning and rearing separately. Spawning acres were restricted to a minimum depth of 1.0 foot, maximum depth of 10 feet and restricted to lands flooded for a minimum duration of 8 consecutive days. A minimum water depth of 1.0 foot allows adults to access shallow, flooded areas; a water depth less than 1.0 foot is not considered realistic due to physical limitations in the spawning process. Flood duration of at least 8 consecutive days ensures suitable time for nest construction and other spawning activities by the adults and recognizes that shorter durations may result in the eggs becoming stranded and desiccated if water recedes too quickly. Alternatively, if the water recedes too rapidly off the floodplain, organic matter, nutrients, and newly hatched aquatic organisms may be carried into the river instead of remaining in the floodplain and permanent backwaters. The minimum one foot, 8-day duration rule is considered a conservative value to delineate spawning requirements for warm water fish species found in the Mississippi River basin. This rule guarantees an effective spawning window, emphasizes longer development times, and provides a margin for temporal variation in spawning activities (i.e., adult movement onto the floodplain, nest construction, and guarding/dispersal of fry). Rearing acres were calculated for water depths of 0.1 - 20 feet with a flooding minimum duration of 1 day. Once hatched, rearing fishes, including yolk-sac and post yolk-sac larval phases, have volitional behaviors to change locations within the floodplain. The maximum depth of 20 feet assumes that mostly channel habitat occurs beyond 20 feet in depth and hypoxia occurs in deeper water during inundation.

The majority of species that spawn and rear in riverine floodplains are pre-adapted to structurally complex habitats such as bottomland hardwoods. Therefore, cleared lands have less value for spawning and rearing habitat and eggs and larvae have a higher risk of becoming stranded or preyed upon in cleared lands as floodwaters recede. The HSI values reflect this trend, with optimum conditions occurring for bottomland hardwoods (HSI = 1.0); intermediate values for fallow fields (HSI = 0.5); and the lowest value for cleared, agricultural lands (HSI = 0.2). These values represent a community-level perspective on the biological response (i.e., spawning and rearing) of the fishes of the Yazoo Study Area to flooding. Further information on HSI development and modeling spawning and rearing habitat in floodplains are provided in the EnviroFish 1.0 manual (Killgore et al. 2012), which was certified in October 2020 by the Ecosystem Restoration National Planning Center of Expertise for this project.

Because the Proposed Plan would reduce flooding within the Yazoo Backwater, loss in Average Annual Habitat Units between the No Action Alternative and the Proposed Plan was calculated and mitigation requirements determined to offset loss in aquatic habitat. This analysis made certain assumptions on the application of EnviroFish to calculate ADFAs:

1. Larval fish have the potential to utilize the same habitat as spawning sites. Larval fish have smaller physical dimensions that allow access to shallower (< 1.0 feet) water than physically available for spawning needs (typically ≥ 1.0 feet depth, 8 days duration). The EnviroFish software was used to define minimum and maximum allowable depths for spawning and/or rearing to accurately represent a specific situation.
2. Habitat acres were quantified for floodplain habitat only. This was done because the project would impact the extent of floodplain habitat with no/minimal effect on channel and other permanent aquatic habitat.
3. Many factors dictate the overall timing of the spawning and rearing period. Optimum conditions for spawning occur when the flood pulse and warmer temperatures are coupled. Although there are multiple variables that dictate when fishes will actually spawn, the model assumed that spawning takes place from 1 March to 30 June.
4. Flooded bottomland hardwoods in the 2-year flood frequency are the preferred spawning and rearing habitat.

Results and Discussion

ADFAs and AAHUs were compared between the No Action Alternative and the Proposed Plan (Table 2). The ADFAs for each reach of the six reaches were summed for the spawning and rearing season, multiplied by the appropriate HSI value to calculate AAHUs, and impacts of the project calculated. The Proposed Plan resulted in a reduction of 2,838 and 3,232 AAHUs for spawning and rearing, reflecting a loss of 2,404 and 3,861 ADFAs, respectively (Table 2). For mitigation calculations, Average Annual Habitat Units (AAHUs) were calculated for the conversion of agricultural land to BLH over a 54-year project life. This calculation assumed four years of project construction, and ten years for the reforested areas to obtain full, functional value for spawning and rearing of fishes (Table 3). This analysis resulted in 0.71 AAHU gained per acre of reforested agriculture land (Table 3). Thus, reforestation of 3,998 acres would generate the 2,838 HUs (3,998 x .71) required to offset the spawning impacts of the Proposed Plan. Reforestation of 4,553 acres would generate the 3,232 HUs (4,553 x .71) required to offset the rearing impacts of the Proposed Plan. Mitigating rearing habitat, which does not have any hydraulic restrictions but represents a greater area, will fully mitigate spawning habitat.

The effects of hypoxia on spawning and rearing were considered by calculating a relative value index (RVI) to weight the difference in HSI values between hypoxic and normoxic water (see next section on dissolved oxygen). The RVI is used to document value judgements made during resource planning efforts (USFWS 1980). For this application, the RVI is a ratio to compare total abundance of larval and juvenile fish in hypoxic (dissolved oxygen < 3.0 milligrams per liter, mg/l)) and normoxic (> 3.0 mg/l) water collected with light traps between 1990 and 2008 in the Yazoo Study Area (Table 4). The mean number of individuals collected in hypoxic water was divided by the mean number of individuals collected in normoxic water to obtain the percent difference in total abundance of larval and juvenile fishes (0.6). This value served as a weighting factor for the widespread hypoxia that occurs during backwater conditions and was multiplied by the previously calculated AAHU and reforestation mitigation acres for the Proposed Plan (Table 3). The RVI decreased AAHU loss from 2,828 to 1,703 for spawning, and 3,232 to 1,939 for rearing. For mitigation during the spring, the RVI decreased reforestation requirements to 2,399 and 2,732 acres for spawning and rearing, respectively indicating that reforestation of the floodplain has limited benefits to fish reproductive success. Out-of-kind mitigation using environmental flows was included to offset reduction in reforestation (See Part 4, this appendix). The impacts of hypoxia on fishes are discussed in the next section.

Part 2. Dissolved Oxygen

Background

Most backwaters in the Lower Mississippi River basin become hypoxic as water temperature warms. Backwaters include oxbow lakes and any deep waterbody that becomes ponded or stratified for long periods of time. The hypolimnion of thermally-stratified water becomes hypoxic or anoxic. Oxygen replenishment by vertical mixing, oxygen demand, and residence time of bottom water jointly determine the oxygen budget and the temporal and spatial extent of bottom hypoxia (Kuo et al. 1991).

Hypoxia has been measured during Yazoo Study Area flooding events on numerous occasions (Figure 1). Hypoxia in general has negative impacts on fishes and other aquatic organisms. In the Big Sunflower River, fish species richness was shown to be directly related to dissolved oxygen concentration and ordination using nonmetric multidimensional scaling indicated strong association between fish community structure and dissolved oxygen (Shields and Knight 2011). Species adapted for aerial and surface film respiration often dominated the fish assemblage in hypoxic waters including the Big Sunflower, whereas less tolerant species such as bass, darters, and larger benthic fishes avoid hypoxic waters due to physiological limitations (Hoover and Killgore 1998, Killgore and Hoover 2001).

Objective

Fish and habitat data have been collected in the Big Sunflower-Steele Bayou drainage since the early 1990’s. These data were collected for different reasons related to flood control or habitat restoration, but field techniques have been consistent. An analysis of this database was performed to evaluate biotic responses to a range of dissolved oxygen regimes in the Yazoo Study Area. In addition, the estimated volume of hypoxic water during a major hydrologic event was estimated for different stratification scenarios to evaluate the geographic scope of the issue. Recent dissolved oxygen measurements below the outlet of the Steele Bayou water control structure are also summarized. The information will be used to evaluate biological impairment identified in the Yazoo Basin, including low dissolved oxygen (303d listed by Mississippi Department of Environmental Quality) and U.S. Environmental Protection Agency (EPA), in addition to discussion of the potential problems with reforestation to address hypoxic waterbodies.

Approach

Volume

The volume of water that spreads out across the Yazoo Study Area was estimated for the 2019 flood for waters 1 – 5, 5 – 10 and > 10 feet deep. These depth intervals were based on different stratification depths of the water column measured at multiple locations (see Water Quality Appendix N). On 23 May 2019, the water level on the landside of the Steele Bayou water control structure peaked at 98.23 feet NGVD (USACE 2019). The assumption was made that water would back up across the Yazoo Study Area filling any area with an elevation lower than 98.2 feet NGVD. For this application, the Yazoo Study Area (area of interest) was defined as the area south of Highway 82 composed of the Steele, Sunflower, and Quiver watersheds, as defined by the National Hydrography Dataset (USGS 2016), extending to the Yazoo Backwater Connecting Channel and excluding the area protected by the Yazoo backwater levee. The elevation-area and elevation-volume by depth interval was calculated using the FESM model for elevations 75 through 108 feet NGVD.

Fish

Two databases were used to evaluate relationships between dissolved oxygen and biotic response variables. The light trap database consisted of larval and juvenile fish collected by slotted Plexiglas traps (1 square foot) baited with chemical light sticks set overnight. Traps were set in littoral areas throughout the Yazoo Study Area in river and floodplain habitats between 1990 and 2008. The electroshocking database consisted of mostly adult and juvenile fish collected by a boat-mounted electroshocker in the Yazoo Study Area in 2003, 2009, 2015, and 2019. Each sample represented five minutes of pedal (electricity on) time. Dissolved oxygen was measured during each sampling event. Bivariate plots were created of dissolved oxygen and percent fish abundance for each database.

Probability density functions were fitted to the data using three methods: lognormal, Weibull, and Gamma distributions. These plots were visually inspected to evaluate effects of hypoxia on fish abundance. A box and whisker plot was created of the weighted distribution of fish over the range of dissolved oxygen measured in the Yazoo Study Area. Fish were divided by family to evaluate tolerance taxonomically. Abundance was weighted according to the number of individuals as:

$$Xw_{\mathrm{i}} = \frac{\sum_i W_i X_i}{\sum Wi}$$

where W_i is the number of individuals and X_i is the dissolved oxygen.

Results and Discussion

Volume

The volume of water during the 2019 flood was mapped (Figure 2) and calculated (Table 5) for three different depths to represent possible thermoclines below which water may become hypoxic (< 3.0 mg/l) or anoxic (< 1.0 mg/l) near the bottom. Stratification depths were based on monitoring data summarized in the Water Quality Appendix N. At a thermocline depth of 5 feet, 58% of the total volume could be hypoxic compared to 29% at a thermocline depth of 10 feet (Table 5). Even with a shifting thermocline, hypoxia could be extensive during prolonged flooding events occurring in spring and summer. Dissolved oxygen was also monitored below the Steele Bayou Structure. Those measurements were compared to a natural backwater, Forest Home Chute, and the Yazoo River above the confluence of Steele Bayou. A total of six to seven measurements were taken in August 2019 and May – June 2020. The mean (± 1 standard deviation) dissolved oxygen below Steele Bayou was 2.0 ± 0.7 mg/l compared to Forest Home Chute (7.7 ± 1.0 mg/l) and the Yazoo River (5.1 ± 1.5 mg/l). These data further support the presence of hypoxia during and after a flooding event. The response of fishes to hypoxia is discussed in the next section.

Fish

A total of 26,233 larval and juvenile fish representing at least 32 species were collected with light traps (n = 398) in the Big Sunflower-Steele Bayou drainage from 1990 through 2003 (Table 6). More species were collected, but taxonomic identification of larval fish is tenuous for some species and can only be identified to genus or family level. Five taxa represented over 90% of the total assemblage. Shad (Gizzard and Threadfin) were most abundant followed by Buffalo (likely Smallmouth and Bigmouth). Buffalo are obligate floodplain spawners. The sunfish genus *Lepomis* was the third most abundant taxa. Up to nine species in this genus have been documented in the Yazoo Study Area (see Table 7, Electroshocking data) and all are nest builders in shallow areas. Crappie were fourth in abundance represented by White and Black. Mosquitofish, which are live-bearing fish, are often attracted to light traps and were fifth in abundance. Other common taxa collected included Common Carp, Gar (Spotted, Longnose, and Shortnose) and various species of minnows and shiners.

Probability density functions fitted to a histogram of percent abundance of larval/juvenile fish over a range of dissolved oxygen indicates a slightly skewed normal distribution with the highest abundance at 6.0 to 7.0 mg/l of dissolved oxygen, then rapidly declining below 5.0 mg/l (Figure 3). The distribution is also skewed to the right where abundance rapidly declines above 8.0 mg/l. There are several possible reasons for this trend. Average 24-hr dissolved oxygen levels are rarely above 6.0 to 7.0 mg/l. Higher levels are typically associated with super saturation occurring late in the day. The same areas experiencing super saturation are often hypoxic in the mornings, resulting in lower fish abundance. These data confirm that hypoxic conditions occurring during flood events can have negative impacts to spawning and rearing fishes. Even slight increases in dissolved oxygen, at least above 2.0 mg/l, may be adequate for longer survival and recruitment of fish in the Yazoo Study

Area.

Both adult and older juveniles are included in the electroshocking data. A total of 2,126 individual fish were collected with the electroshocker in 83, 5-minute samples (total shocking time of 415 minutes) during 2003, 2009, 2015, and 2019 (Table 7). A total of 41 species were collected with Shad (mostly Gizzard), Buffalo (Smallmouth and Bigmouth), Spotted Gar, and Bluegill representing 70 percent of all species combined. Probability density functions fitted to the histogram of percent abundance over a range of dissolved oxygen were similar to the light trap data (Figure 4). Percent abundance of total individuals peaked around 6.0 mg/l and then rapidly declined below 3.0 mg/l. Percent abundance also declined above 7.0 mg/l probably for similar reasons described for light trap data.

The electroshocking data was evaluated by family using a box and whiskers plot (Figure 5). The weighted abundance confirmed that taxa with alternative modes or respiration (bowfin – Amiidae; gars – Lepisosteidae) typically occurred at low dissolved oxygen levels and are often the top predators in hypoxic environments. Suckers (Catostomidae) including buffalo were usually found in normoxic (6.0 to 7.0 mg/l) waters, along with shad (Clupeidae) and catfish (Ictaluridae). These families are less tolerant to low dissolved oxygen and may experience higher mortality during hypoxic conditions or move out of the area if possible. The speciose families of sunfishes (Centrarchidae) and minnows/shiners (Cyprinidae) had a wide distribution across the dissolved oxygen range sampled, but mean values fall in the range of 4 to 6 mg/l.

Field collections in the Yazoo Study Area and upper reaches of the Big Sunflower-Steele Bayou drainage over the past 30 years occurred over a wide range of dissolved oxygen concentrations from extreme hypoxic (< 1.0 mg/l) to saturated (> 10.0 mg/l) waters. Statistical measures of this database indicate a strong positive relationship between fish abundance and dissolved oxygen for all life stages. Dissolved oxygen concentrations greater than 5.0 mg/l is widely accepted as a standard for the protection of fish, although this value varies among state and federal agencies (Doudoroff and Shumway 1970). Some warm water fishes are adapted to dissolved oxygen concentrations below 5.0 mg/l without effects on growth, development, and behavior (Ekau et al. 2010). One study reported that dissolved oxygen concentrations will have to decline below 2.0 mg/l to severely impact fish assemblage composition in vegetated areas (Killgore and Hoover 2001). Those species maladapted for aerial and surface film respiration are eliminated and may contribute to a decline in fish species richness and abundance in riverine backwaters, river channels, and lakes (Shields and Knight 2011). Low dissolved oxygen along with other major impairments to aquatic habitat in the Yazoo Study Area has resulted in a fish community dominated by habitat and water quality tolerant species. However, more sensitive species do occur in lower numbers indicating potential recolonization if habitat conditions improve.

Avoidance of hypoxic areas is one adaptive mechanism of fish. In shallow areas, only the surface layer can serve as a refuge, but in deep waters many organisms have developed vertical migration strategies to use, pass through, and cope with hypoxic zones (Ekau et al. 2010).
Unobstructed backwaters also provide horizontal and lateral avenues of escape from hypoxic waters. Once Steele Bayou water control structure is closed, the only avenue of escape is to move upstream or laterally into shallower water or smaller tributaries. The extensive area of hypoxia

during flooding in the Yazoo Study Area (see Water Quality Appendix N) require fish to move upstream over 55 miles beyond the old Lock and Dam into the shallower, upper reaches of the drainage. The spatial extent of hypoxia in the Yazoo Study Area and the limited avenues of escape in regulated floodplains become a death trap for unwary fish (Jones and Stuart 2008).

Part 3. Fish Species Status and Trends

Background

Five families of fish taxonomically dominate the ichthyofauna of the Mississippi Alluvial Valley (MAV): Cyprinidae (83 spp.), Percidae (46 spp.), Centrarchidae (22 spp.), Catostomidae (21 spp.), and Ictaluridae (19 spp.) (Cross et al. 1986). The Mississippi River Basin is a principal center of diversity of the North American fish fauna (Burr and Page 1986, Conner and Suttkus 1986, Robison 1986). Fish species share a common distribution throughout the alluvial valley, with current variation in occurrence and abundance due to river engineering and subsequent environmental conditions (Baker et al. 1991, Schramm et al. 2016).

Prior to European settlement, 10 million hectares of bottomland hardwood forests occurred in the MAV from Illinois down to the mouth of the Mississippi River (Schoenholtz et al. 2001). In 1820, Audubon was traveling downstream on the Mississippi River and recorded the following as he stopped at the mouth of the Yazoo River (Rhodes 2004): "a beautiful stream of transparent water, covered with thousands of geese and ducks and filled with fish." Many of the tributaries of the Lower Mississippi River during the time of Audubon were likely tannin-stained, blackwater streams with sandy and gravel substrates, perennial flows, and bordered by almost an endless bottomland hardwood forest. However, by the mid-1980s, all that remained of the valley's forested land was roughly 6.6 million acres (Oswalt 2013).

Today, most low-gradient streams in the MAV, including the Yazoo Basin, have soft, unconsolidated substrates of silt and mud, depressed hydrographs due to groundwater depletion and other forms of irrigation, and minimal forested riparian zones (Schoenholtz et al. 2001, Clark et al. 2011). Consequently, flood control and agricultural practices in this ecoregion have impaired physical habitat, water quality, and fish communities (Chen et al. 2016). This section evaluates long-term trends in the fish assemblage of the Big Sunflower – Steele Bayou drainage that includes the Yazoo Study Area as agricultural development peaked and flood control projects were completed in the latter part of the 20th century. The intent is to provide supporting documentation on the status of the aquatic environment as part of the Proposed Plan.

Objective

1. Compare diversity indices between the Big Sunflower – Steele Bayou drainage and reference sites in the lower MAV.
2. Evaluate multi-decadal trends in species abundance in the Big Sunflower – Steele Bayou drainage.

Approach

Comparison Among Drainages

Existing seining data were used to describe and compare fish communities among different drainage

basins in the Lower Mississippi River Valley. The drainages represent a gradient in habitat impairment ranging from highly impacted to least disturbed (Stoddard et al. 2006).
Sampling occurred within the MAV in Stahler Stream Orders 4 - 7 (Figure 6). Localities occur in two different USEPA Level III Ecoregions (Mississippi Alluvial Plain and South Central Plains) but in a single biotic province, the Austroriparian Zone (Blair 1950; Hubbs 1957).
Drainages sampled were Big Sunflower and tributaries (i.e., Big Sunflower River, Quiver River, Bogue Phalia, and Steele Bayou); White River in Arkansas (i.e., river kilometers, rkm 314-443); Cache River in Arkansas within the Rex Hancock-Black Swamp Wildlife Management Area (i.e., rkm 87.4 – 117.8); Cypress Bayou system in East Texas (i.e., Little Cypress Bayou, Black Cypress Bayou, Big Cypress Bayou, and 12-Mile Bayou that flows into the Red River); and the Red River (i.e., rkm 370.3 – 436.4, between Shreveport, Louisiana and Arkansas State Line).
Sampling years and frequency varied by drainage, but all samples used in this analysis were collected during the summer and autumn (Julian Day range = 173 - 341). The Big Sunflower drainage represents chronic agricultural impacts to aquatic habitat: minimal riparian zone, deep, soft substrates, and intermittent flows. An exception was the Big Sunflower gravel bar reach sampled in 2014 - 2015; this site experiences perennial flow and is considered least disturbed in the Yazoo River Basin. Other drainages served as reference sites. The White and Red River drainages are surrounded by agriculture but have perennial flows with more stable substrates. The Cache River sites in the White River drainage are also heavily forested with mostly perennial flows. Cypress Bayou drainage in East Texas lies within the West Gulf Coastal Plain ecoregion, is a tributary of the Red River, and was sampled below Lake O' the Pines including Big Cypress Bayou, Little Cypress Bayou, and Black Cypress Bayou. Cypress Bayou represents a less disturbed drainage similar to intact bottomland hardwood ecosystems in the MAV with a heavily forested riparian zone, stable to soft substrates, and flows ranging from intermittent to perennial.

Fish were collected using a 3.0 meter by 2.5 meter, 50 millimeter mesh seine. Seining was conducted in water < 1.5 meters and a sample consisted of 10 hauls. Catch per unit effort (CPUE) was quantified by species as number/10 seine hauls or percentage of the total number collected. Fish metrics were selected to represent attributes of the assemblage that could be correlated to the principal stressors. Informative metrics describing taxonomic composition, tolerance of poor habitat and water quality, and affinity for flowing water were calculated from the individual samples and applied across a broad zoogeographic range in the MAV, which encompasses multiple ecoregions but with similar fish faunas. Taxonomic metrics included:

1. Percent darters, benthic and sight-predators characteristic of firm substrates, clear water, and flowing water;
2. Percent minnows (Cyprinidae), many of which are facultative or obligate rheophilic species;
3. Percent black bass (*Micropterus* spp.) indicative of forage availability and/or food web complexity;
4. Percent *Lepomis* sunfishes, a group of tolerant species ubiquitous in impaired delta streams, characterized three ways - Orangespotted Sunfish (*Lepomis humilus)*, juvenile *Lepomis* sp., and juvenile White Crappie (*Pomoxis annularis*);
5. Percent Mosquitofish *Gambusia affinis,* often numerically dominant in impaired delta

streams.

Functional fish metrics were based on qualitative classifications of each species as “intolerant” (I) or “tolerant” (T) of degraded structural habitat (e.g., reduced coarse substrates, instream cover, shading), water quality (e.g., increased turbidity and temperature, reduced dissolved oxygen), and flow (e.g., slack water, reduced depth, as well as reduced depth and hydraulic variability). Tolerance designations of most species were based on a published consensus of experts (Jester et al. 1992). Species not addressed in that study were assigned tolerances based on regional Index of Biotic Integrity studies (Paller et al. 1996, Emery et al. 2003, Bramblett et al. 2005). A binary designation (I vs T) was used rather than an ordinal scale (intolerant, moderately intolerant, moderately tolerant, tolerant) for parsimony and clarity. Functional metrics included: percent habitat intolerant fish (i.e., sensitive to reductions in clean surfaces, crevices for spawning and cover for hiding), percent water quality intolerant fish (i.e., sensitive to hyperthermia, hypoxia, and suspended solids), and percent flow intolerant fish (i.e., rheophilic, sensitive to diminished base flows).

Assemblages were ordinated among drainages using non-metric multidimensional scaling on Bray-Curtis similarity matrices of fourth-root transformed CPUE (Clarke and Gorley 2015). Fourth-root transformation increases the contribution of rare species and reduces the effect of dominant species so that natural disparities in species abundance are made more equitable (Goodsell and Connell 2002). Means of biotic metric values by drainage were statistically compared using MANOVA and the test statistic Wilks’ Lambda to evaluate multivariate differences among drainages (Proc GLM, SAS Institute 2015). For this test, the combined dependent variables were compared among the different drainages, and if the model was significant ($p < 0.05$), further testing was conducted using univariate ANOVA. If a significant difference in individual metrics among drainages was detected from the ANOVA, mean values were compared using the Student–Newman–Keuls multiple range test (SAS Institute 2015). All biotic metric percentages were arcsine transformed prior to analyses.

Temporal Trend Analysis

Changes in species richness over time were evaluated for 21 sites in the Big Sunflower – Steele Bayou drainage (Table 8). Samples were collected between 1993 and 2014. Most sites were sampled repeatedly on a seasonal basis but not necessarily annually. Fish were sampled the same as previously described for the interbasin comparison where a unit of effort was species abundance per 10 seine hauls. Rarefaction was used to determine species richness, which is a measure of the number of species “expected” in a sample of 100 (Clarke and Gorley 2015). Rarefaction is not as sensitive to sample size as raw species richness. A box plot was created of the annual rarefaction values in the drainage during this time period. Mean values of the four reference streams previously described were provided as a comparison to the Big Sunflower-Steele Bayou fish assemblage structure.

Results and Discussion

Comparison Among Drainages

A total of 84,697 fish representing 101 species and 20 families were collected in 175 samples from 1990 to 2015 (Table 9). Our species list is comparable to zoogeographic accounts by Conner and

Suttkus (1986) and Cross et al. (1986) in the Lower Mississippi River Valley who report five families that dominate the taxonomic diversity of the ichthyofaunal. Number of species for these families in our study were: Cyprinidae (33 spp.), Centrarchidae (15 spp.), Percidae (13 spp), Catostomidae (8 spp.), and Ictaluridae (8 spp.).

Cyprinidae was the dominant family in the White-Cache drainage with 21 species collected and 8 unique to the drainage. Darters consisted mainly of the *Etheostoma* complex and were more diverse in the White-Cache and Cypress drainages where *Percina* and *Ammocrypta* were also represented. Shovelnose Sturgeon (*Scaphirhynchus platorynchus)* and Chub Shiner (*Notropis potteri)* were collected only in the Red River. Bowfin (*Amia calva)* and American Eel (*Anguilla rostrata)* were collected only in the Big Sunflower-Steele Bayou drainage, although both of these species are widespread throughout the MAV.

Biotic metrics further illustrated faunal differences among drainages (Table 10). The Big Sunflower-Steele Bayou drainage had lower species richness and lower abundance of intolerant species. The Big Sunflower gravel bars were similar to the overall drainage except species richness was higher, considerably more minnows were present, and the assemblage was comprised of more habitat intolerant species. Metrics for the three reference drainages (Cypress Bayou, Red, and White/Cache) were relatively comparable among each other, with some exceptions, but values were statistically higher compared to the Big Sunflower-Steele Bayou drainage.

The Non-metric Multidimensional Scaling (NMDS) showed clear separation of the resemblance matrix of transformed species abundance values between the Big Sunflower-Steele Bayou drainage and reference sites (Figure 7). Stress values for the NMDS ordinations were less than 0.2 (2-D stress = 0.19, 3-D stress = 0.13) indicating good representation of the sample patterns across drainages. Stress measures how well the reduced number of dimensions in the NMDS ordination represents the original position of samples (and assemblage structure) in the complete multidimensional space. Stress values greater than 3.0 indicate poor representation. Stress increases with number of samples, number of variables, and potential outliers.

Biotic metrics followed a similar pattern as previously described. Tolerant species such as Mosquitofish, juvenile *Lepomis*, and Orangespotted Sunfish were dominant in the Big Sunflower-Steele Bayou drainage. As forested habitat increased along Axis 1, darters, *Micropterus* bass, and other habitat intolerant species were more common in the Cypress Bayou drainage where woody structure was present with stable substrates. The White and Red drainages with higher discharge were ordinated along Axis 2 associated with greater numbers of rheophilic minnows and shiners.

Long-term impacts to the aquatic environment are typified by the Big Sunflower-Steele Bayou drainage where fish communities are impaired. The assemblage is usually dominated numerically by a few species (i.e., Orangespotted Sunfish, juvenile *Lepomis*, and Mosquitofish) and most fishes are considered “moderately tolerant” or “tolerant” of degraded water quality and habitat (Jester et al. 1992). Homogenization of fish assemblages in the Yazoo Study Area reflects long periods of low water, excessive sedimentation, and land-use alterations over the past century. Possible solutions to restore and mitigate aquatic habitat conditions is discussed in the following section.

Temporal Trend Analysis

This analysis focused on temporal trends of the fish assemblage in the Big Sunflower-Steele Bayou drainage. It included 212 collections of fish at the 21 sites shown in Table 8 sampled during 10 different years spanning a 21 year time period. All seasons were included in this analysis, rather than summer-autumn only in the previous interbasin comparison, resulting in a higher sample size. The majority of collections were made in the Big Sunflower (n = 175), followed by Quiver (n = 27), and Steele Bayou (n = 10). Sample frequency ranged from 4 in 2006 to 81 in 1993. Years with small samples sizes were retained in graphical analyses of the annual trends.

Species richness derived from rarefaction ranged from 4.0 - 21.0 with a mean (± 1 standard deviation) value of 10.9 ± 3.1. There was considerable interannual variation, but mean values and the range of most observations each year in the Big Sunflower-Steele Bayou drainage were less than reference drainages with improved flow and forested riparian buffers (Figure 8). The Cache River had the highest mean richness value (19.2 ± 7.3, n = 4), followed by the Red River (18.5 ± 2.7, n = 10), White River (16.2 ± 5.0, n = 9) and Cypress Bayou (14.8 ± 4.0, n = 26). Low species richness in the Big Sunflower drainage further supports the findings of degraded habitat conditions and impairment of the fish assemblage.

Major changes have not been observed in the Big Sunflower-Steele Bayou drainage fish assemblage since 1993. Previously, a pollution control study by Mississippi Game and Fish Commission documented fish assemblages occurring in 1971 – 1972 (Mississippi Game and Fish Commission 1972). Fish were collected using rotenone, but despite different sampling methodologies from the current approach, only two species (Cypress Minnow (*Hybognathus hayi)*, Chain Pickerel, which was probably Redfin Pickerel (*Esox americanus)*) collected in 1971-1972 were not collected in the 1990-2000’s collections. However, the abundance of rheophilic minnows and madtoms were substantially higher in the 1970’s including Emerald Shiner, Tadpole Madtom, and Freckled Madtom. As with other collections, fish were numerically dominated by Gizzard Shad, bullheads, and several species of sunfish.

Both of the studies referenced in the previous paragraph indicate that the fish assemblage in the Big Sunflower-Steele drainage was already impacted by anthropogenic impacts prior to the 1970’s. The Mississippi Board of Water Commissioners (1966) reported that irrigation withdrawals in the Yazoo Study Area were not appreciable prior to 1951 but steadily increased after that time affecting low flows in the streams. Furthermore, low-flow indices for the Big Sunflower, Hushpuckena, and Bogue Phalia show reductions in low-flow indices of 27 – 36% resulting from withdrawals for irrigation since 1951. By the 1970’s, rheophilic and benthic-oriented species were in decline due to low flows and excessive sedimentation, and by the 1990’s, the fish assemblage was highly altered consisting of habitat-tolerant species. The combined loss of perennial flows, loss of trees along the streambanks, and accretion of sediments in the channel are identified as the primary stressors that could be addressed in restoration programs.

Part 4: Mitigation

Background

Cost-effective remediation of hypoxia in the Yazoo Study Area will require better understanding of autotrophic and heterotrophic processes that control dissolved oxygen and the relationship of these processes to discharge (Shields and Knight 2011). Considerations should be made to evaluate alternatives that reduce the magnitude and duration of hypoxia during floods. Recent data suggest that even slight increases in dissolved oxygen (> 2.0 mg/l) could lead to higher survival of many species after the flood recedes.

Reforestation of the 2-year floodplain in the Yazoo Study Area has been successful, including use of the Wetlands Reserve Program, and is the primary mitigation method to compensate for spawning and rearing impacts of the Proposed Plan. However, periodic hypoxia during spring and summer floods indicate that reforestation efforts may provide limited benefits to spawning and rearing fishes. Adult fishes spawning during a flood event must cope with the physiological stress of low dissolved oxygen; and once eggs hatch, larval fishes moving into deeper water encounter hypoxic conditions that likely lead to higher mortality. In addition, reforestation does not address all primary stressors to the Big Sunflower-Steele Bayou drainage including the Yazoo Study Area. Reduction of surface flows and abundance of fine sediments are not addressed. These stressors severely limit aquatic habitat and reduce spawning and foraging opportunities. Therefore, reforestation up to the 2-year flood event may not be the best method to mitigate for fish community impacts. Consideration of both in-kind mitigation by reforesting the floodplain and out-of-kind mitigation by establishment of environmental flows is proposed as a better solution to offset impacts of the Proposed Plan.

Objective

The objective of this section is to evaluate and discuss alternative methods of mitigation and describe the benefits of environmental flow establishment.

Approach

Land use alterations in the Big Sunflower-Steele Bayou drainage are pressed environmental disturbances culminating over a century resulting in stream degradation. The loss of forested riparian corridors, fine sediment accumulation in the channels, and reduction of surface flows are the principal or primary stressors to aquatic life in low-gradient warm water streams (Wang et al. 1997; Wood and Armitage 1997). These stressors influence other parameters (e.g., nutrients, dissolved oxygen) in a hierarchical organization of environmental influences that determine fish composition (Dembkowski and Miranda 2012). Management of land use disturbances, or the principal environmental variables impacting fish communities, can reverse or possibly restore stream habitat condition and recovery of the fish community.

Mitigation measures that could potentially benefit recovery of the fish community are discussed. The approach is to consider the life cycle of fishes and associated anthropogenic impairments to each life stage. Flood-induced hypoxia during the spring and early summer likely impacts successful spawning and rearing regardless of reforestation. The juvenile and adult life stages that do survive through the flood season are faced with extreme low flows during the fall. Therefore, improving low flows may compensate for impacts of hypoxia during the spring using both in-kind and out-of-kind mitigation.

Results and Discussion

Flow augmentation, or creation of environmental flows (E-flows), from the proposed 34 supplemental low flow groundwater wells in the tributaries of the Big Sunflower – Steele drainage will restore perennial flow and shall consider at least three criteria:

1. Provide adequate water to avoid desiccation of established mussel beds. Mussels are widespread and abundant in the Big Sunflower-Steele Bayou drainage and include regional and federally protected species (Jones et al. 2005). Empirical relationships between river stage and wetted perimeter of mussel beds can establish minimum discharge requirements. Additional analysis of E-flow benefits to mussels are discussed below under "Mussel Recruitment."
2. Ensure periodic fish passage flows over weirs for spawning movements and recolonization. The old Lock and Dam on the Big Sunflower River and other weirs in the drainage are impediments to upstream/downstream movements of fish during low water. Environmental flows should consider the minimum water depth over the weir crest for passage of target species. Additional analysis of fish passage, including a telemetry study that monitored fish passage over a weir, is discussed below under "Fish Passage."
3. Manage hydraulic connectivity between the river channel and low-elevation backwaters or tributary mouths. Slight increases in discharge can potentially re-connect large areas of backwaters otherwise isolated during non-flowing conditions.

Abstraction of water has caused formerly perennial rivers to become intermittent, and this trend is expected to increase due to climatic drying and water appropriation (Thibault et al. 2014). The Big Sunflower River is a key example of a once perennial stream that now does not flow in the fall due to groundwater depletion. Prior to the 1980's, low flow discharge of the Big Sunflower River at Sunflower, Mississippi was approximately 100 cubic feet per second (cfs) (Figure 9, 10% frequency). By the 1990's into the 2000's, low flow fall discharge was less than 20 cfs and lower reaches of the Big Sunflower River usually cease flowing (see Engineering Appendix G for more information on low flows).

Thirty four supplemental low flow groundwater wells placed primarily along Highway 1 extending from near Clarksdale (Coahoma County) south to Arcola (Washington County) are proposed to augment stream flows in multiple systems within the Yazoo Study Area. Three reaches in the Big Sunflower were established to reflect benefits of low flows to endangered mussels (i.e., Rabbitsfoot and Sheepnose) that occur in the upper reach between Clarksdale and Indianola. Eleven wells in Harris Bayou and Hushpuckena River watersheds would supplement low flows in this upper reach. Eleven wells in the Bogue Phalia Basin watershed would augment flows in the middle Big Sunflower River from Indianola down to the Little Callao gage near the Old Lock and Dam. Established mussel beds occur in this reach, particularly below the Old Lock and Dam, although the two endangered species have not been collected in this reach. Five wells in the Deer Creek watershed would augment flows in the lower Big Sunflower reach between the Steele Bayou structure and the Old Lock and Dam through Rolling Fork Creek. Recent sampling in the lower reach did not detect the two endangered species and they are unlikely to occur. In addition, five wells in Main Canal and two in upper Black Bayou (Fish Lake Bayou) will augment flows in the Steele Bayou watershed.

The wells would only be operated during the fall low flow period after irrigation return flows cease. Irrigation return flows from the agricultural fields maintain summer low flows in most of the stream channels. Minimum flow targets will be established for downstream locations based on the and the number of wells operated will vary so that the target flows are met. The minimum flows will be established through the Monitoring and Adaptive Management Program for this project. The wells will be located in areas near the Mississippi River levee to minimize possible impacts to the alluvial aquifer. The groundwater elevation will be monitored at all sites to evaluate the impact of well usage to the aquifer. All wells will be located outside of the current zone of depression in the groundwater table. Three scenarios were developed as illustrative examples of benefits to aquatic systems gained by the implementation of supplemental flows.

Instream habitat - To assess the potential for improvements to instream aquatic habitats as the result of supplemental flows, stage and discharge data were evaluated at the USGS gage (7288280) on the Big Sunflower River near Merigold, Mississippi (Sunflower County). The gage is located within the upper reach between Indianola-Clarksdale that contain the only extant populations of federally listed Sheepnose and Rabbitsfoot mussels in the Yazoo Basin. Mean daily values for both stage (feet) and discharge (cfs) were compiled for the period of record for the gage (discharge: 1 October 1992 - 12 August 2020; stage: 5 March 1993 - 12 August 2020). Values for the two parameters were plotted against each other and using a best fit line approach, a 3rd order polynomial curve was fit to the data (R2 = 0.9936) (Figure 10). Equation 1 was used to predict stage for a given discharge value.

Equation 1. y = 2E-11x3 - 6E-07x2 + 0.0069x + 4.1112

A predicted stage at Merigold was calculated for a range of discharge values (0 - 150 cfs) based on the estimated discharge proposed for the supplemental low flow groundwater wells (Table 11). Examination of the data indicates an increase of 25 cfs at the Merigold gage would correspond to an increase in 2.08 inches in stage height beyond the baseline conditions. Similarly, a 50 cfs supplemental flow would result in a 4.17 inch increase in stage. Supplemental flows during low flow conditions, particularly August – October (Figure 11), would improve stream conditions during this critical period, likely resulting in improved water quality in the affected streams. Even slight increases in stage would provide an increase in wetted perimeter resulting in an increase in available habitat for aquatic species such as fishes, mussels, and macroinvertebrates. Mussel species would experience reduced mortality associated with elevated water temperature during low water conditions. Improvement in water quality and macroinvertebrate production may improve the condition factor of fishes resulting in increases in survivorship during the following winter and spring periods. This improved health would transfer to the spring spawning period and positively benefit annual recruitment cycles. In addition, one would likely see increases in overall abundance and richness at most sites, particularly with the fishes.

Fish passage - Declining alluvial aquifer levels in the Mississippi Delta in combination with reduced base level stream flows have been the subject of much debate among agricultural, commercial, environmental, and residential interests (McKee 2011). These concerns have prompted discussions regarding interbasin transfer of water as a possible approach to supplement base level stream flows and improve aquifer recharge capabilities. There have also been discussions on the amount of water that is needed to maintain biotic sustainability of the associated stream fauna (i.e., environmental flows), the need for weirs to pool water at different locations within the watershed to accommodate flood risk management concerns (Bednarek 2001), and assuring sources for surface water withdrawal (Acreman and Dunbar 2004). Pooling water through construction of weirs or other features has the potential to impact fish movement within these systems, especially given the current number of weirs already in place, this impact could be offset by supplemental flows.

Slack et al. 2020 (in Press) conducted a telemetry-based project to evaluate fish passage over a weir in a Mississippi Delta stream. The target species for the study, buffalo fish (Catostomidae: *Ictiobus* sp.), is a large, migratory species well known for its migratory behavior within streams and rivers in the MAV for spawning, rearing and feeding purposes (Swingle 1957, Johnson 1963, Wrenn 1969, Moen 1974). These data evaluated the weir as a barrier to fish passage with respect to frequency and timing of passage events (movement windows) in relation to ambient environmental factors (e.g., temperature) and river conditions (e.g., stage). This work was critical given the pervasive nature of weir and instream structure placement in low gradient streams within the region for channel maintenance and water supply purposes (Shields et al. 1998, Killgore et al. 2008, Shields et al. 2013).

Fish passage in the study area was observed during periods of elevated stage and varied with upstream and downstream direction. In all cases but one, passage events occurred when stage exceed 97.24 feet. The crest elevation of the weir in the study area was 96 feet. The most extensive period for passage was during the spring when water temperature ranged 11.6 - 21.4 C (Mean = 16.6) and was likely an indication of pre-spawning migration behavior.

The probability of passage is increased during periods of elevated river stage. A compilation of historic stage data for the gage station located in the Yazoo Study Area (USACE gage at Highway 12) indicates a distinct seasonal pattern of probable fish passage events (Figure 12).
May - November is the period with the greatest percentage of days when water stage elevation ≤ weir crest height thus representing the period when passage probability is low (Mean = 18.1% of days, range = 10.7 - 30.0). In contrast, December - April represents the period when the probability of passage is higher given the lower percentage of days ≤ weir crest height (Mean = 2.0% of days, range = 0 - 2.7) thus providing a larger proportion of days where stage exceeds weir crest height.

Supplemental flows within this region during critical periods of low flow could improve the probability of fish passage events by increasing the number of days when weir crest height is exceeded (Figure 13). Incremental increases in stage causes a general shifting of the cumulative frequency curve to the right with the curve of each respective stage interval (e.g., 3, 6, 9, 12 inches) encompassing a larger percentage of days with weir crest exceedance.

Weirs will continue to be an important part of channel stabilization and maintenance in agricultural landscapes. They are also becoming an important element in restoration and water supply.

Incorporating supplemental flows into these operations is beneficial to support fish passage, particularly in smaller streams, and can directly affect fisheries resources by improving dispersal capabilities for many species. In addition, improved fish passage benefits mussels. Infected mussel host fish could access new areas of suitable habitat for mussel colonization (population expansion) or provide additional fish hosts access to current mussel habitat during the glochidia release period thereby increasing probability of infestation.

Fish Habitat Units- Re-establishing perennial flows with the supplemental low flow groundwater wells may offset high mortality of larvae and juvenile fish in the spring from hypoxia with higher rates of survival of juveniles and adults during autumn. This approach addresses the overall aquatic community during all life stages.

Changes in fish biotic metrics (Table 10) were evaluated between seining samples collected with and without flow in seven different drainages (Table 12). Two metrics were significantly different (ANOVA, $p < 0.001$) between the two flow scenarios. Percent abundance of rheophlic (flow-oriented) fishes increased 40% with flow while percent abundance of minnows and shiners increased 60% (Table 12).

Wetted acres of streams and rivers were determined to quantify spatial extent of the environmental flows. Average width of the primary waterbodies was determined from cross sections taken during seining samples (Table 13). Stream length was provided by MVK and acres were calculated (Table 14). A total of 9,321 acres of streams will be influenced by supplementation of environmental flows. Mean percent abundance of minnows and shiners for non-flowing and flowing scenarios (Table 12) were applied as HSI scores and multiplied by acres to obtain AAHUs (Table 14). Average Annual Habitat Units increased 40% with flows, further justifying benefits of supplemental flows.

Mussel recruitment- The freshwater mussel fauna of Mississippi is quite diverse and includes 83 described species (Jones et al. 2019) ranking fifth within the nation in terms of total diversity (Jones et al. 2005). The Yazoo drainage ranks second in the state in terms of richness (n = 44) (Jones et al. 2019) and contains 18 Species of Greatest Conservation Need (MMNS 2015) including three federally listed species (Fat Pocketbook, Rabbitsfoot, and Sheepnose).

Suitable water conditions are critical to freshwater mussel survival and health, and the group is strongly reliant on natural flow regimes (Strayer 2008, Haag 2012). Habitat and stream flow alterations can have significant impacts on native species and have been the primary cause for decline in many species (Bogan 1993, Haag and Williams 2014). Freshwater mussels require a fish host to complete the reproductive process as glochidia are released from the female mussel and encyst on the host fish. This strategy evolved as a dispersal mechanism for sessile benthic organisms with limited mobility. Mussels also possess substantial life history diversity with the development of unique reproductive strategies to improve fish host infection rates. In addition, species differ in the timing of reproductive specific milestone, but can generally be considered either short or long-term brooders. For short-term brooders, the activities associated with spawning, glochidia brooding and release occur within a single season compared to long-term brooders in which glochidia are typically brooded over winter following the spawning event and released the following year (Cummings and Graf 2015, Landis and Stoeckel 2016; Figure 14).

Thus, sufficient flow conditions during these critical phases is extremely important to promote mussel recruitment.

Within the Yazoo drainage, 67% (n = 31) of mussels exhibit a long-term reproductive strategy (bradytictic) which includes the Fat Pocketbook mussel. Short-term brooders (tachytictic) comprise 33% (n = 15) of species including both the Sheepnose and Rabbitsfoot mussel. For the Big Sunflower River upper reach between Indianola and Clarksdale, low flow conditions occur August - October and generally coincide with the spawning and brood period for long-term brooders, and the brooding and glochidia release period for short-term brooders. Providing supplemental flows during this period would improve mussel fish host interaction due to increased instream habitat and also enhance survivorship of newly recruited mussel as they release from their respective fish hosts and transition to riverine habitats.

Summary of Out-of-Kind Mitigation

A watershed approach for compensatory mitigation of adverse impacts of the project on fishery resources was considered during the planning process. A watershed approach recognizes the overall resource needs of the entire riverine system during all seasons rather than on-site mitigation that considers only locally important functions and values. Reforestation of agricultural lands has been the primary in-kind mitigation feature of the project area. However, despite over 30 years of reforesting lands in the project area, increases in fish diversity and/or richness has not been evident since monitoring began in the 1990's. Fish diversity metrics measured in the Big Sunflower-Steele Bayou drainage are typically 20-50% lower than reference watersheds in the same ecoregion (Table 8). Hypoxia within the floodplain during prolonged inundation periods has been identified as a primary deterrent to mitigating adverse impacts in the project area using reforestation. Therefore, reforesting agricultural lands in the project area does not fully compensate adverse impacts justifying consideration of out-of-kind mitigation that provides greater ecological importance to the overall aquatic resources in the watershed.

Low flows during late summer and autumn has been identified as a major contributor to depressed fishery resources in the watershed. Beginning in the 1950's and continuing today, the Big Sunflower-Steele Bayou drainage has been transformed from a perennial to an intermittent stream during seasonal low flow periods due to water abstraction. Fish spawning and rearing during the spring must cope with low dissolved oxygen during prolonged flooding that reduces the ecological value of reforestation in the floodplain, and those individuals that do survive are further impacted by prolonged periods of low flows during the summer-fall thereby affecting annual fishery recruitment strength. Meaningful mitigation must consider the entire life cycle of fishes and the associated anthropogenic impairments to each life stage. These ecological issues can more effectively be addressed through both in-kind and out-of-kind mitigation.

In-kind mitigation will include reforestation up to 2405 acres in the Yazoo Project Area that fully compensates wetland, terrestrial, and waterfowl impacts and partially compensates aquatic impacts. In-kind mitigation requirements for aquatic resources calculated by EnviroFish was 3,998 and 4,553 acres for spawning and rearing, respectively. Mitigating rearing impacts will fully compensate for spawning impacts. However, these values were reduced to 2,399 and 2,732 acres for spawning and rearing when adverse impacts of hypoxia on reproductive success were included.

Recognizing that low flows during the summer-autumn season provides greater ecological lift than simply more reforestation, 34 supplemental low flow groundwater wells are proposed to augment stream flows in multiple stream systems within the Big Sunflower-Steele Bayou drainage (i.e., environmental flows). Well field operation will occur on an annual basis regardless of flooding conditions in the lower reach of the Yazoo Project Area. Re-establishing perennial flow with supplemental low flow groundwater wells is considered out-of-kind mitigation, but will benefit all reaches from the headwaters to the mouth at Steele Bayou structure. This approach offsets the high mortality of larvae and juvenile fishes occurring in the spring during hypoxic events with increased survival rates of juvenile and adult fishes during autumn. Environmental flows also benefit mussels, including federally endangered species, as reproductive success in freshwater mussels is dependent on diverse and functional fish assemblages. Environmental flows benefit a total of 9,321 acres of streams, and based on a statistical habitat model, yields 1,678 AAHU's, which is a 40% increase compared to existing conditions. A maximum loss of 3,232 AAHU's for fish rearing without hypoxia calculated by Envirofish will be partially mitigated by reforesting 2,405 acres and the remainder will be compensated by the well fields. This analysis demonstrates that using both in- kind and out-of-kind mitigation fully compensates for adverse impacts of the project, takes a watershed approach rather than localized, and addresses all life stages of fishes during the year.

Part 5: Entrainment and Impingement

The proposed project would install and operate twelve pumps with an overall capacity of approximately 14,000 cubic feet per second in the Yazoo Basin to reduce seasonal flood elevations above 87 feet National Geodetic Vertical Datum (NGVD). Fish approaching the intakes are susceptible to entrainment by the pumps, which have axial flow impellers operating at 145 to 151 RPM's creating intake velocities of 1.7 ft/sec increasing to 2.3 ft/sec at the trash rack, and 5.8 ft/sec at the formed suction intake. The trash racks are spaced approximately 5.5 inches apart preventing larger fish from entering the intakes, although adult fish could become trapped against the racks (i.e., impingement). Small-bodied fish could be entrained and are susceptible to physical strike of the impeller and can be subjected to rapid changes in shear stress, pressure, acceleration, and turbulence.

To evaluate species composition of potentially entrained fish, the outlet below Steele Bayou Structure was sampled with paired "bongo" nets (0.75-m diameter, 4.5-m long, 505-µm mesh) during August 2019 and May-June 2020 after the Steele Bayou gates were open following impoundment. Net samples were taken below the water surface and each sample was of 5-min duration fished from a stationary boat. A General Oceanics Model 2035-B flow meter was mounted in the mouth of each net to measure velocity of water passing through the net. Meter readings and duration of sampling were converted to an estimate of water volume filtered for each sample. Samples were fixed and preserved in 5% buffered formalin. In the laboratory, fishes were identified to the lowest practical taxon and enumerated. Catch was expressed as density (e.g., number of larval fishes/100 m3 of water filtered) and used to describe temporal patterns in occurrence and relative abundance.

USACE acknowledges that entrainment may occur during operation of the pumps, but does not anticipate significant impacts to fish populations in the study area based on the reasons listed below. However, fish passing though the pumps will be monitored with bongo nets as part of the Monitoring and Adaptive Management Plan. Fish will be examined either in the field or laboratory for injury associated with impingement or propeller strikes. If significant mortality is observed, population models will be developed to evaluate long-term impacts on fish recruitment and potential mitigation strategies recommended to offset pump-induced mortality.

a. Over 98 percent of the fishes collected with bongo nets were either Gizzard or Threadfin Shad, and of these individuals, 99 percent were larvae or juveniles (Table 15). Gizzard and Threadfin Shad are ubiquitous throughout the lower Mississippi Valley and are often the most abundant fish species in lakes and rivers. No protected or rare species were collected.
b. The pump station will draw water near the bottom of the inlet channel, which is approximately 27 feet in total depth. Based on the Water Quality and Aquatic Appendix, deeper water during impoundment is hypoxic (less than three milligrams per liter of dissolved oxygen) and avoided by fish.
c. Most adult fish, including minnows, have burst speeds of three feet per second or greater that can be maintained for at least 30 seconds, which exceeds the water velocity at the trash intake but not the formed intake. Most fish avoid moving backwards in a current (at the point of entrainment) and will exhibit burst swimming speeds to move out of the intake area if possible. Fish entrained and not injured would move through the outlet into the Yazoo River where access to floodplain and riverine habitat is widely available.
d. Studies of fish entrainment through power plant turbines concluded that overall mortality is less than five percent (Cada 1990). However, entrainment and impingement will be monitored during pumping operations to determine potential injury of fish as they pass through the pumps.

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Table 1. Floodplain landuse percentages in the Yazoo Study Area over a range of flood frequencies from 1 to 100 years.							
Landuse	Flood Frequency (year) – Yazoo Study Area						
	1	2	5	10	20	50	100
Agriculture/Developed	0.03	0.12	0.26	0.34	0.40	0.45	0.48
Fallow	0.00	0.04	0.04	0.04	0.04	0.05	0.05
Bottomland Hardwoods	0.64	0.76	0.65	0.58	0.52	0.47	0.44
Waterbodies	0.33	0.08	0.05	0.04	0.03	0.03	0.04
Total	1	1	1	1	1	1	1

Table 2. Average Daily Flooded Acres (ADFA) in the 2-year floodplain and Spawning-Rearing Average Annual Habitat Units for the No Action Alternative and the Propose Plan. Cleared Lands represent 86% agricultural lands and 14% fallow lands within the 2-year floodplain (see Table 1). Habitat Suitability Index values for spawning and rearing were multiplied by the ADFA to obtain Average Annual Habitat Units (AAHU) over the project life: Agriculture – 0.2, Fallow – 0.5, and BLH – 1.0.

	Spawning						Rearing				
Reach	Cleared Lands	Agriculture	Fallow	BLH	Total		Cleared Lands	Agriculture	Fallow	BLH	Total
No Action Alternative											
Holly Bluff	66	57	9	459			118	101	16	828	
Little Callao	17	15	2	51			32	28	4	112	
Anguilla	155	133	22	110			324	279	45	238	
Little Sunflower	726	625	102	4,070			1,177	1,012	165	6,811	
Grace	36	31	5	466			73	63	10	869	
Steele Bayou	386	332	54	3,979			630	542	88	6,841	
Total ADFA	1,387	1,192	194	9,135	10,521		2,354	2,024	330	15,700	18,053
AAHU		238	971	9,135	10,344			405	165	15,700	16,269
Proposed Plan											
Holly Bluff	45	39	6	335			84	72	12	636	
Little Callao	16	14	2	48			30	26	4	108	
Anguilla	75	64	10	89			228	196	32	209	
Little Sunflower	415	357	58	2,824			724	623	101	4,924	
Grace	32	28	5	441			68	59	10	828	
Steele Bayou	223	192	31	3,573			390	336	55	5,965	
Total ADFA	807	694	113	7,310	8,117		1,524	1,311	213	12,668	14,192
AAHU		139	56	7,310	7,506			262	107	12,668	13,037

Table 3. Calculation of reforestation mitigation acreage in the 0 to 5-year floodplain to compensate for loss of Average Annual Habitat Units (AAHU) with the Proposed Plan. Loss of AAHU's and Average Daily Flooded Acres (ADFA) are shown in Table 2. Calculation of reforestation credits assume 4 years of construction and a 50-year project life. Derivation of the Relative Value Index (RVI=0.6) for hypoxia shown in Table 4 resulting in a reduction in AAHU's and reforestation requirements.

Variable	Spawning	Rearing
Proposed Plan AAHU loss without Hypoxia	2,838	3,232
Proposed Plan ADFA loss without Hypoxia	2,404	3,861
Proposed Plan AAHU loss with Hypoxia	1,703	1,939
Proposed Plan ADFA loss with Hypoxia	1,442	2,316
Agricultural land without reforestation (54 years @0.2)	10.8	10.8
Transition to fallow land (10 Years @0.5)	5	5
Reforested AAHUs (44 years@1.0)	44	44
Net AAHU Value (with-without)	38.2	38.2
AAHUs gained per acre without hypoxia (38.2/54)	0.71	0.71
Reforestation acres without Hypoxia (0.71 AAHU per acre credit)	3,998	4,553
AAHU's with Hypoxia RVI = 0.6	2,399	2,732

Table 4. Number of larval and juvenile fish caught in light traps (n=number of traps) set in hypoxic (dissolved oxygen < 3.0 mg/l) and normoxic (dissolved oxygen =>3.0 mg/l) waters, Yazoo Study Area, 1990-2008. The mean number of individuals collected in hypoxic water was divided by the mean number of individuals collected in normoxic water to obtain the percent difference in total abundance of larval and juvenile fishes (0.6).

TYPE	n	Mean	Standard Deviation	Minimum	Maximum
Hypoxic	173	74	487	1	6,387
Normoxic	186	121	827	1	11,225

Table 5. The estimated acre feet of water by depth interval within the Yazoo Study Area at the 23 May 2019 flood peak of 426,308 acres

Volume by Depth	Acre-Feet	Percent of Total
0 to 5 ft vol.	1,712,943.5	58
5 to 10 ft vol.	855,688.4	29
> 10 ft vol.	397,059.8	13
Total	2,965,691.6	100

Table 6. Number of indivudals by taxa collected with light traps (n = 398) in the Big Sunflower-Steele Bayou drainage from 1990 - 2003. Taxa are arranged in order of abundance.

Taxa	Common Name	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Clupeidae	Shad	6,702	25.55	6,702	25.55
Ictiobus sp.	Buffalo	5,268	20.08	11,970	45.63
Lepomis sp.	Sunfish	4,586	17.48	16,556	63.11
Pomoxis sp.	Crappie	2,309	8.8	18,865	71.91
Gambusia affinis	Mosquitofish	2,132	8.13	20,997	80.04
Dorosoma cepedianum	Gizzard Shad	1,953	7.44	22,950	87.49
Cyprinus carpio	Common Carp	1,232	4.7	24,182	92.18
Aplodinotus grunniens	Freshwater Drum	425	1.62	24,607	93.8
Lepisosteus sp.	Gar	291	1.11	24,898	94.91
Cyprinidae	Minnows/Shiners	243	0.93	25,141	95.84
Catostomidae	Suckers	187	0.71	25,328	96.55
Pomoxis annularis	White Crappie	174	0.66	25,502	97.21
Dorosoma petenense	Threadfin Shad	95	0.36	25,597	97.58
Lepomis cyanellus	Green sunfish	86	0.33	25,683	97.9
Lepisosteus oculatus	Spotted Gar	83	0.32	25,766	98.22
Notemigonus crysoleucas	Golden Shiner	72	0.27	25,838	98.49
Percidae	Darters	59	0.22	25,897	98.72
Pomoxis nirgomaculata	Black Crappie	44	0.17	25,941	98.89
Centrarchus macropterus	Flier	35	0.13	25,976	99.02
Morone chrysops	White Bass	33	0.13	26,009	99.15
Labidesthes sicculus	Brook Silverside	30	0.11	26,039	99.26
Centrarchidae	Sunfish	27	0.1	26,066	99.36
Mendia beryllina	Inland Silverside	20	0.08	26,086	99.44
Notropis lutrensis	Red Shiner	20	0.08	26,106	99.52
Notropis.sp.	Minnows	19	0.07	26,125	99.59

Lepomis symmetricus	Bantam Sunfish	18	0.07	26,143	99.66
Hypophthalmichthys nobilis	Bighead Carp	15	0.06	26,158	99.71
Micropterus salmoides	Largemouth Bass	10	0.04	26,168	99.75
Etheostoma sp.	Darter	9	0.03	26,177	99.79
Lepisoteus osseus	Longnose Gar	9	0.03	26,186	99.82
Micropterus sp	Black Bass	6	0.02	26,192	99.84
Ctenopharyngodon idella	Grass Carp	6	0.02	26,197	99.86
Ellasoma zonatum	Banded Pygmy Sunfish	5	0.02	26,202	99.88
Atherinidae	Silverside	4	0.02	26,206	99.9
Lepomis gulosus	Warmouth	4	0.02	26,210	99.91
Lythrurus sp.	Shiner	3	0.01	26,213	99.92
Pimephales vigilax	Bullhead Minnow	3	0.01	26,216	99.94
Aphredoderus sayanus	Pirate Perch	2	0.01	26,218	99.94
Carpiodes sp.	Redhorse	2	0.01	26,220	99.95
Fundulus sp.	Topminnow	2	0.01	26,222	99.96
Lepisoteus platostomus	Shortnose Gar	2	0.01	26,224	99.97
Lepomis miniatus	Redspotted Sunfish	2	0.01	26,226	99.97
Esox americanus	Grass Pickerel	1	0	26,228	99.98
Fundulus notatus	Blackstripe Topminnow	1	0	26,229	99.98
Fundulus chrysotus	Golden Topminnow	1	0	26,230	99.99
Ameiurus natalis	Yellow Bullhead	1	0	26,231	99.99
Lepomis macrochirus	Bluegill	1	0	26,232	100
Minytrema melanops	Spotted Sucker	1	0	26,233	100

Table 7. Number of individuals by taxa collected with an electroshocking boat (n = 83, 5-minute samples) in the Big Sunflower-Steele Bayou drainage during 2003, 2009, 2015, and 2019. Taxa are arranged in order of abudnance.

Taxa	Common Name	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Ictiobus sp.	Ictiobus sp.	439	20.65	439	20.65
Dorosoma cepedianum	Gizzard Shad	401	18.86	840	39.51
Dorosoma petenense	Threadfin Shad	285	13.41	1,125	52.92
Lepisosteus oculatus	Spotted Gar	118	5.55	1,243	58.47
Lepomis macrochirus	Bluegill	88	4.14	1,331	62.61
Ictiobus cyprinellus	Bigmouth Buffalo	76	3.57	1,407	66.18
Ictiobus bubalus	Smallmouth Buffalo	68	3.2	1,475	69.38
Lepomis megalotis	Longear Sunfish	54	2.54	1,529	71.92
Micropterus salmoides	Largemouth Bass	46	2.16	1,575	74.08
Lepomis gulosus	Warmouth	45	2.12	1,620	76.2
Lepisosteus platostomus	Shortnose Gar	44	2.07	1,664	78.27
Hypophthalmichthys molitrix	Silver Carp	38	1.79	1,702	80.06
Lepomis humilis	Orangespotted Sunfish	37	1.74	1,739	81.8
Cyprinella lutrensis	Red Shiner	34	1.6	1,773	83.4
Pomoxis sp.	Pomoxis sp.	34	1.6	1,807	85
Cyprinus carpio	Common Carp	32	1.51	1,839	86.5
Micropterus sp.	Micropterus sp.	32	1.51	1,871	88.01
Gambusia affinis	Mosquitofish	31	1.46	1,902	89.46
Cyprinella venusta	Blacktail Shiner	28	1.32	1,930	90.78
Lepomis cyanellus	Green Sunfish	25	1.18	1,955	91.96
Lepomis miniatus	Redspotted Sunfish	19	0.89	1,974	92.85
Aplodinotus grunniens	Freshwater Drum	17	0.8	1,991	93.65
Lepisosteus osseus	Longnose Gar	17	0.8	2,008	94.45
Notemigonus crysoleucas	Golden Shiner	16	0.75	2,024	95.2

Ictiobus niger	Black Buffalo	14	0.66	2,038	95.86
Notropis atherinoides	Emerald Shiner	14	0.66	2,052	96.52
Amia calva	Bowfin	12	0.56	2,064	97.08
Pomoxis annularis	White Crappie	11	0.52	2,075	97.6
Carpiodes carpio	River Carpsucker	9	0.42	2,084	98.02
Lepomis symmetricus	Bantam Sunfish	8	0.38	2,092	98.4
Morone chrysops	White Bass	7	0.33	2,099	98.73
Pomoxis nigromaculatus	Black Crappie	5	0.24	2,104	98.97
Lepisosteus sp.	Lepisosteus sp.	4	0.19	2,108	99.15
Ictalurus furcatus	Blue Catfish	3	0.14	2,111	99.29
Micropterus punctulatus	Spotted Bass	3	0.14	2,114	99.44
Ameiurus natalis	Yellow Bullhead	1	0.05	2,115	99.48
C.venusta X lutrensis	C.venusta X lutrensis	1	0.05	2,116	99.53
Ctenopharyngodon idella	Grass Carp	1	0.05	2,117	99.58
Fundulus chrysotus	Golden Topminnow	1	0.05	2,118	99.62
Fundulus notatus	Blackstripe Topminnow	1	0.05	2,119	99.67
Fundulus sp.	Topminnow	1	0.05	2,120	99.72
Lepomis marginatus	Dollar Sunfish	1	0.05	2,121	99.76
Lepomis microlophus	Redear Sunfish	1	0.05	2,122	99.81
Menidia beryllina	Inland Silverside	1	0.05	2,123	99.86
Morone saxatilis	Striped Bass	1	0.05	2,124	99.91
Polyodon spathula	Paddlefish	1	0.05	2,125	99.95
Pylodictis olivaris	Flathead Catfish	1	0.05	2,126	100

Table 8. ERDC seining sampling sites in the Big Sunflower-Steele Bayou drainage between 1993 and 2014 used to calculate annual diversity indices over a 21-year time period.	
Location/Site	Comments
Big Sunflower at Choctaw Bayou 32.86401°N; 090.80994°W	Sampling began in early 90's. Represents lower reach of Big Sunflower (below Lock and Dam)
Big Sunflower at Auter above HWY 14 33.04308°N; 090.70070°W	Sampling began in early 90's. Represents lower reach of Big Sunflower (below Lock and Dam)
Big Sunflower at mouth of Bogue Phalia (BGPHA MTH2) 33.25412°N; 090.72991°W	Sampling began in early 90's. Represents middle reach of Big Sunflower between the Lock and Dam and mouth of Quiver River
Big Sunflower below Brumfield Landing (Kinlock 3) 33.27681°N; 090.72366°W	Sampling began in early 90's. Represents middle reach of Big Sunflower between Lock and Dam and mouth of Quiver River
Big Sunflower at Brumfield Landing (Kinlock 2) 33.30694°N; 090.70505°W	Sampling began in early 90's. Represents middle reach of Big Sunflower between Lock and Dam and mouth of Quiver River
Big Sunflower above mouth of Quiver River 33.46959°N; 090.526824°W	Sampling began in early 90's. Represents upper reach of Big Sunflower between mouth of Quiver and Clarksdale
Big Sunflower east of Merigold (UPPR and Winery Rushing) 33.83261°N; 090.67196°W	Sampling began in early 90's. Represents upper reach of Big Sunflower between mouth of Quiver and Clarksdale
Big Sunflower south of Hopson 34.15674°N; 090.55031°W	Sampling began in early 90's. Represents upper reach of Big Sunflower between mouth of Quiver and Clarksdale
Bogue Phalia at the mouth 33.2432°N; 090.73046°W	Sampling began in early 90's. Represents lower reach of Bogue Phalia
Bogue Phalia at HWY448 33.60297°N; 090.85279°W	Sampling began in early 90's. Represents middle reach of Bogue (below cut-off)
Bogue Phalia at HWY 61 33.44744°N; 090.85888°W	Sampling began in early 90's. Represents upper reach of Bogue Phalia (above cut-off)
Quiver River 1.0 mi above mouth 33.47467°N; 090.55401°W	Sampling began in early 90's. Represents lower reach of Quiver River
Quiver River at Hwy 3 (including weir) 33.48892°N; 90.51881°W	Lower Reach
Quiver River at HWY 442 33.9413°N; 90.4639°W	Middle Reach
Quiver River at Hwy 32 33.9132°N; 90.4683°W	Upper Reach
Steele Bayou at Control Structure 32.46214°N; 090.89490°W	Downstream confluence of Steele and Big Sunflower river systems. Steele Bayou Restoration Monitoring
Steele Bayou at Hwy 1 32.55023°N; 90.57430°W	Middle Reach

Steele Bayou at Hwy 14 Weir 32.9072°N; 90.9531°W	Long-term sampling site, Middle Reach
Steele Bayou near Grace 32.9959 °N ; 90.9734°W	Weir Site
Steele Bayou at Yazoo NWR 33.074540°N; 90.961094°W	Upper Reach
Black Bayou at HWY 12 weir 33.157642°N; 90.924679°W	Weir at Leroy Percy State Park

Table 9. Mean catch per unit effort (CPUE; number/10 seine hauls) and grand total of fish species collected in streams, rivers, and bayous in the Mississippi Alluvial Plain and South Central Plain USEPA Level III ecoregions between 1990 to 2015 during summer and autumn. Metric classifications are Intolerant(I) or Tolerant (T) for habitat (HAB), water quality (WQ), and flow (FLOW) with I_{FLOW} = yes and T_{FLOW} = no.

Scientific Name	Common Name	Big Sunflower, n=119	Big Sunflower Gravel Bars, n=7	White/Cache, n=13	Red, n=10	Cypress, n=26	Grand Total, n=175	Metric Classification
Scaphirhynchus platorynchus	Shovelnose Sturgeon				0.50		5	I_{HAB}, I_{WQ}, I_{FLOW}
Lepisosteus oculatus	Spotted Gar	0.20	0.14	0.08	0.10		27	T_{HAB}, T_{WQ}, T_{FLOW}
Lepisosteus osseus	Longnose Gar	0.13			0.60		22	T_{HAB}, T_{WQ}, I_{FLOW}
Lepisosteus platostomus	Shortnose Gar	0.24			0.20		31	T_{HAB}, T_{WQ}, T_{FLOW}
Amia calva	Bowfin	0.01					1	T_{HAB}, T_{WQ}, T_{FLOW}
Hiodon alosoides	Goldeye			0.08			1	T_{HAB}, I_{WQ}, I_{FLOW}
Anguilla rostrata	American Eel	0.01					1	I_{HAB}, I_{WQ}, I_{FLOW}
Alosa chrysochloris	Skipjack Herring				0.10		1	I_{HAB}, I_{WQ}, I_{FLOW}
Dorosoma cepedianum	Gizzard Shad	20.08		2.54	15.70	0.12	2,583	T_{HAB}, T_{WQ}, T_{FLOW}
Dorosoma petenense	Threadfin Shad	3.85		0.15	13.10	9.65	842	I_{HAB}, T_{WQ}, I_{FLOW}
Esox americanus	Redfin Pickerel			0.15		0.27	9	I_{HAB}, I_{WQ}, T_{FLOW}
Campostoma anomalum	Central Stoneroller			0.15			2	I_{HAB}, I_{WQ}, I_{FLOW}
Cyprinella galactura	Whitetail Shiner			0.08			1	I_{HAB}, I_{WQ}, I_{FLOW}
Cyprinella lutrensis	Red Shiner	14.87	16.14		307.00	0.62	4,969	T_{HAB}, T_{WQ}, I_{FLOW}

Cyprinella venusta	Blacktail Shiner	134.16	185.71	121.31	3.10	6.19	19,034	THAB, TWQ, IFLOW
Cyprinella whipplei	Steelcolor Shiner			0.08			1	IHAB, IWQ, IFLOW
Cyprinus carpio	Common Carp[I]	1.06		0.15	0.10	0.04	130	THAB, TWQ, TFLOW
Erimystax x-punctatus	Gravel Chub			0.62			8	IHAB, IWQ, IFLOW
Hybognathus hayi	Cypress Minnow					0.04	1	IHAB, IWQ, IFLOW
Hybognathus nuchalis	Mississippi Silvery Minnow			41.46	0.20	0.04	542	IHAB, IWQ, IFLOW
Hybopsis amblops	Bigeye Chub			5.54			72	IHAB, IWQ, IFLOW
Hybopsis amnis	Pallid Shiner			2.08		0.73	46	IHAB, IWQ, IFLOW
Luxilus chrysocephalus	Striped Shiner					0.12	3	IHAB, IWQ, IFLOW
Luxilus pilsbryi	Duskystripe Shiner			0.23			3	IHAB, IWQ, IFLOW
Lythrurus fumeus	Ribbon Shiner			8.38		11.19	400	IHAB, IWQ, IFLOW
Lythrurus umbratilis	Redfin Shiner		0.14			1.23	33	IHAB, IWQ, IFLOW
Macrhybopsis hyostoma	Shoal Chub	23.45	138.14	0.62	15.40		3,920	IHAB, IWQ, IFLOW
Macrhybopsis storeriana	Silver Chub	0.01			2.40		25	IHAB, IWQ, IFLOW
Notemigonus crysoleucas	Golden Shiner	0.77	0.14	0.62		0.12	104	THAB, TWQ, TFLOW
Notropis atherinoides	Emerald Shiner	5.03	10.43	6.62	137.60		2,134	THAB, TWQ, IFLOW
Notropis buchanani	Ghost Shiner	38.57	5.14		4.30		4,669	THAB, TWQ, IFLOW
Notropis chalybaeus	Ironcolor Shiner					3.54	92	IHAB, IWQ, TFLOW

Notropis maculatus	Taillight Shiner			0.46		0.08	8	I_{HAB}, I_{WQ}, T_{FLOW}
Notropis nubilus	Ozark Minnow			0.08			1	I_{HAB}, I_{WQ}, I_{FLOW}
Notropis potteri	Chub Shiner				77.30		773	I_{HAB}, I_{WQ}, I_{FLOW}
Notropis rubellus	Rosyface Shiner			0.62			8	I_{HAB}, I_{WQ}, I_{FLOW}
Notropis sabinae	Sabine Shiner			1.54			20	I_{HAB}, I_{WQ}, I_{FLOW}
Notropis shumardi	Silverband Shiner				34.50		345	I_{HAB}, I_{WQ}, I_{FLOW}
Notropis telescopus	Telescope Shiner			5.00			65	I_{HAB}, I_{WQ}, I_{FLOW}
Notropis texanus	Weed Shiner			9.77		12.85	461	I_{HAB}, I_{WQ}, T_{FLOW}
Notropis volucellus	Mimic Shiner	0.58		38.92			575	I_{HAB}, I_{WQ}, T_{FLOW}
Opsopoeodus emiliae	Pugnose Minnow	0.07		11.62	0.40		163	I_{HAB}, I_{WQ}, T_{FLOW}
Pimephales notatus	Bluntnose Minnow					2.19	57	T_{HAB}, T_{WQ}, T_{FLOW}
Pimephales vigilax	Bullhead Minnow	14.49	94.00		306.70	5.62	5,595	T_{HAB}, T_{WQ}, T_{FLOW}
Carpiodes carpio	River Carpsucker			0.08	2.50		26	I_{HAB}, I_{WQ}, I_{FLOW}
Cycleptus elongatus	Blue Sucker				1.60		16	I_{HAB}, I_{WQ}, I_{FLOW}
Hypentelium nigricans	Northern Hogsucker			0.15			2	I_{HAB}, I_{WQ}, I_{FLOW}
Ictiobus bubalus	Smallmouth Buffalo	0.61		0.08			80	T_{HAB}, T_{WQ}, I_{FLOW}
Ictiobus cyprinellus	Bigmouth Buffalo	0.20		0.31	0.10		29	T_{HAB}, T_{WQ}, I_{FLOW}
Ictiobus niger	Black Buffalo	0.04		0.15			7	T_{HAB}, T_{WQ}, I_{FLOW}
Minytrema melanops	Spotted Sucker					0.50	13	I_{HAB}, I_{WQ}, I_{FLOW}

Moxostoma erythrurum	Golden Redhorse			3.23			42	IHAB, IWQ, IFLOW
Ameiurus melas	Black Bullhead	0.03					3	THAB, TWQ, TFLOW
Ameiurus natalis	Yellow Bullhead	0.18				0.04	22	THAB, TWQ, TFLOW
Ictalurus furcatus	Blue Catfish	1.00		0.31	4.90		172	THAB, TWQ, IFLOW
Ictalurus punctatus	Channel Catfish	5.44	4.29	3.00	4.30	0.08	761	THAB, TWQ, IFLOW
Noturus eleutherus	Mountain Madtom			0.46			6	IHAB, IWQ, IFLOW
Noturus gyrinus	Tadpole Madtom	0.46		0.08		0.62	72	IHAB, IWQ, TFLOW
Noturus nocturnus	Freckled Madtom	0.22	6.71			0.08	75	IHAB, IWQ, TFLOW
Pylodictus olivaris	Flathead Catfish	0.28	0.57		0.30	0.08	42	THAB, TWQ, IFLOW
Aphredoderus sayanus	Pirate Perch	0.06		0.85		0.38	28	IHAB, IWQ, TFLOW
Fundulus blairae	Western Starhead Topminnow					1.15	30	THAB, IWQ, TFLOW
Fundulus chrysotus	Golden Topminnow	0.24				0.23	34	THAB, IWQ, TFLOW
Fundulus notatus	Blackstripe Topminnow			0.08		9.04	236	THAB, IWQ, TFLOW
Fundulus olivaceus	Blackspotted Topminnow			2.00			26	THAB, IWQ, IFLOW
Gambusia affinis	Mosquitofish	165.95	116.29	11.15	0.70	25.69	21,382	THAB, TWQ, TFLOW
Labidesthes sicculus	Brook Silverside	0.23		18.77	0.80	40.31	1,327	IHAB, IWQ, IFLOW
Menidia audens	Inland Silverside	1.63			13.90	5.58	478	IHAB, IWQ, IFLOW
Morone chrysops	White Bass	0.03			0.80		11	THAB, TWQ, IFLOW

Morone mississippiensis	Yellow Bass				0.10		1	I_{HAB}, I_{WQ}, I_{FLOW}
Elassoma zonatum	Banded Pygmy Sunfish	0.07		0.15		0.15	14	I_{HAB}, I_{WQ}, T_{FLOW}
Centrarchus macropterus	Flier	0.02		0.08			3	I_{HAB}, I_{WQ}, T_{FLOW}
Lepomis cyanellus	Green Sunfish	3.18	1.86	0.38		0.04	397	I_{HAB}, I_{WQ}, I_{FLOW}
Lepomis gulosus	Warmouth	3.61		0.46		0.54	450	T_{HAB}, T_{WQ}, T_{FLOW}
Lepomis humilis	Orangespotted Sunfish	39.17	0.43	0.69	6.20	0.04	4,736	T_{HAB}, T_{WQ}, T_{FLOW}
Lepomis macrochirus	Bluegill	29.20	0.43	4.92	3.80	9.96	3,839	T_{HAB}, T_{WQ}, T_{FLOW}
Lepomis marginatus	Dollar Sunfish	0.58		2.00	0.30	2.62	166	T_{HAB}, I_{WQ}, T_{FLOW}
Lepomis megalotis	Longear Sunfish	2.10		2.00	3.20	8.35	525	I_{HAB}, I_{WQ}, I_{FLOW}
Lepomis microlophus	Redear Sunfish	0.02		0.15	0.30	3.73	104	T_{HAB}, T_{WQ}, T_{FLOW}
Lepomis miniatus	Redspotted Sunfish	0.40	2.14	1.15	0.30	2.23	139	T_{HAB}, I_{WQ}, T_{FLOW}
Lepomis symmetricus	Bantam Sunfish	0.50		0.23		0.31	71	I_{HAB}, I_{WQ}, T_{FLOW}
Micropterus dolomieu	Smallmouth Bass			0.08			1	I_{HAB}, I_{WQ}, I_{FLOW}
Micropterus punctulatus	Spotted Bass			1.38	0.10	0.58	34	I_{HAB}, I_{WQ}, I_{FLOW}
Micropterus salmoides	Largemouth Bass	0.06		0.62	1.30	2.62	96	I_{HAB}, T_{WQ}, T_{FLOW}
Pomoxis annularis	White Crappie	5.40	0.43	0.08	0.20	0.04	650	T_{HAB}, T_{WQ}, T_{FLOW}
Pomoxis nigromaculatus	Black Crappie	0.14			0.30	0.23	26	T_{HAB}, T_{WQ}, T_{FLOW}
Ammocrypto clara	Western Sand Darter			2.31			30	I_{HAB}, I_{WQ}, I_{FLOW}
Ammocrypta vivax	Scaly Sand Darter			0.15		0.85	24	I_{HAB}, I_{WQ}, I_{FLOW}

Crystallaria asprella	Crystal Darter			0.54			7	I_{HAB}, I_{WQ}, I_{FLOW}
Etheostoma asprigene	Mud Darter			0.77		0.58	25	I_{HAB}, I_{WQ}, I_{FLOW}
Etheostoma caeruleum	Rainbow Darter			0.15			2	I_{HAB}, I_{WQ}, I_{FLOW}
Etheostoma chlorosoma	Bluntnose Darter	0.30		2.46		1.96	119	I_{HAB}, I_{WQ}, I_{FLOW}
Etheostoma gracile	Slough Darter	0.03		0.23	0.10	0.23	13	I_{HAB}, I_{WQ}, I_{FLOW}
Etheostoma histrio	Harlequin Darter	0.06		0.00		0.54	21	I_{HAB}, I_{WQ}, I_{FLOW}
Etheostoma proeliare	Cypress Darter	0.30		0.00		2.92	112	I_{HAB}, I_{WQ}, I_{FLOW}
Etheostoma stigmaeum	Speckled Darter	0.02		0.00			2	I_{HAB}, I_{WQ}, I_{FLOW}
Percina caprodes	Logperch			0.00	0.10	1.58	42	I_{HAB}, I_{WQ}, I_{FLOW}
Percina maculata	Blackside Darter			0.00		0.92	24	I_{HAB}, I_{WQ}, I_{FLOW}
Percina sciera	Dusky Darter			0.00	0.10	0.31	9	I_{HAB}, I_{WQ}, I_{FLOW}
Aplodinotus grunniens	Freshwater Drum	2.16		0.62	2.00		285	T_{HAB}, T_{WQ}, I_{FLOW}
Oreochromis niloticus	Nile Tilapia[I]		3.86	0.00			27	T_{HAB}, T_{WQ}, T_{FLOW}
Total number of species		54	19	65	45	54	101	
Total number of individuals		62,058	4,109	4,176	9,682	4,672	84,697	
[I] *Introduced species*								

Table 10. Un –transformed mean (standard deviation) and minimum-maximum values of biotic metrics by drainage basin. Mean metric values with different superscript letters along the row are significantly different ($p < 0.05$) among drainage basins according to the Student–Newman–Keuls multiple range test. Data was arcsine transformed prior to ANOVA.

Metric	Big Sunflower n=119	Big Sunflower Gravel Bars n=7	Cypress Bayou n=26	Red n=10	White n=13
Percent Minnows	0.33 (0.29)^{a} 0-0.95	0.8 (0.21)^{b} 0.35-0.95	0.32 (0.23)^{a} 0-0.76	0.85 (0.14)^{b} 0.5-0.98	0.71 (0.29)^{b} 0.06-0.99
Percent *Lepomis*	0.23 (0.24)^{a} 0-0.89	(0.01)^{b} 0-0.02	0.19 (0.16)^{a} 0.02-0.51	0.01 (0.02)^{b} 0-0.05	(0.05)^{b} 0-0.15
Percent *Micropterus*	0^{a} 0-0.01	0^{a} 0	(0.02)^{b} 0-0.09	0 (0.01)^{b} 0-0.04	(0.01)^{b} 0-0.05
Percent Darters	0 (0.01)^{a} 0-0.06	0 (0)^{a}	0.06 (0.05)^{b} 0-0.24	0 (0)^{a}	0.06 (0.09)^{b} 0-0.32
Percent Orangespotted Sunfish	0.11 (0.15)^{a} 0-0.8	0 (0)^{b} 0-0.01	0 (0)^{b}	0 (0.01)^{b} 0-0.03	0 (0)^{b} 0-0.01
Percent Habitat Intolerant	0.01 (0.06)^{a} 0-0.65	0.22 (0.09)^{b} 0.1-0.36	0.17 (0.17)^{b} 0-0.58	0.10 (0.08)^{c} 0-0.28	0.2 (0.15)^{b} 0-0.49
Percent Water Quality Intolerant	0 (0)^{a}	0 (0)^{a}	0.04 (0.08)^{b} 0-0.26	0.09 (0.08)^{c} 0-0.28	0.05 (0.06)^{b} 0-0.24
Percent Rheophilic	0.35 (0.27)^{a} 0-0.95	0.65 (0.2)^{b} 0.32-0.93	0.44 (0.17)^{a} 0.11-0.86	0.66 (0.21)^{b} 0.38-0.91	0.57 (0.22)^{b} 0.07-0.83

Table 11. Predicted stage output values for specified discharge input values based on historic data at USGS gage (7288280) on the Big Sunflower River. Incremental change presents the increase in stage between a specific discharge and the initial baseline discharge rate (0).

Discharge input (cfs)	Stage output (feet)	Incremental change (inches)
0	4.11	0.00
5	4.15	0.42
10	4.18	0.83
15	4.22	1.25
20	4.25	1.66
25	4.28	2.08
30	4.32	2.50
35	4.35	2.92
40	4.39	3.33
45	4.42	3.75
50	4.46	4.17
55	4.49	4.59
60	4.53	5.01
65	4.56	5.43
70	4.60	5.85
75	4.63	6.27
80	4.67	6.69
85	4.70	7.11
90	4.74	7.54
95	4.77	7.96
100	4.81	8.38
105	4.84	8.80
110	4.88	9.23
115	4.92	9.65
120	4.95	10.08
125	4.99	10.50
130	5.02	10.92
135	5.06	11.35
140	5.09	11.77
145	5.13	12.20
150	5.16	12.63

Table 12. Percent difference in the abundance of minnows, shiners, and other rheophilic fishes with and without flow. Data derived from seining collections from the following drainages: Bayou Bartholomew, Big Sunflower, Cache River, Quiver River, Cypress Bayou, Middle White River, and Red River above Shreveport, Louisiana. Flowing water classified as surface water velocity greater than 5 centimeters per second (cm/s), N = number of samples

Flowtype	Variable	N	Mean cm/s	Std Dev	Minimum cm/s	Maximum cm/s
Non-flowing	Percent Rheophilic	28	0.3	0.2	0.0	0.8
	Percent Minnows and Shiners	28	0.2	0.2	0.0	1.0
Flowing	Percent Rheophilic	80	0.5	0.3	0.0	1.0
	Percent Minnows and Shiners	80	0.5	0.3	0.0	1.0

Table 13. Wetted width (feet) of stream reaches during summer and fall in the Big Sunflower-Steele drainage used to calculate acres benefitting from environmental flows. N = number of measurements.

Stream Reach	N	Mean	Standard Deviation	Minimum	Maximum
Big Sunflower	54	167	116	23	510
Black Bayou	17	87	40	19	141
Bogue Phalia	15	87	27	43	130
Deer Creek	15	99	39	19.8	156
Main Canal	9	95	45	32	168
Steele Bayou	9	168	80	51	273
Stream Order 1-2 (Harris, Huschpukena, Richies)	3	33	21	17	57

Table 14. Calculation of wetted acres of receiving streams and rivers from 34 supplemental low flow groundwater wells and Average Annual Habitat Units (AAHU) with and without flow. The Habitat Suitability Index weighting factors in parenthesis were mean values of the percent abundance of minnows and shiners collected in flowing water compared to non-flowing samples (Table 12).

Stream	Km	Miles	Width, feet	Length, feet	Acres	Without Flow AAHU (0.28)	With Flow AAHU (0.46)
Big Sunflower	355	208	167	1,096,128	4,202.3	1,177	1,933
Harris	30	17	33	91,344	69.2	19	32
Richies	15	9	33	46,464	35.2	10	16
Hushpuckena	93	54	33	286,176	216.8	61	100
Bogue Phalia	137	80	87	422,400	843.6	236	388
Little Sunflower	48	27	95	144,672	315.5	88	145
Steele Bayou	116	68	168	359,568	1386.8	388	638
Main Canal	21	13	95	66,000	143.9	40	66
Black Bayou	38	22	87	116,160	232.0	65	107
Deer Creek	267	156	99	825,264	1875.6	525	863
Total	1,118	654		3,974,256	9,321	2,610	4,288
Percent Difference in Habitat Units	0.39						

Table 15. Abundance of fish species collected in bongo nets directly below the outlet of Steele Bayou during summer 2019 and spring-summer 2020 after the Steele Bayou structure was opened following impoundment. Abundance is expressed as number of fish/100 m^3 of water filtered.

Scientific Name	Common Name	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Clupeidae	Shad	1643.0	47.4	1643.0	47.4
Dorosoma sp.	Shad (either Gizzard or Threadfin)	1101.6	31.8	2744.6	79.1
Dorosoma cepedianum	Gizzard Shad	673.6	19.4	3418.2	98.6
Pomoxis nigromaculatus	Black Crappie	19.0	0.6	3437.2	99.1
Lepisosteus oculatus	Spotted Gar	10.8	0.3	3448.0	99.4
Hypophthalmichthys molitrix	Silver Carp	4.7	0.1	3452.7	99.6
Pomoxis annularis	White Crappie	3.8	0.1	3456.4	99.7
Ictiobus sp.	Buffalo	3.7	0.1	3460.2	99.8
Micropterus salmoides	Largemouth Bass	2.2	0.1	3462.4	99.8
Centrarchus macropterus	Flier	1.7	0.1	3464.1	99.9
Morone chrysops	White Bass	1.4	0.0	3465.5	99.9
Gambusia affinis	Mosquitofish	1.2	0.0	3466.7	100.0
Aphredoderus sayanus	Pirate Perch	0.7	0.0	3467.5	100.0
Lepomis sp.	Sunfish	0.7	0.0	3468.2	100.0

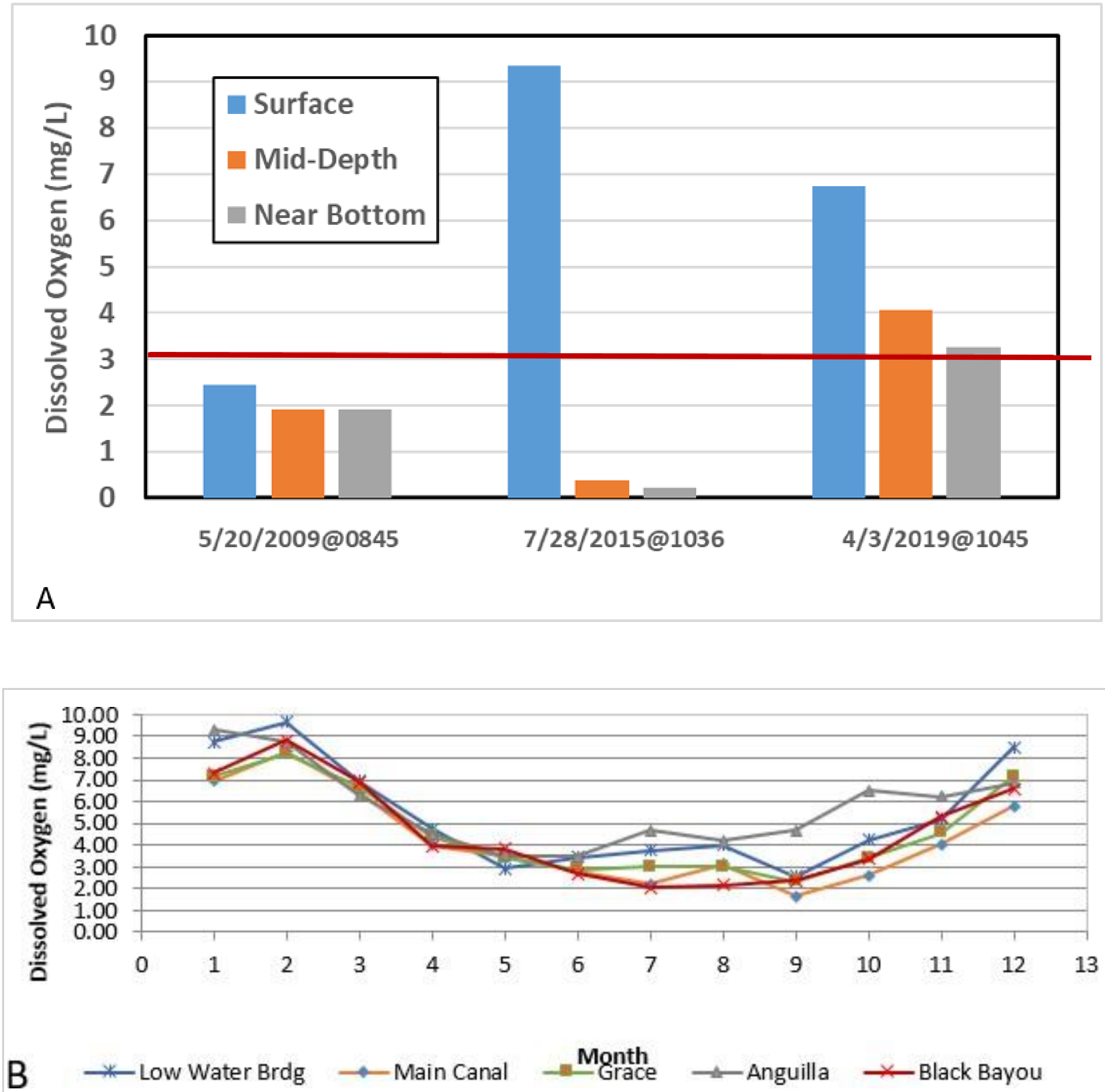


Figure 1. Dissolved oxygen at surface, mid, and near bottom depths above the Steele Bayou Structure during three sampling events when the Steele Bayou Structure was closed (Panel A), and monthly surface dissolved oxygen measurements at five locations in the Yazoo Study Area from 2005-2015 (Panel B) (Figures obtained from MVK, B. Johnson and D. Johnson). Red horizontal line in Panel A indicates EPA's threshold of physiological impairment.

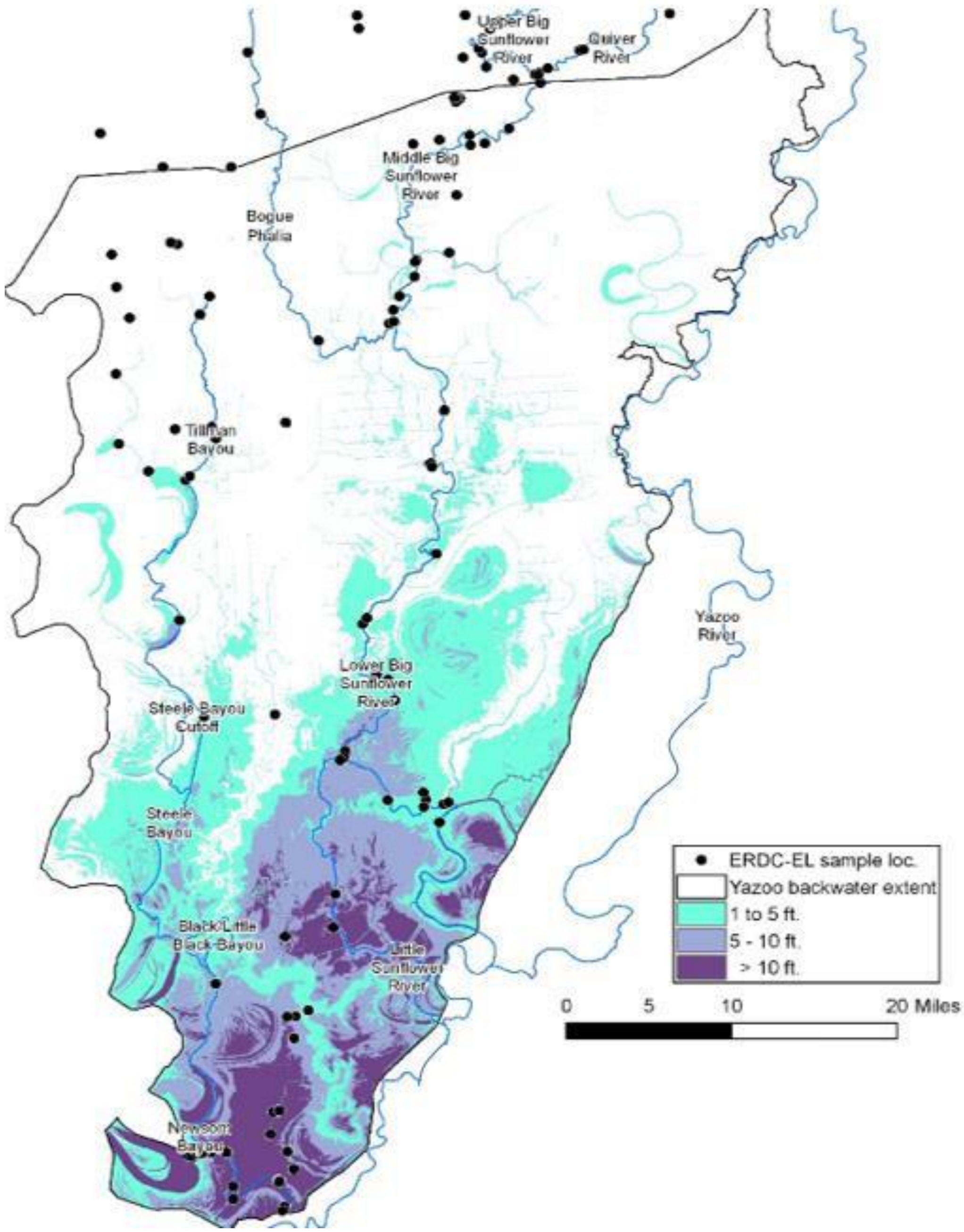


Figure 2. Map of water volume at different depths during a Yazoo Study Area flooding event at 98.2 feet, NGVD elevation. Volumes used to estimate area of hypoxia beginning at hypothesized depths of 5 or 10 feet.

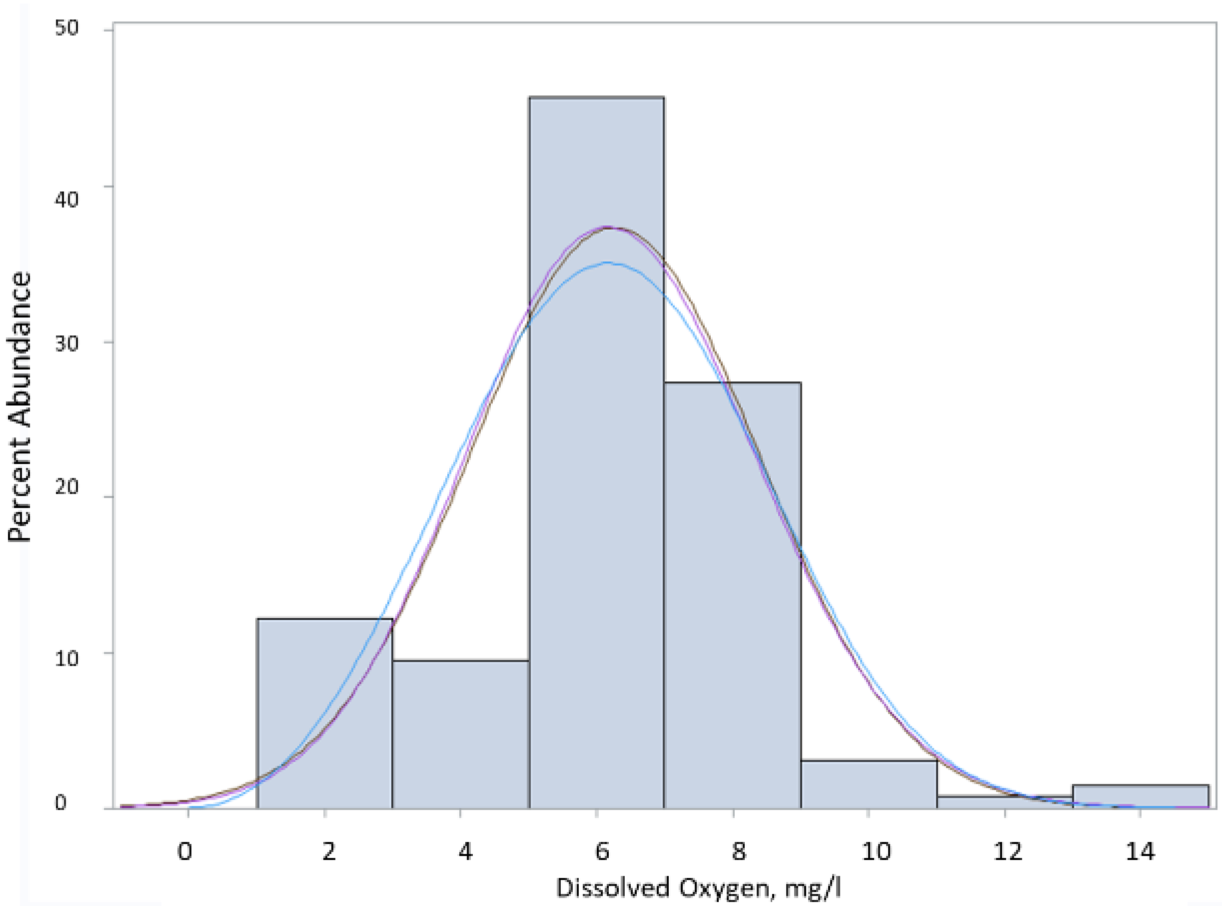


Figure 3. Percent abundance of all taxa (see Table 6) collected with light traps (n = 398) over a range of dissolved oxygen in the Big Sunflower-Steele Bayou drainage from 1990 through 2003. Lines represent probability density functions fitted to the data using three methods: lognormal, Weibull, and Gamma distributions.

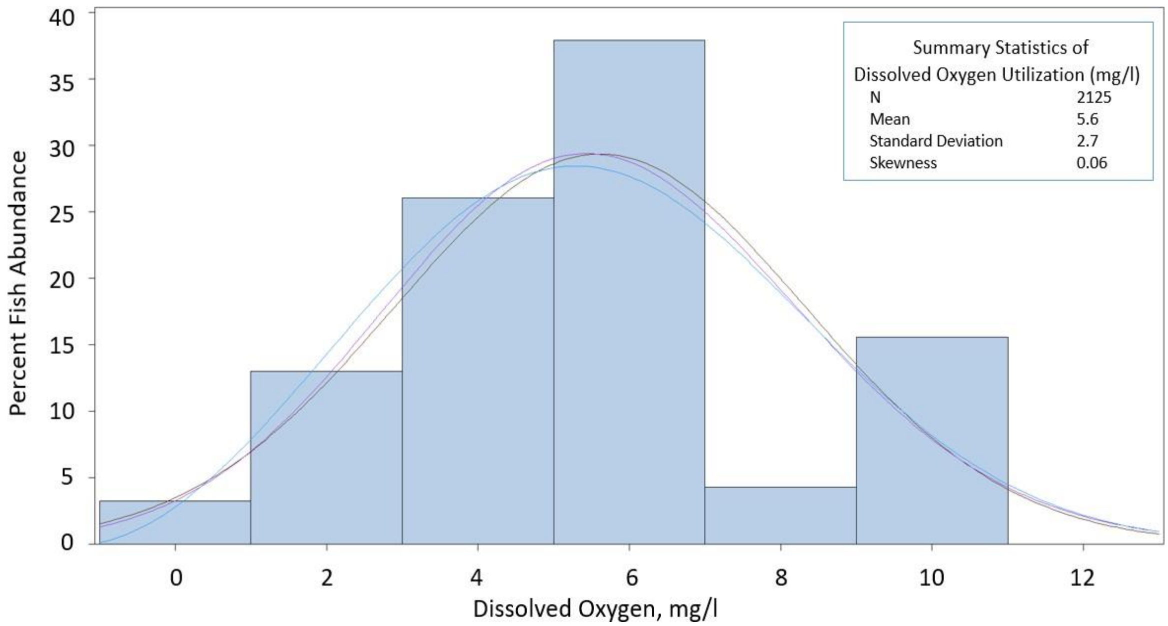


Figure 4. Percent abundance of total individuals (n = 2,126) of fish collected with a boat-mounted electroshocker (n = 83, 5-min samples) over a range of dissolved oxygen in the Yazoo Study Area. Data collected in 2003, 2009, 2015, and 2019. Probability density curves are shown for lognormal (blue), Weibull (brown), and Gamma (purple) distributions.

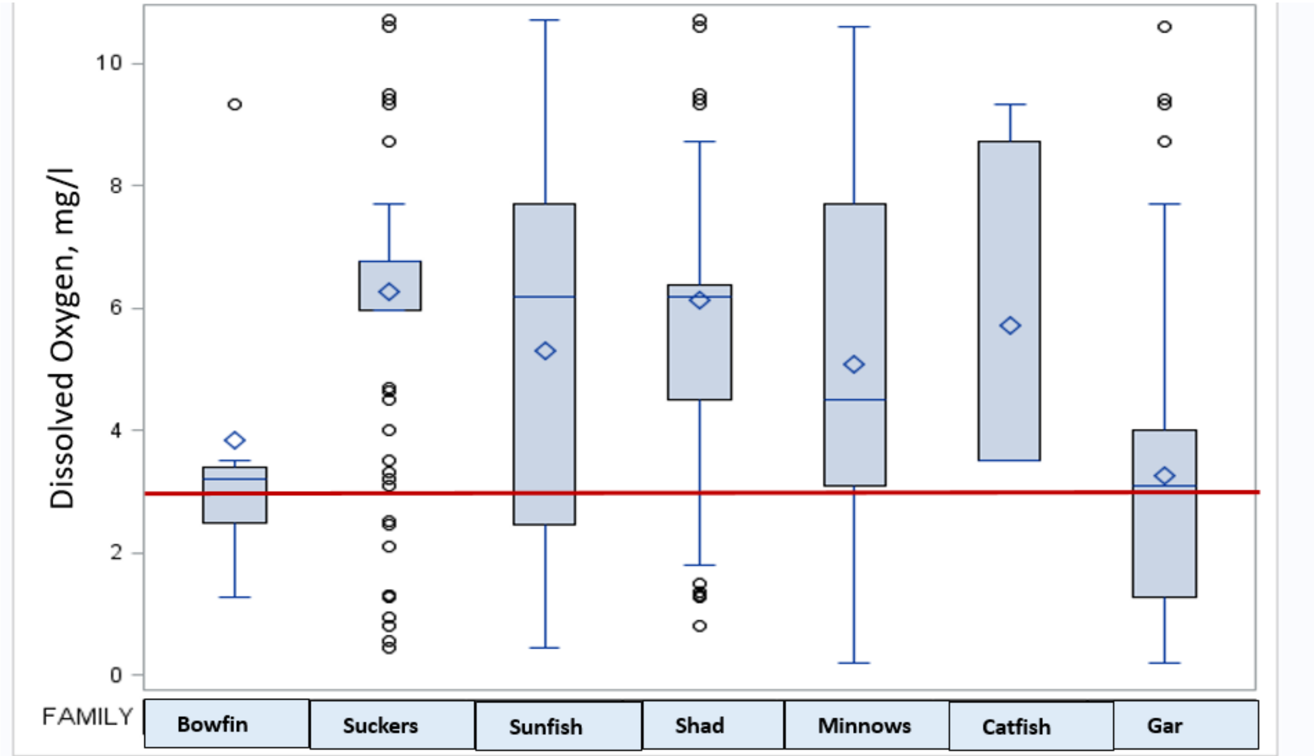


Figure 5. Box and whiskers plot of the weighted distribution of fish families over the range of dissolved oxygen measured in the Big Sunflower-Steele Bayou in 2003, 2009, 2015, and 2019. Total sample size was 2,025 individuals. Each box includes mean weighted abundance (diamond), median (horizontal line inside box), first and third quartile (lower and upper edge of box, respectively) and minimum and maximum values (endpoint of lower and upper whisker, respectively). Circles represent extreme values outside of the normal distribution. Red line indicates EPA's threshold of physiological impairment.

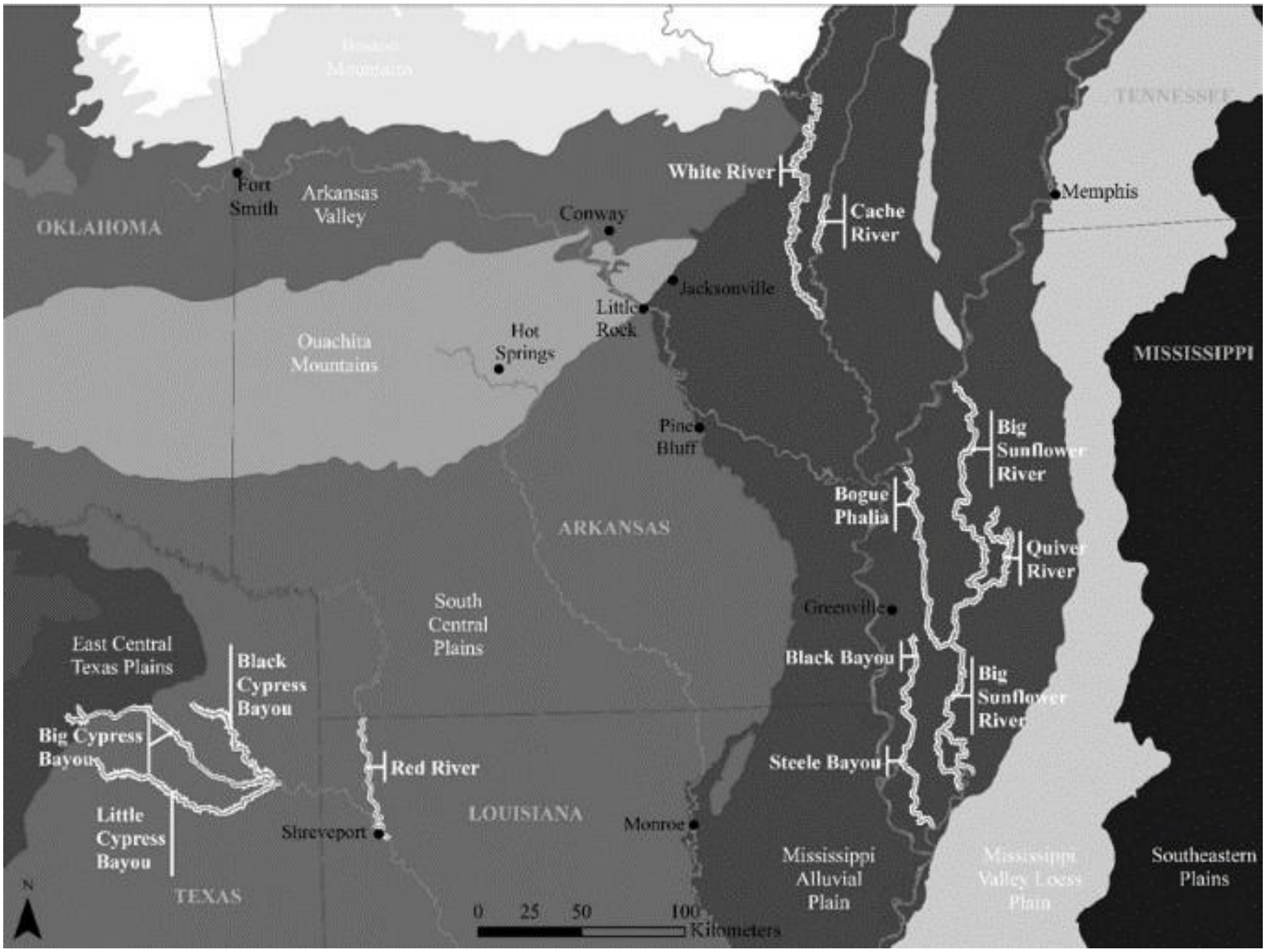


Figure 6. Sampling locations in the Mississippi River Alluvial Plain and South Central Plains USEPA Ecoregions.

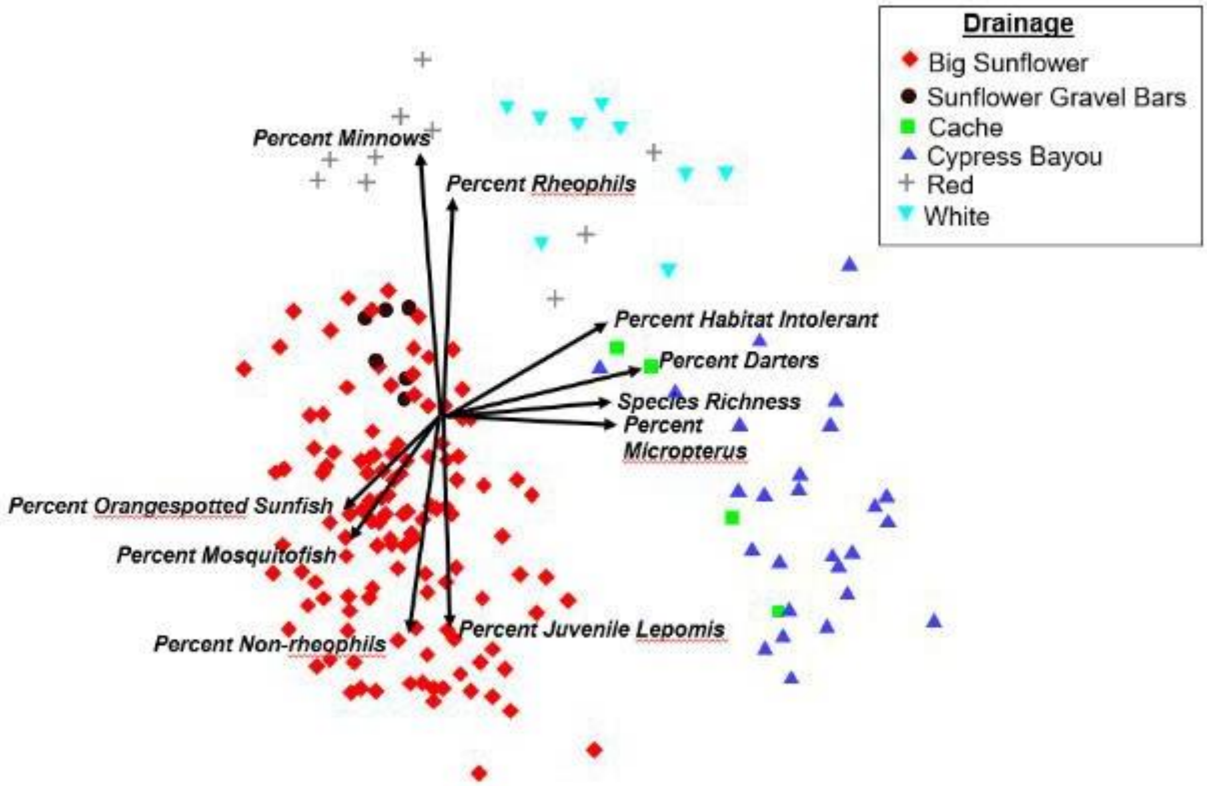


Figure 7. Nonmetric multidimensional scaling (NMDS) ordinations of species abundance for delta streams in the Mississippi Alluvial Prairie and South Central Plains Level III Ecoregions. Vectors on the NMDS plot identify the direction of correlation with biotic metrics, and vector length identifies the relative strength of the correlations; only variables with Spearman correlation ≥ 0.4 are shown.

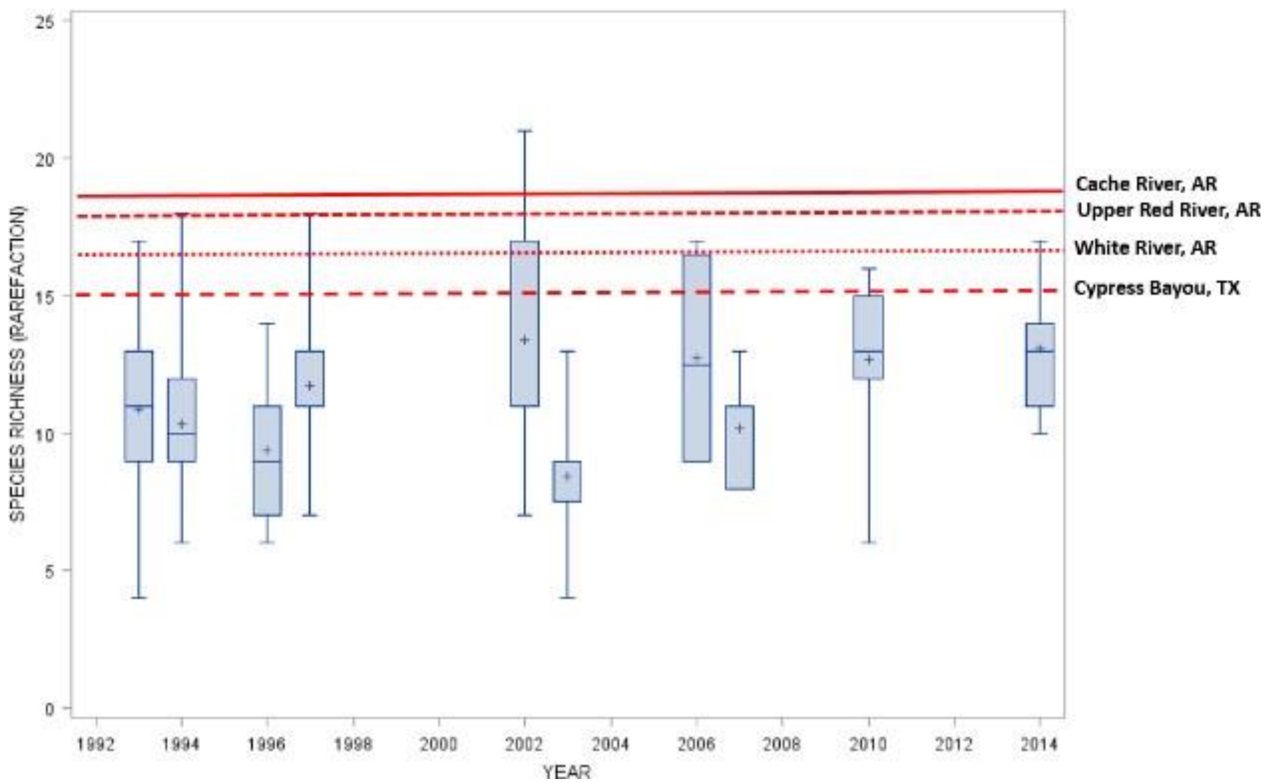


Figure 8. Box and whisker plot of species richness determined by rarefaction from 1992 to 2014 for the Big Sunflower – Steele Bayou drainage. Mean species richness by rarefaction for reference drainages are shown by red lines.

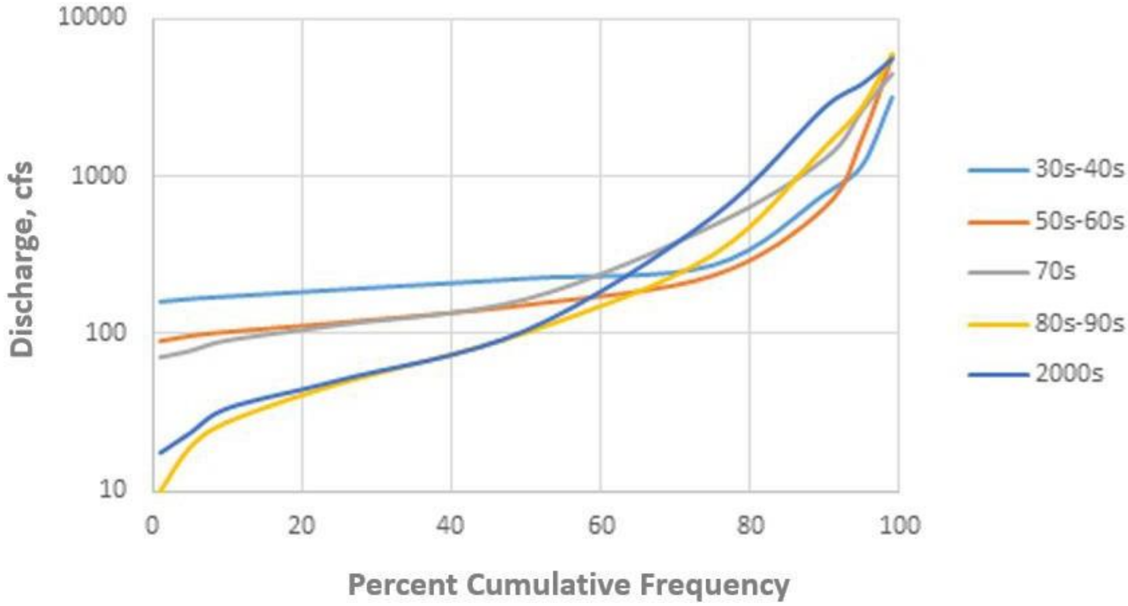


Figure 9. Big Sunflower discharge (cfs) at Sunflower, Mississippi during autumn. Graph provided by D. Johnson, MVK.

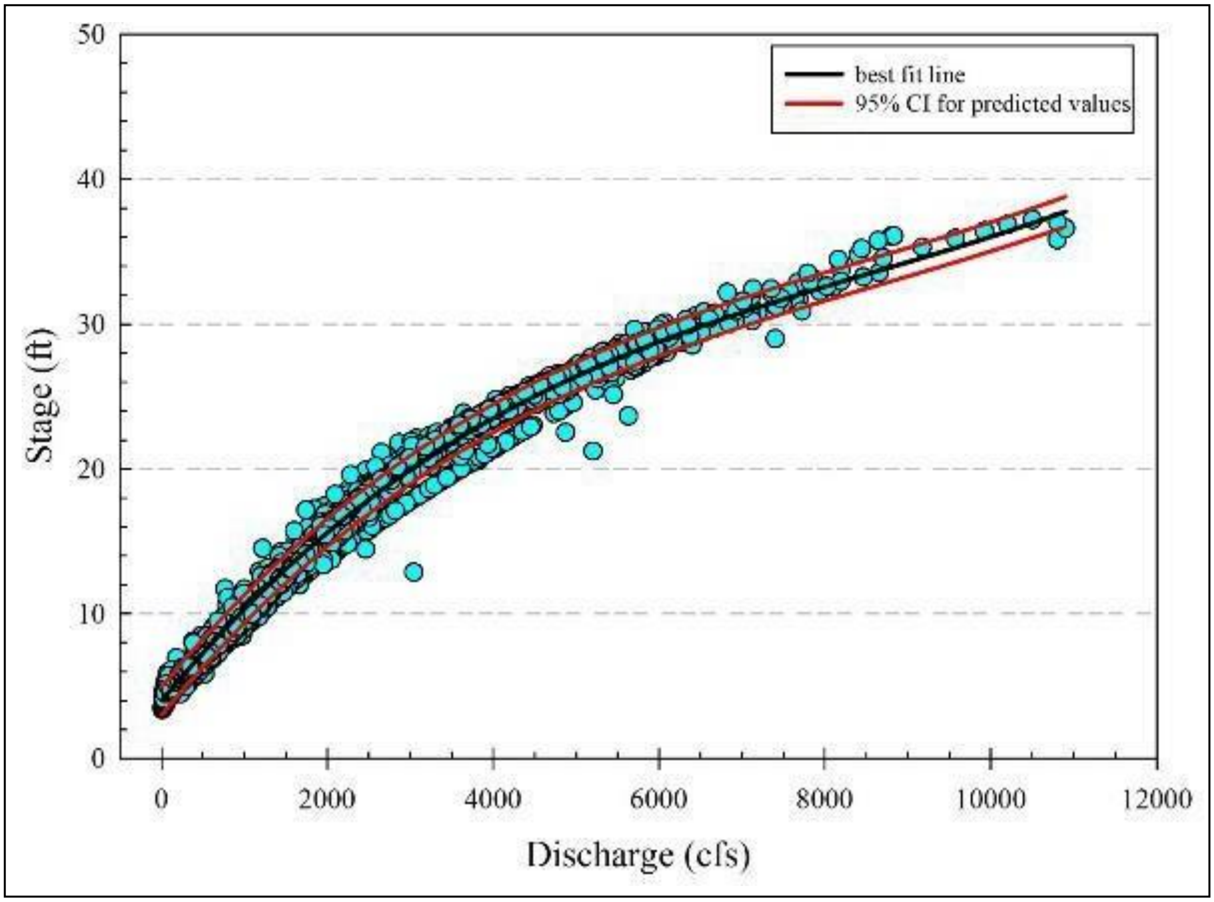
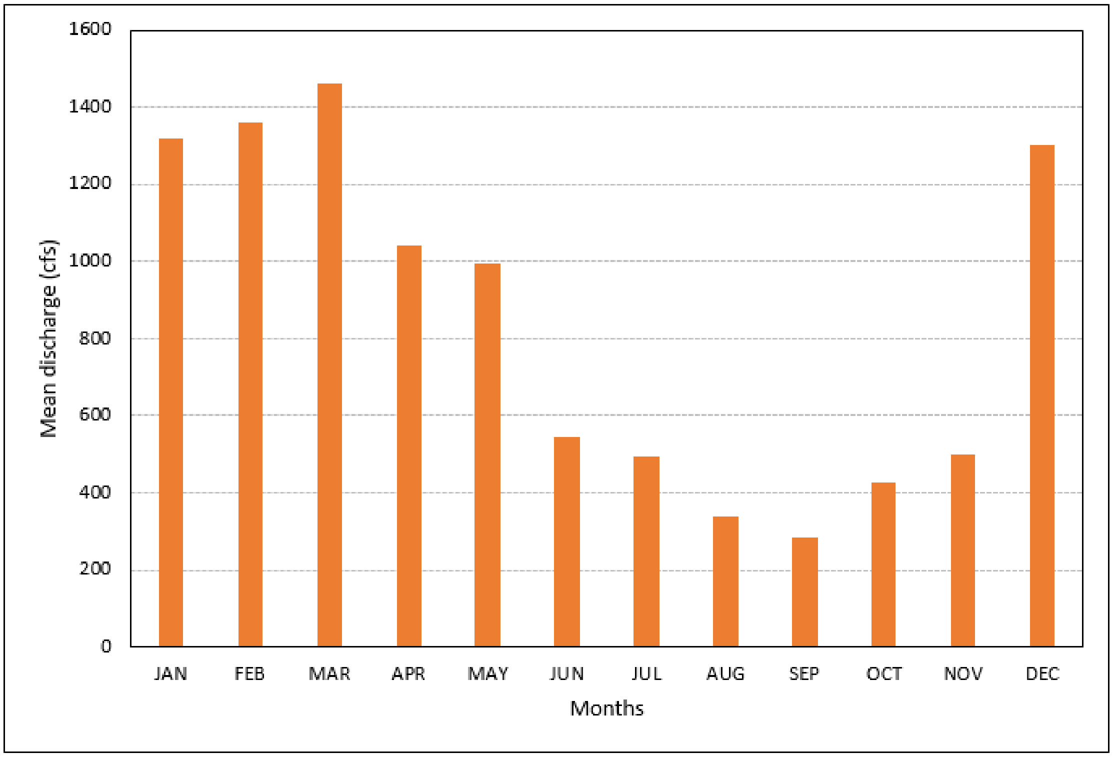


Figure 10. Compiled stage and discharge data for Merigold gage (USGS 7288280) including best fit line and 95% confidence intervals for predicted stage values.



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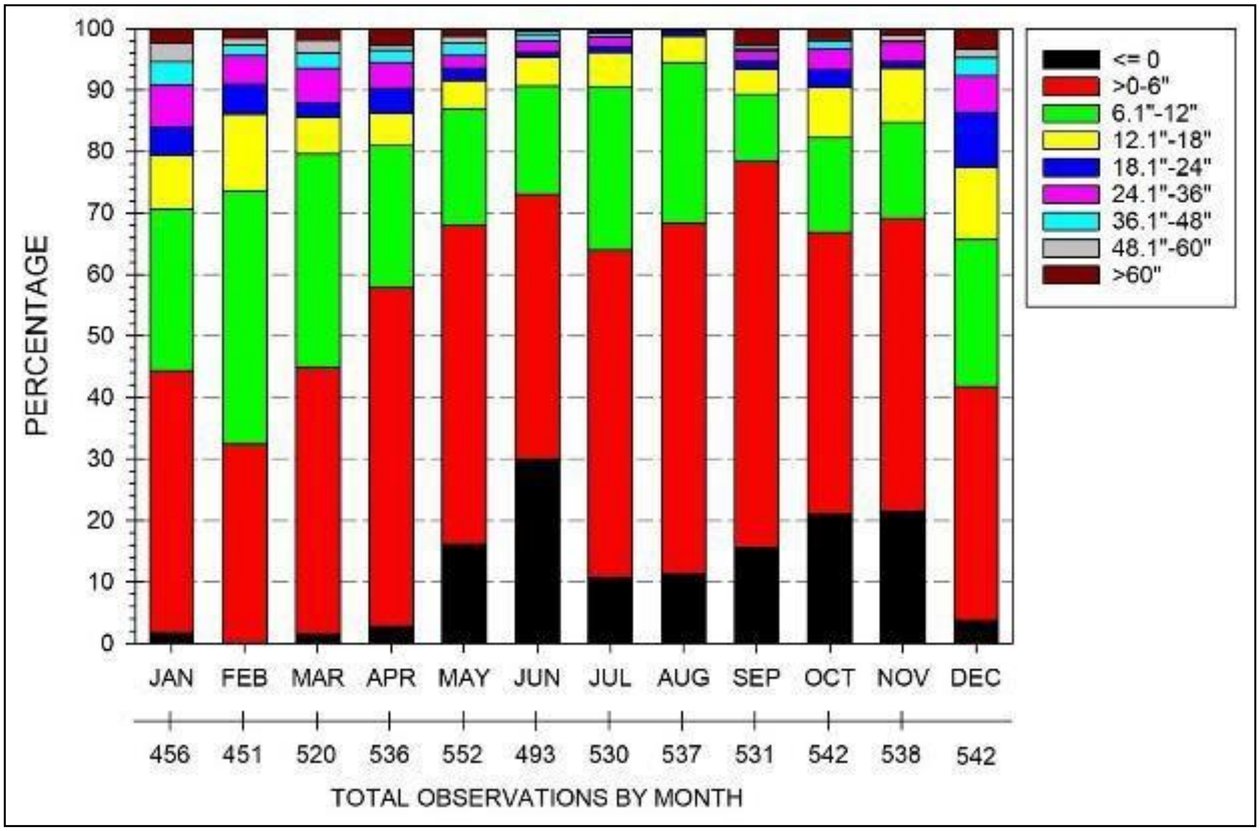

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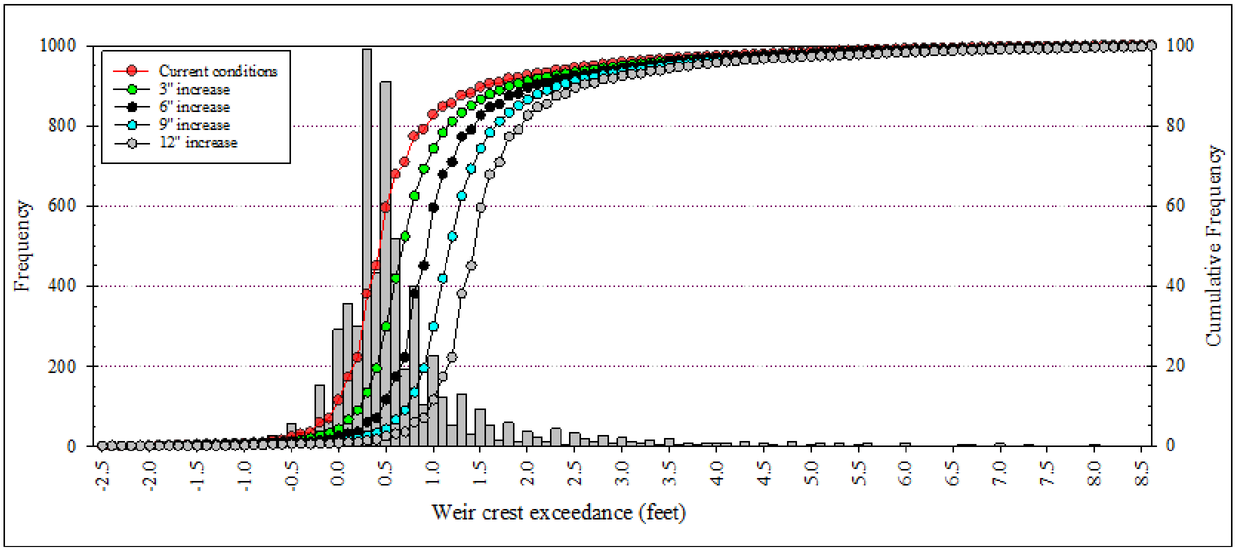

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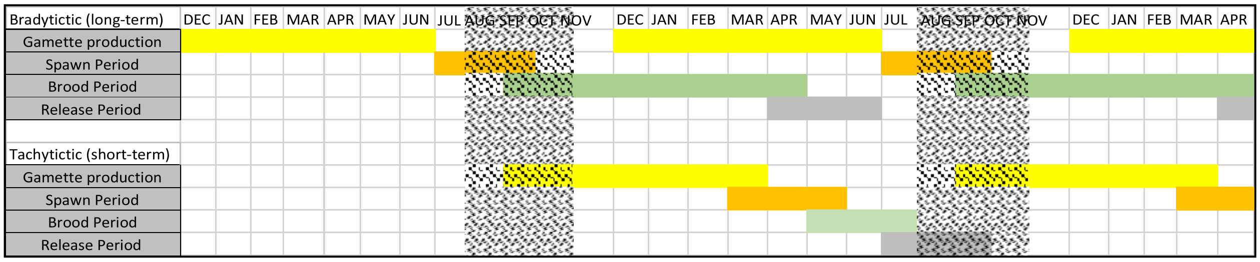

Figure 14. General schematic depicting relative timing of reproductive stages for long-term and short-term brooding strategies in freshwater mussels. Months with diagonal hatch represent low flow months at Merigold gage (Figure 11). Recent studies provide support that gametogenisis in long-term brooders likely occurs throughout the entire year.

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Environmental Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

EnviroFish, Version 1.0: User's Manual

K. Jack Killgore, Barry Bruchman, Robert Hunt, L. Yu Lin, Jan Jeffrey Hoover, Don Johnson, Dave Johnson, Gary Young, Kent Parish, Ron Goldman, and Andy Casper

August 2012

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Final report

Abstract: EnviroFish is both a modeling approach and a computer software. As a modeling approach, EnviroFish estimates the value of floodplain habitat suitable for fish reproduction under a given set of hydrologic and hydraulic conditions. As a software, EnviroFish is a Java computer program facilitating the application of the modeling approach. This manual describes both the modeling approach and the software.

The EnviroFish approach integrates hydrology, hydraulics, land use, and empirically based knowledge of fish reproductive strategies in riverine floodplains to predict a biological response to different flooding scenarios suitable for standard federal planning processes. EnviroFish can be used to calculate Habitat Units for specific floodplain habitats, with each habitat providing different values for spawning and rearing fishes. In order of least to most preferred habitats, are agricultural fields, fallow fields, bottomland hardwood forests, and floodplain waterbodies. EnviroFish was initially developed for flood control projects in the lower Mississippi River Valley. However, the approach is applicable to any alluvial river system where floodplain fish spawning habitat is being managed, mitigated, or restored, by determining applicable land use categories and HSIs for representative fish species.

The EnviroFish software is designed to directly accept data in the Corps of Engineers Data Storage System (DSS) file format. EnviroFish calculates ADFA for an array of project alternatives. The user specifies values of hydraulic criteria (flooding depth and duration) for successful spawning and rearing of fishes and also specifies land use categories to calculate ADFA.

This *User's Manual* discusses the biological basis of EnviroFish, elements of the model, using the software, application considerations, and an example problem.

Contents

Figures and Tables

Figures

Tables

Preface

This work was performed by the U.S. Army Engineer Research and Development Center (ERDC) in cooperation with the U.S. Army Engineer District, Vicksburg (MVK) and the U.S. Army Engineer District, Memphis (MVM). The original version of *EnviroFish* was written in FORTRAN by Ron Goldman, Basil Arthur, and Charlie McKinnie, MVK, based on input from Dr. Jack Killgore and Dr. Jan Hoover, ERDC, and Gary Young, MVK, on hydrologic and hydraulic criteria for floodplain spawning fishes. Under the supervision of Kent Parrish and Dave Johnson, MVK, *EnviroFish* was revised by Don Johnson, MVK, and written in JAVA. Andy Casper, ERDC, assisted in initial development of the *User's Manual*. Barry Bruchman and Dr. Robert Hunt (MVM), and Dr. L. Yu Lin, Christian Brothers University, wrote the final version of the User's Manual chapters for running and applying EnviroFish including figures and tables. Final development of the software was conducted under the supervision of Dr. L. Yu Lin, Professor of Civil Engineering, Christian Brothers University, Memphis, Tennessee.

Funding was provided by the U.S. Army Engineer Districts, Vicksburg and Memphis, the System-wide Water Resource Program, and the Ecosystem Management and Restoration Research Program at ERDC.

This work was performed under the general supervision of Dr. Tim Lewis, Chief, Aquatic Ecology and Invasive Species Branch, Environmental Lab (EL), Drs. David J. Tazik and Edmond Russo, Chief, Ecosystem Evaluation and Engineering Division, EL, and Dr. Elizabeth C. Fleming, Director, EL. COL Kevin J. Wilson was Commander of ERDC. Dr. Jeffery P. Holland was Director.

EnviroFish software and accompanying programs (HEC DSSVue, example .dss file) can be downloaded at the following site: http.el.erdc.usace.army.mil/products.cfm?Topic=model&Type=other .This report should be cited as follows:

Killgore, K. J., B. Bruchman, R. Hunt , L. Lin, J. J. Hoover, D. Johnson, D. Johnson, G. Young, K. Parrish, R. Goldman, and A. Casper. 2012. *EnviroFish Version 1, User's Manual*. ERDC/EL TR-12-19. Vicksburg, MS: Engineer Research and Development Center.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
feet	0.3048	meters

1 Introduction

EnviroFish is both a modeling approach and a computer software. As a modeling approach, EnviroFish estimates the value of floodplain habitat suitable for fish spawning and rearing under certain hydrologic and hydraulic conditions. As a software, EnviroFish is a Java computer program facilitating the application of the modeling approach. This manual describes the modeling approach of EnviroFish and serves as a user's manual for the software.

EnviroFish integrates the needs of reproducing fish with the reproductive opportunities afforded by a flooded landscape, as shown in Figure 1-1. To the upper left of Figure 1-1, fish requirements are reflected by a reproductive strategy of fishes in riverine floodplains and the values of different land uses for spawning and rearing. To the upper right of Figure 1-1, reproductive opportunities at a project site are reflected by the hydrology, hydraulics, and land uses present. The integration of requirements and opportunities is reflected in average daily flooded area (ADFA) by land use category type. The ADFA, when multiplied by a weighting index (Habitat Suitability Index), culminates in a consolidated measure of habitat for the project landscape as a whole, expressed in Habitat Units (HUs). The response variable, HUs, allows Habitat Evaluation Procedures (HEP) to be used to complete the analysis of project alternatives (USFWS 1980). This approach can be used to assess whether a flood control alternative, restoration / mitigation activity, or another water allocation decision would have positive or negative effects on floodplain fish habitat. Different alternatives can be compared during project planning; this is consistent with standard Army Corps of Engineers policy.

EnviroFish has been applied in the planning of Corps of Engineers flood control projects in the lower Mississippi River Valley, and continues to be refined and updated. However, the approach is applicable to any alluvial river system where floodplain fish spawning habitat is being managed. EnviroFish was developed over a 15-year period, beginning in the early 1990s, to predict a quantitative response by the fish assemblage to altered flood regimes. EnviroFish can be used to predict changes in functional reproductive habitat over large or small geographic areas. There is no limit to the size of the project area, if suitable hydraulic and land use data are available or can be synthesized.

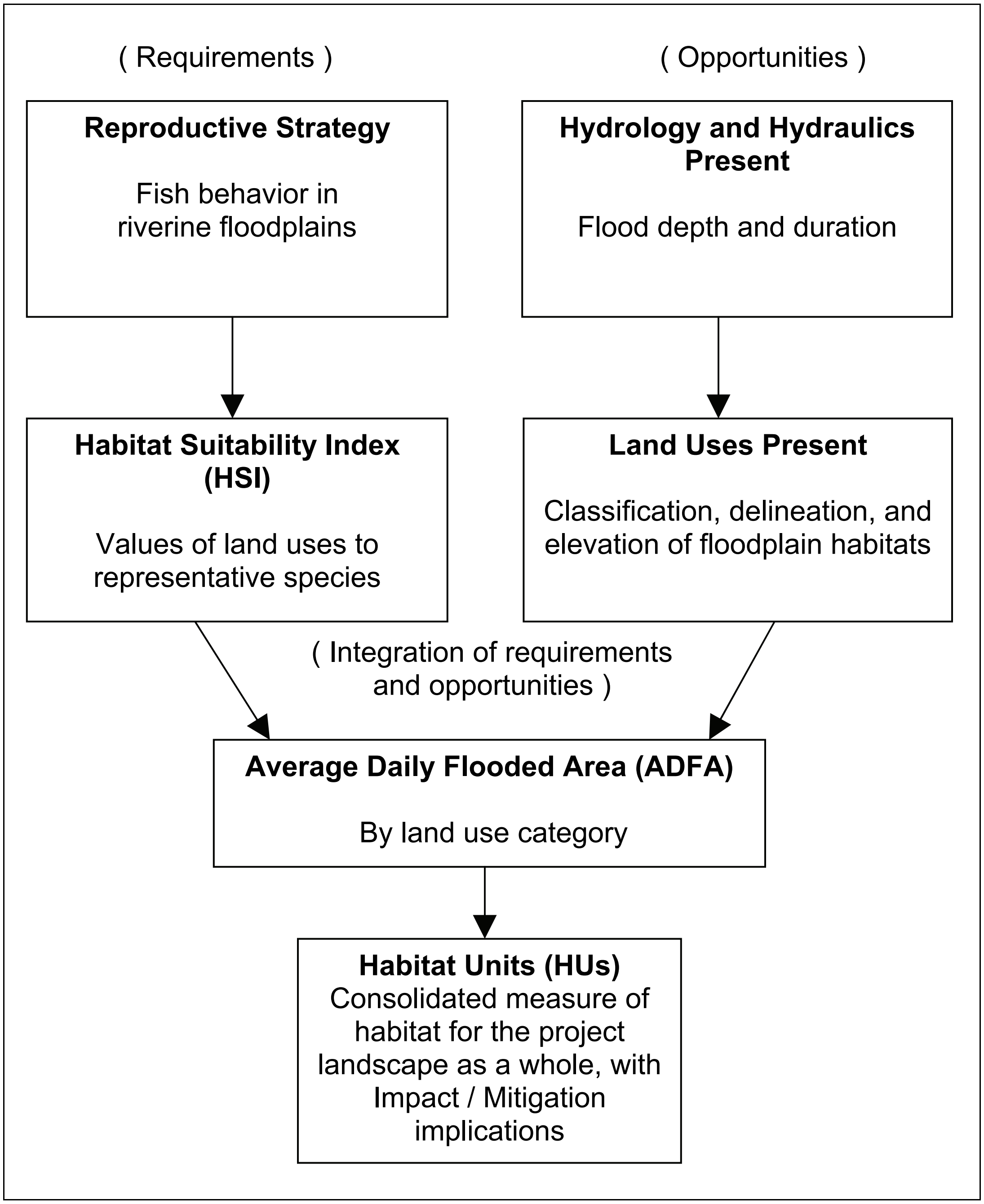


Figure 1-1. Flow Chart of the EnviroFish Approach Culminating in Quantification of Habitat Units for a Project Landscape.

Purpose

The purpose of this manual is to describe the background and approach of modeling fish spawning and rearing habitat in floodplains. This manual makes this approach available to a wide range of stakeholders drawn from government, academia, environmental organizations, and the communities for which water resources and environmental projects are planned.

Approach

The EnviroFish method may be outlined according to its modeling approach and its software characteristics. As a modeling approach, EnviroFish:

1. applies knowledge regarding fish spawning and rearing requirements to the evaluation of reproductive opportunities afforded over time and space in a project landscape;
2. assigns values to different land uses for fish spawning and rearing;
3. quantifies the elevation vs. area relationships of different land uses in a project landscape;
4. quantifies the effects of land use change;
5. quantifies the effects of climatic variability;
6. quantifies the effects of proposed project alternatives; and
7. quantifies the effects of operational modifications to project alternatives.

As a software, EnviroFish:

1. is coded in a current programming language facilitating its continued development and dissemination;
2. uses a proven, well-documented, and widely used water resources database management software, the Corps of Engineers Data Storage System (DSS); and
3. runs in a user-friendly windows format familiar to users.

Scope

The *User's Manual* focuses on how the body of knowledge regarding fish spawning and rearing has supported the development of modeling concepts that can be applied in computer software to realistically characterize project situations. The software calculates Average Daily Flooded Area (usually in acres). Weighting of these acres using Habitat Suitability Index values to calculate Habitat Units must be done in a spreadsheet external to the EnviroFish software. The Habitat Index Suitability values used in the analysis must be developed specifically to represent the habitats and fish species being assessed in the project area. The material in the manual is not a substitute for the professional knowledge and experience in fish biology required to appropriately plan an EnviroFish analysis. Preparation of input to the model requires the services of hydrologists, hydraulic engineers, biologists, and Geographic Information Systems (GIS) specialists.

Organization of the *User's Manual*

The following chapters present a detailed explanation of the EnviroFish approach and software. Chapter 2 explains the biological basis of EnviroFish. Chapter 3 provides a detailed description of the mechanics of the EnviroFish spawning and rearing habitat analysis. Chapter 4 introduces the use of the EnviroFish software and describes the input required. Chapter 5 describes EnviroFish software output. Chapter 6 discusses application of EnviroFish to various situations. Chapter 7 presents an example of EnviroFish use.

2 Biological Basis

The biological basis of EnviroFish follows the HEP (USFWS 1980). In the HEP framework, Habitat Units (HUs), calculated by multiplying a Habitat Suitability Index (HSI) value ranging from 0.0 (unusable habitat) to 1.0 (optimum habitat) by a measurement of area (e.g., acres of flooded bottomland hardwood), express the quality and quantity of fish habitat for different project plans. The fundamental assumption is that the abundance and distribution of the fish species or group of species being modeled respond in a predictable fashion to changes in quality and quantity of habitat. However, for a variety of reasons unrelated to habitat (disease, exploitation, population cycles), changes in HUs may not always affect population density of fish in an area. A more current perspective is that areas with higher quantity and quality of HUs are assumed to have greater potential to support more fish than areas with lower HUs.

The reproductive cycles of most floodplain fishes are closely related to timing, spatial extent, and duration of flooding. Numerous fish species undergo regular migrations to use inundated floodplains for a variety of reproductive purposes such as spawning, short-term incubation of eggs, and eventually as nursery habitat for yolk-sac (non-feeding) larvae (Guillory 1979, Ross and Baker 1983, Finger and Stewart 1987, Copp 1989, Scott and Nielson 1989). Once the yolk-sac is absorbed, larval fish must forage in the floodplain or adjacent waterbodies for small insects and zooplankton (Lietman et al. 1991). These early life history stages are often the limiting factor in population growth, and inter-annual variations in flooding regime of rivers affect reproductive success and year-class strength of many species (Starrett 1951, Guillory 1979, Larson et al. 1981; Zeug 2005).

EnviroFish was developed to quantify the importance of seasonally inundated floodplains as well as floodplain waterbodies such as oxbow lakes during periods of increased energetic needs for reproduction and growth of healthy fisheries (Benke et al. 2000; de la Cruz 1978; Lambou 1990; Miranda 2004; Ward et al. 1999; Whitaker 1977). EnviroFish characterizes the hydraulic environment of the floodplain in terms of water depth and duration of flooding. Fish move onto the floodplain during rising elevations to exploit additional food resources and spawning sites. Lateral movements of adult fish on the floodplain, however, can decrease exponentially with reductions in water surface elevation (Kwak 1988). Spawning failure may occur if water levels remain low and population numbers are high (Starrett 1951). However, those waterbodies that are connected to main river channels, either continuously or during floods, could function as important fish nursery areas (Beecher et al. 1977; Dewey and Jennings 1992; Hoover et al. 1995). EnviroFish is designed to track changes in functional floodplain habitat as water elevations are modified or controlled. In addition, EnviroFish can be used to track the annual variation in flooded habitat, providing an average over a selected period of record.

Defining Fish Reproductive Criteria

EnviroFish calculates the area of functional floodplain habitat in terms of fish spawning or rearing. Specific rules were established to describe spawning versus rearing. Floodplain spawning habitat is area available for the deposition and incubation of eggs. Spawning habitat is delineated hydraulically in the model; water depth and duration are user-defined variables in the computer model. For example, minimum water depth for spawning can be set to 1-foot below a water surface, and duration could be at least 8 days. A minimum water depth of 1 foot allows adults to access shallow, flooded areas; depths less than 1 foot may impose physical limitations in the spawning process and greater risk of predation. Flood duration of at least 8 days ensures that suitable time is allowed for nest construction and other spawning activities by the adults. Shorter flood durations may result in the eggs becoming stranded and desiccated if water recedes too quickly. The minimum 1-ft deep, 8-day duration rule is considered a conservative value to delineate spawning requirements for most warmwater fish species found in the Mississippi River basin (Breder and Rosen 1966; Carlander 1969; Carlander 1977; Becker 1983; Robison and Buchanan 1988). This rule guarantees an effective spawning window, emphasizes longer development times, and provides a margin for temporal variation in spawning activities (adult movement onto the floodplain, nest construction and guarding, dispersal of fry). However, these are only examples and the user is responsible for parameterizing the model.

Once hatched, rearing fishes (including yolk-sac and post yolk-sac larval phases) can potentially use any area of the inundated floodplain regardless of flood depth and duration, although a minimum depth of 0.1 feet or more can be applied to satisfy physical limitations. However, during falling elevations of a flood, EnviroFish provides an option to restrict larval fish habitat to the minimum user-defined water depth. This rule assumes that larval fish will move with the receding water and not utilize the shallow

(<1 ft), temporally inundated lands; otherwise, fish may become stranded or highly susceptible to predation.

Delineating the Boundaries of the Functional Floodplain

In an EnviroFish analysis, functional floodplain refers to inundated areas available for fishes to use in spawning and rearing. The boundaries of the functional floodplain can be limited by defining an upper elevation beyond which the usability and functionality of the floodplain is diminished. If an upper limit is established in EnviroFish, flooded area above this elevation will not be considered in average daily flooded area (ADFA) calculations. The elevation-area table in DSS must be revised to establish an upper limit to the functional floodplain. Any flood frequency can be used in the EnviroFish software to establish an upper limit if suitable biological, land use, and gage data are available.

An example is the designation of the 2-year frequency flood elevation. This flood frequency could be justified according to the following reasons:

1. Most fish species reach sexual maturity at an age of 1 or 2 years. Since the 2-year flood is the flood with a 50% annual chance of exceedance, the 2-year flood is sufficiently frequent to affect the first reproductive season of a significant fraction of individual fish of the species under consideration. Moreover, the life span of small-sized species is only 2-3 years, and some may only reproduce once. Thus, the floods larger and less frequent than the 2-year flood — although not harmful — are not events that short-lived fish can generally benefit from. Larger-sized species can live up to 10 years, and, in riverine floodplains, are exposed to high and low flood elevations on an annual basis. For these longer-lived species, the more extreme floods may result in higher fish abundance, but do not represent flooding regimes that maintain baseline population levels over the life of most projects (i.e., a 50-year project life).
2. In agricultural landscapes, lands that are flooded less frequently than those inundated by a 2-year flood are mostly unsuitable as reproductive habitat for two reasons. First, the floodplain closest to the river provides immediate access to reproductive fishes undergoing spawning migrations. Fish may have to travel miles from the mainstem river to reach lands corresponding to a 3-year or greater flood frequency. Second, even if adults do move great distances to spawn, eggs deposited in cleared lands far removed from the mainstem river have a greater risk of becoming trapped in isolated pools during receding elevations.

Flood frequency elevation can be determined through hydrologic and hydraulic analysis as described in engineering publications such as *Hydrologic Frequency Analysis* and *River Analysis System User's Manual* (See Appendix A).

Habitat Types within the Functional Floodplain

Satellite imagery and other GIS information can be used to delineate floodplain habitats relevant to fish reproduction. In the lower Mississippi River Valley examples used as case studies, five habitat types were determined based on position (e.g., mainstem or floodplain), land use/vegetation type (e.g., agriculture, fallow field, bottomland hardwoods), permanence of water (e.g., oxbow lake), and elevation:

1. Seasonally inundated agricultural land
2. Seasonally inundated fallow and herbaceous marsh land
3. Seasonally inundated bottomland hardwoods
4. Oxbow lakes or other large (>1-acre) floodplain waterbodies seasonally connected to the mainstem river
5. Small, waterbodies (scatters, brakes, sloughs, and tributary mouths) seasonally connected to the mainstem river

Floodplain waterbodies are those that retain water during the reproductive season, but may become dewatered outside this seasonal window. Furthermore, floodplain waterbodies should be connected at least once during the reproductive season to provide access to adult fish that are undergoing spawning movements. Additional floodplain habitats can be delineated according to project- or site-specific needs and objectives. However, before adding new categories, the user must consider how well new land use categories can be delineated and whether corresponding HSI values exist for the species of interest or whether they can be determined.

Calculation of Area

EnviroFish calculates ADFA for a defined analysis period (e.g., 20 years), using historical or synthetically derived water surface elevations. ADFA incorporates variations in the hydroperiod (flood onset, depth, and duration) and is a realistic estimate of the flooding regime for a baseline condition and any number of project alternatives. If an acre is the unit of area selected for a particular application, one ADFA is equivalent to one acre of inundated land satisfying the depth/duration criteria for successful spawning or rearing. In general, the magnitude of area satisfying depth/duration criteria is less than the total area of land inundated.

Selecting Habitat Suitability Index Values

To obtain HUs, HSI values need to be multiplied by ADFA for each land use category. HSI values must be determined for each project area to reflect characteristic fish assemblages and their affinity to different floodplain habitats. An example of HSI values combining spawning and rearing into one life stage is shown in Table 2-1. These values evolved from numerous applications of the model in the lower Mississippi River Valley and were initially developed by consensus of an interagency team of biologists (e.g., Delphi technique, Crance 1987), supplemented by published field data on fish reproduction in floodplains (Baker et al. 1991; Hoover et al. 1995; Killgore and J.A. Baker 1996; Hoover and Killgore 1998) and best professional judgment.

Table 2-1. Habitat Suitability Index (HSI) Values for Spawning and Rearing of Fishes used to Evaluate Riverine Floodplains of the Lower Mississippi River Valley.

Land use Category	HSI
Agricultural land	0.2
Fallow	0.5
Herbaceous marsh	1.0
Bottomland hardwoods	1.0
Large (>1 acre), floodplain waterbodies (e.g., oxbow lakes)	1.0
Small, floodplain waterbodies (e.g. scatters, brakes, sloughs)	1.0

The example HSI values for combined life history stages make at least three assumptions:

1. Larval fish utilize the same habitat as spawning sites, with one exception. Larval fish have smaller physical dimensions that allow access to more shallow (<1.0 ft) water than physically available for spawning needs (typically ≥ 1.0 ft depth, 8 days duration). The EnviroFish software provides considerable flexibility. User-defined minimum and maximum allowable depths for spawning or rearing may be input to accurately represent a specific situation. For spawning, EnviroFish user options are also available to control how falling or rising water surface elevations are treated on the spawning period days immediately following the day on which an egg is deposited in a nest. These options give the biologist more control in dealing with the possibility of larval fish becoming stranded if

water levels should drop too quickly or being swept downstream (Harvey 1989) and in dealing with larval preferences for deeper water where food and structure are plentiful.
2. The majority of species that spawn and rear in riverine floodplains are pre-adapted to structurally complex habitats such as bottomland hardwood wetlands (BLH). Therefore, cleared lands have less value for spawning and rearing. The example HSI values reflect this trend, with optimum conditions occurring for BLH (i.e., HSI = 1.0), intermediate values for fallow fields (HSI = 0.5), and the lowest value for cleared, agricultural lands (HSI = 0.2).
3. Similar to BLH, floodplain waterbodies are optimum (HSI=1.0) for spawning and rearing if the waterbody is periodically connected to the mainstem river during the reproductive season. This assumes that floodplain waterbodies provide adequate spawning substrates for egg deposition, and larval fish have high growth rates for survival in waterbodies that retain water during periods of early development.

The example HSI values represent a community-level perspective of the biological response of warmwater fishes to flooding in riverine systems. In most large floodplain river systems, this could encompass a very large assemblage of fish species. Characteristic fish species represented by this community-level model can be presented as a guild (Table 2-2 and Table 2-3). Species within a guild are assumed to share similar reproductive requirements. In this case, fish species in the lower Mississippi River Valley were grouped based on substrate used by spawning adults and characteristic habitat (channel vs. floodplain) used by larvae. For species that spawn and rear in floodplains, different substrates or structural conditions are preferred to deposit eggs or construct nests: vegetation, sand, and/or crevices. For these reasons, BLH and floodplain waterbodies have optimum HSI values because of their habitat heterogeneity. In addition, some species have floating eggs (i.e., pelagophils). Considering these multiple reproducetive strategies, at least four guilds with almost 50 species total could be influenced by changes in river elevations in the lower Mississippi River Valley, and these species are represented by the example HSI values. Guilds could be expanded if seasonal considerations (early, mid, and late spawners) and separate life stages (spawning versus rearing) were included (*sensu* Floyd et al. 1984; Mathews 1984). The user is responsible for selecting either a guild or individual species approach, as well as designating the appropriate HSI values.

Table 2-2. Guild of Warmwater Fish Species in the Lower Mississippi River Valley that Spawn and Rear Primarily in River Channels.

Pelagophils	Lithophils	Phytophils	Litho-Psammophils	Speleophils
Skipjack herring	Shovelnose sturgeon		Silverband shiner	Red shiner
Gizzard shad	Paddlefish		River carpsucker	Spotfin shiner
Threadfin shad	Quillback		Harlequin darter	Blacktail shiner*
Goldeye	Blue sucker		Logperch	Bullhead minnow
Mooneye	Northern hog sucker		Blackside darter	Bluntnose minnow
Plains minnow	Spotted sucker		Saddleback darter	Blue catfish
Silver chub	River redhorse		Dusky darter	Flathead catfish
Speckled chub	Golden redhorse		River darter	Channel catfish*
Emerald shiner	Shorthead redhorse			Freckled madtom
River shiner	White bass*			Tadpole madtom
Freshwater drum*	Yellow bass			Johnny darter
	Striped bass			
	Smallmouth bass			
	Sauger			
	Walleye			
	Chestnut lamprey			

Table 2-3. Guild of Warmwater Fish Species in the Lower Mississippi River Valley that Spawn and Rear Primarily in Floodplains.

Pelagophils	Lithophils	Phytophils	Litho-Psammophils	Speleophils
Mimic shiner*		Spotted gar	MS silvery minnow	Black bullhead
Channel shiner		Longnose gar	Ribbon shiner	Yellow bullhead
		Shortnose gar	Golden shiner	Pirate perch*
		Bowfin	Ironcolor shiner	
		Grass pickerel	Weed shiner	
		Chain pickerel	Pugnose minnow	
		Smallmouth buffalo*	Creek chubsucker	
		Bigmouth buffalo	Shadow bass	
		Black buffalo	Flier	
		Golden topminnow*	Green sunfish	
		Blackstripe topminnow	Warmouth	
		Blackspotted topminnow	Orangespotted sunfish	
		Banded pygmy sunfish	Bluegill	
		Mud darter	Longear sunfish*	
		Bluntnose darter	Redear sunfish	
		Slough darter	Redspotted sunfish	
		Cypress darter*	Spotted bass	
		Brook silverside	Largemouth bass*	
		Inland silverside	White crappie*	
			Black crappie	

Calculation of Average Annual Habitat Units

Average Annual Habitat Units (AAHUs) are Habitat Units annualized over the life of the project and are the last step in a series of data inputs and outputs to calculate a biological response to flooding over long time periods (Figure 2-1). Annualization is calculated according to the guidance of the HEP, and can be completed in a spreadsheet program outside of the EnviroFish software. AAHUs are calculated to reflect changes in land use (e.g., reforesting frequently flooded agricultural lands), construction impacts, and predicted longevity of project benefits. Changes in land use and construction impacts will alter the HSI value for specific acres of habitat over the project life. By calculating HUs for each year using the appropriate Average Daily Flooded Area derived from EnviroFish software and the HSI values, then summing the total HUs and dividing by the number of years over the project life, an accurate portrayal of the long-term biological response to floodplain alteration and management can be obtained. AAHUs can be compared among project alternatives, and applied to an incremental cost analysis to select the preferred alternative for any type of project (e.g., flood control, mitigation, restoration).

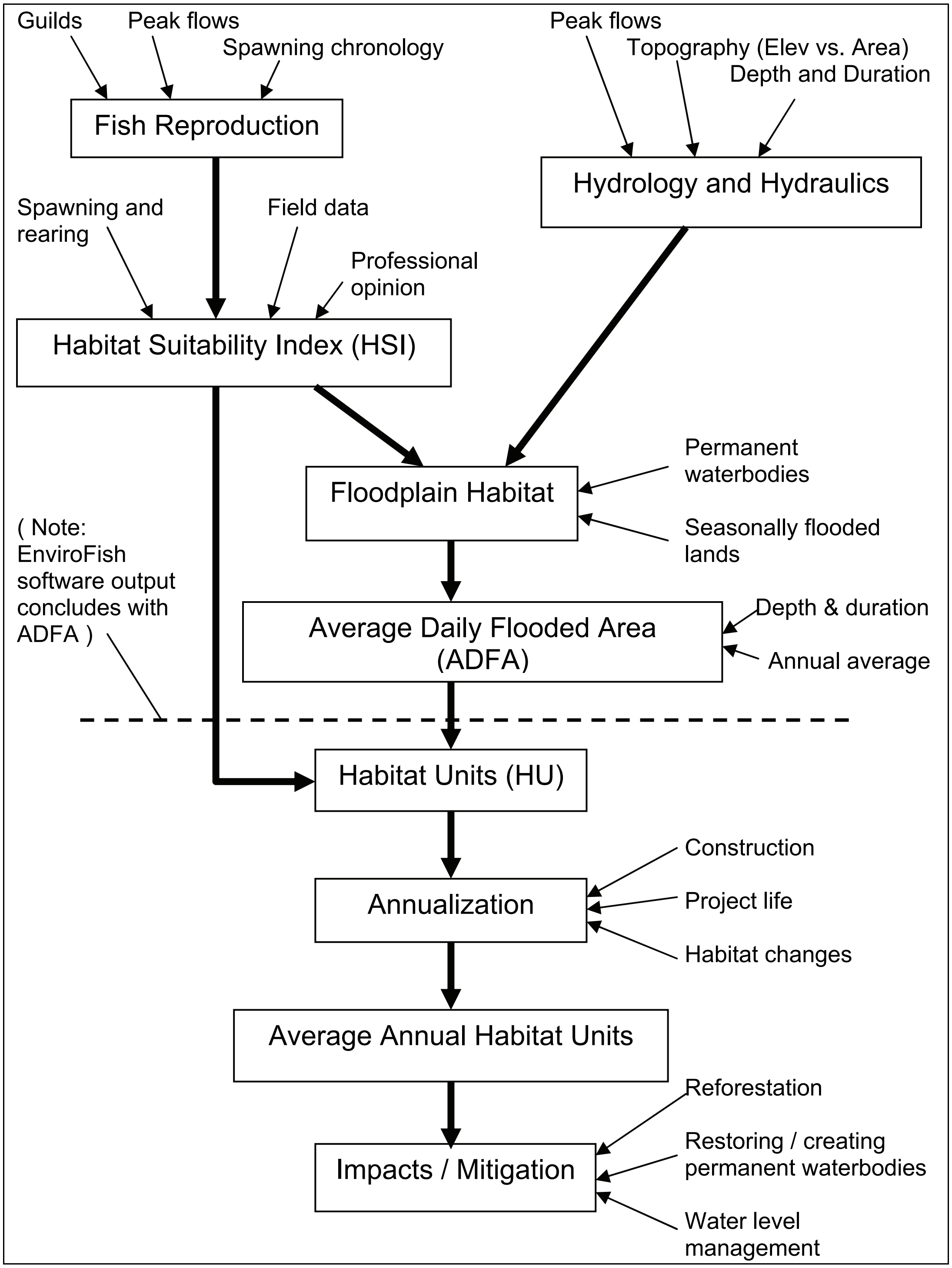


Figure 2-1. Flow Chart of EnviroFish Approach Culminating in Evaluation of Project Impacts and Mitigation.

3 Model Elements

This chapter presents six modeling elements of the EnviroFish approach. Based on input reflecting species selection, topography, land use, daily water surface elevations, and procedures for calculating spawning and rearing habitat areas, a measure of fish reproductive habitat area is determined for a landscape.

The EnviroFish software concludes output with an average daily flooded area for each land use over the multi-year analysis period. The comparative value of a given land use is represented by a weighting factor known as the HSI, which ranges from zero to unity. The product of ADFA and HSI is the measure of Habitat Units for a given land use within the landscape being evaluated. Habitat Units are calculated after completion of an EnviroFish program run. EnviroFish calculates ADFA, and these values can be copied to a computer spreadsheet to perform the Habitat Unit calculations. A flowchart of the overall approach is shown in Figure 3-1. Application of the modeling elements reflect both the variability of habitat suitability across a landscape as well as the variability of inundation within a single season, and across many years of spawning and rearing seasons.

Species Selection

An EnviroFish analysis estimates the habitat available for a single species of fish, or for a guild (or groups) of fish species that can be evaluated appropriately using the selected parameters. The inputs of spawning season, spawning period, limiting depths, and the value of land cover should be compatible with the habitat preferences and requirements of the species or guild selected.

Topography

The EnviroFish approach requires input describing the topography of the land subject to inundation. Topographic information facilitates determination of how much inundated land area satisfies the adopted habitat constraints for a given water surface elevation. Topography is characterized by a table of elevation vs. land area at and below a given elevation, which is equivalent to the area that would be flooded by a level pool of water at a given elevation. The areas listed in the table are

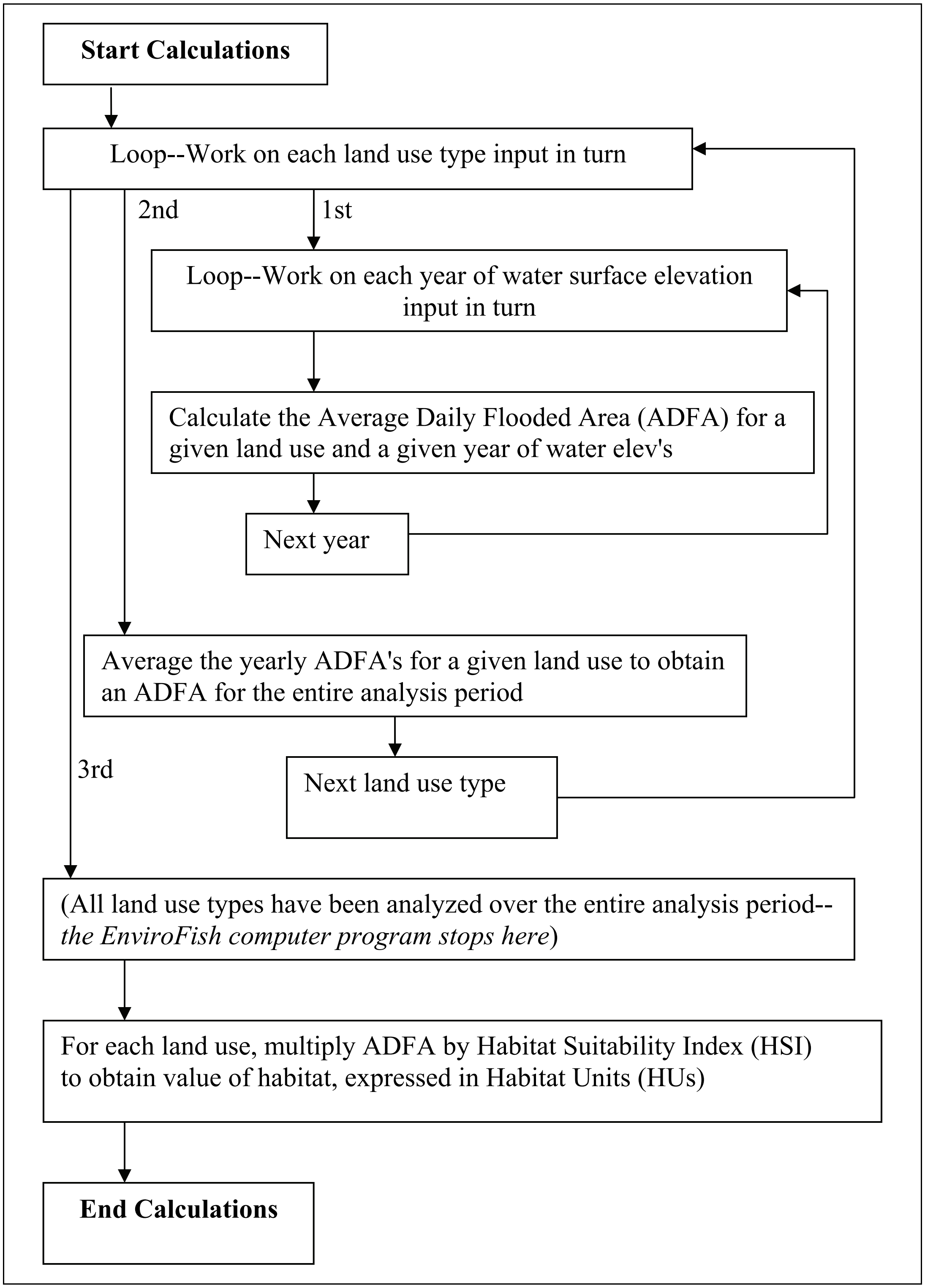


Figure 3-1. Flowchart for the Calculation of Habitat Units for Multiple Land Uses Over a Multi-Year Period of Record.

cumulative, rather than incremental. In the EnviroFish software, land area values are input for each land use category used in the analysis, rather than as a total landscape area, as discussed under the land use section below.

In the EnviroFish approach, the land described by an elevation vs. area table is treated as a single bowl-shaped depression. Figure 3-2 and Figure 3-3 illustrate how an elevation vs. area table may, or may not, realistically characterize a landscape for a spawning and rearing analysis. In both figures, a landscape subject to inundation is located alongside a levee. A culvert through the levee can evacuate surface water from connected depressions down to an elevation of 10 feet.

In Figure 3-2, there truly is one depression, although it is branched. As a water surface falls within this single bowl-shaped depression, the pooled water, shown as a blue line, is always collected into a single central body. The area of pooled water in this single depression is accurately described by an elevation vs. area table. Also, there is no isolated pool in which eggs or larvae could become stranded as the water recedes.

In Figure 3-3 there are two depressions. As in Figure 3-2, the surface water can be evacuated from the lower depression down to elevation 10 feet by the culvert. The higher, isolated depression has a bottom elevation of approximately 17 feet and a spillover elevation of 33 feet along the dividing ridge between the two depressions. The higher, isolated depression will retain water if it should become filled during flooding. Furthermore, eggs and larvae could be stranded in the isolated pool as the lower depression recedes. An elevation vs. area table for the entire landscape of Figure 3-3 would accumulate all the area in the landscape at a given elevation, even if the area were physically separated into two depressions. The scenario illustrated in Figure 3-3 is that of a water surface that has been higher than elevation 33 feet and has fallen to an elevation of approximately 26 feet in the lower depression, but a pool at elevation 33 has been stranded within the isolated depression. Due to the isolated pool, the water surface area on the landscape is actually greater than the area an elevation vs. area table would indicate for a water surface elevation of 26 feet. Alternatively, if the isolated depression contained no water and the water surface elevation in the lower depression were 26 feet, then the actual water surface area on the landscape would be less than indicated by an elevation vs. area table.

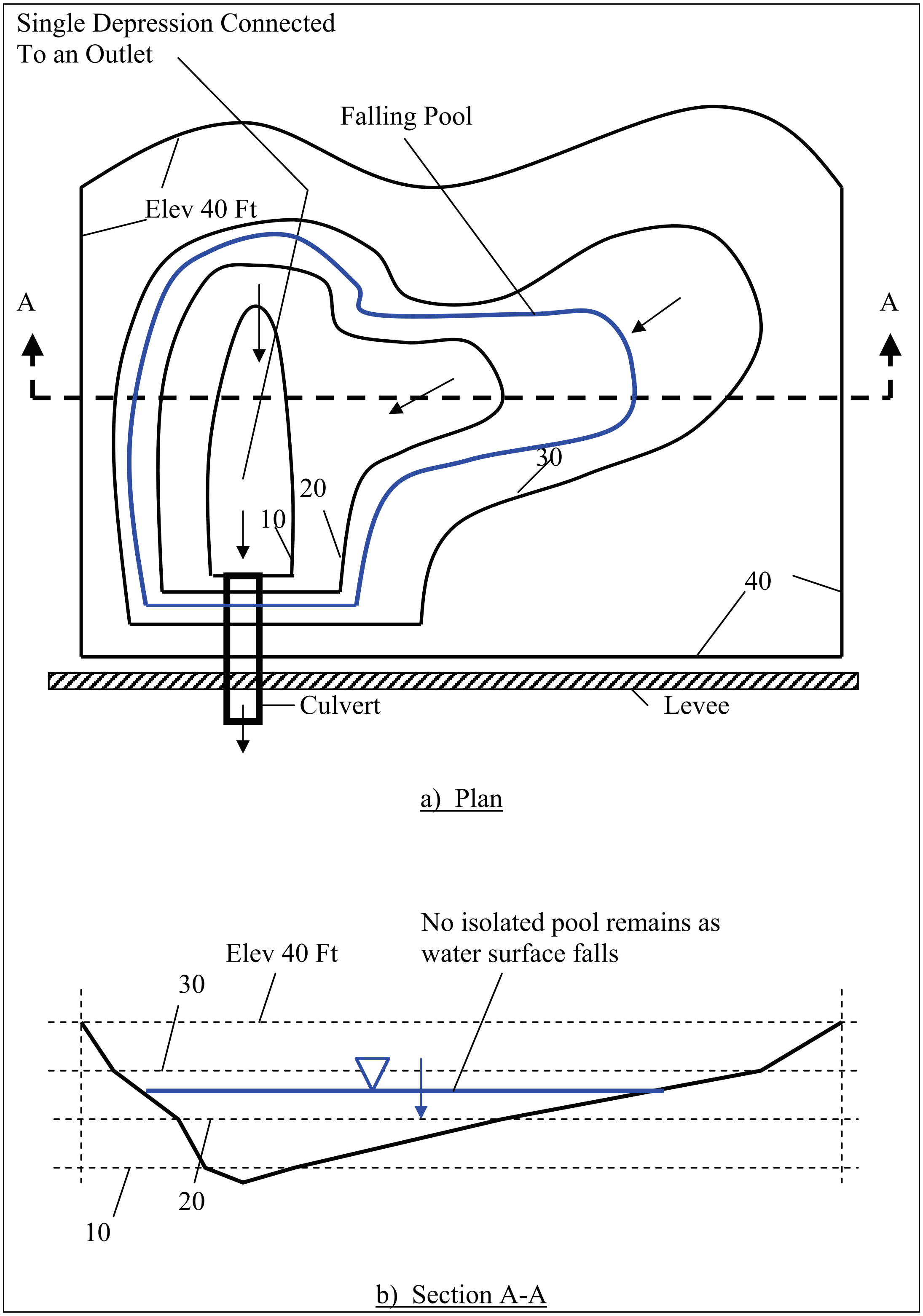


Figure 3-2. Landscape with Single Depression Connected to an Outlet.

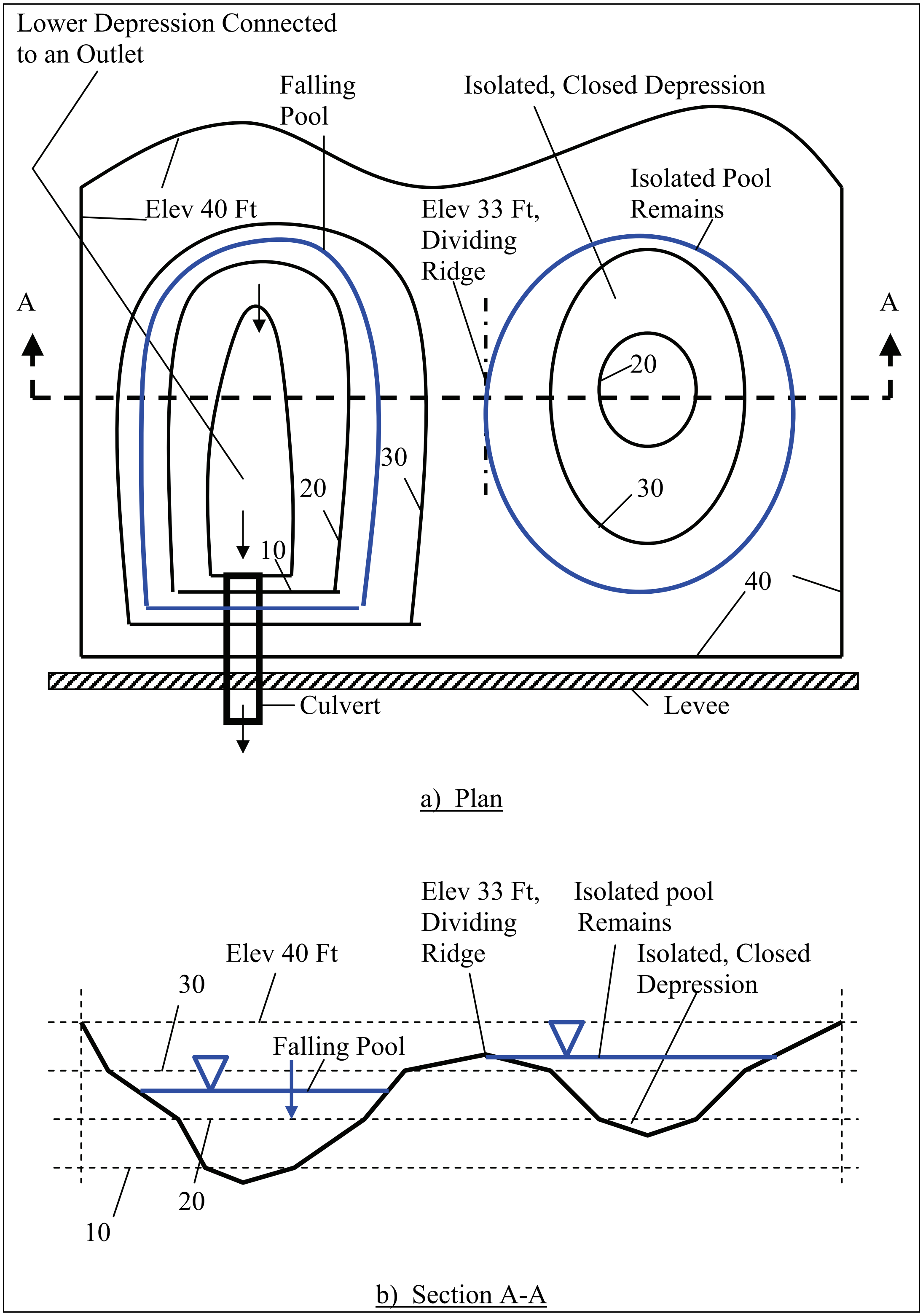


Figure 3-3. Landscape with Isolated, Closed Depression.

An isolated depression, such as the one shown in Figure 3-3, can easily exist within an actual project landscape. Careful coordination between the hydrologist, the GIS specialist, and the biologist is needed in the planning stages of an EnviroFish analysis to assure that the input reflects the topographic characteristics of the landscape with respect to the opportunities for fish to spawn and for eggs and larvae to avoid being stranded. For example, if an isolated, closed depression has ample drainage area, it may function as a permanent waterbody. If a land use classification is established for floodplain water bodies, then the isolated depression may be dealt with easily. Otherwise, the water pooled in the isolated depression may disappear during the reproductive season, due to evaporation or seepage losses, requiring continuous simulation to represent realistically. If an otherwise well-defined and isolated depression is connected by a drainage ditch to the lowest depression in the landscape, and the connection has ample flow capacity, then the water level in the isolated depression may rise and fall at essentially the same rate as that in the lowest depression. In such a case, the level pool, single depression approach of EnviroFish is realistic. However, if the connecting drainage ditch has minimal capacity, the water surface elevation in the isolated pool may considerably lag the rises and falls in the lowest depression, requiring continuous simulation to represent realistically.

Land Use

The suitability of inundated floodplains for fish during the spawning and rearing season is determined by the surface characteristics of the inundated land. These characteristics include the species and density of vegetative cover and the texture of any exposed earth. In the EnviroFish approach, land use is categorized to reflect the distribution of surface characteristics across the landscape, and boundaries of the various land uses are delineated on a map of the landscape. When combined with topographic information, elevation vs. land area tables are produced for each land use category.

For rural landscapes, land use is typically classified according to various species of crops and native trees, to stream channels, to floodplain waterbodies, and to areas of bare earth, such as loose sand. Typically the following land use categories can be delineated: agricultural, fallow, herbaceous wetlands, bottomland hardwoods, and floodplain waterbodies. The biologist classifies land use based on the selected fish species or guilds and assigns a habitat suitability index to each land use classification.

EnviroFish calculates area of each land use category referred to as Average Daily Flooded Area (ADFA).

Water Elevation

In the simplest case, the water inundating a landscape is considered to have a level surface, described by a single value of water surface elevation applicable to a 24-hour day. Daily changes in water surface elevation during the reproductive season determine how much inundated area can be successfully used for spawning and rearing. Analysis over a period of several years is necessary to ensure the variability between wet, dry, and normal years is reflected in the output. To apply the EnviroFish approach, daily water surface elevation must be entered within the spawning and rearing seasons for any year of the analysis period. For some projects, gage data may not be available to characterize existing conditions; consequently, all daily water surface elevations for existing conditions and project alternatives must be synthesized using continuous hydrologic and hydraulic simulations. If gage data are available to describe existing conditions, it may be necessary to synthesize daily water surface elevations for project alternatives that would produce significant changes in the hydrology or hydraulics of the landscape.

Spawning

In the EnviroFish approach, spawning refers to the total time necessary for deposition, fertilization, incubation, and hatching of fish eggs. For species that construct nests, additional time may be necessary prior to deposition of eggs. Some species may not actually construct nests, but scatter eggs over the substrate or attach eggs to woody debris or herbaceous vegetation. In any of these circumstances, deposited eggs are considered sessile until hatched. The term “nest” is used for all of these spawning situations. The total time for all spawning activities is referred to as the spawning period. Deposition and fertilization in a nest are considered to occur on Day 1 of the spawning period. Hatching is considered to occur on the final day of the spawning period. The spawning season is defined by the beginning and ending dates, inclusive, on which deposition and fertilization of eggs can be successfully accomplished. For the purpose of reporting, the EnviroFish approach assigns the spawning habitat available to Day 1 of the spawning period.

Figure 3-4 illustrates how spawning season and spawning period are related.

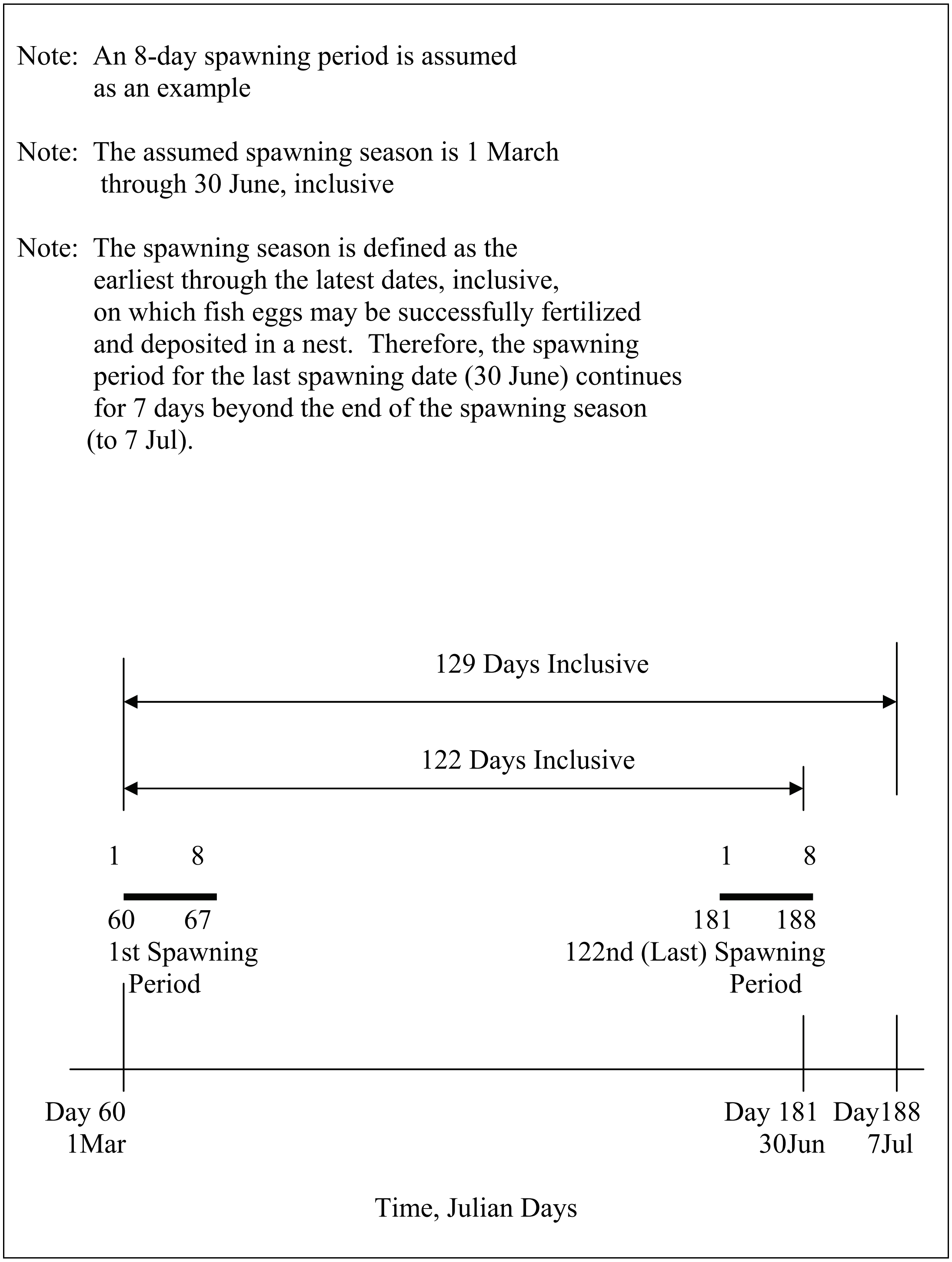


Figure 3-4. Relationship between Spawning Season and Spawning Period.

In this example, the spawning season runs from March 1 to June 30, inclusive, which is a total of 122 days. The spawning period is 8 days. A heavy horizontal bar in Figure 3-4 represents the spawning period beginning on March 1 and ending on March 8. However, each day within the spawning season is the beginning day of a spawning period. Therefore, there are 122 spawning periods within the example spawning season. The spawning period associated with the last day of the spawning season (June 30) is also represented by a heavy horizontal bar. If the spawning that occurs on the last day of the spawning season is to be successful, suitable water depths must persist for 7 days after the ending date of the spawning season (July 7). Therefore, a total of 129 days of water surface elevation input must be analyzed. It is for this reason that the water surface elevation input to the EnviroFish program must extend for additional days past the ending date of the spawning season. The exact number of additional days required is equal to the number of days in the spawning period minus one day.

The EnviroFish approach makes use of minimum and maximum allowable spawning depths. A minimum depth of water is required for successful spawning. First, adult fish require a minimum water depth to make a nest and spawn. Secondly, after the eggs are laid in the nest, a certain depth of water cover is needed throughout the spawning period. The EnviroFish software allows the user to specify one minimum allowable spawning depth, which applies throughout the entire spawning period. If fish of the selected species or group avoid spawning at greater than a maximum limiting depth, a maximum allowable spawning depth should be applied. The EnviroFish software allows the user to specify one maximum allowable spawning depth, which applies throughout the entire spawning period.

Figure 3-5 illustrates in plan and section views a very simple bowl-shaped landscape on the first day (Day 1) of a spawning period, and the use of minimum and maximum allowable depths to locate a zone of satisfactory spawning habitat for Day 1. In section view, the water surface, shown in blue, is at elevation 100 feet. Since the example minimum allowable depth is 1 foot, the minimum allowable depth surface is at elevation 99 on Day 1. The example maximum allowable depth is 10 feet, so the maximum depth surface is at elevation 90 on Day 1. The zones satisfying depth constraints appear as green cross-hatched triangles on the left and right sides of the section. In plan view, the zone that satisfies the depth constraints on Day 1 is shaded in a green cross-hatched pattern. The fringe around the edge of the pool where the water depth ranges from 0 to 1 foot is considered unsatisfactory for spawning. Since the bottom of the bowl is deeper than elevation 90, the inundated land below elevation 90 is also considered unsatisfactory for spawning.

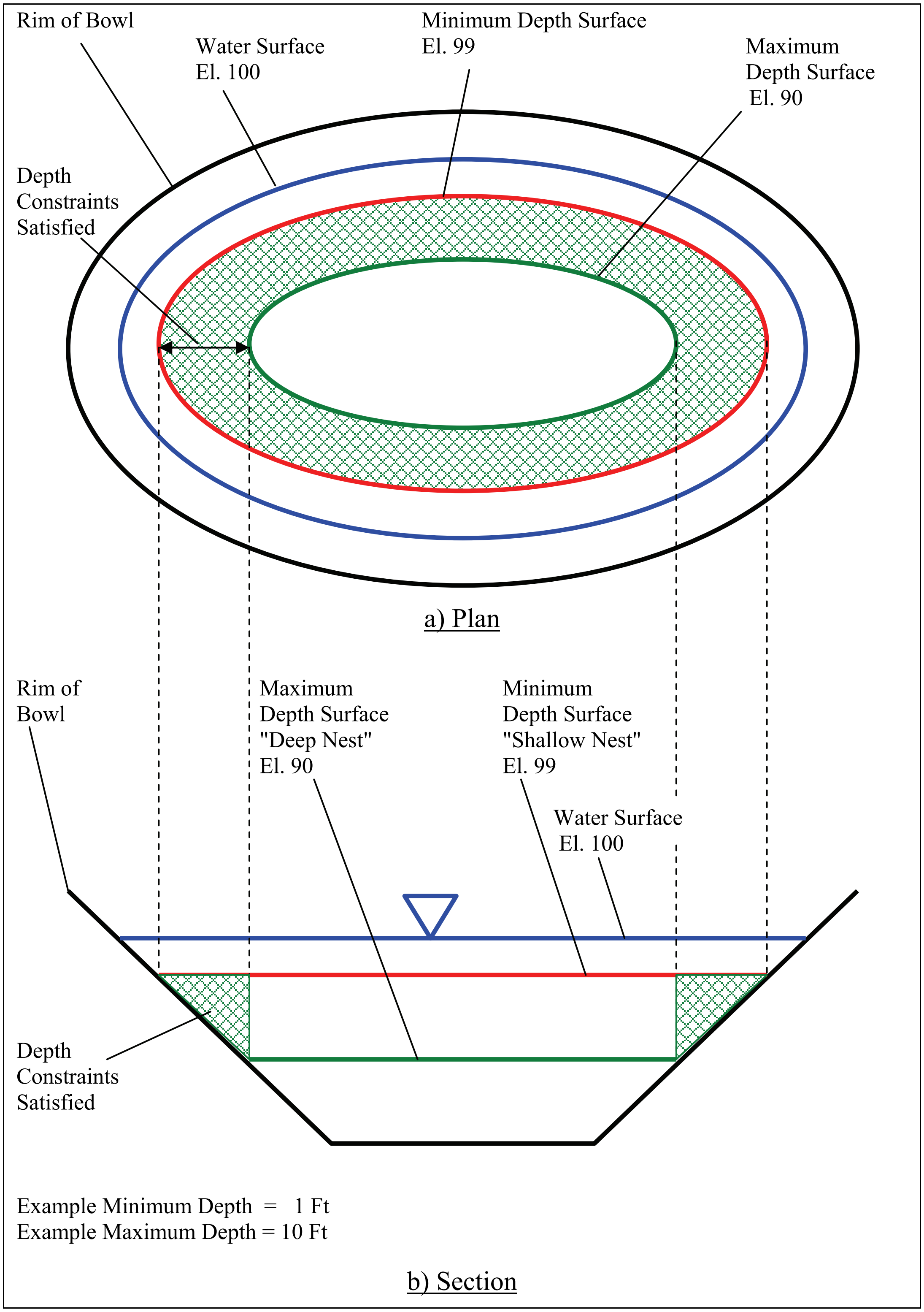
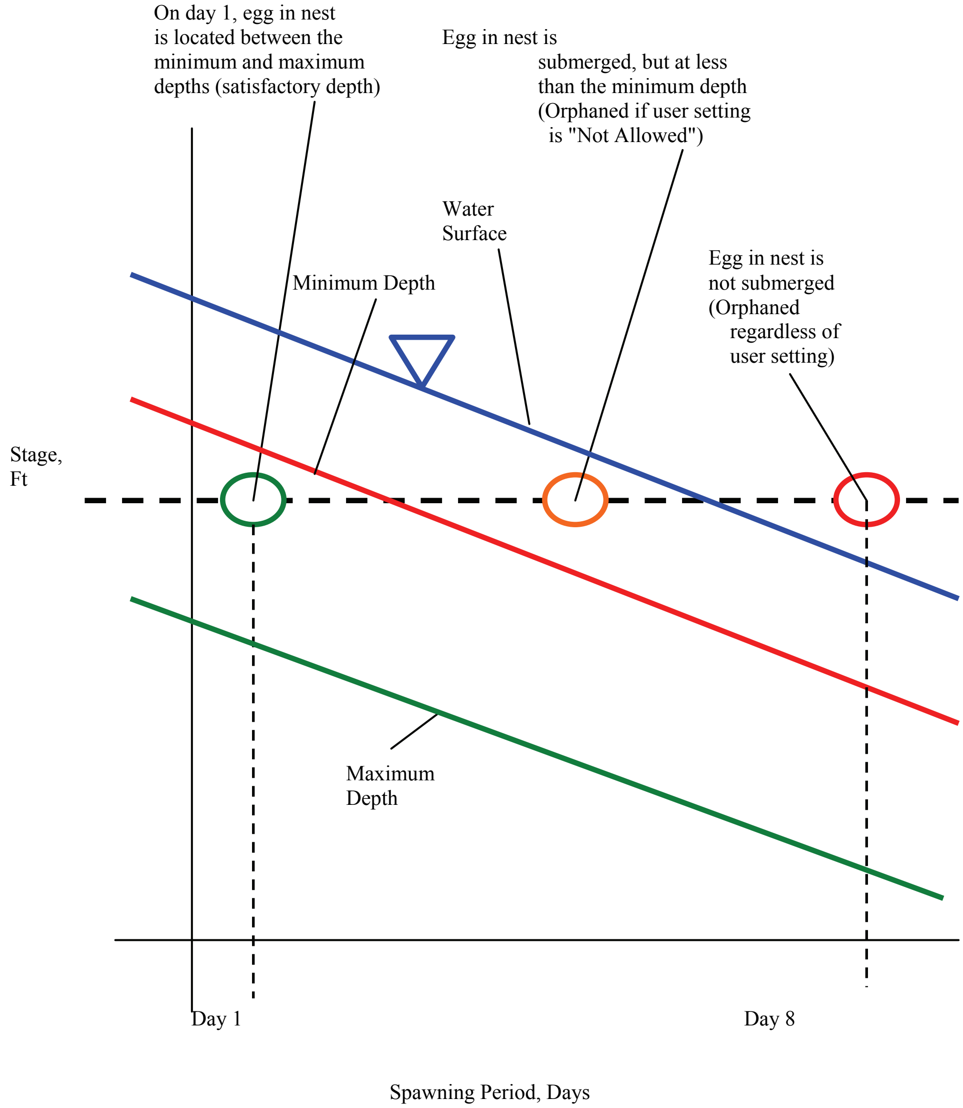


Figure 3-5. Plan and Section Views Spawning Depth Constraints within a Hypothetical Bowl of Inundated Land (Day 1).

It is important to realize that although minimum and maximum allowable depths are constant through the analysis, the water surface elevation typically varies daily. Therefore, an egg that was deposited on Day 1 within the depth range considered satisfactory on Day 1 can be subjected to unsatisfactory depths before the spawning period ends. For example, as shown in Figure 3-6, if the water level drops so much that the egg in the nest is exposed to air, then the spawning is unsuccessful. In Figure 3-6, the horizontal axis represents time and the vertical axis represents elevation. Since the egg must remain in its nest until hatching, the elevation of the deposited egg is constant throughout the spawning period. The fall in the water surface throughout the spawning period at the fixed location of the nest is represented by the blue water surface line that slopes downward to the right. The minimum and maximum allowable spawning depth lines that parallel the water surface line beyond Day 1 represent the spawning depth limits for subsequent spawning periods. On Day 1, the egg (green oval) is deposited within the satisfactory depth range. Approximately midway through the spawning period, the egg (orange oval) is still submerged, but is in water shallower than the minimum allowable depth for a subsequent spawning period. On Day 8, at the end of the spawning period, the water surface has fallen so much that the egg (red oval) is exposed to air. The egg that was deposited on Day 1 within a satisfactory depth range did not survive the spawning period.

The EnviroFish computer program has two options called "Orphaned (otherwise known as “shallow”) Nests" and "Deep Nests" that allow the user to override allowable depth restrictions. If the Orphaned Nests Allowed option is selected, the minimum allowable depth is in effect on Day 1 of a spawning period, but on the remaining days of the spawning period, depths shallower than the minimum allowable depth are considered acceptable, provided the egg is not exposed to air. Likewise, if the Deep Nests Allowed option is selected, the maximum allowable depth is in effect on Day 1 of a spawning period, but on the remaining days of the spawning period, depths greater than the maximum allowable depth are considered acceptable. Whether or not the Orphaned Nests Allowed or Deep Nests Allowed options are selected, the satisfactory depth range throughout the spawning period can never be greater than that in effect on Day 1 of the spawning period.



Note: An 8-day spawning period is assumed as an example

Note: The stage at which the egg is nested is constant over time, but the water surface in this example is falling over time.

Figure 3-6. Stage Hydrograph of Spawning Constraints During Falling Stages and the Fate of an Individual Fish Egg in Its Nest.

Figure 3-7 illustrates four possible cases for selection of the Orphaned Nests and Deep Nests options for a spawning period during falling water surface elevations. For Case 1 and Case 2, the depth range that is satisfactory on Day 1, indicated by the height of the green cross-hatched area, remains in effect throughout the 8-day spawning period, even though the water is shallower

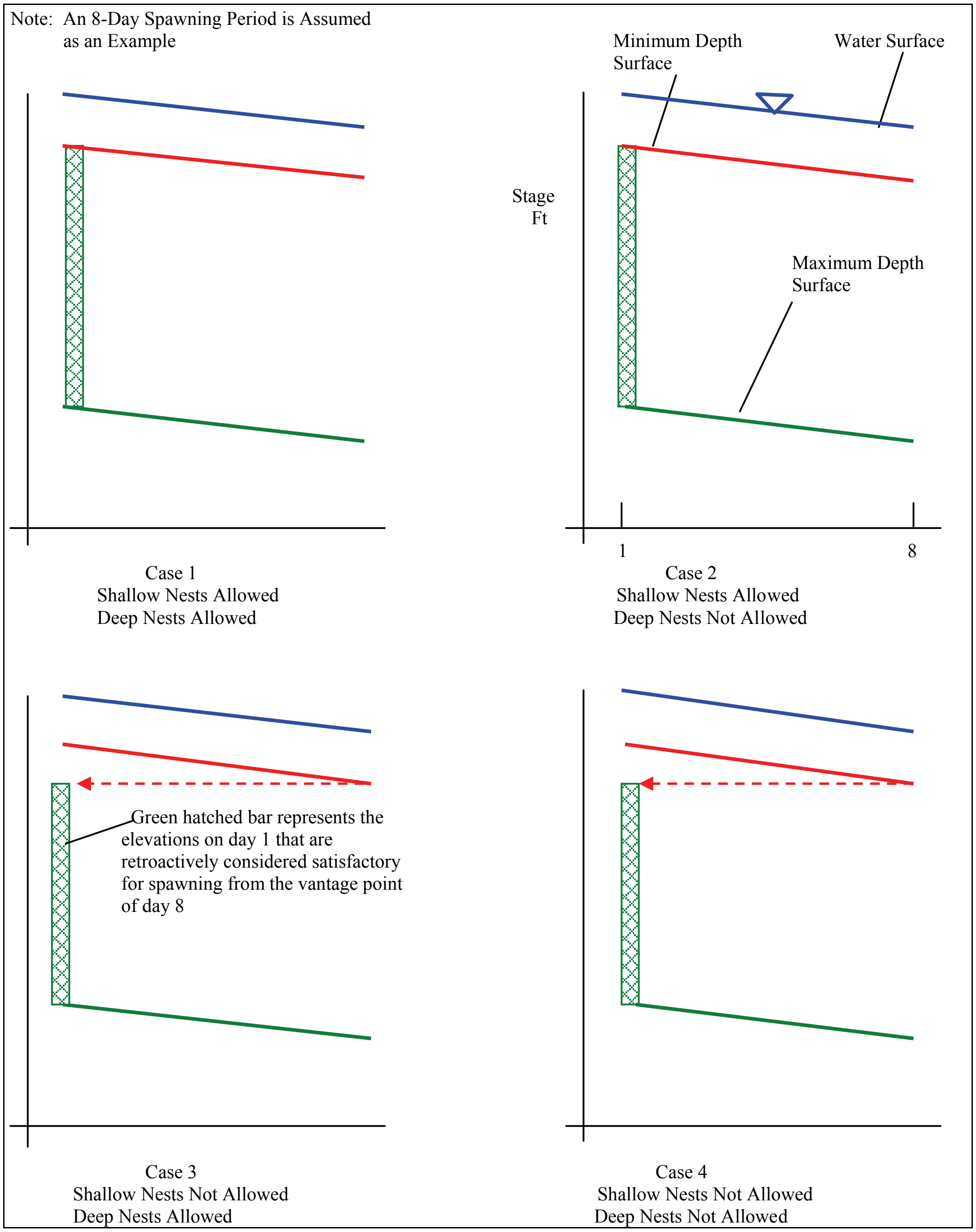


Figure 3-7. Spawning Depth Constraints for Falling Stages for the Four Possible Combinations of Shallow Nest and Deep Nest User Settings.

on Day 2 through Day 8. For Case 3 and Case 4, the depth range that is satisfactory on Day 8 is more restrictive than that for Day 1, due to the falling water surface elevation and the selection of Orphaned Nests Not Allowed. Therefore, for Case 3 and Case 4, the satisfactory depth range applicable for the entire spawning period is the reduced satisfactory depth range that has evolved by Day 8.

Figure 3-8 illustrates four possible cases for selection of the Orphaned Nests and Deep Nests options for a spawning period during rising water surface elevations. For Case 1 and Case 3, the depth range that is satisfactory on Day 1, indicated by the height of the green cross-hatched area, remains in effect throughout the 8-day spawning period, even though the water is deeper on Day 2 through Day 8. For Case 2 and Case 4, the depth range that is satisfactory on Day 8 is more restrictive than that for Day 1, due to the rising water surface elevation and the selection of Deep

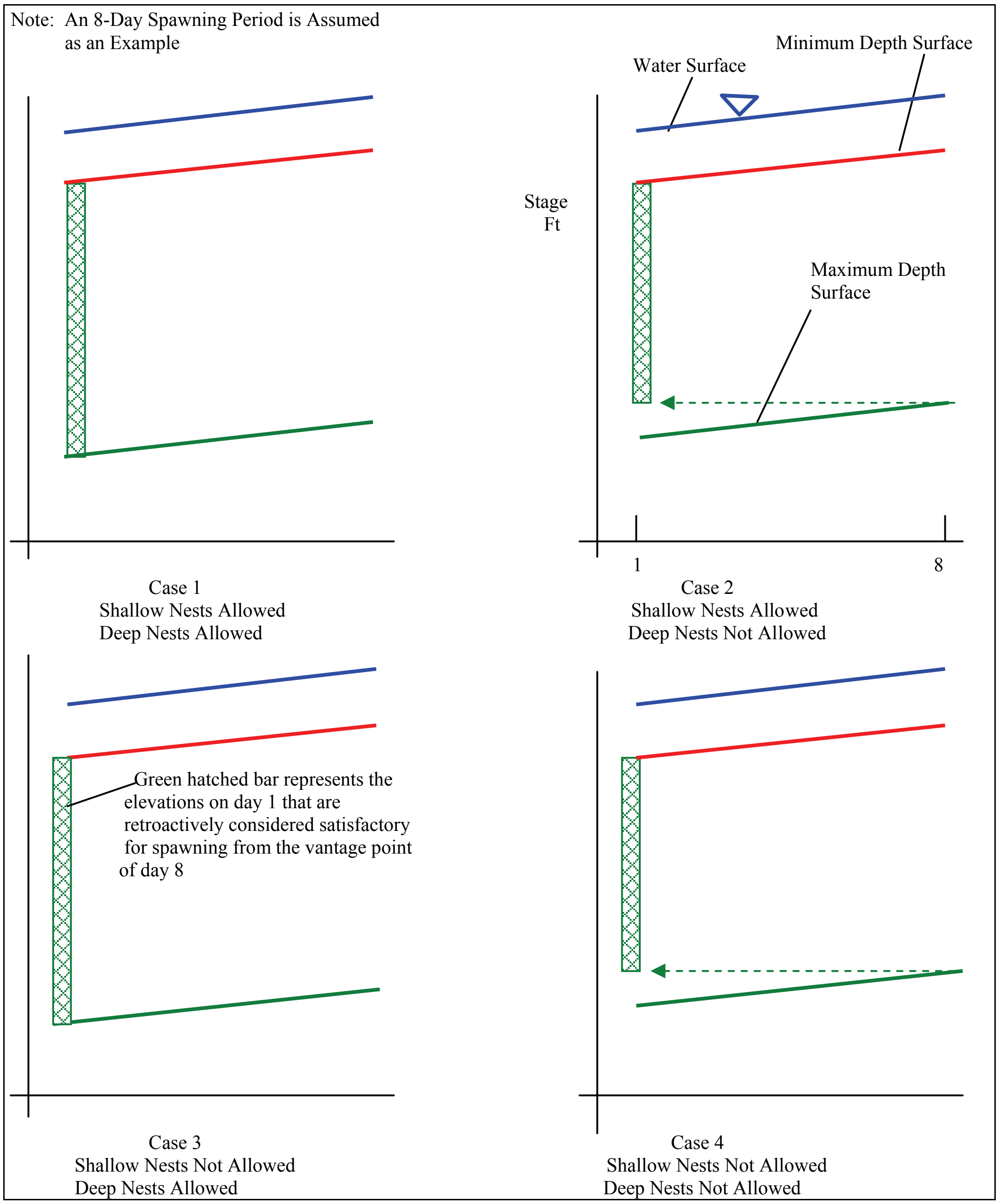


Figure 3-8. Spawning Depth Constraints for Rising Stage for the Four Possible Combinations of Shallow Nest and Deep Nest User Settings.

Nests Not Allowed. Therefore, for Case 2 and Case 4, the satisfactory depth range applicable for the entire spawning period is the reduced satisfactory depth range that has evolved by Day 8.

In the EnviroFish software, with both the Orphaned Nests Not Allowed and the Deep Nests Not Allowed options selected, it is possible for water surface elevations to change so much during a spawning period that the minimum and maximum allowable depths conflict, as shown in Figure 3-9 and Figure 3-10. In Figure 3-9, the water surface elevation is falling throughout the spawning period. The depth restriction imposed by Orphaned Nests Not

Note: An 8-day spawning period is assumed as an example

Note: In this example the fall in the water surface over the 8-day period is greater than the vertical distance between the minimum depth surface and the maximum depth surface, resulting in conflicting spawning depth constraints

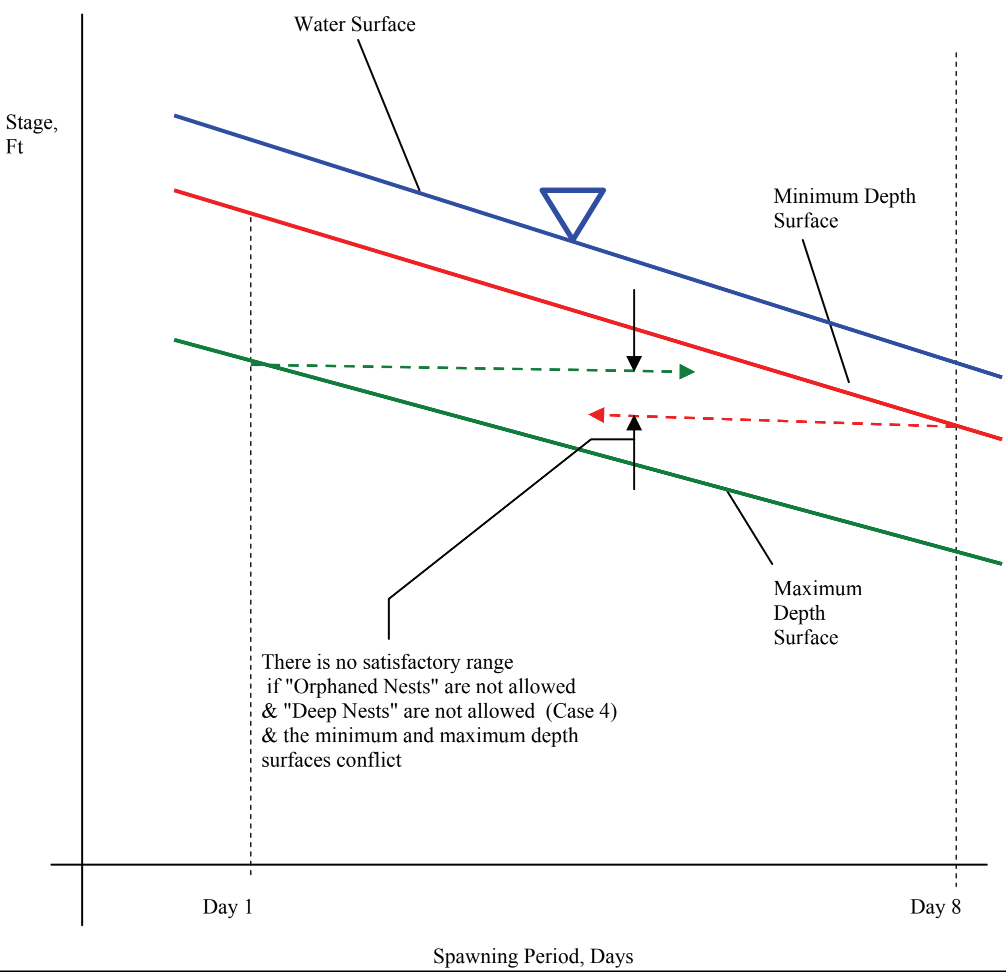


Figure 3-9. Stage Hydrograph of Spawning Constraints during Falling Stages for Case 4, with Conflicting Minimum and Maximum Depth Surfaces.

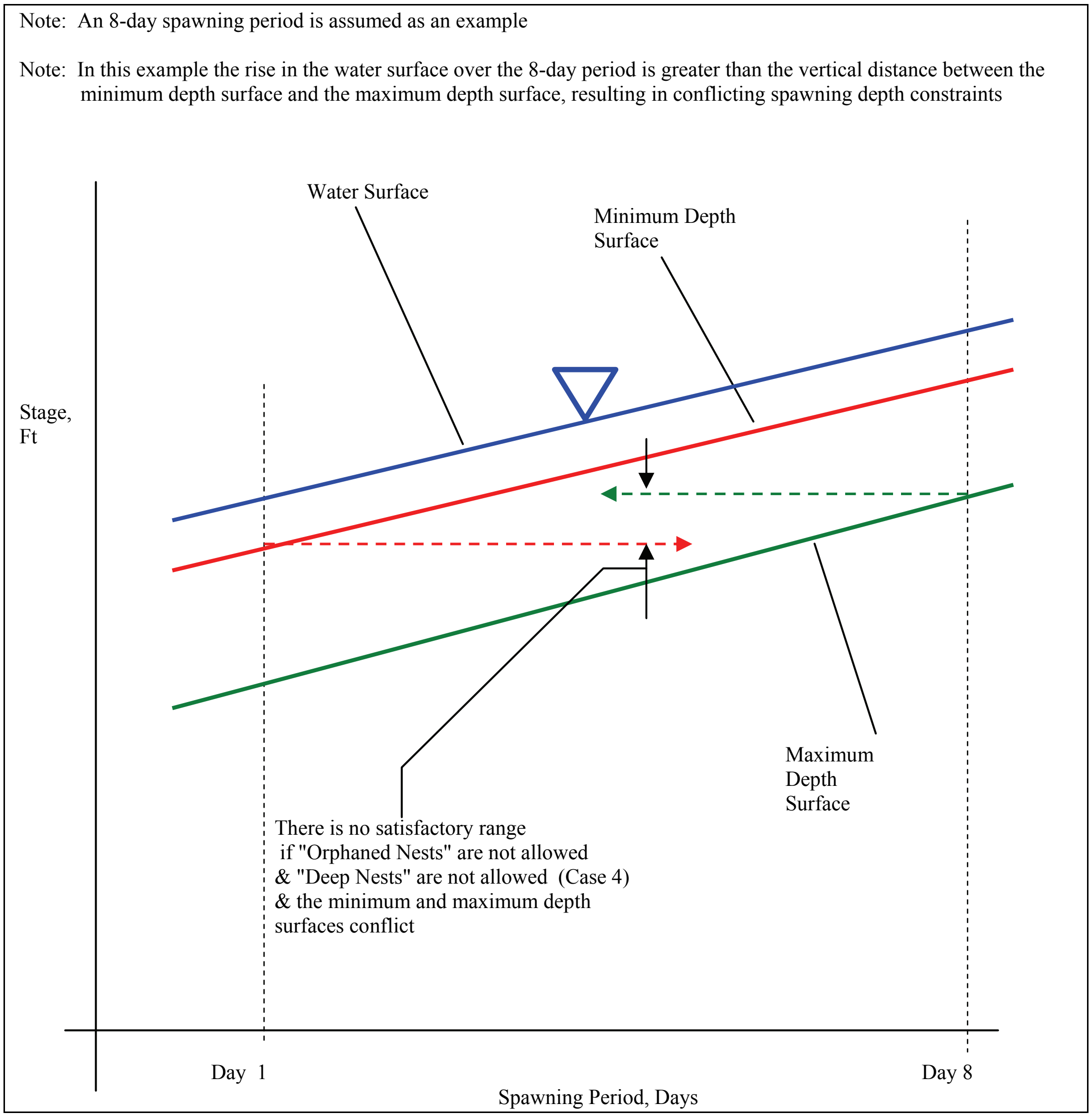


Figure 3-10. Stage Hydrograph of Spawning Constraints During Rising Stages for Case 4, with Conflicting Minimum and Maximum Depth Surfaces.

Allowed is represented by the red dashed arrow. The depth restriction imposed by Deep Nests Not Allowed is represented by the green dashed arrow. Since the deep nest restriction is associated with a higher elevation than is the Orphaned nest restriction, an unsatisfactory depth condition exists and the spawning period is considered unsuccessful. Likewise, in Figure 3-10, the water surface elevation is rising throughout the spawning period. The depth restriction imposed by Orphaned Nests Not Allowed is represented by the red dashed arrow. The depth restriction imposed by Deep Nests Not Allowed is represented by the green dashed arrow. Again, since the deep nest restriction is associated with a higher elevation than is the Orphaned nest restriction, an unsatisfactory depth condition exists and the spawning period is considered unsuccessful.

Figure 3-11 and Figure 3-12 illustrate more complex examples of changing water surface elevations throughout a spawning period, with both the Deep Nests Not Allowed and the Orphaned Nests Not Allowed options selected (Case 4). These two figures also depict the daily water surface elevations as constant during a one day time step, rather than falling or rising continuously, as is depicted in Figure 3-6 through Figure 3-10. The resultant stair-step pattern is more representative of the daily water surface elevation input to EnviroFish. Figure 3-11 depicts a fall in the

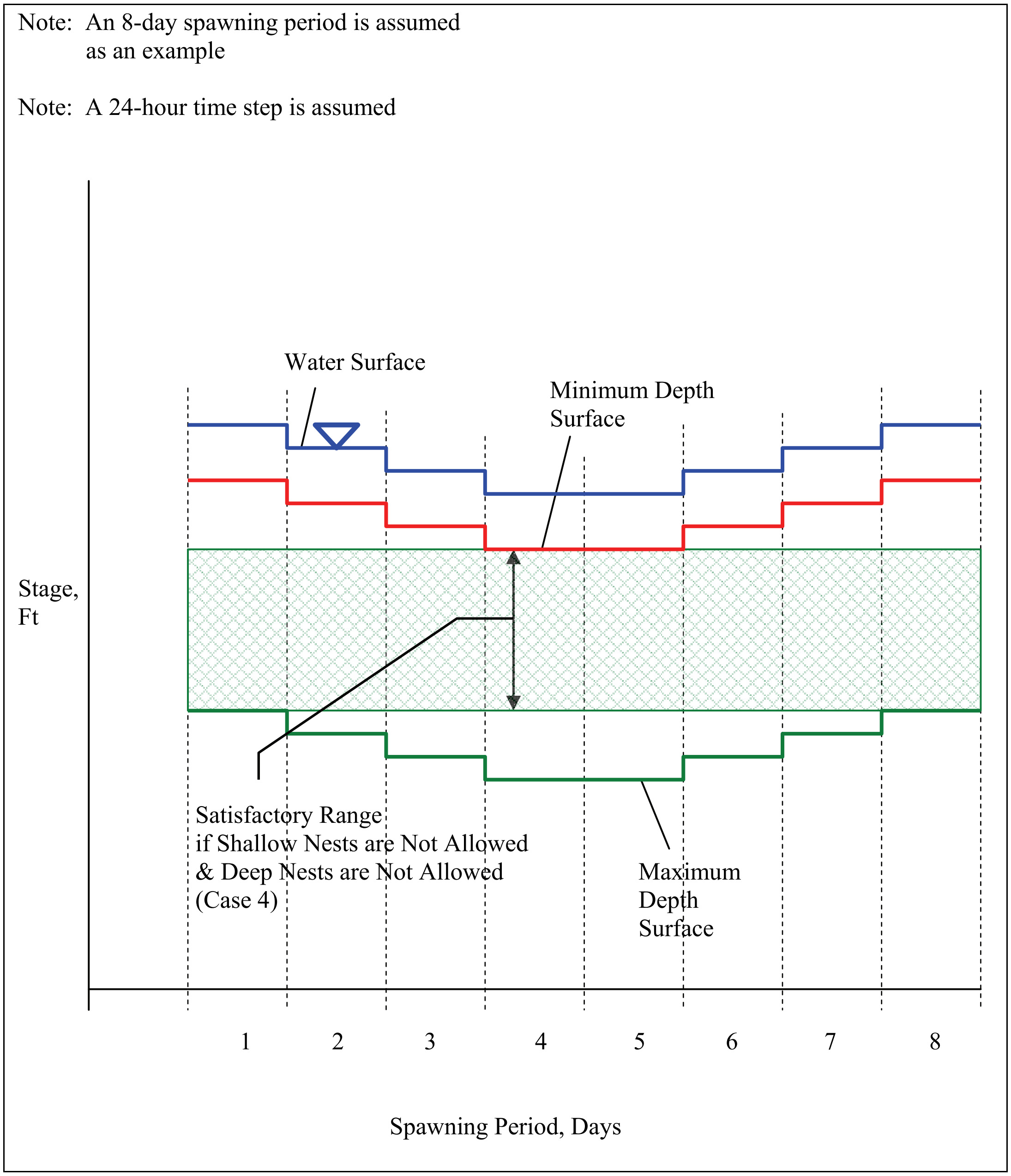


Figure 3-11. Stage Hydrograph of Spawning Constraints during Falling Stages Followed by Rising Stages for Case 4.

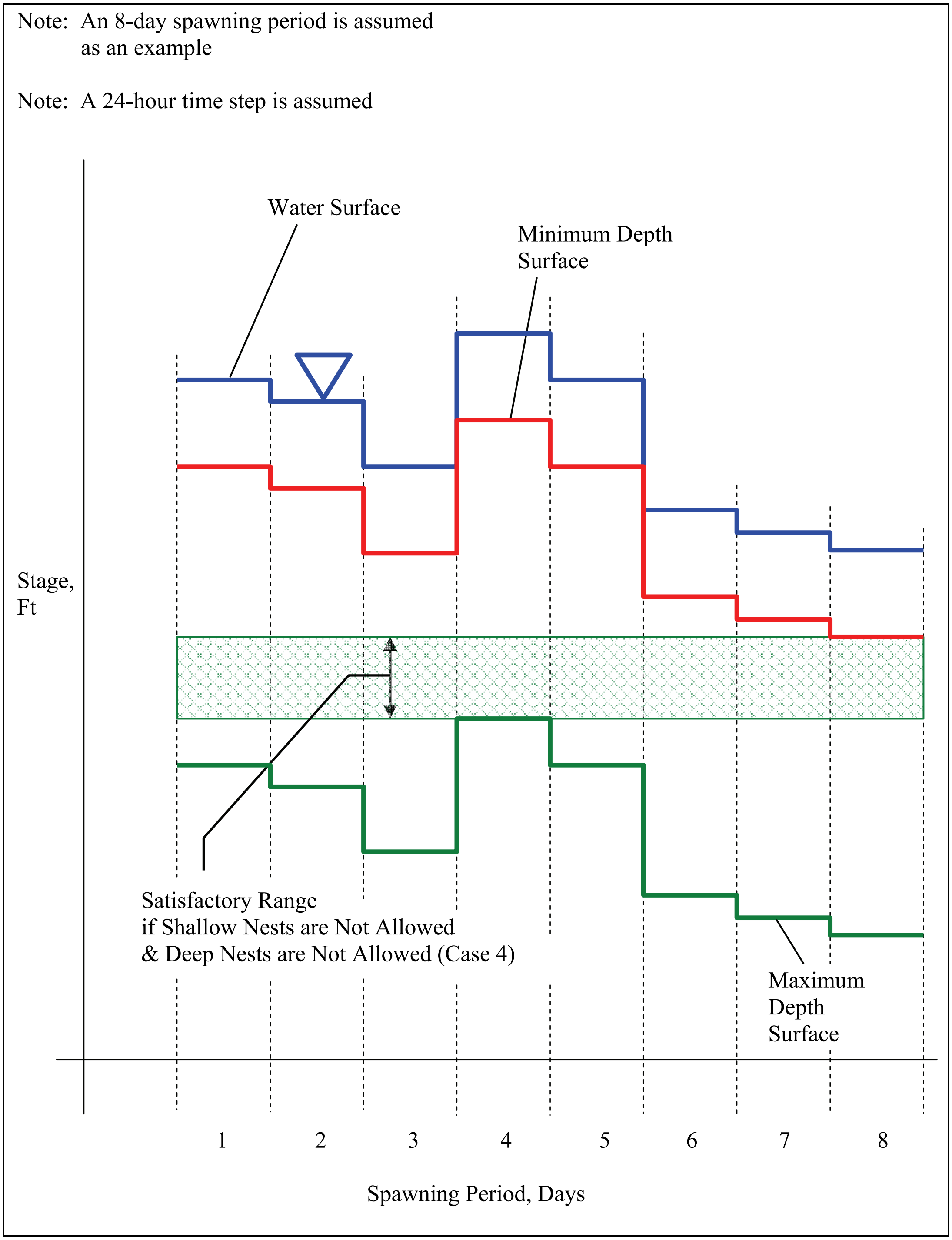


Figure 3-12. Stage Hydrograph of Spawning Constraints During Falling Stages Followed by a Rise and a Fall for Case 4.

water surface elevation, followed by a rise, during a spawning period. Since Orphaned Nests and Deep Nests are not allowed, the resultant satisfactory depth range is much smaller than the satisfactory depth range that is in effect on Day 1. Figure 3-12 depicts a fall in the water surface elevation, followed by a rise and then another fall, during a spawning season. Again, since Orphaned Nests and Deep Nests are not allowed, the resultant satisfactory depth range is much smaller than the satisfactory depth range that is in effect on Day 1.

Rearing

In the EnviroFish approach, rearing refers to the larval life stage immediately after hatching when the individual attains the ability for volitional movement (e.g., swimming off the nest, moving with or away from the flood pulse, selecting specific habitats). If necessary, multiple larval stages can be used to characterize different developmental periods, but each stage must be run separately in EnviroFish. The rearing season coincides with the spawning period, as shown in Figure 3-13. Unlike spawning, for which each day of a multi-day spawning period must be satisfactory, each day of rearing is evaluated without respect to conditions on other days. The EnviroFish software provides two approaches to model rearing: total rearing depth and restricted rearing depth.

For the total rearing option, depths from zero to the maximum depth of the waterbody are considered satisfactory for rearing, encompassing the entire liquid volume of the waterbody. Figure 3-14 illustrates total rearing in plan and section views for a very simple bowl-shaped landscape on a given day, with zones satisfactory for rearing shaded in green cross-hatch. The EnviroFish program records the entire surface area of the waterbody as satisfactory rearing on the given date.

Compared to total rearing, the restricted depth rearing option provides a way to limit the area considered satisfactory for rearing. Restricted depth rearing treats time in the same way as total rearing and uses depth restrictions in the same way as spawning. Like total rearing, each day of restricted depth rearing is evaluated as an individual instance of a rearing opportunity, without respect to conditions on other days. Like spawning, restricted depth rearing features minimum and maximum allowable depths. For example, the minimum allowable depth may be set at 0.1 feet to prevent counting the area in a feather edge around the fringe of the waterbody where larvae could become stranded due to fluctuating water levels. A maximum allowable rearing depth may be applied if larvae avoid deep water (e.g., to minimize predation) or otherwise do not derive benefits at greater depths.

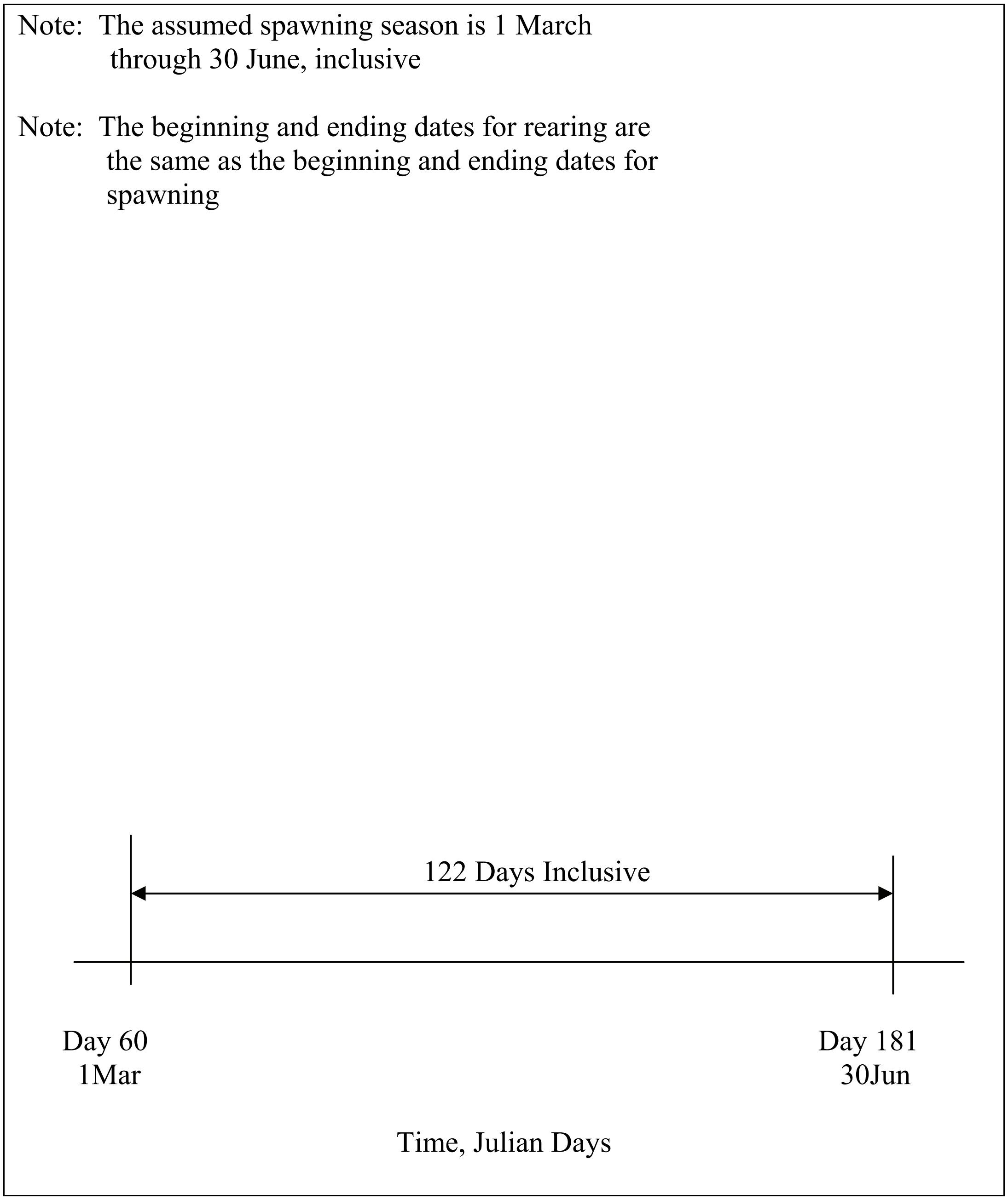


Figure 3-13. Timeline of Rearing Period.

Figure 3-15 illustrates in plan and section views a very simple bowl-shaped landscape, and the use of minimum and maximum allowable depths to locate a zone of satisfactory restricted depth rearing. In section view, the water surface, shown in blue, is at elevation 100 feet. Since the example minimum allowable depth is 0.1 foot, the minimum allowable depth surface is at elevation 99.9. The example maximum allowable depth is 10 feet, so the maximum depth surface is at elevation 90. The zones satisfying depth constraints appear as green cross-hatched triangles on the left and

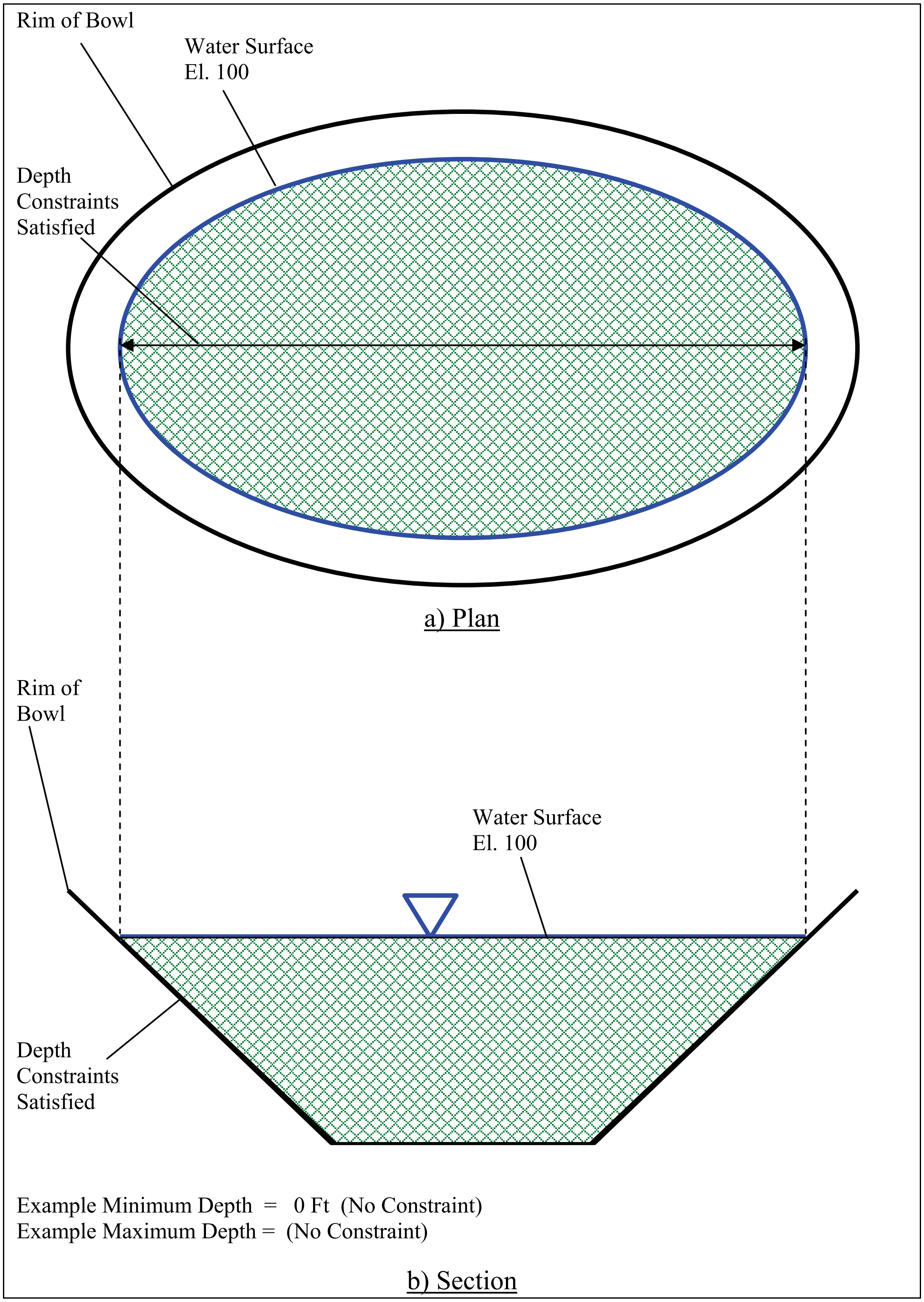


Figure 3-14. Plan and Section Views of Total Rearing Depth Constraints within a Hypothetical Bowl of Inundated Land.

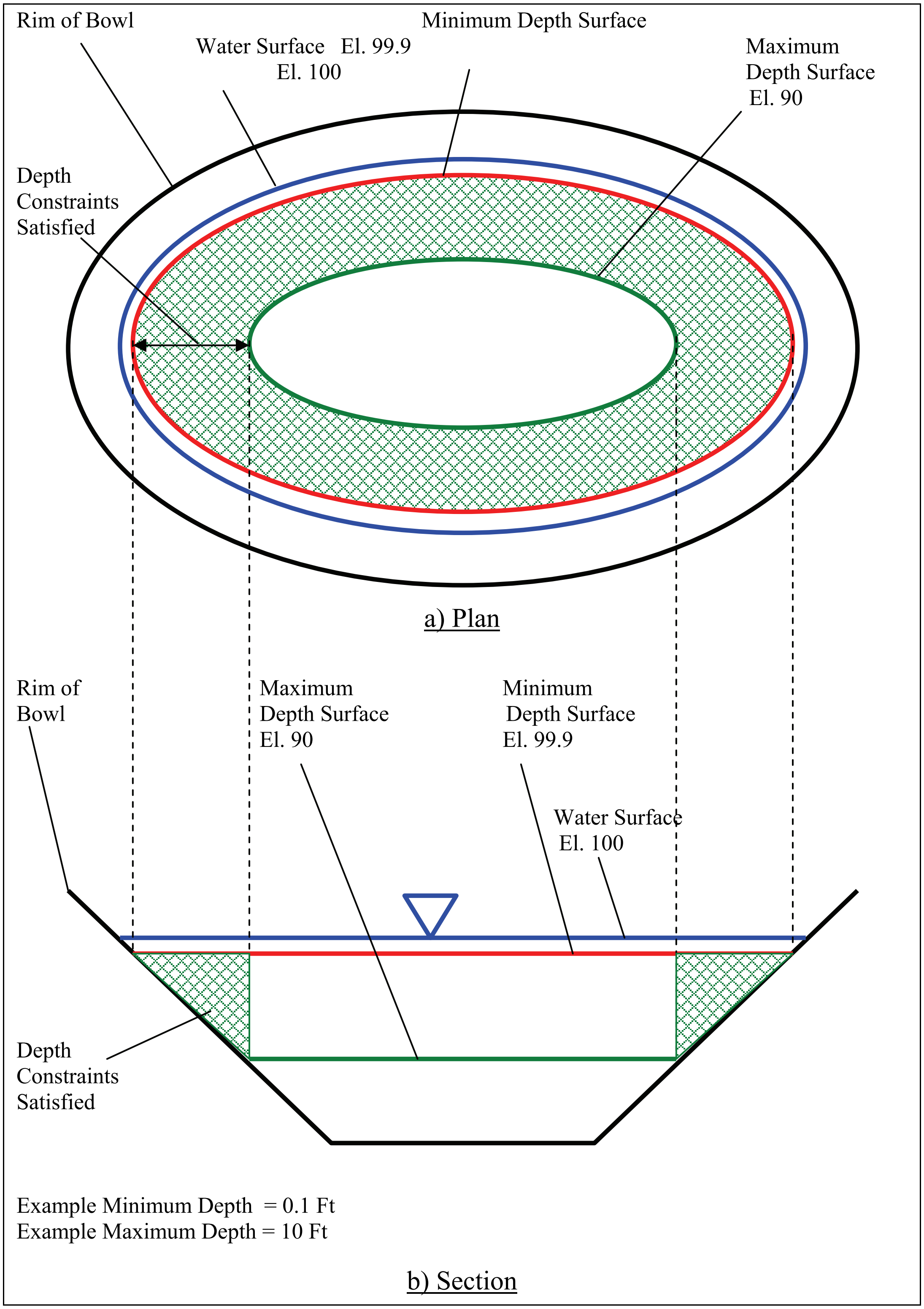


Figure 3-15. Plan and Section Views of Restricted Rearing Depth Constraints within a Hypothetical Bowl of Inundated Land.

right sides of the section. In plan view, the zone that satisfies the depth constraints is shaded in a green cross-hatched pattern. The fringe around the edge of the pool where the water depth ranges from 0.0 to 0.1 foot is considered unsatisfactory for rearing. Since the bottom of the bowl is deeper than elevation 90, the inundated land below elevation 90 is also considered unsatisfactory for rearing.

4 Running EnviroFish

This chapter describes running the EnviroFish program, including loading input, initiating a program run, and obtaining output. The example input and output is in the example problem of Chapter 6. The content of this chapter is organized under eight headings—operating system, input required, navigation, input steps, input description, initiating a program run, viewing output, and output description. A detailed description of EnviroFish calculations is shown in Appendix C.

Operating System

The EnviroFish computer program runs under the Microsoft Windows computer operating system. Figure 4-1 is a screen shot of the EnviroFish main page upon program startup. The page is blank, because no DSS file has been loaded and no habitat constraints have been entered.

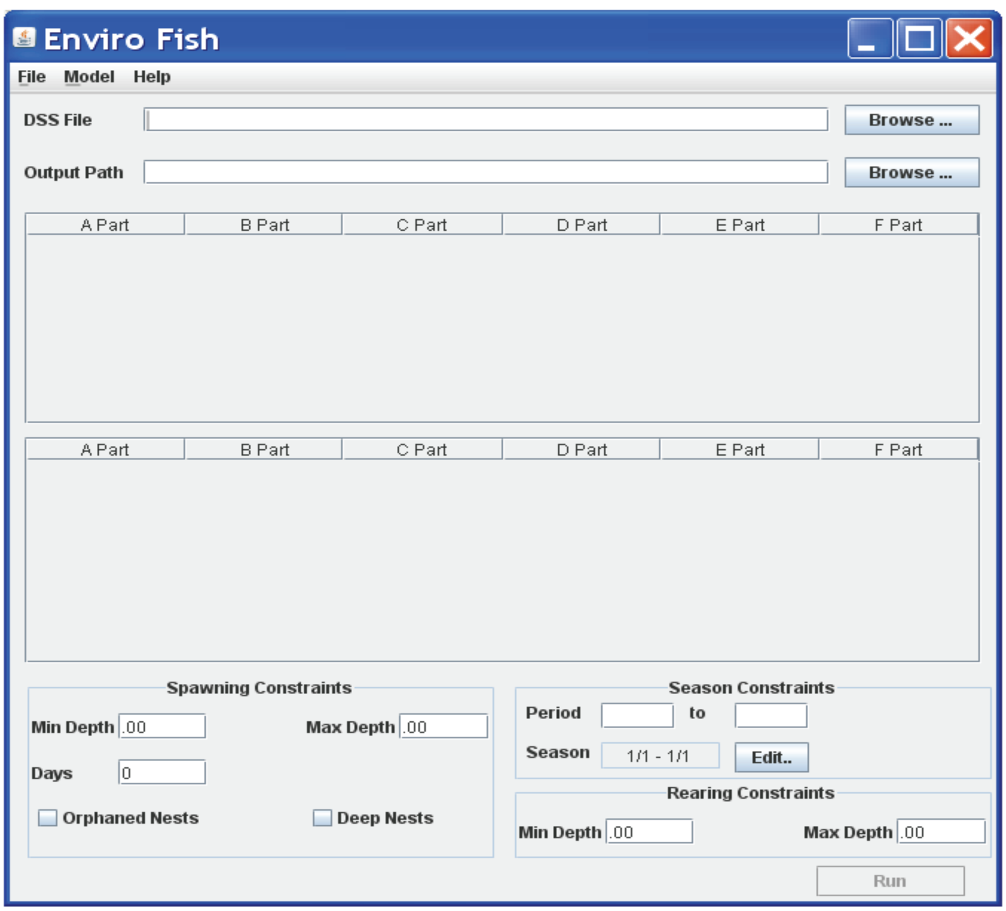


Figure 4-1. EnviroFish Main Screen on Start-up.

Input Required

The input requirements for EnviroFish are simple, although the preparation of that input may be complex. The first body of input required is daily water surface elevations throughout the analysis period for the landscape being analyzed, referred to as "daily elevations" below. Typically, different alternatives have different water surface elevation input for the same analysis period. The second body of input is a set of elevation vs. area tables, with one table for each category of land use in the landscape. Both the daily elevations and the elevation vs. area tables must be stored in the DSS file format established by the Corps of Engineers Hydrologic Engineering Center. EnviroFish loads only one DSS file for a program run, so the elevation data and the elevation vs. area data must both be stored in one DSS file. Therefore, a program run is required for each combination of elevation (e.g., Alternatives) and elevation-area (e.g., each land use category) data. See Appendix B for more information about using DSS files to incorporate land use in EnviroFish.

Figure 4-2 is a screen shot of the EnviroFish main page with an example DSS file named **Any River Basin.dss** loaded. The DSS pathname containing the elevation data to be used is highlighted in the upper DSS window, and the pathname containing the elevation-area data to be used is highlighted in the lower DSS window. Different combinations of elevation and elevation vs. area may be selected.

In addition to the input provided in DSS format, habitat constraints regarding time and depth must be entered for spawning and rearing. The constraints are entered from the keyboard directly into the EnviroFish main window.

Navigation

Navigating the EnviroFish view screens may be performed by placing the cursor of the mouse over the desired area to be selected and pressing the left button of the mouse. The Tab key on the computer keypad may be used to accept input data and move from one area to another. The Arrow keys on the computer keypad may be used to navigate to a particular area; the Enter key may be used to accept data.

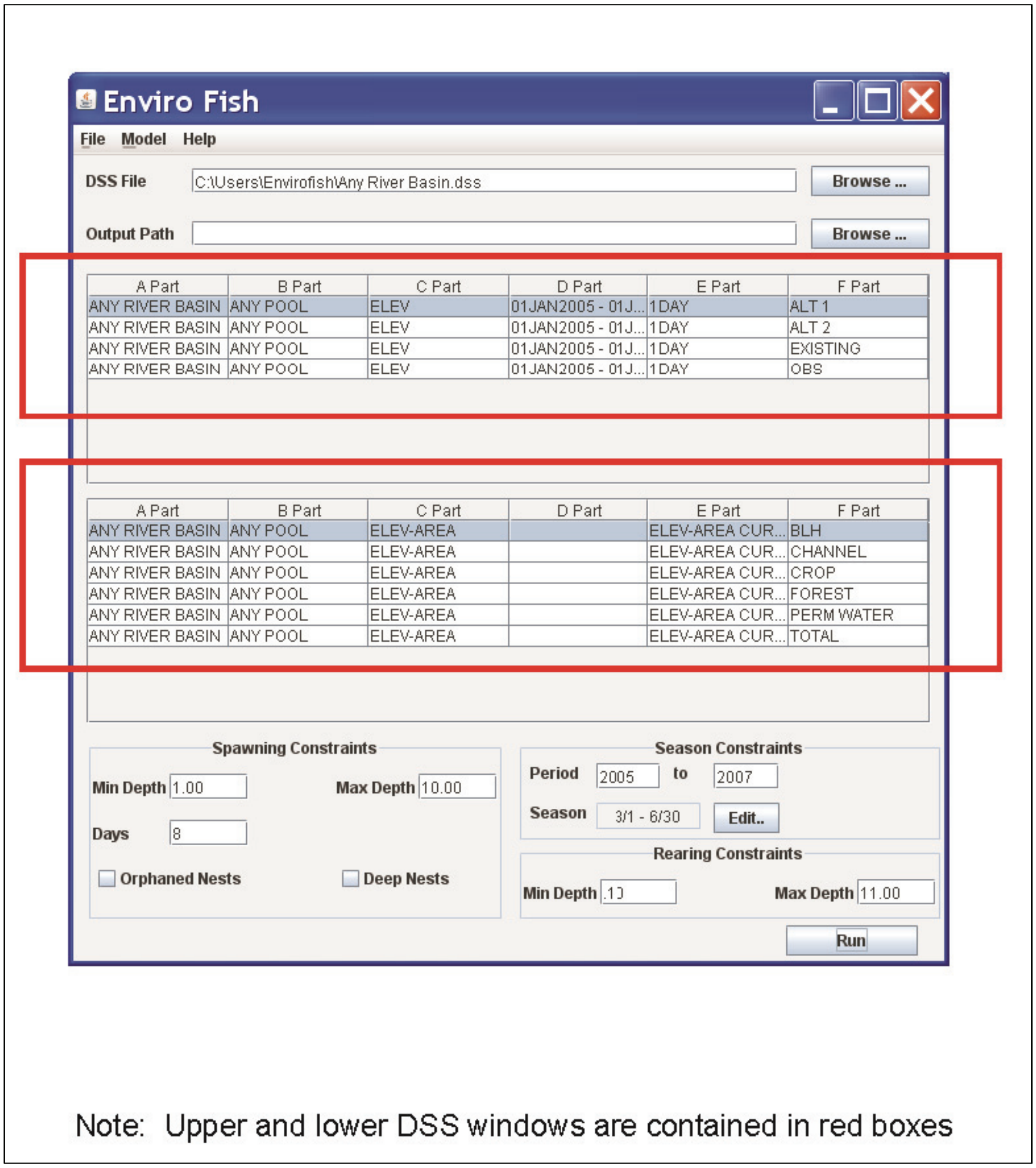


Figure 4-2. EnviroFish Main Screen, Upper and Lower DSS Windows.

Input Steps

From the EnviroFish main screen, shown in Figure 4-1, the following four input steps are required (data may be entered or loaded in any order):

1. Open the DSS file containing the elevation and elevation-area data, either using the **Browse** button in the upper right corner of the EnviroFish main screen or by selecting **Open** from the **File** pull down menu in the upper left corner of the EnviroFish main screen. Click to select the desired elevation vs. area path.

(Note that DSS file C Part pathnames must be identical to those found under the **Preferences** tab from the **File** pull down menu. The default C Part pathnames are **ELEV** and **ELEV-AREA** for the elevation and elevation-area data, respectively. If the DSS file contains different C Part pathnames, the **Preferences** tab can be used to change the C Part pathnames to match the DSS file C Part pathnames, or HEC-DSSvue must be used to change the DSS file C Part pathnames to match the default EnviroFish C Part pathnames. Pathname parts associated with elevation data will appear in the upper DSS EnviroFish window and those associated with elevation-area data will appear in the lower DSS EnviroFish window on the EnviroFish main screen when data has been successfully retrieved. See Figure 4-2.)

2. Set the habitat constraints on the EnviroFish main screen. See Figure 4-3 for the location of habitat constraint windows on the EnviroFish main screen. A description of the EnviroFish habitat constraint variables is provided below in the Input Description section.
3. From the **Model** pull down menu in the upper left corner of the EnviroFish main screen, select **Calc Summary** and/or **Calc Daily**. **Calc Summary** (*.evf file), which lists seasonal and analysis period summaries, and **Calc Daily** (*.txt file), which lists daily results for the entire analysis period, can be saved in *.txt, *.csv, and *.xls (Excel) formats.
4. An output path can be specified from the **Browse** button, located opposite from **Output Path** on the EnviroFish main screen. Upon execution of the EnviroFish program, the *.evf file generated from the **Calc Summary** option is copied to the specified output path.

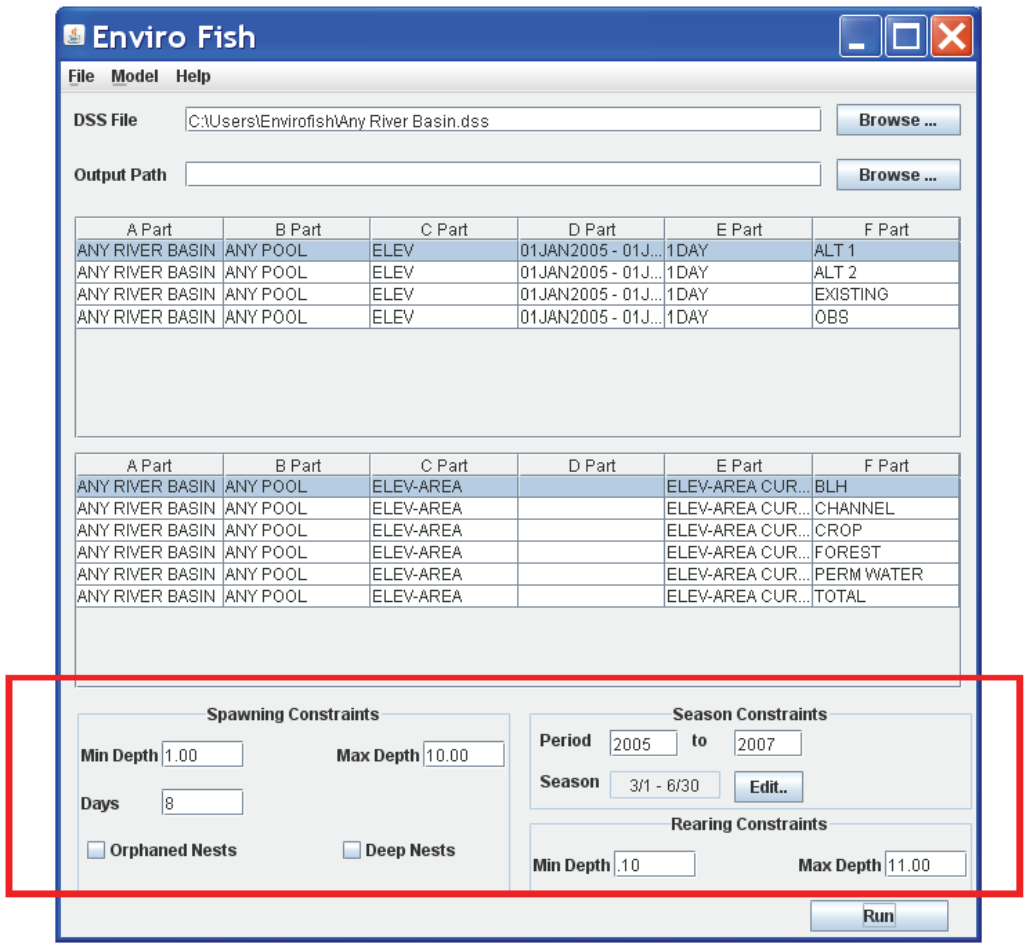
Input Description

The defined and described terms highlighted in bold below appear on the main screen of EnviroFish as guides for entering input and setting constraints.

Rearing. The larval stage in the life-cycle of a fish from hatching to juvenile.

Rearing Constraints. The minimum and maximum depths for restricted rearing.

Max Depth, i.e. Maximum Depth. The vertical distance below the water surface that establishes the lower boundary for each day.



Note: Habitat constraints are contained in red box

Figure 4-3. EnviroFish Main Screen, Habitat Constraints.

Min Depth, i.e. Minimum Depth. The vertical distance below the water surface that establishes the upper boundary for each day.

Season Constraints. Calculation limits for spawning.

Period. The beginning and ending years for spawning calculations.

Season. The beginning and ending calendar dates for spawning calculations for the period selected. Note that a spawning constraint duration that is greater than one day will include information that extends beyond the ending calendar date.

Spawning. The stage in the life-cycle of a fish that includes nest construction, egg deposition, incubation, and hatching.

Spawning Constraints. Time and depth requirements for spawning.

Days. Spawning duration in days.

Deep Nests. If this box is checked, it indicates that eggs deposited near the maximum spawning depth on Day 1 survive during a rising river stage. An unchecked box is the default setting, indicating that any departure from the allowable user-defined depth and duration criteria will not be counted.

Max Depth, i.e. Maximum Depth. The maximum vertical distance below the water surface that a fish can or will deposit eggs.

Min Depth, i.e. Minimum Depth. The minimum vertical distance below the water surface that a fish can or will deposit eggs.

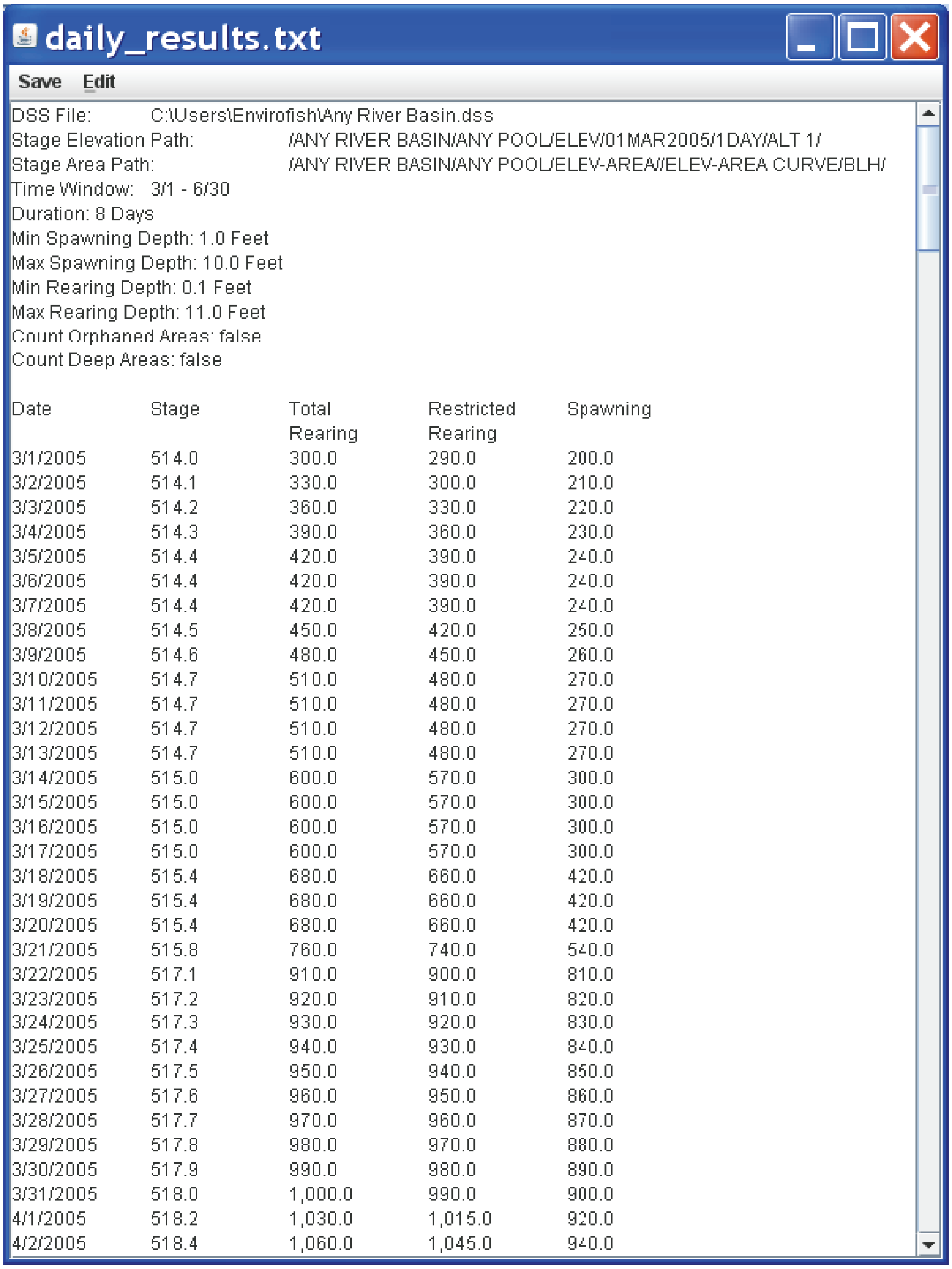
Orphaned Nests. If this box is checked, it indicates that eggs deposited near the minimum spawning depth on Day 1 survive during a falling river stage until exposed to air. An unchecked box is the default setting, indicating that any departure from the allowable user-defined depth and duration criteria will not be counted.

Initiating a Program Run

To initiate a program run, after completing the input steps, place the cursor of the mouse over the **Run** button located in the lower right corner of the EnviroFish main screen (see Figure 4-2) and press the left button on the mouse. The EnviroFish computer program will execute and the output file type(s) selected will be available for viewing on the computer Desktop.

Viewing Output

EnviroFish is capable of producing two output files—a daily results file and a summary file. Each output represents a single EnviroFish run of elevation and elevation-area data. Screen shots of example daily results and summary files are provided in Figure 4-4 and Figure 4-5, respectively. The output shown in the two figures is based on the input selections shown in Figure 4-2.


daily_results.txt

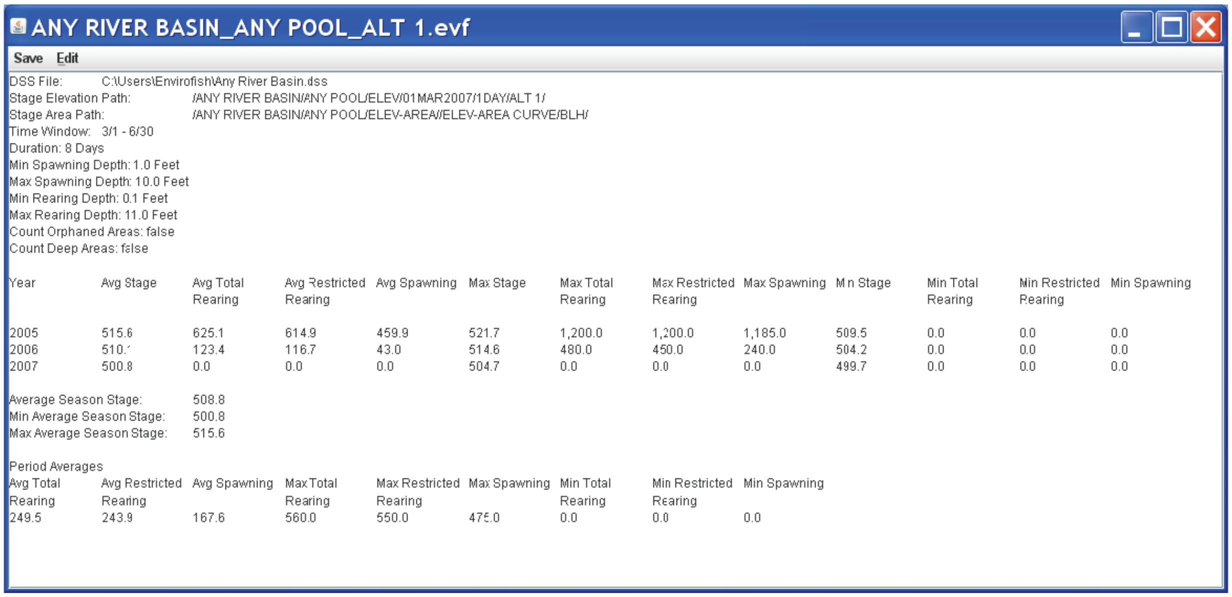
Save Edit

DSS File: C:\Users\Envirofish\Any River Basin.dss
Stage Elevation Path: /ANY RIVER BASIN/ANY POOL/ELEV/01MAR2005/1DAY/ALT 1/
Stage Area Path: /ANY RIVER BASIN/ANY POOL/ELEV-AREA//ELEV-AREA CURVE/BLH/
Time Window: 3/1 - 6/30
Duration: 8 Days
Min Spawning Depth: 1.0 Feet
Max Spawning Depth: 10.0 Feet
Min Rearing Depth: 0.1 Feet
Max Rearing Depth: 11.0 Feet
Count Orphaned Areas: false
Count Deep Areas: false

Date	Stage	Total Rearing	Restricted Rearing	Spawning
3/1/2005	514.0	300.0	290.0	200.0
3/2/2005	514.1	330.0	300.0	210.0
3/3/2005	514.2	360.0	330.0	220.0
3/4/2005	514.3	390.0	360.0	230.0
3/5/2005	514.4	420.0	390.0	240.0
3/6/2005	514.4	420.0	390.0	240.0
3/7/2005	514.4	420.0	390.0	240.0
3/8/2005	514.5	450.0	420.0	250.0
3/9/2005	514.6	480.0	450.0	260.0
3/10/2005	514.7	510.0	480.0	270.0
3/11/2005	514.7	510.0	480.0	270.0
3/12/2005	514.7	510.0	480.0	270.0
3/13/2005	514.7	510.0	480.0	270.0
3/14/2005	515.0	600.0	570.0	300.0
3/15/2005	515.0	600.0	570.0	300.0
3/16/2005	515.0	600.0	570.0	300.0
3/17/2005	515.0	600.0	570.0	300.0
3/18/2005	515.4	680.0	660.0	420.0
3/19/2005	515.4	680.0	660.0	420.0
3/20/2005	515.4	680.0	660.0	420.0
3/21/2005	515.8	760.0	740.0	540.0
3/22/2005	517.1	910.0	900.0	810.0
3/23/2005	517.2	920.0	910.0	820.0
3/24/2005	517.3	930.0	920.0	830.0
3/25/2005	517.4	940.0	930.0	840.0
3/26/2005	517.5	950.0	940.0	850.0
3/27/2005	517.6	960.0	950.0	860.0
3/28/2005	517.7	970.0	960.0	870.0
3/29/2005	517.8	980.0	970.0	880.0
3/30/2005	517.9	990.0	980.0	890.0
3/31/2005	518.0	1,000.0	990.0	900.0
4/1/2005	518.2	1,030.0	1,015.0	920.0
4/2/2005	518.4	1,060.0	1,045.0	940.0

Figure 4-4. EnviroFish Daily Results Example.

Both the daily and summary output files can be saved in *.txt, *.csv, and *.xls (Excel) formats. After an EnviroFish output file has been opened, place the cursor over the **Save** pull down menu in the upper left corner and press the left button on the mouse. Using a similar process, select the file type, select the output path location by using the browser, type in the desired filename, and finally select the **Save** button in the lower right corner of the window box.



ANY RIVER BASIN_ANY POOL_ALT 1.evf

Save Edit

DSS File: C:\Users\Envirofish\Any River Basin.dss
Stage Elevation Path: /ANY RIVER BASIN/ANY POOL/ELEV/01MAR2007/1DAY/ALT 1/
Stage Area Path: /ANY RIVER BASIN/ANY POOL/ELEV-AREA//ELEV-AREA CURVE/BLH/
Time Window: 3/1 - 6/30
Duration: 8 Days
Min Spawning Depth: 1.0 Feet
Max Spawning Depth: 10.0 Feet
Min Rearing Depth: 0.1 Feet
Max Rearing Depth: 11.0 Feet
Count Orphaned Areas: false
Count Deep Areas: false

Year	Avg Stage	Avg Total Rearing	Avg Restricted Rearing	Avg Spawning	Max Stage	Max Total Rearing	Max Restricted Rearing	Max Spawning	Min Stage	Min Total Rearing	Min Restricted Rearing	Min Spawning
2005	515.6	625.1	614.9	459.9	521.7	1,200.0	1,200.0	1,185.0	509.5	0.0	0.0	0.0
2006	510.1	123.4	116.7	43.0	514.6	480.0	450.0	240.0	504.2	0.0	0.0	0.0
2007	500.8	0.0	0.0	0.0	504.7	0.0	0.0	0.0	499.7	0.0	0.0	0.0

Average Season Stage: 508.8
Min Average Season Stage: 500.8
Max Average Season Stage: 515.6

Period Averages

Avg Total Rearing	Avg Restricted Rearing	Avg Spawning	Max Total Rearing	Max Restricted Rearing	Max Spawning	Min Total Rearing	Min Restricted Rearing	Min Spawning
249.5	243.9	167.6	560.0	550.0	475.0	0.0	0.0	0.0

Figure 4-5. EnviroFish Summary Results Example.

Output Description

The defined and described terms highlighted in bold below appear in the EnviroFish daily and summary output files. Daily results are listed first. Summary results are listed second.

1. Daily results--this output file lists daily results for the entire analysis period:

   Date. The month/day/year corresponding to each day's results.

   Restricted Rearing. The amount of land area confined by the minimum and maximum rearing depths.

   Spawning. The amount of land area limited by the minimum and maximum spawning depths, spawning duration, and orphaned and deep nest selections.

   Stage. The daily stage (referred to as elevation in this *User'sManual*) utilized for spawning and rearing calculations usually associated with an alternative.

   Stage Area Curves. A tabulation of the stage area curve (referred to as elevation-area data in this *User's Manual*) utilized in rearing and spawning calculations obtained from the DSS stage area file. The area 1 column consists of the land use (e.g., bottomland hardwoods) area input values, each of which defines the total amount of area at and below a corresponding stage or elevation. The stage column consists of the stage or elevation input values that correspond to the land use area input values.

Total Rearing. The amount of land area below the water surface.

2. Summary results--this file summarizes results for the entire analysis period; descriptions below are divided into (A) a seasonal sub-list and (B) an analysis period sub-list:

    a. Output that provides summary data for each season (year) independently.

    Avg Restricted Rearing, i.e., Average Restricted Rearing. Arithmetic mean daily restricted rearing value.

    Avg Spawning, i.e., Average Spawning. Arithmetic mean daily spawning value.

    Avg Stage, i.e., Average stage. Arithmetic mean daily stage.

    Avg Total Rearing, i.e., Average Total Rearing. Arithmetic mean daily total rearing value.

    Min Restricted Rearing, i.e., Minimum Restricted Rearing. Lowest daily restricted rearing value.

    Min Spawning, i.e., Minimum Spawning. Lowest daily spawning value.

    Min Stage, i.e., Minimum Stage. Lowest daily stage.

    Min Total Rearing, i.e., Minimum Total Rearing. Lowest daily total rearing value.

    Max Restricted Rearing, i.e., Maximum Restricted Rearing. Highest daily restricted rearing value.

Max Spawning, i.e., Maximum Spawning. Highest daily spawning value.

Max Stage, i.e., Maximum Stage. Highest daily stage.

Max Total Rearing, i.e., Maximum Total Rearing. Highest daily total rearing value.

Year. The year corresponding to each season's results.

b. Overall Summary Results. Output that provides summary data for the entire analysis period.

Average Season Stage. Arithmetic mean daily stage.

Avg Restricted Rearing, i.e., Average Restricted Rearing. Arithmetic mean daily restricted rearing value.

Avg Spawning, i.e., Average Spawning. Arithmetic mean daily spawning value.

Avg Total Rearing, i.e., Average Total Rearing. Arithmetic mean daily total rearing value.

Max Average Season Stage, i.e., Maximum Average Season Stage. Highest average season stage value.

Max Restricted Rearing, i.e., Maximum Restricted Rearing. Arithmetic mean of the highest daily restricted rearing values in each season.

Max Spawning, i.e., Maximum Spawning. Arithmetic mean of the highest daily spawning values in each season.

Max Total Rearing, i.e., Maximum Total Rearing. Arithmetic mean of the highest daily total rearing values in each season.

Min Average Season Stage, i.e., Minimum Average Season Stage. Lowest average season stage value.

Min Restricted Rearing, i.e., Minimum Restricted Rearing. Arithmetic mean of the lowest daily restricted rearing values in each season.

Min Spawning, i.e., Minimum Spawning. Arithmetic mean of the lowest daily spawning values in each season.

Min Total Rearing, i.e., Minimum Total Rearing. Arithmetic mean of the lowest daily total rearing values in each season.

5 Application Considerations

This chapter addresses five considerations that are likely to arise in applying the EnviroFish approach to typical projects: multiple spawning seasons, project alternatives, mitigation, water surface elevation input, and pools and flowlines.

Multiple Spawning Seasons

Although the discussion and the example problem in this *User's Manual* are limited to consideration of a single spawning season, the EnviroFish approach can be used to analyze multiple spawning seasons. To analyze multiple spawning seasons with the EnviroFish software, the spawning seasons are analyzed in separate program runs.

Project Alternatives

If enough data are available, or may be synthesized, the EnviroFish approach can be applied to a wide range of project alternatives, including existing conditions, future without project conditions, particular project alternatives, and pristine conditions.

Mitigation

If project impacts are to be mitigated within the project landscape, the EnviroFish approach may be applied to the mitigation area itself, to evaluate the value of the mitigation as affected by project-induced changes in hydrology and hydraulics.

Water surface elevation input

The EnviroFish approach uses one water surface elevation value to characterize inundation over a 24 hour period for the landscape being analyzed. Missing water surface elevation data within the spawning season is not permitted in an EnviroFish analysis. Typically, available raw gage data has missing data and is not suitable as direct input into EnviroFish. Moreover, the use of EnviroFish for analyzing project alternatives may require the synthesis of water surface elevation input. Issues related to the development of water surface elevation input for EnviroFish include:

1. choice of stage versus elevation format;

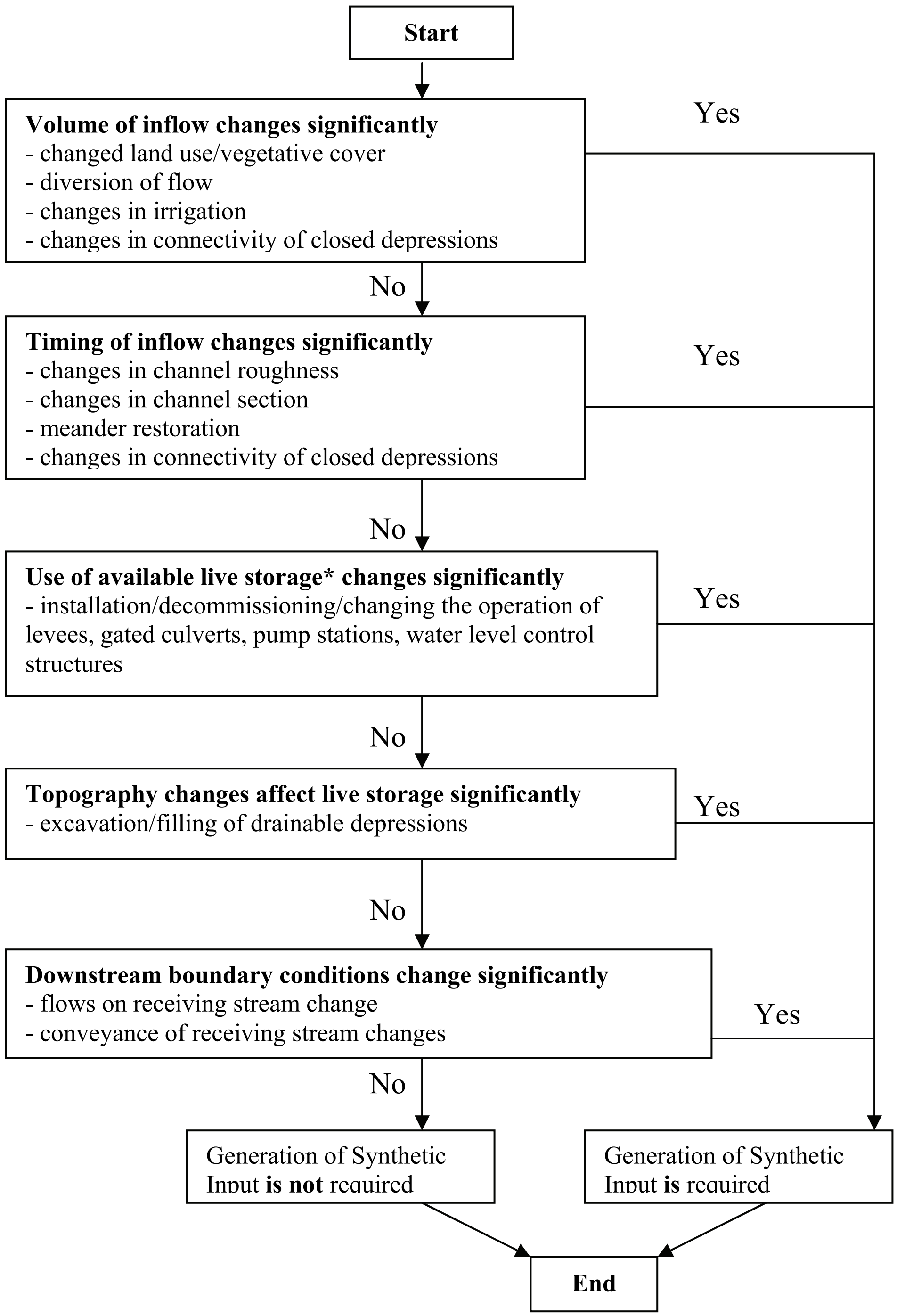
2. selection of a clock time;
3. treatment of missing historical (gage) data;
4. generation of synthetic data; and
5. analysis period.

The format of historical gage data as stages or as elevations is not an issue, except for the requirement that the water surface and the topography be based on the same datum, since the differences between water surface and land surface elevations are the depths used in analysis. Since topographic data for the site will almost certainly be based on a datum related to sea level, and the conversion of stages of arbitrary datum to sea level elevations is very easy to accomplish, it is usually advisable to adopt an elevation format for water surface elevations.

Clock time for daily water surface elevation input is arbitrary, but should be held consistent throughout the period of record, if possible. For example, consider an EnviroFish analysis that will be based on a period of gage record that begins with a subset of years during which the gage was a staff gage read by eye once a day at 0800 hours, while during the remaining years in the period of record stages were collected mechanically on the hour. Suppose further that the 0800 readings are the daily stages that have been published in annual gage reports throughout the entire period of record. The selection of the 0800 stages for the entire period of record is not only the easiest approach, but also the approach that stakeholders will prefer as they compare EnviroFish output to published stage reports.

Missing data is not permitted in an EnviroFish analysis. Historical daily gage data should be checked for missing data prior to input to EnviroFish, and estimates of elevations should be entered for those dates on which data is missing. It is important to inform stakeholders about the flaws that are to be expected in historical data and to point out the necessity for interpretation of data in preparation of input to EnviroFish.

The EnviroFish approach may necessitate the synthesizing of water surface elevation input. Some project sites have no historic gage data. For some project sites the alternatives to be characterized are so unlike existing conditions that any available gage data is not usable for those alternatives. Situations that would likely require the synthesizing of water surface elevations include the installation of levees, gated culverts, water level control structures, pump stations, and alterations in the operation of existing facilities. The flowchart shown in Figure 5-1 illustrates how changes in volume of inflow, timing of inflow, use of live storage, topography, and downstream boundary conditions can make it necessary to synthesize water surface elevations for a project alternative.



* The volume of water stored permanently in a depression is *dead storage*, since it does not affect routing--only volumes that can alternately store and release water affect routing computations and are referred to as *live storage*.

Figure 5-1. Flowchart of Alternative Changes Requiring the Generation of Synthetic Water Surface Elevation Input for EnviroFish.

Typically, water surface elevation input is synthesized by first using hydrologic techniques to estimate flows and hydraulic techniques to determine the resultant water surface elevations. In many cases, the hydrologic and hydraulic techniques are combined in a single computer program, because each day is a time step requiring a complete solution before the following day can be analyzed. Although EnviroFish only uses the dates within the spawning season, continuous hydrologic and hydraulic simulation must be performed on all days of the year for every year in the analysis period.

Unlike flood damage reduction studies, which emphasize the characterization of large, rare floods, the EnviroFish approach can emphasize the more frequent floods that maintain baseline populations of fish throughout their comparatively short lives. For this reason, the EnviroFish analysis period need not be as extensive as that to support flood damage reduction studies, although a long analysis period is certainly an advantage to reveal the effects of hydrologic variability. In all hydrologic and hydraulic modeling, there is uncertainty concerning the magnitude of computed data; the shorter the analysis period, the greater the uncertainty. However, the strength of the EnviroFish approach is its utility in characterizing the relative differences between project alternatives — as an aid in making decisions — despite uncertainty regarding water surface elevations. For many projects, an analysis period of 20 years should be sufficient to draw reliable conclusions from an EnviroFish analysis.

Pools and Flowlines

The EnviroFish approach assumes that although water surface elevations change from one day to the next, the water surfaces remain parallel to each other. Parallel water surfaces over time permit correct computation of the depths used to evaluate spawning and rearing. Level pools satisfy the parallel water surface assumption. In general, a stream flowline does not satisfy the parallel water surface assumption. Therefore, the application of EnviroFish to flowing streams necessitates the use of a suitable technique to minimize error.

Pooled water has a level surface. Pooled water sites may include man-made reservoirs, borrow pits, natural depressions, and sump areas on the land side of gated culverts or pump stations. Figure 5-2 shows, in plan and profile views, a sump area on the land side of a levee and culvert where water is ponded. Since the water surface is level, the edge of the pool

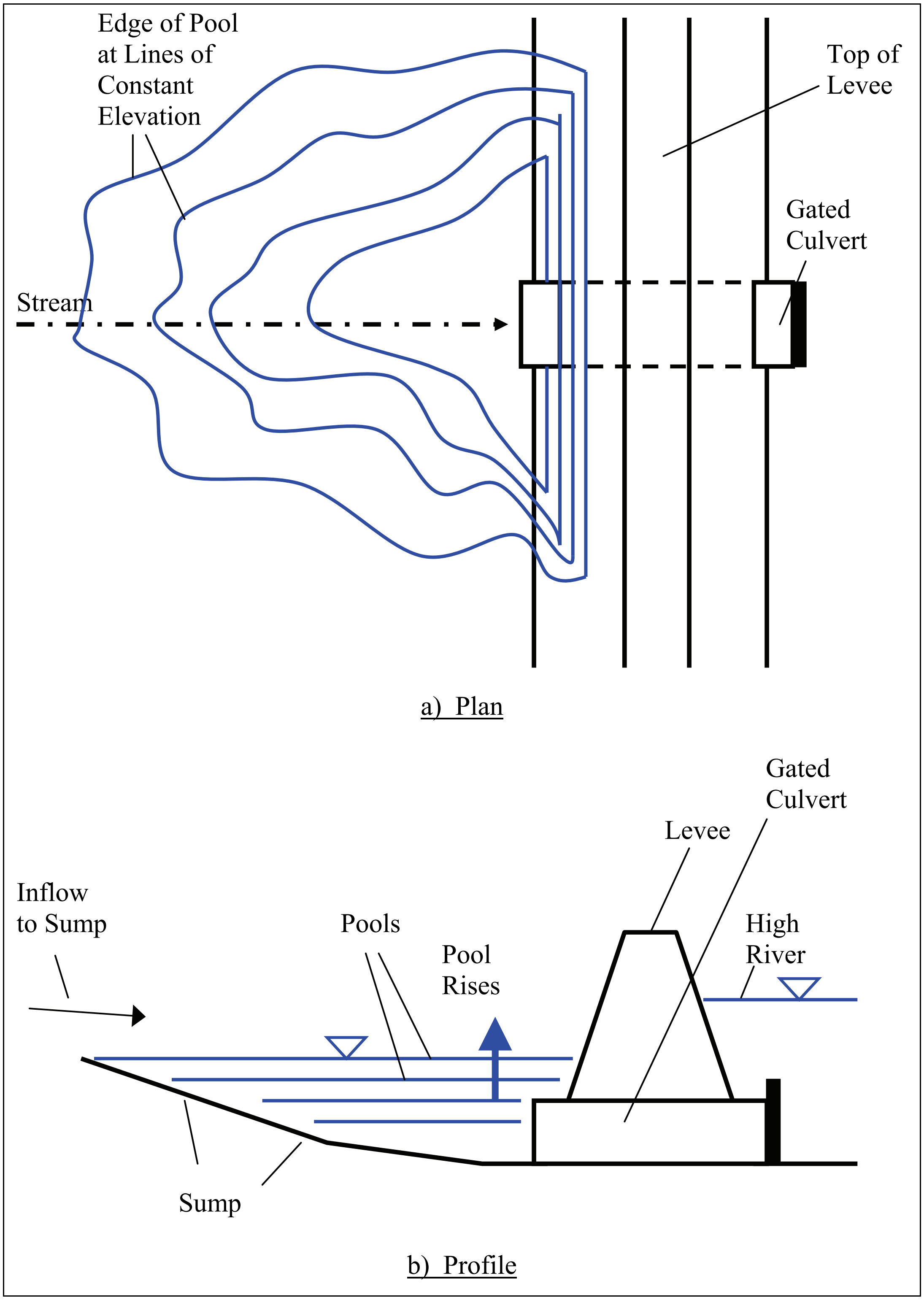


Figure 5-2. Profile of Pools at a Closed Culvert through a Levee.

coincides with a topographic contour. In this example, the culvert gate is shut against high river stages and the water surface on the land side rises as inflow to the sump occurs. In this situation, an elevation vs. area table accurately reflects the area of inundated land.

Even during a time when the river is low and the culvert gate is open, there may be cases where the pool upstream of the culvert is essentially level. For example, if the inflow rate is great enough, a pool may form at the sump. Also, if there is considerable area in the sump at, or below, the culvert invert elevation, a level pool may form in the sump even though water falls freely into the culvert inlet. Figure 5-3 shows the profile of a pool on the land side of an open culvert. In Figure 5-3 the lower two pools spill freely into the culvert, and the higher two pools submerge the culvert. The four pools are essentially level.

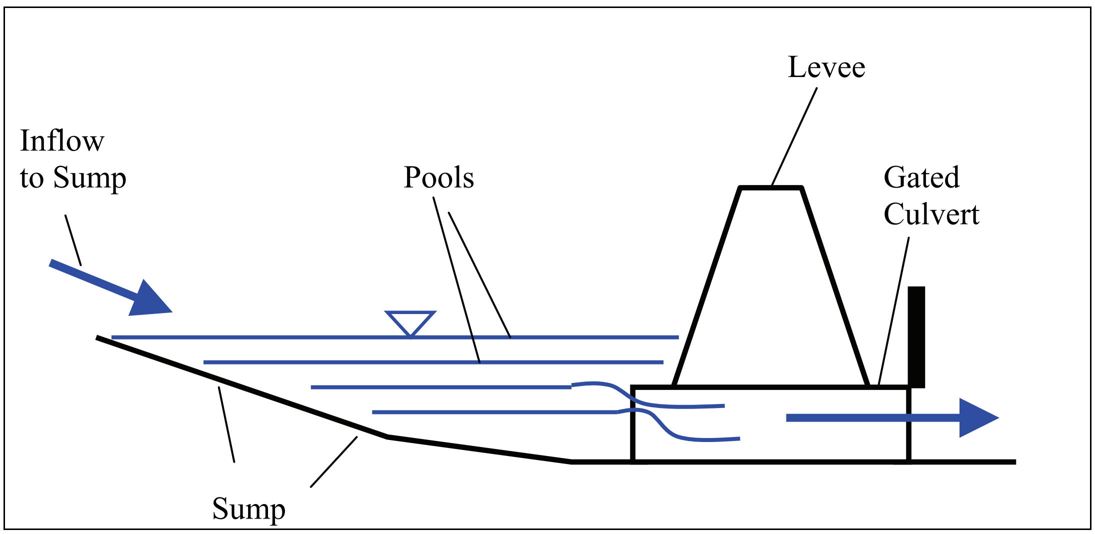


Figure 5-3. Profile of Approximately Level Pools at an Open Culvert through a Levee.

Level pools are simple cases. More complex situations for application of the EnviroFish approach involve flowing streams with water surface profiles, or flowlines, falling in the downstream direction. Flowlines can be inferred from the data gathered from a series of gages along a stream reach, or can be estimated using hydraulic computer models such as HEC-RAS. For a set of flowlines, the higher the elevation of the flowline, the greater the magnitude of flow. A set of flowlines along a river reach constitutes a family of curves, so named because adjacent flowlines closely resemble each other—much like the resemblance between two members of a family. In general, a family of flowlines is made up of individual flowlines that are not straight, not parallel to each other, and not parallel to the stream bed or to the valley floor.

The occurrence of strictly parallel flowlines along a stream is unlikely, but in a sufficiently short reach flowlines may occur that may be considered parallel within a margin of error. Figure 5-4 illustrates an idealized case of two flowlines, flowline 1 and flowline 2, that are parallel, although not parallel to the stream bed. The vertical distances at the downstream and upstream ends of the reach, $H_{d/s}$ and $H_{u/s}$, respectively, are equal. If flowline 1 occurs on a given day and flowline 2 occurs on the following day, then the EnviroFish assumption of parallel water surfaces from one day to the next is valid. Valley section views of the upstream and downstream ends of the valley reach are shown in Figure 5-5. The difficulty in applying EnviroFish to this situation is the requirement that the elevation vs. land area tables for each land use category must reflect sloping surfaces in the landscape, parallel to the flowlines. In an actual application, although flowlines that are closely spaced vertically may be nearly parallel, there is often an overall trend in flowline slope between the lowest flowlines that are confined to the channel and the highest flowlines that inundate the floodplain. Thus, a slope applicable to the channel may not apply to the floodplain. Furthermore, differences in alternatives may require the preparation of alternative-unique elevation vs. area tables for each land use category.

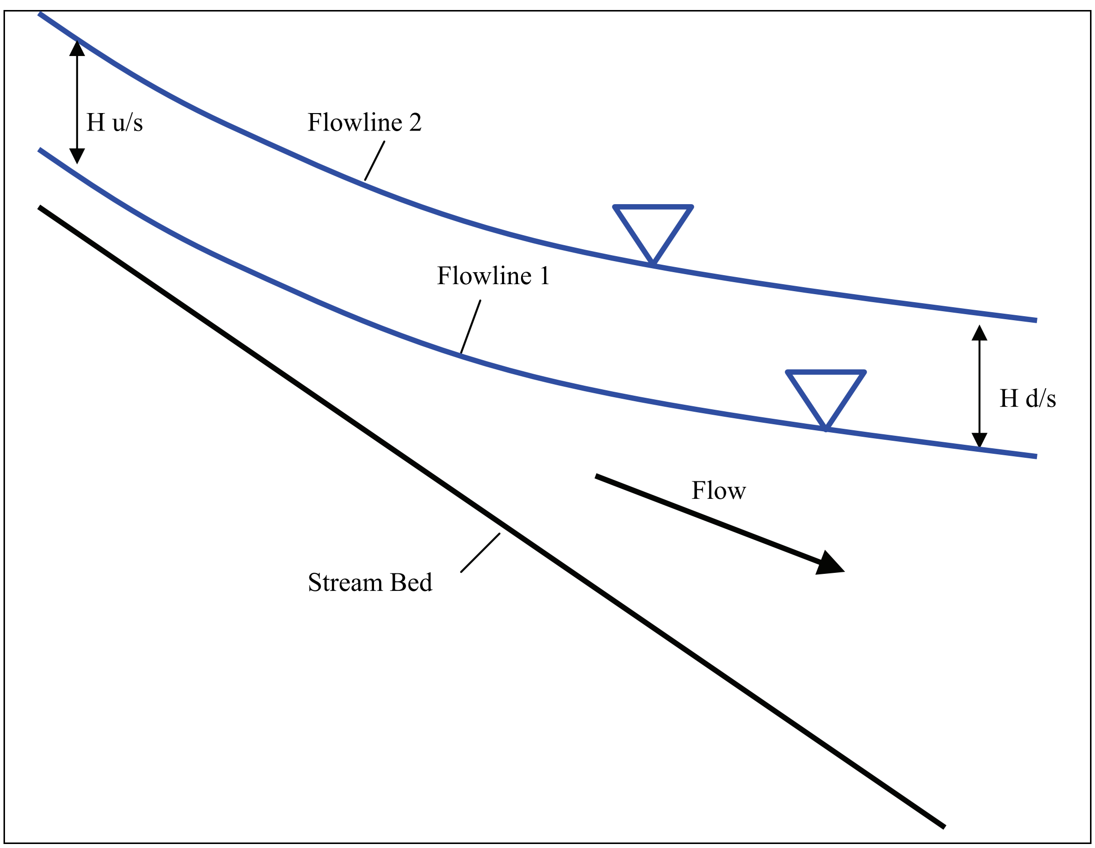


Figure 5-4. Profile of Parallel Flowlines in a Stream.

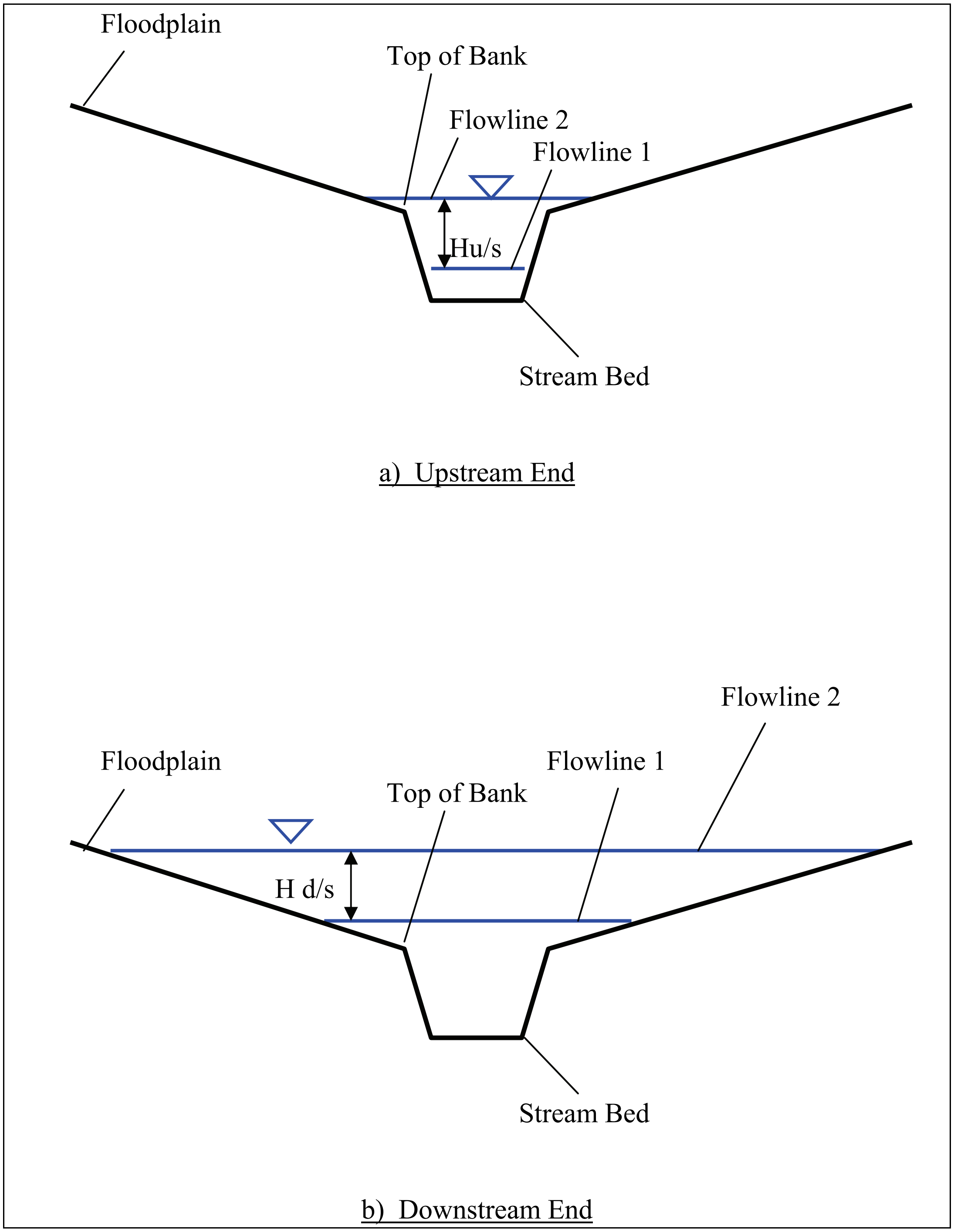


Figure 5-5. Valley Sections for Parallel Flowlines.

In the EnviroFish approach, greater difficulties arise with flowlines that are not parallel. As shown in the profile view of the stream reach in Figure 5-6, if the vertical distance, $H_{d/s}$, between flowline 1 and flowline 2 at the downstream end of the reach were 10 feet, the vertical distance, $H_{u/s}$, at the upstream end of the reach might only be 5 feet. If flowline 1 occurs on a

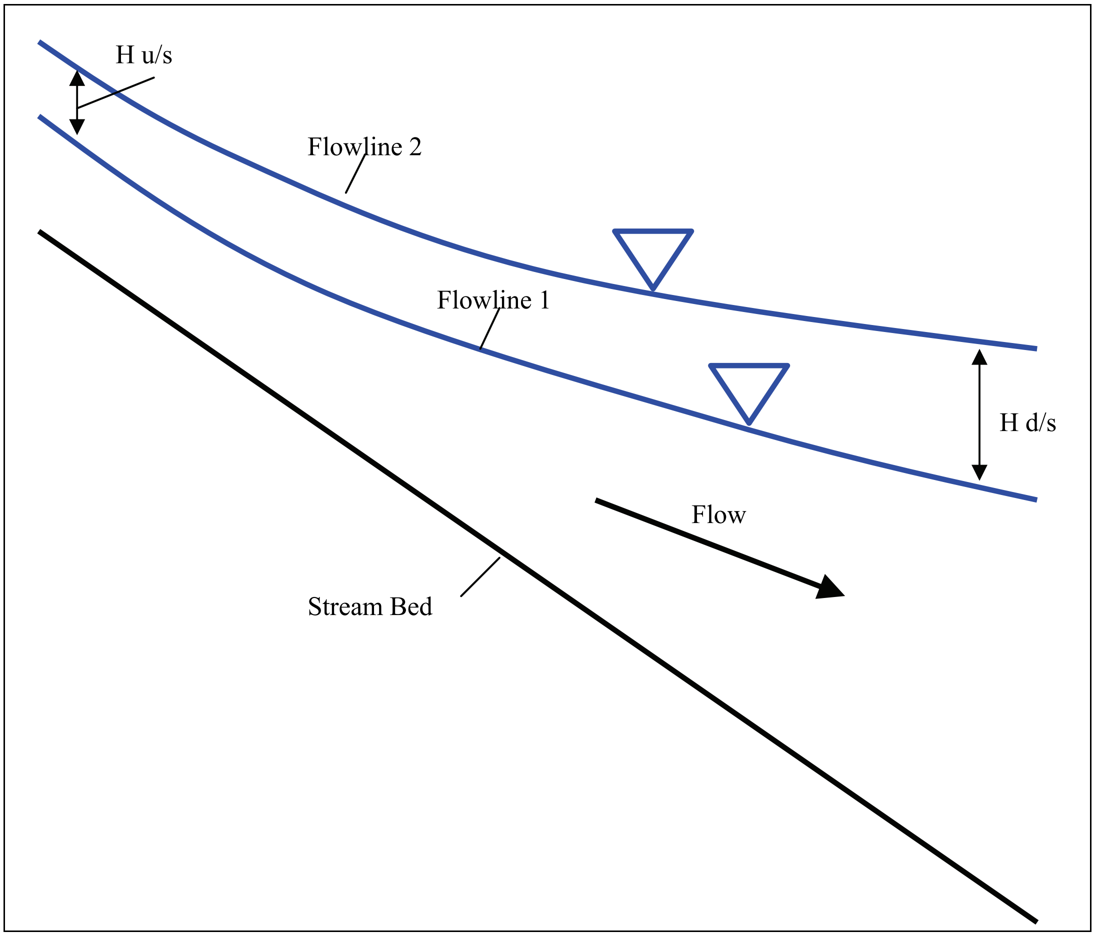


Figure 5-6. Profile of Non-Parallel Flowlines in a Stream.

given day and flowline 2 occurs on the following day, then the EnviroFish assumption of parallel water surfaces from one day to the next is not valid. Valley section views of the upstream and downstream ends of the valley reach are shown in Figure 5-7.

In view of such difficulties with non-parallel flowlines, perhaps the most practical approach is to divide the valley reach longitudinally into short segments. As shown in the profile view of a valley reach in Figure 5-8, the segments are short enough that the fall in the water surface from the upstream end to the downstream end is moderate and the water surface may be considered level within a margin of error. Daily water surface elevations are assigned to each segment and each segment is analyzed as a separate EnviroFish problem. Such an approach is laborious, but it can be taken to attain a specified degree of accuracy and makes use of conventional elevation vs. area tables that can be applied to all alternatives and can be readily understood by stakeholders.

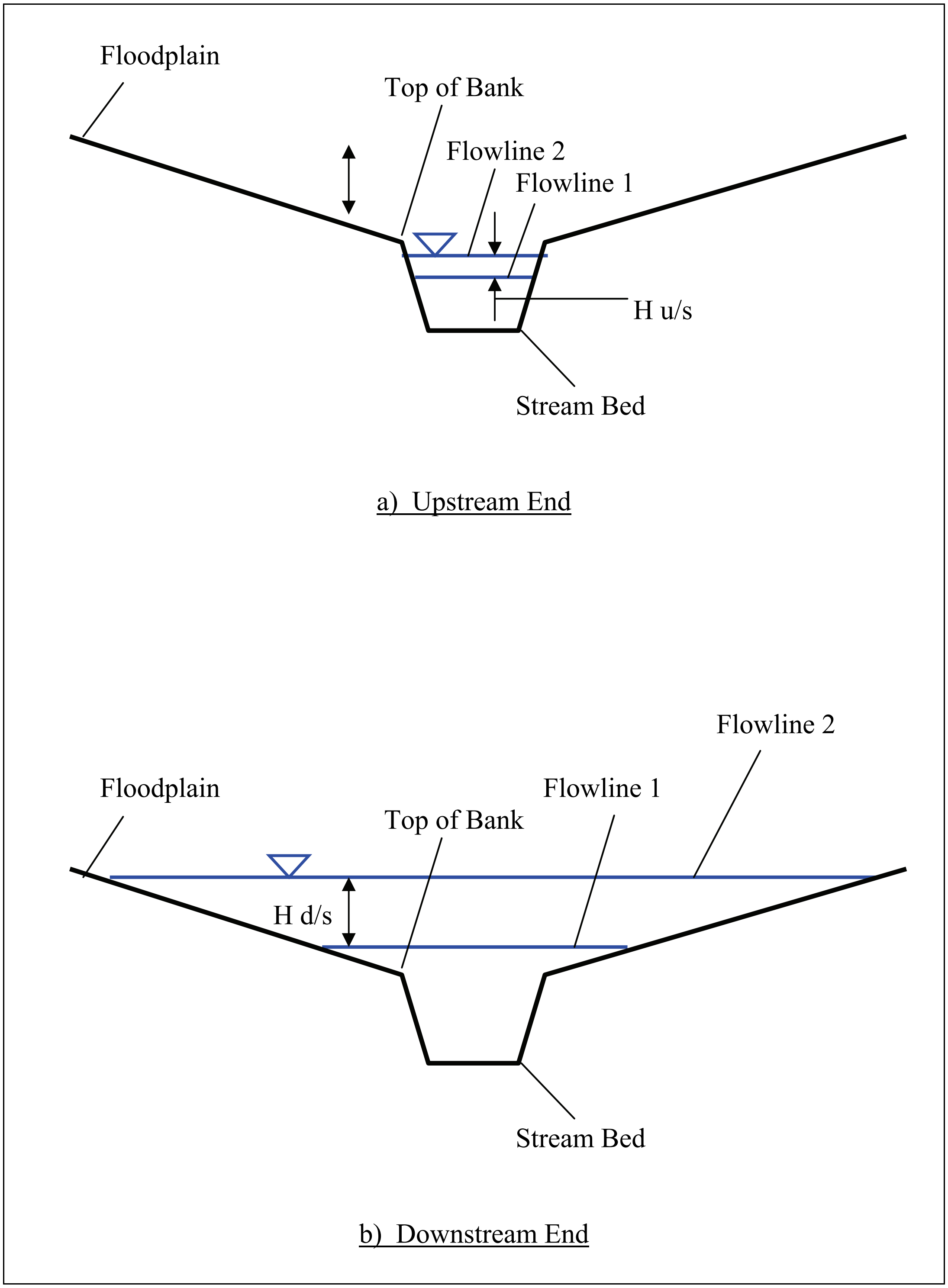


Figure 5-7. Valley Sections for Non-Parallel Flowlines.

Whatever technique is applied to dealing with pools and flowlines, cooperation between experienced hydraulic engineers, GIS personnel, and biologists is required to obtain a high quality product. Professional judgment, supported by iteration and sensitivity checks, is essential.

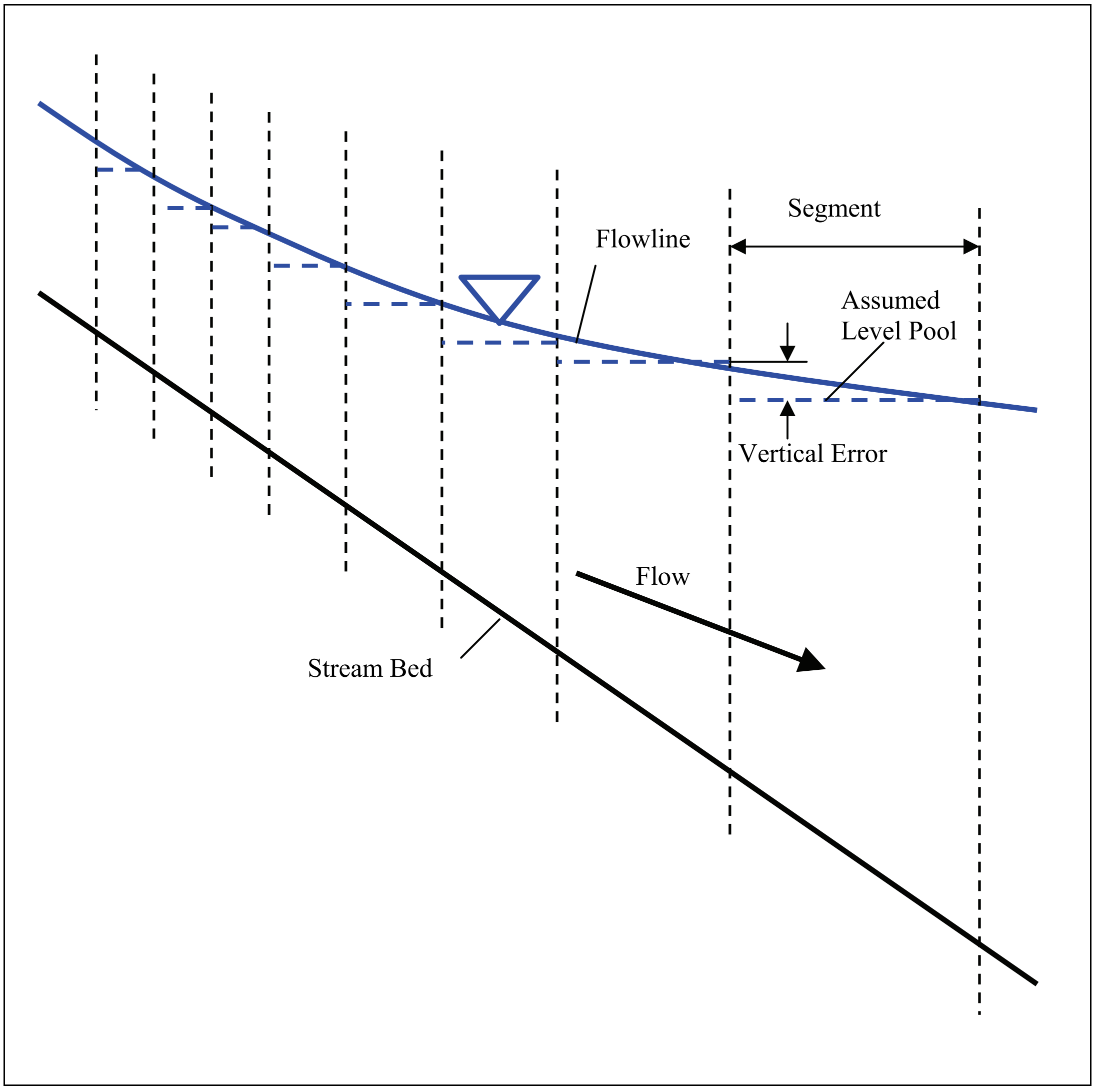


Figure 5-8. Profile of a Valley Reach Divided into Segments for Separate EnviroFish Analyses.

6 Example Problem

This chapter presents a simple example of using EnviroFish software. The example problem is based on a hypothetical landscape and hydrology. The landscape is an idealized surface of very simple geometry. Likewise, the water surface elevation input is idealized, exhibiting the least detail needed to illustrate the example. The example has been prepared in this way to emphasize the simple workings of the EnviroFish software itself, rather than the complexities of mapping and hydrology that may be encountered in an actual project. The EnviroFish input and output shown in Chapter 4 are taken from this example problem.

Setting

The example problem involves a flood damage reduction project, and the setting is a stream that is tributary to a larger river in an agricultural landscape. Both the scope of the flood damage reduction and the EnviroFish analysis are limited to the stream and its floodplain. Under existing conditions, there is no levee and no culvert. However, the levee and culvert are shown in all the site figures and are mentioned in the initial descriptions because they provide a downstream limit for the landscape to be analyzed. Two project alternatives are proposed. Alternative 1 consists of the installation of a levee and gated culvert. Alternative 2 is the same as Alternative 1, except a pump station is also included.

The project levee of Alternative 1 and Alternative 2 parallels the river and protects the floodplain of the stream from river flooding. A culvert through the levee allows the flow in the stream to join with the flow in the river whenever the culvert gate is open. The stream has a broad floodplain, which is subject to flooding from the stream in two situations. In the first situation, the river level is low and the culvert gate is open, but the flow in the stream is so great that flooding occurs. In the second situation, the culvert gate is shut against high river levels, and although the stream flow may be minimal, the floodplain eventually floods, simply due to the accumulation of headwater that cannot exit through the culvert. In this example, all flooding is treated as level pools.

As described in Chapter 4, the spawning season is March 1 through June 30. The spawning period is 8 days. The minimum and maximum allowable depths for spawning are 1.0 feet and 10.0 feet, respectively. The minimum and maximum allowable depths for restricted rearing are 0.1 feet and 11.0 feet, respectively. Both the "count orphaned areas" and "count deep areas" options are not checked, meaning that any departure from user-defined depth and duration criteria will not be counted.

Topography

The topography of the hypothetical site is designed to produce elevation contour outlines that are similar in shape and to facilitate calculations for elevation vs. area tables. The topography reflects existing conditions, and no changes in topography will occur for project alternatives.

As shown in a plan view of the landscape in Figure 6-1, the stream is straight and is perpendicular to the river levee, which is represented by a horizontal green line. The downstream end of the stream channel is at the levee culvert, represented as a red rectangle. The paired, parallel, vertical brown and red lines, symmetrical about the centerline of the stream, represent features of the channel, the floodplain, and the confining bluffs. These lines represent edges between sloping plane surfaces and are not level, but fall at a slope of 0.5 feet vertical per 1000 feet horizontal. (Referring to the section views in Figure 6.2 and the profile in Figure 6.3 should be helpful in following the description of these lines in plan view.) In Figure 6-1, the innermost pair of brown lines represent the corners of the stream channel bed. The pair of red lines represent the tops of the stream banks. The next pair of brown lines represent the toes of the confining bluffs. The left and right floodplains lie between the top of bank line and the toe of the bluff line. The outermost pair of lines are brown and represent the top lines of the bluffs. Having high bluffs along both edges of the landscape makes it easy to picture the floodwaters having a definite lateral limit. The total width of the left floodplain, channel topwidth, and right floodplain is 12,000 feet. The total width between the tops of the bluffs is 16,000 feet. The location where Section A-A and Section B-B cut across the channel and floodplain are shown by heavy black arrows. The distance between Section A-A and Section B-B is 50,000 feet. The dashed blue lines represent contour elevations at 505, 510, 515, 520, and 525 feet.

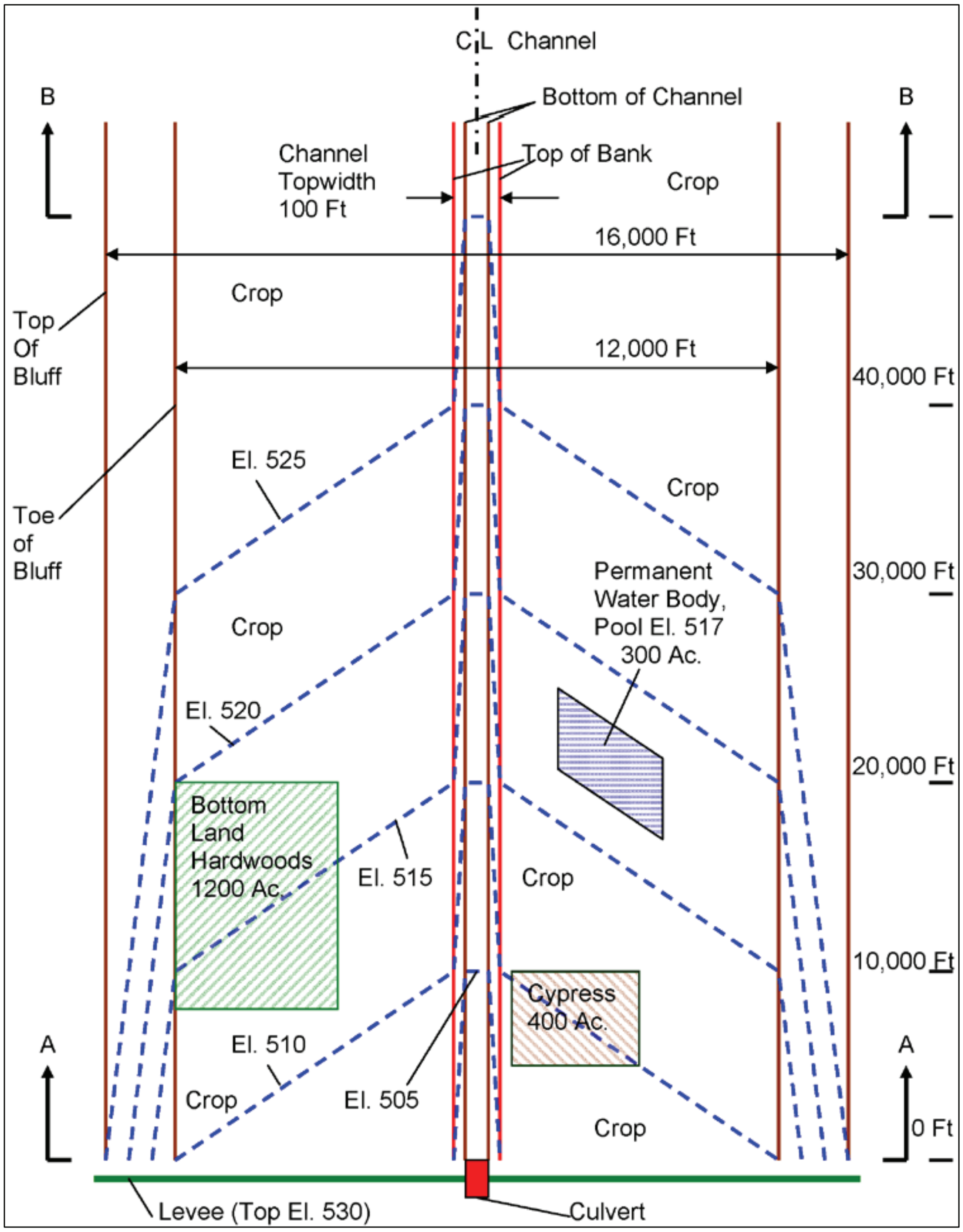


Figure 6-1. Plan View of Example Project Area.

Since flooding is being modeled as level pools, the contours are blue to emphasize that these contours are also flood outlines at these elevations. The shape of the contours can be understood by examining the contour segments for the 525 foot contour. The upstream-most segment of the contour is a horizontal line, which represents where the contour turns around in the bed of the stream. The segment is horizontal because the channel bed is level. Since the contour is symmetrical, it will suffice to examine only the branch of the contour on the right side of the figure. Proceeding down the page and downstream, the contour segment lies

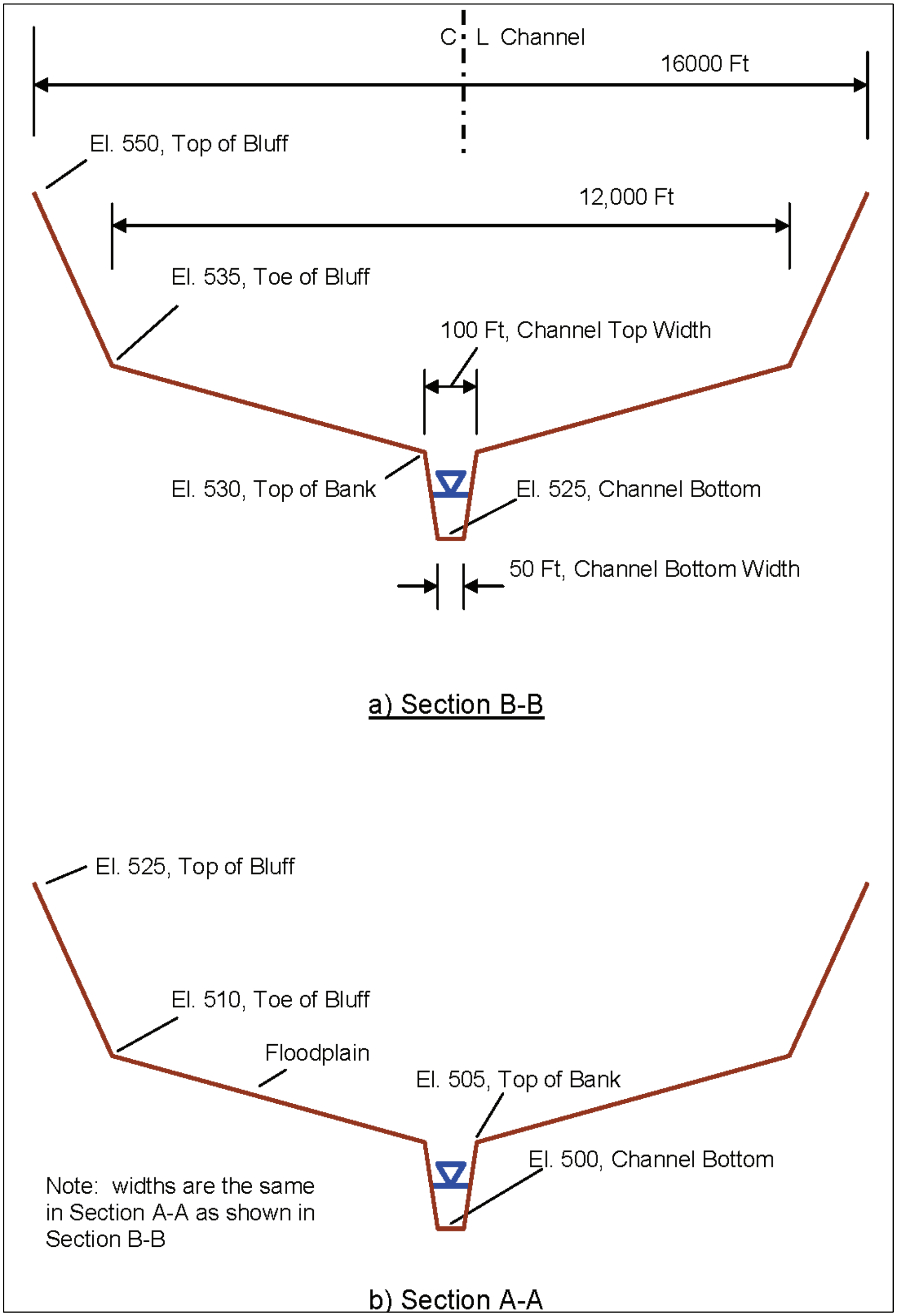


Figure 6-2. Sections of Example Project Area.

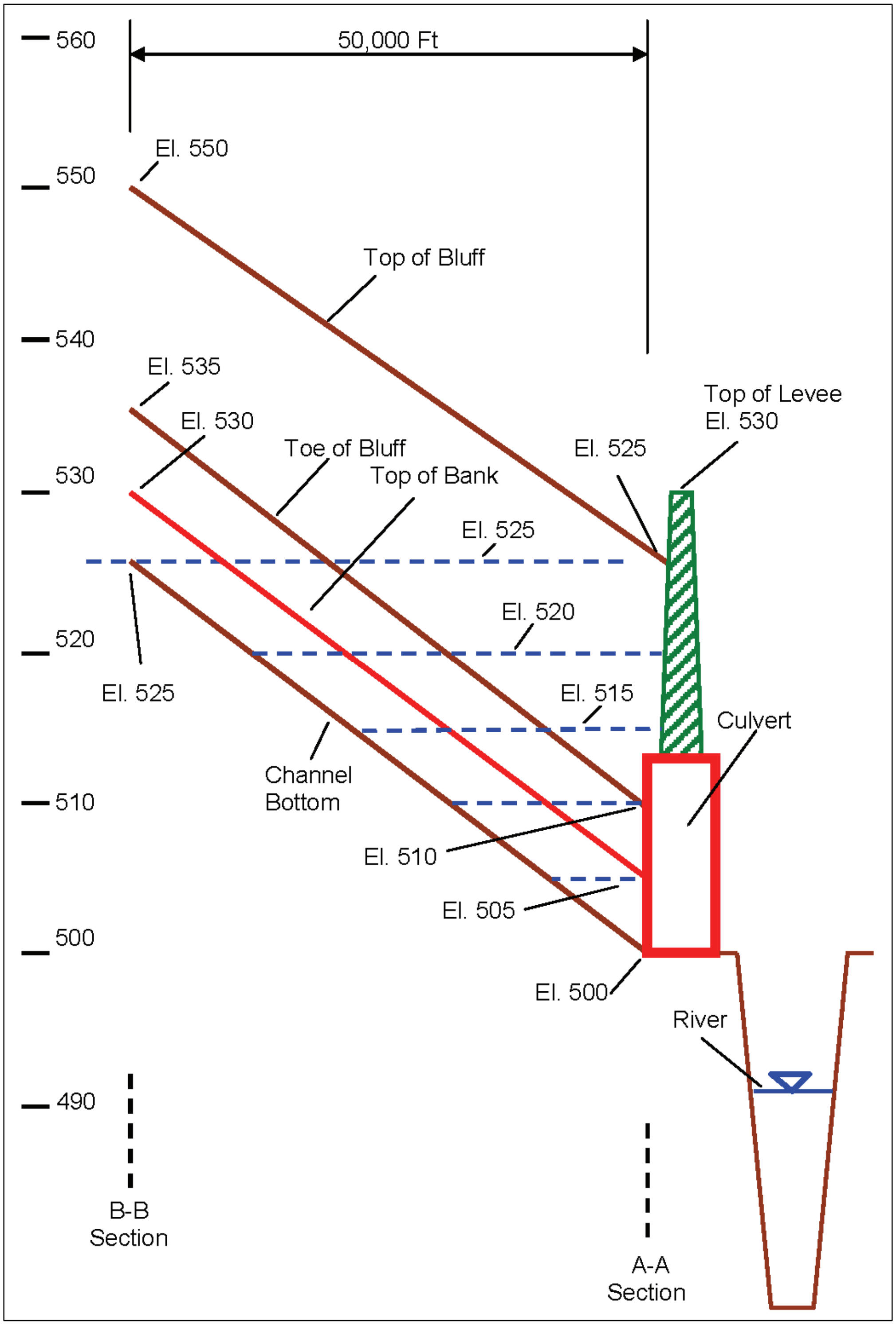


Figure 6-3. Profile View of Example Project Area.

within the channel to a distance of 40,000 feet from the levee, where it ends at the top of the channel bank. Another segment begins at the top of the bank and crosses the floodplain, ending at the toe of the bluff. A final segment begins at the toe of the bluff and ends at the top of the bluff at the levee. The contours at lower elevations are geometrically similar to the 525-foot contour, except that the outmost contour segments are progressively truncated for the lower elevations. Although the stream channel and floodplain have a definite and abrupt end at the levee, the upstream end of the landscape has purposely been made indefinite, because it is the upstream extent of the flooding that governs, and this length may vary from day to day.

Two section views of the landscape are shown in Figure 6-2. Section A-A is perpendicular to the stream channel and is located at the downstream end of the landscape at the culvert. Section B-B is also perpendicular to the stream channel and is located 50,000 feet upstream of Section A-A. The size and shape of the two sections are the same. The elevations of the channel bed for Section A-A and Section B-B are 500 feet and 525 feet, respectively. Therefore, Section B-B is an exact copy of Section A-A, but translated 25 feet higher. The bottom width of the stream channel is 50 feet and the channel topwidth is 100 feet. The left and right floodplains slope uniformly toward the channel at 0.84 feet vertical per 1000 feet horizontal. The left and right bluffs slope uniformly toward the channel at 7.5 feet vertical per 1000 feet horizontal.

A profile view of the landscape is shown in Figure 6-3. The profile cuts through the levee and the culvert, which are shown in green and red hatched lines, respectively. The top of the levee is at elevation 530 feet. The invert of the culvert is at elevation 500 feet. To the far right, the river is also shown in section. The parallel lines in brown and red, sloping downward to the right, represent features of the channel, the floodplain, and the confining bluffs. The bottom sloping brown line represents the stream channel bed. The sloping red line represents the top of the channel bank. The next higher sloping brown line represents the toe of the bluff. The highest brown line represents the top of the bluff. The locations where Section A-A and Section B-B are cut across the channel and floodplain are indicated by heavy dashed lines near the bottom of the figure. The distance between Section A-A and Section B-B is 50,000 feet. The sloping lines are parallel to each other, having a slope of 0.5 feet vertical per 1000 feet horizontal. The horizontal dashed blue lines are lines of constant elevation at 505, 510, 515, 520, and 525 feet. These horizontal blue lines correspond to the blue dashed contour lines in Figure 6-1. Examining the top dashed horizontal line, which represents elevation 525 feet, it is evident that the contour intersects the top of the bluff at the levee. Progressing left on the figure and upstream, it is also evident where the 525-foot contour intersects the toe of the bluff, the top of the channel, and the channel bed.

Land Use

A very simple example pattern of five land uses has been delineated in Figure 6-1, consisting of cropland, a cypress forest, a bottomland hardwood forest, and a single permanent waterbody. The cypress forest, delineated as a brown hatched rectangle, has an area of 400 acres and straddles the 510-foot contour. The bottom land hardwood forest (BLH), delineated as a green hatched rectangle, has an area of 1200 acres and straddles the 515-foot contour. The permanent waterbody, delineated as a blue hatched parallelogram, has an area of 300 acres lying between the 515-foot and 520-foot contours and has a surface elevation of 517 feet. The channel area, defined as all of the channel between left and right top of bank, has a rectangular shape in plan view and occupies 109.0 acres between the levee and a distance of 50,000 feet from the levee. All other land use is cropland.

A combined table of elevation vs. area for the five land uses is shown in Figure 6-4. The elevations range from 500 feet, which is the elevation of the stream channel bottom at the culvert, to 525 feet, which is the elevation of the stream channel bottom 50,000 feet upstream of the levee. The daily water surface elevations that will be input into EnviroFish are limited to this elevation range.

Examining the cypress forest area values in Figure 6-4, the highest elevation with a zero area of cypress forest is elevation 508 feet, which corresponds to the location of the bottom left corner of the rectangle, at approximately 508 feet. The lowest elevation having the maximum area of cypress forest, 400 acres, is elevation 512 feet, which corresponds to the location of the top right corner of the rectangle, at approximately 512 feet. Above elevation 512 feet, the values remain at 400 acres, emphasizing that the area values are cumulative rather than incremental.

Examining the bottomland hardwood forest area values in Figure 6-4, the highest elevation with a zero area of BLH forest is elevation 511 feet, which corresponds to the location of the bottom right corner of the rectangle, at approximately 511 feet. The lowest elevation having the maximum area of cypress forest, 1200 acres, is elevation 520 feet, which corresponds to the location of the top left corner of the rectangle, at 520 feet. Above elevation 520 feet the values remain at 1200 acres.

Elevation Feet	Area					
	Cypress Forest Acre	BLH Forest Acre	Permanent Water Body Acre	Channel Acre	Cropland Acre	Total Acre
500	0	0	0	0.0	0.0	0.0
501	0	0	0	2.5	0.0	2.5
502	0	0	0	5.5	0.0	5.5
503	0	0	0	9.0	0.0	9.0
504	0	0	0	12.9	0.0	12.9
505	0	0	0	17.2	0.0	17.2
506	0	0	0	21.8	54.6	76.4
507	0	0	0	26.4	218.5	244.9
508	0	0	0	31.0	491.7	522.7
509	50	0	0	36.6	823.2	909.8
510	200	0	0	40.2	1165.9	1406.1
511	350	0	0	44.7	1568.5	1963.2
512	400	50	0	49.3	2033.2	2532.5
513	400	200	0	53.9	2460.2	3114.1
514	400	300	0	58.5	2949.4	3707.9
515	400	600	0	63.1	3250.9	4314.0
516	400	800	0	67.7	3664.6	4932.3
517	400	900	0	72.3	4190.5	5562.8
518	400	1000	300	76.9	4428.7	6205.6
519	400	1150	300	81.5	4929.2	6860.7
520	400	1200	300	86.1	5541.8	7527.9
521	400	1200	300	90.6	6216.9	8207.5
522	400	1200	300	95.2	6904.0	8899.2
523	400	1200	300	99.8	7603.4	9603.2
524	400	1200	300	104.4	8315.1	10319.5
525	400	1200	300	109.0	9038.9	11048.0

Figure 6-4. Elevation vs. Area Table for Example Problem.

Examining the permanent waterbody area values in Figure 6-4, the highest elevation with a zero area of permanent water is elevation 517 feet, and the lowest elevation with the maximum area of 300 acres is at elevation 518 feet. Since the pool is level at elevation 517 feet, the area of the waterbody does not gradually increase with increasing elevation, as do land uses on sloping land. The shape of the waterbody was chosen as a parallelogram, so it would seem to fit neatly on contour between the contour lines of 515 feet and 520 feet. Since the resolution of the table is one foot, an arbitrary choice is made for the elevation at which to begin entering the area of the waterbody. The entries could properly begin at elevation 517 feet, rather than at 518 feet. For an actual project, tables can be prepared to finer increments, such as 0.1 feet, and waterbody elevations may also be recorded to 0.1 feet, minimizing error.

Examining the channel area values in Figure 6-4, the highest elevation with a zero area of channel is elevation 505 feet, which corresponds to the downstream end of the channel at top of bank elevation. The maximum area of 109.0 acres corresponds to elevation 525 feet, which is the elevation of the channel bottom 50,000 feet upstream of the levee. Since the channel has a fixed width and falls at a uniform slope, the area of the channel accumulates linearly with increasing elevation. The area values are shown to the nearest 0.1 acre, due to the small cumulative values calculated for the lower elevations.

Examining the cropland area values in Figure 6-4, the highest elevation with a zero area of cropland is elevation 505 feet, which corresponds to the downstream end of the channel at top of bank elevation. The maximum area of 9038.9 acres corresponds to elevation 525 feet, which is the elevation of the channel bottom 50,000 feet upstream of the levee. The area values for cropland were calculated by subtracting all other land uses from the total landscape area.

The values in the rightmost column of the table in Figure 6-4 are the total area of the landscape at a given elevation and were calculated using a spreadsheet. The total values are not used as input to EnviroFish, since they reflect a mixture of land uses, but are only provided as an aid in understanding the example.

The elevation vs. area relationships for the five land uses and the total area are plotted in Figure 6-5. The plot emphasizes that the area in the channel is negligible below elevation 505 feet. The plot also emphasizes how the areas of forest and permanent water comprise only a small fraction of the total landscape, which is mostly cropland.

The EnviroFish computations for the example conclude with values of average daily flooded acres. To complete the example by calculating habitat quantities in Habitat Units, hypothetical habitat suitability indices for the five land uses are listed in Table 6-1. These values were selected simply to illustrate the use of EnviroFish and should not be interpreted as being necessarily applicable to a real project landscape.

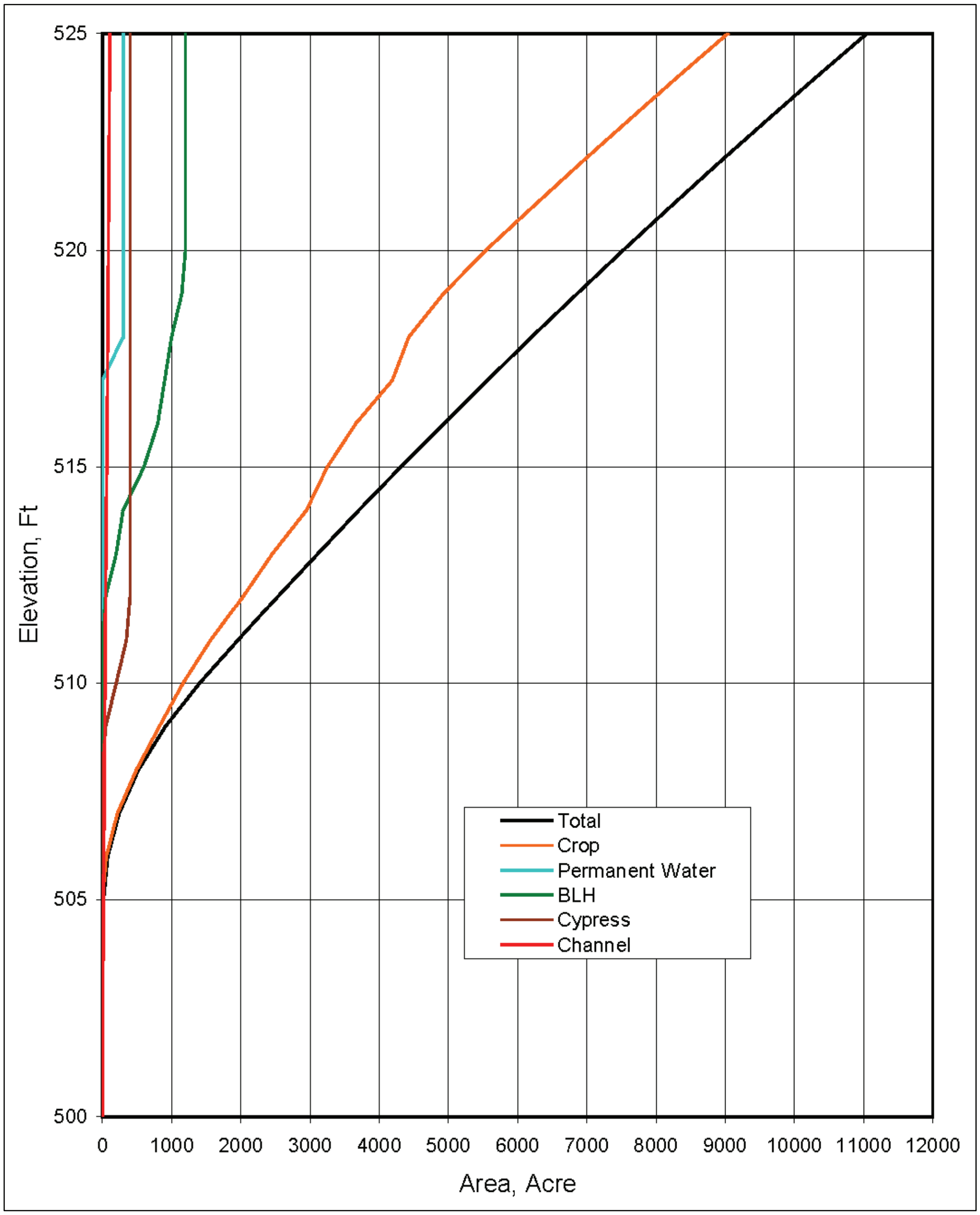


Figure 6-5. Elevation vs. Area for the Land Uses in the Example Problem.

Table 6-1. Habitat Suitability Indices for Example Problem.

Land Use	Habitat Suitability Index
Cypress Forest – small wetlands	0.9
BLH Forest	1.0
Large Floodplain Waterbody	0.8
Channel	0.5
Agricultural Cropland	0.2

Water Surface Elevations

Hypothetical daily water surface elevations have been developed for the three consecutive years of 2005 through 2007. The year 2005 is a very wet year, with severe flooding. The year 2006 features a normal range of water levels. The year 2007 is a very dry year, with no flooding.

Since the example is based on a spawning season of March 1 through June 30, the water levels input for the four months of the spawning season are realistically detailed, but the water levels for the other months of the year are shown constant throughout the month for simplicity. Plots of the daily elevation values for the example are shown in Figure 6-6. Figure 6-7, Figure 6-8, and Figure 6-9 are plots of daily elevation values for the years 2005, 2006, and 2007, respectively. These plots of water surface elevation versus time are called hydrographs. The solid red line represents the water elevation of the river at the confluence with the stream. The dashed green line represents the water surface elevation of the pool formed by flood water along the stream under existing conditions. The solid blue line represents the water surface elevation of the pool for Alternative 1 (installation of levee and gated culvert). The dashed brown line represents the water surface elevation of the pool for Alternative 2 (installation of levee, gated culvert, and pump station). Since some of the lines coincide at intervals, the dashed lines allow the solid lines to be visible between the dashes at some points.

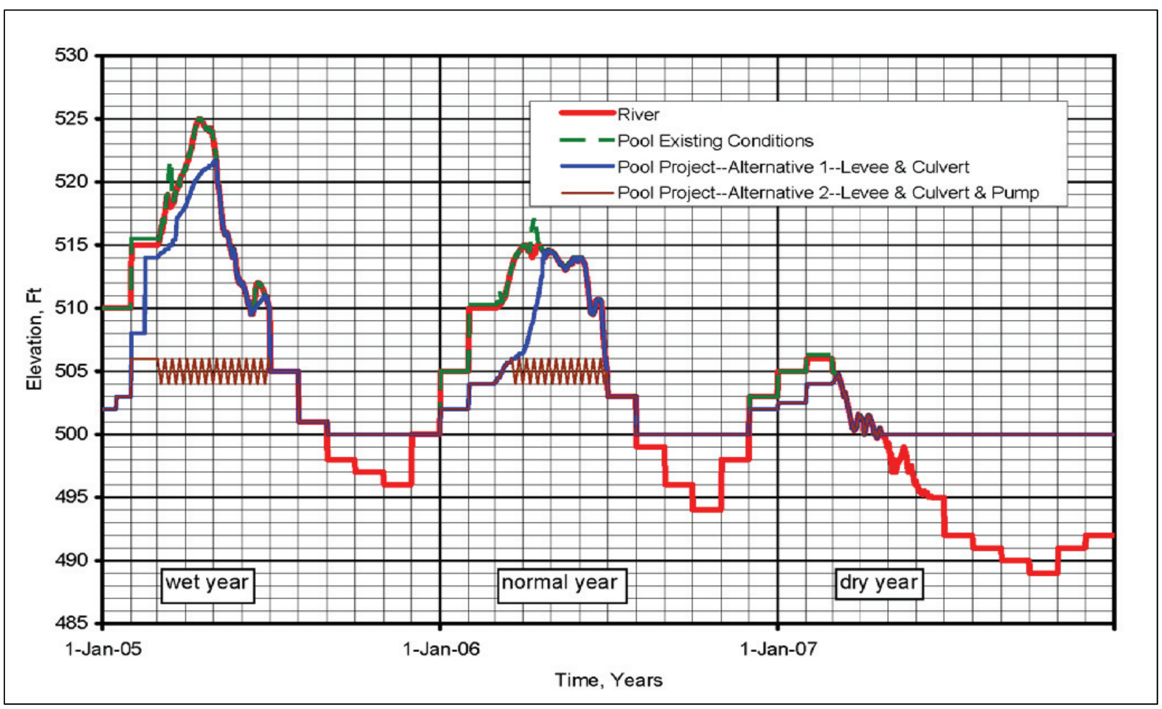


Figure 6-6. Example Hydrographs throughout 3-year Analysis Period.

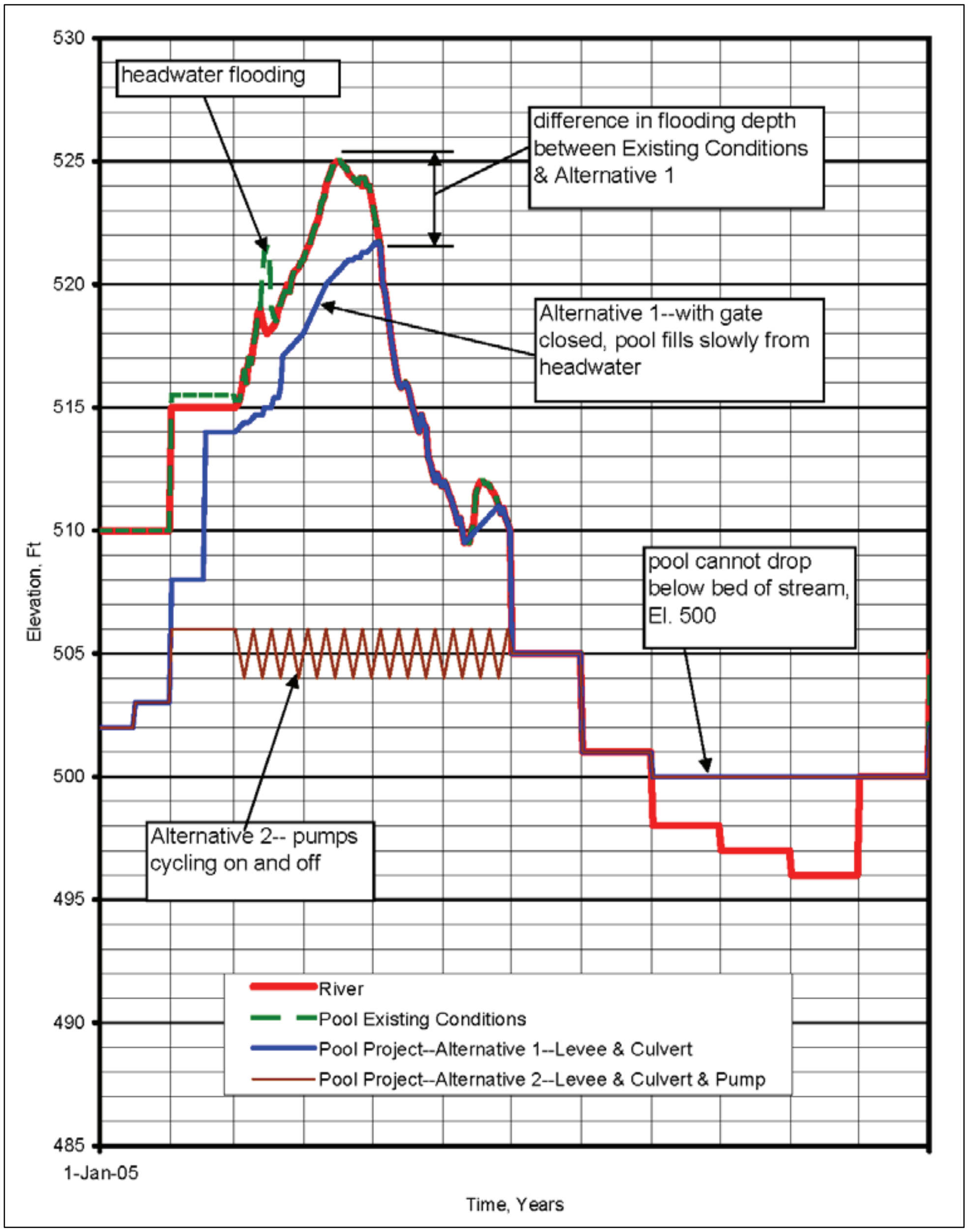


Figure 6-7. Example Hydrographs for Wet Year.

Under existing conditions, the water level in the river dominates the flooding in the stream floodplain. Without protection from a levee and a shut culvert gate, the flooding in the stream floodplain can never be lower than that in the river. This relationship is reflected by the fact that no curve in Figure 6-6 is lower than the red line.

Under existing conditions, water can occasionally rise to a higher level in the stream floodplain than that in the river. This is due to headwater flows in the stream channel being greater than what the channel can convey

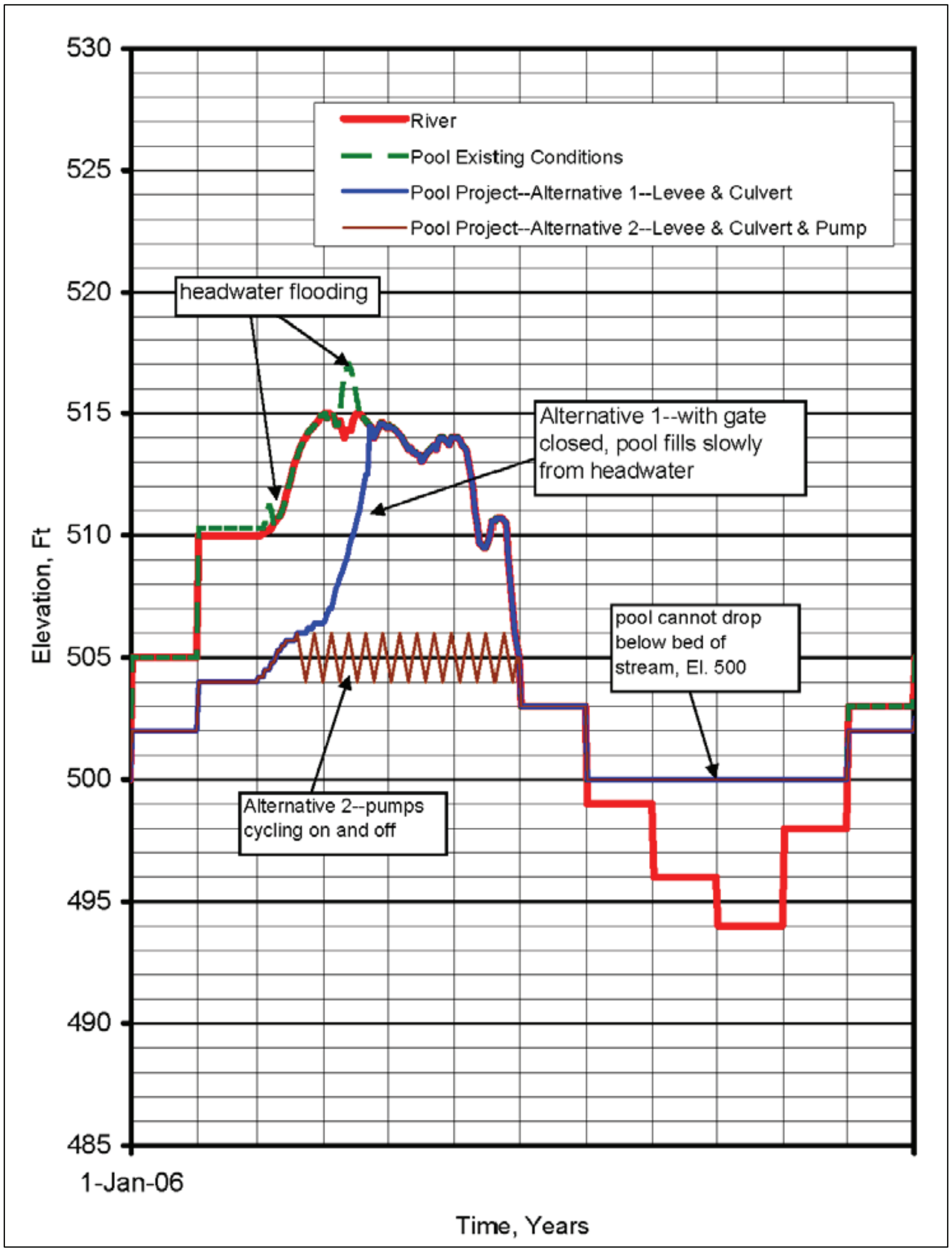


Figure 6-8. Example Hydrographs for Normal Year.

within its banks. Headwater flooding may occur in the stream floodplain whether the river level is high or low. The elevation spikes in the dashed green line for March, 2005 and for April, 2006 are signatures of headwater flooding within the project area.

Under project alternative 1, the stream floodplain is protected by the levee and the gated culvert from flooding by high river levels. However, with the culvert gate closed, accumulations of headwater runoff cannot be evacuated until the river falls, because there is no pump station. The signature of levee

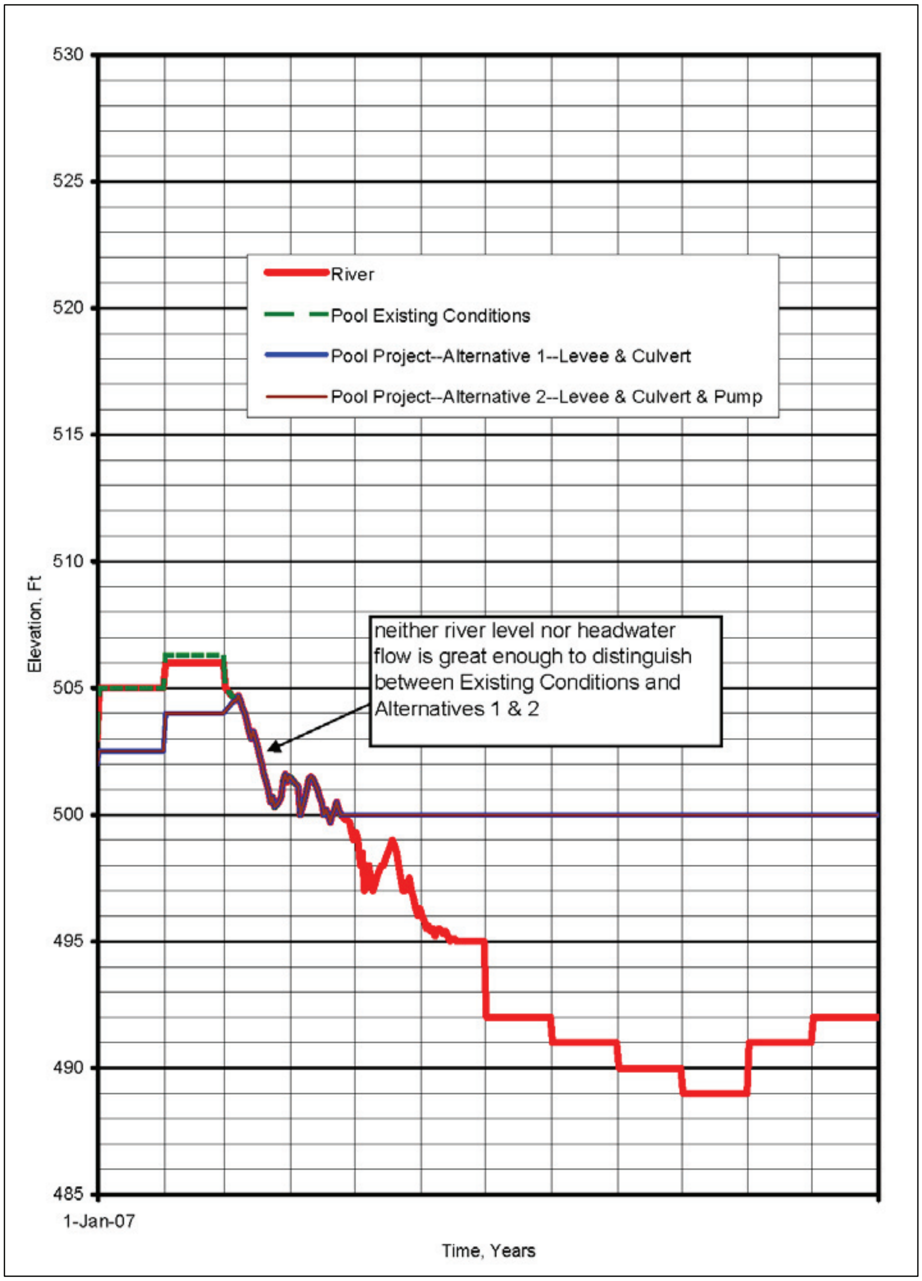


Figure 6-9. Example Hydrographs for Dry Year.

protection without pumping is the lagging rise of the blue line in March and April, 2005 and in April, 2006. In April, 2005 the pool level does eventually rise to the same level as the river (Elev. 522 feet), but it never attains the maximum level that would have occurred (Elev. 525 feet) without the levee at all. Since the river is falling on the date when the pool level matches the river level, the culvert gate is opened on that date and the pool level falls with the river level through May, 2005.

Under project alternative 2, the stream floodplain is protected by the levee and gated culvert from flooding by high river levels. Moreover, accumulations of headwater runoff can be evacuated in spite of high river levels, because there is a pump station. The signature of levee protection with pumping is the zigzagging of the brown line in March through June, in both 2005 and 2006. The pool hydrograph zigzags between elevation 504 feet and 506 feet because the pumps are set to come on at elevation 506 feet and to cut off at elevation 504 feet. For the pool elevation to never exceed the start pump elevation of 506 feet implies that the pumps have a great deal of capacity, and the example has been set up this way to keep the figure simple. For actual projects, the elevations would rise above the start pump elevation and gradually be brought down to the stop pump elevation, but a similar zigzag pattern would still be present.

EnviroFish Results and Interpretation

Loading the example input into EnviroFish and producing the output files are included in Chapter 4 and Chapter 5, respectively.

The EnviroFish program was run 15 times to generate the 15 values of ADFA listed in Table 6-2. For a given land use, the ADFA values listed in Table 6-2 are a maximum for existing conditions and a minimum for Alternative 2. The values for Alternative 1 are on the same order of magnitude as those for Existing conditions, but the values for Alternative 2 are essentially 1 to 2 orders of magnitude smaller than those for existing conditions. The example was intentionally designed to provide large differences between alternatives, and the results shown in Table 6-2 should not be interpreted as necessarily typical for actual projects. The ADFA values shown in Table 6-3 are for restricted rearing and show the same proportions as spawning between existing conditions, alternative 1, and alternative 2. However, the values are larger than the values for spawning, because the range of depths (0.1 ft to 11.0 ft) is less restrictive than for spawning (1.0 ft to 10.0 ft). The ADFA values shown in Table 6-4 are for total rearing and also show the same proportions as spawning between existing conditions, alternative 1, and alternative 2. The values are larger than the values for restricted rearing, because the range of depths (0.0 ft to unlimited depth) is less restrictive than for restricted rearing (0.1 ft to 11.0 ft). The ADFA values shown in Table 6-2, Table 6-3, and Table 6-4 are the concluding output of EnviroFish for this example problem. At this point, Average Daily Flooded Area by land use category can be copied to a spreadsheet to calculate Habitat Units.

Table 6-2. EnviroFish Spawning ADFA Values for the Analysis Period of 2005 – 2007.

Land Use	Existing Acre	Alternative 1 Acre	Alternative 2 Acre
Cypress Forest	134.1	120.4	0
BLH Forest	192.7	167.6	0
Large Permanent Waterbody	38.5	23.2	0
Channel	21.3	20.0	6.3
Cropland	1350.2	1074.4	0

Table 6-3. EnviroFish Restricted Rearing ADFA Values for the Analysis Period of 2005 – 2007.

Land Use	Existing Acre	Alternative 1 Acre	Alternative 2 Acre
Cypress Forest	200.1	178.5	0
BLH Forest	316.9	243.9	0
Large Permanent Waterbody	49.8	35.2	0
Channel	32.2	28.9	12.0
Cropland	2069.8	1576.5	7.9

Table 6-4. EnviroFish Total Rearing ADFA Values for the Analysis Period of 2005 – 2007.

Land Use	Existing Acre	Alternative 1 Acre	Alternative 2 Acre
Cypress Forest	242.9	194.5	0
BLH Forest	338.3	249.5	0
Large Permanent Waterbody	50.1	36.1	0
Channel	43.5	36.4	12.3
Cropland	2370.7	1704.4	9.3

EnviroFish ADFA values are multiplied by the HSI values to obtain HUs for each land use. The sum of the HSI for all land uses is the total HUs for a project alternative. The multiplication can be performed in a simple computer spreadsheet, as shown in Figure 6-10. Figure 6-10 lists the HSI used, the ADFA by land use and alternative, the calculated HUs, and the totals of the HUs. A comparison of the spawning existing conditions ADFA values with the HUs for cropland and BLH emphasizes how a high value land use of small area can provide habitat value equivalent to a low value land use of large area.

The HU values listed in Table 6-5 are present in bar-chart form in Figure 6-11. For all three alternatives, HUs increase at a decreasing rate for spawning, restricted rearing, and total rearing. The HUs for alternative 1 are more than half the HUs for existing conditions, but the HUs for alternative 2 are negligible. This extreme example illustrates how a project alternative that would totally prevent overbank flooding would negate the spawning and rearing opportunities that the floodplain would otherwise afford.

Habitat Suitability Indices

Land Use	HSI
cypress	0.9
blh	1.0
water	0.8
channel	0.5
crop	0.2

Spawning Habitat

Land Use	Existing Conditions		Alternative 1		Alternative 2	
	ADFA acre	HU acre	ADFA acre	HU acre	ADFA acre	HU acre
cypress forest	134.1	120.7	120.4	108.4	0.0	0.0
BLH	192.7	192.7	167.6	167.6	0.0	0.0
permanent water	38.5	30.8	23.2	18.6	0.0	0.0
channel	21.3	10.7	20.0	10.0	6.3	3.2
cropland	1350.2	270.0	1074.4	214.9	0.0	0.0
HU Totals :		**624.9**		**519.4**		**3.2**

Restricted Rearing Habitat

Land Use	Existing Conditions		Alternative 1		Alternative 2	
	ADFA acre	HU acre	ADFA acre	HU acre	ADFA acre	HU acre
cypress forest	200.1	180.1	178.5	160.7	0.0	0.0
BLH	316.9	316.9	243.9	243.9	0.0	0.0
permanent water	49.8	39.8	35.2	28.2	0.0	0.0
channel	32.2	16.1	28.9	14.5	12.0	6.0
cropland	2069.8	414.0	1576.5	315.3	7.9	1.6
HU Totals :		**966.9**		**762.5**		**7.6**

Total Rearing Habitat

Land Use	Existing Conditions		Alternative 1		Alternative 2	
	ADFA acre	HU acre	ADFA acre	HU acre	ADFA acre	HU acre
cypress forest	242.9	218.6	194.5	175.1	0.0	0.0
BLH	338.3	338.3	249.5	249.5	0.0	0.0
permanent water	50.1	40.1	36.1	28.9	0.0	0.0
channel	43.5	21.8	36.4	18.2	12.3	6.2
cropland	2370.7	474.1	1704.4	340.9	9.3	1.9
HU Totals :		**1092.9**		**812.5**		**8.0**

Figure 6-10. EnviroFish ADFA Output and Resultant HU Values.

Table 6-5. EnviroFish Habitat Units for the Analysis Period of 2005 – 2007.

Land Use	Existing Acre	Alternative 1 Acre	Alternative 2 Acre
Spawning	624.9	519.4	3.2
Restricted Rearing	966.9	762.5	7.6
Total Rearing	1092.9	812.5	8.0

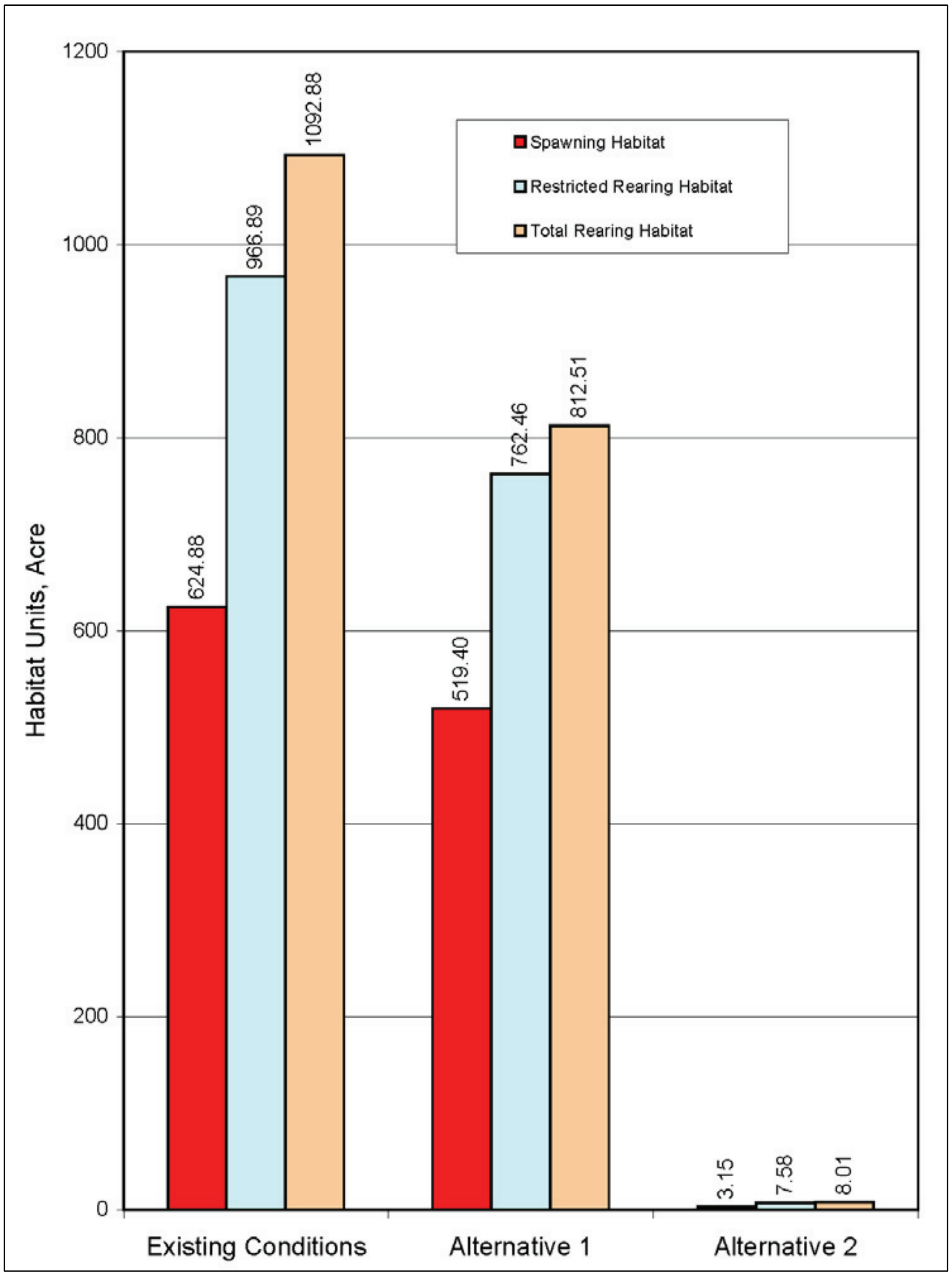


Figure 6-11. Habitat Units for Example Problem Alternatives.

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Appendix A: HEC Modeling Software

The successful use of the EnviroFish approach depends heavily on the use of hydrologic and hydraulic software to prepare input. Although the EnviroFish user may not become directly involved in the hydrologic modeling, a general awareness of the available approaches to hydrologic modeling, and the strengths and weaknesses of the various approaches, is needed to plan a feasible EnviroFish analysis. This appendix provides a brief overview of the U.S. Army Corps of Engineers hydrologic software developed by the Hydrologic Engineering Center (HEC) in Davis, California.

HEC Software

The three HEC computer programs that the EnviroFish user should be aware of include:

1. the Hydrologic Modeling System (HMS);
2. the River Analysis System (RAS); and
3. the Interior Flood Hydrology (IFH).

Programs evaluate different features of water management:

Features of the Different HEC Software Programs				
Feature	HEC IFH	HEC HMS	HEC RAS Unsteady	Demo Level Pool
Continuous simulation of rainfall-runoff		X		X
Level pool routing	X	X		X
Pool evaporation loss				X
Pool seepage loss				X
Culvert hydraulics	X		X	X
Weir hydraulics		X	X	X
Levee seepage	X			X
Gated culverts	X		X	X
Gated culverts with seasonally controlled opening rules				X
Gated culverts with seasonal control to hold habitat pool on land side				X
Pump stations (flood control)	X	X	X	X
Well pumps (water supply) controlled by elevation & season				X
Seepage wells (water supply)				X
Flashboards controlled by season				X
Daily water surface profiles			X	

References for these programs:

USACE. 1993. Engineering and Design – Hydrologic Frequency Analysis. EM 1110-2-1415. Washington DC: U.S. Army Corps of Engineers.

USACE. 2008. HEC RAS River Analysis System User's Manual, Version 4.0. Davis, CA: Hydrologic Engineering Center.

Hydrologic Versus Hydraulic Modeling Software

Hydrologic modeling software estimates volumes and flows, and hydraulic modeling software estimates the energy losses associated with known flows. Flow is the rate of water movement, expressed as a volume per unit time, such as cubic feet per second. Hydrologic software may model rainfall depth, depth of runoff, runoff volumes accumulated in reservoirs, and the flows in channels. Hydraulic software may apply known channel flows to estimate how high the water surface is in a channel, whether flow occurs in the floodplain, whether flood water overtops a road, or how much horsepower is required by a pump. In practice it is difficult to keep hydrology and hydraulics separate, because the hydrologic aspects of a system must be known to characterize the hydraulic aspects, and the hydraulic aspects of the system must be known to characterize the hydrologic aspects. In some cases iteration is required between hydrologic and hydraulic software to arrive at input that is hydrologically and hydraulically consistent.

Appendix B: Data Storage System (DSS)

EnviroFish accepts some of its input only in a Data Storage System (DSS) file format. Version 1.2.10b of HEC-DSSVue must be used with EnviroFish software. Specifically, the elevation vs. land area input for each land use type and the daily water elevation input must both be stored in a single DSS file prior to an EnviroFish program run. The spawning and rearing constraints input data are not stored in DSS, but data are entered from the keyboard into the EnviroFish main window.

DSS is a hydrologic data management software, rather than a modeling software, and was developed by the Corps of Engineers Hydrologic Engineering Center (HEC) in Davis, California. DSS can be used to store historical hydrologic data collected from gages or other instruments. DSS can also be used to store input into, and output from, hydrologic and hydraulic models. Within a Corps of Engineers district setting, the hydrologic/hydraulic modeler is likely to be the person who stores the model results in a DSS file for use as input into EnviroFish.

DSS Paths

DSS information is organized by paths. A path name may have six descript-tive parts, known as A, B, C, D, E, and F. Part A is used to name the river basin or project name. Part B is used to name a location. Part C identifies the data variable. Part D identifies the starting date for time series data. Part E identifies the time step for time series data. Part F is an additional descriptor. Paired data makes different use of the D and E parts.

Each EnviroFish elevation vs. area table for a land use is identified by a unique path name. In the example problem of Chapter 6, there are five elevations vs. area paths because there are a total of five land uses in the problem.

In the example problem of Chapter 6, each combination of a calendar year of daily water surface elevation with a project alternative is identified by a unique path name. There are 15 paths for water elevation in the example problem, because there are three years of water elevation input and five land uses (3 x 5 = 15). This is necessary because the random, climatic variability of the three historical years must be related to the systematic behavior associated with the different project alternatives.

Paired Data

The information in an elevation vs. area table is referred to as paired data, in the sense that the two variables can be plotted as coordinate pairs, x and y, having no reference to time. In the example problem of Chapter 6, the elevation vs. land area part names are A=ANY RIVER BASIN, B=ANY POOL, C=ELEV-AREA, D= (blank), E= ELEVATION-AREA CURVE, and F=BLH, etc. The user chooses the wording of the entries for Parts A, B, and F. An entry for Part E is optional, and is a freely worded description. The entries for C should not be freely worded, but should be a pair of hyphen-separated words selected from a list of DSS terms.

Time Series Data

The water surface elevation input used by EnviroFish is referred to as time series data, in the sense that a single variable, elevation, is ordered with respect to time. In the example problem of Chapter 6, the water surface elevation part names are A=ANY RIVER BASIN, B=ANY POOL, C=ELEV D= 01JAN2005.., etc, E= 1 DAY, and F=ALT 1, etc. The user chooses the wording of the entries for Parts A, B, C, and F. The entries for Part D and E must be chosen from a list of DSS terms. "ELEV" is the recommended Part C entry for use with EnviroFish. EnviroFish is coded to make use of daily water surface elevation input only. Therefore, the Part E entry must be "1 DAY" only. Entries for Part E depend on the beginning calendar year of input, but should use the date format "ddmmmyyyy," such as 01JAN2005.

DSS User Manuals

The following four DSS user's manuals, are available for web download from HEC:

1. *HEC-DSS User's Guide and Utility Manuals*, CPD-45. (Corps 1995)
2. *HECLIB Volume 1: HECLIB Subroutines, Programmer's Manual*, CPD-58. (Corps 1987)
3. *HECLIB Volume 2: HECDSS Subroutines, Programmer's Manual*, CPD-57. (Corps 1991)
4. *HEC Data Storage System Visual Utility Engine User's Manual (DSSVue)*, Version 1.2, CPD-75. (Corps 2005).

The *HEC-DSS User's Guide and Utility Manuals* is the basic introduction to DSS for users such as hydrologists and hydraulic engineers. Although written for pre-windows operating environments, the methods described in the *User's Guide* are applicable to the current uses of DSS. Many users of EnviroFish would benefit by referring to this manual, since it provides a broad picture of the requirements for a hydrologic database and explains why DSS operates as it does.

HECLIB Volume 1 and *HECLIB Volume 2* were written for pre-windows operating environments and are written for hydrologists, hydraulic engineers, and computer programmers. These manuals describe how DSS stores and retrieves information, and how routine calculations are executed. These manuals are extremely detailed and are unlikely to be helpful to the non-programmer.

Most users of EnviroFish would benefit greatly by referring to the *DSSVue* manual. *DSSVue* is a windows software that facilitates the viewing, inputting, and editing of information in DSS files. *DSSVue* can present information in either tabular or graphical formats. There is not a substitute for using *DSSVue* in the windows environment. For example, the information stored in a DSS file cannot be edited with a text editor.

Appendix C: EnviroFish Calculations

This appendix describes EnviroFish calculations in greater detail than is provided in the main body of the manual.

In all cases, EnviroFish calculates averages as the arithmetic mean. No use is made of the median in EnviroFish.

Terms displayed below in bold type are EnviroFish variables.

Time Constraints

There are four levels of time constraint in EnviroFish. From the highest to lowest level, the time levels are analysis period, spawning season, spawning period, and a single day.

The analysis period is the highest level of time constraint. **Season Constraints** include a user-defined beginning year and ending year and the beginning and ending days of a user-defined fisheries season. As an example, suppose that the user-defined season starts on March 1st and ends on June 30th (displayed as **Season** 3/1 – 6/30 on **Season Constraints** input screen); the user-defined period is from 1980 to 1982 (displayed as **Period** 1980 **to** 1982 on the **Season Constraints** input screen); and the user-defined Spawning period is 8 days (displayed as **Days** 8 on the **Spawning Constraints** input screen). The EnviroFish program will evaluate rearing and spawning for each day from March 1st through June 30th for the years 1980, 1981, and 1982. In this example, a total of 122 daily calculations each for **Total Rearing**, **Restricted Rearing**, and **Spawning** will be performed for the three years in the period of record. The duration period evaluated for each calculation is one day for **Total Rearing** and **Restricted Rearing** and 8 days for **Spawning**.

Spawning

Unlike daily computations of rearing area, daily computations of spawning area evaluate changes in water surface elevation that occur during the spawning duration period, i.e., the daily value of spawning area evaluates conditions that occur on subsequent days. As an example, suppose that the user-defined season starts on March 1st and ends on June 30th (displayed as 3/1 – 6/30 on **Season Constraints** input screen) and the user-defined spawning duration period is 8 days (displayed as **Days** 8 on the **Spawning Constraints** input screen). The Day 1 spawning calculation evaluates conditions that occur on Day 1 plus the subsequent seven days, which are March 1st through March 8th, the Day 2 calculation evaluates conditions that occur from March 2nd through March 9th, and the Day 122 calculation evaluates conditions that occur from June 30th through July 7th. As an additional example, suppose that the user-defined season starts on March 15th and ends on May 31st (displayed as 3/15 – 5/31 on **Season Constraints** input screen), and the user-defined spawning duration is 3 days (displayed as **Days** 3 on the **Spawning Constraints** input screen). The Day 1 spawning calculation evaluates conditions that occur on Day 1 plus the subsequent two days, which are March 15th through March 17th, the Day 2 calculation evaluates conditions that occur from March 16th through March 18th, and the Day 78 calculation evaluates conditions that occur from May 31st through June 2nd.

The parameters that are utilized for the daily spawning computations are elevation, area, **Season Constraints**, and **Spawning Constraints**. The user-defined **Spawning Constraints** are the minimum depth (**Min Depth**), maximum depth (**Max Depth**), spawning duration (**Days**), shallow nests (**Orphaned Nests**), and deep nests (**Deep Nests**). The **Min Depth** and **Max Depth** are identical to the corresponding **Rearing Constraints**, except that the selected constants may have different values. Shallow nests are those nests that are constructed near the water surface and deep nests are those nests that are constructed at greater depths. The effect of each of these variables on spawning is described in the following paragraphs.

The first day of any daily spawning calculation defines the maximum upper and lower boundaries for the daily calculation. The land surface area available during the first day of the spawning duration period is computed precisely as for **Restricted Rearing** described above. For a spawning duration of one day, the spawning daily calculations will follow an identical process as for **Restricted Rearing** daily calculations.

The effects of shallow nests and deep nests work in tandem and can only impact the daily spawning calculation for a spawning duration greater than one day. Shallow nests relate to the upper spawning boundary or “shallow” portion, and deep nests relate to the lower spawning boundary or “deep” portion. Two user-defined settings each are possible for shallow nests. A checkmark symbol in the box before the words **Orphaned Nests** indicates that “abandoned” shallow nests are “allowed,” i.e., a reduction in the upper boundary elevation will only occur if the minimum water surface elevation in a spawning duration period is below the first day **Min Depth** elevation. An empty box before the words **Orphaned Nests** indicates that “abandoned” shallow nests are “not allowed,” i.e., a reduction in the upper boundary elevation will occur if the minimum water surface elevation in a spawning duration period is below the first day water surface elevation. A checkmark symbol in the box before the words **Deep Nests** indicates that “abandoned” deep nests are “allowed,” i.e., the lower boundary elevation is maintained at the first day **Max Depth** elevation. An empty box before the words **Deep Nests** indicates that “abandoned” deep nests are “not allowed,” i.e., an increase in the lower boundary elevation will occur if the maximum water surface elevation in a spawning duration period is above the first day water surface elevation.

There are four possible combinations of shallow nests and deep nests that can be selected for a period of record simulation:

1. Both shallow nests and deep nests are allowed.
2. Shallow nests are allowed and deep nests are not allowed.
3. Shallow nests are not allowed and deep nests are allowed.
4. Neither shallow nests nor deep nests are allowed.

The least restrictive of the four combinations occurs when both shallow nests and deep nests are allowed. For each spawning period calculation, two cases are possible:

a. The first day **Min Depth** elevation is less than or equal to the minimum water surface elevation for every subsequent day of the spawning period.
b. The first day **Min Depth** elevation is greater than the minimum water surface elevation for a subsequent day of the spawning period.

If case (a) governs, the upper boundary is equal to the first day **Min Depth** elevation and the lower boundary is equal to the first day **Max Depth** elevation. The resultant spawning period value is the land surface area bounded by the upper boundary and the lower boundary. If case (b) governs, the upper boundary is the minimum water surface elevation during the spawning period and the lower boundary is equal to the first day **Max Depth** elevation. The resultant spawning period value is the land surface area bounded by the upper boundary and the lower boundary.

Next, consider combination (2), in which shallow nests are allowed and deep nests are not allowed. The upper boundary is determined by following the process for combination (1). The lower boundary is determined by subtracting the **Max Depth** spawning constraint value from the maximum water surface elevation during the spawning duration period. The resultant spawning period value is equal to the land surface area bounded by the upper boundary and the lower boundary.

Consider combination (3), in which shallow nests are not allowed and deep nests are allowed. The upper boundary is determined by subtracting the **Min Depth** spawning constraint value from the minimum water surface elevation during the spawning period. The lower boundary is the first day **Max Depth** elevation. The resultant spawning period value is the land surface area bounded by the upper boundary and the lower boundary.

Finally, consider combination (4), in which neither shallow nests nor deep nests are allowed. This combination is the most restrictive of the four combinations. The upper boundary is determined by subtracting the **Min Depth** spawning constraint value from the minimum water surface elevation during the spawning period. The lower boundary is determined by subtracting the **Max Depth** spawning constraint value from the maximum water surface elevation during the spawning period. The resultant spawning period value is the land surface area bounded by the upper boundary and the lower boundary.

For each of the possible four combinations in the EnviroFish program, the minimum area value for any day cannot be less than zero. Any daily evaluation of spawning that computes an upper boundary elevation equal to or less than the lower boundary elevation results in a total area value of zero.

Rearing

Daily computations of rearing area evaluate only the water surface elevation for one day, i.e., the daily value evaluates neither water surface elevations that have occurred on previous days nor on subsequent days. The Day 1 computation uses the water surface elevation on Day 1 only; the Day 2 computation uses the water surface elevation on Day 2 only, etc. The parameters used to compute the rearing computations for each day are elevation, area, **Season Constraints**, and **Rearing Constraints**. The **Rearing Constraints** are the minimum depth (**Min Depth**), and maximum depth (**Max Depth**). **Min Depth** and **Max Depth** are user-defined numeric values that are constant for the period of record selected. The parameter **Total Rearing** is computed for each day in the period of record and is simply the amount of land surface area at and below the water surface elevation and is the maximum potential area available to rearing fishes. **Restricted Rearing** is computed for each day in the period of record and is the amount of land surface area that is bounded by the user-defined **Rearing Constraints** related to the daily water surface elevation. The **Restricted Rearing** value for each day in the period of record is that quantity of area that has an upper boundary at the **Min Depth** below the water surface elevation and has a lower boundary at the **Max Depth** below the water surface elevation. As an example, suppose that the water surface elevation on Day 25 is 100 feet, the **Min Depth** is 1 foot, and the **Max Depth** is 10 feet. The **Restricted Rearing** value for Day 25 is the amount of land surface area that has an upper boundary of 99 feet and a lower boundary of 90 feet.

Appendix D: Hydrologic Plan

A hydrologic plan is a prerequisite for a successful application of Enviro Fish. The planner of an EnviroFish analysis needs a general understanding of how hydrologic methods support the application of EnviroFish. This chapter is a brief introduction to some of the hydrologic issues that may arise in planning an EnviroFish analysis and includes the following four topics:

1. Site hydrologic classification
2. Water control components and passive processes
3. Comparison of HEC-HMS and HEC-RAS
4. Assembling the hydrologic plan

Site Hydrologic Classification

The planner of an EnviroFish analysis should identify the characteristics of the site that dominate how hydrologic data can be used and how hydrologic modeling can be performed. The simple site classification system described below can serve as an initial planning aid, although it does not include all possible aspects of EnviroFish applications. The classification system identifies the operational and tailwater characteristics of the site.

Operational controls permit people to change flows and water levels within the site. Examples of controls are gated culverts, flashboard weirs with changeable crest elevations, flood control pumps, and water supply pumps. Controls should be distinguished from project alternatives that do change water levels, but have only a fixed operation. For example, an alternative to install a low earthen dam with a fixed spillway would change water levels at the site, but the water levels would be entirely determined by flows, topography, and the fixed spillway characteristics. Under both existing conditions and the alternative, such a site is uncontrolled.

Tailwater elevation is the water surface elevation immediately downstream of the EnviroFish analysis site. Tailwater elevation is important, because it controls the site water surface elevation required to force headwater flow through the site. The tailwater characteristics are classified as either dependent or independent. If the elevation of tailwater depends only on the amount of flow through the site, then the tailwater is dependent. Under dependent tailwater conditions, the greater the flow through the site, the higher the water surface elevation at the site, and the fixed relationship between flow and elevation can be listed in a single rating table or plotted in a single rating curve. Alternatively, if the elevation of tailwater can be affected by any other cause than the flow passing through the site, then the tailwater is independent. Under independent tailwater conditions, it is not possible to develop a single rating table or a single rating curve that accurately describes the relationship between flow through the site and the water surface elevation at the site for all possible conditions downstream of the site.

Based on the possible combinations of control and tailwater, there are four categories in the classification system:

1. Uncontrolled, dependent tailwater
2. Uncontrolled, independent tailwater
3. Controlled, dependent tailwater
4. Controlled, independent tailwater

Six examples of site hydrologic classification are provided below. The first two examples concern the establishment of forest in a floodplain. The remaining examples concern the installation of a low dam and shallow reservoir.

Example 1. Uncontrolled, dependent tailwater (forest)

An example of an uncontrolled, dependent tailwater site is shown in plan and section views in Figure D-1. The plan view shows an unforested stream and floodplain under existing conditions, with the project alternative to be the establishment of a small patch of forest, shown as a green hatched rectangle. There is no downstream tributary to affect flowlines at the site. No controllable dam is downstream of the site. The elevation of floodwater at the site is solely a function of the flow through the site, therefore, the site has dependent tailwater. No on-site controllable structures are included with the establishment of the forest; therefore, the site is uncontrolled.

Continuing with the example of Figure D-1, the patch of forest is considered small enough to have a negligible effect on flood flows and elevations through the stream reach. If suitable gage data is available for

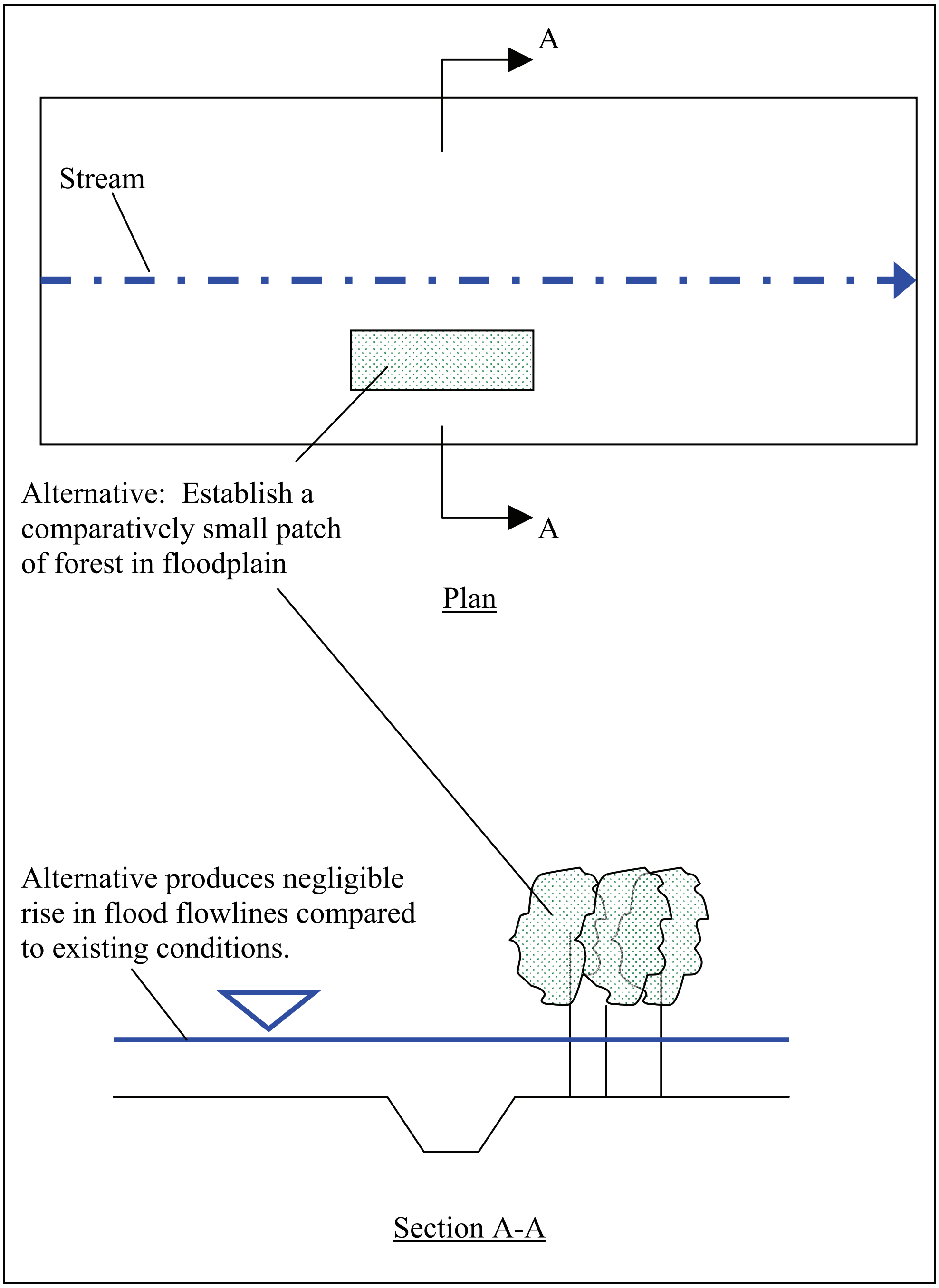

Figure D1. Uncontrolled Site with Dependent Tailwater, Alternative – Establish Forest.

input to EnviroFish, that data can be used for both existing conditions and for the alternative. Or, if gage data is not available, the hydrologic and hydraulic analyses sufficient to describe existing conditions should also describe the alternative satisfactorily. However, if the patch of forest is large enough to significantly increase the resistance to flood flows, then modeling is required to distinguish between existing conditions and the alternative. For example, even if gage data were available to describe existing conditions without modeling, hydrologic and hydraulic models would be required to quantify the higher water surface elevations that would be caused by the increased flow resistance of the forest.

Example 2. Uncontrolled, independent tailwater (forest)

An example of an uncontrolled, independent tailwater site is shown in plan and section views in Figure D-2. The plan view shows an unforested stream and floodplain under existing conditions, with the project alternative to be the establishment of a small patch of forest, shown as a green hatched rectangle. Just downstream of the site, the stream joins a much larger river. Although no downstream controllable dam is close enough to affect flowlines at the site, the elevation of floodwater at the site is not solely a function of the flow through the site, because many combinations of flow in the stream and in the river upstream of the confluence could produce the same water surface elevation at the site. Therefore, the site has independent tailwater. The possibility of different flow conditions causing the same water surface elevation at the site is shown in Figure D-3. In Figure D-3 the stream is shown in profile and the river is shown as a trapezoidal section. The solid blue line sloping downward to the right represents a headwater flood flowline for the stream at a time when the river is low. The flowline is parallel to the top of stream bank and the short, red, double-headed arrows indicate the depth of flooding above the stream bank and floodplain. The twin trees shown in hatched green foliage represent the location of the site. Alternatively, the dashed blue line represents the flowline for the stream at a time when the river is high. At the far left of the figure, the dashed blue line is below the top of the stream bank and is falling to the right, indicating that the stream flow is not great enough to flood the stream floodplain. However, the river flow from upstream of the confluence is great enough to cause flooding in the floodplain of the river. This river floodwater backs into the stream and produces a level flowline with respect to the stream profile. The river flooding is high enough that backwater flooding occurs in the stream floodplain at the project site. The backwater flooding is indicated by the green double-headed arrows. Within the project site there is point, "D," at which the depth of flooding due to headwater and backwater are the same. No on-site controllable structures are included with the establishment of the forest; therefore, the site is uncontrolled.

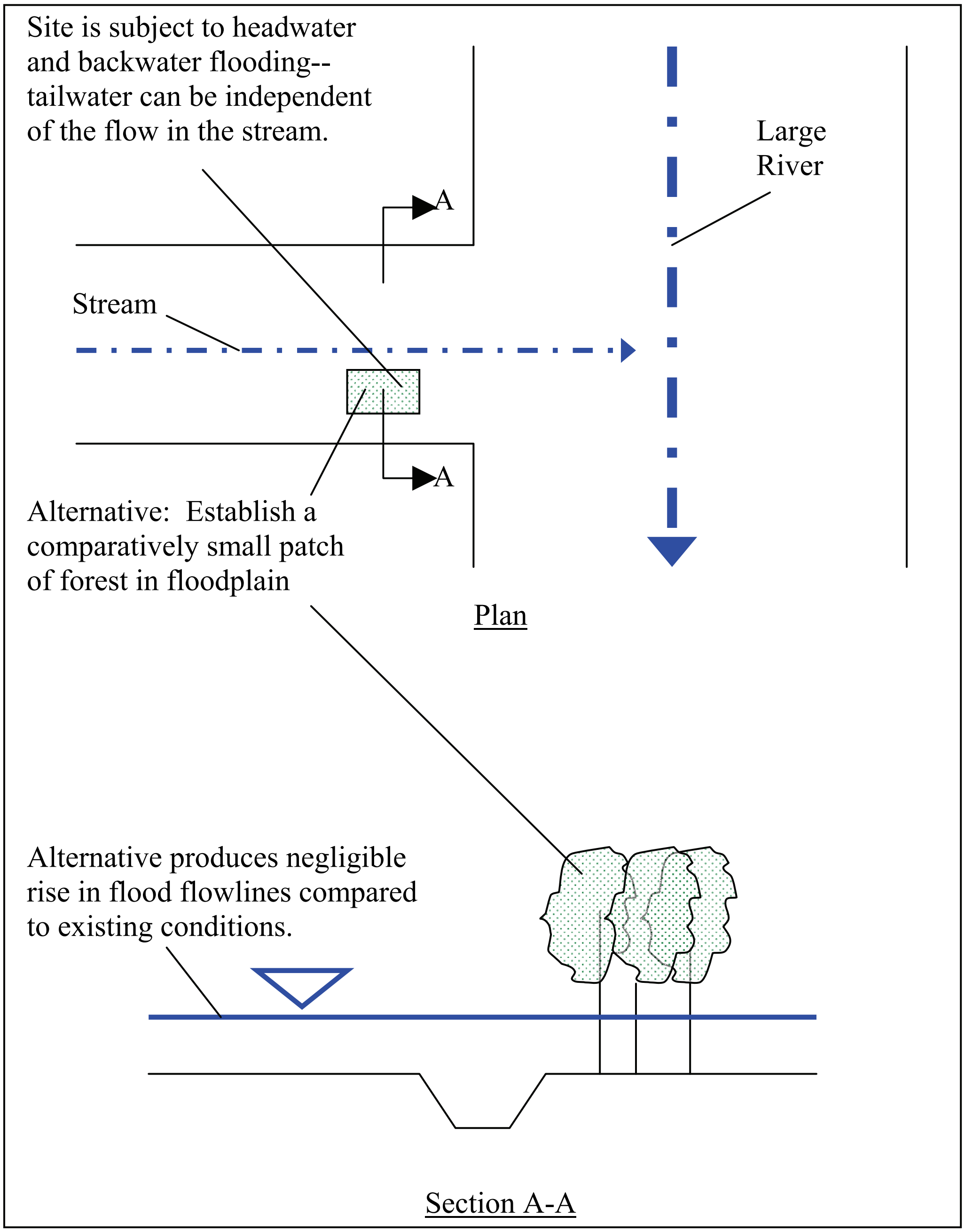

Figure D2. Uncontrolled Site with Independent Tailwater, Alternative – Establish Forest.

Continuing with Example 2, the data and modeling considerations for the patch of forest are the same as for Example 1, except that the gage data used should reflect both the behavior of the stream and the river. For example, a gage fortuitously located at the site would reflect the combined effects of headwater and backwater flooding. If no gage is located at the site, then a gage farther upstream on the stream and another gage on the river together might furnish usable data if a satisfactory method is available to transform the elevations to values appropriate for the site.

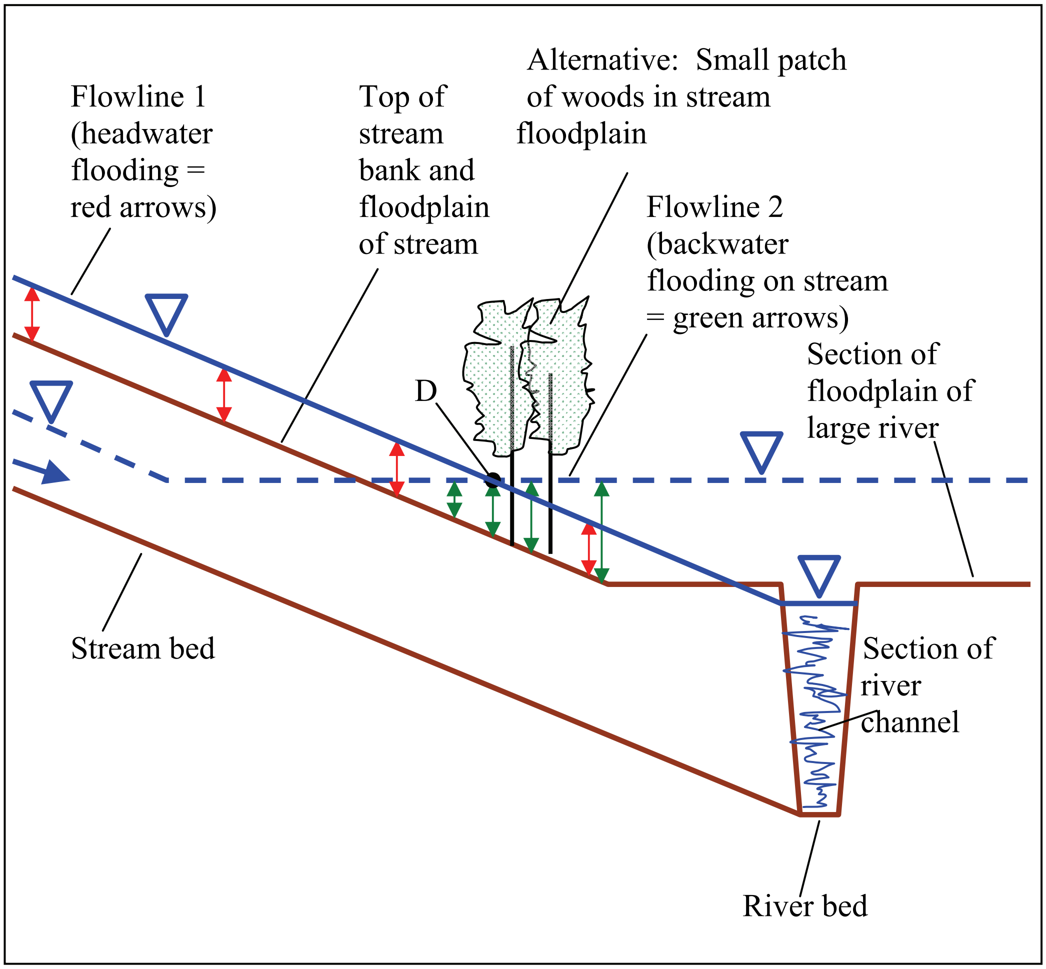

Figure D3. Uncontrolled Site with Independent Backwater, Profile of Headwater and Backwater Flooding, Alternative – Establish Forest.

Example 3. Uncontrolled, dependent tailwater (dam)

A second example of an uncontrolled, dependent tailwater site is shown in plan and section views in Figure D-4. The plan view shows an unforested stream and floodplain under existing conditions, with the project alternative to be the installation of a low dam and shallow reservoir. No tributary joins the stream close downstream of the site. No controllable dam is close downstream of the site. The elevation of floodwater at the site is solely a function of the flow through the site; therefore, the site has dependent tailwater. The dam has a fixed spillway and no other controllable features are included; therefore, the site is uncontrolled.

Continuing with Example 3, although the dam is uncontrolled, it does change water levels at the site. If suitable gage data is available for input to EnviroFish, that data can be used for existing conditions, but not for the alternative, which requires modeling.

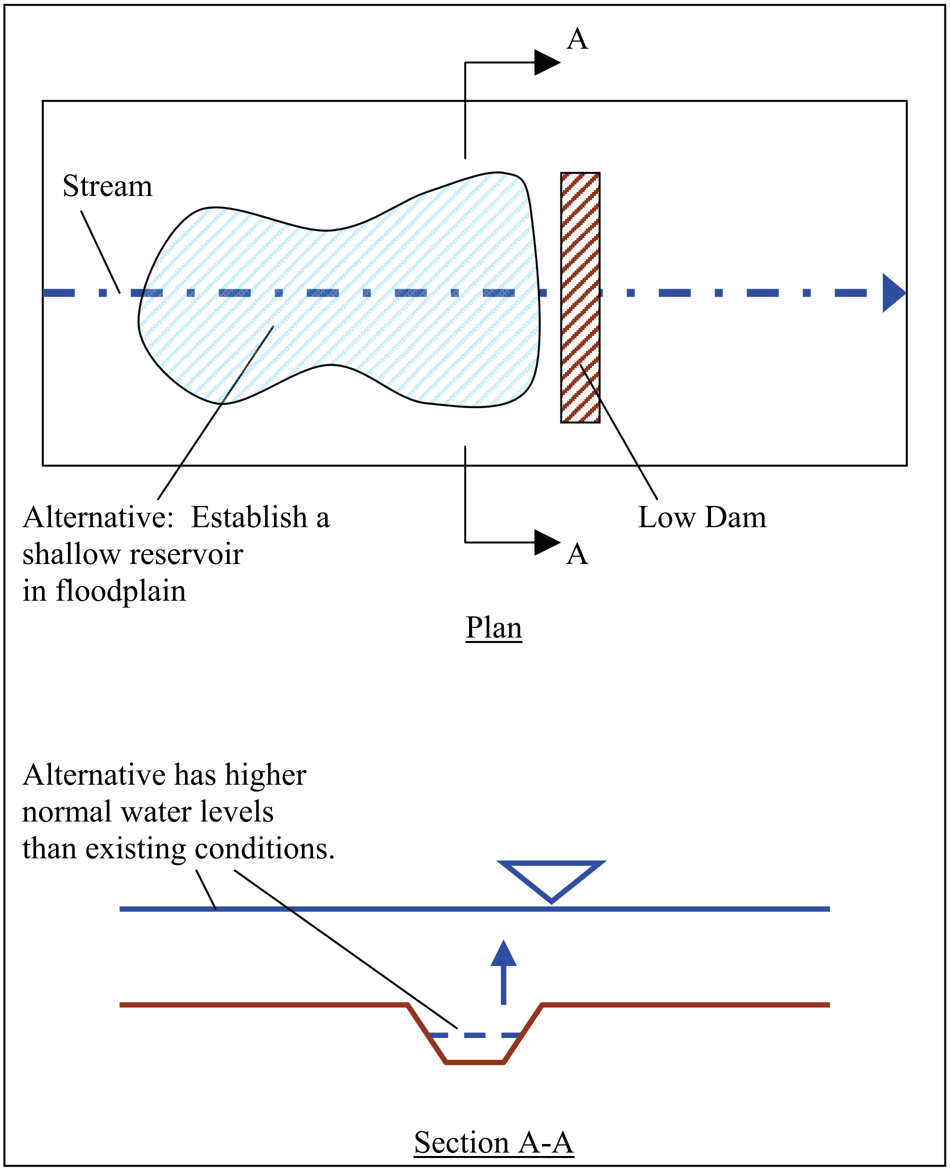

Figure D4. Uncontrolled Site with Dependent Tailwater, Alternative – Install Dam.

Example 4. Uncontrolled, independent tailwater (dam)

A second example of an uncontrolled, independent tailwater site is shown in plan and section views in Figure D-5. The plan view shows an unforested stream and floodplain under existing conditions, with the project alternative to be the installation of a low dam and shallow reservoir. Just downstream of the site, the stream joins a much larger river. For the same reasons described in Example 2, this site also has independent tailwater. The dam has a fixed spillway and no other controllable features are included; therefore, the site is uncontrolled. Although available gage data may be satisfactory as input to EnviroFish, the low dam must be modeled.

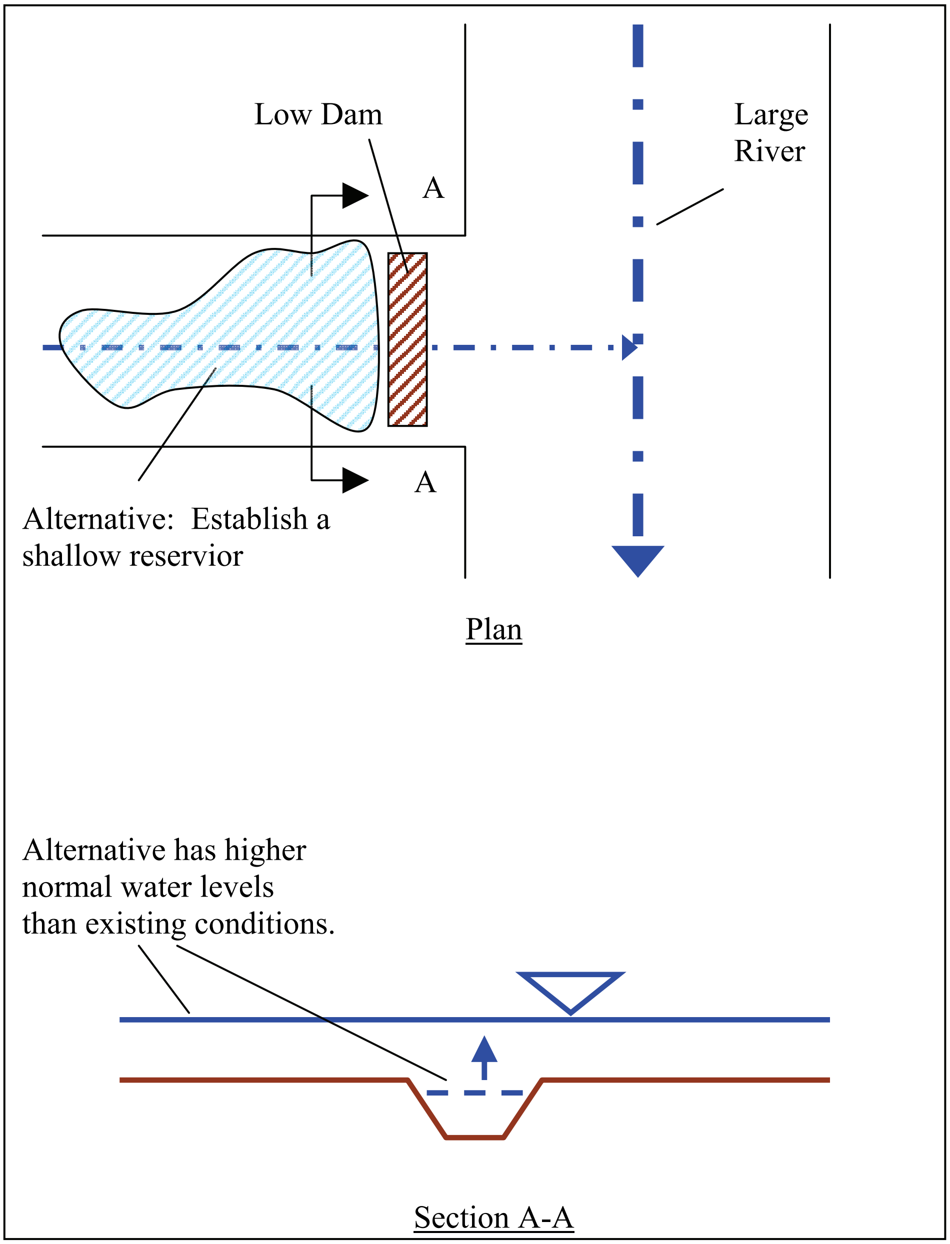

Figure D5. Uncontrolled Site with Independent Tailwater, Alternative – Install Dam.

Example 5. Controlled, dependent tailwater (dam)

If a dam with controllable spillways were substituted for the dam featured in Example 3, then the alternative would be controlled, with dependent tailwater. Water supply pumps would also provide control. Modeling is required to characterize this alternative, even if gage data is available to characterize existing conditions.

Example 6. Controlled, independent tailwater (dam)

If a dam with controllable spillways were substituted for the dam featured in Example 4, then the alternative would be controlled, with independent tailwater. As in Example 5, water supply pumps would also provide control, and modeling is required to characterize this alternative, even if gage data is available to characterize existing conditions.

Water Control Components and Passive Processes

The effect of project water control components and passive processes should be reflected in an EnviroFish analysis. The hydrologic plan should identify which controls and passive processes will be accounted for, and which software capable of modeling the site realistically has been selected for modeling. An example list of six control components and passive processes is provided below.

The first four items are control components and the last two items are passive processes:

1. gated culverts
2. flood control pumps
3. flashboard weirs
4. pumped wells
5. levee under seepage
6. seepage wells

Gated culverts (control component)

Although the purpose of a levee is to protect the land side from river flooding, a levee also obstructs the normal flow of runoff from the land side to the river. Gated culverts installed through levees allow land side runoff to flow into the river. The gate is normally kept open while the river is low. If the river is high, the gate is shut to prevent river water from flowing backward through the culvert and flooding the land side of the levee.

The operation cycle of a gated culvert through a levee is illustrated in Figures D-6, D-7, and D-8. In this example, the gate is operated solely for flood protection on the land side of the levee. Figure D-6, Step 1 shows the gated culvert in its normal condition, with the river low and the gate open.

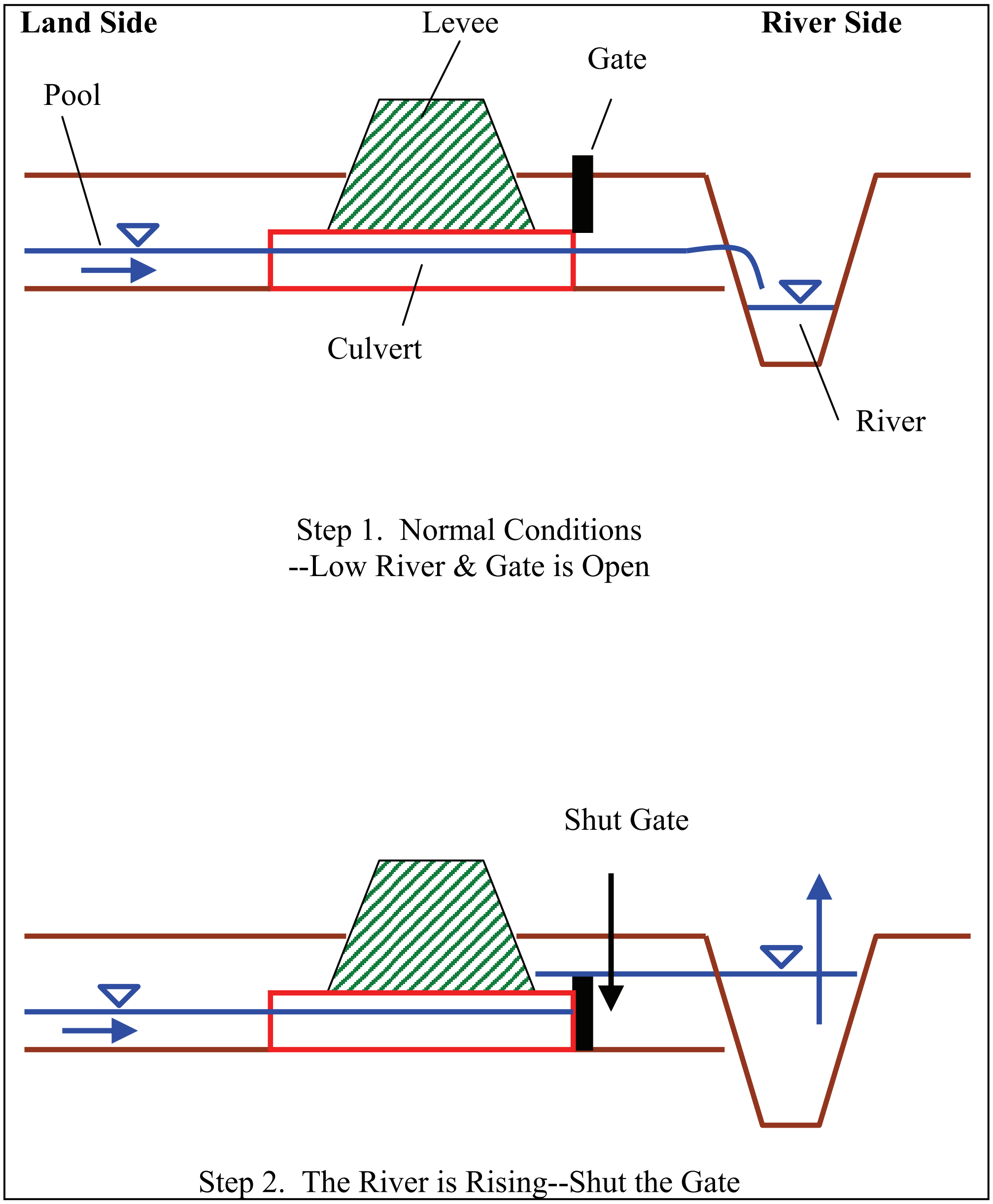

Figure D6. Gate Operation Cycle at Culvert Through Levee (Steps 1 and 2).

Runoff does not accumulate on the land side of the levee, but instead flows freely though the culvert and flows into the river. Step 2 shows the river rising. The gate is shut to prevent the river water from flowing backward through the culvert. Runoff has not yet had time to accumulate on the land side. In Figure D-7, Step 3, the river has risen higher. Runoff has had time to accumulate on the land side of the levee and the pool is also rising. In some situations, levee underseepage also contributes to the accumulation of water on the land side. The pool level on the land side is not as high as the river level, and the gate remains shut, since — if the gate were opened — river water would flow into the land side area and increase the flooding

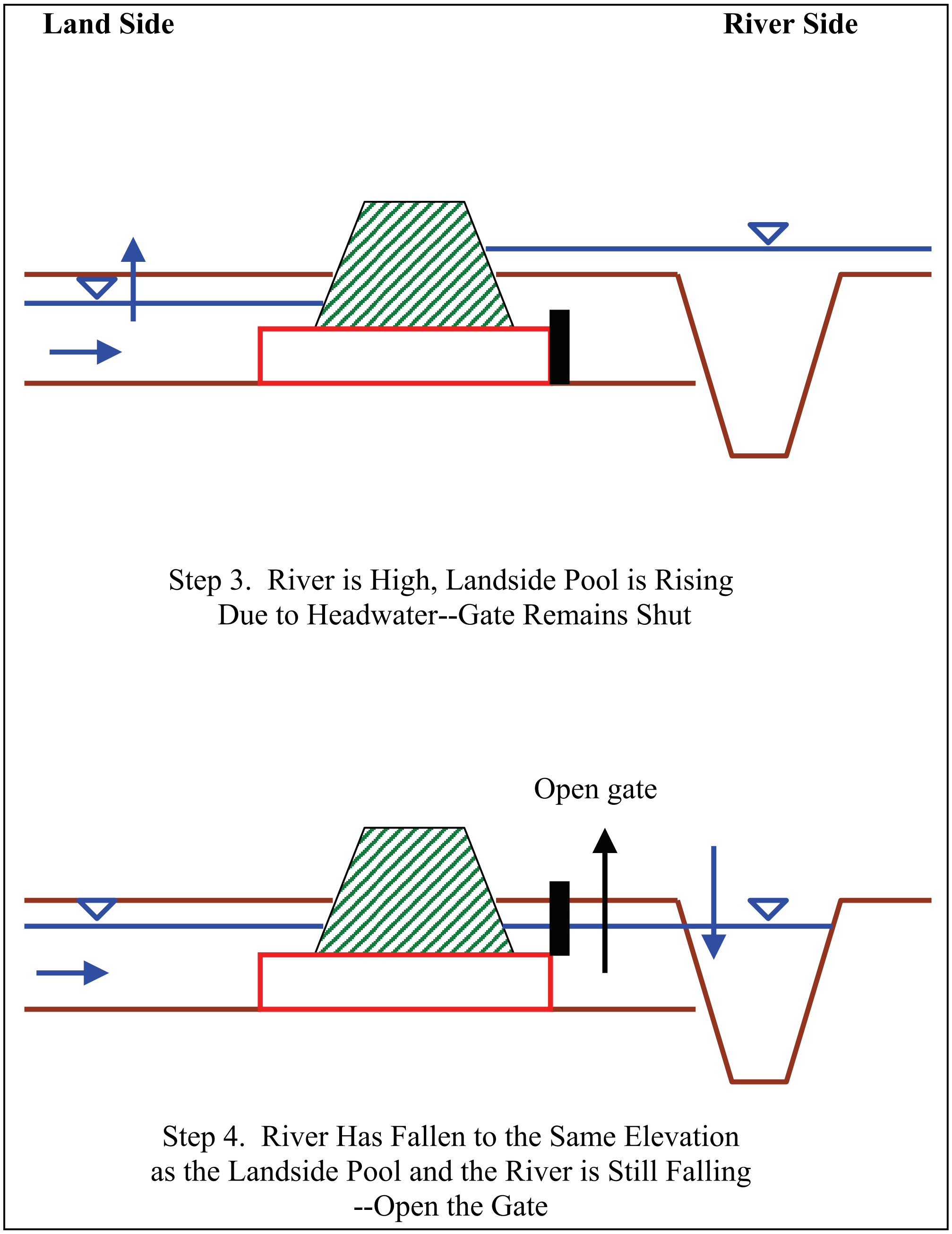

Figure D7. Gate Operation Cycle at Culvert Through Levee (Steps 3 and 4).

there. In Step 4, the river has fallen to the same elevation as the accumulated runoff on the land side, and the river continues to fall. The gate is opened, since the falling river allows the pool on the land side of the levee to fall also. In Figure D-8, Step 5, the river continues to fall. The gate remains open and the pool falls also. In Step 6, normal conditions have resumed. The river is low, the gate is open, and land side runoff flows into the river.

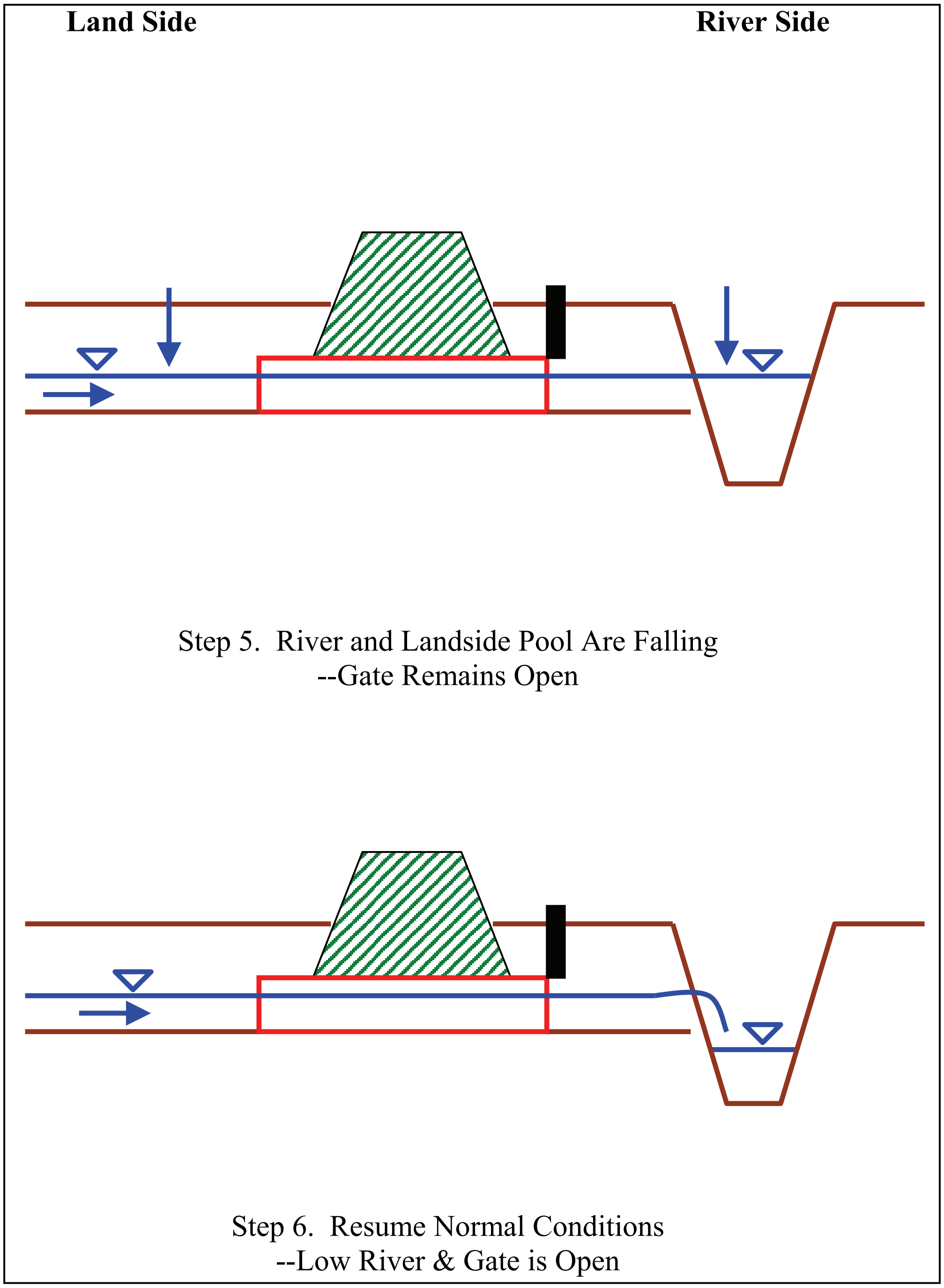

Figure D8. Gate Operation Cycle at Culvert Through Levee (Steps 5 and 6).

The operation cycle of gated culverts for flood control projects can be continuously simulated using the HEC-RAS software in the unsteady flow mode. The more difficult HEC-RAS task is to impose seasonal rules for gate operation, including the holding of land side pools against a low river.

Closed culvert gates are subjected to heavy forces if water levels are not equal on either side of the levee. As shown in Figure D-9, gates are usually installed on the river side end of the culvert. The high water level in the river shown in Figure D-9 exerts a large force against the shut gate. The shallow ponded water on the land side of the gate also exerts force in the opposite direction against the gate, but the net force from the river side is considerable, nevertheless. The massive concrete at the end of the culvert is able to support the net pushing force exerted by the gate. The gate presses against a heavy, smooth iron surface embedded in the culvert concrete. The greater the force on the gate, the tighter the seal.

If a project alternative would require a gated culvert to hold a pool for habitat on the land side of the levee against a lower river level, a careful structural check should be performed. As shown in Figure D-10, the water force on the shut gate from the land side is greater than the force from the river side, because the river level is lower than the pool level. The net force on the gate tends to push the gate away from the end of the culvert. There are heavy iron supports that hold the gate against the iron seal, but there is a limit to the tension the supports can withstand. Also, the greater the net force from the land side, the poorer the seal and the greater the tendency for leakage. Not only should the specifications of the gate be checked, but other structural and geotechnical design checks of the culvert and foundation may also be required. In the case of a new gated culvert installation, the designers should be advised at the beginning of the design process that the structure is to hold a land side pool against a low river.

Flood control pumps (control component)

Flood control pumps control the level of the pool that the water is pumped from, and operate only if gravity outflow is not possible. A typical application of flood control pumps is to protect the land side of a levee, as shown in Figure D-11. Sources of inflow to the land side pool may include direct rainfall onto the pool, runoff from upstream, and levee under seepage.

Flood control pumps can be controlled seasonally to maintain a pool elevation within desired limits. The pumps operate in an on/off cycle. If the pool elevation rises to an elevation referred to as "start pump" elevation, the pump is turned on. Pumping continues until the pool falls to an elevation referred to as "stop pump" elevation.

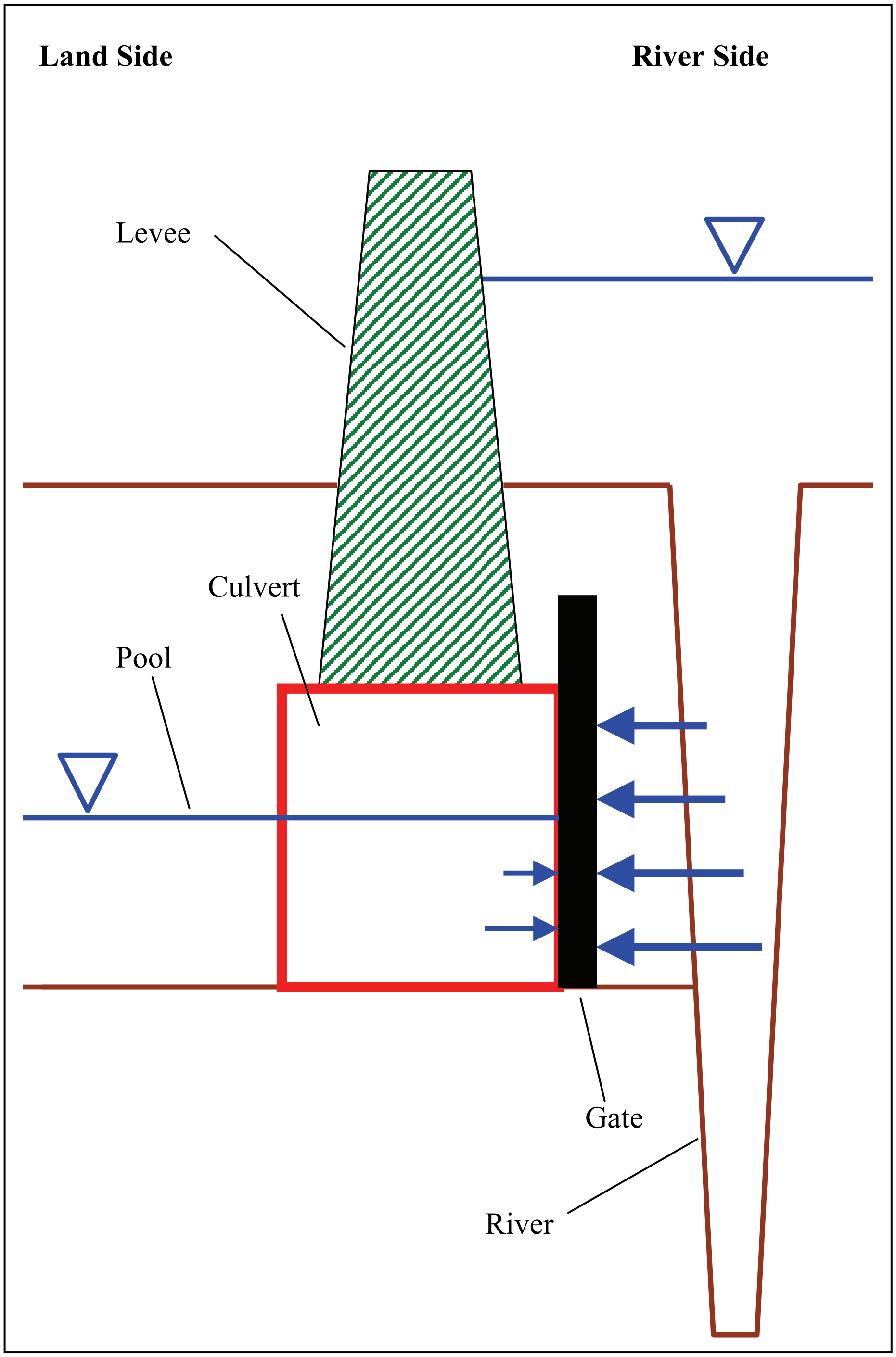

Figure D9. Forces on Shut Culvert Gate Due to High River.

Flashboard weir (control component)

A flashboard weir is a small spillway installed in a low earthen dam. The pool held upstream of the dam and flashboard weir is shallow. The crest elevation of a flashboard weir can be adjusted for seasonal control of water levels.

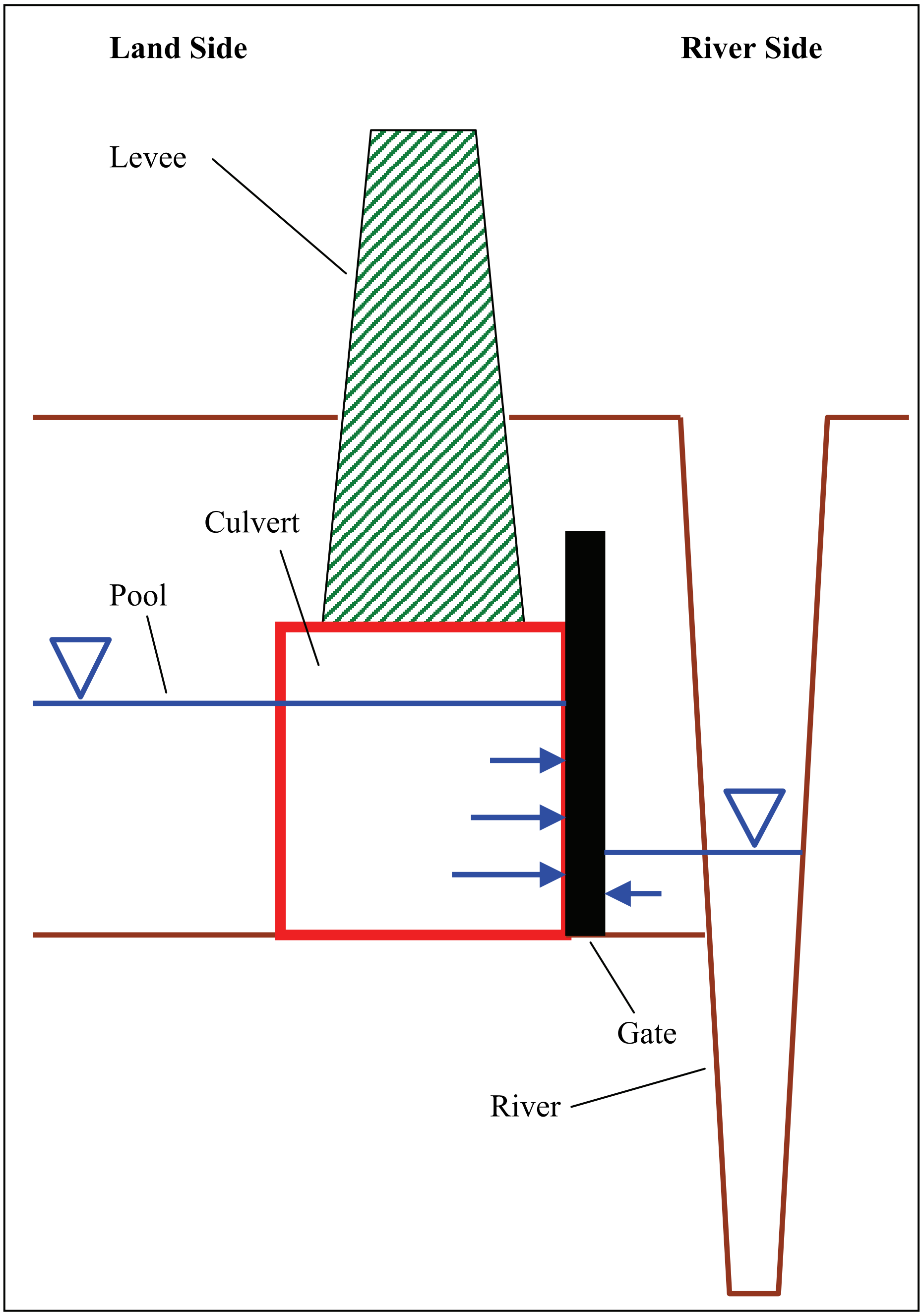

Figure D10. Forces on Shut Culvert Gate Due to High Land Side Pool.

In the simplest design, shown in Figure D-12, timber flashboards are stacked on top of each other until the desired crest elevation is achieved. Any excess water in the reservoir spills over the crest. If, for example, the five stacked flashboards shown in Figure D-12 were used to hold high water levels during the non-growing season, then the top two flashboards could be removed to set lower water levels for the growing season. If the pool needs to be lowered as much as possible for maintenance, all five flashboards could be removed.

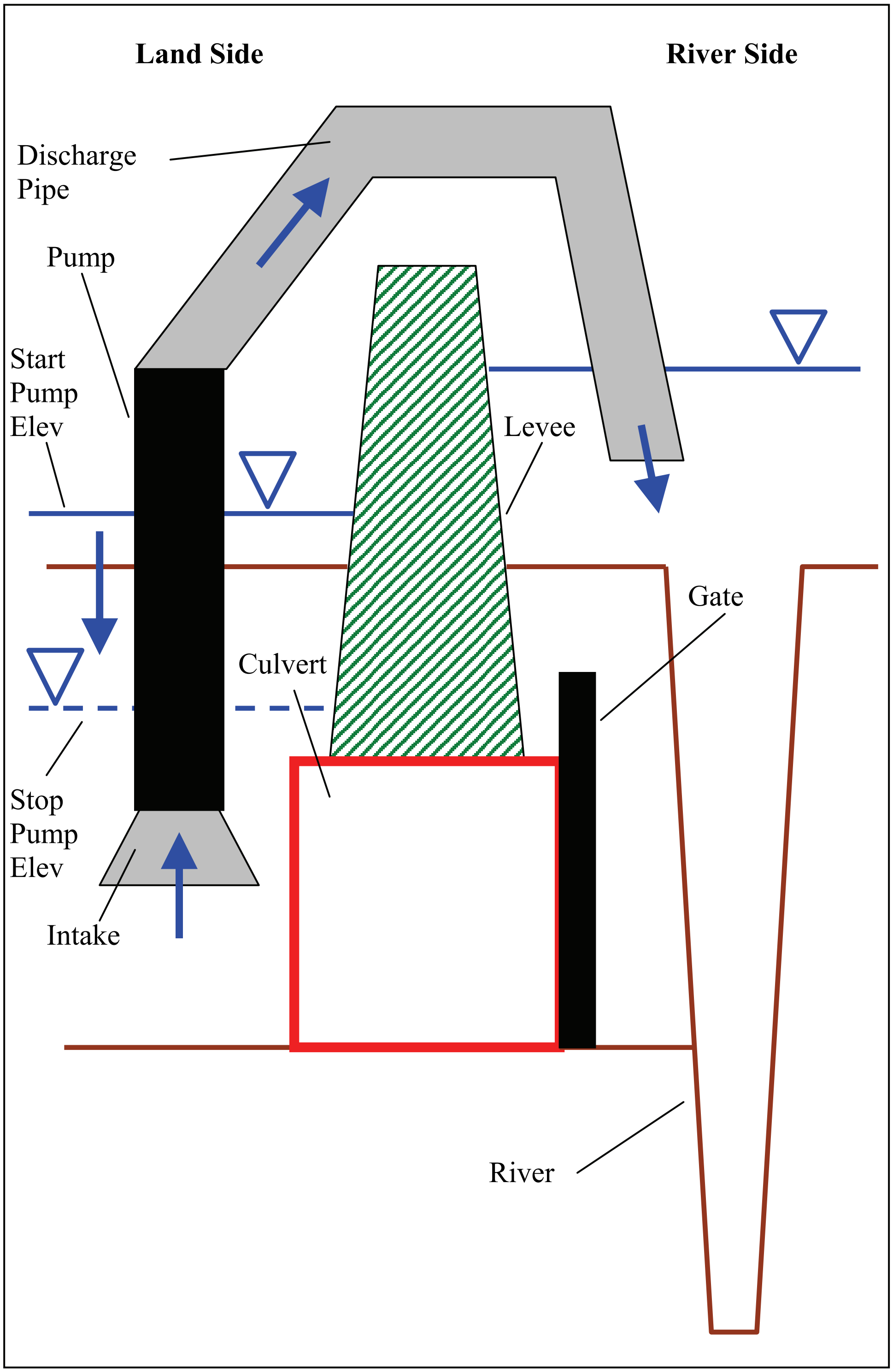

Figure D11. Flood Control Pumping Due to High River.

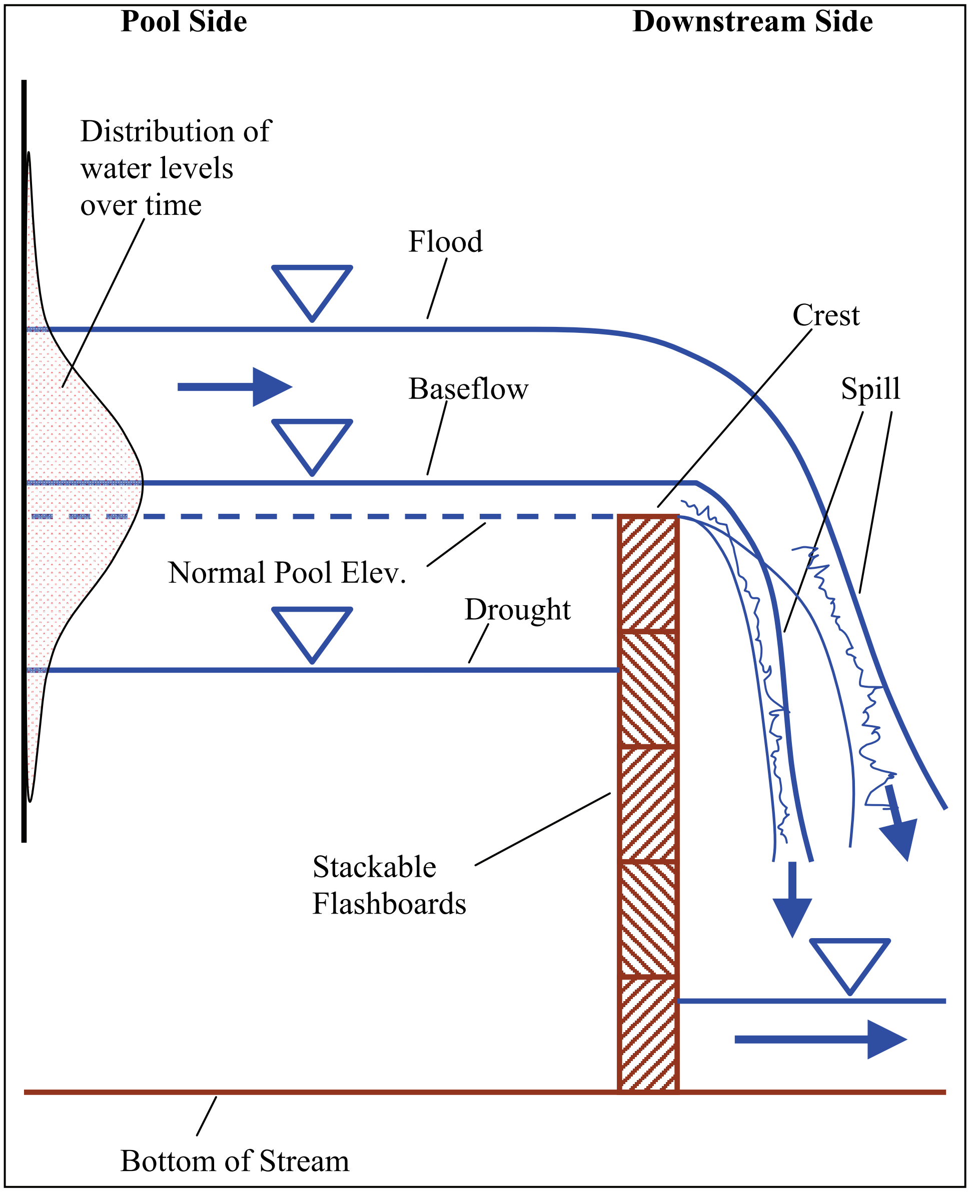

Figure D12. Flashboard Weir.

In general, the water surface elevation of the pool upstream of the flashboards ranges both above and below the normal pool elevation set by the crest of the flashboards. This range of water levels is illustrated by the bell curve to the left of the figure. Pool elevation occasionally rises to flood levels and occasionally falls below the flashboard crest due to drought; however, most of the time the pool level is near normal pool elevation, provided there is enough drainage area. The shorter the flashboard weir, the higher the pool will rise above normal pool elevation to pass flood-waters downstream, if tailwater level does not control. Continuous simulation can be used to estimate how high the pool will rise during floods of various magnitudes.

Pumped wells (control component)

Pumped wells control the level of the pool that the water is pumped into; they operate if the supply of direct rainfall and runoff to the pool is not sufficient. Pumped wells are a source of water that can be controlled seasonally to maintain a pool elevation within desired limits. Controlled pumped wells operate in an on/off cycle. As shown in Figure D-13, if the pool elevation drops to an elevation referred to as "start pump" elevation, the well pump is turned on. Pumping continues until the pool rises to an elevation referred to as "stop pump" elevation.

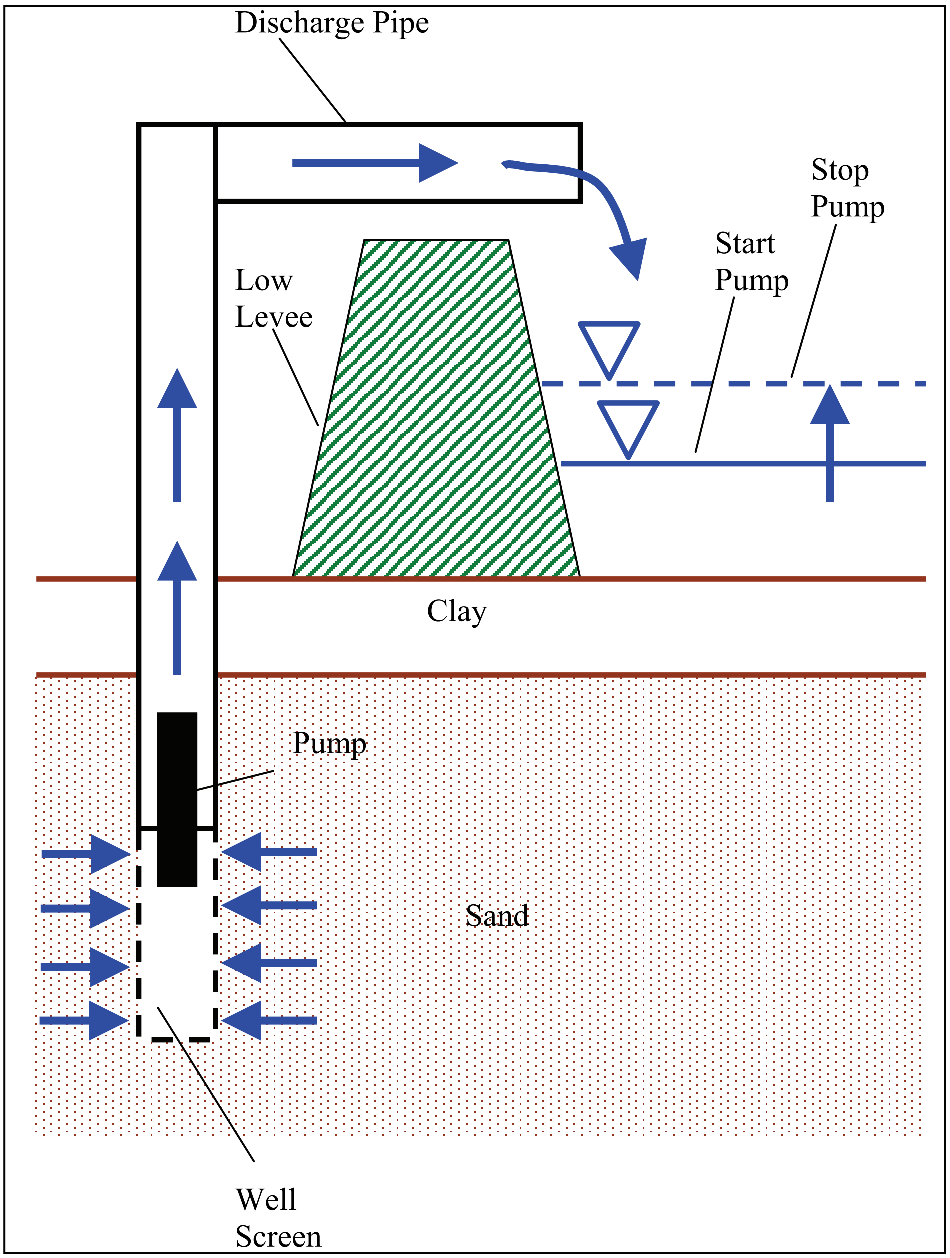

Figure D13. Pumped Well.

Levee underseepage (passive process)

Levee underseepage may be a source of water to an EnviroFish analysis site. As shown in Figure D-14, a high river level may drive water deep beneath a levee and cause seepage water to emerge on the land side of the levee and accumulate.

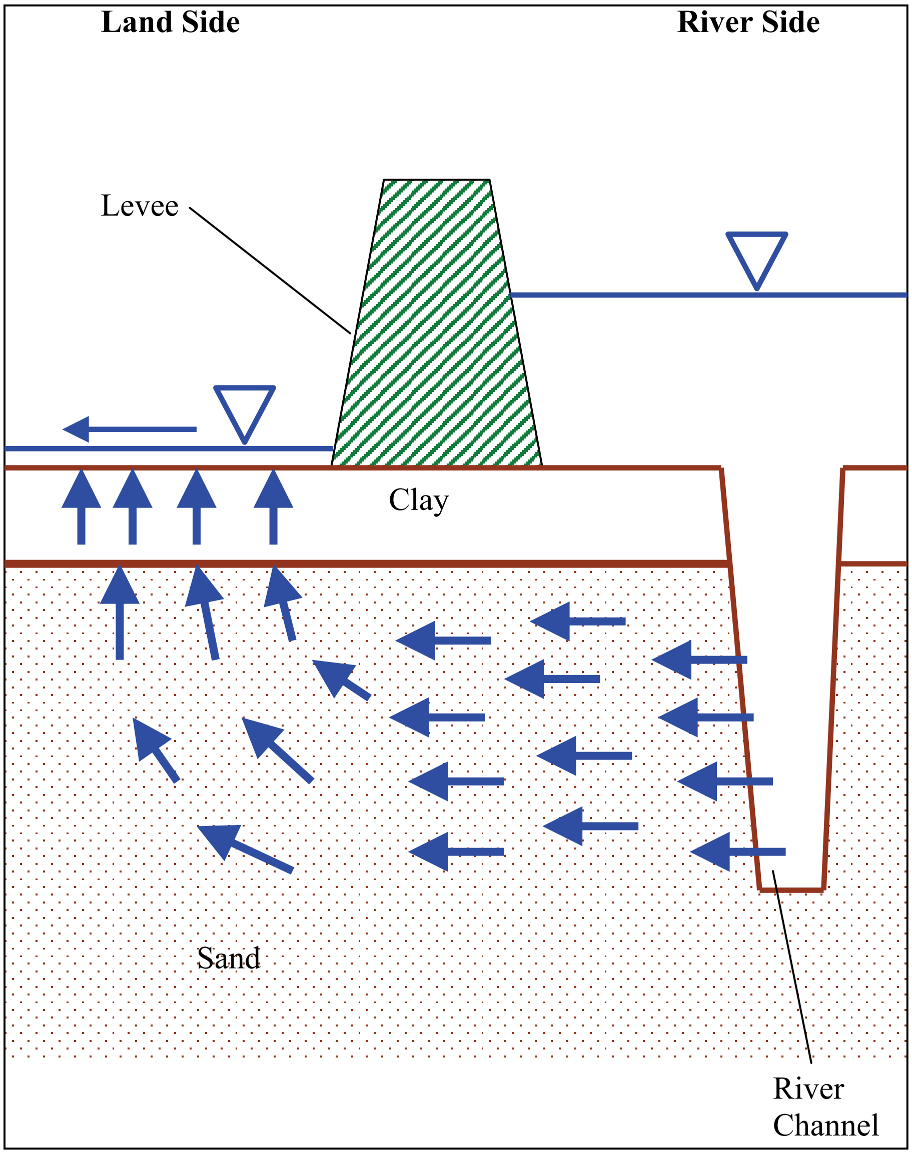

Figure D14. Levee Under Seepage Due to High River.

Levee underseepage is not desirable from a levee stability standpoint, and typically is kept to a practical minimum. Although the rate of seepage may be very low per unit length of levee, the accumulated volume can be significant for a long levee over an extended period of time.

There is no connection for fish between the river and the land side while underseepage occurs. Not only is the levee itself a barrier against fish movement, but the gate is also shut on any culvert through the levee.

To plan an EnviroFish analysis it is necessary first to estimate the amount of seepage, and secondly to include that seepage quantity in a continuous simulation model. One method to estimate seepage quantities is to identify a threshold water surface elevation in the river at which seepage begins on the land side of the levee. This method assumes that the rise in water level on the land side is negligible. For river elevations higher than the threshold, seepage is estimated in units of cubic feet per second per linear foot of levee per foot of river, with the water depth above the threshold elevation. If the daily water surface elevations in the river are independent of the operation of the project on the land side of the levee, then the daily seepage values can be calculated independently and input as time-series flows to the continuous simulation hydrologic model. HEC-RAS unsteady will accept such input, for example. It is also possible to devise a HEC-RAS unsteady model that calculates seepage while performing the overall continuous simulation.

Seepage wells (passive process)

Seepage wells are passive wells intended to allow levee underseepage to occur without damaging the levee. As shown in Figure D-15, the seepage water emerges from the well and accumulates on the land side of the levee. A certain amount of seepage may still emerge through the soil despite the action of the seepage well. Seepage wells may be sources of water for environmental restoration sites, flowing during the normal flood season of the river. The lack of pumping costs and controls is an attractive feature of seepage wells, although several wells may be needed to deliver the desired volume of water. The method for estimating the quantity of seepage via seepage wells and the introduction of the seepage quantities into a hydrologic model are similar to those described for levee underseepage.

HEC-HMS and HEC-RAS

Hydrology and hydraulics are two complementary approaches to describing water movement. Hydrology focuses on the volume and timing of water in movement, and on probability. Hydraulics focuses on the mechanics of water movement. In practice, it is difficult to keep hydrology and hydraulics separate, because the hydrologic aspects of a system must be known to

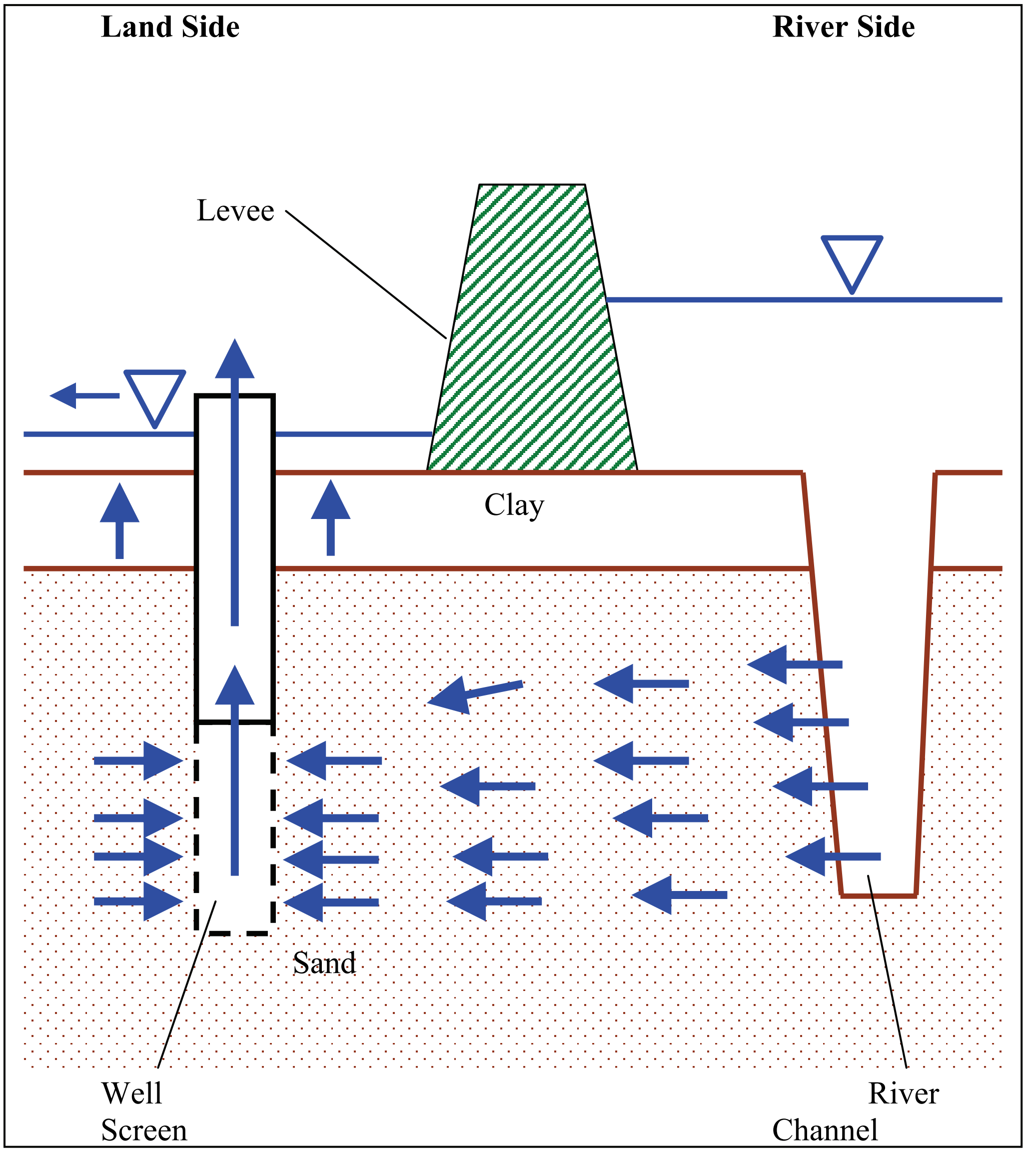

Figure D15. Levee Seepage Well.

characterize its hydraulic aspects, and the hydraulic aspects of a system must be known to characterize its hydrologic aspects. In this section, first the differences between hydrology and hydraulics are described; secondly, the HEC-HMS and HEC-RAS types of software are compared, as an aid in preparing a hydrologic plan for an EnviroFish analysis.

Hydrology

Hydrologic considerations involving an EnviroFish site may include:

1. runoff volume resulting from rainfall;
2. direct rainfall into a pool of water;

3. the varying rate at which runoff water flows into the site (described by the storm hydrograph);
4. evaporation from a pool of water;
5. evapotranspiration from soil;
6. the attenuation of flood hydrographs through a stream reach;
7. inflows and outflows due to seepage;
8. the availability of surface water or ground water to be diverted or pumped to the site;
9. floodplain storage;
10. baseflow; and
11. irrigation withdrawals and releases.

Hydrologic variables include volume, flow, and time. Volumes may be expressed as cubic feet, acre-inch, or acre-foot. Flow is typically expressed not as a velocity (e.g., feet per second), but as a volume rate, (e.g., cubic feet per second). Time scales vary from seconds to decades, depending on the needs of a particular analysis. The description of hydrologic events, both historical and synthetic, is facilitated by division of time into time steps. For example, a flood lasting 3 days, may be modeled by performing computations in time steps of five minutes, and then be described by reporting results in time steps of one hour. Hydrologic models may require short computational time steps to prevent the computations from going awry.

Hydraulics

Hydraulic considerations involving an EnviroFish site may include:

1. the water surface elevation in a stream at a point;
2. the curvature of a flowline along a length of a stream and the water surface elevations at various locations along the flowline;
3. the water surface elevation in a reservoir;
4. the speed of flowing water in a channel;
5. the resistance to flow caused by vegetation;
6. the required size and shape of spillways and culverts; and
7. the energy cost of operating pumps.

Hydraulic variables include area, velocity, flow, and time. Cross sectional flow area may be expressed in units of square feet. Velocity may be expressed in units of feet per second. Flow may be expressed in units of cubic feet per second. The use of time in a hydraulic analysis depends on whether the flow is considered steady or unsteady. A steady flow hydraulic analysis assumes that flow is known and remains constant. As an example, most FEMA flood insurance studies are based on steady flow hydraulic analyses of the stream and floodplain. The magnitude of the FEMA flood flows are derived from a hydrologic model, such as HEC-HMS. The HEC-HMS flows are then input into a hydraulic model, such as HEC-RAS, set to operate under steady state conditions. An unsteady hydraulic analysis assumes that flow is known, but changes through time. As with a hydrologic analysis, time is divided into time steps. Again, a flood lasting 3 days may be modeled by performing computations in time steps of five minutes, and then reported in time steps of one hour. Like hydrologic models, unsteady hydraulic models may require short computational time steps to prevent the computations from going awry.

+Comparison of HEC-HMS and HEC-RAS

HEC-HMS and HEC-RAS have the capability to be used to model many Enviro Fish sites. HMS has the ability to synthesize rainfall runoff flows, but is limited as a hydraulic software. RAS is a powerful hydraulic software, but cannot synthesize rainfall runoff flows. All flows must be provided to RAS. The significance of this is that HMS can be used as the sole modeling software for simple situations, but more complex situations will typically require the use of both HMS and RAS. HMS and RAS are described below, and a table of features is provided to facilitate comparison between the two software.

HEC-HMS is a hydrologic program, but it is capable of performing limited hydraulic computations, such as the flow over a weir or through a pipe spillway. HMS has the ability to synthesize rainfall-runoff flows in a continuous simulation covering a multi-year analysis period, and to route the flows through a system. HMS can serve as the only modeling software used to model EnviroFish sites with level pools, limited controls, and simple tailwater characteristics. HMS can model flood control pumps also. Although HMS may not explicitly provide for every possible flow source and control that can be encountered in an EnviroFish analysis, an experienced modeler can use available HMS features to simulate many aspects of a site.

HEC-RAS is a hydraulic program, but, in unsteady mode, it is capable of performing flood wave routing through a system. Like HMS, RAS can perform a multi-year, daily continuous simulation. RAS cannot calculate rainfall runoff flows like HMS, but can accept runoff flow values previously calculated using HMS, and route them through a system. HMS is more powerful than HMS in dealing with complex controls and complex tailwater characteristics. Like HMS, RAS can model flood control pumps. RAS is not limited to modeling level pools, but can calculate curved flowlines throughout an open channel system. An experienced modeler can use RAS to realistically model situations that are not explicitly listed among the software capabilities. If need be, seasonal changes in controls can be modeled in RAS by performing a chain of analyses through each season of a multi-year analysis period.

Table D-1 lists some of the features of HMS and RAS that can be of importance in an EnviroFish analysis. Comparison of these features can be helpful in selecting software to be listed in the hydrologic plan. Table D-1 indicates there is much overlap in the capabilities of the two types of software; however, an experienced modeler is needed to point out the feasibility of using HMS or RAS for a particular task.

Table D-1. Comparison of HEC-HMS and HEC-RAS Features Related to an EnviroFish Analysis.

Feature	HEC HMS 3.4	HEC RAS 4.0 Unsteady
Continuous simulation of rainfall-runoff	X	
Level pool routing	X	X
Culvert hydraulics	X	X
Weir hydraulics	X	X
Gated culverts	X	X
Pump stations (flood control)	X	X
Flowlines		X

Assembling the Hydrologic Plan

The topics described in this appendix facilitate the development of a hydrologic plan for an EnviroFish analysis. The planner needs to consult repeatedly with experienced hydrologic and hydraulic modelers as the overall EnviroFish plan develops. Figure D-16 and Figure D-17 are example worksheets for an EnviroFish hydrologic plan.

Worksheet 1 of 2, shown in Figure D-16, is used to classify the site hydrologically and to list available hydrologic and meteorological data. Under the site classification heading, there are four selections. The

Enviro Fish Hydrologic Plan, Worksheet 1 of 2
Site Classification and Data

Item	Exist	Future w/o Proj	Alt 1	Alt 2
Site Classification				
uncontrolled & dependent tailwater				
uncontrolled & independent tailwater				
controlled & dependent tailwater				
controlled & independent tailwater				
Hydrologic / Meteorological Data				
stage, river, period of record:		---	---	---
stage, landside, period of record:		---	---	---
stage, other: , period of record:		---	---	---
stage, quality--can the data be used as input to Enviro Fish without hydrologic modeling?				
rainfall, period of record:		---	---	---
evaporation, pan, period of record:		---	---	---
other: , period of record:		---	---	---
other: , period of record:		---	---	---
analysis period, beginning year: ending year:	same	same	same	same

Figure D16. Hydrologic Plan Worksheet, Sheet 1 of 2.

Enviro Fish Hydrologic Plan, Worksheet 2 of 2
Hydrologic Software to Use for Continuous Simulation

Control Components & Passive Processes	HEC-HMS	HEC-RAS Unsteady	Other Software	Exist	Future w/o Proj	Alt 1	Alt 2
none (Enviro Fish will use only historical stage data as input)	---	---	---				
runoff, synthesize daily rainfall-runoff							
routing, level pool							
routing, sloping water surface							
gated culvert, flood control only, no seasonal variations							
gated culvert, flood control and seasonal variations in operation and/or holding pool on land side of levee							
flashboard weir, with seasonal variation in crest elevation							
levee under seepage, synthesize daily inflows							
levee seepage wells, synthesize daily inflows							
pumping, flood control, no seasonal control							
pumping, flood control, with seasonal variation in operation							
pumping, water supply wells, with seasonal variation in operation							
other:							

Figure D17. Hydrologic Plan Worksheet, Sheet 2 of 2.

classification that is suitable for existing conditions may not be suitable for the future without project conditions or for project alternatives. Under the data heading, the availability of stage data is documented. The availability of both landside and riverside data should be determined for projects involving a levee. The quality and continuity of the data should be determined. The suitability of the data for direct input to EnviroFish should be determined. Determination of the availability of meteorological data, such as rainfall and evaporation, may be required. Finally, the period of years selected for analysis should be identified, which may be a small subset of the period of record. The reasons for the adoption of the analysis period should be documented.

Worksheet 2 of 2, shown in Figure D-17, is used to identify which types of software will be used to perform specific hydrologic and hydraulic modeling tasks for existing conditions and project alternatives. HEC-HMS and HEC-RAS are the types of software normally used in Corps projects, but other software may be useful for modeling a site. The components and passive processes appropriate for existing conditions may not be appropriate for project alternatives.

Worksheet 1 and Worksheet 2 are examples of hydrologic planning aids. The planner of an EnviroFish analysis should devise worksheets that are appropriate for the site. The process of recognizing the hydrologic setting, collecting and evaluating data, and planning the use of modeling techniques, although time consuming and laborious, is essential for planning an EnviroFish analysis that is feasible, accurate, and defensible.

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14. ABSTRACT

EnviroFish is both a modeling approach and a computer software. As a modeling approach, EnviroFish estimates the value of floodplain habitat suitable for fish reproduction under a given set of hydrologic and hydraulic conditions. As a software, EnviroFish is a Java computer program facilitating the application of the modeling approach. This manual describes both the modeling approach and the software.

The EnviroFish approach integrates hydrology, hydraulics, land use, and empirically based knowledge of fish reproductive strategies in riverine floodplains to predict a biological response to different flooding scenarios suitable for standard federal planning processes. EnviroFish can be used to calculate Habitat Units for specific floodplain habitats, with each habitat providing different values for spawning and rearing fishes. In order of least to most preferred habitats, are agricultural fields, fallow fields, bottomland hardwood forests, and floodplain waterbodies. EnviroFish was initially developed for flood control projects in the lower Mississippi River Valley. However, the approach is applicable to any alluvial river system where floodplain fish spawning habitat is being managed, mitigated, or restored, by determining applicable land use categories and HSIs for representative fish species.

The EnviroFish software is designed to directly accept data in the Corps of Engineers Data Storage System (DSS) file format. EnviroFish calculates ADFA for an array of project alternatives. The user specifies values of hydraulic criteria (flooding depth and duration) for successful spawning and rearing of fishes and also specifies land use categories to calculate ADFA.

This User's Manual discusses the biological basis of EnviroFish, elements of the model, using the software, application considerations, and an example problem.

15. SUBJECT TERMS

EnviroFish	Flood control	Hydraulics
Fish reproduction	Floodplain fish spawning habitat	Hydrology
	HEC Data Storage System (DSS)	Land use

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