Analysis of Instream Flows for the Sulphur River: Hydrology, Hydraulics & Fish Habitat Utilization

Final Report

Volume I – Main Report

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Executive Summary

This report addresses potential impacts of water development projects to the hydrology, aquatic habitat and flood plain in the Sulphur River basin. Proposed main-channel reservoir projects in the basin have the potential to cause significant changes to the hydrological regime and information presented in this report will aid future planning efforts in determining the magnitude of the changes.

Regional characteristics of the Sulphur River basin are presented along with historical stream flow records that are analyzed for changes in historical flow regime over time. Recent and historical studies of the fisheries of the lower Brazos River are reviewed and discussed. A total of five different analyses on two different datasets collected in the Sulphur River basin are presented. Two Texas A&M University (TAMU) studies were based upon fish habitat utilization data collected in two areas of the Sulphur River over one season. One area, downstream of the confluence of the North and South Sulphur Rivers, was channelized and the other area, downstream of the proposed Marvin Nichols I Reservoir site, was unchannelized. Two additional TAMU studies were based upon fish habitat utilization data collected in two areas (channelized and unchannelized) of the South Sulphur River near the proposed George Parkhouse I Reservoir site. A fifth analysis completed by the Texas Water Development Board (TWDB) compared all data collected for the earlier four TAMU studies on a common basis. Four analyses showed the fish communities to be composed largely of habitat generalists, while the fifth showed some degree of specialization. Rare species were identified and habitat utilization of fluvial specialists were investigated.

To aid future efforts to quantify the effects of a change in flow regime on the availability of fish habitat on the Sulphur River, two representative stream segments were chosen: Site 1 was located on the main stem Sulphur River just downstream of the confluence of the North and South Sulphur Rivers, and Site 2 was located on the short stretch of the main channel between the proposed dam site and the upper reaches of Wright Patman Reservoir. A spatial habitat model was developed for each site capable of mapping hydraulic mesohabitats and structural habitats. Two-dimensional hydraulic models were developed for both sites to quantify depth and velocity variation within each study reach. The habitat model was applied to depth and velocity data in order to quantify the area of available habitat for a range of flow rates.

To investigate the significance of flow regime on the flood plain riparian areas, the area of inundation was quantified for six frequently-occurring flood events. The flood events ranged from that historically occurring once every three years to events that occur several times a year, each event lasting at least 14 continuous days. A previous contract study enabled the inundated area of each vegetation type in the basin (e.g., bottomland hardwood forest, Oak-Hickory forest, etc.) to be quantified, and the analysis presented in this report enabled the frequency and duration of occurrence of inundation to be quantified. Additional field data would improve this preliminary analysis.

This report describes preliminary and necessary steps required to complete a full instream flow study. Conclusions based on these studies are discussed and recommendations are made for design and implementation of future studies that will establish flow regime recommendations for maintenance of instream flows. Future studies are to be conducted under directives of Texas Senate Bill 2 with the cooperation of the Texas Parks and Wildlife Department, Texas Commission on Environmental Quality and interested cooperators.

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1. Introduction

Four water development projects have been proposed in the Sulphur River basin (Figure 1.1). Two projects have been proposed in the Upper Sulphur River basin: George Parkhouse I Reservoir located on the South Sulphur River just downstream of the existing Jim Chapman Lake, and George Parkhouse II Reservoir located on the North Sulphur River just upstream of the confluence with the main stem Sulphur River. George Parkhouse II was recommended in the 1997 Texas Water Plan, but was not recommended in the 2002 Texas Water Plan. In the lower Sulphur River watershed, two projects have been proposed. Marvin Nichols I reservoir is proposed for the main stem of the Sulphur River and the alternative Marvin Nichols II reservoir was proposed for White Oak Creek. Marvin Nichols I reservoir is recommended in the 2002 Texas Water Plan to meet the state's water needs by 2050. Marvin Nichols II reservoir is no longer proposed and portions of the area have been designated a wildlife management area.

This study, partially funded by the US Army Corps of Engineers, Fort Worth Disctrict (USACE), evaluates instream fish habitat utilization for four sites in the Sulphur River basin, and also evaluates frequency, duration and spatial extent of common flood flows. The goal of the instream flow analysis presented in this report is to provide tools to effectively determine the instream flow regime required to maintain sound instream and riparian ecosystems.

The availability of fish habitat over a range of flows in the Sulphur River can be used to assess the potential impacts of changes to the flow regime that result from development projects. Fish community health is a good indicator of overall ecosystem health because fish communities integrate properties of the entire watershed. Fish are relatively long-lived, widespread and easy to identify; they live in a variety of habitats and occupy a range of trophic levels (Perry and Vanderklein, 1996). Alterations in the flow regime result in a change in availability of fish habitat and these changes in habitat cause changes (potentially positive or negative) in the fish community; therefore, management of fish habitat increases the likelihood of a healthy fish community. A healthy aquatic system includes far more features of biological interest than just fish; however, because of the complexity of biological interactions and the extensive data collection effort required, very few instream flow studies have considered all biological aspects of a river.

To determine the abundance and spatial distribution of fish species within each of the habitats of each reach, two biological field surveys on a total of 13 sampling sites were conducted by researchers at Texas A&M University (TAMU). The fish collection surveys included measurements of velocity and depth of water where the fish were sampled, habitat observations and classifications, and information on channel geomorphic conditions (including channelized versus unchannelized classification). Collections targeted high, medium and low flow conditions in both summer and winter seasons.

Five separate analyses have been performed on the fisheries datasets collected for this study. Gelwick and Morgan (2000) analyzed fish habitat utilization based upon visually classified mesohabitats and upon structural habitat at two locales in the mainstem Sulphur River for two seasons spanning 1998 and 1999. Data was collected at an upstream channelized area located just downstream of the confluence of the North and South Sulphur Rivers to investigate potential impacts of the proposed Parkhouse projects, and data was collected in an unchannelized downstream area downstream of the proposed Marvin Nichols I site. Using a data subset of that study, Morgan (2002) investigated fish habitat utilization during low-flow summer events. Gelwick and Burgess (2002) analyzed fish habitat utilization based upon visually classified mesohabitats and upon structural habitat at two locales on the South Sulphur River, in the vicinity of the proposed George Parkhouse I reservoir site. This field study spanned two seasons between 2001 and 2002. Using a subset of data collected during that study, Burgess (2003) investigated fish habitat utilization based upon habitat heterogeneity for summer low flow conditions. The results of these four studies are described in more detail in this report.

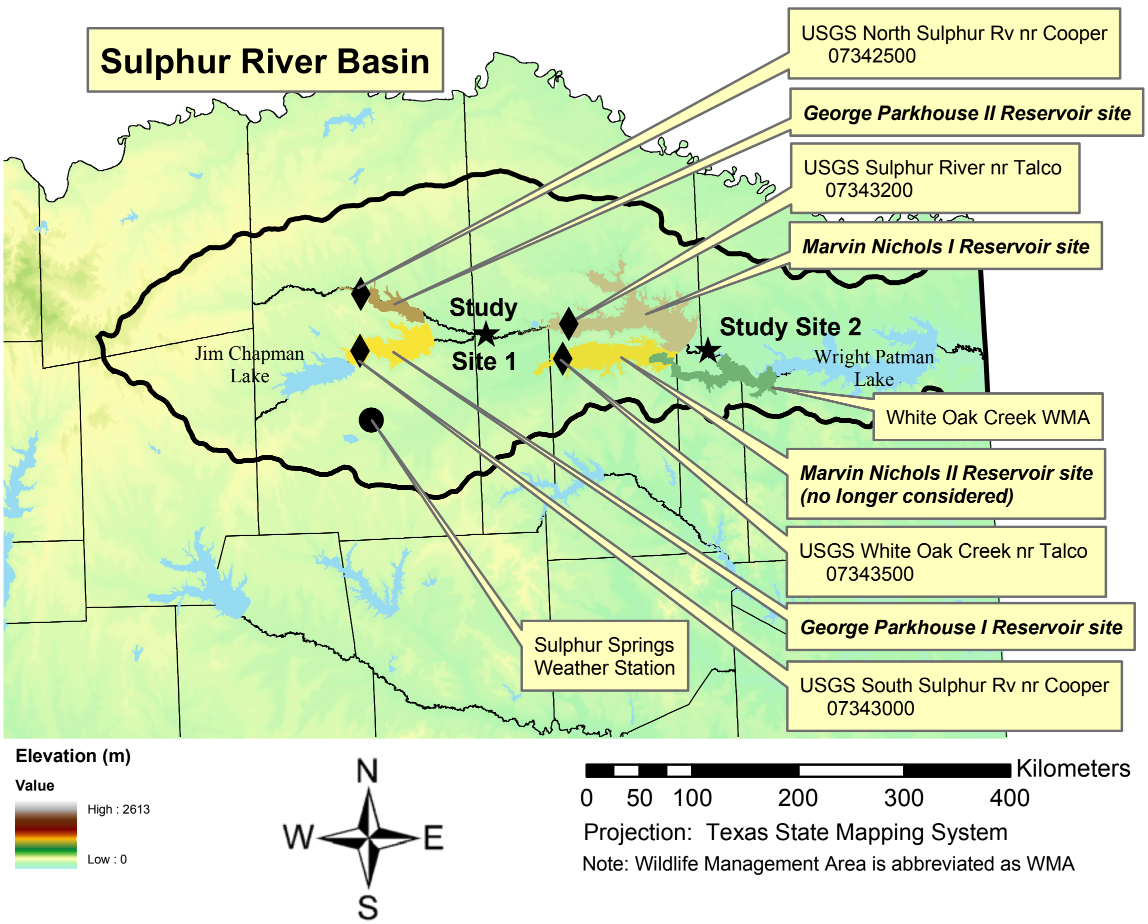

Figure 1.1 - Sulphur River basin and points of interest

The Texas Water Development Board (TWDB) conducted a fifth analysis for the purpose of investigating the data on an area-specific basis. A total of four study areas were defined based upon location of 13 field collection sites. Data presented in the Gelwick and Morgan (2000) Sulphur River study was divided into a channelized area (4 biological study sites) and an unchannelized area (3 study sites). Data presented in the Gelwick and Burgess (2002) South Sulphur River study was similarly divided into channelized (3 biological sites) and unchannelized (3 study sites) areas. Data for all sampling events, all seasons and all flows were included in the TWDB investigation.

Physical channel geometry, flow measurements and variation of water surface elevation with flow (boundary conditions used to develop the hydraulic model) were collected by TWDB in separate field study efforts at two study sites (Site 1 and Site 2; see Figure 1.1) that encompassed 4 of the Gelwick and Morgan (2000) biological sampling sites. The biological data and hydraulic model outputs were combined to determine the variation of habitat area with changing flow. Quantitative assessments are provided for the area of available mesohabitat and structural habitat at each analyzed flow at each of the study sites. This information will aid in future determinations of the effects of a change in flow regime on available habitat.

A preliminary analysis of high-frequency flood events is also presented that quantifies area of inundation, frequency of inundation, duration of inundation and area of vegetation impacted by inundation. Six high-frequency flood events are evaluated representing ordinary high flow events occurring with a typical frequency of less than 3 years. Additional data is required to improve this analysis for use in future management decisions; however, the analysis serves as an indicator of the magnitude of potential impacts.

1.1 Proposed water development projects

Four reservoir projects have been proposed and recommended for legislative protection in the Sulphur River basin (TWDB 2002). A brief overview of these projects is presented below.

1.1.1 George Parkhouse I and II

The George Parkhouse I reservoir project has been proposed for construction on the South Sulphur River, just upstream of the confluence of the North and South Sulphur Rivers, and downstream of the existing Jim Chapman Lake reservoir on the South Suphur River. The George Parkhouse II reservoir project has been proposed for construction on the North Sulphur River, just upstream of the confluence of the North and South Sulphur Rivers. Both projects were recommended for legislative designation as a unique reservoir site in the 2002 State Water Plan, but neither is recommended by the North East Texas Planning Group.

1.1.2 Marvin Nichols I and II

The proposed Marvin Nichols I reservoir site is located at river mile 114.7 on the main stem of the Sulphur River upstream of its confluence with White Oak Creek, in Red River and Titus Counties about 120 miles east of the City of Dallas and about 45 miles west of the City of Texarkana. According to the 1997 State Water Plan, the potential beneficiaries of the Marvin Nichols I reservoir include municipal and industrial water users in the vicinity of the project within the Sulphur River basin, water users in the Cypress Creek Basin, and/or water users in the Dallas-Ft. Worth Metroplex. Other potential benefits include recreation, hydroelectric power generation, and flood control.

The yield of the proposed reservoir is dependant on the release requirements that will be identified through this and other work, and on the potential development of either of the Parkhouse projects in the upper basin. The 1997 State Water Plan states the yield of Marvin Nichols I reservoir is likely to be more than 550,000 ac-ft, quite high compared to reservoirs of similar volume in Texas. The local climate, the flashy hydrology of the drainage basin, and the fact that the reservoir is to be located on the main channel are all factors that contribute to the reservoir's high yield and offset the evaporative losses of the proposed broad, shallow reservoir. The Marvin Nichols I Reservoir was recommended by the North East Texas Regional Planning Group D (TWDB 2002); however, the planning group passed an amendment in December 2002 to change the "recommended" status of the Nichols I project to "potential."

Marvin Nichols II Reservoir was formerly proposed as an in-channel reservoir located on White Oak Creek, just upstream of the confluence of White Oak Creek and the Sulphur River. Marvin Nichols II is no longer considered for construction and a portion of the previously proposed area has been designated as the White Oak Creek Wildlife Management Area.

2. Regional description

Figure 2.1 shows the geographic location within Texas of the Sulphur River basin. Figure 1.1 shows the proposed reservoir sites, representative weather stations, and the USGS Talco stream gauge. Land-resources, geology and land cover/land use maps for the Sulphur River basin are shown in Figures 2.2 through 2.4.

2.1 Sulphur River basin

The Sulphur River is a relatively small river basin in the State of Texas with a drainage area totaling approximately 9,211 square kilometers (3,558 square miles). Water in the Sulphur River flows into the Red River within the boundaries of the State of Arkansas. White Oak Creek, which has a drainage area of 794 square kilometers (494 square miles), is the only major tributary of the Sulphur River, and its confluence is just upstream of the existing Wright Patman Reservoir, downstream of the proposed Marvin Nichols I project.

Three smaller channels join to form the main channel of the Sulphur River: the North Sulphur River, the Middle Sulphur River, and the South Sulphur River. All three forks have headwaters in Fannin County and all traverse approximately 80 km (50 miles) before their confluence. The North Sulphur River drains eastward along the Delta and Lamar County line to the confluence with the South Sulphur River. The Middle Sulphur River drains southward approximately 37 km (23 miles) through Hunt County then turns east through Delta County to its confluence with the South Sulphur River. The South Sulphur River drains southward approximately 57 km (35 miles) through Hunt County then east along the Hopkins and Delta County line, passing through Jim Chapman Lake, to its confluence with the Middle Sulphur River. Continuing along the same county line, the South Sulphur River traverses an additional 40 km (25 miles) east to its confluence with the North Sulphur River. All distances mentioned above are approximate straight-line horizontal distances, not river miles.

The Sulphur River and tributaries flow through two distinctly different land resource areas (based on NRCS classification). The upper reaches, encompassing the proposed Marvin Nichols I and George Parkhouse I Reservoir sites, are within the Blackland Prairie area, while the lower reaches downstream of the proposed reservoir sites lie within the West Gulf Coastal Plain area. Soils of the Blackland Prairie are predominantly silty clay and clay, topography is generally flat, and the region is used primarily for agriculture (Bureau of Economic Geology 1992). Different from the Blackland Prairie, soils within the West Gulf Coastal Plain are predominantly sandy clay soils associated with the Wilcox formation, topography is characterized by gentle rolling hills, and forestry is the major land use.

The river basin lies within three geological regions that are sedimentary in origin primarily characterized by the Navarro and Taylor Groups within the northwestern part of the basin and the Claiborne Group within the southeastern part of the basin (Figure 2.3).

Ewing (1991) described the tectonic features of Texas, including the Sulphur River basin, and the accompanying tectonic map of Texas (northeast quadrant) shows that the Talco Fault Zone clearly crosses the Sulphur River about where the Blackland Prairie and West Gulf Coastal Plain land resource areas separate. During field reconnaissance of the Sulphur River basin, we noted a change from the silty clay to sandy clay substrate composition below the proposed Marvin Nichols Reservoir site on the Sulphur River. Fault zones frequently result in changes in slope, where coarser sediments collect (Greg Malstaff, Geomorphologist with the TWDB, personal communication). It is important to tie in as many features as possible in the soil, geology, vegetation, and land use characteristics of a river basin in order to understand the resulting ecological functions.

The Sulphur River also flows through two of the seven biotic provinces of Texas based on those established by Blair (1950), including the Texan (George Parkhouse I site), and Austroriparian (Marvin Nichols I site). The classification of aquatic habitats within the state is based on these biotic provinces (Edwards et al. 1989). There exist a number of ecosystem classifications that relate to the different ecosystems that the Sulphur River flows through. For instance, Gould (1960) classified the Sulphur River basin into three major ecological regions, which are from west to east the Black Prairies, Post Oak Savannah, and Pineywoods; TPWD (http://www.tpwd.state.tx.us/images/tx-eco95.gif) describes 11 ecoregions of Texas, three of which are within the Sulphur River basin, including the Blackland Prairie, Oak Woods & Prairies, and Piney Woods; and McMahan et al. (1984) describe several vegetation types within the Sulphur River basin. The ecosystem type delineations are generally based on physiognomic designations and vegetative cover.

Instream uses of the Sulphur River near the confluence of the South Sulphur and North Sulphur Rivers include aquatic life, contact recreation and fish consumption. Instream uses of the Sulphur River in the vicinity of the proposed Marvin Nichols I Reservoir project include contact recreation, aquatic life, and fish consumption. There are no state parks located in the vicinity of the proposed reservoir; however, the White Oak Creek Wildlife Management Area is located near the confluence of White Oak Creek and the Sulphur River just upstream of Wright Patman Lake. Steep riverbanks limit access to the river for recreational boating. The river has a high turbidity level due to the highly erode-able soils in the watershed.

Located more than 200 river miles from the coast, the Sulhpur River does not have a legally binding inflow requirement. The river flows into Wright Patman Reservoir downstream of the proposed reservoir site, and then flows into the Red River in Arkansas, turning south into Louisiana, and eventually flows into the Mississippi River.

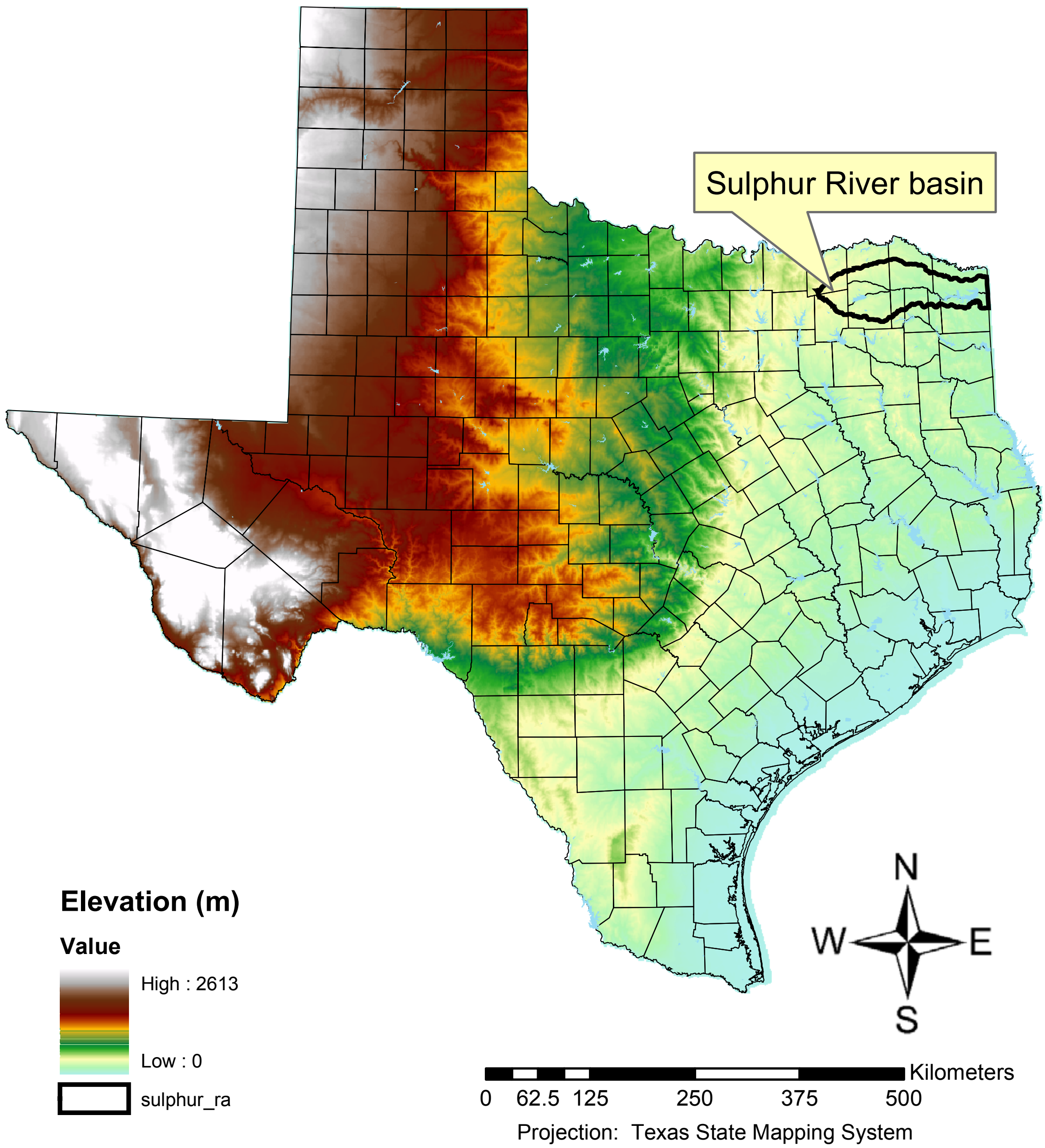

Figure 2.1 - Elevation contour map for Texas and location of Sulphur River basin

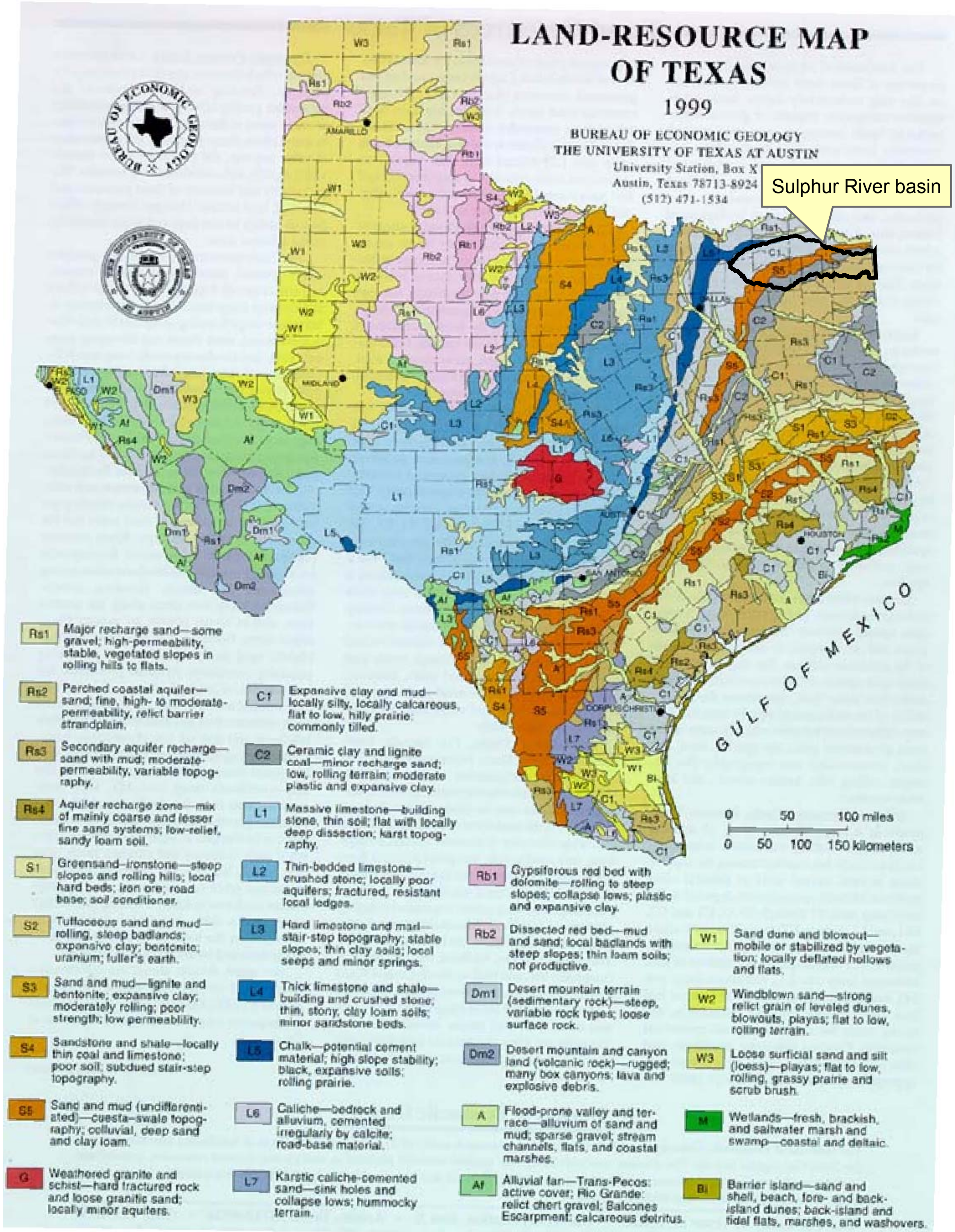

Figure 2.2 - Land resource map of Texas and the Sulphur River basin

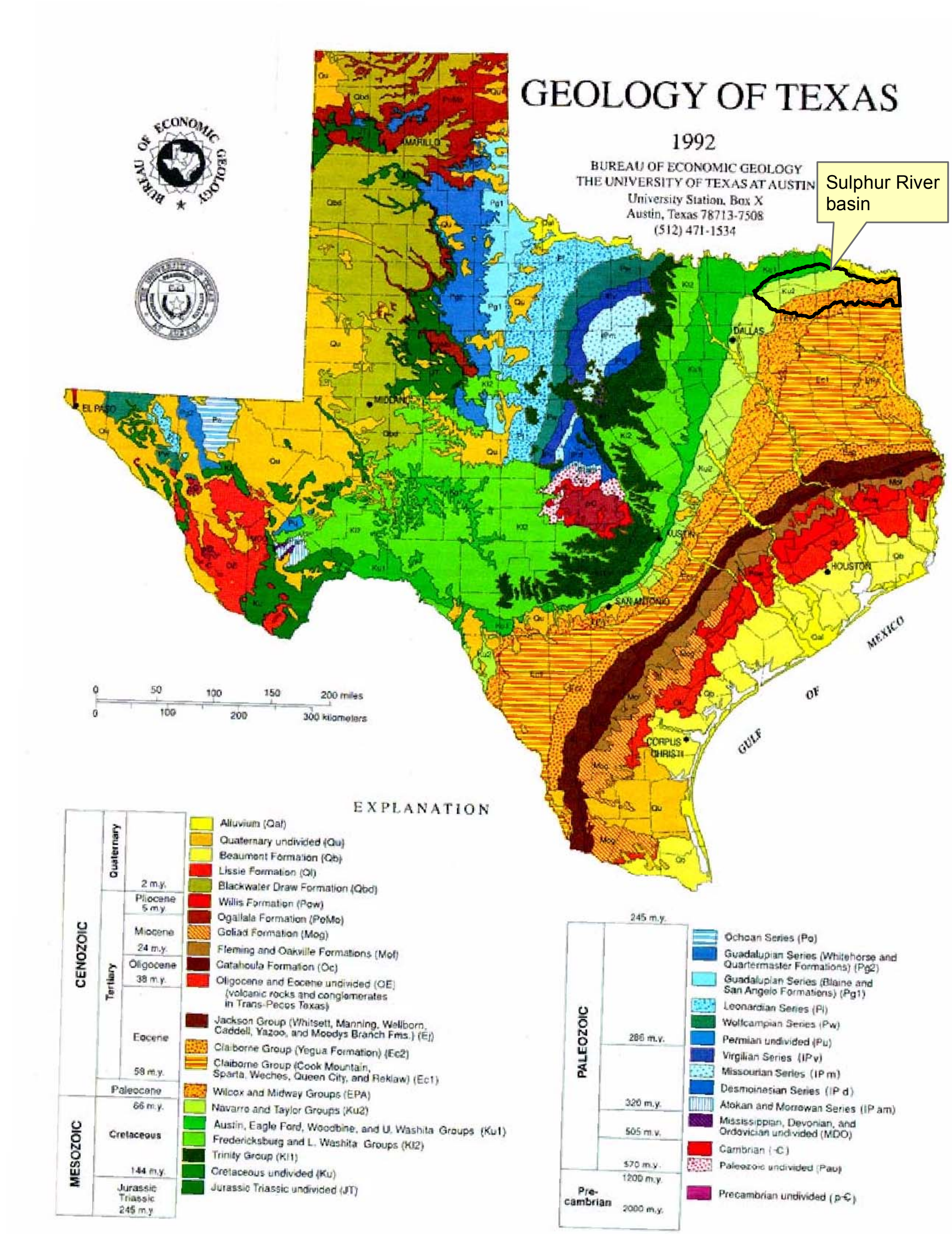

Figure 2.3 - Geological map for Texas and the Sulphur River basin

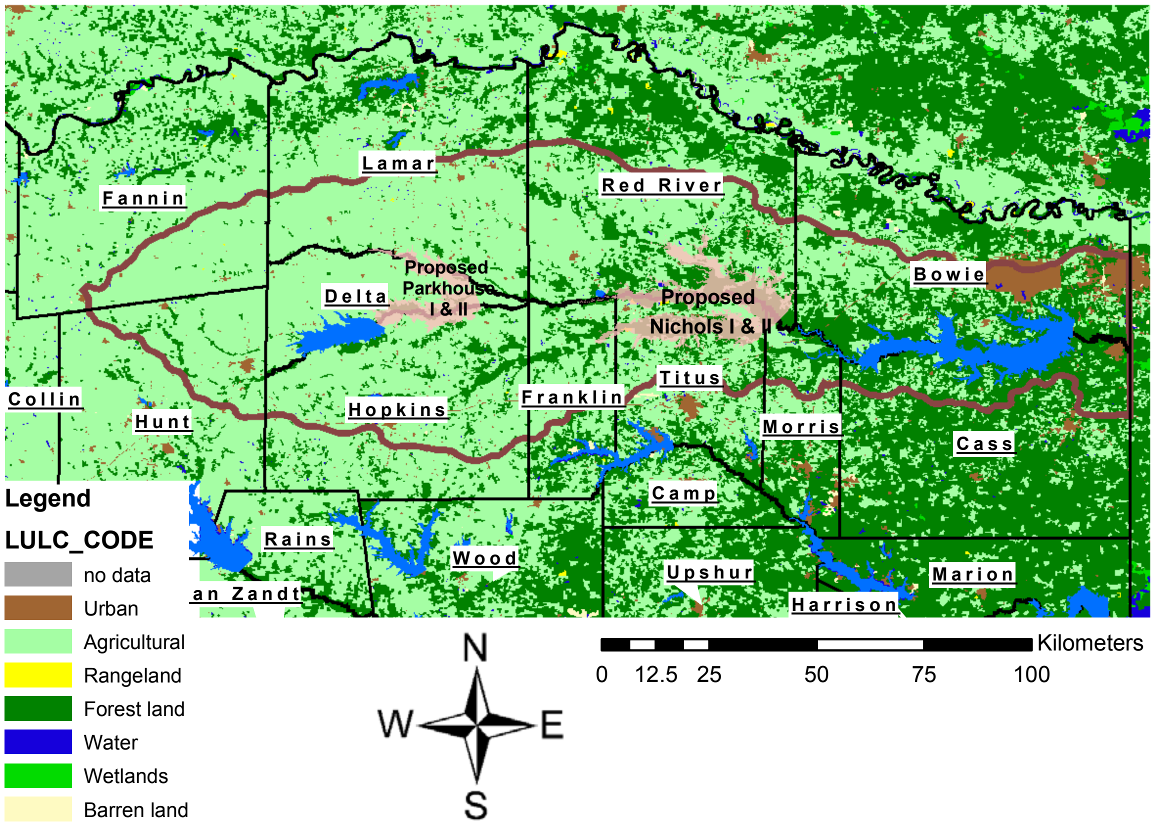

Figure 2.4 - Land Cover and Land Use in the Sulphur River basin. Counties in Texas are noted.

2.2 Climate

The average annual rainfall compiled using many available sources, including National Climatic Data Center station 20025542, and this station is generally representative of rainfall patterns existing in the Sulphur River watershed above Wright Patman Lake. Average annual rainfall in the TWDB quadrangle region 412 (Jia 2002), is 46.87 inches. Heavier rains generally occur during the late spring. Average rainfall by month is shown in Figure 2.5. Temperatures are illustrated in Figure 2.6.

2.3 Land use

Land use in the Sulphur River basin is comprised primarily of crops (17.6% of the basin), pasture (54.3 %), and timber (23.9%) (Figure 2.4). Most of the floodplains near the river have been cleared for use as pasture. Most croplands are located in the uplands, on an upper terrace of the river, or behind a levy for protection from the frequent flood events. The middle-to-western portion of the watershed area, that along the main stem of the river and within the proposed Marvin Nichols I Reservoir inundation area, remains in timber. Land use within the proposed George Parkhouse I and II reservoir inundation area is predominantly agriculture, with some forest. This area is flat, with frequent and prolonged flooding that occurs primarily in the winter months.

2.4 Soils and erosion

The Sulphur River flows through three ecoregions of Texas, including the Blackland Prairie, Post Oak Savannah, and Pineywoods. The eastern 55% of the Sulphur basin from the headwaters in Fannin County to proposed upper reaches of Marvin Nichols I Reservoir lies in the Blackland Prairies. Soils are predominantly silty clay and clay, topography is generally flat, and the region is used primarily for agriculture.

The western 45% of the Sulphur basin, from State Highway 37 near the upper reaches of proposed Marvin Nichols I Reservoir and east to the state line, lies in the West Gulf Coastal Plain. Soils are predominantly sandy clay soils associated with the Wilcox formation. Topography can be characterized as gentle, rolling hills.

Some segments of the North, South and upper main stem Sulphur Rivers were straightened and levied to control flooding. Evidence of channel erosion and incision exists in some areas.

In the entire basin, gully and stream bank erosion account for almost 50% of the eroded material produced, and sheet and rill erosion processes account for just over 50% of sediment produced (Greiner, 1982). The channelized portions of the upper basin contribute almost 70% of the total sediment produced in the entire basin.

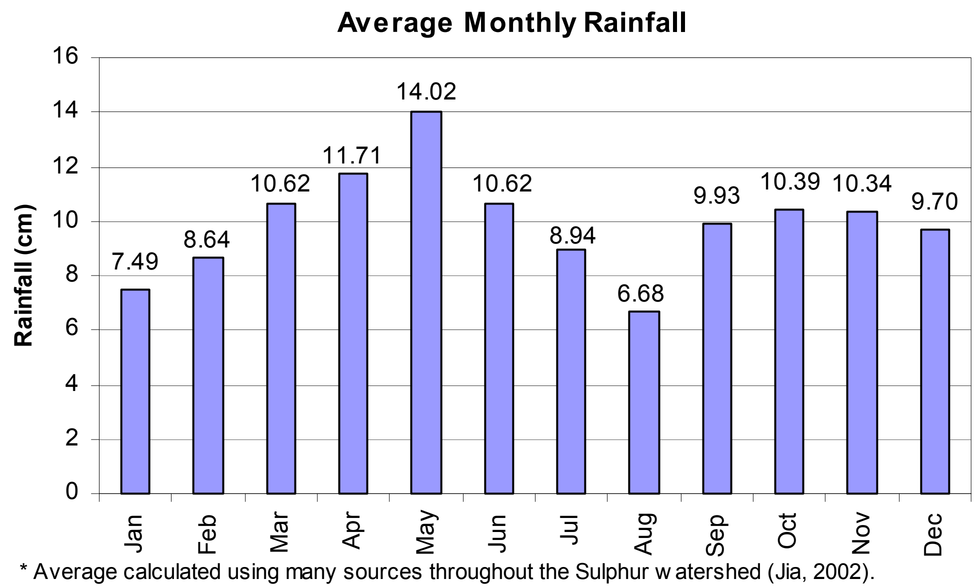

Figure 2.5 - Average rainfall (cm) by month for the upper Sulphur River basin

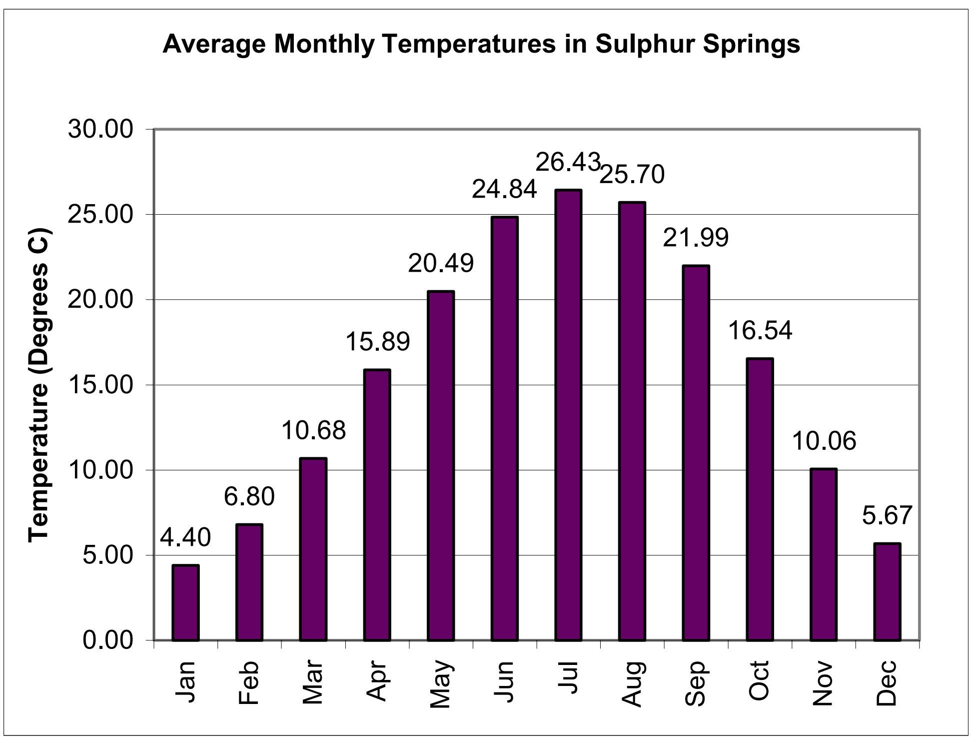

Figure 2.6 - Average temperature (C) by month at the Sulphur Springs weather station.

2.5 Hydrology

The Sulphur River watershed comprises approximately 9,211 square kilometers (3,558 square miles) within the state of Texas. The Sulphur River has one main tributary, White Oak Creek, whose watershed comprises 794 square kilometers (494 square miles) of the Sulphur River's 9,211 square kilometers (3,558 square mile) total.

Jim Chapman Lake is a water supply and flood control impoundment on the South Sulphur River with a storage volume of 382.76 million cubic meters (mcm) (310,312 acre-feet) and a firm yield of 134.9 mcm (109,397 acre-feet). Jim Chapman Lake is located upstream of all of the proposed projects described in this report. Wright Patman Lake is a water supply and flood control impoundment on the Sulphur River located downstream of all of the proposed projects near the Texas-Arkansas border. Wright Patman Lake has a storage volume of 136.8 mcm (110,900 acre-feet) and a firm yield of 222 mcm (180,000 acre-feet).

The proposed Marvin Nichols I Reservoir is a main-stem reservoir project with a watershed comprising of approximately 5,025 square kilometers (1,941 square miles). The watershed area draining to the existing Jim Chapman Lake (formerly known as Cooper Reservoir), located upstream and to the west on the South Sulphur River, comprises of approximately 2,208 square kilometers (853 square miles).

The drainage area upstream of the Talco gauge (USGS ID 07343200, Sulphur River at Talco, Latitude 33°23'26", Longitude 95°03'44" NAD 27) is approximately 3,637 square kilometers (1,405 square miles), all contributing. Statistics for this study on the Sulphur River were generated using all available daily historical data collected at the Talco gauge because of its centralized location with respect to the study sites. Details of this and all other gauges referenced in this report can be found in Appendix E. Figure 2.7 shows the drainage area to points of interest in the Sulphur Basin.

The median daily flow for the entire period of record at Talco is 2.21 cms (76 cfs). The mean flow, 38.56 cms (1,362 cfs), is much larger than the median flow 2.21 cms, indicating a somewhat flashy hydrological response to rainfall events. The lowest monthly average flow was near zero (0.002 cfs as published on the USGS web site) which occurred in October, 1978; the highest monthly average flow was 349 cms (12,330 cfs), in May, 1982. Analysis of the daily data indicates that the 7Q2 flow is 0.03 cms (1.07 cfs), and the 7Q10 flow is not measureable (0.0013 cms; 0.046 cfs). Additional flow statistics are presented in Figure 2.8 and Table 2.1. The tabular summary also presents separate flow statistics for the period before and the period after completion of Cooper Dam (now Jim Chapman Lake). Comparing the twelve-year post-construction flow record to the 33-year pre-construction flow record, it can be noted that flows below the 20^{th} percentile have generally increased after construction and flows above the 40^{th} percentile have decreased somewhat significantly since construction.

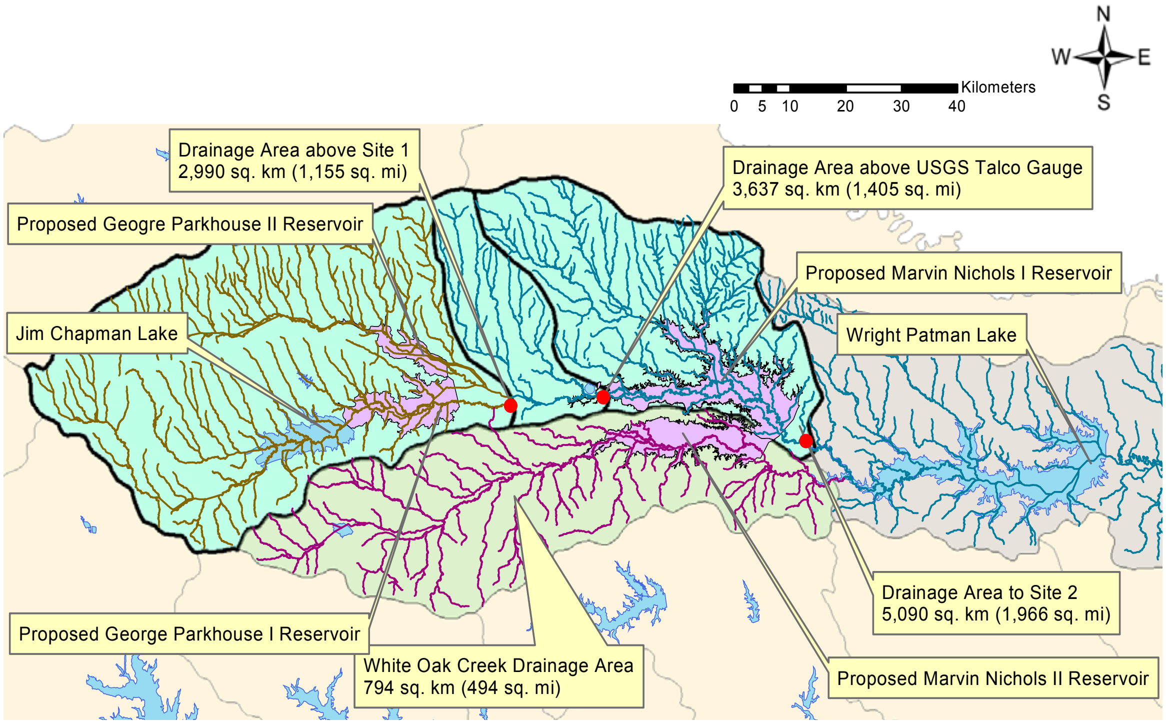

Figure 2.7 - Sulphur River watershed boundaries and drainage areas

Two representative sites were chosen for detailed study. TWDB Site 1 is located approximately 121 river kilometers (54.8 miles) upstream from analysis Site 2 and has a drainage area of approximately 2,990 square km (1,155 square miles). The Talco gauge is located between the two sites, approximately 88 river kilometers (75.3 miles) upstream of Site 2. The drainage area of Site 2 is approximately 5,090 square km (1,966 square miles).

A relationship between river flow at each of the study sites and the gauge at Talco is difficult to pinpoint because of the fast channel response of the Sulphur River. Discrete measured flows at each site are shown on Figure 2.9, plotted with the flow time series from the Talco gauge. Pressure transducers were installed on each study site, and, by using flood peaks at each site and at the Talco gauge, approximate attenuation times have been determined.

Shown in Figure 2.10 is a selected time series of water surface elevation data generated by pressure transducers installed at each analysis site, the USGS gauge at Talco, and the USGS gauge at Wright Patman Lake. Time lag between rainfall event peaks is evident as well as the water surface slope between each site. Average lag from Site 1 to the Talco gauge is 28 hours, and lag from Talco to Site 2 is 45 hours. Approximately 27.43m (90’) of water surface elevation drop from Site 1 to Site 2 is evident.

Table 2.1 - Frequency analysis of historical daily flows at USGS Talco gauge #7343200

		Entire Record 1956/10/01 to 2004/05/03		**Pre-Cooper Dam** 1956/10/01 to 1990/12/31		**Post-Cooper Dam** 1992/01/01 to 2004/05/03	
Probability of Exceedance	**Percentile**	**Flow (cms)**	**Flow (cfs)**	**Flow (cms)**	**Flow (cfs)**	**Flow (cms)**	**Flow (cfs)**
1%	99%	**555.80**	19,628	**622.97**	22,000	**261.45**	9,233
5%	95%	**207.85**	7,340	**259.10**	9,150	**105.06**	3,710
10%	90%	**83.48**	2,948	**108.51**	3,832	**59.35**	2,096
20%	80%	**23.96**	846	**23.81**	840.8	**24.76**	874.4
30%	70%	**7.22**	255	**7.78**	274.6	**4.36**	153.8
40%	60%	**2.97**	105	**3.62**	128	**1.67**	59
50%	50%	**1.53**	54	**1.87**	66	**0.96**	34
60%	40%	**0.82**	29	**0.96**	34	**0.57**	20
70%	30%	**0.42**	15	**0.45**	16	**0.40**	14
75%	25%	**0.31**	11	**0.28**	10	**0.32**	11.245
80%	20%	**0.23**	8	**0.17**	6	**0.27**	9.5
85%	15%	**0.14**	5	**0.10**	3.6	**0.23**	8.251
90%	10%	**0.07**	2.6	**0.05**	1.8	**0.22**	7.9
95%	5%	**0.02**	0.64	**0.01**	0.4	**0.09**	3.2
97%	3%	**0.01**	0.19	**0.00**	0.1	**0.06**	1.982

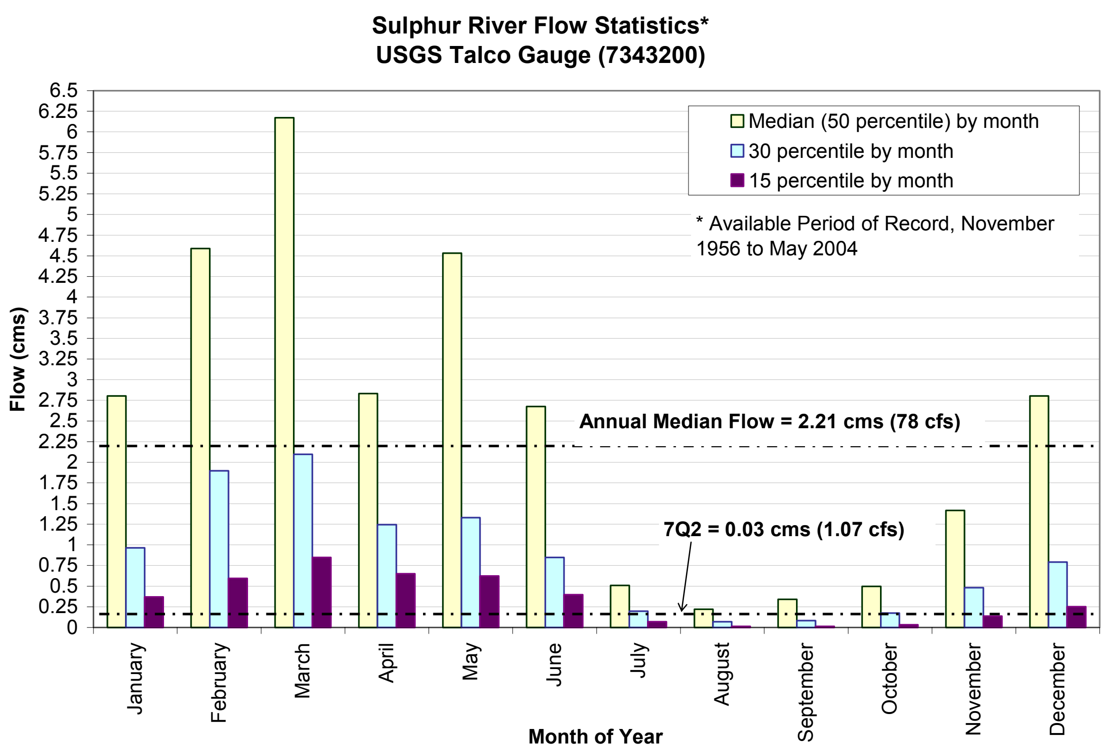

Figure 2.8 - Frequency statistics by month at Talco.

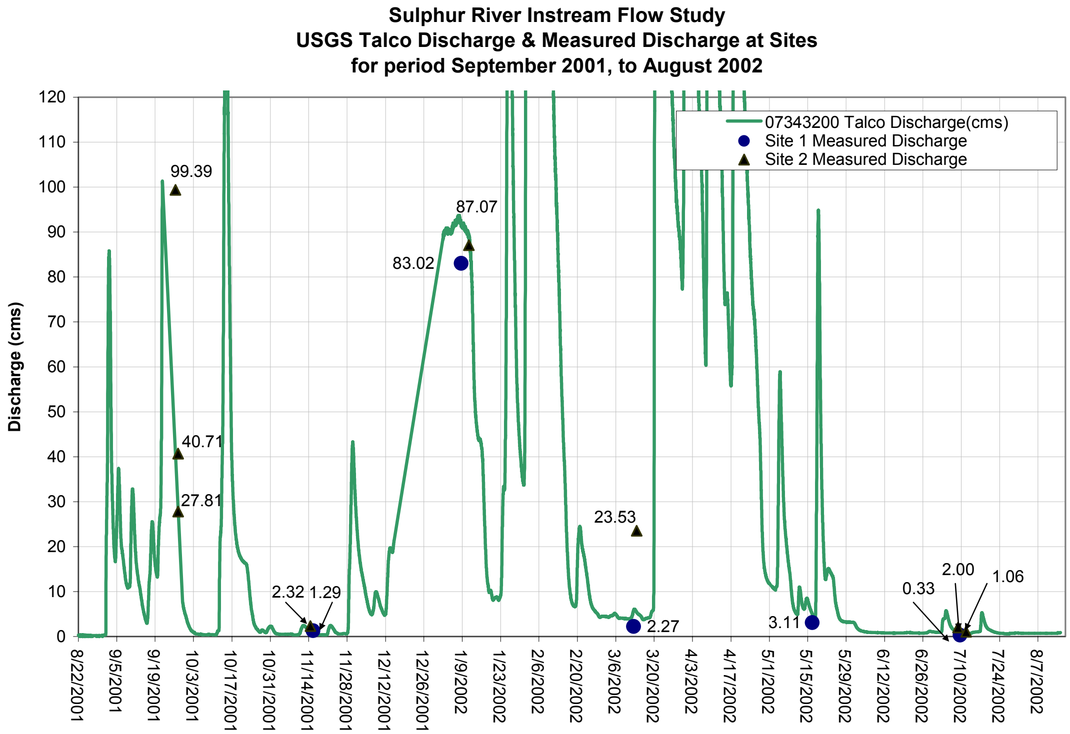

Figure 2.9 - Measured flow rates at each analysis site and Talco gauge flow rate time series.

The water level of Wright Patman Lake is also shown. While conservation pool elevation varies intra-annually between 220.60' and 227.50' (summer months), the lake regularly exceeds this elevation. Recent pool elevations are reported as high as 239.50' in December of 2001, and 251' in March of 2001. The maximum recorded pool elevation is 252.64' on May 10, 1966.

Water surface elevations at Site 2 were measured near 238' at low flows. Since the channel is generally deep even for the lowest flows (greater than 10' deep in many places), some influence on water level at Site 2 exists when Wright Patman's water level exceeds 228' elevation.

Figure 2.11 shows peak stream flow for each year on historical record at the Talco gauge. In 18 of 45 years on record has a peak flow rate of less than 850 cms (30,000 cfs) occurred, and in 13 years on record a peak flow rate has been higher than 1,133 cms (40,000 cfs).

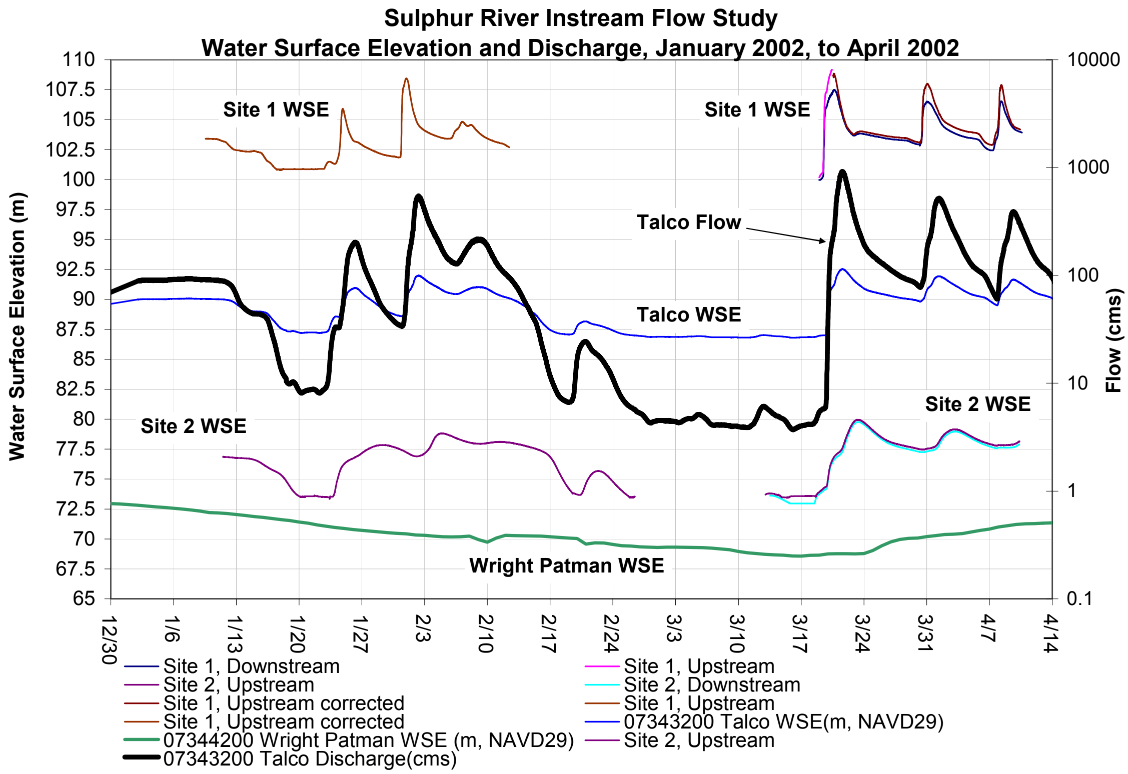

Figure 2.10 - Time series of water surface elevation at Site 1, Talco gauge, Site 2, and Wright Patman Reservoir.

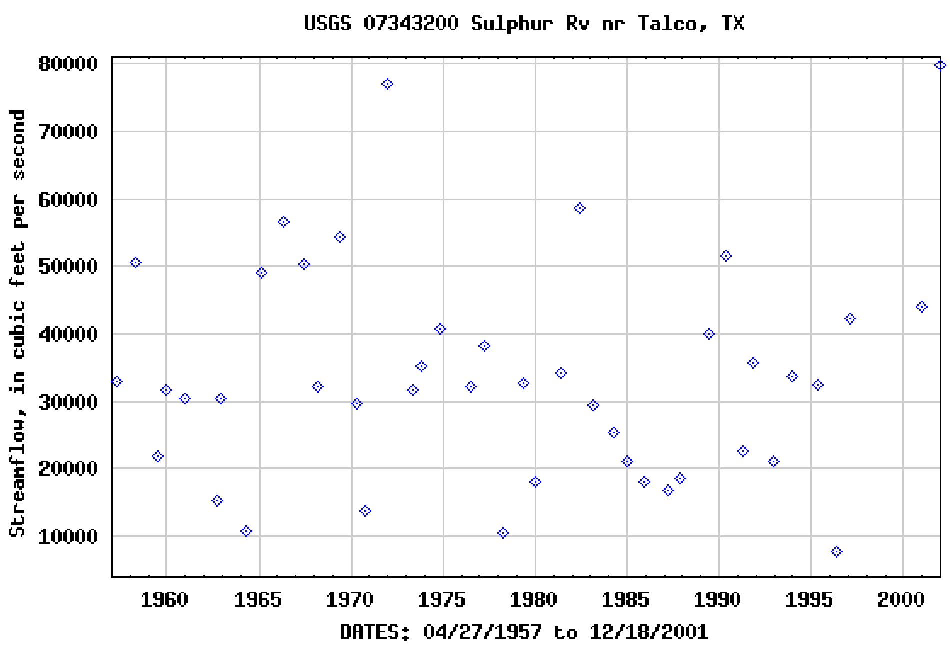

Figure 2.11 – Peak stream flow for each year of record (1957 to 2002) at USGS Sulphur River near Talco gauging station (source: USGS NWISweb)

2.6 Water quality

Water quality data are available from the Texas Commission on Environmental Quality (TCEQ) (previously known as Texas Natural Resource Conservation Commission, TNRCC). These segment data are summarized in the TNRCC State Water Quality Inventory, which is done on a bi-annual basis. Additionally, the Draft 2002 Texas Water Quality Assessment and List of Impaired Waters (TNRCC 2002) summarizes the status of the state's surface waters, including concerns for public health, fitness of use by aquatic species and other wildlife, and specific pollutants and their possible sources. Three segments are detailed below because of their potential to affect the proposed reservoir projects.

The Upper South Sulphur River, designated Segment 0306, stretches from Jim Chapman Lake to the headwaters of the South Sulphur River in Fannin County. Segment 0306 is listed as an impaired water body for depressed dissolved oxygen (DO) levels, high bacteria loads, and for high pH level. Jim Chapman Lake is primarily affected by this segment, but all proposed downstream reservoirs could potentially be affected, especially the proposed George Parkhouse I Reservoir on the South Sulphur.

In May 2002, a fish kill on the South Sulphur of approximately 2,000 fish was reported in this segment by biological contractor, Dr. Fran Gelwick, Texas A&M University (personal observation), and it was her understanding that the Texas Parks and Wildlife Department (TPWD) was investigating this fish kill. The kill apparently resulted from very low DO caused by a disruption (near cessation) of flow releases from the Jim Chapman Lake. Lake operators reported many fish floating in the stilling basin. A second fish kill was attributed to pesticide use on cotton crops within the floodplain, which was washed into the Sulphur River after an unexpected heavy rainfall the day after application of the pesticide. Results are not yet available from the TPWD investigation.

The Middle Sulphur River, designated Segment 0307A, is an unclassified water body but may be of concern since it represents water that flows into the proposed Marvin Nichols I Reservoir. Middle Sulphur Segment 0307A extends from its confluence with the South Sulphur River near Jim Chapman Lake in Hopkins County to the upstream perennial portion of the Middle Sulphur River east of Wolfe City in Hunt County. Designated uses in Segment 307A are contact recreation, aquatic life, and fish consumption. No fish consumption advisories or closures for that segment currently exist (TNRCC 2002), and the aquatic life and fish consumption uses are fully supported by the TNRCC in their Draft 2002 Texas Water Quality Monitoring and Assessment Report (TNRCC 2002).

The main portion of the Sulphur River that extends from a point 0.9 miles downstream of Bassett Creek in Bowie and Cass Counties, near the upper reaches of Wright Patman Lake, to Cooper Dam (Lake Jim Chapman) in Delta and Hopkins Counties is a classified segment denoted as Segment 0303. This is the stream segment that encompasses the proposed reservoir site. Segment 0303 has designated uses for contact recreation, aquatic life, general use, and fish consumption. The only water quality parameter of concern reported in the Inventory is dissolved oxygen (DO) because of depressed levels (TNRCC 2002). The main stem of the Sulphur River in the vicinity of the proposed reservoir site is also noted in the TNRCC's 2002 List of Impaired Waters as a water body with concerns for aquatic life use impairments because of the depressed dissolved oxygen.

2.7 Ecologically unique river segments

As a part of Texas Senate Bill 1 (31 TAC § 357.8), regional water planning groups may include recommendations for river and stream segments of unique ecological value in their regional water plans. The recommendations may be for the entire river or for designated portions. The criteria for designation of river and stream segments of ecological value in the statute include provisions for unique attributes for biological function or hydrologic function; for riparian conservation areas; for areas with high water quality, exceptional aquatic life, and/or high aesthetic value; and for threatened or endangered species/unique communities.

Although the North East Texas Regional Water Planning Group-D did not nominate such a segment, the Texas Parks and Wildlife Department (TPWD) published a report recommending fifteen (15) segments in Region D. One recommended segment was 0.9 miles downstream of Bassett Creek in Bowie/Cass County upstream to IH 30 in Bowie/Morris County (Norris and Linam 2000). This segment stretches from the approximate upper reaches of existing Wright Patman Lake, half way to the proposed dam for the Marvin Nichols I Reservoir project, just past the confluence of the Sulphur River and White Oak Creek.

Additionally, the U.S. Fish and Wildlife Service (USFWS) has identified 94,252 acres of bottomland along the Sulphur River west of Wright Patman Reservoir as being priority bottomland hardwood forest (USFWS 1985). Portions of the hardwood forest are very high quality and are comprised of water and willow oak, sweetgum, water hickory, ash, hackberry, elm, and overcup oak, according to the TPWD report.

The area has a favorable hydrologic regime with numerous sloughs and documented frequent flooding. This flow regime enhances the value of the habitat for waterfowl, white-tail deer, furbears (including beavers and river otters), squirrels, and numerous migratory birds, such as nesting American redstarts, Cerulean warblers, and Kentucky warblers (USFWS 1985).

This section of the Sulphur River is also within the target recovery area set by the TPWD for the state threatened paddlefish, due to the sluggish, fertile waters found above Wright Patman Reservoir that provides excellent paddlefish feeding habitat (Pitman 1991). The candidate segment is located downstream of the proposed dam site for Marvin Nichols I reservoir, and thus would be affected by the alterations in riverine flow.

2.8 Threatened and endangered species

The proposed Marvin Nichols I reservoir site in Red River and Titus Counties, Texas, is within the range of several threatened and endangered species. The construction and operation of the reservoir will impact the diverse bottomland forest community in the proposed reservoir project area. The bottomland hardwoods and associated wetlands of eastern Texas represent major and valuable habitat to waterfowl in Texas. The riparian wetlands support substantial wintering populations of a number of waterfowl species, principally mallards, but also breeding and wintering wood ducks.

Bottomland forest in eastern Texas, including that encompassed by the proposed Nichols reservoir site, supports a large number of plant and other animal species including over 100 species of special concern because of rarity (Neal 1989). Some of the threatened and endangered migratory species are expected to lose habitat within their range as a result of the reservoir construction and operation; however, their usage of this area is not well understood at this time. The bald eagle may benefit by the proposed reservoir because of increased availability of lake habitat.

The range of the state-listed, endangered Paddlefish previously included habitats within the proposed Marvin Nichols I reservoir site. The TPWD has a recovery program for this species (Pitman 1991), which includes the area of the proposed reservoir site. The state-threatened creek chubsucker is also reported in the proposed reservoir site area.

Natural plant communities reportedly present in George Parkhouse I and II reservoir sites, and thus by close proximity likely present in the proposed Marvin Nichols reservoir area, include the Silveanus dropseed series and the Sugarberry-Elm series. The Silveanus dropseed series is listed by TPWD as imperiled and very rare globally and in Texas (Bauer et al. 1991). Other protected species are listed in the area, including Bachman's sparrow, alligator snapping turtle, paddlefish, interior least tern, bald eagle, American swallow-tailed kite, timber rattlesnake, and southeastern myotis. A total of 48 rare plant species of special concern are found in bottomland hardwoods and associated wetlands (Texas Organization for Endangered Species 1983, Poole 1984, USFWS 1985).

The ironcolor shiner, *Notropis chihuahua*, and the Tailgate shiner, *Notropis maculatus*, are listed respectively as watch-list and threatened species by the Texas Organization for Endangered Species-TOES (1995). Each species ranges within the Sulphur River drainage; however, these species have not been collected in the contract studies. Other listed species include the mole salamander, *Ambystoma talpoideum*, TOES watch-listed; alligator snapping turtle, *Macroclemys temminckii*, a state threatened species; Louisiana pine snake, *Pituophis melanoleucus ruthveni*, a state and federally listed endangered species; the Texas garter snake, *Thamnophis sirtalis annectens*, a federal candidate species; and the Cerulean warbler, *Dendroica cerulea*, a federal candidate species in northeast Texas bottomland hardwoods (Texas Organization for Endangered Species 1995).

3. Site selection and hydraulic analysis

For the purposes of investigating the impact of the proposed water development projects on aquatic habitat in the Sulphur River basin, two study reaches, Site 1 and Site 2, were selected for detailed analysis. Scientists and engineers from TPWD, TCEQ, TAMU, USACE and the TWBD participated in the reconnaissance and selection process.

3.1 Hydraulic Analysis Sites

Two sites on the main stem of the Sulphur River were chosen for detailed hydraulic and physical habitat analysis. Each site encompasses one or more of the biological sampling sites as shown in Figure 3.1. High-resolution bathymetric and water surface elevation measurements, as well as flow rating measurements, were taken at each site. Field data was used to develop a two-dimensional depth-averaged steady-state hydraulic model at each site. Hydraulic model output was used to delineate physical habitat areas, the results of which are presented later in the report.

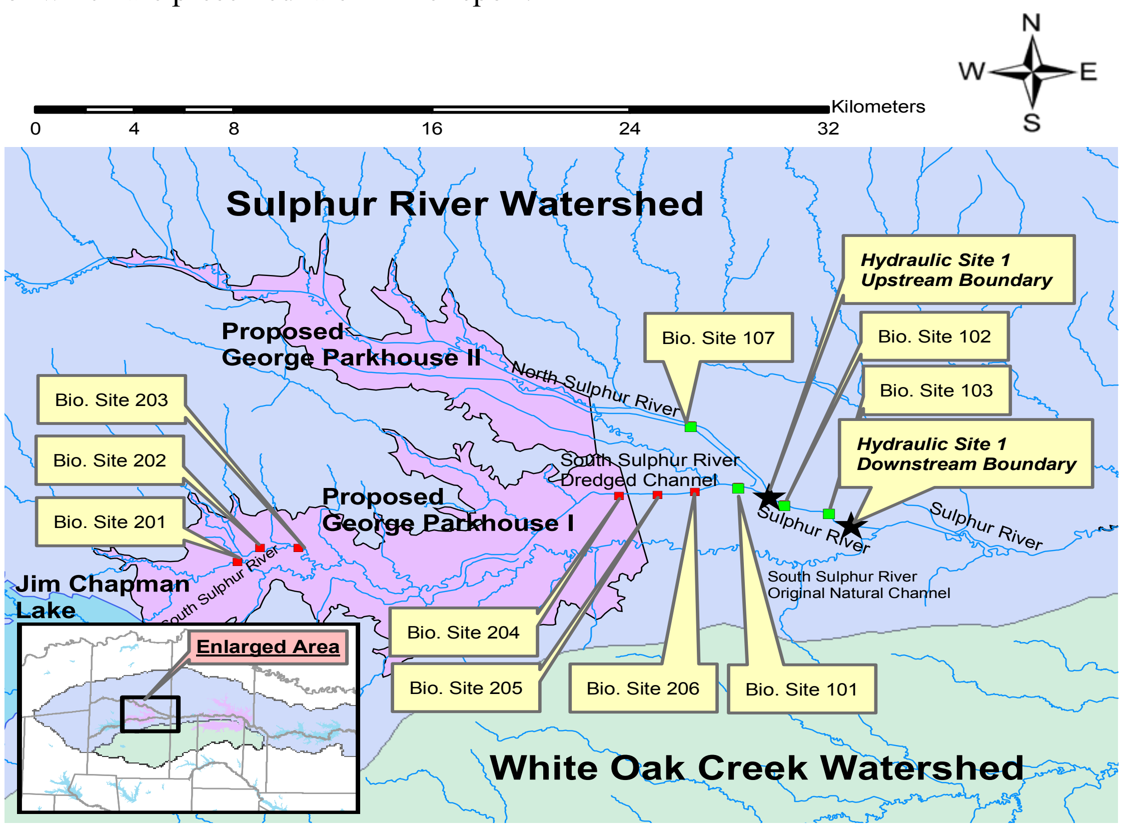

Figure 3.1 - Biological and hydraulic sampling sites in the upper basin, downstream of proposed George Parkhouse I and II

Site 1 is located on the main stem of the Sulphur River, just downstream of the confluence of the North Sulphur River and the South Sulphur River at the eastern tip of Delta County. This site is approximately 16 km (10 miles) directly upstream or 33 river km (20.5 river miles) upstream of the headwaters of the proposed Marvin Nichols I Reservoir and approximately 10 km (6 miles) downstream of the proposed George Parkouse I reservoir (Figure 3.1). Site 2 is located approximately 6 km (3.7 miles) or 16 river km (10 river miles) downstream of the proposed Nichols reservoir, and is just upstream of the existing Wright Patman Reservoir (Figure 3.2).

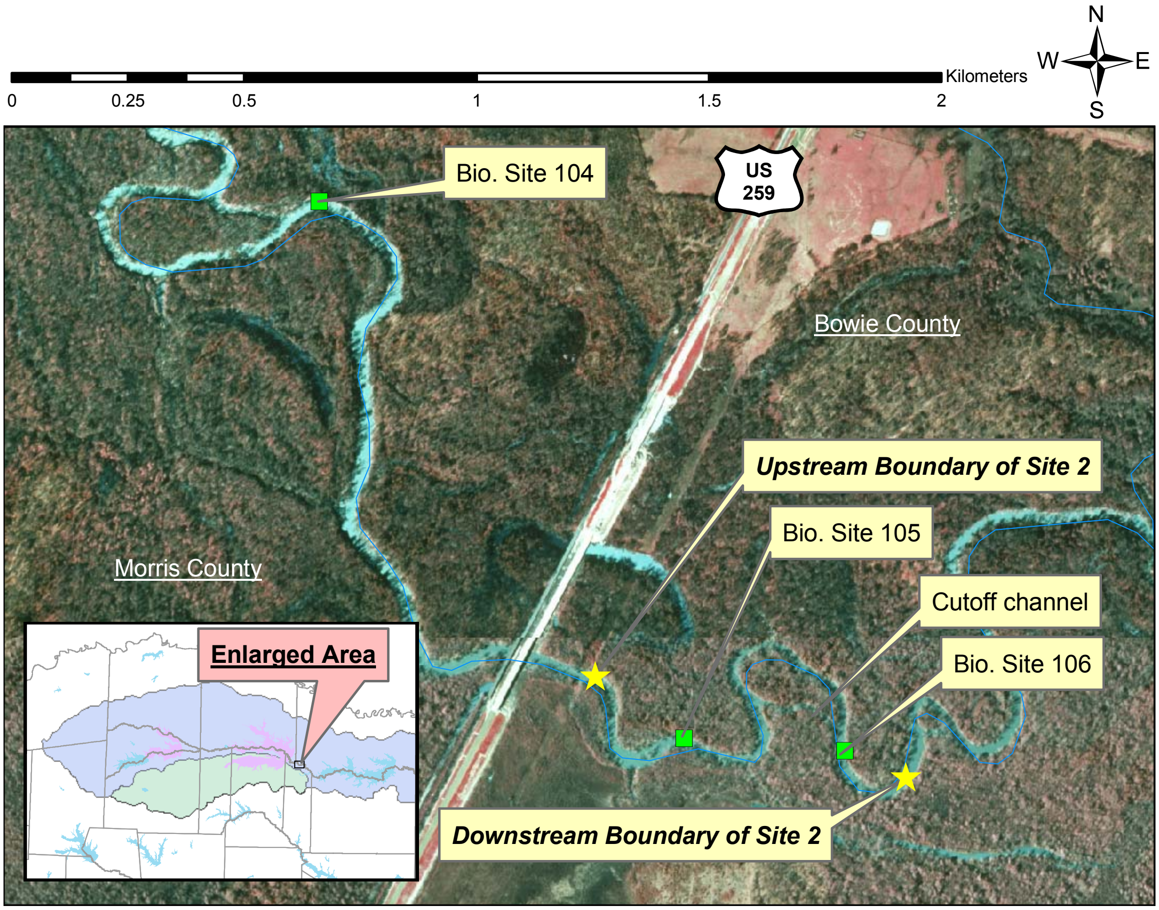

Figure 3.2 - Biological Sampling Sites downstream of Marvin Nichols I near Site 2

3.1.1 Site 1

Land use and land cover in the immediate vicinity of Site 1 and in the upstream watershed is primarily agricultural (both pastureland and crops) with secondary use as harvestable hardwood forest. Jim Chapman Lake is located upstream of the site on the South Sulphur River and during dry periods the primary flow in the river originates as releases from Chapman Lake. Site 1 is approximately 4.3 river km (2.67 river miles) in length and encompasses two of the fish habitat sites near the confluence sampled by

TAMU (sites 102 and 103). Total drainage area to Site 1 is 2,990 square kilometers (1,155 square miles). An aerial photograph of the site is shown in Figure 3.3.

This entire segment of the Sulphur River, from State Highway 37 upstream to the confluence, has been channelized by the US Army Corps of Engineers (USACE). Additional channelization was performed further upstream on both the North Sulphur branch and the South Sulphur branch. Channelization is evident in the steep uniform banks, the un-meandering straight channel, and the progressive downstream transition of bank height. Banks are comparatively high upstream near the confluence and they transition downstream to the natural height at SH37 where channelization ends. From observation, the channel was deepened (or has incised since channelization) significantly near the confluence and the hydraulic result at low flows is a continuous, almost level pool surface from SH37 all the way upstream to the confluence. At 1.29 cms (45.5 cfs) a water surface elevation difference of only 5 cm (2 inches) was measured from the downstream boundary of analysis Site 1 to a point 4 km (2.49 miles) upstream, yet the water remained deep enough to navigate the length of the site with our motorized jon boat. This backwater is also likely the result of a large logjam located just downstream of the SH37 crossing that has completely blocked the main channel.

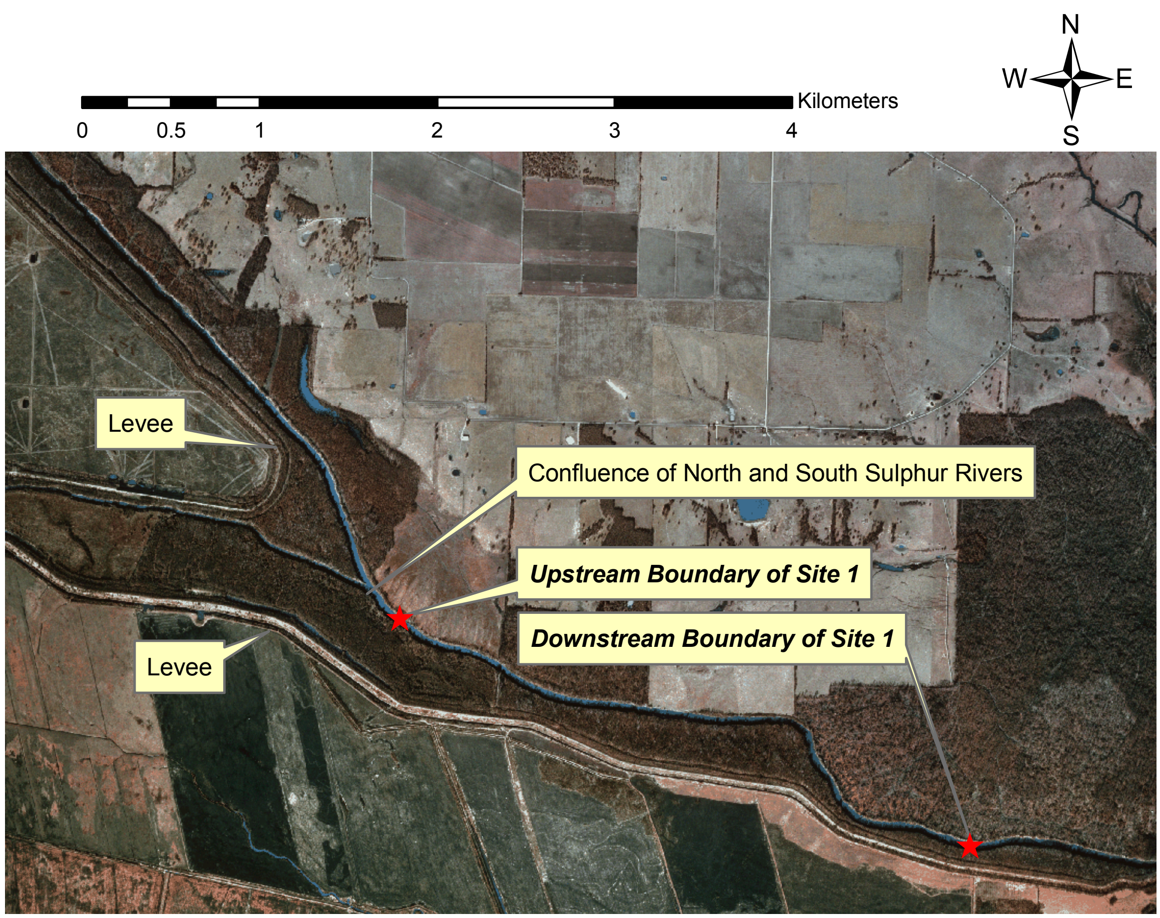

Figure 3.3 - Aerial photograph and landmarks at Site 1

As described previously, channelization has caused incision resulting in significant erosion of the banks of the river. Bank sloughing is easily observed, and while performing fieldwork on more than one occasion immediately after a flood event, slabs of clay were seen separating from the banks and falling into the water.

A significant amount of Large Woody Debris (LWD) was observed resting on the channel bed near the banks. No debris is oriented laterally across the river to restrict flow; flood events keep the center of the channel clear and LWD aligned with flow direction and along the banks. This LWD orientation on this site is in sharp contrast to the less-organized LWD orientation evident in the study sites were no channelization has been performed. Figure 3.4 illustrates typical LWD at Site 1.

Figure 3.4 - Photo of Large Woody Debris, Site 1, High Flow = 2,900 cfs

Channel substrate and bank material in this area is uniform, dark brown cohesive clay. The only exception is one small area located approximately 300 m (1,000 feet) downstream of the confluence that extends for less than 100 m (328 feet), where substrate consists of a different strain of light brown/grey, compacted clay. The compacted clay in this 100 m section has resisted erosion and prevented channel incision equal to upstream and downstream incision; as a result, at low flows this short shallow area creates a pool upstream that transitions through the section to pools downstream. At low flows, the transition consists of a high velocity, high slope section, though flow still remains subcritical. This shallow area accumulates sand material and, at the lowest flows, the channel becomes mildly braided. At low flows, the slope in the bulk of the study reach approaches 0%, but slope in the shallow transition area approaches 1%.

Generally, Site 1 is representative of the Sulphur River upstream of the proposed Marvin Nichols I Reservoir. Site 1 consists of the same long, deep pools, the same frequency of LWD habitat, and the same slow velocity fields that are found in the remainder of the channelized portion of the Sulphur River downstream of the confluence of the North and South Sulphur Rivers.

Upstream of the confluence, the North Sulphur River is channelized and exhibits the same characteristics as Site 1. The North Sulphur River, however, contributes less than half the total flow to the Sulphur downstream, so velocity-dependant habitat types (run, riffle) may not occur as frequently in the North Sulphur River.

Similarly, the South Sulphur was channelized, but not to the same extent that the North Sulphur was channelized, and the hydraulic conditions of the South Sulphur are more similar to the unchannelized Sulphur farther downstream. Trees and debris are more prevalent in this reach than in the remainder of the channelized Sulphur downstream.

Site 1 contains within its boundaries the only shallow riffle area that we observed in the entire segment upstream of the proposed reservoir. As the only shallow area, habitat resulting from the shallow area may over-represent shallow run or riffle habitat in the rest of the river as a whole.

3.1.2 Site 2

Unlike Site 1, Site 2 is a good example of the Sulphur River in its natural state. Site 2 is located in Bowie and Morris Counties, just north of IH-30 and just west of the US-259 bridge that crosses the river. Total drainage area above Site 2 is 5,090 square kilometers (1,966 square miles). The site is 1.36 river km (0.85 river miles) long and is approximately 2 river km (1.25 river miles) upstream of Wright Patman Lake. Site 2 is illustrated in the aerial photograph of Figure 3.5.

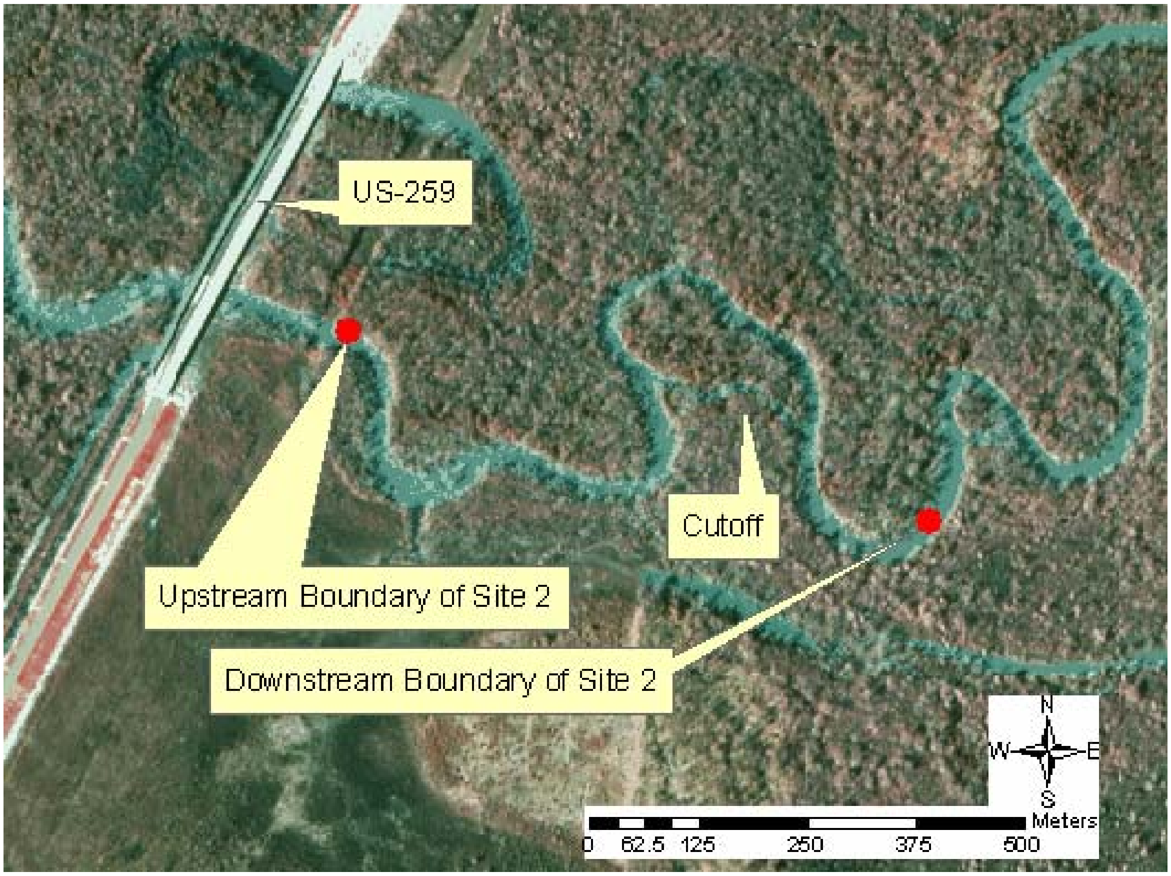

Figure 3.5 - Aerial photograph of Site 2

Incorporated into Site 2 is a 200 m (656 foot) cutoff channel that allows flows above 800 cfs and short-circuits a 432m (1,420 foot) long debris-clogged meander. Large woody debris (LWD) in the meander covers the bottom of the channel and makes navigation at low flows very difficult. The position and orientation of debris was observed to change frequently after flood events; however, the density of debris remained roughly the same. Typical woody debris found on Site 2 is shown in Figure 3.6.

Figure 3.6 - Typical large woody debris at Site 2

Site 2 resembles the natural portion of the Sulphur River downstream of the proposed reservoir. The meandering nature of the natural Sulphur River has created numerous oxbow lakes and a large floodplain that sustains a diverse bottomland hardwood forest. One large meander is included in the site, as well as forested floodplain and a large amount of instream LWD.

High water levels in Wright Patman Lake influence hydraulics at this site. At low flows, if the lake's water level is high, the water level at Site 2 may be higher than what may be naturally attributable to the slope of the river. The exact extent of the influence of the lake level is hard to determine from our limited data. Obviously, sites farther upstream are not influenced by the lake and will have slightly shallower pools at low flows.

An important consideration of this site is that while the proposed Marvin Nichols I reservoir will inundate a large area of land and forest, and permanently change the stretch of river that will be impounded, the distance between the Marvin Nichols I embankment and the upper reaches of Wright Patman is very short.

3.2 Hydraulic modeling

To characterize both lateral and longitudinal velocity variations, a two-dimensional hydrodynamic model was developed for both study Site 1 and study Site 2. The model generated depth and velocity data at points spaced roughly 7 meters (23 feet) apart throughout each study site, and the model was executed for a variety of steady-state flow rates. This section describes the hydraulic modeling exercise; subsequent chapters discuss use of the model output for habitat characterization.

3.2.1 RMA-2

As discussed by Wentzel (2001, PhD thesis), and others (e.g., Leclerc et al. 1995; Moyle 1998; Railsback 1999; Crowder and Diplas 2000), the results of one-dimensional (1-D) hydrodynamic modeling for instream flow assessment are often dependant upon the location of the modeled river transects. Bates (1997) reported that when using PHABSIM, a common 1-D model used for instream flow analysis, transects should be selected to avoid areas of severe contraction and expansion of flow, transverse flow and across-channel variation in water surface elevations. If any of these conditions occur in the segment, then 1-D modeling may not be suitable (USACE 1993).

Two-dimensional hydrodynamic models are designed to resolve such conditions and a number of features of 2-D finite element modeling contribute to increased hydrodynamic accuracy in river systems with complex morphologies. Depth-averaged 2-D modeling of stream hydrodynamics assumes that water column properties do not change in the vertical direction. This assumption is valid if the effects of the benthic and surface boundary layers are not important for the purposes of the modeling, if the river is not tidally influenced and if the velocity fields near structures (e.g., banks and large woody debris) are not required at an extremely high resolution. A lengthy discussion of the utility of 2-D models is provided in Appendix V in the Draft Texas Instream Flow Studies Technical Overview document (see Appendix V, Chapter 4, Hydrology and Hydraulics).

RMA-2 was used in this study to generate in-channel depth and velocity fields for use in a spatial fish habitat model. It is a two-dimensional, depth-averaged, finite element, hydrodynamic, numerical model. Water surface elevations and horizontal velocity flow fields were calculated from the Reynolds-averaged form of the Navier-Stokes equations for fluid flows. Bottom friction was determined from the Manning's or Chezy equation and eddy viscosity coefficients were used to define turbulence characteristics. The code was originally developed in 1973 for the US Army Corps of Engineers (USACE) with subsequent enhancements made by Resource Management Associates (RMA) and the USACE Waterways Experiment Station (WES). The current version of RMA-2 is supported by the Surface Water Modeling System (SMS) and TABS-MD. SMS was used by TWDB for this study and control of nearly all parameters, boundary conditions and file management options required to run RMA-2 were accessible from inside SMS. Post-processing and visualization of model results was also performed using SMS.

In practical execution of the model, the inflow velocity profile was assumed to be distributed based on depth; bottom roughness and eddy viscosity were used as calibration parameters. SMS and RMA-2 allow the latter two variables to be adjusted in space. RMA-2 allows an adjustment to Manning's N based on depth, and Wentzel (2001) reported that this option is very effective in obtaining a well-calibrated model. Roughness coefficients used for this study were derived from Arcement and Schneider (1983), and eddy viscosity was determined based upon Peclet number (after Donnell et al. 2001). More information regarding both the application of RMA-2 to this project and verification of RMA-2 output with field data is provided in Appendices M and Q.

3.2.2 Data Collection

To develop and execute the RMA-2 model, three key environmental forcing variables needed to be determined. Very high spatial resolution bathymetric data was collected using a Global Positioning System (GPS) and a depth sounder mounted on a boat. To adjust for the slope of the river surface the bathymetric data was referenced to local temporary benchmarks and reference points that were established adjacent to the study site. In addition, to account for the effects of changes in river stage during the bathymetry data collection period, a combination of staff gauges and pressure transducers were set up at strategic locations along the river to monitor short and long-term changes in the water surface level. The elevation of each pressure transducer and staff gauge was measured using high vertical-resolution surveying techniques so that the relative elevation difference between all equipment sites was determined. The gauges and pressure transducers were used to measure the water surface elevation difference between the upstream and downstream boundaries of the finite element mesh, another requirement for the RMA-2 model calibration.

Flow rates and stage rating curves were determined by actual field measurement since there were not any established stream gauges located adjacent to the sites. The RD Instruments ADCP was used in this study to measure flow rate in water deeper than approximately 3 feet. When use of the ADCP was not possible, the portable AVM unit manufactured by Sontek to record a series of point velocity measurements along the cross-section, which were integrated to calculate flow rate.

Further detail on the data collection methodology can be found in Appendix F and in Appendix V.

3.2.3 Mesh generation

In addition to its use in the execution of RMA-2, the Surface Water Modeling System (SMS) developed by Brigham Young University was used to develop the finite element mesh for modeling conducted at both Site 1 and Site 2. The bathymetry point file for each site was imported into SMS, as well as DOQQs for the site. The mesh boundary was established by viewing the extent of the bathymetry point file, simultaneously with the DOQQs. To more clearly define the mesh boundaries, the water's edge was measured with a laser range-finder, but only in limited areas for some flow rates.

After the mesh boundary was established, a high-resolution mesh was generated. Within the guidelines discussed below, mesh resolution was determined by engineering judgment and experience; areas with complex hydraulics (steep longitudinal bathymetry, bridge areas, island areas, flow restrictions, flow obstructions, etc.) were afforded more elements than simple areas with relatively uniform bathymetry. The mesh was generated as fine as possible to maximize the resolution of depth and velocity points that were later utilized for the fish habitat Geographic Information System (GIS) analysis. A hydraulic mesh with a resolution similar to the GIS grid ensures adequate resolution of velocity fields on a scale comparable to that for which hydraulic data will be utilized. The GIS grid cell size used for the fish habitat analysis for Site 1 and Site 2 (see Chapter 5), was 1.5 meters. The finite element mesh generated for both sites consisted of nodes spaced roughly 3 m apart laterally (across the channel) and 5 m apart longitudinally (in the direction of flow). The discrepancy between the GIS grid cell resolution (1.5 m) and the hydraulic model resolution (3 m x 5 m) exists as a result of limitations in the resolution of the bathymetric data used to assign elevation within the hydraulic model and as a result of the limitations of hydraulic modeling assumptions. Generally, the hydraulic mesh should not be generated at a scale finer than the average distance between bathymetric measurements since bathymetry significantly affects model output. The hydraulic model mesh remained coarse to reflect the most accurate bathymetry data collected and to avoid resolving velocity fields over a bed form that may not truly be present. Similarly, minimum mesh size was limited by the assumptions of the specific model being used. Typical model formulations (including RMA-2) utilizing the depth-averaged, hydrostatic, shallow-water assumptions should not be used to resolve horizontal flow perturbations smaller than 1 times the depth, and extra caution should be exercised when resolving perturbations smaller than 5 times depth. It can be noted, however, that reasonable model results have been reported with meshes that were far finer than resolvable by the theoretical model. While they were far outside the suggested sizes given above, Crowder and Diplas (2000) went so far as to report exceptional calibrated results modeling flow obstructions with RMA-2 using an 8cm by 8cm grid in water of 2-meter depth. Increasing resolution often improves model convergence and will be investigated for future use; however, model accuracy is not improved by increased resolution when using RMA-2 at such small scale.

The spatial distribution of nodes and elements for the mesh was carefully controlled since their shape affects the accuracy of model results. The users manual for RMA-2 (Donnell et al. 2001) states that elements should be planar (no concave or convex elements), should not have interior angles less than 10 degrees, and should not differ in area by more than 50% from their adjacent elements.

To determine the elevation of the nodes in the finite element mesh, it was necessary to interpolate elevation from the bathymetry data. In practice, this proves somewhat complicated because the traditional interpolation techniques such as Inverse Distance Weighted (IDW), Thiessen Polygon and Cubic Spline do not take into account the known general shape of a river channel (eg., the high vertical gradient near the banks and the relatively low gradient along the length of the channel). While a curvilinear Kriging approach will be investigated in the future, a modified Inverse Distance Weighted technique was instead developed (Osting 2003). This new IDW algorithm, written as a FORTRAN program, uses rectangular search areas in selecting the interpolant data points, with the larger rectangle dimension location parallel to the river thalwag. By placing greater influence on points upstream or downstream of the point to be interpolated this technique increased interpolation accuracy because river bathymetry variations are greatest in the lateral direction. This technique performed remarkably well and was used for interpolating the node bathymetries in this and other recent projects. More information on this technique is provided in Appendix G and in Osting (2003).

An additional caveat considered when assigning bathymetric elevations to mesh nodes was the presence of steep bed gradients oriented in the direction of flow. Most 2-D models use the shallow-water equations with the hydrostatic assumption that are not capable of resolving vertical pressure gradients. Steep bed gradients (slopes greater than 20%) in the direction of flow, however, cause real world vertical pressure gradients and possible flow separations to occur. In some areas where the mesh slope exceeded 20% and model convergence problems occurred, the mesh bathymetry values were manually adjusted to reduce the bed slope.

A limit of 30,000 nodes and 10,000 elements exists in the widely distributed version of RMA-2. Computing effort becomes high with increasing number of nodes (run time approximately squares with a doubling of the number of nodes) so therefore every attempt was made to keep the model coarse enough to adequately model the flow and yet fine enough to pick out the detail of small areas of fish habitat. In the end it was necessary to obtain a recompiled version of RMA-2 that supported the use of 165,000 nodes and 55,000 elements. This made for longer run time, but allowed great resolution of the mesh.

The extent of the Site 1 mesh is shown in Figure 3.7, and individual mesh elements are detailed in Figure 3.8.

The mesh for Site 2 was also developed in SMS at a similar resolution and is shown in Figures 3.9 and Figure 3.10. Additional discussion of the mesh generated for Site 2 is located in Section 6.2 Large Woody Debris.

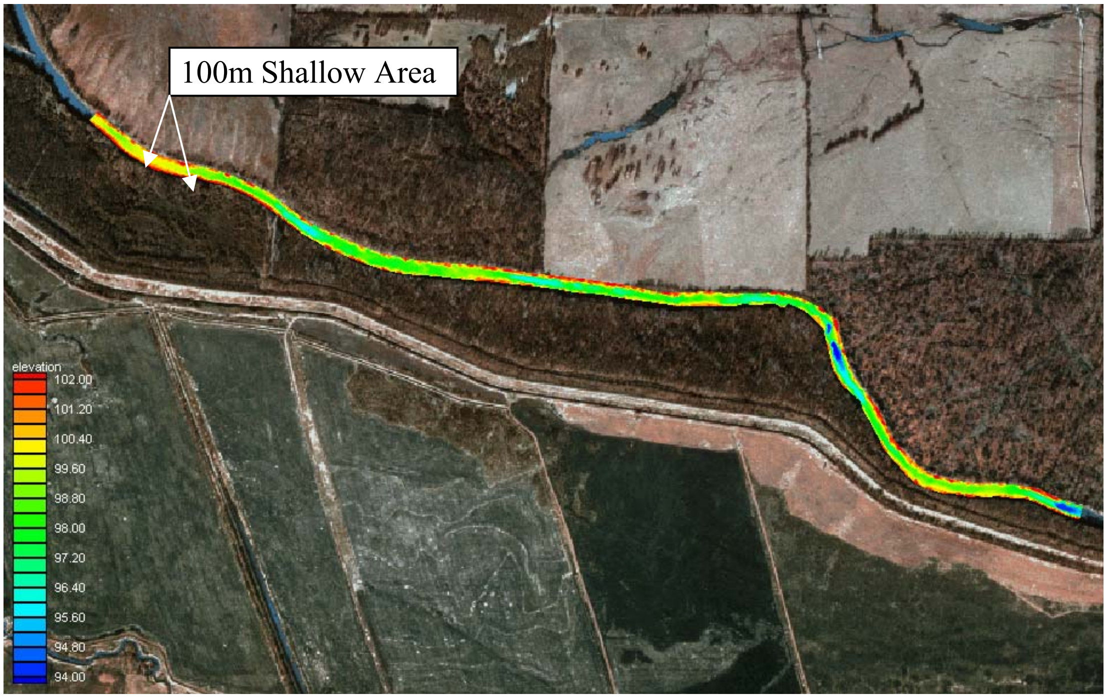

Figure 3.7 – Extent of the finite element mesh at Site 1. Elevation contours, in meters, plotted against aerial photos, DOQQ. The shallow area is shown above.

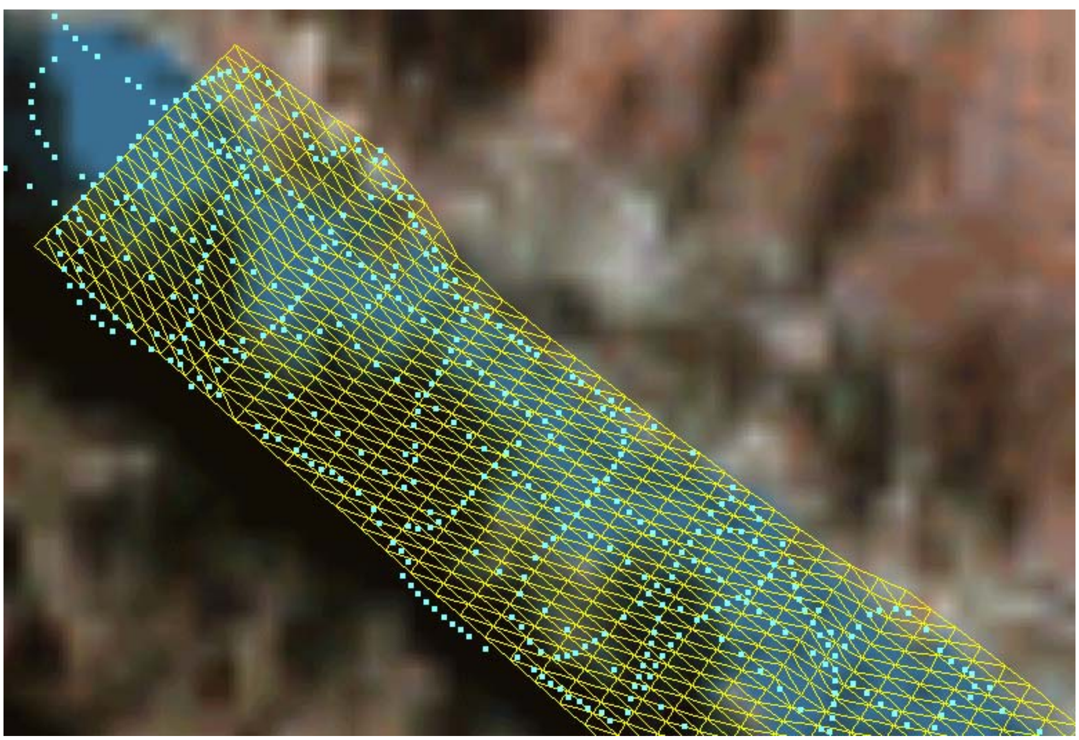

Figure 3.8 – Mesh resolution Site 1, showing western end analysis site. Mesh elements (shown in yellow) are approximately 4.5m x 2m. Cyan circles indicate bathymetry points measured by depth sounder. Background is aerial photo, DOQQ.

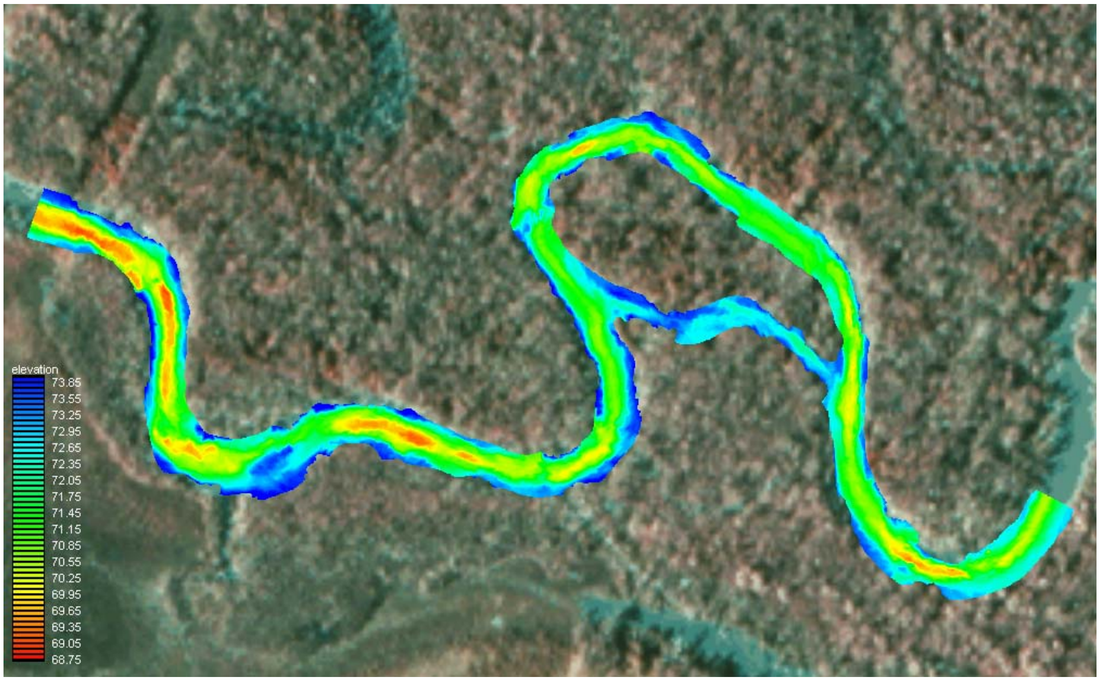

Figure 3.9 – Extent of the finite element mesh at Site 2. Elevation contours, in meters, plotted against aerial photos, DOQQ.

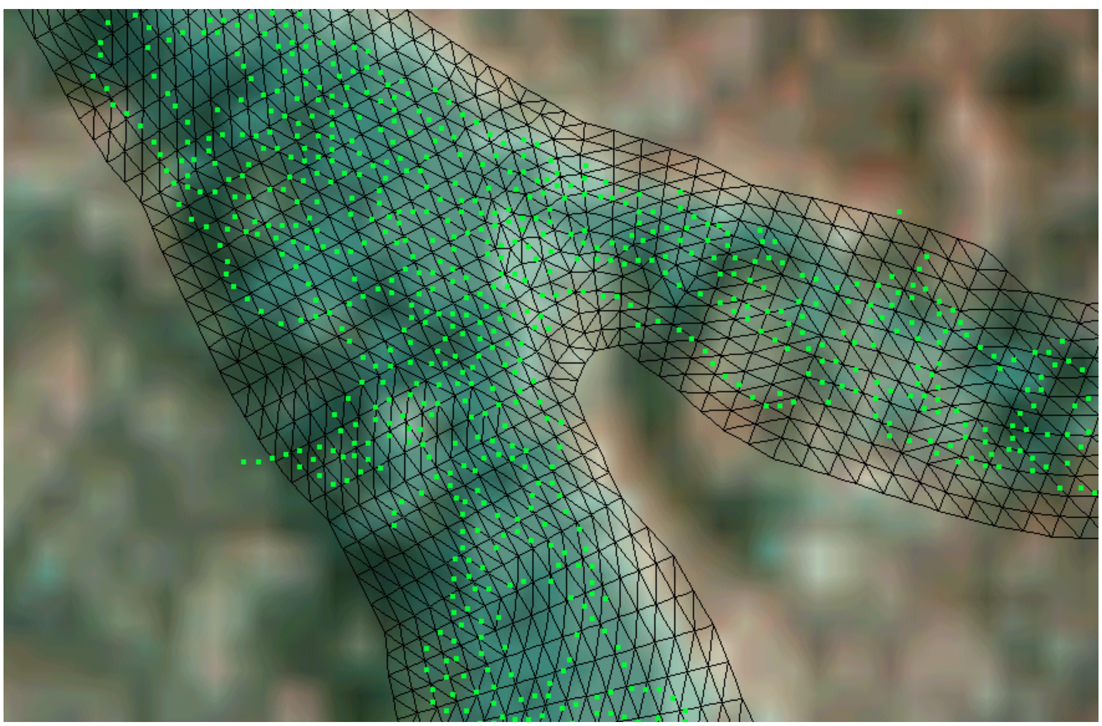

Figure 3.10 – Mesh resolution Site 2, showing western end of cutoff. Mesh elements (shown in black) are approximately 3m x 2m. Green circles indicate bathymetry points measured by depth sounder. Plotted against aerial photo, DOQQ.

3.3 Hydraulic assessment

3.3.1 Site 1

Ten flow rates were modeled on Site 1 and all are presented in this report (Table 3.1. Detailed field measurements were recorded at 0.32 cms (11.5 cfs), 1.27 cms (45 cfs), 2.26 cms (80 cfs), 3.11 cms (110cfs), and 83.02 cms (2932 cfs) and these measurements were used to calibrate the model. Field measurements are presented in a chart showing flow versus water surface elevation, Figure 3.11.

Table 3.1 – Flow rates modeled at Site 1.

Flow #	cms	cfs	Field Observed	Notes
1	0.32	11.5	Y	Median Summer Monthly Low Flow
2	0.71	25		
3	1.27	45	Y	
4	2.26	80	Y	Median Average Daily Flow
5	3.11	110		
6	5.66	200		Median Winter Flow
7	8.5	300		
8	11.33	400		
9	14.16	500		
10	83.02	2932	Y	

The lowest flow modeled (0.31 cms or 11.5 cfs) roughly corresponds to the median summer monthly flow. Lower flows were not modeled because they would not illustrate any behavior of the river that is significantly different than behavior at 0.31 cms (11.5 cfs).

Median average daily flow for the entire period of record at the Sulphur River USGS gauging station at Talco is 2.15 cms (76 cfs). A measured flow of 2.26 cms (80 cfs) is modeled to approximate hydraulic and habitat conditions at median flow at the study site. Flows have been modeled above the median flow rate because the winter median flow approaches 5.66 cms (200 cfs).

The measured flow at 83.02 (2932 cfs) was modeled in order to calibrate the model at flows higher than 3.11 cms (110 cfs). Unfortunately, we were unable to measure any flow rate between these two flows. Upstream water surface elevation for flows above 3.11 cms (110 cfs) were generally not influenced by the shallow area near the confluence; however, all flows below 3.11 cms (110 cfs) were heavily influenced by the shallow area.

Spatial depth and velocity plots for selected flows of the model output are presented in Appendix L. Model verification data is presented in Appendix M.

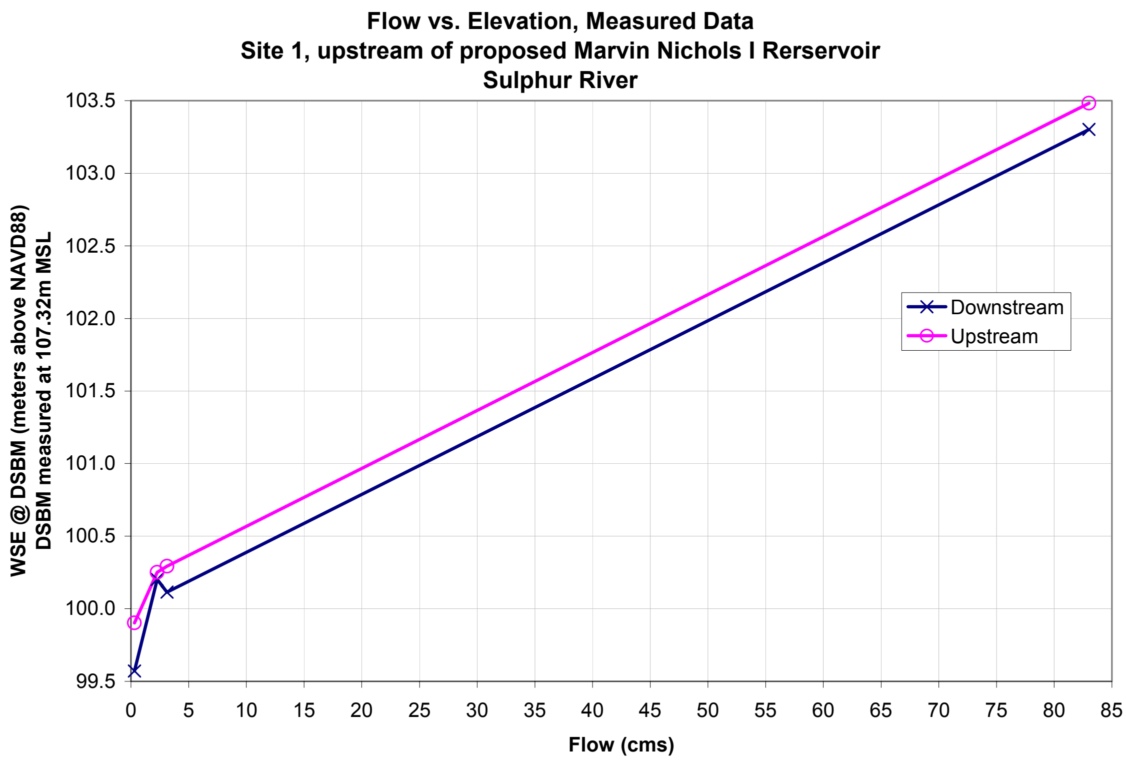

Figure 3.11 - Water surface elevation vs. flow for measurements at Sulphur River Site 1.

3.3.2 Site 2

Seven flow rates were modeled on Site 2 and all are presented in this report (Table 3.2). Detailed field measurements were recorded at 1.05 cms (37 cfs), 2.32 cms (82 cfs), 23.53 cms (831 cfs), and 99.39 cms (3,510 cfs) and these measurements were used to calibrate the model. Field measurements are presented in a chart showing flow versus water surface elevation, Figure 3.12.

Table 3.2 – Flow rates modeled at Site 2.

Flow #	cms	cfs	Field Observed	Notes
1	1.05	37	Y	
2	2.32	82	Y	Annual Median Daily Flow
3	5.66	200		Median Winter Flow
4	11.33	400		
5	16.99	600		
6	23.53	831	Y	Flooding of Secondary Channel
7	99.39	3510	Y	Overbanking Flow

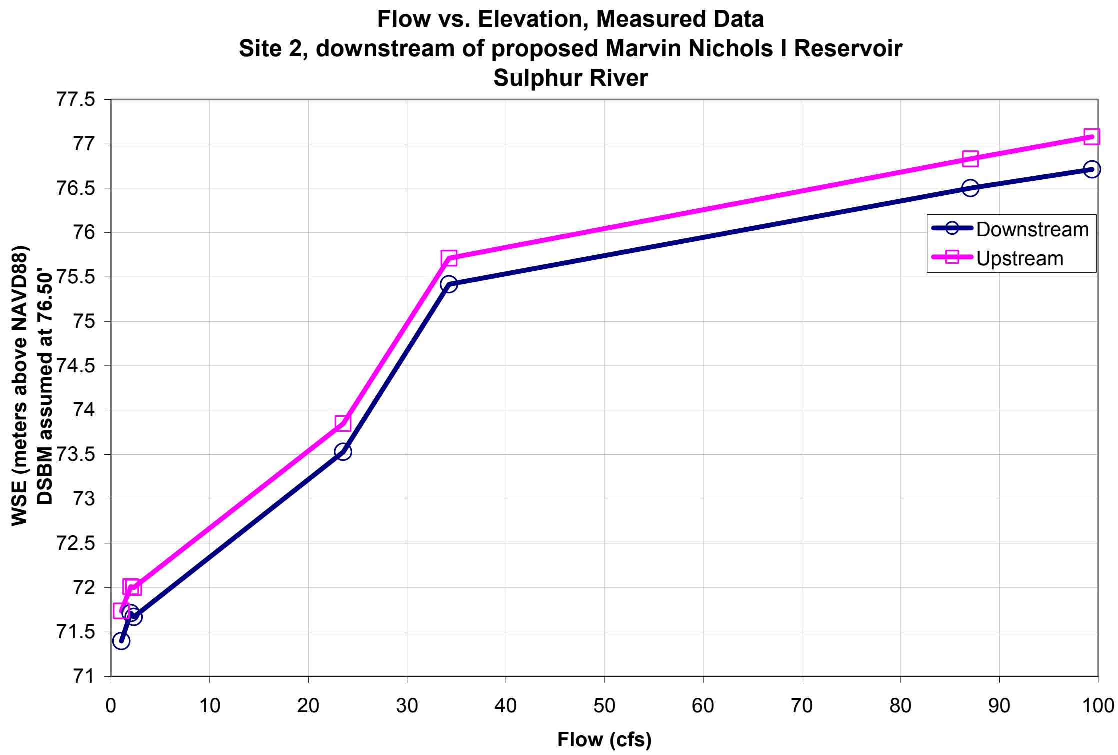

Figure 3.12 - Water surface elevation vs. flow for measurements at Sulphur River Site 2.

The lowest flow rate modeled was 1.05 cms (37 cfs). At this lowest flow, the presence of structure in the channel increased the difficulty of modeling. A large degree of flow variation attributable to structure could not be accounted. The measured flow rate of 2.32 cms (82 cfs) was modeled because it roughly corresponds to the annual median daily flow. Lower flows are not modeled because the model was difficult to calibrate at lower flows. Flows higher than the annual daily median of 2.15 cms (76 cfs) are modeled in order to analyze winter monthly median flows that range from 4.25 cms (150 cfs) to 8.50 cms (300 cfs).

The measured flow at 99.39 cms (3,510 cfs) was modeled in order to determine calibration of the model at over bank flows. The model calibrated well to the field data even though, at that water level, much of the floodplain was inundated. The model of the channel was calibrated to flow measured only in the channel.

The measured flow at 23.53 cms (831 cfs) was modeled because this is the flow near which the cutoff channel begins conveying water. At flows lower than 23.53 cms (831 cfs), the full flow is directed through the main channel meander (See Figure 3.5, 3.9). At flows higher than 23.53 cms (831 cfs), some percentage of the flow bypasses the meander through the cutoff. Additionally, over banking flows are evident at flows near 23.53 cms (831 cfs). Over banking is discussed in detail in chapter 6.

Velocity and depth plots for selected flows of the model output are presented in Appendix P. Model verification data is presented in Appendix Q.

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4. Fisheries overview: historical and recent studies

Evaluating fish habitat requirements in the warm water systems of the Southwest is particularly difficult because most of the existing assessment techniques have been developed for coldwater mountain streams with relatively few species. These methods generally do not work well in the warm, species-rich streams of Texas. In addition to the "flashy" hydrologic conditions in the state, the biological requirements of many warm water species are not well known.

4.1 Biological sampling sites

Four study reaches were established for biological sampling on the Sulphur River and its two forks, the north and south fork. Each reach was sampled for fish habitat utilization at different flows and seasons. The study sites were selected to provide background information for assessing the instream flow needs of the fishery in the vicinity of these potential reservoir sites. Two contract studies with Texas A&M University's Department of Wildlife and Fisheries Sciences provided information on the relationship between habitat availability and habitat utilization at different flows within the normal flow regime of the river (Gelwick and Morgan 2000; Gelwick and Burgess 2002). The ecological and hydrologic diversity of all sites reflects the disturbance history, range of habitat conditions, and changes in the fishery composition for the overall Sulphur River drainage.

4.1.1 South Sulphur River near Jim Chapman Lake (Gelwick and Burgess 2002)

Three sample sites on the South Sulphur River near Jim Chapman Lake, noted as sites 201, 202 and 203, are shown in Figure 2.7. While the upper half of the Sulphur River Basin was extensively channelized and levied in an attempt to alleviate frequent flooding of the surrounding farmland, some areas like those in the vicinity of sites 201, 202 and 203 have remained in their natural state. Unchannelized areas of this fork of the river typically contain spatially heterogeneous habitats varying in width, depth, and velocity that generate mesohabitats such as pools, riffles, runs, and backwaters. Without levees, these unchannelized areas have natural tributaries and oxbow lakes which provide habitats for different life-history stages of many riverine fishes (Gelwick and Burgess 2002).

At low through normal flows, these areas consist primarily of pool habitats, and at higher flows mainly run habitats. The three study sites were selected in this reach based on their characteristics representative of the river reach and on accessibility. Habitats within each site were categorized based on hydraulic characteristics into one of four mesohabitat types (pools, runs, riffles, and backwater areas). Mesohabitat delineation in the field was performed by TWDB and Texas A&M University (TAMU) staff scientists, based on the definitions developed by Jowett (1993) for pools, runs, and riffles. Backwaters have little or no flow, and are still connected, but adjacent to the main channel. Site length was equivalent to 20 times the wetted river width at base flow, which TWDB scientists determined as the minimum length necessary for inclusion of all the geomorphologic, hydrologic, and biological habitat features of the river.

4.1.2 South Sulphur River near the confluence (Gelwick and Burgess 2002)

The lower reach of the South Sulphur River downstream of the proposed George Parkhouse I Reservoir site and just upstream of its confluence with the North Sulphur River has been channelized. In contrast to unchannelized reaches, channelized reaches of the South Sulphur River have straighter channels and relatively uniform depth and velocity contours contributing to fairly homogenous habitat characteristics (Gelwick and Burgess 2002). Levees constructed along the channelized reach have cut off several connections between the main stem and its tributaries, as well as reduced the frequency of natural flood flows that connect the river hydrologically to once-common landscape features such as oxbow lakes and other floodplain habitats.

Three sites, 204, 205 and 206, were selected in the channelized reach downstream of the proposed reservoir site. Comparisons between the habitats and fishery of channelized and unchannelized sites were considered ecologically important to this instream flow assessment.

4.1.3 Main stem Sulphur River downstream of confluence (Gelwick and Morgan 2000)

This study reach on the main stem of the Sulphur River was selected because it is downstream of the confluence of both North and South Forks of the Sulphur River, and downstream of both alternative reservoir sites identified in the State and Regional Water Plans (George Parkhouse I and II). This reach of the river has been channelized. Two sampling sites on the main stem of the Sulphur River, sites 102 and 103, were selected for fish habitat utilization studies in this reach in the same manner as described for those on the South Sulphur River. All of the channellized sites (204, 205, 206 (Gelwick and Burgess 2002), and 107, 101 and 102 (Gelwick and Morgan 2000) are ecologically similar in many ways, and are representative of the overall fishery of this study reach. These sites were generally straight with steep banks and levees due to the historic channelization by the U.S. Army Corps of Engineers (USCOE), U.S. Natural Resource Conservation Service (NRCS), and private individuals (E. Kangas, USCOE-Ft. Worth District, personal communication).

4.1.4 Sulphur River downstream of proposed Marvin Nichols I (Gelwick and Morgan 2000)

Three sites, 104, 105 and 106, on the main stem of the Sulphur River downstream of the proposed Marvin Nichols Reservoir site and upstream of the existing Wright Patman Lake were studied for fish habitat utilization (Figure 2.8). These sites were not channellized and exhibited steep banks with meanders and cutoff channles. This unchannelized part of the river could be characterized as much more pristine than the upper main stem Sulphur River, and it had higher value habitat conditions and thus supported a greater diversity of fish. These study sites were selected for their position downstream of the proposed Marvin Nichols Reservoir dam site so that baseline information would be available for determining the instream flow needs of the fishery downstream of the proposed dam site. They also provided a comparison of channelized verses unchannelized portions of the main stem of the river when compared to sites 101 and 102.

4.2 Flow rates for fish sampling events

As shown in Tables 4.1 and 4.2, numerous fish habitat samplings were performed by Texas A&M University (TAMU) (Gelwick and Morgan 2000; Gelwick and Burgess 2002) for 13 sites in three regions of the Sulphur River watershed for a range of flows in both the summer and winter seasons. Sampling dates, flow rates, percentile rank of flow rate, and flow range for each sampling period are shown in Tables 4.1 and 4.2. Site numbers correspond to Figure 2.7.

Table 4.1 – Biological sampling dates, flows, and percentiles for Summer season, May through October.

Site	Date	Hours (24-hour)	Mean Daily Discharge (cms)	Mean Daily Discharge (cfs)	Summer percent rank of flow	Annual percent rank of flow	Flow Range
			recorded at USGS Talco gauge		(for period of record 1956-1998)		
South Sulphur River, unchannelized sites downstream of Jim Chapman Lake							
201	August 4, 2001		0.19	6.6	40.40%	32.10%	L
	May 18, 2002		6.85	242	71.70%	65.30%	H
	July 9, 2002		0.01	0.47	6.80%	4.40%	L
202	August 4, 2001		0.19	6.6	24.90%	18.40%	L
	May 18, 2002		6.85	242	71.70%	65.30%	H
	July 9, 2002		0.01	0.47	6.80%	4.40%	L
203	August 4, 2001		0.19	6.6	40.40%	32.10%	L
	May 18, 2002		6.85	242	71.70%	65.30%	H
	July 9, 2002		0.01	0.47	6.80%	4.40%	L
Site 1, near confluence of North and South Sulphur Rivers, downstream of prop. George Parkhouse I and II Reservoirs							
101	July 30, 1998	1045-1645[a]	0.24	8.6	10.70%	20.90%	L
	June 9, 1999	1436-1731	0.99	35	38.70%	47.20%	M
	June 17, 1999	1012-1154	4.39	155	59.80%	67.20%	H
102	July 31, 1998	1002-1645	0.23	8.1	27.30%	20.30%	L
	June 10, 1999	1345-1542	0.82	29	44.20%	35.80%	M
	June 17, 1999	0938-1515	4.30	152	67.00%	59.60%	H
103	July 31, 1998	0926-1440	0.24	8.4	27.80%	20.60%	L
	June 10, 1999	0942-1629	0.82	29	44.20%	35.80%	M
	June 18, 1999	0945-1350	2.72	96	61.30%	53.10%	H
107	June 19, 1999	1007-1250	0.20	6.9	25.30%	18.70%	L
204	August 6, 2001		0.17	6.1	24.20%	17.80%	L
	May 20, 2002		11.10	392	75.80%	70.20%	H
205	July 11, 2002		0.62	22	40.40%	32.10%	M
	August 6, 2001		0.17	6.1	24.20%	17.80%	L
	May 20, 2002		11.10	392	75.80%	70.20%	H
	July 11, 2002		0.62	22	40.40%	32.10%	M
206	August 6, 2001		0.17	6.1	24.20%	17.80%	L
	May 20, 2002		11.10	392	75.80%	70.20%	H
	July 11, 2002		0.62	22	40.40%	32.10%	M
Site 2, Sulphur River, downstream of proposed Marvin Nichols I Reservoir							
104	August 1, 1998	0854-1306	0.23	8.1	27.30%	20.30%	L
	May 25, 1999	1049-1415	3.71	131	65.10%	57.40%	H
	June 9, 1999	0821-1043	1.08	38	48.30%	39.80%	M
105	August 1, 1998	1442-1632	0.23	8.1	27.30%	20.30%	L
	June 8, 1999	1520-1740	1.25	44	50.40%	41.80%	M
	June 16, 1999	1530-1855	6.51	230	71.20%	64.60%	H
106	August 2, 1998	0847-1220	0.23	8.1	27.30%	20.30%	L
	May 25, 1999	1009-1737	3.68	130	65.00%	57.30%	H
	June 8, 1999	1257-1509	1.33	47	51.50%	42.80%	M
Summer Season:				Summer flow ranges:	75 to 50 pctl	500 to 64 cfs	H
	May to October				50 to 30 pctl	64 to 16 cfs	M
					< 30 pctl	< 16 cfs	L

Table 4.2 – Biological sampling dates, flows, and percentiles for Winter season, November through April.

Site	Date	Hours (24-hour)	Mean Daily Discharge (cms)	Mean Daily Discharge (cfs)	Winter percent rank of flow	Annual percent rank of flow	Flow Range
			recorded at USGS Talco gauge		(for period of record 1956-1998)		
South Sulphur River, unchannelized sites downstream of Jim Chapman Lake							
201	November 10, 2001		0.27	9.6	11.60%	22.10%	L
	March 1, 2002		-	-			
	April 28, 2002		12.91	456	64.30%	71.70%	H
202	November 10, 2001		0.27	9.6	11.60%	22.10%	L
	March 1, 2002		-	-			
	April 28, 2002		12.91	456	64.30%	71.70%	H
203	November 10, 2001		0.27	9.6	11.60%	22.10%	L
	March 1, 2002		-	-			
	April 27, 2002		13.14	464	64.50%	71.80%	H
Site 1, near confluence of North and South Sulphur Rivers, downstream of prop. George Parkhouse I and II Reservoirs							
101	March 26, 1999	1120-1736	22.94	810	70.30%	76.80%	H
102	March 27, 1999	0958-1307	21.92	774	69.80%	76.40%	H
103	March 27, 1999	1144-1717	21.63	764	69.70%	76.20%	H
204	November 11, 2001		0.24	8.6	28.10%	20.90%	L
	March 3, 2002		2.86	101	42.40%	53.90%	M
	April 29, 2002		12.77	451	64.20%	71.60%	H
205	November 11, 2001		0.24	8.6	28.10%	20.90%	L
	March 3, 2002		2.86	101	42.40%	53.90%	M
	April 29, 2002		12.77	451	64.20%	71.60%	H
206	November 11, 2001		0.24	8.6	28.10%	20.90%	L
	March 3, 2002		2.86	101	42.40%	53.90%	M
	April 29, 2002		12.77	451	64.20%	71.60%	H
Site 2, Sulphur River, downstream of proposed Marvin Nichols I Reservoir							
104	November 22, 1998	0589-1604	32.14	1135	74.40%	79.90%	H
	January 14, 1999	0815-1045[a]	7.48	264	57.50%	66.30%	H
105	November 23, 1998	0822-1326	28.37	1002	73.00%	78.90%	H
	January 13, 1999	0913-1524	9.49	335	60.60%	68.80%	H
106	January 14, 1999	1113-1548	7.39	261	57.30%	66.20%	H
Winter Season:				Winter flow range:	75 to 50 pctl	1190 to 340 cfs	H
	November to April				50 to 30 pctl	340 to 33 cfs	M
					< 30 pctl	< 33 cfs	L

Individual species habitat models for selected species (see Section 4.4) were developed for each of the flow ranges shown in Table 4.1. Available hydraulic habitat utilization area for each species was determined at each of the two hydraulic analysis sites using the depth and velocity criteria described in Section 4.3. For each species, hydraulic criteria were developed by combining all of the available data for that species and those criteria were applied at all modeled flows.

Observed fish habitat utilization, mesohabitat area availability, and target species habitat area availability were analyzed for a range of flows in both the summer and winter seasons. It should be noted that habitat area availability does not imply actual habitat utilization; available area is best described as area that meets criteria that was developed using field data collected for utilization of a particular habitat.

4.3 Instream fisheries

The instream fisheries and their mesohabitat utilization at different flows in the South Sulphur River in the vicinity of the proposed George Parkhouse I Reservoir have been studied by Gelwick and Burgess (2002). The fisheries of the Sulphur River above and below the proposed Marvin Nichols I Reservoir have been studied by Gelwick and Morgan (2000) for investigation of fishery-habitat-flow relationships. Two additional studies were performed by Morgan (2002) and by Burgess (2003). These four studies provided information that was used in this instream flow assessment. All four studies showed weak habitat specialization and Burgess (2003) showed weak or no differences between channelized and unchannelized habitats. Two fluvial specialist species were in unchannelized habitat.

Seven study sites (101, 102, 103, 107, 204, 205, 206) were selected in the confluence area of the Sulphur River and the North and South forks downstream of the proposed George Parkhouse I and II Reservoirs. Biological sites 102 and 103 were contained within TWDB Site 1. These sites were previously channelized. Three sites (201, 202 and 203) were selected in natural (unchannelized) reaches of the South Sulphur River, upstream of the confluence.

Three sites (104, 105, 106) composed the Gelwick and Morgan (2000) study for fish habitat utilization downstream of the proposed Marvin Nichols I Reservoir, and the composite of these were used for instream flow analyses referred to as TWDB site # 2. These sites had steep banks with meanders and had not been channelized.

Table 1 in Appendix D lists the 38 fish species collected and the habitat type they were most frequently associated with, as sorted by cluster analysis into habitat groups, based on the contract study reaches located downstream George Parkhouse I and Marvin Nichols I reservoir site (Gelwick and Morgan 2000). TAMU's detailed analysis of habitat utilization resulted in habitat guilds based on their mesohabitat association and large woody debris components (see Appendix D). The dominant mesohabitat was pools during low through normal flows. Large woody debris (LWD) was the major structural habitat, and it significantly influenced the habitat utilization within mesohabitats, especially pools. Both mesohabitats (pools, runs, riffles, backwaters) and sub-mesohabitats (sub-divided mesohabitats into parts with LWD, edge habitat, and open water) were analyzed for their fish utilization over a range of flow conditions and groupings into fishery guilds in this study.

A total of 2,584 individual fish were collected during the contract study by Gelwick and Morgan (2000) representing 38 species and 12 families collected from 20 habitat types. Red shiners were most abundant (48%) followed by Mississippi silvery minnows (12%) and western mosquitofish (6%).

This compares closely to collections made for a taxonomic survey of fishes in the Sulphur River from the headwaters to Wright-Patman Reservoir (Turner 1978), which resulted in 47 species in 14 families. A total of 33,911 fish specimens were collected over a broader area than the contract study, which emphasized the George Parkhouse I and Marvin Nichols I reservoir sites in the Sulphur River.

4.4 Excerpts from Gelwick and Morgan (2000)

The text in this section was excerpted directly from Gelwick and Morgan (2000). The full text is included as Appendix H on the CDROM that accompanies this report. **Additional text was added to this section by the authors for clarification and that text is shown in bold.**

Biological data collection sites designated in Figure 2.7 as Sites 101, 102, 103 and 107 are the same sites as those sites referred to by Gelwick and Morgan (2000) as sites 1, 2, 3 and 7, respectively. Similarly, Sites 104, 105 and 106 shown in Figure 2.8 are sites 4, 5 and 5, respectively.

INTRODUCTION

Two potential reservoir sites, George Parkhouse I and Marvin Nichols I, were identified by the Texas Water Development Board (1997) on the Sulphur River in Northeast Texas. This study was designed to provide information about the fishes in the affected downstream segments for the Microhabitat Assessment Technique (MAT) (Mathews and Bao 1991) for flow assessment by the Texas Water Development Board. The flow assessment is focused on the relationships between physical habitat availability and use of the habitats by fish during targeted flow regimes and seasons. Published studies of fish surveys of the Sulphur River can be found in Bonn and Inman (1955), Carroll et al. (1977), and Turner (1978). A comprehensive list of fish species known from museum records for the Sulphur River basin can be found in Turner et al. (1994).

The goals of this study were to: 1) assess and map habitats, 2) measure ambient water quality parameters, 3) report the number of each fish species collected in each habitat at each of three sample sites for each reservoir site, 4) assess stream health using an Index of Biological Integrity (Karr et al. 1986), and 5) identify habitat groups based on fish species.

METHODS AND MATERIALS

Habitat assessment and identification

Twenty habitat types were distinguished based on their occurrence at least once during the study period. A habitat type was characterized by a mesohabitat based on hydraulic characteristics and a microhabitat based on physical characteristics. Mesohabitats included riffles, runs, pools, and backwaters. Microhabitats included bank snags, channel snags, snag complexes, undercut banks, rootwads, debris dams, edge, vegetation, and tree. Three additional microhabitat categories were created: edge, vegetation, and tree. Edge microhabitat was bare stream bank. Vegetation microhabitat was riparian plants such as willow (Calex sp.) or tree branches which, when submerged at high flows, created complex habitat. Tree microhabitat was submerged, live tree trunks. Typically, only woody habitats that appeared relatively permanent were selected for sampling.

Fish collection

All representative habitat types present at a site were sampled for fish, using a variety of gear, including seines, gillnets, and electrofishers. All sampling was conducted during daylight hours. Straight seines (5-mm mesh) were 1.2 m deep and 2.4 m, 3.0 m, and 6.1 m long as appropriate for the habitat sampled. Seining effort continued until no additional species were collected in three consecutive hauls and no new habitats were encountered. One 38.1-m long experimental gillnet that consisted of five panels each 7.6 m long x 1.8 m deep with 2.5, 3.8, 5.1, 6.3, and 7.6-cm bar mesh, was set perpendicular to the current in pools. Gillnets were allowed to fish up to 8 hours while other work was being performed.

Two electrofishing units were used; a Coffelt Mark 10 backpack unit powered by a Honda 350EX generator and a 4.9-m aluminum Jon-boat powered by a 15 horsepower outboard motor. The boat used for electrofishing had a Wisconsin ring attached to a fixed boom, a 5000 watt Honda generator, and a Smith-Root Model 1.5-KVA control box. Direct current (DC) output on each unit was set at 200-350 V and 5-8 A depending on conductivity. Because depth was primarily greater than 2 m at most sites, boat electrofishing was the primary sampling method and was typically conducted in an upstream direction. Individual habitats (at least 5-m apart) were electrofished separately for habitat-specific data collection.

Fishes greater than 50 mm were identified, weighed, (nearest 1 g), measured for total length (nearest 1 mm), and released in the field. Small and uncommon fishes were preserved in 10% formalin and returned to the lab for identification and enumeration. At least one specimen of each fish species (except spotted gar, bigmouth buffalo, and smallmouth buffalo) was preserved in 70% EtOH and deposited in the Texas Cooperative Wildlife Collection (TCWC) at Texas A&M University.

Physicochemical parameters

Dissolved oxygen, temperature, conductivity, and percent oxygen saturation were measured at the water surface with a YSI Model 85 multiparameter meter at each study site for all collection dates. pH was measured at each site using a Hach digital probe or pH paper. Mean daily discharges (cfs) were obtained from USGS gage number 07343200 (Sulphur River Nr Talco, TX). A representative depth and velocity measurement was taken at each habitat type at the time it was sampled. Depth to the nearest 0.1 m was measured using either a Hondex digital depth sounder or a graduated wading rod. Velocity was measured at 0.6 depth with a Marsh-McBirney Model 2000 digital flow meter.

Index of Biological Integrity

Karr et al. (1986) proposed an Index of Biological Integrity (IBI) that used fish community attributes to assess stream health. Because watershed characteristics and fish communities from the Sulphur River differ from those for Midwestern headwater streams originally used by Karr et al. (1986), we modified the metrics. Of the 12 original metrics, three were omitted and three were modified. The modifications generally followed the format of those developed for the Brazos-Navasota watershed (Texas) reported by Winemiller and Gelwick (1999). Original metric 10, number of individuals in sample, was omitted because this data was sensitive to the species by area relationship and the number of samples. Metric 11, proportion of individuals as hybrids, was omitted due to the inherent difficulty in accurately identifying hybrids (Karr et al. 1986). Metric 12, proportion of individuals with disease or other anomaly, was omitted because few reliable data exist for setting criteria for this metric (Karr et al. 1986). For metric 2, number of darter species, freckled madtom (Noturus nocturnus) was added because it fills a similar trophic niche. For metric 6, proportion of individuals as green sunfish, mosquitofish (Gambusia affinis) was substituted because they are a tolerant, rapid colonizer and also because green sunfish were uncommon in collections. For metric 8, proportion of individuals as insectivorous cyprinids, invertivores of all families were substituted again because cyprinid species were less common overall. Assignment of trophic status and intolerance/tolerance was based on Linam and Kleinsasser (1993). Because data for suitable reference streams comparable to the Sulphur River were not yet available (R. Kleinsasser, Texas Parks and Wildlife Department - Austin, Texas, personal communication) and because only seven sites were sampled at restricted locations on the river, ranks were assigned to each metric for each site rather than a true IBI score that is normally relativized to a suite of least disturbed reference sites for such evaluations (Karr et al. 1986). Thus, sites were evaluated relative to only each other.

Habitat groups and indicator species

Because fish species collected in low abundances cannot be characterized accurately, species making up < 1% of the total individuals of all species collected were omitted from this analysis. Habitats used in the analysis were those in which at least one species had been collected. Data were standardized by relativizing abundance across species for each habitat type and cluster analysis was run using the software package PC-ORD (McCune and Mefford 1997). Thus, habitats were clustered based on species relative abundances. Indicator species analysis (Dufrêne and Legendre 1997) provided by PC-ORD was used to determine what species could be indicators of the habitat groups identified in the cluster analysis.

RESULTS AND CONCLUSIONS

Physicochemical

Mean daily discharges varied during the study period with a low of 7.1 cfs and a high of 9040 cfs. For all sites, conductivity ranged from 50.4-811.1 μS/cm and pH ranged from 7.0 to 8.4. Dissolved oxygen ranged from 3.55-14.62 mg/L and the corresponding percent oxygen saturation ranged from 49.9-197.6. Water temperature ranged from 25.4-34.1 °C. Part of the variation in oxygen and temperature measurements depended on cloud cover and time of day during sampling. Depths ranged from 0.1-4.3 m and velocities ranged from 0-0.54 m/s at the habitats. Generally, velocities associated with pool mesohabitats were slower (< 0.2 m/s) than those associated with riffle and run mesohabitats (> 0.3 m/s). The velocity measurements in this report reflect the value at the time for a representative example of a habitat type in which fish were collected during a particular flow condition and season. This should be taken into consideration when interpreting our results and the flow models developed at a later time by the Texas Water Development Board.

Fish species and microhabitat utilization

A total of 2584 individuals representing 36 species and 12 families were collected from 20 habitat types. Red shiners were most abundant (48%) followed by Mississippi silvery minnows (12%) and mosquitofish (6%). We note that for two large-river fish groups (gar, Lepisosteidae, and buffalo fishes, Ictiobus); all species known to occur in Texas were included in our collections.

Index of Biological Integrity

The range of the possible total value for IBI metrics was that for the possible sum of the ranks (10-70). Site 3 had the highest sum of the ranks (56.5) and therefore the highest percentage (81%) of the maximum score. Sites 7, 4, and 6 had the lowest sums of the ranks and therefore the lowest percentages of the maximum score (47%, 46%, and 40% respectively).

The mean of scores for the upstream sites 1, 2, and 3 (within the channelized area to be influenced by George Parkhouse I) was 69.3% (63.8% if site 7 was included in that average). The mean of scores for the downstream sites 4, 5, and 6 (to be influenced by Marvin Nichols I) was 48.3%. This is an interesting result given that the habitat of the upstream sites would appear to be strongly degraded by channelization. Thus, it may be that the metrics which were most sensitive to generally recognized biological criteria (e.g., number of sucker species, percentage of tolerant species) were not necessarily correlated to those of habitat degradation. This may also be a consequence of having no established reference sites at this time. However, the difference between scores for the two groups of sites was not statistically significant (ANOVA, $F = 0.25$, $P = 0.64$). Therefore, results of the IBI analysis should be interpreted as only a relative index within the Sulphur River until more comprehensive IBI assessments can be done that include reference sites for large rivers in this region of Texas.

Habitat groups and fish species indicators

The cluster analysis distinguished 4 habitat groups with which more than 1 species was associated. Riffle-channel snag habitat contained only red shiner and occurred only once so indicator values could not be evaluated. Group 4 had species with the highest indicator values and contained some of the most structurally complex habitats, i.e., snag complex and vegetation. Freshwater drum and centrarchids (bluegill, orangespotted sunfish, longear sunfish, and white crappie) dominated this group. This is reasonable given that sunfish (Centrarchidae) are characteristically associated with slower water velocities and complex structure.

Group 2 consisted of pool-rootwad, backwater, and backwater-bank snag habitats and contained the second largest number of species occurrences. Backwater habitats, having lower velocities, are refuges for many species of fish and are often nursery areas. Group 1 had few species associated with it except red shiners which were dominant in the run mesohabitat that occurred only once and only at site 4. Bank snags, channel snags, and trees are relatively simple habitats structurally compared to rootwads, snag complexes, and vegetation.

Although distinguished in the cluster analysis, group 3 (riffle-snag complex, riffle-debris dam, and riffle-edge) was poorly differentiated by fish occurrences for any species. This is likely in large part due to the low occurrence of these habitat types across the sample sites. The fast velocities and complex hydraulics found in habitat types in this group likely limit their use primarily to that of corridors, or as delivery systems for drifting invertebrate prey for invertivores stationed downstream of them. Generally, more species were associated with structurally complex habitats with slower velocities. This is reasonable given the predominance of pool mesohabitat in the Sulphur River.

Results of Additional Data Collection on IBI and Indicator Species

Fish Collections and Habitat Measurements

Additional data were collected during January 2000 for abundance of fishes in each habitat type that was present at each site. Extensive measurements of depth and velocity in run and riffle habitats for use in models to be developed for these sites by the Texas Water Development Board.

Index of Biological Integrity

The range of possible total value for IBI metrics was the sum of the ranks (10-70). Based on the additional data, site 3 again had the highest sum of ranks (52.2) and therefore highest percentage (75%) of the maximum score. Site 7 had the lowest sum of ranks (32) and therefore the lowest percentage of the maximum (46%). Intermediate IBI values among sites 2, 4, and 6 were very similar to each other (35.5, 36.5, and 37 respectively), as were those of sites 1 and 5 (44.5 and 42 respectively).

The mean of scores for the upstream sites 1, 2, and 3 (within the channelized area to be influenced by George Parkhouse I) was 63.3% (59.0% if site 7 was included in that average). The mean of scores for the downstream sites 4, 5, and 6 (to be influenced by Marvin Nichols I) was 55.0%. As for the initial data, IBI values for the two site groups did not differ (ANOVA, $F = 2.46$, $P = 0.18$). To determine if IBI values changed when the ancillary data was added, IBI values for initial data and combined data (initial plus ancillary) were considered as separate dependent variables measured on the same sites, and therefore analyzed using a one-way Multivariate Analysis of Variance (MANOVA). The difference between site groups for mean IBI values was smaller for combined data than for initial data **but still not significant** ($F = 5.56$, $P = 0.08$).

Indicator species

The additional collections allowed the use of more species and data for rarer habitat types (e.g., riffle-channel snag and riffle-bank snag). As for the analysis of initial data, habitat groups could be characterized by a basic separation into mesohabitat groups based on stream hydraulics. Two groups primarily included riffles and runs, and two included primarily pools and backwaters. Significant indicator species for the riffle-channel snag, riffle-snag complex and run group (group 1) were slough darter, bullhead minnow, channel catfish and freckled madtom. Slough darter, and freckled madtom were almost exclusively found in these habitats, which were most abundant at downstream sites 4 and 6. Red shiner was moderately significant as an indicator of this habitat group, but was more associated with habitat group 2, which included not only edge, bank, and debris dams in riffles, but also undercut banks, debris dams, and trees in pools. Three other species (smallmouth buffalo, longnose gar, and white bass) were more strongly associated with habitat group 2 than other groups, but were not significant indicators.

Bigmouth buffalo and spotted gar were significant indicators for habitat group 3, most likely because they were almost exclusively found in those kinds of pool habitat types. Six species were indicators of habitat group 4, including freshwater drum, longear sunfish, bluegill, white crappie, orangespotted sunfish, and mosquitofish. These species are associated with lentic conditions and somewhat shallower habitats than are indicator species in habitat group 3. In addition, all individuals, including those of larger-bodied species (freshwater drum, white crappie) collected in group 4 habitats were young-of-the-year or juveniles. This likely indicates the importance of these habitats as “nurseries” or “predator-free” habitats for smaller fishes.

4.5 Excerpts from Morgan (2002)

The text in this section was excerpted directly from Michael Morgan’s MS Thesis, Morgan (2002). The full text is included as Appendix R on the CDROM that accompanies this report.

The data used for this thesis was a sub-set of the Gelwick and Morgan (2000) dataset. Morgan (2002) concentrates his anlaysis on summer low-flow collections.

ABSTRACT

As part of an instream flow study, information on summer distribution of fishes and habitat variables was collected from six sites at each of three flows in the Sulphur River, Texas. The following were evaluated: (1) spatiotemporal relationships between instream habitat features and fish assemblage structure, (2) variation in fish assemblage structure explained by combinations of hydraulic and structural instream habitat features at three levels of habitat aggregation (coarse, intermediate, fine), and (3) the potential to accurately describe summer habitat associations for fishes in southern prairie rivers. Most fishes occurred in a variety of habitats in the Sulphur River and did not reveal discrete habitat associations. The range of explained variance was relatively low for relationships among species and habitat variables across three levels of habitat aggregation. Variation in fish assemblage structure explained by habitat changed from 24, to 30, and to 36 percent as the level of aggregation changed from coarse, to intermediate, and to fine. After accounting for the variance explained by hydraulic variables, the remaining variance explained by structural habitat variables was 7.2% for the coarse aggregation, 13.2% for the intermediate aggregation, and 19.3% for the fine aggregation. In this river, where pools were predominant, microhabitat variables independently explained greater variance in species distribution (6.1%) than did mesohabitat (3.7%) or location (2.3%) variables at the intermediate aggregation level. The ability to describe summer habitat associations for fishes in southern prairie rivers, such as the Sulphur River, is complicated by poor stream access and by problems posed by gear-related biases in sampling a variety of instream habitat types. Identifying appropriate habitat criteria for instream flow studies on the Sulphur River poses a challenge due to the abundance of habitat generalists in this system.

INTRODUCTION

Understanding the relationships between fishes and their habitats is important for conservation and resource management. Habitat, a major organizing factor of biological communities, influences feeding, reproduction, and survival via effects on physiology, behavior, and genetics (Schoener 1974, Southwood 1977). Relationships between physical habitat structure and stream-fish assemblage structure are well-documented (Gorman & Karr 1978, Schlosser 1982, 1985, 1987a, Capone & Kushlan 1991). Fishes may use physical structure as shelter from current (Schlosser & Toth 1984, Fausch & Northcote 1992), foraging sites (Wallace & Benke 1984, Benke et al. 1985), spawning substrates (Matthews 1998), or hiding places (Angermeier & Karr 1984, Shirvell 1990). However, fish species respond differently to variation in distribution of stream habitat types (Leonard & Orth 1988, Aadland 1993).

Information about habitat use by fishes in the affected downstream segments of proposed reservoirs is often collected as part of preimpoundment instream flow assessments. Instream flow methodologies, such as the Instream Flow Incremental Methodology (IFIM), were initially developed for high-gradient, montane streams in the western U.S. and relied heavily on the relationship of fish distribution to hydraulic characteristics of their habitat (i.e., depth, velocity, and substrate). The low numbers of species in these coldwater systems enabled habitat suitability criteria to be developed for individual species (e.g., Moyle & Baltz 1985). In contrast, warmwater streams in the U.S. can have up to 70 species (Rabeni & Jacobson 1999), inhibiting effective development of separate habitat criteria for individual species (Bain & Knight 1996, Bowen et al. 1998). Therefore, community-level approaches to instream flow studies were recommended for warmwater streams (Leonard & Orth 1988, Lobb & Orth 1991, Vadas & Orth 2000).

Moreover, spatial heterogeneity and abundance of hydraulic habitat types in low-gradient warmwater streams differ greatly from those in high-gradient streams for which instream flow methods were initially developed. For example, low-gradient prairie streams mostly contain sluggish pools and backwaters and have relatively homogeneous clay-silt substrata, but riffles, cobble, and gravel are uncommon (Matthews 1988). Therefore, hydraulic variables traditionally measured for instream flow studies might explain little of the variation in fish assemblage structure for low-gradient prairie streams.

Although habitats in warmwater prairie streams can be spatially homogeneous, highly dynamic flow regimes (frequent spates and seasonal drying) cause strong temporal variation in habitat characteristics. In such streams, generalist species that can use a variety of habitats are common and may comprise a large component of the assemblage (Poff & Allan 1995). Therefore, assemblage structure might not be strongly related to variation in hydraulic habitat measurements. Alternatively, instream woody debris in prairie streams might function similarly to cobble-boulder substrate, insofar as providing variation in physical structure and velocity in an otherwise homogeneous habitat. Woody debris (much like substrate heterogeneity) influences a range of physical, chemical, and biological processes in streams (Harmon et al. 1986, Maser & Sedell 1994). Woody debris provides structure and cover for fishes, and such habitats are among the richest in number and diversity of fishes (Matthews 1998). Woody debris also can support aquatic invertebrates that provide important food resources for many, if not most, warmwater stream fishes. A. Benke and colleagues (Wallace & Benke 1984, Benke et al. 1985) have shown the importance of woody debris for aquatic macroinvertebrate production in southern streams.

The goal of this study was to better understand relationships between features of stream habitat and fish assemblage structure of the preimpoundment reaches in the Sulphur River during summer discharges. The objectives were as follows: 1) determine spatiotemporal relationships between instream habitat features and fish assemblage structure, 2) determine the variation in fish assemblage structure explained by combinations of hydraulic and structural instream habitat features at three levels of habitat aggregation, and 3) evaluate the potential to accurately describe summer habitat associations for fishes in southern prairie rivers.

Analyses

Spatiotemporal Assemblage Patterns

Detrended Correspondence Analysis

Species having low relative abundance in samples are not well characterized by ordination (Gauch 1982). Therefore, species that occurred in $< 10\%$ of all samples were omitted prior to performing analyses. Detrended correspondence analysis (DCA) (Hill & Gauch 1980, Gauch 1982), using the software package CANOCO (ter Braak & Smilauer 1998), was used to examine spatial and temporal relationships of fish assemblage structure.

Habitat Aggregations

Classification and canonical ordination were used to evaluate relationships between explanatory variables (i.e., instream habitat variables) and species' densities across three levels of habitat aggregation (fine, intermediate, coarse). The fine aggregation variables consisted of the original 16 categorical, habitat types identified in the field. The intermediate aggregation variables consisted of 13 categorical habitat features: edge, channel, both (representing a location component), snag, rootwad, tree, vegetation, debris dam, no structure (representing a microhabitat component), pool, backwater, riffle, and run (representing a mesohabitat component). The coarse aggregation variables consisted of categorical, habitat groups formed by a cluster analysis of species densities (see below). Core explanatory variables (included in analyses for all aggregations) consisted of two quantitative variables (depth, velocity) and two categorical variables: discharge range (high, middle, low) and river reach (upstream, downstream).

Cluster Analysis and Indicator Species Analysis

The coarse level of habitat aggregation was based on cluster analysis using the software package PC-ORD (McCune & Mefford 1995). Clusters were formed based on species' distributions across the 16 habitat types at the fine level of aggregation. For each habitat type, mean density (catch/area across all samples at all sites) was calculated for each species. Thus, coarse habitat clusters were based on mean relative density of each species in each habitat type. To give less weight to species having high densities, species relative densities were log (10x+1) transformed (Jongman et al. 1995).

Because groupings defined by any cluster analysis are inherently subjective and may have limited statistical validity (Strauss 1982), indicator species analysis

(Dufrêne & Legendre 1997), in PC-ORD, was used as a validation technique to identify species that best characterized each habitat group. This method tested the probability that each species was an indicator for each group. Indicator values were based on combining a species relative density with its relative frequency of occurrence from the habitat groups formed in the cluster analysis. Indicator values can range from zero (no indication) to 100 (perfect indication). Monte Carlo simulation (1000 iterations) was used to test the null hypothesis that the maximum indicator value for a species was no larger than expected by chance.

Canonical Correspondence Analysis

Canonical correspondence analysis (CCA), in CANOCO, was used to quantify the variation in species' distributions (dispersion among samples) that could be accounted for by explanatory variables. CCA is a direct gradient analysis that assumes target variables (here fish species) have unimodal (rather than linear) distributions with respect to explanatory variables and that peak abundances (for species) among samples can be identified by linear combinations of those explanatory variables (Jongman et al. 1995).

RESULTS

Habitat types within pool mesohabitat had the largest amount of area across all samples. Pool, pool-edge, pool-bank snag, and pool-channel snag were the most common habitat types overall. Pool-tree and pool-vegetation were only present during the high flow period. Habitat types containing riffle, run, and backwater mesohabitats were uncommon across most samples and occurred mostly during the low and middle flow periods. Riffle mesohabitat occurred primarily in the downstream reach at sites 4 and 6. Run mesohabitat occurred exclusively at site 4.

A total of 2,190 specimens representing 34 species were collected during the study, of which 6 species were considered rare based on their low occurrence across samples. The rare species were alligator gar (Atractosteus spatula), shortnose gar (Lepisosteus platostomus), emerald shiner (Notropis atherinoides), blackstripe topminnow (Fundulus notatus), pirate perch (Aphredoderus sayanus), brook silverside (Labidesthes sicculus), striped bass (Morone saxatilis), green sunfish (Lepomis cyanellus) and black crappie (Pomoxis nigromaculatus). Species richness displayed relatively little variation with respect to site (range 17-25) or flow period (range 23-27). More fish were collected in the downstream reach (sites 4-6) than in the upstream reach (sites 1-3), and the number of individual fish collected increased as discharge decreased.
Measured values for temperature, conductivity, and dissolved oxygen were within normal limits for streams of this region supporting fish populations.

Spatiotemporal Assemblage Patterns
Detrended Correspondence Analysis

Eigenvalues (indicating dispersal of species among collections) for the third and fourth axes were lower than those for the first two axes (approximately 40% of the first two axes). Because the dominant patterns of species assemblages are typically reflected in the first two axes of DCA (Gauch 1982), only the first two axes were analyzed further. Despite a considerable spread, most fish collections exhibited little separation in multivariate space with respect to site, flow, mesohabitat, or microhabitat.

Habitat Aggregations
Cluster Analysis and Indicator Species Analysis – Coarse Aggregation Level

Cluster analysis distinguished five habitat groups for the coarse aggregation. These groups were interpreted qualitatively based on field observations. Three groups were generally characterized by hydraulic attributes (fast-water, back-water, and open-water), and two groups were characterized by physical structure (single and multiple). Most species (12 of 25) had their highest indicator values in the back-water group. However, only the following four species were significant indicators of the back-water group: mosquitofish (Gambusia affinis), orangespotted sunfish (Lepomis humilis), Mississippi silvery minnow (Hybognathus nuchalis), and white crappie (Pomoxis annularis). Three species were significant indicators for the fast-water group: red shiner (Cyprinella lutrensis), freckled madtom (Noturus nocturnus), and juvenile channel catfish (Ictalurus punctatus)—red shiner and freckled madtom occurred almost exclusively in riffle samples. Four species were significant indicators for the open-water group: smallmouth buffalo (Ictiobus bubalus), bigmouth buffalo (I. cyprinella), river carpsucker (Carpiodes carpio), and common carp (Cyprinus carpio), but only smallmouth buffalo was a significant indicator. Only warmouth (Lepomis gulosus) had its highest indicator value in the multiple-structure group—no other species had its highest value in either the multiple-or single-structure groups.

Canonical Correspondence Analysis

Coarse Aggregation Level

The coarse aggregation CCA indicated that, together, the core and habitat explanatory variables accounted for 23.8% of the total variance in fish species' distributions among samples. The first two axes explained 59.9% of this relationship and axes 3 and 4 explained an additional 24.6%. Partial CCA showed that core variables independently explained 11.4% of the variation in species’ distribution, and habitat variables independently explained 7.2%. Significant core explanatory variables were: middle flow, velocity, and both high flow and upstream reach. Significant habitat groups were fast-water and open-water.

Channel catfish and freckled madtoms were positively correlated with higher velocities and the fast-water group. Bluegill (Lepomis macrochirus) and longear sunfish (L. megalotis) were negatively correlated with velocity and were associated with the back-water group and samples made during the middle flow range. In this same quadrant, warmouth, white crappie, and threadfin shad (Dorosoma petenense) showed a close association with the multiple-structure group. River carpsuckers were correlated with the open-water group, deeper water, sites in the upstream reach, and samples made during the high flow range. Mississippi silvery minnows, mosquitofish, and bullhead minnows (Pimephales vigilax) were associated with the single-structure group, shallower water, sites in the downstream reach, and samples made during the low flow range.

Intermediate Aggregation Level

The intermediate aggregation CCA accounted for 29.9% of the total variance in species' distributions. Overall, habitat variables explained 13.2% of the variance. Partial CCA showed that this total included variance independently explained by location (2.3%), microhabitat (6.1%), and mesohabitat (3.7%) components, plus 1.1% (total minus the sum of the independent contributions) that was shared. Significant habitat variables included snag, rootwad, pool, and backwater. Core explanatory variables were significant primarily on the first (velocity, middle flow) and second (high flow, upstream reach) axes. Depth was not a significant explanatory variable on any of the first four axes.

Channel catfish, freckled madtom, flathead catfish (Pylodictus olivarus), blue catfish (Ictalurus furcatus), and red shiner were positively associated with higher velocities; with tree, debris dam, riffle, and run habitat variables; and with samples made during the low flow range in the downstream reach. Threadfin shad, gizzard shad (Dorosoma cepedianum), dollar sunfish (Lepomis marginatus), and longnose gar were strongly associated with edge, channel, vegetation, snag, and pool habitat variables. River carpsucker, white bass (Morone chrysops), bigmouth buffalo, smallmouth buffalo, and common carp were positively associated with depth, upstream reach, and high flow range variables.

Fine Aggregation Level

The CCA for the fine aggregation accounted for the highest amount (35.8%) of explained variation in species’ distributions. The first two axes explained 45.3%

of this relationship and axes 3 and 4 explained an additional 21.9%. Partial CCA showed that habitat variables independently explained 19.3% of the variance. Significant core variables yielded axes that were similar to those of the intermediate aggregation model with the exception of middle-flow range, which was significant on axis 1 for both aggregation levels, but for the fine aggregation was significant on axes 3 and 4 as well. All habitat variables were significant on axis 2. Significant habitat variables on axis 4 were riffle-snag complex, riffle-debris dam, riffle-edge, run, pool-channel snag, pool-rootwad, pool-debris dam, pool-edge, pool-tree, pool-vegetation, and pool-backwater. Pool was the only habitat type significant on axis 3.

Freckled madtom, channel catfish, blue catfish, flathead catfish, and red shiner were positively associated with higher velocities and with riffle-oriented habitat types and shallower depths that occurred during the low flow range. River carpsucker, white bass, bigmouth buffalo, smallmouth buffalo, common carp, and gizzard shad were positively associated with greater depths in the upstream reach and with pool habitats during the high flow range.

DISCUSSION

Spatiotemporal Assemblage Patterns

Most fishes occurred in a variety of habitats in the Sulphur River and did not reveal discrete habitat associations. The number of fishes collected was not consistent across samples at different flows. No sampling method for stream fishes is without bias over a variety of fluctuating water levels (Meador & Matthews 1992). In rivers, electrofishing is usually most effective at lower flows (Reynolds 1996). Conductivity is the most important environmental factor affecting electrofishing efficiency (Reynolds 1996). High conductivity values (mean 833.7 $\mu S\ cm^{-1}$) encountered during the low flow period exceeded the power capacity of the electrofishing generators, as visibly evidenced by fish not responding to the electric field, and thus reduced capture efficiency. High water temperatures (mean 31.6 °C) during this period also reduced electrofishing efficiency in two ways; by increasing conductivity and also by increasing fish metabolism, thereby enhancing a fish's ability to perceive and escape an electric field of lower power density (Reynolds 1996). Additionally, seining was possible only in water < 1.5 m deep, but extensive coverage of woody debris that overlaid the stream bottom inhibited effective seining at some sites. The combination of electrofishing and seining difficulty, due to the physicochemical and physical habitat conditions present, severely limited sampling effectiveness during the low flow period, particularly at sites 2, 3, and 5. Of all habitat types present at these sites, only edge, open pool, and one rootwad (at site 3) could be effectively sampled by the gears, and some gear types only worked well in some habitat types. Limitations imposed on the sampling gear by environmental conditions strongly influenced the number of fish collected during the low flow period.

The lowest number of fishes collected was during the high flow sampling period. River electrofishing can be less effective at higher flows. For example, electrofishing catch rates were inversely related to water level in the upper Mississippi River (Pierce et al. 1985) as well as in Village Creek, east Texas (Moriarty & Winemiller 1997). Electrofishing efficiency was probably reduced at higher flows in this study because, as depth increased, the electric field was less likely to extend through the entire water column (assuming the size of the electric field remained constant). Overall, the lack of a strong spatiotemporal pattern was probably due to limitations in sampling efficiency.

Habitat Aggregations

Variation in fish assemblage structure explained by habitat changed from 24, to 30, and to 36 percent as the level of aggregation changed from coarse to intermediate, and to fine. The range of explained variation in species' distributions for each level of aggregation was relatively low, but it can still hold ecologically relevant information (Gauch 1982). For example, these data indicated that there were relationships among species and habitat variables at several levels of habitat aggregation. The relatively small difference in explained variance between each level of aggregation was consistent with Hawkins et al. (1993) who suggested that variation in species distributions often reflects responses by fish to broad environmental gradients rather than discrete patches of habitat at different scales.

Another possible reason that habitat variables explained relatively little of fish species' distributions is that microhabitat use is highly flexible (Bart 1989, Bain 1995), meaning that certain species can be found in multiple habitats. Assemblages in streams with unpredictable flow regimes, such as the Sulphur River, contain relatively more generalist species which can exploit habitats and resources as they become available (Horwitz 1978, Poff & Allan 1995). The general patterns of habitat use by many species in these studies add further evidence to these findings. For example, red shiner is considered a well-known generalist species (Matthews & Hill 1980) and is usually the most abundant species in its native range (Matthews 1980). Likewise, red shiner had the highest relative abundance (50%) of any species and was collected from nearly all habitat types. However, some species in this study might have appeared to be specific in their use of habitats merely because they could be collected in high abundance from readily accessible and "confined" areas, i.e., shallow riffles, which were seined more effectively than deeper habitats with complex physical structure. Factors not analyzed in this study that could have explained the residual variance in fish assemblages include physicochemical variables (Matthews & Hill 1980), landscape influences (Schlosser 1991, Richards et al. 1996), biotic interactions, and effects of gear type.

In general, hydraulic variables strongly influence stream-fish assemblage structure (Leonard & Orth 1988, Aadland 1993), and habitat heterogeneity is typically evaluated in terms of depth, velocity, and substrate (see, for example, Schlosser 1982). In this study, each set of core (depth, velocity, discharge, reach) and structural variables explained some of the variation in species' distributions at each aggregation level, but their relative contributions differed. For both the coarse and intermediate aggregations, core explanatory variables accounted for more of the variation in species' distributions compared to the structural explanatory variables. However, structural variables explained the largest amount of variation at the fine aggregation level.

The indicator species analysis suggested that the habitat groups identified at the coarse level of habitat aggregation were primarily determined by 8 of the 25 species (32%). These results, as with those for both the indirect and direct ordinations, suggested fish assemblages in the Sulphur River consisted mainly of generalist species.

As in other studies, differentiation among groups in the Sulphur River was primarily related to hydraulic characteristics (fast-water, back-water, and open-water). The swift velocities and complex hydraulics of habitat types in the fast-water group probably limit their function to primarily that of corridors or delivery systems for invertebrate prey to drift-feeding invertivores (Brittain & Eikeland 1988, Matthews 1998). Many species had highest indicator values for the back-water group, due in part to the large number of individuals collected in these habitats. Among those species that were significant indicators, mosquitofish, orangespotted sunfish, and white crappie are characteristically associated with slower water velocities found in backwater areas (Robison & Buchanan 1988). The open-water group was dominated by catostomids (smallmouth buffalo, bigmouth buffalo, and river carpsucker) and common carp. These fishes are primarily benthic-invertivores and are typical inhabitants of mainstem prairie rivers (Robison & Buchanan 1988, Matthews 1998). In this study, two habitat groups (single-structure, multiple-structure) were based on structural habitat features derived from woody debris, in addition to the primarily hydraulic groups described in previous studies. Although single-structure and multiple-structure groups were distinguished by the cluster analysis, these groups were poorly differentiated by fish occurrences. All species had their highest indicator value in another group except for spotted gar and warmouth, and neither of these two species was a significant indicator.

Habitat guilds are an attractive concept for use in warmwater instream flow studies. They decrease study costs by simplifying analyses (Austen et al. 1994) and, once identified, may reduce sampling effort by focusing on species rather than relying on extensive habitat assessment.

Stream fish assemblage structure can also be related more generally to habitat diversity rather than to discrete patches of specific habitat types. For example, Kraft (1972) proposed that stream-habitat diversity is probably maximized at some intermediate value for discharge because habitat diversity decreases as flows approach extreme low and high values. Due to this potential importance of habitat diversity, explained variation in fish species' distributions, at the intermediate level of habitat aggregation, was partitioned into components of location, mesohabitat, and microhabitat, to examine their separate relationships to assemblage structure. Leonard & Orth (1988) considered lateral position within larger warmwater streams an important variable. Accordingly, location variables included mid-channel habitats (e.g. channel snag, open pool) and stream-margins (e.g. bank snag, edge). Although these locations also spanned a depth gradient, they contributed an independent (albeit small), additional percentage to explained variation in species' distributions apart from that of the core explanatory variables. Deep water typically contains large species (Power 1987, Harvey & Stewart 1991) and promotes habitat stability by reducing the effects of flow fluctuation (Lobb & Orth 1991). Shallow water is important habitat for small-bodied fish (Schlosser 1987b), but it is more variable and sensitive to fluctuations in discharge than deep water (Bowen et al. 1998). However, depth (a core explanatory variable) was not a significant variable except on the fourth CCA axis of the coarse level of aggregation. This was probably because shallow areas were uncommon, and the portion of explained variance in species' distribution that was shared (correlated) between depth and coarse aggregation variables was smaller compared to the larger shared variances at the intermediate and fine levels of aggregation.

Mesohabitats have been advocated as a relevant scale for instream flow studies based on lower cost and lower difficulty of data collection as well as easier presentation, use, and interpretation of results (Parasiewicz 2001). For example, Matthews et al. (1994) determined that individual stream pools represent biologically meaningful and discrete spatial units for studying stream fish. The mainstem Sulphur River was composed almost entirely of a single mesohabitat during this study (94% pool, 3% run, 2% riffle, 1% backwater). Thus, mesohabitat variables understandably explained little (3.6%) of the variation in species' distributions at the intermediate level of habitat aggregation. Riffles, defined according to standard methods (Arend 1999) and as visually identified by most biologists in the field, would not exist in the prairie streams of central and east Texas, except for effects of woody debris on velocity and depth. Moriarty & Winemiller (1997), working on a stream in east Texas, identified "riffle-like" habitats which resembled "true" riffles in some physical characteristics. Thus, instream flow studies based solely on mesohabitat classification would provide little information about fish distribution in streams of the southern prairies.

At the intermediate level of habitat aggregation, microhabitat variables (i.e., woody debris) explained more of the variation in species' distributions than either location or mesohabitat variables. Numerous studies have identified characteristic associations between fish and woody debris, not only in North America (Angermeier & Karr 1984, Benke et al. 1985, Reeves et al. 1993, Flebbe & Dolloff 1995, Lehtinen et al. 1997, Madejczyk et al. 1998), but also Europe (Thevenet & Statzner 1999) and Australia (Crook et al. 2001). Complex habitats formed by snags in the Mississippi River have higher fish-species richness than habitats lacking snags (Lehtinen et al. 1997, Madejczyk et al. 1998). Woody debris in low-gradient streams supports and enhances secondary production of invertebrates important as prey for stream fishes, and provides a more stable habitat for attachment compared to bare sand and silt substrata (Wallace & Benke 1984, Benke et al. 1985). Large woody debris in stream channels can affect erosion and deposition of streambed and bank material that in turn controls local channel geometry, development of meander cutoffs, midchannel and point bars, and storage of sediment and debris (Keller & Swanson 1979, Bilby & Bisson 1998). Consequently, woody debris strongly influences habitat diversity in streams (Reeves et al. 1993). In larger southern prairie streams with relatively low hydraulic habitat heterogeneity, woody debris should be a distinct factor to consider in studies of instream flow requirements of fishes.

Potential To Evaluate Summer Fish-Habitat Associations In Prairie Rivers

Some of the greatest knowledge-gaps about prairie-stream fish assemblages are for larger streams (Matthews 1988). Most published studies on fish ecology in the southern prairies have typically focused on creeks (seasonally water-limited) and the wadeable portions of mainstem rivers. The Sulphur River may be considered among large streams because the average depth of > 1 m necessitated the use of a boat for sampling at all locations and discharges.

Environmental characteristics, such as stream hydrological patterns and bank morphology, also influence access to the large streams of the southern prairies. Lowland rivers are typically characterized as floodplain ecosystems (Welcomme 1979). The dynamic flow regime of lowland rivers in the southern prairies includes high discharges that regularly overspill stream banks and inundate the adjacent floodplain.

CONCLUSIONS

I used several different approaches to evaluate fish assemblages as they relate to habitat in the Sulphur River, including: spatiotemporal patterns, three levels of structural habitat aggregation, and mesohabitat (hydraulic) and microhabitat (structural) variables. Across all of these approaches, evidence for distinct fish-habitat associations was weak, indicating that few species in the Sulphur River use specific, discrete, habitat types. Because flow fluctuations have little direct effect on species with broad habitat requirements (Kinsolving & Bain 1993, Poff & Allan 1995), which habitat criteria are used may be of small consequence given the predominance of generalist species.

An alternative approach may be to focus on the habitat associations of threatened/endangered species or assemblages of fluvial specialists (Kinsolving & Bain 1993), which would have narrower habitat requirements than generalist species. Their greater sensitivity to altered flow regimes (Petts 1984), should make distribution of fluvial specialists good predictors of related environmental changes. However, it is possible many of such species that once occurred in the Sulphur River (Travis et al. 1994) may have already been eliminated, or had their populations severely reduced, by the effects of impoundment and channelization. The only fluvial specialist (out of 34 species) collected in my study was the freckled madtom.

4.6 Excerpts from Gelwick and Burgess (2002)

The text in this section was excerpted directly from Gelwick and Burgess (2002). The full text is included as Appendix I on the CDROM that accompanies this report.

Sites designated in Figure 2.7 as Sites 201, 202, 203, 204, 205 and 206 correspond directly to sites noted in Gelwick and Burgess (2002) as 1, 2, 3, 4, 5 and 6, respectively.

INTRODUCTION

George Parkhouse I was identified as a potential reservoir site by the Texas Water Development Board (1997) for construction on the South Sulphur River in northeast Texas. This aquatic survey of a future reservoir site is designed to provide information about the stream fishes upstream and downstream of the proposed dam for instream flow assessment. In addition, this information will be used to identify the fish assemblages and habitat associations in the unchannelized as well as the presently channelized and diverted South Sulphur River for consideration of mitigation. Published studies of fish surveys of the Sulphur River can be found in Bonn and Inman (1955), Carroll et al. (1977), and Turner (1978). A comprehensive list of fish species known from museum records for the Sulphur River basin can be found in Travis et al. (1994).

The goals of this study were: 1) map, photograph, and assess habitats, 2) measure ambient water quality parameters, 3) report the abundance of fishes of each species collected in each habitat at each of three sample sites upstream (unchannelized reach) and three sample sites downstream (channelized reach) of the proposed reservoir, 4) evaluate the relative health of sites using an Index of Biotic Integrity (Karr et al. 1986) that was regionalized for use in Texas streams (Linam and Kleinsasser 2002), and 5) identify instream habitats based on the relative abundance of fishes sampled using an indicator species analysis (Dufrêne and Legendre 1997).

RESULTS AND DISCUSSION

Physicochemical parameters

For all sites, water temperature ranged from 5.7 to 34.4 °C. Conductivity ranged from 103 to 629 μS/cm. Dissolved oxygen ranged from 5.0 to 13.0 mg/L, and the corresponding percent oxygen saturation ranged from 62.7 to 108.0 %. Part of the variation in oxygen and temperature measurements depended on cloud cover and time of day during sampling. Depths ranged from 0.04 to 2.3 m and velocities ranged from -0.08 to 0.69 m/s upstream from the microhabitats. Negative velocities indicate flow in an upstream direction. Generally, velocities associated with pools and backwater mesohabitats were slower than those associated with riffle and run mesohabitats. Pools averaged 0.04 m/s and backwaters -0.01 m/s, while riffles averaged 0.29 m/s and runs 0.21 m/s. The velocity measurements in this report reflect the value at the time for a representative microhabitat type in which fish were collected during a particular flow condition and season. This should be taken into consideration when interpreting our results and the flow models developed from measurements taken at a later time by the Texas Water Development Board.

Index of Biotic Integrity

To assess stream health Karr et al. (1986) proposed an Index of Biotic Integrity (IBI) based on fish community attributes. Because watershed characteristics and fish communities from the Sulphur River differ from those for Midwestern headwater streams originally used by Karr et al. (1986), a regionalized adaptation was developed (Linam and Kleinsasser 2002). The IBI is used to determine the relative biological "health" of a stream by examining particular characteristics of a fish assemblage (Karr et al. 1986). Metrics used in the IBI analysis for representative streams in this ecoregion are in Linam and Kleinsasser (2002). Assignment of trophic status and intolerance/tolerance was based on Linam and Kleinsasser (1993). Gill net samples were eliminated from the IBI analysis because they were not used in the construction of the regionalized IBI metrics. Only those samples collected in July 2002 and August 2001 were used to compute the IBI because only samples made during June through September were used in creation of the regionalized metrics.

The range of the possible total value for IBI metrics was that for the possible sum of the ranks (11-55). Sites 5 and 6 were tied for the highest overall score (50) and therefore the highest percentage (91%) of the maximum score. Site 3 had the lowest overall score (44) and therefore the lowest percentage (80%) of the maximum score. The overall scores for sites 1, 2, 3, and 4 fell within the high range for an overall rating, and sites 5 and 6 fell within the exceptional range.

The mean of the overall scores for the upstream sites 1, 2, and 3 (within the unchannelized reach) was 45.3 or 82.4% of the maximum score. The mean of scores for the downstream sites 4, 5, and 6 (within the channelized reach) was 48.3 or 87.9% of the maximum score. This is an interesting result given that the habitat of the downstream sites would appear to be degraded by channelization. Thus, the metrics which were most sensitive to generally recognized biological criteria (e.g., percentage of tolerant species) might not necessarily be correlated with those of habitat degradation. However, the difference between scores for the two groups of sites was small and not statistically significant (ANOVA, $F = 2.531$, $P = 0.187$).

Fish species and microhabitat utilization

A total of 10,962 individuals representing 42 species and 13 families were collected from 4 mesohabitat types and 7 microhabitat types. Red shiners were most abundant (59%) followed by mosquitofish (10%) and bullhead minnows (9%).

Habitat groups and fish species indicators

Data were standardized by calculating densities (# individuals per m^2 sampled) for each mesohabitat and an indicator species analysis was run using the software package PC-ORD (McCune and Mefford 1997). Indicator species analysis (Dufrêne and Legendre 1997) calculates the probability that a species could indicate predetermined mesohabitat types (pool, riffle, run, backwater). It is based on the proportional abundance of the species in each habitat type and its proportional occurrence in all collections in each habitat type.

Forty-two fish species were entered for analysis as indicators of habitat types. Only five of those species were significant indicators. Bluegill indicated backwater areas. This is reasonable given that backwater areas are generally low velocity habitats frequently having large woody debris to provide cover, which this species prefers. Freckled madtoms indicated riffle mesohabitats. This species was collected at site 1 where a large amount of riffle habitat was present, and was usually absent at all other sites. River carpsuckers indicated pool mesohabitats. Longnose gar indicated pool mesohabitats. However, longnose gar were caught primarily by gill nets, which were set only in pools. Ghost shiners were indicated pool mesohabitat and were found exclusively in the downstream channelized reach. Pools were the most commonly encountered mesohabitat type. Very few species were indicators of a particular mesohabitat type, but the South Sulphur River contains mostly generalist species that use a variety of habitats.

Fish kills

Three fish kills were observed during the study period. The first occurred in May 2001 below Cooper Dam three months prior to the first sampling period. The primary species affected were stripped bass, white bass, buffalo, common carp, and gizzard shad. However, the cause and number of fish lost was unable to be determined (A. Whisenant, Texas Parks and Wildlife, personal communication). The second occurred in September 2001 between sampling periods. The primary species affected were reported to be bottom feeders including suckers (catastomidae) and freshwater drum. The source of the September kill was determined to be chemicals washed into the North Sulphur River during a storm and was estimated at 8,000 fishes (A. Whisenant, Texas Parks and Wildlife, personal communication). During our November 2001 samples, we caught very few of the affected species, particularly in sites 4, 5, and 6 that were near the confluence of the north and south forks of the Sulphur River. The last observed kill occurred in May 2002 when Cooper Dam was closed for maintenance. This caused the stilling pond to dry out, killed most of the fish in the area, and the carcasses were washed downstream (John Rael, U.S. Army Corps of Engineers – Cooper Dam, personal communication). Dead fish were observed only at the upstream sites (1-3). A wide range of species were affected including catfish, freshwater drum, white bass, stripped bass, bigmouth buffalo, smallmouth buffalo, gizzard shad, and white crappie (personal observation).

4.7 Excerpts from Burgess (2003)

The text in this section was excerpted directly from Christine Burgess's MS Thesis, Burgess (2003). The full text is included as Appendix S on the CDROM that accompanies this report.

The data used for this thesis was a sub-set of the Gelwick and Burgess (2002) dataset. Burgess (2003) concentrates her analysis on summer low-flow collections.

ABSTRACT

A conceptual model proposed by Schlosser (1987) was used to compare channelized and unchannelized reaches of the South Sulphur River, Texas. This model suggests that fish assemblage structure can be predicted based on the level of habitat heterogeneity, especially with regard to the level of pool development (Figure 4.1). Based on Schlosser's model, it was hypothesized that habitat heterogeneity would be greater in the unchannelized (as compared to channelized) reach of the South Sulphur River, which would therefore have more stable fish assemblages. Fish assemblages in this reach would have similar total fish density and higher species richness, in addition to lower density and higher biomass of larger-bodied fish (primarily piscivores and omnivores), as well as lower density and biomass of juveniles and adults of small-bodied species (primarily invertivores) as compared to the channelized reach. Habitat characteristics conformed to my predictions, but fish assemblage attributes were opposite those hypothesized. Schlosser's study focused on biotic processes more than the abiotic effects of a highly variable, stochastic environment. Most fish species present in the South Sulphur River are considered habitat generalists, have evolved to cope with extreme changes in environmental conditions, and are able to populate a variety of available habitats.

INTRODUCTION

Fish assemblages were compared in channelized versus unchannelized reaches of the South Sulphur River, Texas, sampled during summer low-flow conditions in each of two consecutive years. An assemblage is defined (c.f. Matthews 1998) as comprising fishes found together in one particular place or "locality" and a locality as a place included in a typical sample such that individual fishes have at least a reasonable chance of encountering each other during normal daily activities, although some may be more nocturnal than diurnal (Helfman 1981). Fish assemblages can be characterized by attributes such as species richness, species density, total density of individuals, trophic structure, and life history stages. Habitat characteristics include physical heterogeneity of depth, velocity, and substrate size, and assessment of overall quality relative to a reference condition. In particular, descriptions were made for (1) habitat characteristics, (2) fish assemblage structure, 3) fish-habitat relationships, and compared the results of this study to patterns expected from ecological theory and published results from other streams. Based on Schlosser's model of Jordan Creek (Schlosser 1987), it was hypothesized that habitat heterogeneity would be greater in the unchannelized (as compared to channelized) reach of the South Sulphur River, which would therefore have more stable fish assemblages. Fish assemblages in this reach would have similar total fish density and higher species richness, in addition to lower density and higher biomass of larger-bodied fish (primarily piscivores and omnivores), as well as lower density and biomass of juveniles and adults of small-bodied species (primarily invertivores) as compared to the channelized reach.

STUDY AREA

The upper half of the Sulphur River Basin was extensively channelized (but not lined by concrete) in an attempt to alleviate the flooding of farmland (Figure 4.2). The entire North Sulphur River and a small section of the upper main stem were channelized in the 1930's. In the 1950's the lower third of the South Sulphur River was channelized, straightened, and moved north of its original location. The old channel of the South Sulphur River still exists, but it remains dry for much of the year, and a levee currently blocks any connection to the newer channel.

Only a few studies are available that historically document fish species from the Sulphur River Basin such as Bonn & Inman (1955), Carroll et al. (1977), Turner (1978), Capone and Kushlan (1991). However, several studies have been recently completed that document fish assemblages and their relationships to available habitat including Gelwick and Morgan (2000), Morgan (2002), and Gelwick and Burgess (2002).

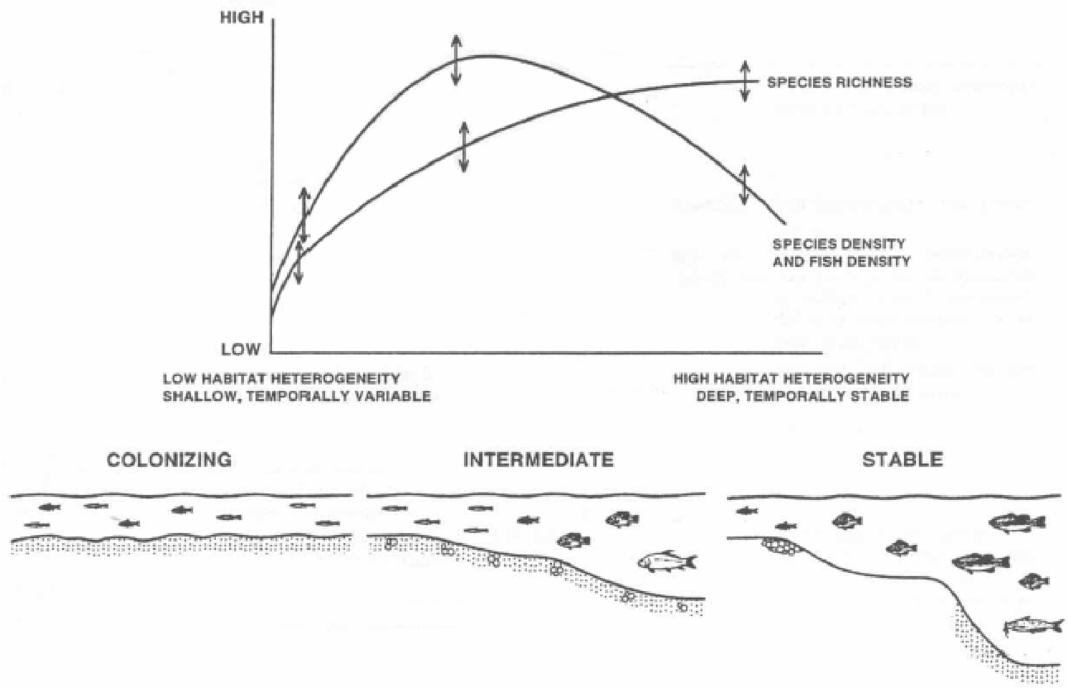

Figure 4.1 - Conceptual model for fish communities in warmwater streams along a gradient of an increasing level of pool development (Schlosser 1987).

METHODS

Site and Habitat Identification

Three representative sites were selected as replicate samples in the unchannelized reach (sites 1, 2, and 3) and three in the channelized reach (sites 4, 5, and 6) of the South Sulphur River based upon access (Figure 4.2). Habitats within each site were categorized based on hydraulic characteristics into one of the four following mesohabitat types: pools, runs, riffles, and backwater areas. Definitions for mesohabitats are as follows: pools may vary in depth and be flowing, but have a smooth surface; runs vary in depth but generally up to 50% of their water surface is turbulent, or wavy, whereas in riffles >50% of the surface is turbulent (Jowett 1993); and backwaters have little or no flow, and are still connected, but adjacent to the main channel. Site length was equivalent to 20 times the wetted stream width at base flow in order to encompass the habitat types present within each reach. Low-flow conditions are important limiting factors for stream fishes that test the ability of fishes to persist through harsh environmental conditions (Stalnaker 1981), and thus influence the stability of assemblage structure. Low-flow periods have been reported to cause the greatest spatial variation of stream-fish assemblages because habitat diversity is also at its highest due to a variety of riffle, pool, and run habitats (Gido et al. 1997).

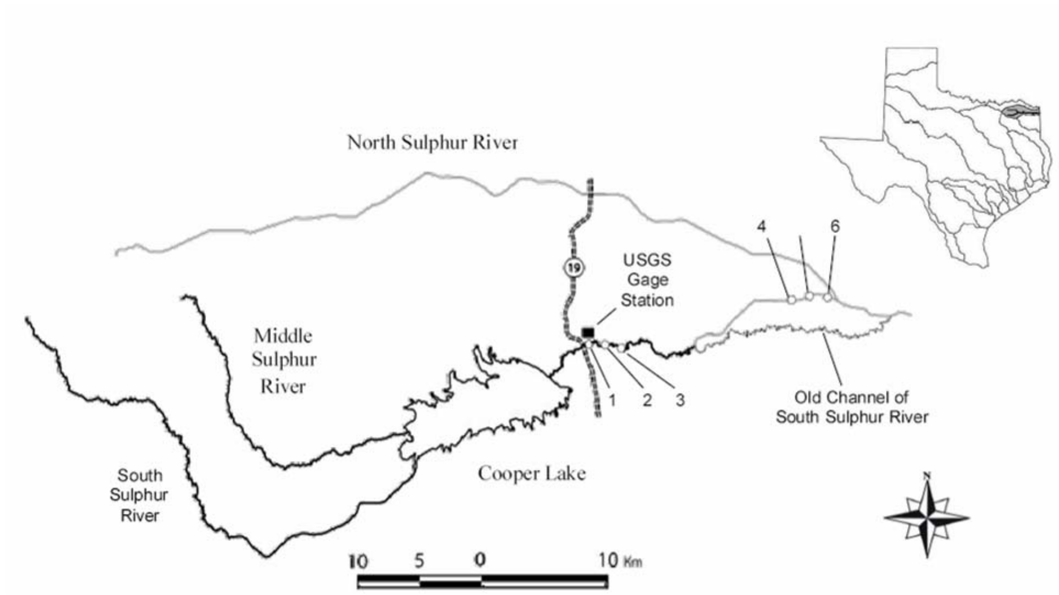

Figure 4.2 – Map of the western half of the Sulphur River basin showing the location of sites sampled during the August 2001 and July 2002.
Channelized reaches are displayed in gray.

RESULTS

Habitat Characteristics

Actual mean daily discharge during summer 2001 remained steady at 0.2 cm/s and ranged from 0.2-2.4 cm/s during summer 2002. Unchannelized sites had a greater variety of mesohabitats, which collectively included all types categorized (pool, riffle, run, and backwater). Habitats in channelized sites were comprised of pools almost exclusively, except for one run observed at site 4 in summer 2002.

Fish Assemblage Structure

Seines were most effective at capturing small-bodied cyprinids and mosquitofish, and the most effective gear for sampling invertivore biomass, but not omnivore and piscivore biomass. Electrofishers were effective for sampling centrarchid biomass in complex structural habitats, such as undercut banks, tree roots, and woody debris, and contributed to samples of piscivore and invertivore biomass, but not omnivores. Seines and electrofishers captured fishes in all mesohabitat types, however seines captured schooling fishes (small cyprinids and juvenile sunfishes) in open water, and electrofishers captured fishes associated with complex habitat structure. Gill nets captured 10 out of the 21 common species. Gill nets also captured more of the large-bodied piscivores and were the only gear that captured omnivores, which in this river system comprised most of the large-bodied species. Gill nets were only deployed in pool mesohabitats and, therefore, only represented species captured in pools. A total of 6,799 fish representing 35 species was collected during the study. Of these, 31 species were collected in both reaches. Warmouth, ghost shiner, tadpole madtom, and shortnose gar were collected only in channelized areas. However, of those species, only shortnose gar were considered common (i.e., >1% of the total catch) and included in multivariate analyses. For total fish density summed across all gears and collections, red shiner was most abundant (23.7%), followed by smallmouth buffalo (16.9%), bullhead minnows (12.1%), and western mosquitofish (8.2%). For total fish density by gear type summed across collections, gill nets caught proportionally more large-bodied species. Seines and electrofishing captured primarily small cyprinids and western mosquitofish, but electrofishing also caught a greater proportion of centrarchids and freckled madtom.

Univariate Analyses

There was no significant year or year-by-reach interaction for any of the univariate analyses. Species richness did not differ between reaches; 18.0 species (± 0.62 SE) were captured in the unchannelized reach and 18.8 (± 0.62 SE) in the channelized reach. As expected, sites in the unchannelized reach contained a greater mean proportion (13.0 % ± 0.02 SE) of the total fish density across both years than did sites in the channelized reach (3.6 % ± 0.02 SE). On average 39.1% of the total catch was caught in the unchannelized reach and 10.9% in the channelized reach. Number of tolerant species was higher in the channelized (8.8 ± 0.17 SE) than unchannelized (8.2 ± 0.17 SE) reach. Overall scores of the IBI were similar for the unchannelized (44.7 ± 1.05 SE) and channelized (45.3 ± 1.05 SE) reaches. Both reaches indicated an overall aquatic life use rating of “high”.

Multivariate Analyses

Eigenvalues from the ordination axes indicate the maximized dispersion of the species scores, and is thus a measure of the importance of the axes. Values over 0.5 often denote a good separation of the species along the axis, and therefore display biologically relevant information (Jongman et al. 1995). Eigenvalues were greater than 0.5 on the first two axes, and generally less than 0.5 on axes 3 and 4.

CA of Mesohabitat Level x Species Density.—Axes 1 and 2 explained 18.6% and 15.1% of the variation in distribution of species' abundances. Axis 1 indicates a gradient of mesohabitat types from pools to riffles, and separates species associated with channelized and unchannelized sites. Species associated with channelized pools included common carp, flathead catfish, smallmouth buffalo, longnose gar, and orangespotted sunfish. Species associated with unchannelized pools included unidentified juvenile sunfishes (Lepomis spp.), western mosquitofish, and longear sunfish. The only backwater habitat across all sites occurred at site three in the unchannelized reach, and was associated with bluegill in 2001, but with red shiner in 2002. Species dominating runs were red shiner, mimic shiner, and redfin shiner captured by electrofishing—redfin shiner in seine samples was associated with deeper and more sluggish pool or backwater habitats. Riffle habitats were associated with freckled madtom.

CA of Mesohabitat Level x Juvenile and Adult Species Density.—Axes 1 and 2 explained 16.2% and 13.5% of the spatial variation in species abundance. Juvenile slough darters were associated with pools in both channelized and unchannelized reaches; whereas adults were more affiliated with run mesohabitat in the unchannelized reach. Similarly, juvenile green sunfish remained associated with pools in the channelized reach and backwaters in the unchannelized reach, whereas adults were more associated with pools in the channelized reach.

CA of Site Level x Species Density.—Axis 1 and 2 account for 26.6% and 23.9% of the variance in spatial species distribution. Differences among assemblages within and between reaches were greater in 2001 than 2002. In 2001, sites in the channelized reach were most strongly associated with species in gill netted samples and included gizzard shad, white crappie, shortnose gar, longnose gar, and river carpsucker, whereas sites in the unchannelized reach were associated with species captured by multiple gears, including redfin shiner, mimic shiner, channel catfish, bluegill, and common carp. In 2002, sites in the channelized reach were associated with smallmouth buffalo and orangespotted sunfish, and sites in the unchannelized reach were associated with red shiner, freckled madtom, longear sunfish, as well as unidentified juvenile sunfish, bullhead minnow, and western mosquitofish.

CA of Site Level x Juvenile and Adult Species Density.—Axis 1 and 2 of the CA explained 25.4% and 22.7% of the variation in species abundance and distribution and similar to that for the CA of species density. Adult bluegill were more associated with sites in the unchannelized reach in 2001, whereas in 2002 they were not strongly associated with either reach. Juvenile longnose gar were strongly associated with channelized sites, whereas adults were not strongly associated with either reach. Adult orangespotted sunfish were primarily captured in 2002 and were associated with channelized sites, whereas juveniles were not strongly associated with either reach. The association of smallmouth buffalo with channelized sites was primarily due to adults in both years, whereas in 2001 juveniles were associated with both reaches. Adult slough darters were more associated with unchannelized sites than were juveniles.

CA of Site Level x Species Biomass.—A CA was done on relative biomass to determine the trophic structure of each reach. Axis 1 and 2 explained 25.4% and 22.4% of the variation in species distribution. Sites in the channelized reach included species with higher biomass attributed to piscivores and omnivores. The unchannelized reach was associated with more species and higher biomass of invertivores as compared to the channelized reach. Species associated with the channelized reach included piscivorous longnose and shortnose gar, and omnivorous gizzard shad and river carpsucker. Orangespotted sunfish was the only invertivorous species associated with the channelized reach. Cyprinids (redfin shiner, red shiner, mimic shiner, and bullhead minnow) were associated with the unchannelized reach, along with four other invertivores—freckled madtom, longear sunfish, bigmouth buffalo, and western mosquitofish. Two piscivores—flathead catfish and white crappie—and one omnivore—channel catfish were also associated with the unchannelized reach. There were no herbivorous species collected in either reach, likely due to lack of algae and absence of submerged vegetation.

MANOVAR.—Percentage of biomass differed across trophic groups, but differently depending on reach. Effects of year and reach independently on trophic biomass were not statistically significant. Across both years and both reaches, omnivores comprised the highest proportional biomass (50%), followed by invertivores (30%), and piscivores (20%). However, there was a significant trophic group by reach interaction. The proportional biomass of piscivores was higher in the channelized reach, but for both invertivores and omnivores, it was higher in the unchannelized reach.

CCA.—The variable pool was excluded from the CCA because it had negligible variance, whereas run and habitat quality scores were excluded because they were collinear to the remaining variables, causing erroneous correlation coefficients due to overfitting the model. Species associated with the channelized reach were gizzard shad, shortnose gar, white crappie, orangespotted sunfish, longnose gar, and river carpsucker. Species associated with the unchannelized reach were bullhead minnow, flathead catfish, freckled madtom, red shiner, longear sunfish, western mosquitofish, bigmouth buffalo, unidentified juvenile sunfish, redfin shiner, and mimic shiner. Species associated with backwater habitats were bluegill and redfin shiner collected by electrofishing, whereas species associated with riffles included bullhead minnow, freckled madtom, and red shiner.

ISA of Mesohabitat Level x Species Density.—Among the four mesohabitat types, pool and riffle each had one indicator species, run had none, and backwater had two indicator species. The significant indicator of pool habitat was smallmouth buffalo (caught only in gill nets) and riffle habitat was indicated by freckled madtom. Bluegill and unidentified juvenile sunfish (captured by seining) were indicators of backwaters.

ISA of Mesohabitat Level x Juvenile and Adult Species Density.—Juveniles and adults that were significant mesohabitat indicators in this ISA were the same species and mesohabitat indicators as those in the ISA of species density. However, two species showing high (but nonsignificant) values indicated trends in mesohabitat segregation by life-history stage. Red shiner adults had higher indicator values for riffles, whereas juveniles had higher indicator values for runs; slough darter adults had higher indicator values for runs, whereas juveniles had higher indicator values for pools.

ISA of Reach x Species Density.—The unchannelized reach had four indicator species, but the channelized reach had only one significant indicator species. Red shiners, bullhead minnows, western mosquitofish, and longear sunfish were indicators of the unchannelized reach; orangespotted sunfish was the indicator of the channelized reach.

ISA of Reach x Juvenile and Adult Species Density.—As for the mesohabitat level ISA, juveniles and adults that were significant indicators in this ISA were the same species and reach indicators in the ISA of species density. Slough darter adults had higher indicator values for the unchannelized reach, whereas juveniles had higher indicator values for the channelized reach; green sunfish adults had higher indicator values for the channelized reach, whereas juveniles had higher indicator values for the unchannelized reach.

DISCUSSION

Based on Schlosser's model of Jordan Creek (Schlosser 1987), it was hypothesized that habitat heterogeneity would be greater in the unchannelized (as compared to channelized) reach of the South Sulphur River, which would therefore have more stable fish assemblages. Fish assemblages in this reach would have similar total fish density and higher species richness, in addition to lower density and higher biomass of larger-bodied fish (primarily piscivores and omnivores), as well as lower density and biomass of juveniles and adults of small-bodied species (primarily invertivores) as compared to the channelized reach. Whereas habitat heterogeneity conformed to predictions, results for others did not, and in fact, results for species richness and trophic biomass were opposite of this study hypotheses. These predictions of assemblage structure were based on assumptions regarding processes and mesohabitat characteristics and the corresponding ecological responses of fish species. This system has been anthropogenically modified beyond just channelization. Levees, dams, agricultural runoff, limited riparian vegetation, and tributaries that have been cut off from the main channel were factors in the unchannelized reach as well as the channelized reach. These results indicate that these factors and their influence on stream processes and habitat contributed to discrepancies between observed and predicted results for fish assemblage structure.

Habitat Characteristics

Following the Schlosser (1987) model, habitat heterogeneity in the unchannelized (upstream) reach of the South Sulphur River was greater as compared to the channelized (downstream) reach. Total habitat heterogeneity (3.14) at site 1 in my unchannelized reach was similar to the reach in Jordan Creek that had highest pool development (3.15). Heterogeneity in sites 2 and 3 (2.95 and 2.91) in my unchannelized reach, and site 4 (2.45) in my channelized reach was similar to that in Jordan Creek (2.84) that had intermediate pool development. Heterogeneity in sites 5 and 6 (2.08 and 1.76) in my channelized reach was similar to the modified upstream reach (2.07), which had the least pool development in Jordan Creek. However, the model strongly relied on pool development, especially with regard to depth. Overall, both reaches had moderate to deep water, very slow currents, and silty substrate.

The variety of mesohabitat types was greater in the unchannelized reach as it contained pools, riffles, runs, and backwaters, whereas the channelized reach comprised almost entirely pool habitat, no riffles or backwaters, and only one site included a run, which formed in summer 2002. Not all mesohabitats persisted at every site across years. In the unchannelized reach, pools and runs were common in all sites during each collection, but presence of riffles and backwaters differed across sites and years. Riffles were consistently present at site 1, but only occurred during summer 2001 at site 3, and never at site 2. Backwaters only occurred at site 3 and were present in both years. Well-developed riffle-pool patterns persisted at Site 1, but were less-well developed at sites 2 and 3, where pools were only slightly better developed (deeper) than those in the channelized reach. Unlike Jordan Creek (Schlosser 1987), the range of depths in all sites of the South Sulphur River included those that were not limiting for large-bodied species of both omnivores and piscivores.

Scores for habitat quality included both instream and riparian metrics. As expected, overall instream habitat quality was lower in the channelized reach and reflected channel alteration, reduced sinuosity, and greater sediment deposition. Pool variability (high scores indicating mix of large, small, shallow and deep pools) scored highest (12) for site 1 in the unchannelized reach, and lowest (4) for site 4 in the channelized reach, but was similar across other sites (ranging from 5 to 7). Thus, pools were only slightly more developed in unchannelized than those of the channelized reach.

Scores for riparian vegetation were similar and high to moderate across all sites. However, the overall total score for habitat quality in the unchannelized reach was reduced due to lower scores for bank stability (raw areas with high erosion potential during floods) at sites having high sinuosity. Thus, despite the presence of levees to protect agricultural areas in the unchannelized reach, some evidence was present of the natural tendency for streams in this region to form oxbows.

Fish Assemblage Structure

Because many species of fish exhibit strong association with certain types of habitat, stream reaches with higher habitat heterogeneity can be expected to have greater species richness than reaches with fewer habitats for fishes to exploit (Gorman and Karr 1978; Schlosser 1982a; Angermeier and Karr 1984; Reeves et al. 1993). However, the results showed that despite higher habitat heterogeneity in the unchannelized reach, species richness was similar to that in the channelized reach. Other studies conducted on the South Sulphur River (Carroll et al. 1977, Capone and Kushlan 1991) reported similar results. Carroll et al. (1977) found no difference in species richness between unchannelized and channelized reaches of the South Sulphur River, and Capone and Kushlan (1991) were unable to predict species density (number of species per area) based on habitat heterogeneity, in contrast to predictions of the conceptual model proposed by Schlosser (1987).

Of the total number of species collected in the South Sulphur River, approximately half were classified as tolerant species, and although there were more in the channelized than unchannelized reach, the actual difference was small (9 versus 8). Linam and Kleinsasser (1998) classified tolerant species as those that typically show increased distribution and abundance despite historical degradation of their environment and tend to be the dominant species in disturbed habitats. Tolerant species that were dominant in the channelized reach were gizzard shad, longnose gar, shortnose gar, and river carpsucker, which all occur primarily in sluggish, pool habitats (Robison and Buchannan 1988). Tolerant species that were dominant in the unchannelized reach were western mosquitofish, red shiner, and bigmouth buffalo, which occur across a wide variety of habitats. Species such as red shiner are considered tolerant and habitat generalists that inhabit a variety of habitat conditions. However, in this study (during summer low-flow conditions) they were more abundant and occurred most often in faster moving run and riffle habitats. Intolerant species are those that are sensitive to environmental conditions and are typically the first to disappear following a disturbance. There were two intolerant species in my study—freckled madtom, and mimic shiner. Both species were more associated with the unchannelized than the channelized reach and generally occupy riffle habitat having gravel substrates (Orth and Maughan 1982; Robison and Buchanan 1988), both of which were only found in the unchannelized reach. Freckled madtom, although a significant indicator of riffle habitat, was not a significant indicator of the unchannelized reach because it occurred in too few of those collections.

Schlosser (1987) predicted a peak in density of fish in habitats intermediate between homogeneous, shallow habitats—his channelized reach—and heterogeneous habitats that included deeper pools—his downstream, natural reach. I found higher density of fishes overall in the unchannelized reach of the South Sulphur River, and relative density of certain species differed between reaches. Red shiner, western mosquitofish, bullhead minnow, and longear sunfish were indicators of the unchannelized reach whereas, orangespotted sunfish was the only indicator of the channelized reach. Bluegill and juvenile sunfish were indicators of backwater habitat, which only occurred in one unchannelized site, and therefore, it was not an indicator of the unchannelized reach.

Fish-Habitat Relationships

During summer low- flow conditions in the South Sulphur River, juveniles and adults of most species were collected in the same mesohabitats and reaches. Perhaps this was due to reduced habitat volume and lower opportunity for habitat segregation among life stages, or to the large proportion of habitat generalists in the fish assemblage. With regard to distribution of body size and trophic-group biomass in channelized versus natural reaches, my results were directly opposite of those predicted by the Schlosser (1987) model. In the unchannelized reach, there were more small-bodied fishes (primarily invertivores) and fewer large-bodied omnivores (channel catfish) and large-bodied predators (white crappie and flathead catfish), but the predators were not small juveniles of large-bodied species, as was found in Jordan Creek. In neither reach of the South Sulphur River was depth limiting to the distribution of large-bodied fishes (omnivores and piscivores), as compared to Jordan Creek, where channelized reaches were too shallow to support large fishes. Compared to the unchannelized reach, the channelized reach of the South Sulphur River had fewer small-bodied fishes, more and larger omnivores (river carpsucker and gizzard shad), and more piscivores (primarily gar). With regard to life-history characteristics of assemblages in each reach of the South Sulphur River, my results also opposed the trend predicted by Schlosser. In the Schlosser model, assemblages corresponding to homogeneous, channelized habitats contained more fishes with colonizing life-history attributes—prolonged breeding seasons, higher population growth rates, and greater dispersal capability of young—as compared to the more heterogeneous, unchannelized habitat, which had more fishes adapted to less-variable (more stable) conditions—longer time to maturity, shorter reproductive season, and lower population growth rates.

Discrepancies in results as compared to Schlosser (1987) are probably related to several factors. This system had been heavily modified by activities other than just channelization. For both reaches, these included an upstream dam, levees, reduced vegetation in riparian zones, agricultural runoff, and frequent (approximately two per year from 1997 to 2001) fish kills (Adam Whisenant, biologist for Texas Parks and Wildlife, unpublished data), each of which can affect the structure of fish assemblages (Sharpe et al. 1984; Bryan and Rutherford 1993; Gafny et al. 2000). This system was originally channelized in the 1950's and fish assemblages might have experienced some recovery in the last half century. There were also regional differences in stream systems and faunal composition as compared to Jordan Creek. Many of the species collected in the South Sulphur River have prolonged breeding seasons, and my summer samples would have included breeding individuals and young fishes, which would have contributed to reversed trends in fish density and biomass compared to Jordan Creek. If habitat volume was temporarily reduced during summer low-flow, then fish might have been forced into suboptimal habitat, thus increasing habitat overlap between juveniles and adults, as well as piscivores and their smaller-bodied prey. In addition, many conclusions regarding the model (Schlosser 1987) were based on results for temporal variation in seasonal patterns, which was not addressed in this study.

Schlosser's model relied on spatial variation in depth and habitat volume, which set the habitat template for the important biotic processes of predation and competition that were primary forces controlling fish assemblage structure. This was especially the case for the natural reach of Jordan Creek, where temporal environmental variability and stochasticity were less important as compared to factors in the shallow channelized reach, which was more temporally variable. Harsh summer conditions can limit the ability of larger and less tolerant fish to persist in streams (Matthews and Styron 1981). Results of my summer low-flow sampling in the South Sulphur River more strongly support abiotic factors and processes as the primary forces structuring fish assemblages. In particular, the large number of tolerant species and habitat generalists in the South Sulphur River suggests that physicochemical factors are important and that the system experiences considerable environmental variation.

Fluctuations in flow can eliminate juveniles and smaller species from pools (Harvey 1987), and over the short term these habitats may never approach a stable state. Stream flows in this region are highly variable relative to the long-term mean. There is a predictable wet season (November-April) and a dry season (May-October), but floods and droughts are unpredictable within those seasons. Capone and Kushlan (1991) also found that physical processes such as stream morphology and highly unstable, temporally variable stream flows were more important regulators of Sulphur River fish assemblages among pools than were biotic factors such as predation and competition, and suggested that northeast Texas streams possibly represent the extreme left of Schlosser's (1987) hypothesized model.

In addition to the unpredictable nature of the natural flow regime for streams in the area, Cooper dam was recently constructed in 1991 a short distance upstream from the unchannelized sites sampled in this study. While fish assemblages may have experienced some recovery from past channelization, Cooper dam is a relatively recent addition to the system, and fish assemblages might still be adjusting to this change in their environment thus contributing to differences from the Jordan Creek model. Flow management in regulated reaches has major impacts on local hydraulic conditions, which influence species abundance and fish diversity (Gorman and Karr 1978; Orth and Maughan 1982). Water release and retention can have a larger influence on the variability of local stream flows and fish assemblages in reaches relatively close to a dam (as in the unchannelized reach) as opposed to those located a significant distance downstream (as in the channelized reach) (Kinsolving and Bain 1993).

Species that inhabit streams with large environmental variability have evolved to cope with disturbance in areas where environmental conditions can be extreme and somewhat unpredictable (Poff and Ward 1990). Many of these species can readily inhabit a variety of habitats and still thrive, and thus they are considered habitat generalists. The Sulphur River Basin is composed largely of habitat generalists, many of which are classified as tolerant. The abundance of tolerant habitat generalists in this system suggests a fish assemblage that has adapted to persist through harsh environmental conditions. This pattern is seen in other variable warmwater streams throughout the country (Matthews 1987; Meador and Matthews 1992; Kinsolving and Bain 1993; Poff and Allen 1995; Matthews 1998). South Sulphur River fish assemblages have evolved to inhabit areas with extreme environmental changes due to physical influences, including not only droughts and floods, but also fluctuations in chemical influences such as dissolved oxygen, pH, temperature, agricultural runoff and anoxic dam releases. However, flow regime is likely the most influential environmental factor in streams of this region.

Fluvial specialists can be described as those species that require flowing water for much of their life cycle. Very few fluvial specialists are currently present in the Sulphur River Basin. Intolerant fluvial specialists (such as freckled madtom and mimic shiner) have narrow ranges of habitat use. These results suggest that these species occur more frequently in unchannelized areas. Several previously common species of fish have been reduced in number or have been extirpated (Garrett 1999), and other rare or non-native forms have increased in abundance. Species such as the paddlefish (Polyodon spathula), taillight shiner (Notropis maculatus), and orangebelly darter (Etheostoma radiosum) were previously documented in these areas before anthropogenic modifications to the stream caused their numbers to decline dramatically such that they now are under various levels of protection (Garrett 1999). These species are dependent on riffle habitats for various life history stages, probably removed during channel modifications.

Access to all areas of the stream is restricted mainly to bridge crossings. Access by boat to many areas of the stream was difficult due to low flows and some were impassable due to large accumulations of woody debris. Because of these factors, study sites were chosen based upon access rather than random placement. Therefore, it gives a somewhat biased view of the river. Lack of persistent mesohabitats may also have hampered the ability to reflect accurately South Sulphur River fish assemblages. Further study concentrating on the variability of flow should be done particularly on the effects of drought and floods. Effective management should include identification of fluvial specialists and habitat suitability requirements for those species. Whenever possible, release of water from Cooper dam should reflect the instream flow needs of these species.

CONCLUSIONS

The results did not conform to the conceptual model proposed by Schlosser (1987). His study focused on biotic processes more than the abiotic effects of a highly stochastic environment. It was proposed that abiotic processes, particularly extreme fluctuations in flow regimes, are likely to be the most influential factors affecting fish assemblages in the South Sulphur River. Streams in this region are naturally subject to extreme variations in streamflow, but unchannelized sites may have been more directly influenced by water release or retention from the relatively recent construction of Cooper Dam located just upstream, whereas channelized sites, located much further downstream, were probably less affected. Most fish species present in the South Sulphur River are considered habitat generalists, have evolved to cope with extreme changes in environmental conditions, and are able to populate a variety of available habitats. Therefore, future management of this stream should reflect the needs of the few remaining fluvial specialists in this system, such as the intolerant freckled madtom and mimic shiner.

4.8 Discussion and analysis of visually classified mesohabitats

To understand the hydraulic partitioning of visually classified mesohabitats utilized for the TAMU studies, the depth-velocity pairs collected for each sample location were investigated. As shown in Figure 4.3, the pairs exhibited distinguishable grouping among like visual classifications. Backwater habitats exhibited some of the lowest velocities, and pool habitats exhibited velocities generally less than 10 cm/s. Run habitats exhibited a range of depths and velocities that increased along both axes. Riffle habitats exhibited velocities within the same range as runs, but generally less deep.

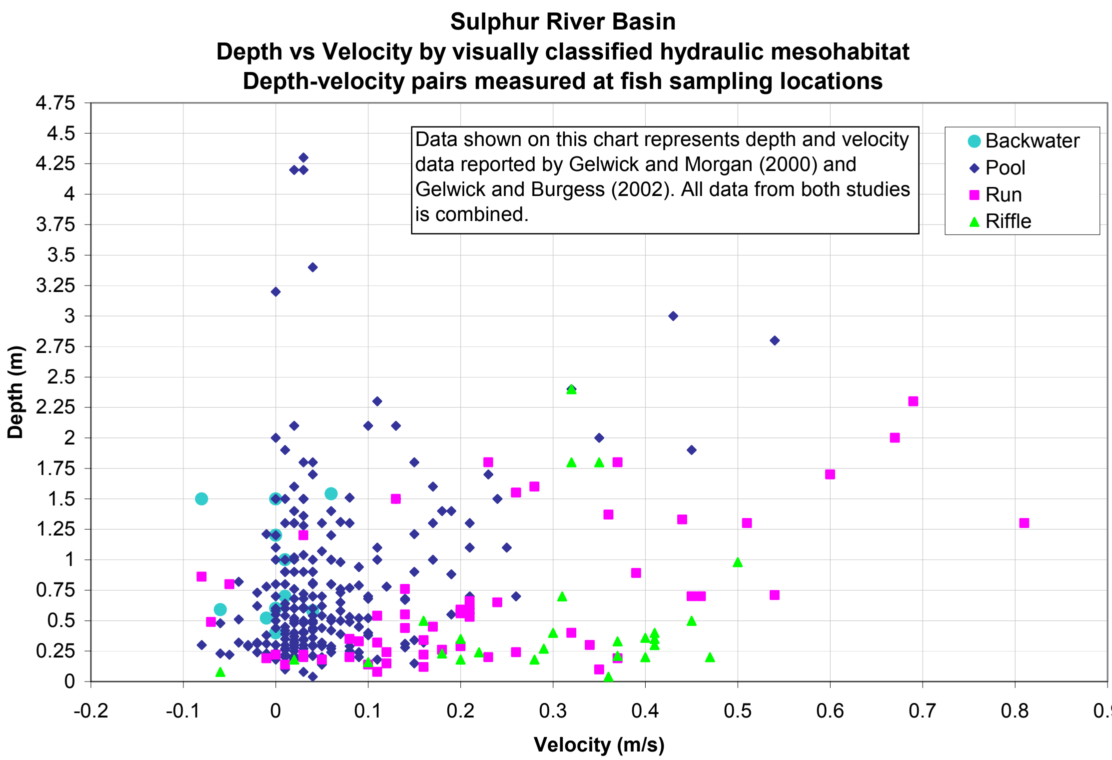

Figure 4.3 – Depth and velocity pairs for each visually classified mesohabitat (Gelwick and Morgan 2000; Gelwick and Burgess 2002).

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5. TWDB fisheries analysis

Using the Gelwick and Morgan (2000) and Gelwick and Burgess (2002) fish habitat utilization datasets, the TWDB analyzed habitat utilization for the four areas for which data were collected: unchannelized South Sulphur River, channelized South Sulphur River, channelized Sulphur River and unchannelized Sulphur River. Two earlier studies described in chapter 4 (Gelwick and Morgan 2000, Gelwick and Burgess 2002) analyzed fish habitat utilization based upon visually classified mesohabitats, upon structural habitats upon environmental parameters and upon season. Two additional studies described in Chapter 4 use datasets limited to summer low-flow conditions to investigate fish habitat utilization based upon mesohabitat and structural habitat (Morgan 2002), and based upon habitat heterogeneity (channelized versus unchannelized areas) (Burgess 2003).

None of these earlier studies investigated the four unique study areas individually. This chapter presents a new analysis by the TWDB that investigates the fish habitat utilization individually at each of the four areas. To support the analysis a spatial (GIS) model was developed in two of the areas (specifically, at Site 1 and at Site 2) that quantified area of mesohabitat and area of structural habitat. Using all depth and velocity data reported for each habitat sample by Gelwick and Morgan (2000) and Gelwick and Burgess (2002), hydraulic mesohabitat classifications were developed. Additionally, using structural habitat descriptions presented in those same fish studies, field data were analyzed to define structural habitat with each hydraulic mesohabitat after White (2003) and White et al. (2004). The area of available those habitats over a range of modeled flows was quantified in the two reaches, Site 1 and Site 2.

Using the same datasets presented in Gelwick and Morgan (2000) and Gelwick and Burgess (2002), each fish sample was reclassified based upon the new mesohabitat and structural habitat classifications. The distribution of fish among the newly classified habitats was further analyzed using a simple standardization procedure, thus investigating patterns of utilization among those TWDB-classified mesohabitats and structural habitats.

This chapter describes the development of the new habitat classifications using field data, the application of habitat criteria to a spatial (GIS) model, analysis of the availability of habitat for varying flow conditions and a simple standardized analysis of the observed fish utilization within the new habitats.

5.1 Development of a mesohabitat model

Each of the biological sampling locations was categorized in the field with respect to hydraulic conditions at the site (i.e. riffles, pools, runs, backwaters) (Gelwick and Morgan 2000, Gelwick and Burgess 2002). Depth and velocity measurements within each category of hydraulic habitat were combined for all 13 sites and all flows during both seasons (summer and winter) (see Figure 4.3) and the distribution of each of these habitats with respect to depth and velocity was analyzed. The visual classifications were considered significant within the context of hydraulic measurements, so hydraulic criteria was developed based upon the distribution of those visually classified habitats.

Maximum and minimum criteria for each mesohabitat were developed based upon the cumulative frequency probability distribution after Wentzel (2001). The criteria were developed to give a 50% probability of finding a particular mesohabitat that satisfies both the depth and velocity qualifications. Assuming that depth and velocity are independent variables and that each are normally distributed (in reality, neither of these conditions is satisfied), the 50% probability for satisfying both criteria means that the probability bounds for each independent variable is 70.7% (0.707*0.707 = 0.50).

Determination of the 70.7% bounding criteria is shown in Figure 5.2 depicting the cumulative frequency probability for mid-channel mesohabitat for depth. The measured parameter data for both depth and velocity is combined and sorted in ascending order. The cumulative distribution is determined and a range that includes 70.7% of all collected data points is singled out using 85.35 percentile as the upper bound and 14.65 percentile as the lower bound (85.35 - 14.65 = 70.7). Thus, the habitat occurred most between the upper and lower bounds (between 100 and 225 cm, per Figure 5.1).

Figure 5.2 shows the cumulative fraction of all combined samples with respect to depth. Additional series are included showing the Riffle, Run and Pool mesohabitats components of the combined series. As evidenced by the “All Samples” series, habitats sampled ranged from 0.15 meters to 2.0 meters (0.5’ to 6.5’), with a limited number of samples shown on either end of that range. The range encompassing 70.7% of the samples had bounds of 0.23 m and 1.42 m (0.75’ and 4.65’). Run and Pool samples were collected within the same range. Riffle samples were generally limited to depths less than 0.75 m (2.5’).

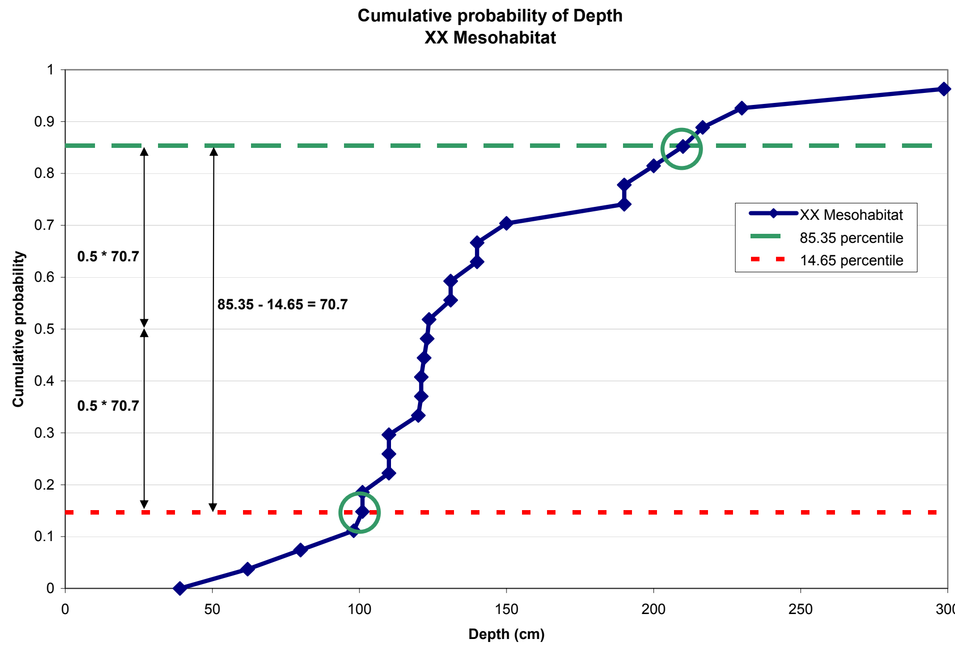

Figure 5.1 - Graphic depicting cumulative frequency probability distribution and parameter criterion ranges for mid-channel mesohabitat. Upper and lower bounds are circled.

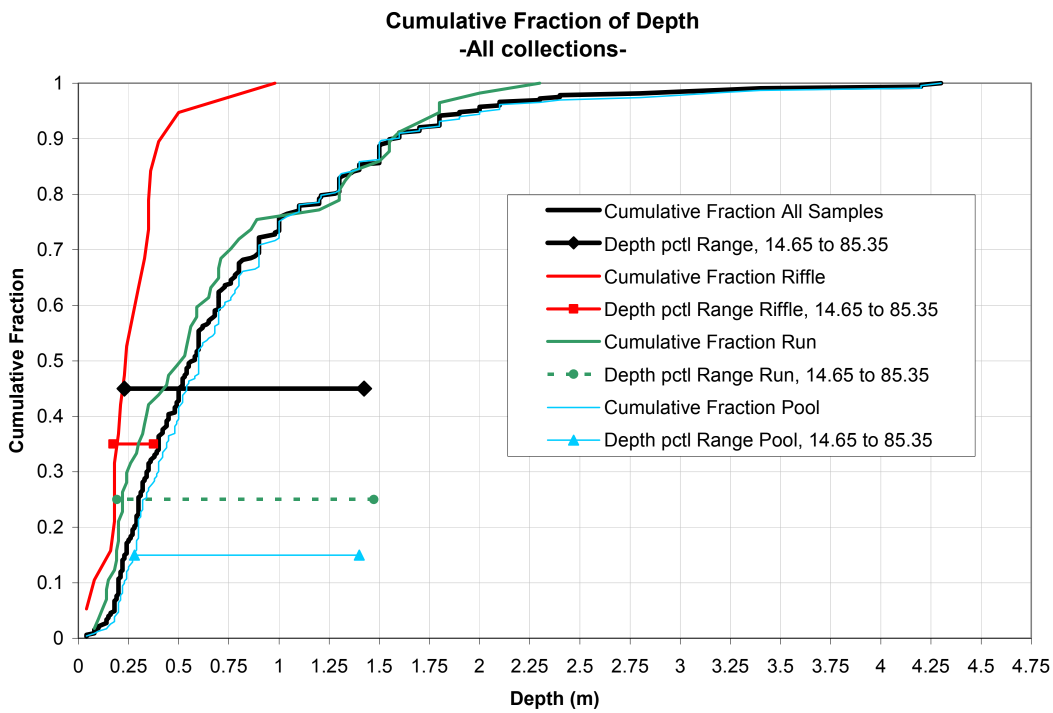

Figure 5.2 – Cumulative fraction of depth for all samples

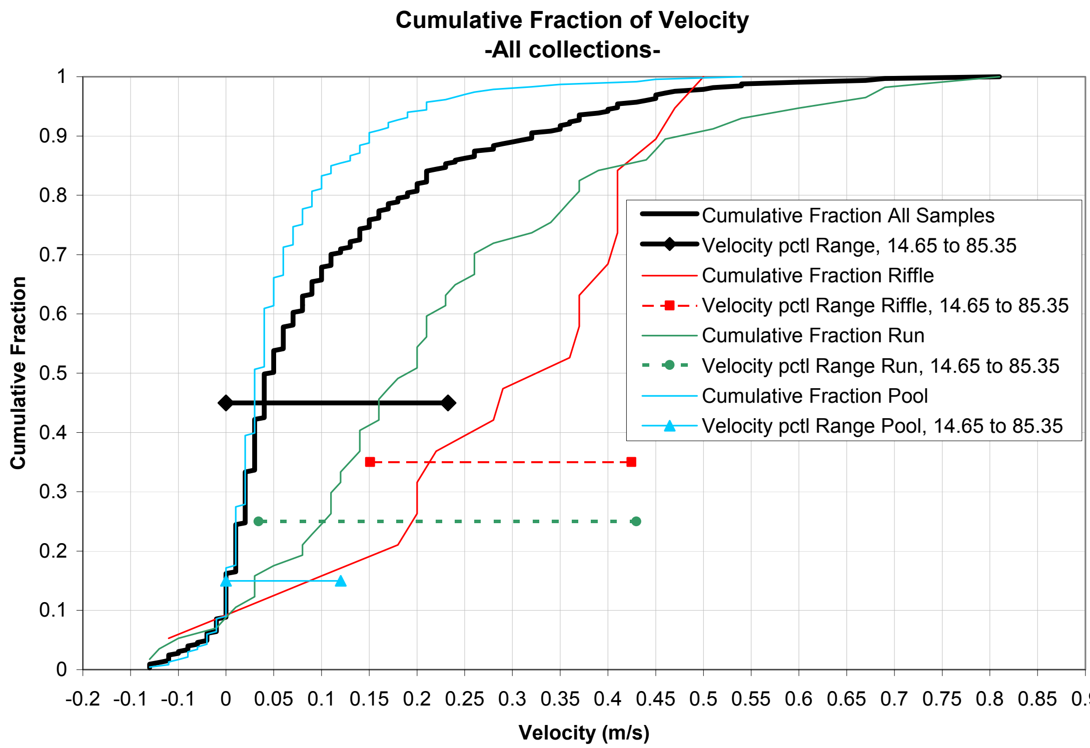

Figure 5.3 – Cumulative fraction of velocity for all samples

The distribution of samples with respect to velocity is shown in Figure 5.3. The combined range of all samples ranged from 0 meters per second (m/s) to 0.35 m/s (0 feet per second to 1.15 fps) with some samples collected at either end of the range. Seventy point seven percent of the samples were collected within the range 0.0 to 0.23 m/s (0 fps to 0.75 fps) range. Riffle samples were collected at higher velocities, as were Run samples and their 70.7 percent ranges overlapped. Pool samples were collected at lower velocities, and overlapped run samples. Backwaters were not shown on any of the figures because few samples were recorded in that mesohabitat. Of those collected, all exhibited negative (reverse) velocities.

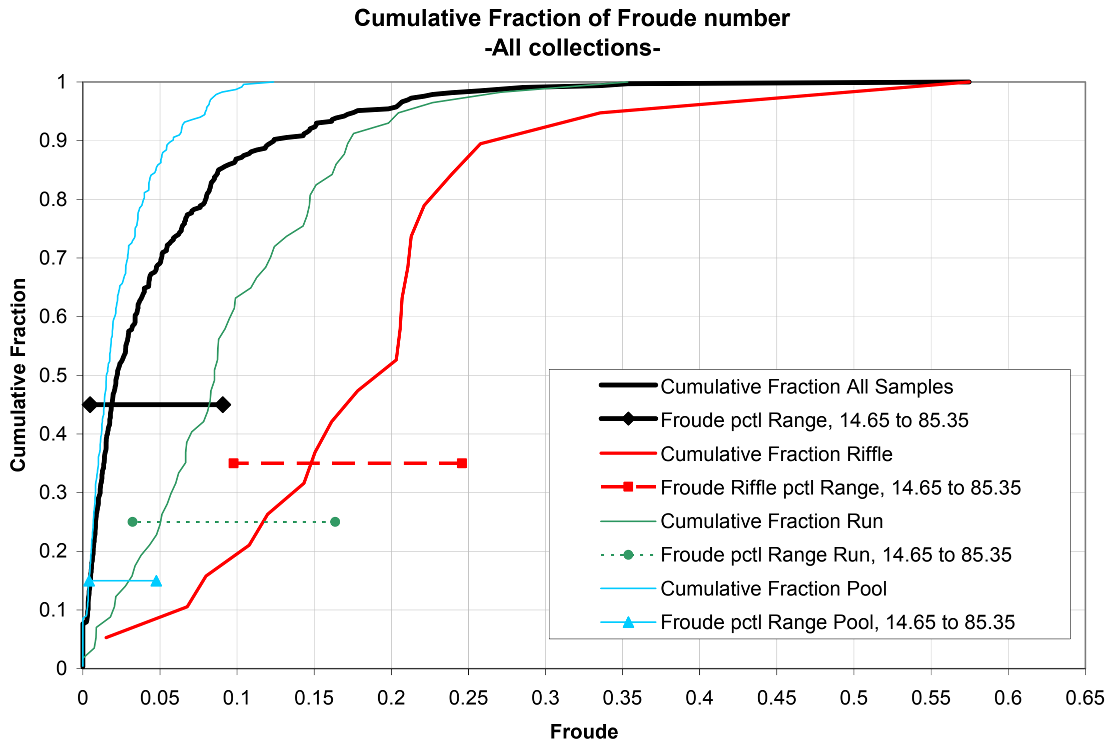

Figure 5.4 – Cumulative fraction of Froude number for all samples and for Riffles

The distribution of samples collected with respect to Froude number, calculated from depth-velocity pairs, is shown in Figure 5.4. Of depth, velocity and Froude number distributions, the most significant separation is observed among mesohabitats with respect to Froude number. Riffle mesohabitats were collected at significantly higher Froude numbers than were Pool mesohabitats and the 70.7% range for those mesohabitats did not overlap. Some overlap is observed of Run habitats over both Riffle and Pool mesohabitats.

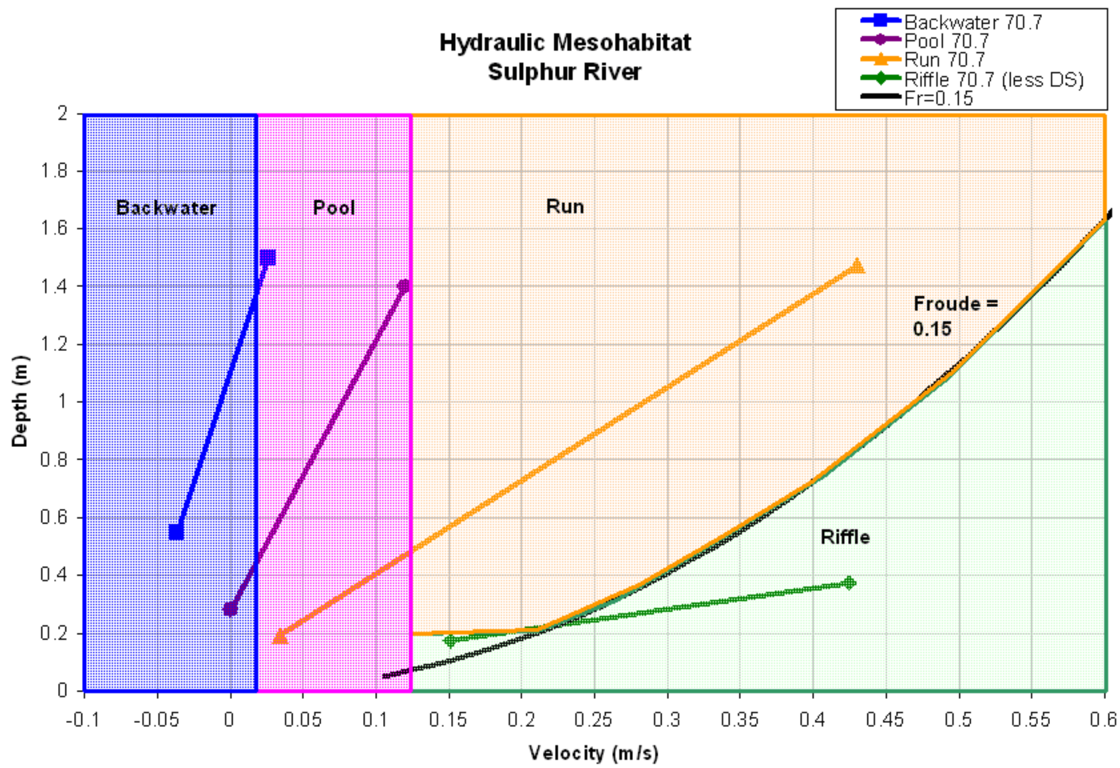

Figure 5.5 - Chart showing criteria used to delineate mesohabitat.

Using the upper and lower 70.7% bounds for each of the mesohabitats were used to establish non-overlapping mesohabitat criteria. Upper and lower bounds for each mesohabitat are shown in Figure 5.5. Bounds are plotted as depth versus velocity with lines connecting the upper depth, velocity coordinate to the lower bound depth, velocity coordinate. Distinct mesohabitats were delineated and final criteria generated based upon their relationship to cumulative frequency bounds and to the bounds of neighboring mesohabitats. Figure 5.5 illustrates the relationship between upper and lower probability bounds and the final criteria. The final criteria are tabulated in Table 5.1.

Figure 5.6 shows the depth-velocity pairs that were used to develop the criteria. As shown, there exists significant overlap of Pool mesohabitat into the backwater range, and significant overlap of Run into the Pool range. Additional analysis could likely improve these hydraulic habitat definitions.

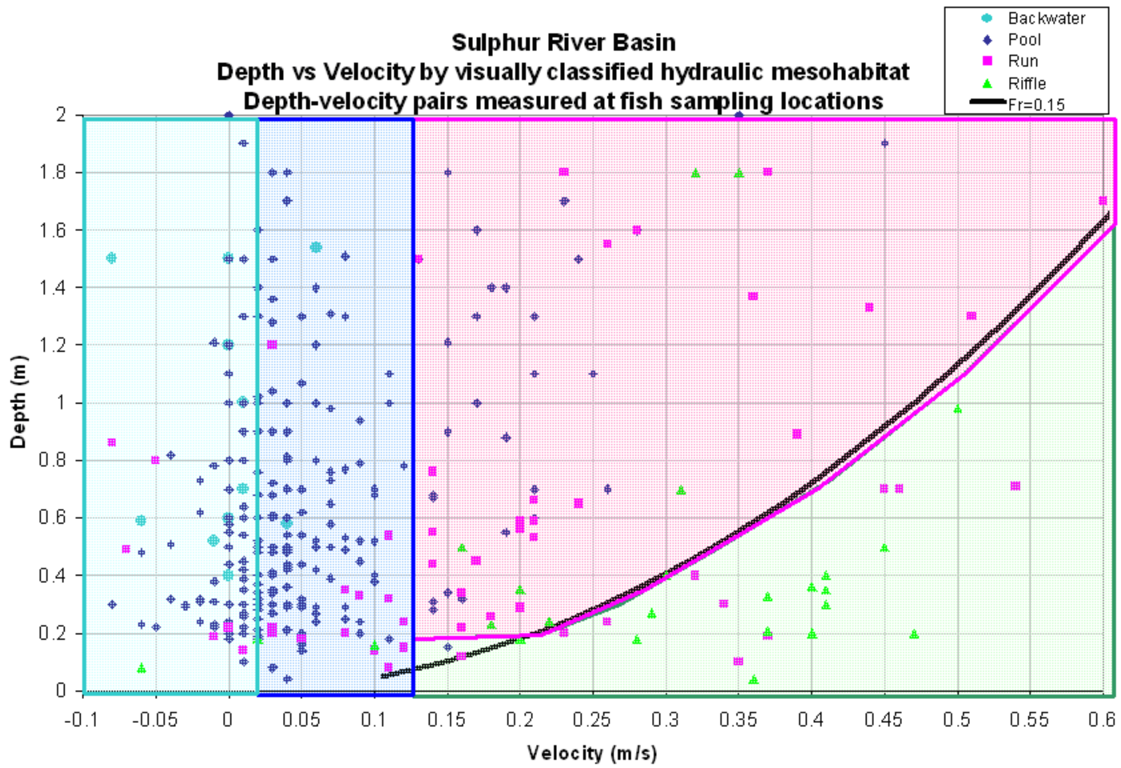

Figure 5.6 – Mesohabitat criteria and depth-velocity pairs from source data.

Table 5.1 - Criteria used to delineate mesohabitats, shown in SI units (top) and English units (bottom).

Mesohabitat Criteria in Meters		**Depth (meters)**		**Velocity (mps)**		**Froude #**
		low	**high**	**low**	**high**	
Backwater		> 0	> 0	< 0.015	0.015	
Pool		0	> 0	0.015	0.125	
Run		0.2	> 0.2	0.125	> 0.125	< 0.15
Riffle		> 0	0.2	0.125	0.21	
	or	> 0	0.2	0.21	> 0.21	> 0.15

Mesohabitat Criteria in Feet		**Depth (feet)**		**Velocity (fps)**		**Froude #**
		low	**high**	**low**	**high**	
Backwater		> 0	> 0	< 0.0045	0.005	
Pool		0.000	> 0	0.005	0.038	
Run		0.061	> 0.061	0.038	> 0.038	< 0.15
Riffle		> 0	0.061	0.038	0.064	
	or	> 0	0.061	0.064	> 0.064	> 0.15

5.2 Incorporation of structural habitat data

Four additional habitat types are utilized in this analysis to describe physical structure, namely open-channel, edge, bank structure, and channel structure. These habitat types further divide each mesohabitat into sub-mesohabitats. The sub-mesohabitats were condensed by the TWDB from habitats reported by TAMU: edge, bank snag, undercut bank, rootwad, vegetation, tree, channel snag, snag complex, and debris dam. The physical locations of the observed habitats as reported by TAMU, were not accurate enough for a direct incorporation into the spatial GIS model presented in this report. The four structural sub-mesohabitats, as consolidated by TWDB, are more easily delineated by the spatial analysis. TAMU habitats are consolidated as follows: bank snag, snag complex, undercut bank, rootwad, vegetation, and tree habitats are consolidated under the "bank structure" sub-mesohabitat; channel snag and debris dam habitats are consolidated under the "channel structure" sub-mesohabitat. Edge habitat and open water habitats each remain under their own titles. The four mesohabitats are combined with the four structural sub-mesohabitats to describe a total of sixteen different habitat areas (Table 5.2):

Table 5.2 – Structural sub-mesohabitats used in GIS analysis

Mesohabitat	Sub-mesohabitat	Habitat number (GIS)
Backwater	Open water	1
Backwater	Edge	2
Backwater	Bank structure	3
Backwater	Channel structure	4
Pool	Open water	5
Pool	Edge	6
Pool	Bank structure	7
Pool	Channel structure	8
Run	Open water	9
Run	Edge	10
Run	Bank structure	11
Run	Channel structure	12
Riffle	Open water	13
Riffle	Edge	14
Riffle	Bank structure	15
Riffle	Channel structure	16

Since structural habitats were found to be important to habitat utilization (Gelwick and Morgan 2000, Gelwick and Burgess 2002), structure habitats were incorporated into the spatial habitat model. Edge and structure data were derived from site observations, from simple GIS analysis of hydraulic model outputs, and from filtering of raw bathymetric data (White, 2003). All data was transferred to the ESRI grid format and the habitat model was executed using Spatial Analyst and a custom ArcGIS extension developed for ArcGIS 8.3 by the Center for Research in Water Resources at the University of Texas at Austin (UT-CRWR) (Wentzel 2001 and Merwade 2001). GIS grids were developed to show the spatial occurrence (or absence) of edge and structure habitat within the Sulphur River channel.

The edge grid was generated using the depth output for each flow that was modeled. Edge habitat was defined in two stages: (1) all area having depth less than 0.25m, and (2) all area within 2m of the boundary of those areas having depth less than 0.25m. Figure 5.7 shows an example of the depth grid for Site 2 at 2.32 cms (82 cfs).

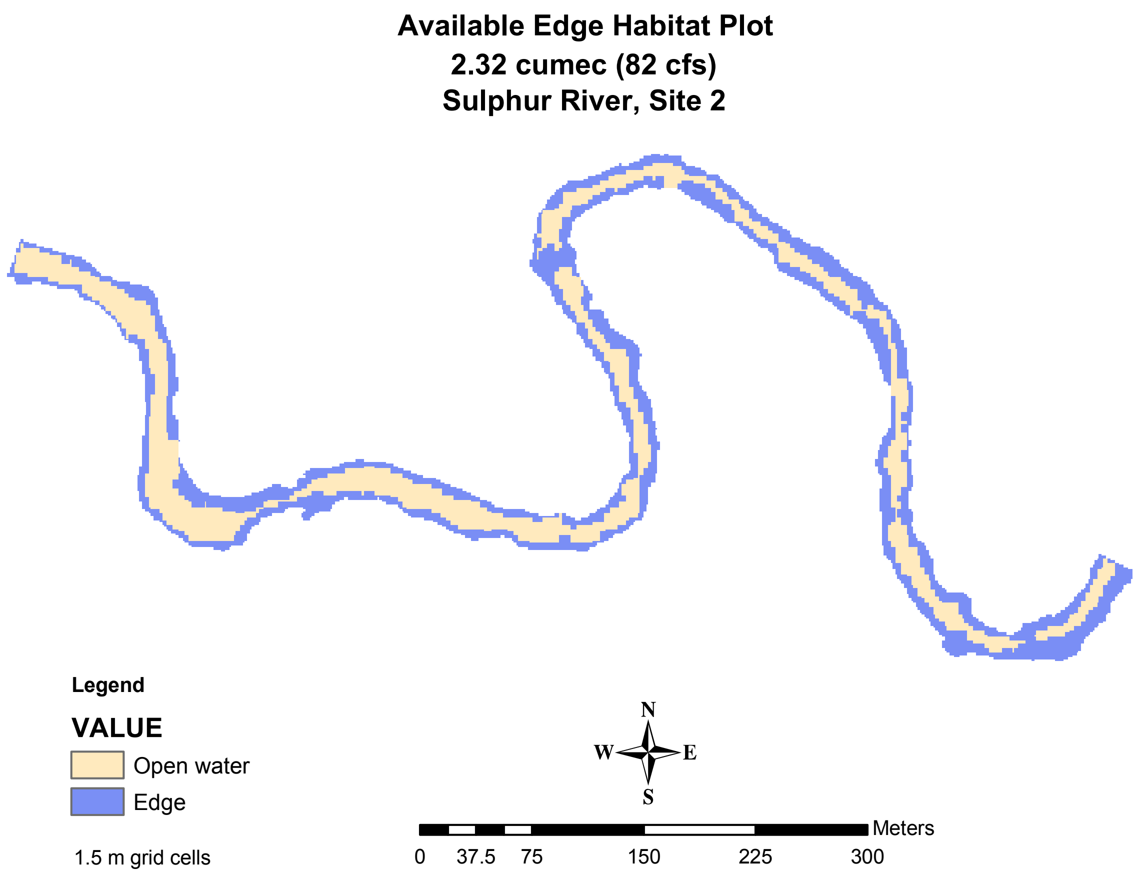

Figure 5.7 – Edge grid used in habitat analysis; 2.32 cms (82 cfs), Site 2.

Structure in the Sulphur River was characterized as Large Woody Debris (LWD), and was widespread on both Site 1 and Site 2. Areas with structure on Site 2 are shown in Figure 5.8. The LWD grid was generated using a new technique developed by UT-CRWR under a TWDB contract (White 2003, White et al. 2004). Raw depth sounder data (the same data used to define the bathymetry) was processed using a median filter that separates the background bed form signal from higher-amplitude signals that can be characterized as underwater structure. Initial testing of this algorithm with verified field data has shown that it identified structure well; however, additional testing and verification is required. Limitations of this mapping algorithm were as follows: debris not located along a bathymetric survey line was not identified; minimum size of identified debris was dependant upon resolution of the bathymetric data; and exact orientation and configuration of identified debris was not known (for example, a snag complex cannot be differentiated from a debris dam).

Since the objective of this study was to identify potential changes in available habitat area for different flow rates, these limitations did not significantly decrease the utility of the LWD grid. The LWD grid exhibited representative density and spatial distribution of LWD; therefore, the modeled differences in available area at different flow rates are likely proportional to the differences in actual area of available habitat.

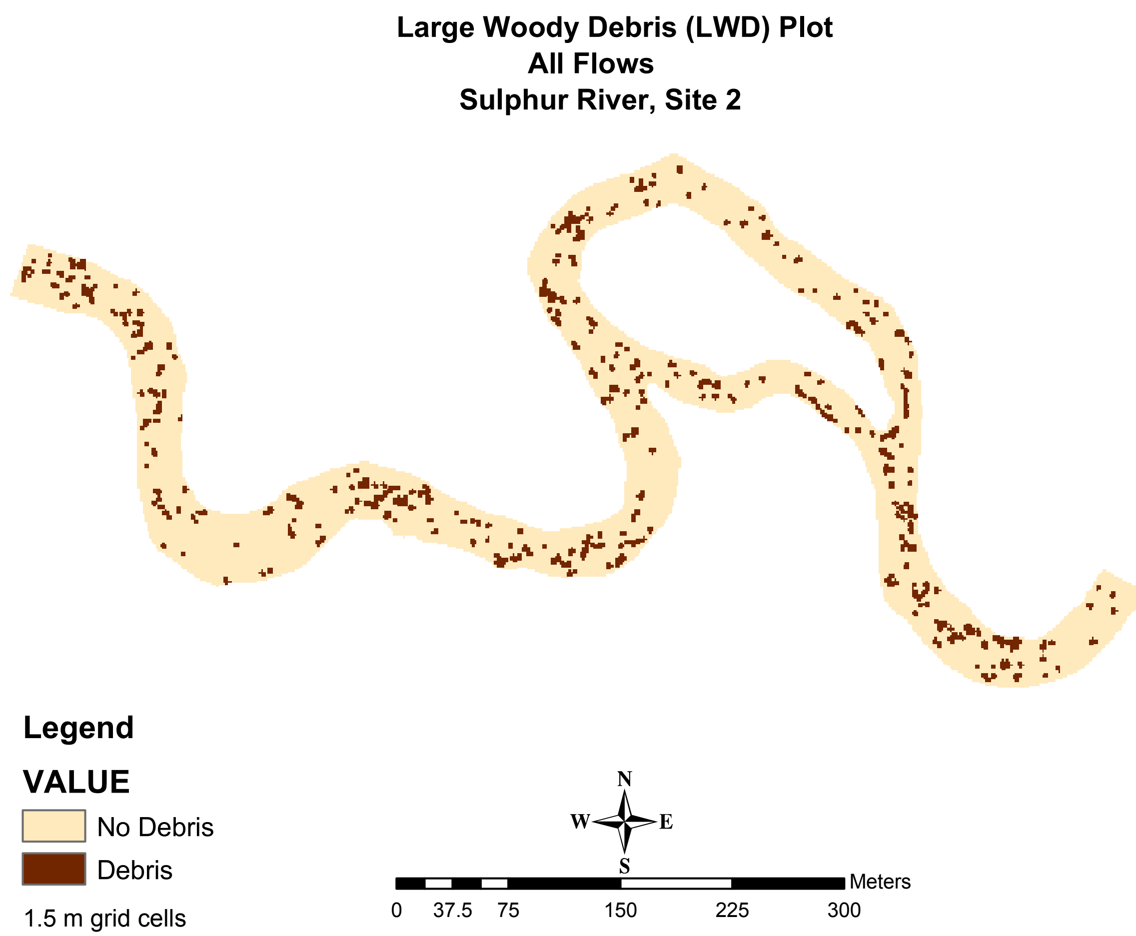

Figure 5.8 – Structure grid used for all flows at Site 2 in habitat analysis.

The above-described UT-CRWR algorithm filtered point bathymetric data and did not directly generate the LWD grid. Points identified as LWD were imported into GIS, buffered by 2m, dissolved, and then converted to the grid shown in Figure 5.8.

Edge and LWD grids were combined to synthesize a habitat grid describing the sub-mesohabitats. Four resultant sub-mesohabitats are identified: open water, edge, bank structure, and channel structure. Structure is defined as any debris identified in the LWD grid. Bank structure was defined as that structure that was located within the edge region and channel structure was defined as that structure located outside of the edge region. The resultant habitat grid for Site 2 at 2.32 cms (82 cfs) is shown in Figure 5.9.

Verification of the GIS habitat model was conducted and is presented in Appendix O. A fair correlation was found between field data, for which accurate location information was not available, and the GIS habitat model; accurate positioning of each fish sample is recommended for all future studies.

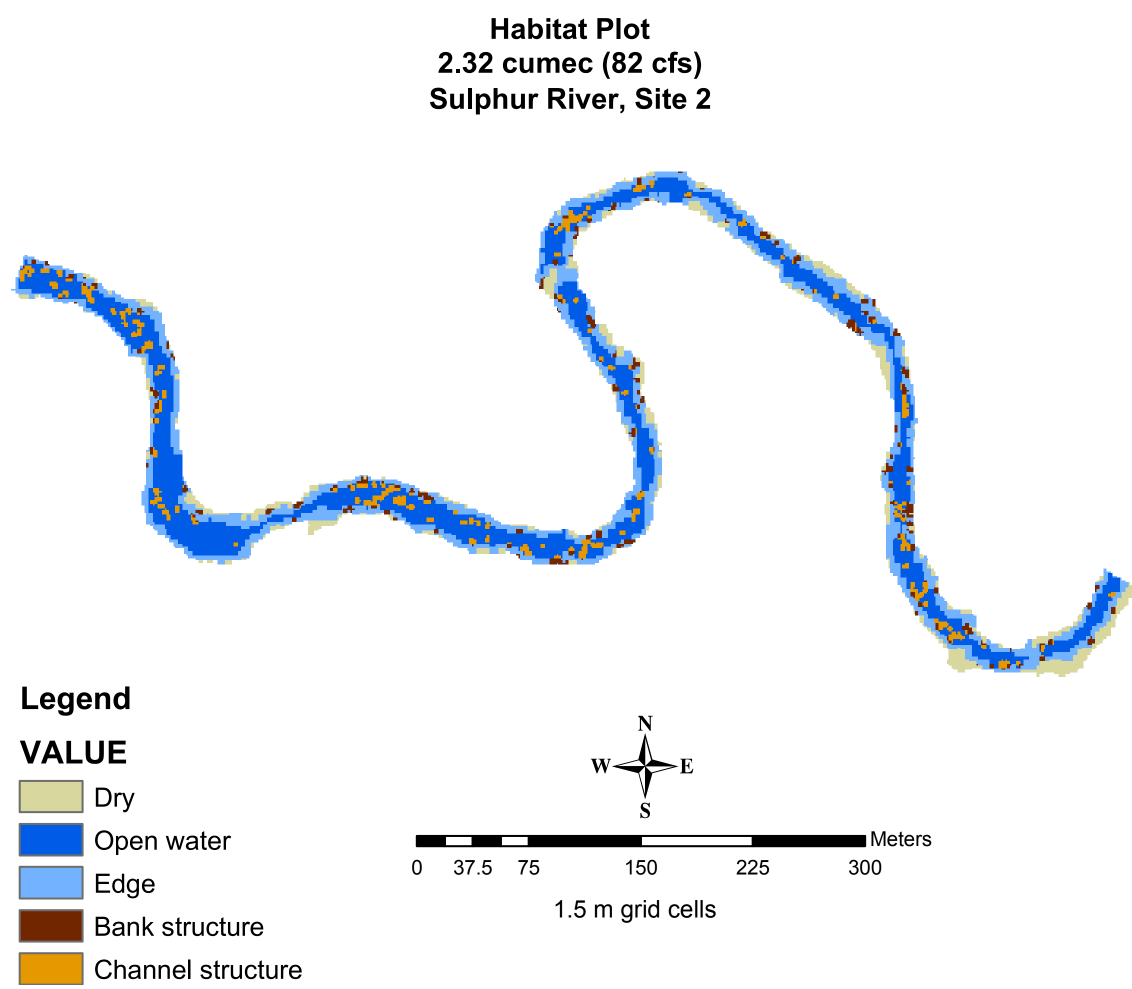

Figure 5.9 – Habitat grid used to delineate sub-mesohabitats; 2.32 cms (82 cfs), Site 2.

5.3 Area of available habitat

Using the mesohabitat and structural sub-mesohabitat criteria described above and shown in Figure 5.5 and Tables 5.1 and 5.2, the area of available habitat was quantified at each of the TWDB study sites. The criteria were applied to spatial depth and velocity data that was generated by the hydraulic model (see Chapter 3).

5.3.1 Available habitat at Site 1

Habitat modeling was performed at channelized Site 1 for four flow rates, 0.31 cms (11.5 cfs), 0.71 cms (25 cfs), 3.11 cms (110 cfs), and 14.16 cms (500 cfs). These flow rates capture the summer and winter low flow range (0.31 cms), the summer high and winter middle flow range (3.11 cms), and the winter high flow range (14.16 cms) (see Tables 4.1 and 4.2).

Figures 5.10 and 5.11 illustrate the relationship between flow and structural sub-mesohabitat availability, repsectively. The 3.11 cms (110 cfs) flow level is a peak availability for all of the pool sub-guilds, including open water pools, pools with channel and bank structure. Riffle edge habitat becomes very reduced at flows greater than 3.11 cms, however riffles without any kind of structure become increasingly available at flows greater than 3.11 cms. Run habitats become increasingly available with increasing flows. The 3.11 cms point in the flow modeling appears to be an important hydraulic region with regard to the availability of habitat. Plots depicting the spatial distribution of each mesohabitat are located in Appendix J, and a tabular summary of available habitat area is shown in Table 5.2.

5.3.2 Available habitat at Site 2

Habitat modeling was performed at unchannelized Site 2 for four flow rates, 1.05 cms (37 cfs), 2.32 cms (82 cfs), 5.66 cms (200 cfs) and 23.53 cms (831 cfs). Figures 5.12 and 5.13 illustrate the relationship between flow and the major sub-guilds at Site 2. Available habitat area is summarized in tabular form in Table 5.3. The availability of habitat area for each of the sub-guilds is summarized from the results GIS spatial mapping (spatial plots for each flow are located in Appendix N). Open water habitat becomes much more available with increasing flows, however channel and bank structure only benefit slightly from increases in flow. Edge structure is somewhat more available at flows greater than 5.66 cms, although that habitat is more available at low flows than at mid-range flows around 5.66 cms.

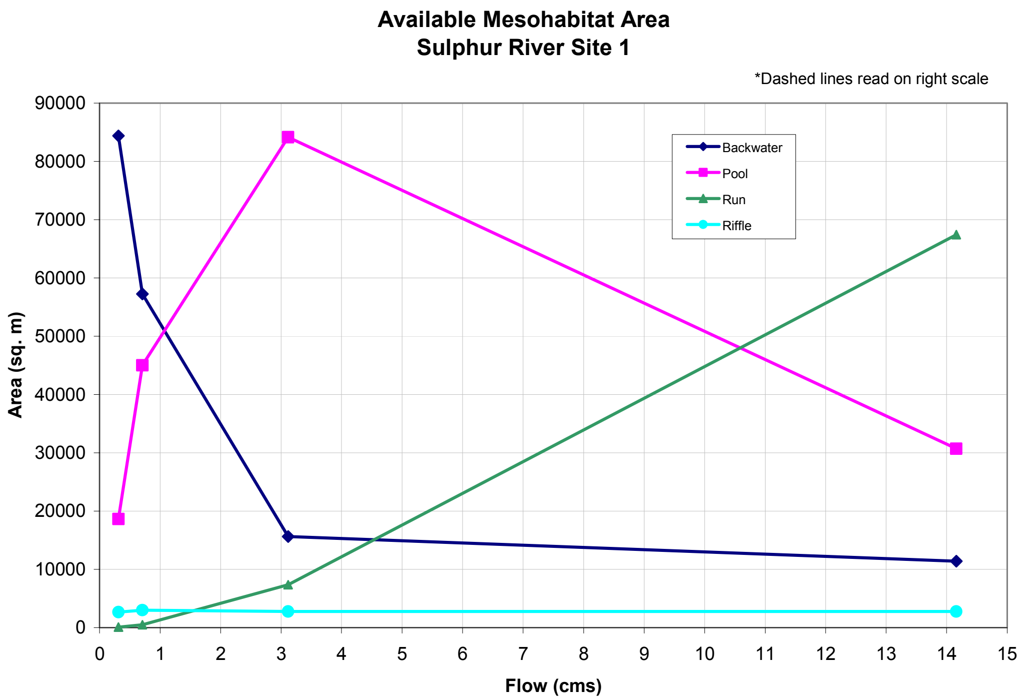

Figure 5.10 – Available mesohabitat area, Site 1.

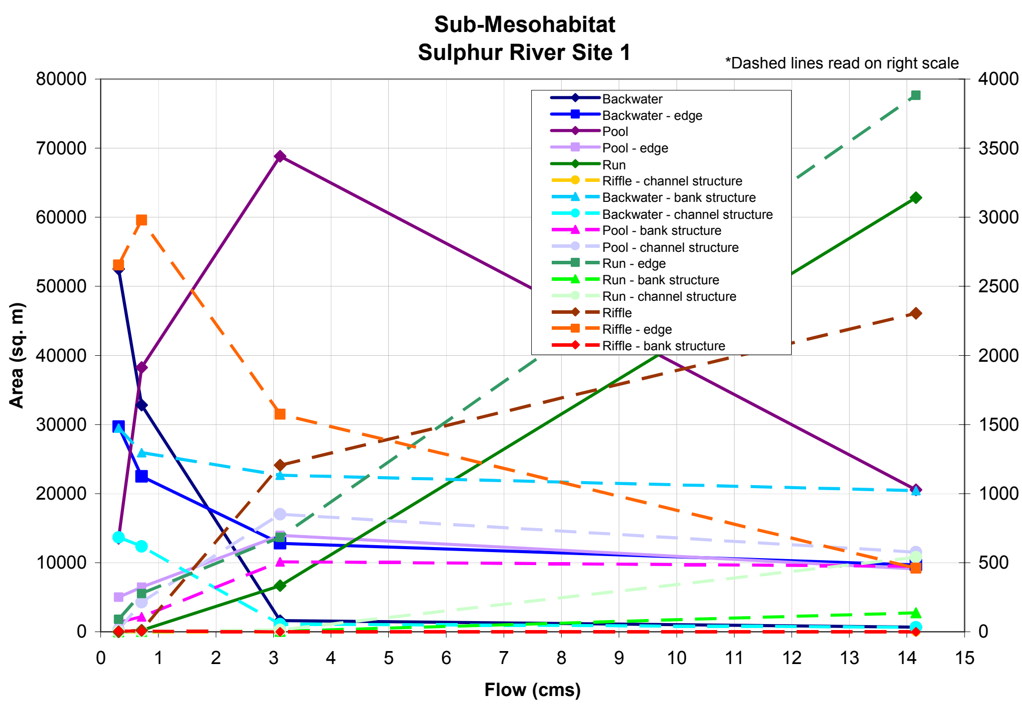

Figure 5.11 – Available sub-mesohabitat area, Site 1.

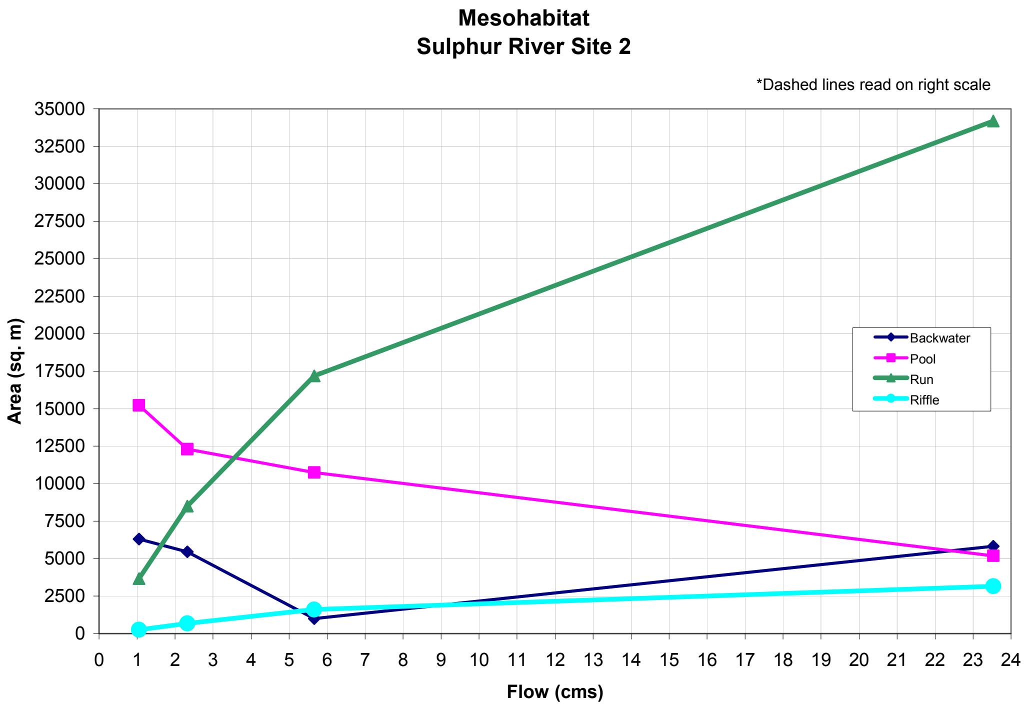

Figure 5.12 – Available mesohabitat area, Site 2.

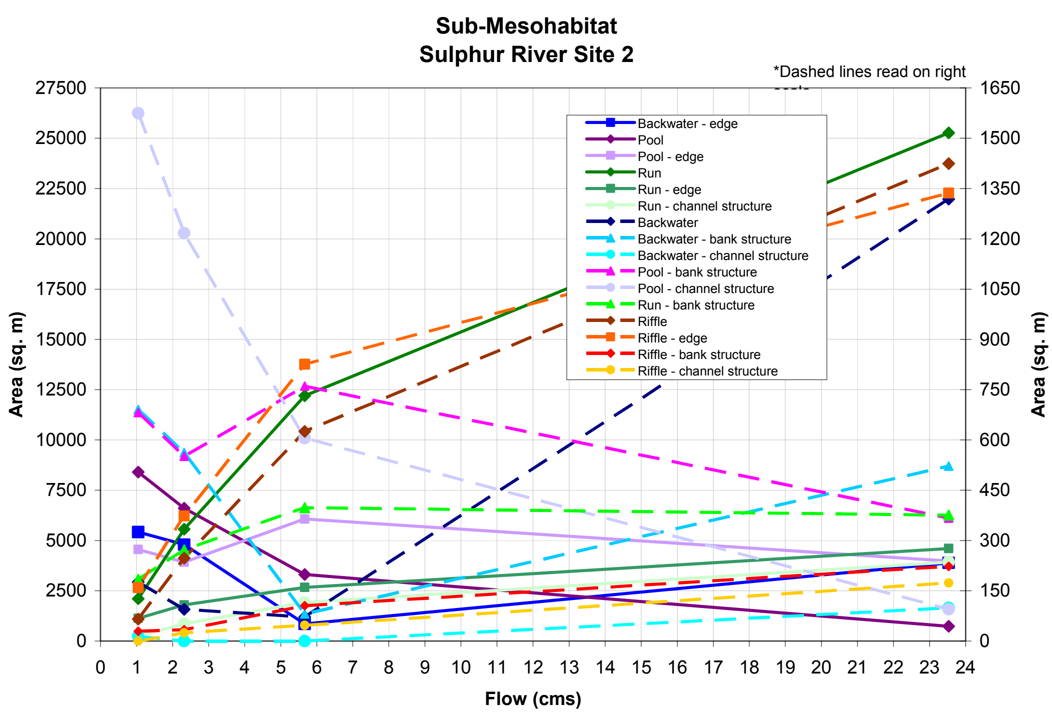

Figure 5.13 – Available sub-mesohabitat areas, Site 2.

Table 5.2 – Habitat area within Site 1

	Area of habitat (meters squared) for each flow				Percent of area habitat for each flow			
	0.31 cms	**0.71 cms**	**3.11 cms**	**14.16 cms**	**0.31 cms**	**0.71 cms**	**3.11 cms**	**14.16 cms**
Structural habitat	11 cfs	25 cfs	110 cfs	500 cfs	11 cfs	25 cfs	110 cfs	500 cfs
Backwater	52506	32818.5	1615.5	657	49.65%	31.03%	1.47%	0.59%
Backwater - edge	29711.25	22502.25	12813.75	9686.25	28.09%	21.28%	11.66%	8.63%
Backwater - bank structure	1473.75	1296	1134	1021.5	1.39%	1.23%	1.03%	0.91%
Backwater - channel structure	684	618.75	56.25	33.75	0.65%	0.59%	0.05%	0.03%
Pool	13540.5	38252.25	68841	20540.25	12.80%	36.17%	62.62%	18.29%
Pool - edge	5008.5	6446.25	13952.25	9110.25	4.74%	6.10%	12.69%	8.11%
Pool - bank structure	67.5	108	506.25	474.75	0.06%	0.10%	0.46%	0.42%
Pool - channel structure	15.75	213.75	850.5	576	0.01%	0.20%	0.77%	0.51%
Run	0	225	6675.75	62851.5	0.00%	0.21%	6.07%	55.98%
Run - edge	90	276.75	684	3883.5	0.09%	0.26%	0.62%	3.46%
Run - bank structure	0	2.25	4.5	137.25	0.00%	0.00%	0.00%	0.12%
Run - channel structure	0	4.5	13.5	540	0.00%	0.00%	0.01%	0.48%
Riffle	0	11.25	1206	2306.25	0.00%	0.01%	1.10%	2.05%
Riffle - edge	2655	2979	1575	461.25	2.51%	2.82%	1.43%	0.41%
Riffle - bank structure	6.75	4.5	0	0	0.01%	0.00%	0.00%	0.00%
Riffle - channel structure	0	0	0	4.5	0.00%	0.00%	0.00%	0.00%

	0.31 cms	**0.71 cms**	**3.11 cms**	**14.16 cms**	**0.31 cms**	**0.71 cms**	**3.11 cms**	**14.16 cms**
Mesohabitat only	11 cfs	25 cfs	110 cfs	500 cfs	11 cfs	25 cfs	110 cfs	500 cfs
Backwater	84375	57235.5	15619.5	11398.5	79.78%	54.12%	14.21%	10.15%
Pool	18632.25	45020.25	84150	30701.25	17.62%	42.57%	76.55%	27.34%
Run	90	508.5	7377.75	67412.25	0.09%	0.48%	6.71%	60.04%
Riffle	2661.75	2994.75	2781	2772	2.52%	2.83%	2.53%	2.47%

Table 5.3 – Habitat area within Site 2

Structural habitat	Area of habitat (meters squared) for each flow 1.05 cms 37 cfs	2.32 cms 82 cfs	5.66 cms 200 cfs	23.53 cms 831 cfs	Percent of area habitat for each flow 1.05 cms 37 cfs	2.32 cms 82 cfs	5.66 cms 200 cfs	23.53 cms 831 cfs
Backwater	176	95	72	1319	0.69%	0.35%	0.24%	2.73%
Backwater - edge	5418	4795	848	3886	21.30%	17.81%	2.78%	8.04%
Backwater - bank structure	691	563	81	522	2.72%	2.09%	0.27%	1.08%
Backwater - channel structure	14	0	0	99	0.05%	0.00%	0.00%	0.20%
Pool	8408	6602	3317	740	33.05%	24.52%	10.85%	1.53%
Pool - edge	4556	3924	6071	3980	17.91%	14.57%	19.87%	8.23%
Pool - bank structure	682	551	761	367	2.68%	2.05%	2.49%	0.76%
Pool - channel structure	1575	1217	605	95	6.19%	4.52%	1.98%	0.20%
Run	2102	5564	12197	25274	8.26%	20.67%	39.92%	52.27%
Run - edge	1132	1796	2673	4608	4.45%	6.67%	8.75%	9.53%
Run - bank structure	185	272	398	376	0.73%	1.01%	1.30%	0.78%
Run - channel structure	250	866	1926	3929	0.98%	3.22%	6.30%	8.13%
Riffle	65	248	626	1424	0.26%	0.92%	2.05%	2.95%
Riffle - edge	160	374	826	1337	0.63%	1.39%	2.70%	2.76%
Riffle - bank structure	29	34	106	223	0.11%	0.13%	0.35%	0.46%
Riffle - channel structure	0	25	47	173	0.00%	0.09%	0.15%	0.36%
Total Area	25441	26924	30553	48350				

Mesohabitat only	1.05 cms 37 cfs	2.32 cms 82 cfs	5.66 cms 200 cfs	23.53 cms 831 cfs	1.05 cms 37 cfs	2.32 cms 82 cfs	5.66 cms 200 cfs	23.53 cms 831 cfs
Backwater	6298	5452	1001	5825	24.75%	20.25%	3.28%	12.05%
Pool	15221	12294	10753	5182	59.83%	45.66%	35.19%	10.72%
Run	3668	8498	17195	34187	14.42%	31.56%	56.28%	70.71%
Riffle	254	680	1604	3157	1.00%	2.52%	5.25%	6.53%
Total Area	25441	26924	30553	48350				

5.4 Species distribution within hydraulic mesohabitats and structural sub-mesohabitats

In many river systems, mesohabitats have been shown to be a relevant scale for some instream flow studies (Parasiewicz 2001, Mathews and Bao 1991), and in others individual pools represented biologically meaningful spatial units (Matthews et al. 1994). To evaluate the distribution of fish species among the hydraulic mesohabitats and structural sub-mesohabitats, each sample collected during the TAMU studies (Gelwick and Morgan 2000; Gelwick and Burgess 2002) was reclassified into the TWDB habitat classifications based upon depth, velocity and structure field data reported in the TAMU studies. Figure 5.6 showed the distribution of reported field-classified samples within the TWDB classifications.

The field data was grouped according to location, creating four groups consisting of the unchannelized South Sulphur River sample sites, channelized South Sulphur River sites, channelized Sulphur River sites and unchannelized Sulphur River sites. Data in each group was standardized based upon area sampled, using the same method described in Morgan (2002) and Burgess (2003). Tables for absolute abundance and relative standardized abundance are included at the end of this chapter. Table 5.4 summarizes the applicability of each table with respect to the area and to the biological sampling sites used for source data.

5.4.1 Spatial heterogeneity of mesohabitats

Understanding the relationships between fish and their habitats is important for resource allocations and management, instream flow assessments, and water planning issues. Fish species generally exhibit strong associations with certain types of habitats, and as a result stream reaches with higher habitat heterogeneity generally have greater species richness than reaches with fewer habitats for fishes to utilize (Gorman and Karr 1978; Schlosser 1982a; Angermeier and Karr 1984; Reeves et al. 1993). However, Morgan (2002) and Burgess (2002) reported that despite higher heterogeneity in the unchannelized reaches, species richness was similar to that in the channelized reaches. Other studies on the South Sulphur River by Carroll et al. (1997) and Capone and Kushlan (1991) found similar results. Most fishes occurred in a variety of habitats in the Sulphur River and did not reveal discrete habitat associations, according to Morgan (2002).

Morgan (2002) reported that the mainstem Sulphur River during summer flows was composed almost exclusively of a single mesohabitat, pools (94%), leaving the remaining habitats with very little composition (3% runs, 2% riffles, and 1% backwaters). Based upon this reported mesohabitat occurrence, mesohabitat variation explained little (3.6%) of the variation in species' distributions (Morgan 2002).

Table 5.4 – List and organization of tables presented in this chapter

Sulphur River	
Channelized Sample sites 101, 102, 103 and 107	**Unchannelized** Sample sites 104, 105 and 106
5.5 - Absolute abundance by season	5.6 - Absolute abundance by season
5.7 - Absolute abundance by season - rare species	5.8 - Absolute abundance by season - rare species
5.9 - Relative standardized abundance by season	5.10 - Relative standardized abundance by season
5.11 - Relative standardized abundance by season - rare species	5.12 - Relative standardized abundance by season - rare species
5.13 - Absolute abundance by habitat	5.14 - Absolute abundance by habitat
5.15 - Relative standardized abundance by habitat	5.16 - Relative standardized abundance by habitat

<table>
<tr><th colspan="2">South Sulphur River</th></tr>
<tr><th>Channelized
Sample sites 204, 205 and 206</th><th>Unchannelized
Sample sites 201, 202, 203</th></tr>
<tr><td>5.17 - Absolute abundance by season</td><td>5.18 - Absolute abundance by season</td></tr>
<tr><td>5.18 - Absolute abundance by habitat</td><td>5.19 - Absolute abundance by habitat</td></tr>
<tr><td colspan="2">5.21 - Absolute abundance by season - rare species</td></tr>
<tr><td colspan="2">5.22 - Absolute abundance by habitat - rare species</td></tr>
<tr><td>5.23 - Relative standardized abundance by season</td><td>5.24 - Relative standardized abundance by season</td></tr>
<tr><td>5.25 - Relative standardized abundance by habitat</td><td>5.26 - Relative standardized abundance by habitat</td></tr>
<tr><td colspan="2">5.27 - Relative standardized abundance by season - rare species</td></tr>
<tr><td colspan="2">5.28 - Relative standardized abundance by habitat - rare species</td></tr>
</table>

Conversely, modeled results for 3.11 cms (110 cfs) flow at Site 1 illustrate mesohabitat composition of that site to be 56% Run, 35% Pool. At 14.16 cms (500 cfs) flow the Sulphur River was a Run dominated system (71%), with Pools only accounting for 11% of the mesohabitat composition (Table 5.2). Similarly, Backwaters account for 25% of the mesohabitat composition at 0.31 cms (11 cfs), and Riffles 5 % at 3.11 cms. The habitat compositions generated by the GIS model are shown in Tables 5.2 and 5.3. Verification of the GIS habitat model was conducted and is presented in Appendix O. The differences between visual and GIS methods illustrate the importance of accurate depth, velocity and location information that can be used for verification of results.

In addition to mesohabitat composition, structure is an important habitat. The channelized reaches of both the South and mainstem Sulphur River were dominated by pool mesohabitats at all but high flows (Table 5.2).The diversity of mesohabitat types was greater in the unchannelized reaches (Site 2), composed primarily of both pools and runs with a much greater component of riffles, backwaters and structure.

Some seasonal variation of heterogeneity was also observed. The winter flows have much higher volumes and, therefore, faster velocities (Table 4.2). While summer comparisons are important for their stated purpose, to study the potential impacts of low flow limiting conditions, additional analysis of winter and high-flow periods is required to estimate the dynamic habitat conditions over the full range of flows for the Sulphur River.

5.4.2 Discussion of species distribution amongst habitats found by earlier studies

The data indicated that there were relationships among species and habitat variables at several levels of habitat aggregation. While Morgan (2002) found that the explained variance between each level of aggregation was small based on fish associations within visually delineated mesohabitats, he considered that to be consistent with Hawkins et al. (1993) who suggested that variation in species distributions often reflects responses by fish to broad environmental gradients rather than discrete patches of habitat at different scales. In addition, in river systems typified by multiple habitat use by numerous fish species (esp. generalist types), statistical applications show low levels of explained variance. Species like the red shiner, a well-known generalist species (Matthews and Hill 1980) were collected from nearly all habitat types in high abundance. Some species were more habitat specialist, such as the freckled madtom, mimic shiner, channel catfish, and blue catfish, which were positively associated with high velocities and with riffle-oriented habitat types and shallower depths. Specific habitat associations were also found for the river carpsucker, white bass, bigmouth buffalo, smallmouth buffalo, common carp, and gizzard shad for greater depths in Morgan's (2002) upstream reach, and with pool habitats at higher flows. Morgan (2002) suggested that the stream fish assemblage of the Sulphur River may be related more generally to habitat diversity than to discrete patches of specific habitat types. Burgess (2002) hypothesized that if habitat volume was temporarily reduced during summer low-flow, then fish might have been forced into suboptimal habitat, thus increasing habitat overlap between juveniles and adults, and piscivores and their smaller-bodied prey. Predation and competition are important biotic processes affecting fish assemblage structure, and were not the focus of our habitat utilization studies. Hot summer conditions accompanied by low flows and dissolved oxygen concentrations can limit the ability of larger and less tolerant fish to persist in streams. Matthews and Styron (1981) and Burgess (2002) reported that abiotic factors and processes were the primary forces structuring fish assemblages. In particular, she believed that the large number of tolerant species and habitat generalist in the South Sulphur River suggests that physicochemical factors are affecting the fishery and that the river basin is subjected to considerable environmental variation. Species that inhabit streams with large environmental variability have evolved to cope with disturbance where environmental conditions can be extreme and somewhat unpredictable (Poff and Ward 1990). Many of these species readily inhabit a variety of habitats and still thrive, and thus they are considered habitat generalist. The Sulphur River is composed largely of habitat generalist according to Burgess (2002) and Morgan (2002), many of which are classified as tolerant. The abundance of tolerant habitat generalist in this system suggest a fish assemblage that has adapted to persist through harsh environmental conditions according to Burgess (2002), which is a pattern seen in other warmwater streams (Matthews 1987; Meador and Matthews 1992; Kinsolving and Bain 1993; Poff and Allen 1995; Matthews 1998).

Morgan (2002) conducted an indicator analysis to show differentiation among groups in the Sulphur River, which he found were primarily related to hydraulic characteristics, such as fast-water, backwater, and open-water. He hypothesized that the fast-water group was primarily associated with feeding function, because these areas tend to provide hydraulic corridors for drifting invertebrate prey (Brittain and Eikeland 1988, Matthews 1998), which would include species like the freckled madtom, mimic shiner, and channel and blue catfish that feed on insects in faster flowing currents.

Backwaters were used by a large number of fishes in the mainstem of the Sulphur River, which resulted in numerous significant indicator species, including mosquitofish, orangespotted sunfish, and white crappie. These species are typically found in slow velocity and backwater areas (Robison and Buchanan 1998, Matthews 1998). Burgess (2002) reported that backwaters only occurred in the unchannelized reach of the South Sulphur River, probably because levee construction in the channelized reach prevented the formation of backwaters. Bluegill had their strongest association with South Sulphur River backwaters in 2001, but that species was replaced by red shiner in 2002. The mainstem open-water group was dominated by catostomids (smallmouth buffalo, bigmouth buffalo, and river carpsucker) and common carp. These species are primarily benthic-insectivores that feed on the bottom of open pools and runs, which is similar to findings in other studies (Robison and Buchanan 1988). In comparison, species associated with channelized pools in the South Sulphur River included numerous species, including the common carp, flathead catfish, smallmouth buffalo, longnose gar, and orangespotted sunfish.

A much less diverse species association was found in unchannelized pools, which included western mosquitofish and longear sunfish. This greater diversity of fish associations in channelized pools is probably because pools dominate channelized reaches of the South and mainstem Sulphur River. Juvenile slough darters were associated with pools in both channelized and unchannelized reaches. Red shiner, mimic shiner, and redfin shiner in the South Sulphur River dominated runs, although slough darter adults had a high indicator value for this type of mesohabitat. Riffle habitats were associated with freckled madtoms and mimic shiners in both South and mainstem Sulphur River reaches, and these species are considered fluvial specialist because of the narrow ranges of habitat that they utilize.

Channelization was performed in the Sulphur River basin during the 1950's, and the affects on habitat and fishery composition is still very apparent today. Altered stream channels may never regain their previous habitat diversity (Gregory et al. 1994), and even after 50-years, channelized areas are dominated by deeply incised pools. In an overall comparison with all habitats included of channelized verses unchannelized reaches of the South Sulphur River, Burgess (2002) reported that the channelized reach had strong associations with gizzard shad, white crappie, shortnose gar, longnose gar, and river carpsucker in 2001, and smallmouth buffalo and orangespotted sunfish in 2002. This compares to strong associations in the unchannelized reach with redfin shiner, mimic shiner, channel catfish, bluegill, and common carp in 2001; and with the red shiner, freckled madtom, longear sunfish, bullhead minnow, and western mosquitofish in 2002. The only darter found in the South Sulphur River, the slough darter, was more associated with the unchannelized reach in their adult stage. Juvenile longnose gar were strongly associated with the channelized sites. The unchannelized reach was associated with more species and higher biomass of invertivores in comparison to the channelized reach, while the channelized reach included fewer species with higher biomass attributed to piscivores and omnivores. The invertivores that dominated the unchannelized reach of the South Sulphur River included mainly cyprinids (redfin shiner, red shiner, mimic shiner, and bullhead minnow) and freckled madtom, longear sunfish, bigmouth buffalo, and western mosquitofish. In addition, two piscivores, the flathead catfish and white crappie, and one omnivore, the channel catfish was also associated with the unchannelized reach. The piscivores that dominated the channelized reach were the longnose and shortnose gar, and the dominant omnivores were the gizzard shad and river carpsucker. Due to the lack of algae and absence of submerged aquatic vegetation, there were no herbivorous fish species in either reach of the South Sulphur River.

Structural habitat features in the form of woody habitat were incorporated into the contract studies by Gelwick and Morgan (2000) and Gelwick and Burgess (2002) because of their importance to fishes that was reported in previous studies by Mathews and Bao (1991) and Bao and Mathews (1991). Morgan's (2002) analysis of this data showed fish habitat associations for single-structure and multiple-structure woody debris. These associations were poorly differentiated by fish occurrences, with fish showing greater associations with other habitat conditions. However, the spotted gar and warmouth did have high indicator values for woody structure, but those associations were not significant. Based on the overestimation of pool habitat in Morgan's study, it is probable that this reduced the effectiveness of cluster analyses in distinguishing woody habitat associations. Large woody debris (LWD) and snag habitats make an important contribution to the structure and function of the macroinvertebrate community in many streams (Benke et al., 1984; Jacobi and Benke 1991). Benke et al. (1984) showed that in the coastal backwaters of the southeastern U.S. snag habitats may only account for 6% of the potential invertebrate habitat spatially. However, macroinvertebrate standing stock biomass, annual production and densities in snag habitats are 16-50% greater than adjacent benthic habitats. In another TWDB funded study, Wood et al. (1994) reported that the macroinvertebrate standing stock biomass, secondary production and invertebrate densities in snag habitats in Allens Creek and the Brazos River exceeded that of benthic habitats by 10% to more than 50%. Similarly, Benke et al. (1984) in a study of the Setilla River found that invertebrate production in snag habitats exceeded that of the adjacent benthic habitats by 84%. In addition, LWD strongly influences habitat diversity in streams (Reeves et al. 1993). Based on this information, we believe that snag habitat present in the Sulphur River are ecologically important, and we recommend that further assessment of the importance of woody habitat to fish and macroinvertebrates is needed for this river system.

Fish assemblages may not follow traditional patterns described for similar river systems (Schlosser 1987) as a result of an upstream dam, reduced riparian zone vegetation, agricultural runoff, and frequent fish kills. Jim Chapman Lake (formerly Cooper Reservoir) on the South Sulphur River, a federal flood control project, was completed in 1991, and fish assemblages may still be adjusting to this change in their hydrologic regime. Flow management in regulated reaches has major impacts on local hydraulic conditions that influence species abundance and fish diversity (Gorman and Karr 19789; Orth and Maughan 1982).

Fish kills have reportedly occurred at the rate of approximately two per year between 1997 and 2001 (Adam Whisenant, TPWD biologist, unpublished data), which can greatly effect fish assemblages for varying amounts of time (Sharpe et al. 1984; Bryan and Rutherford 1993; Gafny et al. 2000). Agricultural runoff (including insecticides and herbicides) may be responsible for some of these fish kills

Some presently rare species, such as the paddlefish, taillight shiner, and orangebelly darter that previously occurred in northeast Texas river systems in relative abundance, have declined in numbers to these anthropogenic modifications to the extent that they are now under various levels of protection (Garrett 1999). These species are dependent on riffle habitats for various life history stages, which were lost during channelization. A total of 2,190 specimens representing 34 species were collected during Gelwick and Morgan's (2000) study of the mainstem Sulphur River, of which 6 species were considered rare based on their low occurrence across samples (Morgan 2000). The rare species were the alligator gar, shortnose gar, emerald shiner, blackstripe topminnow, pirate perch, brook silverside, and black crappie. He further reported that species richness displayed relatively little variation with respect to site or flow period; however more fish were collected at the unchannelized downstream reach than in the upstream channelized reach. The number of individual fish collected increased as discharge decreased, which may be related to increases in sampling efficiency when concentrating fishes in less volume or possibly reduced effectiveness of sampling gear at higher flows.Morgan stated that measured values for temperature, conductivity, and dissolved oxygen were within normal limits for streams of this region supporting fish populations, and therefore those parameters do not appear to be limiting to the fishery.

Both Morgan (2002) and Burgess (2002) made concluding comments in their respective thesis that effective management of the Sulphur River should include identification of fluvial specialist, in addition to the ones they identified (freckled madtom and mimic shiner) and maintenance of habitat suitability requirements for those species. Fluvial specialists have a greater sensitivity to altered flow regimes (Petts 1984), and thus targeting these species for maintenance flow requirements is probably prudent.

5.4.3 Species distribution across sampling sites and mesohabitats

Habitat utilization patterns observed in TWDB-differentiated habitats are different for channelized and unchannelized reaches; run habitat is the most utilized in unchannelized reaches, while pool habitat is most utilized in channelized reaches; riffle habitat is utilized by a diverse and abundant assemblage of fishes in unchannelized reaches, but by only a few species in low abundance within channelized reaches. Species relative standardized abundances are highlighted green for species that are the highly abundant, with bold font where they are the most abundant.

Species accounts of interest with respect to mesohabitat utilization include those where 100% of the collections occur for a particular species, such as the orangespotted sunfish in unchannelized pools and ghost shiner in unchannelized runs in the South Sulphur River (Table 5.26). The orangespotted sunfish is tolerant of high turbidity and extensive fluctuations in water level (Cross 1967), which make it well adapted to pool conditions in the South Sulphur River. The ghost shiner is a schooling species that generally is found in sluggish flowing, high turbidity areas of rivers (Robinson and Buchanan 1988). Therefore, the high abundance of ghost shiners in South Sulphur River runs is consistent with its occurrence in other river systems.

Also of interest is the number of highly abundant species accounts in unchannelized runs and channelized pools. Run mesohabitat was greatly underestimated by both Morgan (2002) and Burgess (2002) based on hydraulic modeling results, so it is important to note that our results show that runs are the most utilized mesohabitat in unchannelized reaches of the South Sulphur River (Tables 5.25, 5.26), and runs were also a highly utilized mesohabitat in the mainstem of the Sulphur River (Tables 5.15 and 5.16).

Other sub-mesohabitats in the Sulphur River that had strong associations were the threadfin shad and red shiner in unchannelized riffles with snags (Table 5.16), bluegill in open backwaters of the channelized reach (Table 5.15), white bass and smallmouth buffalo in channelized pools with bank snags (Table 5.15) and mosquitofish in channelized open water runs (Table 5.15). The red shiner inhabits quiet waters in sluggish rivers as well as swift currents in moderate gradient rivers, and is tolerant of high turbidities and siltation making this species one of the most widespread in the Sulphur River habitats. Threadfin shad are primarily an inhabitant of moderate to large rivers, and is more abundant in currents than the gizzard shad (Robinson and Buchanan 1988), which explains its abundance in riffle habitats of the Sulphur River. It is an important forage fish in Texas because of its small size; however, it is often associated with thermal shock that results in large die-offs in Texas rivers and reservoirs. Smallmouth buffalo are also widespread, adaptable, and abundant in the Sulphur River basin, usually found in pools with slow current, where they are an opportunistic bottom feeder on small organisms (McComish 1967). The mosquitofish has broad ecological tolerances for temperature and dissolved oxygen (Ahuja 1964, Bacon et al. 1968); preferring slow flowing runs, pools, and backwaters, where it is a surface feeder on a variety of terrestrial and aquatic insects, small crustaceans, and plant material. Bluegill are found in quiet warm waters with cover (e.g., LWD and vegetation) as found in the Sulphur River backwaters, where they are a sight feeder on insects, crayfish, snails, and small fish (Carlander 1977).

5.4.4 Species distribution across seasons

Seasonal patterns in distribution of fishes in the South Sulphur and Sulphur Rivers showed pronounced trends that were definitively different for channelized verses unchannelized reaches (Tables 5.23, 5.24, 5.9, 5.10, respectively). In the Sulphur River, the traditional generalist species (e.g., red shiner and mosquitofish) were much more abundant during the summer than winter collections, which may be a result of high winter die-offs. Although mosquitofish showed a similar trend in the South Sulphur River, red shiners were somewhat weakly in the reverse trend. Juvenile sunfish (shown as *Lepomis* sp. in these tables), Mississippi silvery minnow, and threadfin shad were much more abundant in summer channelized areas of the Sulphur River (Table 5.9). However, over-wintering juvenile sunfish were much more abundant in unchannelized areas of the Sulphur River, probably because cover (LWD), backwaters, and other shallow water protective habitats were more available there (Table 5.10).

In the South Sulphur River, strong seasonal trends were also seen for unchannelized winter occurrences of bluegill, longear sunfish, bullhead minnows, and threadfin shad (Table 5.24). Summer pulses in the occurrence of Mississippi silvery minnows (early June), and smallmouth buffalo and white bass (late-May and mid-June) occurred in unchannelized reaches of the Sulphur River. These pulses may be related to spawning runs in the case of the white bass, and spawning behavior for the Mississippi silvery minnows and smallmouth buffalo. Mississippi silvery minnow pulses occurred during this same period in channelized areas. However, seasonal pulses in channelized areas of the Sulphur River, not seen in the unchannelized areas included mid-June and late-July occurrences of longear sunfish, threadfin shad, mosquitofish, longnose gar, and smallmouth buffalo. Many of these seasonal distributions are subject to interpretation, and additional studies of their life history, food habitats, spawning behaviors, and competitive interactions are necessary for more informed assessments.

5.4.5 Habitat utilization of rare species and fluvial specialists

The 94,252 acres of priority bottomland hardwood forest along the Sulphur River floodplain in the vicinity of the proposed Marvin Nichols I reservoir (USFWS 1985) supports a diverse forest community with abundant wildlife and waterfowl. This large scale community composition is important to the fishery of the Sulphur River, providing many of the conditions that evolved the complexity of this riverine system. The bottomland forest provides the woody structure that forms vast amounts of large woody debris (LWD) which are so important as fishery and macroinvertebrate habitat. Floodplain wetlands are important sources of nutrients that drive the energetics of heavily forested river systems, according to Mitsch and Gosselink (1986). These inputs are primarily through hydrologic pathways that result in the ecosystem function, sources, sinks, leaf litter breakdown, and transformations of chemicals that characterize complex forested river systems. The composition, structure, and diversity of woody vegetation in bottomland hardwood floodplains provide habitat for fish (Wharton et al. 1982).

Fish depend on water level fluctuations to limit intra- and interspecific competition for food, space, and spawning grounds (Lambou 1959). Fish distribution and abundance are known to be keyed to this cyclic phenomenon (Lambou 1959, 1962; Bryan and Sabins 1979; Hern et al. 1980). The link between these water level fluctuations, flow rates, and habitat variability has not been well studied, however, and this study has attempted to provide preliminary information critical to that understanding. Alterations in the flow regime though reservoir construction and operation, agricultural practices, channelization, and other land uses have resulted in the loss of paddlefish, taillight shiner, and orangebelly darter in much of their northeast Texas range (Garrett 2000), all of which now appear to be extirpated from the Sulphur River. Morgan (2000) considers six other fish species found in low abundance in the Sulphur River rare. These species include the alligator gar, shortnose gar, emerald shiner, blackstripe topminnow, pirate perch, and black crappie. In addition, fluvial specialist, such as the freckled madtom and mimic shiner were found in fast-waters and riffle habitat (Morgan 2000; Burgess 2002), which are very limited hydraulic habitats in the Sulphur River system. The focus of the following discussion is on these species that are either fluvial specialist or rare in the Sulphur River.

5.4.5.1 Rare species

Morgan (2000) categorized the six species in the Sulphur River as rare because of their low abundance observed in this study. Some of the reasons that these species are rare in the Sulphur River are natural, having to do with turbidity and siltation tolerance. For instance, the emerald shiner's eggs are non-adhesive, negatively buoyant, and sink to the bottom, which is not a problem in Arkansas where they are one of the most abundant fishes in medium to large rivers with flows over sandy substrates. However, this egg dispersal strategy in the Sulphur River most likely results in many of the eggs being quickly covered with silt, clay, and mud that would suffocate them in a short period of time. Therefore, their low abundance is very predictable. Species that build nests and fan them to keep sediments off of the eggs, have buoyant eggs, or attach eggs to woody structure are more abundant in the Sulphur River. Emerald shiners spawn in Arkansas in late spring through early summer when water temperatures exceed 72º F (Robinson and Buchanan 1988). The small fish feed primarily on algae, and adults shift over to a diet of zooplankton, cladocerans, copepods, and insects. This species primarily utilized riffle habitats with bank snags and secondary utilization in run habitats with channel snags in the unchannelized reach of the mainstem Sulphur River (Tables 5.14 and 5.16) during mid-summer through early winter periods (Table 5.10). None were found in the South Sulphur River.

The blackstripe topminnow is found in low gradient turbid rivers, and eggs are deposited singly on algae, aquatic vegetation, woody structure, or leaf litter. The eggs are not guarded and the nests are not fanned by the parents, which may be the reason this species is rare in the Sulphur River. Silt deposition and accumulation on eggs, and predation on eggs and fry are factors that would select against this species gaining abundance in this river system. This species was found in equal abundance in South Sulphur River pools and backwaters (Tables 5.28) from mid-late Summer (Table 5.27). This species was only found in open backwaters of the unchannelized Sulphur River (Table 5.16) in early August (Table 5.12). In the South Sulphur River its distribution was more diverse, with occurrences in the backwaters and pools of both channelized and unchannelized reaches during the summer (Tables SS1-3).

Black crappie occupy essentially the same habitat as white crappie, but they are less tolerant of turbidity and siltation (Robinson and Buchanan 1988). Therefore, white crappie are more adapted to the high turbidity and silt loads of the Sulphur River, and the low abundance of the black crappie is primarily due to competitive exclusion by white crappie. Black crappie frequent quiet backwaters and pools forming lose schools near LWD during the day, and move to deeper waters at night. They spawn in colonies in quiet waters near cover, primarily LWD, where males construct depressed nest sites in bottom substrates (Hansen 1965) during early spring in Texas, according to Carlander (1977) when the water temperature reaches 64-68º F. Females may spawn with several males and males guard the nest sites. Crappie are an important game fish in northeast Texas. Black crappie were very abundant in the South Sulphur River from March 2nd - April 29th (Table 5.21, 5.27), which is consistent with their reported spawning period. However, those collected from the mainstem of the Sulphur River were all collected in mid-June (Table 5.11, 5.12).

Pirate perch are confined to freshwater and are the only surviving genus and only species of the monotypic (refers to a taxonomic group with only one subgroup at the next smaller taxonomic level; for example, a monotypic genus has only one species) North American family Aphredoderidae (Becker 1983). It is a solitary species inhabiting quiet pools, sluggish mud bottomed rivers and streams, and oxbow lakes with abundant LWD. This species has a strong association with LWD for cover and feeding (Dolloff and Warren 2003). Pflieger (1975), Smith (1979), Boltz and Stauffer (1986) have reported that the eggs of pirate perches are incubated in the female's gill cavities. Ecological principals generally state that high levels of parental care, such as this case of gill incubation, are usually associated with species that are found in low abundance, have high individual survivorship, and are long-lived (Odom 1971). That appears to be the case in the Sulphur River. Pirate perch were exclusively found in the channelized reaches of the mainstem and South Sulphur pools with bank snags (Tables 5.27 and 5.28).

In general, gars do very well in Texas rivers. There are seven living species of this primitive bony fish family, five of which live in the U.S., and four of which are found in Texas. All four species range in northeast Texas rivers, which include the alligator, longnose, shortnose, and spotted gars. The spotted gar was not collected during our contract studies in the Sulphur and South Sulphur Rivers (Gelwick and Morgan 2000; Gelwick and Burgess 2002), and the Fishes of Texas Data Base at the University of Texas Memorial Museum only shows two historical collections of this species in this river system. All the gars are voracious predators on other fishes, and all spawn in a similar pattern. One to several males accompanies each female as they congregate in shallow waters during the breeding season (Robison and Buchanan 1988). Recently hatched gars have larvae that attach themselves to objects, such as LWD or the bottom, by an adhesive structure on their snout (Suttkus 1963). Gars are able to survive in waters that are very low in dissolved oxygen concentration because of a vascularized lung-like air bladder, which supplements gill respiration. Morgan (2002) considered both the alligator and shortnose gars to be rare, based on locally low abundance in the Sulphur River. The alligator gar is the largest species of freshwater fish in Texas, with specimens reported as long as 7.5-feet and weighing as much as 302 pounds, which is the state record taken from the Nueces River. They frequent sluggish pools and backwaters, especially where there is abundant LWD that they use for ambush shelter and camouflage to prey on other fish species. They spawn from April to July in Louisiana (Suttkus 1963), and during May in Oklahoma (May and Echelle 1968), which is the time period that they were collected in the Sulphur River (Table 5.17, 5.18). Shortnose gar are more tolerant of silt and high turbidity than other gars, according to Robison and Buchanan (1988), and are often found in currents over sand substrates and backwaters. They reportedly spawn from May to July in Arkansas when water temperatures range between 66-74º F in shallow backwaters (Robison and Buchanan 1988), which is also when they were collected in the Sulphur River (Table 5.17, 5.18). These gars may be competitively excluded from the Sulphur River by the much more abundant longnose gar, which is probably the most widespread gar in Texas. They are well adapted to sluggish pools and backwaters with LWD, as typified by the Sulphur River mesohabitats. In fact, the state record longnose gar was taken from the Sulphur River in 1997, and was 5.6-feet long and weighed 36.5 pounds based on TPWD records that are available at there website (http://www.tpwd.state.tx.us/fish/infish/records/freshwater/fwunr.htm). Shortnose gar had their peak occurrence during late April in South Sulphur River runs (Tables 5.27 and 5.28), and in the mainstem of the Sulphur River they only utilized run mesohabitats with bank snags (Table 5.12 and 5.16).

5.4.5.2 Fluvial specialists

There are two fluvial specialist in the Sulphur River according to Morgan (2002) and Burgess (2002), which are the freckled madtom and mimic shiner.

The freckled madtom inhabits low to moderate gradient streams of small to moderate size with current over sand and gravel substrates (Robison and Buchanan 1988). They are most frequently found in riffles and flowing pools with accumulated leaf-packs and woody debris. Dolloff and Warren (2003) reported this species has a strong association with large woody habitat in the southeastern U.S. for cover. It may be that this species association to LWD is a function of locating themselves in areas with restricted hydraulic flows that form riffle-like conditions that are not typically visually delineated by biologists. However, from a fish's perspective, they function as a riffle in terms of current, but without the coarse substrates normally found in the riffles of other large river systems. Spawning has been reported in May at water temperatures averaging 77º F, and their nests are located in riffles with reduced flow and some form of protective structure guarded by a single male, according to Robison and Buchanan (1988). This species was almost exclusively found in unchannelized reaches of the South Sulphur River riffles (Tables Tables 5.19, 5.20, 5.25, 5.26) during mid-summer periods (Tables 5.17, 5.18, 5.23, 5.24). In the mainstem of the Sulphur River it was found in riffle mesohabitats with channel snags in the channelized reach (Table 5.13 and 5.15) and primarily in Runs and Riffles in the unchannelized reach (Table 5.14 and 5.16).

The mimic shiner is a schooling minnow in midwater to surface areas of medium to large rivers with current, and their diurnal migrations to and from river margins and deep pools have been noted by Moyle (1973). Black (1945) suggested that this species is a nocturnal spawner, using deep water areas with LWD or dense vegetation as spawning sites. Edwards (1997) reported in a TWDB contract study of the ecological profiles of selected stream-dwelling Texas freshwater fishes that museum collections suggest that spawning occurs in late spring through summer in Texas, with a peak in mid-summer. This species was found primarily in South Sulphur River unchannelized riffles and runs in early November (Tables 5.18 and 5.24), and channelized pools with LWD (Tables 5.19 and 5.25) in August and November (Tables 5.17 and 5.23). Mimic shiner were not collected in the mainstem reaches of the Sulphur River.

Table 5.5 - Absolute abundance of fishes in CHANNELIZED reaches of the Sulphur River by season and by collection period (source data from Gelwick & Morgan 2000)

			Clark Hubbs Seasons			Collection periods									
			Summer	**Winter**		**Summer**						**Winter**			
Species			(April to October)	(Nov. to March)	**Date**	June 17-18, 1999[1]		June 9-10, 1999[1]		July 30-31, 1998[1] June 19, 1999[2]		Mar. 26-27, 1999[1]			
Species with abundance greater than 1% across all collections					**Flow (m^3/s)**	73-127[1]		22-28[1]		6.6[1] and 5.5[2]		603-649[1]			
Scientific Name	**Common Name**	**abundance**			**% Rank**	53.1 - 67.2%[1]		35.8 - 47.2%[1]		20.6%[1]	18.7%[2]	76.2 - 76.8%[1]			
Channelized Sampling Sites Species						a	s	a	s	a	s	a	s	a	s
Cyprinella lutrensis	Red shiner	44	38	6				1	1	37	5	6	1		
Hybognathus nuchalis	Mississippi silvery minnow	2	2					2	2						
Pimephales vigilax	Bullhead minnow	2	2					1	1	1	1				
Gambusia affinis	Mosquitofish	18	16	2				13	1	3	3	2	1		
Lepomis spp.		45	36	9		1	1	1	1	34	4	5	2		
Ictiobus bubalus	Smallmouth buffalo	95	62	33		22	6	19	8	21	3	24	9		
Dorosoma petenense	Threadfin shad	44	43	1				14	5	29	2	1	1		
Lepomis megalotis	Longear sunfish	21	20	1		7	4	13	4			1	1		
Lepomis macrochirus	Bluegill	47	43	4		4	4	34	10	5	1	4	3		
Lepomis humilis	Orangespotted sunfish	22	17	5		8	4	9	3			4	3		
Morone chrysops	White bass	10	10			5	1	5	1						
Lepisosteus osseus	Longnose gar	15	8	7		3	3	4	4	1	1	5	3		
[1]data for sampling sites 1, 2, and 3; [2]data for sampling site 7					**Total Number of Samples**		23		41		20		24		

Table 5.6 –Absolute abundance of fishes in UNCHANNELIZED reaches of the Sulphur River by season and by collection period (source data from Gelwick & Morgan 2000)

			Clark Hubbs Seasons			Collection periods									
			Summer	Winter		Summer						Winter			
Species			(April to October)	(Nov. to March)	Date	May 25, 1999[3] June 16-18, 1998[4]		June 8-9, 1999[3]		August 1-2, 1998[3]		Nov. 22-23, 1998[5]		Jan. 13-14, 1999[3]	
Species with abundance greater than 1% across all collections					Flow (m^3/s)	103[3] and 175-190[4]		30-38[3]		6.4		788-928[5]		205-278[3]	
Scientific Name	Common Name	abundance			% Rank	57.4%[3] 64.6%[4]		39.8 - 42.8%[3]		20.3%[3]		78.9 - 79.9%[5]		66.2 - 66.8%[3]	
Unchannelized Sampling Sites Species						a	s	a	s	a	s	a	s	a	s
Cyprinella lutrensis	Red shiner	1663	808	855		237	11	232	6	339	339	66	2	262	6
Hybognathus nuchalis	Mississippi silvery minnow	354	266	88		3	1	139	4	124	124			23	7
Pimephales vigilax	Bullhead minnow	153	27	126		3	1	2	1	22	22	9	1	2	2
Gambusia affinis	Mosquitofish	131	81	50		6	2	41	4	34	34	38	1	11	2
Lepomis spp.		84	53	31		6	4			47	47	19	1	12	3
Ictiobus bubalus	Smallmouth buffalo	12	10	2		2	2	6	3	2	2			1	1
Dorosoma petenense	Threadfin shad	30	16	14		1	1			15	15	1	1	13	1
Lepomis megalotis	Longear sunfish	51	31	20		6	3	25	6			7	2	2	1
Lepomis macrochirus	Bluegill	25	9	16		3	2	6	2					16	2
Lepomis humilis	Orangespotted sunfish	43	28	15		10	5	18	5			7	2	8	3
Morone chrysops	White bass	27	8	19		4	1			4	4	1	1	2	2
Lepisosteus osseus	Longnose gar	22	18	4		11	6	3	3	4	4	3	3	1	1
[3]data for sampling sites 4 and 6; [4]data for sampling site 5; [5]data for sampling sites 4 and 5					Total Number of Samples		39		34		591		14		31
Note: a = absolute abundance and s = number of samples															

Table 5.7 – Absolute abundance of rare fish species in CHANNELIZED reaches of the Sulphur River by season and by collection period (source data from Gelwick & Morgan 2000)

			Clark Hubbs Seasons			**Collection periods**									
			Summer	**Winter**		**Summer**						**Winter**			
Species			(April to October)	(Nov. to March)	**Date**	June 17-18, 1999[1]		June 9-10, 1999[1]		July 30-31, 1998[1] June 19, 1999[2]		Mar. 26-27, 1999[1]			
Species with abundance greater than 1% across all collections					**Flow (m^3/s)**	73-127[1]		22-28[1]		6.6[1] and 5.5[2]		603-649[1]			
Scientific Name	**Common Name**	**abundance**			**% Rank**	53.1 - 67.2%[1]		35.8 - 47.2%[1]		20.6%[1]	18.7%[2]	76.2 - 76.8%[1]			
Channelized Sampling Sites Species						a	s	a	s	a	s	a	s	a	s
Atractosteus spatula	Alligator gar	1	1			1	1								
Lepisosteus platostomus	Shortnose gar	0													
Notropis atherinoides	Emerald shiner	0													
Noturus nocturnus	Freckled madtom	1	1							1	1				
Fundulus notatus	Blackstripe topminnow	0													
Labidesthes sicculus	Brook silverside	11	11							11	1				
Aphredoderus sayanus	Pirate perch	0													
Pomoxis nigromaculatus	Black crappie	1	1	1		1	1								
[1]data for sampling sites 1, 2, and 3; [2]data for sampling site 7			**Total Number of Samples**				2				2				

Table 5.8 – Absolute abundance of rare fish species in UNCHANNELIZED reaches of the Sulphur River by season and by collection period (source data from Gelwick & Morgan 2000)

			Clark Hubbs Seasons			Collection periods									
			Summer	Winter		Summer						Winter			
Species					Date	May 25, 1999[3] June 16-18, 1998[4]		June 8-9, 1999[3]		August 1-2, 1998[3]		Nov. 22-23, 1998[5]		Jan. 13-14, 1999[3]	
Species with abundance greater than 1% across all collections					Flow (m^3/s)	103[3] and 175-190[4]		30-38[3]		6.4		788-928[5]		205-278[3]	
Scientific Name	Common Name	abundance			% Rank	57.4%[3] 64.6%[4]		39.8 - 42.8%[3]		20.3%[3]		78.9 - 79.9%[5]		66.2 - 66.8%[3]	
Unchannelized Sampling Sites Species						a	s	a	s	a	s	a	s	a	s
Atractosteus spatula	Alligator gar	0													
Lepisosteus platostomus	Shortnose gar	2	2			2	1								
Notropis atherinoides	Emerald shiner	3	1	2						1	1			2	2
Noturus nocturnus	Freckled madtom	5	5					1	1	4	3				
Fundulus notatus	Blackstripe topminnow	2	2							2	1				
Labidesthes sicculus	Brook silverside	0													
Aphredoderus sayanus	Pirate perch	1	1					1	1						
Pomoxis nigromaculatus	Black crappie	1		1										1	1
[3]data for sampling sites 4 and 6; [4]data for sampling site 5; [5]data for sampling sites 4 and 5					Total Number of Samples		1		2		5				3
Note: a = absolute abundance and s = number of samples															

Table 5.9 - Relative standardized abundance of fish species in CHANNELIZED reaches of the Sulphur River by season and by collection period (Source data from Gelwick and Morgan 2000)

			Clark Hubbs Seasons		**Collection periods**					
			Summer	**Winter**		**Summer**			**Winter**	
Species			(April to October)	(Nov. to March)	**Date**	June 17-18, 1999[1]	June 9-10, 1999[1]	July 30-31, 1998[1] June 19, 1999[2]	Mar. 26-27, 1999[1]	
Species with abundance greater than 1% across all collections					**Flow (m^3/s)**	73-127[1]	22-28[1]	6.6[1] and 5.5[2]	603-649[1]	
Scientific Name	**Common Name**	**Relative Standardized Abundance**			**% Rank**	53.1 - 67.2%[1]	35.8 - 47.2%[1]	20.6%[1] 18.7%[2]	76.2 - 76.8%[1]	
Channelized Samples Species						**Relative Standard Abundance**				
Cyprinella lutrensis	Red shiner	0.19157	54.61%	45.39%			0.51%	54.10%	45.39%	
Hybognathus nuchalis	Mississippi silvery minnow	0.0052083	100.00%				**100.00%**			
Pimephales vigilax	Bullhead minnow	0.043617	100.00%				6.42%	**93.58%**		
Gambusia affinis	Mosquitofish	0.094073	69.19%	30.81%			59.82%	9.37%	30.81%	
Lepomis spp.		0.53445	97.10%	2.90%		1.20%	6.93%	**88.97%**	2.90%	
Ictiobus bubalus	Smallmouth buffalo	0.095334	83.31%	16.69%		18.19%	7.91%	**57.22%**	16.69%	
Dorosoma petenense	Threadfin shad	0.11342	83.67%	16.33%			8.36%	**75.32%**	16.33%	
Lepomis megalotis	Longear sunfish	0.054332	98.16%	1.84%		13.61%	**84.55%**		1.84%	
Lepomis macrochirus	Bluegill	0.10046	96.95%	3.05%		**62.21%**	18.94%	15.80%	3.05%	
Lepomis humilis	Orangespotted sunfish	0.045989	93.65%	6.35%		18.38%	**75.27%**		6.35%	
Morone chrysops	White bass	0.42767	100.00%			**77.94%**	22.06%			
Lepisosteus osseus	Longnose gar	1.0282	99.55%	0.45%		1.72%	0.58%	**97.26%**	0.45%	
[1]data for sampling sites 1, 2, and 3; [2]data for sampling site 7										

Table 5.10 – Relative standardized abundance of fish species in UNCHANNELIZED reaches of the Sulphur River by season and by collection period (Source data from Gelwick and Morgan 2000)

			Clark Hubbs Seasons		**Collection periods**					
			Summer	**Winter**		**Summer**			**Winter**	
Species					**Date**	May 25, 1999[3] June 16-18, 1998[4]	June 8-9, 1999[3]	Aug. 1-2, 1998[3]	Nov. 22-23, 1998[5]	Jan. 13-14, 1999[3]
Species with abundance greater than 1% across all collections					**Flow (m^3/s)**	103[3] 175-190[4]	30-38[3]	6.4	788-928[5]	205-278[3]
Scientific Name	**Common Name**	**Relative Standardized Abundance**			**% Rank**	57.4%[3] 64.6%[4]	39.8 - 42.8%[3]	20.3%[3]	78.9 - 79.9%[5]	66.2 - 66.8%[3]
Unchannelized Samples Species						**Relative Standard Abundance**				
Cyprinella lutrensis	Red shiner	2.2627	51.70%	48.30%		9.09%	23.57%	19.04%	15.68%	32.62%
Hybognathus nuchalis	Mississippi silvery minnow	1.0047	97.32%	2.68%		1.04%	**79.98%**	16.31%		2.68%
Pimephales vigilax	Bullhead minnow	2.3488	3.72%	96.29%		0.44%	1.70%	1.57%	**95.79%**	0.49%
Gambusia affinis	Mosquitofish	10.166	2.95%	97.05%		0.09%	2.33%	0.53%	93.45%	3.61%
Lepomis spp.		4.9236	2.86%	97.14%		0.16%		2.70%	**96.47%**	0.67%
Ictiobus bubalus	Smallmouth buffalo	0.28131	82.23%	17.77%		**71.10%**	7.18%	3.95%		17.77%
Dorosoma petenense	Threadfin shad	1.2705	29.16%	70.84%		15.74%		13.42%	19.68%	**51.16%**
Lepomis megalotis	Longear sunfish	0.30201	21.31%	78.69%		2.67%	18.64%		12.46%	**66.22%**
Lepomis macrochirus	Bluegill	0.58668	9.09%	90.91%		1.68%	7.41%			**90.91%**
Lepomis humilis	Orangespotted sunfish	0.11151	43.62%	56.38%		8.68%	34.94%		16.52%	39.86%
Morone chrysops	White bass	0.84971	64.69%	35.31%		**52.31%**		12.39%	29.42%	5.88%
Lepisosteus osseus	Longnose gar	0.10698	86.85%	13.15%		25.45%	46.74%	14.66%	10.27%	2.88%

[3]data for sampling sites 4 and 6; [4]data for sampling site 5; [5]data for sampling sites 4 and 5

Table 5.11 - Relative standardized abundance of rare fish species in CHANNELIZED reaches of the Sulphur River by season and by collection period (source data from Gelwick & Morgan 2000)

			Clark Hubbs Seasons		Collection periods					
			Summer	Winter		Summer			Winter	
Species			(April to October)	(Nov. to March)	Date	June 17-18, 1999[1]	June 9-10, 1999[1]	July 30-31, 1998[1] June 19, 1999[2]	Mar. 26-27, 1999[1]	
Species with abundance greater than 1% across all collections					Flow (m^3/s)	73-127[1]	22-28[1]	6.6[1] and 5.5[2]	603-649[1]	
Scientific Name	**Common Name**	**Relative Standardized Abundance**			% Rank	53.1 - 67.2%[1]	35.8 - 47.2%[1]	20.6%[1] 18.7%[2]	76.2 - 76.8%[1]	
Channelized Samples Species						**Relative Standard Abundance**				
Atractosteus spatula	Alligator gar	0.066667	100.00%			**100.00%**				
Lepisosteus platostomus	Shortnose gar	0								
Notropis atherinoides	Emerald shiner	0								
Noturus nocturnus	Freckled madtom	0.22222	100.00%					**100.00%**		
Fundulus notatus	Blackstripe topminnow	0								
Labidesthes sicculus	Brook silverside	0.034921	100.00%					**100.00%**		
Aphredoderus sayanus	Pirate perch	0								
Pomoxis nigromaculatus	Black crappie	0.0064103	100.00%			**100.00%**				

[1]data for sampling sites 1, 2, and 3; [2]data for sampling site 7

Table 5.12 – Relative standardized abundance of rare fish species in UNCHANNELIZED reaches of the Sulphur River by season and by collection period (source data from Gelwick & Morgan 2000)

			Clark Hubbs Seasons		Collection periods					
			Summer	**Winter**		**Summer**			**Winter**	
Species					**Date**	May 25, 1999[3] June 16-18, 1998[4]	June 8-9, 1999[3]	Aug. 1-2, 1998[3]	Nov. 22-23, 1998[5]	Jan. 13-14, 1999[3]
Species with abundance greater than 1% across all collections					**Flow (m^3/s)**	103[3] 175-190[4]	30-38[3]	6.4	788-928[5]	205-278[3]
Scientific Name	**Common Name**	**Relative Standardized Abundance**			**% Rank**	57.4%[3] 64.6%[4]	39.8 - 42.8%[3]	20.3%[3]	78.9 - 79.9%[5]	66.2 - 66.8%[3]
Unchannelized Sampling Sites Species						**Relative Standard Abundance**				
Atractosteus spatula	Alligator gar	0								
Lepisosteus platostomus	Shortnose gar	0.22222	100.00%			**100.00%**				
Notropis atherinoides	Emerald shiner	0.070833	29.41%	70.59%				29.41%		**70.59%**
Noturus nocturnus	Freckled madtom	0.038349	100.00%				52.15%	47.85%		
Fundulus notatus	Blackstripe topminnow	0.022727	100.00%					**100.00%**		
Labidesthes sicculus	Brook silverside	0								
Aphredoderus sayanus	Pirate perch	0.0086957	100.00%				**100.00%**			
Pomoxis nigromaculatus	Black crappie	0.1		100.00%						**100.00%**

[3]data for sampling sites 4 and 6; [4]data for sampling site 5; [5]data for sampling sites 4 and 5

Table 5.13 – Absolute abundance of fishes in CHANNELIZED reaches of the Sulphur River by mesohabitat
(source data from Gelwick and Morgan 2000)

Species			**Mesohabitat**																															
Species with abundance greater than 1% across all collections			**Backwater**		**Backwater**		**Backwater**		**Backwater**		**Pool**		**Pool**		**Pool**		**Pool**		**Run**		**Run**		**Run**		**Run**		**Riffle**		**Riffle**		**Riffle**		**Riffle**	
Scientific Name	**Common Name**	**abundance**	Open Water		Edge		Bank Snag		Channel Snag		Open Water		Edge		Bank Snag		Channel Snag		Open Water		Edge		Bank Snag		Channel Snag		Open Water		Edge		Bank Snag		Channel Snag	
Channelized Sampling Sites Species			a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s
Cyprinella lutrensis	Red shiner	44			6	3	1	1					10	1					6	1													21	1
Hybognathus nuchalis	Mississippi silvery minnow	2	1	1	1	1																												
Pimephales vigilax	Bullhead minnow	2			2	2																												
Gambusia affinis	Mosquitofish	18			2	2							1	1			13	1	2	1														
Lepomis spp.		45	1	1	30	2	3	2	2	1			3	2			3	2	3	1														
Ictiobus bubalus	Smallmouth buffalo	95	3	1	18	5	5	2			19	4	21	9	21	4	4	3					2	1									2	1
Dorosoma petenense	Threadfin shad	44			31	3	4	1					4	2			4	1											1	1				
Lepomis megalotis	Longear sunfish	21	8	1	3	2	4	1					1	1			5	4																
Lepomis macrochirus	Bluegill	47	22	1	6	5	3	3	1	1			9	4			6	4																
Lepomis humilis	Orangespotted sunfish	22	7	1	2	1	4	2	1	1			2	2			4	3	2	1														
Morone chrysops	White bass	10					5	1							5	1																		
Lepisosteus osseus	Longnose gar	15	1	1	2	2	1	1	1	1	3	3	2	1	2	1	2	2											1	1				
Rare Species																																		
Atractosteus spatula	Alligator gar	1													1	1																		
Lepisosteus platostomus	Shortnose gar	0																																
Notropis atherinoides	Emerald shiner	0																																
Noturus nocturnus	Freckled madtom	1																															1	1
Fundulus notatus	Blackstripe topminnow	0																																
Labidesthes sicculus	Brook silverside	11											11	1																				
Aphredoderus sayanus	Pirate perch	0																																
Pomoxis nigromaculatus	Black crappie	2									1	1					1	1																
Total Number of Samples				7		28		14		4		8		24		7		21		4				1						2				3
Percent of Samples Collected in each Habitat			5.69%		22.76%		11.38%		3.25%		6.50%		19.51%		5.69%		17.07%		3.25%				0.81%						1.63%				2.44%	
Note: a = absolute abundance and s = number of samples																																		

Table 5.14 – Absolute abundance of fishes in UNCHANNELIZED reaches of the Sulphur River by mesohabitat
(source data from Gelwick and Morgan 2000)

Species			**Mesohabitat**																															
Species with abundance greater than 1% across all collection			**Backwater**		**Backwater**		**Backwater**		**Backwater**		**Pool**		**Pool**		**Pool**		**Pool**		**Run**		**Run**		**Run**		**Run**		**Riffle**		**Riffle**		**Riffle**		**Riffle**	
Scientific Name	**Common Name**	**abundance**	Open Water		Edge		Bank Snag		Channel Snag		Open Water		Edge		Bank Snag		Channel Snag		Open Water		Edge		Bank Snag		Channel Snag		Open Water		Edge		Bank Snag		Channel Snag	
Unchannelized Sampling Sites Species			a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s	a	s
Cyprinella lutrensis	Red shiner	1663	52	3	106	2			1	1	4	1	137	3	8	3	13	4			150	5	77	3	273	3	365	2	11	2	212	1	254	5
Hybognathus nuchalis	Mississippi silvery minnow	354	70	3	93	2			1	1	1	1	15	4	55	3	48	3			29	3			12	2	16	3	6	1	3	1	5	2
Pimephales vigilax	Bullhead minnow	153	11	2									3	1	3	1	5	2			3	2	9	1	79	2	39	2			1	1		
Gambusia affinis	Mosquitofish	131	31	3	7	2							4	2	14	1					24	1	38	1			6	1			4	1	3	3
Lepomis spp.		84	38	2	1	1							3	1	2	1							19	1			1	1	2	2	10	1	8	3
Ictiobus bubalus	Smallmouth buffalo	12	1	1	5	3					1	1			2	2	2	1							1	1								
Dorosoma petenense	Threadfin shad	30	15	1																			1	1	1	1					13	1		
Lepomis megalotis	Longear sunfish	51	2	1			2	1	2	1			10	4	11	3	5	2			11	2	2	1	2	1	4	1						
Lepomis macrochirus	Bluegill	25	15	1									4	2	5	2															1	1		
Lepomis humilis	Orangespotted sunfish	43	12	2	5	2							8	3	9	2	2	1			3	3							3	1	1	1		
Morone chrysops	White bass	27									14	1	2	2	1	1							5	2							1	1	4	1
Lepisosteus osseus	Longnose gar	22	1	1									2	2	3	3	3	3					6	3	1	1	2	2	3	1			1	1
Rare Species																																		
Atractosteus spatula	Alligator gar	0																																
Lepisosteus platostomus	Shortnose gar	2																					2	1										
Notropis atherinoides	Emerald shiner	13											1	1	1	1	2	1							4	1	3	1	1	1	1	1		
Noturus nocturnus	Freckled madtom	6	1	1																	1	1			1	1							3	2
Fundulus notatus	Blackstripe topminnow	2	2	1																														
Labidesthes sicculus	Brook silverside	0																																
Aphredoderus sayanus	Pirate perch	1															1	1																
Pomoxis nigromaculatus	Black crappie	2	1	1													1	1																
Total Number of Samples				23		12		1		3		4		25		23		19				17		14		13		13		8		10		17
Percent of Samples Collected in each Habitat			11.39%		5.94%		0.50%		1.49%		1.98%		12.38%		11.39%		9.41%				8.42%		6.93%		6.44%		6.44%		3.96%		4.95%		8.42%	
Note: a = absolute abundance and s = number of samples																																		

Table 5.15 – Standardized abundance of fishes in CHANNELIZED reaches of the Sulphur River by mesohabitat
(source data from Gelwick & Morgan 2000)

Species			Mesohabitat															
Species with abundance greater than 1% across all collections			**Backwater**	**Backwater**	**Backwater**	**Backwater**	**Pool**	**Pool**	**Pool**	**Pool**	**Run**	**Run**	**Run**	**Run**	**Riffle**	**Riffle**	**Riffle**	**Riffle**
Scientific Name	**Common Name**	**abundance**	Open Water	Edge	Bank Snag	Channel Snag	Open Water	Edge	Bank Snag	Channel Snag	Open Water	Edge	Bank Snag	Channel Snag	Open Water	Edge	Bank Snag	Channel Snag
Channelized Sampling Sites Species			**Relative Standard Abundance**															
Cyprinella lutrensis	Red shiner	1.1765		0.23%	0.71%			0.13%			7.39%							**91.54%**
Hybognathus nuchalis	Mississippi silvery minnow	0.0099775	**95.45%**	4.55%														
Pimephales vigilax	Bullhead minnow	0.00090734		**100.00%**														
Gambusia affinis	Mosquitofish	0.051765		1.75%				0.29%		41.96%	55.99%							
Lepomis spp.		0.10412	9.15%	13.07%	24.06%	6.72%		0.44%		4.81%	41.76%							
Ictiobus bubalus	Smallmouth buffalo	0.62621	4.56%	1.30%	6.67%		10.99%	0.51%	52.60%	1.07%			5.91%					16.38%
Dorosoma petenense	Threadfin shad	0.073275		19.19%	45.59%			0.83%		9.12%						25.27%		
Lepomis megalotis	Longear sunfish	0.11946	**63.78%**	1.14%	27.96%			0.13%		6.99%								
Lepomis macrochirus	Bluegill	0.25218	**83.08%**	1.08%	9.93%	1.39%		0.54%		3.98%								
Lepomis humilis	Orangespotted sunfish	0.14045	47.47%	0.65%	23.78%	2.49%		0.22%		4.76%	20.64%							
Morone chrysops	White bass	0.12019			34.74%				65.26%									
Lepisosteus osseus	Longnose gar	0.086684	10.99%	1.05%	9.63%	4.03%	12.54%	0.35%	36.19%	3.86%						21.36%		
Rare Species																		
Atractosteus spatula	Alligator gar	0.015686							100.00%									
Lepisosteus platostomus	Shortnose gar	0																
Notropis atherinoides	Emerald shiner	0																
Noturus nocturnus	Freckled madtom	0.051282																100.00%
Fundulus notatus	Blackstripe topminnow	0																
Labidesthes sicculus	Brook silverside	0.0016672						100.00%										
Aphredoderus sayanus	Pirate perch	0																
Pomoxis nigromaculatus	Black crappie	0.005294					68.44%			31.56%								

Table 5.16 – Standardized abundance of fishes in UNCHANNELIZED reaches of the Sulphur River by mesohabitat
(source data from Gelwick & Morgan 2000)

Species			**Mesohabitat**															
Species with abundance greater than 1% across all collections			**Backwater**	**Backwater**	**Backwater**	**Backwater**	**Pool**	**Pool**	**Pool**	**Pool**	**Run**	**Run**	**Run**	**Run**	**Riffle**	**Riffle**	**Riffle**	**Riffle**
Scientific Name	**Common Name**	**abundance**	Open Water	Edge	Bank Snag	Channel Snag	Open Water	Edge	Bank Snag	Channel Snag	Open Water	Edge	Bank Snag	Channel Snag	Open Water	Edge	Bank Snag	Channel Snag
Unchannelized Sampling Sites Species																		
Cyprinella lutrensis	Red shiner	14.921	1.94%	1.33%		0.12%	0.19%	0.55%	0.16%	0.19%		1.74%	5.32%	8.86%	3.38%	0.47%	**71.04%**	4.72%
Hybognathus nuchalis	Mississippi silvery minnow	1.1999	32.41%	14.47%		1.49%	0.58%	0.74%	13.91%	8.67%		4.18%		4.84%	1.84%	3.21%	12.50%	1.15%
Pimephales vigilax	Bullhead minnow	0.66731	9.16%					0.27%	1.36%	1.62%		0.78%	13.90%	**57.33%**	8.08%		7.49%	
Gambusia affinis	Mosquitofish	0.88004	19.57%	1.49%				0.27%	4.83%			4.72%	44.52%		0.94%		22.73%	0.94%
Lepomis spp.		0.95307	22.15%	0.20%				0.19%	0.64%				20.55%		0.15%	1.35%	52.46%	2.33%
Ictiobus bubalus	Smallmouth buffalo	0.037083	14.98%	25.18%			18.73%		16.37%	11.69%				13.06%				
Dorosoma petenense	Threadfin shad	0.74849	11.13%										1.38%	0.65%			**86.84%**	
Lepomis megalotis	Longear sunfish	0.27685	4.01%		45.15%	12.90%		2.14%	12.06%	3.91%		6.87%	7.45%	3.50%	2.00%			
Lepomis macrochirus	Bluegill	0.15088	55.23%					1.57%	10.06%								33.14%	
Lepomis humilis	Orangespotted sunfish	0.18682	35.68%	5.00%				2.54%	14.62%	2.32%		2.78%				10.29%	26.76%	
Morone chrysops	White bass	0.21407					45.42%	0.55%	1.42%				24.08%				23.36%	5.18%
Lepisosteus osseus	Longnose gar	0.11381	4.88%					1.04%	8.00%	5.71%			54.35%	4.25%	2.43%	16.90%		2.43%
Rare Species																		
Atractosteus spatula	Alligator gar	0																
Lepisosteus platostomus	Shortnose gar	0.020619											**100.00%**					
Notropis atherinoides	Emerald shiner	0.087893						0.68%	3.45%	4.93%				22.04%	4.72%	7.29%	56.89%	
Noturus nocturnus	Freckled madtom	0.020439	27.18%									8.46%		23.69%				40.66%
Fundulus notatus	Blackstripe topminnow	0.011111	**100.00%**															
Labidesthes sicculus	Brook silverside	0																
Aphredoderus sayanus	Pirate perch	0.0030349							**100.00%**									
Pomoxis nigromaculatus	Black crappie	0.0077224	**71.94%**							28.06%								

Table 5.17 – Absolute abundance of fishes in CHANNELIZED reaches of the South Sulphur River by season and by collection period (Source data from Gelwick and Burgess 2002)

			Clark Hubbs Seasons			Collection periods											
			Summer	Winter		Summer						Winter					
Species			(April to October)	(Nov. to March)	Date	May 18-20, 2002		July 9-10, 2002		August 6-7, 2001		April 28-29, 2002		March 2-3, 2002		Nov. 10, 2001	
Species with abundance greater than 1% across all collections					Flow (m^3/s)	232		17		4.8		358		80		6.8	
Scientific Name	**Common Name**	**abundance**			% Rank	70.2%		32.1%		17.8%		71.6%		53.9%		20.9%	
Channelized Samples Species						a	s	a	s	a	s	a	s	a	s	a	s
Lepisosteus osseus	longnose gar	86	80	6		69	3	9	3	2	2			2	2	4	1
Dorosoma cepedianum	gizzard shad	74	73	1		2	1	43	3	28	2	1	1				
Dorosoma petense	threadfin shad	82	0	82								69	1			13	3
Cyprinella luternsis	red shiner	1359	451	908				234	4	217	3	371	1	425	3	112	2
Lythrurus umbratilis	redfin shiner	0	0	0													
Notropis buchananai	ghost shiner	233	117	116				33	3	84	3	1	1			115	3
Notropis volucellus	mimic shiner	310	97	213						97	1					213	2
Pimephales vigilax	bulhead minnow	436	411	25				251	3	160	3	2	1	1	1	22	3
Noturus nocturnus	freckled madtom	1	1	0						1	1						
Gambusia affinis	western mosquitofish	465	400	65				151	4	249	3	3	1	11	3	51	3
Lepomis cyanellus	green sunfish	159	143	16				47	4	96	3	13	1	2	1	1	1
Lepomis humilis	orangespotted sunfish	202	174	28				162	4	12	2	2	1			26	2
Lepomis macrochirus	bluegill	218	182	36				32	3	150	3	27	1	4	3	5	2
Lepomis megalotis	longear sunfish	60	41	19				18	4	23	3	4	1			15	2
Lepomis	sp.	134	121	13				99	4	22	3					13	2
Pomoxis annularis	white crappie	26	11	15				6	3	5	3	13	1	2	1		
data is for sampling sites 4, 5, and 6			**Total Number of Samples**				3		4		3		3		4		3
Note: a = absolute abundance and s = number of samples																	

Table 5.18 – Absolute abundance of fishes in UNCHANNELIZED reaches of the South Sulphur River by season and by collection period (Source data from Gelwick and Burgess 2002)

			Clark Hubbs Seasons			Collection periods											
			Summer	Winter		Summer						Winter					
Species					Date	May 18, 2002		July 9, 2002		Aug. 4, 2002		Apr. 28, 2002		Mar. 1, 2002		Nov. 10, 2001	
Species with abundance greater than 1% across all collections					Flow (m^3/s)	192		0.37		5.6		362		N/A		8.0	
Scientific Name	**Common Name**	**abundance**			% Rank	65.3%		4.4%		32.1%		71.7%		N/A		22.1%	
Unchannelized Samples Species						a	s	a	s	a	s	a	s	a	s	a	s
Lepisosteus osseus	longnose gar	18	13	5		12	2			1	1	3	3			2	2
Dorosoma cepedianum	gizzard shad	19	7	12		4	2	2	2	1	1	2	1	10	2		
Dorosoma petense	threadfin shad	226	2	224		2	2					224	6				
Cyprinella luternsis	red shiner	3793	2665	1128		470	2	1969	8	226	6	343	6	280	7	505	9
Lythrurus umbratilis	redfin shiner	126	116	10						116	5					10	2
Notropis buchananai	ghost shiner	1	1	0		1	1										
Notropis volucellus	mimic shiner	131	131	0						131	2						
Pimephales vigilax	bulhead minnow	650	587	63		28	4	379	8	180	9	19	4	24	3	20	5
Noturus nocturnus	freckled madtom	94	87	7		1	1	70	4	16	2					7	1
Gambusia affinis	western mosquitofish	776	675	101		21	4	474	8	180	9	6	2	1	1	94	6
Lepomis cyanellus	green sunfish	89	66	23		21	3	8	3	37	7	21	5	2	1		
Lepomis humilis	orangespotted sunfish	1	1	0				1	1								
Lepomis macrochirus	bluegill	138	99	39		21	4	8	5	70	7	17	5	11	5	11	4
Lepomis megalotis	longear sunfish	119	93	26		18	4	64	7	11	6	18	4	6	3	2	2
Lepomis	sp.	140	140	0				133	6	7	3						
Pomoxis annularis	white crappie	92	3	89				1	1	2	1	72	6	17	5		
data is for sampling sites 1, 2, and 3					**Total Number of Samples**		5		8		9		7		10		9
Note: a = absolute abundance and s = number of samples																	

Table 5.19 – Absolute abundance of fishes in CHANNELIZED reaches of the South Sulphur River by mesohabitat (source data form Gelwick and Burgess 2002)

Species			Mesohabitat							
Species with abundance greater than 1% across all collections			Backwater		Pool		Riffle		Run	
Scientific Name	**Common Name**	**abundance**								
Channelized Samples Species			a	s	a	s	a	s	a	s
Lepisosteus osseus	longnose gar	86	5	2	11	5	1	1	69	3
Dorosoma cepedianum	gizzard shad	74	17	2	54	3			3	2
Dorosoma petense	threadfin shad	82			13	3			69	1
Cyprinella luternsis	red shiner	1359	215	2	487	8	286	3	371	1
Lythrurus umbratilis	redfin shiner	0								
Notropis buchananai	ghost shiner	233	9	2	223	7			1	1
Notropis volucellus	mimic shiner	310			310	3				
Pimephales vigilax	bulhead minnow	436	230	2	203	7	1	1	2	1
Noturus nocturnus	freckled madtom	1			1	1				
Gambusia affinis	western mosquitofish	465	114	2	334	8	14	3	3	1
Lepomis cyanellus	green sunfish	159	30	2	108	6	8	1	13	1
Lepomis humilis	orangespotted sunfish	202	142	2	57	5	1	1	2	1
Lepomis macrochirus	bluegill	218	28	2	161	7	2	2	27	1
Lepomis megalotis	longear sunfish	60	7	2	46	6	3	1	4	1
Lepomis	sp.	134	93	2	40	6	1	1		
Pomoxis annularis	white crappie	26	1	1	7	4	5	2	13	1
Total Number of Samples				2		8		4		6
Percent of Samples Collected in each Habitat			10.00%		40.00%		20.00%		30.00%	
Note: a = absolute abundance and s = number of samples										

Table 5.20 – Absolute abundance of fishes in UNCHANNELIZED reaches of the South Sulphur River by mesohabitat (source data form Gelwick and Burgess 2002)

Species			**Mesohabitat**							
Species with abundance greater than 1% across all collections			**Backwater**		**Pool**		**Riffle**		**Run**	
Scientific Name	**Common Name**	**abundance**								
Unchannelized Samples Species			a	s	a	s	a	s	a	s
Lepisosteus osseus	longnose gar	18			3	3			15	5
Dorosoma cepedianum	gizzard shad	19	1	1	5	3			13	4
Dorosoma petense	threadfin shad	226	3	1					223	6
Cyprinella luternsis	red shiner	3793	112	6	1314	12	957	8	1405	15
Lythrurus umbratilis	redfin shiner	126			64	4	22	2	40	1
Notropis buchananai	ghost shiner	1							1	1
Notropis volucellus	mimic shiner	131					47	1	84	1
Pimephales vigilax	bulhead minnow	650	41	6	313	7	101	7	195	13
Noturus nocturnus	freckled madtom	94			1	1	87	4	6	4
Gambusia affinis	western mosquitofish	776	32	3	505	12	134	5	105	9
Lepomis cyanellus	green sunfish	89	6	2	23	4	6	2	54	12
Lepomis humilis	orangespotted sunfish	1			1	1	10	2		
Lepomis macrochirus	bluegill	138	46	7	30	9	1	1	52	12
Lepomis megalotis	longear sunfish	119	7	3	65	8	8	3	39	12
Lepomis	sp.	140	14	2	112	4	3	1	11	2
Pomoxis annularis	white crappie	92	12	3	3	1			77	9
Total Number of Samples				8		12		10		18
Percent of Samples Collected in each Habitat			16.67%		25.00%		20.83%		37.50%	
Note: a = absolute abundance and s = number of samples										

Table 5.21 – Absolute abundance of rare fish species in all reaches of the South Sulphur River by season and by collection period (source data from Gelwick and Burgess 2002)

			Clark Hubbs Seasons			Collection periods											
			Summer	Winter		Summer						Winter					
Species			(April to October)	(Nov. to March)	**Date**	May 18-20, 2002		July 9-10, 2002		August 6-7, 2001		April 28-29, 2002		March 2-3, 2002		Nov. 10, 2001	
Endangered Species					**Flow (m^3/s)**	232		17		4.8		358		80		6.8	
Scientific Name	**Common Name**	**abundance**			**% Rank**	70.2%		32.1%		17.8%		71.6%		53.9%		20.9%	
Channelized Samples Species						a	s	a	s	a	s	a	s	a	s	a	s
Lepisosteus platostomus	shortnose gar	4	2	2				1	1	1	1	2	1				
Aphredoderus sayanus	pirate perch	16	15	1				3	3	12	2			1	1		
Fundulus notatus	blackstripe topminnow	8	6	2				3	1	3	1			2	1		
Pomoxis nigromaculatus	black crappie	1	0	1										1	1		
data is for sampling sites 4, 5, and 6			**Total Number of Samples**				3		4		3		3		4		3
Note: a = absolute abundance and s = number of samples																	

			Clark Hubbs Seasons			Collection periods											
			Summer	Winter		Summer						Winter					
Species					**Date**	May 18, 2002		July 9, 2002		Aug. 4, 2002		Apr. 28, 2002		Mar. 1, 2002		Nov. 10, 2001	
Endangered Species					**Flow (m^3/s)**	192		0.37		5.6		362		N/A		8.0	
Scientific Name	**Common Name**	**abundance**			**% Rank**	65.3%		4.4%		32.1%		71.7%		N/A		22.1%	
Unchannelized Samples Species						a	s	a	s	a	s	a	s	a	s	a	s
Lepisosteus platostomus	shortnose gar	2	1	1		1	1					1	1				
Aphredoderus sayanus	pirate perch	2	2	0						2	1						
Fundulus notatus	blackstripe topminnow	8	8	0				1	1	7	4						
Pomoxis nigromaculatus	black crappie	7	0	7								5	2	2	1		
data is for sampling sites 1, 2, and 3			**Total Number of Samples**				5		8		9		7		10		9
Note: a = absolute abundance and s = number of samples																	

Table 5.22 – Absolute abundance of rare fish species in all reaches of the south Sulphur River by mesohabitat (source data from Gelwick and Burgess 2002)

Species			Mesohabitat							
Endangered Species			Backwater		Pool		Riffle		Run	
Scientific Name	**Common Name**	**abundance**								
Channelized Samples Species			a	s	a	s	a	s	a	s
Lepisosteus platostomus	shortnose gar	4	1	1	1	1			2	1
Aphredoderus sayanus	pirate perch	16	1	1	13	3	2	2		
Fundulus notatus	blackstripe topminnow	8	3	1	5	2				
Pomoxis nigromaculatus	black crappie	1					1	1		
Total Number of Samples				2		8		4		6
Percent of Samples Collected in each Habitat			10.00%		40.00%		20.00%		30.00%	
Unchannelized Samples Species			a	s	a	s	a	s	a	s
Lepisosteus platostomus	shortnose gar	2							2	1
Aphredoderus sayanus	pirate perch	2			2	1				
Fundulus notatus	blackstripe topminnow	8	5	2	3	3				
Pomoxis nigromaculatus	black crappie	7							7	3
Total Number of Samples				8		12		10		18
Percent of Samples Collected in each Habitat			16.67%		25.00%		20.83%		37.50%	
Note: a = absolute abundance and s = number of samples										

Table 5.23 – Standardized abundance of fishes in CHANNELIZED reaches of the South Sulphur River by season and by collection period (source data from Gelwick and Burgess 2002)

			Clark Hubbs Seasons			**Collection periods**					
			Summer	**Winter**		**Summer**			**Winter**		
Species			(April to October)	(Nov. to March)	**Date**	May 18-20, 2002	July 9-10, 2002	August 6-7, 2001	April 28-29, 2002	March 2-3, 2002	Nov. 10, 2001
Species with abundance greater than 1% across all collections					**Flow (m^3/s)**	232	17	4.8	358	80	6.8
Scientific Name	**Common Name**	**Relative Standardized Abundance**			**Percentile Rank**	70.2%	32.1%	17.8%	71.6%	53.9%	20.9%
Channelized Samples Species						**Relative Standardized Abundance**					
Lepisosteus osseus	longnose gar	1.0313	98.70%	1.30%		**96.96%**	1.36%	0.37%		0.46%	0.84%
Dorosoma cepedianum	gizzard shad	0.1368	98.05%	1.95%		21.19%	**48.96%**	27.89%	1.95%		
Dorosoma petense	threadfin shad	0.2128		100.00%					**86.69%**		13.31%
Cyprinella luternsis	red shiner	3.0468	26.76%	73.24%			15.59%	11.17%	32.56%	32.67%	8.01%
Lythrurus umbratilis	redfin shiner										
Notropis buchananai	ghost shiner	0.4710	39.83%	53.57%			10.91%	28.98%	0.57%		**53.20%**
Notropis volucellus	mimic shiner	0.7072	34.38%	65.62%				34.38%			**65.62%**
Pimephales vigilax	bulhead minnow	0.7080	92.15%	7.85%			**55.22%**	36.93%	0.75%	0.33%	6.77%
Noturus nocturnus	freckled madtom	0.0014	100.00%					**100.00%**			
Gambusia affinis	western mosquitofish	0.9166	84.21%	15.79%			35.72%	**48.49%**	0.87%	2.79%	12.12%
Lepomis cyanellus	green sunfish	0.3945	89.41%	10.59%			**55.96%**	33.45%	0.88%	1.22%	0.55%
Lepomis humilis	orangespotted sunfish	0.3491	82.24%	17.76%			**77.56%**	4.68%	1.53%		15.94%
Lepomis macrochirus	bluegill	0.3719	75.12%	24.88%			13.40%	**61.72%**	19.41%	2.54%	2.93%
Lepomis megalotis	longear sunfish	0.1638	73.52%	26.48%			**50.89%**	22.62%	6.53%		19.95%
Lepomis	sp.	0.2378	88.09%	11.91%			**72.60%**	15.49%			11.91%
Pomoxis annularis	white crappie	0.1120	64.85%	35.15%			**57.74%**	7.10%	31.04%	4.11%	
data is for sampling sites 4, 5, and 6											

Table 5.24 – Standardized abundance of fishes in UNCHANNELIZED reaches of the South Sulphur River by season and by collection period (source data from Gelwick and Burgess 2002)

			Clark Hubbs Seasons			**Collection periods**					
			Summer	**Winter**		**Summer**			**Winter**		
Species					**Date**	May 18, 2002	Jul. 9, 2002	Aug. 4, 2002	Apr. 28, 2002	Mar. 1, 2002	Nov. 10, 2001
Species with abundance greater than 1% across all collections					**Flow (m^3/s)**	192	0.37	5.6	362	N/A	8.0
Scientific Name	**Common Name**	**Relative Standardized Abundance**			**Percentile Rank**	65.3%	4.4%	32.1%	71.7%	N/A	22.1%
Unchannelized Samples Species						**Relative Standardized Abundance**					
Lepisosteus osseus	longnose gar	0.0595	61.17%	38.82%		**54.92%**		6.24%	24.90%		13.93%
Dorosoma cepedianum	gizzard shad	0.0813	30.75%	69.24%		13.24%	12.00%	5.48%	10.74%	**58.51%**	
Dorosoma petense	threadfin shad	1.1398	2.43%	97.57%		2.43%			**97.57%**		
Cyprinella luternsis	red shiner	44.6654	42.16%	57.84%		3.72%	31.00%	7.44%	23.96%	13.98%	19.90%
Lythrurus umbratilis	redfin shiner	1.3486	96.95%	3.05%				**96.95%**			3.05%
Notropis buchananai	ghost shiner	0.0036	100.00%			**100.00%**					
Notropis volucellus	mimic shiner	2.3987	100.00%					**100.00%**			
Pimephales vigilax	bulhead minnow	6.5329	81.33%	18.67%		1.66%	36.53%	43.14%	1.40%	13.39%	3.87%
Noturus nocturnus	freckled madtom	0.9518	85.29%	14.71%		0.29%	**67.00%**	18.00%			14.71%
Gambusia affinis	western mosquitofish	6.7993	71.37%	28.63%		1.11%	29.91%	**40.35%**	0.34%	0.09%	28.20%
Lepomis cyanellus	green sunfish	0.6387	68.64%	31.36%		9.24%	4.35%	**55.06%**	15.05%	16.31%	
Lepomis humilis	orangespotted sunfish	0.0028	100.00%				**100.00%**				
Lepomis macrochirus	bluegill	1.8228	64.66%	35.34%		4.76%	1.76%	**58.15%**	5.06%	16.27%	14.01%
Lepomis megalotis	longear sunfish	0.6285	75.48%	24.52%		20.96%	**36.59%**	17.93%	13.01%	5.61%	5.90%
Lepomis	sp.	0.6850	100.00%				**81.88%**	18.12%			
Pomoxis annularis	white crappie	1.0499	5.42%	94.58%			0.66%	4.76%	**80.36%**	14.21%	
data is for sampling sites 1, 2, and 3											

Table 5.25 - Standardized abundance of fishes in CHANNELIZED reaches of the South Sulphur River by mesohabitat (source data from Gelwick and Burgess 2002)

Species			Mesohabitat			
Species with abundance greater than 1% across all collections			**Backwater**	**Pool**	**Riffle**	**Run**
Scientific Name	**Common Name**	**Relative Standardized Abundance**				
Channelized Samples Species			**Relative Standardized Abundance**			
Lepisosteus osseus	longnose gar	1.03130	0.76%	2.06%	0.22%	**96.96%**
Dorosoma cepedianum	gizzard shad	0.13678	19.36%	**57.50%**		23.15%
Dorosoma petense	threadfin shad	0.21281		13.31%	0.00%	**86.69%**
Cyprinella luternsis	red shiner	3.04678	10.99%	31.34%	25.11%	32.56%
Lythrurus umbratilis	redfin shiner					
Notropis buchananai	ghost shiner	0.47095	2.98%	**90.05%**		0.57%
Notropis volucellus	mimic shiner	0.70716		**100.00%**		
Pimephales vigilax	bulhead minnow	0.70800	50.60%	48.32%	0.33%	0.76%
Noturus nocturnus	freckled madtom	0.00136		**100.00%**		
Gambusia affinis	western mosquitofish	0.91658	19.37%	**66.58%**	13.17%	0.88%
Lepomis cyanellus	green sunfish	0.39445	11.85%	38.78%	40.56%	8.81%
Lepomis humilis	orangespotted sunfish	0.34912	**63.35%**	29.38%	5.73%	1.53%
Lepomis macrochirus	bluegill	0.37189	11.73%	**67.62%**	1.24%	19.41%
Lepomis megalotis	longear sunfish	0.16379	6.65%	**50.18%**	36.63%	6.53%
Lepomis	sp.	0.23780	**60.92%**	30.68%	8.41%	0.00%
Pomoxis annularis	white crappie	0.11200	1.39%	9.89%	**57.22%**	31.04%

Table 5.26 - Standardized abundance of fishes in UNCHANNELIZED reaches of the South Sulphur River by mesohabitat (source data from Gelwick and Burgess 2002)

Species			**Mesohabitat**			
Species with abundance greater than 1% across all collections			**Backwater**	**Pool**	**Riffle**	**Run**
Scientific Name	**Common Name**	**Relative Standardized Abundance**				
Unchannelized Samples Species			**Relative Standardized Abundance**			
Lepisosteus osseus	longnose gar	0.0595		20.18%		**79.82%**
Dorosoma cepedianum	gizzard shad	0.0813	8.54%	31.46%		**60.01%**
Dorosoma petense	threadfin shad	1.1398	13.16%			**86.84%**
Cyprinella luternsis	red shiner	44.6654	9.48%	12.58%	43.22%	34.72%
Lythrurus umbratilis	redfin shiner	1.3486		18.60%	24.36%	**57.04%**
Notropis buchananai	ghost shiner	0.0036				**100.00%**
Notropis volucellus	mimic shiner	2.3987			32.66%	**67.34%**
Pimephales vigilax	bulhead minnow	6.5329	19.55%	12.65%	25.11%	**42.69%**
Noturus nocturnus	freckled madtom	0.9518		0.32%	**89.23%**	10.45%
Gambusia affinis	western mosquitofish	6.7993	7.87%	**41.69%**	30.47%	19.97%
Lepomis cyanellus	green sunfish	0.6387	18.80%	13.67%	13.67%	**53.87%**
Lepomis humilis	orangespotted sunfish	0.0028		**100.00%**		
Lepomis macrochirus	bluegill	1.8228	**59.26%**	11.48%	8.91%	20.36%
Lepomis megalotis	longear sunfish	0.6285	11.62%	33.79%	14.55%	40.04%
Lepomis	sp.	0.6850	24.74%	38.23%	5.41%	31.63%
Pomoxis annularis	white crappie	1.0499	**59.00%**	1.74%		39.26%

Table 5.27 – Relative standardized abundance of rare fish species in all reaches of the South Sulphur River by season and collection period (source data from Gelwick and Burgess 2002)

			Clark Hubbs Seasons			**Collection periods**					
			Summer	**Winter**		**Summer**			**Winter**		
Species			(April to October)	(Nov. to March)	**Date**	May 18-20, 2002	July 9-10, 2002	August 6-7, 2001	April 28-29, 2002	March 2-3, 2002	Nov. 11, 2001
Rare Species					**Flow (m^3/s)**	232	17	4.8	358	80	6.8
Scientific Name	**Common Name**	**Relative Standardized Abundance**			**Percentile Rank**	70.2%	32.1%	17.8%	71.6%	53.9%	20.9%
Channelized Samples Species						**Relative Standardized Abundance**					
Lepisosteus platostomus	shortnose gar	0.031905	9.15%	90.85%			4.88%	4.27%	90.85%		
Aphredoderus sayanus	pirate perch	0.041768	94.48%	5.52%			55.34%	39.14%		5.52%	
Fundulus notatus	blackstripe topminnow	0.013591	64.45%	35.54%			34.38%	30.07%		35.54%	
Pomoxis nigromaculatus	black crappie	0.002304		100.00%						100.00%	
data is for sampling sites 4, 5, and 6											
					Date	May, 18 2002	July, 9 2002	August, 4	Apr. 28, 2002	Mar. 1, 2002	Nov. 10, 2001
					Flow (m^3/s)	192	0.37	5.6	362	N/A	8.0
					Percentile Rank	65.3%	4.4%	32.1%	71.7%	N/A	22.1%
Unchannelized Samples Species						**Relative Standardized Abundance**					
Lepisosteus platostomus	shortnose gar	0.006893	38.78%	61.21%		38.78%			61.21%		
Aphredoderus sayanus	pirate perch	0.008928	100.00%					100.00%			
Fundulus notatus	blackstripe topminnow	0.052285	100.00%				5.81%	94.19%			
Pomoxis nigromaculatus	black crappie	0.041533		100.00%					49.31%	50.69%	
data is for sampling sites 1, 2, and 3											

Table 5.28 – Standardized abundance of rare species in all reaches of the South Sulphur River by mesohabitat
(Source data from Gelwick and Burgess 2002)

Species			**Mesohabitat**			
Rare Species			**Backwater**	**Pool**	**Riffle**	**Run**
Scientific Name	**Common Name**	**Relative Standardized Abundance**				
Channelized Samples Species			**Relative Standardized Abundance**			
Lepisosteus platostomus	shortnose gar	0.031905	4.88%	4.27%		90.85%
Aphredoderus sayanus	pirate perch	0.041768	3.73%	42.87%	53.40%	
Fundulus notatus	blackstripe topminnow	0.013591	34.38%	65.62%		
Pomoxis nigromaculatus	black crappie	0.002304			100.00%	
Unchannelized Samples Species			**Relative Standardized Abundance**			
Lepisosteus platostomus	shortnose gar	0.006893				100.00%
Aphredoderus sayanus	pirate perch	0.008928		100.00%		
Fundulus notatus	blackstripe topminnow	0.052285	78.54%	21.46%		
Pomoxis nigromaculatus	black crappie	0.041533				100.00%

6. Periodic flood plain inundation

Both terrestrial and aquatic species benefit from periodic inundation and nutrient exchange caused by floodwater. Proposed water development projects that have the potential to alter the flow regime also have the potential to alter the inundation frequency of low-lying flood-prone areas. Since native species could be affected by such an alteration to their regime, an analysis of inundation extent has been performed to quantify the flooded area for typically recurring floods.

6.1 Value of Sulphur River flood plain habitat to fisheries

Text in this section was excerpted from text prepared for TWDB by Dr. Gary Grossman (University of Georgia) and Dr. Fran Gelwick (Texas A&M University). The text was edited by the authors for continuity.

> The Texas Water Development Board recognizes that there are important habitats for Sulphur River fish populations that were not sampled in the aquatic studies completed during our contract studies with Texas A&M University, Department of Fisheries and Wildlife Science. In particular, the seasonally-flooded, bottomland hardwood forest areas probably represent ecologically significant fish habitat. Many studies have shown that similar bottomlands provide important ecological services to riverine ecosystems including: (1) sources for organic matter for biological production within rivers (Sparks 1995; Anderson et al. 1998; Wissmar & Beschta 1998; Ward et al. 1998; Schramm et al. 2000), (2) areas of increased prey availability for foraging fishes (O'Connell 2003), (3) nursery areas for fishes including families of species (e.g., cyprinidae, centrarchidae, cyprinodontidae) found in the Sulphur River (Finger & Stewart 1987; Brown & Coon 1994; Turner et al. 1994; Fontenot et al. 2001), (4) habitat associated with reproductive success and maintenance of high population size for some fishes (Ross & Baker 1983); and (5) corridors for genetic flow and recolonization for species inhabiting backwater and floodplain habitats (Scheerer 2002). The significant ecological roles that these bottomlands probably play can be maintained if a natural to semi-natural flow regime can be maintained during high flow periods.
>
> The Sulphur River has been channelized in the downstream reaches of the North and South Forks, as well as several kilometers of the main stem reach below the confluence and above the road crossing of SH 37. The channelized reaches are straight and highly incised, and some were leveed for additional flood protection. The channelized/leveed reaches do not have adjacent functional bottomland hardwood forest due to the lack of overbanking flows that previously supported that forest community. In the unchannelized reaches of the Sulphur River, the river is characterized by considerable meandering and riparian bottomland hardwood forest communities.

In general, an abundance of fishes that use, exploit, or breed on floodplains is not expected; however, fish do move about during overbanking flood flows and occupy floodplain habitats for various periods of time. Fishes present in recent 1999 to 2002 TAMU samples on the Sulphur River are discussed below in terms of potential floodplain function to these species. Some fish "require" shallow, sluggish backwaters that are available within the river channel. Fishes that would use those types of riverine habitats, may also use floodplain habitats (sloughs, oxbows, backwaters) when the floodplain is inundated. Many of these fishes probably did use the floodplain extensively before channelization, but are now mostly found in headwaters or lake shorelines (e.g., sunfishes, suckers, topminnows, mosquitofish, some minnows), or are no longer present in such numbers to be likely found opportunistically in the main stem river.

Another consideration is that many fish species that use floodplain habitats stay there throughout the summer to feed and repeatedly reproduce then move back into the river on the fall flood pulse (e.g., *Lepomis* sunfishes, crappie, and largemouth bass). Croplands behind levees that flood and then dewater through large storm drains, may support fishes that require only a few days for their eggs to develop when temperatures are right (e.g., weed shiners, which were not present in TAMU samples, and golden shiners which were present in TAMU samples). These fishes may occur in floodplain habitats as adults that spawn, and as larval fishes that hatched on the floodplain, at least some of which might return to the river rather quickly.

However, once in the river, habitat for young-of-the-year (yoy) fishes is rather scarce until later in summer low discharge, due to channelization and levee construction, and as evidenced in our study that backwater habitats were somewhat rare in our survey area. Also, fishes like bowfin, which nest in vegetation and have adults that attend to their yoy for weeks, and gar, which have young that are attached to vegetation or detritus until the yolk sac is used up, would not likely have time to fully develop to a self-sufficient stage before water drained from floodplain.

The following fishes were collected during TAMU studies, and are known to use floodplain habitats or similar habitats within the shallow, sluggish portion of river channels: (1) gars (alligator, spotted, longnose, shortnose), which spawn in shallow sluggish water in spring, so ideal habitat would be floodplain backwaters, and young attach to vegetation or other objects after hatching for a while; (2) shads (gizzard, threadfin) broadcast adhesive eggs in shallow water; (3) smallmouth, bigmouth, black buffalo fishes do use shallow floodplain habitats naturally for breeding, but obviously can do well with access to shallow shoreline habitats.

Topminnows, mosquitofish, silversides (*Fundulus notatus, Gambusia affinis* and *Labidesthes sicculus*) are all early succession, opportunist species that exploit floodplain habitats following rises in river water stage to feed and breed (their eggs are adherent to detritus and vegetation not commonly found in the river). Pirate perch likely brood eggs in their brachial pouch, and are very night active on floodplains. Sunfishes (largemouth bass, *Lepomis* sunfishes, especially *L. marginatus, L. macrochirus*, and crappies) but of course these need extended flooding and parental care of nests and young.

Species that might be found in the smaller upstream system that are less associated with floods, but use backwater, slough habitats maintained by flood flows, and that should be studied in future floodplain utilization assessments include bluntnose and slough darters (*Etheostoma chlorosomum, E. gracile)*, and some shiners (e.g., weed shiner).

Future studies should consider fishery surveys of intermittent tributary streams during high water along the South Sulphur and main stem of the Sulphur River to look for use by fishes that refuge from fast flows, and use them as access to floodplain habitats for feeding and spawning. At present, we don't know the fate of any fishes that might use the old South Sulphur channel when discharge and runoff conditions allow access across the diversion dam below Hwy 19.

6.2 Value of Sulphur River flood plain habitat, bottomland hardwood forest and riparian zone

The ecological aspects of riverine flood plains in the southeastern U.S. are often segregated into definitive units that include riparian forest, bottomland hardwood forest, and wetlands, which have been a focus of state and federal agency study and concern for many years (Wharton et al. 1982, U.S. Fish and Wildlife Service 1985, Liu et al. 1997, and Terry et al. 1998). Ecological relationships functioning in flood plain systems are based on geomorphological and hydrological processes in concert with the biota that they support to form the structure and function of bottomland hardwood forest ecosystems. These forests and their fauna comprise remarkably productive riverine communities adapted to fluctuating river systems in the southeastern U.S. (Odum 1969). The bottomland hardwood communities support distinct assemblages of plants and animals that are associated with particular landforms, soils and hydrologic regimes. Because flood plains occupied by bottomland hardwoods are transitional in the aquatic continuum between permanent water and terrestrial uplands, they are difficult to classify (Wharton et al. 1998); however, the ecological importance of these areas has been identified by the U.S. Fish and Wildlife Service (1982) and the Texas Agricultural Extension Service (Terry et al. 1998).

The following 3 sections detail recent projects in and around the Sulphur River basin and are illustrative of the value of the Sulphur River ecosystem and its many habitats. Unless indicated otherwise, all statements in each subsection are referenced from the citation given in the subsection heading.

6.2.1 U.S. Fish and Wildlife Service (1985)

The U.S. Fish and Wildlife Service (USFWS, 1985) identified as being priority BHF 94,252 acres along the Sulphur River west of Wright Patman Lake. This designation was part of an effort to identify and protect Texas bottomlands through a survey of BHF sites in Texas and Oklahoma and recommendations of wildlife biologists. A system of prioritizing these sites was developed, which included criteria for evaluating each site in terms of its (1) hydrological regime, (2) habitat diversity and quality, (3) waterfowl utilization and production, (4) degree and imminence of threats, and (5) presence of federal endangered or threatened species and State species of special concern. The ratings ranged from the highest Priority 1 sites to the lowest Priority 6 sites. They categorized the area that would include Marvin Nichols I reservoir as a Priority I site, while that for George Parkhouse I site was categorized as a Priority 4 site.

6.2.2 Texas Water Development Board/Texas Parks and Wildlife Department (Liu et al. 1997)

In 1997, the Texas Water Development Board (TWDB) in a joint effort with the Texas Parks and Wildlife Department (TPWD) initiated studies of three bottomland hardwood forest ecosystems. The study sites in this project were the two proposed reservoir sites on the Sulphur River (Marvin Nichols I and George Parkhouse I) and the proposed New Bonham reservoir on a tributary to the Red River. The four forest types identified were: 1) bottomland hardwood forest, 2) bottomland hardwood swamp, 3) secondary bottomland hardwood forest, and 4) willow-sugarberry forest (The latter forest type is considered as a forested wetland according to Frye and Curtis, 1990). Bottomland hardwood forests form within the first or second terraces of floodplains and flats along river channels. Bottomland hardwood forest species commonly occurring in the Sulphur River basin include water oak, willow oak, blackgum, American elm, overcup oak, green ash, deciduous holly, sugarberry, boxelder, and American hornbeam. Periodic inundation prevents the establishment of upland species and maintains the functioning of bottomland hardwood forest systems. Frequent flooding at the Marvin Nichols I site favors bottomland hardwood swamp species such as blackgum, willow, green ash, river birch, willow oak, and American hornbeam. The presence of water resistant species (water oak, birch, and American elm), frequent flooding, and water-logging conditions was said to characterize the bottomland hardwood swamp type .. The species composition of the secondary bottomland hardwood forests is similar to the bottomland hardwood forests, is successional toward bottomland hardwood forests, but is less diverse and composed of much younger trees. As succession proceeds, the differences between these forest types may become indistinguishable. Lastly, the willow-sugarberry forests occur in narrow bands along the river and creek channels, depressed areas, and at the confluence of lakes and creeks. Wetlands such as these are critical to the survival of a wide variety of plants and animals.

Their studies quantified the area of direct impact of the three proposed reservoirs on bottomland forests for the TWDB to consider in water planning. From this study, it was concluded that about twice as much acreage of bottomland hardwood forests would be lost to Marvin Nichols I reservoir than to the George Parkhouse I and New Bonham sites combined. However, substantial agricultural land would be lost at the George Parkhouse I site (11,734 acres), while there would be less of an agricultural land loss at the Marvin Nichols I site (10,688 acres).

The Marvin Nichols I site has the largest spatial extent, covering 91,380 acres at the estimated maximum pool elevation (See Table 6.3) and 67,957 acres at the estimated mean pool elevation. Of the area flooded at mean pool elevation, 38% (25,900 acres) would consist of bottomland hardwood forest, with an additional 15% (10,278 acres) would consist of bottomland hardwood swamp. Although agricultural practices have impacted the bottomland hardwood forests in this area, frequent flooding has prevented further development within this forest type. High quality bottomland hardwood forests were reported along the main channel, with the average riparian width at about 2.5 miles, in contrast to about 1.3 miles at the George Parkhouse I site. It was also reported that the quality of bottomland hardwood forests at the George Parkhouse I site is not as good as at the Marvin Nichols I site due in part to existing alterations of the hydrology by Lake Jim Chapman (formerly Cooper Lake, a U.S. Army Corps of Engineers flood control reservoir) and fragmentation of the forest cover by farmland and pastures.

The contract report (Liu et al. 1997) is included at the end of this document as Appendix T.

6.2.3 Norris and Linam (2000) & Others

In order to further assist the TWDB and the Northeast Texas Regional Water Planning Group-D, the TPWD prepared a document on ecologically significant river and stream segments, which includes a section on the Sulphur River. The TPWD recommended the Sulphur River west of Wright Patman Lake in Bowie, Cass, and Morris Counties as an ecologically significant river system for consideration by the Northeast Texas Regional Water Planning Area-D. They reported that the river segment's favorable hydrologic regime with numerous sloughs and frequent flooding enhances the value of the habitat to waterfowl, white-tailed dear, furbearers (including beaver and river otters), squirrels, and numerous migratory birds such as nesting American redstarts, Cerulean warblers, and Kentucky warblers. This section of the Sulphur River is also within the target recovery area set by the TPWD for the state threatened paddlefish feeding habitat (Pitman 1991 and 1992, TPWD 1998). The candidate segment for paddlefish feeding habitat is from a point 0.9 miles downstream of Bassett Creek in Bowie/Cass County upstream to IH 30 in Bowie/Morris County.

6.3 Development of a flood plain inundation model

To investigate the impact of flow regime change on areas within the Sulphur River flood plain, a rough analysis of the flood inundation extent was performed. Inundation areas were determined for six frequently occurring flood events. This section presents the sources of data and the development of six floods whose water surfaces extend across the Sulphur River basin.

6.3.1 Spatial data sources

Time-series and spatial data was used to establish quantitative measures of connectivity between the river and the important flood plain areas. Data sources used in this analysis are described below.

Public domain Geographical Information Systems (GIS) data provided base topographic information for the crude flood plain determination. Gridded topographic data in the form of 7.5 minute (1:24,000) Digital Elevation Models (DEMs) are available from the Texas Natural Resources Information Systems (TNRIS) with a grid spacing of 30 meters. The horizontal projection of the original USGS source data was NAD83 inside an appropriate UTM zone in meters; however, the dataset obtained from TNRIS for this analysis was in geographic coordinates on the NAD83 datum (GCS_NorthAmerican_NAD83). The vertical projection was NGVD29 in either feet or meters, and the reported vertical accuracy varies from 0.10 to 1.0 meters.

Flood elevation and flow rate data are collected at stream and lake gauging stations maintained by the United States Geological Survey (USGS). These data are publically-available from the USGS website (www.usgs.gov) and were used as the basis for estimating flood surface elevations. USGS gauging stations from which data was derived are tabulated in Table 6.1. Water level data obtained from TWDB-installed water level loggers were also used in determining elevations at Site 1 and Site 2.

Table 6.1 - USGS Gauging stations from which flood elevation data was derived.

Gauge No.	Description	Published Datum	
		NGVD29 (ft)	NGVD29 (m)
07343000	North Sulphur River near Cooper, TX	372.42	113.514
07342500	South Sulphur River near Cooper, TX	371.91	113.358
07343200	Sulphur River near Talco, TX	275.48	83.966
07343500	White Oak Creek near Talco, TX	286.45	87.310
07344200	Wright Patman Lake near Texarkana, TX	0	0

Gridded vegetation data generated by the Texas Parks and Wildlife Department (TPWD) under contract with the Texas Water Development Board (TWDB) was used to determine vegetation types that are inundated for six floods. Using satellite imagery and color infrared aerial photography, along with field data collection, TPWD quantified nine distinct vegetation types in the Sulphur River basin (Liu et al. 1997, included as Appendix T). That study identified the area of each vegetation type that would be lost beneath the proposed New Bonham, George Parkhouse I (Table 6.2) and Marvin Nichols I (Table 6.3) reservoir projects. The vegetation grid generated by Liu et al. (1997) for each project was sufficiently large to include the proposed George Parkhouse II reservoir, the North, South and main stem Sulphur River channel areas downstream of those projects to the headwaters of the proposed Nichols I reservoir, and the Sulphur River channel downstream of Nichols I to its confluence with White Oak Creek. Sufficient coverage also existed to perform the same inundation analysis for the formerly proposed Marvin Nichols II reservoir site area and the channel of White Oak Creek between the USGS White Oak Creek near Talco gauge and the Creek's confluence with the Sulphur River.

Table 6.2– Extent of flooded vegetation due to the proposed George Parkhouse I Reservoir (from Liu et al., 1997)

Table 2 Summary of Land Cover Types in the Flooded Areas of Proposed George Parkhouse I Reservoir

No.	Cover Type	Mean Pool Level (401 ft.)			Maximum Pool Level (406 ft.)		
		hectare	acre	%	hectare	acre	%
1	Water	335.9	830.1	2.8	874.0	2159.5	6.5
2	Bottomland Hardwood	3817.7	9433.5	32.3	3851.6	9517.2	28.8
3	Secondary Bottomland Hardwood	792.7	1958.7	6.7	811.0	2004.0	6.1
4	Oak-Hickory	924.4	2284.0	7.8	1199.1	2963.0	9.0
5	Cedar-Hardwood/Pine-Hardwood	65.2	161.0	0.6	90.3	223.1	0.7
6	Pure Cedar/Pine	3.0	7.4	0.0	3.2	7.9	0.0
7	Grassland	4748.9	11734.3	40.2	5417.3	13385.9	40.5
8	Crop/Managed Grassland	1073.9	2653.7	9.1	1075.6	2657.7	8.0
9	Bare Soil/Ground	47.7	117.9	0.4	49.6	122.6	0.4
	Total	11809.4	29180.6	100.0	13371.6	33040.8	100.0

Table 6.3 Extent of flooded vegetation due to the proposed Marvin Nichols I Reservoir (from Liu et al., 1997)

Table 3 Summary of Land Cover Types in the Flooded Areas of Proposed Marvin Nichols I Reservoir

No.	Cover Type	Mean Pool Level (312 ft.)			Maximum Pool Level (322.5 ft.)		
		hectare	acre	%	hectare	acre	%
1	Water	661.2	1633.9	2.4	899.9	2223.6	2.4
2	Bottomland Hardwood	10481.7	25899.9	38.1	12301.7	30397.1	33.3
3	Bottomland Hardwood Swamp	4159.4	10277.6	15.1	4255.8	10515.8	11.5
4	Oak-Hickory	6802.7	16809.3	24.7	10327.2	25518.1	27.9
5	Cedar-Hardwood/Pine-Hardwood	1020.3	2521.1	3.7	1771.0	4376.0	4.8
6	Pure Pine/Cedar	49.6	122.4	0.2	89.3	220.7	0.2
7	Grassland	4325.4	10687.9	15.7	7333.0	18119.6	19.8
8	Crops/Managed Grassland	1.7	4.1	0.0	2.9	7.3	0.0
9	Bare Soil/Ground	0.4	1.0	0.0	1.0	2.5	0.0
	Total	27502.3	67957.3	100.0	36981.8	91380.7	100.0

The TPWD data were converted from Albers Conical Equal Area projection (datum NAD83) to geographic coordinates for this analysis (GCS_NorthAmerican_NAD83). The geographic coordinate system adopted as standard for this project was not the ideal coordinate system for spatial analysis; however, to minimize the effect of interpolating elevation data to a new grid in a different coordinate system, the original topographic surface dataset in the original coordinate system was used.

6.3.2 Determining inundated areas

Hydraulic modeling was not conducted in determining flood surfaces for this project. With the gridded DEM topographic data was available at a horizontal resolution of 30 meters and with vertical accuracy varying between 1.0 and 0.10 vertical meters, the marginal quality of input cross-sections generated from DEM topographic data would preclude verification of hydraulic model output. Additionally, the channel width measured on-site at Site 1 and Site 2 was roughly 30m, the same as the grid resolution; cross-sections generated from 30m DEM data cannot properly resolve the Sulphur River channel, so channel conveyance cannot be properly modeled. Aside from this point is the fact that the larger flood events presented herein are not constrained within the channel, but rather extend across the flood plain. For these reasons, hydraulic flood modeling was not performed for this preliminary analysis; rather, the flood surface was derived from a hypothetical steady-state flood surface that was linearly interpolated between data points with measured stage elevations.

Stage elevation was derived for seven locations within the Sulphur River drainage between Lake Wright Patman (downstream) and Cooper, TX (upstream). Figure 6.1

shows the locations of available flood stage data in the basin. Six flow events were chosen based upon flood peaks recorded at the USGS gauging station on the Sulphur River near Talco, TX. The flood peaks were chosen from the Talco data set because of the simple correlation to flood peaks observed in TWDB level meter data at Site 1 and Site 2 (Figure 6.2). These measured peaks also represented a spectrum of flood flows at the Talco gauge, ranging from 10.25 cms to 906.14 cms, which represents a percentile rank in flow between 68.4 and 99.7 for the historical record at Talco ("cms" is shorthand for m^3/s). This range includes flows that were completely contained within the channel at both Sites 1 and 2 (10.25 cms), flows that were observed to crest the banks at Site 2 (24.41 cms), and high flows that inundate significant portions of the flood plain (84.95 cms, 201.90 cms, 518.20 cms, and 906.14 cms).

Concurrent stage data was available for all seven sites for the period from January to April, 2002; however, the spatial variability of rainfall events resulted in non-uniform stream flow peaks across the basin. For example, occurrence of a flood peak at the South Sulphur River gauge near Cooper, TX does not necessarily correspond to a flood peak occurring at either the North Sulphur River near Cooper or at White Oak Creek near Talco, TX gauges.

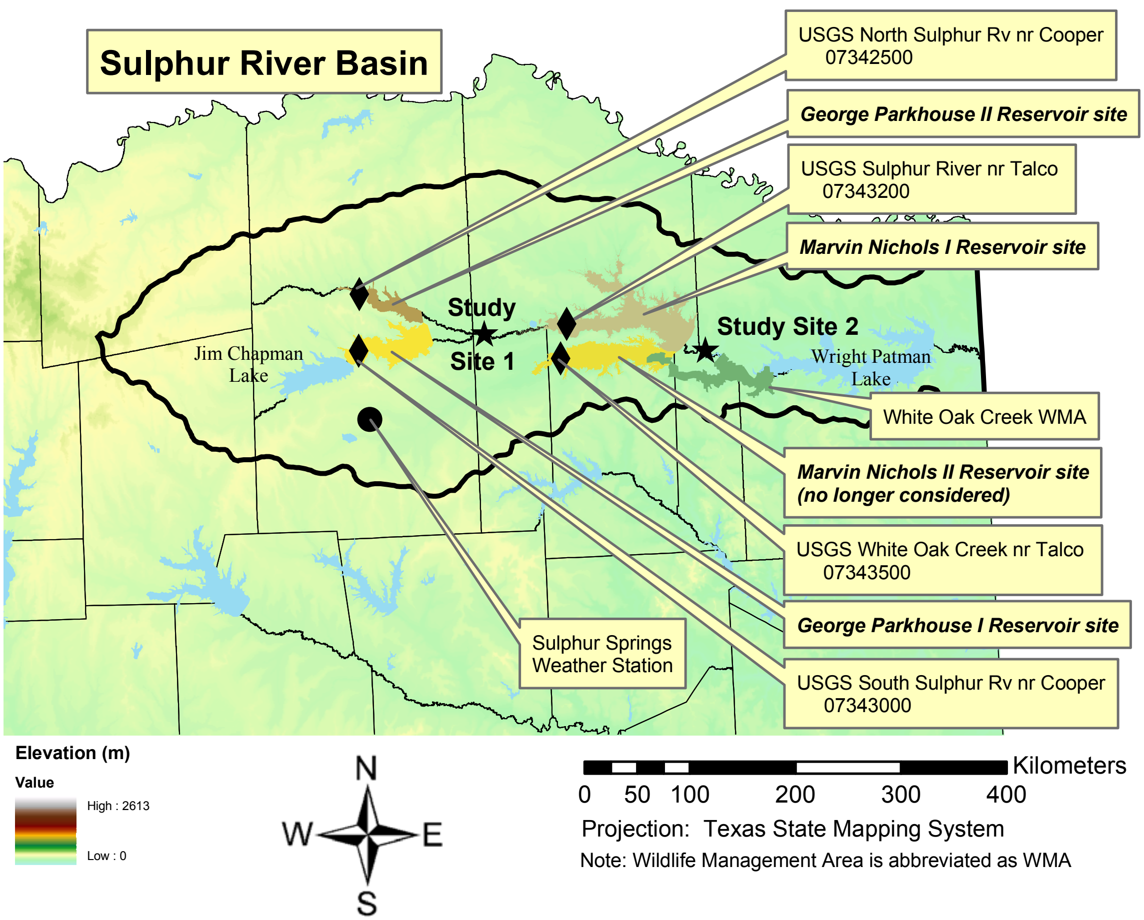

Figure 6.1– Sulphur River Basin, points of interest and river gauging stations.

To address basin-wide hydrologic variability, the stage elevations at the North Sulphur River near Cooper, South Sulphur River near Cooper, White Oak Creek near Talco gauges were estimated from historical flow statistics. At Site 1 (at two locations, one at the upstream boundary and one at the downstream boundary of the 3-km long site), at the Talco gauge, and at Site 2 the stage elevation was applied directly to each flood surface based upon unique event peaks. The percentile rank of each flow event at Talco was calculated for the Talco historical record using all available data (1949 to present). The flow rate corresponding to each percentile was determined at each of the North Sulphur, South Sulphur and White Oak Creek gauges using all historical data at each of the respective gauges sites. Since these rivers have been observed to incise and therefore change the gauge height flow rating, the stage was determined for each percentile flow rate using the most recent 2 years of data at each of the gauges. Tables 6.4 to 6.9 and Figures 6.2 to 6.3 present relevant information for each flood event evaluated.

Figure 6.2 shows the water surface elevation observed at each of the seven locations of interest. Figure 6.3 depicts the same water surface elevation data, and also indicates the flood peaks that were used to derive elevations for each flow rate. As earlier stated, elevations observed at TWDB Site 1, the USGS Sulphur River Talco gauge and at TWDB Site 2 were used in the flood surface concurrently (Table 6.4). The concurrent water surface elevations observed at USGS North Sulphur River near Cooper gauge, USGS South Sulphur River near Cooper gauge and USGS White Oak Creek near Talco gauge were not used directly; rather the percentile rank of the flows utilized from the Sulphur River at Talco (for the period from October 1956 to September 2002) was determined (Table 6.5). The flow at each of the other three gauging stations corresponding to the same percentile was used to determine a water surface elevation at the gauge (Tables 6.6, 6.7 and 6.8). Table 6.9 shows the flow rates at each gauge associated with each percentile of interest, and Table 6.4shows the final elevation used at each location.

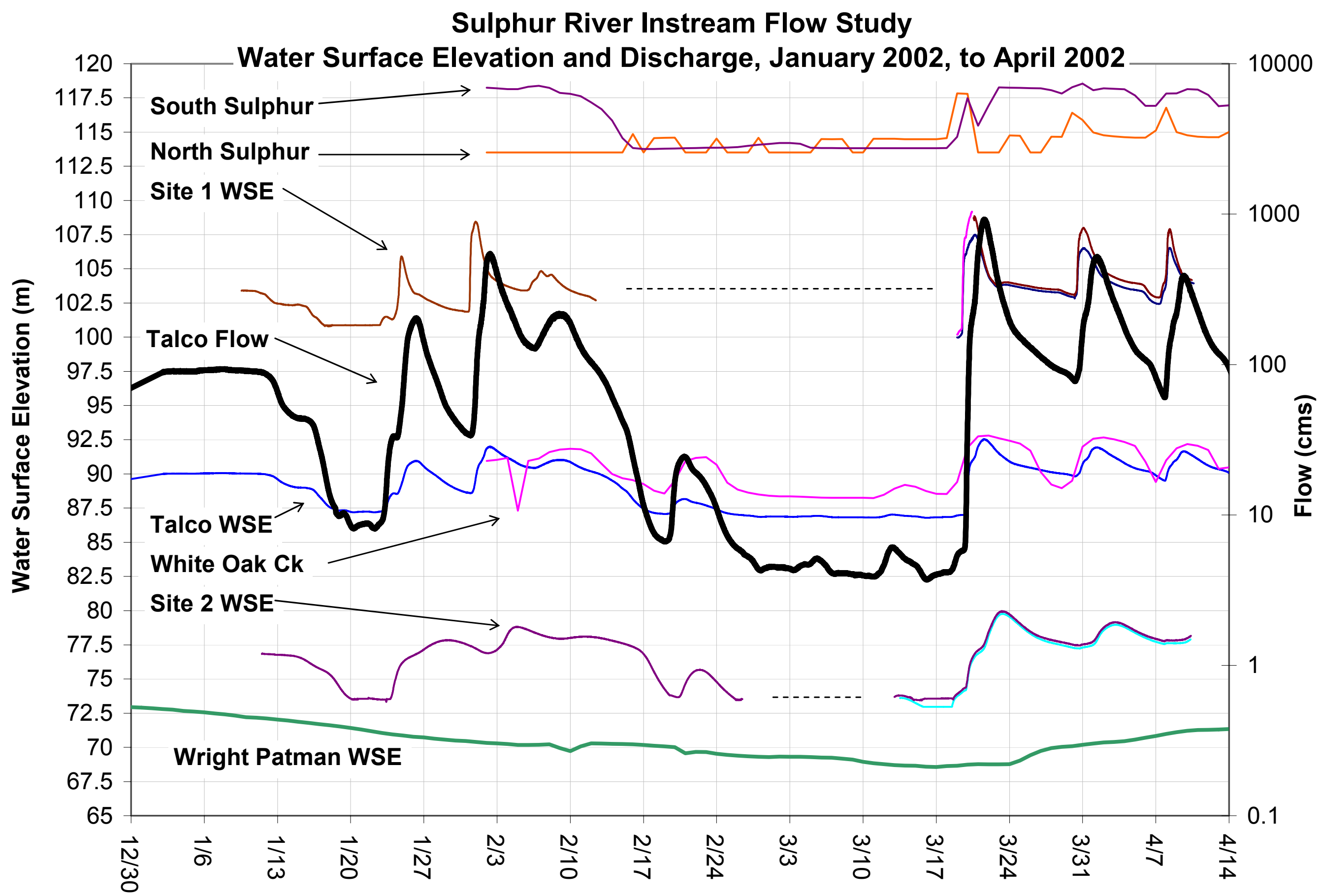

Figure 6.2– Time series of water surface elevations in the Sulphur River basin for four months in 2002.

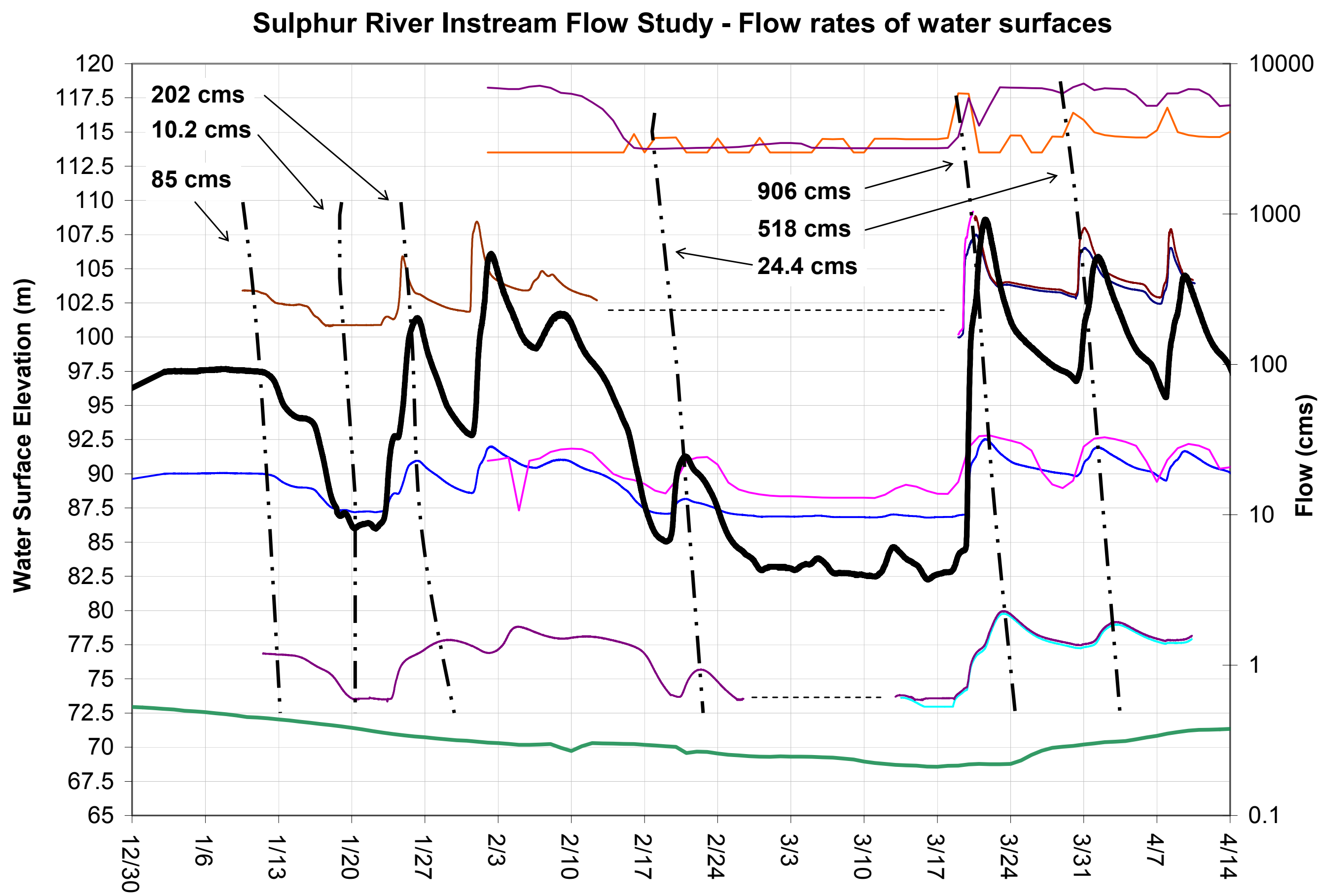

Figure 6.3– Stage chart from Sulphur River basin showing flow rates at which WSE was generated; flow rate shown for USGS Sulphur River near Talco gauge.

Table 6.4– Stage data used to generate basin-wide, steady-state flood surfaces.

Percentile Rank of Flow at Talco		N Sulphur River nr Cooper, TX	S Sulphur River nr Cooper, TX		TWDB Site 1 (upstream)	TWDB Site 1 (downstream)	Sulphur River nr Talco, TX	White Oak Creek nr Talco, TX	TWDB Site 2	Wright Patman Lakr nr Texarkana, TX
Annual		Elevation (m)	Elevation (m)		Elevation (m)	Elevation (m)	Elevation (m)	Elevation (m)	Elevation (m)	Elevation (m)
68.6%		**114.59**	**114.00**		**100.88**	**100.88**	**87.03**	**88.85**	**73.50**	**69.34**
				date	1/19/2002 0:00	1/19/2002 0:00	1/19/2002 6:00		1/20/2002 0:00	
76.7%		**114.65**	**114.39**		**101.52**	**101.52**	**88.17**	**89.41**	**75.67**	**69.34**
				date	3/19/2002 12:00	3/19/2002 12:00	2/20/2002 22:00		2/22/2002 9:5	
88.3%		**114.70**	**115.82**		**103.38**	**103.38**	**89.95**	**91.18**	**76.67**	**69.34**
				date	1/10/2002 18:25	1/10/2002 18:25	1/12/2002 0:00		1/14/2002 15:08	
94.3%		**114.93**	**117.66**		**105.46**	**105.46**	**90.95**	**91.99**	**77.84**	**69.34**
				date	1/25/2002 0:00	1/25/2002 0:00	1/26/2002 7:00		1/29/2002 9:27	
98.7%		**115.71**	**118.64**		**108.00**	**106.18**	**91.93**	**92.57**	**79.14**	**69.34**
				date	3/31/2002 0:00	3/31/2002 0:00	4/1/2002 10:00		4/3/2002 3:00	
99.7%		**117.13**	**119.61**		**109.17**	**107.51**	**92.28**	**92.89**	**79.97**	**69.34**
				date	3/20/2002 10:11	3/20/2002 16:54	3/21/2002 13:30		3/23/2002 7:56	

Table 6.5– Historical statistics of daily-averaged flows recorded at USGS Talco gauge.

Flow at USGS Sulphur River at Talco gauge #07343200		Percentile Rank of Flow at Talco			
		entire period of record			to 9-30-2002
cms	cfs	Winter	Summer	Annual	Annual
10.25	362	61.5%	75.3%	69.3%	**68.6%**
24.5	862	71.0%	81.9%	77.4%	**76.7%**
86	3000	85.5%	91.0%	88.7%	**88.3%**
202	7130	92.7%	95.1%	94.5%	**94.3%**
518	18300	98.7%	98.7%	98.7%	**98.7%**
906	32000	99.8%	99.7%	99.8%	**99.7%**

Table 6.6– Water surface elevation and historical statistics of daily-averaged flows recorded at USGS South Sulphur River near Cooper gauge.

# USGS 07342500 S Sulphur Rv nr Cooper, TX from 6/1/1942 to 9/30/2002						
Historical flows			**Flood flows**			
percentile	**flow (cms)**	**flow (cfs)**	**percentile**	**flow (cms)**	**flow(cfs)**	**WSE(m)**
min	0.00	0	99.7%	314.01	11089.2	**119.61**
max	1095.86	38700	98.7%	156.88	5540	**118.64**
			94.3%	63.70	2249.48	**117.66**
99%	180.92	6389.2	88.3%	29.73	1050	**115.82**
95%	69.38	2450	76.7%	5.24	185	**114.39**
90%	37.10	1310	68.6%	1.70	60	**114.00**
85%	19.13	675.6				
80%	8.83	311.8	Flow rate statistics were calculated using all historical data available for this gauge.			
75%	3.96	140				
70%	2.01	71				
65%	1.13	40	Water surface elevation (WSE) was determined using flow vs. gauge height rating information compiled from the most recent period of record: from February 2, 2002 to February 1, 2001			
60%	0.68	24				
55%	0.45	16				
50%	0.31	11				
45%	0.21	7.5				
40%	0.15	5.3				
35%	0.10	3.7				
30%	0.07	2.4				
25%	0.04	1.5				
20%	0.02	0.85				
15%	0.01	0.4				
10%	0.00	0.04				
5%	0.00	0				
1%	0.00	0				

Table 6.7– Water surface elevation and historical statistics of daily-averaged flows recorded at USGS North Sulphur near Cooper gauge.

 # USGS 07343000 N Sulphur Rv nr Cooper, TX
from 10/1/1949 to 9/30/2002

Historical flows			Flood flows			
percentile	**flow (cms)**	**flow (cfs)**	**percentile**	**flow (cms)**	**flow(cfs)**	**WSE(m)**
min	0.00	0	99.7%	362.25	12792.9	**117.13**
max	1158.16	40900	98.7%	136.02	4803.59	**115.71**
			94.3%	25.25	891.604	**114.93**
99%	167.76	5924.3	88.3%	6.43	227.231	**114.70**
95%	30.06	1061.5	76.7%	1.76	62	**114.65**
90%	8.89	314	68.6%	0.99	35	**114.59**
85%	3.94	139				
80%	2.29	81	Flow rate statistics were calculated using all historical data available for this gauge.			
75%	1.53	54				
70%	1.10	39				
65%	0.82	29	Water surface elevation (WSE) was determined using flow vs. gauge height rating information compiled from the most recent period of record: from February 2, 2002 to February 1, 2001			
60%	0.59	21				
55%	0.42	15				
50%	0.34	12				
45%	0.23	8.2				
40%	0.16	5.7				
35%	0.11	3.8				
30%	0.06	2.2				
25%	0.03	1.2				
20%	0.01	0.5				
15%	0.00	0.1				
10%	0.00	0				
5%	0.00	0				
1%	0.00	0				

Table 6.8– Water surface elevation and historical statistics of daily-averaged flows recorded at USGS White Oak Creek near Talco gauge.

# USGS 07343500 White Oak Ck nr Talco, TX						
from 12/1/1949 to 9/30/2002						
Historical flows			**Flood flows**			
percentile	**flow (cms)**	**flow (cfs)**	**percentile**	**flow (cms)**	**flow(cfs)**	**WSE(m)**
min	0.00	0	99.7%	374.10	13211.2	**92.88**
max	1076.04	38000	98.7%	170.31	6014.56	**92.57**
			94.3%	63.71	2250	**91.99**
99%	202.76	7160.4	88.3%	31.71	1120	**91.18**
95%	71.92	2540	76.7%	9.12	322	**89.41**
90%	37.94	1340	68.6%	4.05	143	**88.85**
85%	22.25	785.6				
80%	13.03	460	Flow rate statistics were calculated using			
75%	7.48	264	all historical data available for this gauge.			
70%	4.59	162				
65%	3.00	106	Water surface elevation (WSE) was determined			
60%	2.10	74	using flow vs. gauge height rating information			
55%	1.53	54	compiled from the most recent period of record:			
50%	1.10	39	from February 2, 2002			
45%	0.79	28	to February 1, 2001			
40%	0.54	19				
35%	0.37	13				
30%	0.26	9.3				
25%	0.18	6.4				
20%	0.12	4.1				
15%	0.07	2.6				
10%	0.04	1.26				
5%	0.01	0.3				
1%	0.00	0				

Table 6.9– Flow rates at each gauge by flow percentile.

Flow percentile	**68.6**	**76.7**	**88.3**	**94.3**	**98.7**	**99.7**
flow (cms) N. Sulphur	0.99	1.76	6.43	25.25	136.02	362.25
flow (cms) S. Sulphur	1.7	5.24	29.73	63.7	156.88	314.01
flow (cms) White Oak	4.05	9.12	31.71	63.71	170.31	374.1
flow (cms) Sulphur River at Talco	10.25	24.41	84.95	201.90	518.20	906.14
flow (cfs) Sulphur River at Talco	*362*	*862*	*3000*	*7130*	*18300*	*32000*

With the flood surface elevation at each of the gauge sites for each of the six flow rates determined, a flood surface encompassing the entire study area was generated using a triangulated irregular network (TIN). The TIN was linearly interpolated between each of the location of available stage date (Table 6.4) using ArcInfo and the 3D Analyst extension. The TIN was transformed to a 3D raster grid in the project standard coordinate system (GCS_NorthAmerican_NAD83).

It shall be noted that each flood surface does not vary linearly along the river channel, rather it varies linearly along the river valley. As such, the surface is an approximation of a steady state, basin-wide flood. The approximation of a linear flood surface was not considered a realistic flood surface; rather, it was considered a reasonable estimate of the water level for higher flows that are not contained within the banks. The linear surface does not account for a flood pulse moving through the system; rather it attempts to characterize a flood surface elevation that may be expected to occur at a given frequency at a particular point in the basin.

To determine inundated area for each of the six floods, each flood surface grid was subtracted from the DEM topography. The inundated area grids were used as masks to determine the area of each vegetation type inundated by each flood. The results of the inundation analysis are presented in following sections.

6.4 Significance of modeled flood surfaces

The percentile of each of the flood surfaces was described in the preceding section. To further place the chosen flood surfaces in perspective, a site-specific overbank survey was performed at Site 2 and a duration of occurrence analysis was performed for each flow rate. Additionally the recurrence interval of the flood surfaces observed with historical data was investigated.

6.4.1 The 68.6 percentile flow event

The most frequent event analyzed (68.6 percentile), also the lowest flow rate analyzed (10.25cms, 362cfs at Talco), was observed on both Site 1 and Site 2 to be contained within the banks. Inundation area analysis performed on this frequently occurring low flow showed that the flood surface was not significantly outside of the banks represented by the DEM topographic surface. Since the inundation model showed the wetted area to be confined to the river channel, the model was consistent with field observations.

Figure 6.4 shows the Sulphur River near the SH37 bridge (downstream side) at low flow. The stage in this area was observed to be influenced by the immense logjam located less than a mile farther downstream, so stage observed in this area may be artificially elevated by a backwater effect.

Figure 6.4– Sulphur River downstream of the SH37 bridge at low flow downstream of Site 1, May 16, 2002 (5.32 cms, 188 cfs at Talco gauge)

6.4.2 The 76.7 percentile flow event

The 76.7 percentile flow event (24.41 cms; 862 cfs) at Talco was observed at Site 2 to be transitional between in-channel flow and overbank flow. Analysis of inundated areas for this flow (presented in subsequent sections) showed support for the transitional nature of this flow in unchannelized areas; however, this flow remained completely contained within the banks in channelized areas.

In unchannelized areas, the meandering of the unaltered Sulphur River has created oxbow lakes, cutoff channels, and a large floodplain that sustains a diverse bottomland hardwood forest. Field measurements were made to determine a generalized overbanking elevation, but a precise elevation at which overbanking occurs in the vicinity of TWDB Site 2 is difficult to quantify. Hydraulic connection of the river to any specific area behind the channel's natural levy is dependant not only on local flow conditions, but also on conditions farther downstream, including pool elevation in Wright Patman Lake.

The invert elevation of the largest tributary creek adjacent to Site 2 was surveyed at a point where overbanking influenced by high Sulphur flows appears to occur. The overbanking elevation measured was 241.45 feet above mean sea level (NAVD88), which corresponds to a flow of roughly 24 cms (850 cfs). This should be considered a very approximate estimate of a stage which triggers overbank flows. Proximity to Wright Patman Lake, a flood-control reservoir whose pool elevation fluctuates during flood events, influences hydraulic conditions at Site 2 by artificially elevating the water surface elevation at the site. As a result, flows lower than 850 cfs may actually induce overbanking when the lake pool elevation is at the normal summer conservation pool elevation of 227.50'. While every effort was made to locate the lowest possible overbanking location, the search was limited to the vicinity of the study site. The possibility exists that overbank water located adjacent to the study site originates from an overtopped bank located far downstream, rather than originating from a bank in the immediate vicinity of the study site. An exact determination of the overbanking elevation requires a more extensive regional topographic survey, though a study limited to a series of specific cutoff bendways may be more practical.

A conservative estimate is that for all flows above 22.65 cms (800 cfs), some portion of the flood plain downstream of the proposed Marvin Nichols I project is inundated (or "connected" to the main channel).

6.4.3 The 88.3, 94.3 and 99.7 percentile flows

Figure 6.5 shows flow within the main Sulphur River channel for a medium flow or 88.3 percentile (flow at Talco was reported at 90.6 cms; 3,200 cfs). The photo was taken looking upstream towards the confluence of the North Sulphur and South Sulphur Rivers; the confluence may be visible in the photo but is difficult to discern. As shown in the photo, water was at this flow was completely contained within the high channelized banks at Site 1. While no photo is available, flow in the vicinity of Site 2 where the channel exhibits natural patterns (unchannelized) was out of the banks. Three days after the photo shown at Site 1, the flow rate was measured at Site 2 (87.07 cms; 3,075 cfs). Water surface elevation measured at Site 2 was approximately 2 cm (1 inch) above the temporary benchmark that TWDB had installed on top of the high bank; water was significantly out of the channel and extended well into the forest at depths ranging from 5 cm to 152 cm (2" to 5 feet) deep.

Field data was not collected for the 94.3 percentile flow (201.9 cms; 7,130 cfs), but field data was collected for a slightly higher flow of 97.1 percentile (342.6 cms; 12,100 cfs). Figure 6.6 shows typical Sulphur River flow through the forest for a high flow (flow at Talco was reported at 342.6 cms; 12,100 cfs). The flow rates and water surface elevations at each site were not measured; however, near Site 1, the water surface was within one foot of the bottom beam of the SH37 bridge. Figure 6.6 shows the water surface approximately 2 km (1.25 mile) upstream of the SH37 bridge; this portion of the river has been channelized. Near Site 1 which has also been channelized, located approximately 13 km (8 miles) upstream of the SH37 bridge, flow was contained within the high channelized banks (Figure 6.7).

Figure 6.5 - Photo of typical floodplain inundation at medium flow downstream of the confluence, near the upstream boundary of Site 1
January 8, 2002 (90.6 cms, 3,200 cfs at Talco).

During the same event near Site 2, the water surface was several feet above the forest floor and completely covered the parking surface at the public access and boat launch area at US 259 (Figure 6.8).

Figure 6.7 also shows debris and sandy sediment deposition that topped the high bank (debris was observed at elevations higher than the base of the GPS tripod). The deposition likely occurred during two high flow events that occurred in the months preceding the site visit; a high daily-averaged flow of 1,815 cms (64,100 cfs) was measured at Talco on December 18, 2001 (four months preceding the site visit) and another high daily-averaged flow of 818.35 cms (28,900 cfs) was measured on March 21, 2002 (two weeks preceding the site visit). This second event corresponds to the 99.7 percentile event.

Figure 6.6 - Photo of typical floodplain inundation at high flow downstream of Site 1, April 9, 2002 (342.6 cms, 12,100 cfs at Talco).

Figure 6.7– Photo of inundation in channelized section at high flow at upstream boundary of Site 1, downstream of the confluence, April 9, 2002 (342.6 cms, 12,100 cfs at Talco).

Figure 6.8– Photo of inundation in an unchannelized section at high flow at upstream boundary of Site 2, April 10, 2002 (297.3 cms, 10,500 cfs at Talco).

6.4.4 Flow rate duration and exceedance analysis

Using the entire historical daily-averaged flow record for the USGS Sulphur River at Talco gauge, the recurrence interval was calculated for each of the flow rates of interest (Table 6.10). Separating the historical record at Talco into two eras, before construction of Lake Jim Chapman and after construction, the observed recurrence interval investigation was repeated. Lake Jim Chapman (formerly Cooper Lake) impounds the South Sulphur River and was completed and operational in 1991. Using a pre-construction era consisting of the years 1957 (the first complete year on record at Talco) to the end of 1990 (the year before the dam at Lake Jim Chapman was closed), the occurrence of high flow events was less frequent than for the later era defined as the beginning of 1992 (just after the dam closed) to the end of 2003 (the last full year on record). The 99.7 percentile event reccurred once every 3.09 years (ratio of 34 years divided by occurrence in 11 years) for the early era, compared to once in 6 years in the later era (12 years divided by 2 occurrences). Similarly, the 98.7 percentile flow decreased in occurrence frequency in the later era. The post-construction era is significantly shorter than the pre-construction era so some uncertainty exists;

incorporation of a time-series analysis of historical rain fall events is required for further investigation.

Table 6.10– Observed occurrence of flood flows on the Sulphur River near Talco.

USGS Sulphur River near Talco			Flood occurrences					
	Flow		entire record 1957 to 2003		pre-Jim Chapman 1957 to 1990		post-Jim Chapman 1992 to 2003	
Percentile	(cms)	*(cfs)*	47 years	ratio	34 years	ratio	12 years	ratio
68.6	10.25	*362*	47	1	34	1	12	1
76.7	24.41	*862*	47	1	34	1	12	1
88.3	84.95	*3000*	46	1.02	34	1	11	1.09
94.3	201.90	*7130*	44	1.07	34	1	9	1.33
98.7	518.20	*18300*	32	1.47	25	1.36	6	2
99.7	906.14	*32000*	13	3.62	11	3.09	2	6

The number of occurrences of each flow rate at the Talco gauge is shown in Figure 6.9. Using the example of the year 1958, Figure 6.9 shows that a flow corresponding to the 68.6 percentile was equaled or exceeded 112 days of the year. Similarly, the 76.7 percentile flow was equaled or exceeded 83 days, the 88.3 percentile flow 45 days and the 94.3 percentile 15 days. The 98.7 percentile flow was equaled or exceeded only 7 days and the 99.7 percentile equaled or exceeded 4 days in the year of 1958. The number of days that equal or exceed the 98.7 percentile decreases after 1992 (subsequent to construction of Lake Jim Chapman) as compared to the era before 1990.

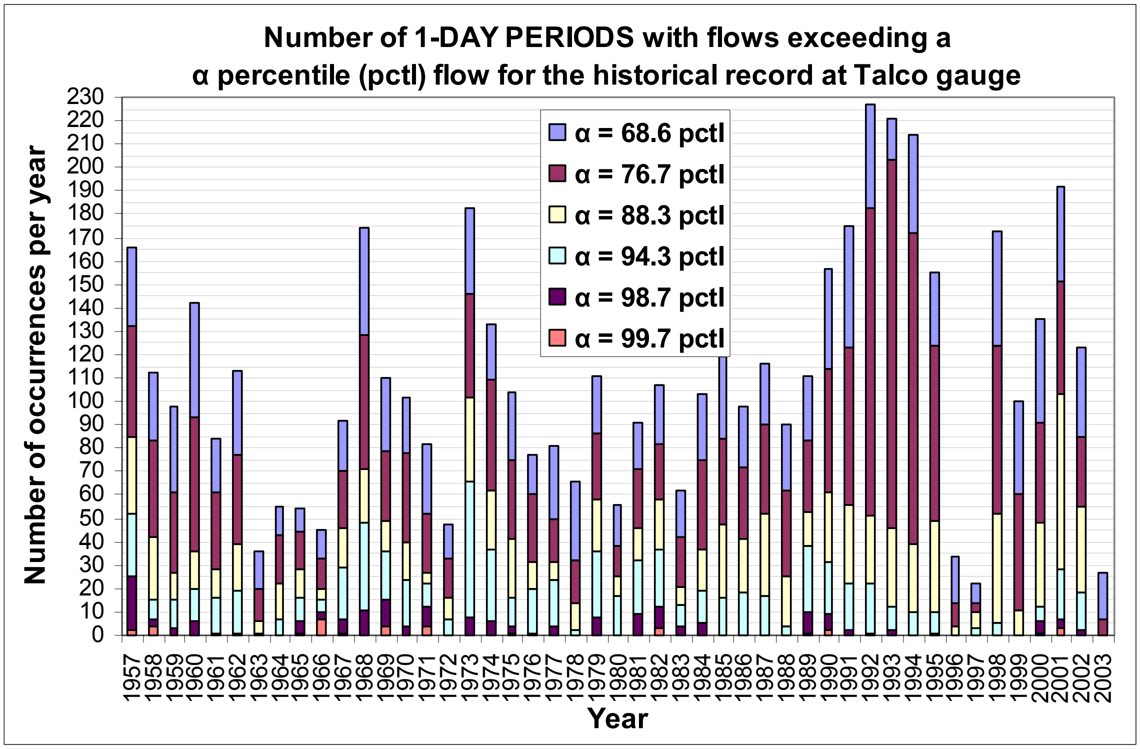

Figure 6.9 - Number of 1-day periods with flows exceeding the percentile flows of interest at the USGS Talco gauge.

Figure 6.9 shows the number of days (or the number of 1-day periods) where flow rate measured at the USGS Sulphur River Talco gauge equaled or exceeded the percentile flows of interest. Duration of inundation, the amount of time a particular area of the flood plain remains covered with water, is an important consideration for evaluation of riparian and flood plain habitats. The duration of inundation was investigated by counting the number of continuous periods that each percentile flow was equaled or exceeded; a total of six periods were investigated: 1-day, 3-day, 5-day, 7-day, 10-day and 14-day periods (Figures 6.9 to 6.14, respectively).

Again using the example of flow occurrences in 1958, the 88.3 percentile flow occurred on 42 days (or for 42 consecutive 1-day periods) (Figure 6.9), for ten 3-day periods (flow was greater than or equal to the 88.3 percentile flow for three consecutive days on ten different occassions) (Figure 6.10), five 5-day periods (Figure 6.11), two 7-day periods (Figure 6.12), one 10-day period (Figure 6.13) and had zero occurrences where the 88.3 percentile flow was equaled or exceeded for 14 consecutive days (Figure 6.14).

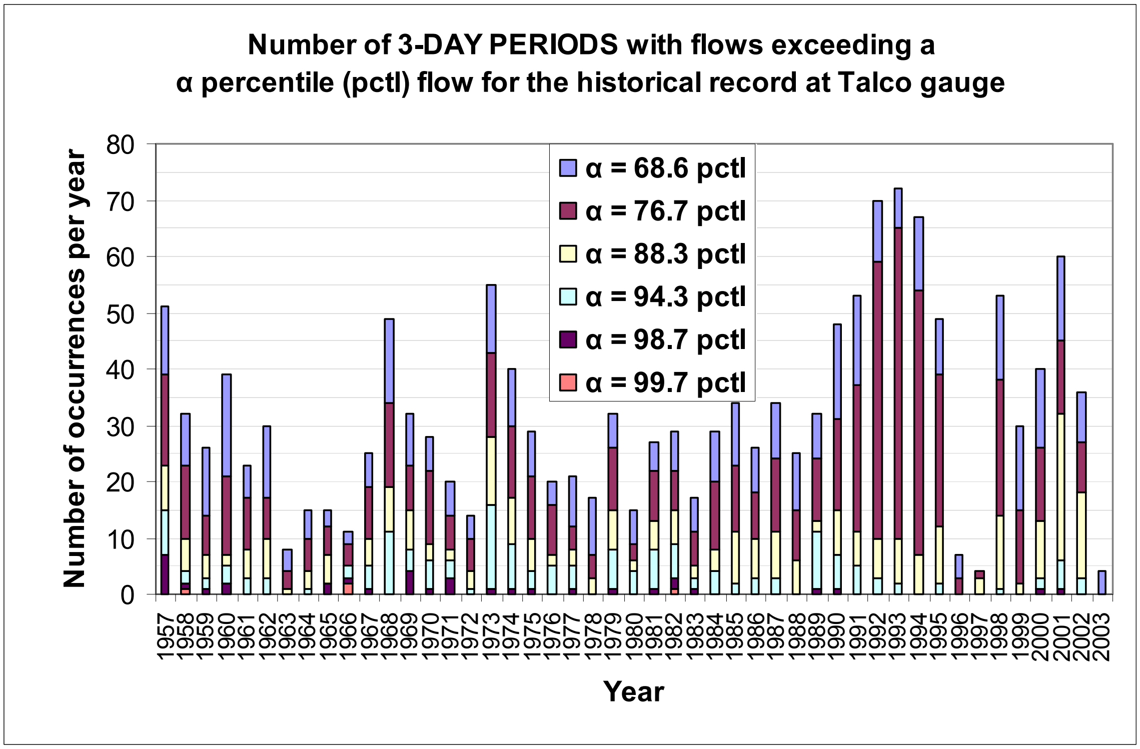

Figure 6.10 - Number of 3-day flow exceedance periods at Talco.

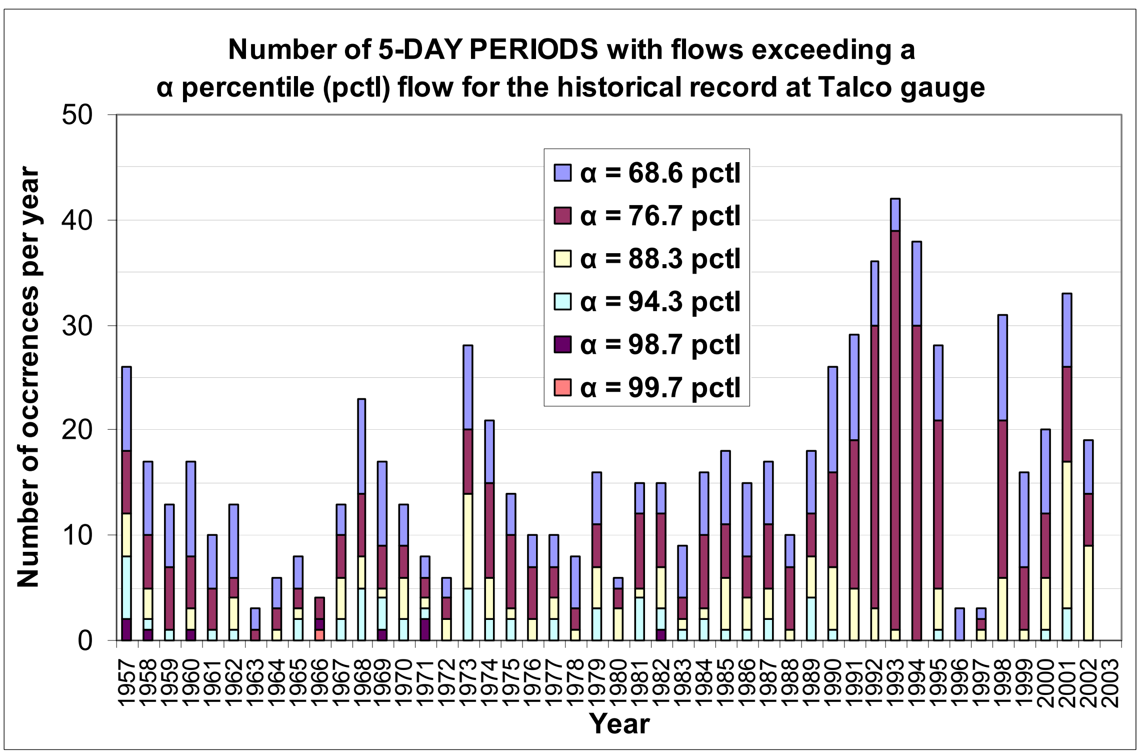

Figure 6.11 - Number of 5-day flow exceedance periods at Talco.

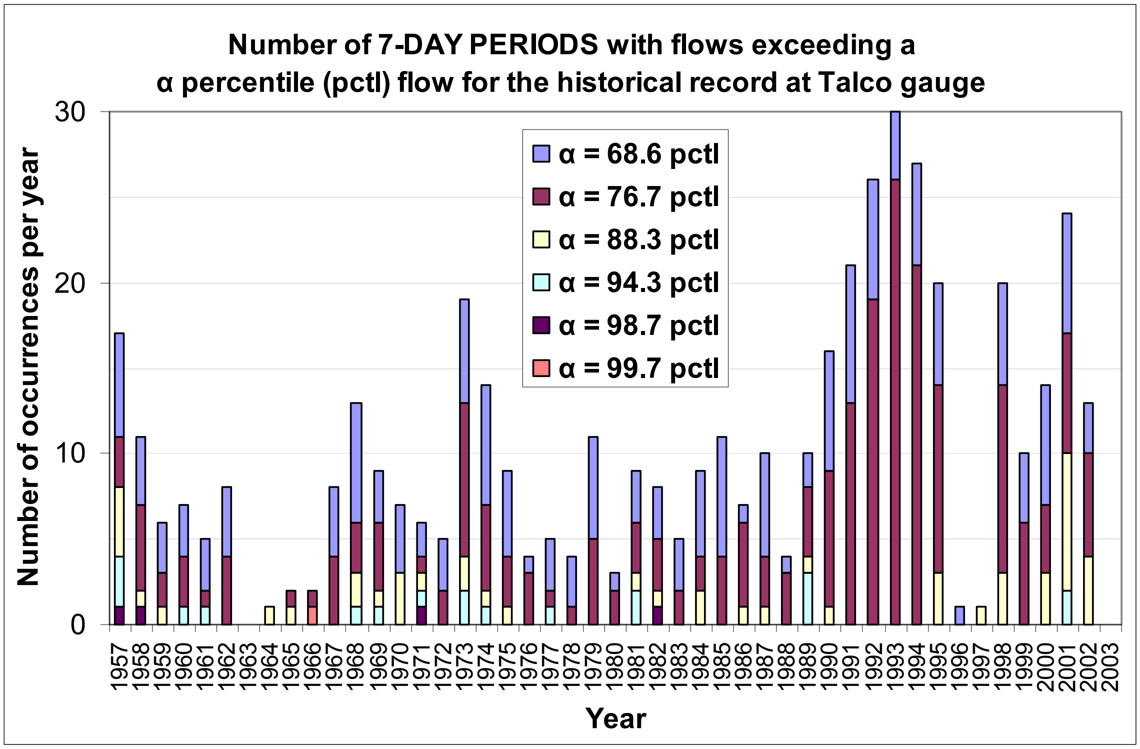

Figure 6.12 - Number of 7-day flow exceedance periods at Talco.

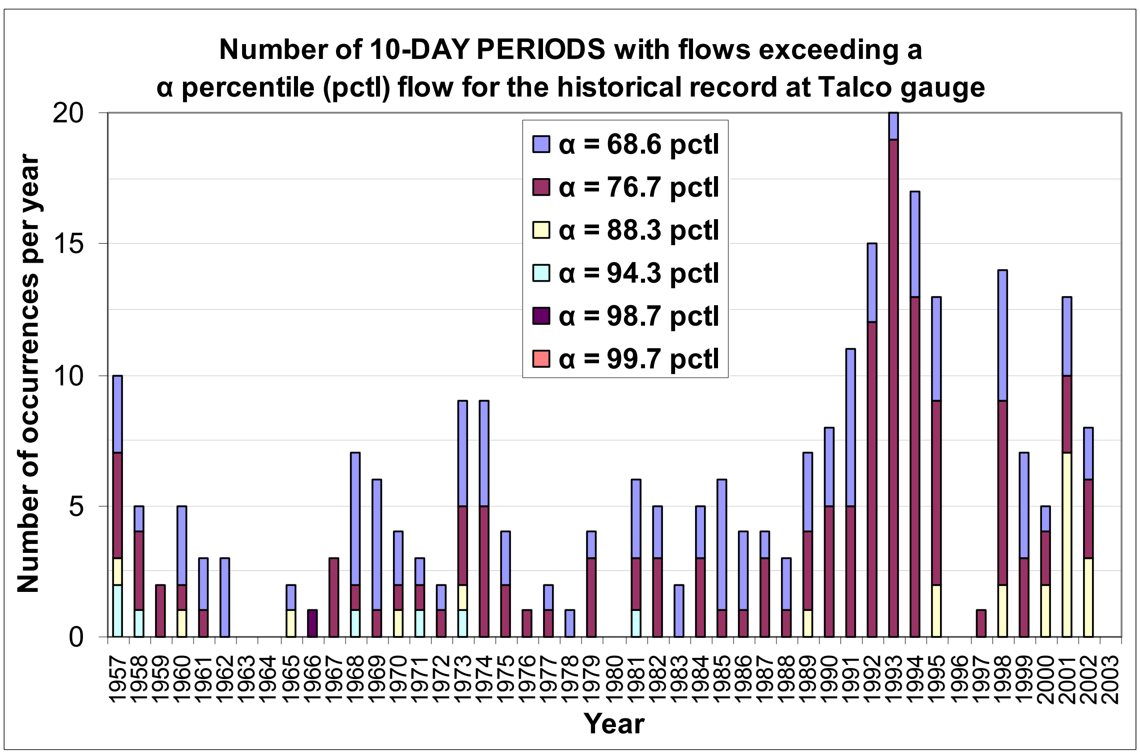

Figure 6.13 - Number of 10-day flow exceedance periods at Talco.

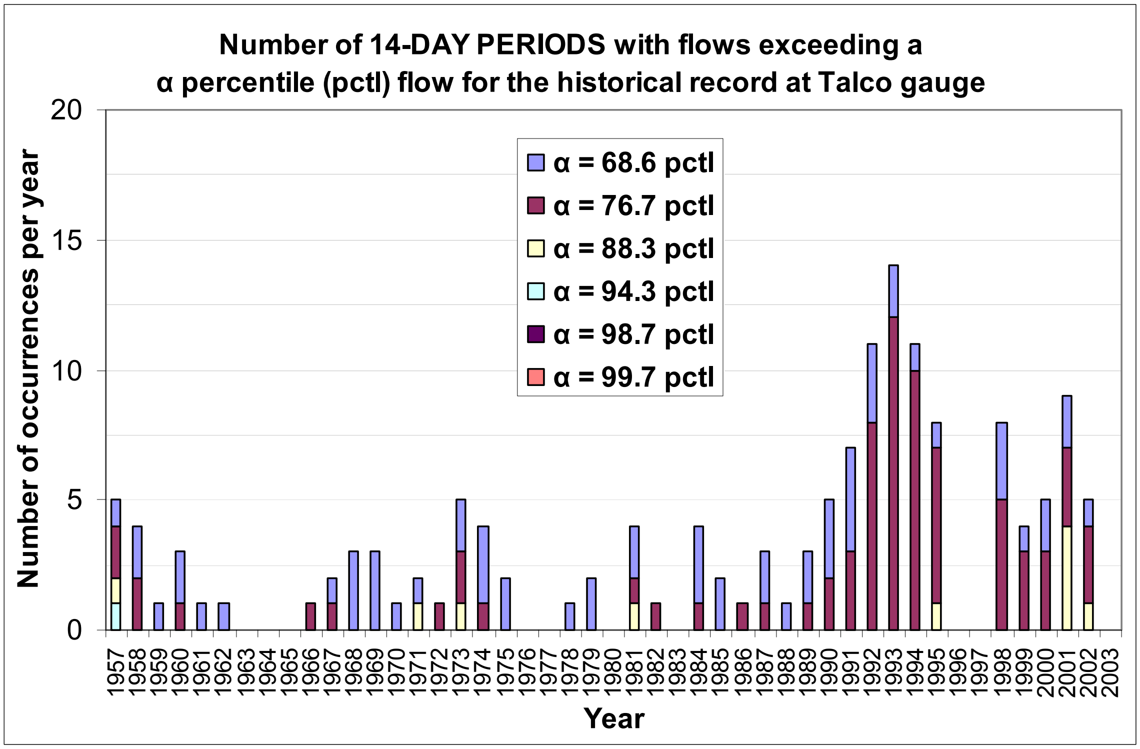

Figure 6.14 - Number of 14-day flow exceedance periods at Talco.

6.5 Area of flood plain

Inundation analysis was performed for nine areas described in Table 6.11 and shown in Figure 6.15. The basin was divided so areas directly impacted by reservoir inundation could be analyzed separately from indirectly impacted areas downstream of the reservoir projects. While Figure 6.15 shows the analyzed areas to encompass the entire basin, the extent of the flood surfaces did not extend farther than approximately 5 km on either side of the river channels; the inundation analysis applies to the area near the North Sulphur River, South Sulphur River, Sulphur River and White Oak Creek channels.

Geographic separation of the analysis allows areas inundated by proposed reservoir projects to be treated separately from the areas downstream of the proposed projects. Since the flood surface was calculated for the Sulphur River channel the analyzed area, while depicted to extend far up tributaries, was limited to that near the channel and did not account for the influence of tributary inflow.

Table 6.11– Description of nine areas of analysis.

Area Designation	Area Description
100	Downstream of George Parkhouse II
101	George Parkhouse I
102	George Parkhouse II
110	Downstream George Parkhouse I
200	Upstream of Marvin Nichols I
201	Marvin Nichols I
202	Marvin Nichols II
210	Downstream Marvin Nichols I
300	Downstream Marvin Nichols II

The Marvin Nichols II reservoir project is included on the list of sites analyzed; however, that project is no longer considered viable. Instead, a 10431 hectare (25,777 acre) area consisting mostly of bottomland hardwood forest located near the confluence of White Oak Creek and the Sulphur River has been designated as the White Oak Creek Wildlife Management Area. The area is included in this analysis because that state-operated and easily-accessible area allows verification of this analysis; no possibility for development of a reservoir exists for this site.

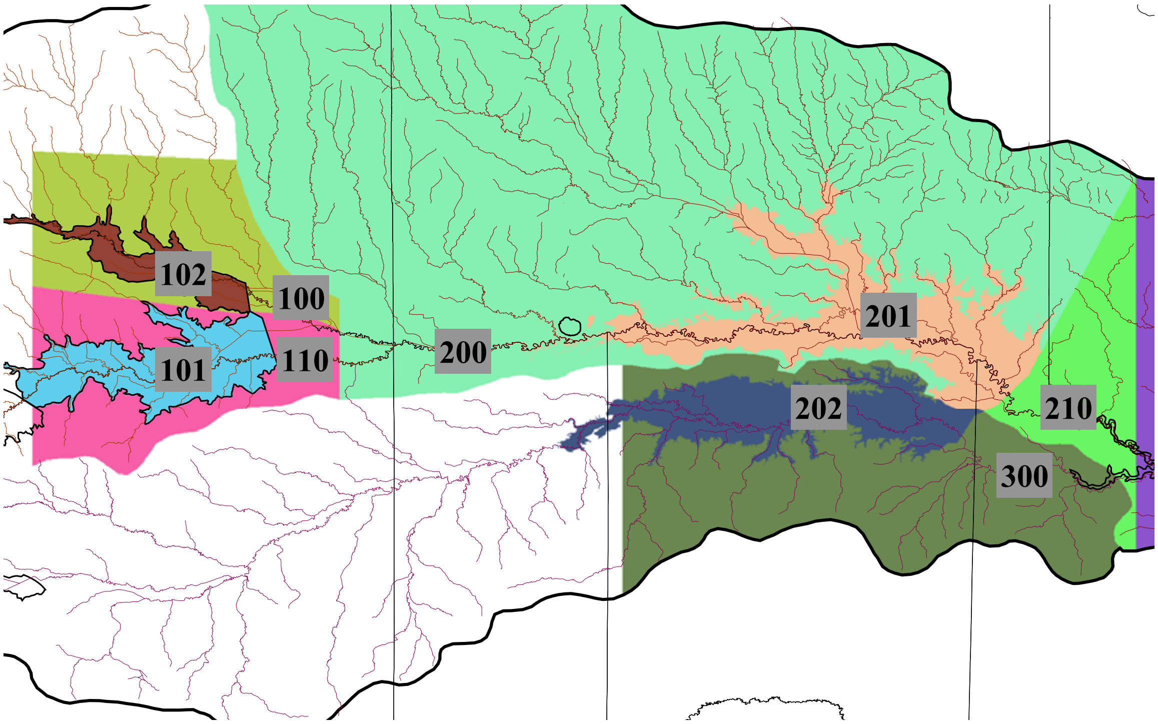

Figure 6.15– Area masks within the Sulphur River basin.

Combining the flow significance analysis in the previous section with this spatial analysis of inundated areas allows observations to be made regarding the time that a specific area remains inundated. For example, the area shown inside of the red contour line (in the following map figures) depicts the area that is inundated by a 94.3 percentile flood. This is a flood that occurs roughly once per year, but has historically only occurred once every 1.33 years for the recent era (1992 to 2003, Table 6.10). Additionally, there were many 3-day duration occurrences each year of the 94.3 percentile flood in the historical record (Figure 6.10), but the number of occurrences decreased for 5-day duration periods (Figure 6.11) and 7-day duration periods (12 of 47 years; Figure 6.12). Only 6 years of the 47 on record exhibited 10-day duration periods equaling or exceeding the 94.3 percentile flow (Figure 6.13) and no occurrences of 14-day duration were recorded (Figure 6.14).

Relating that information to vegetation, the vegetation shown within the red contour line (the 94.3 percentile flow line) gets inundated at least once per year and typically gets inundated for at least 3 days at a time each time it gets inundated. Less frequently but somewhat regularly, the area inside the red contour line gets inundated for periods up to 7 days, but rarely gets inundated for periods exceeding 14 days.

Here it shall be noted that the duration analysis does not account for topographical irregularities that cause pooling and/or retainage of water, and also does not account for evaporation and infiltration. The periods described above are not considered the actual time that an area remains inundated; rather, each duration period can be considered an indicator of the time that an area is in fact inundated. An additional analysis is required to associate the periods described above to actual times of inundation; precise topographic and soil moisture data would be required in addition to a calibrated flood surface hydraulic model.

6.5.1 George Parkhouse I

Area number 101. This area is located on the South Sulphur River and would be inundated by the proposed George Parkhouse I reservoir project. The area extends from the upstream boundary near the USGS South Sulphur River near Cooper gauge downstream to the proposed location of the dam. The upstream portions of this area are unchannelized and downstream areas are channellized. Levee elevations should be examined and verified within the topographic model, as well as incorporated into the flood surface.

Flows between the 94.3 and 98.7 percentile (63.7 and 157 cms, 2,250 and 5,540 cfs; Table 6.6) overtop the banks and impact hardwood areas. Bottomland hardwood is the dominant inundated vegetation type (Table 6.12 and Figures 6.16 and 6.17); Pasture and Crop areas are likely not accurately represented since the flood surface did not account for flood protection provided by levees in the downstream areas. Secondary bottomland hardwood forest is the next most significant inundated area. Flows above the 98.7 percentile (157 cms; 5,540 cms at the USGS South Sulphur River near Cooper gauge) represent nearly maximum inundated area for the bottomland hardwood types.

Table 6.12 – Area (hectares) of vegetation inundated by proposed George Parkhouse I project, South Sulphur River; reservoir max pool elevation assumed 124m MSL.

Area 101	**Area (ha) of vegetation type by flow percentile**						**Total under**
George Parkhouse I	**68.6**	**76.7**	**88.3**	**94.3**	**98.7**	**99.7**	**reservoir**
Bottomland Hardwood	64.160	85.033	221.793	1141.998	2534.285	3096.753	3781.643
Oak-Hickory	0	0	0.454	3.086	26.771	71.239	919.933
Cedar-Hardwood/Pine-Hardwood	0	0	0.091	0.182	3.358	5.536	59.532
Pure Pine/Cedar Grove	0	0	0	0	1.997	1.997	2.904
Pasture/Grassland	3.267	4.175	19.148	315.538	822.195	1369.327	4701.576
Crops/Managed Pasture	0	0	16.880	852.233	1058.871	1064.498	1067.946
Bare Soil/Ground	0	0	0.091	6.806	18.059	23.504	40.565
Secondary Bottomland Hardwood	5.627	7.805	27.044	165.347	352.110	482.427	766.656

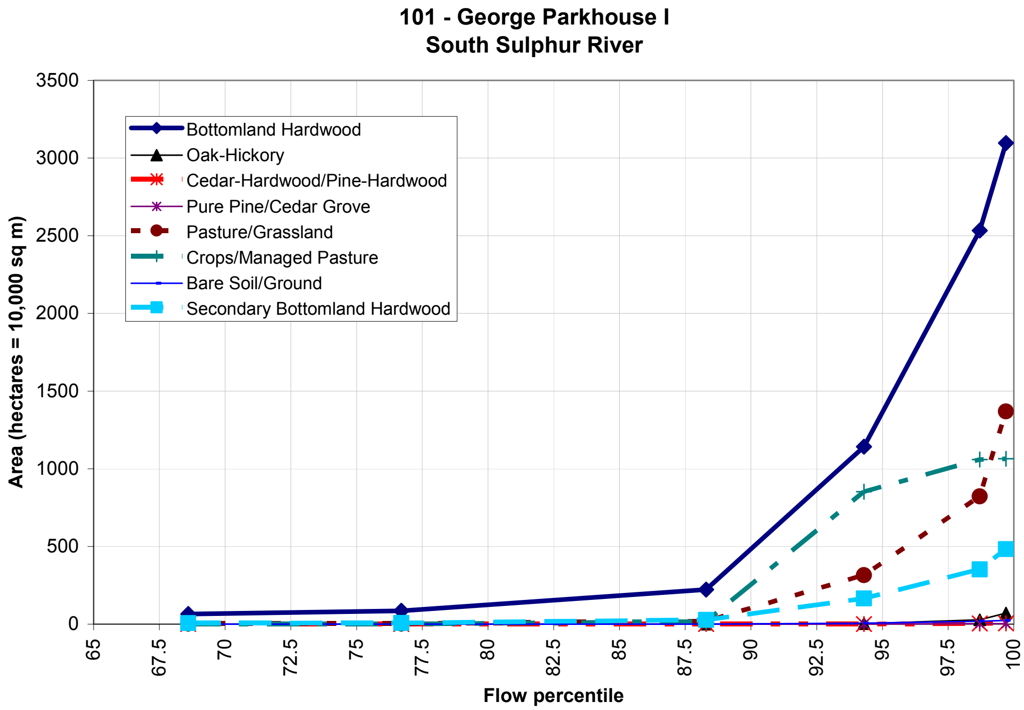

Figure 6.16 – Vegetation areas inundated by George Parkhouse I project, South Sulphur River – by flow percentile.

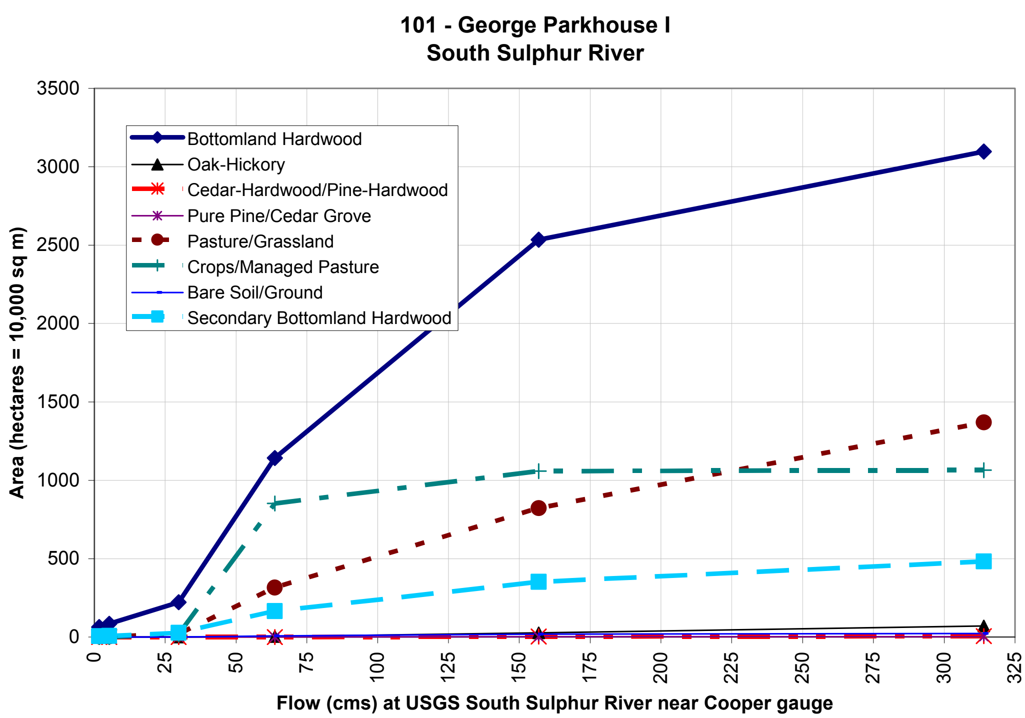

Figure 6.17 – Vegetation areas inundated by George Parkhouse I project, South Sulphur River – by flow rate.

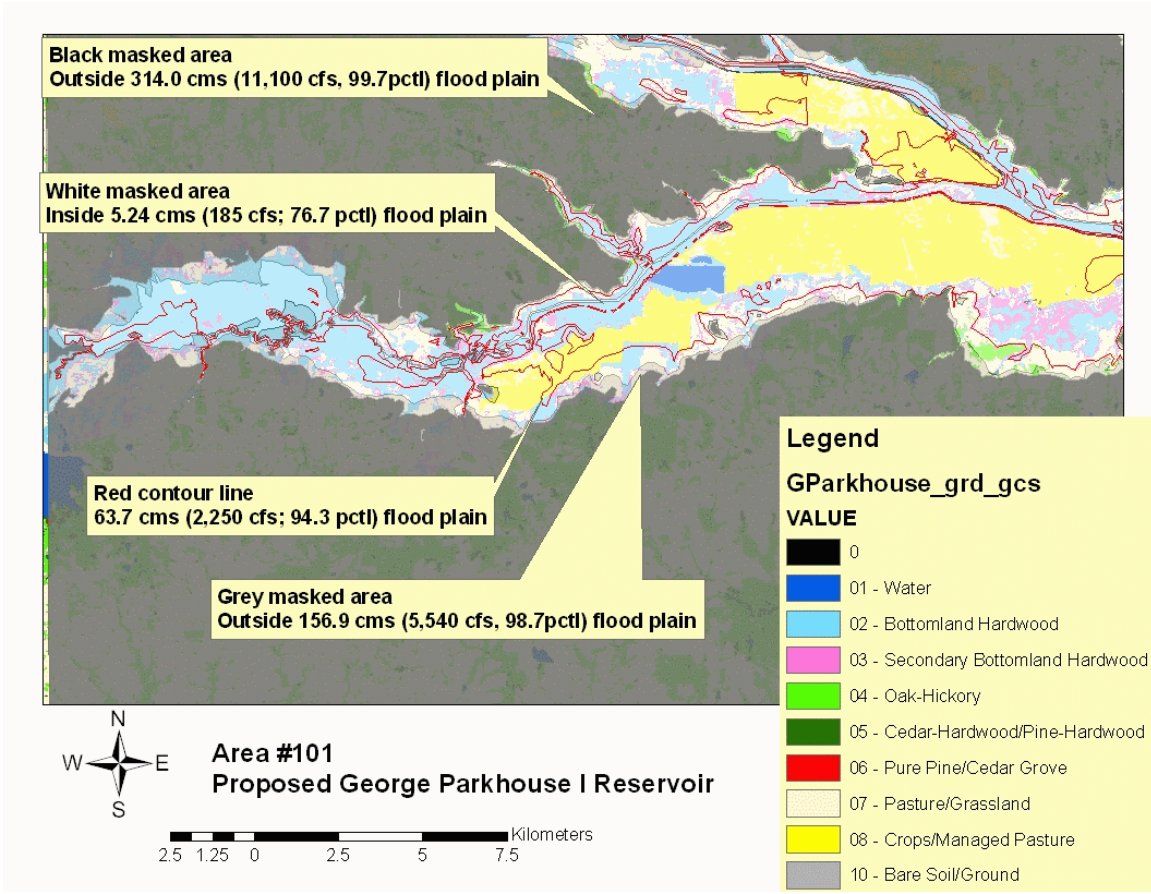

Figure 6.18 - Inundated area and vegetation map, Area 101.

6.5.2 South Sulphur River downstream of George Parkhouse I

Area number 110. This area is located on the channelized South Sulphur River just downstream of the proposed George Parkhouse I reservoir project. The area extends from the proposed dam location downstream to the confluence of the North and South Sulphur Rivers. Levee elevation should be examined and incorporated more realistically into this flood surface model.

Flows above the 94.3 percentile (63.7 cms, 2,250 cfs at the USGS North Sulphur River near Cooper gauge; Table 6.6) overtop the banks; however, levees may in fact prevent flood waters from entering the pasture areas. Excluding pasture and crop land, bottomland hardwood forest and secondary bottomland hardwood forest are the two most dominant vegetation types and begin to be inundated at flows near the 94.3 percentile flow (Table 6.13 and Figures 6.19 and 6.20). Figure 6.21 shows that areas upstream of the confluence are completely contained within the banks. The model shows that areas downstream are less contained, but that may be a result of inadequately resolved levee protection (Figure 6.21).

Table 6.13– Area (hectares) of vegetation downstream of proposed George Parkhouse I project, South Sulphur River.

Area 110	**Area (ha) of vegetation type by flow percentile**					
Downstream George Parkhouse I	**68.6**	**76.7**	**88.3**	**94.3**	**98.7**	**99.7**
Bottomland Hardwood	1.271	4.084	63.071	301.290	355.377	357.646
Oak-Hickory	0	0	0	0.726	56.810	78.408
Cedar-Hardwood/Pine-Hardwood	0	0	0	0	1.815	4.628
Pure Pine/Cedar Grove	0	0	0	0	0	0.182
Pasture/Grassland	0	0.182	45.829	292.215	498.127	569.638
Crops/Managed Pasture	0	0	127.141	1287.107	1317.236	1318.325
Bare Soil/Ground	0	0	0	0.726	5.990	6.716
Secondary Bottomland Hardwood	0	0.998	30.946	155.183	193.479	195.657

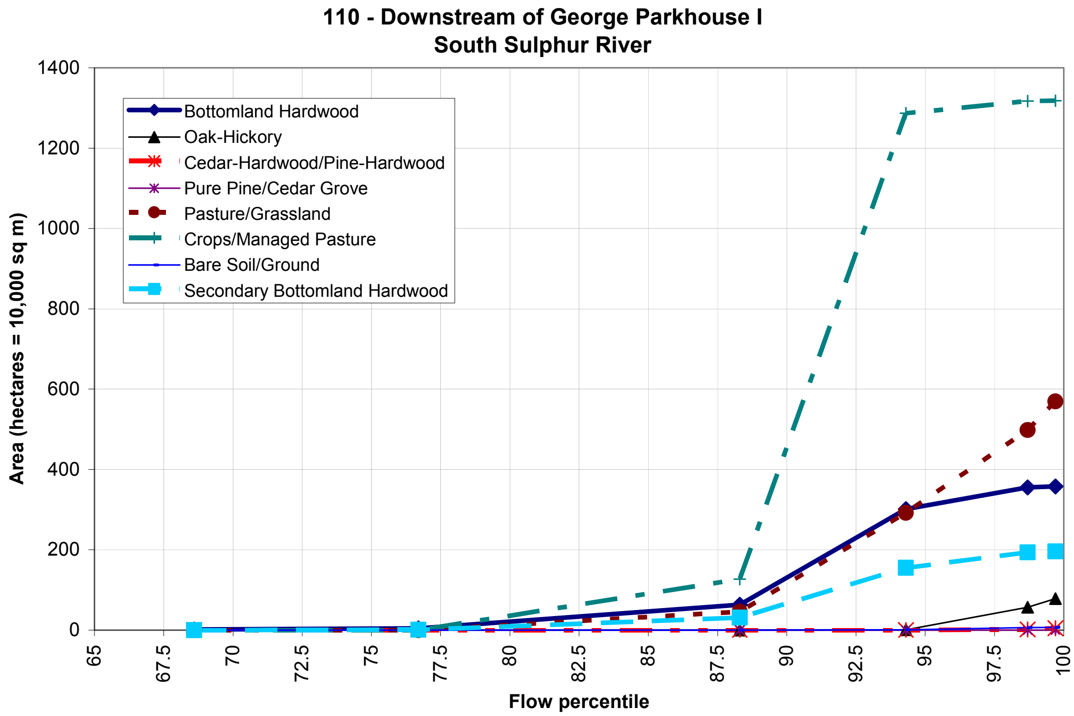

Figure 6.19 – Vegetation areas downstream of proposed George Parkhouse I project, South Sulphur River – by flow percentile.

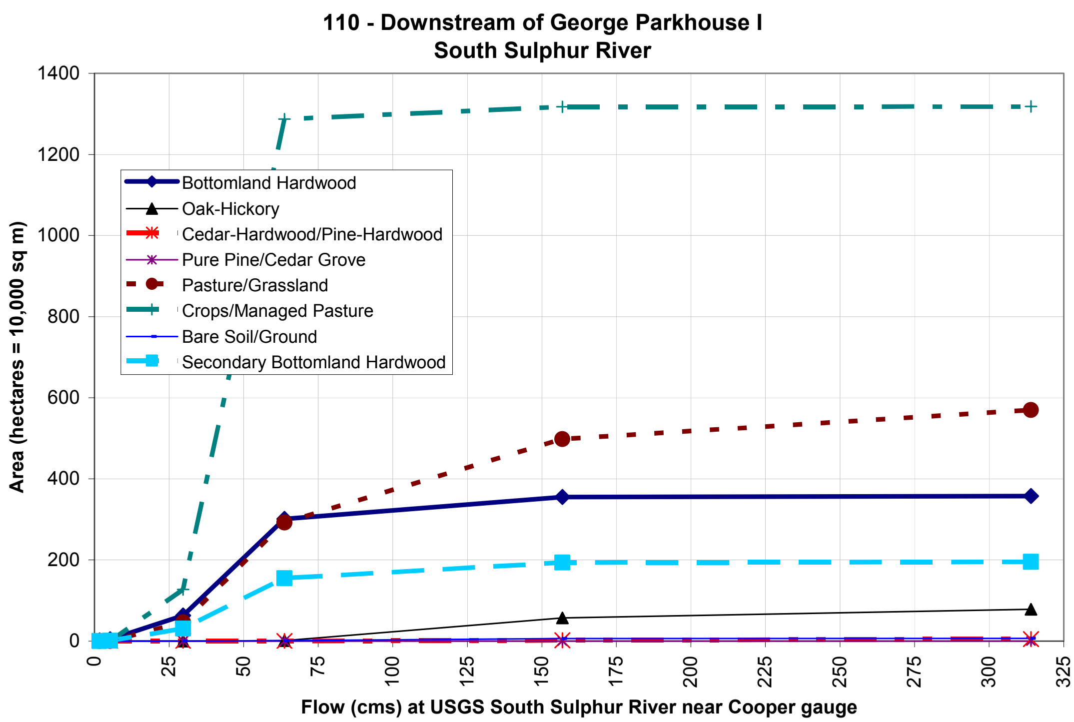

Figure 6.20 – Vegetation areas downstream of proposed George Parkhouse I project, South Sulphur River – by flow rate.

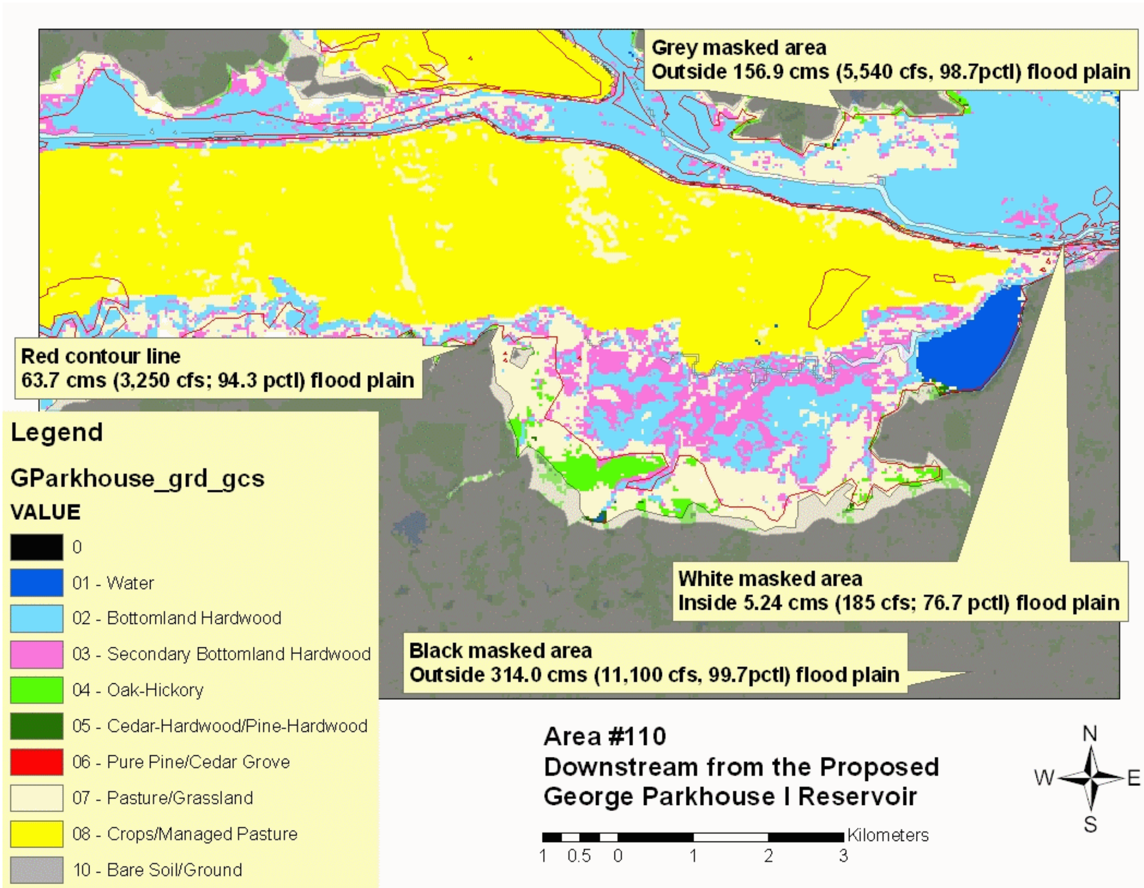

Figure 6.21 - Inundated area and vegetation map, Area 110.

6.5.3 George Parkhouse II

Area number 102. This area is located along the channelized North Sulphur River and would be inundated by the proposed alternative George Parkhouse II project. Levee elevations in this area should be examined and incorporated into the flood surface model.

Flows below 98.7 percentile (136 cms; 4,803 cfs; Table 6.7) were shown to be contained within the channel (Figure 6.24). Bottomland hardwood forest was the dominant inundated vegetation type with Pasture/Grassland being the second-most dominant type (Table 6.14 and Figures 6.22 and 6.23). Significant area of secondary bottomland hardwood forest was inundated at the 98.7 and 99.7 percentile flows.

Table 6.14 – Area (hectares) of vegetation inundated by proposed George Parkhouse II project, North Sulphur River; reservoir max pool elevation assumed 124m MSL.

Area 102	**Area (ha) of vegetation type by flow percentile**						**Total under**
George Parkhouse II	**68.6**	**76.7**	**88.3**	**94.3**	**98.7**	**99.7**	**reservoir**
Bottomland Hardwood	34.667	38.750	53.452	65.431	224.243	404.927	1433.669
Oak-Hickory	0	0	0	0	0.454	0.817	446.762
Cedar-Hardwood/Pine-Hardwood	0	0	0	0	0.091	0.908	47.644
Pure Pine/Cedar Grove	0	0	0	0	0.091	0.091	2.178
Pasture/Grassland	14.883	16.880	24.230	32.307	137.940	352.473	2628.211
Crops/Managed Pasture	0	0	0	0	0.272	0.272	24.049
Bare Soil/Ground	0	0	0	0	0	0	4.084
Secondary Bottomland Hardwood	7.169	7.351	8.712	11.525	59.441	102.729	548.493

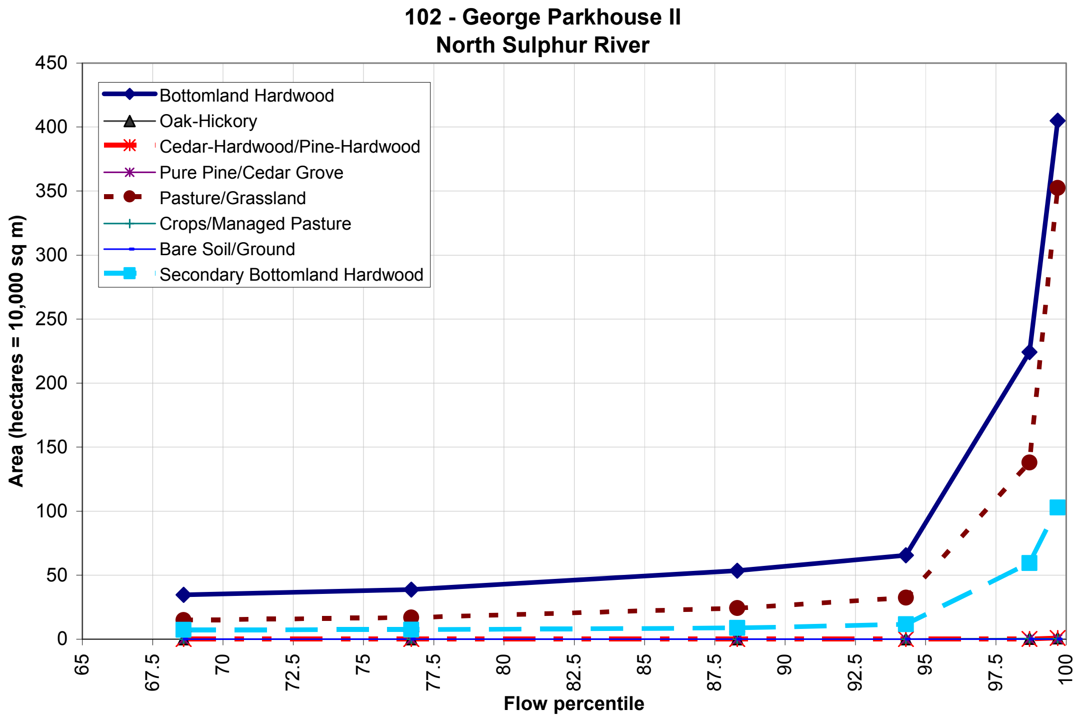

Figure 6.22 – Vegetation areas inundated by proposed George Parkhouse II project, North Sulphur River – by percentile.

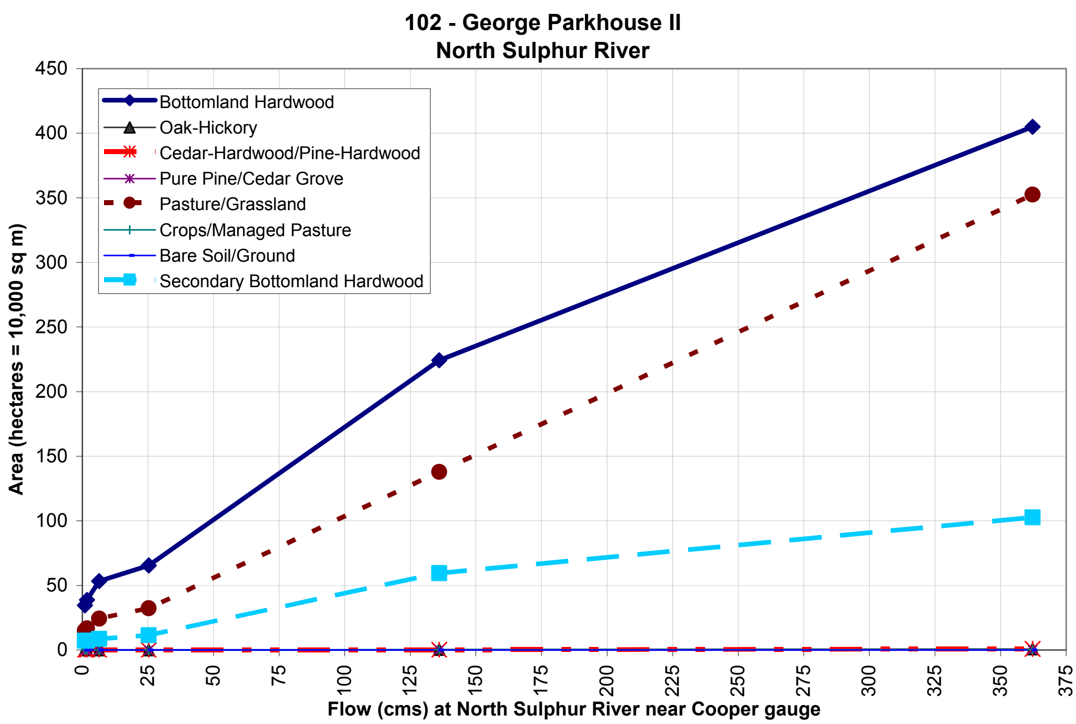

Figure 6.23 – Vegetation areas inundated by proposed George Parkhouse II project, North Sulphur River – by flow rate.

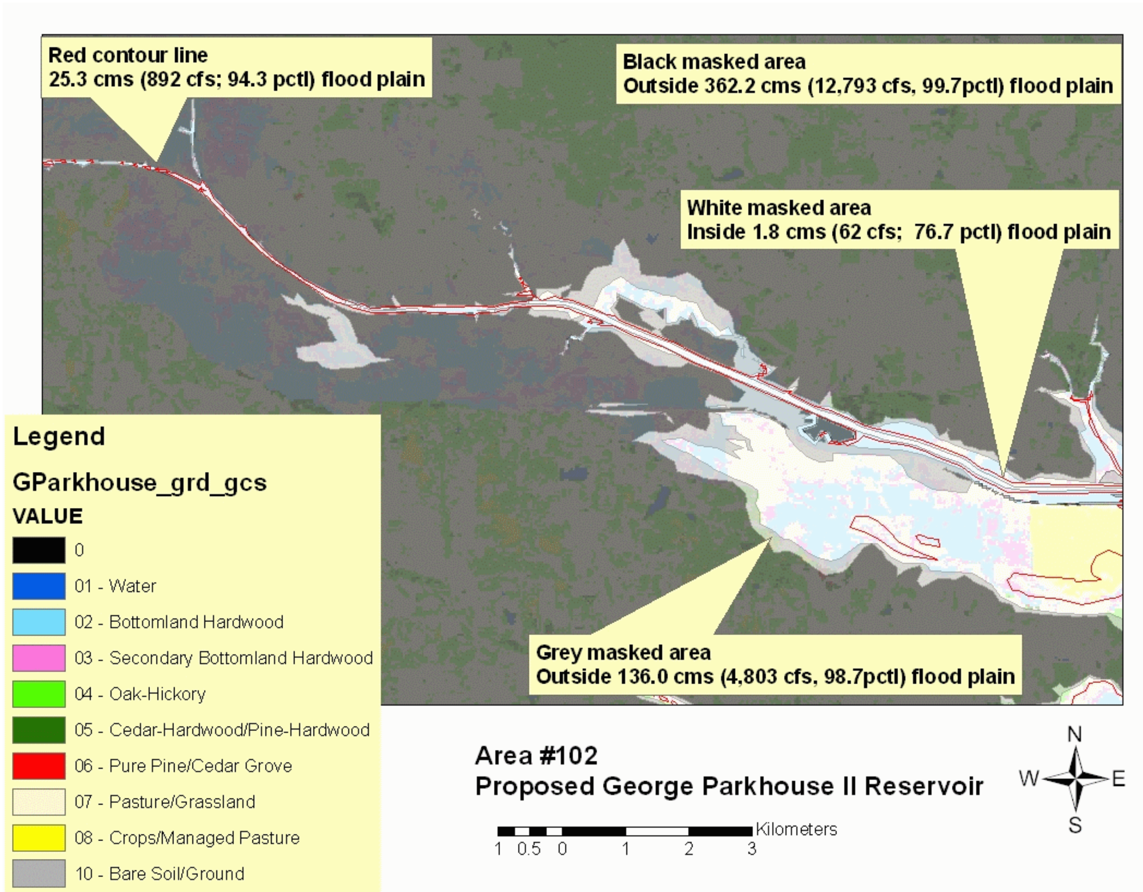

Figure 6.24 - Inundated area and vegetation map, Area 102.

6.5.4 North Sulphur River downstream of George Parkhouse II

Area number 100. This area is located along the channelized North Sulphur River, downstream of the site proposed George Parkhouse II alternative reservoir project. The upstream boundary is the proposed dam location and the downstream boundary is the confluence of the North and South Sulphur Rivers.

Flows between 94.3 and 98.7 percentile appear to overtop the banks to practically the full extent of the flood plain (Table 6.15 and Figures 6.25 and 6.26). In this area, those percentile flows represent flow rates of 25.25 cms (891 cfs) and 136 cms (4,803 cfs) at the USGS North Sulphur River near Cooper gauge (Table 6.7). Most inundated area is classified as crops or managed pasture, with bottomland hardwood area and pasture/grassland having nearly that same area.

Table 6.15 – Area (hectares) of vegetation downstream of proposed George Parkhouse II project, North Sulphur River.

Area 100	**Area (ha) of vegetation type by flow percentile**					
Downstream of George Parkhouse II	**68.6**	**76.7**	**88.3**	**94.3**	**98.7**	**99.7**
Bottomland Hardwood	4.447	12.705	51.546	106.178	337.772	392.494
Oak-Hickory	0	0	0	0.091	8.531	24.503
Cedar-Hardwood/Pine-Hardwood	0	0	0	0	1.906	2.178
Pure Pine/Cedar Grove	0	0	0	0	0	0
Pasture/Grassland	7.442	11.616	19.239	27.679	277.151	360.550
Crops/Managed Pasture	0	0	0	55.902	650.133	658.301
Bare Soil/Ground	0	0	0	0.000	0.182	2.450
Secondary Bottomland Hardwood	2.087	3.539	6.353	12.705	42.743	58.352

Levee elevations should be examined in this area and their accuracy in the topographic surface model should be verified. Since the flood surface extended behind leveed portions of the flood plain, the model may have recorded inundated area where the levee in fact protects that portion of the flood plain from inundation. A significant portion of the yellow Crops/Managed Pasture area shown to be inundated in Figure 6.27 is likely protected and remains uninundated for flows below the 99.7 percentile; this statement is contrary to the inundated areas presented in this report. All low-lying areas were identified as subject to flooding. Future studies of inundation extent should account for levee protection.

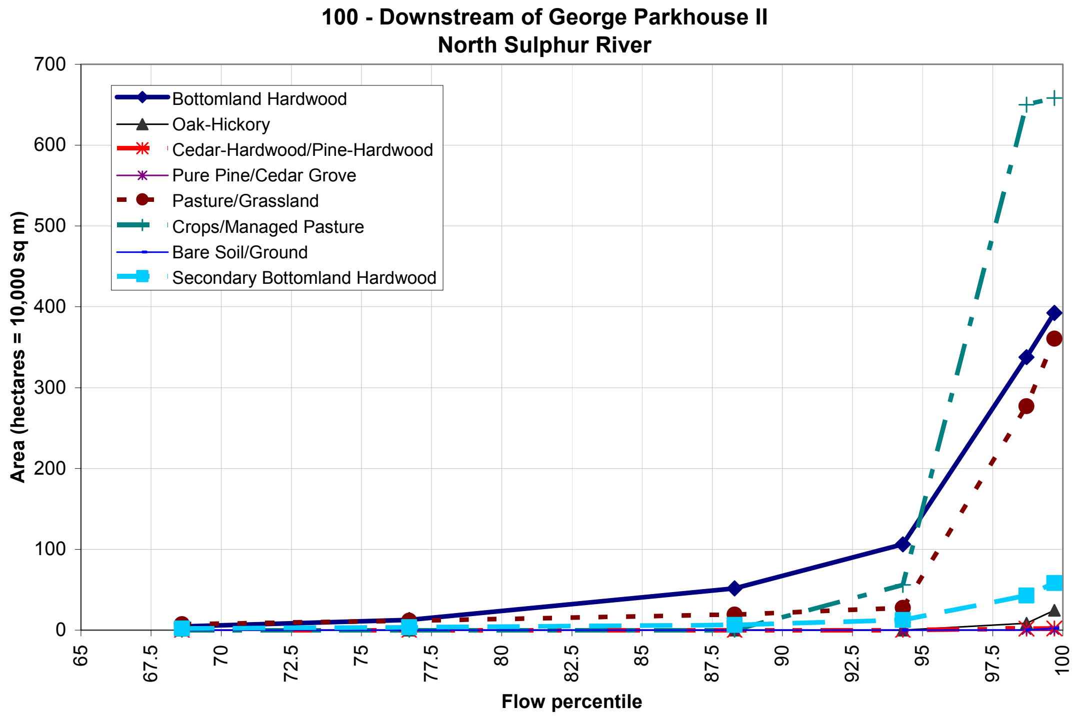

Figure 6.25 – Vegetation areas downstream of proposed George Parkhouse II project, North Sulphur River – by percentile.

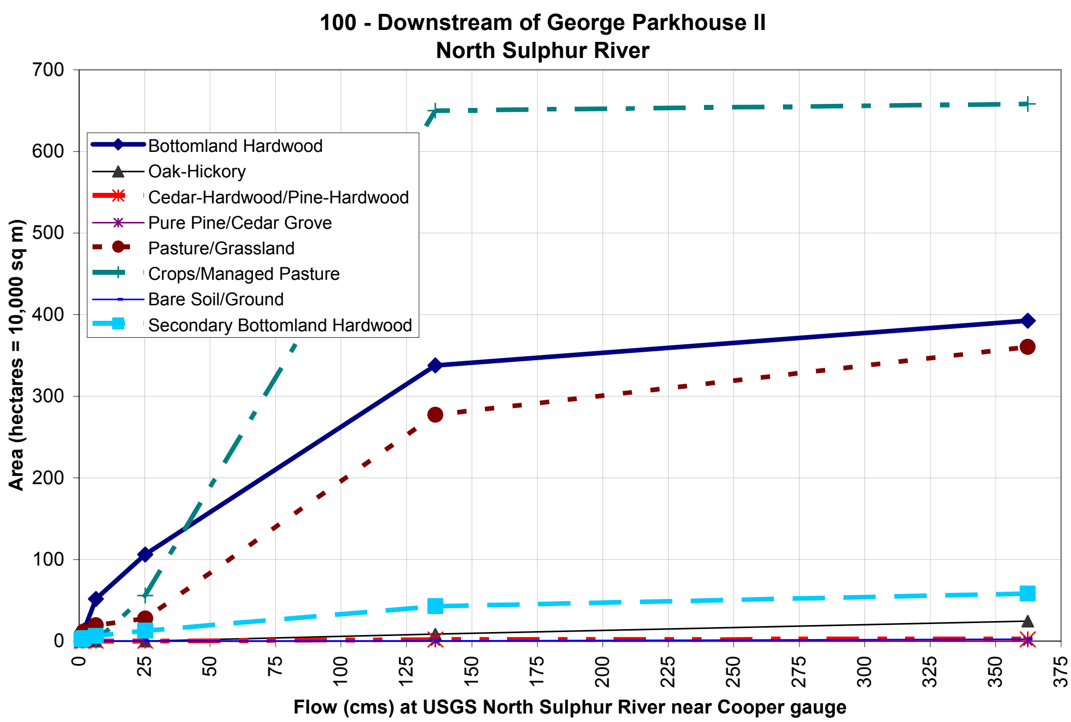

Figure 6.26 – Vegetation areas downstream of proposed George Parkhouse II project, North Sulphur River – by flow rate.

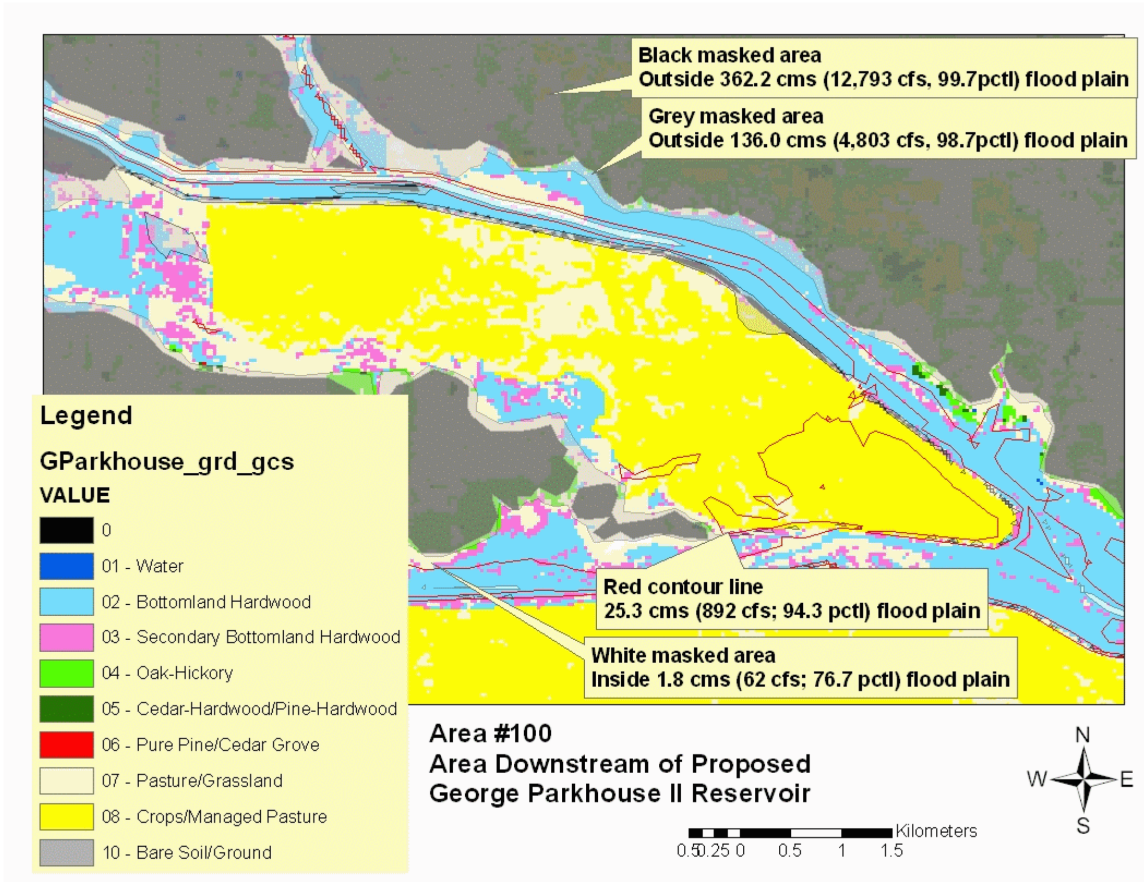

Figure 6.27 - Inundated area and vegetation map, Area 100.

6.5.5 Sulphur River upstream of Marvin Nichols I

Area number 200. This area consists of the channelized portion (upstream of SH37) and unchannelized portion (downstream of SH37/logjam) of the Sulphur River. The dividing line between channelization is approximately the SH37 bridge and embankment. The areas could be separated and viewed independently; however, significant uncertainty existed with respect to change of water surface elevation drop through the logjam area. The water surface was observed in the field to drop approximately 3” in 15’ through a narrow neck at low flows. At higher flows, water velocities appeared to exceed 10 fps through the neck; measurement was not possible because of the danger of the approach. Since uncertainty existed, these areas were lumped together for this analysis.

Flow rates near 76.7 percentile (24 cms; 862 cfs) begin to overtop the banks in the unchannelized portion of this reach and are considerably out of the banks at 85cms (Figure 6.30). This is consistent with the overbanking measurement conducted at TWDB Site 2 which determined overbanking flow to be roughly 22.6cms (800 cfs).

In channelized areas, inundation is contained within the banks for flows up to the 94.3 percentile (Figure 6.30). The elevation of levees in the area were not determined or incorporated into this study, but higher flows may exceed the levee elevation. Flows higher than 94.3 percentile inundate a significantly larger area than the area inundated by the 94.3 percentile flow.

Table 6.16 and Figure 6.28 illustrate the dominant vegetation type to be bottomland hardwood, with a mix of other forested land and agricultural vegetation. Much less swamp area is inundated in this area than in areas farther downstream. The channel is contained within its banks and little vegetation is inundated for flows below the 76.7 percentile and the maximum area of inundation of all vegetation types is approached when flow nears the 94.3 percentile (202 cms; 7,130 cfs at Talco) (Figures 6.29 and 6.30). The inundation of the crops and pasture land may be artificial; the simple flood surface model used in this analysis did not account for flood protection structures. All low-lying areas were identified as subject to flooding.

Table 6.16 – Area (hectares) of vegetation upstream of proposed Marvin Nichols I project, channelized main stem Sulphur River.

Area 200	**Area (ha) of vegetation type by flow percentile**					
Upstream of Marvin Nichols I	**68.6**	**76.7**	**88.3**	**94.3**	**98.7**	**99.7**
Bottomland Hardwood	58.171	169.975	1384.119	3074.519	3515.837	3760.589
Bottomland Hardwood Swamp	3.086	6.897	112.530	322.707	353.925	384.417
Oak-Hickory	5.717	15.972	195.476	647.320	887.626	1185.286
Cedar-Hardwood/Pine-Hardwood	0.272	1.361	10.527	49.731	94.017	145.563
Pure Pine/Cedar Grove	0	0	0.091	0.908	2.632	3.630
Pasture/Grassland	8.803	13.159	226.603	751.047	990.264	1326.311
Crops/Managed Pasture	0	1.906	248.837	829.818	859.675	860.310
Bare Soil/Ground	0	0	0	0	0	0

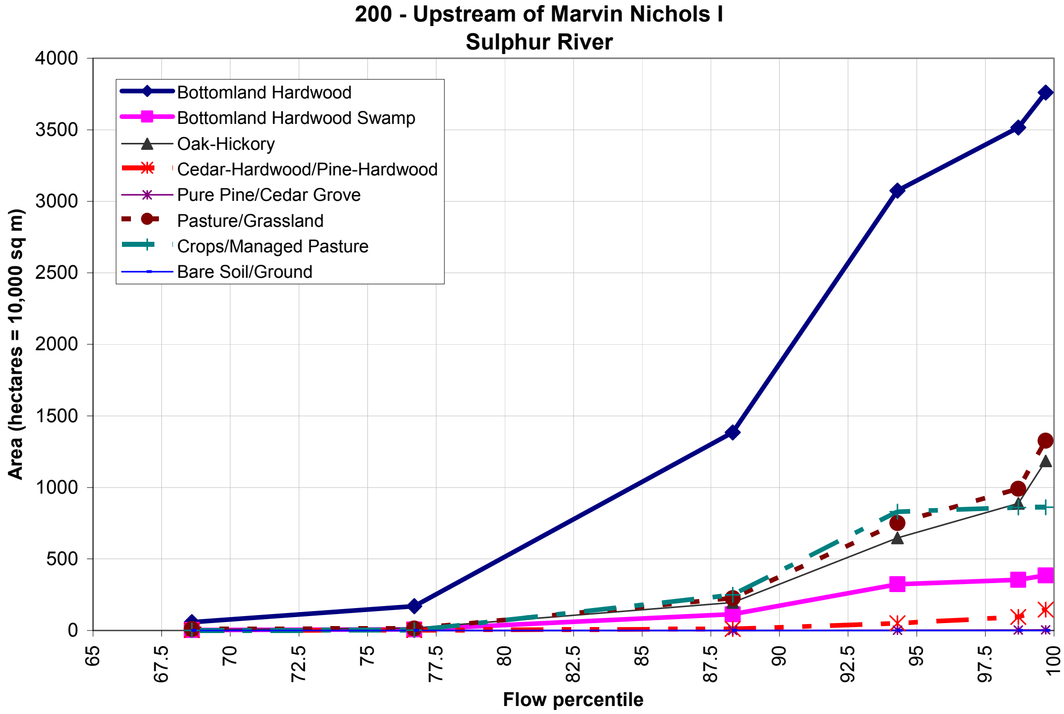

Figure 6.28 – Vegetation areas upstream of proposed Marvin Nichols I project, channelized main stem Sulphur River – by percentile.

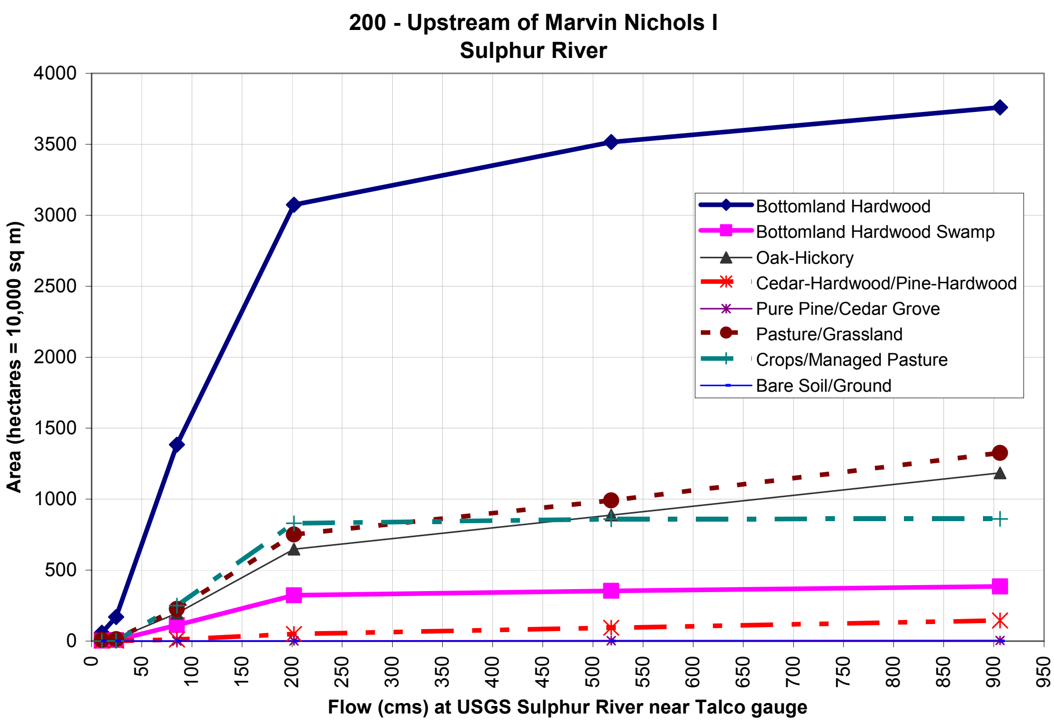

Figure 6.29 – Vegetation areas upstream of proposed Marvin Nichols I project, channelized main stem Sulphur River – by flow rate.

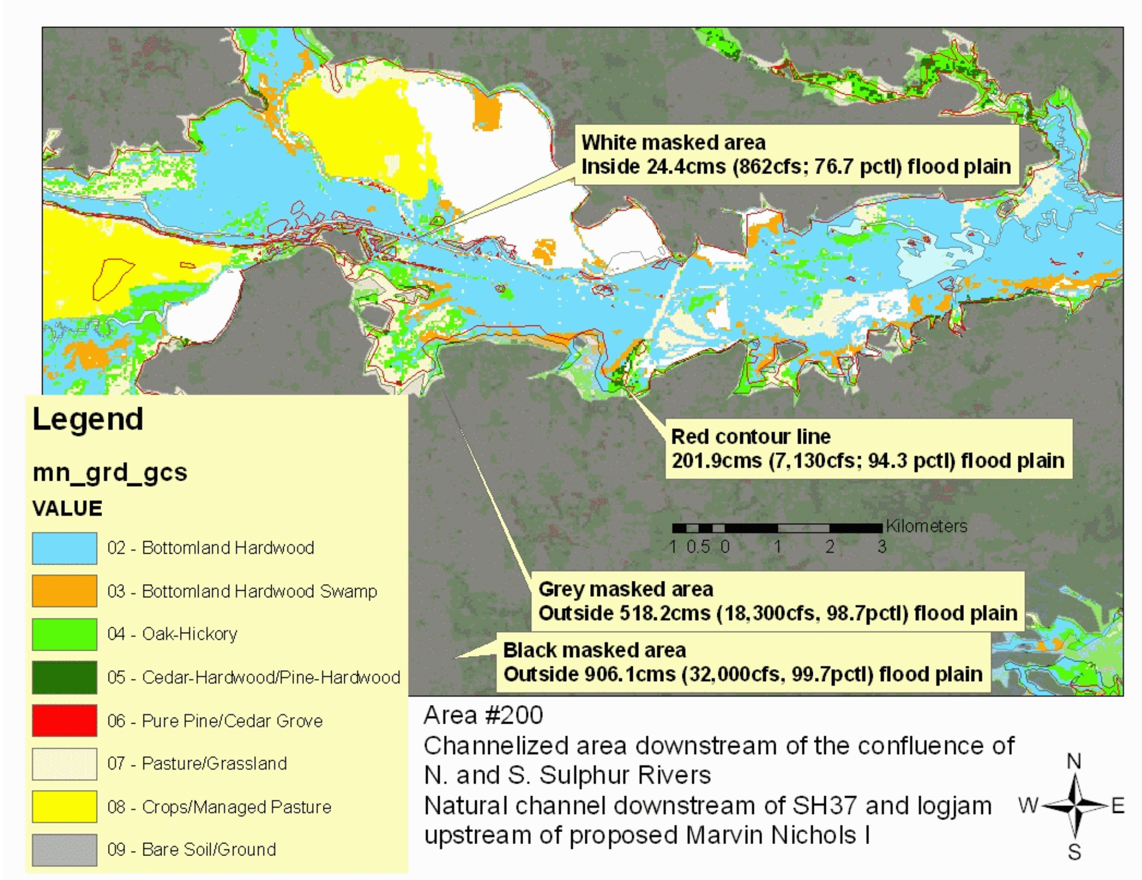

Figure 6.30 – Inundated area and vegetation map, Area 200.

6.5.6 Marvin Nichols I

Area number 201. This area is located on the Sulphur River and incorporates the area that would be inundated by the recommended Marvin Nichols I reservoir. The upstream boundary is located near the USGS Sulphur River near Talco gauge and the downstream boundary is located near the site of the proposed dam.

Table 6.17 and Figure 6.31 show limited areas of inundated hardwood for flows below the 76.7 percentile flow. Inundated area increases nearly linearly for flows between 88.3 and 99.7 percentile for bottomland hardwood. Similarly, bottomland hardwood swamp shows significant increase until nearly all of that vegetation type is inundated near the 94.3 percentile flow.

Table 6.17 – Area (hectares) of vegetation inundated by Marvin Nichols project, main stem Sulphur River; reservoir max pool elevation assumed 96m MSL.

Area 201	**Area (ha) of vegetation type by flow percentile**						**Total under**
Marvin Nichols I	**68.6**	**76.7**	**88.3**	**94.3**	**98.7**	**99.7**	**reservoir**
Bottomland Hardwood	288.857	782.174	3480.444	6351.139	7853.777	8177.846	9420.848
Bottomland Hardwood Swamp	120.788	363.908	2312.129	3473.093	3658.496	3674.195	3706.230
Oak-Hickory	2.632	8.894	72.872	434.330	959.863	1230.298	5600.364
Cedar-Hardwood/Pine-Hardwood	1.815	3.539	8.712	33.668	78.862	114.890	714.203
Pure Pine/Cedar Grove	0	0	0	0.091	0.363	0.545	24.140
Pasture/Grassland	1.543	4.265	29.766	143.204	316.718	439.321	3714.398
Crops/Managed Pasture	0	0	0	0	0	0	1.361
Bare Soil/Ground	0	0	0	0	0	0	0.272

Since the USGS Talco gauge is located immediately upstream, the inundated areas are plotted by flow rate (Figure 6.32). Nearly all of the bottomland areas are inundated for flows above 202 cms (7,130 cfs), the 94.3 percentile flow. This is further illustrated in the map of the area (Figure 6.33) where the red contour line for the waters edge of this flood is shown in many areas to be continuous with the contours for higher flood flows.

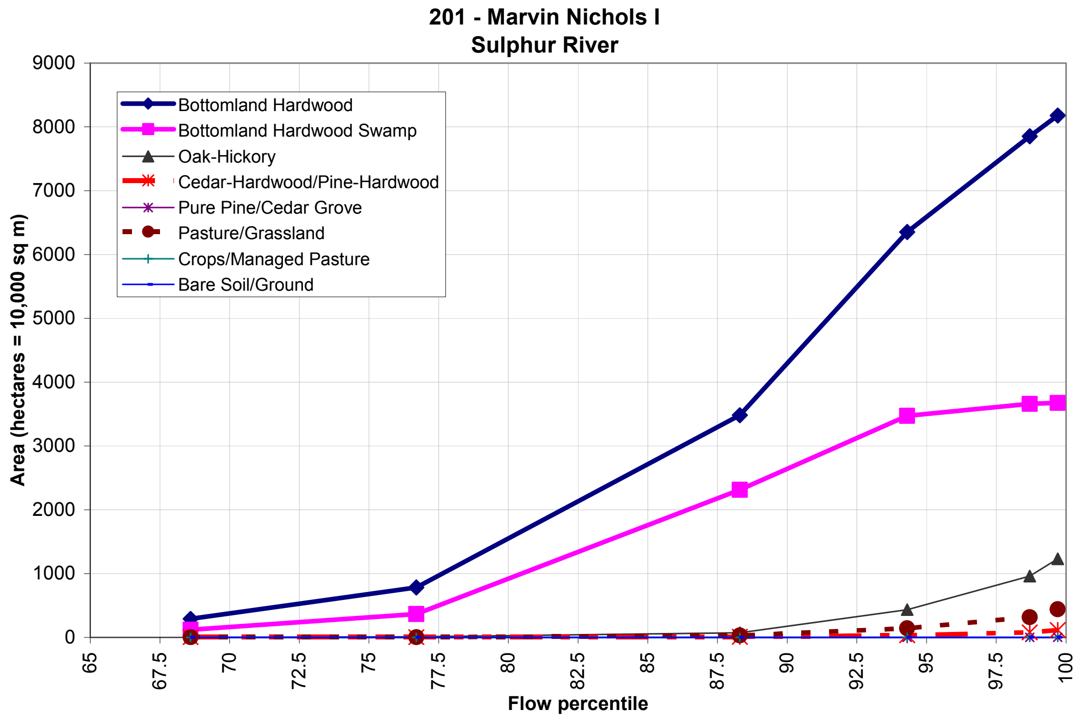

Figure 6.31 – Vegetation areas inundated by Marvin Nichols project, main stem Sulphur River – by percentile.

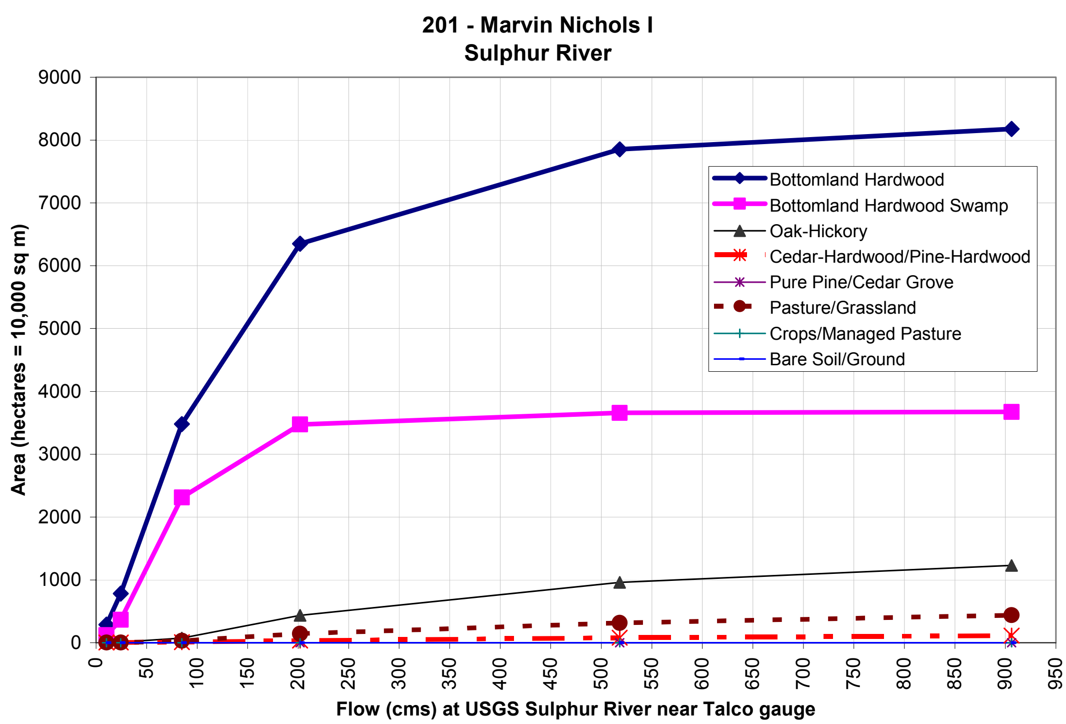

Figure 6.32 – Vegetation areas inundated by Marvin Nichols project, main stem Sulphur River – by flow rate

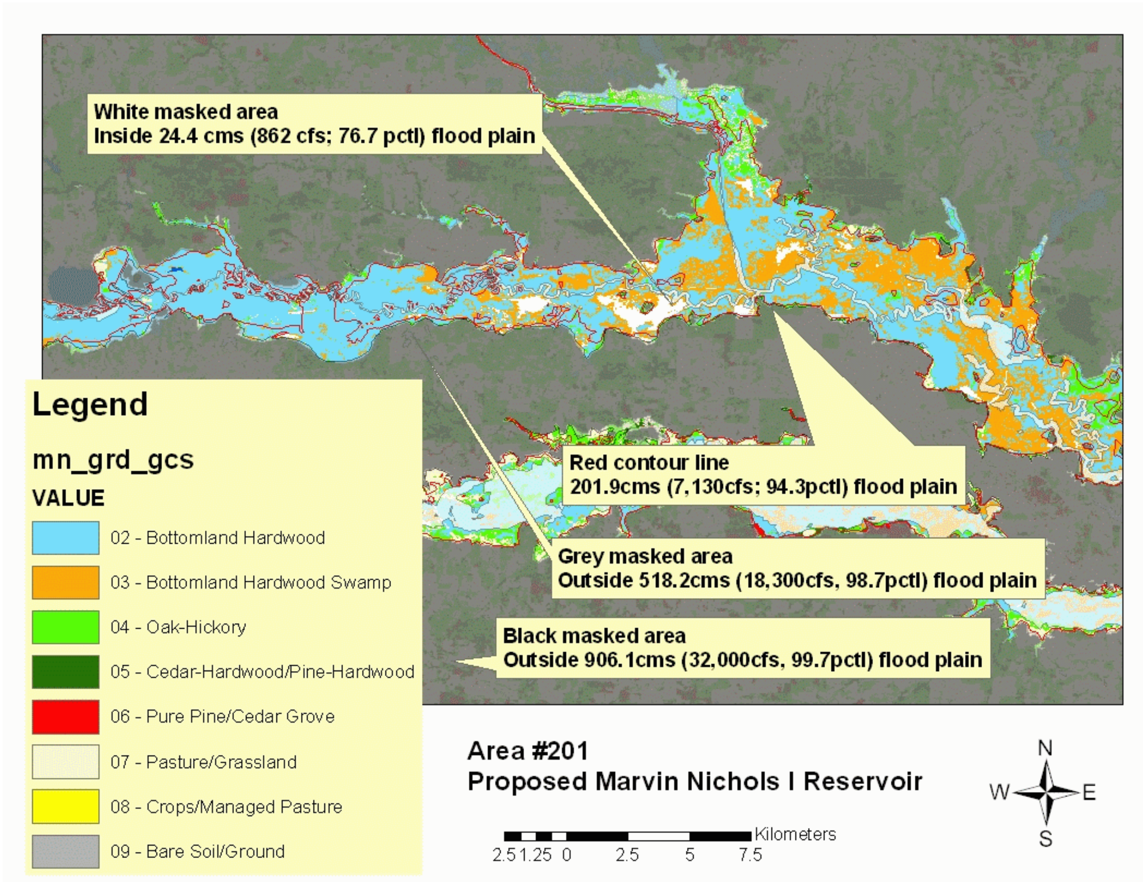

Figure 6.33 – Inundated area and vegetation map, Area 201.

6.5.7 Sulphur River downstream of Marvin Nichols I

Area number 210. This area is located on the Sulphur River, downstream of Marvin Nichols I proposed reservoir site and upstream of the confluence with White Oak Creek. TWDB Study Site 2 is located within the bounds of this area. Portions of this area encompass the White Oak Creek Wildlife Management Area (Figure 6.1).

Consistent with field measurements conducted at TWDB Site 2, overbanking is shown to occur at or below the 76.7 percentile flow (24.4 cms; 862 cfs at the Talco gauge) (Figure 6.35). Table 6.18 and Figure 6.34 also show that area is inundated for flows below the 76.7 percentile and increases significantly for flows higher than the 98.7 percentile. Bottomland hardwood and bottomland hardwood swamp are the two dominant vegetation types that are inundated and some Oak-Hickory forest is inundated under the higher flows.

Table 6.18 – Area (hectares) of vegetation downstream of proposed Marvin Nichols I project, main stem Sulphur River.

Area 210	**Area (ha) of vegetation type by flow percentile**					
Downstream Marvin Nichols I	**68.6**	**76.7**	**88.3**	**94.3**	**98.7**	**99.7**
Bottomland Hardwood	31.127	388.047	638.426	1341.739	1978.078	2106.126
Bottomland Hardwood Swamp	38.115	250.379	462.734	857.406	1011.772	1018.034
Oak-Hickory	0.091	1.180	5.717	41.110	170.247	294.484
Cedar-Hardwood/Pine-Hardwood	0.908	2.087	4.084	15.518	44.921	61.982
Pure Pine/Cedar Grove	0	0	0	0.091	0.363	0.726
Pasture/Grassland	0	0	0.272	5.808	30.855	57.354
Crops/Managed Pasture	0	0	0	0.091	0.363	0.363
Bare Soil/Ground	0	0	0	0	0	0

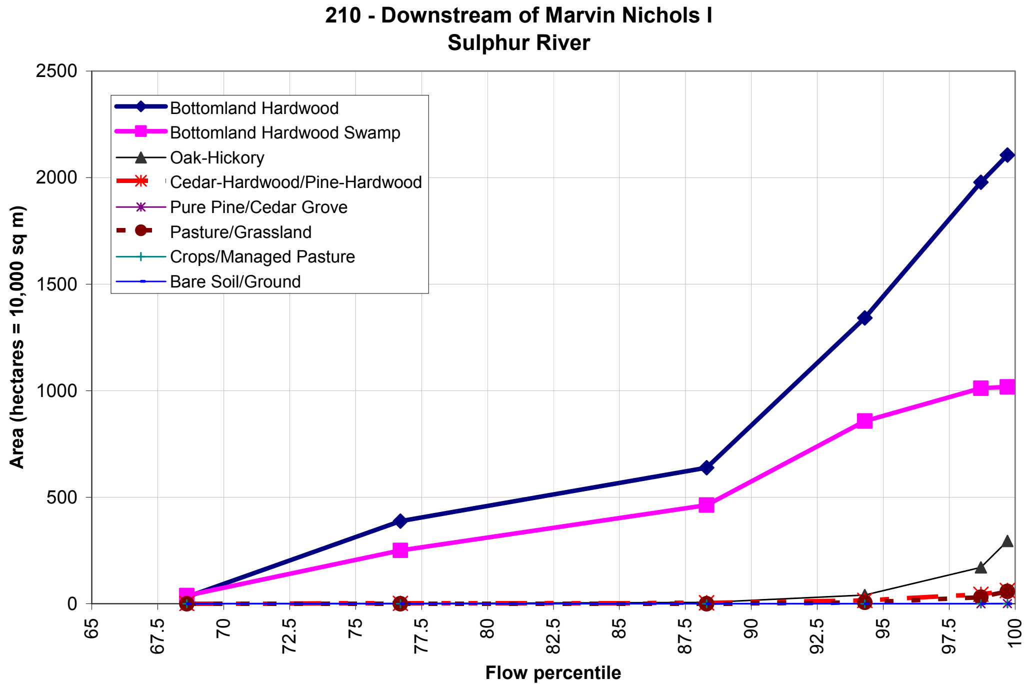

Figure 6.34 – Vegetation areas downstream of proposed Marvin Nichols project, main stem Sulphur River – by percentile.

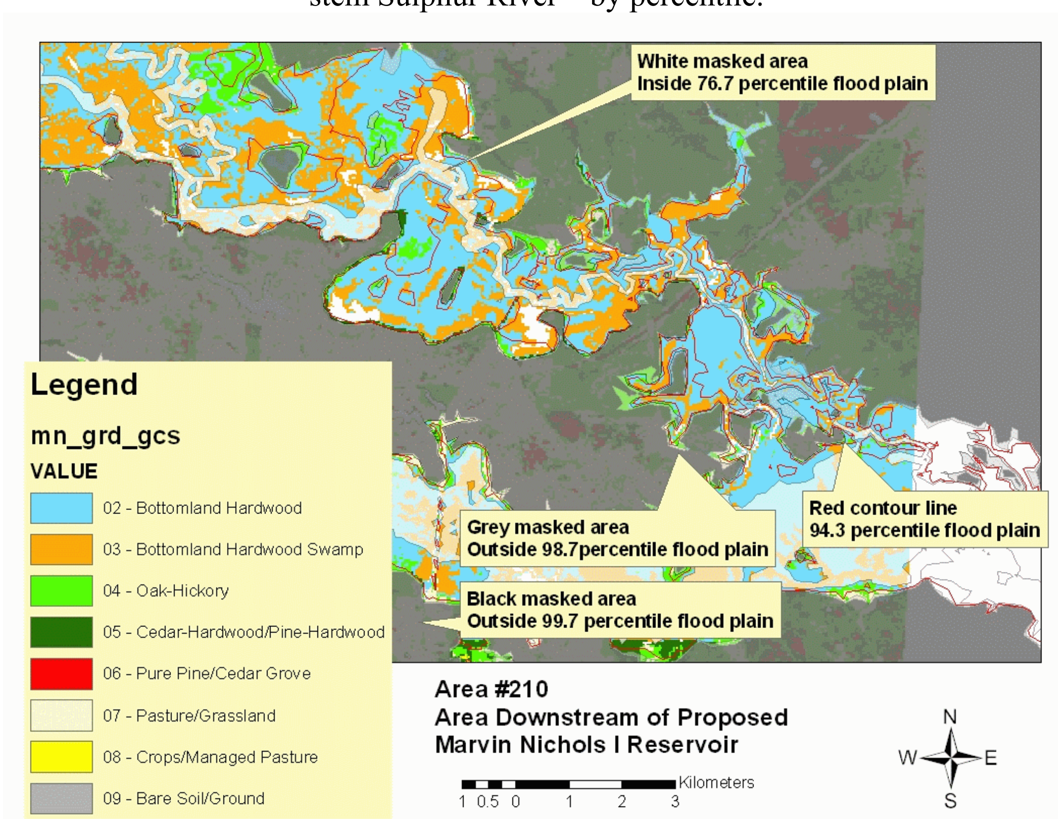

Figure 6.35 – Inundated area and vegetation map, Area 210.

6.5.8 Marvin Nichols II

Area number 202. This area is located in the White Oak Creek drainage. Portions of this area encompass the White Oak Creek Wildlife Management Area (Figure 6.1).

Proposed as a potential project, the Marvin Nichols II Reservoir site was never recommended in any state or regional water plan. Additionally, the site has been designated a Wildlife Management Area, so development is no longer possible. A10431 hectare (25,777 acre) area consisting mostly of bottomland hardwood forest located near the confluence of White Oak Creek and the Sulphur River has been designated as the White Oak Creek Wildlife Management Area. The area is included in this analysis because that data was available for presentation and because the accessible area presents a good opportunity for verification of the extents of inundated areas presented by this analysis.

Table 6.19 – Area (hectares) of vegetation inundated by proposed Marvin Nichols II project, White Oak Creek; reservoir max pool elevation assumed 124m MSL.

Area 202	**Area (ha) of vegetation type by flow percentile**						**Total under**
Marvin Nichols II	**68.6**	**76.7**	**88.3**	**94.3**	**98.7**	**99.7**	**reservoir**
Bottomland Hardwood	207.182	1650.652	3701.602	4297.829	4711.922	4785.883	4914.022
Bottomland Hardwood Swamp	20.056	550.580	939.444	982.006	991.353	992.261	992.714
Oak-Hickory	5.627	156.998	603.034	1054.061	1372.503	1516.614	3886.823
Cedar-Hardwood/Pine-Hardwood	0.182	1.271	15.065	33.578	52.635	79.860	581.345
Pure Pine/Cedar Grove	0	0	0.091	1.543	6.353	14.611	157.088
Pasture/Grassland	5.264	29.040	179.504	410.099	667.103	860.764	4350.464
Crops/Managed Pasture	0	0	0.091	0.091	0.091	0.091	1.452
Bare Soil/Ground	0	0	0	0	0.545	1.089	8.712

Table 6.19 and Figure 6.36 illustrate that bottomland hardwood is the dominant vegetation type occurring in this area. Bottomland hardwood swamp is less prevalent here than in areas farther downstream. Figure 6.37 illustrates the area of inundated vegetation by flow rate measured at the USGS White Oak Creek near Talco gauge. Most area of bottomland hardwood is inundated for flows above 75 cms (2,650 cfs).

The map shown in Figure 6.38 shows the inundated areas of 98.7 and 99.7 percentile flows to vary insignificantly. The 94.3 percentile flow inundates most of the river valley, and the 76.7 percentile flow inundates large, but isolated areas.

When number of occurrences per year of flood durations periods generated from Sulphur River at Talco gauge, the per-Cooper era should be used since the Jim Chapman Lake does not affect drainage in the White Oak Creek watershed.

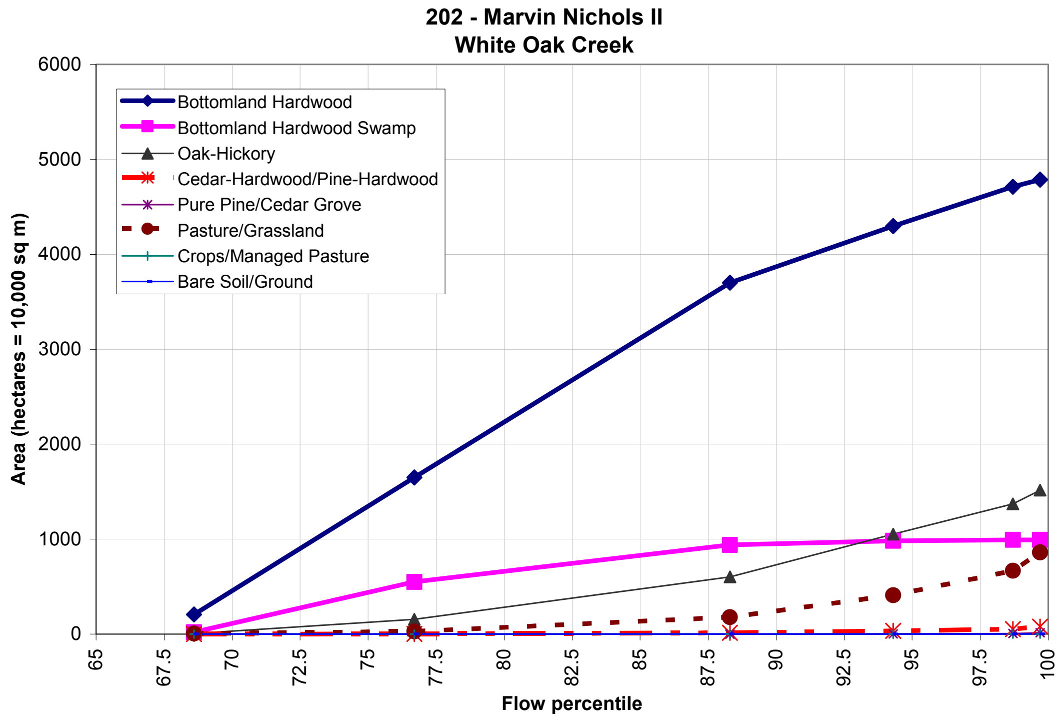

Figure 6.36 – Vegetation areas inundated by proposed Marvin Nichols II project, White Oak Creek – by percentile.

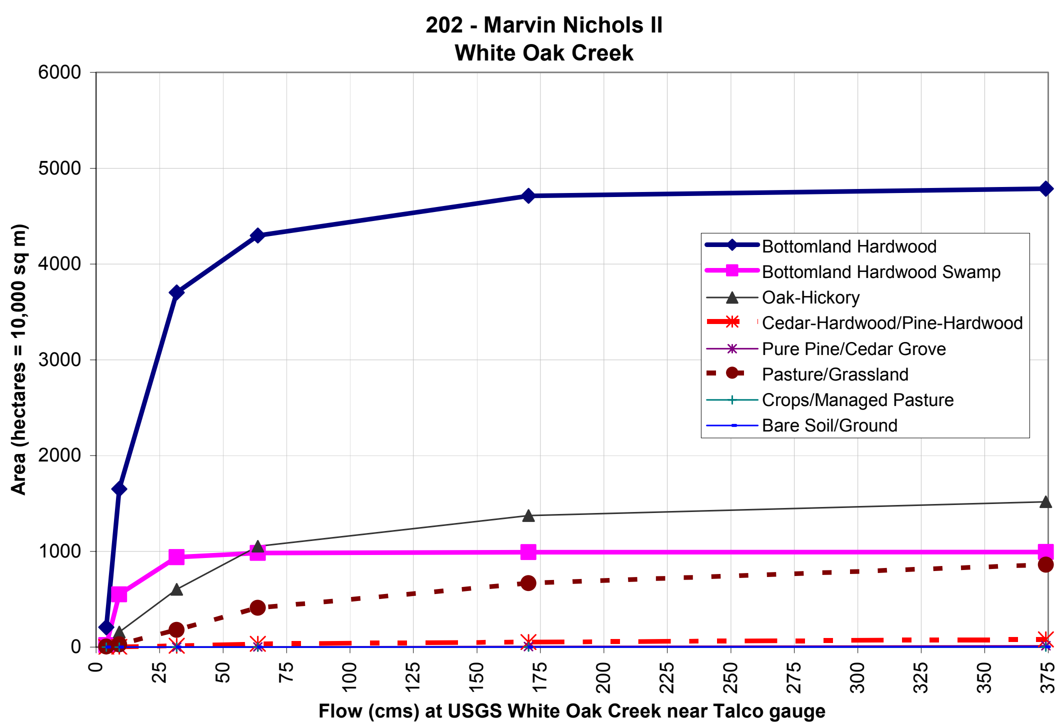

Figure 6.37 – Vegetation areas inundated by proposed Marvin Nichols II project, White Oak Creek – by flow rate.

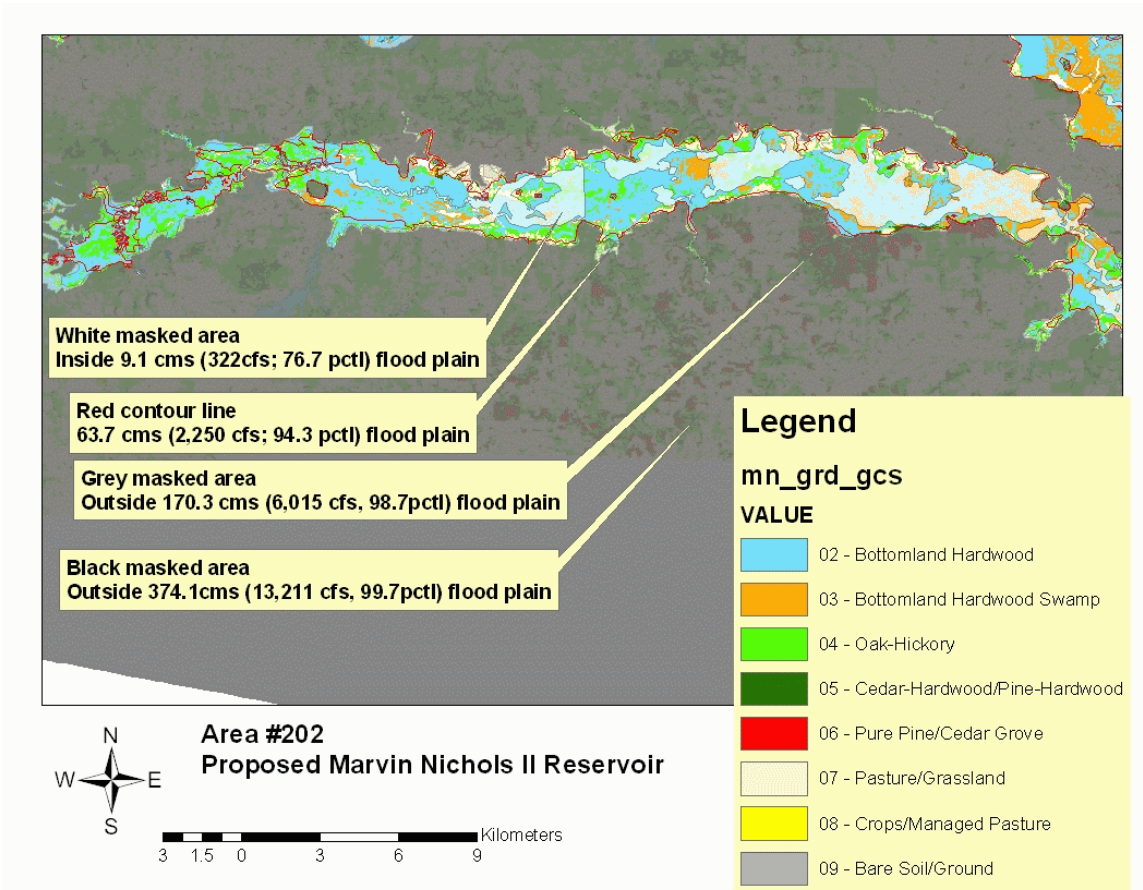

Figure 6.38 – Inundated area and vegetation map, Area 202.

6.5.9 White Oak Creek downstream of Marvin Nichols II

Area number 300. This area is located in the White Oak Creek drainage and incorporates areas just upstream of White Oak Creek's confluence with the Sulphur River. This area encompasses the White Oak Creek Wildlife Management Area (Figure 6.1).

As stated in the previous section, the Marvin Nichols II Reservoir site was never recommended in any state or regional water plan but the state-operated and easily-accessible White Oak Creek Wildlife Management Area presents a good opportunity for verification of the extents of inundated areas presented by this analysis.

Table 6.20 and Figure 6.39 illustrates that more than half of the bottomland hardwood and swamp areas are inundated with the 76.7 percentile flood. The area of Oak-Hickory forest inundated is small (approximately 3% of the inundated bottomland area), but increases significantly at the 99.7 percentile flow (approximately 25% of the inundated bottomland areas).

Table 6.20 – Area (hectares) of vegetation downstream of proposed Marvin Nichols II project, White Oak Creek.

Area 300	**Area (ha) of vegetation type by flow percentile**					
Downstream Marvin Nichols II	**68.6**	**76.7**	**88.3**	**94.3**	**98.7**	**99.7**
Bottomland Hardwood	73.689	805.134	1170.403	1285.837	1340.287	1351.086
Bottomland Hardwood Swamp	27.044	741.065	902.055	924.107	928.645	928.826
Oak-Hickory	0.454	44.921	148.649	274.700	413.911	495.495
Cedar-Hardwood/Pine-Hardwood	0	1.452	9.438	31.400	51.183	64.251
Pure Pine/Cedar Grove	0	0	0.091	0.454	0.635	1.089
Pasture/Grassland	0.363	7.986	30.764	88.391	194.296	278.512
Crops/Managed Pasture	0	0	0	0.182	0.998	1.089
Bare Soil/Ground	0	0	0	0	0	0

Figure 6.40 shows that the extent of inundation for the 76.7 percentile flood occupies a significant out-of-channel area. The extents of inundation for the 88.3 percentile flood are approximately 30% smaller than the 99.7 percentile flood, indicating existence of a well-defined river valley. Almost the entire valley is inundated by the 88.3 percentile flood, which occurs more than once per year for extended durations.

When number of occurrences per year of flood durations periods generated from Sulphur River at Talco gauge, the pre-Lake Jim Chapman era should be used since Lake Jim Chapman does not affect drainage in the White Oak Creek watershed.

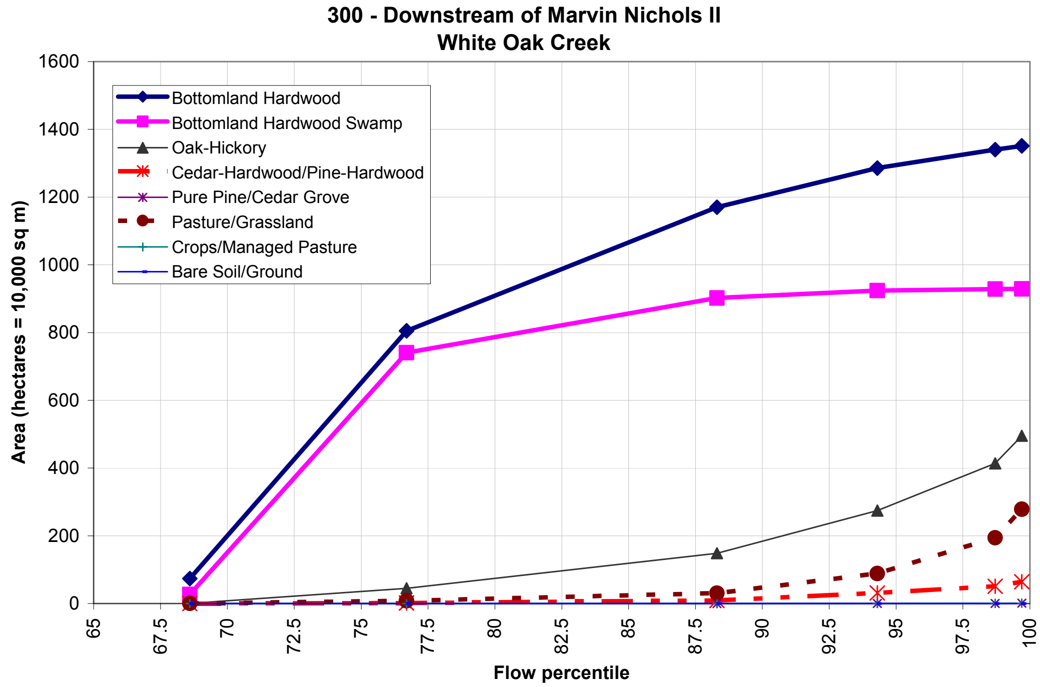

Figure 6.39 – Vegetation areas downstream of proposed Marvin Nichols II project, White Oak Creek.

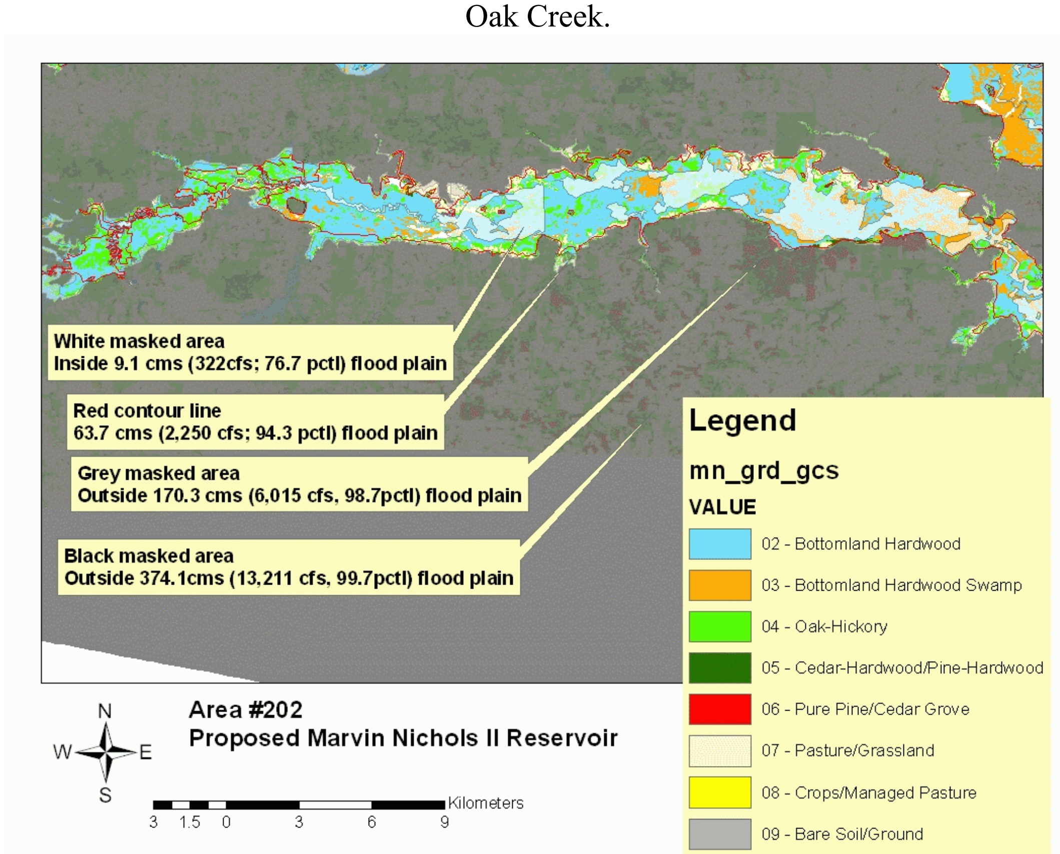

Figure 6.40 – Inundated area and vegetation map, Area 300.

7. Conclusions and recommendations

Directed towards the larger goal of identifying impacts of potential reservoir sites on the Sulphur River, this report presents baseline information on the South and mainstem Sulphur River and presents previous work performed in the basin by the TWDB and partners at Texas A&M University. The input from and cooperation with US Army Corps of Engineers, Texas Commission on Environmental Quality and Texas Parks and Wildlife Department was appreciated and enhanced this analysis.

This report also presents new analyses with respect to hydrology, fish habitat and flood plains (including bottomland hardwood forest) of the Sulphur River. While the work completed to date is considerable, the authors recommend that additional work be performed before flow regime decisions are made that affect future water rights permits in the Sulphur River basin. Future studies will include recommendations that consider maintenance of aquatic habitat and riparian bottomland hardwood forestsin the Sulphur River basin.

7.1 Conclusions

This section summarizes findings included in this report with respect to hydrology, aquatic habitat, hydraulic modeling and floodplains. A total of thirteen biological sites were sampled for fish habitat utilization on both channelized areas and unchannelized areas; sites were chosen on the South Sulphur River which would be directly impacted by the George Parkhouse I reservoir site, and sites on the Sulphur River which would be impacted by the Parkhouse projects and the Marvin Nichols I proposed site.

Two study reaches, Site 1 and Site 2, were chosen for intensive analysis and modeling of aquatic habitat. Study reaches were determined to be representative of the South and mainstem Sulphur River, respectively for each reservoir site, and each site incorporated two biological sampling sites. Intensive studies were performed with respect to hydrology, hydraulics, and fish habitat utilization.

Modeling of areas inundated by frequently occurring flood events (those that have recurred more often than every three years) was performed to determine the frequency, duration, area and impacted vegetation types.

7.1.1 Hydrology

The USGS Sulphur River at Talco, TX, gauge (# 07343200) was used to investigate historical stream flow in the Sulphur River. The gauge was located in the geographic center of the study region and was used to describe the historical flow regime in the Sulphur River. The gauge was not found to be an exact descriptor of flow conditions far upstream (Site 1) or far downstream (Site 2), but the gauge was a good indicator of flow rate at each study site after accounting for time of travel and flood peak attenuation.

Using the entire historical data record, the median flow at Talco was 2.21 cms (78 cfs) and the 7Q2 flow was 0.03 cms (1.07 cfs). Looking at the historical flow record by month, the median flow by month during the months of July through October has been near the 7Q2 flow which is significantly less than median flows experienced in other months of the year. February, March and May exhibited significantly higher flow than the annual median. For thirteen years in the historical record the peak flow event was observed higher than 1,133 cms (40,000 cfs); for eighteen years on record the peak flow was lower than 850 cms (30,000 cfs) (Figure 2.11).

The historical flow record was broken into two eras to compare the flow regime existing before construction of Jim Chapman Lake (formerly Cooper Reservoir) (pre-1990 era) to the most recent era (1992 to 2003). Low flow and high flow events occurred more frequently in the early era, corresponding to flood attenuation and minimum releases from Jim Chapman Lake (Table 2.1); however, the differences in the frequency of occurrence were notable for flow rates less than the 20 percentile and for those flow rates greater than the 90 percentile.

7.1.2 Aquatic habitat

Four study reaches were established for biological sampling on the South Sulphur and the Sulphur Rivers (channelized and unchannelized reaches). Each reach was sampled for fish habitat utilization at different flows and seasons. Using the same sets of data collected on those reaches, five analyses of fish habitat utilization in the Sulphur River were presented in this report. Gelwick and Morgan (2000) and Morgan (2002) examined fish habitat utilization on the basis of visually classified mesohabitats identified within the mainstem of the Sulphur River. Similarly, Gelwick and Burgess (2002) and Burgess (2002) examined fish habitat utilization in channelized and unchannelized reaches of the South Sulphur River. The TWDB in this report examined all of the data in each of the study reaches for all seasons and flows, investigating fish habitat utilization on the basis of hydraulically defined mesohabitats and sub-mesohabitats. The TWDB also presented a spatial GIS model capable of quantifying the area of those habitats available over a range of flow rates.

Gelwick and Morgan (2000) and Morgan (2002) both reported the fish species within the riverine communities to be habitat generalists. Similarly, TWDB showed a large degree of habitat generalization, but also showed consistent use of some mesohabitats and sub-mesohabitats by some species. The utilization of large woody debris (LWD) within these habitats was also found to be an important factor influencing the distribution of the fishery. The four mesohabitats (pool, run, riffle, backwater) were combined with the four structural habitats (i.e., open water, edge, bank snag, channel snag) to describe a total of sixteen different structural sub-mesohabitat areas. Species-specific associations were identified for several of these habitats. Therefore, a hydraulically-based classification of habitat proved effective in better understanding fish relationship to their habitat.

Species relationships to sub-mesohabitat conditions were evident for some species, and fish indicators were determined. For instance, the bullhead minnow was only found in backwater edge habitats, consistent with descriptions noting it as an omnivorous species that feeds on or near the bottom of sluggish rivers on a diet of insects, algae, and other plant material that are abundant in backwater edge habitat (Starrett 1950). Some fish species indicators have specialized body shapes and feeding strategies that are particularly suited for a habitat condition.

Fluvial specialist fish species collected during this study include the freckled madtom and mimic shiner, which were both found in fast-waters and riffle habitat (Morgan 2000; Burgess 2002). Since these habitats are very limited hydraulic habitats in the Sulphur River system, fluvial specialist species should be studied in the future in combination with assessments of that habitat. Rare species collected during this study include the alligator gar, shortnose gar, emerald shiner, blackstripe topminnow, pirate perch, and black crappie.

Aquatic mesohabitats and sub-mesohabitats were defined based upon depth, velocity, location, and structural composition within the study reach. The area of each sub-mesohabitat was quantified by combining within a GIS environment the habitat definitions and hydraulic model output. Verification of the habitat model was performed. The habitat criteria were shown to match visually classified habitat (Figure 5.6); however, the spatial field data associated with the fish samples was insufficient to quantitatively verify the GIS model. Qualitative inspection showed fair correspondence between hand-drawn field maps and GIS spatial habitat outputs (Appendix O).

7.1.3 Hydraulic modeling for aquatic habitat

Hydraulic modeling using RMA-2 generated steady-state depth and velocity data throughout Site 1 for use in the GIS habitat model. The resolution of depth and velocity points was the highest resolution deemed possible considering the source bathymetry data, the domain of nearly 50,000 nodes and the assumptions incorporated into the hydrodynamic model. The calibrated model performed satisfactorily and generated reasonable depth and velocity fields (see verification in Appendices M and Q).

7.1.4 Periodic flood plain inundation

Bottomland hardwood forest ecosystems have reportedly been lost at an accelerated rate over the past 50 years in southern states (Gosselink and Lee 1989), with only about 20 million hectares (ha) remaining out of an historical area of over 100 million ha. Most of the loss has reportedly occurred because of clearing for row crop production, although hydrologic modification by water resource development (esp. flood control projects) has also had an important impact (Gosselink and Lee 1989). Impoundments and other water-level modifications should be based upon an understanding of local plant succession since changes in water regime may modify plant species and seriously impact the bottomland wetland communities (Weller 1989). The TWDB study provides baseline information on the floodplain hydrology that can be related to plant succession in the bottomland hardwood forest community for future studies.

The area of inundation was quantified for six frequently-occurring flood events in order to investigate the significance of flow regime on flood plain riparian areas. Each flood event ranged from a flow rate historically occurring once every three years to events that were shown to occur several times a year, each event lasting at least 14 continuous days. A TPWD study completed under contract with TWDB (Liu et al. 1997) enabled the inundated area of each vegetation type in the basin (e.g., bottomland hardwood forest, Oak-Hickory forest, etc.) to be quantified, and the analysis presented in this report enabled the frequency and duration of occurrence of inundation to be quantified. The primary vegetation types shown to be inundated by the frequently occurring flood flows were bottomland hardwood and farm land (crops and pasture). Additional topographic and time-series stage data would improve this preliminary analysis.

7.2 Recommendations

This section provides recommendations to improve the design for future studies in the Sulphur River basin. Also discussed are some issues that were not easily incorporated in other sections but probably warrant further investigation before determining the instream flow requirements for projects in the basin. This list of recommendations is based on the work presented in this report and is not intended to be a comprehensive list of tasks for future instream flow studies.

7.2.1 Hydrology

Wherever possible, investigation of historical statistics of intra-annual flow variation is recommended for purposes of comparing pre-development flow conditions to post-development flow conditions.

Field verification is recommended of gauge datum elevations for gauges used in slope and riparian inundation analyses.

A time-series flow and habitat analysis that accounts for the proposed operation of proposed projects is recommended. This would enable an analysis of the probability of exceedance of available habitat area which would enable comparison between the pre- and post-development conditions.

7.2.2 Aquatic habitat

7.2.2.1 Habitat sampling recommendations

A significant field sampling effort was performed over the course of this multi-year, seasonal study. Future studies that assess the effects of inter-annual flow variation (wet year, dry year, median year) would provide additional insight.

For future fish habitat studies, reporting of each fish sample is recommended to include the following data: date, sampling gear type, begin time, end time, environmental parameters, substrate, depth and velocity at three locations, GPS position (at depth/velocity locations), area sampled, photograph and additional notes as necessary. Collection of accurate sampling location information is important for verification of both a hydraulic model and a GIS habitat model.

Sampling of an even distribution of habitats is recommended. Additionally, improved sampling of habitats with large woody debris would improve our understanding of the function and benefit it provides to the fishery.

Sampling a range of flow conditions and a range of seasons is also recommended. Field sampling over a range of wet-dry periods to determine how fish respond to flood and drought flows would be helpful to determine how they distribute themselves after fluvial extremes. Spawning season was not targeted for fish collections. Future studies should target flow ranges not covered by the existing data set and to target important life-cycle periods.

Fish size and spawning condition are important considerations and should be recorded when possible. In addition, fish sampling techniques should be limited to those capable of being standardized.

7.2.2.2 Habitat analysis recommendations

Both Morgan (2002) and Burgess (2002) included rigorous statistical analysis and interpretation of fish utilization trends using the visually classified mesohabitats. These studies both found that fish species were habitat generalists. TWDB found evidence of habitat specialization for some fish when mesohabitats were further divided by velocity and depth into mesohabitats and then further divided into structural sub-mesohabitats. The results of TWDB's findings, however, are not easily comparable with the prior studies because the data was not subjected to similar statistical analyses. It is recommended that future studies incorporate hydraulically classified habitat analysis with the rigorous statistical testing used by Morgan (2002) and Burgess (2002).

For investigation of river and stream biological conditions, an IBI analysis using the standard refined regional protocols developed by the Texas Parks and Wildlife Department is recommended in the Sulphur River. Patterns of community organization related to habitat availability and quality, water quality, environmental conditions, and land use are critical to understanding the responses of fluvial systems to alterations in flow regimes.

Sampling procedures for large rivers need to be standardized for different gear types implemented in different depths. Quantitative ecological assessments and statistical analyses require standardized data.

7.2.2.3 Additional aquatic analyses

Macroinvertebrates are an important structural component of river systems and have been frequently used to evaluate the environmental stresses in streams, evaluate functional feeding group composition, and apply to EPA's Rapid Bioassessment protocols to determine effects of various types of impacts. In other river basins, macroinvertebrates showed important differences in secondary production in stream reaches with woody structure, and as a result the relationship between fish and woody structure and the macroinvertebrate community are recommended for future analysis. Our studies and those of our contractors have shown that changes in fish and macroinvertebrate communities along a gradient of increasing habitat heterogeneity and area/volume are important for environmental flow assessment. Spatiotemporal variation in fish-habitat associations is influenced by both stochastic and deterministic processes, which need further analyses.

7.2.3 Hydraulic modeling for aquatic habitat

7.2.3.1 Field data within the bounds of an intensive analysis site

Increased resolution of bathymetric data would improve hydraulic model mesh and also improve the depth aspect of the GIS habitat model. The resolution of the bathymetry data used for this large-river project was suitable for describing square grid habitats with dimensions of approximately 3 meters x 3 meters (10 feet x 10 feet). If increased resolution is required, use of navigational aids during data collection is recommended. If extremely high-resolution bathymetry is required, use of a multi-beam echosounding equipment is recommended, but is only feasible in waters greater than 2m (6 feet) deep, thus making it largely unsuitable for the Sulphur River.

Sufficient echosounding is recommended to resolve bathymetry variation in and around LWD and channel structures. The data filtering tools developed for identification of submerged structures (White et al. 2004, White and Hodges 2004) should be utilized to remove spikes from bathymetry data.

The boundaries for the hydraulic mesh were generated using a combination of the bathymetry field data, GPS water edge data and DOQQ aerial photos. To improve the model mesh and to provide additional model verification data, a significant number of water edge location measurements are recommended for a range of flow rates.

Acoustic flow measurement data was used to determine flow rate on site. Use of the acoustic instrumentation throughout the site is recommended for a range of flow rates. Such data is recommended for verification of the hydraulic models.

Installation of non-vented pressure transducers to continuously measure water level at multiple sites throughout the study site is recommended. Installation of a barometric pressure sensor on site is required to adjust for fluctuation of atmospheric conditions.

Installation of semi-permanent benchmarks located high on the river bank, higher than the stage predicted for a 2-year flood event, is recommended.

Quantitative substrate mapping is recommended to improve habitat descriptions and to better calibrate the effect of bed roughness on hydraulics. Similarly, submerged or partially submerged debris and structure mapping is recommended.

7.2.3.2 Note on ephemeral nature of bed forms

The bathymetry data for both study reaches was collected in five days by TWDB. Apart from the obvious timesaving to TWDB staff, an advantage to collecting all the data in a short period of time is that the change in water surface elevation experienced during data collection is likely minimal as are any changes that may have occurred to the geometry of the riverbed. Subtle changes occur to both the composition of the substrate and its shape with changing flow conditions. Of course large flood events cause dramatic changes, and may even change the course of the river.

This analysis is based on the data collected at the time it was collected. It is assumed that at some time in the future, the results will still be representative of the Sulphur River downstream of the proposed reservoir sites experiencing this flow regime, but reallocation of storage from flood to conservation pool in the existing reservoirs (Jim Chapman Lake and Wright Patman Lake) may result in alterations of the current flow regimes.

Additionally, bathymetry data was collected at a medium-to-high flow. Bed forms existing at such flows may be different than those existing at low flow. Since low flow analysis is one primary objective of instream flow studies, an investigation of the relationship of bed forms and/or substrate to flow rate is recommended. However, cohesive substrate, as found in most areas of the Sulphur River, is not as susceptible to cyclic changes evidenced in sand-bed channels.

7.2.3.3 Note on hydraulics near large woody debris

Evaluation of habitat in rivers with extensive large woody debris (LWD) is problematic. While the importance of LWD for certain fish species has been clearly demonstrated (Angermeirr and Karr 1984; Benke et al. 1985; Lobb and Orth 1991), the large and small-scale effects of LWD on flow and local velocity are particularly difficult to both measure and model. In terms of the hydrodynamics, there are four major issues (Hodges, pers comm., 2002):

1. The scale of the LWD is generally many times smaller than the resolvable flow scales in a typical hydraulic model for a river.
2. The flow effects of LWD are inherently 3D, while hydraulic models currently used for instream flow studies are either 1D or 2D.
3. Flow effects around LWD vary with depth of submergence.
4. LWD is fundamentally ephemeral, so requires either continuous field surveying, acceptance of a “snapshot” in time, or a model, which predicts the collection/removal as a function of river discharge through time.]

The presence of LWD in the Sulphur River modifies the flow (in some places significantly, especially on Site 2) and results in significant changes in the velocity distribution within the water column; however, the resolution of the hydraulic model is not capable of simulations that fine. The areas where a large amount of debris had accumulated were treated as areas with increased roughness.

Main-channel reservoirs, such as those proposed on the Sulphur River, have the possibility of dramatically changing the presence of woody debris in a river; much more so than off-channel impoundments. There are two reasons for this: a) the dam can physically stop LWD from moving downstream from the upper reaches and b) online reservoirs can contain the major floods that tend to uproot trees from the river banks and result in their entrainment into river channels. Neither of these possibilities was considered in this study. Because of the importance of LWD in the Sulphur River, it is recommended that studies assessing the impact of dam operation on the availability and distribution of LWD is needed.

7.2.3.4 Hydraulic model formulation

The vast majority of commercially available hydraulic codes are based upon the hydrostatic assumption. For characterizing flow fields smaller than those noted above (approximately 3 meters scale on this large river), investigation of non-hydrostatic codes is recommended. Additionally, flow in and around Large Woody Debris should be further investigated.

For analyzing sediment movement throughout the study reach, a hydrodynamic code coupled with a sediment transport model is recommended.

Three-dimensional codes may be useful when combined with sediment transport codes, and may also be useful in the event that aquatic habitat utilization could be quantified with respect to an organism's location within the water column.

7.2.4 Flood plain inundation modeling

Additional on-the-ground verification is required of vegetation maps derived from satellite imagery (Liu et al. 1997).

Improved stage data would improve the flood surfaces and possibly enable time-series analysis of flood events.

The topographic dataset used for the analysis presented in this report had a horizontal resolution of 30 m and a vertical resolution of 1 m. Improvement of the topographic dataset would significantly improve this analysis.

Future studies of inundation extent should account for levee protection.

An additional analysis is required to associate the periods described above to actual times of inundation; precise topographic and soil moisture data would be required in addition to a calibrated flood surface hydraulic model.

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Appendix A

Sulphur River Instream Flow Study

Scope of Work

Environmental Section
Texas Water Development Board
March 30th, 2001

Introduction

Potential future reservoir projects in the Sulphur River Basin have been identified in regional water plans submitted to the Texas Water Development Board (TWDB) for inclusion in the forthcoming State Water Plan. It is anticipated that construction of at least one of these projects will be essential for meeting the long-term projected water demands of the region. The impact of the proposed impoundments on streamflows and the resident fish communities in the affected downstream river segments must be investigated before the projects can go much further. The overall goal of this project is to use TWDB's scientific and engineering methods to determine the instream flow needs for maintaining adequate fish habitats thus ensuring the ecological health of the Sulphur River, Texas.

The proposed reservoir projects in the Sulphur River Basin are located about 100 miles northwest of Dallas, Texas (see attached figure). There are four potential reservoir sites, with the Marvin Nichols Reservoir I site being the regionally recommended project.

An instream flow needs study, as proposed by the TWDB, involves identifying and analyzing one or more representative segments of the river. The segments chosen reflect the fish communities and habitat features that are typical and representative of that river, and which may be affected by future changes in flow. Biological field surveys are used to determine the abundance and spatial distribution of fish species among the aquatic habitats in that particular segment. These are called "fish habitat utilization" studies. Streamflow velocity and depth of mesohabitats (e.g., riffles, runs, pools, etc.) are also recorded, primarily at locations that were sampled for fish. This information, along with field surveys of the physical channel geometry (topography and bathymetry) and the variation of water surface elevation with flow, are required for application of a hydrodynamic river model. This part of the investigation is referred to as "fish habitat availability" studies. Subsequently, the biological data on habitat utilization and the hydrodynamic model simulations of habitat availability can be combined to develop response curves that can be used to determine the maintenance flow requirements of the resident fish community.

Data collection requirements and hydrodynamic models

The necessary biological information has been collected at seven (7) sites on the North, Middle and South Sulphur River (see attached figures). Fieldwork started in late 1999 and the report from Texas A&M was delivered to TWDB in July 2000. This portion of the study was supported by a grant from the Research and Planning Fund administered by TWDB.

Field surveys of the river's channel bathymetry and flow characteristics have not yet been performed, but are required for the development and application of the two-dimensional (2-D) finite element model. TWDB uses the RMA-2 hydrodynamic model for this purpose. This widely accepted model formulation is also used by the U.S. Army Corps of Engineers and other groups that seek to simulate river flow patterns. Two segments of the River, one below the proposed Marvin Nichols Reservoir I and the other on the Middle Sulphur River which is below the alternative sites of the George Parkhouse Reservoirs, will be chosen for the modeling (see attached figures). Each of these segments will encompass at least one of the fish sampling sites. The segments will be surveyed to determine differences in the water surface elevations between the top and bottom of the segment. Depth recorders also will be placed at strategic locations to automatically log variations in river stage. In addition to a top-end and bottom-end cross-sectional survey, a comprehensive bathymetric survey will be carried using a high-resolution, shallow-water depth sounder linked to a global positioning satellite (GPS) receiver. This provides a high-resolution, high-quality relative elevation of the riverbed for the entire study reach. In addition, cross-sectional flow and velocity profiles will be taken with an RDI Acoustic Doppler Current Profiler (ADCP) specially designed for use in shallow water. Structural habitat features, such as debris dams and large snags, will be recorded with the expectation that these will be incorporated into the identification of habitat areas.

It is believed that periodic overbank flow is important to maintain certain aquatic habitats for fish and wildlife. In addition to studying the effect of changing flow on the availability of mesohabitat in river channel, the TWDB will attempt to identify the flows at which exchange between the floodplain and main channel may occur. This will be determined from surveying low-lying areas, from hydrodynamic model results, and from an analysis of the historic flows experienced in the area.

Analysis, interpretation and visualization of results

The hydrodynamic model results enable the user to visualize both depth and velocity in 2-dimensional fields for the entire segment at various flow rates. The biologists have already provided definitions of the mesohabitats, in terms of a preference for a range of depth and velocity for each fish species found. Consequently, it is possible to use a geographic information system (GIS) tool, such as ArcView, to perform spatial queries and establish habitat versus flow relationships for each species

Using historical flow information from existing USGS gages, an acceptable range of seasonal flows for the river can be computed. Planners can use this information to determine if the proposed reservoir sites can develop enough yield to be feasible water supply projects with multi-stage operating rules for environmentally safe operation.

Results will be made available to interested persons on a specially developed TWDB web site. The site will be produced using the ArcIMS software package, which allows the user to apply such common GIS tools as the "zoom" function, digital imagery/map/coverage overlays, simple data queries, animations, and distance calculators that will make the site highly interactive and informative to the user. In addition, all results will be coordinated with the Texas Parks and

Wildlife Department and the Texas Natural Resource Conservation Commission for the purpose of meeting state management objectives.

Texas A&M will review the report to ensure that the biology is adequately represented by the models. They will also provide guidance on the development of the Web site.

Proposed time frame

The bathymetric data needs to be collected while the river flow is deep enough to allow use of the instrumentation. In general, the spring months of February through June are the most promising. The earlier months have the added advantage of cooler temperatures and reduced vegetation, which equates to less work for the surveyors. Several fieldtrips are needed in order to move and download depth recorders, and to take velocity and water surface elevation measurements at different flow rates. A further fieldtrip will be planned at low flow in order to better identify any snags or objects submerged during the wet season. The time frame for the proposed project is shown in Table 1; however, the 12-month study period may be extended, at no additional cost to the US Army Corps of Engineers, because of the weather-dependent nature of this project.

Funding

The costs associated with this project are directly related to services of employees, services of equipment, and services of supplies and materials. Table 2 gives a breakdown of these study expenses. *(TABLE 2 NOT INCLUDED IN THIS APPENDIX)*

	April '01	May '01	June '01	July '01	August '01	September '01	October '01	November '01	December '01	January '02	February '02	March '02
Reconnaissance & identification of study segments	■											
Analysis of the data collected by the biologists		■										
Analysis of long-term flow record at sites		■										
Survey and installation of depth recorders			■									
Bathymetry measurements, move and download depth recorders				■								
Survey of river's edge, spot velocity and flow measurements				■								
Analysis and compilation of preliminary data					■							
Development of model mesh					■							
Further flow measurements, move and download depth recorders						■						
Hydrodynamic modeling							■	■				
Analysis of model and fish data and development of GIS database									■	■		
Development of Web site for displaying preliminary results										■	■	
Preparation of report and finalization of Web site											■	■

Table 1. Task Schedule for the Sulphur River Instream Flow Study.

Appendix B

Segment ID: 0303 **Water body name:** Sulphur/South Sulphur River

Freshwater Stream | Sulphur River Basin | Total size: 181 Miles

Assessment Method	Status of Use Support or Concern	Location	Location size	# of samples	# of exceedances	Mean
Aquatic Life Use						
Dissolved Oxygen grab average	Use Concern	Lower 25 miles	25	20	3	
Dissolved Oxygen grab average	No Concern	Middle 25 miles	25	13	1	
Dissolved Oxygen grab average	No Concern	Upper 25 miles	25	35		
Dissolved Oxygen grab minimum	Fully Supporting	Lower 25 miles	25	20	0	
Dissolved Oxygen grab minimum	Fully Supporting	Middle 25 miles	25	13	0	
Dissolved Oxygen grab minimum	Fully Supporting	Upper 25 miles	25	35	0	
Dissolved Oxygen 24hr average	Not Assessed	Lower 25 miles	25	3	1	
Dissolved Oxygen 24hr average	Not Assessed	Middle 25 miles	25	0		
Dissolved Oxygen 24hr average	Not Assessed	Upper 25 miles	25	0		
Dissolved Oxygen 24hr minimum	Not Assessed	Lower 25 miles	25	3	0	
Dissolved Oxygen 24hr minimum	Not Assessed	Middle 25 miles	25	0		
Dissolved Oxygen 24hr minimum	Not Assessed	Upper 25 miles	25	0		
Acute Metals in water	Fully Supporting	Lower 25 miles	25	14	0	
Acute Metals in water	No Concern-Limited Data	Middle 25 miles	25	6	0	
Acute Metals in water	Fully Supporting	Upper 25 miles	25	24	0	
Chronic Metals in water	Fully Supporting	Lower 25 miles	25	14		
Chronic Metals in water	No Concern-Limited Data	Middle 25 miles	25	6		
Chronic Metals in water	Fully Supporting	Upper 25 miles	25	24		
Chronic Toxicity tests in water	No Concern-Limited Data	Upper 25 miles	25	4	0	
Overall Aquatic Life Use	Fully Supporting	Lower 25 miles	25			
Overall Aquatic Life Use	Fully Supporting	Middle 25 miles	25			
Overall Aquatic Life Use	Not Assessed	Remainder of segment	106			
Overall Aquatic Life Use	Fully Supporting	Upper 25 miles	25			

Segment ID: 0303 **Water body name:** Sulphur/South Sulphur River

Freshwater Stream | Sulphur River Basin | Total size: 181 Miles

Assessment Method	Status of Use Support or Concern	Location	Location size	# of samples	# of exceedances	Mean
Contact Recreation Use						
E. coli single sample	Not Assessed	Lower 25 miles	25	0		
E. coli single sample	Not Assessed	Upper 25 miles	25	1	0	
E. coli geometric mean	Not Assessed	Lower 25 miles	25	0		
E. coli geometric mean	Not Assessed	Upper 25 miles	25	1		3
Fecal coliform single sample	Fully Supporting	Lower 25 miles	25	16	1	
Fecal coliform single sample	Fully Supporting	Upper 25 miles	25	12	3	
Fecal coliform geometric mean	Fully Supporting	Lower 25 miles	25	16		76
Fecal coliform geometric mean	Fully Supporting	Upper 25 miles	25	12		128
Overall Recreation Use	Fully Supporting	Lower 25 miles	25			
Overall Recreation Use	Not Assessed	Middle 25 miles	25			
Overall Recreation Use	Not Assessed	Remainder of segment	106			
Overall Recreation Use	Fully Supporting	Upper 25 miles	25			
General Use						
Water Temperature	Fully Supporting	Lower 25 miles	25	20	0	
Water Temperature	Fully Supporting	Middle 25 miles	25	14	0	
Water Temperature	Fully Supporting	Upper 25 miles	25	39	1	
pH	Fully Supporting	Lower 25 miles	25	20	0	
pH	Fully Supporting	Middle 25 miles	25	14	1	
pH	Fully Supporting	Upper 25 miles	25	35	0	
Chloride	Fully Supporting	Lower 25 miles	25	68		19.6
Chloride	Fully Supporting	Middle 25 miles	25	68		19.6
Chloride	Fully Supporting	Remainder of segment	106	68		19.6
Chloride	Fully Supporting	Upper 25 miles	25	68		19.6

Segment ID: 0303 **Water body name:** Sulphur/South Sulphur River

Freshwater Stream | Sulphur River Basin | Total size: 181 Miles

Assessment Method	Status of Use Support or Concern	Location	Location size	# of samples	# of exceedances	Mean
General Use (continued)						
Sulfate	Fully Supporting	Lower 25 miles	25	68		35.1
Sulfate	Fully Supporting	Middle 25 miles	25	68		35.1
Sulfate	Fully Supporting	Remainder of segment	106	68		35.1
Sulfate	Fully Supporting	Upper 25 miles	25	68		35.1
Total Dissolved Solids	Fully Supporting	Lower 25 miles	25	77		246.4
Total Dissolved Solids	Fully Supporting	Middle 25 miles	25	77		246.4
Total Dissolved Solids	Fully Supporting	Remainder of segment	106	77		246.4
Total Dissolved Solids	Fully Supporting	Upper 25 miles	25	77		246.4
Overall General Use	Fully Supporting	Lower 25 miles	25			
Overall General Use	Fully Supporting	Middle 25 miles	25			
Overall General Use	Fully Supporting	Remainder of segment	106			
Overall General Use	Fully Supporting	Upper 25 miles	25			
Fish Consumption Use						
Human Health Criteria	Fully Supporting	Lower 25 miles	25	14		
Human Health Criteria	No Concern-Limited Data	Middle 25 miles	25	6		
Human Health Criteria	Fully Supporting	Upper 25 miles	25	24		
Overall Fish Consumption Use	Fully Supporting	Lower 25 miles	25			
Overall Fish Consumption Use	Not Assessed	Middle 25 miles	25			
Overall Fish Consumption Use	Not Assessed	Remainder of segment	106			
Overall Fish Consumption Use	Fully Supporting	Upper 25 miles	25			
Overall Use Support						
	Fully Supporting	Lower 25 miles	25			
	Fully Supporting	Middle 25 miles	25			

Segment ID: 0303 **Water body name:** Sulphur/South Sulphur River

Freshwater Stream Sulphur River Basin Total size: 181 Miles

Assessment Method	Status of Use Support or Concern	Location	Location size	# of samples	# of exceedances	Mean
Overall Use Support (continued)						
	Fully Supporting	Remainder of segment	106			
	Fully Supporting	Upper 25 miles	25			
Nutrient Enrichment Concern						
Ammonia Nitrogen	No Concern	Lower 25 miles	25	20	0	
Ammonia Nitrogen	No Concern	Middle 25 miles	25	14	1	
Ammonia Nitrogen	No Concern	Upper 25 miles	25	34	0	
Nitrite + Nitrate Nitrogen	No Concern	Lower 25 miles	25	20	0	
Nitrite + Nitrate Nitrogen	No Concern	Middle 25 miles	25	14	0	
Nitrite + Nitrate Nitrogen	No Concern	Upper 25 miles	25	34	0	
Orthophosphorus	No Concern	Lower 25 miles	25	20	0	
Orthophosphorus	No Concern	Middle 25 miles	25	14	0	
Orthophosphorus	No Concern	Upper 25 miles	25	34	0	
Total Phosphorus	No Concern	Lower 25 miles	25	20	0	
Total Phosphorus	Not Assessed	Middle 25 miles	25	0		
Total Phosphorus	No Concern	Upper 25 miles	25	13	0	
Overall Nutrient Enrichment Concerns	No Concern	Lower 25 miles	25			
Overall Nutrient Enrichment Concerns	No Concern	Middle 25 miles	25			
Overall Nutrient Enrichment Concerns	Not Assessed	Remainder of segment	106			
Overall Nutrient Enrichment Concerns	No Concern	Upper 25 miles	25			
Algal Growth Concern						
Chlorophyll a	No Concern	Lower 25 miles	25	20	1	
Chlorophyll a	Not Assessed	Middle 25 miles	25	0		
Chlorophyll a	Not Assessed	Remainder of segment	106			

Segment ID: 0303 **Water body name:** Sulphur/South Sulphur River

Freshwater Stream Sulphur River Basin Total size: 181 Miles

Assessment Method	Status of Use Support or Concern	Location	Location size	# of samples	# of exceedances	Mean
Algal Growth Concern (continued)						
Chlorophyll a	No Concern	Upper 25 miles	25	13	0	
Sediment Contaminants Concern						
Metals in sediment	Not Assessed	Lower 25 miles	25	4		
Metals in sediment	Not Assessed	Upper 25 miles	25	3		
Overall Sediment Contaminant Concerns	Not Assessed	Lower 25 miles	25			
Overall Sediment Contaminant Concerns	Not Assessed	Middle 25 miles	25			
Overall Sediment Contaminant Concerns	Not Assessed	Remainder of segment	106			
Overall Sediment Contaminant Concerns	Not Assessed	Upper 25 miles	25			
Fish Tissue Contaminants Concern						
Overall Fish Tissue Contaminant Concerns	Not Assessed	Lower 25 miles	25			
Overall Fish Tissue Contaminant Concerns	Not Assessed	Middle 25 miles	25			
Overall Fish Tissue Contaminant Concerns	Not Assessed	Remainder of segment	106			
Overall Fish Tissue Contaminant Concerns	Not Assessed	Upper 25 miles	25			
Narrative Criteria Concern						
Overall Narrative Criteria Concerns	No Concern	Lower 25 miles	25			
Overall Narrative Criteria Concerns	No Concern	Middle 25 miles	25			
Overall Narrative Criteria Concerns	No Concern	Remainder of segment	106			
Overall Narrative Criteria Concerns	No Concern	Upper 25 miles	25			

Segment ID: 0303 **Water body name:** Sulphur/South Sulphur River

Freshwater Stream Sulphur River Basin Total size: 181 Miles

Assessment Method	Status of Use Support or Concern	Location	Location size	# of samples	# of exceedances	Mean
Overall Secondary Concern						
	No Concern	Lower 25 miles	25			
	No Concern	Middle 25 miles	25			
	No Concern	Remainder of segment	106			
	No Concern	Upper 25 miles	25			

Segment ID: 0305 **Water body name:** North Sulphur River

Freshwater Stream Sulphur River Basin Total size: 48 Miles

Assessment Method	Status of Use Support or Concern	Location	Location size	# of samples	# of exceedances	Mean
Aquatic Life Use						
Dissolved Oxygen grab average	No Concern	Lower 25 miles	25	19	0	
Dissolved Oxygen grab minimum	Fully Supporting	Lower 25 miles	25	19	0	
Dissolved Oxygen 24hr average	Not Assessed	Lower 25 miles	25	0		
Dissolved Oxygen 24hr minimum	Not Assessed	Lower 25 miles	25	0		
Acute Metals in water	No Concern-Limited Data	Lower 25 miles	25	8		
Chronic Metals in water	No Concern-Limited Data	Lower 25 miles	25	8		
Overall Aquatic Life Use	Fully Supporting	Lower 25 miles	25			
Overall Aquatic Life Use	Not Assessed	Remainder of segment	23			
Contact Recreation Use						
E. coli single sample	Not Assessed	Lower 25 miles	25	1	0	
E. coli geometric mean	Not Assessed	Lower 25 miles	25	1		5
Fecal coliform single sample	Fully Supporting	Lower 25 miles	25	14	1	
Fecal coliform geometric mean	Fully Supporting	Lower 25 miles	25	14		35
Overall Recreation Use	Fully Supporting	Lower 25 miles	25			
Overall Recreation Use	Not Assessed	Remainder of segment	23			
General Use						
Water Temperature	Fully Supporting	Lower 25 miles	25	21	0	
pH	Fully Supporting	Lower 25 miles	25	19	0	
Chloride	Fully Supporting	Lower 25 miles	25	18		46.3

Segment ID: 0305 **Water body name:** North Sulphur River

Freshwater Stream Sulphur River Basin Total size: 48 Miles

Assessment Method	Status of Use Support or Concern	Location	Location size	# of samples	# of exceedances	Mean
General Use (continued)						
Chloride	Fully Supporting	Remainder of segment	23	18		46.3
Sulfate	Fully Supporting	Lower 25 miles	25	18		204.1
Sulfate	Fully Supporting	Remainder of segment	23	18		204.1
Total Dissolved Solids	Fully Supporting	Lower 25 miles	25	24		610.3
Total Dissolved Solids	Fully Supporting	Remainder of segment	23	24		610.3
Overall General Use	Fully Supporting	Lower 25 miles	25			
Overall General Use	Fully Supporting	Remainder of segment	23			
Fish Consumption Use						
Human Health Criteria	No Concern-Limited Data	Lower 25 miles	25	7		
Overall Fish Consumption Use	Not Assessed	Lower 25 miles	25			
Overall Fish Consumption Use	Not Assessed	Remainder of segment	23			
Overall Use Support						
	Fully Supporting	Lower 25 miles	25			
	Fully Supporting	Remainder of segment	23			
Nutrient Enrichment Concern						
Ammonia Nitrogen	No Concern	Lower 25 miles	25	19	0	
Nitrite + Nitrate Nitrogen	No Concern	Lower 25 miles	25	19	2	
Orthophosphorus	No Concern	Lower 25 miles	25	19	0	
Total Phosphorus	No Concern	Lower 25 miles	25	16	0	
Overall Nutrient Enrichment Concerns	No Concern	Lower 25 miles	25			

Segment ID: 0305 **Water body name:** North Sulphur River

Freshwater Stream | Sulphur River Basin | Total size: 48 Miles

Assessment Method	Status of Use Support or Concern	Location	Location size	# of samples	# of exceedances	Mean
Nutrient Enrichment Concern (continued)						
Overall Nutrient Enrichment Concerns	Not Assessed	Remainder of segment	23			
Algal Growth Concern						
Chlorophyll a	No Concern	Lower 25 miles	25	16	1	
Chlorophyll a	Not Assessed	Remainder of segment	23			
Sediment Contaminants Concern						
Metals in sediment	Not Assessed	Lower 25 miles	25	1		
Overall Sediment Contaminant Concerns	Not Assessed	Lower 25 miles	25			
Overall Sediment Contaminant Concerns	Not Assessed	Remainder of segment	23			
Fish Tissue Contaminants Concern						
Overall Fish Tissue Contaminant Concerns	Not Assessed	Lower 25 miles	25			
Overall Fish Tissue Contaminant Concerns	Not Assessed	Remainder of segment	23			
Narrative Criteria Concern						
Overall Narrative Criteria Concerns	No Concern	Lower 25 miles	25			
Overall Narrative Criteria Concerns	No Concern	Remainder of segment	23			
Overall Secondary Concern						
	No Concern	Lower 25 miles	25			
	No Concern	Remainder of segment	23			

Appendix C

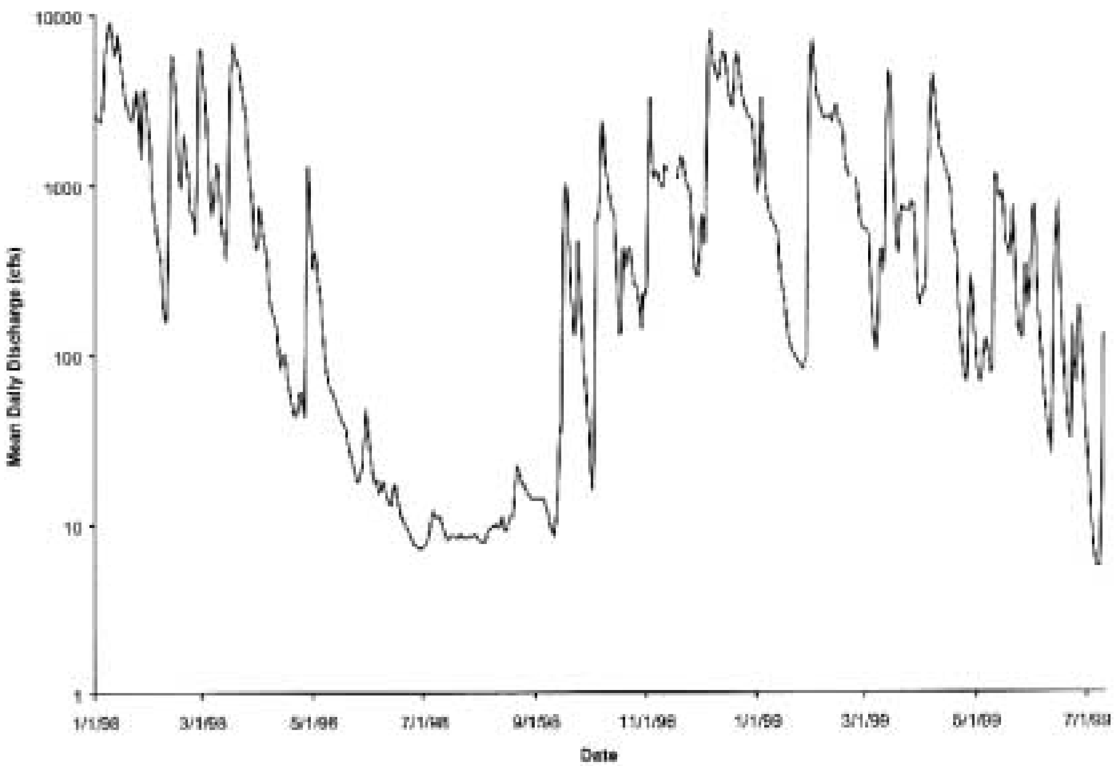


Figure 1. Mean daily discharge recorded during the study period, 1 January 1998 – 1 July 1999, at USGS gauge 07343200 on the Sulphur River.

Table 2. Physicochemical parameters for sites in the Sulphur River during the summer season, April - October.

Site	Date	Time (24 hr)	Flow (cfs)	pH	Temperature (°C)	Conductivity (μS/cm)	DO (mg/L)	% O_2 Saturation
1	30 July 1998	1045-1645[a]	8.6-8.6	8.2	N/A[b]	N/A[b]	N/A[b]	N/A[b]
	9 June 1999	1436-1731	35-35	7.0	32.9	533.0	10.43	155.8
	17 June 1999	1012-1154	158-153	7.0	27.5	353.8	3.55	20.1
2	31 July 1998	1002-1645	8.1-8.1	8.0	31.1	160.0	3.95	52.8
	10 June 1999	1345-1542	30-28	7.0	32.6	541.0	10.32	140.1
	17 June 1999	0938-1515	160-143	7.0	29.9	380.3	8.42	100.3
3	31 July 1998	0926-1440	8.6-8.1	8.2	31.4	50.4	4.25	57.1
	10 June 1999	0942-1629	30-28	7.0	31.8	504.0	14.62	197.6
	18 June 1999	0945-1350	100-92	7.0	28.0	373.9	5.15	71.7
4	1 Aug 1998	0854-1306	8.1-8.1	8.2	30.5	811.1	4.10	66.3
	25 May 1999	1049-1415	130-132	7.0	25.4	281.4	6.45	74.1
	9 June 1999	0821-1043	38-38	7.0	29.2	389.1	5.22	66.2

Table 2. Continued.

Site	Date	Time (24 hr)	Flow (cfs)	pH	Temperature (°C)	Conductivity (μS/cm)	DO (mg/L)	% O_2 Saturation
5	1 Aug 1998	1442-1632	8.1-8.1	8.4	34.1	874.0	5.80	83.4
	8 June 1999	1520-1740	46-43	7.0	30.2	385.4	5.18	63.1
	16 June 1999	1530-1855	240-221	7.0	27.1	340.5	5.32	66.1
6	2 Aug 1998	0847-1220	8.1-8.1	8.2	30.3	816.0	3.7	49.3
	25 May 1999	1009-1737	127-132	7.0	26.0	285.4	6.54	80.6
	8 June 1999	1257-1509	48-46	7.0	30.1	381.3	5.14	67.7
7	19 June 1999	1007-1250	6.9-6.9	7.0	29.4	468.4	10.20	132.8

[a] Estimated.

[b] Not measured due to instrument malfunction.

Table 3. Physicochemical parameters for sites in the Sulphur River during the winter season, November - March.

Site	Date	Time (24 hr)	Flow (cfs)	pH	Temperature (°C)	Conductivity (μS/cm)	DO (mg/L)	% O_2 Saturation
1	26 Mar 1999	1120-1736	800-819	7.0	13.2	131.2	10.65	100.5
2	27 Mar 1999	0958-1307	780-768	7.0	13.3	166.4	9.45	92.1
3	27 Mar 1999	1144-1717	768-760	7.0	13.5	161.8	9.61	91.8
4	22 Nov 1998	0589-1604	1170-1100	7.9	14.4	179.0	8.61	83.2
	14 Jan 1999	0815-1045[a]	267-262	7.0	7.3	172.8	11.04	92.6
5	23 Nov 1998	0822-1326	1010-994	8.1	14.4	181.8	8.96	82.0
	13 Jan 1999	0913-1524	350-319	7.2	7.6	164.6	11.40	246.4
6	14 Jan 1999	1113-1548	264-258	7.0	7.0	169.2	11.62	93.4

[a]Estimated.

Appendix D

Common Name	Scientific Name	Habitat Group Indicator Species**
Common carp	*Cypinus carpio*	1
Bullhead minnow	*Pimephales vigilax*	1
Mississippi silvery minnow	*Hybonathus nuchalis*	1
Red shiner	*Cyprinella lutrensis*	1
Emerald shiner	*Notropis atherinodes*	1
Blue catfish	*Ictalurus furcatus*	1
Channel catfish	*Ictalurus punctatus*	1
Flathead catfish	*Pylodictis olivaris*	1
Freckled madtom	*Noturus nocturnus*	1
Logperch	*Percina caproides*	1
Dollar sunfish	*Lepomis Marginatus*	1
Longnose gar	*Lepisosteus osseus*	2
Smallmouth buffalo	*Ictiobus bubalus*	2
White bass	*Morone chrysops*	2
Alligator gar	Atractosteus spatula	*3*
Shortnose gar	*Lepisosteus platostomus*	3
Spotted gar	*Lepisosteus oculatus*	3
Black buffalo	*Ictiobus niger*	3
Bigmouth buffalo	*Ictiobus cyprinellus*	3
Brook silverside	*Labidesthes sicculus*	3
River carpsucker	*Carpiodes carpio*	3
Pirate perch	*Aphredoderus sayanus*	3
Striped bass	*Morone saxatillis*	3
Spotted bass	*Micropterus punctulatus*	3
Green sunfish	*Lepomis cyanellus*	3
Gizzard shad	*Dorosoma cepedianum*	4
Threadfin shad	*Dorosoma petenense*	4
Blackstripe topminnow	*Fundulus notatus*	4
Golden shiner	*Notemigonus crysoleucas*	4
Freshwater drum	*Aplodinotus grunniens*	4
Western mosquitofish	*Gambusia affinis*	4
Largemouth bass	*Micropterus salmoides*	4
Bluegill sunfish	*Lepomis macrochirus*	4
Orangespotted sunfish	*Lepomis humilis*	4
Longear sunfish	*Lepomis megalotis*	4
Warmouth sunfish	*Lepomis gulosus*	4
White crappie	*Pomoxis annularis*	4
Black crappie	*Pomoxis nigromaculatus*	4

Table 1. Fishery Inventory and their Habitat Indicator Type in the Sulphur River near the Proposed Marvin Nichols Reservoir Site. (Gelwick & Morgan, 2000)

Habitat Descriptions:

Habitat Group 1: Riffle-channel snag, riffle-snag complex, run

Habitat Group 2: Riffle-bank snag, riffle-debris dam, pool-undercut bank, pool-debris dam, pool-tree

Habitat Group 3: Pool, pool-bank snag, pool-channel snag, pool-snag complex, pool-edge, pool-vegetation

Habitat Group 4: Pool-rootwad, backwater, backwater-bank snag

Appendix E

USGS

Water Resources

Data Category: Site Information | Geographic Area: Texas | GO

USGS 07343200 Sulphur Rv nr Talco, TX

Available data for this site: Station home page | GO

Station Description

LOCATION
Latitude 33°23'26", Longitude 95°03'44" NAD27,
Red River County, Texas , Hydrologic Unit 11140302

DRAINAGE AREA
1,405 square miles; Contributing drainage area 1,405 square miles,

GAGE
Datum of gage is 275.48 feet above sea level NGVD29.

STATION TYPE:
Surface Water

STATION DATA:

Data Type	Begin Date	End Date	Count
Real-time	This is a real-time site		
Peak streamflow	1957-04-27	2000-12-28	42
Daily streamflow	1956-10-01	2001-09-30	15340
Water Quality Samples	1965-03-17	2001-09-19	560

SITE OPERATION:
Site is located in Texas; record is maintained by Texas

CONTACT INFORMATION
Email questions about this station to gs-w-tx_NWISWeb_Data_Inquiries@usgs.gov

USGS

Water Resources   skip navigation

Data Category: Site Information   Geographic Area: Texas   GO

USGS 07344200 Wright Patman Lk nr Texarkana, TX

Available data for this site   Station home page   GO

Station Description

LOCATION
Latitude 33°18'16", Longitude 94°09'38" NAD27,
Bowie County County, Texas , Hydrologic Unit 11140302

DRAINAGE AREA
3,443 square miles; Contributing drainage area 3,443 square miles,

GAGE
Datum of gage is 0 feet above sea level NGVD29.

STATION TYPE:
Lake Station

STATION DATA:

Data Type	Begin Date	End Date	Count
Real-time	This is a real-time site		
Water Quality Samples	1966-01-07	1977-09-20	14

SITE OPERATION:
Site is located in Texas; record is maintained by Texas

CONTACT INFORMATION
Email questions about this station to gs-w-tx_NWISWeb_Data_Inquiries@usgs.gov

Appendix F

Data Collection Methodology

F.1 Benchmarks

The engineering data collection process for each field study begins with elevation surveying. A semi-permanent elevation benchmark consisting of a 4" diameter x 18" long PVC pipe filled with concrete is set high on a bank at both the upstream and downstream boundaries of the study reach. Additional benchmarks are set at intermediate positions as necessary. Benchmarks are used as reference points to measure the water surface elevation at each end of the river reach.

Using either traditional leveling techniques or high vertical accuracy Global Positioning System (GPS) techniques, the relative elevation of each benchmark is established. Water surface level is measured with respect to each benchmark.

The benchmark elevation measurements described do not provide absolute benchmark elevations related to a standard datum (i.e. NAVD88). Rather, *relative* elevation information is measured, meaning that benchmark #1 is XX.XX meters higher or lower than benchmark #2. For the purposes of developing and calibrating the hydraulic model, relative elevation is adequate and the absolute elevation is not required; however, where possible, project benchmarks elevations are related to an established vertical datum known at the highest order vertical control point in the vicinity (3^{rd} order or better is preferred).

The most comprehensive source of vertical control point locations and information is the National Geodetic Survey (NGS) who publishes benchmark descriptions nationwide. If NGS data is not available, elevation data from the Texas Department of Transportation (TxDOT) at intersections and bridges is used. If neither source can provide vertical survey control, an assumed datum measured by GPS (GEOID96) to an absolute accuracy of +/- 2m is used.

F.1.1 Traditional Leveling

Traditional leveling techniques are discussed in detail in many texts and in particular in USACE (2002). Three-wire differential leveling with an automatically compensated, telescopic level instrument is used in instream flow studies. Total station instruments are not used for precise elevation surveys.

F.1.2 Global Positioning System

High-accuracy GPS measurements can be taken using a local stationary base station and a mobile rover unit to achieve vertical positional accuracy. Two post-processed, "Static" GPS methods and one real-time kinematic (RTK) GPS method can be applied to ensure high accuracy: single-frequency (L1) GPS with Carrier-Phase post-processing (Trimble ProXRS), dual-frequency (L1/L2) with Carrier-Phase post-processing (Trimble 5700), or dual-frequency (L1/L2) Real-Time Kinematic (RTK) correction (Trimble 5700 with RF transmitter and receiver).

In areas where extended data collection times are tolerable and the distance between the base and rover units is less than 10km, the single-frequency "Static" Carrier-Phase process is used. In areas where data collection time is limited, the distance between the base and rover units is less than 10km, and adequate radio frequency reception is possible, the dual-frequency RTK method is used. If data collection time is limited and the distance between the base station and rover is more than 10km, the dual-frequency Carrier-Phase "Static" method is used.

All methods are rated by the manufacturer at +/- 1cm best horizontal accuracy and +/- 2cm best vertical accuracy (Trimble 2001). From experience, +/- 4 cm of vertical accuracy is reliably achieved for the river surveys. Canopy cover on the banks is usually fairly dense, and steep river banks commonly obstruct the GPS antenna's horizon, so the optimum conditions allowing best accuracy are rarely present. When possible, traditional survey methods (level and stadia rod) are employed to verify GPS measurements. If dense canopy prevents use of GPS, a complete three-wire, two-rod, traditional level loop between benchmarks is performed in lieu of GPS measurements.

F.2 Water Surface Elevation

A measurement of the river water surface elevation is made adjacent to each semi-permanent benchmark. If the benchmarks are located within suitable proximity, the water surface between each benchmark can be assumed to be changing linearly. Thus, a benchmark should exist near every area of major water surface slope breakpoint. If any additional areas of slope change are apparent, additional elevation measurements are taken to determine slope in these areas.

Pressure Transducers (PTs) are installed near each benchmark to continuously measure water surface elevation. These water surface elevation time series can be compared to determine lag time between benchmarks, lag time between study site and USGS gauging station, and, most importantly, the change in water surface slope within the study reach at different flow rates.

Water surface elevations are also collected using staff gauges. Obviously, staff gauges are only useful when a researcher is available to take a visual measurement, so the use of

staff gauges is restricted to field data collection trips. The staff gauges are utilized for PT data verification or when installation of a PT instrument is not feasible.
If needed, a laser range finder coupled to a differential GPS (DGPS) is used to collect points that outline the water's edge. These points are used to delineate the hydraulic model mesh boundary at the flow at which the data is collected.

F.3 Bathymetry

Bathymetry data is collected using a boat-mounted echosounder, a typical example being Knudsen Engineering's 320BP High Frequency 200KHz echosounder. Echosounder depth measurements are accurate to approximately +/- 1 cm, but actual accuracy depends upon many factors including pitch, roll, and gradients of temperature and salinity. Depths can be measured in water as shallow as 0.3m. Typical scatter point depth data is shown in Figure 1.

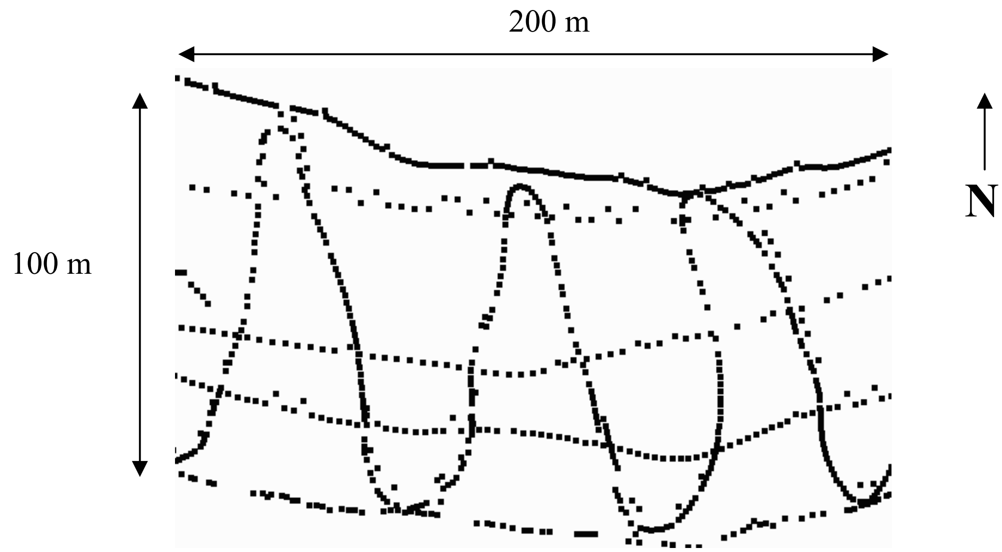


Figure F.1 - Scatter point bathymetric data. Each point represents elevation at a particular horizontal position. Flow in the river is from west to east.

The depth sounder is coupled with a Trimble ProXRS GPS unit that is equipped with an antenna capable of receiving Differential GPS (DGPS) corrections. Omnistar DGPS satellite service provides real-time position corrections good to +/- 1-meter absolute horizontal accuracy. With this setup latitude and longitude are logged every second and depth measurements are logged 6 to 10 per second (depending upon depth). The boat is navigated throughout the river reach to collect point bathymetry data at a very fine resolution until sufficient coverage has been achieved.

Bathymetry data collection is performed at high flows when stage is high and much of the channel cross-section is inundated. Surveying at high stage allows the depth sounder to collect data over the majority of the channel that will be inundated at lower flows (lower flows are, of course, the predominant interest of instream flow studies). No correction is made to the bed to account for the greater energy of the higher flows; a slightly different bed form is likely exhibited at high flow than is exhibited at low energy/low flow. At lower flows sand and silt may accumulate in some areas and this would not be evident in bathymetry data collected at a high flow.

The depth sounder measures bed surface depth relative to the water surface. When converting each depth "ping" into an absolute bed elevation, a water surface elevation correction (derived from PT or staff gauge data) is made (1) to account for the water surface slope, and (2) to account for change in water surface over the survey time period. For example, a 4-meter depth is measured near the upstream boundary of the study segment and a second 4-meter depth is measured 2 km downstream near the downstream boundary. If the water surface slopes 1 meter from upstream to downstream, then the downstream bed elevation is really 4m (depth reading downstream) MINUS 1m below the upstream water surface elevation. Additionally, if the stage changes (-) 0.5m (goes down) between the time the first depth was measured and the time the second depth was measured, the downstream bed depth is really 4m MINUS 1m MINUS (-)0.5m below the upstream water surface elevation. For depths measured at a location between known water surface elevations, the water surface elevation at that point is interpolated linearly and the bed elevation is derived from the interpolated water surface elevation. Stage corrections are particularly important in tidal areas. These corrections are made using the MEBAA software, described in Appendix 4B.

F.4 Flow rate

Flow rate is measured in two ways: using the traditional USGS point velocity method, and using an Acoustic Doppler Current Profiler (ADCP). For shallow depths (less than 1m deep), the USGS method must be used (Prasuhn 1987). A hand-held acoustic Doppler or an electromagnetic velocity probe is used to measure the velocities at evenly spaced stations across a river channel. The point velocities are then integrated over the cross-section to determine the total flow.

For water depths greater than 1m, a vessel-mounted ADCP can be used to measure flow. The instrument is motored across the channel, perpendicular to flow. The ADCP has four transducers that send acoustic signals downward through the water column in a cone pattern. The transducer orientation allows the unit to measure velocity in three dimensions. As the boat travels across the channel, a series of "pings" are recorded that determine velocity in several sections of a vertical column of water. The result is a series of "bins," each generally 25cm in vertical dimension, that discretize the channel cross-section. Each bin represents an average measured velocity value. The velocities in each bin are integrated over their volume and across the entire cross-section to determine the flow (Gordon 1989).

For river cross-sections that contain varying depths, both instruments are used and the sum of the two measurements is used as the total flow. Flow in the shallow portion of the channel is measured using the point velocity method, and flow in the deeper portion is measured using the ADCP.

F.5 References

Gordon, R. Lee. 1989. Acoustic measurement of river discharge. Journal of Hydraulic Engineering, 115 (7), 925-936.

Prasuhn, Alan L. 1987. Fundamentals of Hydraulic Engineering. Harcourt Brace and Jovanovich, Inc., Fort Worth.

Trimble, Inc. 2001. GPS Pathfinder Office 2.90, online help.

U.S. Army Corps of Engineers (USACE). 1 June, 2002. Geodetic and Control Surveying. Engineering Manual EM1110-1-1004.

Appendix G

Mesh Elevating and Bathymetry Adjusting Algorithm (MEBAA)

To improve the geometric accuracy of the hydraulic mesh in the vertical dimension and to speed the mesh generation process, the Texas Water Development Board (TWDB) uses an in-house algorithm for reducing river bathymetry data. The Mesh Elevating and Bathymetry Adjusting Algorithm (MEBAA) is a set of utilities that performs two basic functions:

1. Convert depth sounder point data (x, y, depth) to bathymetry point data (x, y, elevation)
2. Accurately apply the bathymetry point elevation data to nodes of a mesh.

Additional information can be found in Osting (2004).

G.1 Adjustment of bathymetry

Measured echosounder depth data is corrected for change in water surface elevation (either because of water surface slope, changing flow conditions or because of tidal influence). A reference time and water surface elevation is chosen and all data is adjusted using the water surface elevation that was measured at the reference time. The PT time-series data (or staff gauge data) of water level is used for the adjustment.

A poly-line representing the center of the channel is digitized by hand, and the water surface elevation at the normalized time is assigned to each vertex. The water surface elevation is interpolated linearly along the poly-line using the water surface elevation at each vertex. The water surface elevation above each bathymetry point is determined by calculating the water surface elevation at the point's perpendicular bisection of the centerline. Bed elevation is calculated by subtracting the echosounder depth measured at the point from the water surface elevation interpolated at the bisection. The bathymetry data set now contains x position, y position, and bed elevation.

G.2 Assigning elevation to the hydraulic mesh

An x, y (or lat, long) file containing the horizontal position of each of the hydraulic mesh nodes is used to describe the mesh in two planar dimensions. This 2-D mesh (x, y) file, as well as the bathymetry (x, y, elevation) scatter point file, and the poly-line vertex (x, y, water surface elevation) coordinate file, is used by MEBAA to assign the third dimension (elevation) the each node of the hydraulic mesh.

MEBAA transforms the Cartesian coordinate domain of the input mesh data into a coordinate domain based upon the direction of flow; flow direction is determined using the centerline. The coordinate transformation gives MEBAA knowledge of the direction of channel cross-section anisotropy so a user-defined search space containing a subset of scatter points can be defined. The subset consists of scatter points that are most applicable to the interpolant based upon distance along (both perpendicular to and parallel to) the channel centerline. Since bed forms evolve in the direction of flow, gradients in bed surface are lower in the direction of flow than they are transverse to the direction of flow (Julien and Wargadalam 1995; Allen et al. 1994).

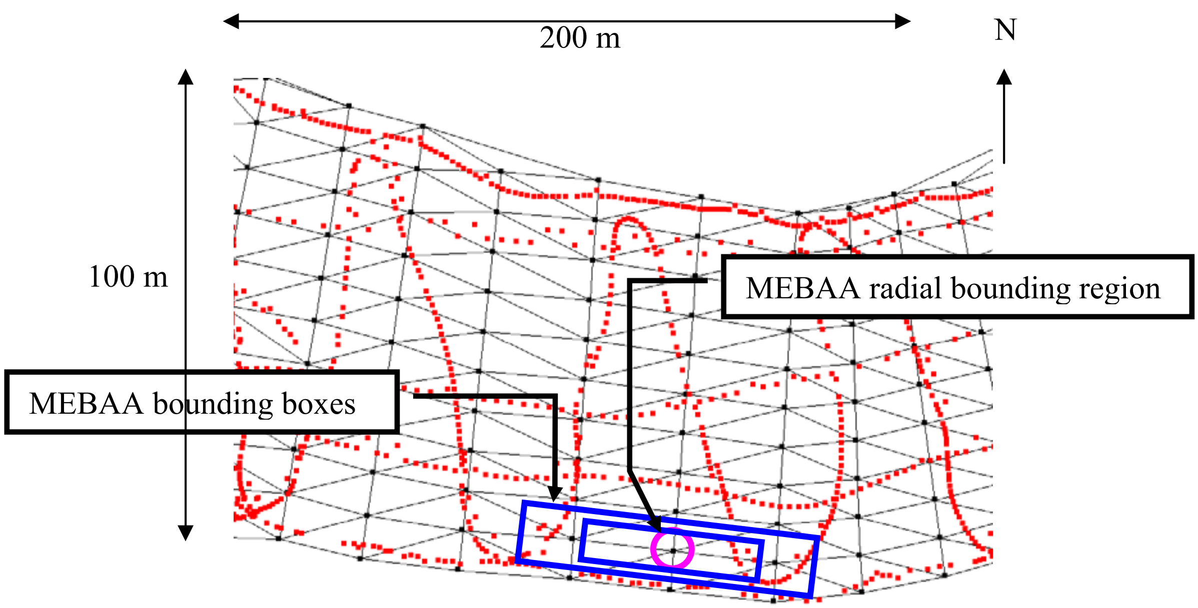


Figure G.1 - Typical bounding search regions superimposed over a typical scatter point set and finite element mesh.

The MEBAA algorithm searches for a user-specifiable, minimum number of bathymetry scatter points within successively larger user-specifiable bounding regions (Figure 1). When the minimum number of points is found, the mesh node elevation is calculated using an Inverse Distance Weighted average of the elevations of the selected bathymetry points. MEBAA utilizes the Shepard's Inverse Distance Weighted (IDW) interpolation method, as modified and presented by Franke and Nielson (1980). This method is termed the Modified Quadratic Shepard's Method and was shown to perform well in a comparison of 29 interpolation methods (Franke 1982).

As noted above, the minimum number of bathymetry points is specifiable; the TWDB has specified 6 points. Bathymetry horizontal position data is collected one point per second, at maximum 1.25 meters per second velocity; therefore, on average, the first and last of six consecutive points collected on non-overlapping lines would be 7.5m apart. Since mesh resolution in coarser regions is generally less than 15m in the flow direction, six points, on average, will be able to be found within a reasonable distance of the node in question.

The bounding regions are also user-specifiable and their exact size will vary with each study segment. As noted above, MEBAA searches for the user-specified number of bathymetry points before calculating the node elevation. If less than the specified number is found in the first region, then the next region is searched. If more than the specified number of points are found, all points found in all searched regions are used for the elevation calculation. When the minimum number of points is found, no more regions are searched.

As many as ten bounding regions are available for user-specification. The first region is always circular, with a user-specifiable search radius (TWDB specifies 0.75 meters). The second region (and all following regions) is rectangular. The length of the rectangle (the distance along the poly-line, in the direction of flow) is specified, as well as the width (the distance perpendicular to the poly-line and the direction of flow). The rectangular size of each of the eight remaining regions can be explicitly specified, or the size can be a multiple of the last explicitly specified region.

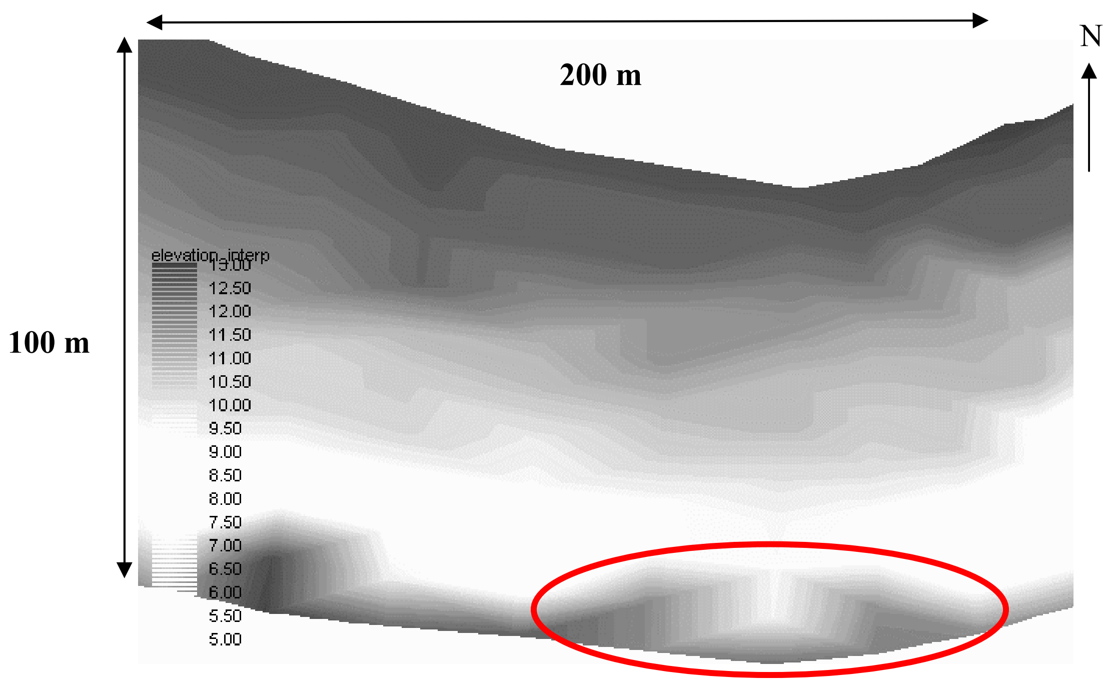


Figure G.2 - Contour fill representing mesh elevations generated using a typical Inverse Distance Weighted (IDW) algorithm. Each mesh node requires at least 6 scatter points to complete the calculation. The area circled can be compared to that circled in Figure 3. Elevations shown are in Meters, from assumed datum near MSL.

The directional search pattern allows the mesh elevation routine to account for erosion and deposition processes in the direction of flow. The rectangle dimensions are specified longer in the flow direction and shorter in the direction perpendicular to flow; generally, bathymetry points located along the same streamline as the mesh node will have a more representative elevation than those bathymetry points collected on parallel streamlines. For example, a mesh node located in the center of a steep bank will have an elevation more similar to a second point 5m directly downstream than to a third point located 5m down the slope, closer to the center of the channel.

A comparison of one standard method of interpolation to the improved MEBAA method is shown in Figures 2 and 3. The right (south) bank is a cut bank with steep, almost vertical, walls. In this and other areas where scatter point data has low resolution when compared to the mesh node resolution (Figure 1), application of the IDW method results in unrealistic bumpy bed forms near the steep slope (Figure 2). The MEBAA routine performs a "directional" IDW calculation (based upon flow direction) to assign an elevation to each mesh node using the scatter point data. The mesh surface generated by the MEBAA method (Figure 3) does not exhibit the artificial bumps generated by the IDW method.

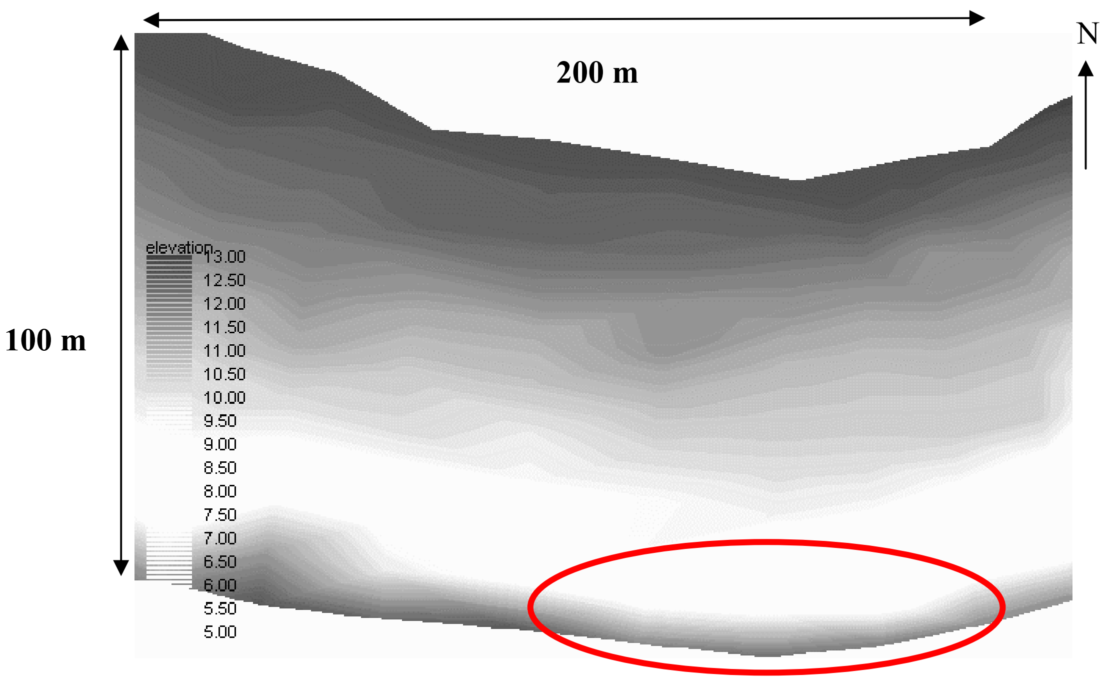


Figure G.3 - Contour fill representing mesh elevations generated using MEBAA (Mesh Elevating and Bathymetry Adjusting Algorithm). Each mesh node requires at least 6 scatter points to complete the calculation. The area circled can be compared to that circled in Figure 2.

G.3 References

Allen, P. M., J. G. Arnold, and B. W. Byars. 1994. Downstream channel geometry for use in planning-level models. Water Resources Bulletin, 30 (4): 663-671.

Franke, R. and G.M. Nielson. 1980. Smooth interpolation of large sets of scattered data. International Journal for Numerical Methods in Engineering 15, 1691-1704.

Franke, R.. 1982. Scattered Data Interpolation: Tests of Some Methods. Mathematics of Computation 38 (157), 181-200.

Julien, P. Y. and J. Wargadalam. 1995. Alluvial Channel Geometry: Theory and Applications. *Journal of Hydraulic Engineering*, 121 (4), 312-325.

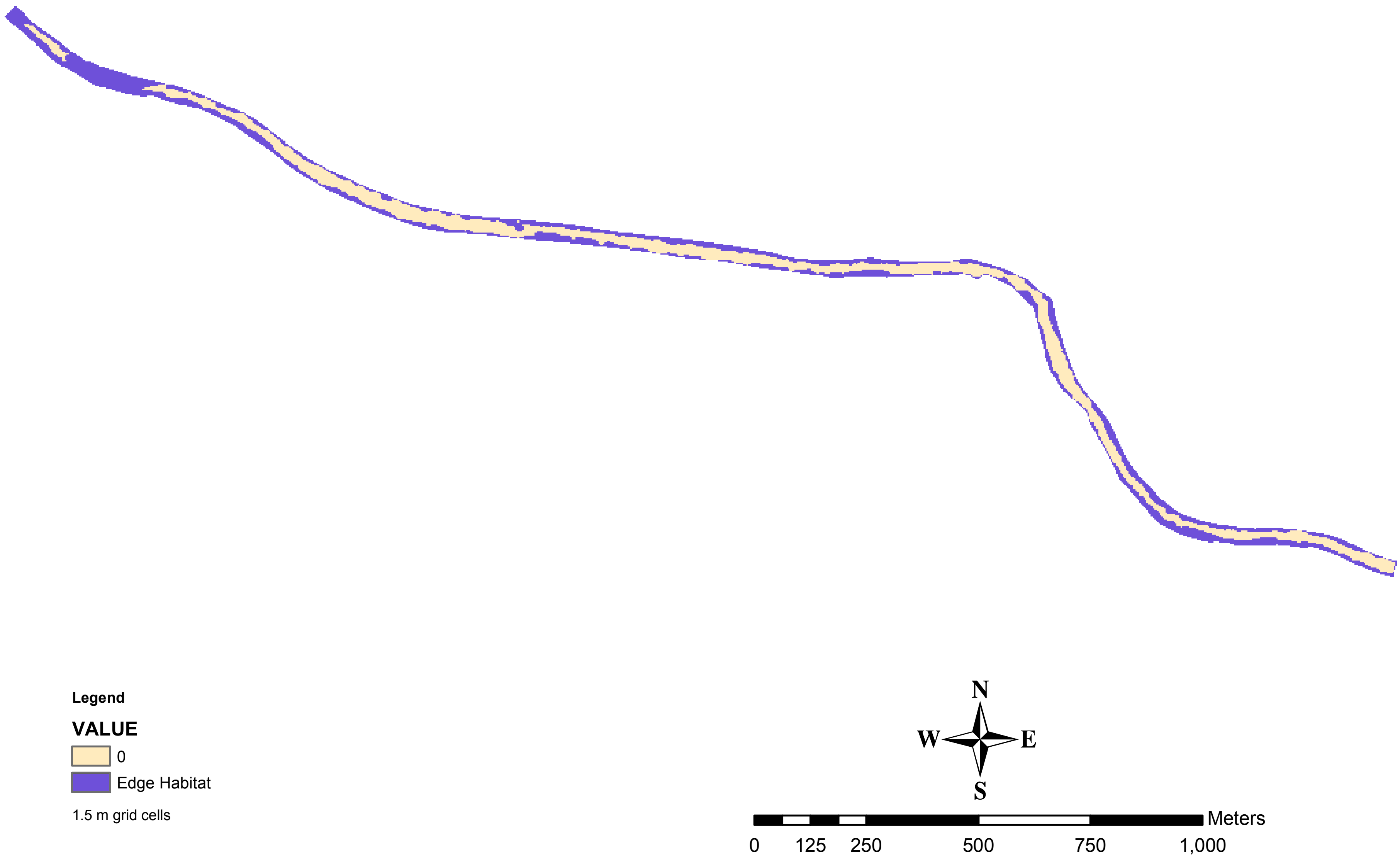
Osting, Tim D. 2003. An improved anisotropic scheme for interpolating scattered bathymetric data points in sinuous river channels. University of Texas Center for Research in Water Resources (CRWR) Online Report 04-1. http://www.crwr.utexas.edu/reports/2004/rpt04-1.shtml

Appendix J

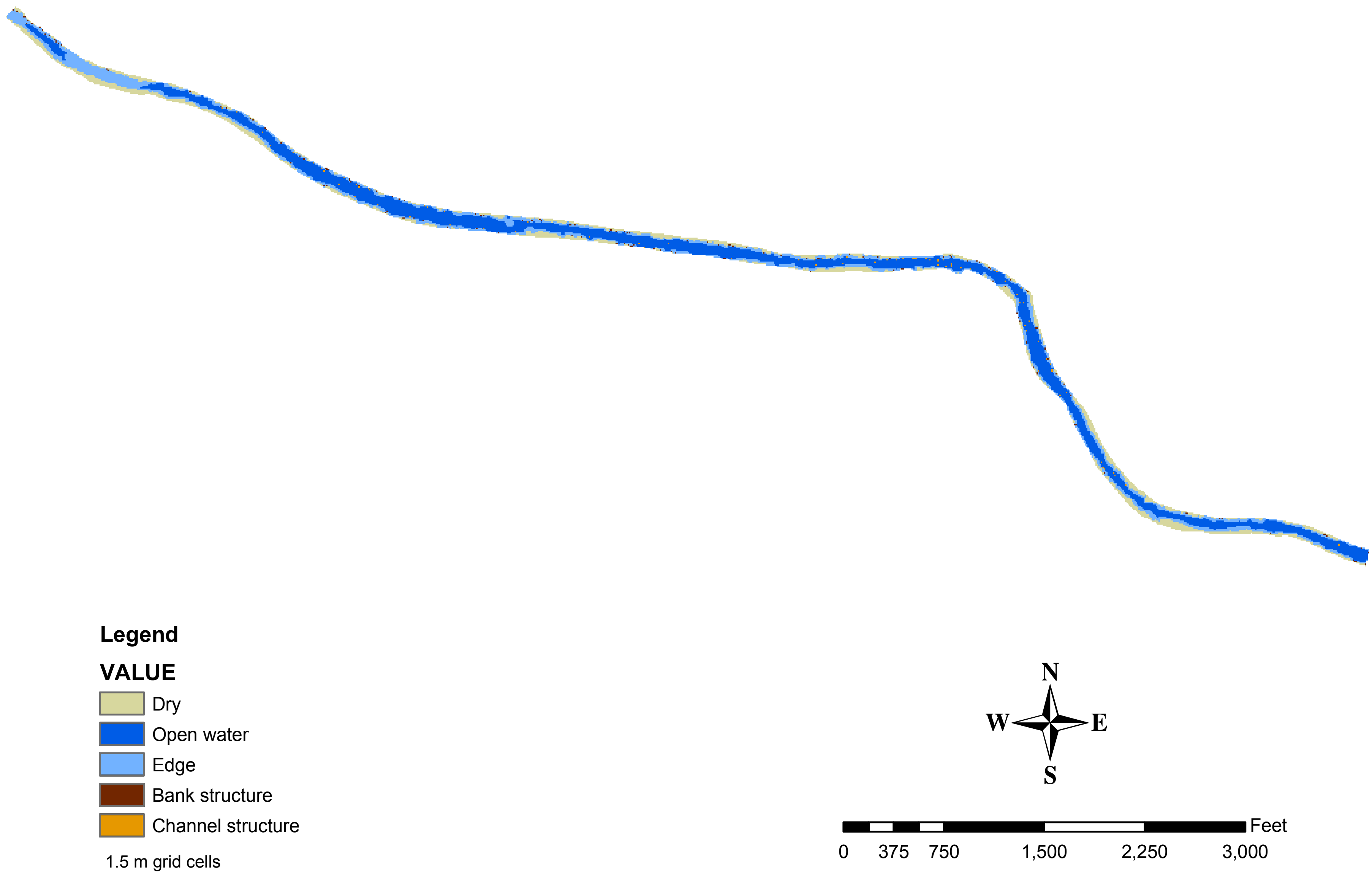
Spatial Availability of Mesohabitat – Site 1

Large Woody Debris (LWD) Plot
All Flows
Sulphur River, Site 1

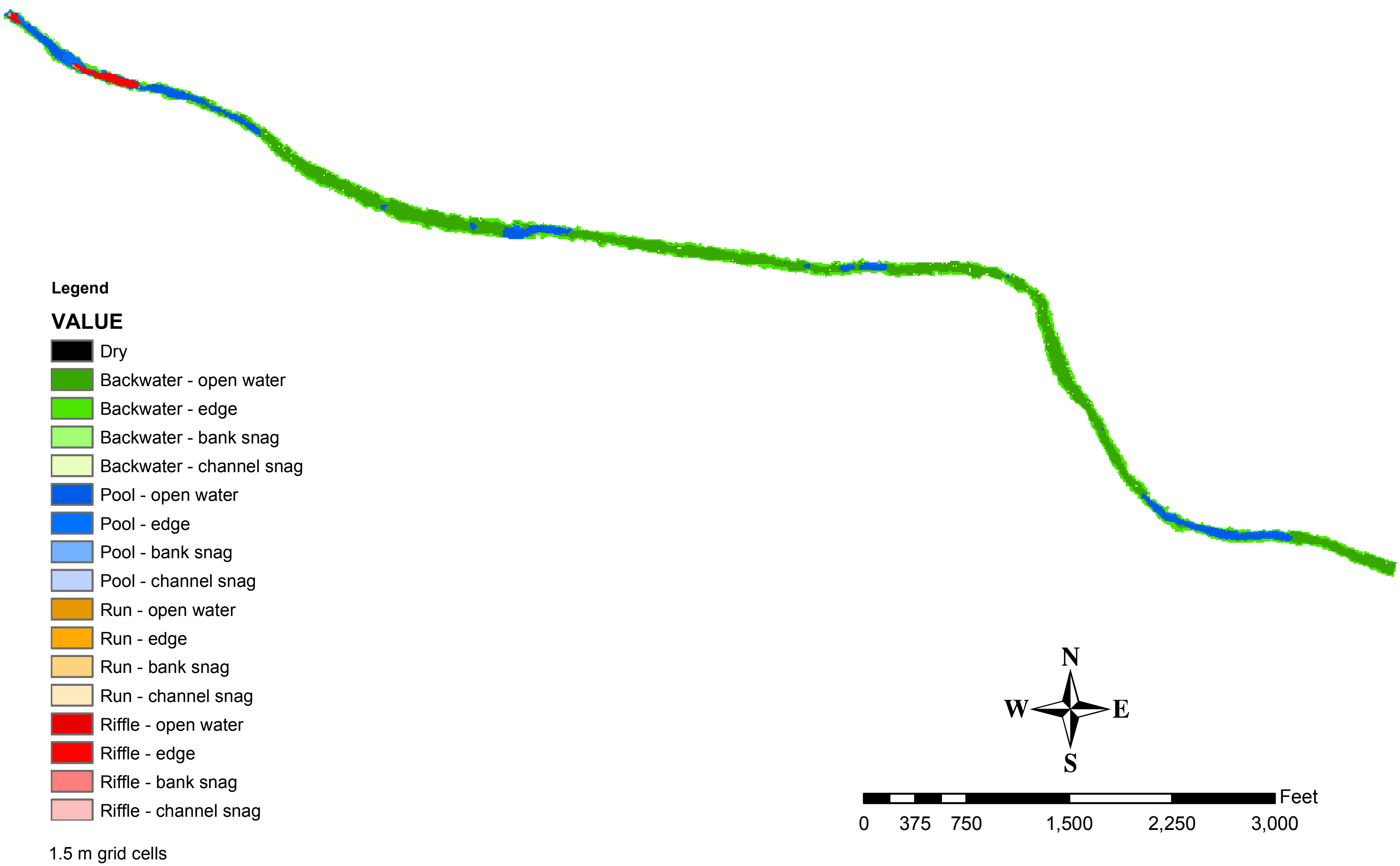
Available Edge Habitat Plot
0.31 cumec (11 cfs)
Sulphur River, Site 1



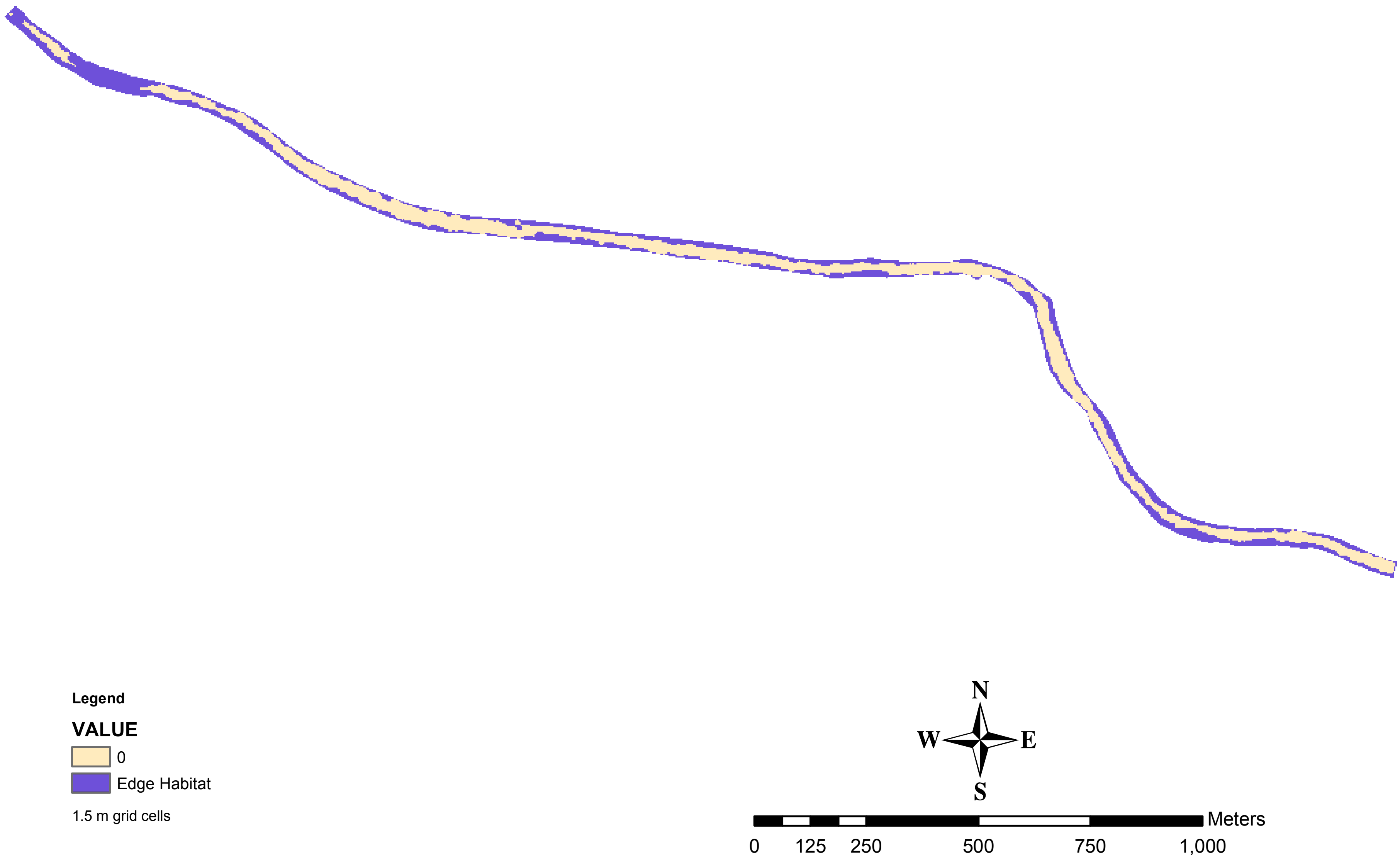
Habitat Plot
0.31 cumec (11 cfs)
Sulphur River, Site 1



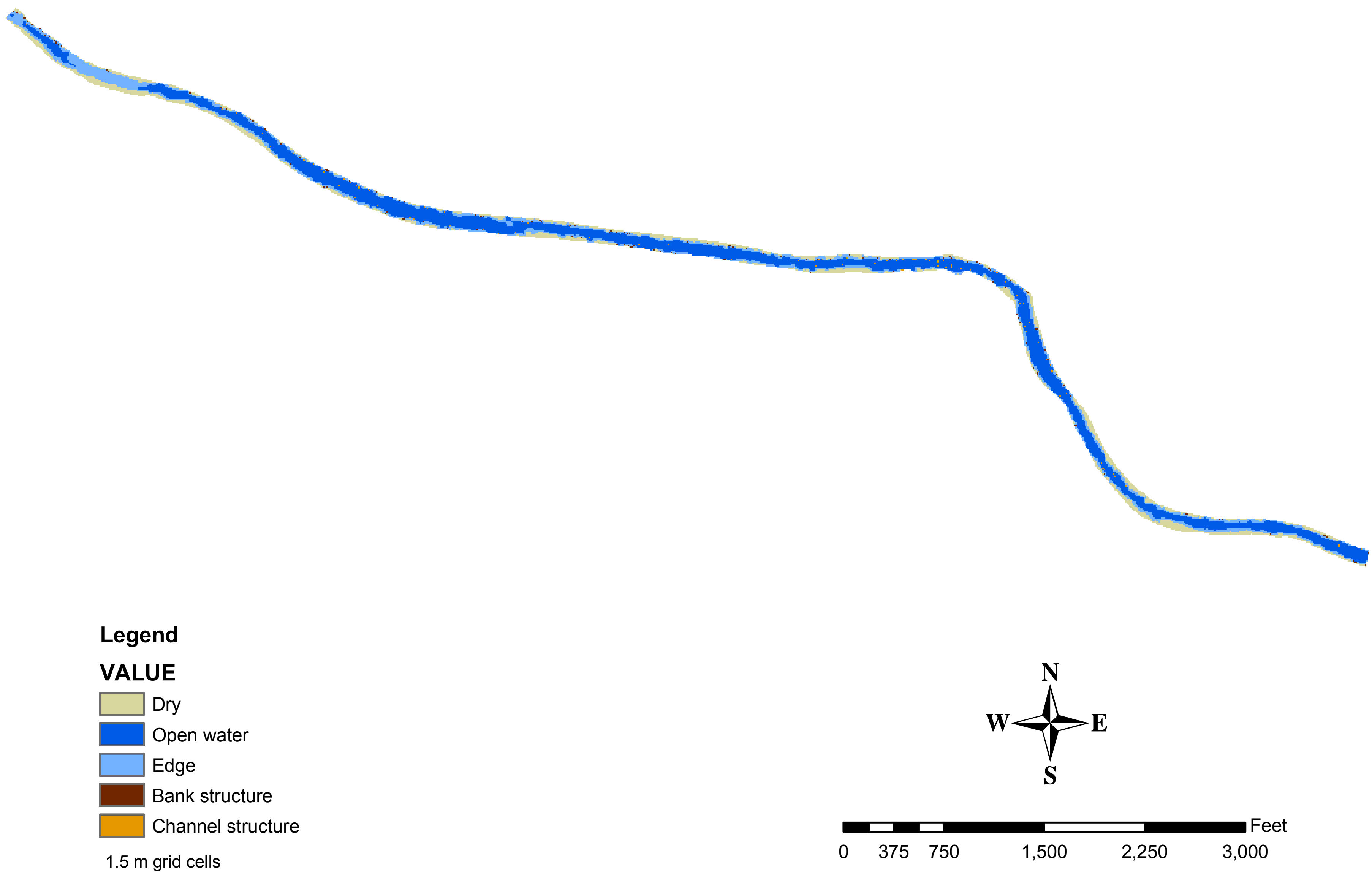
Mesohabitat Plot
0.31 cumec (11 cfs)
Sulphur River, Site 1



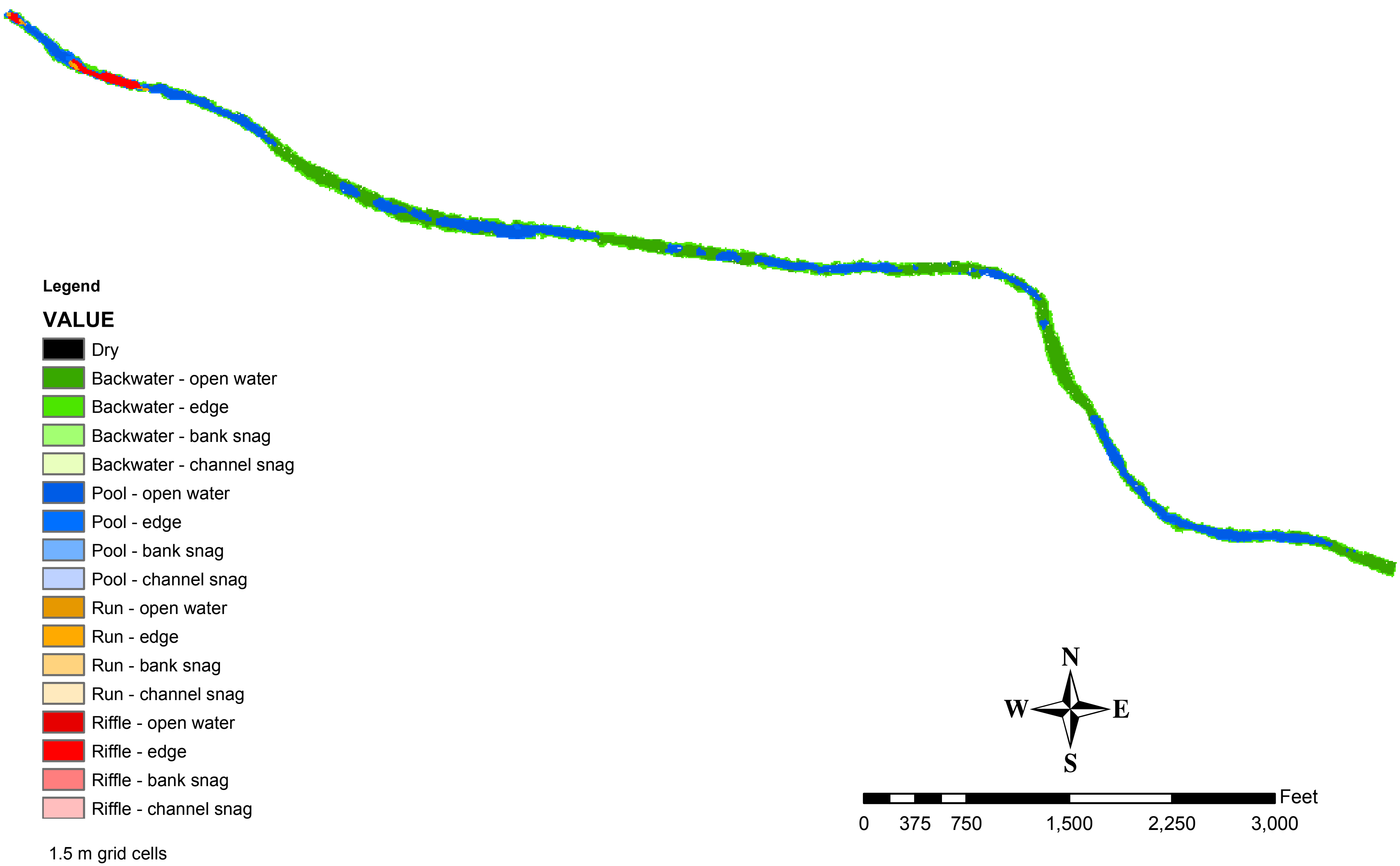
Available Edge Habitat Plot
0.71 cumec (25 cfs)
Sulphur River, Site 1



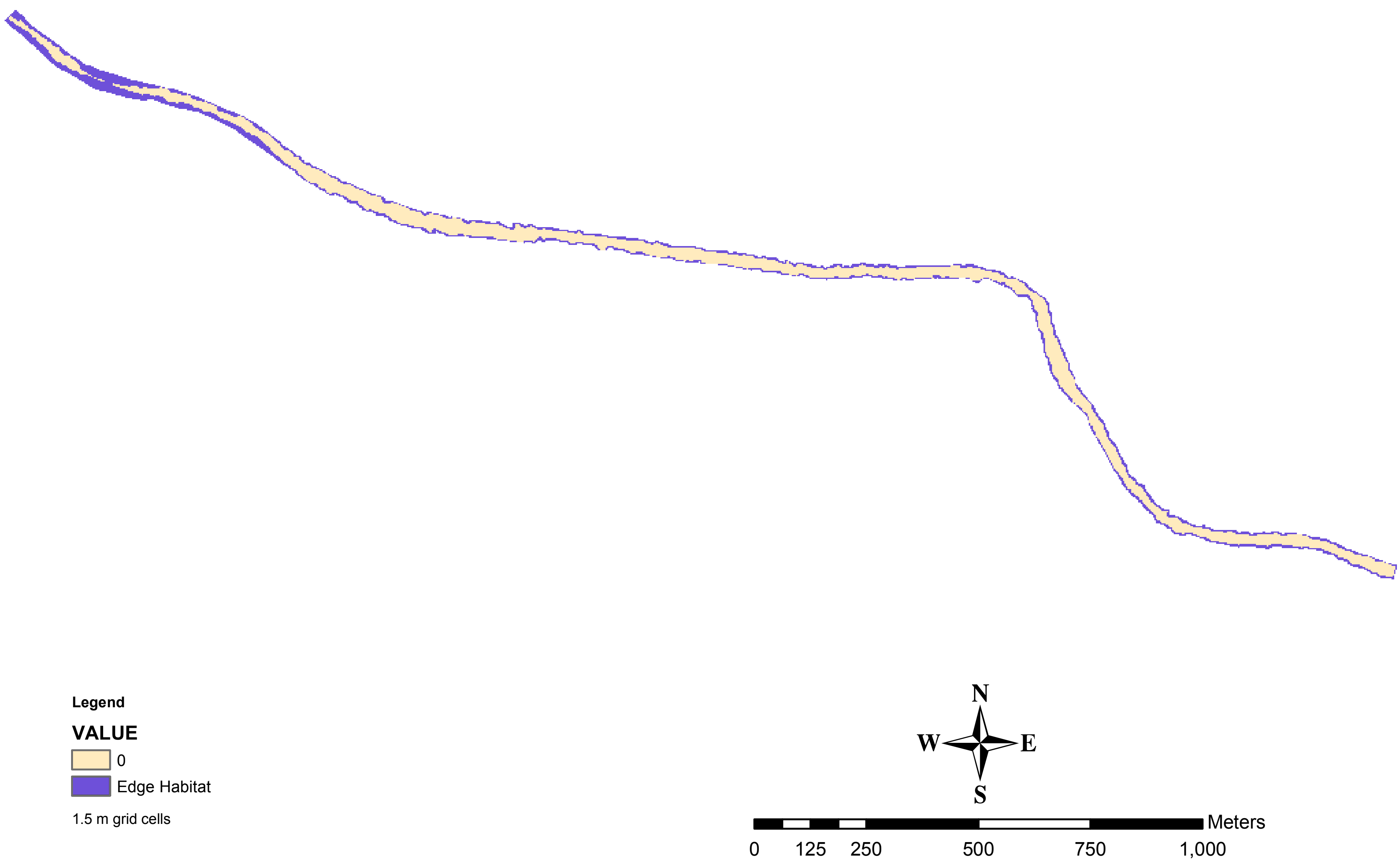
Habitat Plot
0.71 cumec (25 cfs)
Sulphur River, Site 1



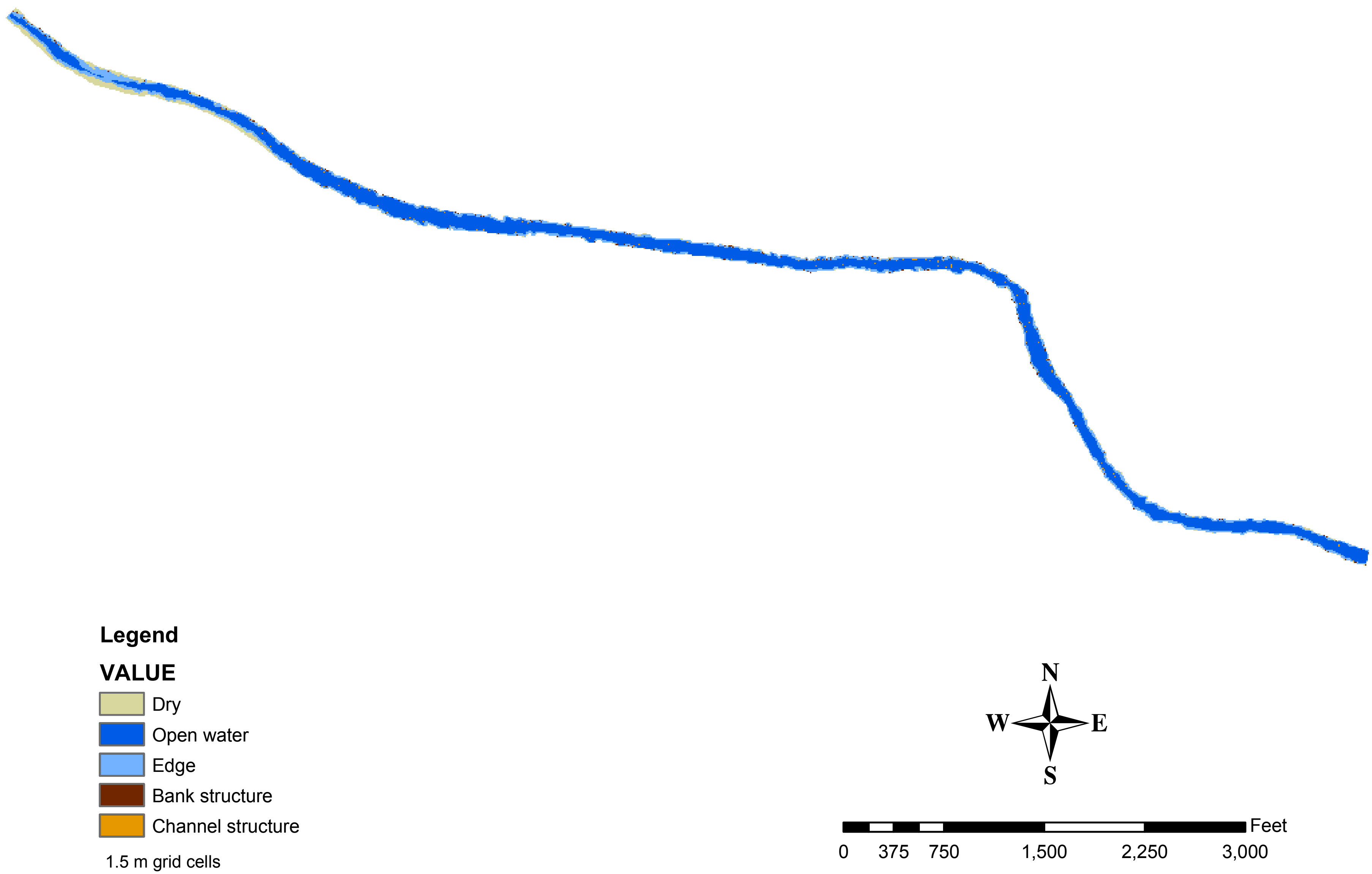
Mesohabitat Plot
0.71 cumec (25 cfs)
Sulphur River, Site 1



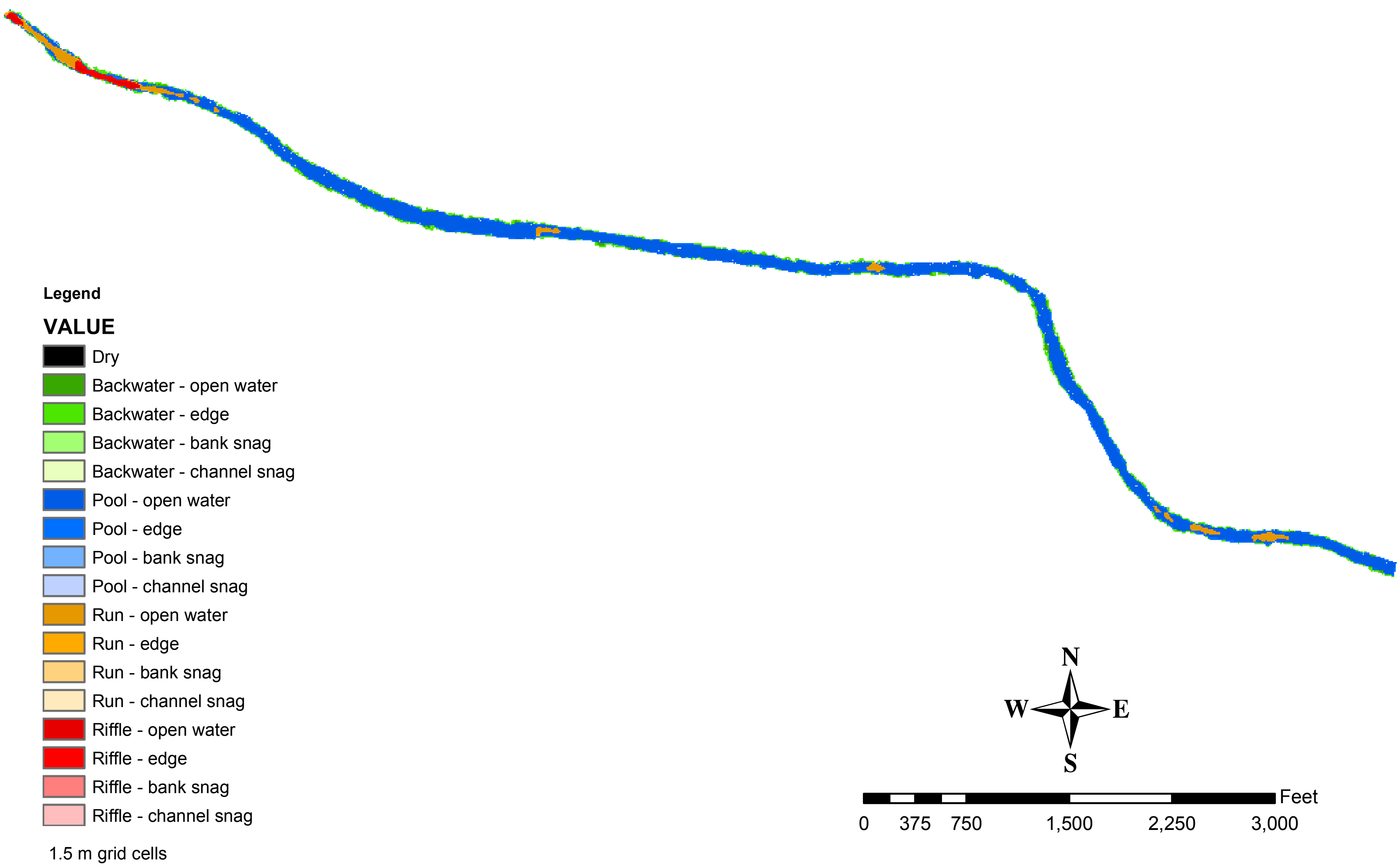
Available Edge Habitat Plot
3.11 cumec (110 cfs)
Sulphur River, Site 1



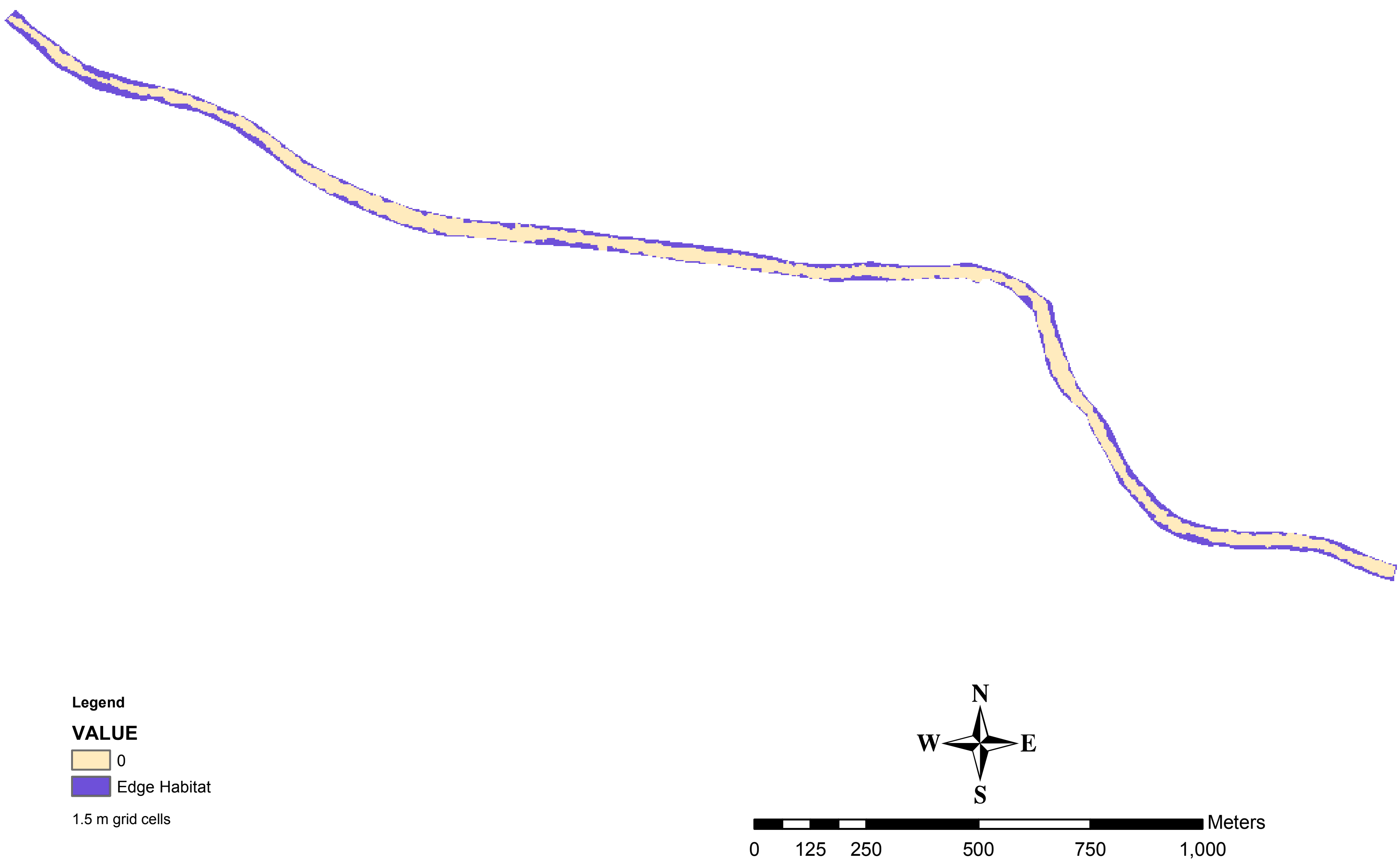
Habitat Plot
3.11 cumec (110 cfs)
Sulphur River, Site 1



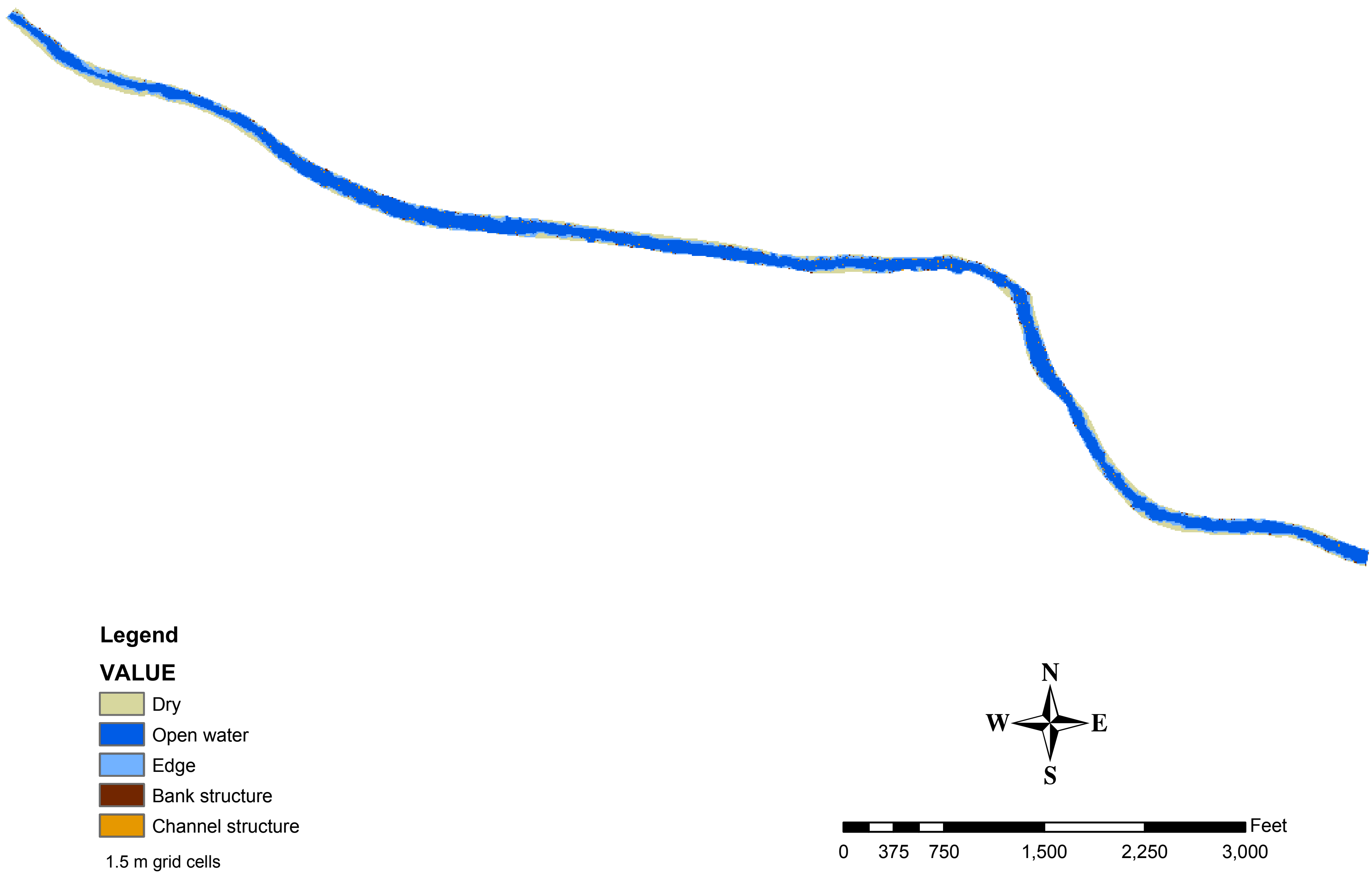
Mesohabitat Plot
3.11 cumec (110 cfs)
Sulphur River, Site 1



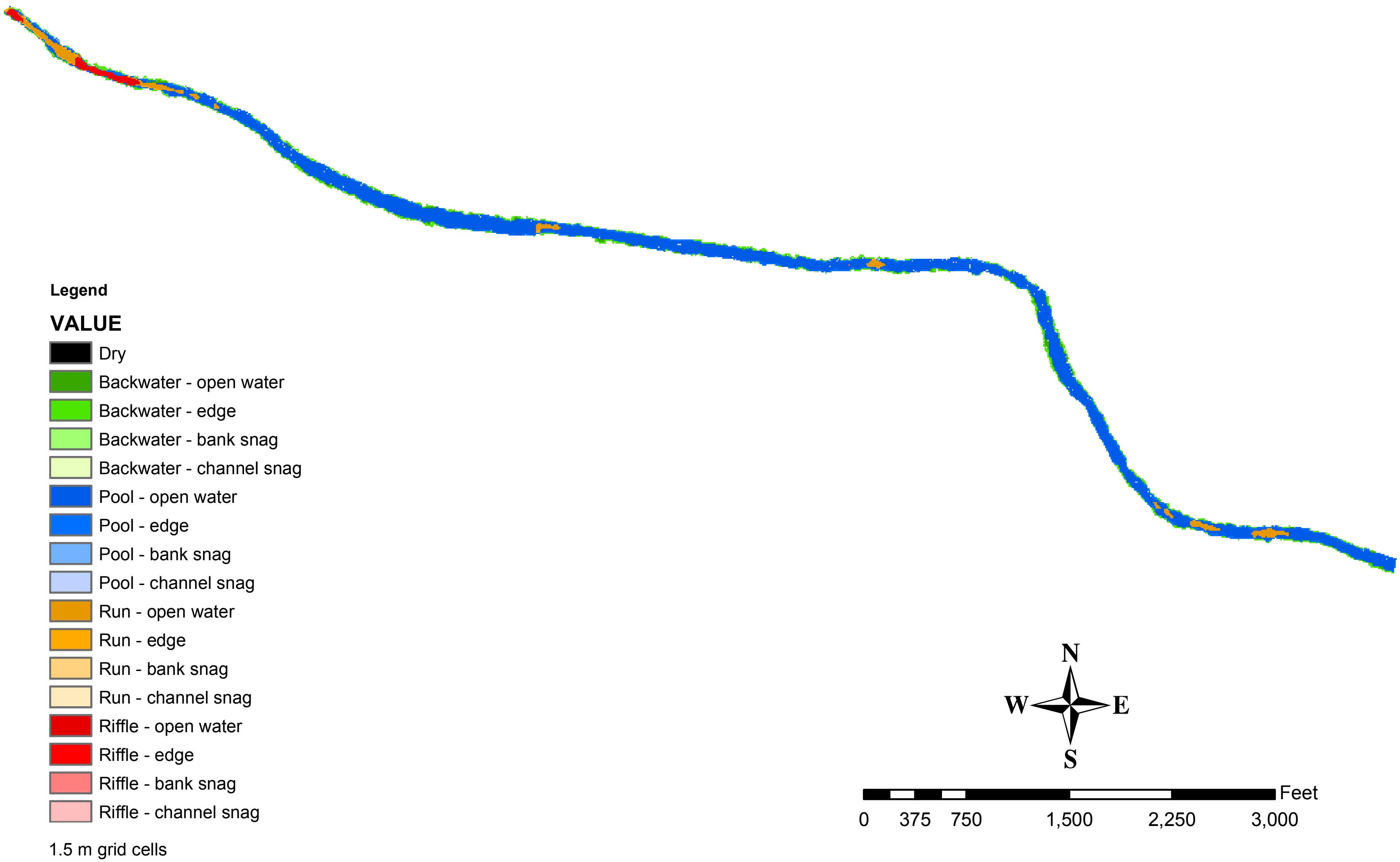
Available Edge Habitat Plot
14.16 cumec (500 cfs)
Sulphur River, Site 1



Habitat Plot
14.16 cumec (500 cfs)
Sulphur River, Site 1



Mesohabitat Plot
14.16 cumec (500 cfs)
Sulphur River, Site 1



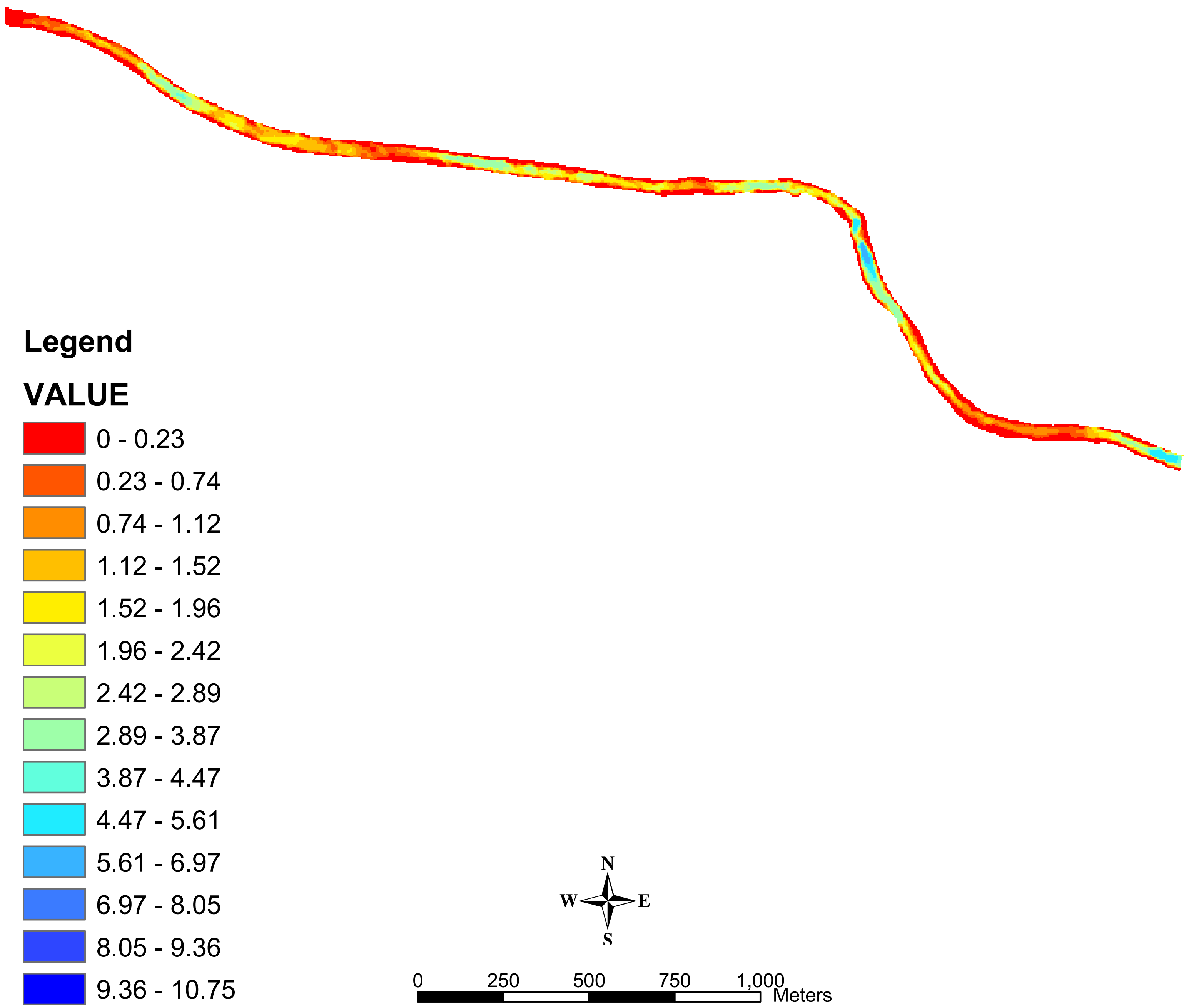
Appendix L

Hydraulic model output for depth and velocity– Site 1

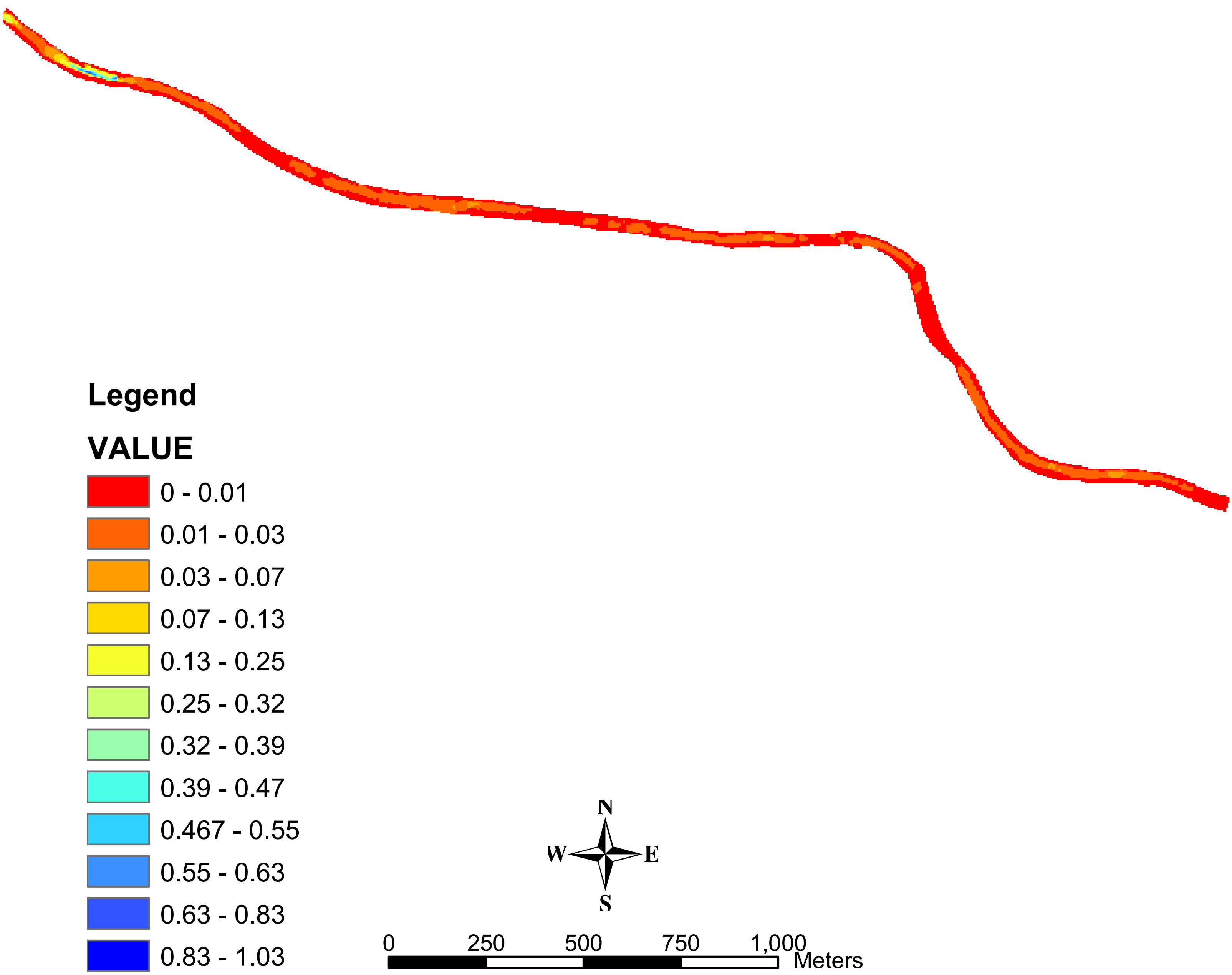
Spatial hydraulic model outputs depicting both depth and velocity are shown for each of the following flow rates:

0.31 cms (11 cfs)	2
0.71 cms (25 cfs)	4
1.29 cms (45 cfs)	6
2.27 cms (80 cfs)	8
3.11 cms (110 cfs)	10
5.66 cms (200 cfs)	12
8.50 cms (300 cfs)	14
11.35 cms (400 cfs)	16
14.16 cms (500 cfs)	18
83.02 cms (2932 cfs)	20

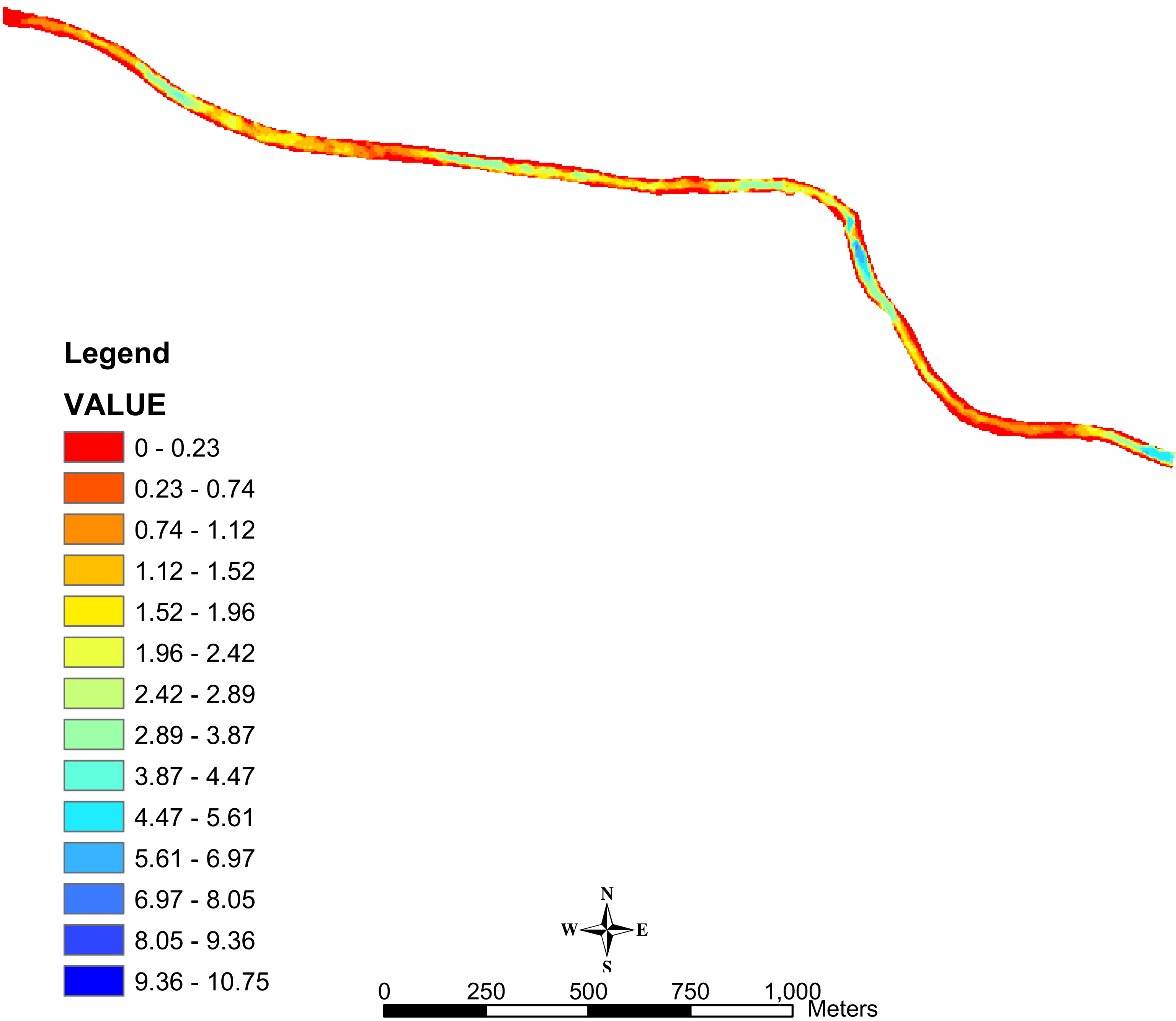
Depth Plot
0.33 cumec (11 cfs)
Sulphur River, Site 1



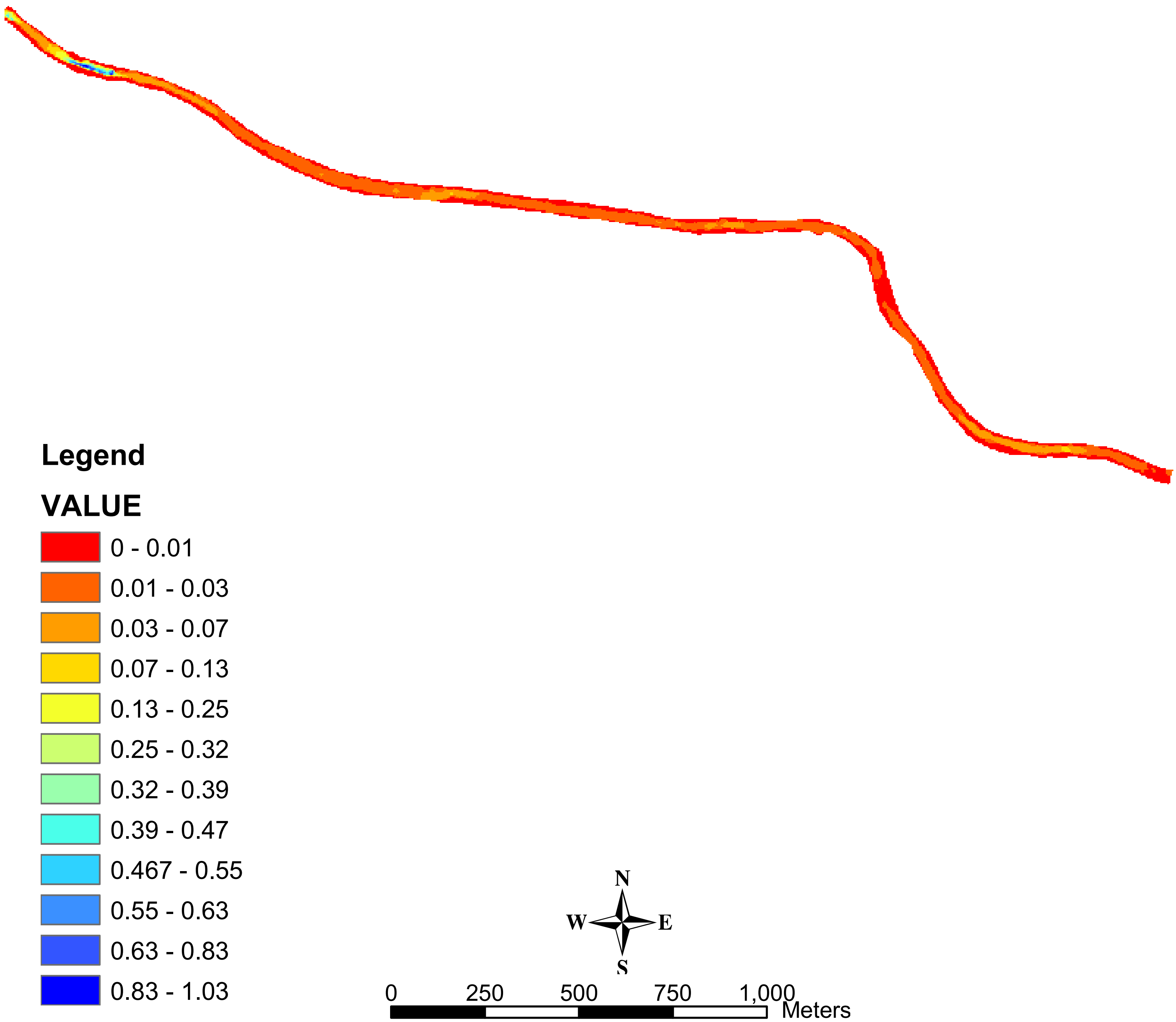
Velocity Plot
0.33 cumec (11 cfs)
Sulphur River, Site 1



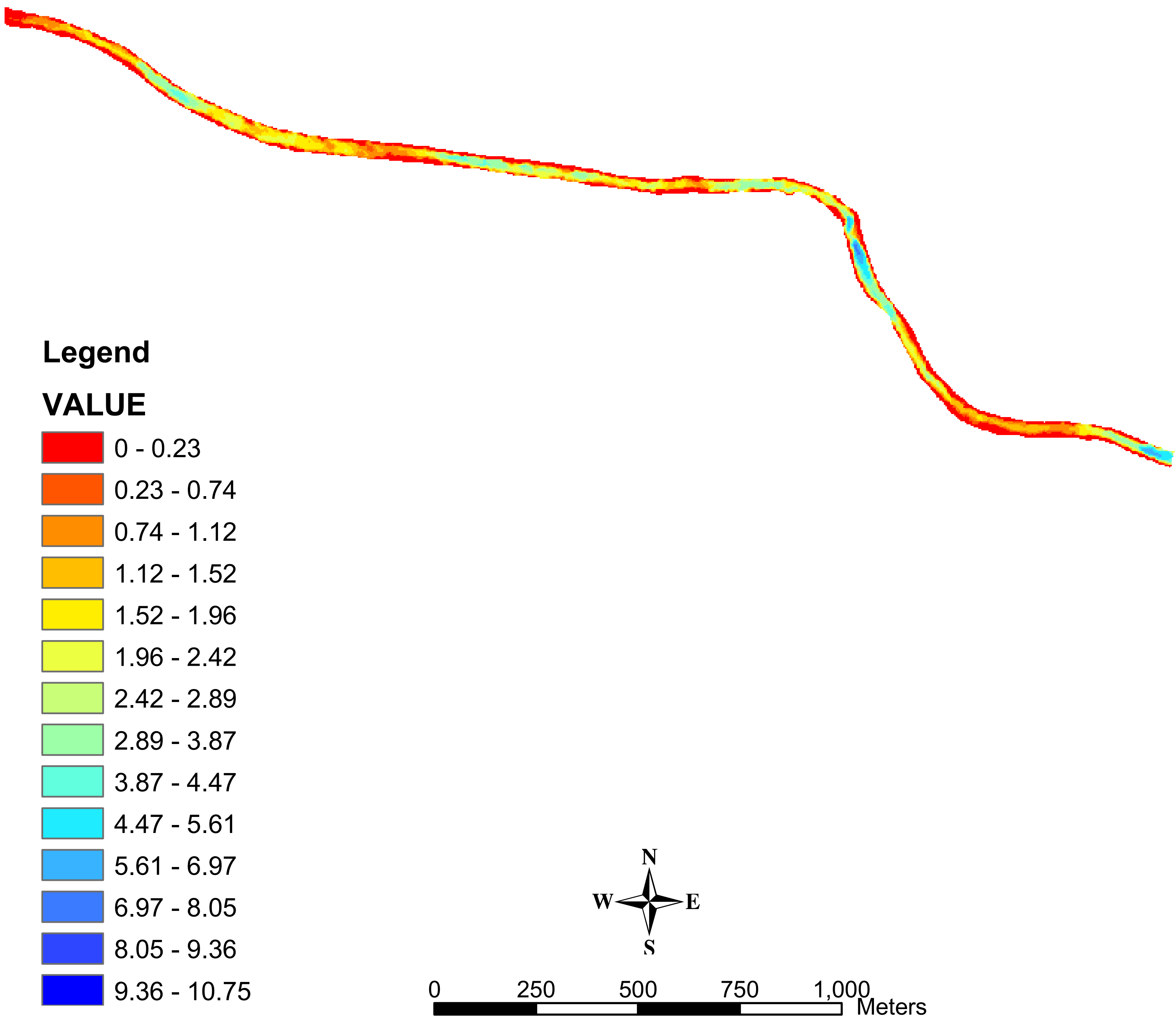
Depth Plot
0.71 cumec (25 cfs)
Sulphur River, Site 1



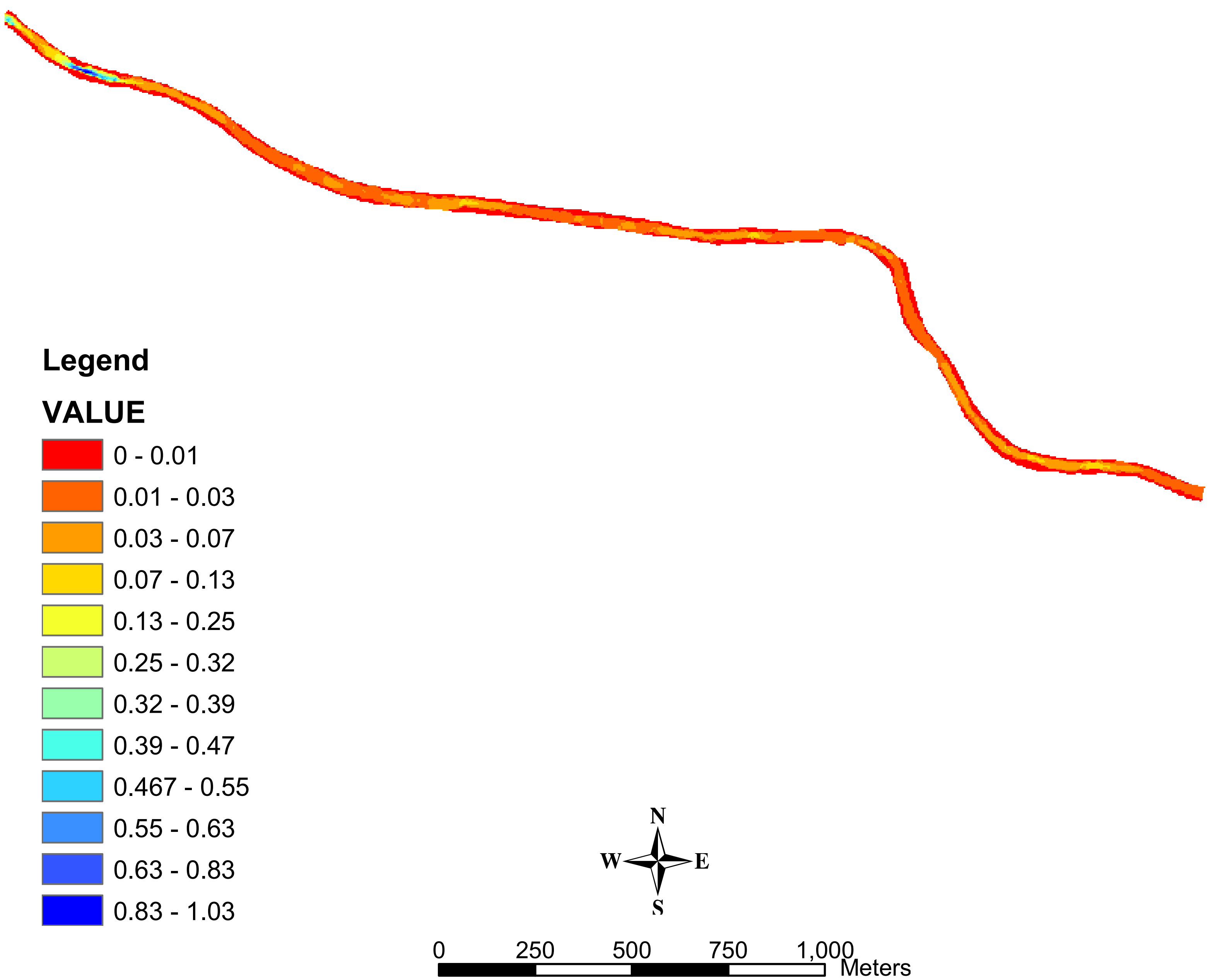
Velocity Plot
0.71 cumec (25 cfs)
Sulphur River, Site 1



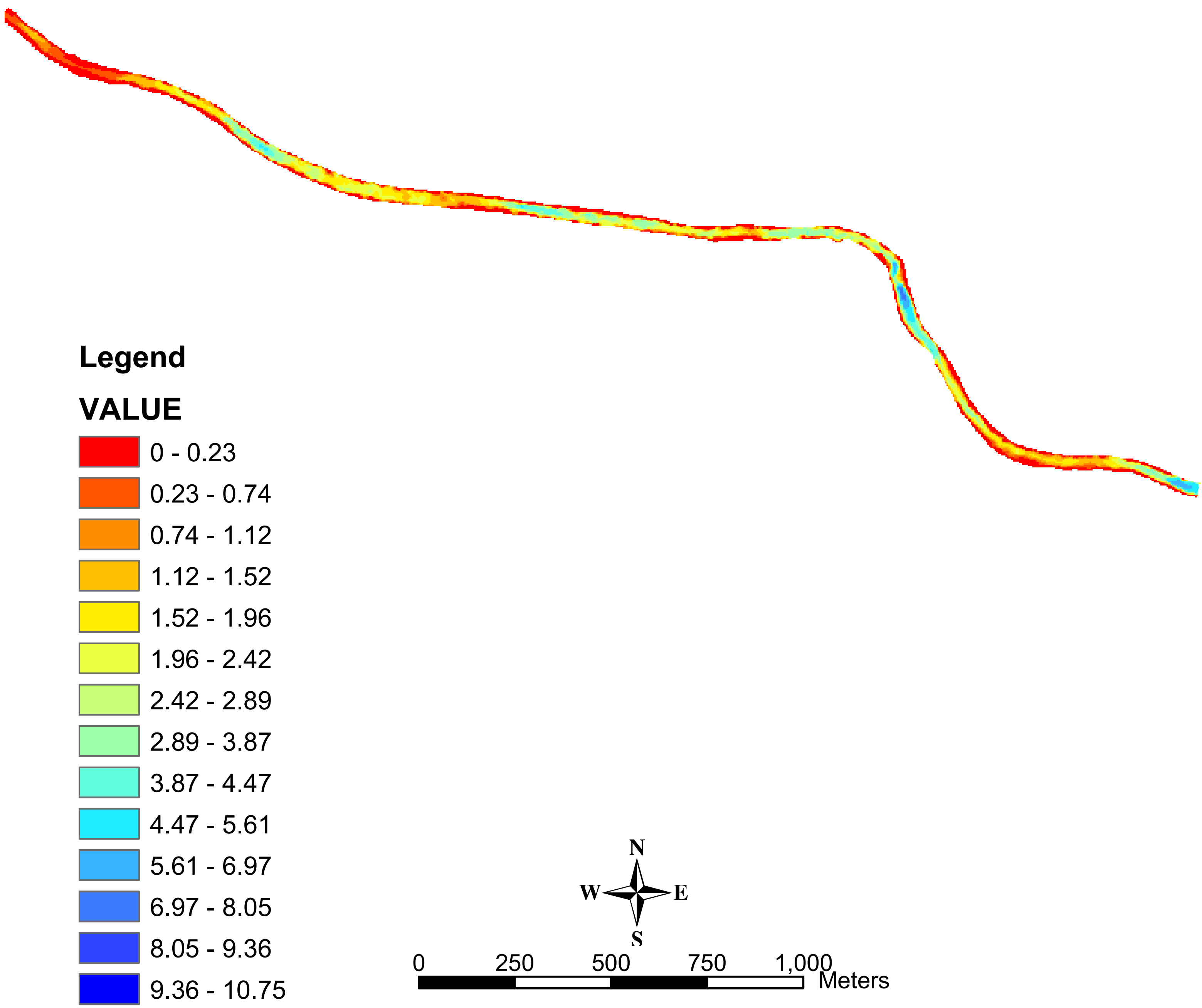
Depth Plot
1.29 cumec (45 cfs)
Sulphur River, Site 1



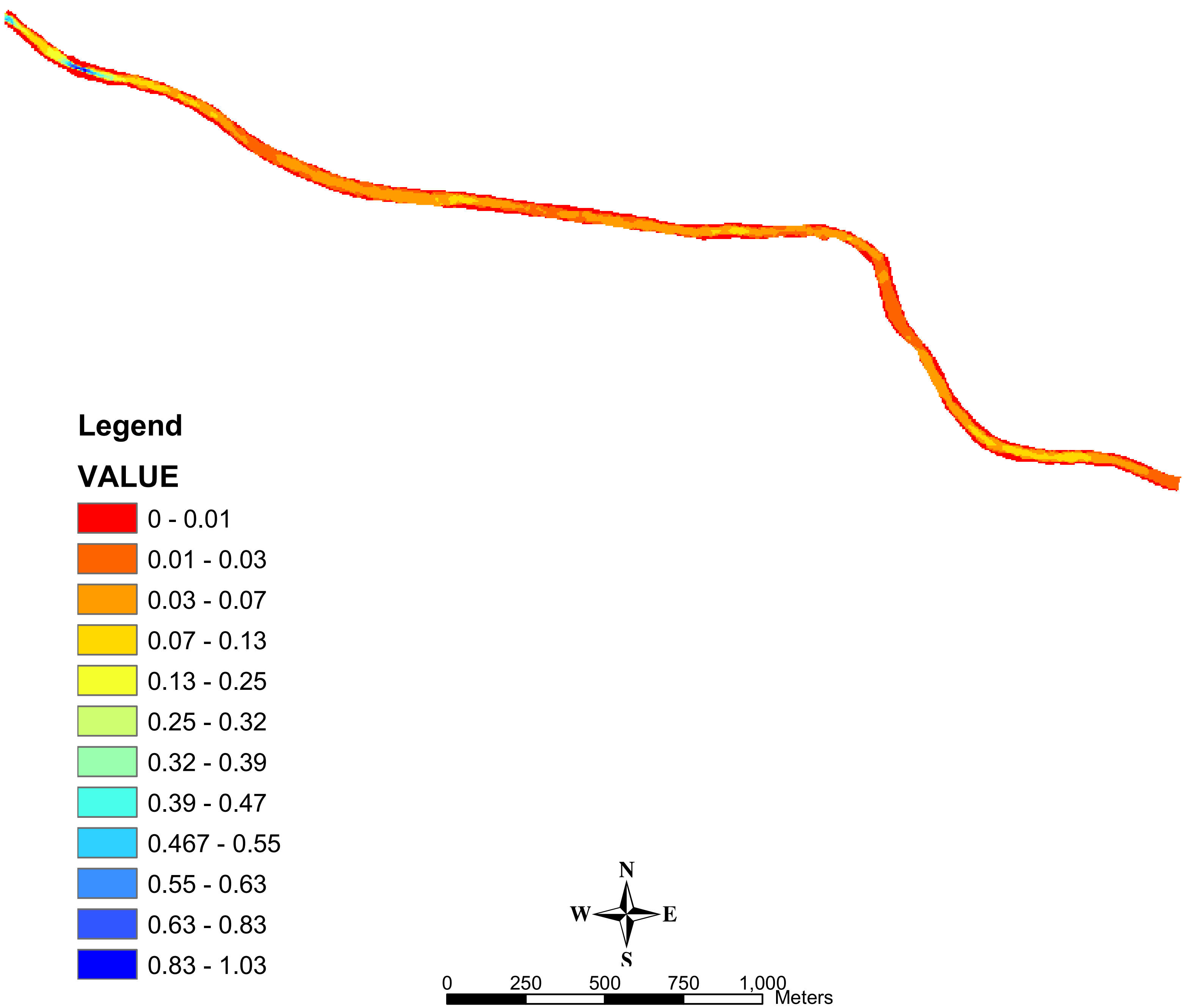
Velocity Plot
1.29 cumec (45 cfs)
Sulphur River, Site 1



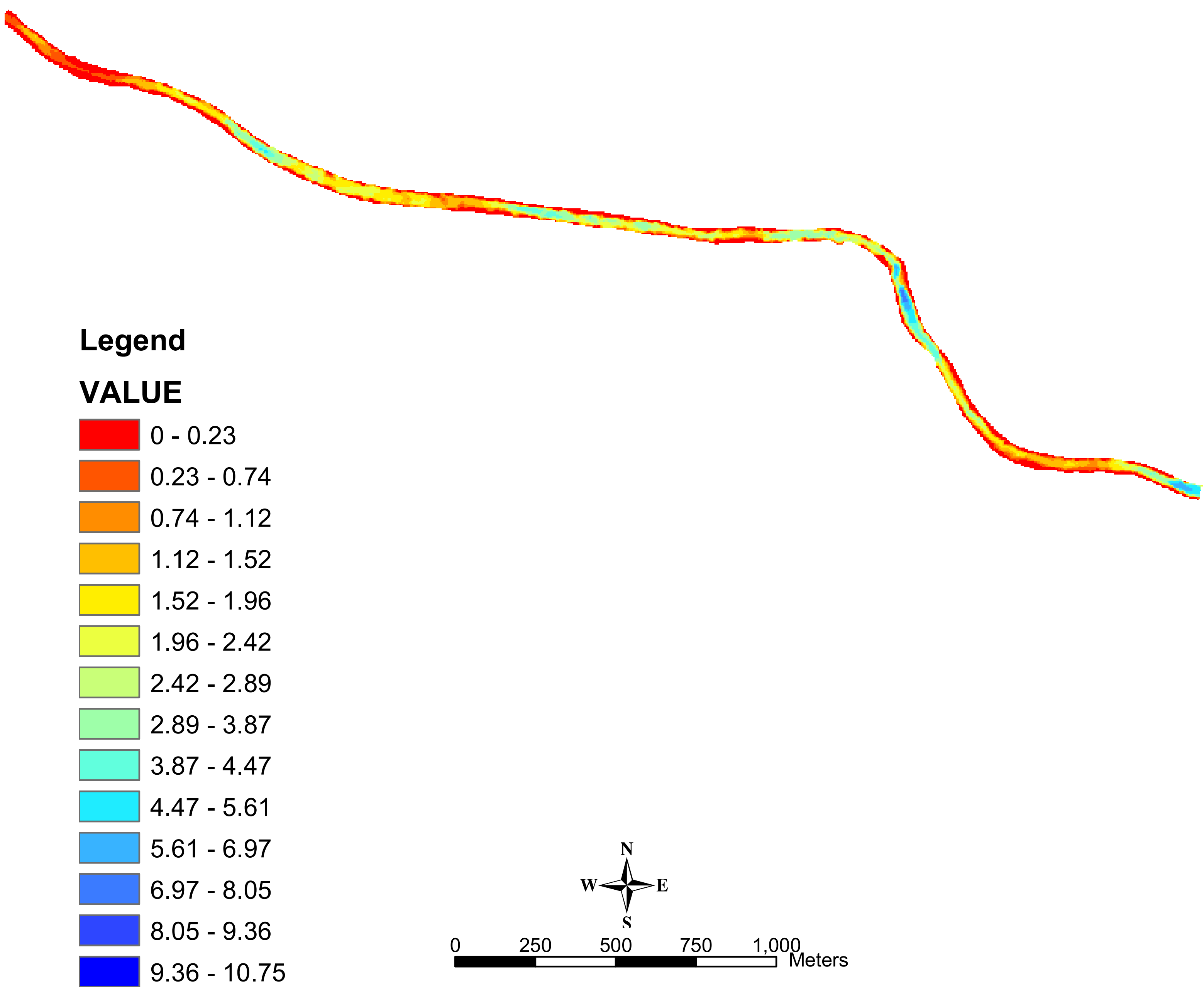
Depth Plot
2.27 cumec (80 cfs)
Sulphur River, Site 1



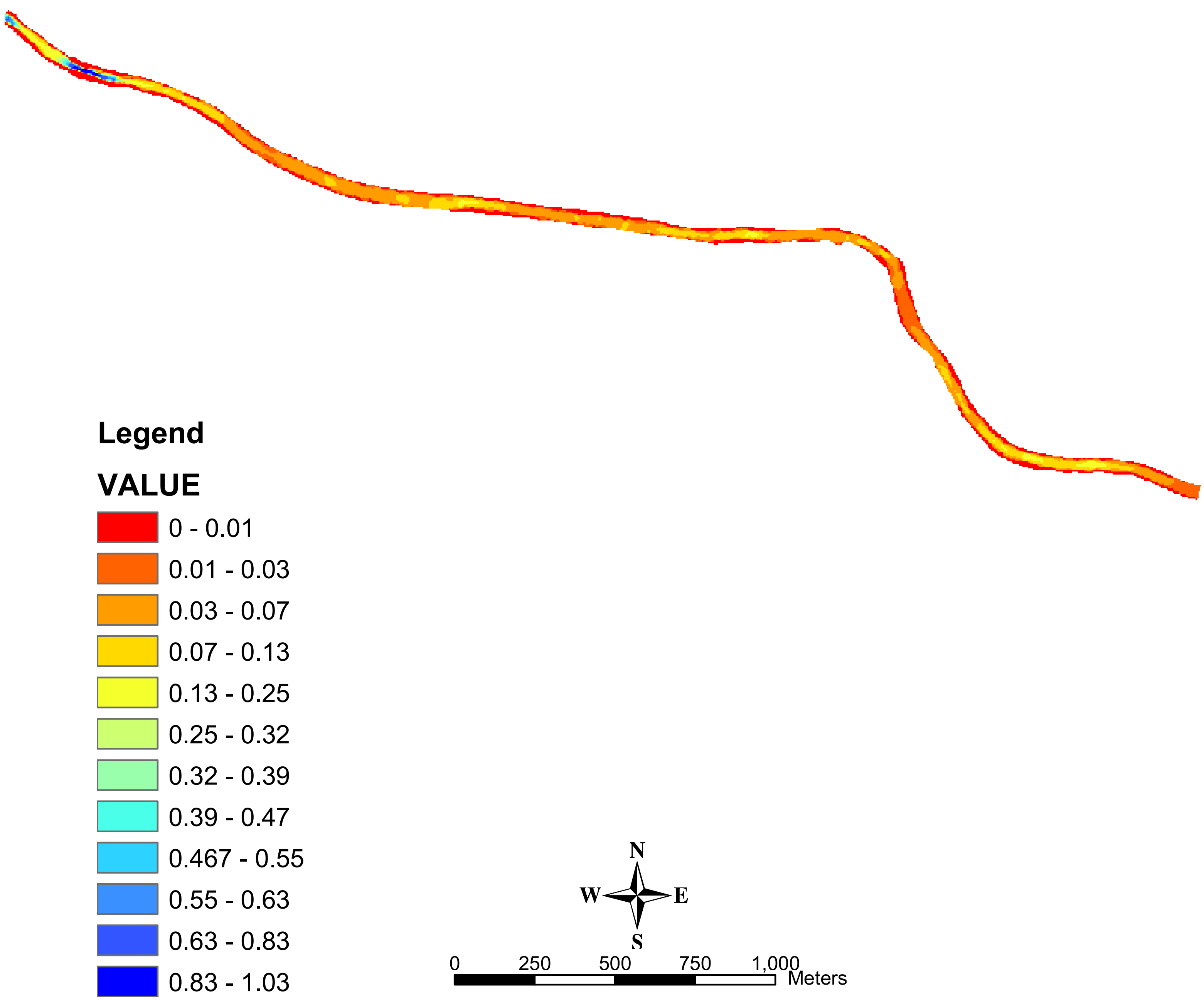
Velocity Plot
2.27 cumec (80 cfs)
Sulphur River, Site 1



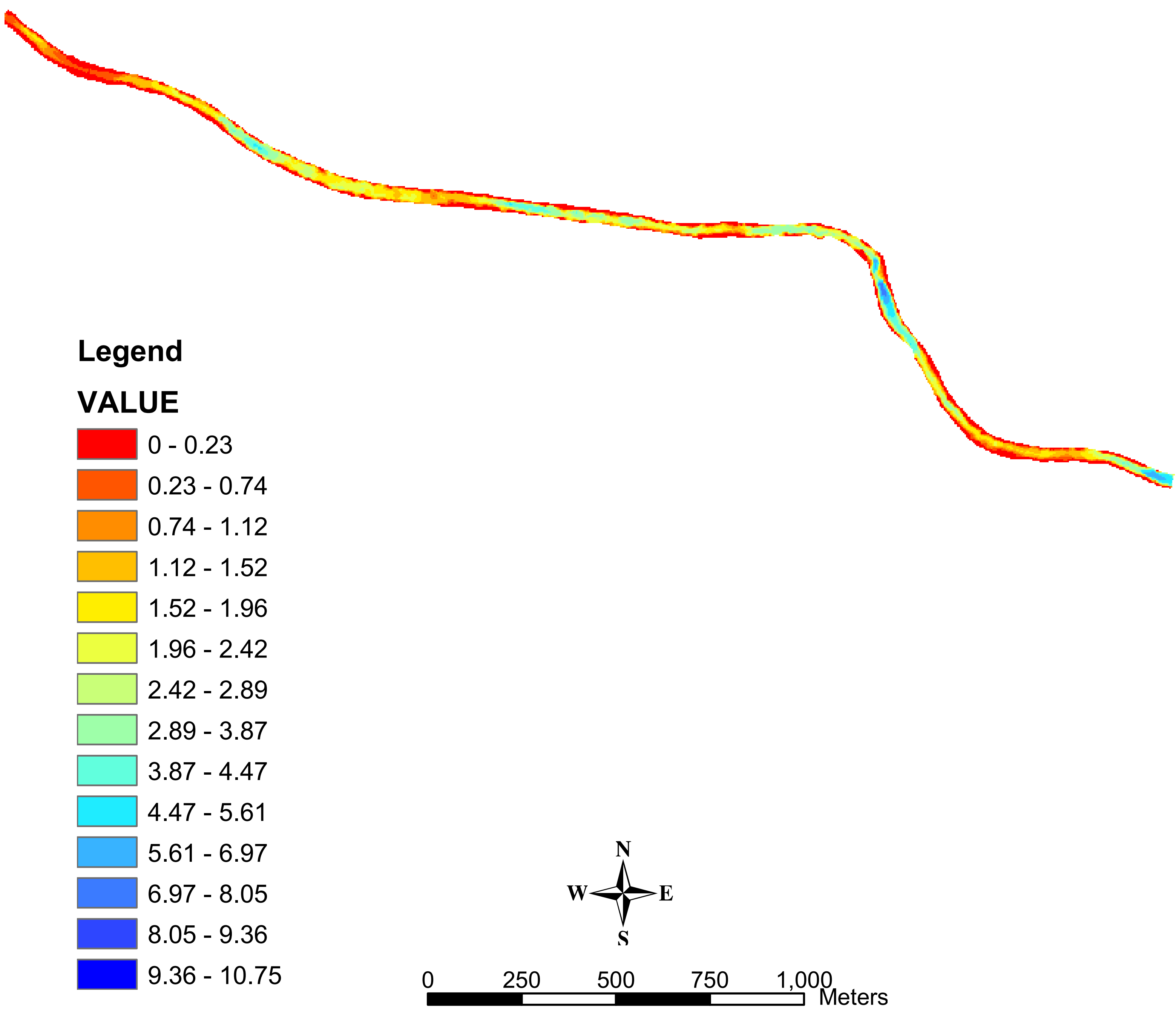
Depth Plot
3.11 cumec (110 cfs)
Sulphur River, Site 1



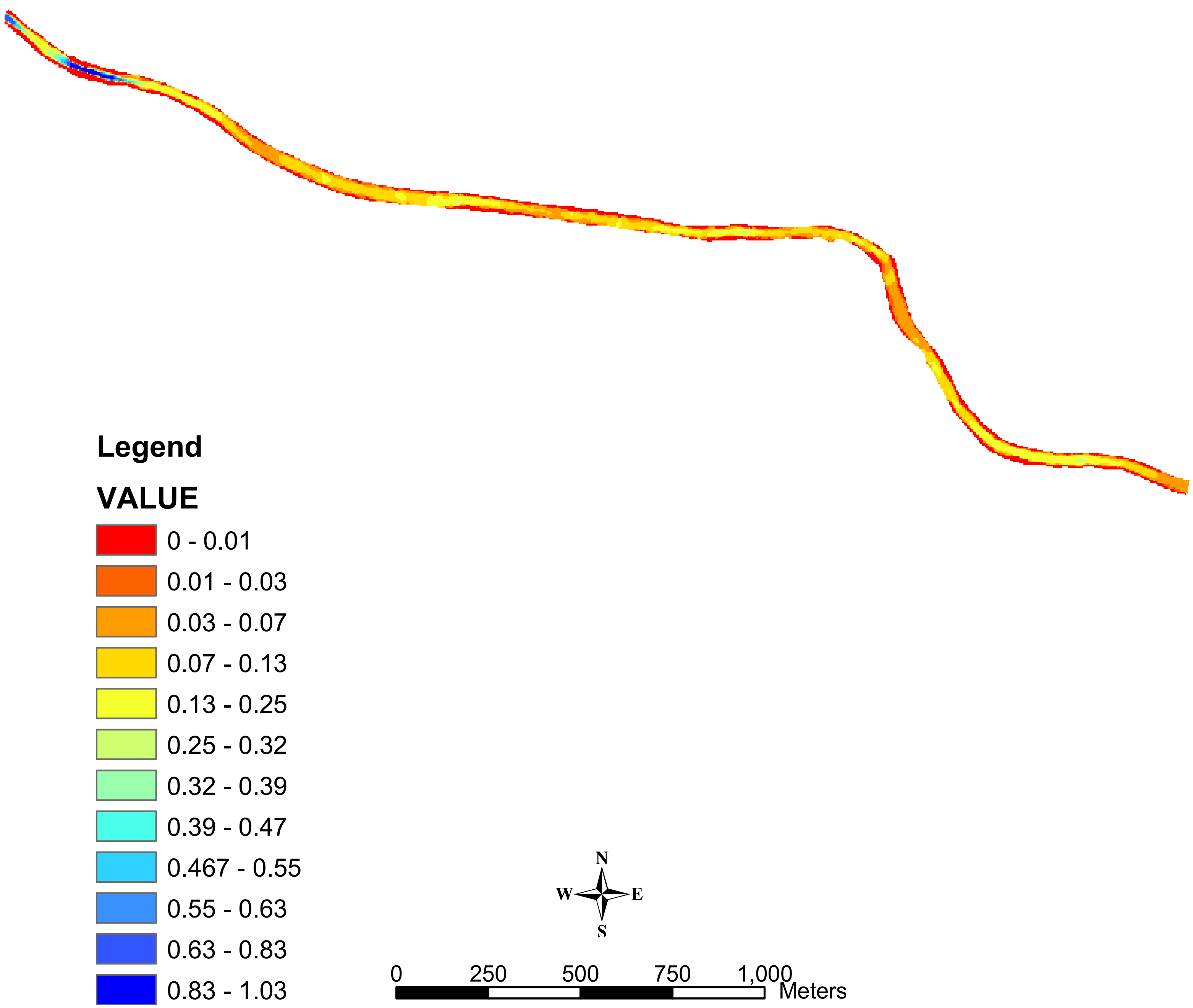
Velocity Plot
3.11 cumec (110 cfs)
Sulphur River, Site 1



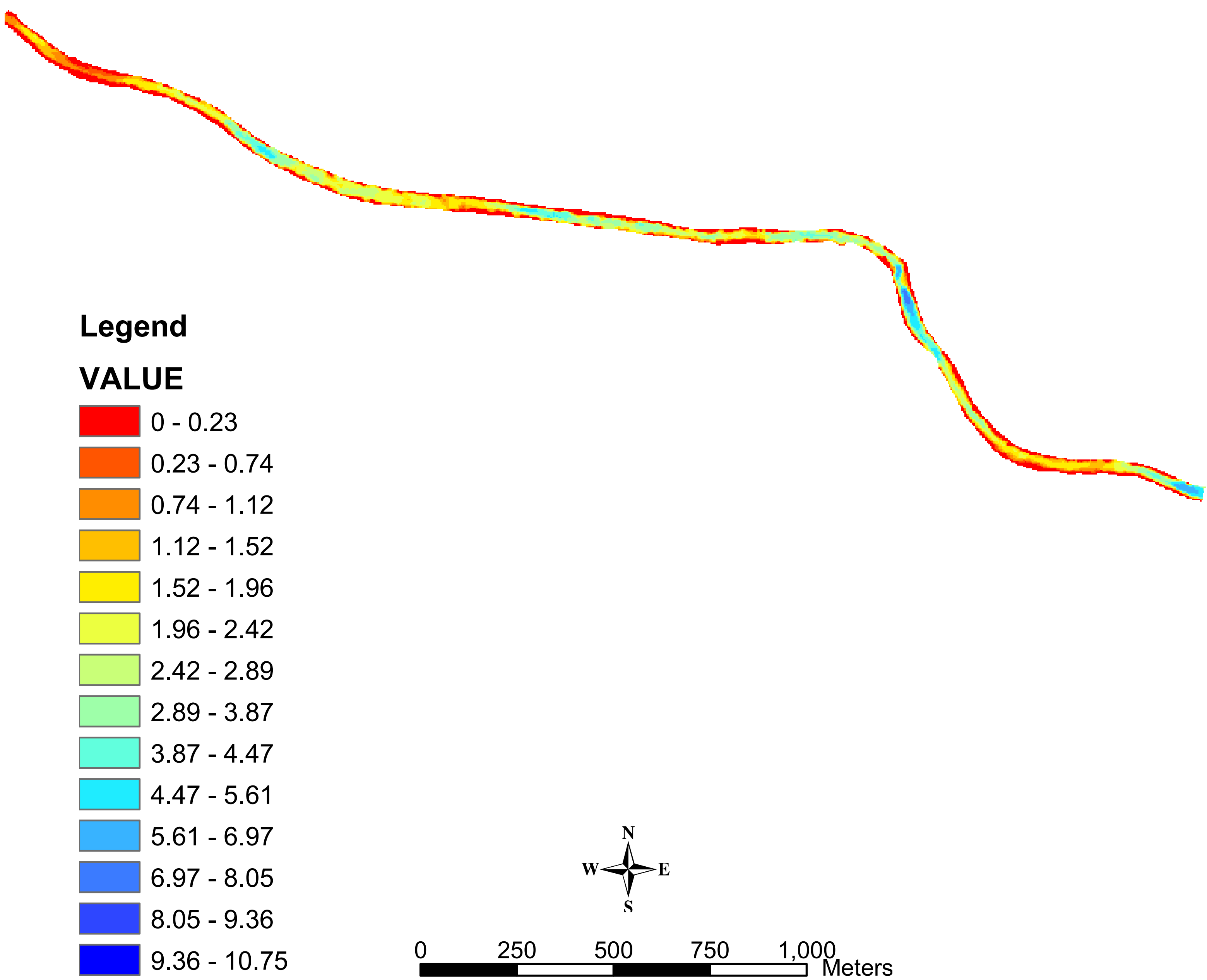
Depth Plot
5.66 cumec (200 cfs)
Sulphur River, Site 1



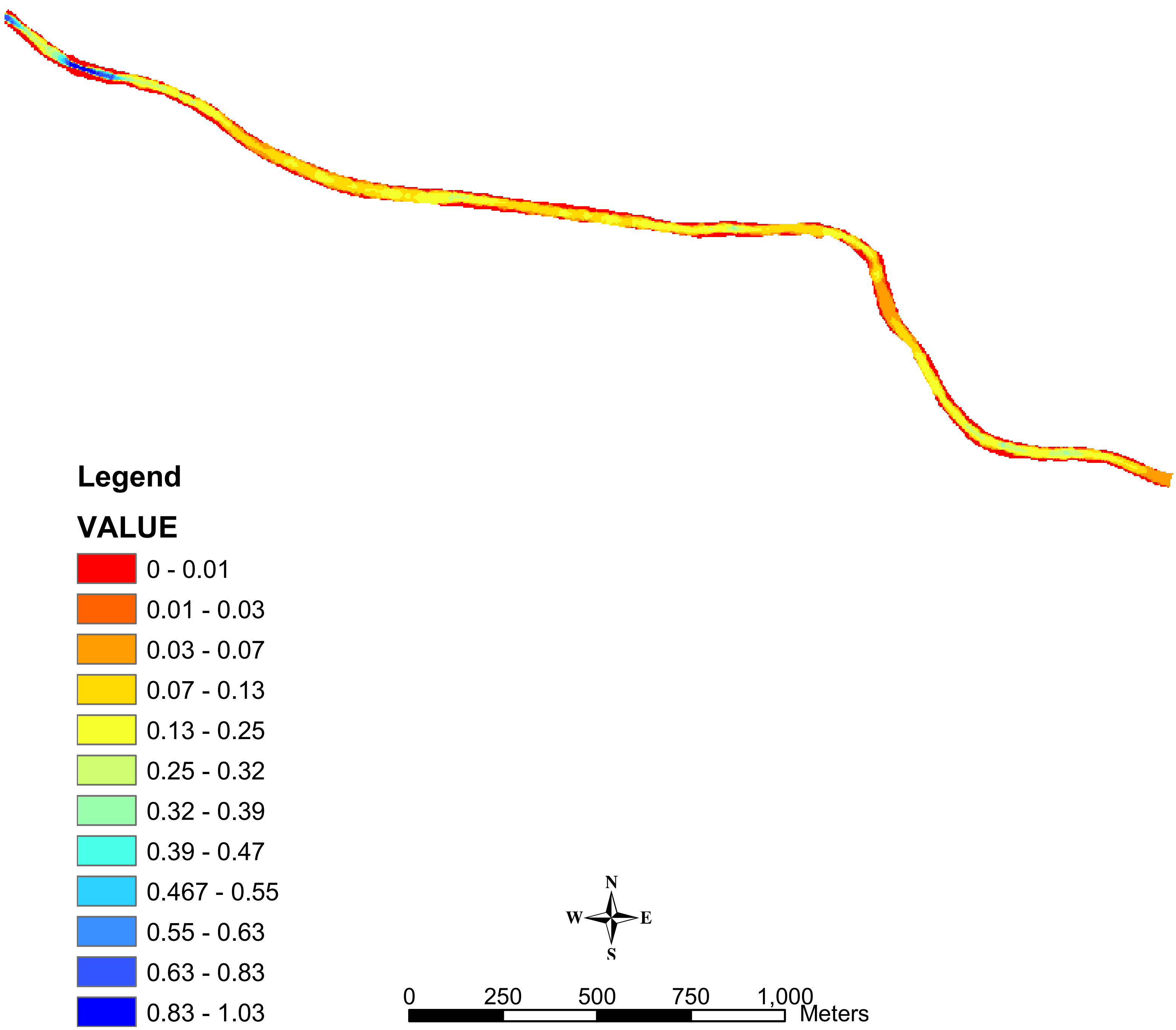
Velocity Plot
5.66 cumec (200 cfs)
Sulphur River, Site 1



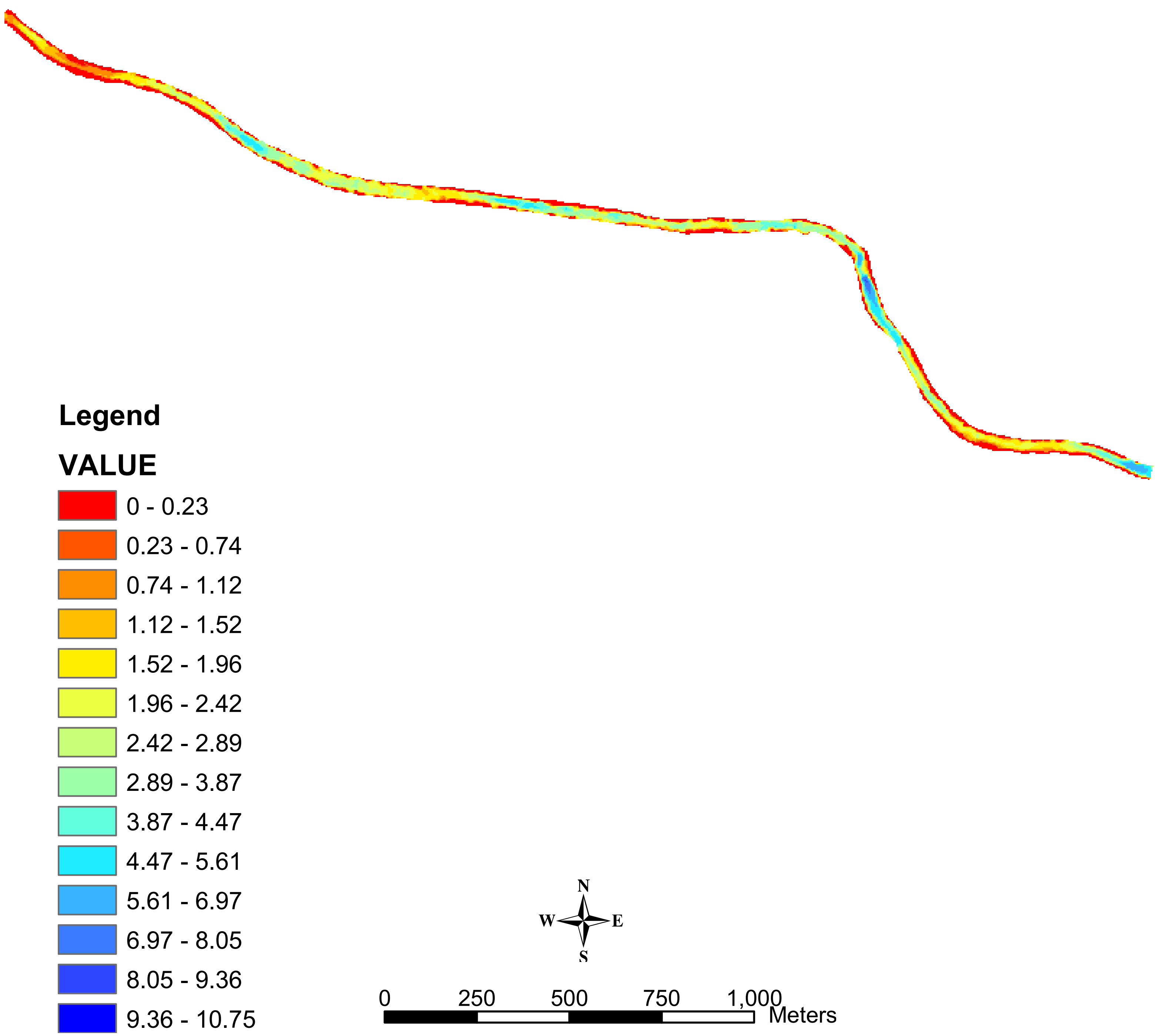
Depth Plot
8.50 cumec (300 cfs)
Sulphur River, Site 1



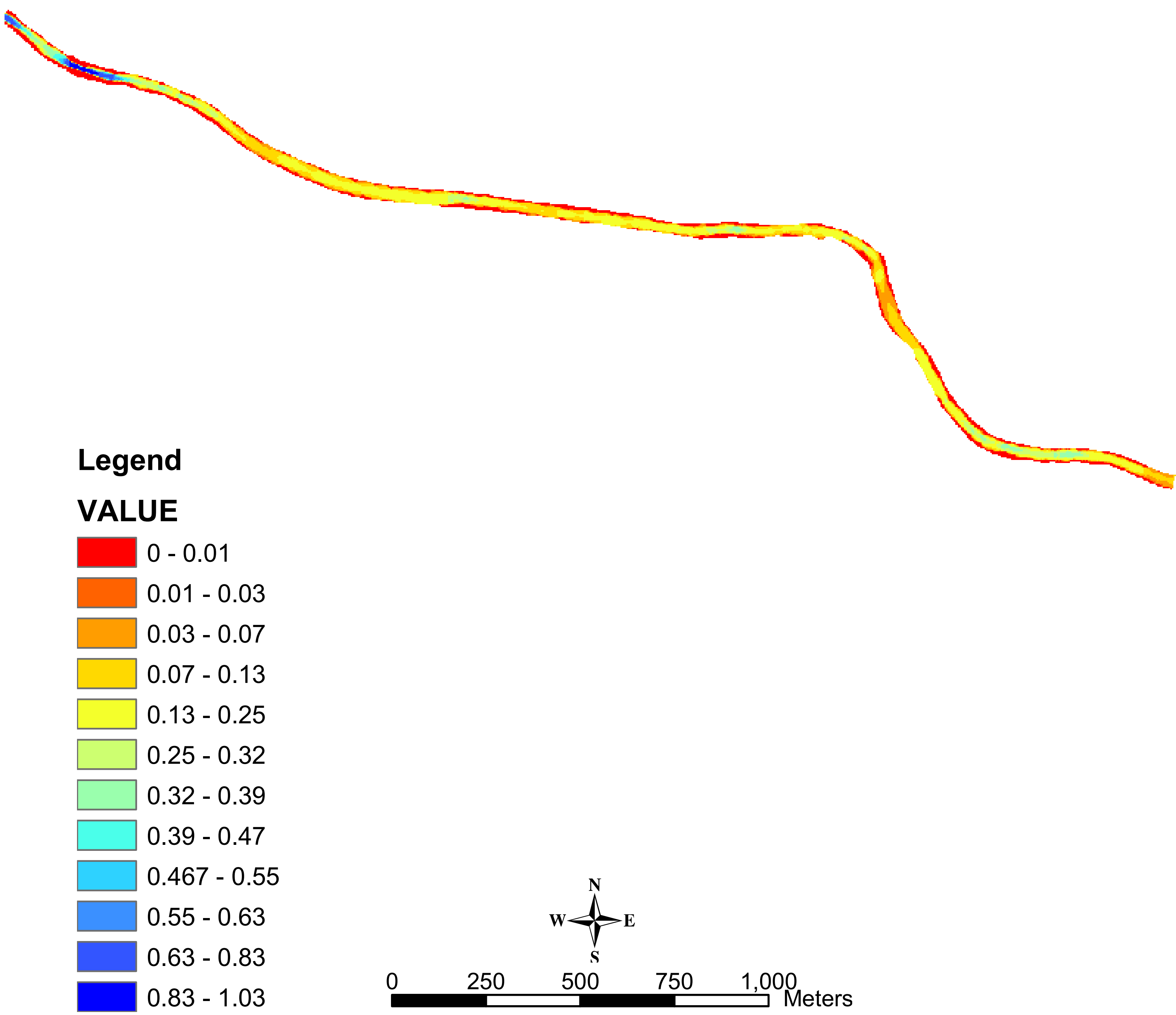
Velocity Plot
8.50 cumec (300 cfs)
Sulphur River, Site 1



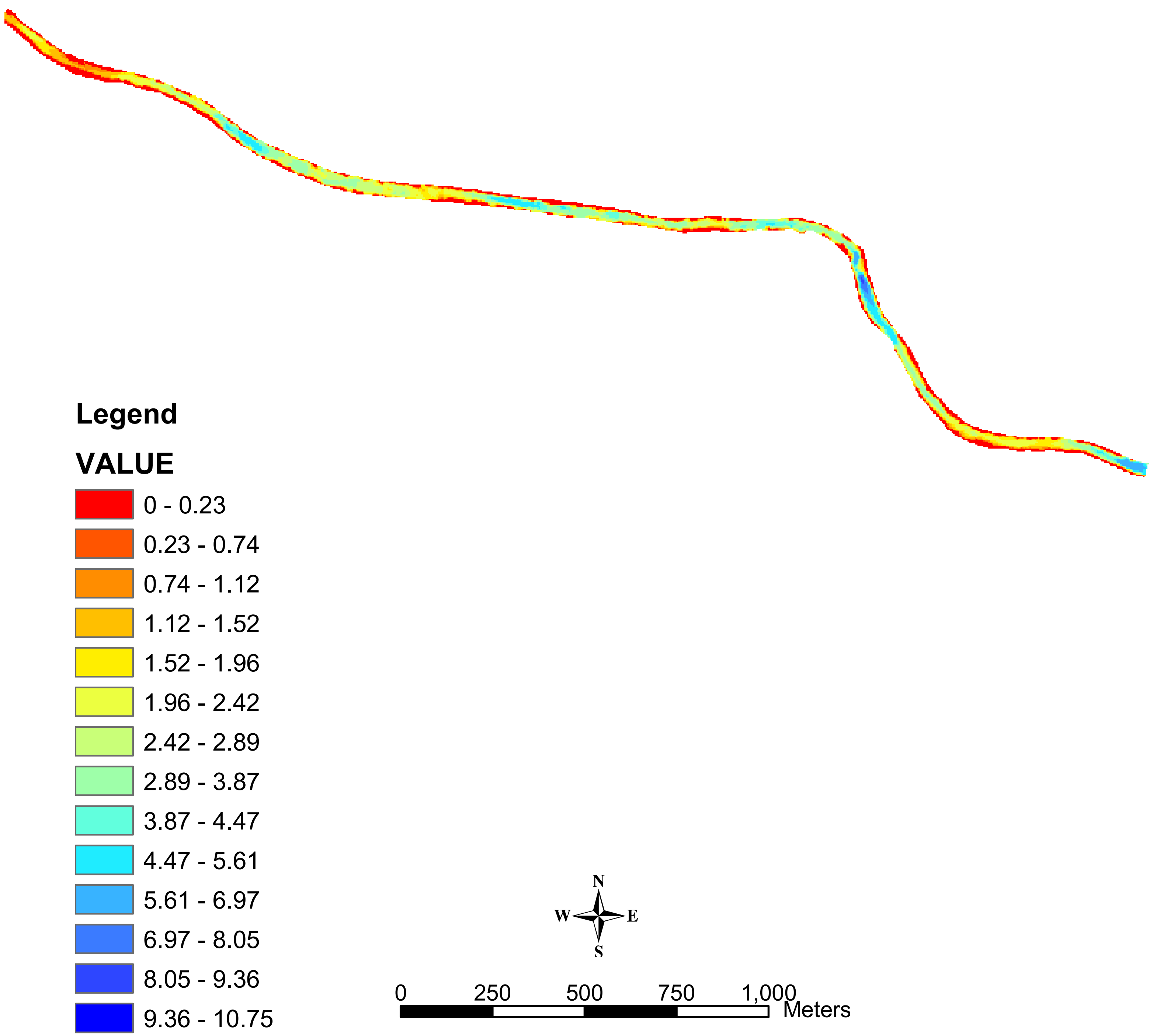
Depth Plot
11.35 cumec (400 cfs)
Sulphur River, Site 1



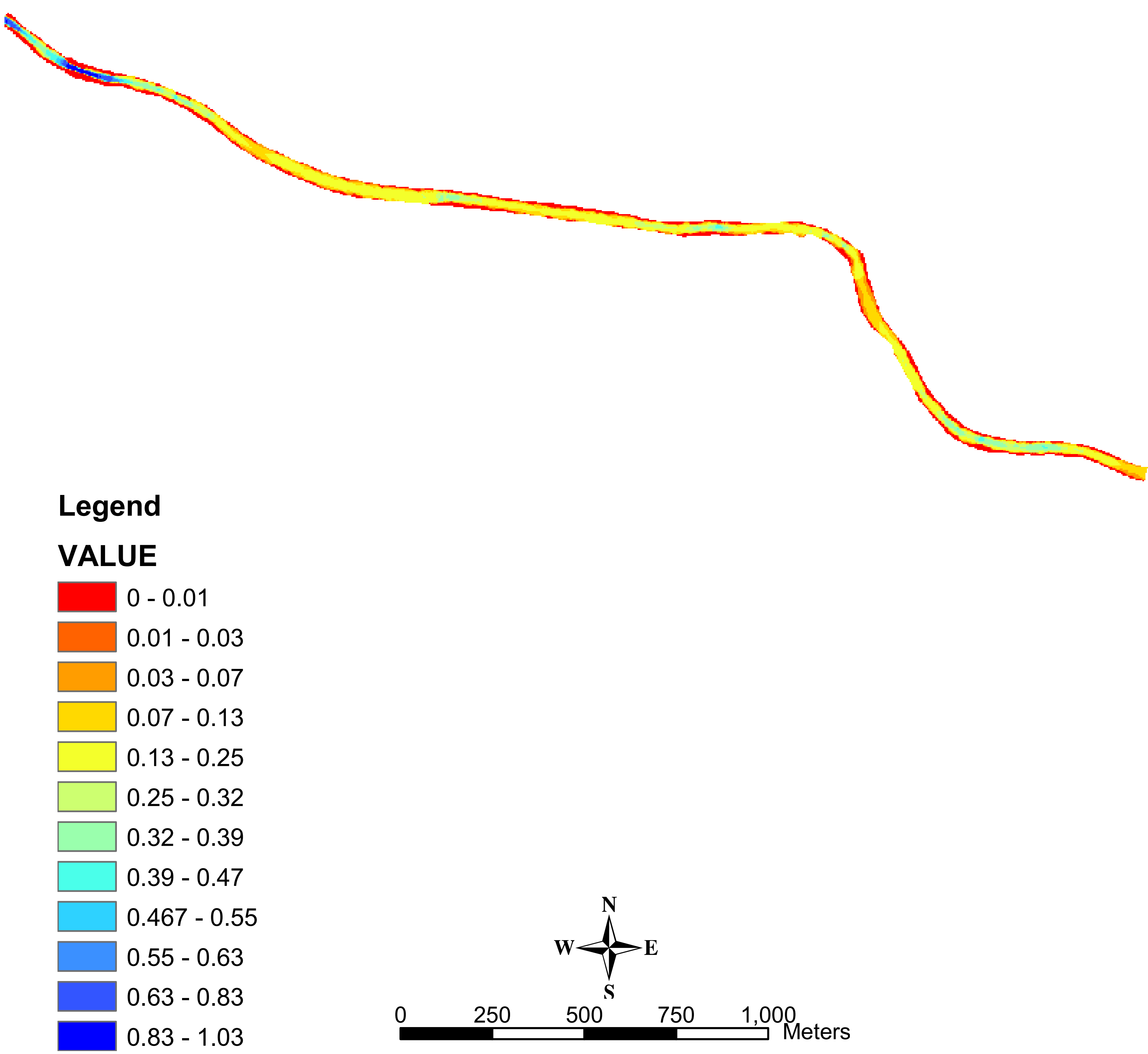
Velocity Plot
11.35 cumec (400 cfs)
Sulphur River, Site 1



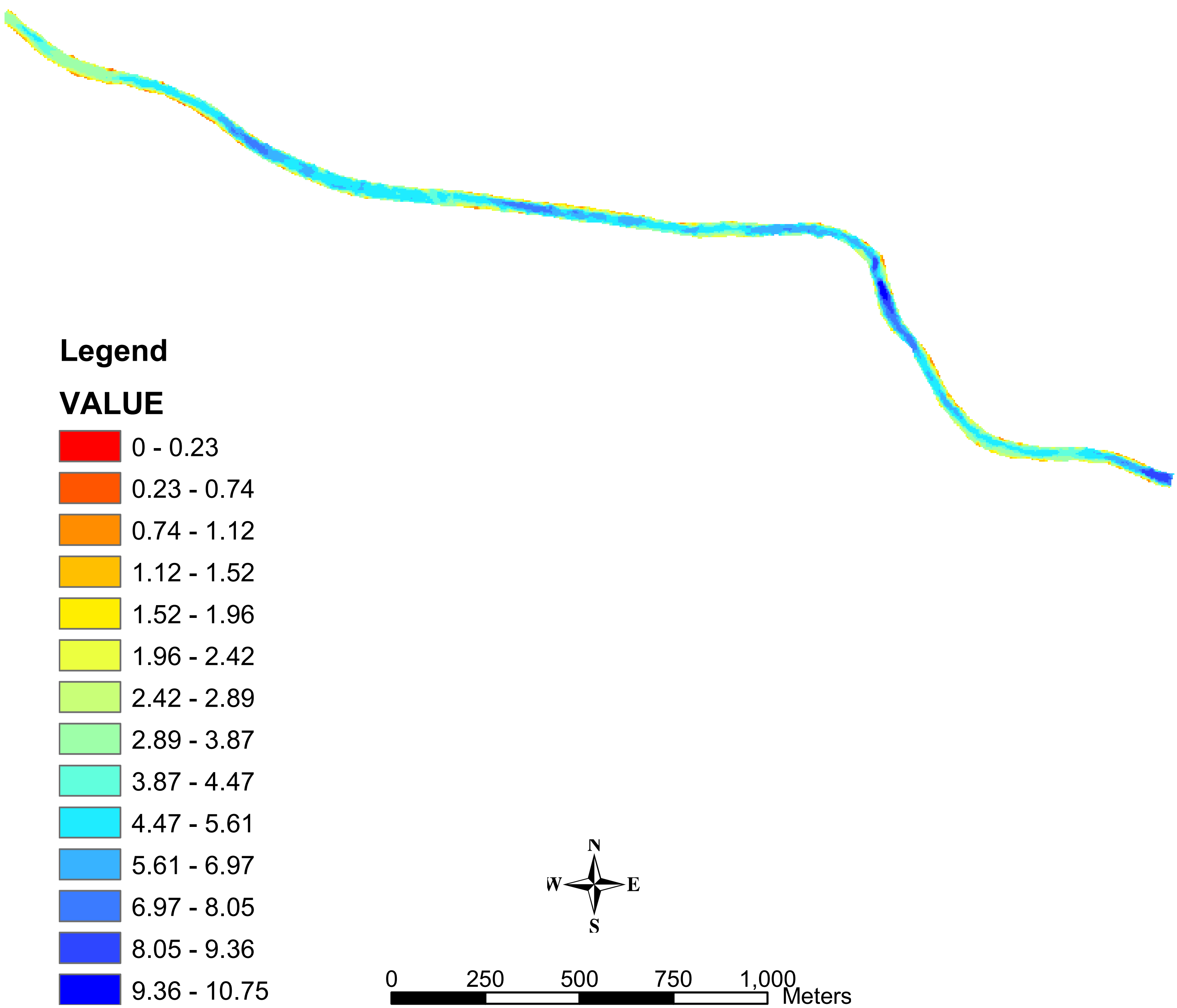
Depth Plot
14.16 cumec (500 cfs)
Sulphur River, Site 1



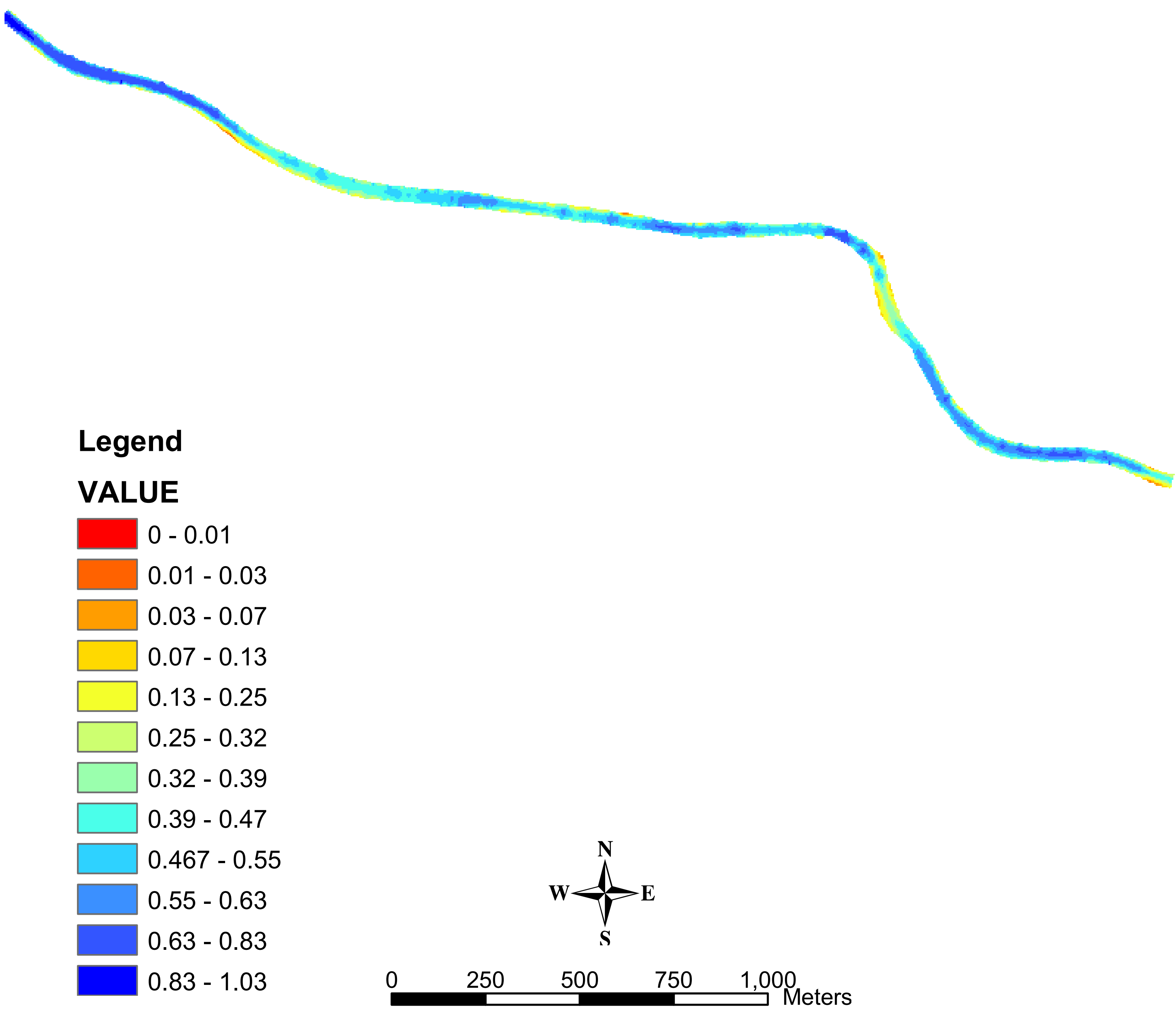
Velocity Plot
14.16 cumec (500 cfs)
Sulphur River, Site 1



Depth Plot
83.02 cumec (2932 cfs)
Sulphur River, Site 1



Velocity Plot
83.02 cumec (2932 cfs)
Sulphur River, Site 1



Appendix M

M. Hydraulic Model Calibration and Verification for Site 1

Ten steady-state models were developed for Site 1 of the Sulphur River. The Surface Water Modeling System (SMS) developed at Brigham Young University for the US Army Corps of Engineers (USACE) is used as a mesh generation and model execution interface for RMA-2. RMA-2 is a depth-averaged, hydrostatic, finite-element code developed by Resource Management Associates for the USACE. The major model inputs are the bottom bathymetric surface, upstream water flow rate, and downstream stage. Major model outputs are velocity and depth at each node of the finite element mesh. The bottom bathymetric surface is represented by a finite element mesh consisting of triangular quadratic elements (Donnell, et al, 1997).

M.1 Boundary Conditions

The complete set of boundary conditions and parameter settings for each flow rate model are shown in Tables M.1 and M.2 below. An identical finite element mesh was used for each model; however for low flow rates some mesh elements were manually disabled when the model's wetting and drying algorithm did not appropriately disable dry elements.

Boundary conditions specified for each model were as follows: flow rate was specified at the upstream boundary (with mass distributed across the boundary based upon depth) and constant water surface elevation across the downstream boundary. The model was calibrated using eddy viscosity and Mannings "n" (Donnell, et al, 1997; Arcement and Schneider, 1989) to match the upstream water surface elevation.

Table M.1 - Model input boundary conditions and parameters.

Flow		WSE			Roughness by Depth				Eddy Viscocity
		Upstream		Downstream	no vegetation		w/ veg.		
		Target	*model output*	boundary	manning n	depth	manning n	rough. Coeff	
cfs	cms	meters	meters	meters		meters			Pa/s
2932	83.02	103.483	*103.491*	103.483	0.04	0.5	0.06	0.04	70
500	14.16	101.150	*101.167*	100.822	0.04	0.5	0.06	0.04	70
400	11.33	101.000	*101.004*	100.641	0.04	0.5	0.06	0.04	70
300	8.50	100.760	*100.827*	100.428	0.04	0.5	0.06	0.04	70
200	5.66	100.520	*100.652*	100.180	0.04	0.5	0.06	0.04	70
110	3.11	100.290	*100.337*	100.110	0.015	0.25	0.025	0.1	70
80	2.27	100.250	*100.294*	100.200	0.015	0.25	0.025	0.1	70
45	1.27	100.040	*100.155*	99.916	0.015	0.25	0.025	0.1	70
25	0.71	99.980	*100.066*	99.678	0.015	0.25	0.025	0.1	70
11	0.31	99.900	*99.97*	99.570	0.015	0.25	0.025	0.1	70

Table M.2 - Additional model parameter settings and convergence criteria.

Standard settings for all models

Marsh Porosity				Wetting and Drying			Convergence Criteria
Distance below	Transition Range	Min. wetted surface		Iterations	Dry Element	Wet Element	
AC1	AC2	AC3	AC4		DSET	DSETD	m
0.91	0.61	0.02	na	na	na	na	0.01

M.2 Verification

Verification of model output was performed using available ADCP and Sontek velocity and depth measurements. The Sontek measurements were needed at lower flows where the shallow water depths did not allow for ADCP measurements. Of the data presented below, only the verification at 83.02 m^3/s (cms - Figure M.7) includes ADCP measurements. In each of the following figures, model output is shown with solid lines and field data collected on-site is shown in dashed lines. The cross-sections are located near the upstream end of the study reach (Figure M.1). Cross section distances are measured from the left bank looking downstream.

The extent to which the model reproduces the field data is demonstrated through qualitative comparisons between the speed and depth measurements and model predictions across each section. Each section follows the boat path taken during collection of field data.

M.2.1 Calculating flow along the boat path

One method of obtaining a quantitative comparison between field and observed data is to compare the modeled and observed flows calculated across each section using equation M.1:

$$Q = \int_{0}^{X} (SH) dx \qquad \text{(M.1)}$$

where Q is the flow through the cross section, X is the length of the cross section, S is the water velocity, H is the water depth and dx is the infinitesimal length between adjacent points along the cross section.

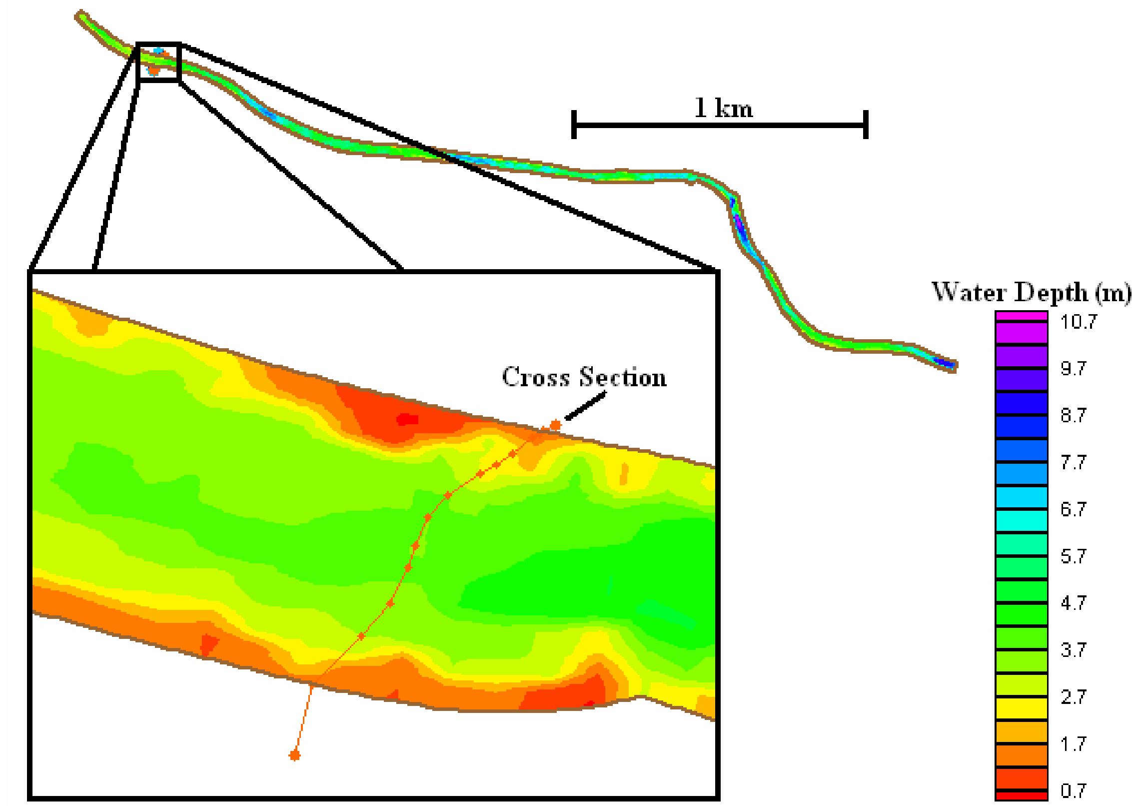


Figure M.1 – Sulphur River Site #1 Study Area Map Showing Cross-Section Location at 83.02 cms (2,932 cfs)

In calculating Q with Eqn. M.1, S and H are assumed to vary linearly between adjacent measurements along the cross section length. Comparisons between observed and modeled flows are given as percentages of the observed flow:

$$\lambda = \left(1 + \frac{Q_m - Q_o}{Q_o}\right) \times 100\%$$
$$\therefore Q_m = Q_o \times \lambda \qquad \text{(M.2)}$$

where the subscripts “m” and “o” refer to “modeled” and “observed,” respectively. The percentage “λ” is given on each figure and the deviation from 100% indicates the cumulative difference between modeled and observed conditions along the section.

As previously noted, the observed cross sections were not taken exactly perpendicular to the river flow (see Figure M.1), causing X to exceed the actual straight-line distance across the river. Therefore the flow values calculated with Eqn. M.1 will not necessarily agree with those reported for each figure since velocity magnitude perpendicular to the cross-section line were used for the flow calculation; in other words, the flow is exaggerated since the cross-sectional length is exaggerated along the boat path. Using the example of a simplified flat-bottomed river as shown in Figure M.2, flow calculated with Eqn. M.1 across cross-section #1, which is perpendicular to the water flow, is Q = 67.5 m^3/s. However, the flow calculated on a parabolic cross section (cross-section #2) is Q = 74.38 m^3/s, despite the fact that the actual water velocities have not changed. Because of these potential discrepancies, the actual flow values for observed and modeled cross sections as calculated with Eqn. M.1 are not shown on the figures.

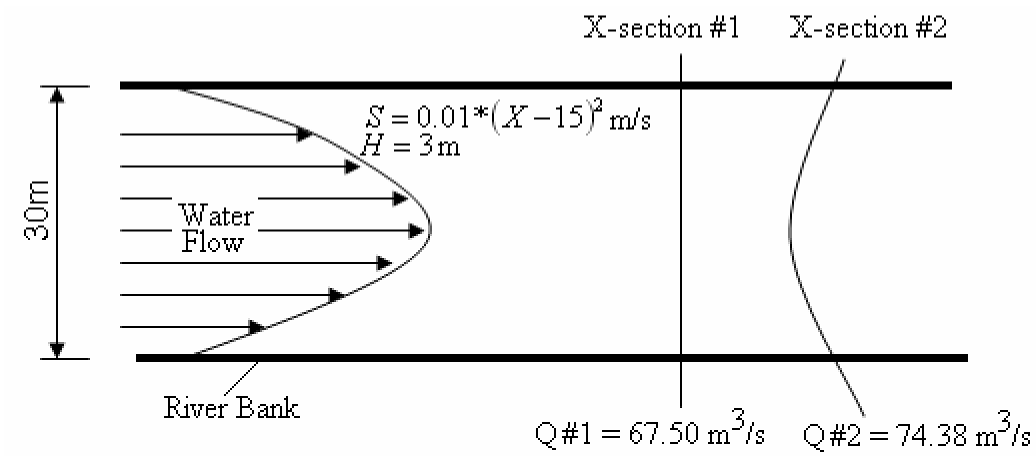


Figure M.2 – Differences in Calculated Flow Due to Cross Section Orientation

M.2.2 Discussion of potential sources of error

One unavoidable source of error between observed and modeled data is the fact that the river bathymetry was measured during high flow periods (2932 cfs) using boat mounted echosounding equipment. This allowed for collection of bathymetry data along the river margins, which would be dry land at lower flows. The consequence of measuring bathymetry at high flows is that the RMA-2 finite element mesh generated from that bathymetry data may be different than the bathymetry actually present in the field. The bathymetry at lower flows is particularly susceptible to change in sand-bed rivers, but not likely to be significant in the Sulphur River that exhibits largely cohesive material for substrate. The error caused by the discrepancy between flows is not capable of being incorporated into the model at this time since it depends on the rate of change of channel bathymetry due to intermittent flooding and sediment scour, transport and deposition. The depths collected at the cross section locations at the time of the ADCP and Sontek data measurements were used for the verification, and some discrepancy between observed and modeled water depth may be attributable to varying bed conditions over time and over a range of flow rates.

Bathymetry interpolation is a second possible source of error incorporated in the model validation process. The bathymetry data measured with the Knudsen Echo Sounder was interpolated to generate the bathymetric surface used in the RMA-2 finite element mesh. This interpolation was carried out with the use of the MEBAA program described in Appendix G, and may produce a smoother bathymetric surface than that observed with the ADCP and Sontek instruments. Also, to facilitate convergence of the RMA-2 model, the finite element mesh must not contain large bathymetric slopes. In areas where such large slopes exist in the river, the model bathymetry must be artificially adjusted. These minimal adjustments may cause discrepancies between the modeled and observed bathymetries shown in the following analysis.

Finally, precise coordinates were not available for the ADCP and Sontek velocity measurement locations. When possible, the cross sections created in SMS were drawn to correspond to field notes on measurement locations and on ADCP directional information; however, errors may have resulted from inaccurate locating of cross-sections. Coordinate measurements are recommended for all future flow measurements.

M.2.3 Comparison of the field data to model output

Between the date of the bathymetry survey and the date of the 0.33 cms section measurement, the bathymetry of the Sulphur river changed (Figure M.3) dramatically. At the low flow, water was confined into a narrow (<5 m wide) channel rather than the 17m wide channel indicated by the model bathymetry. This area exhibited sandy substrate and represented the only coarse-sediment area observed during this study in the Sulphur River. The accumulation of coarse sediment is likely the presence of an outcrop of clay that has resisted erosion whereas the surrounding clay has eroded. Velocities in this constricted channel were greater than those predicted by the RMA-2 model. While comparisons between field and modeled data at 0.33 cms flow are not useful for model validation purposes, it is evident that the approximate distribution of velocities produced by RMA-2 matches that observed in the cross-section. Velocities increase uniformly toward the channel center in a parabolic fashion.

Results obtained from the 45 cfs (1.27 cms) flow (Figure M.4) more closely match field conditions than those shown in Figure M.3. At the time of measurement, the river's depth was between 0.1 and 0.15m greater than that calculated with RMA-2. This suggests that river scouring and sediment re-suspension had occurred between bathymetry sampling and cross-section measurements, which is likely if a flood event occurred in the interim. In conjunction with the shallower modeled bathymetry, the modeled velocities were predominantly 0.1-0.15 m/s faster than those observed with the Sontek. The result is a modeled cross-sectional flow that is only slightly larger than the observed flow. As with the 11 ft^3/s flow (Figure M.3), the distributions of bathymetry and depth across the modeled and observed cross sections both follow the same patterns.

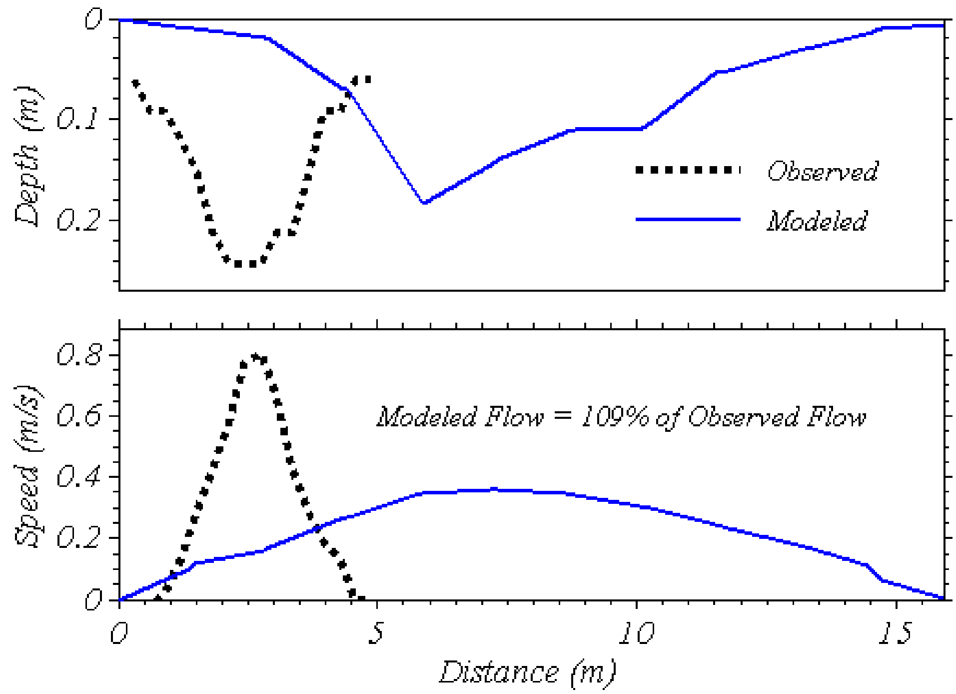


Figure M.3 – Model verification at 0.33 cms (11.5 cfs) for velocity and depth at Sulphur River Site 1. The narrow channel observed in the field was not represented in the model bathymetry.

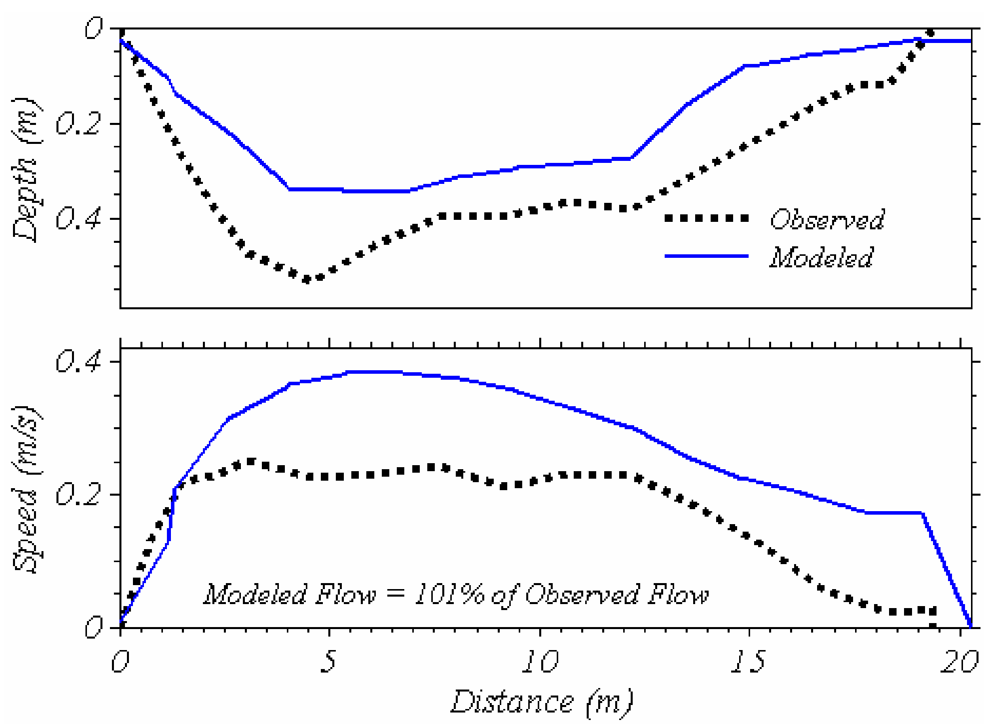


Figure M.4 – Model verification at 1.27 cms (45 cfs) for velocity & depth at Sulphur River Site 1

At 2.27 cms (80 cfs – Figure M.5), the velocities predicted by RMA-2 were nearly uniform across the channel width, and approximately equal to the mean observed cross section velocity. The modeled bathymetry, however, was between 0.1 and 0.15m shallower than the field measurements between 2 and 9m from the left channel bank. Also, the deepest point along the modeled cross section was more toward the left bank than in the observed data. These differences resulted in the modeled cross-section flow (as calculated by Eqn M.1) to be 3% greater than the observed cross-section flow.

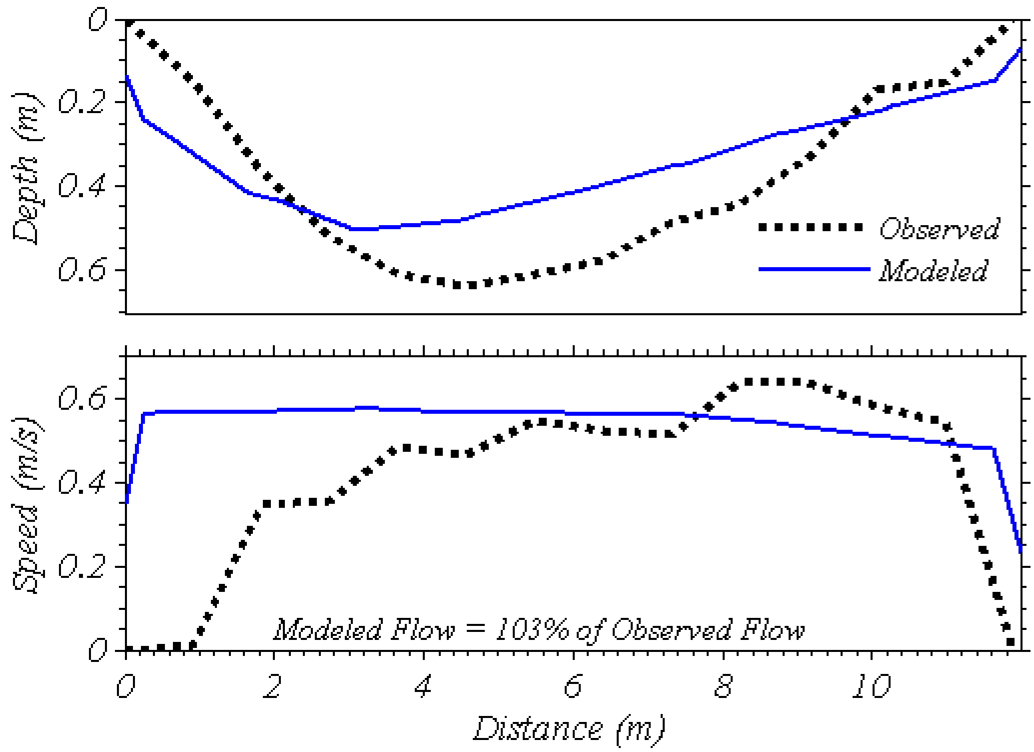


Figure M.5 – Model verification at 2.27 cms (80 cfs) for velocity & depth at Sulphur River Site 1

At 3.11 cms (110 cfs – Figure M.6), general agreement between modeled and observed bathymetry was obtained, although RMA-2 did not reproduce the observed velocity field. The observed velocity field was more uniform across the section, averaging 0.45 m/s. In contrast, the modeled velocity was lower at the cross section edges and increased to a value of 0.65m/s at approximately 8m from the left bank. Therefore the modeled maximum velocity exceeded the maximum observed velocity by approximately 50%. Despite these differences, the flows for the modeled and observed cross sections, as calculated with Eqn. M.1, are identical. This is because the faster modeled water in the channel center is compensated for by the slower modeled water along the section edges.

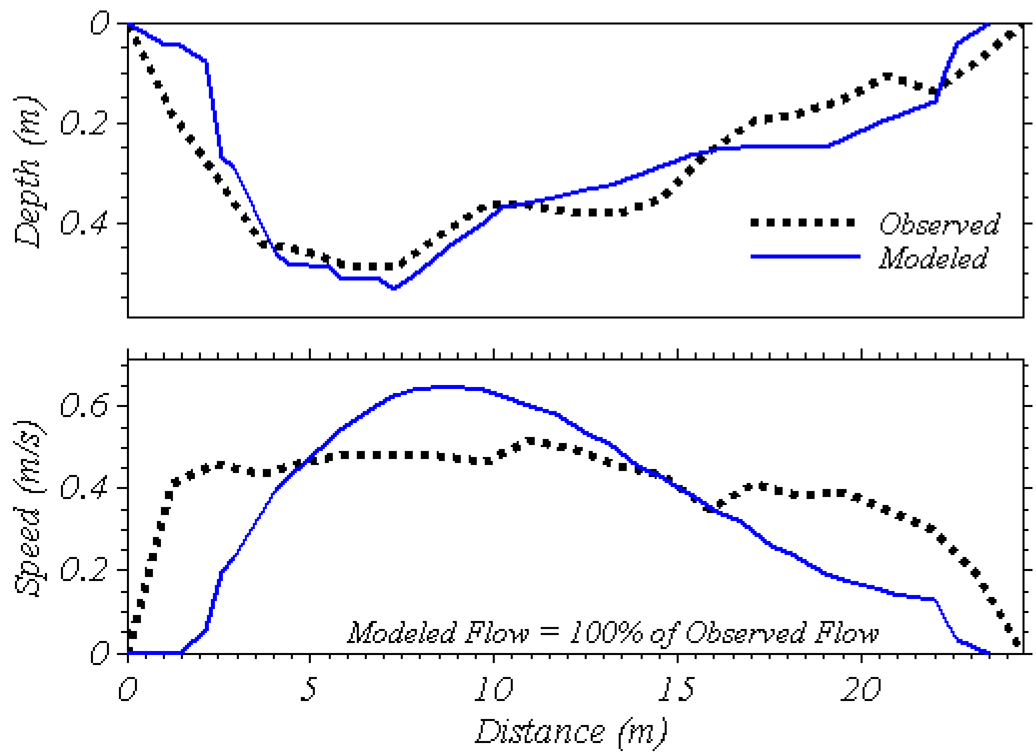


Figure M.6 – Model verification at 3.11 cms (110 cfs) for velocity and depth at Sulphur River Site #1

In Figure M.7 detailing the cross sections for the 83.0 cms (2932 cfs) flow, the best agreement between modeled and observed data was obtained. Measured depths compare well to modeled water depth and bathymetry, although the model was slightly deeper throughout the majority of the cross section. The velocity measurements from the ADCP also matched well with the modeled values, although the model largely under-predicted velocities near the left bank and from 4m to 10m from the left bank. The model was unable to predict the observed oscillations in velocity from 10m to 45m from the left bank, but was able to predict the mean values from the observed velocity fluctuations. The modeled flow for this cross section is 100% of the cross section observed flow.

Additional velocity and depth measurements were measured by the biology contractor; however the discrete location of measurements was not recorded with sufficient accuracy to compare with model output data.

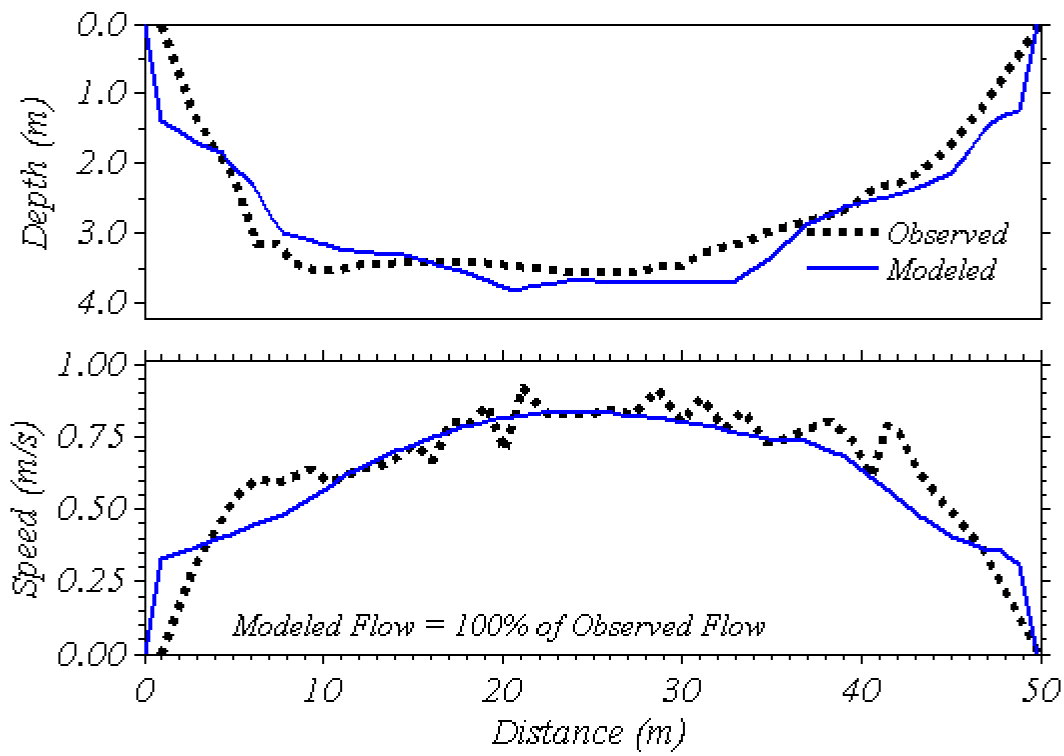


Figure M.7 – Model verification at 83.0 cms (2932 cfs) at Sulphur River Site 1

M.3 Verification of model continuity

Ideally, RMA-2 should calculate velocities that satisfy water mass continuity for each mesh element. Deviations from continuity indicate locations within the finite element mesh where the model is not performing adequately as a result of the governing equations, model discretization (mesh geometry), solution method or, more likely, some combination of all of these factors. Errors in the predicted velocity and depth values at these locations are likely to be large.

RMA-2 performs continuity checks by comparing flows at user-defined sections across the mesh, and by comparing those flows to the flow at the upstream boundary. Numerical model continuity was verified at 19 continuity check points (cross sections) within the study area (Figure M.8). As shown, continuity check points #1 and #19 are the upstream and downstream boundaries of the study area, respectively. Table M.3 presents the deviations calculated at each continuity checkpoint for all of the flows modeled in this study. Deviations greater than 5% are highlighted in Table M.3 and continuity checkpoints and residuals for those sections applicable to figures shown above are shown in bold with a border.

As shown in Table M.3, continuity was maintained within the 5% deviation limit for 99.4% of the check points. Only the flow at check point #2 in the 80 cfs run exceeded the 5% deviation limit. The generally small deviations from continuity are reflective of the fact that the study area contains predominantly straight reaches with few constrictions or expansions. Based on this analysis, the RMA-2 models of Sulphur River Site #1 were numerically well-posed, and discrepancies between field and observed data are more likely to be due to uncertainties in the model boundary conditions (bathymetry, water surface elevation, roughness, and flow).

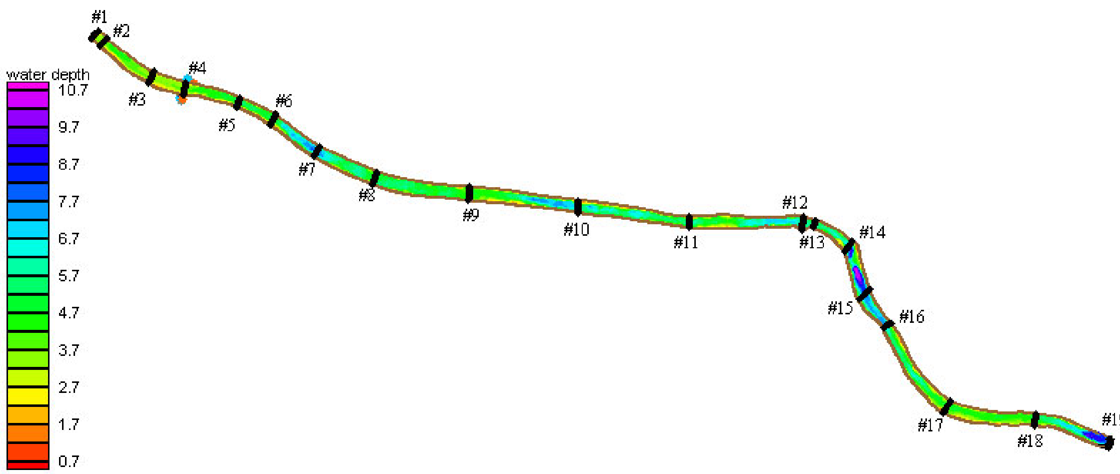


Figure M.8 – Sulphur River Site #1 Study Area Map indicating locations of continuity checkpoints (black cross sections). Numbers refer to the entries in Table M.3. Depths shown are for the 83.02 cms (2932 cfs) flow.

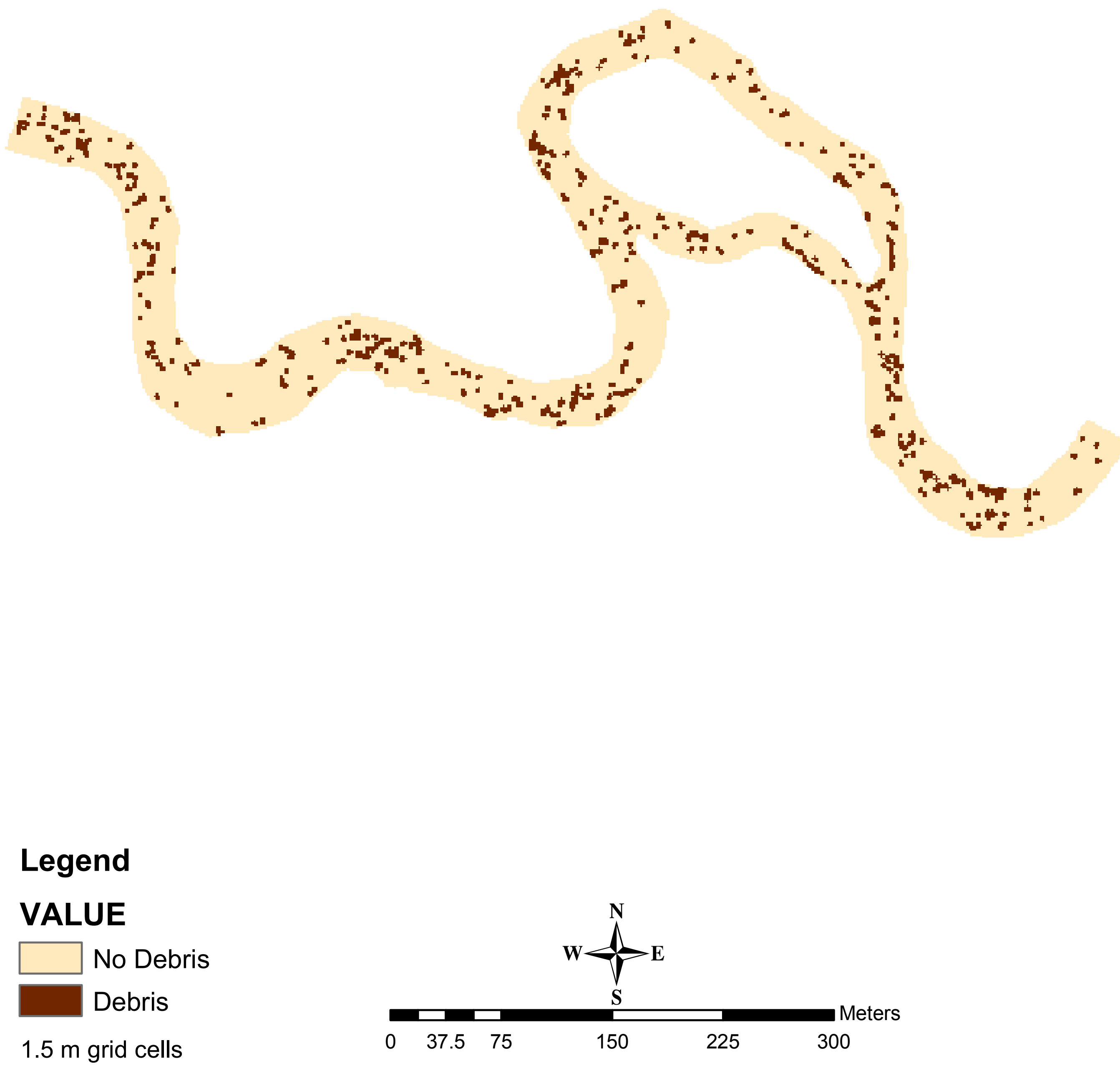
Table M.3 - Percentage Deviation from Flow Continuity at Check Point Cross Sections

Check Point	Flow Rate cms / cfs	0.31 / 11	0.71 / 25	1.27 / 45	2.27 / 80	3.11 / 110	5.66 / 200	8.50 / 300	11.3 / 400	14.2 / 500	83.0 / 2932
1		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2		-1.6	-0.5	0.2	8.2	0.7	0.1	0.4	0.7	0.6	0.0
3		-2.7	-2.6	-2.7	3.8	-2.3	-2.4	-2.5	-2.4	-2.6	-0.4
4		**1.9**	2.1	**2.1**	**0.9**	**1.8**	0.8	0.7	1.2	1.3	**-0.6**
5		-0.7	-0.5	-0.4	-0.3	-0.4	-0.8	-1.0	-0.8	-1.1	-0.3
6		1.5	1.8	2.2	-0.3	-0.5	-0.9	-0.9	-0.7	-0.9	0.2
7		0.6	1.0	1.0	0.7	0.7	-0.1	-0.6	-0.6	-1.0	0.1
8		-0.9	-0.7	-0.7	-0.8	-0.8	-1.2	-1.5	-1.5	-1.8	0.3
9		-4.4	-3.7	-2.6	-2.3	-2.4	-2.7	-2.7	-2.5	-2.7	0.2
10		3.4	3.4	3.2	1.2	1.1	0.1	-0.9	-1.2	-1.8	-0.2
11		-1.7	-1.5	-1.4	-0.1	-0.2	-0.8	-1.1	-1.0	-1.3	0.2
12		0.1	0.1	0.4	-0.4	-0.7	-1.5	-1.8	-1.7	-2.1	-0.4
13		-0.7	-0.4	-0.4	-0.4	-0.5	-1.2	-1.6	-1.7	-2.1	-1.1
14		0.4	0.6	0.1	0.1	-0.1	-1.2	-1.8	-1.9	-2.4	-0.2
15		-0.7	-0.9	0.3	-0.5	-0.5	-1.2	-1.4	-1.2	-1.6	0.3
16		-0.7	-0.4	-0.6	-0.9	-1.1	-1.5	-1.8	-1.7	-2.1	-0.1
17		0.1	0.0	-0.5	-0.7	-0.9	-1.6	-1.9	-1.9	-2.3	0.6
18		-0.2	0.0	0.3	-0.1	-0.1	-0.6	-0.6	-0.2	-0.4	-0.1
19		-0.9	-0.5	-0.2	-0.5	-0.6	-1.2	-1.5	-1.4	-1.8	0.0

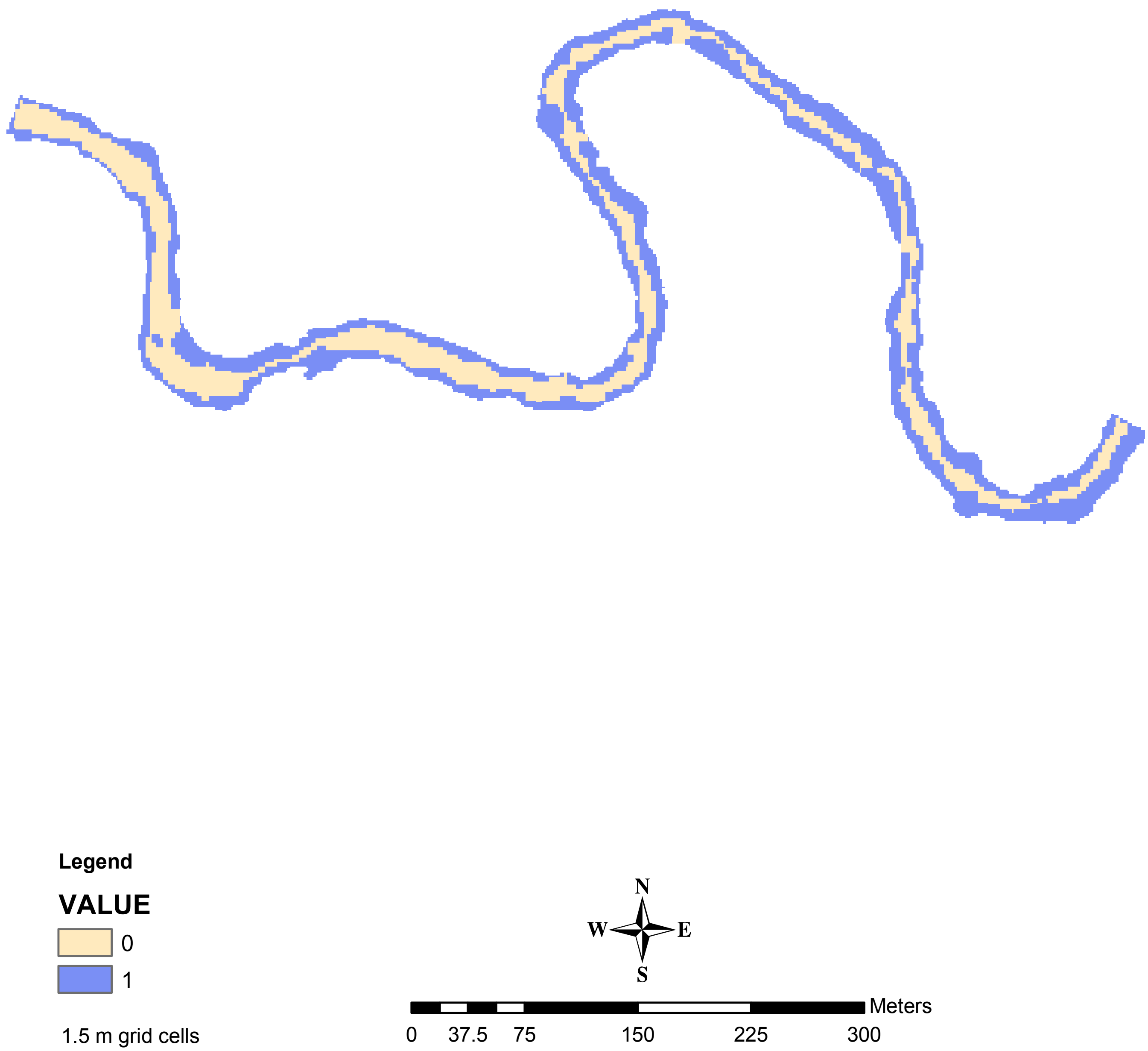
Appendix N

Spatial Availability of Mesohabitat – Site 2

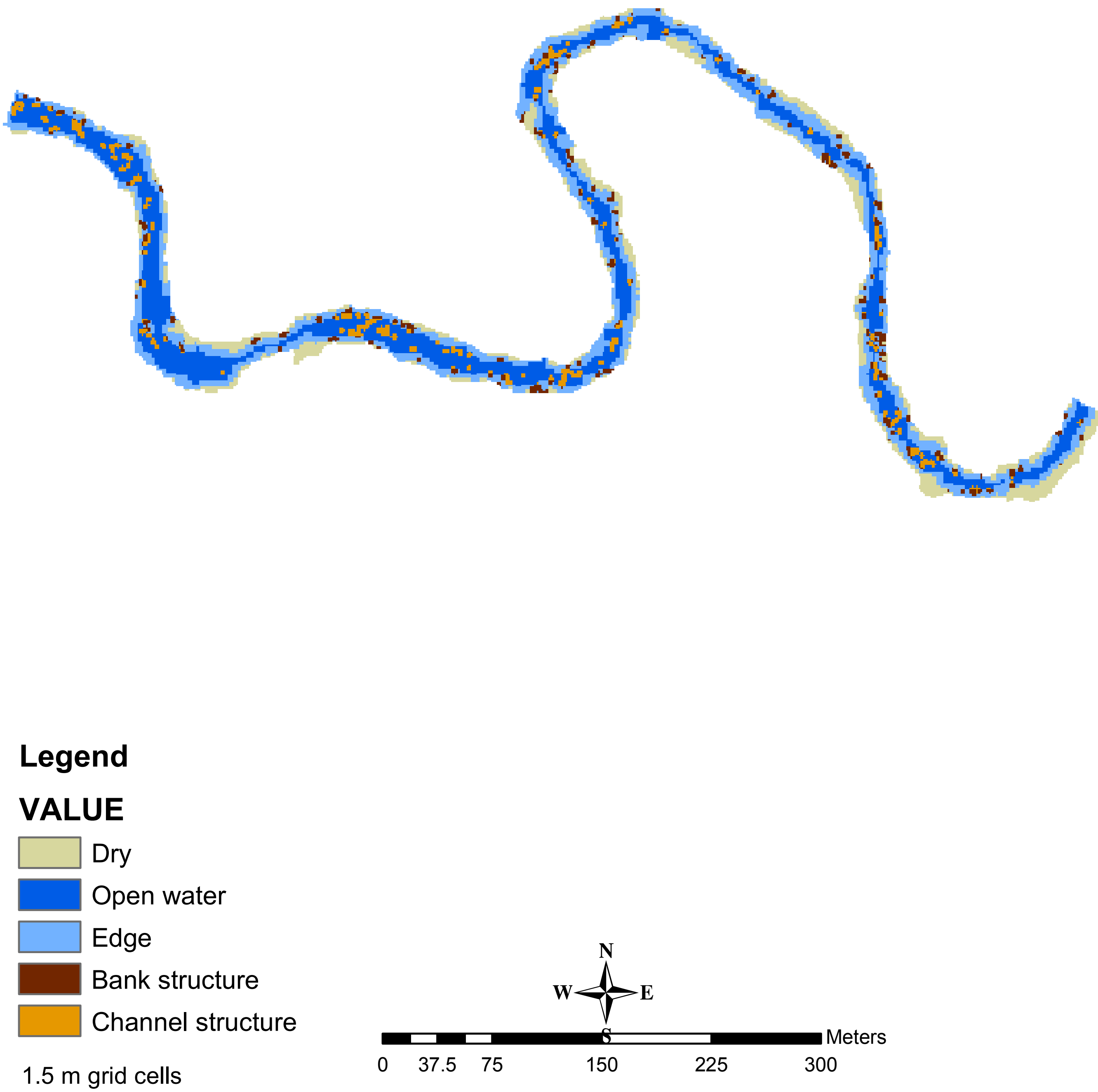
Large Woody Debris (LWD) Plot
All Flows
Sulphur River, Site 2



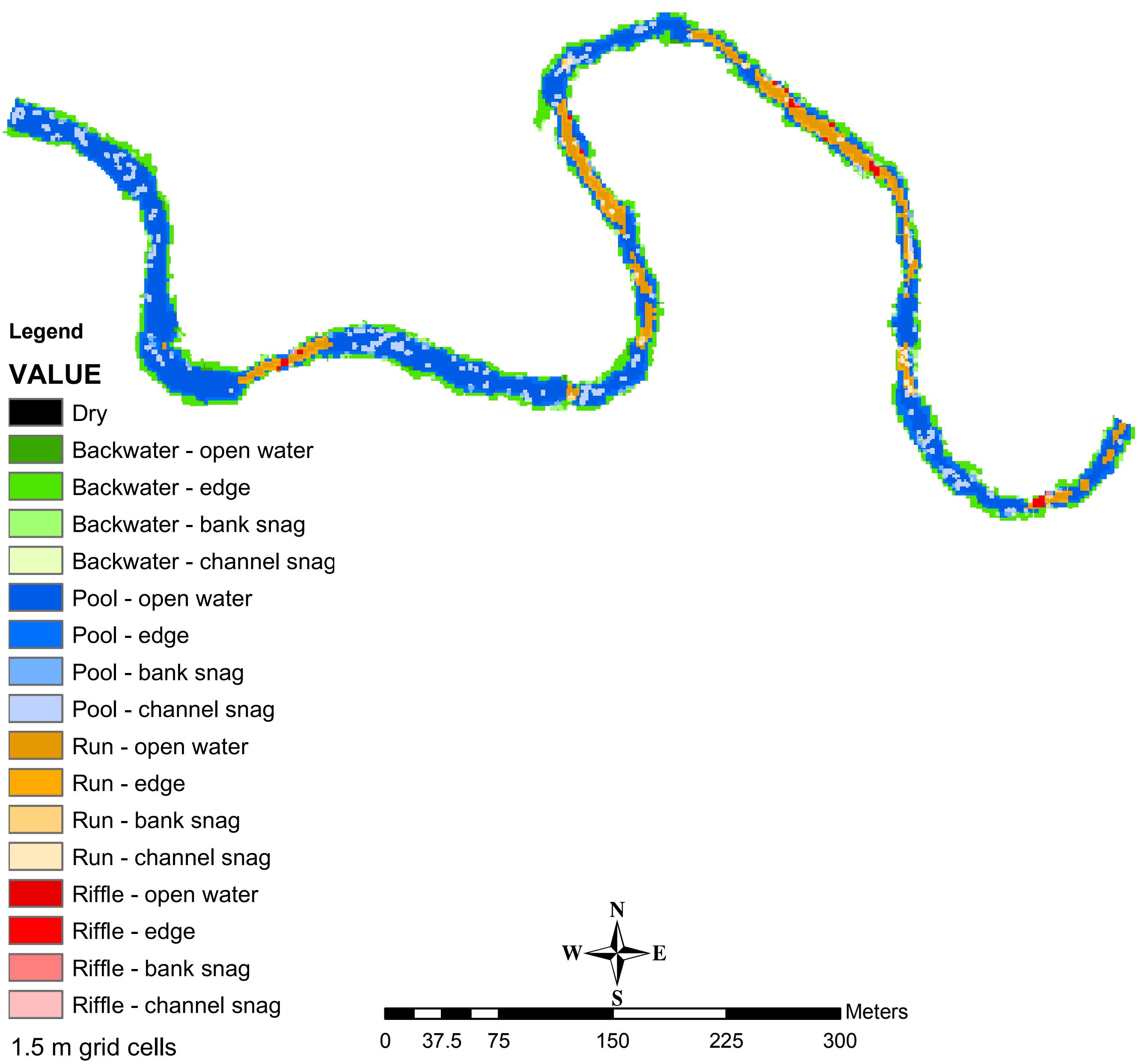
Available Edge Habitat Plot
1.05 cumec (37 cfs)
Sulphur River, Site 2



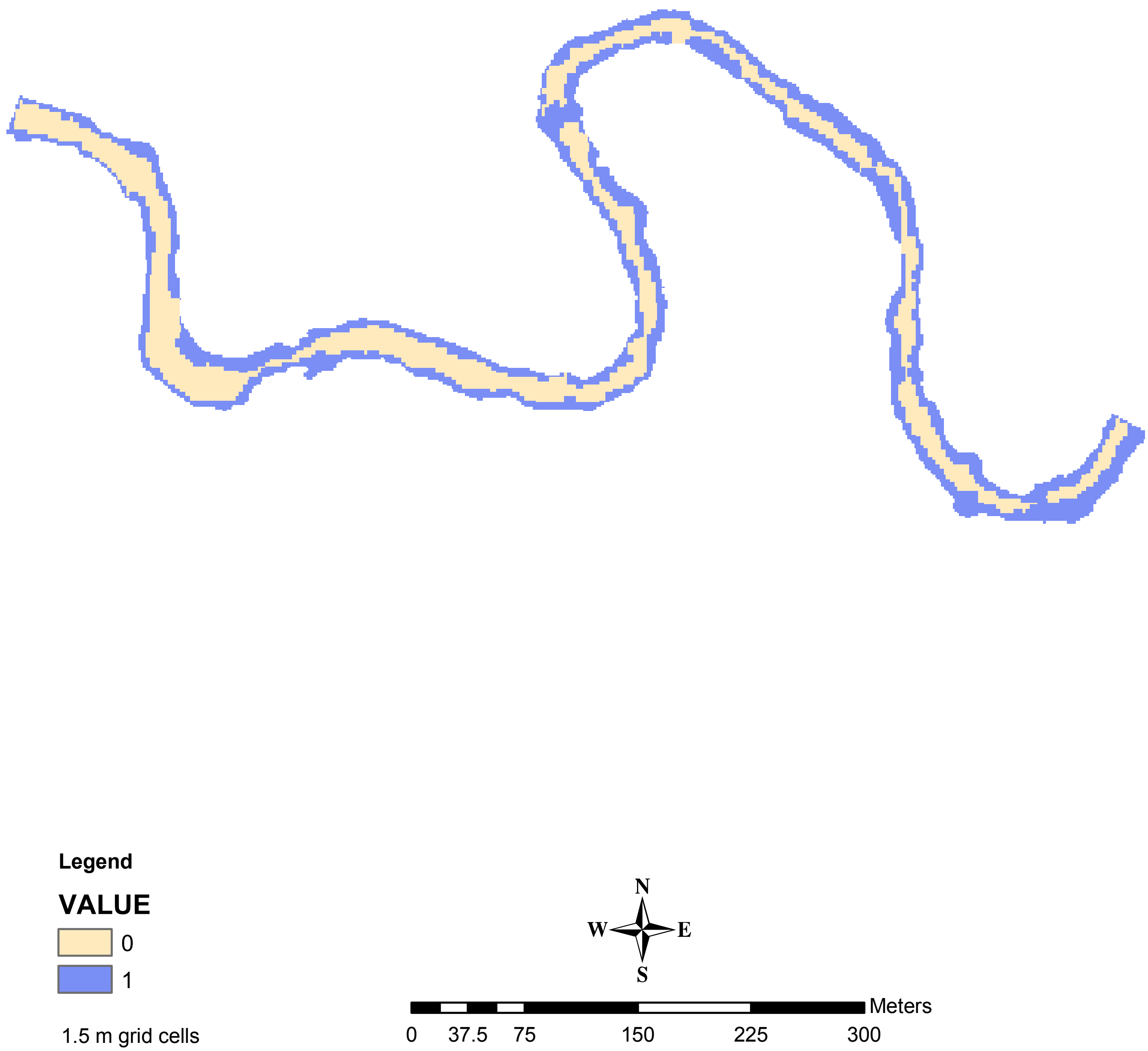
Habitat Plot
1.05 cumec (37 cfs)
Sulphur River, Site 2



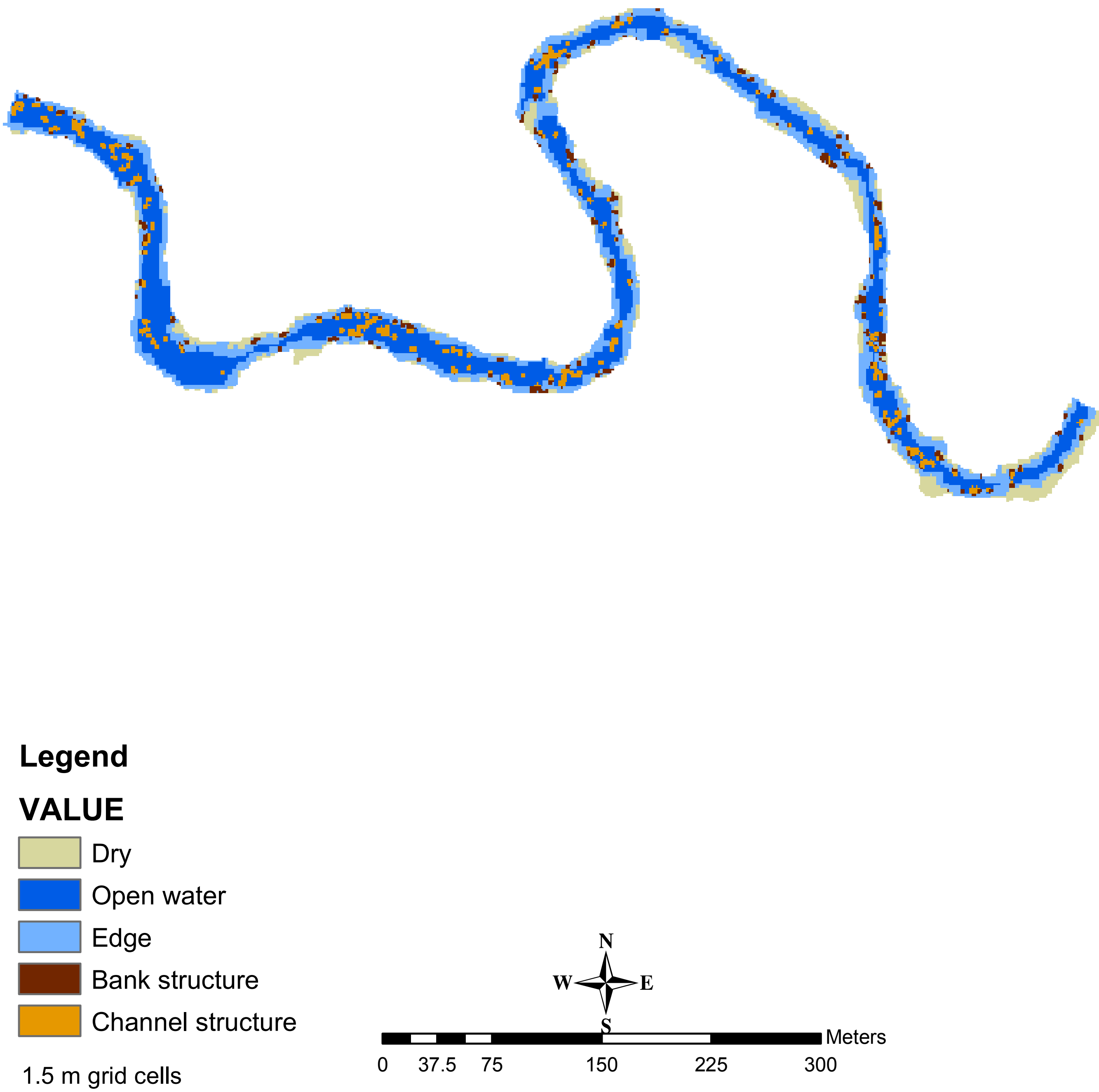
Mesohabitat Plot
1.05 cumec (37 cfs)
Sulphur River, Site 2



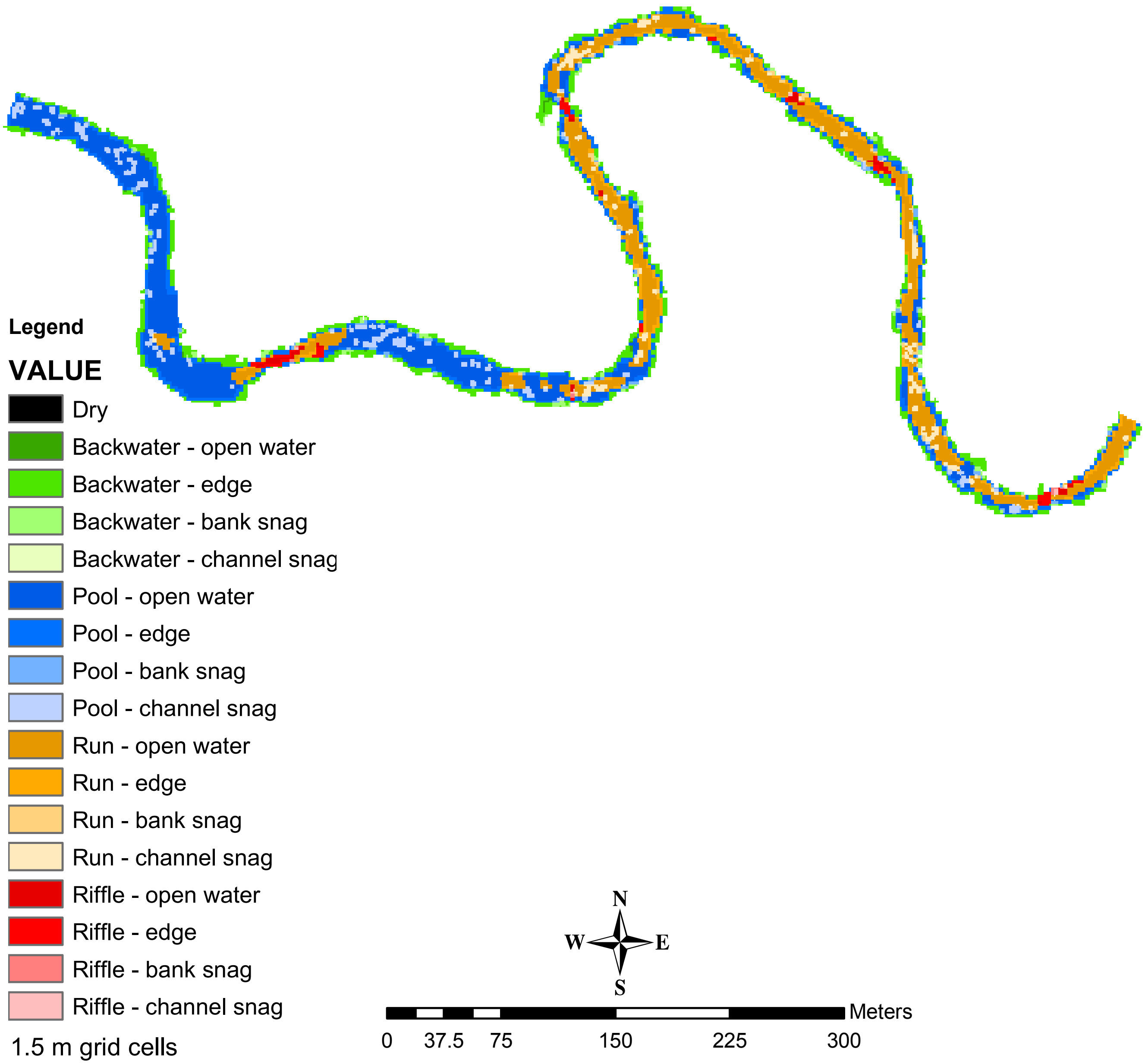
Available Edge Habitat Plot
2.32 cumec (82 cfs)
Sulphur River, Site 2



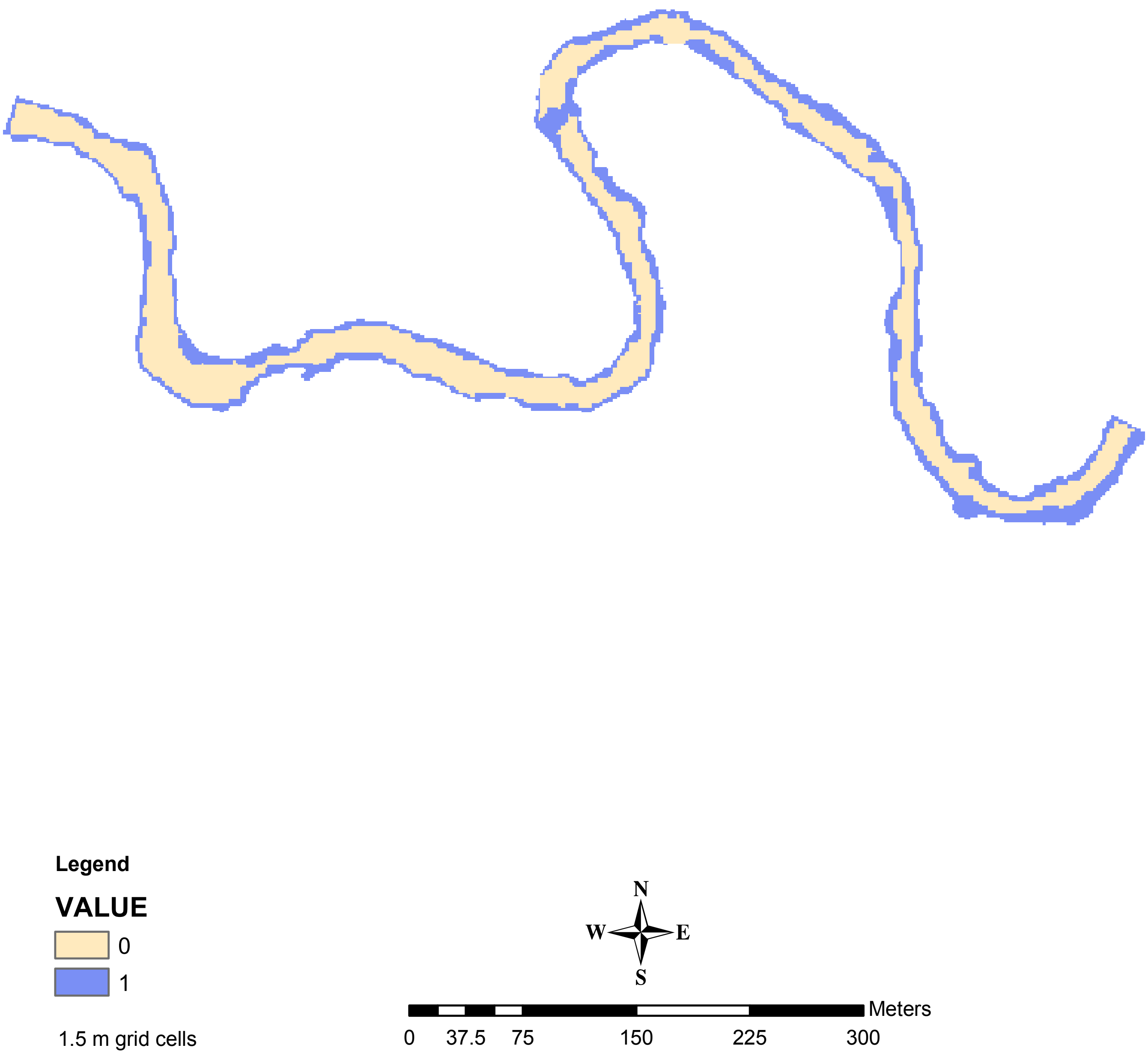
Habitat Plot
2.32 cumec (82 cfs)
Sulphur River, Site 2



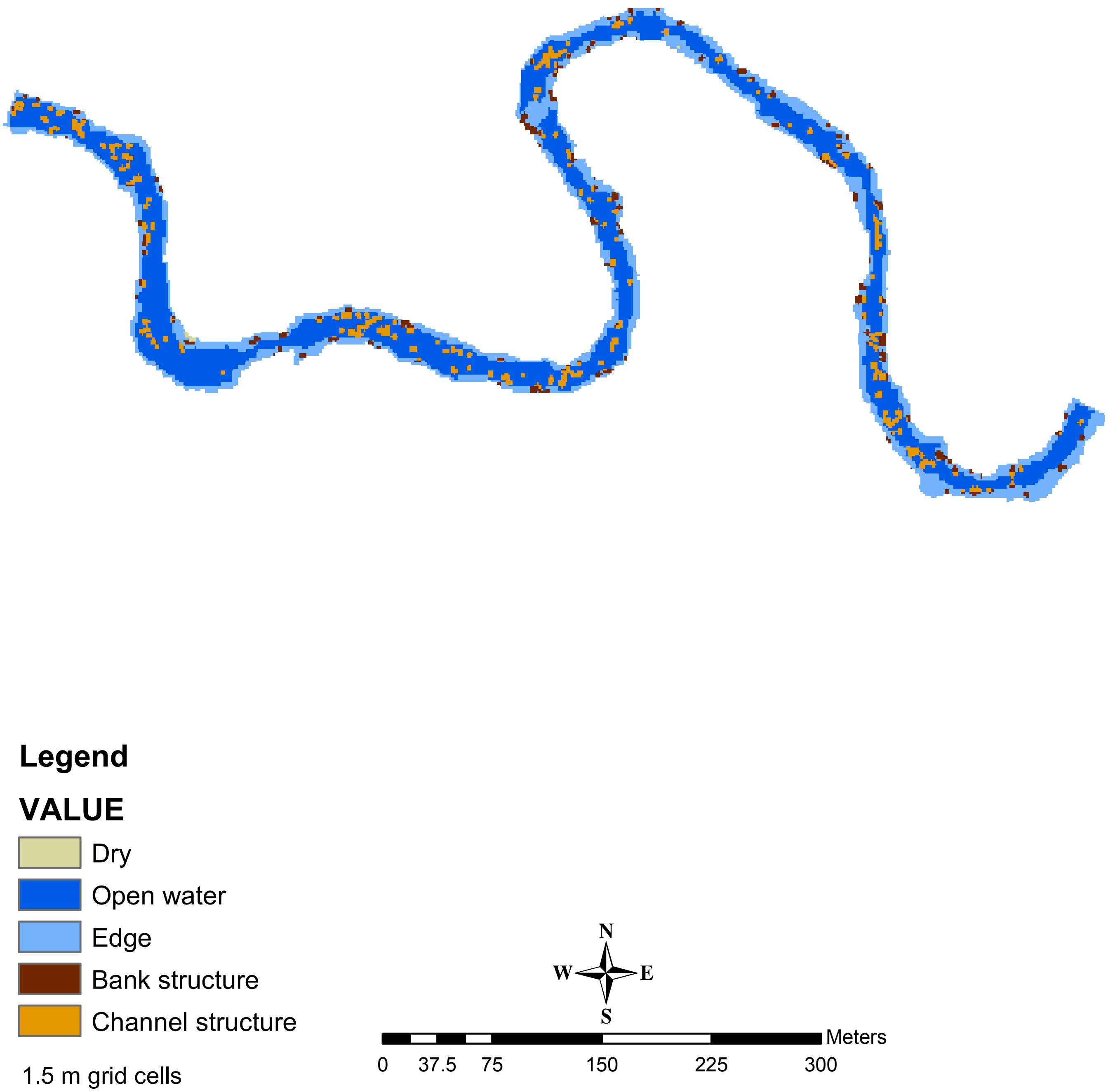
Mesohabitat Plot
2.32 cumec (82 cfs)
Sulphur River, Site 2



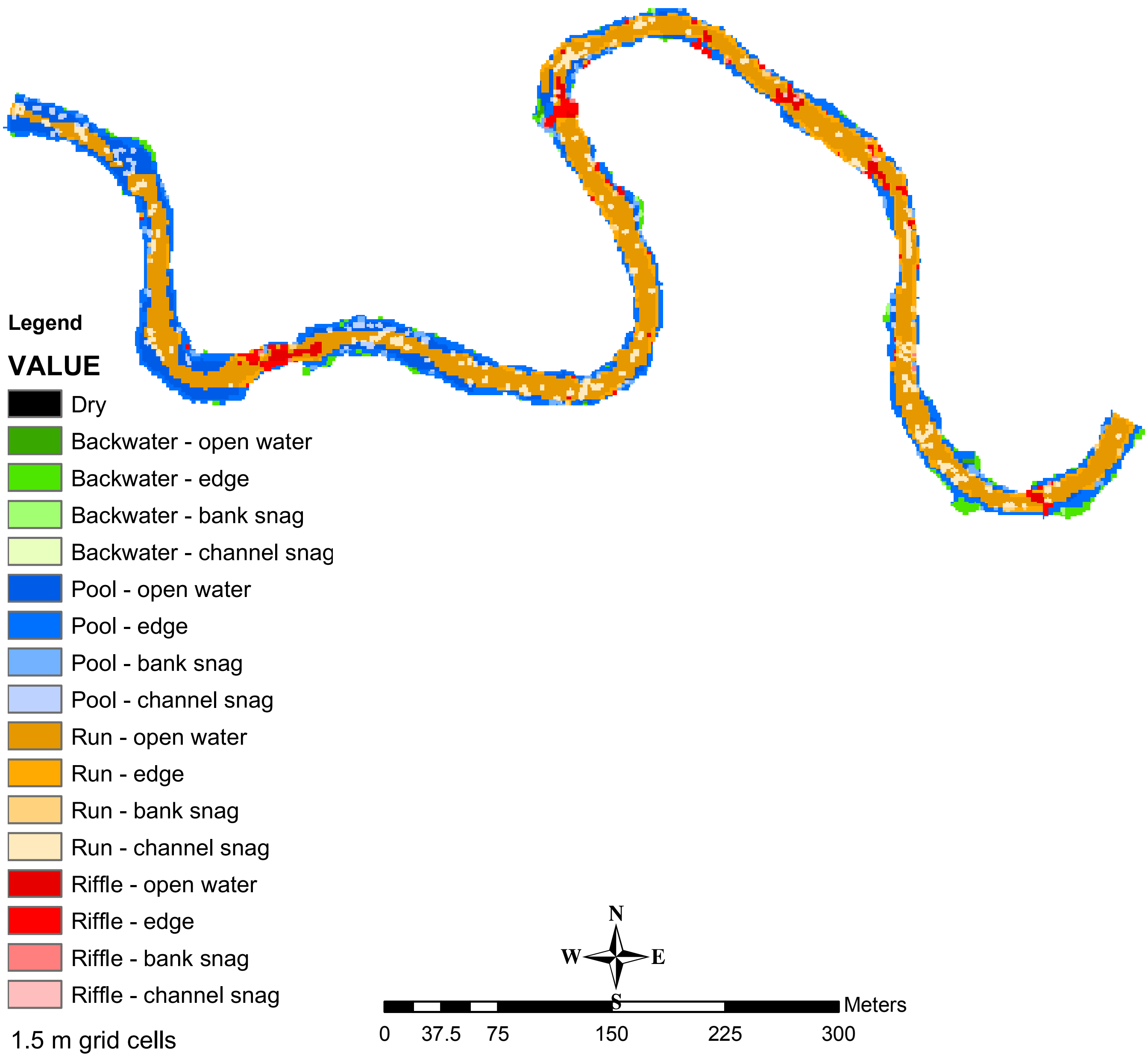
Available Edge Habitat Plot
5.66 cumec (200 cfs)
Sulphur River, Site 2



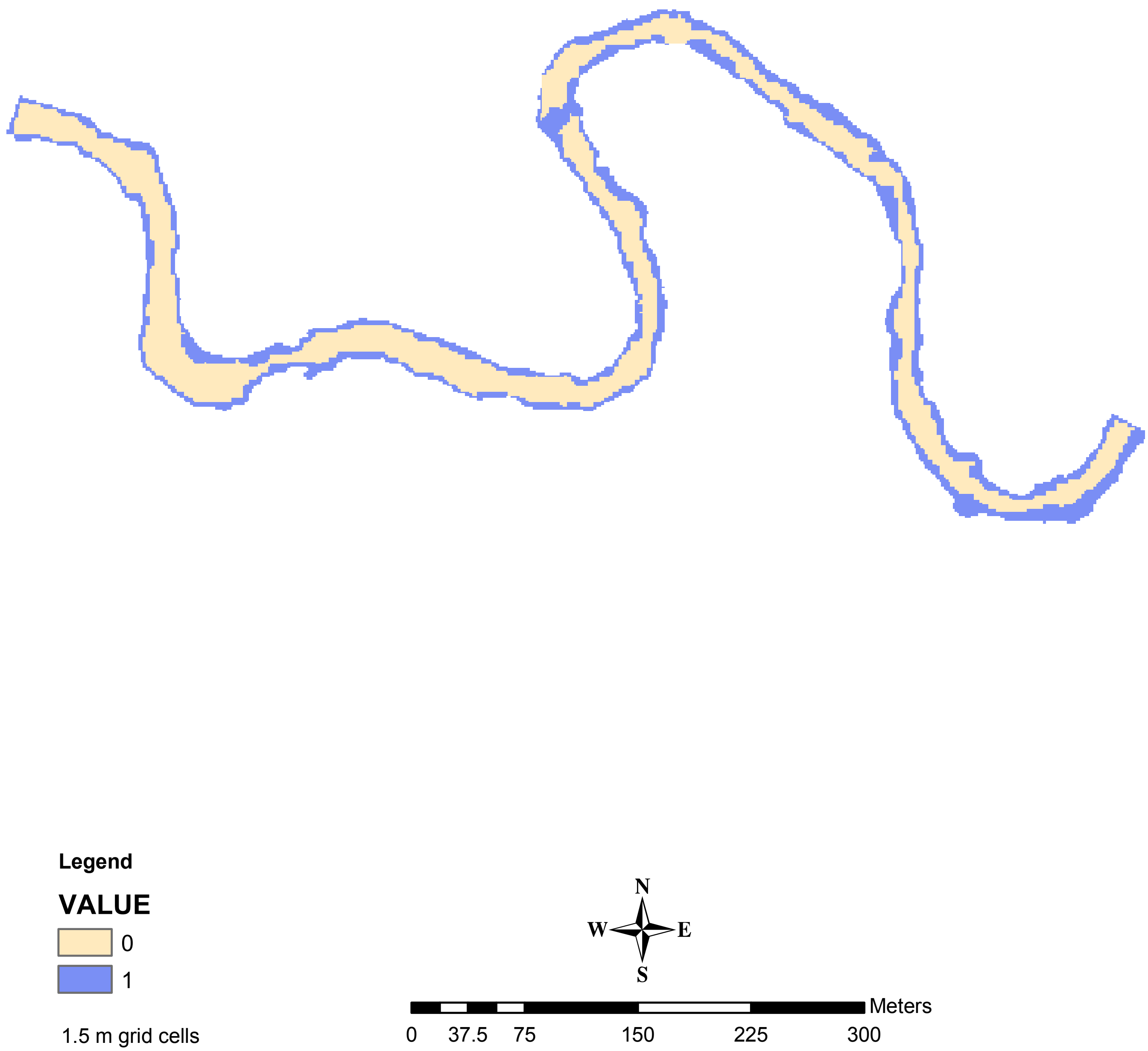
Habitat Plot
5.66 cumec (200 cfs)
Sulphur River, Site 2



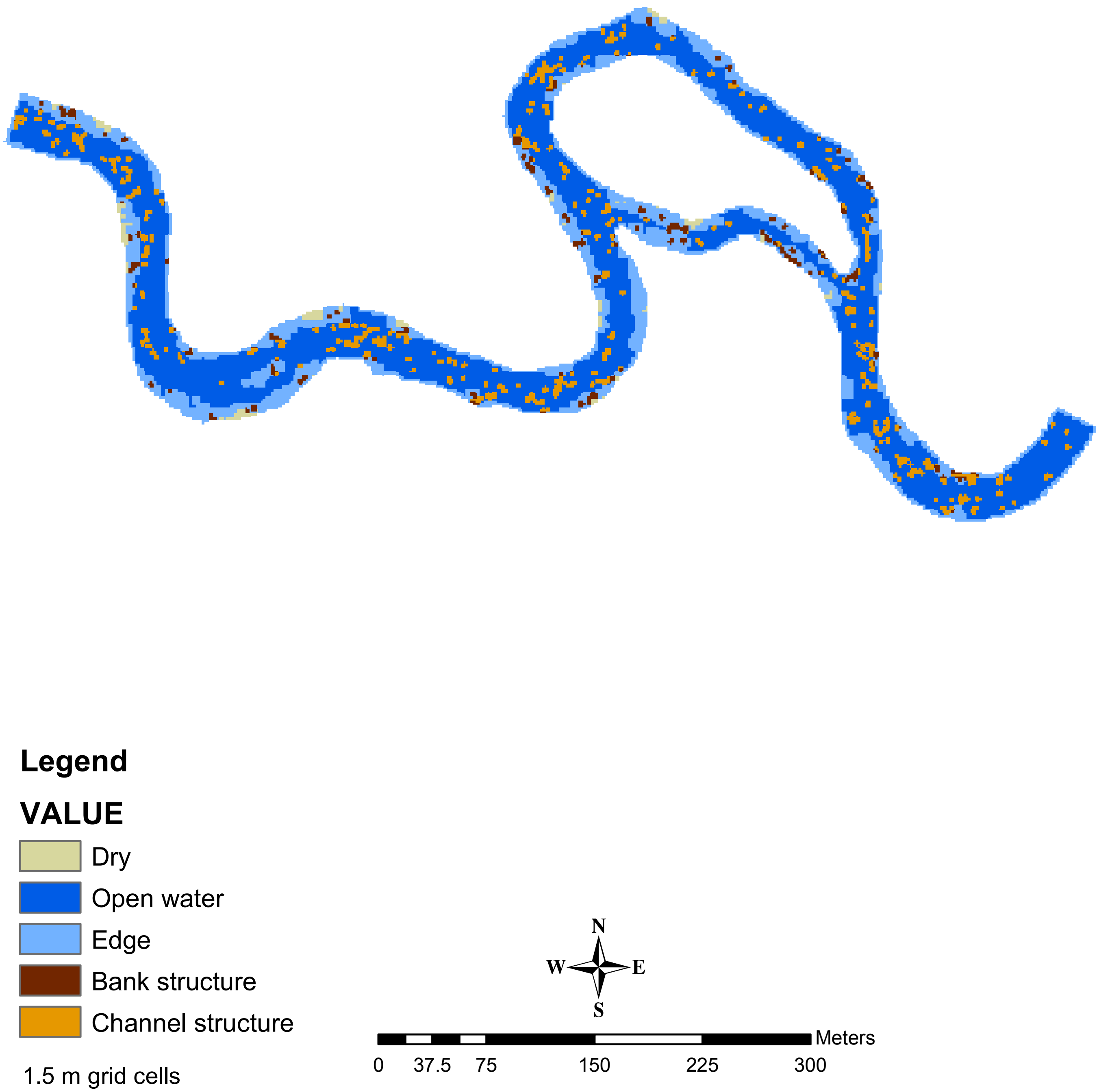
Mesohabitat Plot
5.66 cumec (200 cfs)
Sulphur River, Site 2



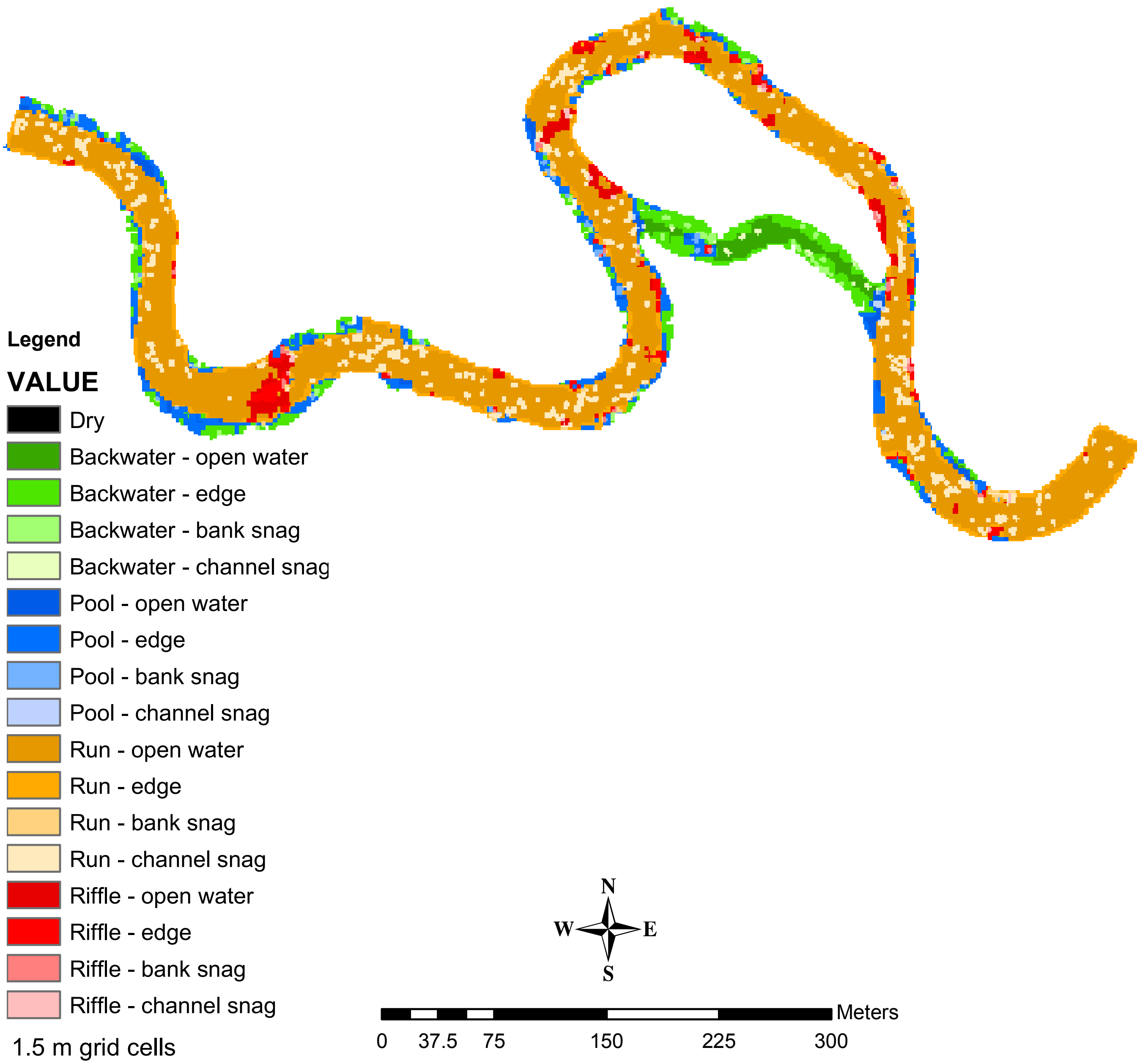
Available Edge Habitat Plot
23.53 cumec (500 cfs)
Sulphur River, Site 2



Habitat Plot
23.53 cumec (831 cfs)
Sulphur River, Site 2



Mesohabitat Plot
23.53 cumec (831 cfs)
Sulphur River, Site 2



Appendix O

Verification of habitat model – Site 1 and Site 2

TWDB Site	Gelwick and Morgan Site	Page
#1	#2 (102)	O-2
#1	#3 (103)	O-9
#2	#5 (105)	O-16
#2	#6 (106)	O-23

Note: Verification provided in this appendix was obtained by comparing the mesohabitat output from the GIS models to the hand-drawn maps from Gelwick and Morgan (2000). The comparison is approximate, as the hand drawn maps are not scaled or geo-referenced.

On Tables O.1-O.16, "GIS Habitat" refers to the model predicted habitat at the approximate location of the sampling point used in Gelwick and Morgan (2000). The "Surrounding Habitats" were visually determined to be in the vicinity of (~3-5 m from) the approximate sampling point location.

Reference:

Gelwick, Francis P., and Morgan, Michael N. (2000) "Microhabitat use and community structure of fishes downstream of the proposed George Parkhouse I and Marvin Nichols I reservoir sites on the Sulphur River, TX". Report Prepared for the Texas water Development Board Contract Number 98-483-234. Available online as of 6/21/04 at: http://www.twdb.state.tx.us/instreamflows/

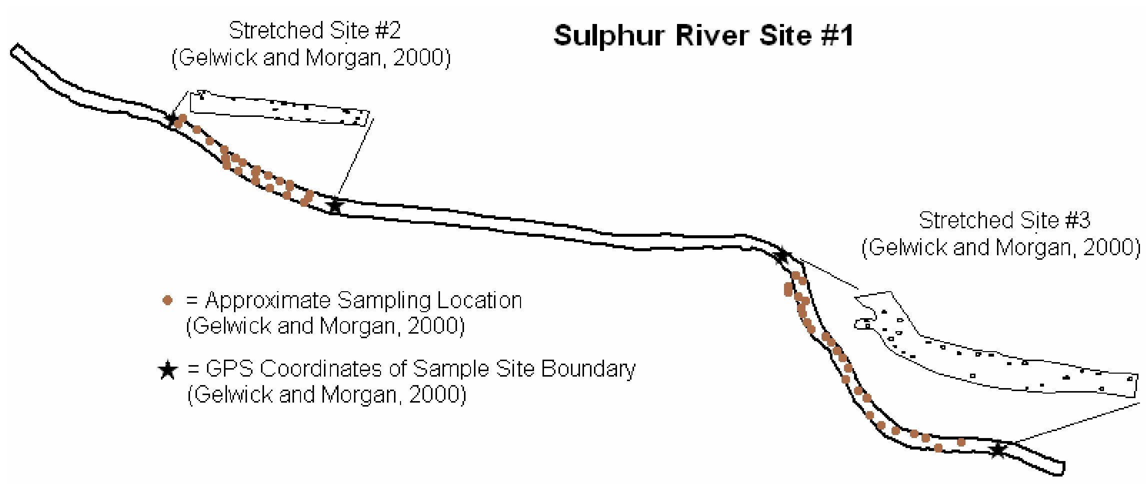


Figure O.1 – Sulphur River Site #1 with approximate sampling locations from Sites #2, #3 based on hand-drawn maps from Gelwick and Morgan (2000). Hand-drawn maps were graphically stretched and adjusted to conform with the geo-referenced site map.

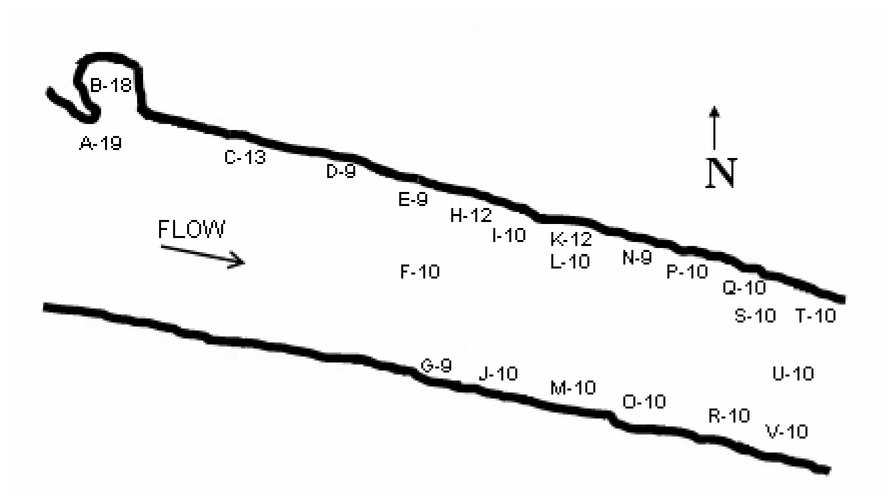


Figure O.2 – Hand Drawn Map of Site #2 from Gelwick and Morgan (2000).

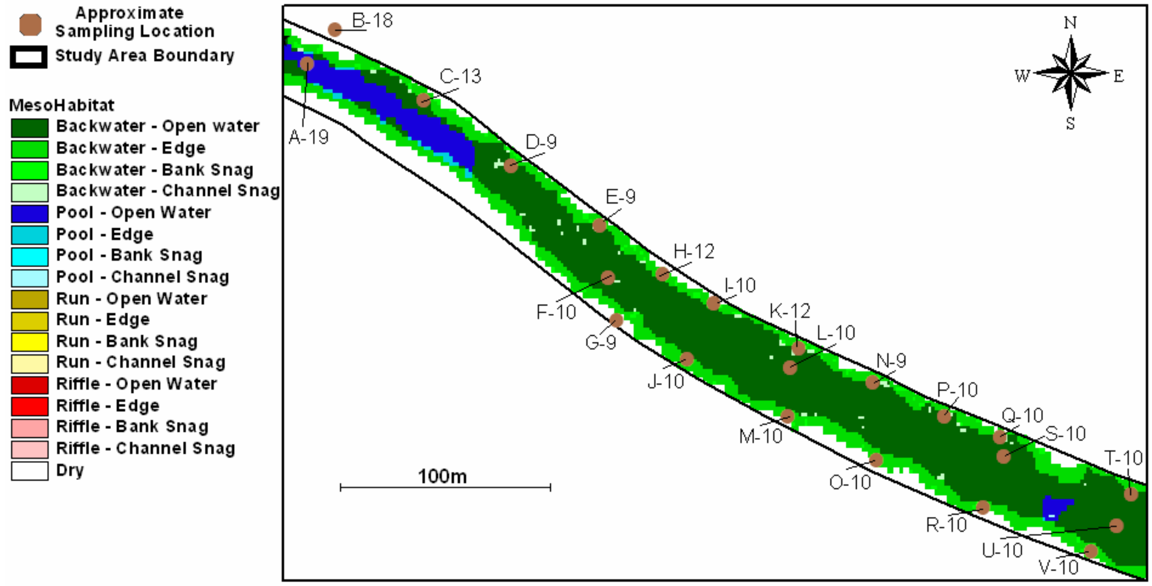


Figure O.3 – Mesohabitats at 11 cfs in the vicinity of Sampling Site #2 of Gelwick & Morgan (2000)

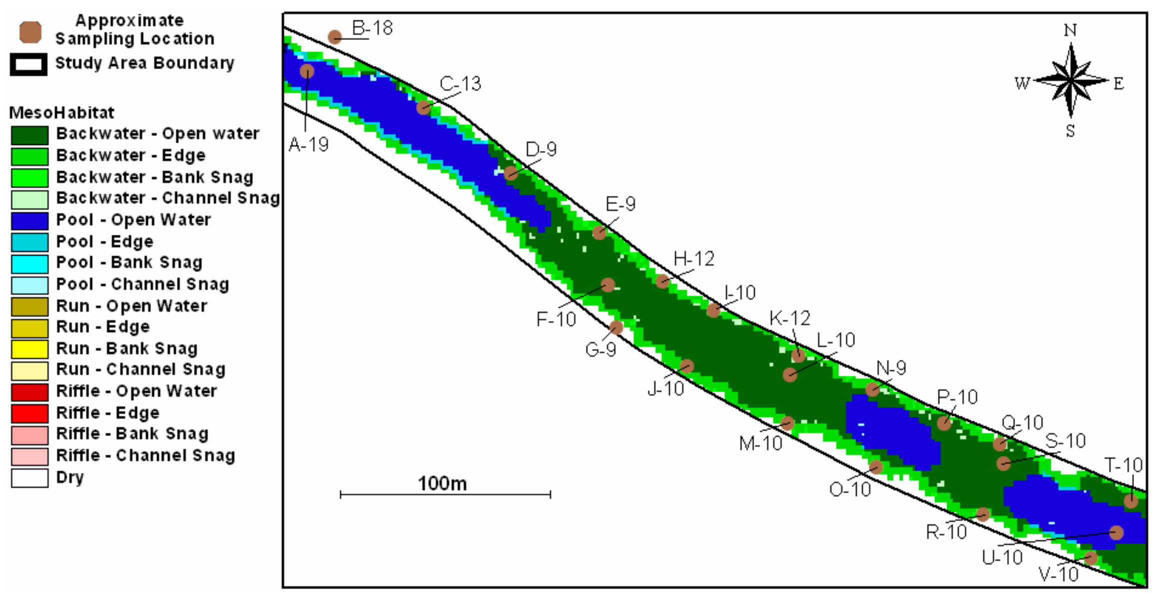


Figure O.4 – Mesohabitats at 25 cfs in the vicinity of Sampling Site #2 of Gelwick & Morgan (2000)

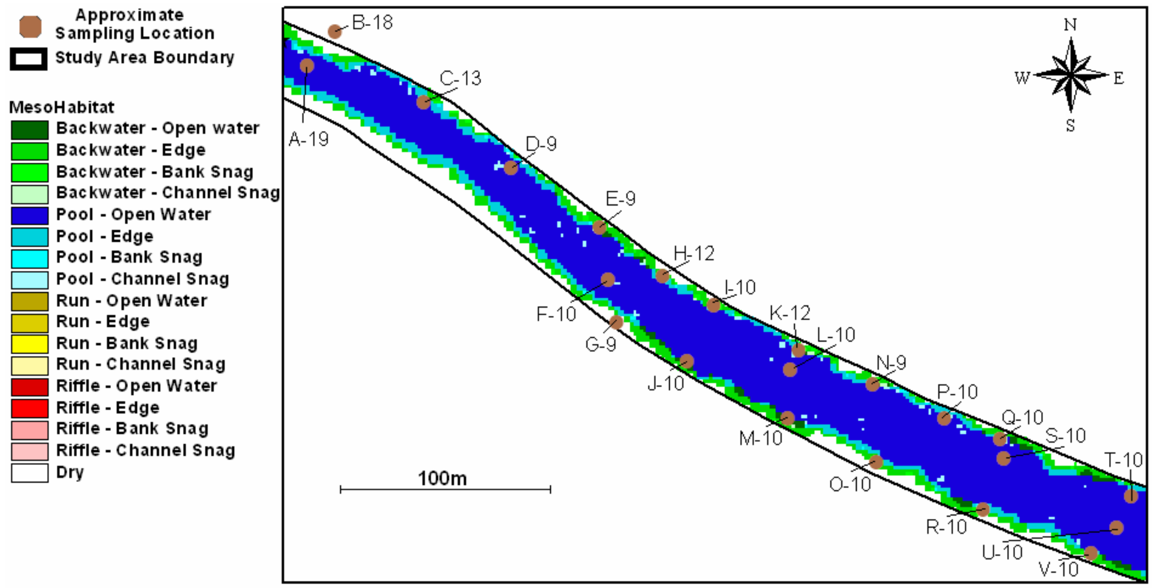


Figure O.5 – Mesohabitats at 110 cfs in the vicinity of Sampling Site #2 of Gelwick & Morgan (2000)

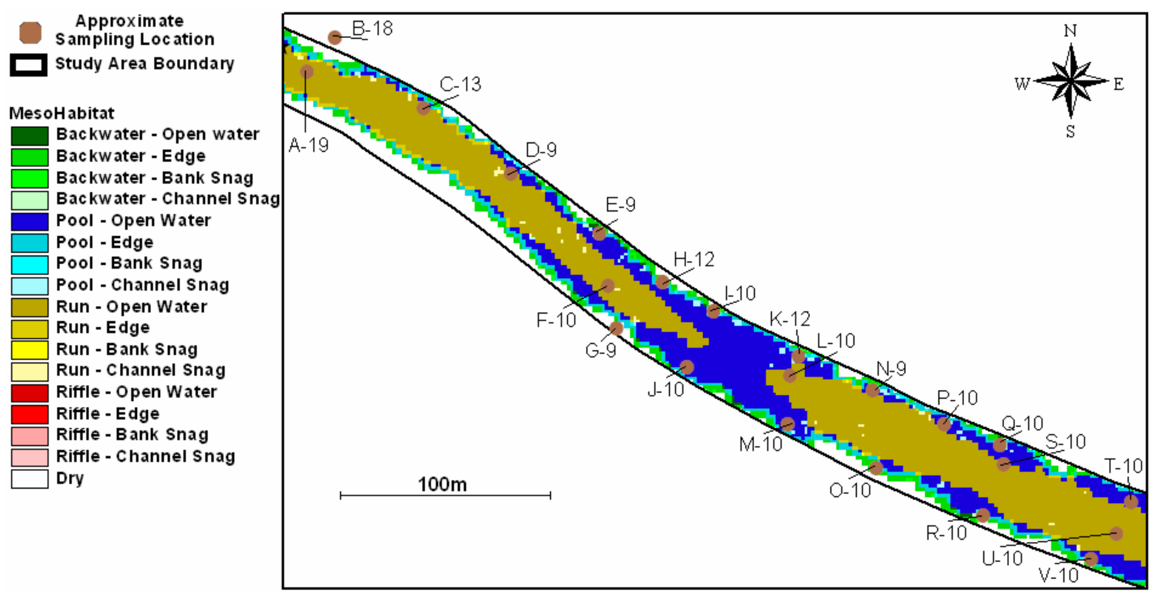


Figure O.6 – Mesohabitats at 500 cfs in the vicinity of Sampling Site #2 of Gelwick & Morgan (2000)

Table – O.1 Sulphur Site #1 - Comparing Morgan's Site 2 and GIS habitats – 11 cfs

Morgan's Point	Morgan Habitat	GIS Habitat	Surrounding Habitats	
A-19	Backwater - bank snag	Pool Open Water	Pool Edge	Backwater Open Water
C-13	Pool - rootwad	Backwater Edge	Backwater Open Water	
D-9	Pool - bank snag	Backwater Edge	Backwater Open Water	
E-9	Pool - bank snag	Backwater Open Water	Backwater Edge	
F-10	Pool - channel snag	Backwater Open Water	Backwater Channel Snag	
G-9	Pool - bank snag	Dry	Backwater Edge	Backwater Bank Snag
H-12	Pool - undercut bank	Backwater Edge	Backwater Open Water	Dry
I-10	Pool - channel snag	Dry	Backwater Edge	Backwater Open Water
J-10	Pool - channel snag	Backwater Edge	Backwater Open Water	
K-12	Pool - undercut bank	Backwater Edge	Backwater Open Water	Backwater Channel Snag
L-10	Pool - channel snag	Backwater Open Water		
M-10	Pool - channel snag	Backwater Edge	Backwater Open Water	
N-9	Pool - bank snag	Backwater Open Water	Backwater Edge	
O-10	Pool - channel snag	Backwater Edge	Dry	
P-10	Pool - channel snag	Backwater Channel Snag	Backwater Open Water	Backwater Edge
Q-10	Pool - channel snag	Backwater Open Water	Backwater Edge	Backwater Channel Snag
R-10	Pool - channel snag	Backwater Edge	Backwater Bank Snag	Dry
S-10	Pool - channel snag	Backwater Open Water		
T-10	Pool - channel snag	Backwater Open Water	Backwater Edge	
U-10	Pool - channel snag	Backwater Open Water		
V-10	Pool - channel snag	Backwater Bank Snag	Backwater Edge	Dry

Table – O.2 Sulphur Site #1 - Comparing Morgan's Site 2 and GIS habitats – 25 cfs

Morgan's Point	Morgan Habitat	GIS Habitat	Surrounding Habitats	
A-19	Backwater - bank snag	Pool Open Water	Pool Edge	Pool Channel Snag
C-13	Pool - rootwad	Backwater Edge	Backwater Open Water	Pool Open Water
D-9	Pool - bank snag	Backwater Edge	Backwater Open Water	Backwater Channel Snag
E-9	Pool - bank snag	Backwater Open Water	Backwater Edge	
F-10	Pool - channel snag	Backwater Open Water	Backwater Channel Snag	
G-9	Pool - bank snag	Dry	Backwater Edge	Backwater Bank Snag
H-12	Pool - undercut bank	Backwater Edge	Backwater Open Water	
I-10	Pool - channel snag	Dry	Backwater Edge	Backwater Open Water
J-10	Pool - channel snag	Backwater Edge	Backwater Open Water	
K-12	Pool - undercut bank	Backwater Edge	Backwater Open Water	Backwater Channel Snag
L-10	Pool - channel snag	Backwater Open Water		
M-10	Pool - channel snag	Backwater Edge	Backwater Open Water	
N-9	Pool - bank snag	Backwater Open Water	Backwater Edge	
O-10	Pool - channel snag	Backwater Edge	Dry	
P-10	Pool - channel snag	Backwater Channel Snag	Backwater Open Water	Backwater Edge
Q-10	Pool - channel snag	Backwater Open Water	Backwater Edge	Backwater Channel Snag
R-10	Pool - channel snag	Backwater Edge	Backwater Bank Snag	Dry
S-10	Pool - channel snag	Backwater Open Water		
T-10	Pool - channel snag	Backwater Open Water	Backwater Edge	
U-10	Pool - channel snag	Pool Open Water		
V-10	Pool - channel snag	Backwater Bank Snag	Backwater Edge	Dry

Table – O.3 Sulphur Site #1 - Comparing Morgan's Site 2 and GIS habitats – 110 cfs

Morgan's Point	Morgan Habitat	GIS Habitat	Surrounding Habitats	
A-19	Backwater - bank snag	Pool Open Water	Pool Edge	Pool Channel Snag
C-13	Pool - rootwad	Pool Open Water	Backwater Open Water	Backwater Edge
D-9	Pool - bank snag	Pool Open Water	Pool Edge	Pool Bank Snag
E-9	Pool - bank snag	Backwater Open Water	Pool Open Water	Pool Channel Snag
F-10	Pool - channel snag	Pool Open Water	Pool Channel Snag	
G-9	Pool - bank snag	Dry	Backwater Edge	Pool Edge
H-12	Pool - undercut bank	Backwater Edge	Pool Edge	Pool Open Water
I-10	Pool - channel snag	Backwater Edge	Pool Edge	Backwater Bank Snag
J-10	Pool - channel snag	Pool Open Water	Backwater Open Water	Backwater Edge
K-12	Pool - undercut bank	Pool Open Water	Pool Edge	Pool Channel Snag
L-10	Pool - channel snag	Pool Open Water		
M-10	Pool - channel snag	Pool Open Water	Backwater Open Water	Backwater Edge
N-9	Pool - bank snag	Pool Open Water	Pool Edge	Backwater Open Water
O-10	Pool - channel snag	Backwater Edge	Pool Edge	Dry
P-10	Pool - channel snag	Pool Channel Snag	Pool Open Water	Pool Edge
Q-10	Pool - channel snag	Pool Channel Snag	Pool Open Water	Backwater Edge
R-10	Pool - channel snag	Backwater Edge	Backwater Bank Snag	Pool Edge
S-10	Pool - channel snag	Pool Open Water		
T-10	Pool - channel snag	Pool Open Water	Pool Edge	
U-10	Pool - channel snag	Pool Open Water		
V-10	Pool - channel snag	Pool Edge	Backwater Edge	Backwater Bank Snag

Table – O.4 Sulphur Site #1 - Comparing Morgan's Site 2 and GIS habitats – 500 cfs

Morgan's Point	Morgan Habitat	GIS Habitat	Surrounding Habitats	
A-19	Backwater - bank snag	Run Open Water	Run Edge	Run Channel Snag
C-13	Pool - rootwad	Run Open Water	Pool Open Water	Pool Edge
D-9	Pool - bank snag	Run Open Water	Pool Open Water	Pool Edge
E-9	Pool - bank snag	Pool Open Water	Backwater Open Water	Pool Edge
F-10	Pool - channel snag	Run Open Water	Run Edge	Pool Open Water
G-9	Pool - bank snag	Dry	Pool Edge	
H-12	Pool - undercut bank	Backwater Edge	Pool Edge	Pool Open Water
I-10	Pool - channel snag	Backwater Edge	Pool Edge	Backwater Bank Snag
J-10	Pool - channel snag	Pool Open Water	Pool Edge	
K-12	Pool - undercut bank	Pool Open Water	Backwater Edge	Pool Channel Snag
L-10	Pool - channel snag	Run Open Water	Pool Open Water	
M-10	Pool - channel snag	Pool Open Water	Pool Bank Snag	
N-9	Pool - bank snag	Pool Open Water	Pool Edge	Run Open Water
O-10	Pool - channel snag	Backwater Edge	Pool Edge	Dry
P-10	Pool - channel snag	Pool Channel Snag	Pool Open Water	Run Channel Snag
Q-10	Pool - channel snag	Pool Channel Snag	Pool Open Water	Pool Edge
R-10	Pool - channel snag	Pool Edge	Backwater Edge	Pool Open Water
S-10	Pool - channel snag	Run Open Water	Pool Open Water	
T-10	Pool - channel snag	Pool Open Water	Run Open Water	
U-10	Pool - channel snag	Run Open Water		
V-10	Pool - channel snag	Pool Edge	Backwater Edge	Backwater Bank Snag

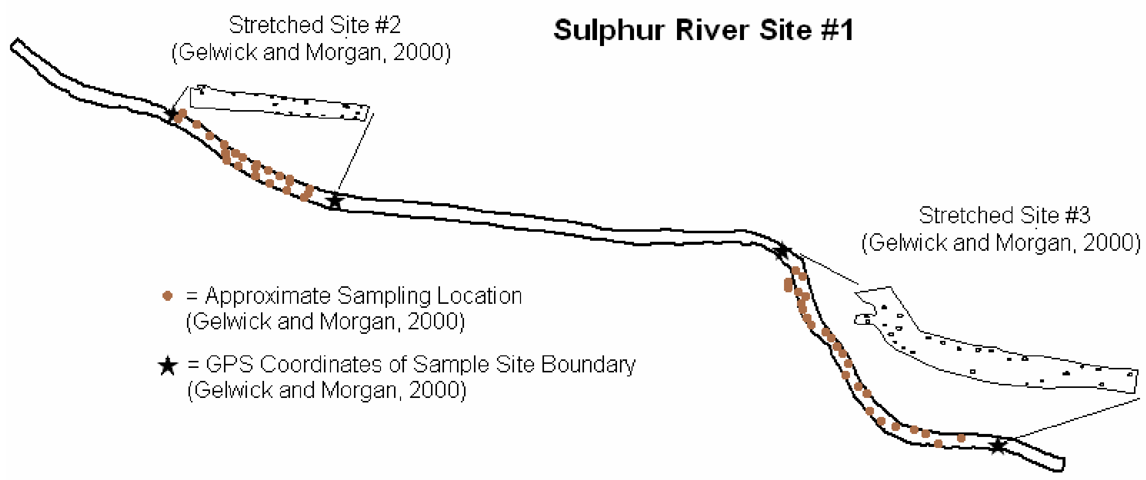


Figure O.7 (Figure O.1, repeated for continuity) – Sulphur River Site #1 with approximate sampling locations from Sites #2, #3 based on hand-drawn maps from Gelwick and Morgan (2000). Hand-drawn maps were graphically stretched and adjusted to conform with the geo-referenced site map.

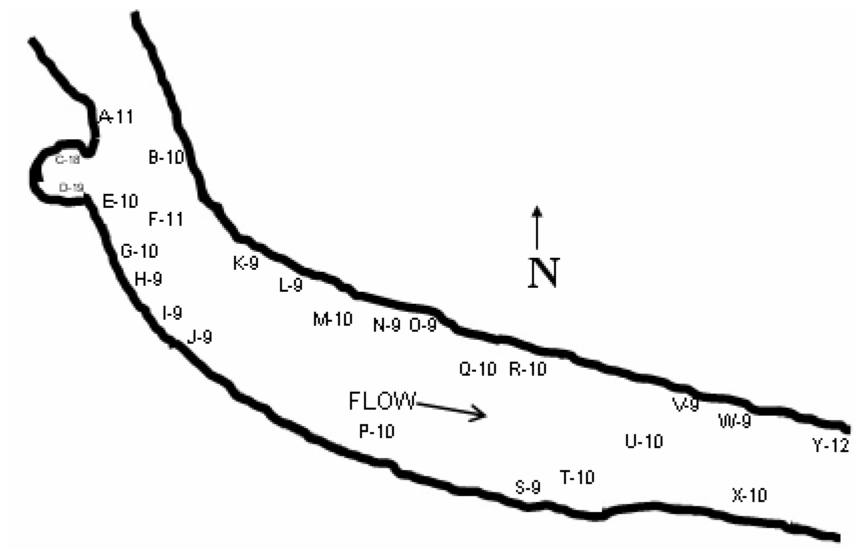


Figure O.8 – Hand Drawn Map of Site #3 from Gelwick and Morgan (2000).

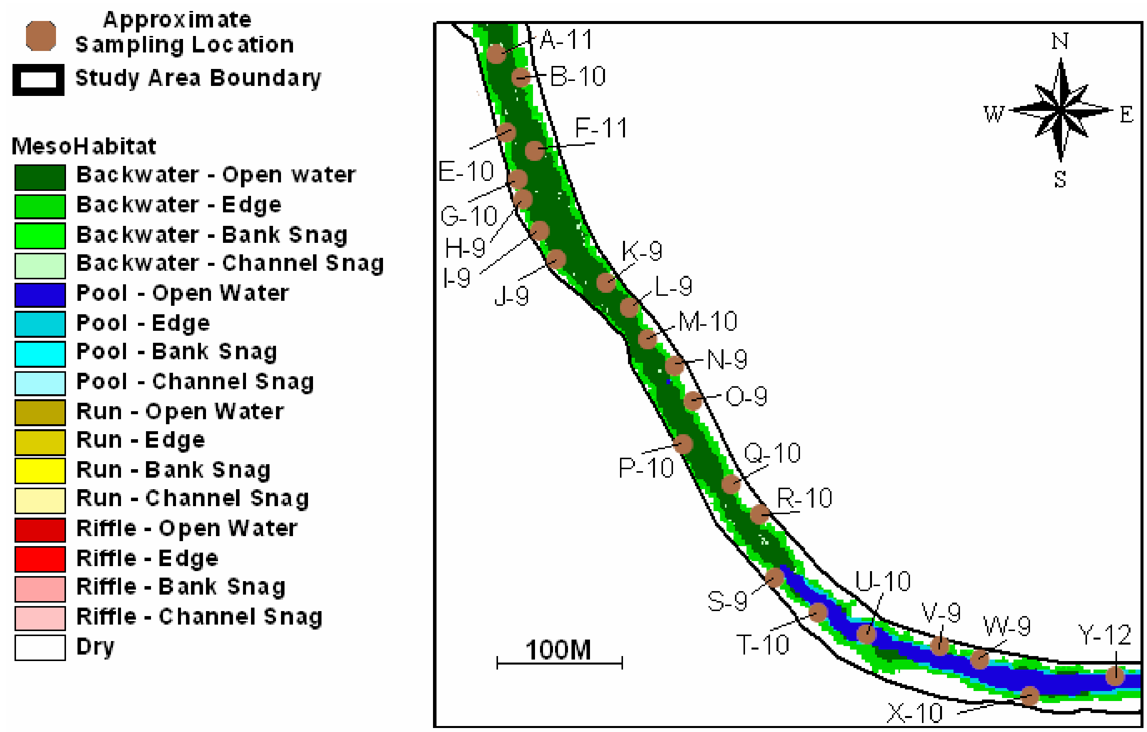


Figure O.9 – Mesohabitats at 11 cfs in the vicinity of Sampling Site #3 of Gelwick & Morgan (2000)

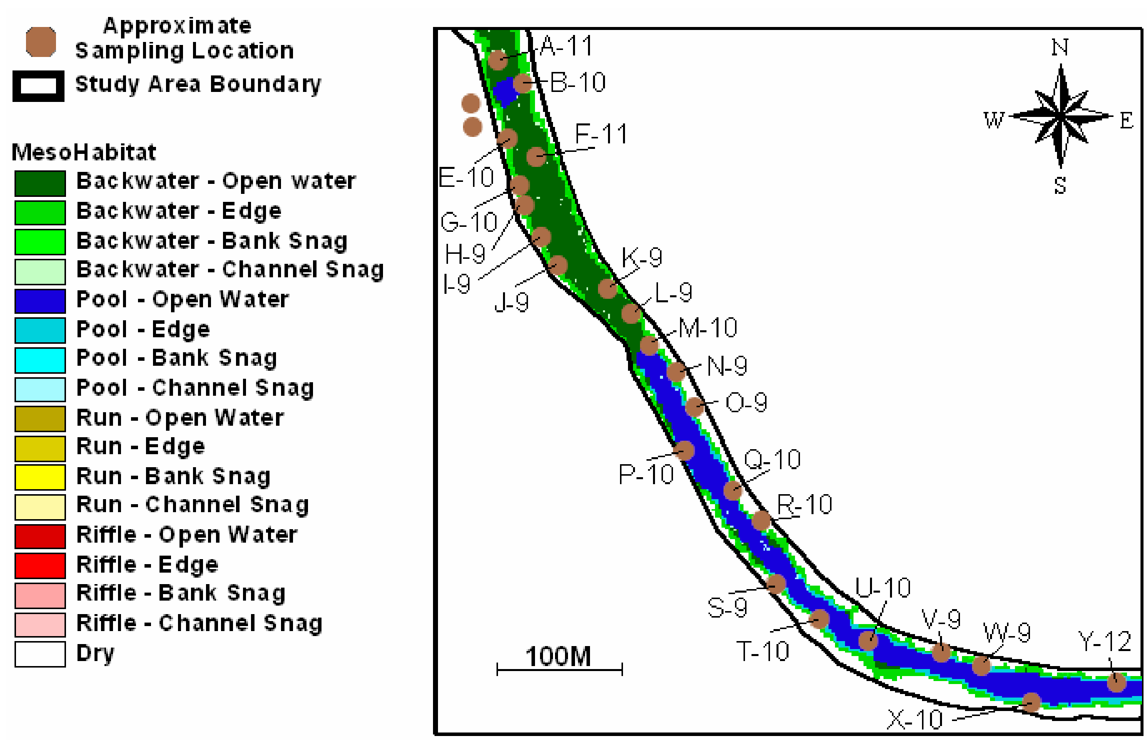


Figure O.10 – Mesohabitats at 25 cfs in the vicinity of Sampling Site #3 of Gelwick & Morgan (2000)

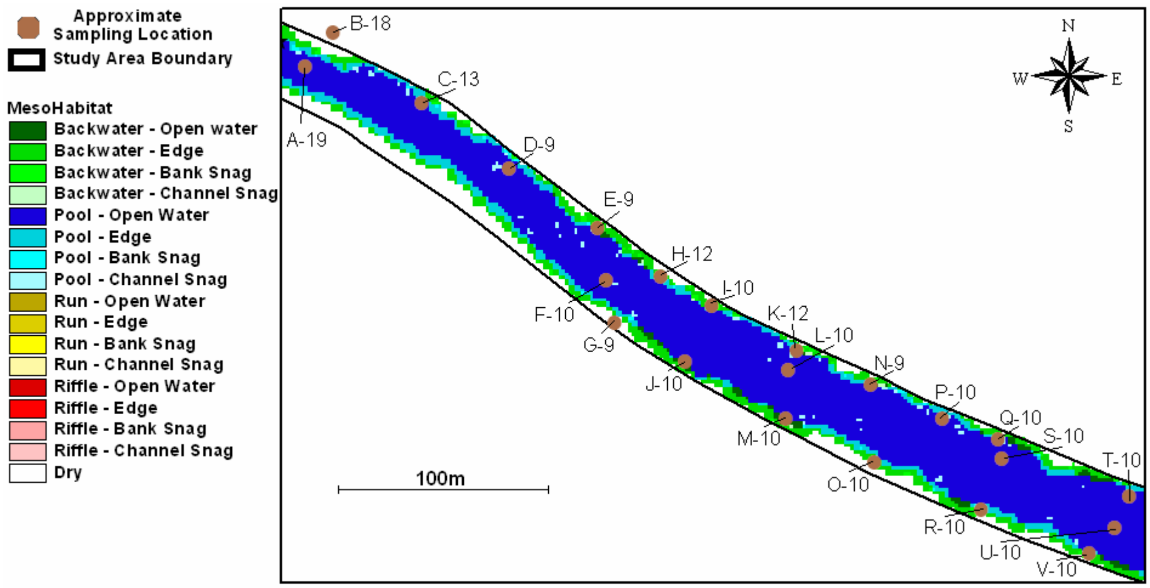


Figure O.11 – Mesohabitats at 110 cfs at Sampling Site #3 of Gelwick & Morgan (2000)

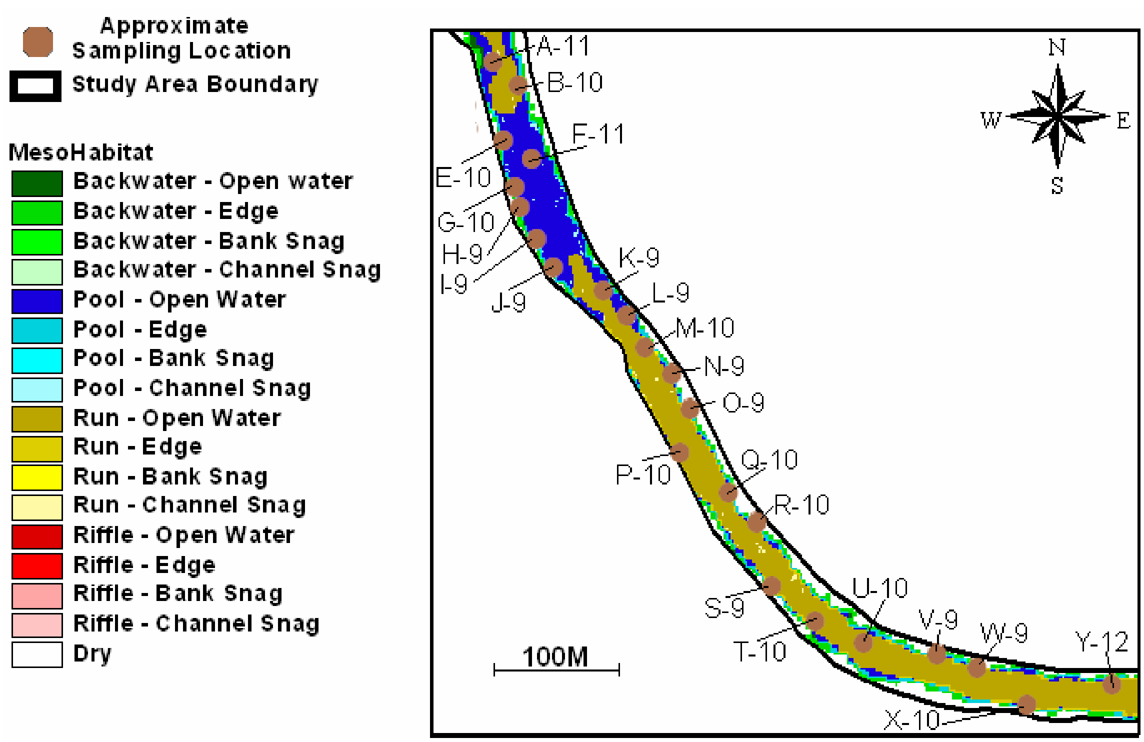


Figure O.12 – Mesohabitats at 500 cfs at Sampling Site #3 of Gelwick & Morgan (2000)

Table – O.5 Sulphur Site #1 - Comparing Morgan's Site 3 and GIS habitats – 11 cfs

Morgan's Point	Morgan Habitat	GIS Habitat	Surrounding Habitats	
A-11	Pool - snag complex	Backwater – Open Water	Backwater – Channel Snag	Backwater Edge
B-12	Pool - undercut bank	Backwater Edge	Backwater Open Water	
E-10	Pool - channel snag	Backwater Edge	Backwater Open Water	Backwater – Channel Snag
F-11	Pool - snag complex	Backwater Open Water		
G-10	Pool - channel snag	Backwater Open Water	Backwater Edge	
H-9	Pool - bank snag	Backwater Open Water	Backwater Edge	Dry
I-9	Pool - bank snag	Backwater Edge	Backwater Open Water	Dry
J-9	Pool - bank snag	Backwater Edge	Backwater Open Water	
K-9	Pool - bank snag	Backwater Open Water	Backwater Edge	Dry
L-9	Pool - bank snag	Backwater Channel Snag	Backwater – Open Water	
M-10	Pool - channel snag	Backwater – Open Water	Backwater Channel Snag	
N-9	Pool - bank snag	Backwater Edge	Backwater Open Water	Dry
O-9	Pool - bank snag	Dry	Backwater Edge	
P-10	Pool - channel snag	Backwater Open Water	Backwater Edge	
Q-10	Pool - channel snag	Backwater Edge	Backwater Open Water	
R-10	Pool - channel snag	Backwater Edge	Backwater Open Water	Dry
S-9	Pool - bank snag	Backwater Edge	Dry	Pool Edge
T-10	Pool - channel snag	Pool Edge	Pool Open Water	Backwater Edge
U-10	Pool - channel snag	Pool Open Water	Pool Edge	
V-9	Pool - bank snag	Backwater Edge	Pool Edge	Dry
W-9	Pool - bank snag	Pool Edge	Backwater Edge	Pool Open Water
X-10	Pool - channel snag	Backwater Edge	Pool Edge	
Y-12	Pool - undercut bank	Pool Open Water	Pool Edge	

Table – O.6 Sulphur Site #1 - Comparing Morgan's Site 3 and GIS habitats – 25 cfs

Morgan's Point	Morgan Habitat	GIS Habitat	Surrounding Habitats	
A-11	Pool - snag complex	Backwater – Open Water	Backwater – Channel Snag	Backwater Edge
B-12	Pool - undercut bank	Backwater Edge	Backwater Open Water	Pool Open Water
E-10	Pool - channel snag	Backwater Edge	Backwater Open Water	Backwater – Channel Snag
F-11	Pool - snag complex	Backwater Open Water		
G-10	Pool - channel snag	Backwater Open Water	Backwater Edge	
H-9	Pool - bank snag	Backwater Open Water	Backwater Edge	
I-9	Pool - bank snag	Backwater Edge	Backwater Open Water	Dry
J-9	Pool - bank snag	Backwater Edge	Backwater Open Water	
K-9	Pool - bank snag	Backwater Open Water	Backwater Edge	Dry
L-9	Pool - bank snag	Backwater Channel Snag	Backwater – Open Water	
M-10	Pool - channel snag	Backwater – Open Water	Backwater Channel Snag	Pool Open Water
N-9	Pool - bank snag	Backwater Edge	Pool Edge	Pool Open Water
O-9	Pool - bank snag	Dry	Backwater Edge	Pool Edge
P-10	Pool - channel snag	Pool Open Water	Pool Edge	Backwater – Open Water
Q-10	Pool - channel snag	Backwater Open Water	Pool Open Water	Backwater Edge
R-10	Pool - channel snag	Backwater Edge	Backwater Open Water	
S-9	Pool - bank snag	Backwater Edge	Dry	Pool Edge
T-10	Pool - channel snag	Pool Open Water	Pool Edge	
U-10	Pool - channel snag	Pool Open Water	Pool Edge	
V-9	Pool - bank snag	Backwater Edge	Pool Edge	Dry
W-9	Pool - bank snag	Pool Edge	Backwater Edge	Pool Open Water
X-10	Pool - channel snag	Backwater Edge	Pool Edge	
Y-12	Pool - undercut bank	Pool Open Water	Pool Edge	

Table – O.7 Sulphur Site #1 - Comparing Morgan's Site 3 and GIS habitats – 110 cfs

Morgan's Point	Morgan Habitat	GIS Habitat	Surrounding Habitats	
A-11	Pool - snag complex	Pool Open Water	Pool – Channel Snag	Backwater – Open Water
B-12	Pool - undercut bank	Pool Open Water	Pool Edge	Backwater Edge
E-10	Pool - channel snag	Pool Edge	Pool Open Water	Pool – Channel Snag
F-11	Pool - snag complex	Pool Open Water		
G-10	Pool - channel snag	Pool Open Water	Backwater Open Water	Backwater Edge
H-9	Pool - bank snag	Pool Open Water	Backwater Open Water	Backwater Edge
I-9	Pool - bank snag	Pool Open Water	Pool Edge	Backwater Edge
J-9	Pool - bank snag	Pool Edge	Pool Open Water	Backwater Edge
K-9	Pool - bank snag	Pool Open Water	Pool Edge	Backwater Edge
L-9	Pool - bank snag	Pool Channel Snag	Pool Open Water	
M-10	Pool - channel snag	Pool Open Water	Pool Edge	
N-9	Pool - bank snag	Backwater Edge	Pool Edge	Pool Open Water
O-9	Pool - bank snag	Dry	Backwater Edge	Pool Edge
P-10	Pool - channel snag	Pool Open Water	Pool Edge	
Q-10	Pool - channel snag	Pool Open Water	Pool Edge	Backwater Edge
R-10	Pool - channel snag	Backwater Edge	Pool Edge	Backwater Open Water
S-9	Pool - bank snag	Pool Edge	Backwater Edge	Dry
T-10	Pool - channel snag	Run Open Water	Pool Open Water	Pool Edge
U-10	Pool - channel snag	Pool Open Water	Run Open Water	
V-9	Pool - bank snag	Pool Edge	Backwater Edge	Pool Open Water
W-9	Pool - bank snag	Pool Edge	Backwater Edge	Pool Open Water
X-10	Pool - channel snag	Pool Open Water	Pool Edge	
Y-12	Pool - undercut bank	Pool Open Water	Run Open Water	

Table – O.8 Sulphur Site #1 - Comparing Morgan's Site 3 and GIS habitats – 500 cfs

Morgan's Point	Morgan Habitat	GIS Habitat	Surrounding Habitats	
A-11	Pool - snag complex	Pool Open Water	Pool – Channel Snag	Run – Open Water
B-12	Pool - undercut bank	Run Open Water	Run Edge	Pool Open Water
E-10	Pool - channel snag	Pool Edge	Pool Open Water	Pool – Channel Snag
F-11	Pool - snag complex	Pool Open Water		
G-10	Pool - channel snag	Pool Open Water	Backwater Open Water	Pool Edge
H-9	Pool - bank snag	Pool Open Water	Backwater Open Water	Pool Edge
I-9	Pool - bank snag	Pool Open Water	Pool Edge	
J-9	Pool - bank snag	Pool Edge	Pool Open Water	Backwater Edge
K-9	Pool - bank snag	Pool Open Water	Run open Water	Pool Edge
L-9	Pool - bank snag	Pool Channel Snag	Pool Open Water	Run Open Water
M-10	Pool - channel snag	Run open Water	Run Edge	Pool Open Water
N-9	Pool - bank snag	Pool Edge	Run Edge	Dry
O-9	Pool - bank snag	Dry	Backwater Edge	Pool Edge
P-10	Pool - channel snag	Run Open Water	Run Edge	
Q-10	Pool - channel snag	Run Open Water	Pool Open Water	Pool Edge
R-10	Pool - channel snag	Backwater Edge	Backwater Open Water	Pool Edge
S-9	Pool - bank snag	Run Edge	Backwater Edge	Pool Edge
T-10	Pool - channel snag	Run Open Water	Run Edge	Pool Edge
U-10	Pool - channel snag	Run Open Water		
V-9	Pool - bank snag	Pool Edge	Backwater Edge	Pool Open Water
W-9	Pool - bank snag	Run Edge	Pool Edge	Run Open Water
X-10	Pool - channel snag	Run Open Water	Pool Open Water	Run Edge
Y-12	Pool - undercut bank	Run Open Water	Pool Open Water	Run Edge

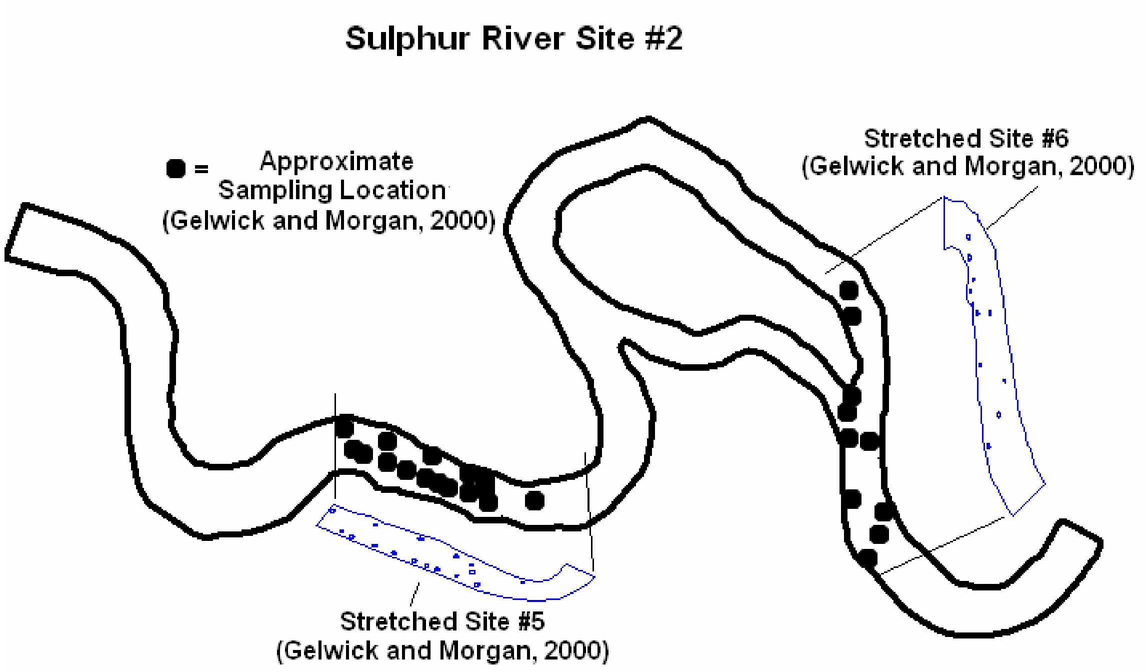


Figure O.13 – Sulphur River Site #2 with approximate sampling locations from Sites #5, #6 based on hand-drawn maps from Gelwick and Morgan (2000). Hand-drawn maps were graphically stretched and adjusted to conform with the geo-referenced site map.

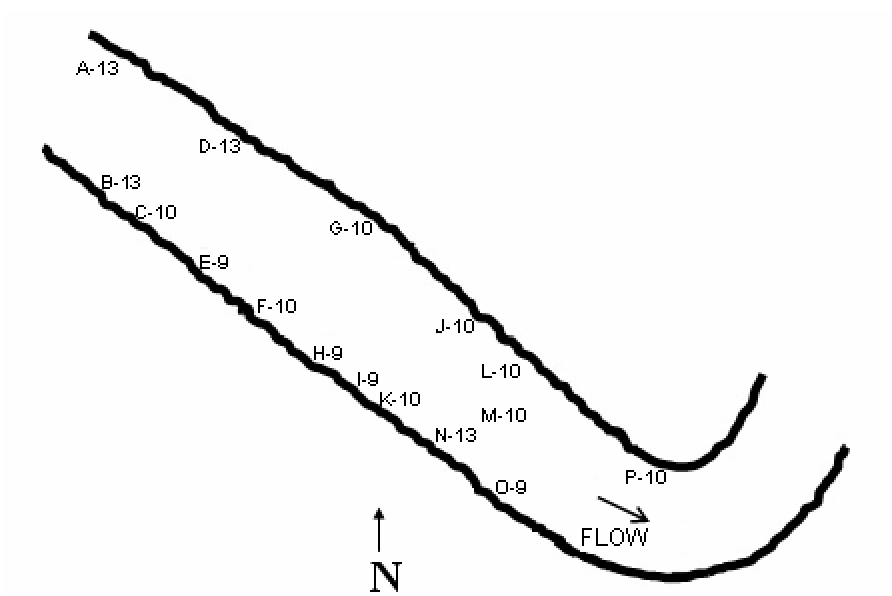


Figure O.14 – Hand Drawn Map of Site #5 from Gelwick and Morgan (2000).

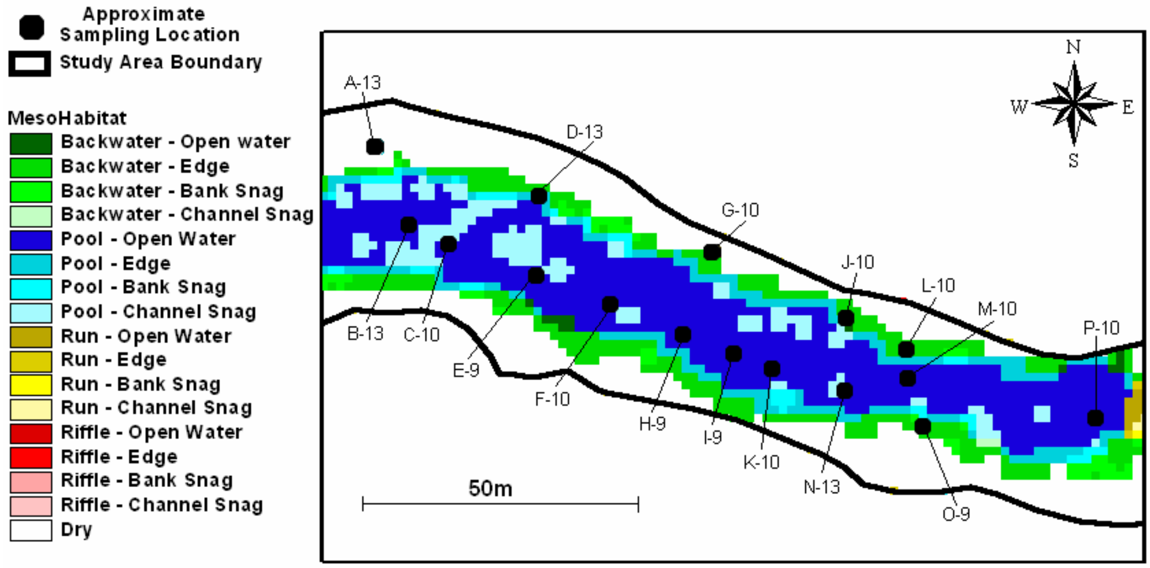


Figure O.15 – Mesohabitats at 37 cfs in the vicinity of Sampling Site #5 of Gelwick & Morgan (2000)

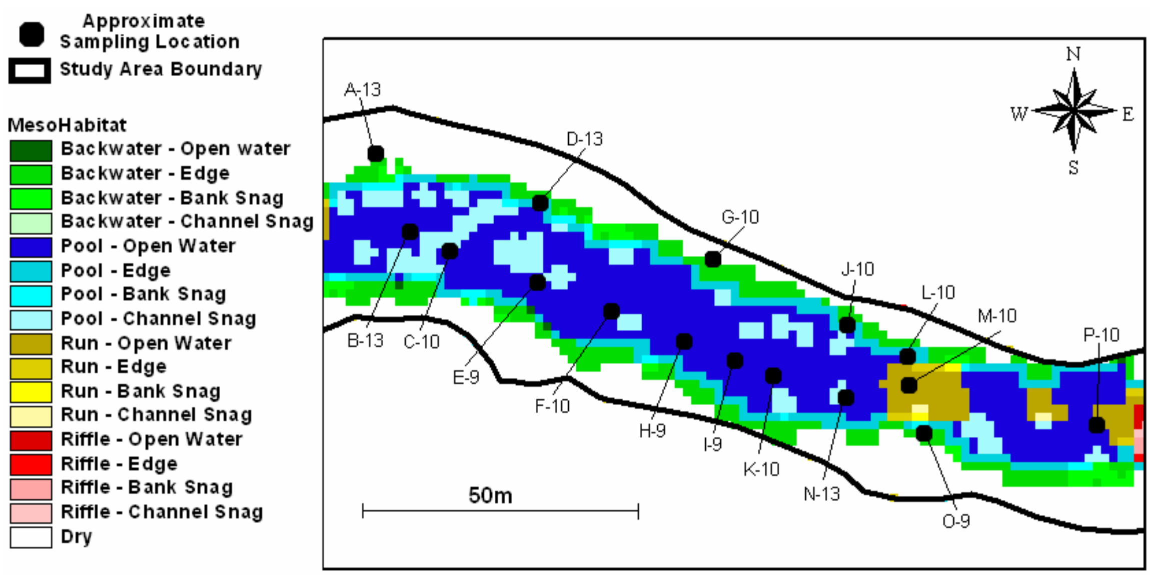


Figure O.16 – Mesohabitats at 82 cfs in the vicinity of Sampling Site #5 of Gelwick & Morgan (2000)

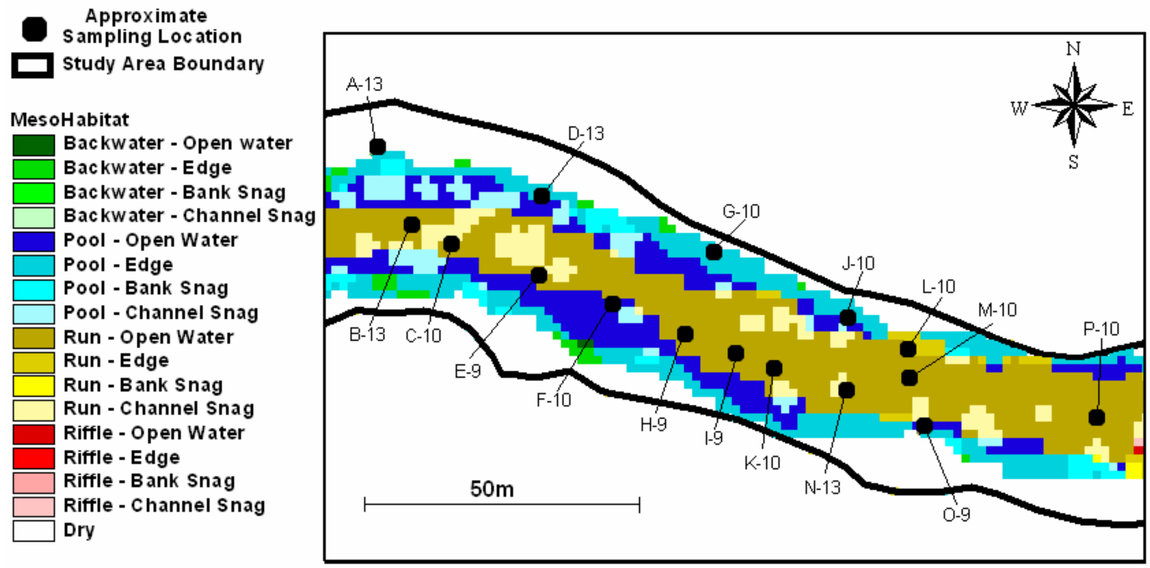


Figure O.17 – Mesohabitats at 200 cfs at Sampling Site #5 of Gelwick & Morgan (2000)

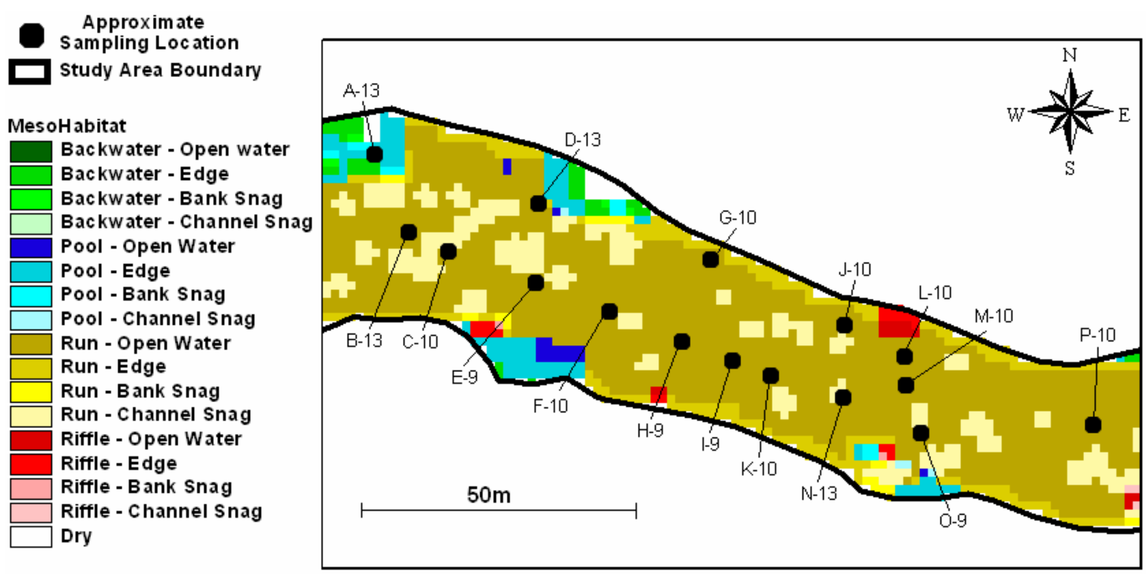


Figure O.18 – Mesohabitats at 831 cfs at Sampling Site #5 of Gelwick & Morgan (2000)

Table – O.9 Sulphur Site #2 - Comparing Morgan's Site 5 and GIS habitats – 37 cfs

Morgan's Point	Morgan Habitat	GIS Habitat	Surrounding Habitats	
A-13	Pool - rootwad	Backwater Edge	Backwater Bank Snag	
B-13	Pool - rootwad	Pool Open-Water	Pool Bank Snag	
C-10	Pool - channel snag	Pool Channel Snag	Pool Open Water	
D-13	Pool - rootwad	Pool Edge	Pool Open Water	Backwater Edge
E-9	Pool - bank snag	Pool Open Water	Pool Channel Snag	
F-10	Pool - channel snag	Pool Open Water	Pool Channel Snag	
G-10	Pool - channel snag	Backwater Edge	Pool Edge	
H-9	Pool - bank snag	Pool Open Water	Pool Edge	
I-9	Pool - bank snag	Pool Open Water	Pool Channel Snag	
J-10	Pool - channel snag	Backwater Edge	Pool Edge	Backwater Open Water
K-10	Pool - channel snag	Pool Open Water	Pool Channel Snag	
L-10	Pool - channel snag	Backwater Edge	Pool Edge	
M-10	Pool - channel snag	Pool Open Water	Pool Channel Snag	Pool Edge
N-13	Pool - rootwad	Pool Open Water	Pool Channel Snag	
O-9	Pool - bank snag	Backwater Edge	Pool Bank Snag	Pool Edge
P-10	Pool - channel snag	Pool Open Water	Pool Edge	

Table – O.10 Sulphur Site #2 - Comparing Morgan's Site 5 and GIS habitats – 82 cfs

Morgan's Point	Morgan Habitat	GIS Habitat	Surrounding Habitats	
A-13	Pool - rootwad	Backwater Edge	Backwater Bank Snag	
B-13	Pool - rootwad	Pool Open-Water	Pool Bank Snag	
C-10	Pool - channel snag	Pool Channel Snag	Pool Open Water	
D-13	Pool - rootwad	Pool Edge	Pool Open Water	Backwater Edge
E-9	Pool - bank snag	Pool Open Water	Pool Channel Snag	
F-10	Pool - channel snag	Pool Open Water	Pool Channel Snag	
G-10	Pool - channel snag	Backwater Edge	Pool Edge	
H-9	Pool - bank snag	Pool Open Water	Pool Edge	
I-9	Pool - bank snag	Pool Open Water	Pool Channel Snag	
J-10	Pool - channel snag	Pool Edge	Backwater Edge	Pool Channel Snag
K-10	Pool - channel snag	Pool Open Water	Pool Channel Snag	
L-10	Pool - channel snag	Pool Open Water	Pool Edge	Run Open Water
M-10	Pool - channel snag	Run Open Water	Run Channel Snag	Run Edge
N-13	Pool - rootwad	Pool Open Water	Pool Channel Snag	
O-9	Pool - bank snag	Backwater Edge	Pool Bank Snag	Pool Edge
P-10	Pool - channel snag	Run Open Water	Pool Open Water	

Table – O.11 Sulphur Site #2 - Comparing Morgan's Site 5 and GIS habitats – 200 cfs

Morgan's Point	Morgan Habitat	GIS Habitat	Surrounding Habitats	
A-13	Pool - rootwad	Dry	Pool Edge	Pool Bank Snag
B-13	Pool - rootwad	Run Open Water	Run Channel Snag	Pool Open Water
C-10	Pool - channel snag	Run Channel Snag	Run Open Water	Pool Channel Snag
D-13	Pool - rootwad	Pool Edge	Pool Open Water	
E-9	Pool - bank snag	Run Open Water	Pool Open Water	Run Channel Snag
F-10	Pool - channel snag	Pool Open Water	Pool Channel Snag	Run Open Water
G-10	Pool - channel snag	Pool Edge	Pool Open Water	
H-9	Pool - bank snag	Run Open Water	Pool Open Water	
I-9	Pool - bank snag	Run Open Water	Run Channel Snag	
J-10	Pool - channel snag	Pool Open Water	Pool Edge	Pool Channel Snag
K-10	Pool - channel snag	Run Open Water	Run Channel Snag	
L-10	Pool - channel snag	Run Open Water	Run Edge	
M-10	Pool - channel snag	Run Open Water	Run Channel Snag	
N-13	Pool - rootwad	Run Open Water	Run Channel Snag	
O-9	Pool - bank snag	Pool Open Water	Run Channel Snag	Pool Edge
P-10	Pool - channel snag	Run Open Water	Run Channel Snag	

Table – O.12 Sulphur Site #2 - Comparing Morgan's Site 5 and GIS habitats – 831 cfs

Morgan's Point	Morgan Habitat	GIS Habitat	Surrounding Habitats	
A-13	Pool - rootwad	Pool Edge	Pool - channel snag	Backwater Edge
B-13	Pool - rootwad	Run Open Water	Run Channel Snag	
C-10	Pool - channel snag	Run Channel Snag	Run Open Water	
D-13	Pool - rootwad	Run Open Water	Run Edge	Pool Bank snag
E-9	Pool - bank snag	Run Open Water	Run Channel Snag	
F-10	Pool - channel snag	Run Open Water	Run Channel Snag	
G-10	Pool - channel snag	Run Open Water	Run Edge	
H-9	Pool - bank snag	Run Open Water	Run Channel Snag	
I-9	Pool - bank snag	Run Open Water		
J-10	Pool - channel snag	Run Open Water	Run Channel Snag	Run Edge
K-10	Pool - channel snag	Run Open Water	Run Channel Snag	
L-10	Pool - channel snag	Run Open Water	Riffle Open Water	
M-10	Pool - channel snag	Run Open Water	Run Channel Snag	
N-13	Pool - rootwad	Run Open Water	Run Channel Snag	
O-9	Pool - bank snag	Run Open Water	Run Channel Snag	
P-10	Pool - channel snag	Run Open Water	Run Channel Snag	

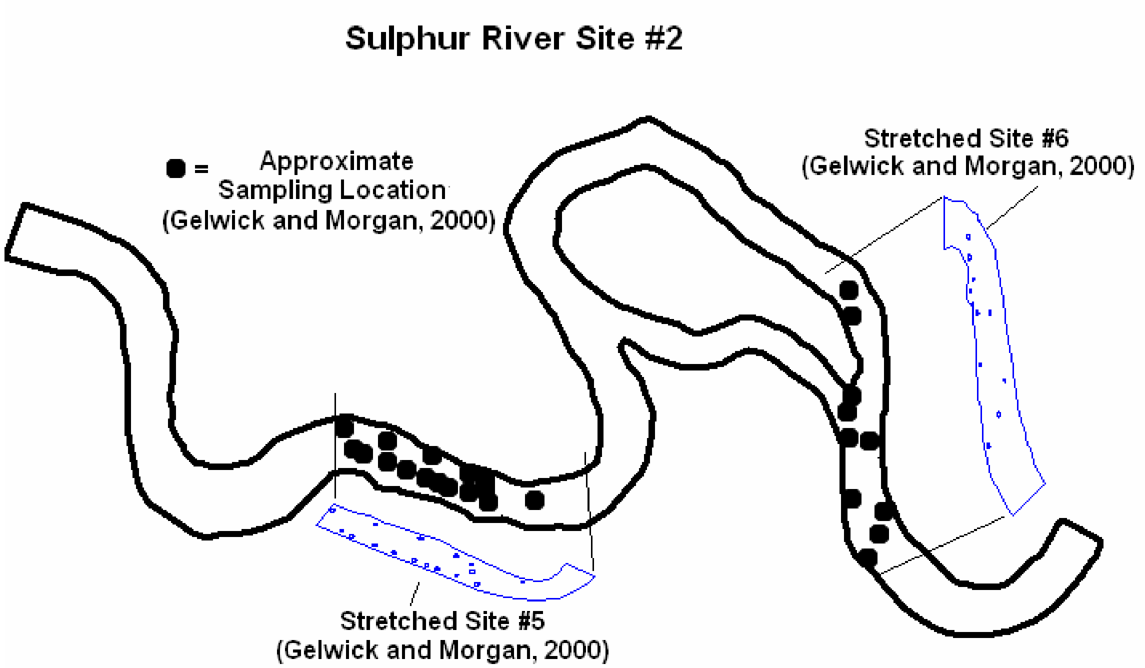


Figure O.13 – (Repeated for Continuity) Sulphur River Site #2 with approximate sampling locations from Sites #5, #6 based on hand-drawn maps from Gelwick and Morgan (2000). Hand-drawn maps were graphically stretched and adjusted to conform with the geo-referenced site map.

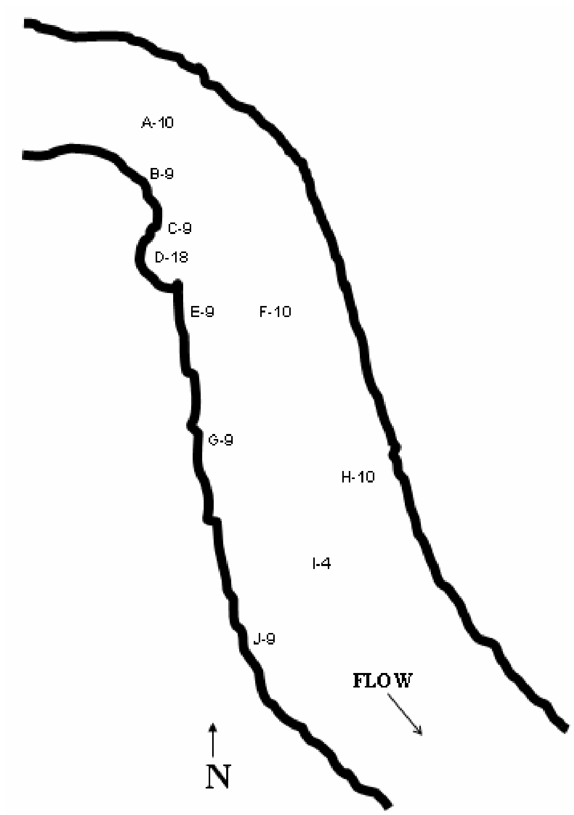


Figure O.19 – Hand Drawn Map of Site #6 from Gelwick and Morgan (2000).

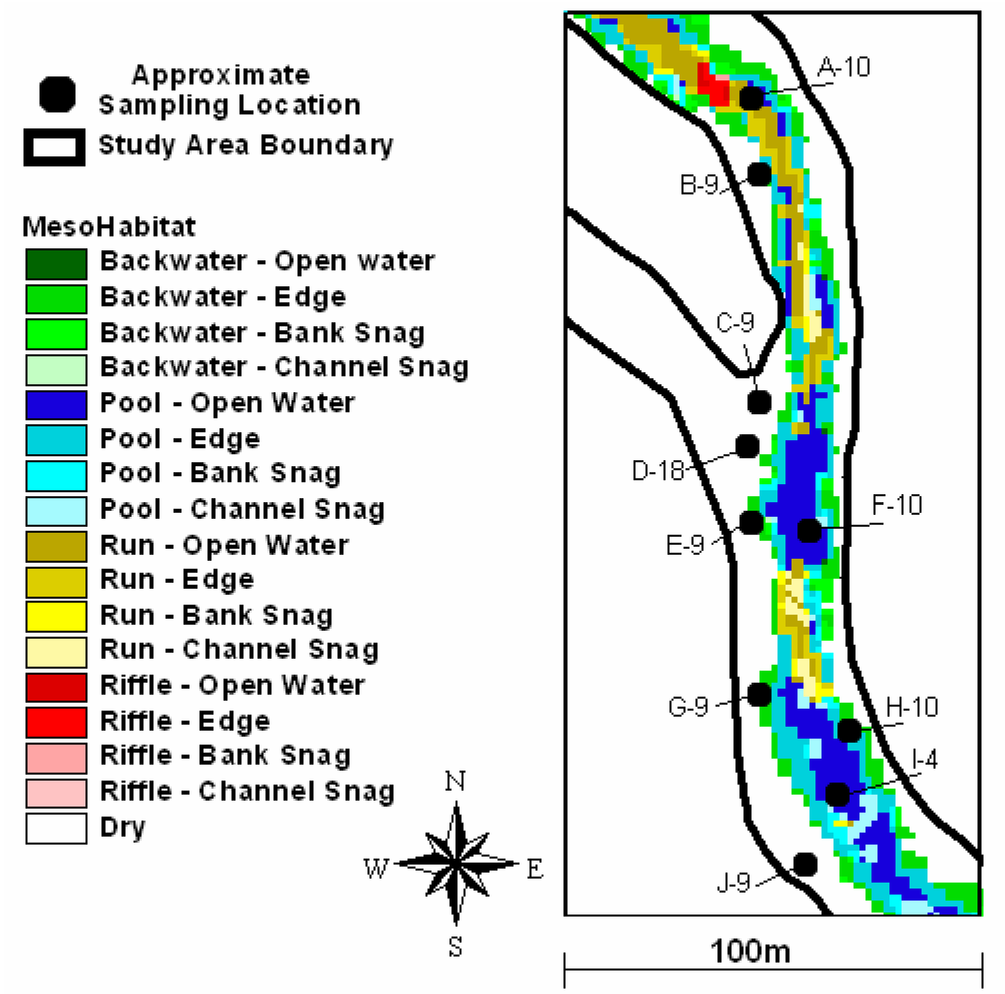


Figure O.20 – Mesohabitats at 37 cfs in the vicinity of Sampling Site #6 of Gelwick & Morgan (2000)

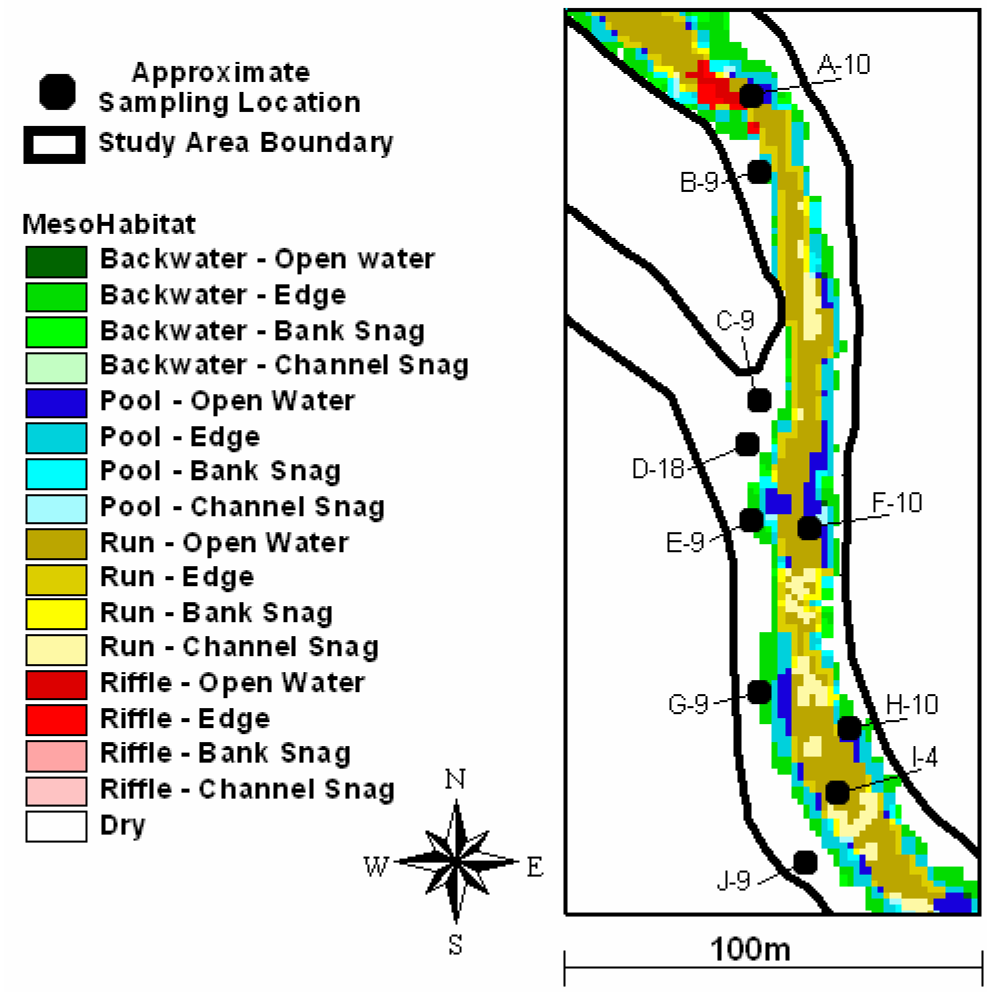


Figure O.21 – Mesohabitats at 82 cfs in the vicinity of Sampling Site #6 of Gelwick & Morgan (2000)

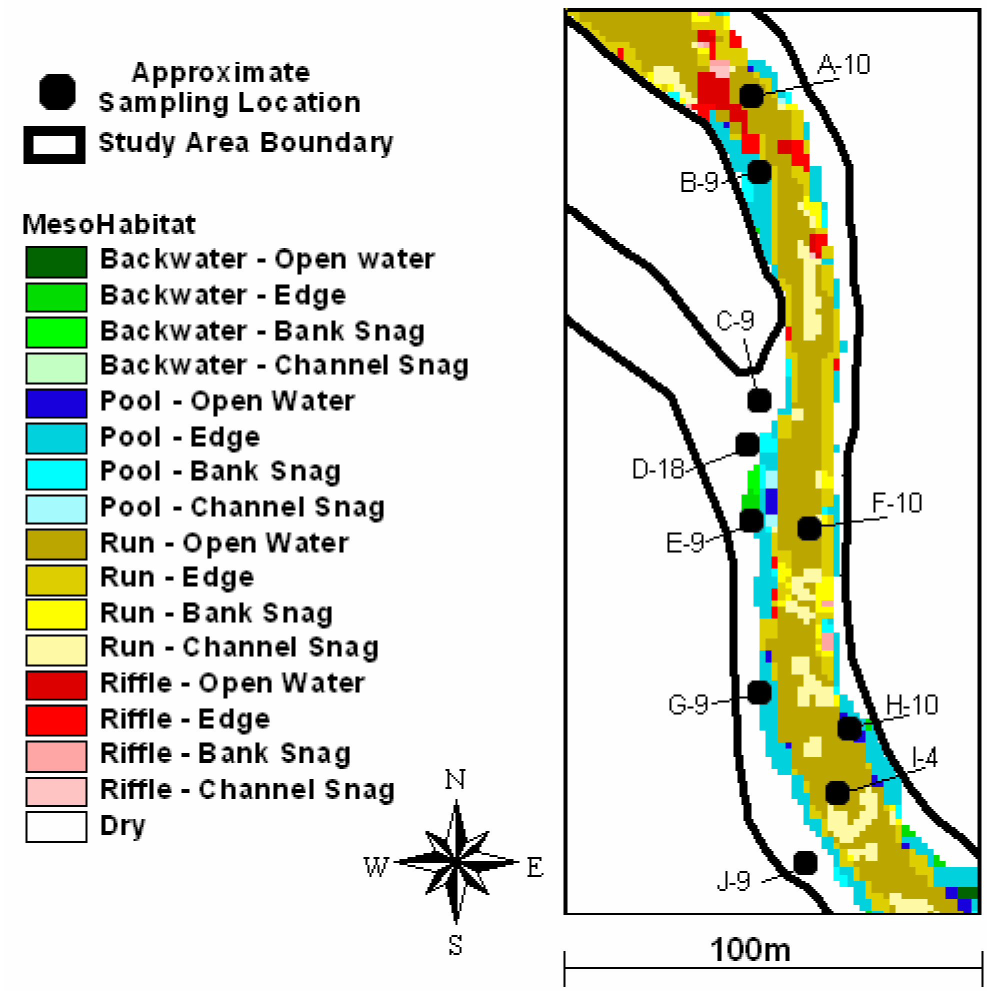


Figure O.22 – Mesohabitats at 200 cfs in the vicinity of Sampling Site #6 of Gelwick & Morgan (2000)

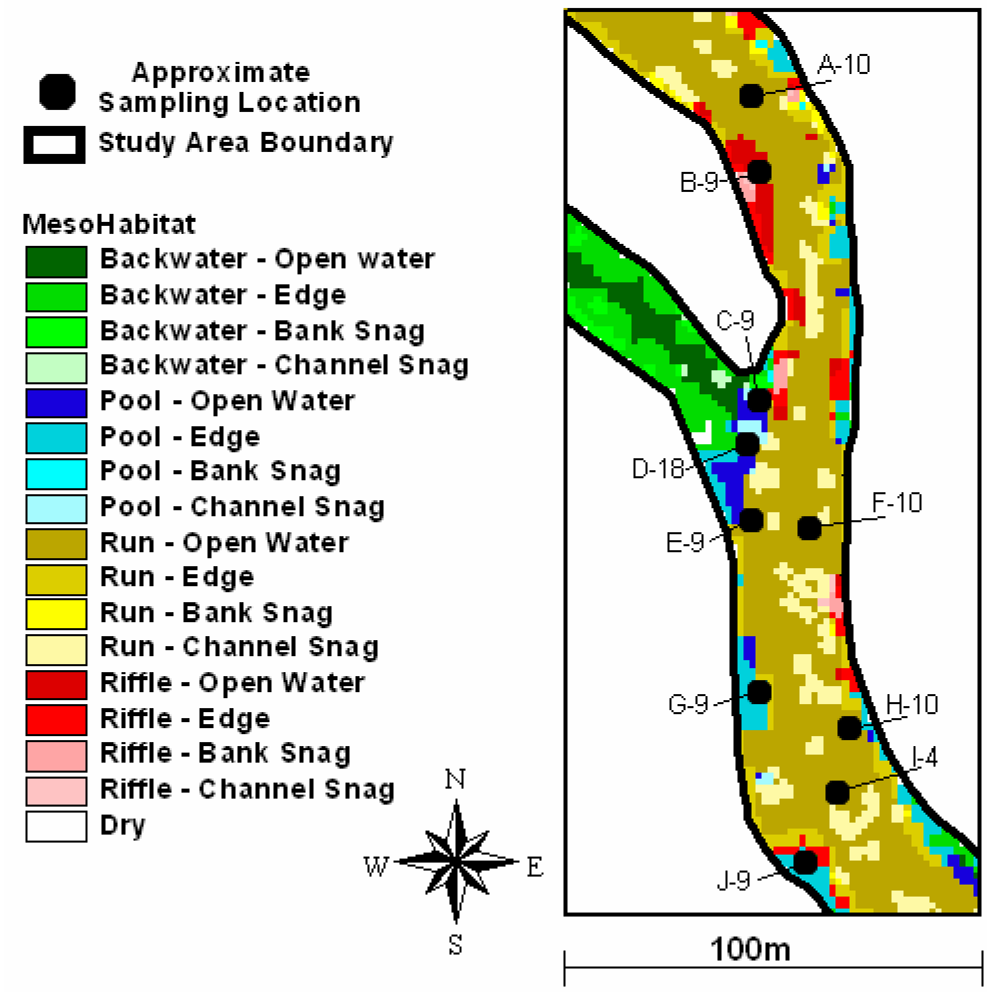


Figure O.23 – Mesohabitats at 831 cfs in the vicinity of Sampling Site #6 of Gelwick & Morgan (2000)

Table – O.13 Sulphur Site #2 - Comparing Morgan's Site 6 and GIS habitats – 37 cfs

Morgan's Point	Morgan Habitat	GIS Habitat	Surrounding Habitats	
A-10	Pool - channel snag	Run Open Water	Pool Open Water	Run Edge
B-9	Pool - bank snag	Backwater Edge	Pool Edge	
C-9	Pool - bank snag	Dry	Backwater Edge	
D-18	Backwater	Dry	Backwater Edge	Backwater bank Snag
E-9	Pool - bank snag	Dry	Backwater Edge	
F-10	Pool - channel snag	Pool Open Water	Pool Channel Snag	
G-9	Pool - bank snag	Dry	Backwater Edge	Pool Edge
H-10	Pool - channel snag	Pool Edge	Backwater Edge	
I-4	Riffle - snag complex	Pool Channel Snag	Pool Open Water	
J-9	Pool - bank snag	Dry	Backwater Edge	

Table – O.14 Sulphur Site #2 - Comparing Morgan's Site 6 and GIS habitats – 82 cfs

Morgan's Point	Morgan Habitat	GIS Habitat	Surrounding Habitats	
A-10	Pool - channel snag	Run Open Water	Pool Open Water	Riffle Edge
B-9	Pool - bank snag	Backwater Edge	Pool Edge	
C-9	Pool - bank snag	Dry	Backwater Edge	Pool Edge
D-18	Backwater	Dry	Backwater Edge	Backwater bank Snag
E-9	Pool - bank snag	Backwater Edge	Pool Edge	
F-10	Pool - channel snag	Pool Open Water	Run Open Water	Pool Channel Snag
G-9	Pool - bank snag	Dry	Backwater Edge	Pool Edge
H-10	Pool - channel snag	Pool Edge	Backwater Edge	Run Edge
I-4	Riffle - snag complex	Run Channel Snag	Run Open Water	
J-9	Pool - bank snag	Dry	Backwater Edge	

Table – O.15 Sulphur Site #2 - Comparing Morgan's Site 6 and GIS habitats – 200 cfs

Morgan's Point	Morgan Habitat	GIS Habitat	Surrounding Habitats	
A-10	Pool - channel snag	Run Open Water	Riffle Open Water	Riffle Edge
B-9	Pool - bank snag	Pool Edge	Run Edge	Pool Bank snag
C-9	Pool - bank snag	Dry	Pool Edge	Run Edge
D-18	Backwater	Dry	Pool Bank Snag	Pool Channel Snag
E-9	Pool - bank snag	Pool Edge	Backwater Edge	Pool Channel Snag
F-10	Pool - channel snag	Run Open Water	Run Channel Snag	Run Edge
G-9	Pool - bank snag	Dry	Pool Edge	Run Open Water
H-10	Pool - channel snag	Run edge	Run open Water	Pool Edge
I-4	Riffle - snag complex	Run Channel Snag	Run Open Water	
J-9	Pool - bank snag	Dry	Pool Edge	

Table – O.16 Sulphur Site #2 - Comparing Morgan's Site 6 and GIS habitats – 831 cfs

Morgan's Point	Morgan Habitat	GIS Habitat	Surrounding Habitats	
A-10	Pool - channel snag	Run Open Water	Run channel snag	Run Edge
B-9	Pool - bank snag	Riffle Edge	Run channel snag	Run Open Water
C-9	Pool - bank snag	Pool Edge	Pool Open Water	Riffle Edge
D-18	Backwater	Pool Open Water	Backwater Edge	Pool Channel snag
E-9	Pool - bank snag	Run Open Water	Pool Open Water	Run Channel Snag
F-10	Pool - channel snag	Run Open Water	Run Channel Snag	
G-9	Pool - bank snag	Pool Edge	Run Edge	Run Open Water
H-10	Pool - channel snag	Run Open Water	Pool Open Water	Pool Edge
I-4	Riffle - snag complex	Run Channel Snag	Run Open Water	
J-9	Pool - bank snag	Backwater Edge	Pool Edge	Riffle Edge

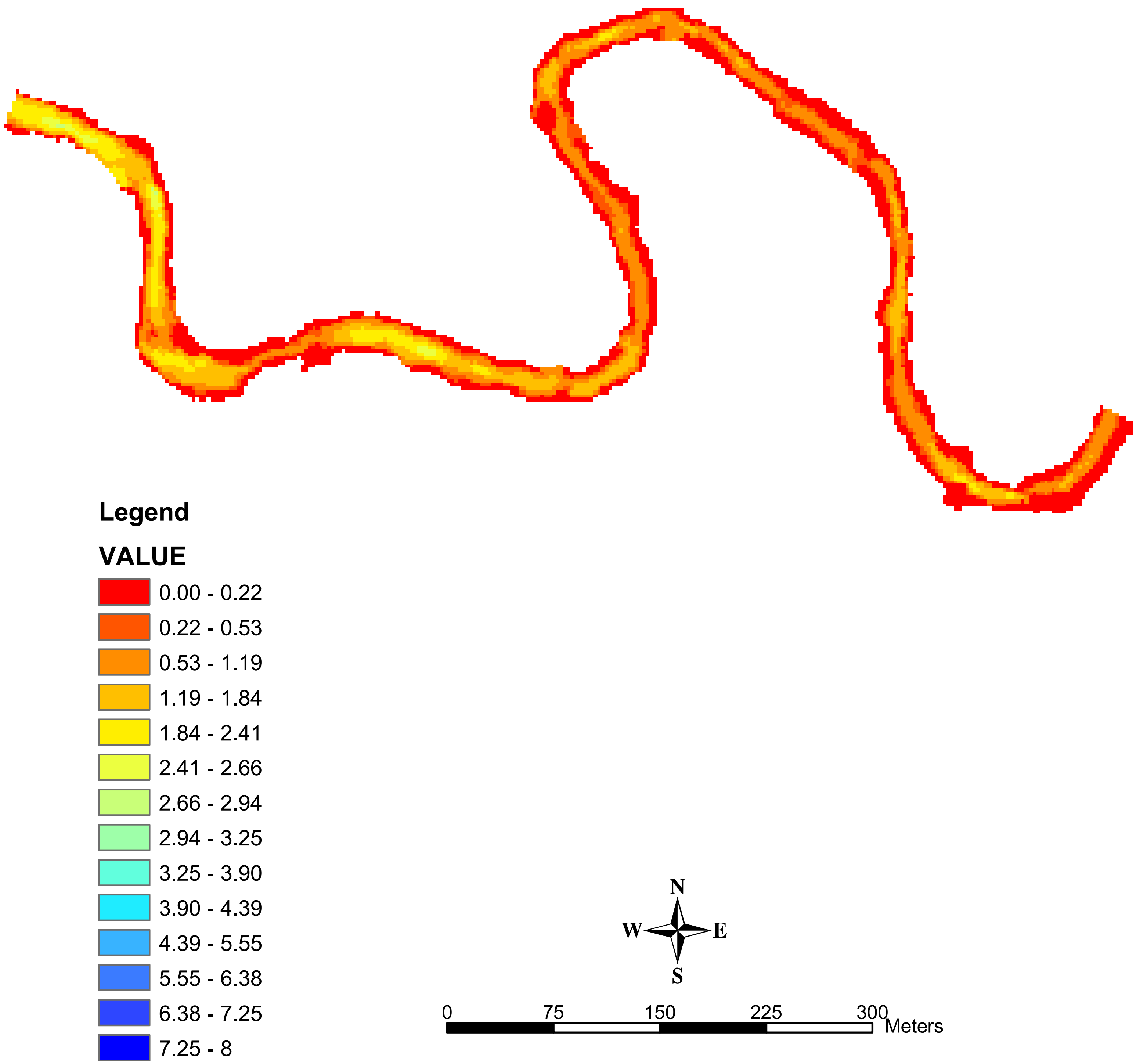
Appendix P

Hydraulic model output for depth and velocity– Site 2

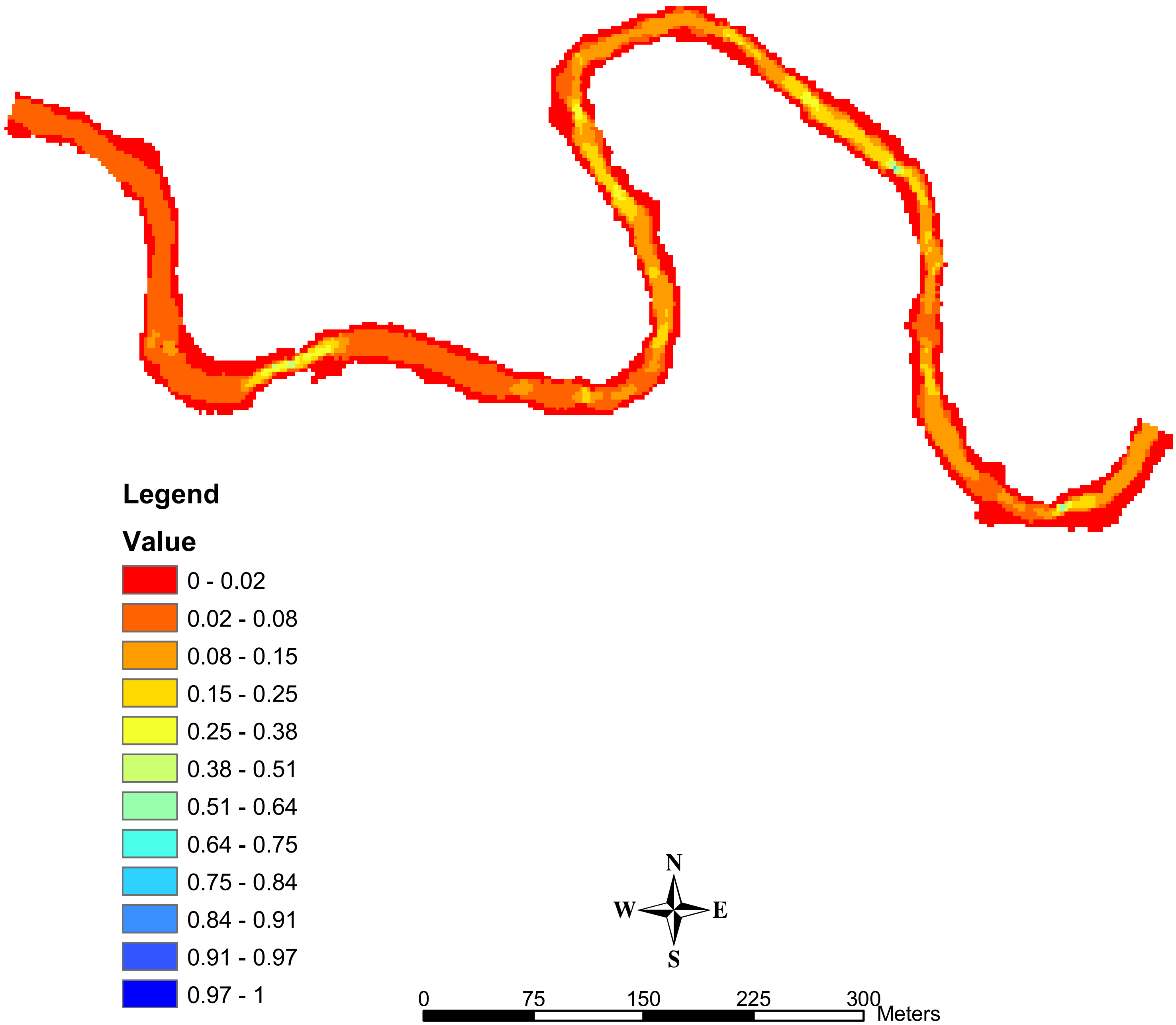
Spatial hydraulic model outputs depicting both depth and velocity are shown for each of the following flow rates:

1.05 cms (37 cfs)	2
2.32 cms (82 cfs)	4
5.66 cms (200 cfs)	6
11.35 cms (400 cfs)	8
16.99 cms (600 cfs)	10
23.53 cms (831 cfs)	12
99.38 cms (3510 cfs)	14

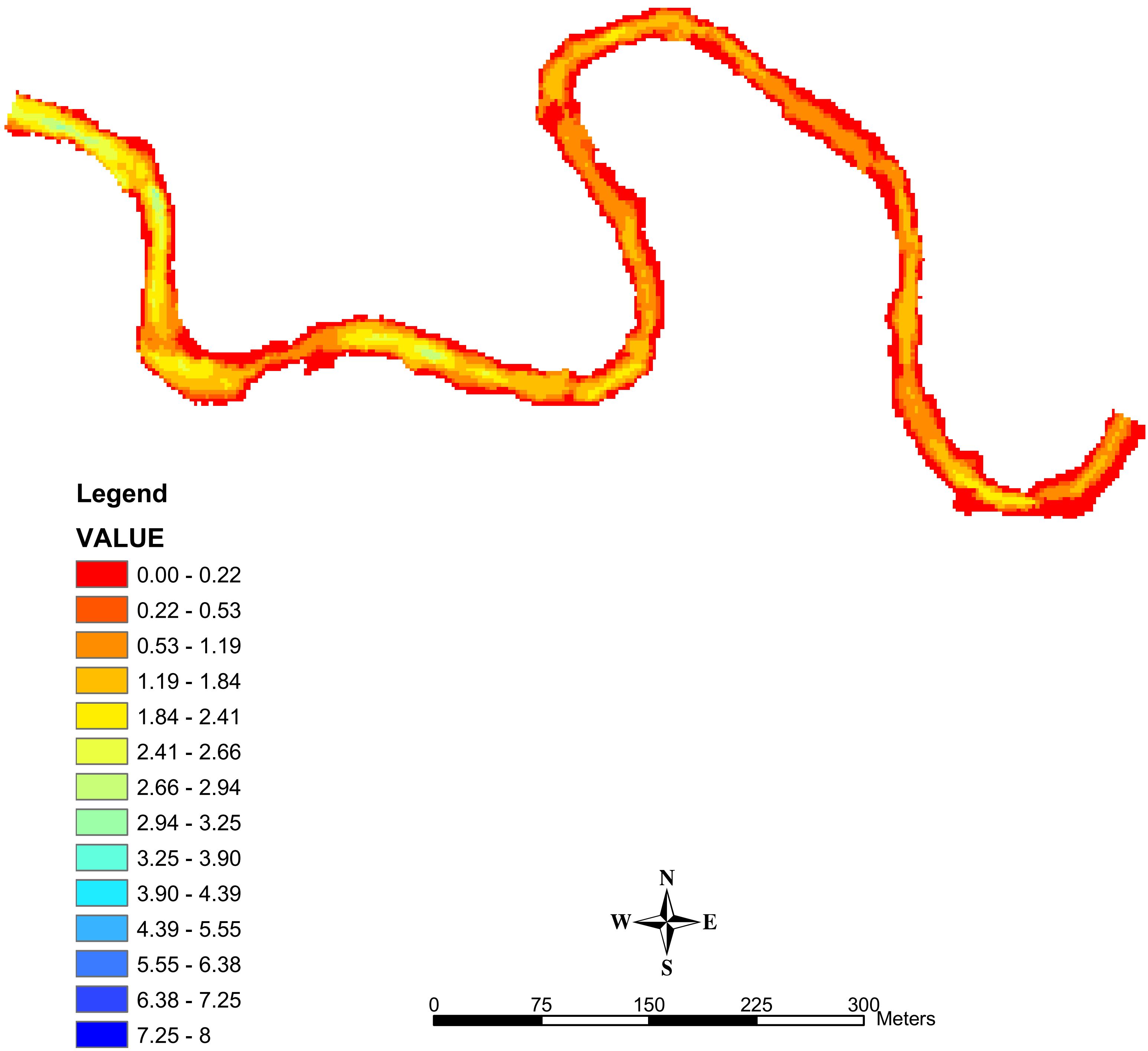
Depth Plot
1.05 cumec (37 cfs)
Sulphur River, Site 2



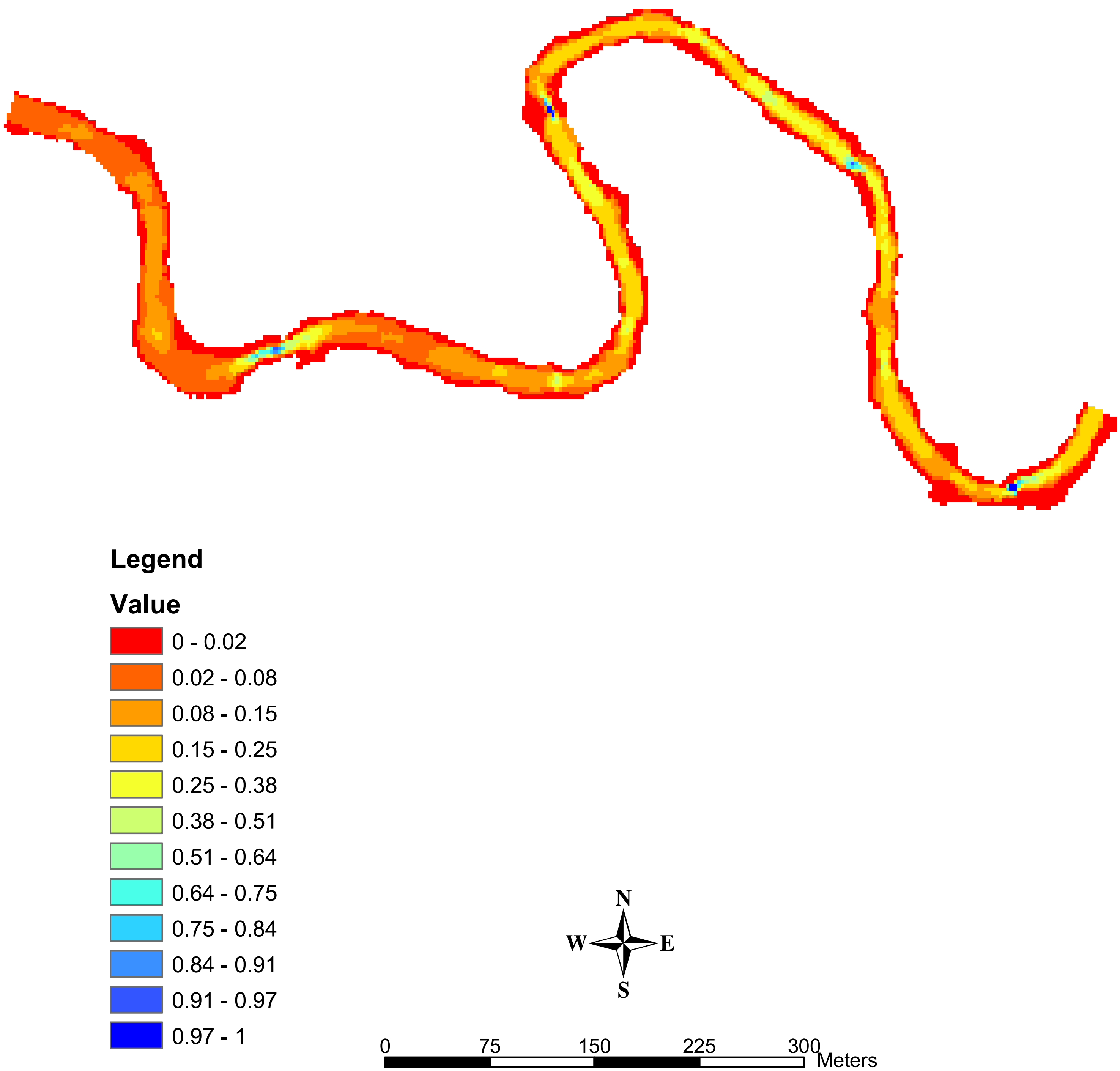
Velocity Plot
1.05 cumec (37 cfs)
Sulphur River, Site 2



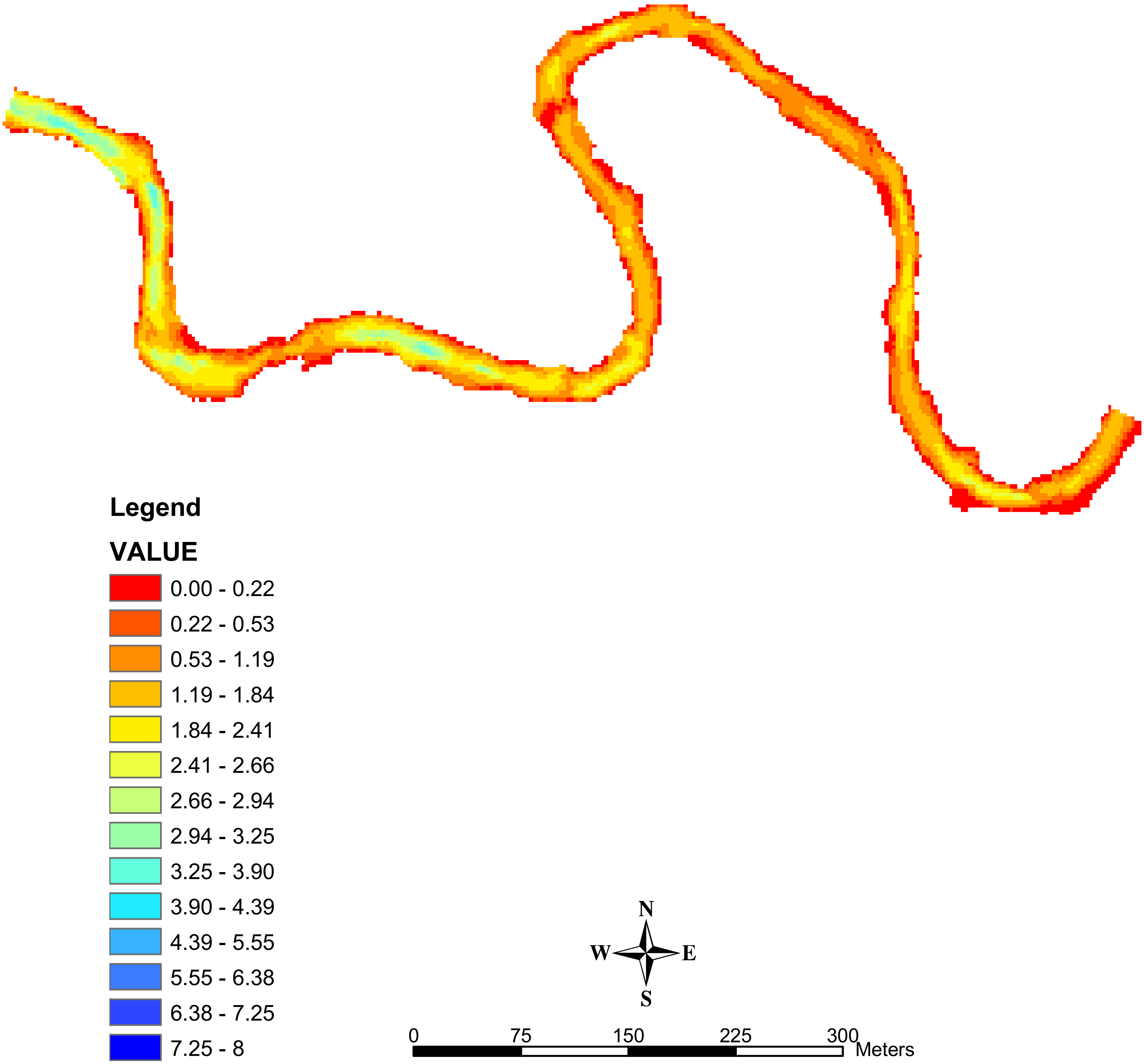
Depth Plot
2.32 cumec (82 cfs)
Sulphur River, Site 2



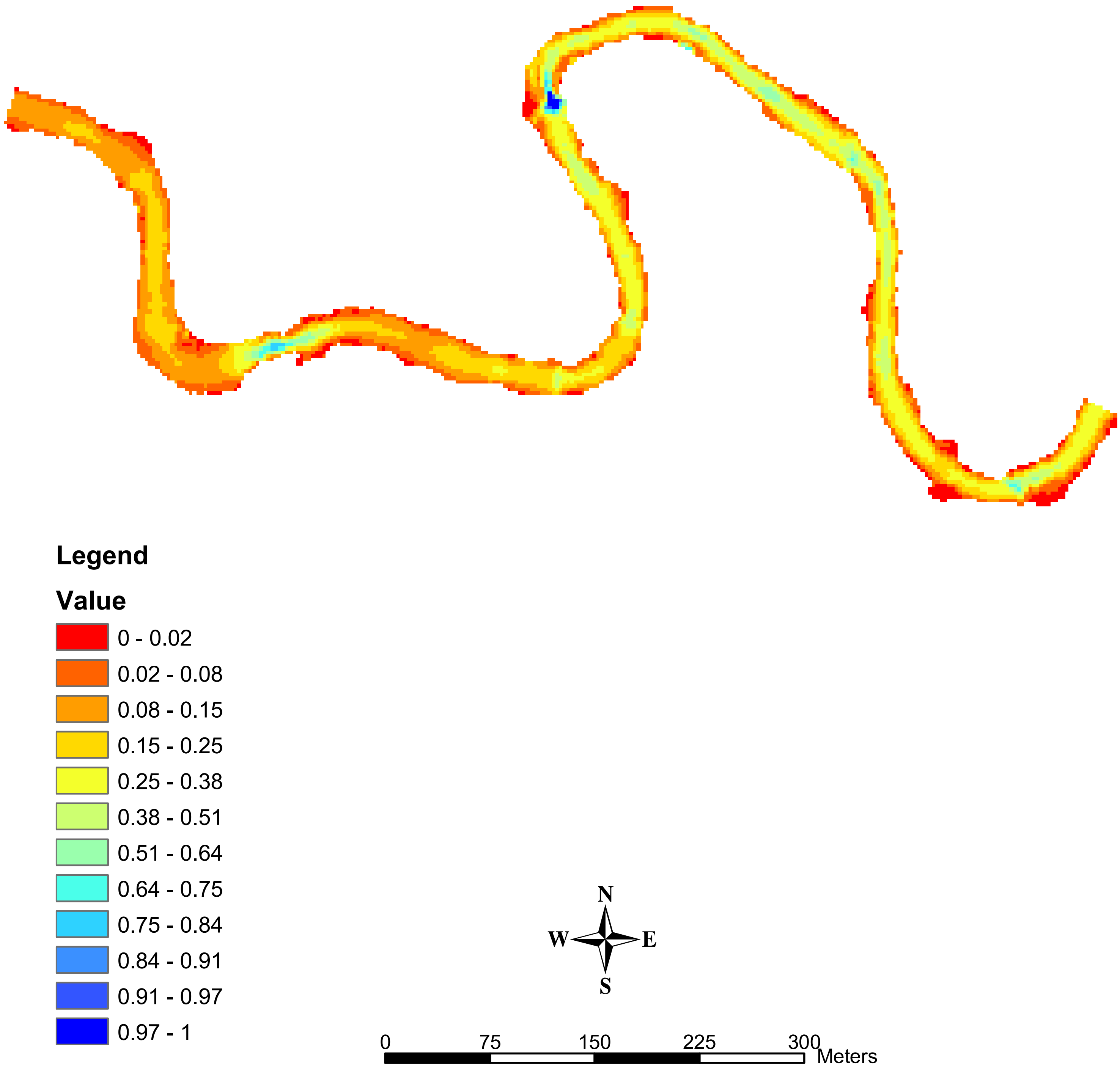
Velocity Plot
2.32 cumec (82 cfs)
Sulphur River, Site 2



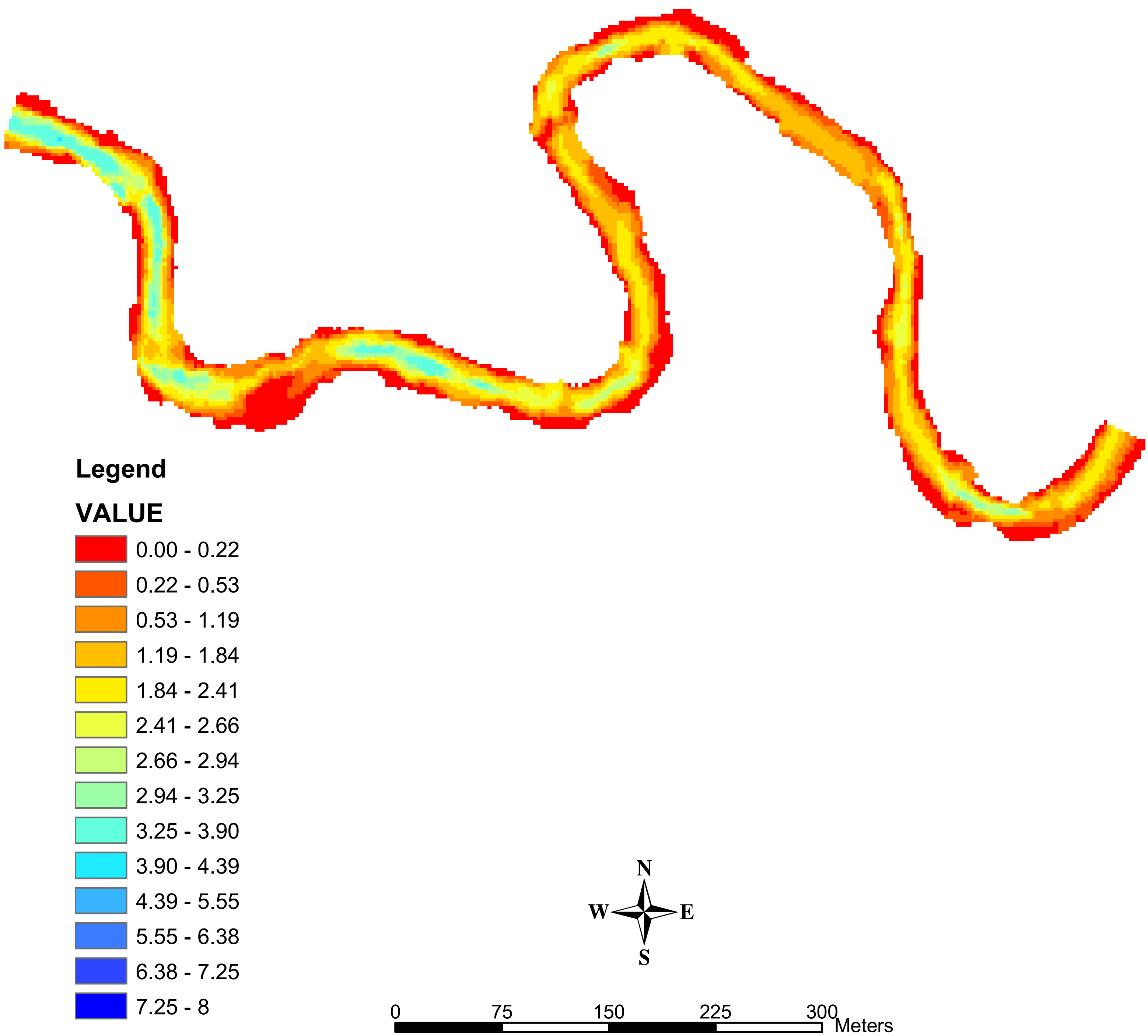
Depth Plot
5.66 cumec (200 cfs)
Sulphur River, Site 2



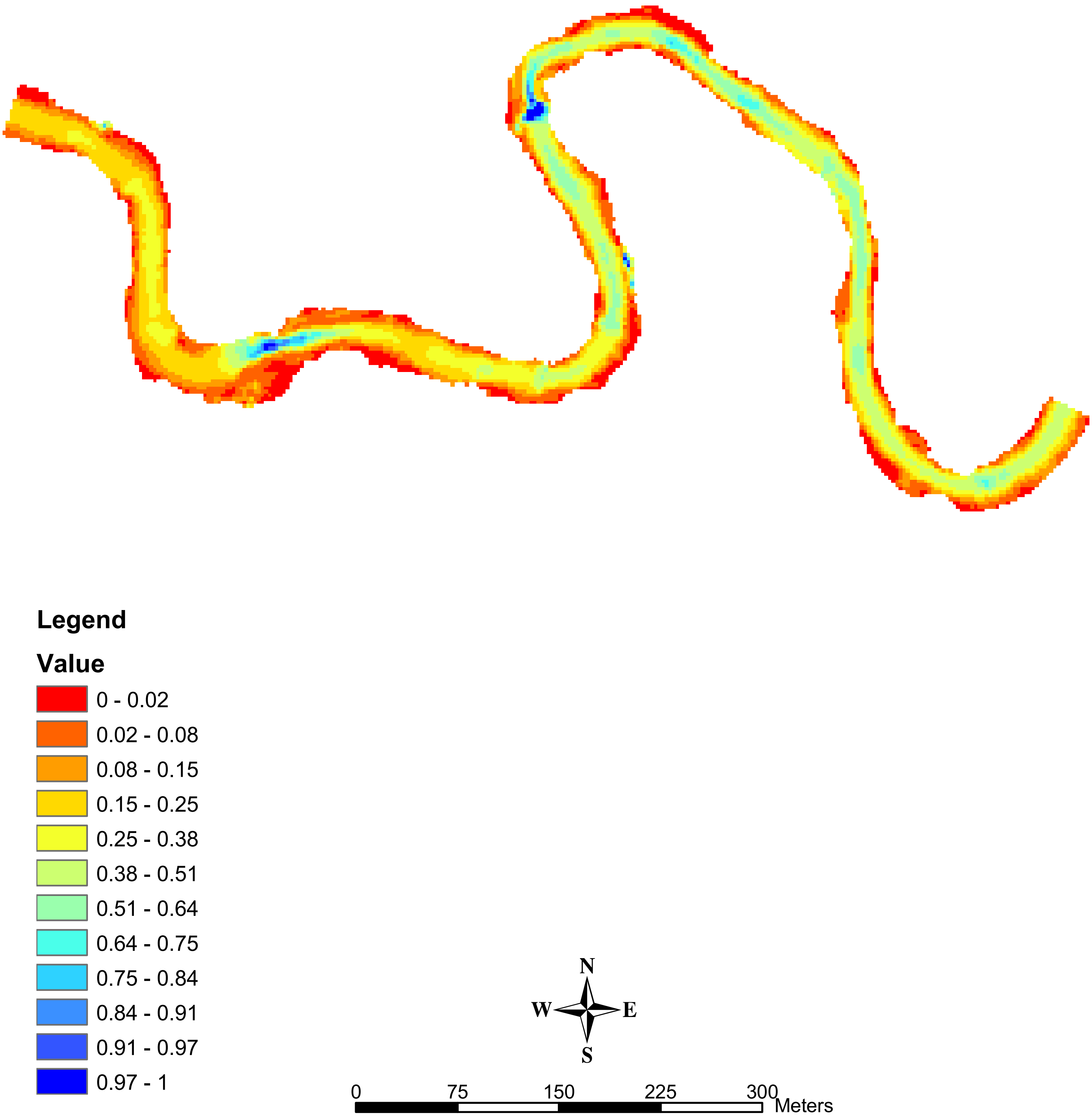
Velocity Plot
5.66 cumec (200 cfs)
Sulphur River, Site 2



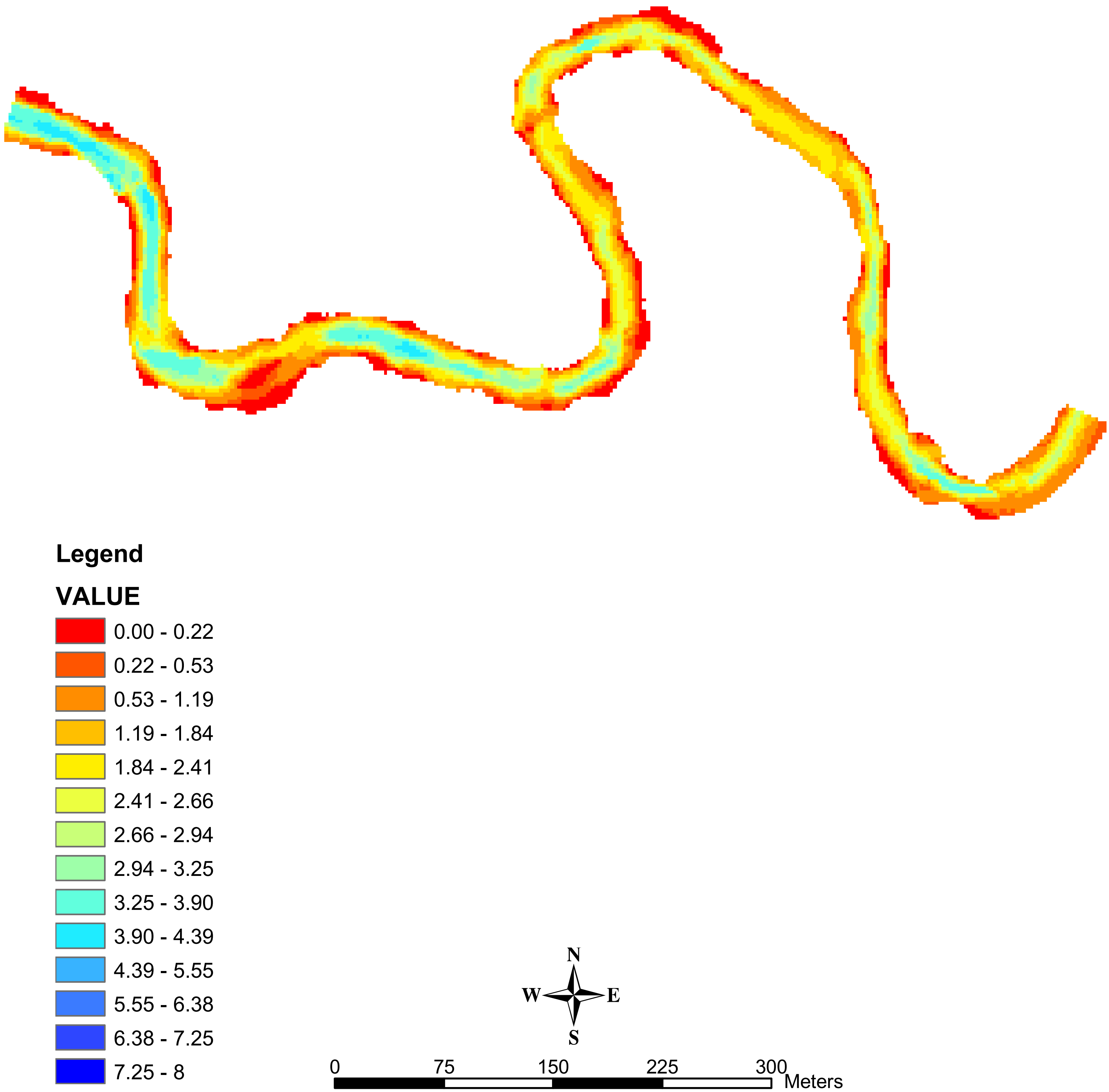
Depth Plot
11.35 cumec (400 cfs)
Sulphur River, Site 2



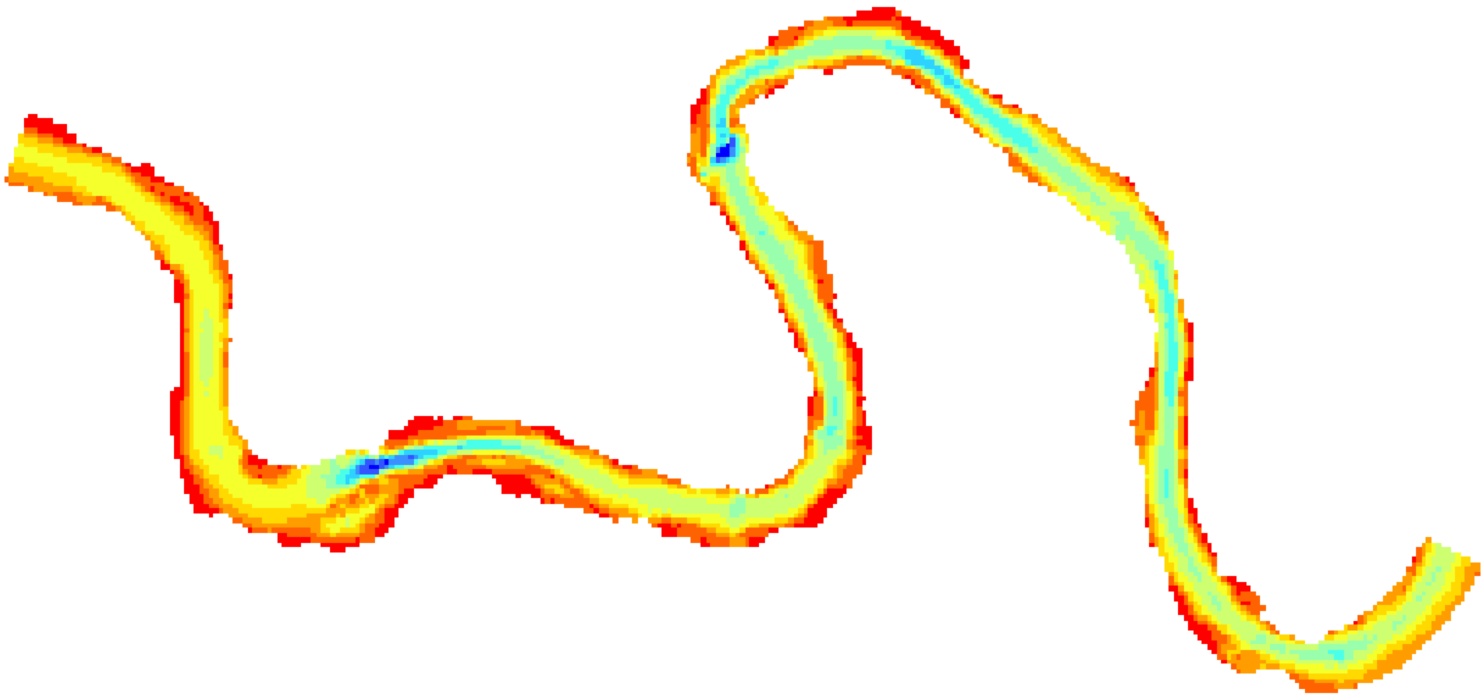
Velocity Plot
11.33 cumec (400 cfs)
Sulphur River, Site 2



Depth Plot
16.99 cumec (600 cfs)
Sulphur River, Site 2



Velocity Plot
16.99 cumec (600 cfs)
Sulphur River, Site 2

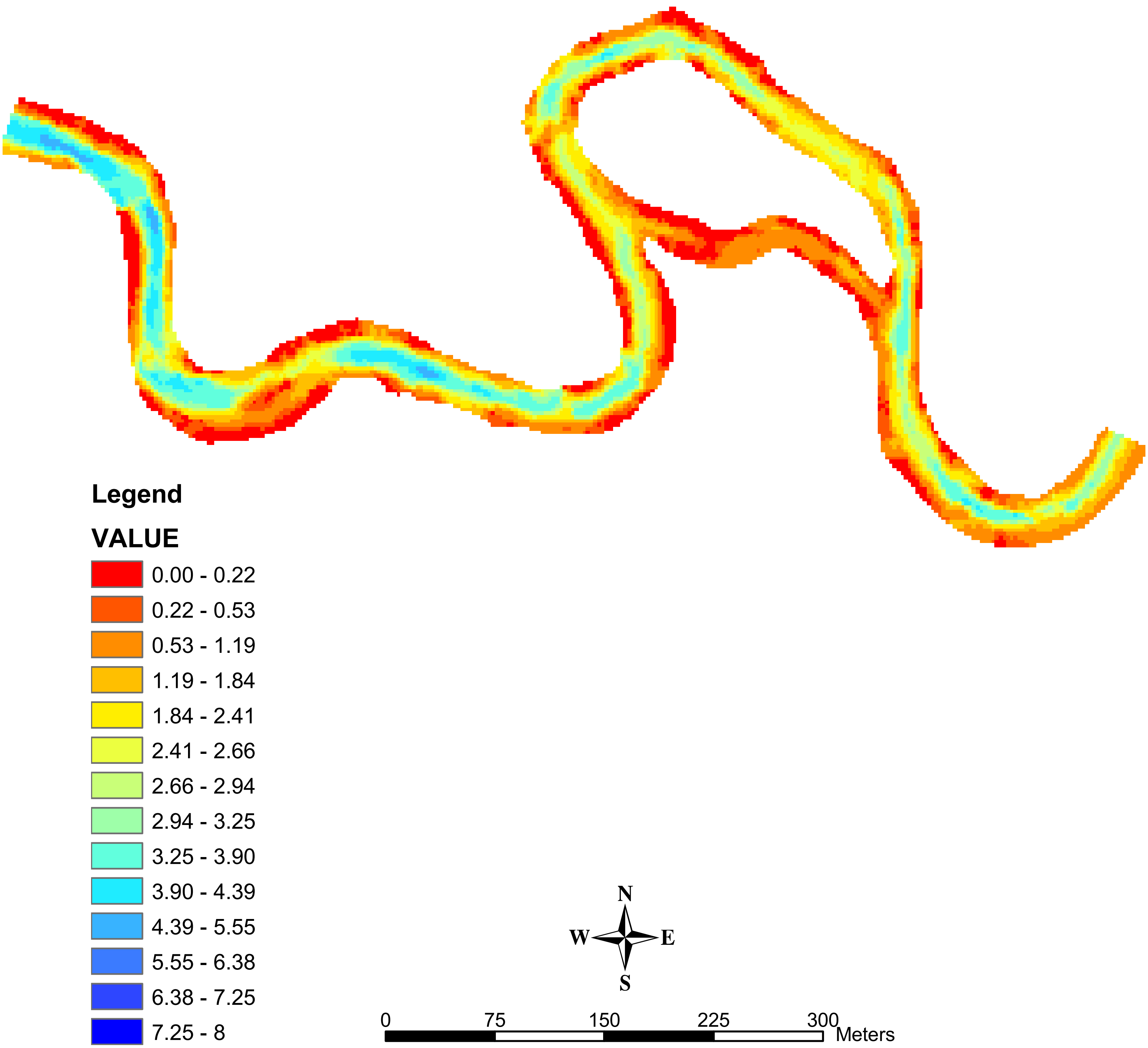


Legend

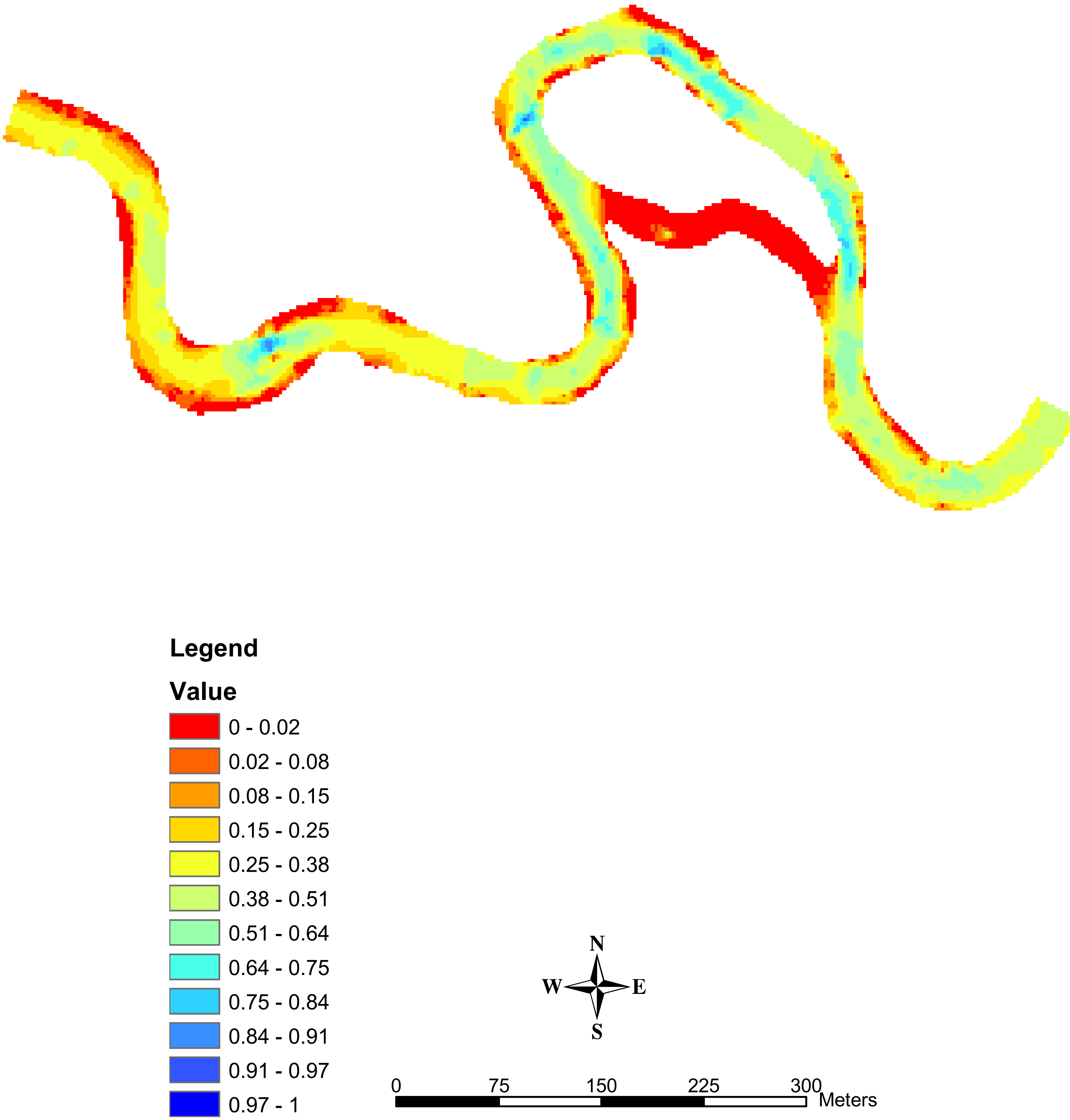
Value

- 0 - 0.02
- 0.02 - 0.08
- 0.08 - 0.15
- 0.15 - 0.25
- 0.25 - 0.38
- 0.38 - 0.51
- 0.51 - 0.64
- 0.64 - 0.75
- 0.75 - 0.84
- 0.84 - 0.91
- 0.91 - 0.97
- 0.97 - 1

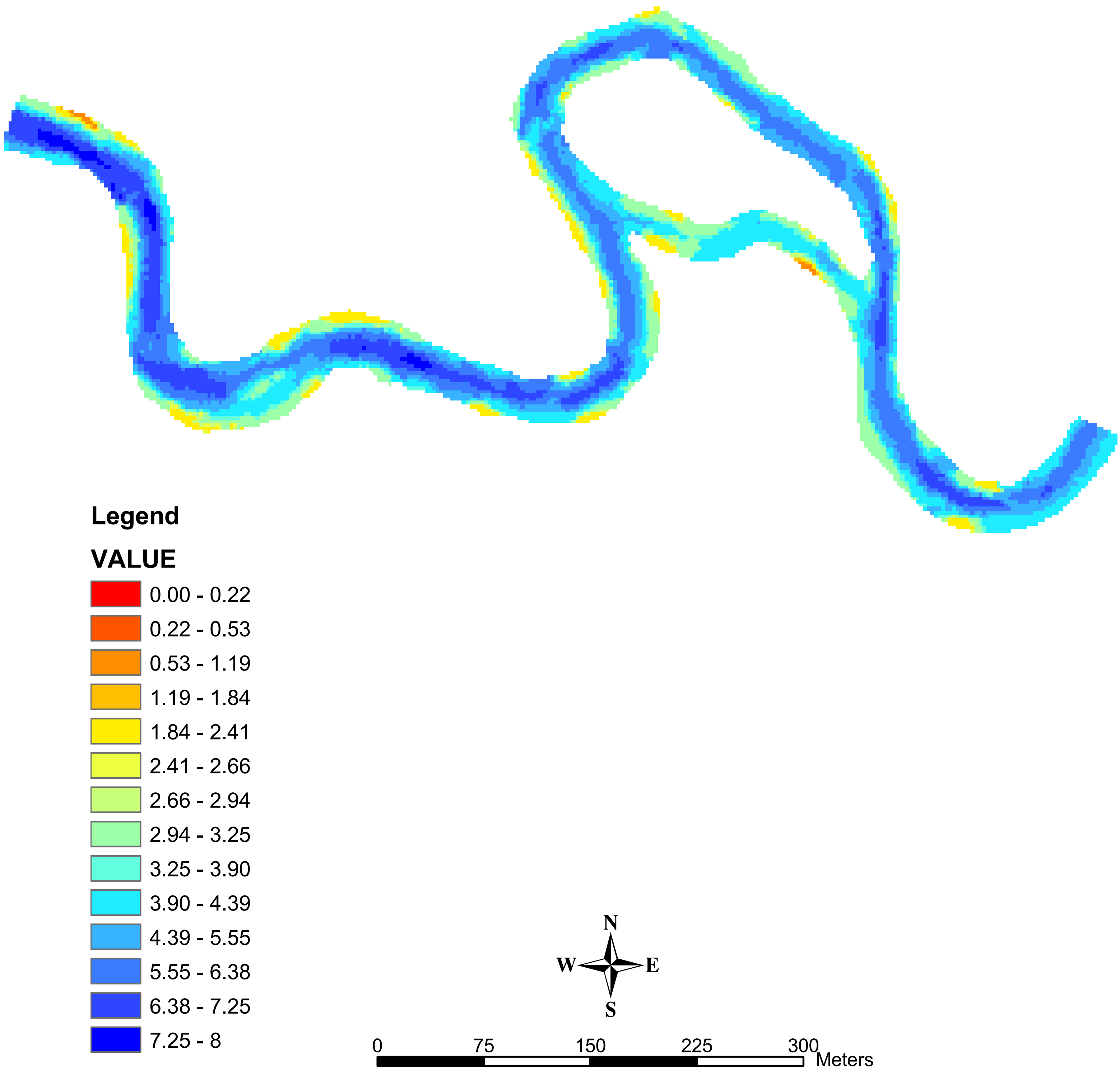
Depth Plot
23.53 cumec (831 cfs)
Sulphur River, Site 2



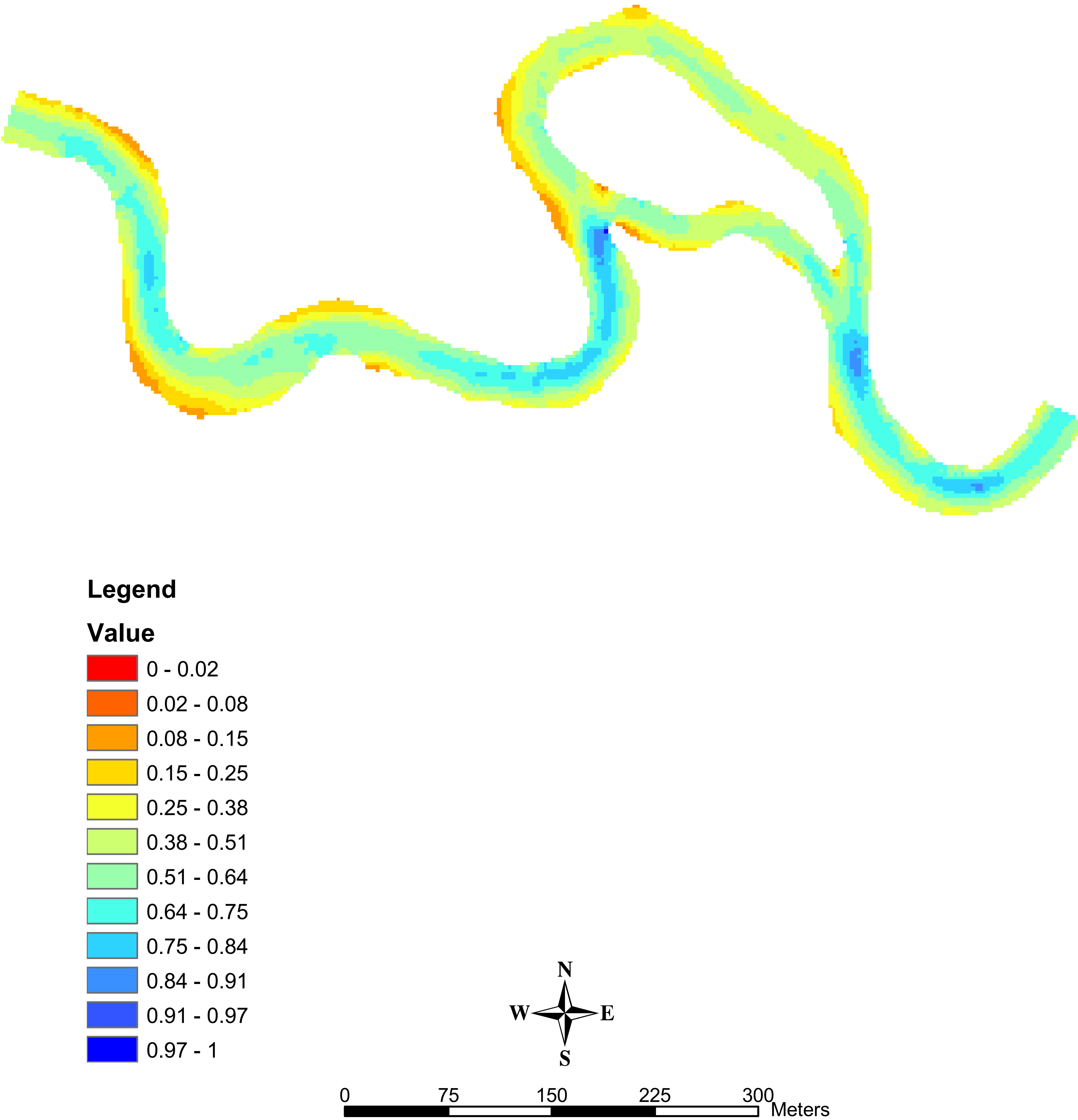
Velocity Plot
23.53 cumec (831 cfs)
Sulphur River, Site 2



Depth Plot
99.39 cumec (3510 cfs)
Sulphur River, Site 2



Velocity Plot
99.39 cumec (3510 cfs)
Sulphur River, Site 2



Appendix Q

Q. Hydraulic Model Calibration and Verification for Site 2

Seven steady-state models were developed for Site 2 of the Sulphur River. The Surface Water Modeling System (SMS) developed at Brigham Young University for the US Army Corps of Engineers (USACE) is used as a mesh generation and model execution interface for RMA-2. RMA-2 is a depth-averaged, hydrostatic, finite-element code developed by Resource Management Associates for the USACE. The major model inputs are the bottom bathymetric surface, upstream water flow rate, and downstream stage. Major model outputs are velocity and depth at each node of the finite element mesh. The bottom bathymetric surface is represented by a finite element mesh consisting of triangular quadratic elements (Donnell, et al, 1997).

Q.1 Boundary Conditions

The complete set of boundary conditions and parameter settings for each flow rate model are shown in Tables Q.1 and Q.2 below. An identical finite element mesh was used for each model; however for low flow rates some mesh elements were manually disabled when the model's wetting and drying algorithm did not appropriately disable dry elements.

Boundary conditions specified for each model were as follows: flow rate was specified at the upstream boundary (with mass distributed across the boundary based upon depth) and constant water surface elevation across the downstream boundary. The model was calibrated using eddy viscosity and Mannings "n" (Donnell, et al, 1997; Arcement and Schneider, 1989) to match the upstream water surface elevation.

Table Q.1 - Model input boundary conditions and parameters.

Flow		WSE			Roughness by Depth				Eddy Viscocity
		Upstream		Downstream	no vegetation		w/ veg.		
		Target	*model output*	boundary	manning n	depth	manning n	rough. Coeff	
cfs	cms	meters	meters	meters		meters			Pa/s
3510	99.39	77.079	*77.060*	76.711	0.080	2.0	0.090	0.08	100
831	23.53	73.848	*73.863*	73.530	0.018	1.0	0.022	0.02	500
600	16.99	73.500	*73.502*	73.180	0.042	1.0	0.052	0.02	20
400	11.33	73.006	*73.010*	72.680	0.021	1.0	0.031	0.02	100
200	5.66	72.513	*72.569*	72.180	0.021	1.0	0.029	0.02	100
82	2.32	72.001	*72.135*	71.670	0.016	1.0	0.023	0.02	170
37	1.05	71.874	*71.882*	71.530	0.016	1.0	0.023	0.02	400

Table Q.2 - Additional model parameter settings and convergence criteria.

Flow		Marsh Porosity				Wetting and Drying			Convergence Criteria
		Distance below	Transition Range	Min. wetted surface		Iterations	Dry Element	Wet Element	
cfs	cms	AC1	AC2	AC3	AC4		DSET	DSETD	m
3510	99.39	na	na	na	na	na	na	na	0.025
831	23.53	na	na	na	na	4	0.084	0.183	0.025
600	16.99	1	0.67	0.03	na	4	0.084	0.183	0.025
400	11.33	1	0.67	0.03	na	4	0.084	0.183	0.025
200	5.66	0.91	0.6	0.02	na	4	0.084	0.183	0.05
82	2.32	0.91	0.6	0.02	na	3	0.084	0.183	0.01
37	1.05	0.91	0.6	0.02	na	3	0.084	0.183	0.01

Q.2 Verification

Verification of model output was performed using available ADCP and Sontek velocity and depth measurements. The Sontek measurements were needed at lower flows where the shallow water depths did not allow for ADCP measurements. Of the data presented below, only the verification at 1.05 m^3/s (cms - Figure Q.3) includes Sontek measurements. In each of the following figures, model output is shown with solid lines and field data collected on-site is shown in dashed lines. With the exception of the 1.05 cms flow (Figure Q.3), all cross-sections are located near the upstream end of the study reach (Figure Q.1). The cross section measured at the 1.05 cms flow was taken at a constriction in the flow further downstream (Figure Q.2). Cross section distances are measured from the left bank looking downstream.

At flows greater than 800 cfs (approximately), a secondary channel forms and diverts flow from the main river channel, and thereby reducing the flows in the northern meander bend (Figure Q.1). Correctly modeling flows above 800 cfs required the inclusion of this channel within the RMA-2 numerical mesh. At lower flows, however, this channel is dry, and was therefore not included in the numerical mesh (Figure Q.2). For model convergence and stability, models with different meshes also had different wetting and drying and marsh porosity parameters (Table Q.2).

The extent to which the model reproduces the field data is demonstrated through qualitative comparisons between the speed and depth measurements and model predictions across each section. Each section follows the field data collection path.

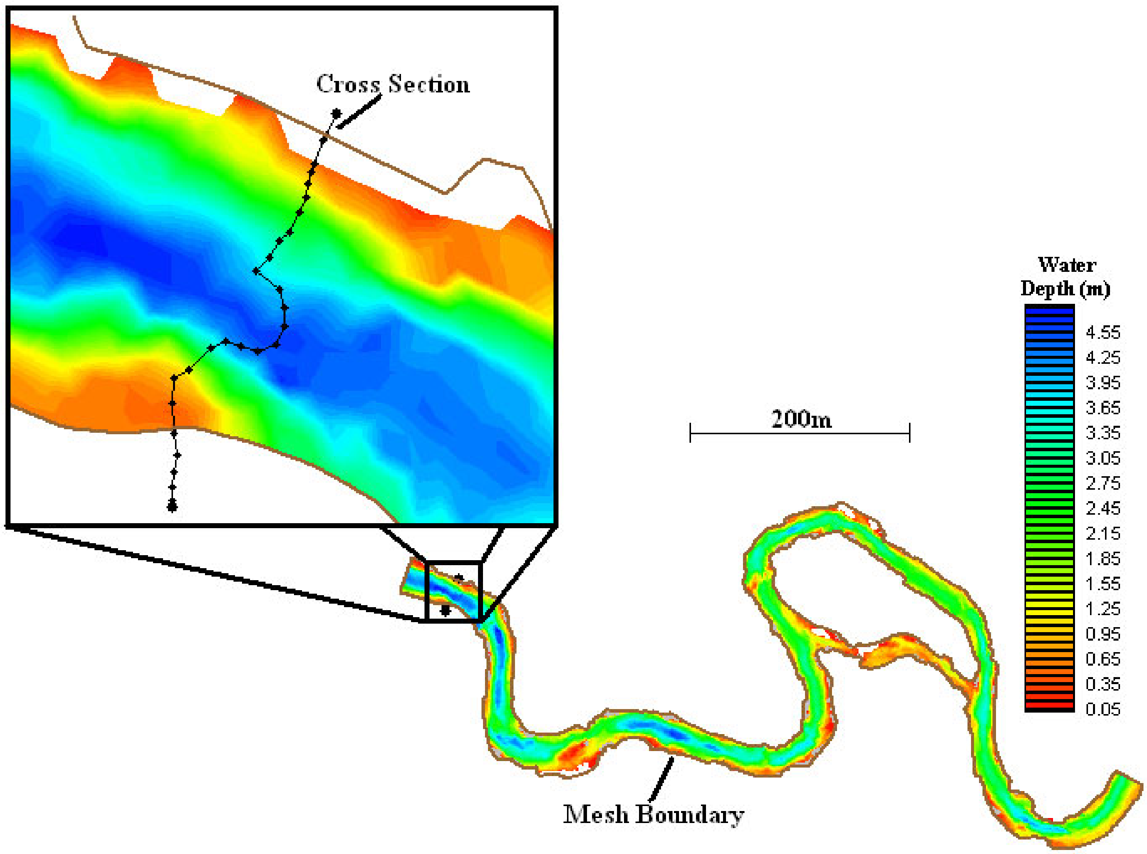


Figure Q.1 – Sulphur River Site #2 Study Area Map Showing Cross-Section Location at 23.53 cms (831 cfs)

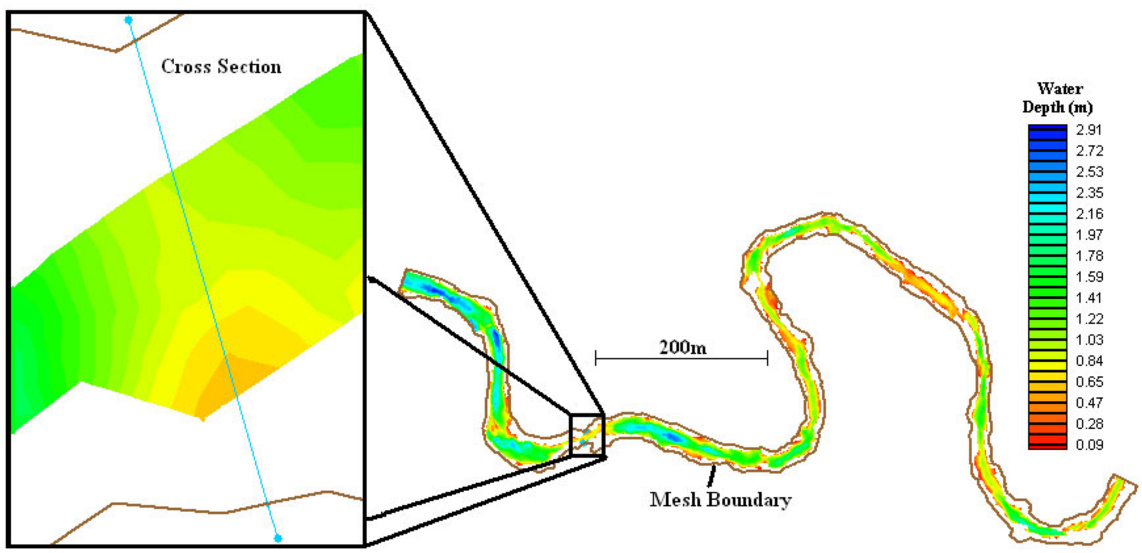


Figure Q.2 – Sulphur River Site #2 Study Area Map Showing Cross-Section Location at 1.05 cms (37 cfs)

Q.2.1 Calculating flow along the boat path

One method of obtaining a quantitative comparison between field and observed data is to compare the modeled and observed flows calculated across each section using equation Q.1:

$$Q = \int_0^X (SH)dx \tag{Q.1}$$

where Q is the flow through the cross section, X is the length of the cross section, S is the water velocity, H is the water depth, and dx is the infinitesimal length between adjacent points along the cross section.

In calculating Q with Eqn. Q.1, S and H are assumed to vary linearly between adjacent measurements along the cross section length. Comparisons between observed and modeled flows are given as percentages of the observed flow:

$$\lambda = \left(1 + \frac{Q_m - Q_o}{Q_o}\right) \times 100\% \\ \therefore Q_m = Q_o \times \lambda \tag{Q.2}$$

where the subscripts "m" and "o" refer to "modeled" and "observed," respectively. The percentage "λ" is given on each figure and the deviation from 100% indicates the cumulative difference between modeled and observed conditions along the section.

As previously noted, the observed cross sections were not taken exactly perpendicular to the river flow (see Figure Q.1), causing X to exceed the actual straight-line distance across the river. Therefore the flow values calculated with Eqn. M.1 will not necessarily agree with those reported for each figure since velocity magnitude perpendicular to the cross-section line were used for the flow calculation; in other words, the flow is exaggerated since the cross-sectional length is exaggerated along the path of data collection. Using the example of a simplified flat-bottomed river as shown in Figure Q.3, flow calculated with Eqn. Q.1 across cross-section #1, which is perpendicular to the water flow, is Q = 67.5 m^3/s. However, the flow calculated on a parabolic cross section (cross-section #2) is Q = 74.38 m^3/s, despite the fact that the actual water velocities have not changed. Because of these potential discrepancies, the actual flow values for observed and modeled cross sections as calculated with Eqn. Q.1 are not shown on the figures.

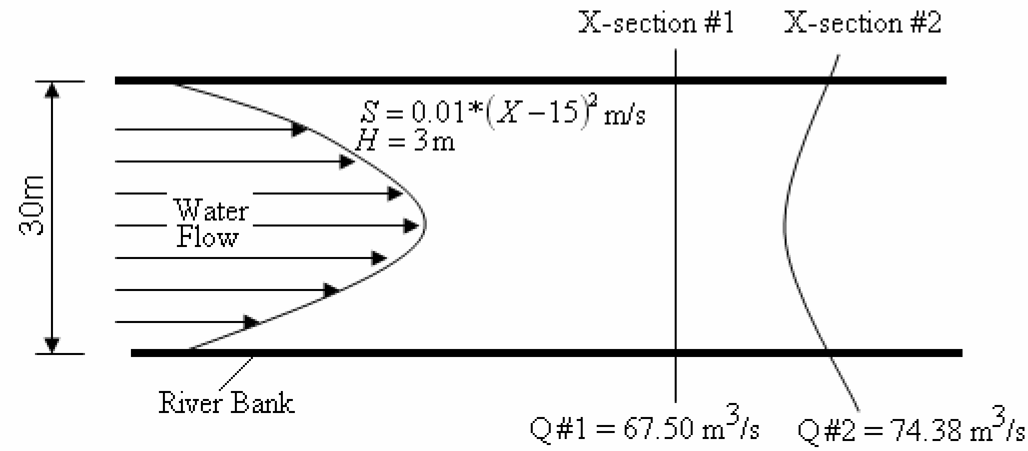


Figure Q.3 – Differences in Calculated Flow Due to Cross Section Orientation

Q.2.2 Discussion of potential sources of error

One unavoidable source of error between observed and modeled data is the fact that the river bathymetry was measured during high flow periods (3510 cfs) using boat mounted echosounding equipment. This allowed for collection of bathymetry data along the river margins, which would be dry land at lower flows. The consequence of measuring bathymetry at high flows is that the data used in creating the finite-element mesh input to the RMA-2 finite element mesh generated from that bathymetry may be different than the bathymetry actually present in the field. In sand-bed rivers, the bathymetry at lower flows is particularly susceptible to change, but the homogeneity of cohesive substrate near this site on the Sulphur River renders this error not significant. The error caused by the discrepancy between flows is not capable of being incorporated into the model at this time since it depends on the rate of change of channel bathymetry due to intermittent flooding and sediment scour, transport and deposition. The depths collected at the cross section locations at the time of the ADCP and Sontek data measurements were used for the verification, and some discrepancy between observed and modeled water depth may be attributable to varying bed conditions over time and over a range of flow rates.

Bathymetry interpolation is a second possible source of error incorporated in the model validation process. The bathymetry data measured with the Knudsen Echo Sounder was interpolated to generate the bathymetric surface used in the RMA-2 finite element mesh. This interpolation was carried out with the use of the MEBAA program described in Appendix G, and may produce a smoother bathymetric surface than that observed with the ADCP and Sontek instruments. Also, to execute the RMA-2 model, the finite element mesh must not contain large bathymetric slopes. In areas where such large slopes exist in the river, the model bathymetry must be artificially adjusted. These adjustments, in some places significant for this site, may cause discrepancies between the modeled and observed bathymetries shown in the following analysis.

Finally, precise coordinates were not available for the ADCP and Sontek velocity measurement locations. When possible, the cross sections created in SMS were drawn to correspond to field notes on measurement locations and on ADCP directional information; however, errors may have resulted from inaccurate locating of cross-sections. Coordinate measurements are recommended for all future flow measurements.

Q.2.3 Comparison of the field data to model output

At 1.06 cms (37 cfs), the Sontek Flowtracker was used for measuring flow at the cross section (Figure Q.4). The cross section was measured downstream of a constriction in the flow, which is an area in which RMA-2 had difficulty modeling accurately (section #6 in Figure Q.8). The modeled bathymetry matched well with that measured, however RMA-2 predicted water velocities 5-10 cm/s greater than were observed. This small error may be attributed to differences between the modeled and observed bathymetry.

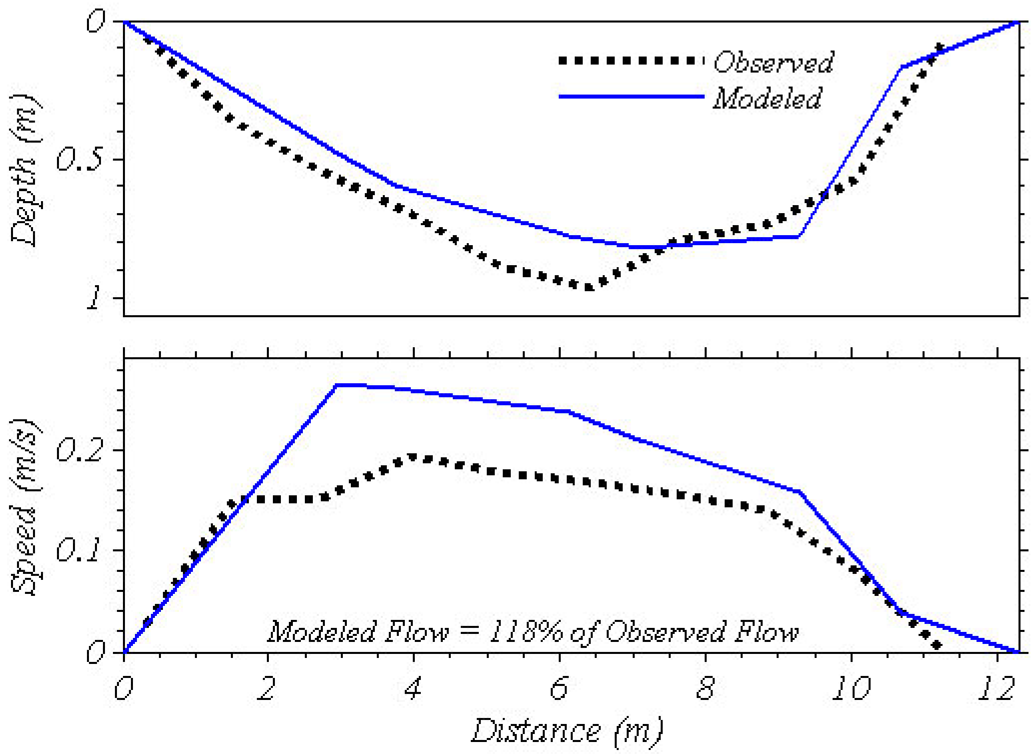


Figure Q.4 – Model verification at 1.06 cms (37 cfs) at Sulphur River Site 2.

At 2.32 cms (82 cfs), depth and velocity measurements were made with the boat mounted ADCP, and the cross section was taken near the upstream end of the study site (Figure Q.1, near section #2 in Figure Q.8). The modeled bathymetry matched well with that measured, however RMA-2 predicted water velocities approximately 4 cm/s less than were observed between 1.5m and 8.5m from the left bank (Figure Q.5). From 8.5m from the left bank all the way to the right bank, RMA-2 over-predicted the water velocities by at most 3 cm/s. RMA-2 was unable to capture the observed velocity variation across the cross-section. This is likely due to the proximity of the section with respect to the model's upstream boundary. At the upstream boundary, the channel is wider and the thalweg is more centered. The short distance between the boundary and the measured cross section in Figure Q.5 was likely insufficient to cause the river curvature to force a larger percentage of the modeled flow toward the left bank. Better results are to be expected if additional length is added to the model mesh for purposes of numerical stability. Despite the inability of RMA-2 to fully reproduce the velocities within the cross section, the flows in the modeled and observed cross sections agree to within 3%.

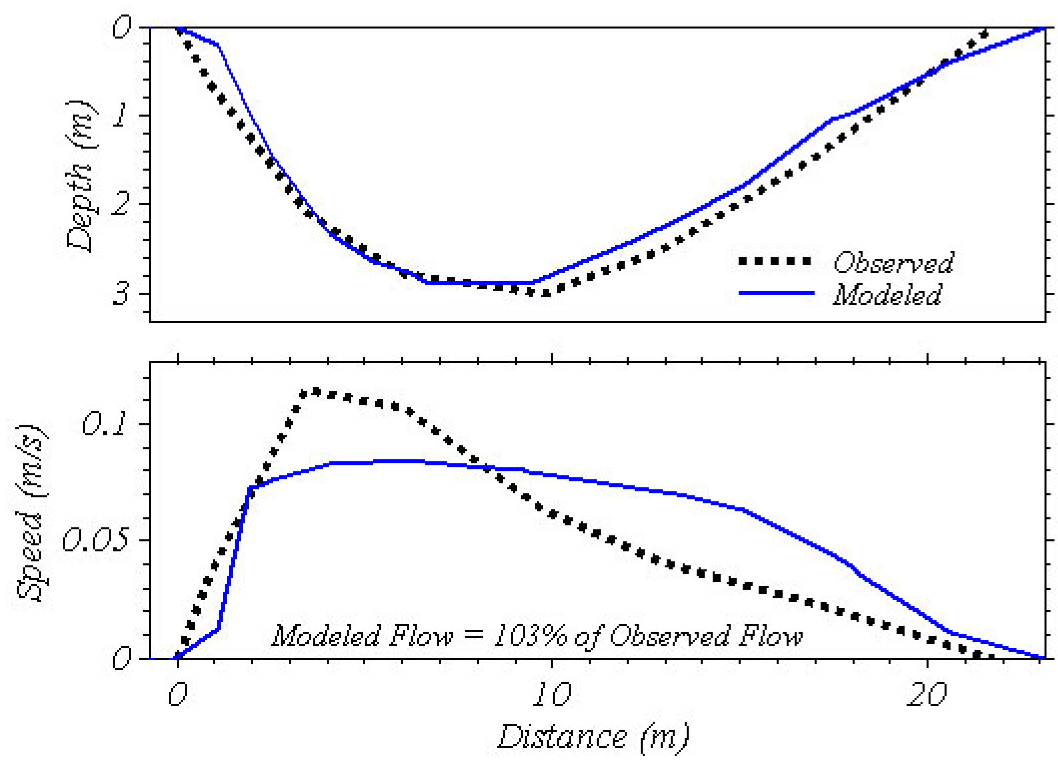


Figure Q.5 – Model verification at 2.32 cms (82 cfs) at Sulphur River Site 2.

At 23.53 cms (831 cfs), depth and velocity measurements were made with the boat mounted ADCP, and the cross section was taken near the upstream end of the study site (Figure Q.1, section #3 in Figure Q.7). The modeled bathymetry matched well with that measured, although it was slightly too shallow near the channel thalweg and left bank (Figure Q.6). As with the 2.32 cms flow (Figure Q.5), RMA-2 predicted nearly uniform velocities across the cross-section width which were generally less than the field observed velocities by 0-10 cm/s; however, the observed increase in velocity toward the left bank was evident. The consistent under-prediction of the observed velocities led the modeled cross section flow to be only 75% of the observed flow.

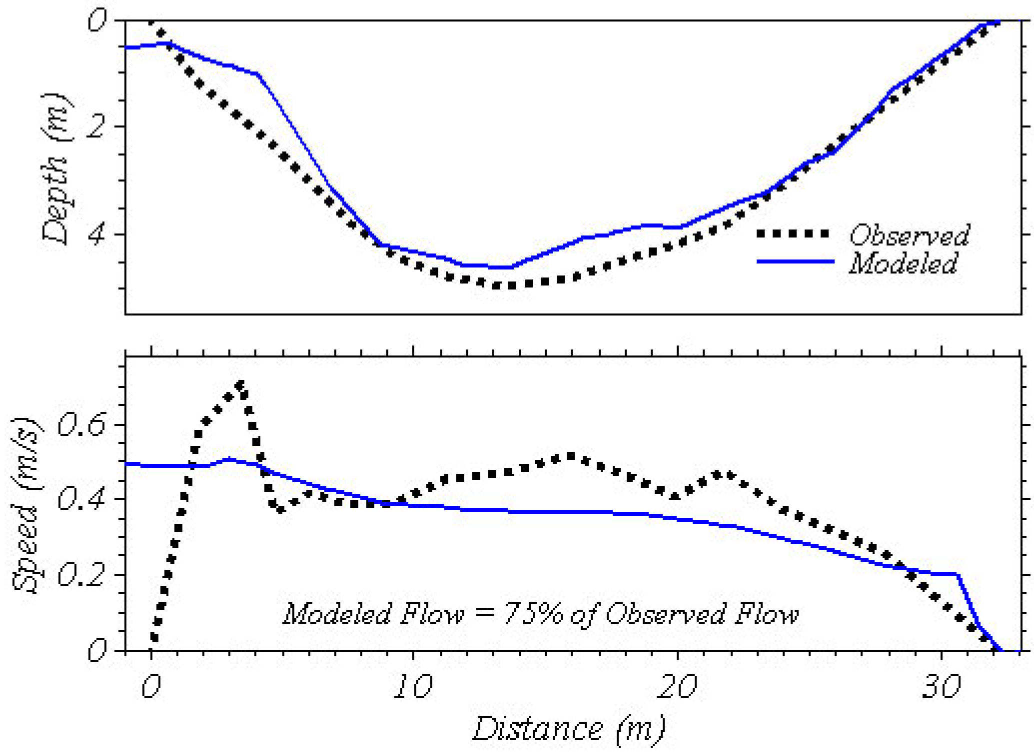


Figure Q.6 – Model verification at 23.53 cms (831 cfs) at Sulphur River Site 2.

Q.3 Model Continuity Verification

Ideally, RMA-2 should calculate velocities that satisfy water mass continuity for each mesh element. Deviations from continuity indicate locations within the finite element mesh where the model is not performing adequately as a result of the governing equations, model discretization (mesh geometry), solution method or, more likely, some combination of all of these factors. Errors in the predicted velocity and depth values at these locations are likely to be large.

RMA-2 performs continuity checks by comparing flows at user-defined sections across the mesh, and by comparing those flows to the flow at the upstream boundary. Numerical model continuity was verified at 15 continuity check points (cross sections) within the study area for flows below 831 cfs (Figure Q.7). At higher flows, 19 continuity check points (cross sections) were used, with check points strategically located around the secondary channel and near its confluences with the main channel (Figure Q.8) within the study area. As shown, continuity check points #1 and #19 are the upstream and downstream boundaries of the study area, respectively. Deviations greater than 5% are shaded (grey) in Table Q.3 and continuity checkpoints and residuals for those sections applicable to figures shown above are shown in bold with a border. Continuity was maintained within the 5% deviation limit for 93.4% of the checkpoints.

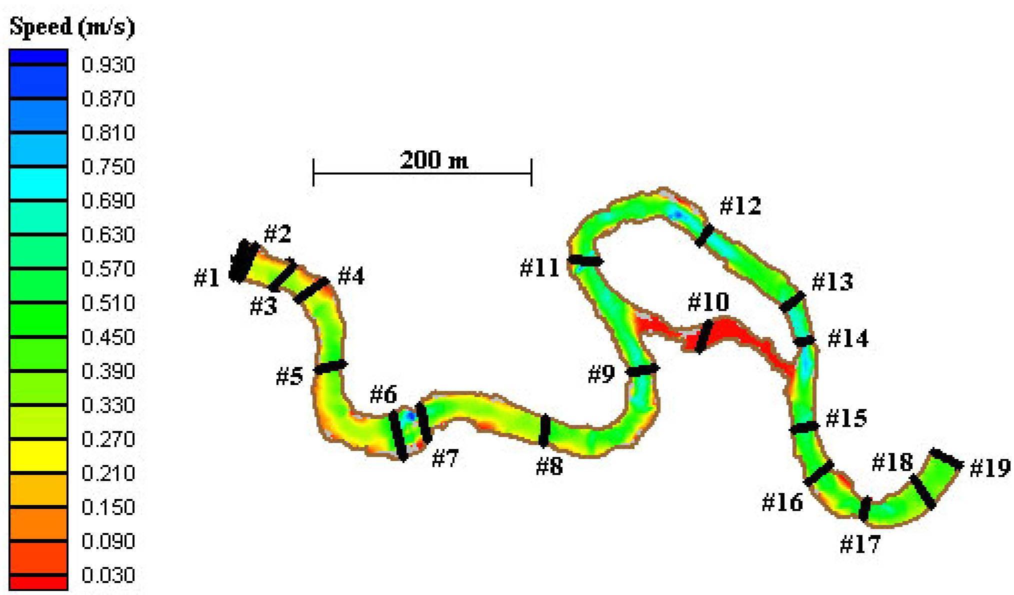


Figure Q.7 – Sulphur River Site #2 Study Area Map indicating locations of continuity checkpoints (black cross sections) for flows greater than 800 cfs.. Numbers refer to the entries in Table Q.3. Speeds shown are for the 23.53 cms (831 cfs) flow.

Continuity deviations occurred in areas where the riverbed is constricted (#6 in Figure Q.8), expanding (#5 in Figure Q.8), and where river bends are rapid (#10 and #14 in Figure Q.8). These areas are difficult to model numerically using RMA-2. The entries highlighted in yellow distinguish checkpoint #10, located along the secondary channel, and those entries highlighted in blue located along main channel between confluences with the secondary channel (for flows greater than 800 cfs). Flow continuity was achieved within these channels, as the sum of the main and secondary channel flows never deviated more than 1.8% from the modeled flows. Based on this analysis, the RMA-2 models of Sulphur River Site #2 were numerically well-posed, and discrepancies between field and observed data are more likely to be due to uncertainties in the model boundary conditions (bathymetry, water surface elevation, roughness and flow) and placement of the field cross sections used in verification.

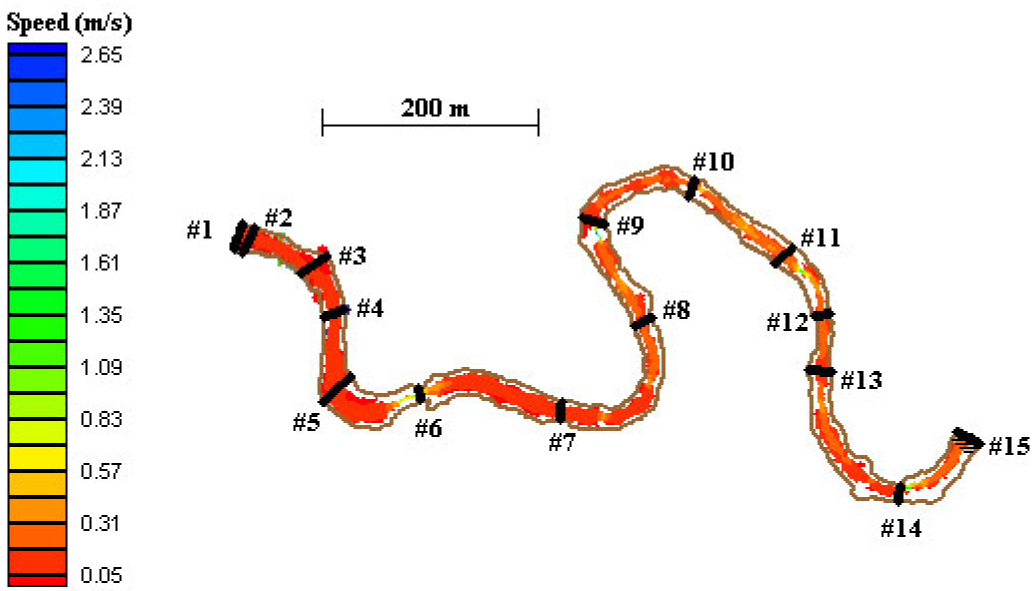


Figure Q.8 – Sulphur River Site #2 Study Area Map indicating locations of continuity checkpoints (black cross sections) for flows less than 800 cfs. Numbers refer to the entries in Table Q.3. Speeds shown are for the 2.32 cms (82 cfs) flow.

Table Q.3 - Percentage Deviation from Flow Continuity at Check Point Cross Sections
(See text for explanation of shading)

Flow Rate

Check Point	cms / cfs	1.05 / 37	2.32 / 82	5.66 / 200	11.33 / 400	16.99 / 600	23.53 / 831	99.39 / 3510
1		0	0	0	0	0	0	0
2		0.3	**-1.2**	-1.4	0	-0.8	0.1	-0.4
3		-2.2	-4	0.1	0.6	1	**0**	-1.2
4		-0.5	-2	-1.3	-2.2	-1.7	-0.9	-0.6
5		1.8	-6.9	-1.5	-1	-1.6	0.5	-0.3
6		14.6	27.6	-2.4	-1.1	-3.3	0.9	0.8
7		-4.1	0.2	-2.2	-0.5	-0.9	2.4	-1.1
8		**-1.4**	-2.4	-0.5	-0.7	0	1.9	-1
9		-1.4	2.2	-7.3	-16.8	1.3	-0.1	0.2
10		-0.9	-16.1	-9	-4.4	-0.9	-99.7	-61.8
11		1.1	-3	1.7	-0.1	-2.8	-1.4	-38.7
12		0	-2.6	-2.5	1	-0.4	-1.4	-39.2
13		0.6	-3.5	-2.6	-0.5	-2.2	0.6	-38.7
14		4.7	-11.9	2.6	-1.2	-0.5	-2.1	-38.3
15		0.9	-1.5	0	-0.5	-0.5	1.1	-0.5
16		<>	<>	<>	<>	<>	-0.8	0.3
17		<>	<>	<>	<>	<>	-0.6	-0.9
18		<>	<>	<>	<>	<>	-1.3	0.3
19		<>	<>	<>	<>	<>	-0.5	-0.3