An Evaluation of Spring Flows to Support the Upper San Marcos River Spring Ecosystem, Hays County, Texas

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Abstract.—The upper San Marcos River spring ecosystem in central Texas is fed by the Edwards Aquifer and provides habitat for a diverse aquatic community. An instream flow study was undertaken to determine the water quantity and quality needs of this spring ecosystem. Instream habitat modeling revealed spatial variation in habitat-spring flow relationships for target aquatic macrophytes. Spring flows between 125 and 200 ft^3/s, of sufficient duration, maintain average habitat conditions for all target species in all study segments. Empirical water quality data indicated a downstream longitudinal trend of increasing temperature in warm months and decreasing temperature during cool months. The temperature model predicted that violations of temperature criteria could occur during hot summer months. Spring ecosystem characteristics which define the upper San Marcos River can only be maintained by a flow regime that consists of normal, less than normal, and greater than normal spring flows concordant with historical duration and frequency, in addition to the full range of peak flows necessary for flushing, scouring, sediment transport, and channel maintenance.

Waters issuing from San Marcos Springs along the Balcones Fault Zone give rise to the San Marcos River within the city limits of San Marcos, Hays County, Texas. The springs are fed by the Edwards Aquifer which extends approximately 180 miles from Kinney County in the west (2000 ft mean sea level [MSL ft]) eastward to Hays County and the San Marcos Springs (574 MSL ft). The aquifer is geohydrologically divided into two segments, the northern (Barton Springs) and southern (San Antonio) segment, which contains the San Marcos Springs (McKinney and Sharp 1995). The aquifer recharge zone lies along the southern and eastern portions of the Edwards Plateau and covers approximately 1101 mi^2 of mostly karst topography (USFWS 1996). San Marcos Springs are the second largest in Texas and have historically exhibited the most constant discharge of any spring system in the southwestern United States, never having ceased to flow within recorded history (Brune 1981).

Uninterrupted habitation of the San Marcos Springs area by Native Americans has been documented from about 9500 BC (Shiner 1983). Use of the upper San Marcos River as a source of irrigation water and as a power source to run mills began in the mid 1800s (Taylor 1904). Spring Lake Dam was constructed in 1849 to run a mill and for irrigation purposes. By 1905 six additional dams, including Rio Vista Dam and Cummings' Dam, had been constructed for various uses. Other activities included dredging, channelization, bank stabilization, construction of diversion canals such as Thompson's millrace and five flood control/recharge structures in the upper San Marcos watershed (USFWS 1996). Currently, the San Marcos River and the Springs are important recreation attractions within the City of San Marcos and are visited by thousands annually (Bradsby 1994).

The San Marcos River provides habitat for a diverse spring flow dependent aquatic community. The foundation of this aquatic ecosystem is the diverse and abundant macrophyte assemblage (Longley 1991). The aquatic community includes common Edwards Plateau species, various introduced species, as well as several endemics which lend evidence that the system is truly unique. Spring flow (hereafter referred to as flow) characteristics include high water clarity and relatively constant flow rates, temperatures, pH, and dissolved ion concentrations (Hannan and Dorris 1970; Ogden et al. 1985; TNRCC 1996; Groeger et al. 1997; Slattery and Fahlquist 1997).

Given the historically stable nature of flow from San Marcos Springs, vulnerability to negative impact is greater than in other aquatic ecosystems accustomed to seasonal changes in water quantity and quality. The Edwards Aquifer remains the principal source and in some cases the sole source of water for a rapidly growing central Texas population and for large metropolitan areas such as San Antonio. Primary threats to the ecosystem include reduction and cessation of flow due to pumping, poor water quality, non-point pollution, habitat modifications, the presence of a multitude of non-native species, impacts due to recreational activities and urbanization of the river corridor (USFWS 1996).

Conservation of the quantity and quality of Edwards Aquifer water emanating from the springs is fundamental to the preservation of this spring ecosystem. In addition, stable flows provide base flows in downstream reaches of the San Marcos and Guadalupe rivers which sustain fish and wildlife resources. When combined, the San Marcos Springs and nearby Comal Springs provide approximately 32% of Guadalupe River base flow to the estuarine environments of San Antonio Bay, Texas, and provide 70% or more of base flow during droughts (GBRA 1988).

The River Studies Program of the Texas Parks and Wildlife Department initiated this instream flow study of the upper San Marcos River in an effort to understand the water quantity and quality needs of the spring ecosystem. Study design was directed at yielding estimates of flow as well as water quality conditions necessary to support and maintain this unique spring run ecosystem. Objectives were to: (1) determine habitat suitability criteria for target species of the aquatic community; (2) develop an instream habitat model that simulates changes in physical habitat in relation to flow; (3) determine how changes in flow relate to suitable habitat for target species; (4) describe trends in water quality from empirical and simulated data sets; and (5) describe flow levels that will conserve and promote the fish and wildlife resources of the San Marcos River.

Historical hydrology.–The period of record used to develop historical hydrology was 26 May 1956 to 30 September 1998 based on daily spring flow data collected at USGS Gage #08170000 (San Marcos River Springflow at San Marcos, TX). Early accounts of the San Marcos Springs describe flow as emerging with sufficient force to form a fountain three feet high and estimates of annual streamflow for the San Marcos River are available as far back as 1892 (Brune 1981); however, records prior to 1916 may not be accurate as they were likely corrupted by various dams and diversions (Guyton & Associates 1979). Other streamflow records collected intermittently by the USGS or estimated by the Texas Water Development Board (TWDB) prior to 1956 have been used to develop a monthly-naturalized streamflow set for the period 1934-1989 (HDR Engineering, Inc. 1993). In addition to incorporating pre-USGS gage data the naturalized flow set includes adjusted flow records for diversions and returns for the period 1956-1988. While Figure 1 indicates that 1939 and 1952 were very dry, the drought of record, which occurred during the summer of 1956, is within the USGS gage flow record.

Monthly median flows (Table 1) exhibit a narrow range (147 to 182 ft^3/s). The long-term mean flow for the period of record is 167 ft^3/s and the long-term median is 157 ft^3/s. Lowest flows occur in the summer months as a result of climatological factors and increased seasonal pumping from the Edwards Aquifer. The lowest flow on record (46 ft^3/s) occurred on 15 and 16 August 1956. Highest spring flows occur in the spring and the highest spring flow on record (451 ft^3/s) occurred on 12 March 1992. Figure 2 shows frequencies of observed flows. The narrow range of flows observed in the San Marcos River is again highlighted by the fact that about 60% of all observed flows were between 118 and 211 ft^3/s.

TABLE 1.—Daily flow (ft^3/s) statistics for USGS Gage #08170000 San Marcos Springs at San Marcos, TX. Based on period of record from May 26, 1956 to September 30, 1998.

Month	Mean	Min	20[a]	Median	80[a]	Max
Jan	163	68	118	152	200	393
Feb	167	65	119	157	200	431
Mar	170	82	118	157	212	451
Apr	170	89	119	162	215	439
May	180	65	127	172	224	421
Jun	190	54	122	182	240	427
Jul	179	48	107	172	231	403
Aug	164	46	114	162	210	353
Sep	155	50	116	152	192	289
Oct	153	59	118	152	193	310
Nov	155	65	118	147	190	316
Dec	160	60	118	147	206	385
All Months	167	46	118	157	211	451

[a] - Percentile

Of 281 major springs in the state, 65 springs have dried up, the vast majority during the 20th century (Ono et al. 1983). Spring systems fed by the Edwards Aquifer account for approximately 55% of the water leaving the Edwards Aquifer, with the remaining 45% removed via pumping (Brown et al. 1992). Pumping from the Edwards Aquifer first began in the late 19th century (Maclay 1989; Ewing 2000). Recharge rates have at times fallen below withdrawal rates causing the Edwards pool level to lower and some spring orifices (such as San Pedro Springs) along the Balcones Escarpment to cease flowing. Given mean annual recharge rates of 600,000 acre-feet (GBRA 1988) it is feared that pumping from the Edwards Aquifer might soon exceed average annual recharge. During the 1956 drought Comal Springs ceased flowing for nearly 6 months and discharge from the San Marcos Springs fell to it's record low. Pumping from the Edwards Aquifer most threatens the San Marcos River spring ecosystem. Projections given current population growth offer only a 50 to 75 percent chance of continuous flow at San Marcos Springs by the year 2020 (USBR 1974).

Peak flows have been altered by five floodwater retention dams built on two creeks (Purgatory and Sink Creeks) which feed the San Marcos River within the city limits (Figure 3).

Water quality.–Waters issuing from the San Marcos Springs are characterized by relatively constant temperatures, pH, and dissolved ion

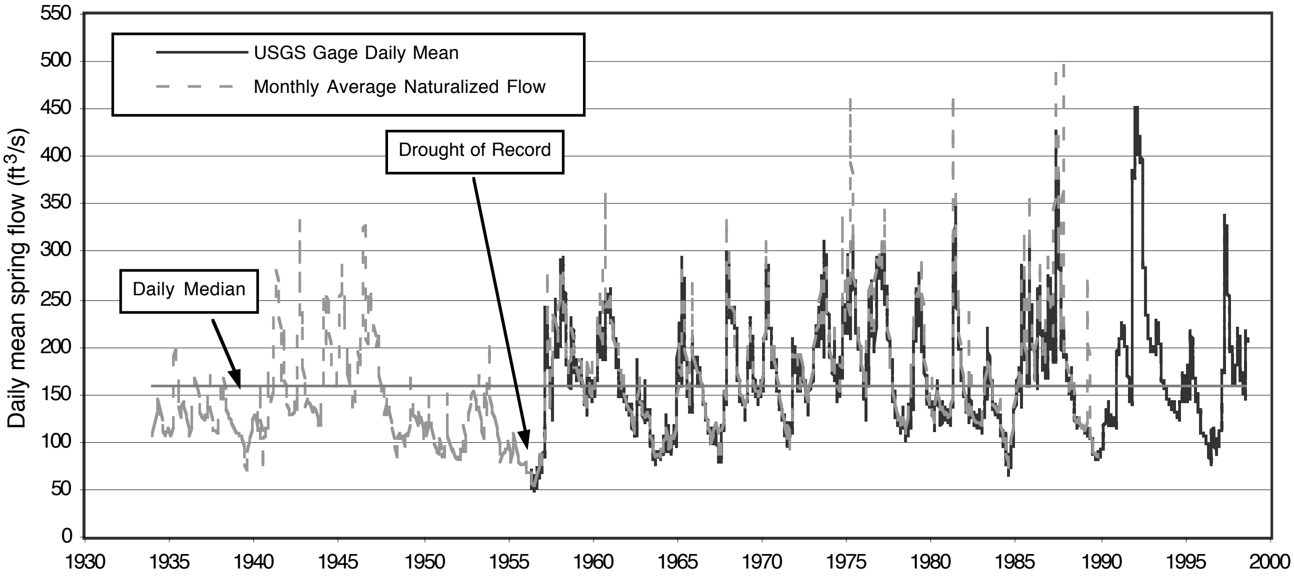

FIGURE 1.—Daily mean flow based on spring flows recorded at USGS Gage #08170000 (San Marcos Springs at San Marcos, TX) for the period of record 26 May 1956–30 September 1998. Monthly average naturalized flows were developed for the period from January 1934–December 1989 (HDR Engineering, Inc. 1993). Daily median equal to 157 ft^3/s based on USGS record.

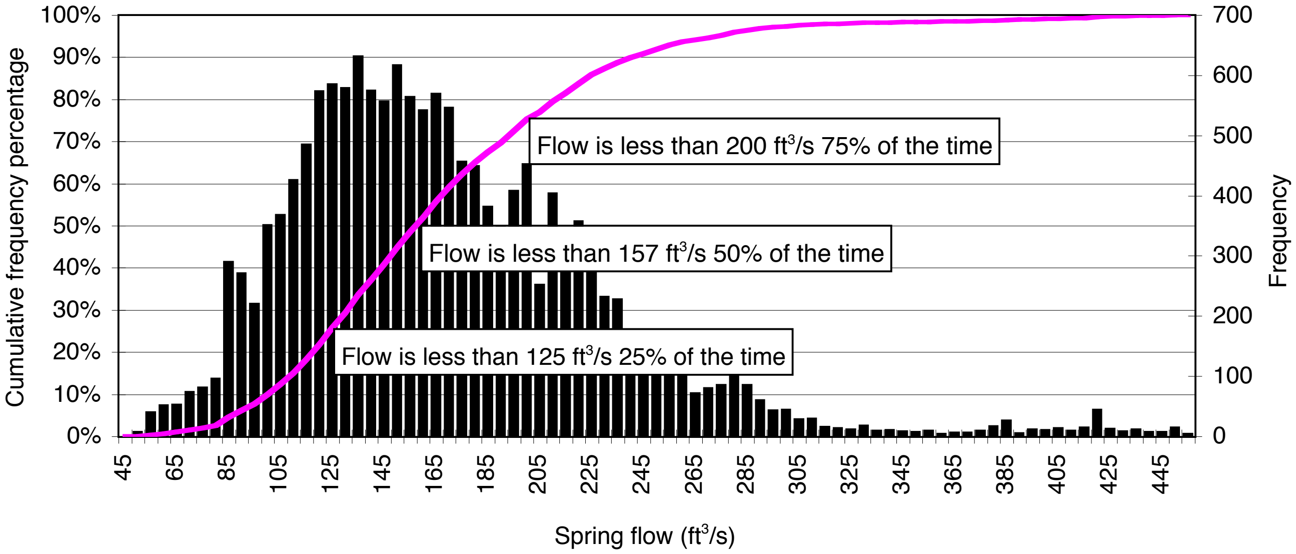

FIGURE 2.—Flow frequencies are based on daily spring flows recorded at USGS Gage #08170000 (San Marcos Springs at San Marcos, TX) for the period of record 26 May 1956–30 September 1998. Bars represent frequency in bins (5 ft^3/s) and solid line represents cumulative frequency percentage. There are 15,468 daily records for this period.

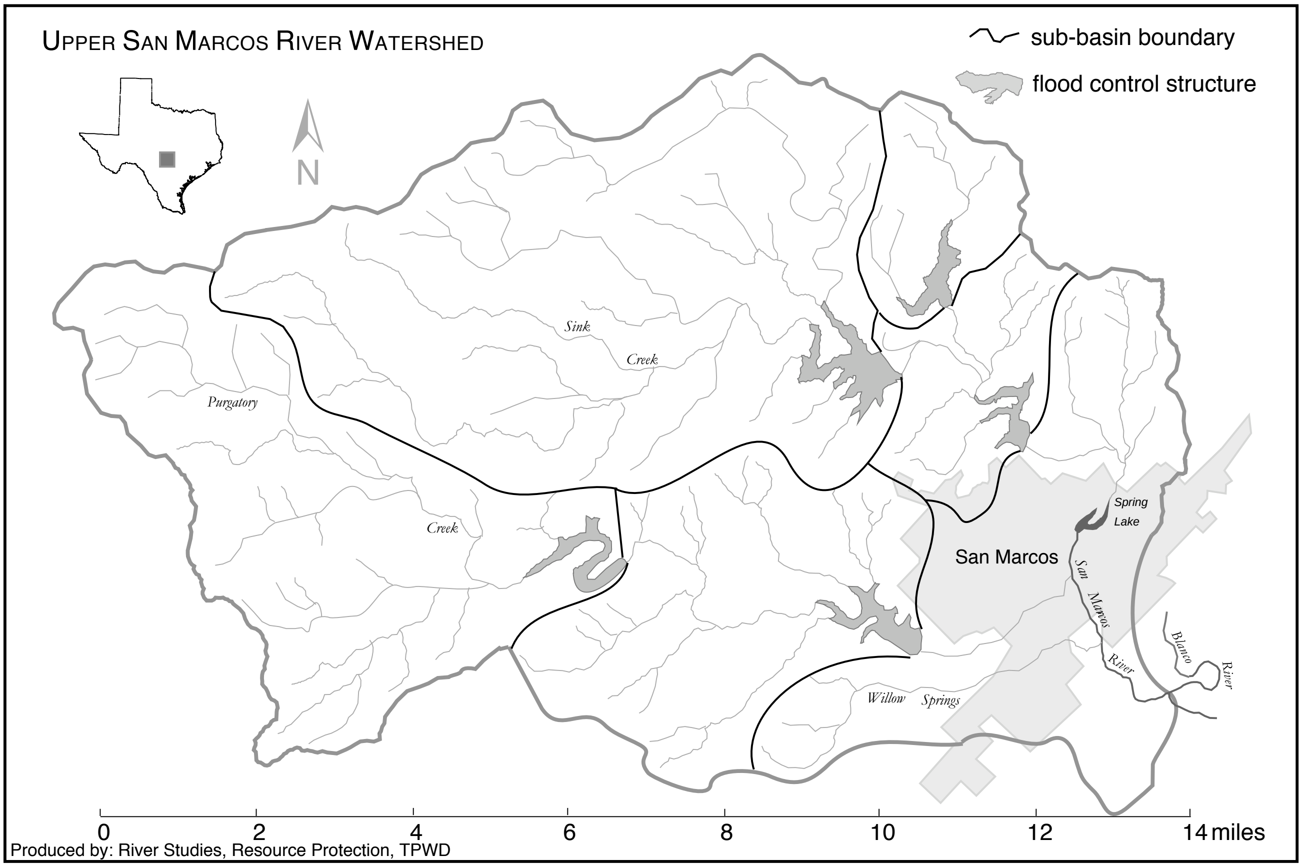

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FIGURE 3.—Watershed of the upper San Marcos River.

concentrations. Water temperatures at the springs average approximately 22°C (Guyton and Associates 1979; Ogden et al. 1985). Temperature variability increases with distance from the springs (Groeger et al. 1997). Spring discharge samples collected in 1984 and 1985 (Ogden et al. 1985) yielded total alkalinity values between 200 and 300 mg/L as CaCO$_3$ with pH values primarily between 7 and 8, conditions which favor stable pH levels in the river downstream. In the upper San Marcos River, median pH in summer 1994 ranged from 7.4 to 7.8 (Slattery and Fahlquist 1997) with higher values noted downstream. At the spring source carbon dioxide (CO$_2$) levels are typically high while dissolved oxygen (DO) levels are depressed (Groeger et al. 1997). DO levels rise rapidly and approach atmospheric equilibrium downstream of Spring Lake as a result of vigorous mixing of water at the spillway (Hannan and Dorris 1970). Downstream from Spring Lake, DO measurements have generally ranged from 7 to 10 mg/L (TNRCC 1996; Groeger et al. 1997; Slattery and Fahlquist 1997). Specific conductance at the springs has generally ranged from 500 to 600 µS/cm (Ogden et al. 1985; Guyton and Associates 1979). Measurements in the upper river for the period 1990-1994 ranged from 444 to 599 µS/cm (TNRCC 1996). Median values during summer 1994 ranged from 577 to 590 µS/cm (Slattery and Fahlquist 1997). Turbidity levels within the upper river are very low, but increase downstream (Groeger et al. 1997). Clear, thermally constant water combined with relatively constant nutrient levels promote an abundant aquatic macrophyte community in the upper river. The aquatic macrophyte community exerts significant effect on DO and CO$_2$ diel variation, and reduces nitrate concentrations (Groeger et al. 1997).

TNRCC designates the upper portion of the San Marcos River (Segment 1814: extending from a point 0.6 mile upstream of the confluence with the Blanco River in Hays County to a point 0.4 mile upstream of Loop 82 in San Marcos) as effluent limited, suitable for contact recreation and to have an exceptional aquatic life use (TNRCC 1995).

Decreased flows are a concern relative to water quality because parameters like water temperature and DO could fluctuate more broadly and significantly reduce the proportion of spring ecosystem habitat in the river. Given the historically stable nature of water quality in the system, spring-adapted species may be adversely affected by wide swings in certain parameters (USFWS 1996). Some have speculated that reduced aquifer levels may result in decreased water quality from intrusion of saline water from the "bad water zone" into the freshwater zone, which directly feeds the springs (USFWS 1996). Decreased flows also magnify concerns about point and non-point source pollution, since the assimilative capacity of the river would be reduced.

Habitat.–Historic accounts of the headwaters of the San Marcos River describe a run-dominated system (Brune 1981; Vaughn 1986). Terrell et al. (1978) described the upper San Marcos River as a rapidly flowing clear river, with firm gravel substrate and many shallow areas alternating with pools. Damming of the river and associated diversions for municipal, industrial and irrigational uses have altered natural hydraulic conditions resulting in loss of run and riffle habitat and an increase in backwater and pool habitat, which are characterized by low current velocity, greater depths and a tendency to accumulate silt. Altered habitat in the lower reach of the upper San Marcos Spring ecosystem is likely due in part to the presence of Cummings' Dam, which has a noticeable physico-chemical effect on the river (Espy, Huston and Associates 1975). Further, the authors stated that flood control structures designed to prevent bank-full flows, when coupled with projected decreases in spring flow, would have a high probability of damaging the aquatic community. The five flood control/recharge dams in the upper San Marcos watershed (Figure 3) have reduced both the intensity and frequency of bank-full events (USFWS 1996) and resulted in increased levels of sedimentation (Wood and Gilmer 1996).

Reductions in flow result in reduced habitat area and altered hydraulic conditions. Long term reductions will result in adjustments in channel morphometry and consequent redistribution of microhabitats (Espy, Huston and Associates 1975). Introduced species, primarily non-native aquatic macrophytes have further altered historic habitat (USFWS 1996).

Biology.–Continuous spring flows, exceptional water quality, moderate temperatures, and an average growing season of 254 days, have over time allowed the diverse aquatic macrophyte community of the San Marcos Springs ecosystem to develop. The macrophyte community provides both forage and cover for fish and other aquatic species. Lemke (1989) reported 31 macrophyte species from the San Marcos spring ecosystem of which 23 are native. *Potamogeton illinoensis* and *Sagittaria platyphylla* were described as dominant species. Of concern is Texas wild-rice (*Zizania texana*), whose population has declined over time and is listed by both state and federal agencies as an endangered species. *Z. texana* has a very limited habitat range and exists world-wide only in the upper portions of the San Marcos River. It is a large perennial aquatic grass adapted to shallow, clear, swift-flowing, and constant temperature water (Emery 1967). At one time the species was abundant and prolific within the upper 2.5 miles of river (Emery 1967) and was a dominant species in the area upstream of Spring Lake Dam during the 1930's and 40's (Watkins 1930; Devall 1940). Annual surveys of areal coverage of *Z. texana* indicate the population is greatly reduced in size compared to historic descriptions (Silveus 1933; Devall 1940; Emery 1967; Beaty 1975; Emery 1977; Terrell et al. 1978; USFWS 1984; Poole and Bowles 1996). Recent floods and dam breaches may have further reduced it's abundance (TPWD observations).

A total of 56 fish species, of which 44 are native, have been reported from the upper San Marcos River (GFCT 1958; Young et al. 1973; Kelsey 1997). Some such as catfish, bass, crappie, and sunfish support sport fishing along the entire San Marcos River. Listed as endangered by the USFWS and the State of Texas are the endemic San Marcos gambusia (*Gambusia georgei*) and the fountain darter (*Etheostoma fonticola*). No San Marcos gambusia have been collected since 1982 and the species is considered extinct (USFWS 1996). Historically fountain darter were found from the spring source to Ottine but currently its' distribution is from the spring source downstream to between the City of San Marcos Wastewater Treatment Plant (WWTP) and the Blanco River confluence (USFWS 1996). Fountain darters utilize habitats with low current velocity and dense aquatic vegetation (Schenck and Whiteside 1976; Linam 1993).

The San Marcos salamander (*Eurycea nana*), San Marcos saddle-case caddisfly (*Protoptila arca)* and the giant river shrimp (*Macrobrachium carcinus*) are of interest given their distribution, population size and susceptibility to anthropogenic impact (USFWS 1996; Bowles et al. 2000).

Introduction of exotic species has exerted significant effect on the system over time and has changed both the diversity and dominance of the macrophyte and fish communities. Species such as *Hydrilla verticillata, Hygrophila polysperma,* and nutria (*Myocaster cypus*) threaten the native aquatic community through foraging, competition, and alteration of habitat and community structure. Displacement of native species by introduced species was noted by Lemke (1989). Of the introduced species, *H. verticillata* was listed as most abundant followed by *Egeria densa*, *Eichhornia crassipes, Myriophyllum brasiliense, Myriophyllum spicatum,* and *Potamogeton crispus* (Lemke 1989). Spring Lake is a source of macrophytes for downstream portions of river and over time has supported a variety of introduced species. Until the early 1960's, Spring Lake was used as a nursery by the aquarium plant industry (Hannan 1969), and various plants such as *H. verticillata, E. densa*, and *H. polysperma* were introduced. Macrophyte control via cutting within Spring Lake has produced clippings of many species, which float downstream and take root, altering community structure in the river. Consequently plant dominance over time has changed dramatically (Watkins 1930; Devall 1940; Hannan and Dorris 1970; Lemke 1989; Lemke 1999), and many native species have reduced distributions as a result of competition with introduced species (Lemke 1989; USFWS 1996). These problems may be exacerbated during extended low flow conditions. Some species, such as the giant ramshorn snail *(Marisa cornuarietis)*, appear to increase in numbers during low flow conditions (Arsuffi et al. 1993). Redistribution of aquatic macrophyte stands due to changing hydraulic and habitat conditions may favor non-native generalist species able to adapt more rapidly. Young et al. (1973) reported that since 1930 approximately 80% of native terrestrial plant species along the river's margin have been replaced by exotic species.

Recreation.—During the early 1900s, swimming facilities on the river, bath houses and the resort at Spring Lake were frequent leisure destinations. The clear, clean and thermally constant water of the San Marcos Springs lends great allure to the San Marcos area and enhances the economic value of recreation. In recognition of the economic value of this resource the City of San Marcos passed the San Marcos River Corridor Ordinance in 1985, which recognizes that “continued economic growth and quality of life of the City is dependent on a pleasing natural environment, quality recreational opportunities and unique natural resources within, and in close proximity to the City...”. The Texas Department of Commerce estimated that tourism generated $30 million in the San Marcos area in 1991 (Wegner 1991).

State and city owned park lands from the headwaters downstream to IH-35 provide uninterrupted access to the river and concentrate recreational use (McCoig et al. 1986). Businesses such as canoe outfitters, tube renters and shuttle services supply many recreational demands. McCoig et al. (1986) reported 25,000 people rented equipment for use on the river in 1985, and Bradsby (1994) reported the Lions Club tube rental alone provided 26,874 rentals during the summer of 1992. Highest recreational use occurred during the early afternoon hours of summer months (Bradsby 1994) and was concentrated in the area from City Park to Rio Vista Dam (McCoig et al. 1986; Bradsby 1994). The placid flow within the city limits offers excellent conditions for beginning water recreationists. The ecosystem provides tremendous opportunities for fishing and nature watching.

Recreational activities have direct and indirect impacts on the San Marcos Springs ecosystem (USFWS 1996). These impacts may be exacerbated under low flow conditions due to reduced water depths. The consequent increase in recreational contact with aquatic macrophytes and substrate disturbance is of concern (Bradsby 1994). Breslin (1997) reported that dogs and boating accounted for the highest percentage of visible damage to *Z. texana*.

Methods

Study area.—The study area encompassed the upper 5.25 miles of the San Marcos River, extending from Spring Lake Dam, downstream to Cummings’ Dam. Instream habitat within Spring Lake does not dramatically change with respect to flow, thus this impoundment was excluded from the instream habitat model. Based on prior knowledge of the system and familiarity with the upper San Marcos River, the study area was subdivided into three segments (Figure 4) for habitat utilization data collection and instream habitat modeling.

Study design.—The study design consisted of two components: an instream habitat model and a water quality element consisting of empirical water quality data and a temperature model. The instream habitat model was developed from hydraulic and physical habitat data collected at representative cross-sections, a hydraulic model, habitat suitability criteria for target species, aquatic macrophyte and mesohabitat mapping, and a physical survey of the study area. English units were chosen as a convention for this study because all field equipment used during the study were designed with English units and published flow records were in English units. The conversion of all units to metric was deemed unnecessary at this time.

Hydraulic and physical habitat data.—Initial surveys of the study area began in April 1993 to identify hydraulic controls and generate rough maps of habitat types. Cross-sections were established in each segment to characterize the hydraulic and physical conditions of representative habitat types. A total of 28 cross-sections were placed within the study reach (Figure 4) and were marked using rebar pins with caps. Cross-section head pins were set on the river right bank (looking downstream) and tail pins were set on the river left bank. Hydraulic data consisted of streambed profile elevations surveyed at stations (verticals) from pin to pin, water surface elevation (WSE) at right and left banks and in the center of the channel when appropriate, and depth and mean column velocity (Marsh McBirney Model 2000 Flow Mate) at each vertical. Substrate at each

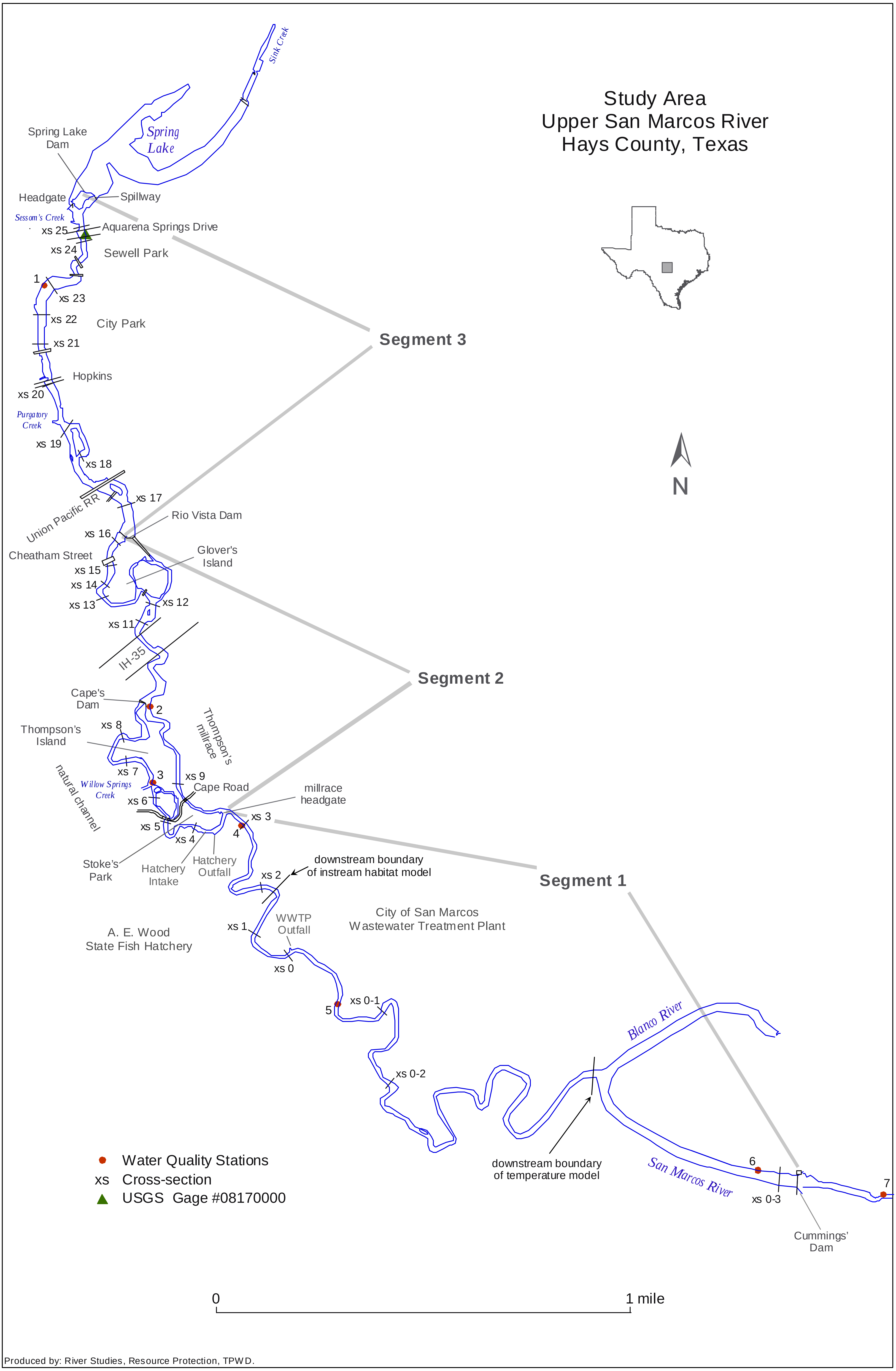

Figure 4.—Study area of the upper San Marcos River.

vertical was characterized using a modified Wentworth substrate scale (Table 2) and classified as either primary, secondary or tertiary based on order of dominance. At each vertical aquatic macrophytes present were recorded. Full sets of hydraulic data were collected at three distinct flow levels: 172 ft^3/s—August 1993; 125 ft^3/s—May-June 1994; and 81 ft^3/s—August 1996. Discharge was measured using a Price AA flow meter and

TABLE 2.—Modified Wentworth scale substrate codes.

Substrate	Letter Code
Organic detritus	DETR
Clay:≤0.004 mm	CLAY
Silt: >0.004 – 0.062 mm	SILT
Sand: >0.062 – 2.0 mm	SAND
Fine gravel: >2 – 4 mm	FGRV
Small gravel: >4 – 8 mm	SGRV
Medium gravel: >8 – 16 mm	MGRV
Coarse gravel: >16 – 32 mm	CGRV
Large gravel: >32 – 64 mm	LGRV
Small cobble: >64 – 128 mm	SCOB
Large cobble: >128 – 256 mm	LCOB
Small boulder: >256 – 512 mm	SBDR
Medium boulder: >512 – 1024 mm	MBDR
Large boulder: >1024 mm	LBDR
Bedrock	BEDR

Hydraulic model.—Cross-sections suitable for hydraulic modeling were calibrated using the IFG4 hydraulic model (Milhouse et al. 1989). This model was used within the Riverine Habitat Simulation Program (RHABSIM Version 2.0, Thomas R. Payne and Associates 1995), which is based on the same algorithms and logical assumptions as PHABSIM (see Milhouse et al. 1989). Hydraulic model input included streambed profile elevations, substrate characterizations, percent of habitat each cross-section represented, SZF, and WSE-discharge pairs and current velocities from three flow levels. WSE-discharge pairs measured at higher flows were available for several cross-sections. Output from the hydraulic model for each cross-section included wetted width (the width of the wetted portion of the cross-section), WSE-discharge relationships, and velocity simulations. WSE-discharge relationships (log/log) and velocities were modeled for unmeasured discharges (50 to 211 ft^3/s for the main channel cross-sections and 25 to 211 ft^3/s for the natural channel cross-sections). Endpoints of the modeled discharges were within the acceptable range of extrapolation for IFG4 (Millhouse et al. 1989). The percentage of stream flow diverted through the millrace and natural channel was inconsistent, thus model results for natural channel cross-sections are presented separately from main channel cross-section results. Current velocity simulations were based on measured velocities from the highest discharge.

Habitat suitability criteria for target species.—Instream habitat analysis focused on macrophytes because they occupy a variety of instream habitats and are important elements in the spring ecosystem. *Z. texana*, *P. illinoensis* and *S. platyphylla* were selected to represent dominant plant associations present in the upper San Marcos River (see Lemke 1999). *Heteranthera liebmannii* and *Vallisneria americana* were selected for evaluation of relatively shallow habitats with high current velocities (e.g., riffle, fast shallow run, etc.). These five species were found in each segment. *Cabomba caroliniana* along with the exotic macrophytes, *H. verticillata*, *H. polysperma*, and *E. densa*, were also evaluated. Although fish observations were made, several problems hindered their utility in the analysis of instream habitat. For example, sample sizes were small, fish fled sampling sites due to extremely clear water when approached, and not all fish could be observed due to the density of aquatic macrophytes at many of the sampling sites. Additional fish data, when available, could be used to complement this study.

To develop habitat suitability criteria for target species, habitat availability and habitat utilization data were collected from 19 March to 2 July 1996 (discharge ranged from 92 to 108 ft^3/s) using a sampling grid (“bio-grid”) comprised of 10 m^2 cells deployed from bank to bank. Each cell was considered an independent sample. A stratified random sampling design was used to determine the location and number of bio-grids deployed in proportion to mesohabitat area in each segment. Locations of bio-grids were determined by generating random numbers to represent upstream distance from the lower boundary of each segment. A total of 43 bio-grids (N = 2055 cells) were used to determine habitat availability and utilization (Figure 5). At the center of each bio-grid cell, physical (substrate and cover) and hydraulic data (depth and mean column velocity) were collected. Aquatic macrophytes were identified and quantified by area occupied using cover class categories (0-5%, 5-25%, 25-50%, 50-75%, 75-95%, 95-100%). Direct fish observations (identification and enumeration) were made when water clarity permitted. Six additional bio-grids (N = 295 cells) were deployed over substantial *Z. texana* stands to collect habitat utilization data for this species (Figure 5) but data from these grids were not used to determine habitat availability.

Habitat suitability criteria were calculated by relating habitat utilization data for *P. illinoensis, S. platyphylla, H. liebmannii* and *V. americana* to the available habitat. *Z. texana* criteria were based on data from the six *Z. texana* bio-grids. Habitat

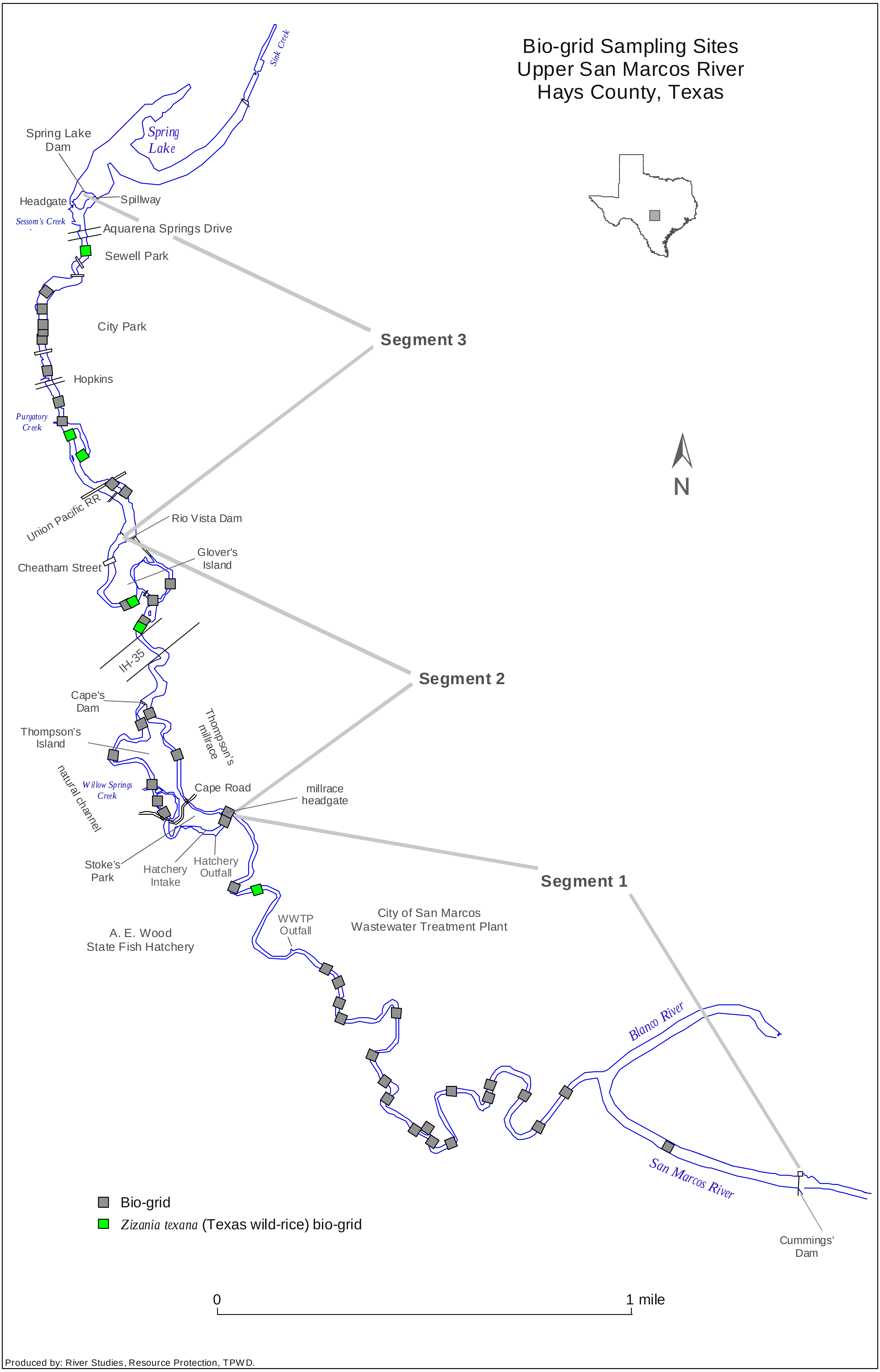

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Figure 5.—Bio-grid sampling sites used for habitat availability and utilization data collection on the upper San Marcos River.

availability was determined by calculating frequency distributions of current velocities, depths and substrates. Suitability criteria for each species were normalized to a scale of 0 to 1.0 (preference index). Because habitat utilization data were collected at flows substantially less than the median, current velocities greater than 0.7 ft/s were not well represented in habitat availability data—85% of current velocities were less than 0.71 ft/s. Thus, additional macrophyte-velocity observations, collected during cross-section surveys at relatively high flows, were used to supplement current velocity utilization and availability frequencies. These supplemented current velocity indices were produced for each target species. Because depth ranges and substrate categories were well represented in the habitat availability data, depth and substrate indices were not supplemented. Finally, idealized habitat suitability curves were generated for use in the instream habitat model. Indices for depth, velocity (preference and/or supplemented) and substrate with values greater than 0.5 were set to 1. Depth and velocity indices with values less than 0.5 were regressed or averaged, when appropriate.

Physical survey.—An extensive physical survey of the study area was conducted during winter 1995 and 1996 in order to take advantage of defoliated vegetation. The extent of the survey was from the headwaters of the San Marcos River (encompassing Spring Lake) downstream to the Westerfield (McGehee) Bridge crossing, located approximately 1.8 miles downstream of the confluence with the Blanco River. Morphometric features included in the survey were river channel boundaries, tributaries, and anthropogenic features such as dams, intake and outfall structures, raceways, bulkheads and spillways. Cross-section head pins and tail pins (survey accuracy was 0.1 foot or less) were tied to a common benchmark elevation. The survey is based on the City of San Marcos local benchmark system (Projection group NAD-83 SP Lambert, Texas plane coordinates, South Central Zone) and was conducted using a Lietz total station, a Sokkia SDR33 electronic field book/data collector and a Topcon auto level. The survey was used to produce an accurate base map of the upper San Marcos River upon which instream habitat and macrophyte distributions were superimposed.

Aquatic macrophyte and mesohabitat mapping.—Aquatic macrophytes were mapped during January to March 1996 in the field using measuring tapes and scale maps. Field measurements were later transferred to the base map. Sparse or small patches of macrophytes were denoted as a symbol and larger stands of macrophytes were located as polygons (see Aquatic Macrophyte Map Set). Macrophyte complexes (i.e., associations of several species) were described according to frequency of occurrence. Seven complexes were identified: *P. illinoensis* complex, *E. densa* complex, *H. polysperma* complex, *C. caroliniana* complex, *H. verticillata* complex, *V. americana* complex, and *S. platyphylla* complex. The composition of macrophyte complexes are described in the Aquatic Macrophyte Map Set. *Z. texana* mapping was conducted during Summer 1995 using a Motorola LGT 1000 GPS unit. Coordinate data were corrected to TXDOT base station datum and overlaid and ground-truthed using the base map.

Mesohabitats were defined as areas with relatively homogeneous physical, hydraulic and biological conditions. Pools were defined as areas of deep, slow-moving water while riffles were areas of shallow, fast-moving water with disruption of the water surface. Runs were defined as areas of moderate depth and current velocity that were not turbulent. Some run mesohabitats were visually classified as deep run, fast run, fast shallow run, slow run and slow shallow run. Backwaters were areas with little or no velocity and found in side channels or sloughs. Plunge pools were found immediately downstream of dams and spillways.

Instream Habitat Model.—Hydraulic model output was coupled with suitability criteria for each species in order to assess changes in usable habitat in relation to flow. At each modeled flow, a composite suitability index was determined by calculating the geometric mean of the three preference indices (depth, velocity and substrate) for each cross-section vertical and then multiplied by the area represented by that vertical to calculate weighted usable area (WUA). WUA calculated for each vertical was then summed for a cross-section total. Cross-section totals were then weighted to account for the mesohabitat area each cross-section represented. By summing the weighted cross-section totals, segment-specific habitat-flow relationships were developed for each of the target species. The natural channel portion of Segment 2 was modeled independently. However, before final relationships were developed each cross-section was evaluated in light of several criteria. These criteria were developed to account for (1) effects of artificial impoundments, (2) areas dominated by dense beds of exotic macrophytes that would preclude colonization of native species and (3) areas limited from habitat use because of the absence of native species.

Habitat time series were produced by coupling %WUA-Q (i.e., WUA relative to gross area vs. flow) relationships with the historical hydrology time series based on a monthly time-step. In order to encompass the full range of historical flows, %WUA-Q relationships had to be extrapolated to 450 ft^3/s.

To establish the general direction of the relationship as flow increased a few data points were modeled beyond the 211 ft^3/s instream habitat model endpoint. Either one or two trend lines were generated for each relationship depending upon how well they fit primary (50 to 211 ft^3/s) and extrapolated (> 211 ft^3/s) data. Trend lines were either based upon logarithmic or polynomial equations. Habitat time series were developed for each target species in each segment but were not generated for the natural channel portion of Segment 2 for aforementioned limitations. A cumulative frequency plot was then generated from each habitat time series to determine the 75th and 25th percentile %WUA frequencies. The 75th percentile was used to identify historical flows that would provide above average habitat conditions which could contribute to the potential for expansion (or increase in biomass/density) of macrophyte stands (i.e., flows that provide relatively high %WUA). The 25th percentile was used to identify historical flows that would provide less than average habitat conditions which could contribute to the potential for contraction (or decrease in biomass/density) of macrophyte stands (i.e., flows that provide relatively low %WUA).

Critical depths for Z. texana.—Depth is an important determinant of survival and growth for *Z. texana* (USFWS 1996; Poole and Bowles 1999). Cross-sections where *Z. texana* was recorded were used in an evaluation of critical depths—defined as those depths at which risk to the survival of individual stands of *Z. texana* increases. The stage/discharge relationship from the hydraulic model was used in conjunction with streambed profile elevations and the distribution of verticals with *Z. texana* present to simulate depths at those verticals for the range of modeled flows. Results of this analysis were then coupled with critical depth criteria to evaluate changes in *Z. texana* habitat in relation to flow. *Z. texana* habitat available at each cross-section was determined by summing the widths of all verticals with *Z. texana* present. The range of critical depth criteria to be evaluated was developed from *Z. texana* habitat utilization data collected during this study and from personal observations of the rapid loss of *Z. texana* (near IH-35) when reduced depths (≤ 0.5 ft) occurred due to two breaches in Cape's Dam (April 1996 and December 1999).

Empirical water quality data.— Water quality data collection was initiated in November 1994 at three sites (Stations 1, 2 and 5) using data loggers, (Hydrolab Corporation), with a fourth site (Station 7) added in December 1995 (Figure 4). Dissolved oxygen, pH, specific conductance and temperature were collected hourly. Data loggers were retrieved once per month for downloading, maintenance, and calibration following guidelines of the manufacturer and TNRCC (1994). A single turbidity sample was collected every two weeks and analyzed using an HF Scientific DRT-15CE Turbidimeter. Three temperature loggers (Onset Stow-away) were subsequently deployed at additional sites (Stations 3, 4 and 6; see Figure 4). Most water quality sites were maintained until May 1997. The water quality stations were chosen to cover the study reach and to reflect changes occurring at different distances from the headwaters (Table 3).

TABLE 3.—Conditions at water quality sampling stations.

Station	Distance downstream from Spring Lake Dam (ft)	Conditions
1	1,466	Run; well mixed from turbulence at Spring Lake Dam
2	8,413	At Thompson's millrace diversion; impounded habitat exposed to sun
3	10,296	Natural channel; shaded; run habitat
4	12,313	620 ft downstream from the A. E. Wood State Fish Hatchery outfall; shaded; run habitat
5	16,048	889 ft downstream of the San Marcos WWTP outfall; heavily shaded; transition from run to pool
6	26,889	In Cummings' Lake near dam; 2,264 ft downstream from the confluence with Blanco River; near bank and shaded
7	29,409	1,830 ft downstream from Cummings' Dam; heavily shaded in fast run

All data were graphed and examined for anomalies resulting from equipment malfunctions, bio-fouling, or tampering. This revealed that DO sometimes drifted during the month-long deployments, a condition that could not be attributed to actual physicochemical changes. This drift sometimes began as early as a week after the sonde was placed in the water. Also, on rare occasions an extremely low specific conductance or improbable temperature value was recorded, presumably due to the instrument being lifted out of the water by a curious recreationist. All such obviously invalid data were deleted before analysis. Retained data, however, covered a variety of conditions, including storm events and drought conditions. Data were analyzed and plotted using Statistical Analysis Systems (SAS) software for personal computers.

Temperature Model.—Water temperature was modeled for a variety of discharges and weather regimes using the USFWS Stream Network Temperature Model (SNTEMP), developed by

Theurer et al. (1984). SNTEMP is a steady state model that predicts daily mean and maximum water temperatures as a function of stream distance and environmental heat flux (Bartholow 1991). The model uses meteorological and hydrological data along with stream geometry inputs to develop predictions, whereas actual stream temperature data are used for validation and calibration purposes (Theurer et al. 1984).

The reach covered by the SNTEMP model extended from Spring Lake Dam to the Blanco River confluence. Empirical data from Station 1 were used as the headwater input to the model. Water temperature for 1995 and 1996 was modeled using hydrological and meteorological data from those years. Empirical stream temperature data from 1995 and 1996 were then used to evaluate model output.

Synthetic flow regimes that were modeled include monthly medians (median flow scenario) and absolute monthly minima (minimum flow scenario). Both scenarios used 1996 water temperatures from Station 1 as a headwater input, that year being the warmer of the two. These hypothetical data sets were modeled with two air temperature regimes, the normal and the 85th percentile daily values, the latter being an attempt to simulate warmer than normal temperatures.

The natural channel and Thompson's millrace downstream of Capes Dam were not evaluated separately. Station 2 was not modeled since the data largely represent Thompson's lake and millrace. Water diversions and effluent discharges from the A.E. Wood State Fish Hatchery were included in the model network along with WWTP discharge data.

Given the system's stability, a monthly time step was used in the modeling, meaning that the model output represents daily water temperatures for an average day within a particular month. Maximum values predicted by SNTEMP were not used, since they did not match well the observed temperatures in the San Marcos River. SNTEMP has limitations in predicting maximum temperatures for reasons discussed by Bartholow (1997). Consequently, daily maximum temperatures in this study were estimated based on linear regressions (by month) between daily mean and maximum water temperatures from empirical data collected during 1995 and 1996.

Meteorological data came from Austin climatological data summaries (NOAA 1995; 1996). Discharge data were obtained from USGS streamflow records. Temperature and flow information for wastewater discharges were obtained from the A.E. Wood State Fish Hatchery and City of San Marcos. Diversions and releases for the hatchery in the synthetic flow scenarios were obtained from a proposed water use plan (personal communication; Todd Engeling, 2000). Stream geometry data were obtained from several sources. Stream widths as a function of flow were taken from cross-sectional data. SNTEMP inputs for shading were based upon field data collected at cross-sections. At each cross section, a clinometer was used to determine the topographic angle to the horizon; a Model A spherical densiometer was used to estimate riparian cover; and a rangefinder and tape were used to estimate the average tree height, crown diameter, and distance from the water's edge. Shade quality was measured with a hand-held light meter and photographic gray card as described by Bartholow (1989).

Results

Segment Description

The most downstream segment (Segment 1) extended 21,809 ft from Cummings' Dam upstream to the confluence of the natural channel and Thompson's millrace. The majority of the segment is influenced by backwater effects from Cummings' Dam which, at a stage of zero flow (SZF), would extend upstream to cross-section 2 (Figure 4). The Blanco River confluence and the WWTP discharge were located in this segment. Upstream of the WWTP, habitat generally consisted of run-type mesohabitats with sand, small gravel, silt and clay substrates and limited instream cover. Aquatic macrophytes were relatively dense; in addition, the only *Z. texana* in the segment occurred upstream of the WWTP. Downstream of the WWTP, deep slow run and pool mesohabitats with clay, silt and sand substrates and significant instream cover (logs, snags, etc.) were common. Macrophytes were generally patchy and sparse due mainly to heavy shading by dense riparian canopy, reduced water clarity and greater water depths. This segment, with it's relatively placid flow, dense riparian canopy and considerable instream cover offers excellent sport fishing for catfish, bass and other sunfish, considerable nature watching opportunities, and is ideal for beginning boaters.

The middle segment (Segment 2) extended, in total, 7,016 ft from the confluence of the natural channel and Thompson's millrace upstream to Rio Vista Dam and was comprised of three portions (Figure 4). The main channel portion of Segment 2 (3,435 ft) is diverted, at Cape's Dam, through Thompson's millrace which is 3,195 ft long yet, most of the river's flow continues down the natural channel (3,581 ft). The main channel portion of Segment 2 consisted of a variety of run, backwater, and riffle mesohabitats with gravel, sand and cobble substrates. Macrophytes were generally patchy but several large dense beds (including *Z. texana*, *C. caroliniana*, and *V. americana*) were present. Pool mesohabitat resulted mostly from backwater effects of Cape's Dam and had sand and clay substrates. *H. verticillata* was very common in this impoundment. This portion of Segment 2 is frequently used for fishing, boating, tubing and swimming. Riparian canopy is relatively limited. The natural channel portion also consisted of a variety of mesohabitats including riffle, run, fast shallow run, fast run, and pool. Shading due to riparian canopy is heavy. With the exception of riffle areas in which sand, gravel and cobble substrates dominated, this portion had mostly combinations of silt, sand, small gravel and some clay. Aquatic macrophytes in the natural channel were mostly sparse or patchy introduced species. *Z. texana* occurred mostly as individual plants in the Stoke's Park area although several plants occurred upstream. The natural channel is a popular recreation destination with fishing and swimming being primary activities. The intake and outfall of the A. E. Wood State Fish Hatchery was also located in the natural channel near its confluence with Thompson's millrace. Thompson's millrace is a man-made canal mostly narrow and deep with slow current and dense *H. verticillata* beds. Tubers often float the millrace pulling out at Stoke's Park.

The upstream segment (Segment 3) extended 4,883 ft upstream from Rio Vista Dam to the Spring Lake Dam (Figure 4). Runs and pools comprised the majority of habitat in this segment and riparian canopy was relatively limited. The upper portion of the segment from Spring Lake Dam through Sewell Park had primarily sand, small gravel and silt substrates. Downstream of Sewell Park the segment had silt, clay and sand as primary substrates with the exception of a small area at City Park and under the Hopkins Street bridge in which sand and gravel were common. Aquatic macrophytes in the segment were diverse and dense. *P. illinoensis* and *Z. texana* formed large stands in run mesohabitats and *E. densa* dominated the impoundment upstream of Rio Vista Dam. The segment is heavily utilized by recreationists (Bradsby 1994) for swimming, tubing, boating and fishing. The area upstream of Aquarena Springs Drive historically was heavily utilized for swimming but is currently closed to the public for safety reasons. Record flooding in October 1998 led to undermining of Spring Lake Dam.

Mesohabitat Description

A refined mesohabitat map that describes general sediment, hydraulic and macrophyte conditions was developed based on surveys conducted from January to March 1996, bio-grid and cross-section data and general field observations. Data were transferred to the base map to facilitate the calculation of mesohabitat areas, refine the instream habitat model and implement the sampling design for habitat utilization data collection.

Segment 1.—Segment 1 was the longest segment and mesohabitats were represented by cross-sections 0-3 through 3. Profile graphs of each cross-section for each round of measurements include channel profile, depth, current velocity, substrate, mesohabitat designation and dominant vegetation types (Appendix I: Figures 1-7). A complete list of aquatic macrophytes observed during cross-section surveys is located in Appendix I: Table 1.

Excluding pool mesohabitat impounded by Cummings' Dam, slow deep runs accounted for 63% of the mesohabitat area in the segment. Slow deep runs were not represented by any cross-section because a large percentage (72%) was influenced by Cummings' Dam backwater during normal flow conditions, supported very few aquatic macrophytes (76% of sampled cells had no vegetation), and was densely shaded by riparian canopy. In slow deep run areas with macrophytes, dominant introduced species were *Colocasia esculenta* and *H. polysperma*. Filamentous algae was the dominant native taxa. Primary substrates were clay, silt, and sand. Runs accounted for 17% of the mesohabitat and were represented by cross-sections 0-2, 0-1, and 1. Substrates were mostly sand, silt, clay, and some fine gravel. In runs the introduced aquatic macrophytes with the highest frequency of occurrence were *H. polysperma, C. esculenta, H. verticillata* and *Cryptocoryne* cf. *beckettii*. Filamentous algae and *H. liebmannii* had highest frequencies of occurrence among native taxa. Fast run mesohabitat accounted for 11% and was represented by cross-sections 2 and 3. Substrates were primarily sand, small gravel, silt, and clay. Introduced macrophytes included *H. verticillata* and *H. polysperma*. Natives included *Z. texana*, *V. americana* and *H. liebmannii*. Fast shallow run represented <2% of mesohabitat and was represented by cross-section 0. Introduced *C.* cf. *beckettii* and *H. polysperma* comprised most of the macrophytes in this mesohabitat type. Substrates were a mixture of gravels. Pool (7%), riffle (<1%) and backwater (<1%) mesohabitats were not represented by cross-sections in this segment.

Segment 2.—Mesohabitats in this segment were represented by cross-sections 4 through 16. Profile graphs for each cross-section are included in Appendix I: Figures 8-19. Macrophyte density was greater and more widespread in this segment than in Segment 1. Excluding the natural channel from area calculations, pools accounted for 31% of mesohabitat area and were represented by cross-section 12. Pool mesohabitat area in this segment is large as a result of the pool habitat created by Cape's Dam. Substrates were primarily silt, sand, and clay. Common vegetation types were filamentous algae and *C. caroliniana* among native species, and *H. verticillata* and *H. polysperma* among introduced species. Run mesohabitat accounted for 20% of area and was represented by cross-sections 11 and 14. Primary substrates were sand and silt with some gravel. common non-native macrophytes were *H. verticillata*, *H. polysperma* and *C. esculenta*. Among native taxa, filamentous algae, *Z. texana* and *V. americana* were most common. Slow deep run mesohabitat covered 19% of the area, was represented by cross-section 9 and occurred primarily in Thompson's millrace. Dominant substrates were silt and sand. *H. verticillata*, *H. polysperma* and *C. esculenta* accounted for most of the vegetation. Among native taxa, filamentous algae was common. Backwater mesohabitat occupied 11% of the area, primarily in the slough at Glover's Island. No cross-sections were placed to represent this mesohabitat since it mostly occurred in a side channel. Silt was the dominant substrate type. Among native macrophytes, *C. caroliniana*, *Pistia stratiotes*, and *Nuphar luteum* occurred most often, while among introduced species *C. esculenta* and *H. polysperma* dominated. Fast run mesohabitat accounted for 5% of the area and was represented by cross-section 15. Dominant substrates were sand and mixed gravel. Among native aquatic macrophytes were *Z. texana* and *V. americana.* Introduced species included *H. verticillata*, *H. polysperma*, and *C. esculenta*. Riffle mesohabitat occurred in 3% of the area and was represented by cross-section 16. Dominant substrates were mixed gravel, sand and cobble. The area was not densely vegetated, with only sparse filamentous algae, *H. liebmannii*, *H. verticillata* and small beds of *V. americana* present. Fast shallow run mesohabitat accounted for slightly less than 2% of mesohabitat areas and was represented by cross-section 13. Primary substrates were sand, mixed gravel and bedrock. Native vegetation included *Z. texana*, filamentous algae, and *V. americana*. Among introduced macrophytes were *H. polysperma*, *H. verticillata*, and *C. esculenta*. Deep run mesohabitat accounted for 6% of mesohabitats and was originally represented by cross-section 10; however, the cross-section was dropped from the study after sewage line construction destroyed the head and tail pins and altered the channel. This mesohabitat type had mostly clay, sand, and silt substrate and with dense *H. verticillata* beds. Plunge pool below Rio Vista Dam accounted for the remaining 3% of the area.

Natural channel portion of Segment 2.—Twenty one percent of the natural channel was run mesohabitat and was not represented by cross-sections. Dominant substrates were silt and sand. *H. verticillata* and *C. esculenta* were the most commonly encountered introduced aquatic macrophytes. Among native macrophytes *N. luteum luteum* was most common. Pool mesohabitat was represented by cross-section 8 and accounted for 20% of area. Primary substrates were silt, sand, and clay. *H. verticillata*, *H. polysperma*, and *C. esculenta* were common. Fast shallow run mesohabitat accounted for 18% of area and was represented by cross-section 7. Sand and gravel were the primary substrates. *H. verticillata*, *C. esculenta*, and *H. polysperma* were the most common introduced macrophytes while *Z. texana*, filamentous algae, and *H. liebmannii* were most common among natives. Riffle mesohabitat accounted for slightly less than 17% of area and was represented by cross-sections 5 and 6. Primary substrates were gravel, cobble, and sand. Native filamentous algae and *Amblystegium riparium* were common. Among introduced species, *H. verticillata* and *C. esculenta* occurred most often. Fast runs accounted for 15% of mesohabitats and were represented by cross-section 4. Primary substrates were sand and gravel. Filamentous algae, *V. americana*, and *Justicia americana* were common native taxa. Among introduced macrophytes *H. verticillata*, *H. polysperma*, and *C. esculenta* had the highest frequencies of occurrence. Fast deep run mesohabitat accounted for 9% of area but was not represented by any cross-section. Gravel and sand were primary substrates. Native filamentous algae, *Amblystegium*, *Z. texana*, and *H. liebmannii* were more common than introduced macrophytes most common of which was *H. verticillata*. The remaining portion of the natural channel was comprised of plunge pool below Cape's Dam which accounted for 1% of the area.

Segment 3.—Mesohabitats in this segment were represented by cross-sections 17 through 25. Profile graphs for each cross-section are included in Appendix I: Figures 20-28. Run mesohabitat accounted for 25% of the area and was represented by cross-section 23 and 24. Primary substrates were silt, sand, gravel and clay. Aquatic macrophytes were diverse with large areas of *P. illinoensis*, *S. platyphylla*, and *Z. texana* present. Among introduced species *H. polysperma* occurred most often. Fast run mesohabitat accounted for 19% of the area and was represented by cross-section 21. Primary substrates were sand and silt. Native *P. illinoensis*, *S. platyphylla*, filamentous algae, and *Z. texana* were more common than introduced species among which *H. polysperma*, *H. verticillata*, and *C. esculenta* had highest frequencies of occurrence. Pool mesohabitat accounted for 18% of the area, in large part due to the impoundment created by Rio Vista Dam. Cross-section 17 represented pool mesohabitat which had mostly silt and sand substrate. *H. verticillata*, *H. polysperma*, *E. densa*, and *C. esculenta* occurred more often than any other taxa. Filamentous algae, *S. platyphylla*, and *C.*

caroliniana were the most common native taxa present. Slow run mesohabitat accounted for 16% of the area and was represented by cross-sections 18 and 22. Primary substrates were silt, sand and gravel. The most common macrophytes were introduced species, primarily *E. densa*, *H. polysperma*, and *H. verticillata*. Native macrophytes included *P. illinoensis* and *C. caroliniana*. Some *Z. texana* was present. Slow shallow run accounted for 4% of mesohabitats and was represented by cross-sections 19 and 20. Primary substrates were sand, silt and clay. Native taxa included *Z. texana*, *S. platyphylla*, *P. illinoensis*, and filamentous algae. Introduced macrophytes included *H. verticillata*, *H. polysperma*, and *C. esculenta*. Fast shallow run accounted for < 1% of mesohabitats and was represented by cross-section 25. Primary substrate was sand and gravel. Common native taxa were filamentous algae, *Hydrocotyle umbellata*, *P. illinoensis* and *Z. texana*. Among introduced species, *H. verticillata*, *H. polysperma* and *C. esculenta* were most common. Of the remaining mesohabitat areas, deep run accounted for 13%, backwater for nearly 3%, riffle for < 1%, plunge pool for < 1% and unclassified areas for 1%. None of these areas were represented by cross-sections.

Hydraulic Models

Wetted width, which decreases with declining discharge, may be used as a measure of habitat available for use by aquatic biota. Depending on the bottom profile and the stage/discharge relationship the amount of change varies. For example, in stream channels with sloping edges (see Appendix I: Figure 24) the wetted width and resulting area of available habitat can change significantly with changes in discharge. In contrast, wetted width changes little as discharge is varied in stream channels with vertical walls (see Appendix I: Figure 27). Wetted width data from pool, run (all types), and riffle cross-sections were averaged and normalized to long-term median values (at 157 ft^3/s) to provide a general characterization of the effect of discharge on the amount of each mesohabitat available. Separate analyses were conducted for the main and natural channel cross-sections. Figure 6 illustrates the effect of discharge on wetted width for main channel pool, run, and riffle mesohabitats (all three segments combined). Run habitat showed nearly immediate but gradual reductions in wetted width as discharge was reduced to 100 ft^3/s. However, as flows were reduced to 50 ft^3/s, more than a 10% reduction in wetted width in run mesohabitat was observed. Riffles exhibited an abrupt decline in wetted width at discharges less than 100 ft^3/s and at 50 ft^3/s wetted width was reduced by 25%. Change in pool habitat exhibited a relatively gradual decline with discharge and about 95% of pool habitat remained at 50 ft^3/s. Changes in wetted width in relation to discharge reflected different patterns in the natural channel (Segment 2; Figure 6). Riffle and pool habitats exhibited little change in wetted width down to 25 ft^3/s (2.8% and 1.3% reductions relative to 140 ft^3/s). Riffles and pools simulated in the natural channel had relatively vertical walls; thus, wetted width was not expected to substantially change. However, wetted widths in run mesohabitat were reduced by 8% at 25 ft^3/s.

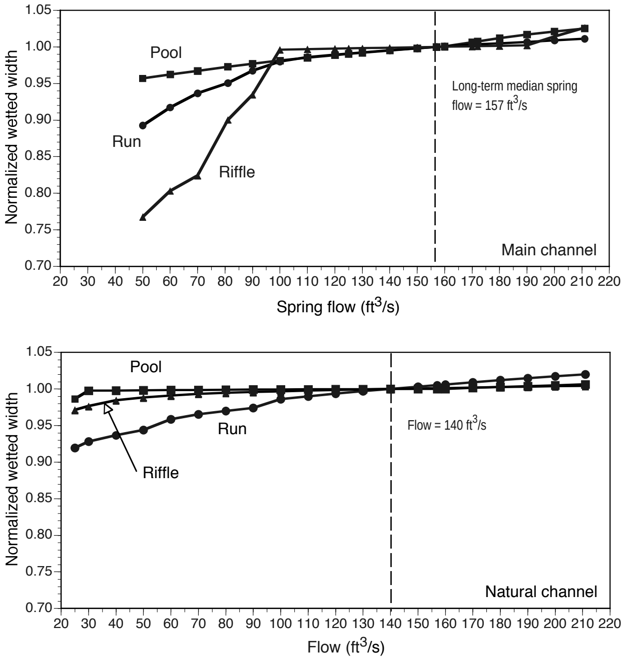


FIGURE 6.—Normalized wetted width in pool, riffle, and run mesohabitats in relation to discharge in the upper San Marcos River. Data based on all modeled cross-sections in the main channel (upper) and in the natural channel (lower). Main channel wetted width normalized to long-term median spring flow (1956-1998). Natural channel wetted width normalized to 140 ft^3/s.

Modeled velocities produced reasonable simulations based on evaluation of velocity adjustment factor curves (a diagnostic tool available in RHABSIM and PHABSIM) and in comparison to measured velocity sets. In some cases such as in deep pools, cross-sections with variable backwater effect, or where vegetation was extremely dense, simulations were not as accurate. Given the limited range of flows available to calibrate velocities and the necessity to maintain accurate depth simulations because of the abundance of sensitive shallow water habitats WSE was not adjusted to alter velocity simulations.

Macrophyte Data Summaries

Based upon the 43 bio-grid samples, 17 native and 7 introduced macrophyte species were identified during this study (Appendix II: Table 1).

Watkins (1930) described 21 aquatic macrophytes in the upper San Marcos River, his list notably did not include the exotic macrophytes, *E. densa, H. verticillata* and *H. polysperma*. Hannan and Doris (1970) documented 19 species and by this time *E. densa* was well established in the system. Brunchmiller (1973) documented 27 species, which included *E. densa*. Espy, Huston and Associates (1975) found 22 species of aquatic macrophytes including both *E. densa* and *H. verticillata.* In 1989, Lemke found 31 species of aquatic macrophytes which included all of the non-native species listed above. In addition, Angerstein and Lemke (1994) reported the occurrence of the introduced macrophyte *H. polysperma*. Native species documented by these previous researchers but not found in this study include *Najas guadalupensis*, *Potamogeton nodosus*, *P. pectinatus, Zannichellia palustris*, among others.

The 43 bio-grid samples indicate that among native taxa *H. liebmannii* and filamentous algae were found in more mesohabitat types than any other native taxa (Appendix II: Table 1). Among species of limited distribution were *Justicia americana*, and *Myriophyllum* spp.. *Z. texana* was found within six different mesohabitats and most often in run and fast runs. This same pattern was observed in the six *Z. texana* bio-grids sampled (Appendix II: Table 2).

Run type mesohabitats exhibited the highest species richness (23 species) followed by pool mesohabitat (19 species). Eleven species were observed in riffle mesohabitat while backwater mesohabitat only yielded nine (Appendix II: Table 1).

Within the 43 bio grids sampled *H. polysperma* had the highest frequency of occurrence of any species and was present in 40% of sampled cells. Using 40% as the highest frequency of occurrence possible, a scale was developed to categorize each species in terms of frequency of occurrence. Species that occurred in 4% or less of the sample cells were considered to have a “low” frequency of occurrence, those which occurred in more than 4% but less than 20% were considered to have “moderate” frequencies of occurrence, and species which occurred in 20% or more of sampled cells were considered to have “high” frequency of occurrence (Appendix II: Table 3). This scale reflects only the likelihood of occurrence of particular taxa and does not reflect areal coverage or abundance.

In the 43 sampled biogrids, 11 macrophytes were found in association with *Z. texana* (Appendix II: Table 3). These included seven native and four introduced taxa. *H. verticillata* was found in association with *Z. texana* in 73% of sample cells and largely mirrored *Z. texana* cover class. Filamentous algae was found in association with *Z. texana* in 66% of sampled cells, *H. polysperma* in 50%, and *P. illinoensis* in 34% and decreased in density as *Z. texana* density increased.

P. illinoensis was found in association with *S. platyphylla* in 87% of cells sampled, but *S. platyphylla* associated with *P. illinoensis* in only 32% of cells. *H. polysperma* occurred in 77% of cells containing *S. platyphylla* (Appendix II: Table 3). *H. liebmannii* associated mostly with *H. polysperma, H. verticillata,* filamentous algae and *P. illinoensis*. *V. americana* was found in association with *H. polysperma, H. verticillata* and *P. illinoensis* in most cells.

In the six *Z. texana* bio-grids sampled, 14 macrophytes were found in association with *Z. texana* (Appendix II: Table 4) of which nine were native and five were introduced. *H. verticillata* was found in 70% of sample cells containing *Z. texana*, and it's vegetative cover class tended to mirror those of *Z. texana*, decreasing only slightly as *Z. texana* cover increased. *H. polysperma* was found in 61% of cells containing *Z. texana*, filamentous algae in 37%, and *P. illinoensis* in 24%; as *Z. texana* cover class increased the cover class for these taxa decreased.

Fish Data Summary

Past comprehensive fish surveys have listed more than 50 species from the upper San Marcos River (GFCT 1958; Young et al. 1973; Kelsey 1997). Twenty-eight fish species were observed in this study. Observations were made in 1,689 bio-grid cells; fish were observed in 600 cells (Appendix II: Table 5). *Gambusia* spp. (*G. affinis* and *G. geiseri*) and *Notropis volucellus*, among native species, occurred in the highest number of mesohabitats (nine & eight, respectively) and were also the most numerous. *Lepomis auritus* and *Astyanax mexicanus* were the most ubiquitous introduced species occurring in eight and six different mesohabitat types, respectively, and were the most numerous introduced species. Slow run mesohabitat exhibited the highest percentage of cells in which fish were observed (75%; Appendix II: Table 5). Run and pool mesohabitats exhibited the highest species richness as well as a high native composition. Fast deep run mesohabitat exhibited the highest percentage of native species (83%).

Suitability Criteria

Habitat availability, from which habitat suitability criteria were derived, is illustrated in Appendix III: Figure 1. Only criteria for *Z. texana*, *H. liebmannii, V. americana*, *S. platyphylla*, and *P. illinoensis* were used in the instream habitat analysis. Poole and Bowles (1999) reported that *Z. texana* was found primarily in shallow water habitat (< 3.3 ft). *Z. texana* tends to accrue silt around the basal growth as stands become more dense, causing observations that *Z. texana* root in silt; however, substrates utilized by *Z. texana* in their study consisted of coarse to coarse-sandy soils based on core samples taken near individual plants. Habitat preferences of *Z. texana* (Appendix III: Figure 2) based upon bio-grid sampling compared reasonably well with their findings for depth and substrate. For *Z. texana*, the greatest preference indices in depth utilization occurred in a range from 0.76 to 3.0 ft. Substrate preferences included sand, and fine to small gravel (roughly equivalent to coarse to coarse-sandy soils) based on visual observations. The greatest velocity preferences in our study occurred in a range from 0.41 to 1.50 ft/s and supplemental velocity indices were greatest in a range from 0.21 to 2.00 ft/s.

Although found in a variety of habitats, *H. liebmannii* exhibited the highest preferences for moderate depths, high velocities, and mainly gravel substrate (Appendix III: Figure 3). *V. americana* had highest preferences for fairly shallow water, moderate to high velocities, and sand and small gravel substrates (Appendix III: Figure 4). *S. platyphylla* (Appendix III: Figure 5) exhibited highest preferences for moderate to deep water with current velocities up to 1 ft/s over silt, sand, and gravel substrates. *P. illinoensis* (Appendix III: Figure 6) showed greatest preferences for moderate to deep water with current velocities up to 2.5 ft/s over mainly silt and sand substrates.

C. caroliniana, *H. verticillata, H. polysperma* and *E. densa* had preferences for a broad range of depths and/or velocities and were typically found in silt. *C. caroliniana* showed little depth preference and was commonly observed at all depths but did show preferences for very low current velocity (0.0-0.1 ft/s) (Appendix III: Figure 7) and for silt sediments. *H. verticillata* (Appendix III: Figure 8) and *H. polysperma* (Appendix III: Figure 9) occurred over a broad range of depths and velocities. *H. verticillata* utilized nearly all substrate types. *E. densa* also showed little depth preference, and was widely distributed across all depths. *E. densa* showed strongest preferences for slow velocities (up to 0.5 ft/s), and silt sediments (Appendix III: Figure 10). Because these species showed little habitat selectivity for measured variables, they were not considered appropriate target species for instream flow evaluation.

Instream Habitat Model

The instream habitat model consisted of hydraulic model output and suitability criteria for the five target species. Habitat-flow relationships (i.e., %WUA vs. flow) were independently developed for each segment and the natural channel portion of Segment 2. The instream habitat model was refined by removing eight cross-sections. Three cross-sections (0-3, 9 and 18) were removed because of hydraulic considerations (e.g., insufficient range in WSE-discharge relationships). Four cross-sections in Segment 1 (0-2, 0-1, 0 and 1) were removed due to the influence of Cummings' Dam, the lack of colonization potential by native macrophytes and/or the dominance of non-natives (see Aquatic Macrophytes Map 1). Thus, the downstream boundary of the instream habitat model was located just downstream of cross-section 2 (see Figure 4). Although hydraulically influenced by Cape's Dam, cross-section 11 (Segment 2) exhibited a strong potential for native macrophyte colonization (see Aquatic Macrophytes Map 2) and was not removed. Cross-section 17 (Segment 3) was removed due to significant impoundment influence from Rio Vista Dam and the dominance of introduced macrophytes (see Aquatic Macrophyte Map 3).

Zizania texana.—Figure 7 illustrates %WUA for *Z. texana* in each segment in relation to flow. Generally, available habitat increased with increasing flow for *Z. texana* in Segments 2 and 3, but maximal %WUA occurred at different flows. Maximal %WUA occurred at 120 ft^3/s in Segment 3, at 190 ft^3/s in Segment 2, and near 80 ft^3/s in Segment 1. For *Z. texana* %WUA was most sensitive to change in flow in Segment 1 where it ranged from 50 to 66%. Change in flow had less effect on %WUA in Segment 2 (31-40%) and Segment 3 (39-50%).

Heteranthera liebmannii.—Figure 8 illustrates %WUA for *H. liebmannii* in each segment in relation to flow. In all segments, habitat availability increased with increasing flow with maximums occurring at the upper end of modeled discharges. The ranges in %WUA over the modeled flows were relatively wide in all three segments: 20-35% in Segment 3, 20-32% in Segment 2, and 32-54% in Segment 1.

Vallisneria americana.—Figure 9 illustrates variability in %WUA for *V. americana* in all segments in relation to flow. Maximal %WUA occurred near 80 ft^3/s in Segments 1 and 3 and at 150 ft^3/s in Segment 2. Segments 1 (26-44%) and 3 (28-37%) had the widest ranges in %WUA for *V. americana* while Segment 2 had a relatively narrow range (17-20%).

Sagittaria platyphylla.— Figure 10 illustrates %WUA for *S. platyphylla* in each segment in relation to flow. Habitat availability improved with increasing flow in Segment 3. Maximal %WUA occurred at 170 ft^3/s in Segment 3, 157 ft^3/s in Segment 2 and at 100 ft^3/s in Segment 1. The widest range in %WUA occurred in Segment 3 (37-59%) while relatively narrow ranges in %WUA were found in Segments 1 (26-34%) and 2 (43-47%).

Potamogeton illinoensis.—Figure 11 illustrates %WUA for *P. illinoensis* in each segment in relation to flow. In all segments, habitat availability was greater with increasing flow with maximums occurring at the upper end of modeled discharges.

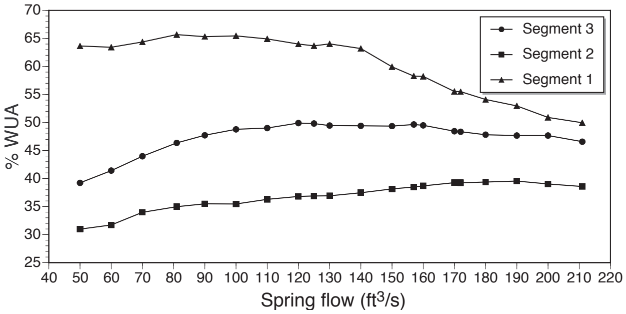


FIGURE 7.—*Zizania texana* percent weighted usable area (% WUA) in relation to spring flow in the upper San Marcos River main channel segments.

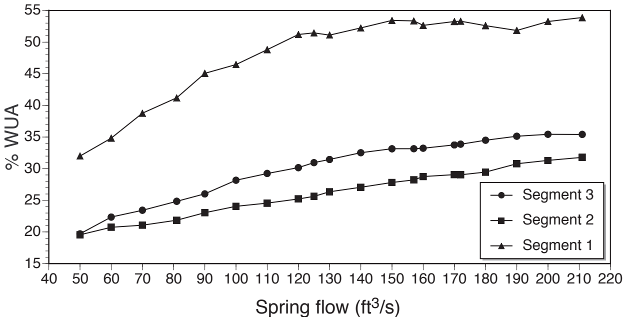


FIGURE 8.—*Heteranthera liebmannii* percent weighted usable area (% WUA) in relation to spring flow in the upper San Marcos River main channel segments.

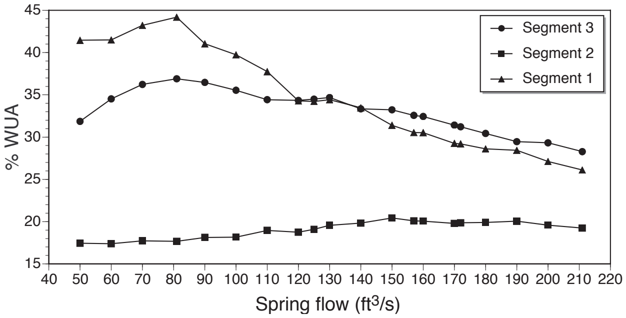


FIGURE 9.—*Vallisneria americana* percent weighted usable area (%WUA) in relation to spring flow in the upper San Marcos River main channel segments.

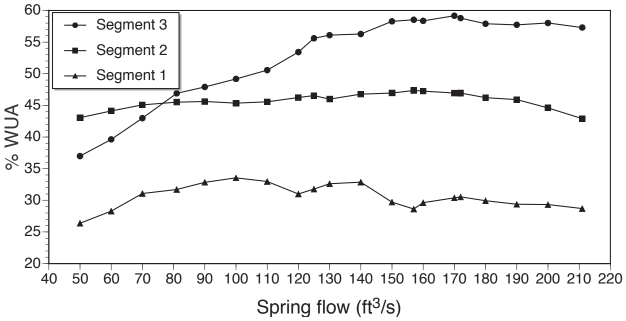


FIGURE 10.—*Sagittaria platyphylla* percent weighted usable area (% WUA) in relation to spring flow in the upper San Marcos River main channel segments.

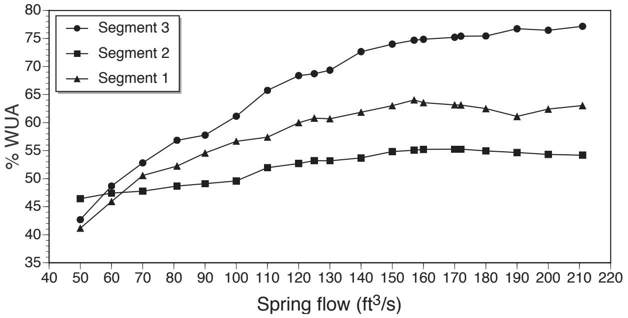


FIGURE 11.—*Potamogeton illinoensis* percent weighted usable area (%WUA) in relation to spring flow in the upper San Marcos River main channel segments.

Wide ranges in %WUA occurred in Segment 3 (43-77%) and Segment 1 (41-64%), while a relatively narrow range in %WUA was exhibited in Segment 2 (46-55%).

Natural channel relationships.—Because the natural channel, in Segment 2, represents roughly 7% of the study reach habitat area and discharge through the natural channel cannot be consistently correlated with flow, limited consideration was given to habitat-discharge relationships in this portion of Segment 2. Appendix IV: Figure 1 illustrates %WUA in relation to discharge in the natural channel for the five target species. In the natural channel, %WUA for *Z. texana* was maximized at 70 ft^3/s but remained relatively high from 50 to 110 ft^3/s; as flows exceeded 110 ft^3/s suitable habitat decreased sharply. *H. liebmannii* %WUA increased as discharge increased with a maximum occurring at 190 ft^3/s; at flows less than 70 ft^3/s a sharp decline in suitable habitat occurred. *V. americana* %WUA was maximal at 60 ft^3/s but remained relatively high between 40 and 90 ft^3/s. *S. platyphylla* %WUA was maximal at 40 ft^3/s but was relatively high from 30 to 110 ft^3/s. *P. illinoensis* %WUA was greatest at 160 ft^3/s but remained relatively high between 90 and 211 ft^3/s. *V. americana*, *P. illinoensis*, and *S. platyphylla* appear less sensitive to changes in flow in the natural channel than *Z. texana* and *H. liebmannii*.

Habitat Time Series

Quartile (25th and 75th percentile) frequencies were chosen to evaluate %WUA in terms of habitat quality in relationship to flow. Habitat (%WUA) frequencies greater than the 75th percentile were chosen to represent above average habitat conditions (i.e., highly suitable—potentially contributing to expansion or an increase in biomass density), while 25th to 75th percentile habitat frequencies represent average habitat quality (i.e., suitable—contributing to biomass and population persistence), and frequencies less than the 25th percentile represent below average habitat conditions (i.e., less than suitable—potentially contributing to loss). Based on these exceedence frequencies, flow ranges responsible for these habitat qualities were identified for each species in each segment (Figures 12-14). Both low and high flow ranges contributed to average (Figure 13) and below average habitat (Figure 14) qualities for some species.

Appendix IV: Figure 2 displays habitat time series for *Z. texana* in all main channel segments. Habitat time series for *Z. texana* reflect the ranges observed in habitat-flow relationships and demonstrate the effect of variable flows on habitat suitability between segments. Flow ranges that contributed to above average habitat quality did not overlap between segments (Figure 12). In Segment 1, above average habitat occurred when flows were less than 125 ft^3/s, while in Segments 2 and 3 above average habitat conditions were at higher flow ranges. In Segment 1, below average habitat conditions for *Z. texana* were due to flows greater than 200 ft^3/s while in Segment 2 below average habitat conditions were attributed to flows greater than 280 ft^3/s and flows less than 110 ft^3/s (Figure 14). In Segment 3, below average habitat conditions were due to flows greater than 200 ft^3/s and less than 85 ft^3/s.

Appendix IV: Figure 3 displays habitat time series for *H. liebmannii* in main channel segments. Above average habitat conditions occurred at high flows in all segments (see also Figure 12). In all segments, below average habitat conditions were due to flows less than 125 ft^3/s while in Segment 1 very high flows (greater than 320 ft^3/s) also contributed to below average habitat conditions (Figure 14).

Appendix IV: Figure 4 displays habitat time series for *V. americana* in all main channel segments. Above average habitat conditions occurred at relatively low flows (less than 125 ft^3/s) in Segments 1 and 3 (see also Figure 12). In Segment 2, a higher range of flows contributed to above average habitat conditions. In Segments 1 and 3, very high flows (> 200 ft^3/s) contributed to below average habitat conditions while in Segment 2 both flows less than 110 ft^3/s and greater than 235 ft^3/s contributed to below average habitat conditions (Figure 14).

Appendix IV: Figure 5 displays habitat time series for *S. platyphylla* in all main channel segments. Habitat time series for *S. platyphylla* also demonstrated the effect of variable flows on habitat suitability between segments. In Segment 1, above average habitat occurred when flows were relatively low, while in Segment 2, above average habitat occurred near median flows (Figure 12). Above average habitat conditions in Segment 3 were due to a wide range of high flows greater than the median. Below average habitat conditions occurred due to a combination of very low flows (< 60 ft^3/s) and relatively high flows (> 200 ft^3/s) in Segments 1 and 2. In Segment 3, flows less than 125 ft^3/s and extremely high flows (> 415 ft^3/s) resulted in below average conditions for *S. platyphylla* (Figure 14).

Appendix IV: Figure 6 displays habitat time series for *P. illinoensis* in all main channel segments. In all

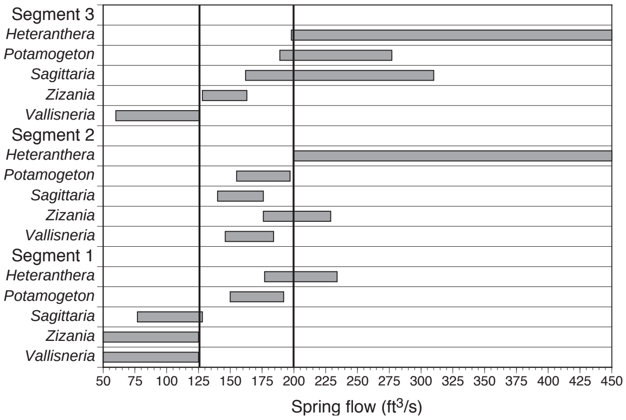


FIGURE 12.—Spring flow ranges that contribute to above average habitat conditions based on 75th percentile %WUA frequencies calculated from habitat time series. Vertical lines represent 25th and 75th percentile spring flows.

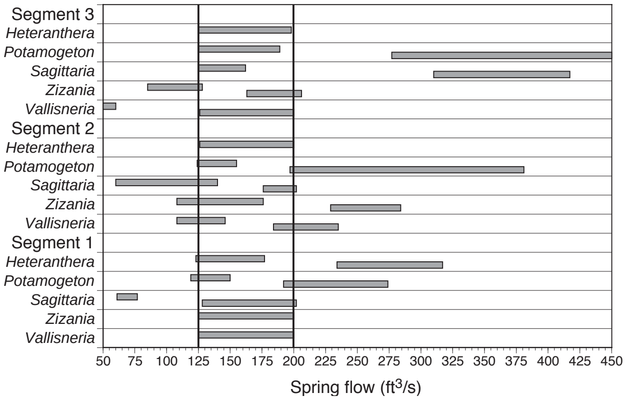


FIGURE 13.—Spring flow ranges that contribute to average habitat conditions based on 25th-75th percentile %WUA frequencies calculated from habitat time series. Vertical lines represent 25th and 75th percentile spring flows.

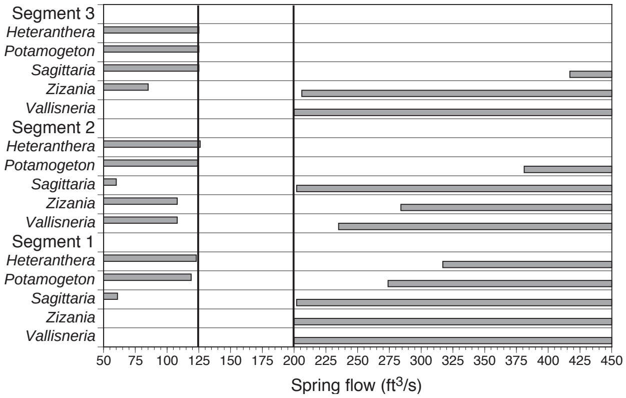


FIGURE 14.—Spring flow ranges that contribute to below average habitat conditions based on 25th percentile %WUA frequencies calculated from habitat time series. Vertical lines represent 25th and 75th percentile spring flows.

segments, flows near the median and higher contributed to above average habitat conditions (Figure 12). In all segments flows less than 125 ft^3/s contributed to below average habitat conditions and in Segments 1 and 2 very high flows resulted in below average habitat conditions (Figure 14).

Critical Depths for Z. texana

Instream habitat modeling indicated that shallow depths could limit suitable habitat for *Z. texana*, particularly in the main channel. Depths of > 1.0, > 1.5, > 2.0 and > 2.5 ft were selected as depth criteria to evaluate the loss of *Z. texana* habitat given reductions in discharge. Criteria less than one foot were not evaluated because: 1) only two data points (0.6 and 0.9 ft) in the *Z. texana* habitat utilization data set were less than one foot during a relatively low flow period (roughly 100 ft^3/s); 2) the highest preference value occurred between 1.51 and 2.25 ft depths; and 3) the rapid desiccation and loss of *Z. texana* stands during two dam breaches that resulted in depths of ≤ 0.5 ft (TPWD observations) at specific stands in Segment 2. Appendix IV: Figure 7 illustrates the effects of discharge on depth at *Z. texana* verticals on cross-section 24 using a depth criteria of > 1.0 ft. At 132 ft^3/s vertical 6 depth is reduced to 1 ft resulting in a 13.4% loss of *Z. texana* habitat. Vertical 5 fails to meet the > 1 ft depth criteria at 53 ft^3/s further reducing *Z. texana* habitat by 13.4%. This critical depth analysis was conducted for all cross-sections in the main channel of the upper San Marcos River where *Z. texana* was recorded. Results were compiled and are illustrated in Appendix IV: Figure 8. Only 37% and 70% of *Z. texana* habitat met a depth criteria of > 2.5 ft and > 2.0 ft, respectively, at the long-term median (157 ft^3/s). At the median flow, 95% of *Z. texana* habitat met a depth criteria of > 1.5 ft, while 100% met a depth criteria of > 1.0 ft. At flows less than 140 ft^3/s, *Z. texana* habitat began to be impacted using a depth criteria of > 1 ft, at less than 90 ft^3/s habitat was moderately impacted, and at 50 ft^3/s approximately 25% of *Z. texana* habitat failed to meet the criteria. Using a more protective depth criteria of > 1.5 ft, loss of nearly 10% of *Z. texana* habitat resulted at a discharge of 140 ft^3/s. At flows between 90 and 100 ft^3/s, 30% of *Z. texana* habitat failed to meet the depth criteria and at 50 ft^3/s, 60% of *Z. texana* habitat failed to meet the depth criteria of > 1.5 ft. Additional analyses of greater depth criteria were not performed because of the low percentage of habitat meeting such criteria at the long-term median flow.

Water Quality

Empirical data.—General statistics for temperature, DO, pH, specific conductance and turbidity are depicted in Table 4. The data for all five water quality parameters demonstrated poor conformance to a normal distribution (Kolmogorov-Smirnov and Shapiro-Wilk tests: $p < 0.05$) for most of the stations. Examination of box plots and histograms showed frequencies to be irregular and skewed due to infrequent but extreme events such as rainstorms and unusually cold or hot periods; log transformation (log$_{10}$+1) was ineffective for most stations. Another problem with statistical testing was that sample variances differed widely among stations. Also, since water quality measurements at each location in the river are partially dependent on the conditions upstream, the samples from the different stations are not independent. Therefore statistical testing of differences among stations was deemed inappropriate. Instead, data were summarized in tables and depicted graphically in box plots to show relative differences in central tendencies and variability between stations.

Temperatures for the entire deployment period are plotted in Figure 15 (see Appendix V: Table 1 for descriptive statistics). Station 1, closest to the springs, had the least variability (Table 4). The sites furthest downstream (i.e., stations 6 and 7) had the greatest variability (Table 4). To illustrate summer and winter conditions, data from 1996 were selected

TABLE 4.—Statistics for temperature, dissolved oxygen, pH, specific conductance and turbidity for San Marcos River water quality stations 1-7. Deployment periods — Stations 1 and 2: Nov-1994 through May-1997; 3 and 4: Feb-1995 through Mar-1997; 5: Nov-1994 through Mar-1997; 6: Mar-1995 through Mar-1997; 7: Dec-1995 through May-1997.

Station	N	Mean	Std Dev	Minimum	Maximum
		Temperature (°C) [a]			
1	19189	21.8	1.04	18.3	24.8
2	17233	21.5	1.66	14.7	26.1
3	16108	21.5	1.84	15.8	26.0
4	17146	21.6	2.08	15.1	26.1
5	17753	21.6	2.21	13.6	26.2
6	17863	22.1	3.27	12.8	28.3
7	10221	21.0	3.35	12.6	27.3
		Dissolved Oxygen (mg/L) [a]			
1	2686	7.7	0.99	5.4	10.6
2	2303	7.4	1.47	3.2	12.2
5	2496	7.5	1.18	4.6	10.8
7	1597	8.2	1.13	5.0	10.5
		pH (standard units) [a]			
1	19188	7.5	0.11	7.2	8.0
2	17233	7.8	0.18	7.3	8.4
5	16512	7.8	0.14	7.4	8.4
7	10135	8.1	0.12	7.6	8.4
		Specific Conductance (μS/cm) [a]			
1	19187	595	20.4	290	637
2	17221	593	26.5	170	641
5	17749	605	33.0	165	665
7	10145	589	45.1	203	644
		Turbidity (NTU) [b]			
1	58	1.17	0.86	0.26	5.75
2	58	1.70	1.03	0.50	6.13
5	57	3.81	2.24	0.40	12.3
7	32	5.51	3.58	0.57	13.4

[a] Hourly measurements
[b] Measured twice monthly

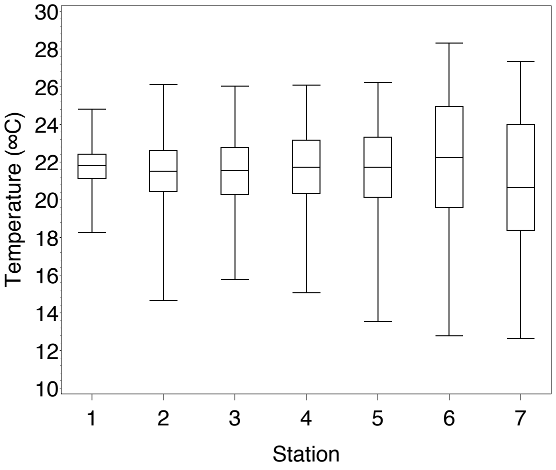


FIGURE 15.—San Marcos River, temperature by station, measured hourly, Nov-1994 through May-1997. Horizontal line in box: sample median. Box top and bottom: 75th and 25th percentiles. Upper and lower fences: limits of data.

due to the relative completeness of the data sets. Figure 16 (summer 1996 data) shows an increase in median temperature and variability from Stations 1 to 2, with an increase in median temperature downstream and little change in variability. Figure 17 (winter 1996 data) shows a decrease in median temperature downstream accompanied by a gradual increase in variability.

Dissolved oxygen measurements exhibited a considerable amount of instrument drift during many of the month-long deployment periods. This was apparently due to biological fouling of the probe membranes. To maximize accuracy and keep data consistent from station to station, all DO data collected after the first four days following calibration were eliminated. The results are summarized in Figures 18-20 (also see Appendix V: Table 2). A review of the raw data showed the lowest values during early morning hours, prior to commencement of active photosynthesis by algae and aquatic macrophytes, and the highest values in the afternoons. Daily means for all stations generally ranged from 6 to 9 mg/L. Plotted data for the entire period (Figure 18) and for summer and winter periods (Figures 19 and 20) show the highest variability occurring at Station 2. Also, an increase in median DO values is evident from Station 5 to Station 7. Median DO values from summer 1996 were lower than those from winter 1996 for Stations 2, 5, and 7 (Figures 19 and 20).

Hourly pH data is plotted in Figure 21 (see Appendix V: Table 3 for monthly statistics). Mean pH ranged from 7.5 at Station 1 to 8.1 at Station 7. Minimum pH ranged from 7.2 (Station 1) to 7.6 (Station 7). Maximum pH ranged from 8.0 (Station 1) to 8.4 (Stations 2, 5, and 7).

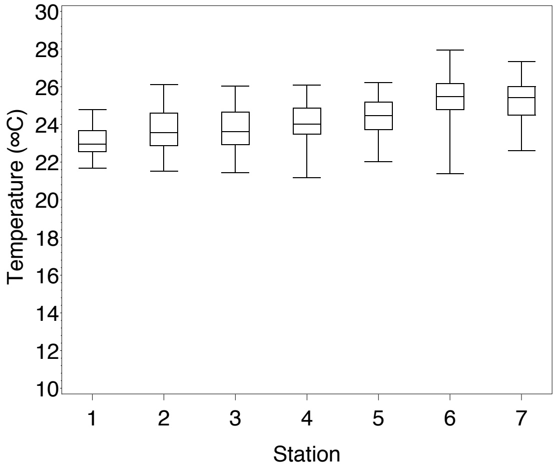


FIGURE 16.—San Marcos River, summer conditions, temperature by station, measured hourly, May-1996 through Jul-1996. Horizontal line in box: sample median. Box top and bottom: 75th and 25th percentiles. Upper and lower fences: limits of data.

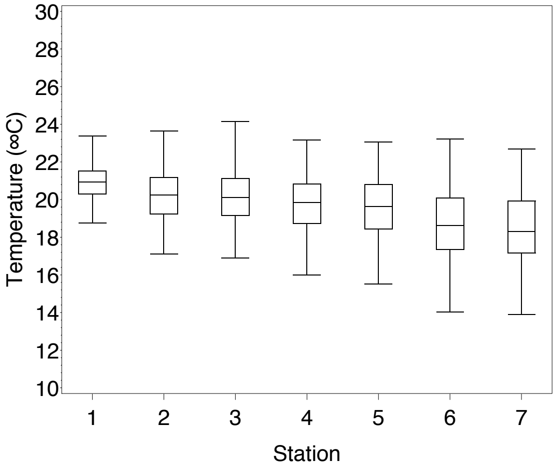


FIGURE 17.—San Marcos River, winter conditions, temperature by station, measured hourly, Dec-1995 through Feb-1996. Horizontal line in box: sample median. Box top and bottom: 75th and 25th percentiles. Upper and lower fences: limits of data.

Hourly specific conductance data is plotted in Figure 22 (see Appendix V: Table 4 for monthly statistics). Most measurements at all four stations fell within a fairly narrow range around 600 μS/cm. Outliers consisting of much lower measurements, however were noted for all stations. An examination of the raw data revealed that many of the extremely low measurements were recorded during periods of only a few hours, such as would result from dilution by heavy rainfall.

Turbidity results are plotted in Figure 23 (see Appendix V: Table 5 for raw data). A downstream trend of increasing variability and slightly higher mean values was noted (mean turbidity ranged from 1.17 nephelometric turbidity units (NTU) at Station 1 to 5.51 NTU at Station 7).

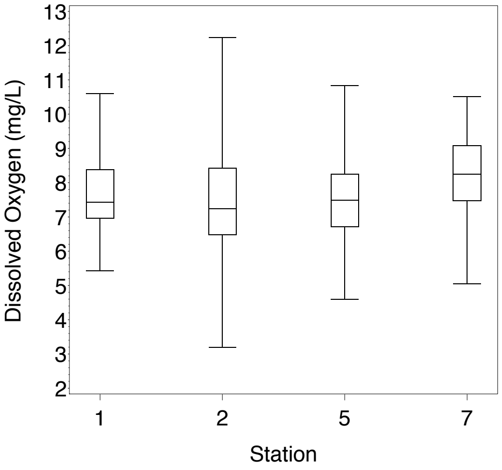


FIGURE 18.—San Marcos River, dissolved oxygen (mg/L) by station, measured hourly, Nov-1994 through May-1997. Horizontal line in box: sample median. Box top and bottom: 75th and 25th percentiles. Upper and lower fences: limits of data.

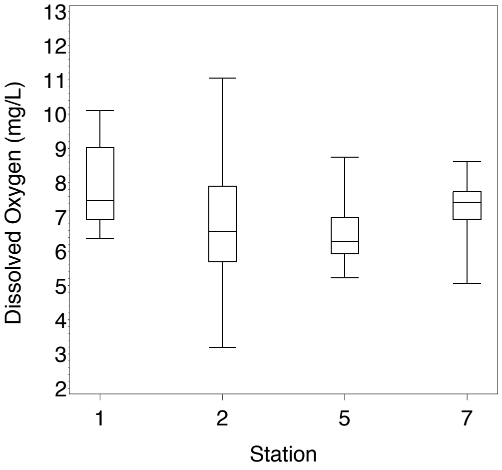


FIGURE 19.—San Marcos River, summer conditions, dissolved oxygen by station, measured hourly, May-1996 through Jul-1996. Horizontal line in box: sample median. Box top and bottom: 75th and 25th percentiles. Upper and lower fences: limits of data.

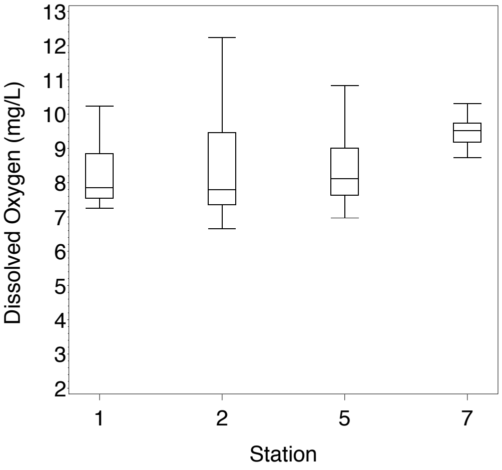


FIGURE 20.—San Marcos River, winter conditions, dissolved oxygen by station, measured hourly, Dec-1995 through Feb-1996. Horizontal line in box: sample median. Box top and bottom: 75th and 25th percentiles. Upper and lower fences: limits of data.

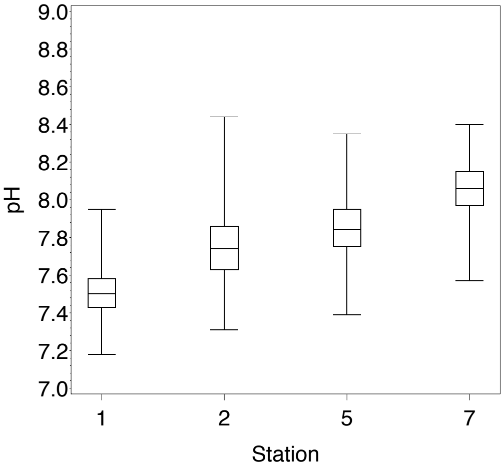


FIGURE 21.—San Marcos River, pH by station, measured hourly, Nov-1994 through May-1997. Horizontal line in box: sample median. Box top and bottom: 75th and 25th percentiles. Upper and lower fences: limits of data.

Temperature model.—SNTEMP was validated by comparing the model's predicted average daily temperatures with two years of observed temperatures at three stations (3, 4, and 5). Validation rules of thumb given by Bartholow (1997) were all satisfied. These include mean error less than 0.5°C, less than 10% of simulated temperatures greater than 1.0°C from observed (dispersion error), maximum error less than 1.5°C and no trend in spatial, temporal or prediction error. The modeled daily average temperature results predicted a mean error over all time periods and locations of 0.13°C less than observed. The maximum model error of 0.93°C less than observed occurred for the January 1996 simulation at Station 4. At no time or location did predicted average daily temperature differ from observed values by more than 1.0°C therefore 0% of the simulated values differed by more than 1.0°C. The mean absolute difference between observed and predicted temperature was 0.46°C. Predicted daily maxima, based on liner regression calculated outside of SNTEMP, also corresponded very closely to the values collected during the course of the study (Appendix V: Table 1). The largest difference between predicted and observed maximum temperature was 1.7°C. There was only one occurrence when difference exceeded 1.0°C.

The observed and predicted temperatures at Stations 3, 4, and 5 are presented in Appendix V: Figures 1-3 (normal air temperature) and Appendix V: Figures 4-6 (85th percentile air temperature).

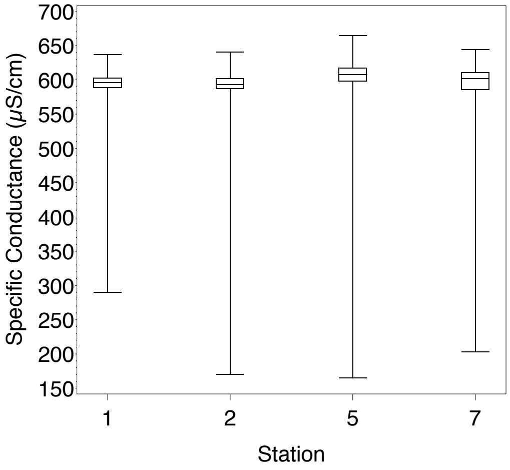


FIGURE 22.—San Marcos River, specific conductance by station, measured hourly, Nov-1994 through May-1997. Horizontal line in box: sample median. Box top and bottom: 75th and 25th percentiles. Upper and lower fences: limits of data.

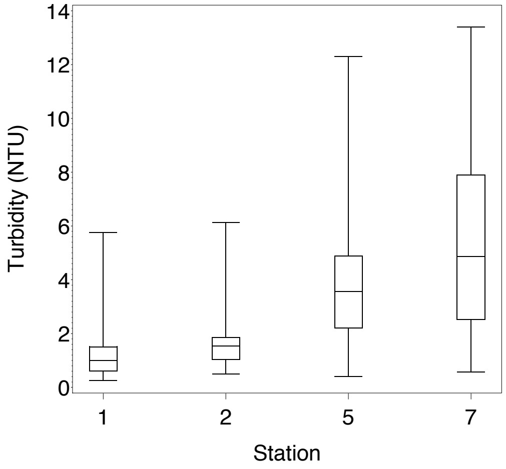


FIGURE 23.—San Marcos River, turbidity by station, measured twice per month, Nov-1994 through May-1997. Horizontal line in box: sample median. Box top and bottom: 75th and 25th percentiles. Upper and lower fences: limits of data.

Table 5 reports the number of months that the predicted water temperatures exceeded various temperature thresholds (see temperature discussion). The model was fairly insensitive to changes in air temperature, predicting only a few more months when water temperatures exceed given thresholds using the 85th percentile air temperatures in place of normal air temperatures. Water temperature simulations based on 1995 and 1996 conditions agreed well with empirical data. Although none of the empirical data collected at stations 4 and 5 exceeded 26.7°C, the model predicts a number of these occurrences. However, there were several times when observed maximum temperatures did exceed 26.0°C and during these months the model slightly overestimated maximum water temperature. The median flow scenario generally produced results that fall between the 1995 and 1996 scenarios. For the minimum flow scenarios daily average temperatures exceeded 25.0°C at Stations 4 and 5, for 2 and 3 months respectively, and maximum temperatures exceeded 25.0°C at all stations for about half of the year and 26.7°C at Stations 4 and 5 during the summer.

An additional analysis was performed using SNTEMP to model temperatures for a flow range of 50 to 450 ft^3/s assuming 1996 water and air temperatures. Appendix V: Figure 7 shows the predicted average and maximum daily water temperatures at three water quality stations for this flow range. These values represent the annual maximum values. Violations of temperature criteria occurred at water quality stations 3, 4, and 5 at 70, 90 and 160 ft^3/s, respectively.

TABLE 5.—Number of months that threshold temperatures are exceeded as predicted by the SNTEMP model for each station (3, 4, and 5). Actual flow and meteorological conditions were used for 1995 and 1996. Synthetic data sets include median and minimum flow scenarios assuming normal and 85th percentile air temperatures.

	1995			1996			Median			Minimum		
Air Temp	3	4	5	3	4	5	3	4	5	3	4	5
No. of months predicted ADWT[a] violates 25°C criteria												
1995	0	0	0									
1996				0	1	2						
Normal							0	0	0	2	2	3
85th							0	0	2	3	3	4
No. of months predicted MDWT[b] violates 26.7°C criteria												
1995	0	0	0									
1996				0	1	4						
Normal							0	0	0	3	3	4
85th							0	0	0	4	4	5

[a] Average daily water temperature.

[b] Maximum daily water temperature.

Discussion

The primary goal of this study was to describe flow levels as well as water quality conditions necessary to conserve this unique spring ecosystem and its fish and wildlife resources. The value in the conservation of this ecosystem and Comal Springs ecosystem extends beyond the boundaries of these spring systems to downstream portions of the Guadalupe River and San Antonio Bay. Spring flows from these systems provide instream flows for downstream portions of the San Marcos, Comal, and Guadalupe rivers and contribute to freshwater inflows necessary for bay and estuary conservation.

Instream flow researchers have emphasized the need to incorporate a variety of instream flow needs into recommendations to address specific purposes or functions (Hill et al. 1991; Poff et al. 1997; Bovee et al. 1998). In order to conserve riverine ecosystems, flow regimes should (1) maintain water quality, (2) conserve ecosystem functions, (3) perform channel maintenance functions, (4) maintain both flood-plain connections and (5) valley-forming functions. Applicable to this study of the spring-fed upper San Marcos River are the first three concerns, but the fourth and fifth are largely inextricable due to the current level of urbanization. The characteristics of this spring ecosystem include: the historical hydrology, a rich biodiversity, dominance of run type mesohabitats, stenothermal water temperatures and very clear water. In this study we attempted to address these spring characteristics and identify parts of a flow regime necessary to conserve this spring ecosystem and its major components.

Historical Hydrology

The historical hydrology of the San Marcos River as reflected by USGS spring flow records includes a pattern of relatively high, moderate, and low flows. One observable pattern is that flows generally tend to be greater than the long-term median (157 ft^3/s) for typically a 2-3 year period followed by a period of approximately 2-3 years of flows less than the long-term median (Figure 1). The springs have never failed to flow in recorded history. However, flow has been affected by aquifer withdrawals since the late 19th century (Maclay 1989; Ewing 2000). In order to maintain this ecosystem, flow regimes should include the natural range of variability, and management of the Edwards Aquifer and it's contributing watershed should minimize alterations to natural flow patterns.

Peak streamflow events that provide flushing and/or channel maintenance functions have been attenuated since the construction of five flood control dams in the contributing watershed of the upper San Marcos River (Figure 3). Since the completion of these dams, increased silt deposition has been observed within the San Marcos River (Wood and Gilmer 1996). The primary areas of major siltation occur in the impounded areas behind the instream dams. Macrophytes (e.g., *Z. texana*, *V. americana*, and *H. liebmannii*) that utilize coarser substrate types, such as sand and gravel, have limited ability to expand into or colonize areas dominated by silt. Peak flows also provide for scouring of attached algae and rooted macrophytes which contributes to a dynamic aquatic community over moderate periods of time. Flows for flushing fine silts, scouring macrophyte beds and periphyton, and other channel maintenance activities are critical for long-term spring ecosystem health.

Rich Biodiversity

Stable flows of sufficient duration contribute to macrophyte expansions and contractions and increases or decreases of biomass. At relatively high flows certain macrophyte species may expand in areal coverage or increase in biomass and other species may contract, lose biomass, or be locally extirpated. During low flow periods some particular plant species may increase in area or biomass and other species may decrease. This scenario is based on the result that the availability of suitable habitat for some species was maximized under relatively high flows and for other species more suitable habitat was available during lower flow periods. Given that expansion or increase in biomass of macrophyte beds occurs over relatively long periods of time (10 months or greater, Biggs 1994), suitable habitat and the flows that maintain that habitat must be consistently available through time. What truly constitutes sufficient duration in this ecosystem is unknown. Habitat time series analysis revealed spatial patterns in habitat availability for the various target species which further justifies the need for a variable range of flows. For example, if only low flows (i.e., a constant flow regime) occurred for long periods of time *S. platyphylla* would do well in Segment 1 but not in Segment 3 (Figures 12 and 14). Specific long-term research is needed to further quantify biological responses to varying durations of flow. A flow regime that combines stable low, median, and high flows, each of sufficient duration, would provide the greatest potential for maintaining the richest diversity of native macrophyte communities and associated faunas in all segments of the upper San Marcos River.

Macrophyte distributions respond to the availability of suitable habitat and a multitude of biotic and abiotic influences on life history traits, such as reproduction, seed dispersion and germination success, vegetative growth and colonization dynamics. Biotic influences include herbivory by native and introduced fish and wildlife (e.g., cichlids, nutria and giant ramshorn snail) and competition for space, light and nutrients with more generalist macrophyte species (sometimes other native but often exotic species). Abiotic influences include the availability of light (influenced by water clarity, depth and the density of canopy cover), nutrient availability, temperatures, macrophyte cutting and disturbance, and significant changes in physical habitat (e.g., conversions of run to pool mesohabitat; increased sediment deposition) and hydraulic conditions (e.g., reduced velocities, increased depths, reduced effectiveness of channel-maintenance flows) due to impoundments and other structures. For example, Vaughan (1986) believed a primary factor in the decline of *Z. texana* to be the multiple dams which have been built in the river. This contention was substantiated by Poole and Bowles (1999). Given *Z. texana* reproductive characteristics, it has greatly reduced habitat in which to sexually reproduce (Vaughn 1986). Further, the dams act as barriers to migration within the river for fish, such as freshwater eels, and giant river shrimp (e.g., Bowles et al. 2000). These abiotic and biotic influences may have contributed to substantial declines in native components of the ecosystem (Vaughn 1986; Rose and Power 1992; USFWS 1996).

Lemke (1989) reported 31 species of aquatic macrophytes from the upper San Marcos. Of these 23 were native. Displacement of native species by non-native species and resulting adverse effects were noted. Of non-native species, *H. verticillata* was reported as the most common. During the course of this study similar distributions were found for most native species and *H. verticillata* was widespread and common in the study reach. Perhaps the most significant change since Lemke (1989) reported on the macrophyte community has been the establishment and rapid colonization of nearly the entire upper San Marcos River by *H. polysperma.* This invasive species is found in virtually every type of mesohabitat and was the most common species encountered in this study. Nearly all parts of this plant are capable of vegetative reproduction and can grow in depths of over 10 ft (Howells 1999), *H. polysperma* can quickly establish new stands in all mesohabitat types. *C.* cf *beckettii* was not reported by Lemke (1989) and was first observed by TPWD staff in 1993 in Segment 1. It occurred in dense beds in runs with sand and silt substrates in moderate to fast current velocities. *C.* cf *beckettii* did not associate with any other macrophytes in this analysis (Appendix II: Table 3). The establishment of this exotic species in upper segments is of concern and warrants further study because of the similarity in its habitat utilization with those of native species such as *Z. texana*. Further, this species has dramatically extended its coverage since the October 1998 record flood (TPWD observations). Many exotic species have demonstrated their ability to out-compete native macrophytes (Vaughn 1986; Rose and Power 1992; USFWS 1995), and thus reduce available habitat. Removal of exotic species from the system is problematic at this time and further study would be necessary to determine if any method of control might yield effective results.

Dominance of Run-type Mesohabitats

The upper San Marcos River historically consisted primarily of run-type mesohabitats (Brune 1981; Terrell et al. 1978; Vaughn 1986) that were fast and shallow to moderately deep and slow. The presence of natural riffles and pools is currently rare. This is in part attributable to the spring flow based discharge of the river. The effects of flood control structures in the upper watershed on instream habitat is ongoing. These dams moderate peak flows and reduce the frequency and intensity of flushing flow events which contribute to major siltation problems noted by Wood and Gilmer (1996). The effects of instream impoundments is clear. Run habitat with sandy, gravel bottoms and swift currents and to some extent riffle habitat have been inundated forming pool mesohabitat with silt substrates and very low current velocities. These impounded areas are dominated by exotic species and do not offer much suitable habitat for most native macrophytes. Longley (1991) proposed as a possible management option the removal of all dams to return the system to its free flowing condition. Removal of Rio Vista Dam, Cape’s Dam, and Cummings’ Dam and management or extirpation of exotic species would restore substantial run habitat for native macrophytes and possibly control velocity sensitive exotic species such as giant ramshorn snail (see Arsuffi et al. 1993).

Native aquatic macrophyte and fish species richness was highest in run mesohabitats. Flow regimes that provide protection to run mesohabitats should be protective of fish communities as well.

Water Quality

Stations 1 through 5 were located upstream from the confluence with the Blanco River and are within TNRCC segment 1814, which is placed in the exceptional aquatic life use subcategory. Stations 6 and 7, downstream from the confluence with the Blanco River, are in segment 1808, which is designated high aquatic life use. Temperature modeling was performed for Stations 3, 4, and 5. Temperature, DO, specific conductance, pH, and turbidity results obtained in this study were compared to the TNRCC surface water quality standards where applicable, and to results obtained by other investigators.

Temperature.—The maximum temperature criteria established by TNRCC are 26.7°C for the upper San Marcos River (Stations 1-5), and 32.2°C for the lower San Marcos River (Stations 6 and 7) (TNRCC 1995). None of the measured temperatures during this study exceeded those criteria. The temperature model (Table 5) predicted that maximum daily temperature may exceed 26.7°C at Stations 3, 4, and 5 using both normal and 85th percentile air temperatures at minimum flow scenarios. A concern regarding temperatures in the San Marcos River centers around *E. fonticola* utilization of a relatively constant temperature regime. The exact temperature range in which *E. fonticola* spawns in the river is unknown, but they have been observed spawning year-round, with two peak periods of ova production, one in August and another in late winter to early spring (Schenck and Whiteside 1977). In a laboratory study on *E. fonticola* spawning and rearing (Brandt et al. 1993), normal larvae were produced over a range of 6-27°C, but maximum egg production occurred from 15 to 24°C. Another laboratory study (Bonner et al. 1998) found *E. fonticola* egg production to be significantly lower at 27 and 29°C than at temperatures of less than or equal to 25°C (actual experimental range = 25.1 – 26.2°C, mean = 25.5°C). Hubbs and Strawn (1957) found an optimal temperature range of 20-23°C for egg production in the greenthroat darter (*Etheostoma lepidum*), and Brungs (1971) reported that egg production in fathead minnow (*Pimephales promelas*) was significantly lower at 26°C than at 20-23°C. Since those laboratory experiments indicate that temperatures exceeding 25°C may reduce reproductive success in *E. fonticola*, the frequency of temperature measurements that exceeded that threshold was determined (Table 6). During the warm summer months, temperature measurements above 25.0°C were numerous at Stations 2 through 7 (particularly at Stations 5, 6, and 7). Only at Station 1 did temperature never exceed 25.0°C. Daily mean temperatures exceeded 25.0°C only at Stations 5, 6, and 7. The warmest temperatures occurred primarily between mid afternoon and late evening hours, with temperatures decreasing by early morning. The temperature model (Table 5) predicted average daily temperature would exceed 25.0°C at Stations 3, 4, and 5 using both normal and 85th percentile air temperatures with minimum flow scenarios and at Station 5 with median flow and 85th percentile air temperatures. The degree to which these elevated water temperatures may impact *E. fonticola* reproduction cannot be assessed from this study. A confounding issue is that the research on temperature tolerance cited above involved controlled conditions at static temperatures, which may not translate to the fluctuating conditions of the river. Also, since fish are mobile, they may be successful in avoiding higher temperature areas during those warmer periods.

TABLE 6.—San Marcos River water temperature measurements greater than or equal to 25° C.

Station	Month	N≥25	Total N	Fraction of total
2	Apr-96	2	497	<0.01
2	May-96	61	681	0.09
2	Jun-96	111	603	0.18
2	Jul-96	158	651	0.24
3	Aug-95	2	738	<0.01
3	May-96	60	736	0.08
3	Jun-96	139	720	0.19
3	Jul-96	172	667	0.26
3	Aug-96	137	744	0.18
3	Sep-96	2	82	0.02
4	Jul-95	9	602	0.01
4	Sep-95	3	675	<0.01
4	Oct-95	1	735	<0.01
4	May-96	79	736	0.11
4	Jun-96	177	720	0.25
4	Jul-96	229	667	0.34
4	Aug-96	171	744	0.23
4	Sep-96	2	720	<0.01
5	May-95	2	712	<0.01
5	Jul-95	17	612	0.03
5	Aug-95	10	644	0.02
5	Sep-95	1	596	<0.01
5	May-96	79	681	0.12
5	Jun-96	198	650	0.30
5	Jul-96	345	652	0.53
5	Aug-96	259	706	0.37
5	Sep-96	16	665	0.02
6	May-95	188	742	0.25
6	Jun-95	431	635	0.68
6	Jul-95	701	720	0.97
6	Aug-95	669	739	0.91
6	Sep-95	166	675	0.25
6	Oct-95	2	736	<0.01
6	May-96	242	736	0.33
6	Jun-96	542	720	0.75
6	Jul-96	661	666	0.99
6	Aug-96	542	744	0.73
6	Sep-96	98	719	0.14
7	May-96	211	681	0.31
7	Jun-96	283	420	0.67
7	Jul-96	547	547	1.00
7	Aug-96	491	706	0.70
7	Sep-96	39	652	0.06

TNRCC temperature data collected in the upper San Marcos segment between 1990 and 1994 ranged from 21.2 to 24.9°C (mean = 22.9°C). TNRCC data for the lower segment exhibited slightly greater variability in temperature (TNRCC: 11-30.5°C, TPWD: 12.6-28.3°C). Data from other sources were also similar to data obtained by TPWD. Temperature measured directly in San Marcos Springs ranged from 21.7 to 23.3°C (Guyton et al. 1979), and from 21.3 to 21.9°C (Ogden et al. 1985). Temperature measurements in the upper San Marcos River in 1964 and 1965 yielded monthly means ranging from 21.0 to 23.3°C (Hannan and Dorris 1970). Temperature measured in the upper San Marcos River from 1992 through 1994 ranged from 20 to 24°C, and in the lower river ranged from 12 to 28°C (Groeger et al. 1997). Median temperature in the upper river from July through August, 1994 ranged from 22.6 to 24.4°C (Slattery and Fahlquist 1997).

Similar temperatures noted in TPWD data and by investigators cited above reflect thermal consistency of ground water emanating from San Marcos Springs. When data from different seasons are combined, sites downstream show increasing variability (Figure 15; see also Groeger et al. 1997). This was not surprising, since the river should steadily cool as it flows downstream during periods when ambient air temperatures are less than water temperature, and increase downstream during periods of warmer air temperatures. A noticeable increase in temperature variability downstream from the confluence with the Blanco River was noted in this study as well as by Groeger et al. (1997). The downstream temperature trend observed during summer conditions (Figure 16) is similar to that reported by Slattery and Fahlquist (1997), with an initial increase in median temperature and variation from the first to second upstream sites, followed by increasing temperature downstream with little or no increase in variability. Data covering only winter conditions (Figure 17) shows a downstream trend similar to the summer conditions, except that temperature decreased downstream.

Primary influences on river temperature would include air and ground temperature, intensity of sunlight and wind, shading and longitudinal distance from the spring source during which heat exchange can occur. Habitat differences among stations influenced temperature (see Table 3). Other factors influencing water temperature would include stormwater runoff, and effluent from the fish hatchery (between Stations 3 and 4) and WWTP (between Stations 4 and 5). The Blanco River was not monitored during this study, but when flowing (the confluence was between stations 5 and 6) may warm the San Marcos River during summer months and provide a cooling effect during winter. Station 7 is probably influenced by the impounded conditions of Cummings' Lake followed by the mixing and turbulent flow of the Cummings' Dam spillway.

Dissolved oxygen.—The mean DO criteria established by TNRCC are 6 mg/L for the upper and 5 mg/L for the lower San Marcos River segments. Mean daily values measured during this study in the upper segment fell below the 6 mg/L criterion thirteen times out of a total of 312 values (Table 7). Only three failures to meet the minimum criteria (4 mg/L) were noted (Station 2). The placement of Station 2 in an impoundment exposed to sunlight and wind probably explains the greater variation seen in the DO values (Figures 18-20). All instances of non-attainment occurred during flows exceeding 58 cfs, the established low flow criterion for the upper San Marcos segment. In the lower segment, the values never failed to meet the applicable criteria. TNRCC (1994) DO measurements in the upper San Marcos between 1990 and 1994 ranged from 7 to 9.5 mg/L (mean = 8.5 mg/L), while data for the lower San Marcos ranged from 7.3 to 10 mg/L (mean = 8.6 mg/L). TNRCC data consists of spot measurements during daylight hours, so one would expect the minima to be higher than was observed during this study. DO measurements reported by Slattery and Fahlquist (1997) and Groeger et al. (1997) showed all data meeting the DO standards, with most concentrations ranging from 7 to 10 mg/L.

pH.—At no time did the pH measurements in this study fail to meet the TNRCC surface water quality criteria (6.5-9 s.u.). The pH ranges were similar to those reported by Slattery and Fahlquist (1997), as was the trend of increasing pH downstream from Spring Lake. Groeger et al. (1997) noted an increase in pH downstream from the springs and Spring Lake, which they attributed to a decrease in CO_2 concentrations as the water attained equilibrium with the atmosphere. They also reported more constant pH values downstream from the confluence with the Blanco River, corresponding with values expected in a limestone-dominated drainage.

TABLE 7.—Dissolved oxygen (DO) values failing to meet TNRCC water quality standards. All data based on first four days of deployment following calibration. Station 7 met all DO criteria (High aquatic life use) for segment 1808.

Station	Date	Time	Temperature (°C)	DO (mg/L)
Daily mean DO values less than 6 mg/L[a]				
2	08/12/95		22.8	5.2
2	08/13/95		23.0	5.6
2	08/14/95		22.9	5.5
2	08/15/95		22.9	5.6
2	06/07/96		23.1	4.8
2	06/08/96		23.1	5.6
5	11/05/94		21.5	5.4
5	11/06/94		21.3	5.3
5	11/07/94		21.4	5.4
5	11/08/94		22.5	5.0
5	05/06/95		22.9	5.8
5	10/15/96		22.8	5.7
5	10/16/96		23.1	5.3
Hourly DO measurements less than 4 mg/L[b]				
2	06/07/96	15:00	22.6	3.7
2	06/07/96	16:00	22.8	3.2
2	06/07/96	17:00	23.2	3.3

[a] 24-hour mean criterion for TNRCC segment 1814.
[b] Minimum DO criterion for TNRCC segment 1814.

Specific conductance.—Specific conductance measurements yielded median values around 600 μS/cm. A slight increase was noted below the WWTP followed by a slight decrease below the confluence with the Blanco River. Periodic low values generally coincided with rainfall events and accompanying dilution of dissolved ions. These results fell within the ranges reported by other investigators. TNRCC (1996) reported ranges of 444–599 μS/cm (mean = 547.7) and 351-657 μS/cm (mean = 517.8) for the upper and lower San Marcos River respectively. Median values reported by Slattery and Fahlquist (1997) fell between 570 and 590 μS/cm, with a noticeable increase below the WWTP. Groeger et al. (1997) reported values from 600 to 700 μS/cm above the WWTP, increasing to approximately 650-750 μS/cm downstream of the WWTP, then decreasing and becoming more variable below the Blanco River confluence. Estimates of total dissolved solids (TDS) made by multiplying specific conductance by 0.65 (TNRCC 1996) resulted in annual means slightly higher than the water quality standards (Table 8). This apparent failure to meet the TDS standard, however, is marginal. Also, since the relationship between specific conductance and TDS varies somewhat and no corresponding TDS samples were analyzed, these data cannot be verified.

Turbidity.—The downstream increase in mean turbidity and variability observed in this study was also noted by Groeger et al. (1997). The springs forming the headwaters are very clear, as indicated

TABLE 8.—Specific conductance results compared to the state surface water quality standard for total dissolved solids (TDS). Attainment of the TDS standard is based on the mean of at least 4 measurements in one year from all stations within the segment.

Year	Specific Conductance	TDS[a]
STATIONS 1, 2, 5 (TNRCC segment 1814)[b]		
1994	600	390
1995	599	389
1996	596	387
1997	597	388
STATION 7 (TNRCC segment 1808)[c]		
1994	No Data	No Data
1995	629	409
1996	598	389
1997	555	361

[a] TDS mg/L = Specific Conductance (μS/cm) X 0.65.
[b] TDS standard = 380 mg/L
[c] TDS standard = 400 mg/L

by very low turbidity values at station 1, nearly all of which were less than 3 NTU. As flow proceeds downstream, increases in suspended sediment contribute to decreasing water clarity. Phytoplankton, particularly in the larger impoundments and downstream of effluent discharges, increase turbidity as well. As water clarity decreases and riparian canopy increases, the euphotic zone becomes shallower, suppressing the growth of submerged macrophytes. These changes are particularly noticeable downstream of the confluence with the Blanco River. One should note however that even at the most downstream station all turbidity measurements were less than 20 NTU, considered a threshold for low turbidity in streams and rivers (USEPA 1999).

Recreation

Recreational boating mostly involves canoeing and kayaking which requires approximately 1ft depths to pass over shallow areas. At these depths paddle strokes occasionally snag aquatic vegetation but are usually not overly destructive as most paddlers avoid entangling and encumbering their paddles with aquatic vegetation.

Tubing is also a very popular activity and during the summer months thousands of recreators use tubes to float down the river (McCoig 1986; Bradsby 1994). Tubers do not have the mobility of paddlers; dangling feet and arms entangle macrophytes and many tubers grasp macrophytes to stop themselves mid-channel. Tubers are often unable to avoid shallow stands of *Z. texana* and impacts in the form of uprooting and or fragmenting of *Z. texana* plants are of concern (Breslin 1997). As depth drops to 1ft or less, passage without deleterious effects becomes almost impossible. At very low flows recreational impacts could become severe.

Spring Flow and Ecosystem Characteristics

Figure 24 provides a flow chart that summarizes the relationship between spring flow and spring ecosystem characteristics and highlights elements of risk to the spring ecosystem. Spring ecosystem characteristics which define the upper San Marcos River can only be maintained by a flow regime that consists of normal, less than normal and above normal spring flows in tune with historical duration and frequency, in addition to the full range of peak flows necessary for flushing, scouring, sediment transport, and channel maintenance.

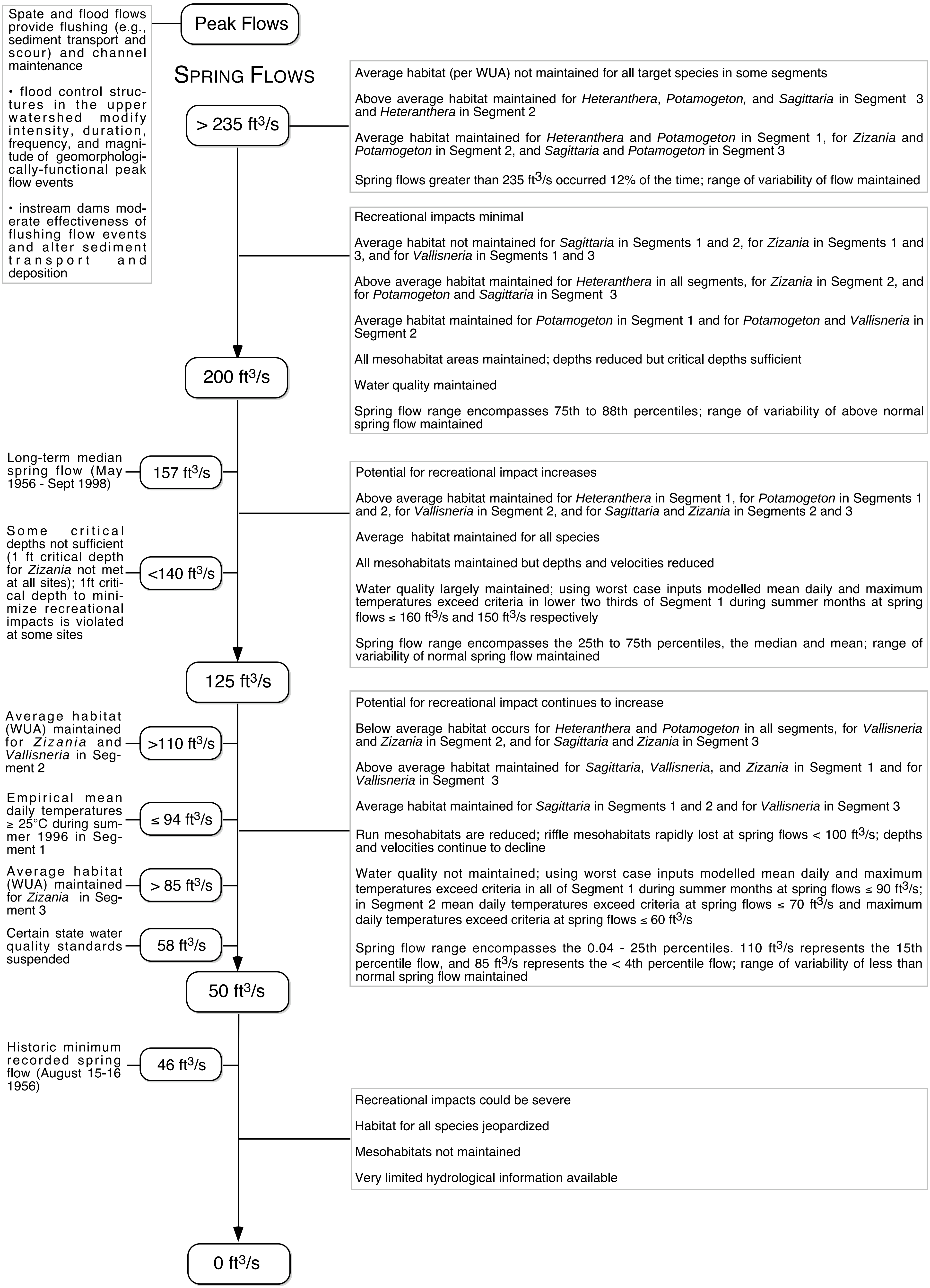
One consideration of flow recommendations is the need to identify when and for how long normal, less than normal and above normal flows are appropriate. Flow regimes vary naturally according to meteorological conditions such as dry, normal, and wet. Based upon gaged spring flow records—altered by historical groundwater withdrawals and recharge zone and watershed modifications—flows of 200 ft^3/s (75th percentile; Figure 2) or greater occur 25% of the time under “wet conditions,” while flows less than 125 ft^3/s (25th percentile) occur 25% of the time under “dry conditions”. Spring flows between 125 and 200 ft^3/s occur 50% of the time during “normal conditions”.

During wet conditions or 25% of the time, flows greater than 200 ft^3/s of sufficient duration would provide average and above average habitat conditions for a variety of ecosystem components in all segments (Figures 12-13). Spring flows in this range maintain water quality, critical depths for *Z. texana* and all mesohabitats, minimize recreational impacts, and play a critical role in maintaining biodiversity. However, below average habitat conditions occur for some species (Figure 14).

During normal conditions or 50% of the time, flows between 125 and 200 ft^3/s of sufficient duration would provide average habitat conditions for all species (Figure 13) and above average habitat conditions for some species in all segments (Figure 12). Spring flows in this range provide protection for all mesohabitats. At flows less than 140 ft^3/s, critical depths for *Z. texana* are violated (Appendix IV: Figure 8) and the potential for recreational impact increases. Generally, water quality is maintained, but during hot summer months (July and August) modeled mean daily water temperatures exceeded 25 °C in Segment 1 even at flows greater than the median.

During dry conditions or 25% of the time, flows up to 125 ft^3/s, of sufficient duration, provide above average habitat conditions for some species in Segments 1 and 3 (Figure 12), average habitat conditions for a limited number of species in all segments (Figure 13), and below average habitat conditions for many species in all segments (Figure 14). Run mesohabitats are reduced in area, riffle mesohabitats are rapidly lost at flows less than 100 ft^3/s (Figure 6), and depths and current velocities appreciably decline (see Appendix I). In addition, at

ECOSYSTEM CHARACTERISTICS AND EXPECTED CHANGES (ELEMENTS OF RISK)



Peak Flows

Spate and flood flows provide flushing (e.g., sediment transport and scour) and channel maintenance

- flood control structures in the upper watershed modify intensity, duration, frequency, and magnitude of geomorphologically-functional peak flow events
- instream dams moderate effectiveness of flushing flow events and alter sediment transport and deposition

> 235 ft³/s

Average habitat (per WUA) not maintained for all target species in some segments

Above average habitat maintained for *Heteranthera*, *Potamogeton,* and *Sagittaria* in Segment 3 and *Heteranthera* in Segment 2

Average habitat maintained for *Heteranthera* and *Potamogeton* in Segment 1, for *Zizania* and *Potamogeton* in Segment 2, and *Sagittaria* and *Potamogeton* in Segment 3

Spring flows greater than 235 ft³/s occurred 12% of the time; range of variability of flow maintained

> 235 ft³/s – 200 ft³/s

Recreational impacts minimal

Average habitat not maintained for *Sagittaria* in Segments 1 and 2, for *Zizania* in Segments 1 and 3, and for *Vallisneria* in Segments 1 and 3

Above average habitat maintained for *Heteranthera* in all segments, for *Zizania* in Segment 2, and for *Potamogeton* and *Sagittaria* in Segment 3

Average habitat maintained for *Potamogeton* in Segment 1 and for *Potamogeton* and *Vallisneria* in Segment 2

All mesohabitat areas maintained; depths reduced but critical depths sufficient

Water quality maintained

Spring flow range encompasses 75th to 88th percentiles; range of variability of above normal spring flow maintained

200 ft³/s – 125 ft³/s

157 ft³/s: Long-term median spring flow (May 1956 - Sept 1998)

<140 ft³/s: Some critical depths not sufficient (1 ft critical depth for *Zizania* not met at all sites); 1ft critical depth to minimize recreational impacts is violated at some sites

Potential for recreational impact increases

Above average habitat maintained for *Heteranthera* in Segment 1, for *Potamogeton* in Segments 1 and 2, for *Vallisneria* in Segment 2, and for *Sagittaria* and *Zizania* in Segments 2 and 3

Average habitat maintained for all species

All mesohabitats maintained but depths and velocities reduced

Water quality largely maintained; using worst case inputs modelled mean daily and maximum temperatures exceed criteria in lower two thirds of Segment 1 during summer months at spring flows ≤ 160 ft³/s and 150 ft³/s respectively

Spring flow range encompasses the 25th to 75th percentiles, the median and mean; range of variability of normal spring flow maintained

125 ft³/s – 50 ft³/s

>110 ft³/s: Average habitat (WUA) maintained for *Zizania* and *Vallisneria* in Segment 2

≤ 94 ft³/s: Empirical mean daily temperatures ≥ 25°C during summer 1996 in Segment 1

> 85 ft³/s: Average habitat (WUA) maintained for *Zizania* in Segment 3

58 ft³/s: Certain state water quality standards suspended

Potential for recreational impact continues to increase

Below average habitat occurs for *Heteranthera* and *Potamogeton* in all segments, for *Vallisneria* and *Zizania* in Segment 2, and for *Sagittaria* and *Zizania* in Segment 3

Above average habitat maintained for *Sagittaria*, *Vallisneria*, and *Zizania* in Segment 1 and for *Vallisneria* in Segment 3

Average habitat maintained for *Sagittaria* in Segments 1 and 2 and for *Vallisneria* in Segment 3

Run mesohabitats are reduced; riffle mesohabitats rapidly lost at spring flows < 100 ft³/s; depths and velocities continue to decline

Water quality not maintained; using worst case inputs modelled mean daily and maximum temperatures exceed criteria in all of Segment 1 during summer months at spring flows ≤ 90 ft³/s; in Segment 2 mean daily temperatures exceed criteria at spring flows ≤ 70 ft³/s and maximum daily temperatures exceed criteria at spring flows ≤ 60 ft³/s

Spring flow range encompasses the 0.04 - 25th percentiles. 110 ft³/s represents the 15th percentile flow, and 85 ft³/s represents the < 4th percentile flow; range of variability of less than normal spring flow maintained

50 ft³/s – 0 ft³/s

46 ft³/s: Historic minimum recorded spring flow (August 15-16 1956)

Recreational impacts could be severe

Habitat for all species jeopardized

Mesohabitats not maintained

Very limited hydrological information available

FIGURE 24.–Flow chart relating San Marcos Springs ecosystem characteristics to spring flow. Peak flows refer to runoff events not included in the San Marcos spring flow record (USGS Gage # 08170000).

100 ft^3/s, approximately 5% of *Z. texana* habitat would be exposed to depths of less than or equal to 1 ft while 30% would be exposed to depths less than or equal to 1.5 ft, (Appendix IV: Figure 8). During hot summer months (June through August) measured water temperatures exceeded 25 °C in downstream portions of this spring ecosystem at flows of 94 ft^3/s. At flows less than 90 ft^3/s, an unacceptable risk exists that decreased depths would be detrimental to *Z. texana* in some segments (Appendix IV: Figure 8) especially as seasonal recreational impacts intensify. At 65 ft^3/s, modeled maximum water temperatures exceed Texas Water Quality Standards (26.7 °C) in May in Segment 1 (using 85th percentile air temperatures). When absolute minima (46–54 ft^3/s) were modeled both modeled average daily and maximum water temperatures exceed criteria in summer months in Segments 1 and 2.

Because of the dominance of slow velocities during relatively low flows (e.g., 85% of velocities were $\leq$ 0.7 ft/s at 100 ft^3/s) species that exhibit high preference for slow velocity habitats would be favored including the invasive macrophytes, *H. verticillata*, *H. polysperma* and *E. densa*, and the exotic giant ramshorn snail which tends to increase in number during low flow conditions (Arsuffi et al. 1993) These species could monopolize more habitats forming large, homogeneous, monotypic stands in the case of exotic macrophytes and or impact native species through herbivory (giant ramshorn snail).

Dynamics of the macrophyte community are fundamental to understanding how this spring ecosystem functions and how biodiversity is related to historical flow. Unfortunately, a “natural” picture will never be available if exotic species are always present, peak flows are always attenuated by flood control structures, and physical and hydraulic conditions continue to be altered by instream dams and channelization.

Narrow focus on a constant flow would have temporal and spatial implications for all spring ecosystem elements. This type of focus would result in decreased system diversity because spatial considerations would not be met. The range of spring flows that maintain the full extent of habitat conditions necessary for each species in each segment varies, thus a narrow focus on specific flows would not be protective of the entire spring ecosystem. In order to protect each species, this spring ecosystem clearly must be maintained—to this end, a flow regime that encompasses the historic flow range is paramount.

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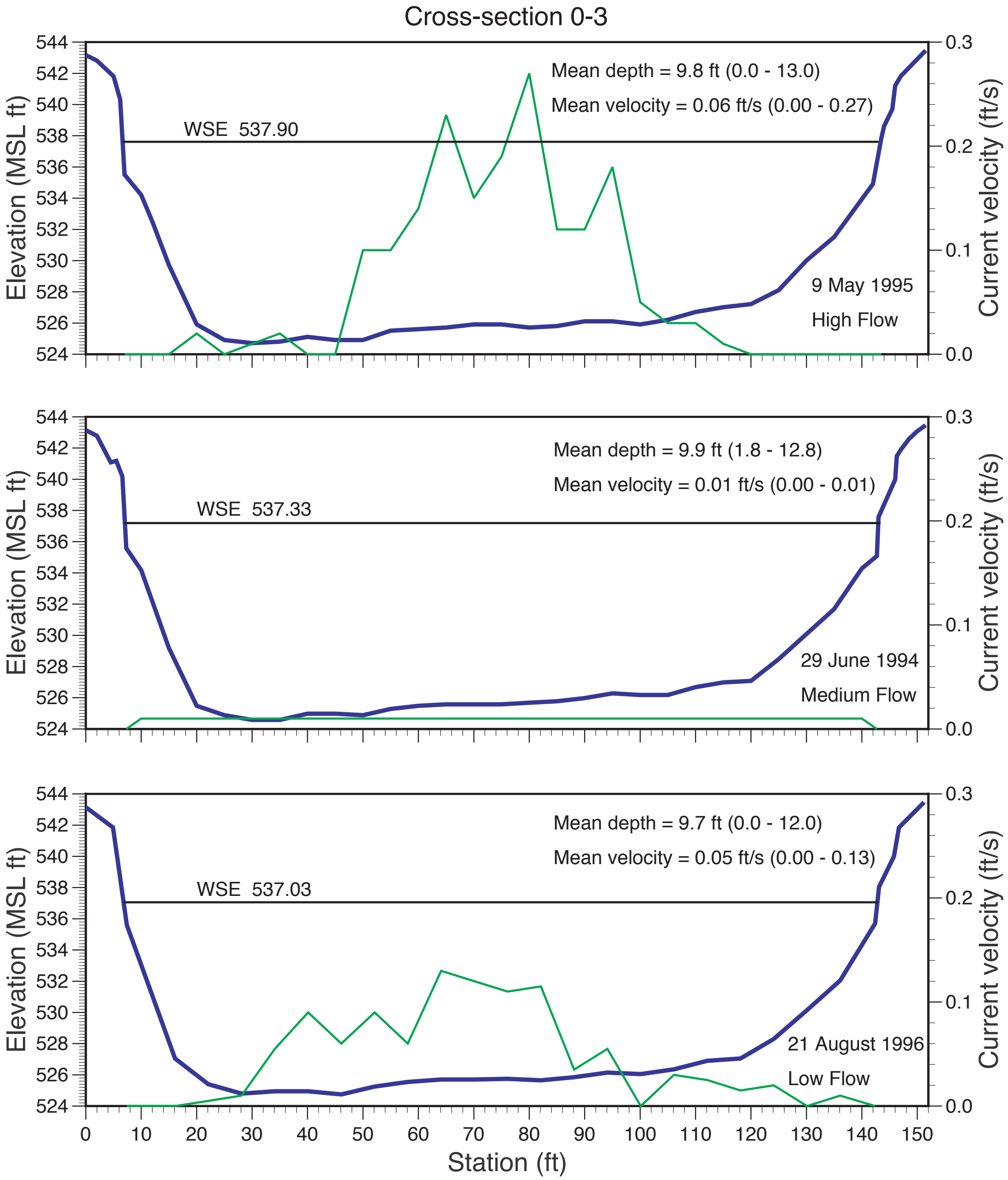
Appendix I
Cross-section Profiles

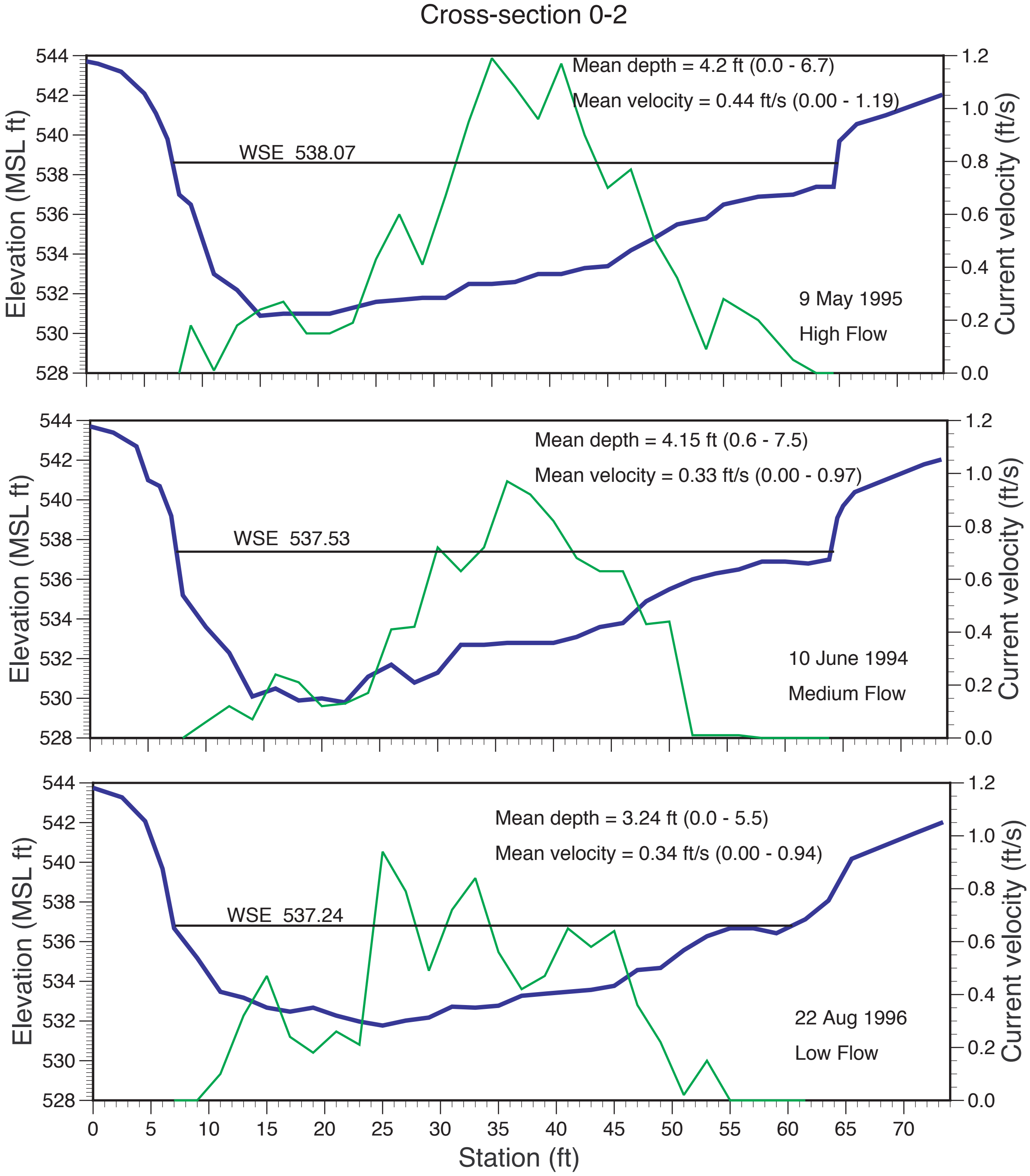
APPENDIX I: TABLE 1.—Aquatic macrophytes observed during cross-section surveys during the period from August 1993 through August 1996.

		Segment 1 Cross-sections							Segment 2 Cross-sections												Segment 3 Cross-sections								
Species	Status[a]	0-3	0-2	0-1	0	1	2	3	4	5	6	7	8	9	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Azolla caroliniana	N																										X		
Cabomba caroliniana	N														X	X		X										X	
Ceratophyllum demersum	N																								X				
Ceratopteris thalictroides	I																					X					X		
Colocasia esculenta	I	X	X						X	X	X	X		X	X	X	X	X		X	X	X	X	X	X		X		X
Cryptocoryne cf. *beckettii*	I			X		X																							
Egeria densa	I					X					X		X		X			X	X		X	X				X	X		
Filamentous algae	N		X	X	X	X	X	X	X		X	X					X	X	X	X			X	X		X	X		X
Heteranthera liebmannii	N					X	X												X	X									
Hydrilla verticillata	I		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X
Hydrocotyle umbellata	N																												X
Hygrophila polysperma	I		X	X	X	X	X		X		X	X	X	X	X	X	X	X	X		X	X	X	X	X		X	X	X
Justicia americana	N						X		X			X							X										
Nuphar luteum	N															X													
Potamogeton illinoensis	N					X												X				X	X	X	X	X	X	X	X
Sagittaria platyphylla	N				X																	X	X	X	X		X	X	
Vallisneria americana	N				X		X	X							X		X	X	X	X		X		X					
Zizania texana	N					X	X	X				X		X	X		X	X	X			X	X				X	X	X

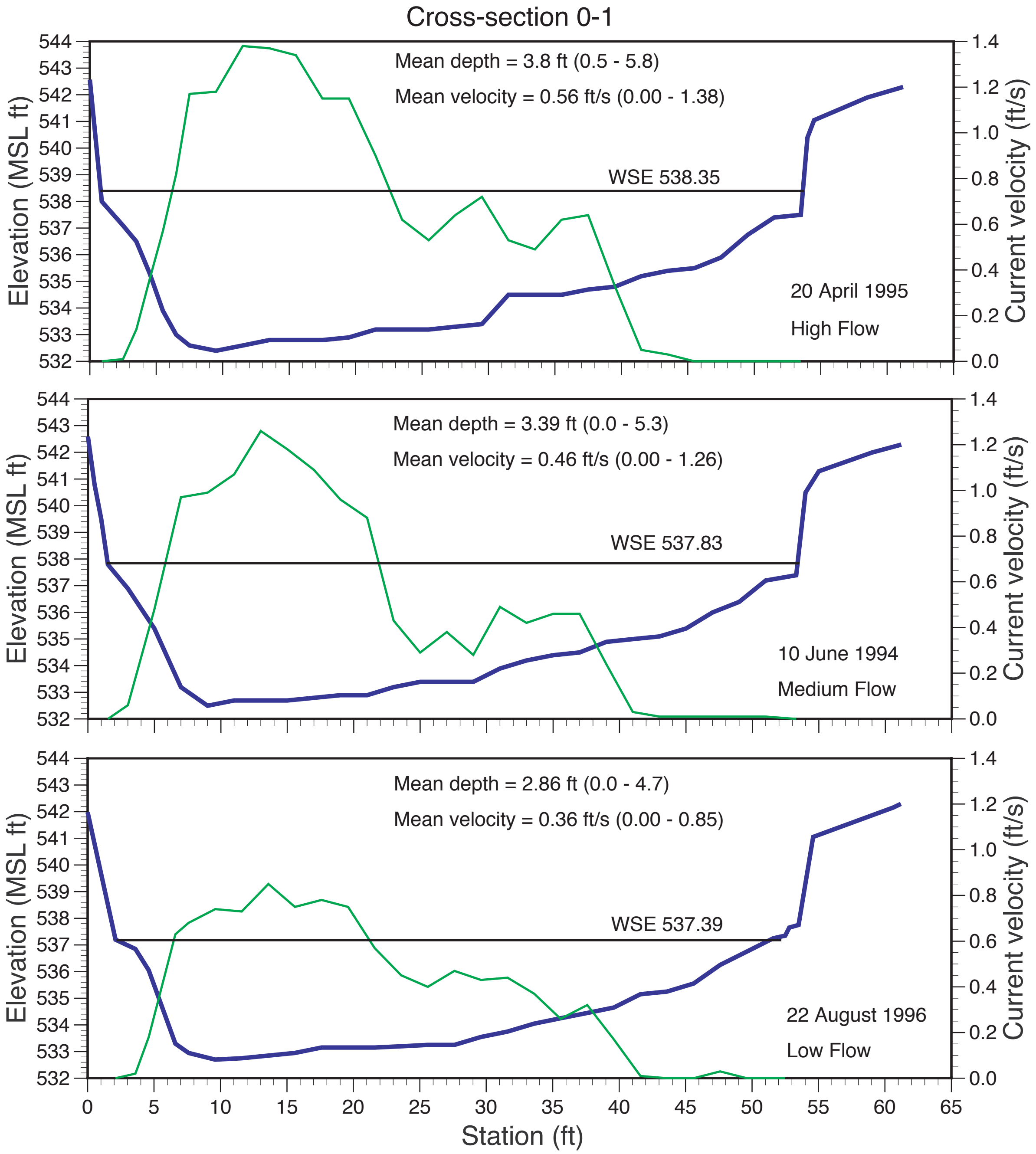
[a] N = native; I = introduced



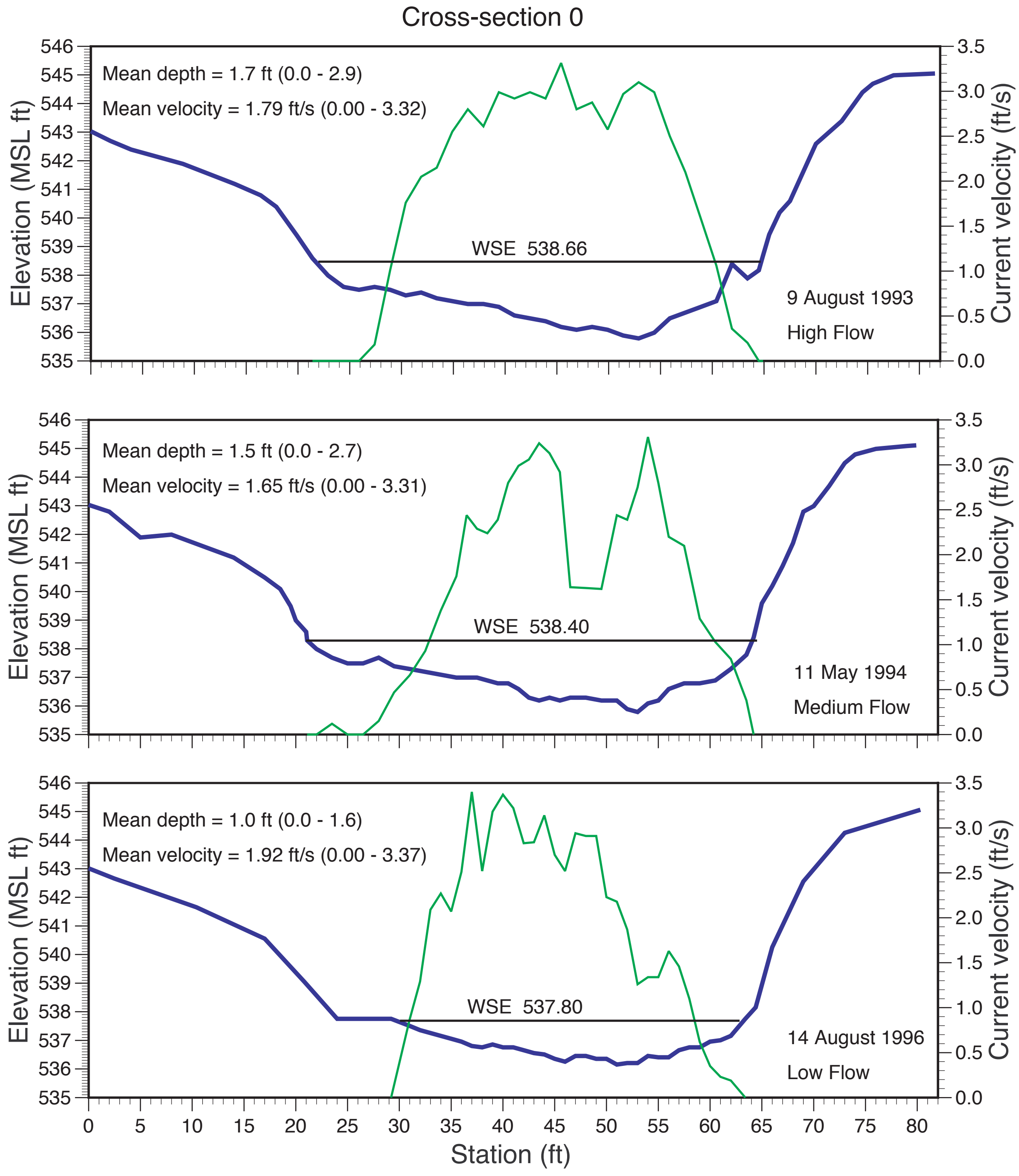
APPENDIX I: FIGURE 1.—Cross-section 0-3: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is pool mesohabitat in Segment 1 with silt substrate and sparse *Colocasia esculenta* and *Nuphar luteum.*



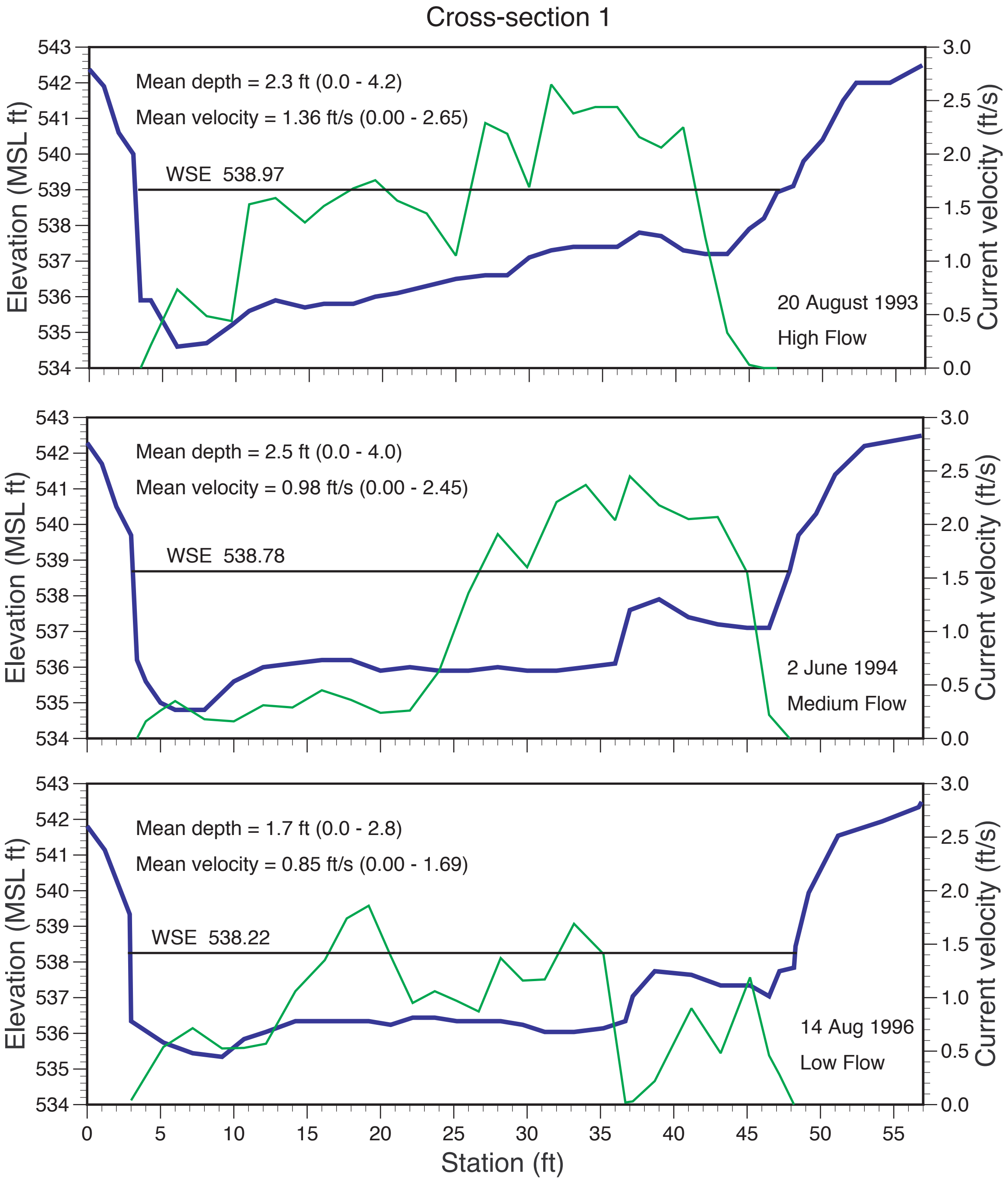
APPENDIX I: FIGURE 2.—Cross-section 0-2: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is run mesohabitat in Segment 1 with silt, clay, and sand substrate and sparse *Colocasia esculenta, Hygrophila polysperma, Hydrilla verticillata,* and filamentous algae.



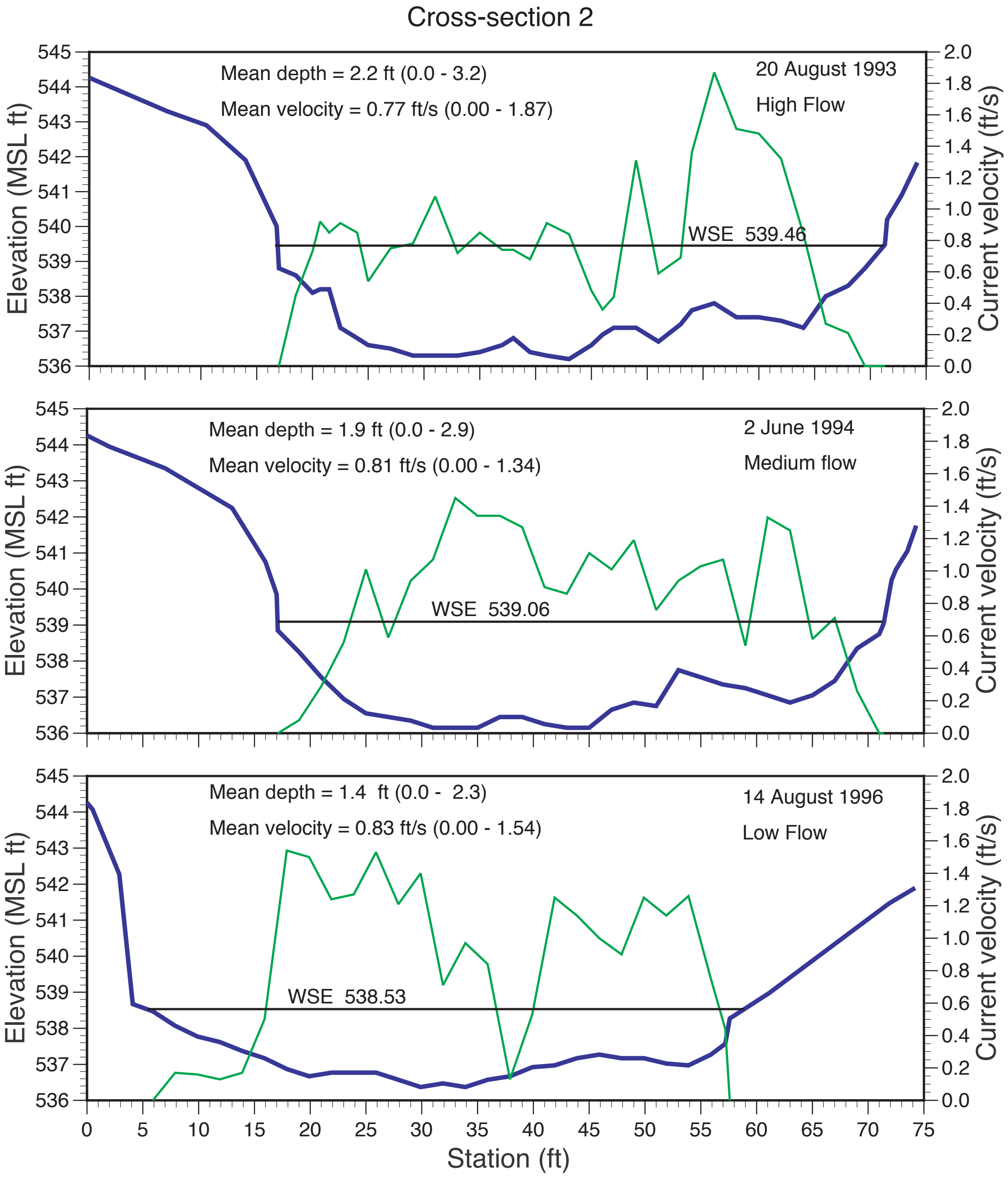
APPENDIX I: FIGURE 3.—Cross-section 0-1: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is run mesohabitat in Segment 1 with silt, clay and sand substrate and sparse *Hygrophila polysperma*, *Cryptocoryne* cf. *beckettii* and filamentous algae.



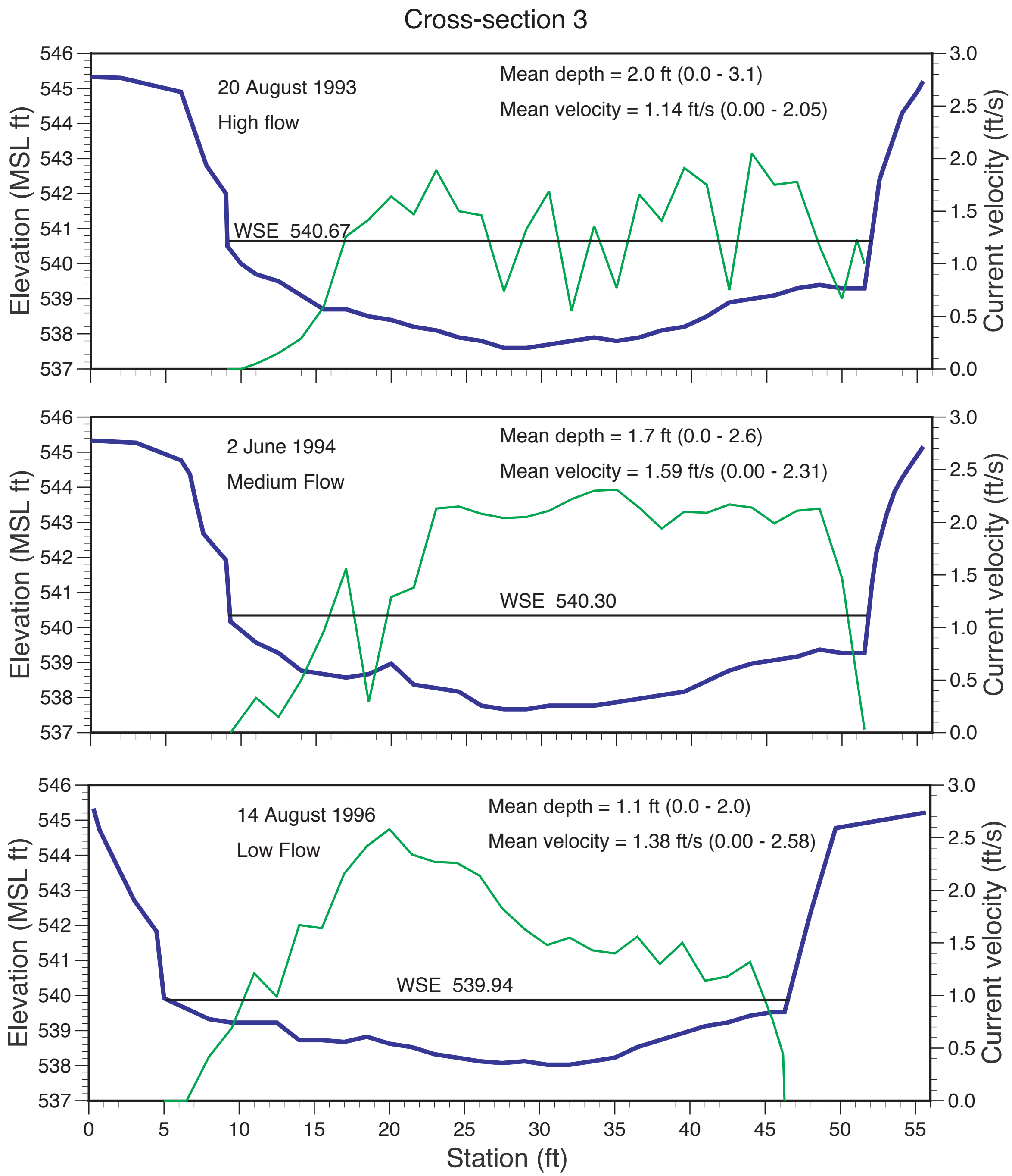
APPENDIX I: FIGURE 4.—Cross-section 0: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is fast shallow run mesohabitat, in Segment 1 with a mixed gravel substrate and sparse *Hygrophila polysperma, Hydrilla verticillata, Vallisneria americana* and filamentous algae.



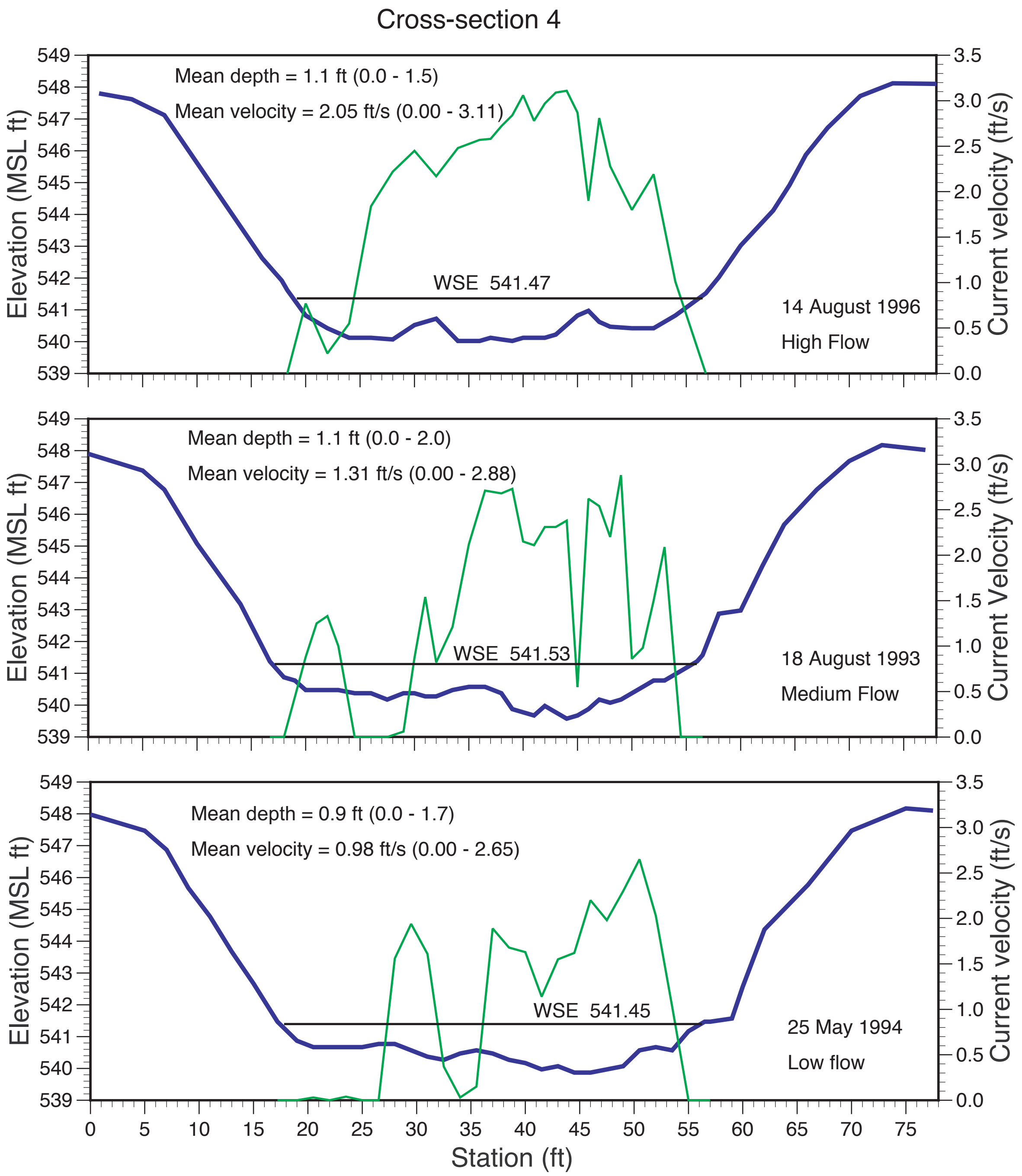
APPENDIX I: FIGURE 5.—Cross-section 1: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is run mesohabitat in Segment 1 with sand, fine gravel, and silt substrate and sparse *Cryptocoryne* cf. *beckettii*, *Hygrophila polysperma, Heteranthera liebmannii, Hydrilla verticillata* and filamentous algae.



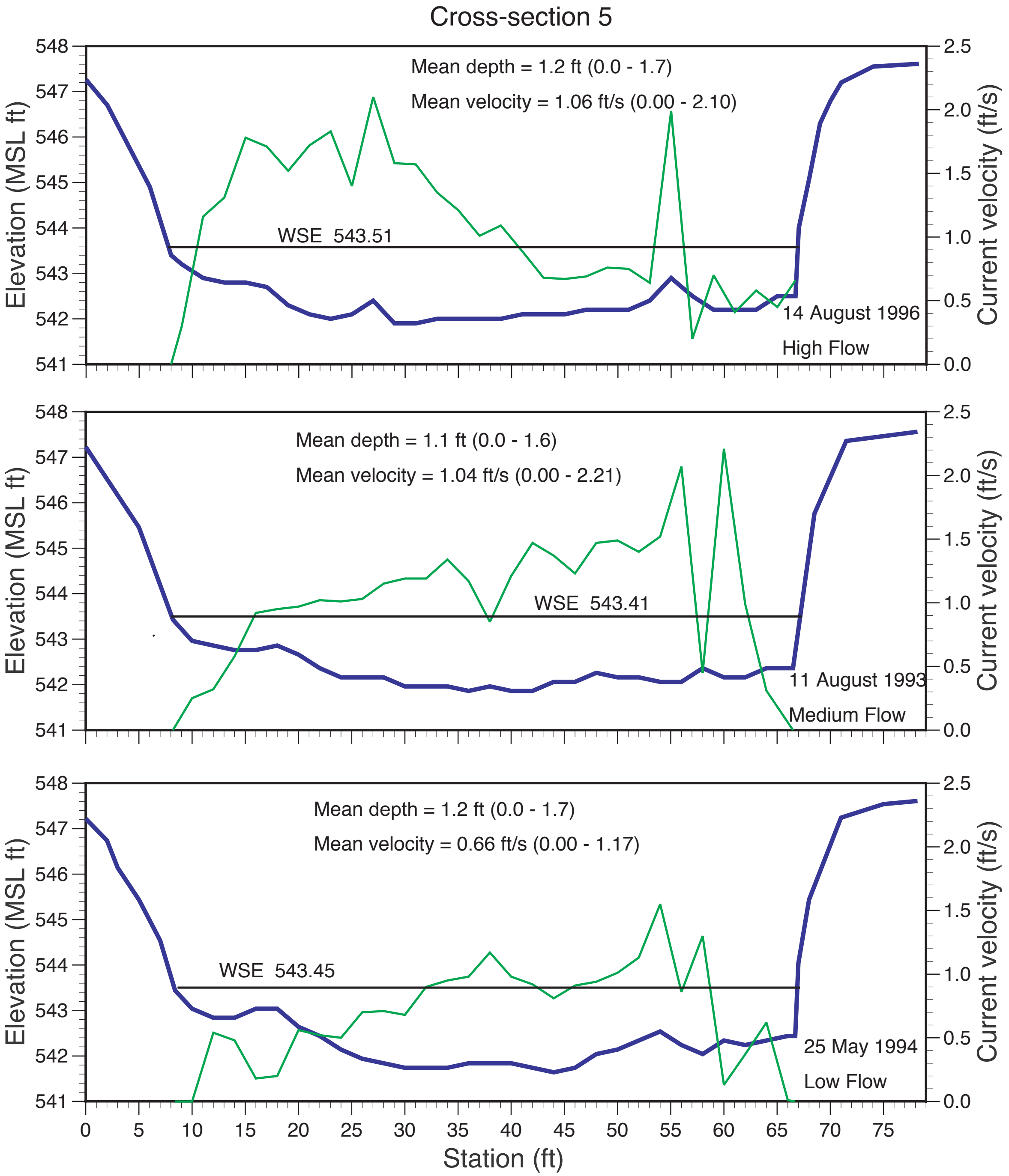
Appendix I: Figure 6.—Cross-section 2: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is fast run mesohabitat in Segment 1 with sand, silt and clay substrate and *Zizania texana, Vallisneria americana, Hygrophila polysperma, Heteranthera liebmannii* and *Justicia americana.*



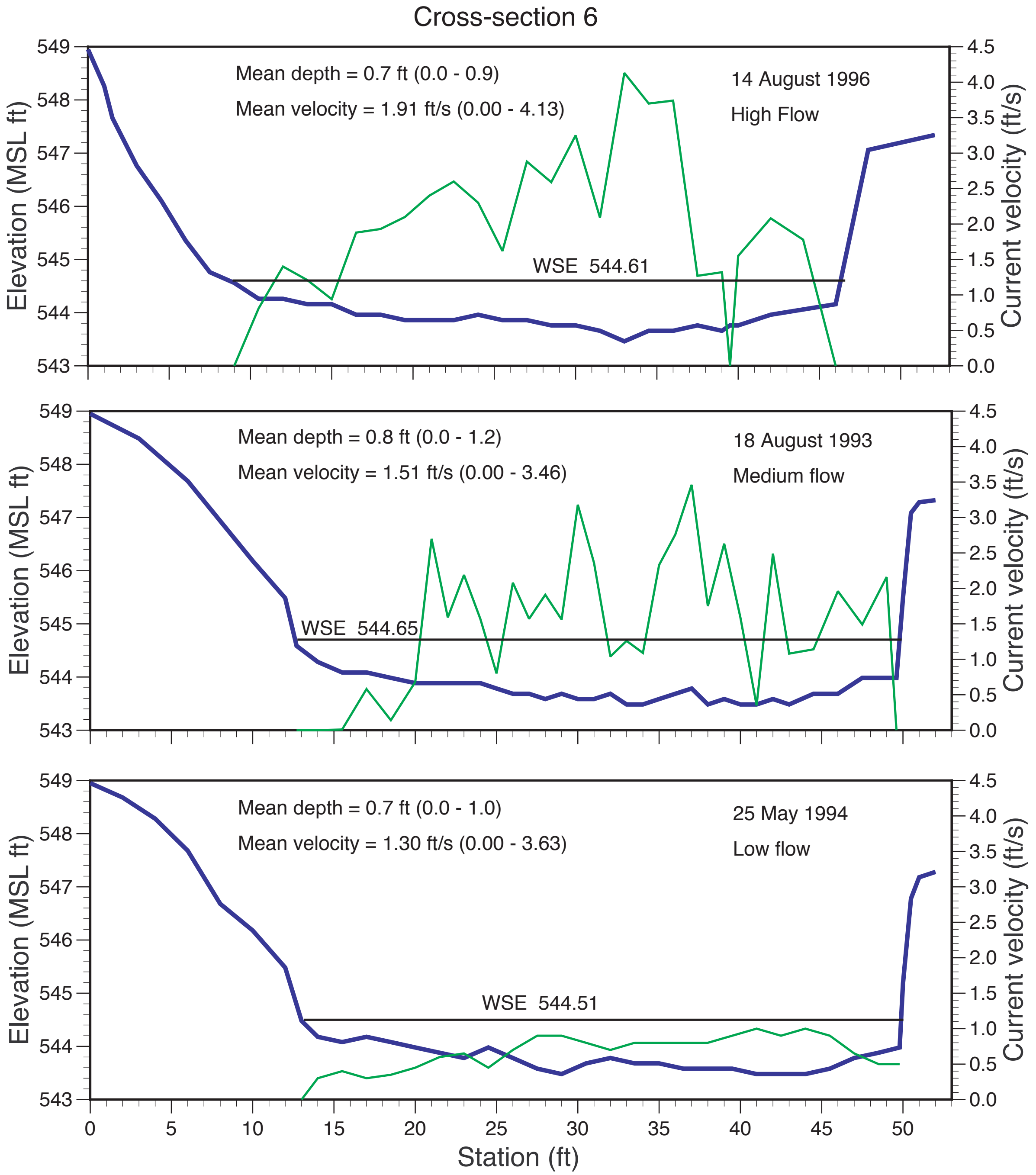
APPENDIX I: FIGURE 7.—Cross-section 3: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is fast run mesohabitat in Segment 1 with sand and gravel substrate and *Zizania texana, Vallisneria americana, Hydrilla verticillata* and filamentous algae.



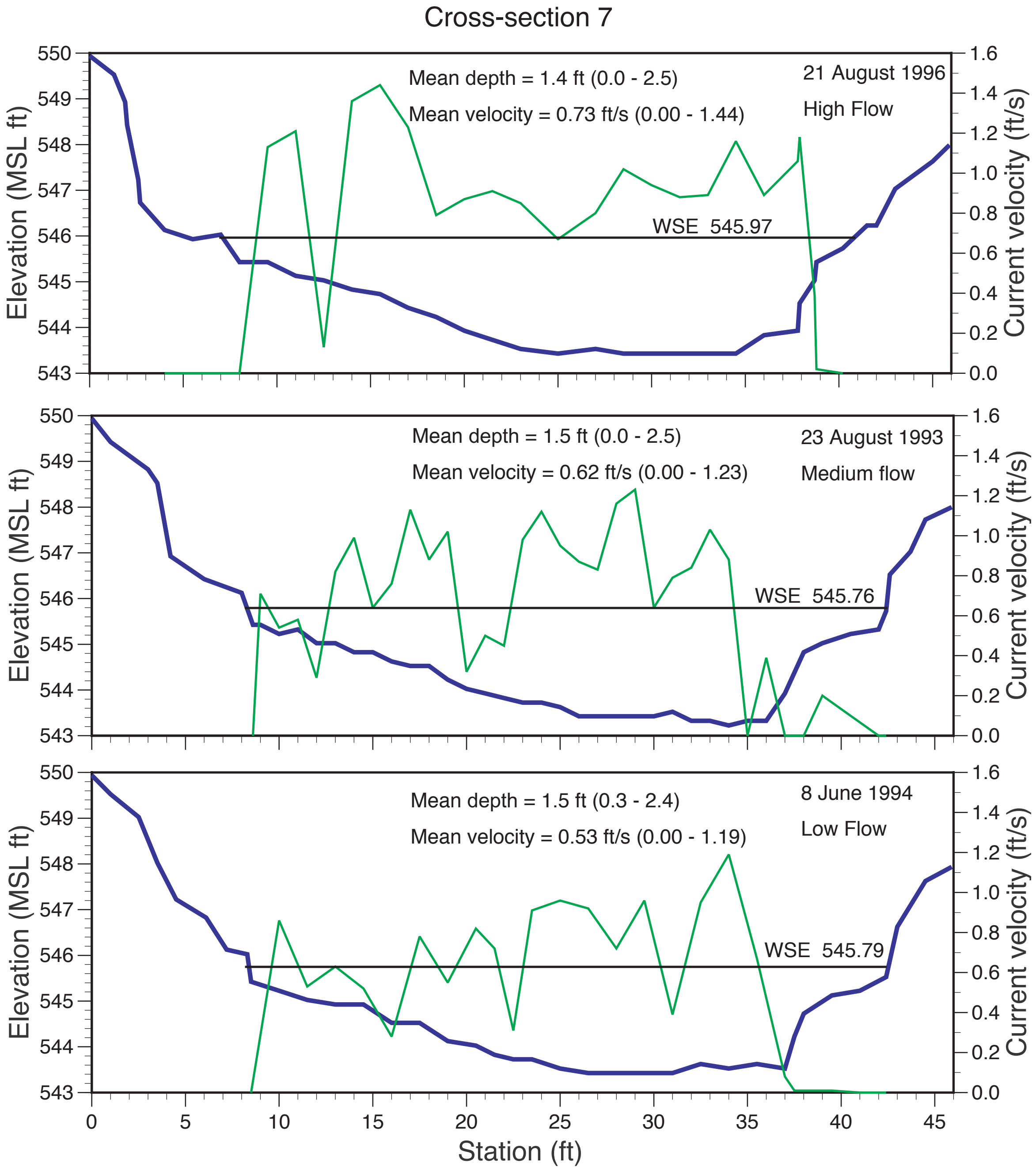
APPENDIX I: FIGURE 8.—Cross-section 4: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is fast run mesohabitat in Segment 2 with sand and small gravel substrate and *Hydrilla verticillata*, filamentous algae, *Hygrophila polysperma, Justicia americana* and *Colocasia esculenta*.



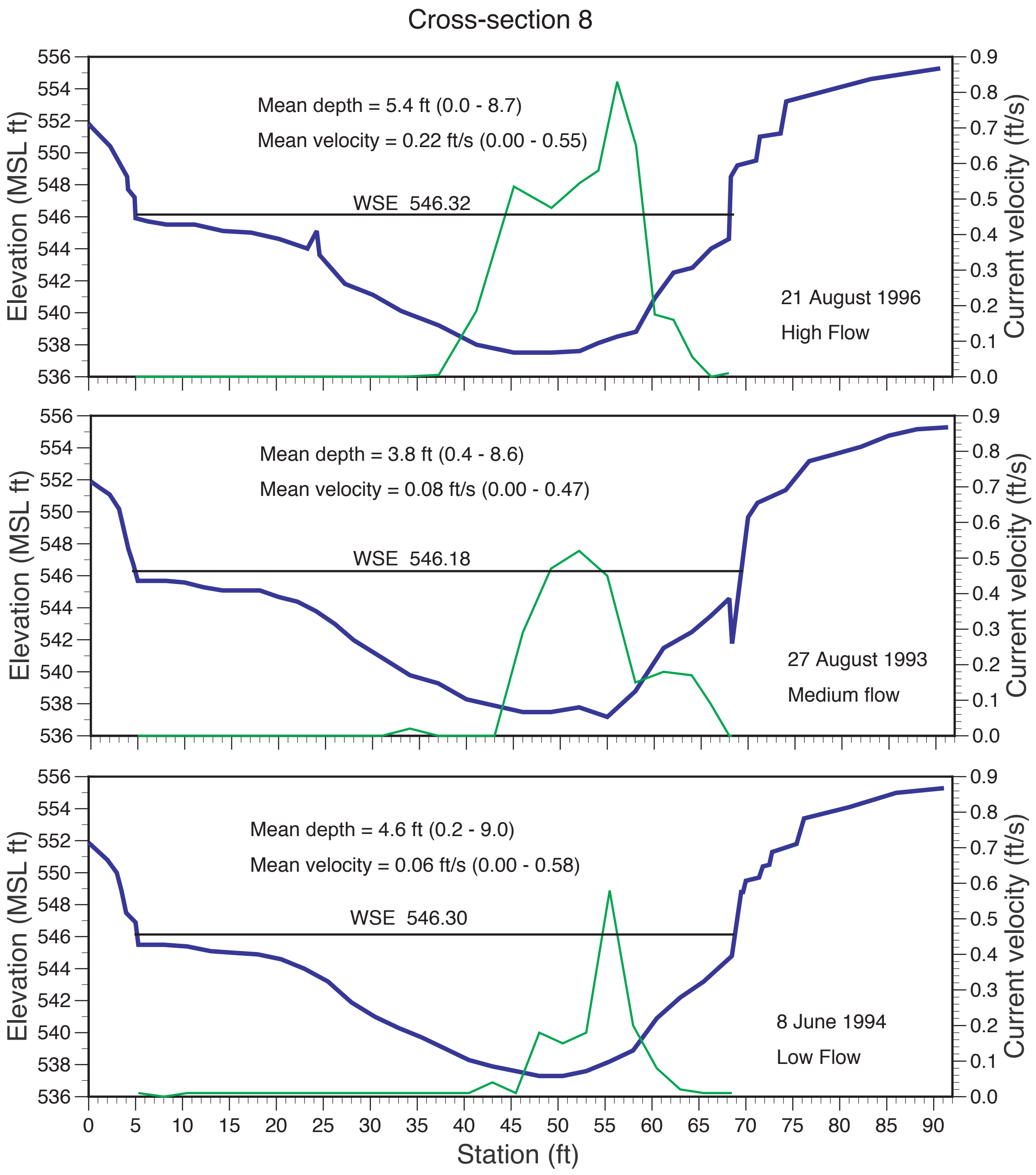
APPENDIX I: FIGURE 9.—Cross-section 5: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is riffle mesohabitat in Segment 2 with sand and mixed gravel and *Hydrilla verticillata, Colocasia esculenta* and *Vallisneria americana.*



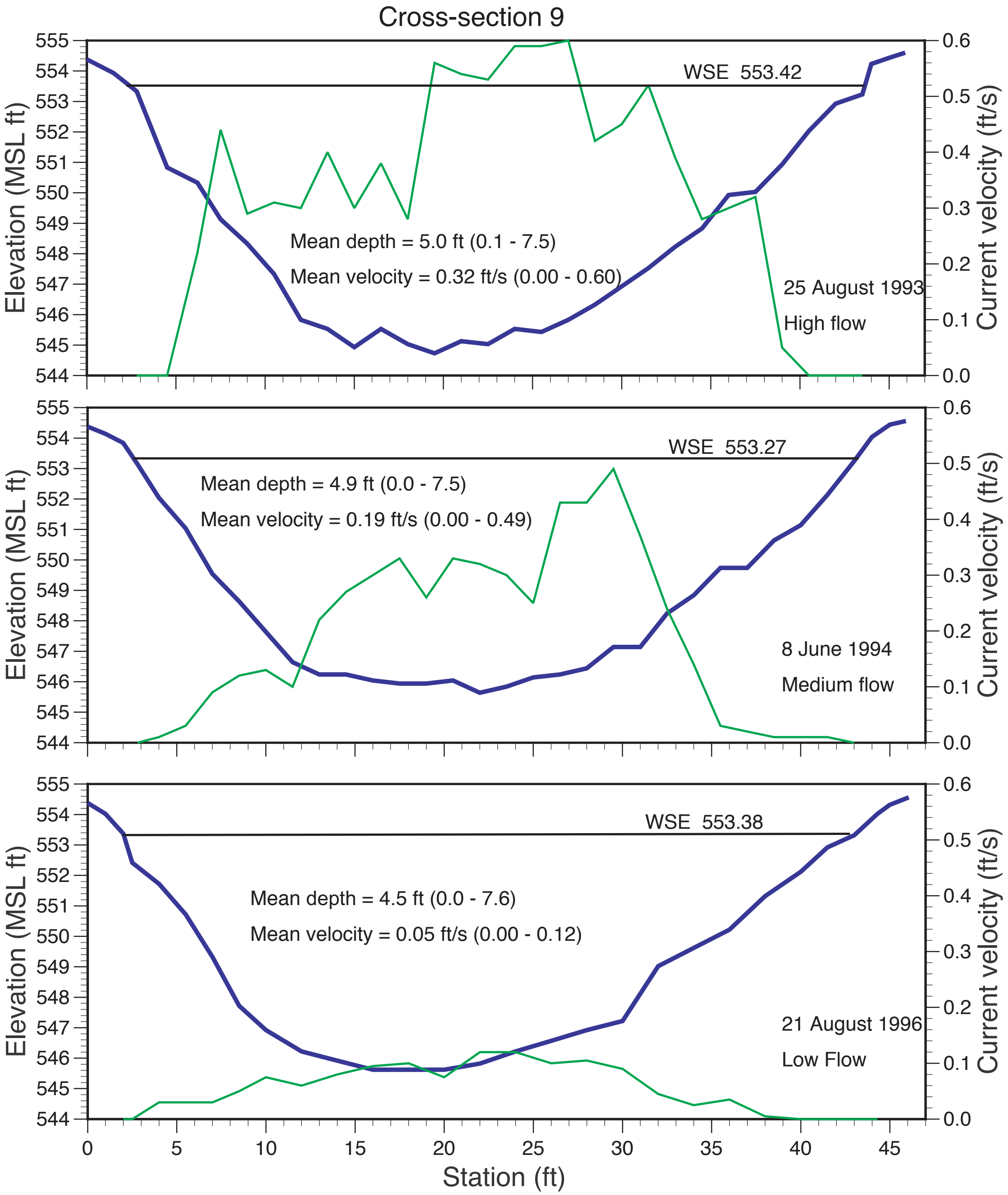
APPENDIX I: FIGURE 10.—Cross-section 6: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is riffle mesohabitat in Segment 2 with coarse and large gravel and some cobble substrate and sparse filamentous algae, *Hydrilla verticillata* and *Colocasia esculenta.*



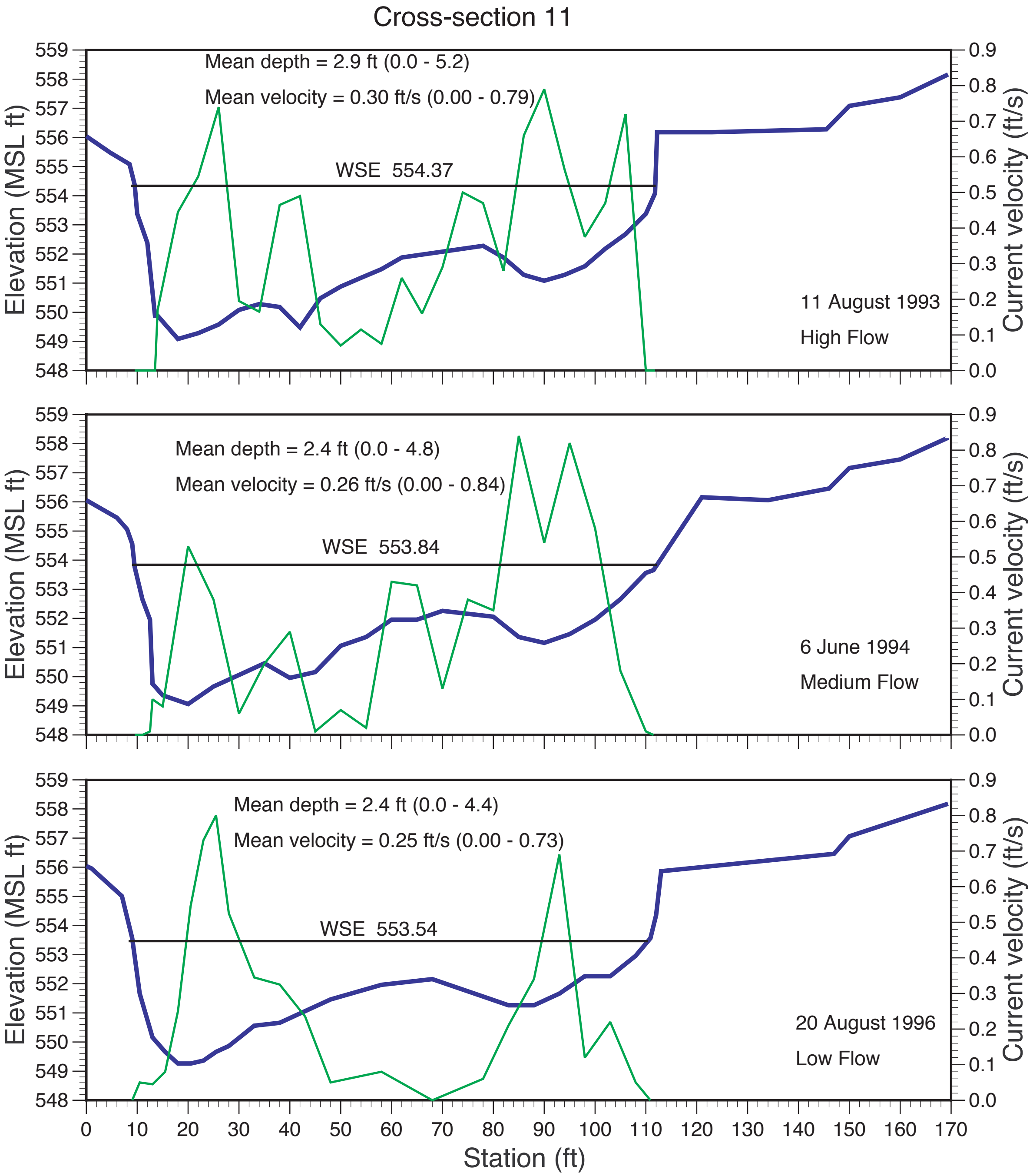
APPENDIX I: FIGURE 11.—Cross-section 7: Bottom profile, water surface elevation (WSE) and current velocity distribution ilustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is fast shallow run mesohabitat in Segment 2 with sand and gravel substrate and *Zizania texana, Hygrophila polysperma,* filamentous algae, *Hydrilla verticillata* and *Colocasia esculenta.*



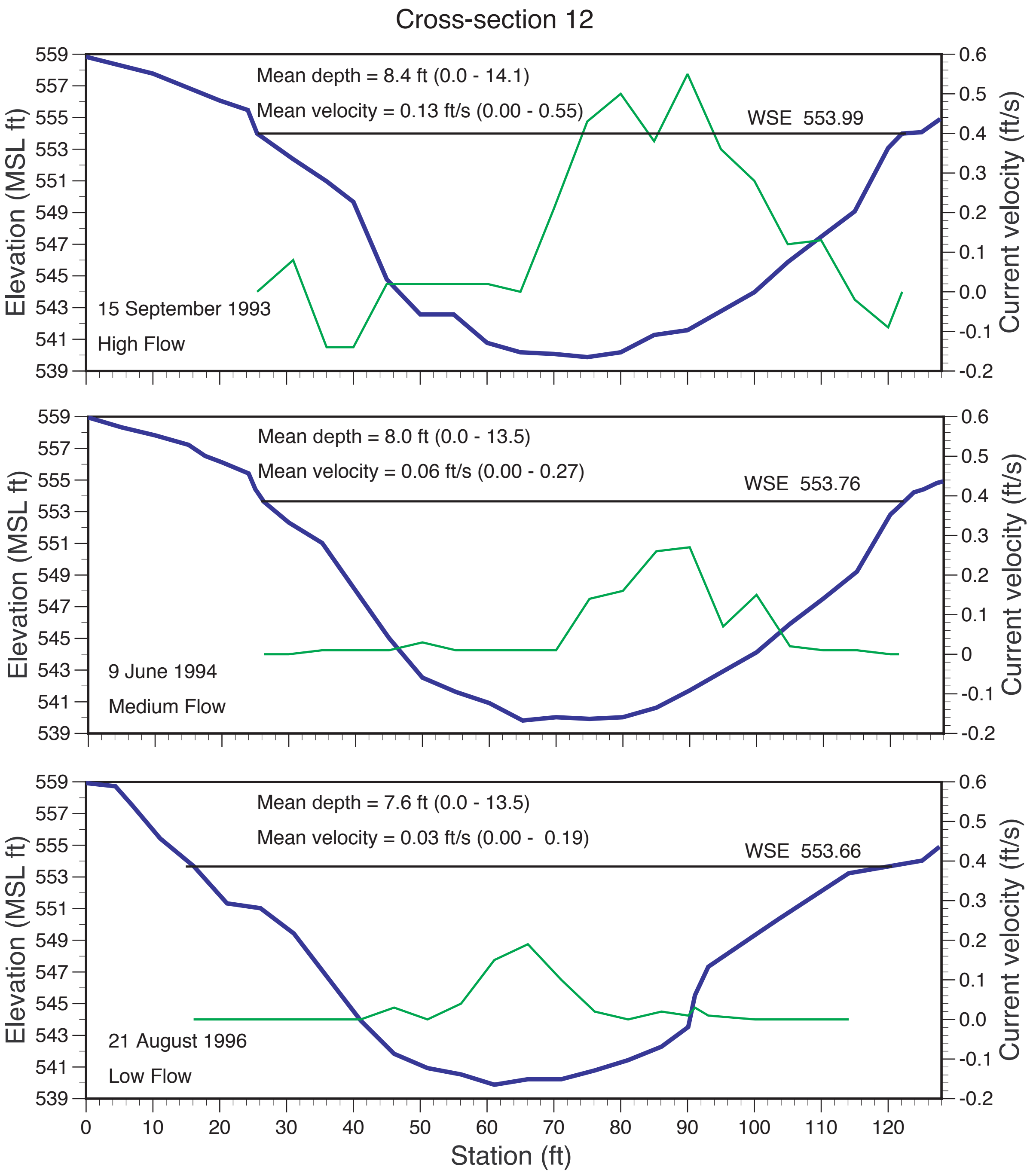
APPENDIX I: FIGURE 12.—Cross-section 8: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is pool mesohabitat in Segment 2 with silt, sand and clay substrate and very sparse *Hygrophila polysperma* and *Hydrilla verticillata.*



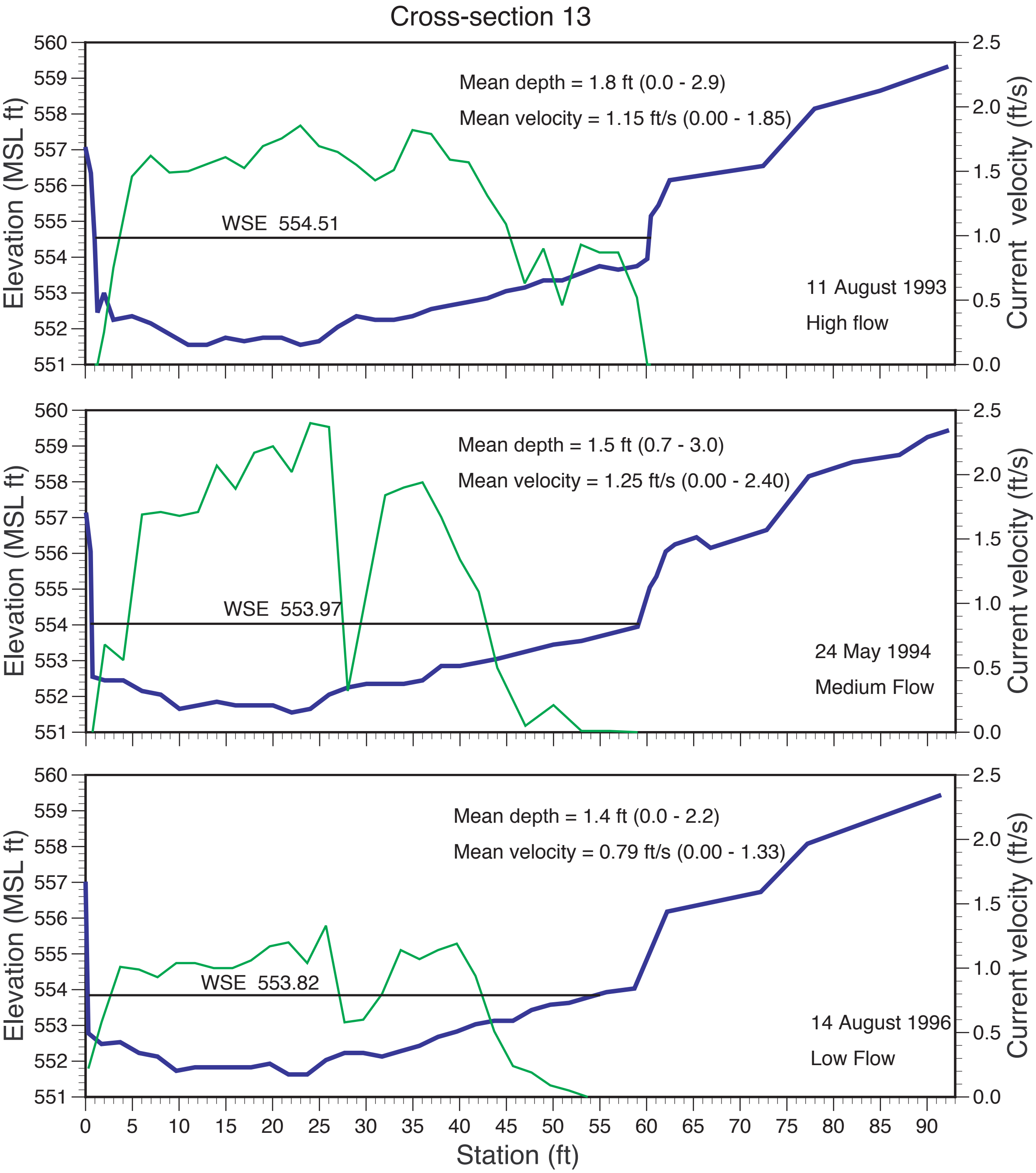
APPENDIX I: FIGURE 13.—Cross-section 9: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is slow deep run mesohabitat in Segment 2 with silt substrate and dense *Hydrilla verticillata*, *Colocasia esculenta* and *Hygrophila polysperma.*



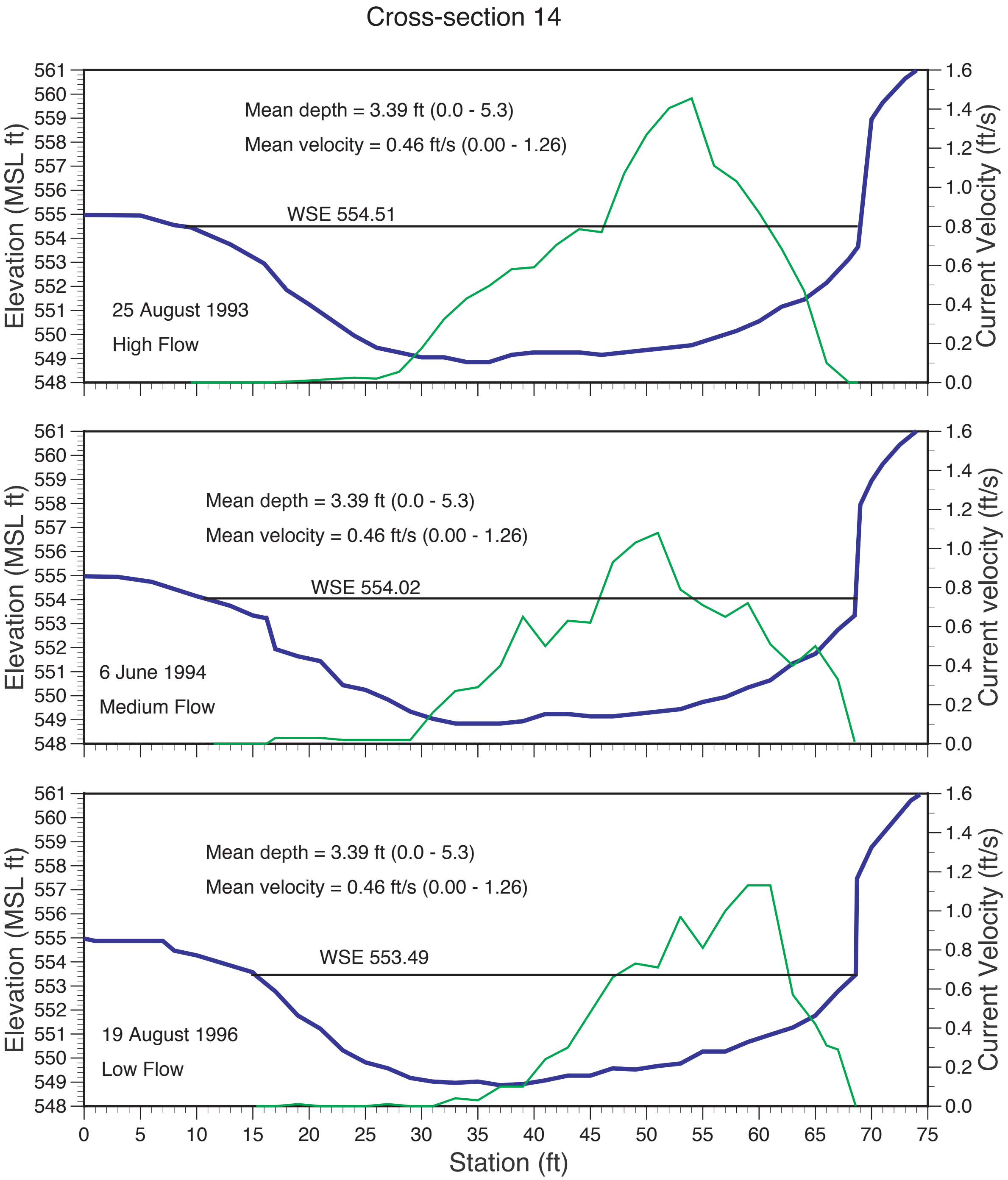
APPENDIX I: FIGURE 14.—Cross-section 11: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is run mesohabitat in Segment 2 with predominately silt and sand substrate and *Zizania texana, Vallisneria americana, Hygrophila polysperma* and *Colocasia esculenta.*



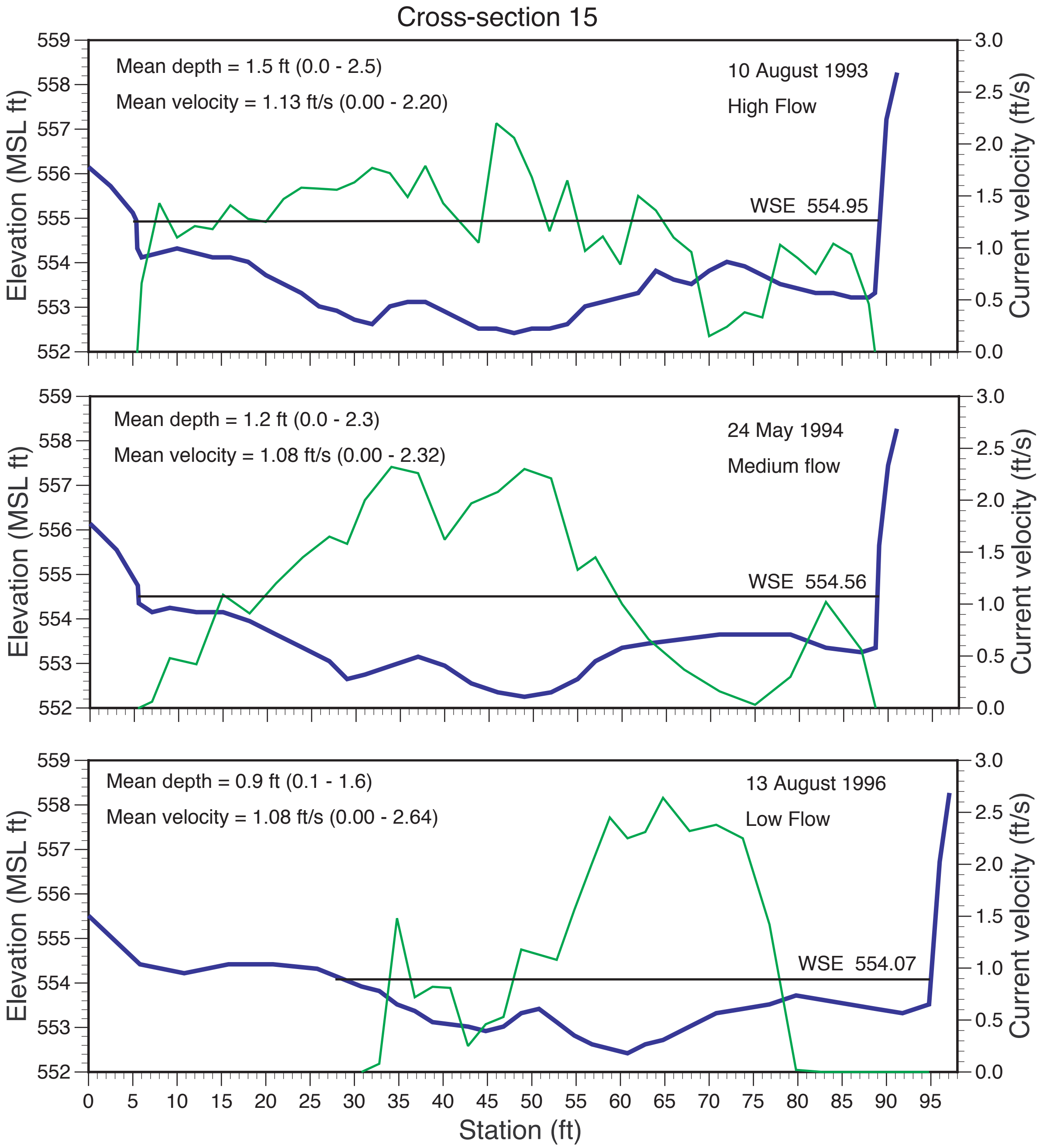
APPENDIX I: FIGURE 15.—Cross-section 12: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is pool mesohabitat in Segment 2 with silt, clay and sand substrate and *Cabomba caroliniana, Hydrilla verticillata, Colocasia esculenta* and *Hygrophila polysperma.*



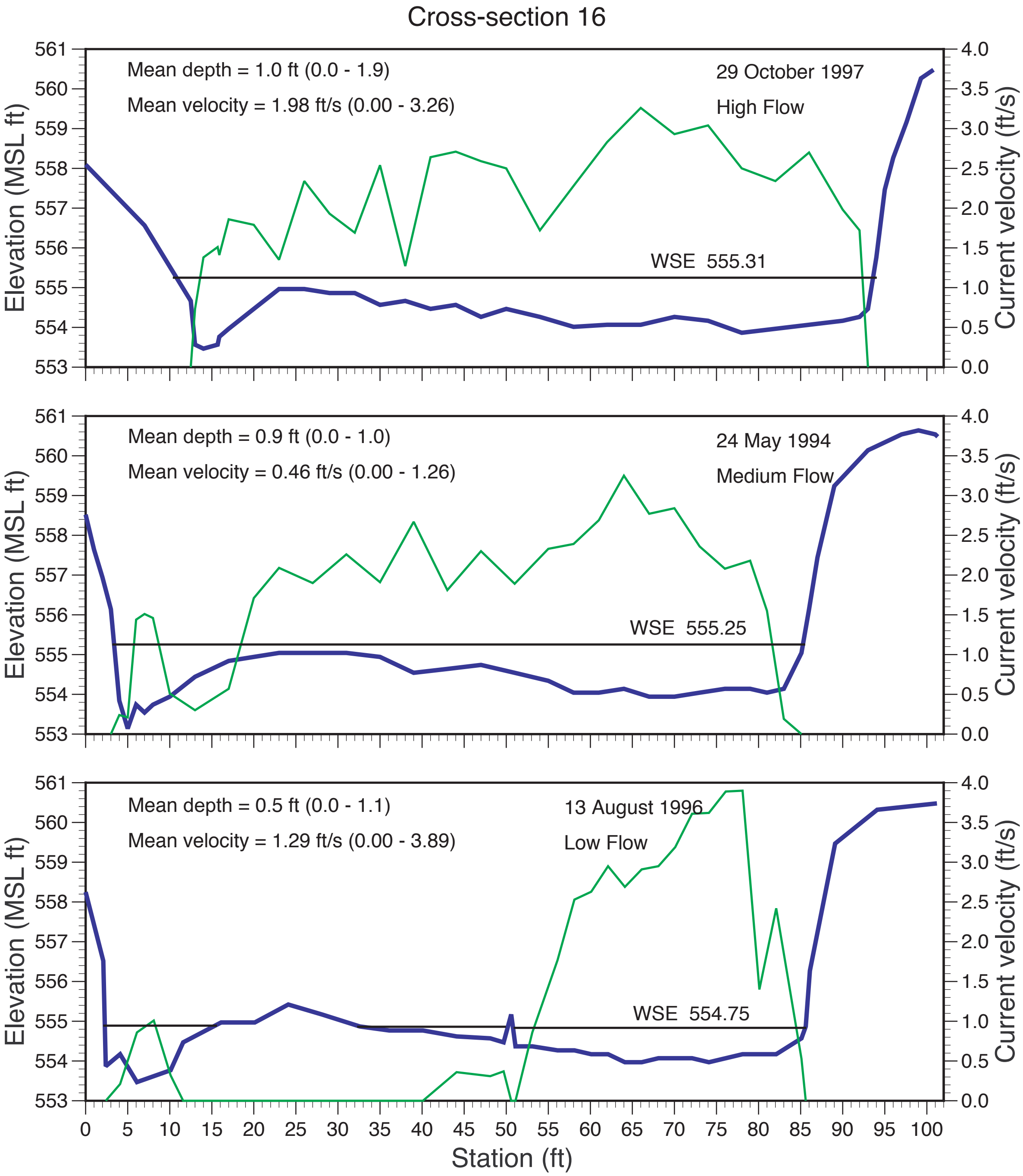
APPENDIX I: FIGURE 16.—Cross-section 13: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is fast shallow run mesohabitat in Segment 2 with sand, gravel and bedrock substrate and *Zizania texana*, *Vallisneria americana*, *Hygrophila polysperma*, filamentous algae and *Colocasia esculenta*.



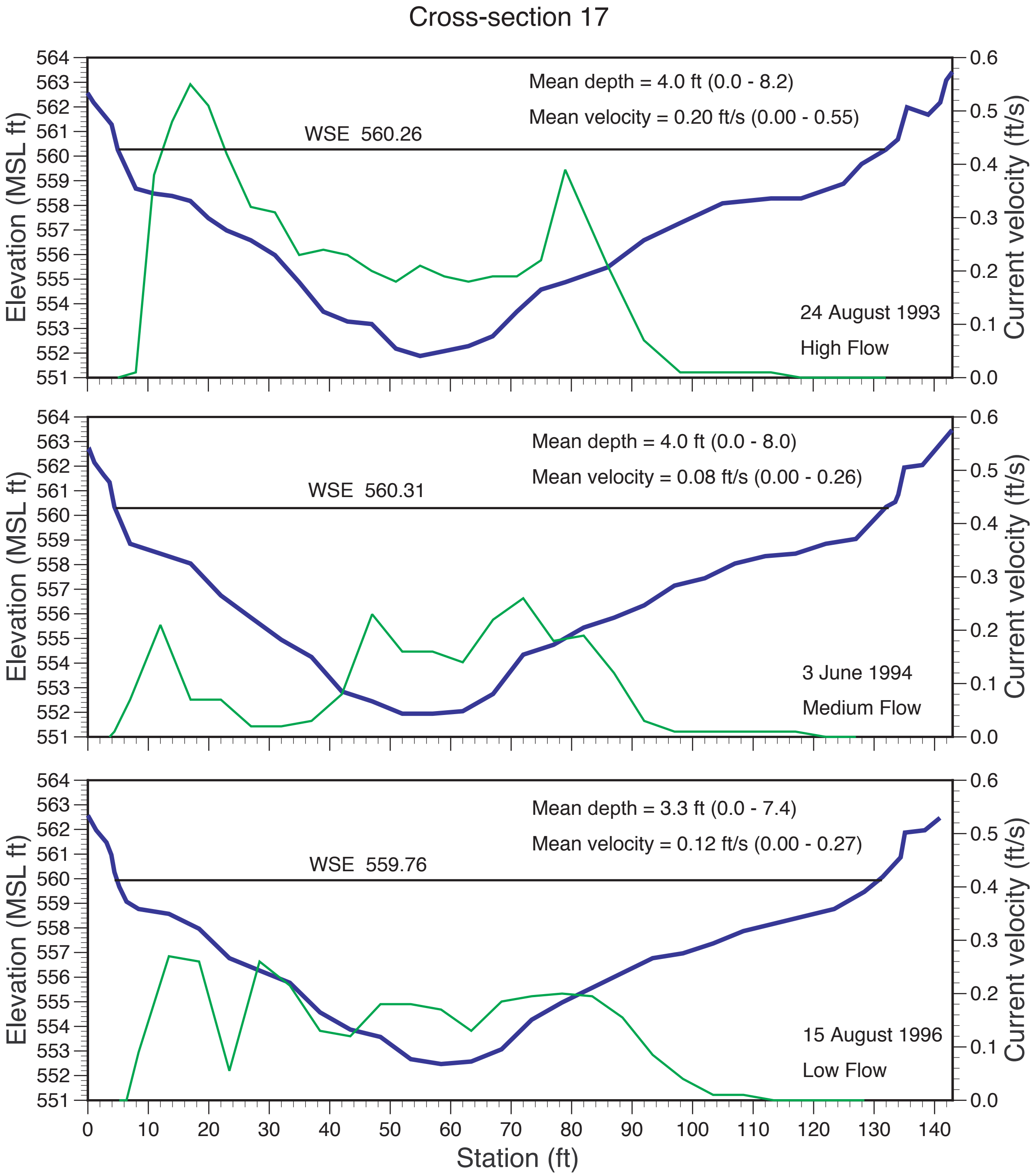
APPENDIX I: FIGURE 17.—Cross-section 14: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is run mesohabitat in Segment 2 with sand and silt substrate and *Zizania texana, Cabomba caroliniana, Colocasia esculenta, Hygrophila polysperma* and *Hydrilla verticillata.*



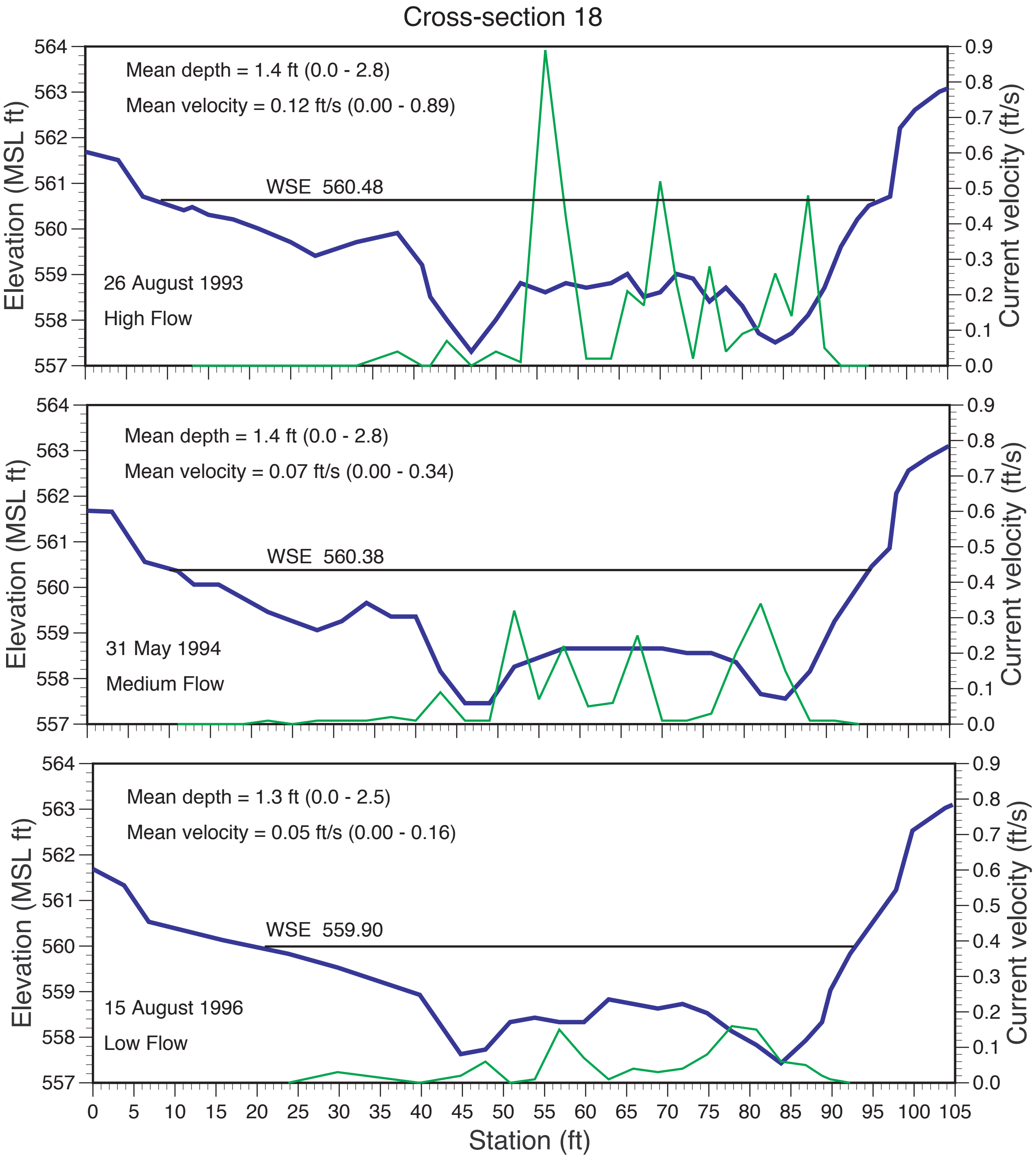
APPENDIX I: FIGURE 18.—Cross-section 15: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is fast run mesohabitat in Segment 2 with sand and mixed gravel substrate and *Zizania texana, Vallisneria americana, Hygrophila polysperma* and *Hydrilla verticillata.*



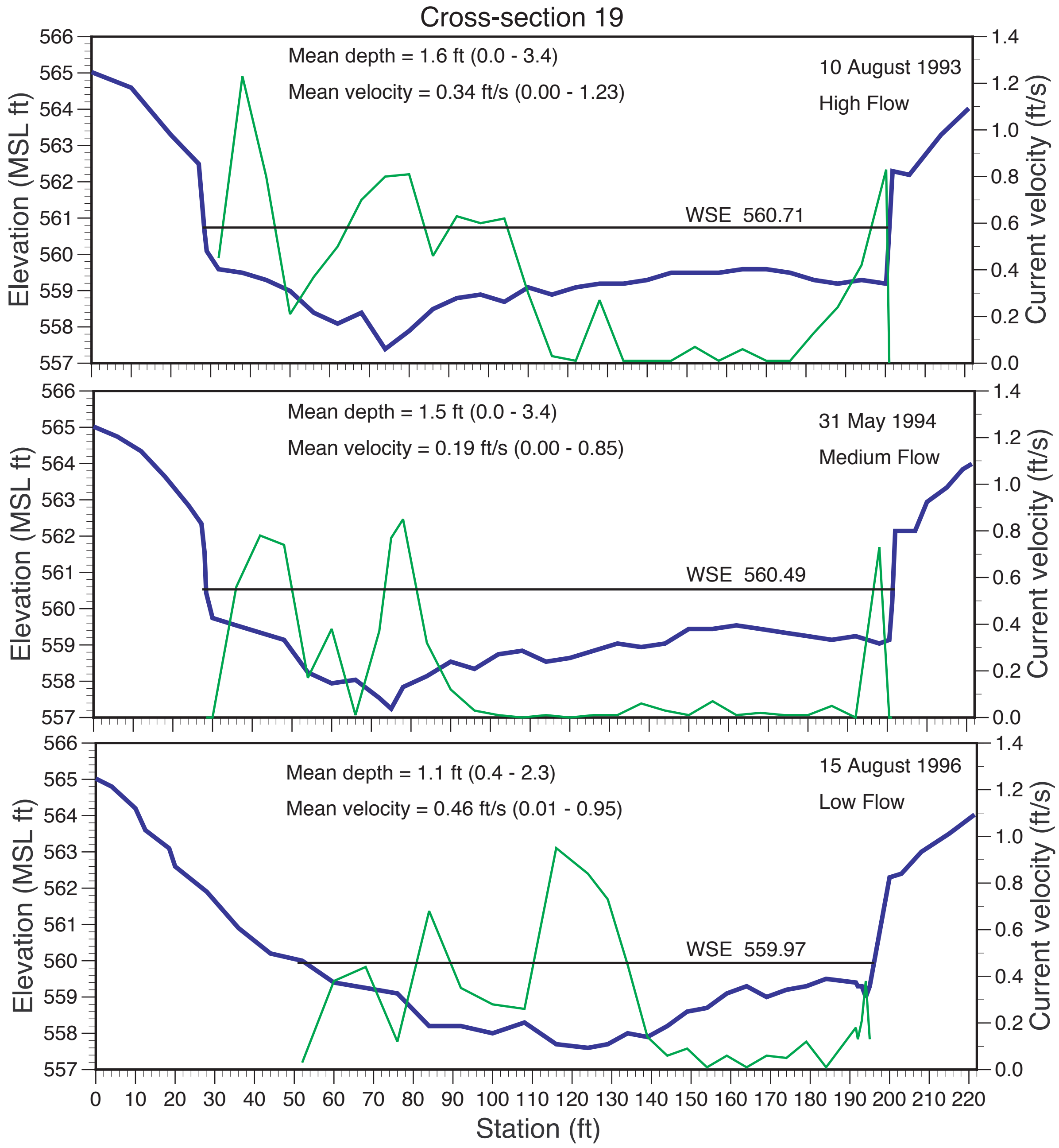
APPENDIX I: FIGURE 19.—Cross-section 16: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is riffle mesohabitat in Segment 2 with mixed gravel, sand and cobble substrate and sparse *Colocasia esculenta*, *Hydrilla verticillata*, filamentous algae and *Vallisneria americana.*



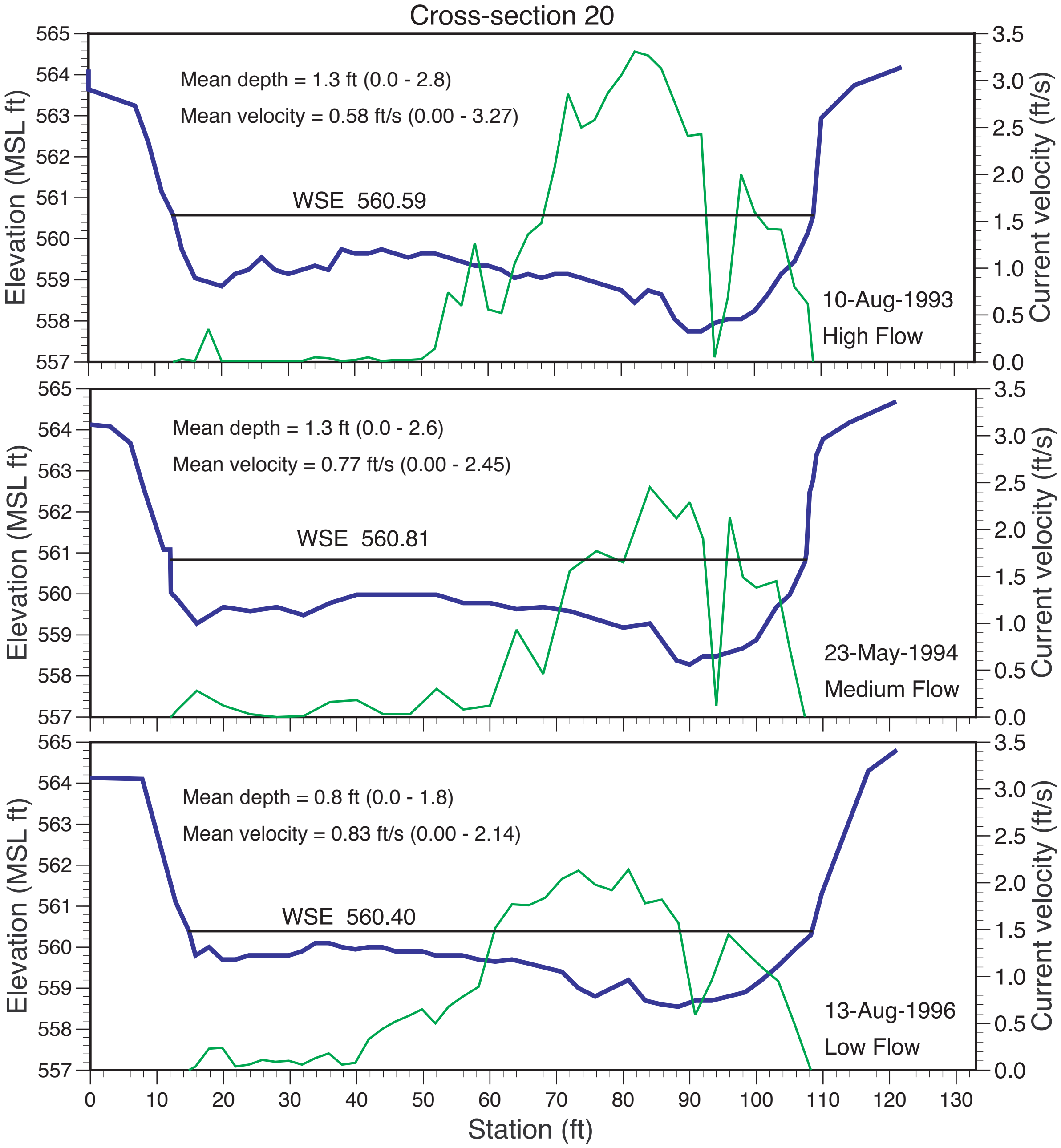
APPENDIX I: FIGURE 20.—Cross-section 17: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is pool mesohabitat in Segment 3 with mostly silt substrate and some sand and dense *Egeria densa, Hydrilla verticillata, Colocasia esculenta* and *Hygrophila polysperma.*



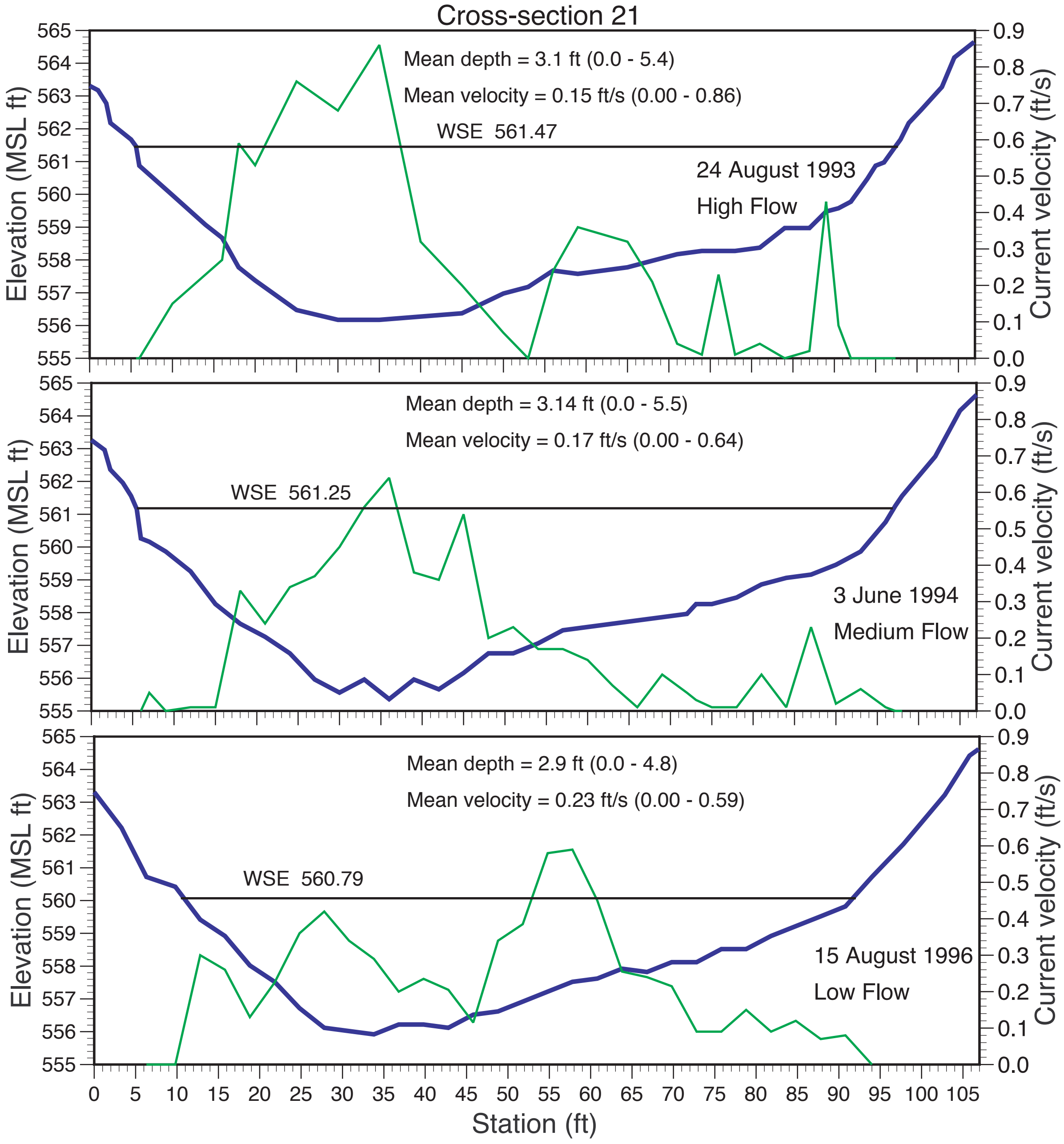
APPENDIX I: FIGURE 21.—Cross-section 18: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is slow run mesohabitat in Segment 3 with silt substrate and *Zizania texana, Hygrophila polysperma, Colocasia esculenta, Vallisneria americana* and *Sagittaria platyphylla.*



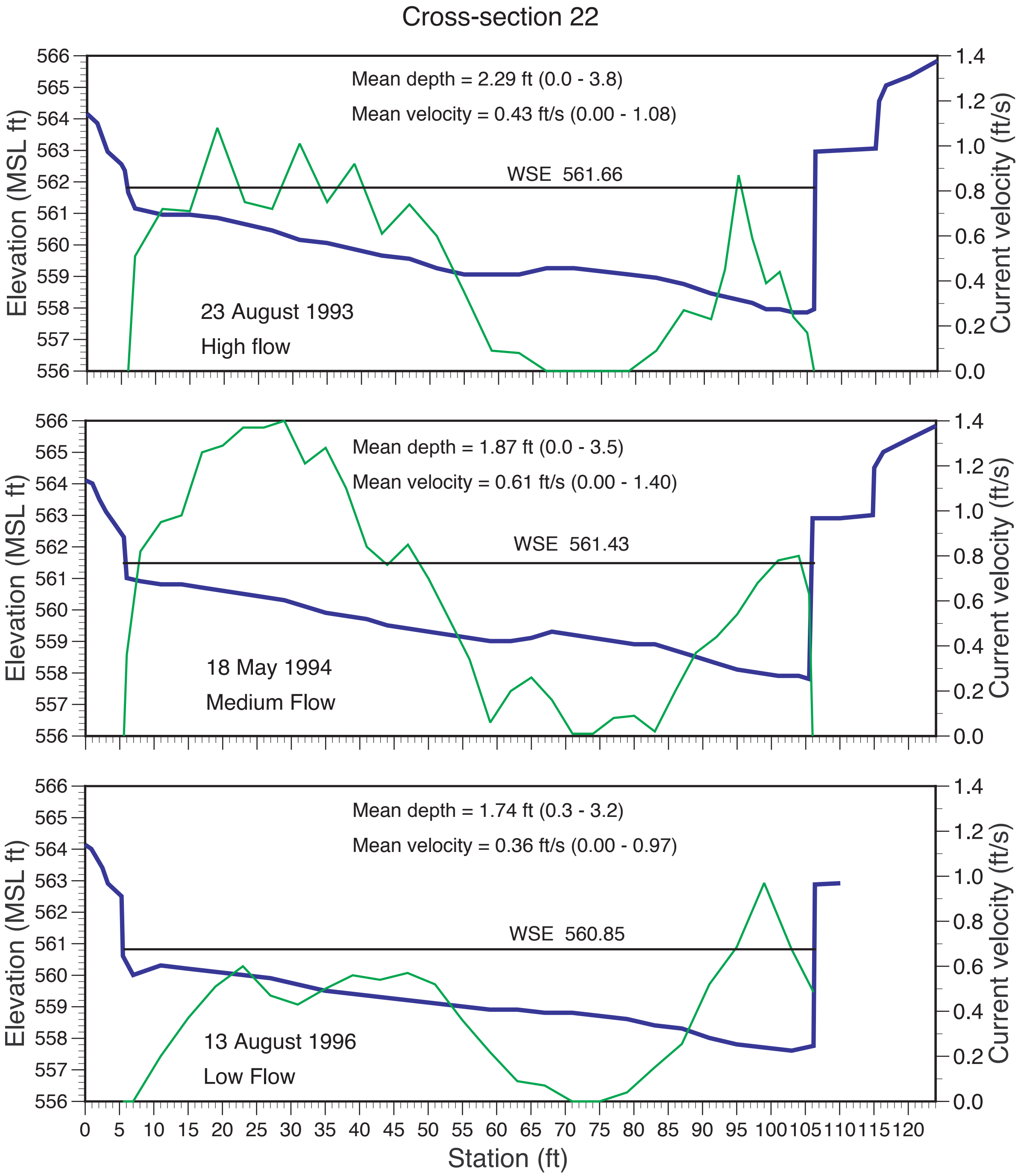
APPENDIX I: FIGURE 22.—Cross-section 19: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This cross-section in Segment 3 represents two mesohabitat types, both with silt and sand substrates. River-left is a slow shallow run with *Zizania texana, Hygrophila polysperma* and *Sagittaria platyphylla*. River-right is a run with *Zizania texana, Sagittaria platyphylla, Hydrilla verticillata* and *Hygrophila polysperma.*



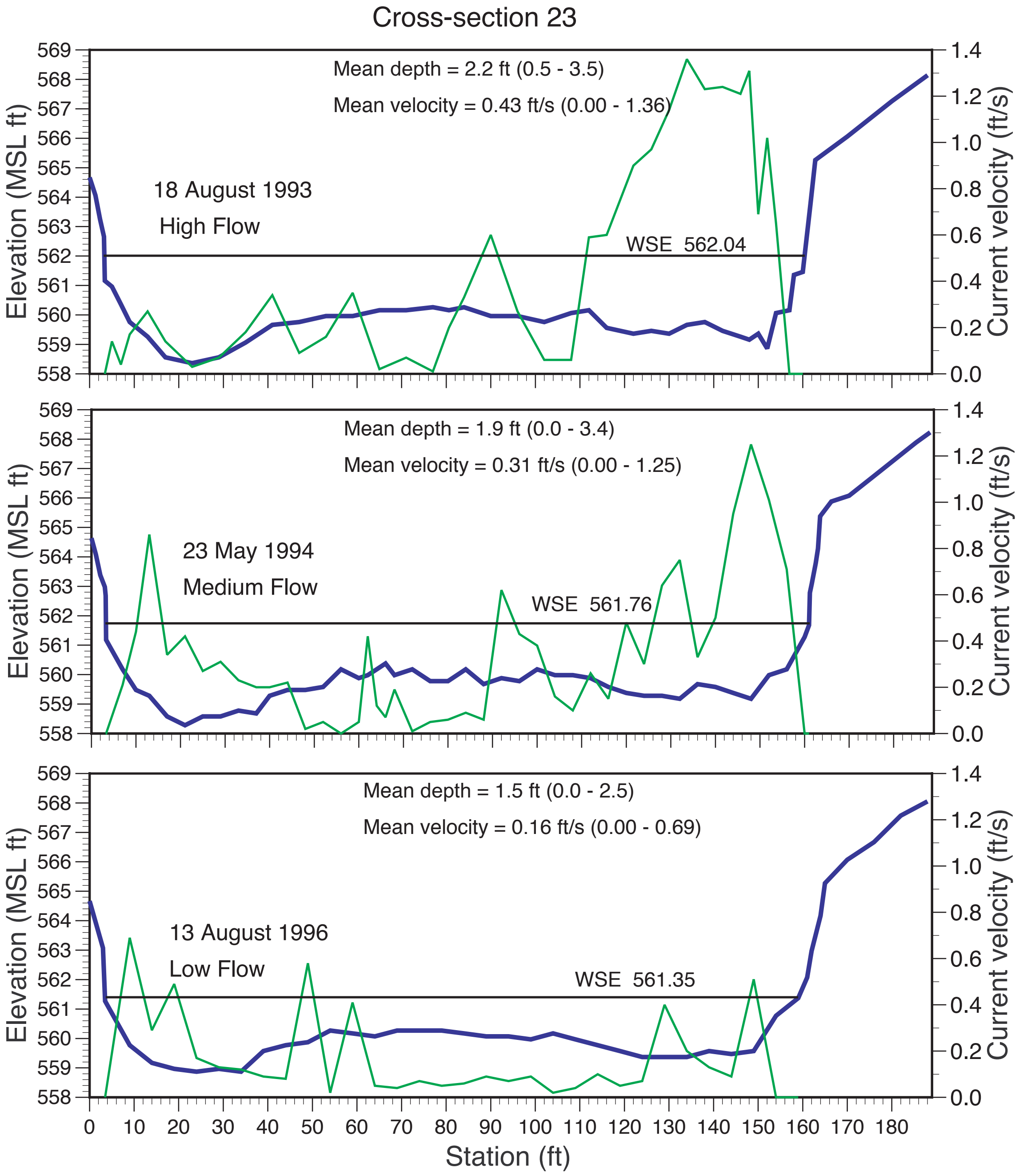
APPENDIX I: FIGURE 23.—Cross-section 20: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This cross-section in Segment 3 represents two habitat types. River-right is a slow shallow run. River-left is a fast run. Both habitats have silt, sand and clay substrates and *Hygrophila polysperma, Hydrilla verticillata, Sagittaria platyphylla* and *Vallisneria americana.*



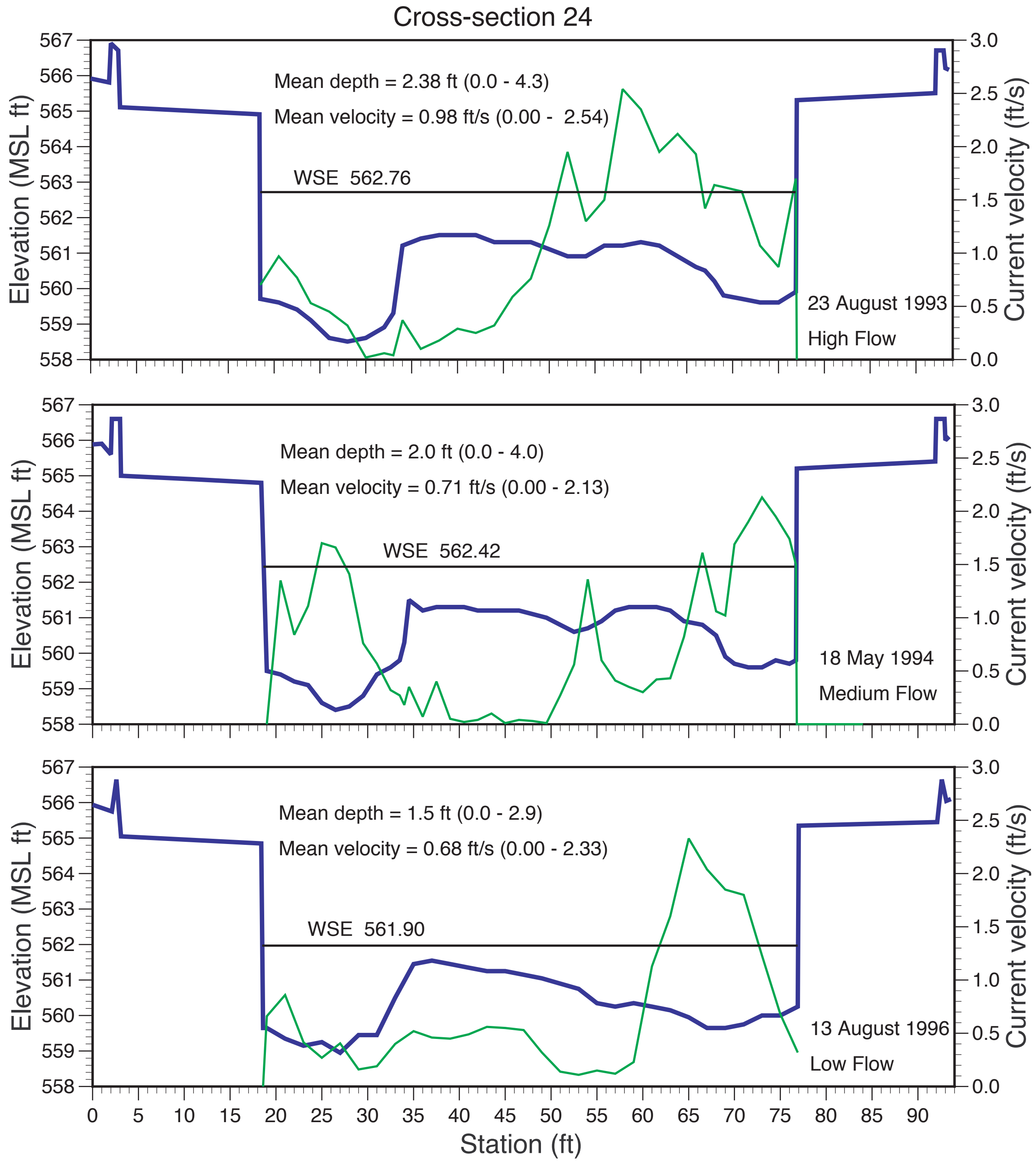
APPENDIX I: FIGURE 24.—Cross-section 21: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This cross-section in Segment 3 represents two types of mesohabitats. Fast run exists on river right, in contrast to slow run on river left. Both habitats have primarily silt substrate with some sand and *Hydrilla verticillata, Sagiittaria platyphylla* and *Colocasia esculenta.*



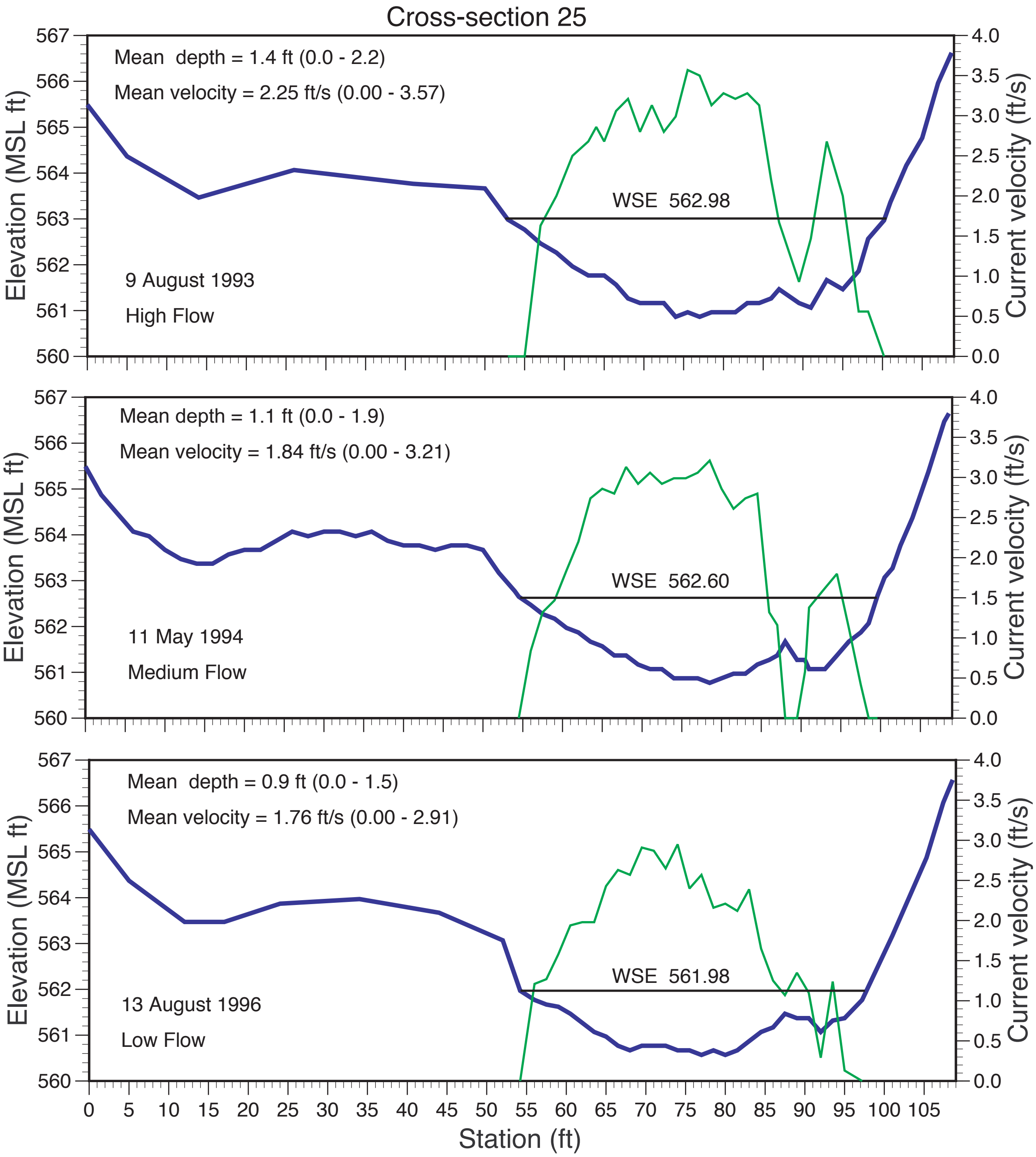
APPENDIX I: FIGURE 25.—Cross-section 22: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflow discharges. Mean depth and current velocity are reported with ranges in parentheses. This is slow run mesohabitat in Segment 3 with mixed gravel and sand substrate and *Hydrilla verticillata, Egeria densa, Potamogeton illinoensis* and filamentous algae.



APPENDIX I: FIGURE 26.—Cross-section 23: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is run mesohabitat in Segment 3 with silt and some clay substrate and dense *Potamogeton illinoensis, Hydrilla verticillata, Sagittaria platyphylla, Hygrophila polysperma,* and sparse *Zizania texana.*



APPENDIX I: FIGURE 27.—Cross-section 24: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is run mesohabitat in Segment 3 with sand, gravel and silt substrate and *Zizania texana, Potamogeton illinoensis, Hydrilla verticillata* and *Hygrophila polysperma.*



APPENDIX I: FIGURE 28.—Cross-section 25: Bottom profile, water surface elevation (WSE) and current velocity distribution illustrated for high, medium and low streamflows. Mean depth and current velocity are reported with ranges in parentheses. This is a fast shallow run mesohabitat in Segment 3 with sand and mixed gravel substrate and *Zizania texana, Potamogeton illinoensis, Hygrophila polysperma* and *Colocasia esculenta.*

Appendix II
Biology

APPENDIX II: TABLE 1.—Aquatic macrophytes identified in the 43 biogrid samples.

Vegetation type	Status[a]	Fast deep run	Fast shallow run	Fast run	Riffle	Fast run/Slow run	Run	Slow run	Slow deep run	Pool	Backwater
Amblystegium riparium	N	23	1		38					1	
Azolla caroliniana	N					28	2				
Cabomba caroliniana	N		1				25	19	4	65	29
Ceratophyllum demersum	N							7	1	2	
Filamentous algae	N	31	3	25	52	5	103	4	70	144	
Heteranthera liebmannii	N	3	2	4	2	8	16	13	4	3	
Hydrocotyle umbellata	N				5		3		7	3	
Justicia americana	N				10						
Ludwigia repens	N			1		8		1			
Myriophyllum heterophyllum	N							2		2	
Nuphar luteum	N						8			18	7
Pistia stratiotes	N					1	1	5	6	8	14
Potamogeton illinoensis	N			119		214	99	44		2	
Riccia fluitans	N					26	4	7	2	1	
Sagittaria platyphylla	N			76		9	54	15		20	
Vallisneria americana	N			10	1	5	20			5	2
Zizania texana	N	5		17		2	38	2		6	
Ceratopteris thalictroides	I							3			4
Colocasia esculenta	I	3	7	37	21	44	68	24	66	50	66
Cryptocoryne cf. *beckettii*	I		6								
Egeria densa	I					81	8	150	15	35	
Eichhornia crassipes	I				2	15	15	16	5	3	5
Hydrilla verticillata	I	16	31	58	23	124	147	75	93	156	7
Hygrophila polysperma	I	1	13	68	22	173	206	142	69	97	24
Number of cells sampled		36	60	126	83	216	296	246	559	391	45
Cells without vegetation		5	13	0	5	1	23	13	387	137	3
Number of native species		4	4	7	6	10	12	11	7	14	4
Number of introduced species		3	4	3	4	5	5	6	5	5	5
Cells with native species		31	7	122	66	214	231	84	83	199	32
Percent cells with native species		86.11	11.67	96.83	79.52	99.07	78.04	34.15	14.85	50.90	71.11
Cells with introduced species		16	46	111	49	215	271	230	152	195	37
Percent cells with introduced species		44.44	76.67	88.10	59.04	99.54	91.55	93.50	27.19	49.87	82.22

[a] N = Native; I = introduced

APPENDIX II: TABLE 2.—Aquatic macrophytes identified in the six *Zizania texana* biogrid samples.

Vegetation type	Status[a]	Fast run	Run	Slow run
Cabomba caroliniana	N		7	
Filamentous algae	N	53	72	
Heteranthera liebmannii	N	21	15	1
Hydrocotyle umbellata	N	2		
Justicia americana	N	2		
Ludwigia repens	N	3		
Potamogeton illinoensis	N	20	44	
Sagittaria platyphylla	N	35		18
Vallisneria americana	N	11	14	4
Zizania texana	N	43	85	18
Colocasia esculenta	I	18	22	8
Egeria densa	I	1		8
Eichhornia crassipes	I			2
Hydrilla verticillata	I	85	112	10
Hygrophila polysperma	I	64	83	20
Number of cells sampled		109	162	24
Cells without vegetation		0	2	0
Number of native species		9	6	4
Number of introduced species		4	3	5
Cells with *Zizania texana*		43	85	18
Percent cells with *Zizania texana*		39.45	52.47	75.00
Cells with native species		104	150	23
Percent cells with native species		95.41	92.59	95.83
Cells with introduced species		106	133	24
Percent cells with introduced species		97.25	82.10	100.00

[a] N = native; I = introduced

APPENDIX II: TABLE 3.—Aquatic macrophyte associations as observed in the 43 bio-grid samples. Note: This table is to be read by column (top to bottom).

	Amblystegium	*Azolla*	*Cabomba*	*Ceratophyllum*	*Ceratopteris*	*Colocasia*	*Cryptocoryne*	*Egeria*	*Eichhornia*	Fil. Algae	*Heteranthera*	*Hydrilla*	*Hydrocotyle*	*Hygrophila*	*Justicia*	*Ludwigia*	*Myriophyllum*	*Nuphar*	*Pistia*	*Potamogeton*	*Riccia*	*Sagittaria*	*Vallisneria*	*Zizania*
Number of cells with species	63	30	144	10	7	356	6	289	61	438	57	730	18	815	10	10	4	34	35	478	40	174	43	70
Total # cells sampled	2058	2058	2058	2058	2058	2058	2058	2058	2058	2058	2058	2058	2058	2058	2058	2058	2058	2058	2058	2058	2058	2058	2058	2058
% of total cells with species	3.06	1.46	7.00	0.49	0.34	17.30	0.29	14.04	2.96	21.28	2.77	35.47	0.87	39.60	0.49	0.49	0.19	1.65	1.70	23.23	1.94	8.45	2.09	3.40
Frequency of Occurrence[a]	L	L	M	L	L	M	L	M	L	H	L	H	L	H	L	L	L	L	L	H	L	M	L	L
Amblystegium riparium		0.00	0.00	0.00	0.00	3.09	0.00	0.00	0.00	13.01	7.02	2.74	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.71
Azolla caroliniana	0.00		0.00	0.00	0.00	3.65	0.00	0.00	13.11	1.14	3.51	0.55	0.00	3.68	0.00	0.00	0.00	0.00	2.86	6.28	25.00	0.00	6.98	0.00
Cabomba caroliniana	0.00	0.00		30.00	100.00	17.42	0.00	9.69	4.92	9.59	5.26	10.41	0.00	11.41	0.00	0.00	25.00	44.12	34.29	0.00	2.50	0.57	6.98	7.14
Ceratophyllum demersum	0.00	0.00	2.08		0.00	0.28	0.00	2.77	0.00	0.00	0.00	0.27	0.00	0.86	0.00	0.00	0.00	0.00	0.00	0.00	2.50	0.00	2.33	0.00
Ceratopteris thalictroides	0.00	0.00	4.86	0.00		1.97	0.00	1.04	0.00	0.00	0.00	0.00	0.00	0.61	0.00	0.00	0.00	0.00	8.57	0.00	0.00	0.00	0.00	0.00
Colocasia esculenta	17.46	26.67	43.06	10.00	100.00		0.00	14.88	27.87	19.86	29.82	25.34	66.67	27.48	0.00	10.00	25.00	26.47	57.14	18.83	30.00	20.11	51.16	0.00
Cryptocoryne cf. *beckettii*	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Egeria densa	0.00	0.00	19.44	80.00	42.86	12.08	0.00		16.39	6.16	21.05	12.05	0.00	27.48	0.00	40.00	50.00	5.88	2.86	19.04	17.50	14.37	4.65	2.86
Eichhornia crassipes	0.00	26.67	2.08	0.00	0.00	4.78	0.00	3.46		0.68	3.51	2.05	5.56	5.15	0.00	0.00	0.00	2.94	31.43	7.74	42.50	6.90	6.98	1.43
Filamentous algae	90.48	16.67	28.47	0.00	0.00	21.63	0.00	9.34	4.92		31.58	34.38	27.78	17.91	0.00	0.00	25.00	5.88	22.86	5.86	0.00	8.05	32.56	65.71
Heteranthera liebmannii	6.35	6.67	2.08	0.00	0.00	4.78	0.00	4.15	3.28	4.11		3.56	0.00	4.29	3.00	0.00	0.00	0.00	0.00	2.93	2.50	2.30	6.98	7.14
Hydrilla verticillata	31.75	13.33	52.78	20.00	0.00	51.97	0.00	30.45	24.59	59.36	45.61		38.89	41.60	0.00	80.00	50.00	38.24	20.00	46.86	37.50	35.06	51.16	72.86
Hydrocotyle umbellata	0.00	0.00	0.00	0.00	0.00	3.37	0.00	0.00	1.64	1.14	0.00	0.96		0.86	10.00	0.00	0.00	0.00	5.71	0.42	0.00	1.15	0.00	0.00
Hygrophila polysperma	1.59	100.00	64.58	70.00	71.43	62.92	0.00	77.51	68.85	35.16	61.40	46.44	38.89		0.00	60.00	100.00	23.53	31.43	73.64	77.50	77.01	83.72	50.00
Justicia americana	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.75	0.14	0.00	0.49		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ludwigia repens	0.00	0.00	0.00	0.00	0.00	0.28	0.00	1.38	0.00	0.00	0.00	1.10	0.00	0.74	3.00		0.00	0.00	0.00	1.88	0.00	0.00	2.33	0.00
Myriophyllum spp.	0.00	0.00	0.69	0.00	0.00	0.28	0.00	0.69	0.00	0.23	0.00	0.27	0.00	0.49	0.00	0.00		0.00	0.00	0.21	0.00	0.57	2.33	0.00
Nuphar luteum	0.00	0.00	10.42	0.00	0.00	2.53	0.00	0.69	1.64	0.46	0.00	1.78	0.00	0.98	0.00	0.00	0.00		11.43	0.00	0.00	0.00	0.00	0.00
Pistia stratiotes	0.00	3.33	8.33	0.00	42.86	5.62	0.00	0.35	18.03	1.83	0.00	0.96	11.11	1.35	0.00	0.00	0.00	11.76		1.26	12.50	0.00	2.33	0.00
Potamogeton illinoensis	0.00	100.00	0.00	0.00	0.00	25.28	0.00	31.49	60.66	7.53	24.56	30.68	11.11	43.19	0.00	90.00	25.00	0.00	17.14		92.50	87.36	34.88	34.29
Riccia fluitans	0.00	33.33	0.69	10.00	0.00	3.37	0.00	2.42	27.87	0.23	1.75	2.05	0.00	3.80	0.00	0.00	0.00	0.00	14.29	7.74		2.30	2.33	0.00
Sagittaria platyphylla	0.00	0.00	0.69	0.00	0.00	9.83	0.00	8.65	19.67	4.11	7.02	8.36	11.11	16.44	0.00	0.00	25.00	0.00	0.00	31.80	10.00		20.93	4.29
Vallisneria americana	0.00	10.00	2.08	10.00	0.00	6.18	0.00	0.69	4.92	3.65	5.26	3.01	0.00	4.42	1.00	10.00	25.00	0.00	2.86	3.14	2.50	5.17		4.29
Zizania texana	6.35	0.00	3.47	0.00	0.00	0.00	0.00	0.69	1.64	10.50	8.77	6.99	0.00	4.29	0.00	0.00	0.00	0.00	0.00	5.02	0.00	1.72	6.98	

[a] L = Low, M = moderate, H = High

APPENDIX II: TABLE 4.—Percent of cells (N=146) in which each macrophyte was found in association with *Zizania texana* using the six *Zizania texana* bio-grid samples.

	Cabomba	*Colocasia*	*Egeria*	*Eichhornia*	Filamentous algae	*Hydrilla*	*Hydrocotyle*	*Hygrophila*	*Justicia*	*Ludwigia*	*Heteranthera*	*Potamogeton*	*Sagittaria*	*Vallisneria*
Percent of Cells	0.00	4.79	4.79	0.00	36.99	69.86	0.00	60.96	0.00	0.00	10.27	23.97	15.07	8.90
Status[a]	N	I	I	I	N	I	N	I	N	N	N	N	N	N

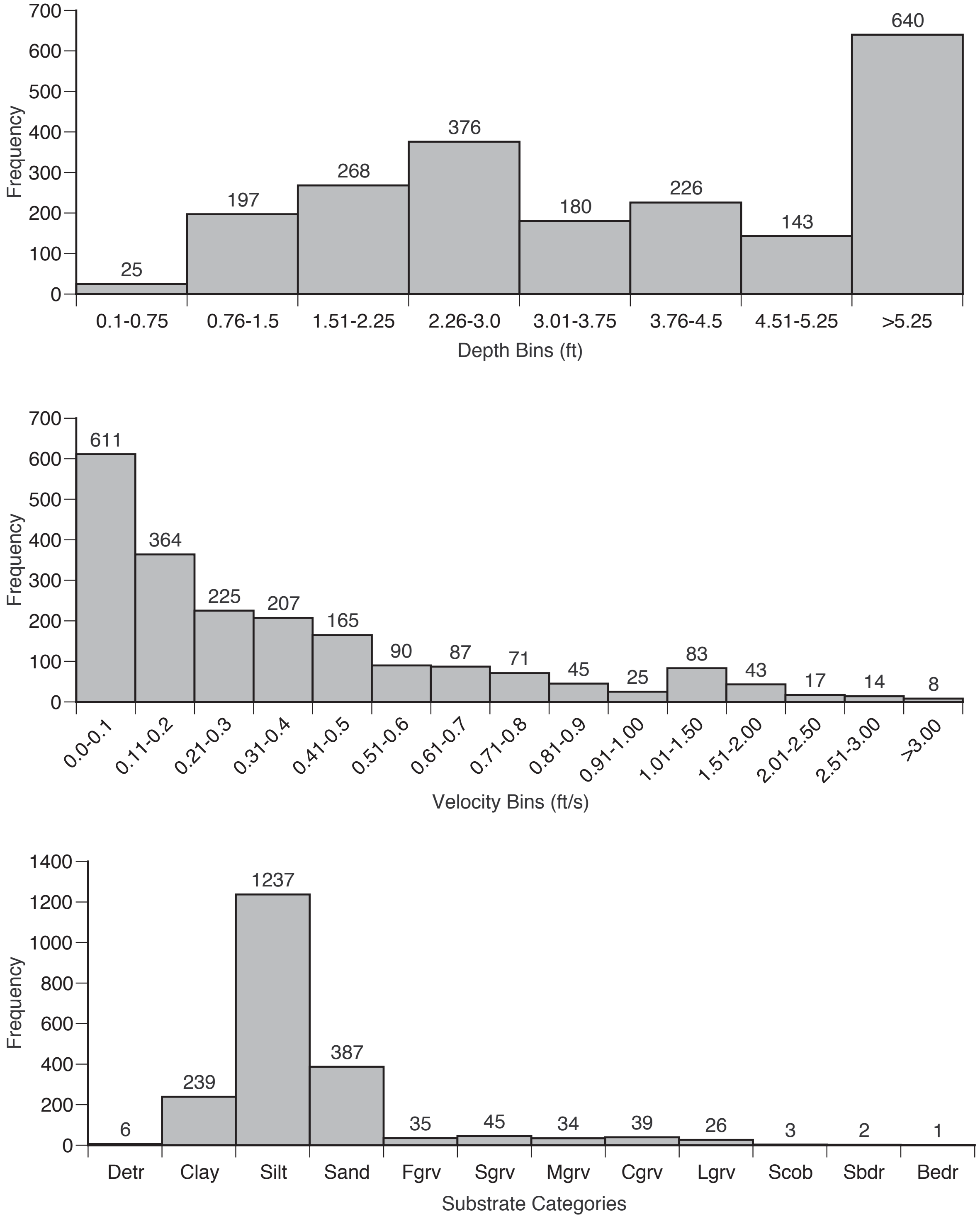
[a] N = native; I = introduced

APPENDIX II: TABLE 5.—Fish species observed during biogrid sampling (N=1689).

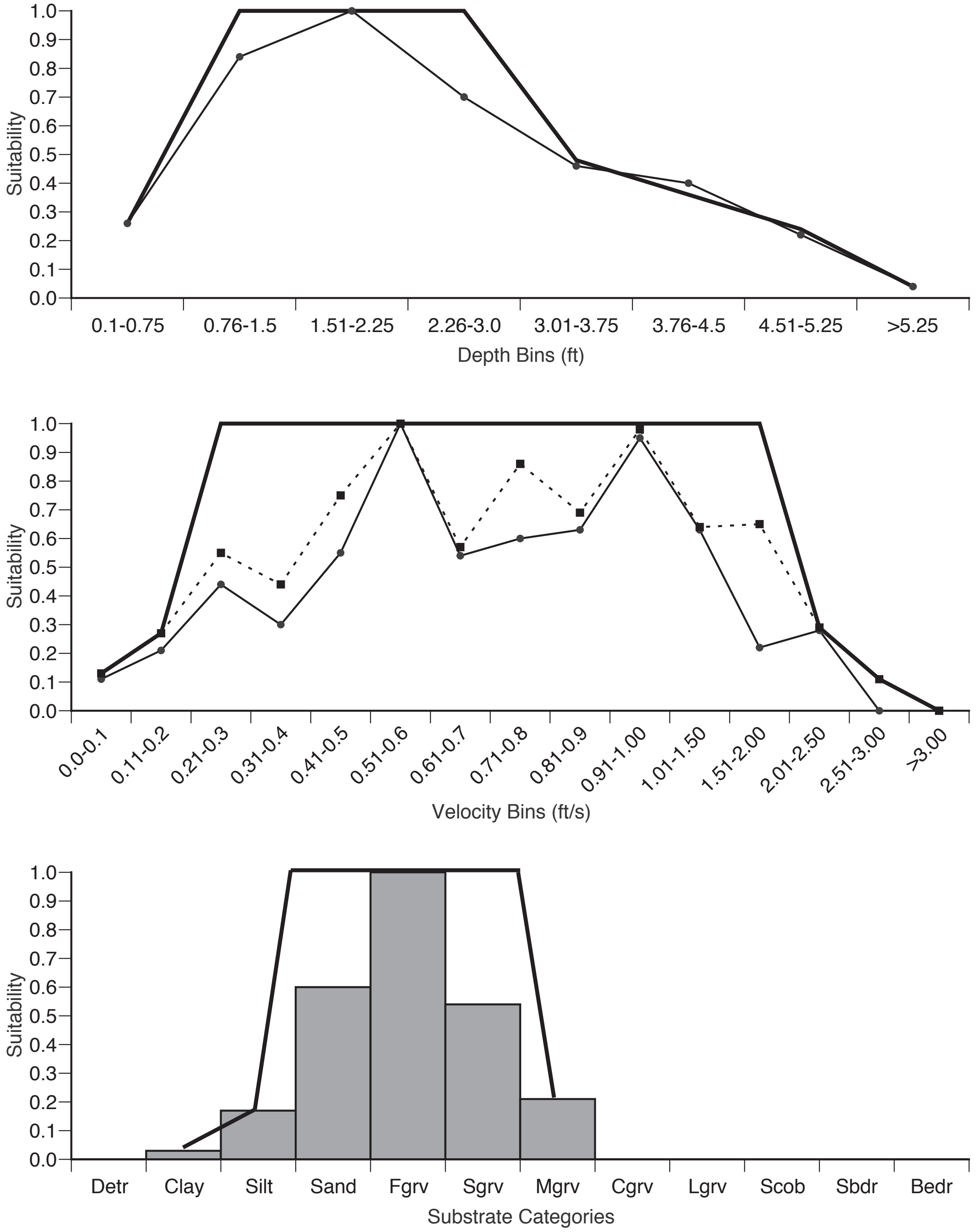
Species	Status[a]	Pool	Backwater	Slow run	Slow deep run	Slow run/fast run	Fast run	Fast deep run	Fast shallow run	Riffle	Run
Cyprinella venusta	N	X						X	X	X	X
Dionda episcopa	N				X						
Etheostoma fonticola	N										X
Gambusia spp.	N	X	X	X	X	X	X	X		X	X
Lepisosteus oculatus	N					X					
Lepomis cyanellus	N	X			X						
Lepomis gulosus	N										X
Lepomis macrochirus	N	X									
Lepomis megalotis	N	X			X				X	X	X
Lepomis microlophus	N	X			X						X
Lepomis punctatus	N	X		X	X	X				X	X
Lepomis sp.	N							x			
Micropterus salmoides	N	X		X	X					X	X
Micropterus treculi	N										X
Moxostoma congestum	N	X									X
Notropis amabilis	N									X	
Notropis chalybaeus	N			X			X				X
Notropis volucellus	N	X			X	X	X	X	X	X	X
Percina carbonaria	N	X						X			
Percina sciera	N	X							X	X	X
Percina sp.	N						X				
Pimephales vigilax	N									X	
Ambloplites rupestris	I									X	
Astyanax mexicanus	I	X			X	X	X			X	X
Cichlasoma cyanoguttatum	I	X		X				X			X
Lepomis auritus	I	X		X	X	X	X		X	X	X
Notemigonus crysoleucas	I	X									
Poecilia latipinna	I		X			X					X
Oreochromis aurea	I	X		X	X	X					
Number of cells sampled		391	42	147	559	72	63	36	60	51	268
Number of cells with no observed fish		257	15	37	494	27	30	21	47	28	133
Number of cells with fish observed		134	27	110	65	45	33	15	13	23	135
Number of species observed		17	2	7	11	8	6	6	5	12	17
Number of native species		12	1	4	8	4	4	5	4	9	13
Number of cells with native species		143	27	114	78	33	32	16	13	35	162
Number of introduced species		5	1	3	3	4	2	1	1	3	4
Number of cells with introduced species		93	1	9	11	16	7	2	2	6	30
Percent native species		70.59	50.00	57.14	72.73	50.00	66.67	83.33	80.00	75.00	76.47
Percent cells with fish		34.27	64.29	74.83	11.63	62.50	52.38	41.67	21.67	45.10	50.37

[a] N = native; I = introduced

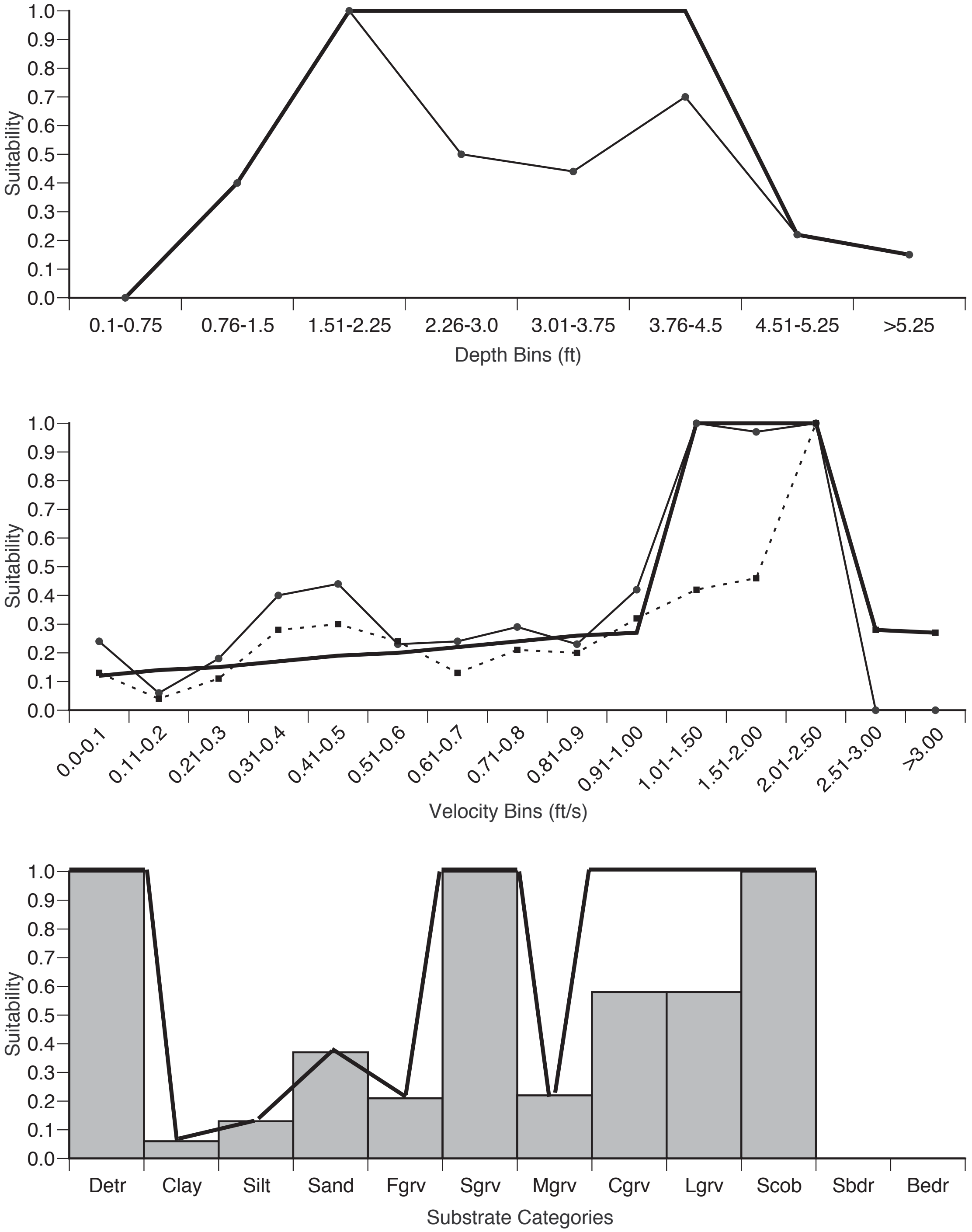
Appendix III
Suitability Criteria



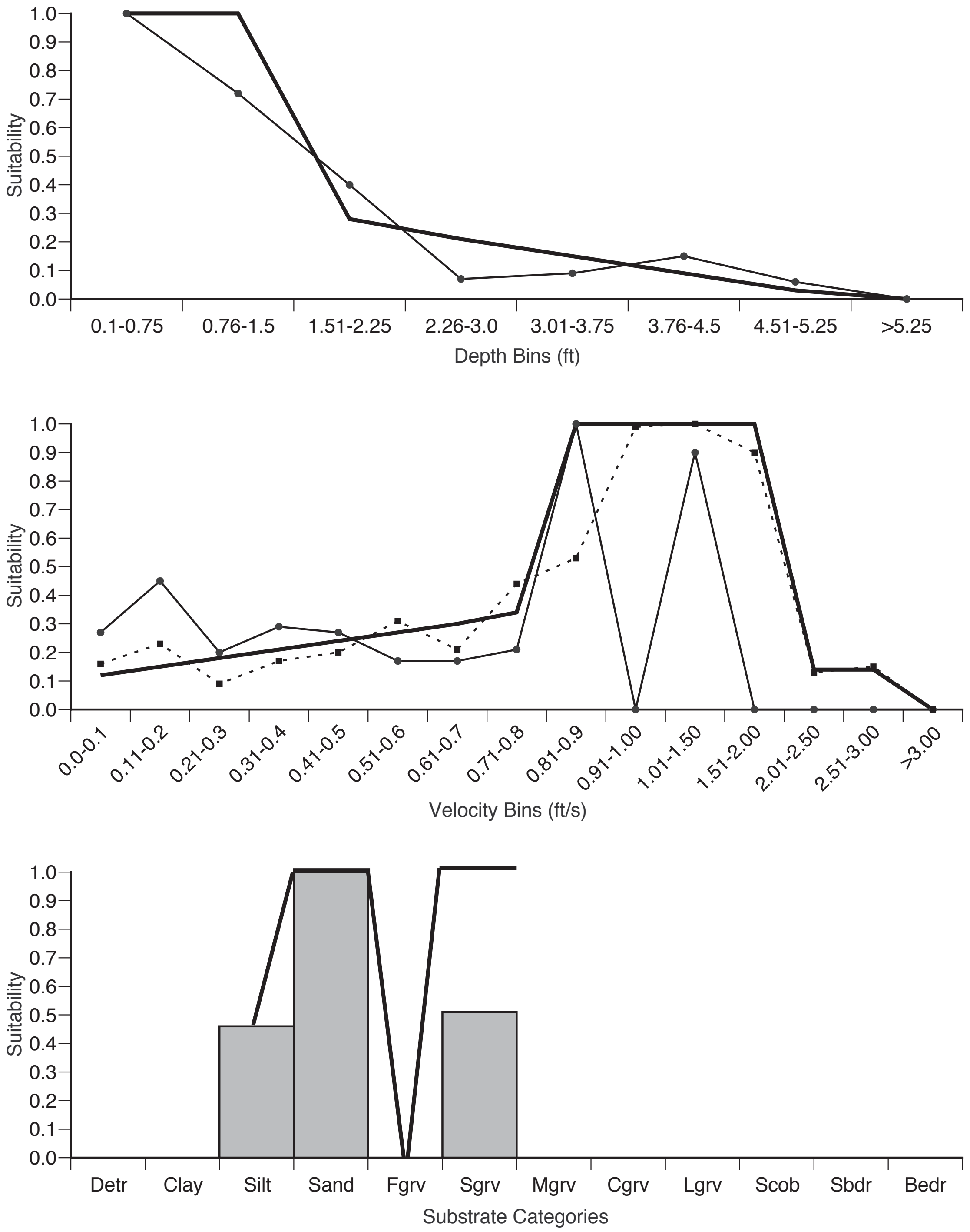
APPENDIX III: FIGURE 1.—Frequency distributions for depth, current velocity, and substrate data collected in the upper San Marcos River (N=2055). Refer to Table 2 for substrate classifications used in this study.



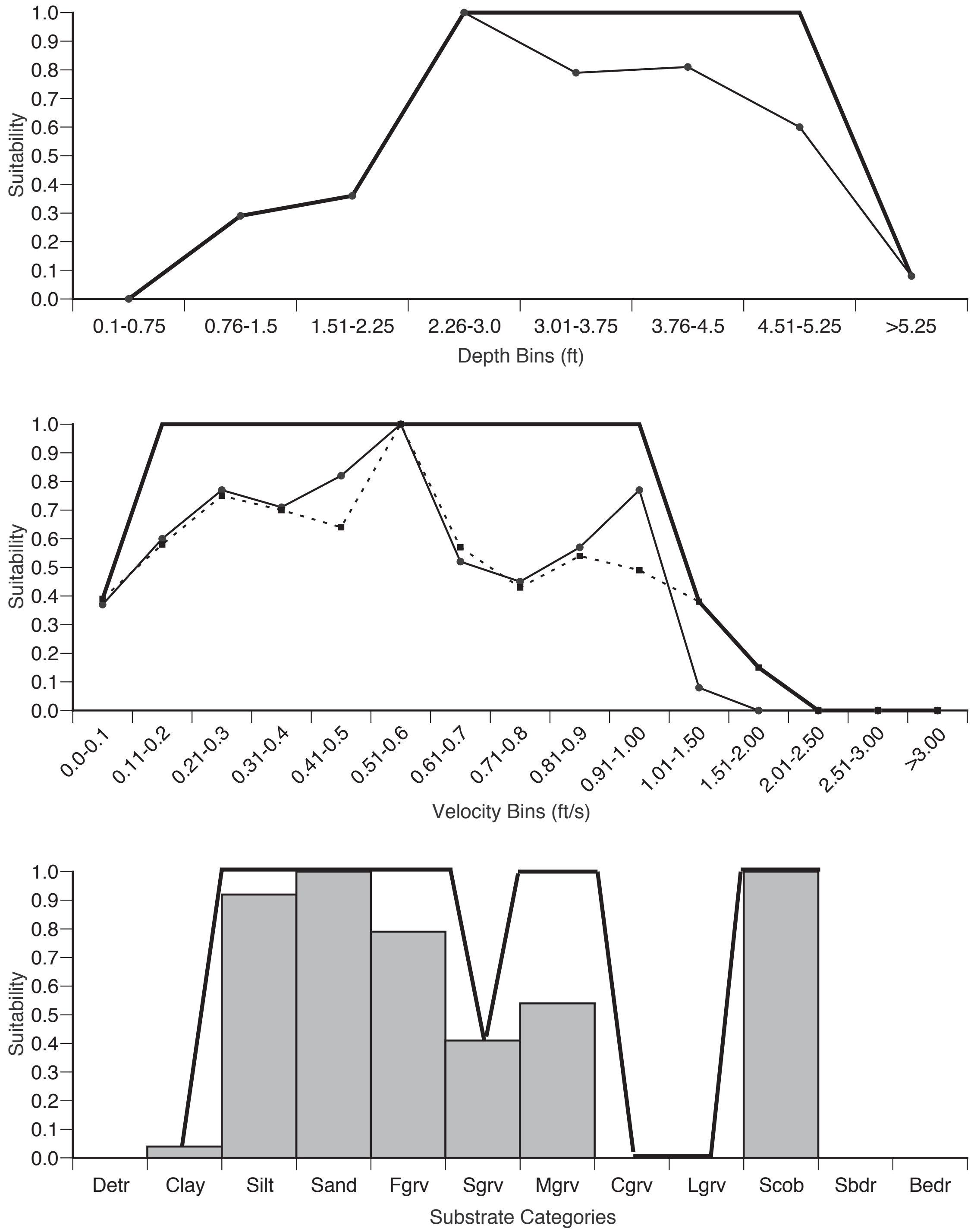
APPENDIX III: FIGURE 2.—Suitability criteria for *Zizania texana* for depth, current velocity, and substrate in the upper San Marcos River. Preference indices are indicated by solid lines or bars (substrate) and supplemental velocity curves are represented by dashed lines. Idealized habitat utilization curves are represented by heavy lines. Refer to Table 2 for substrate classifications used in this study.



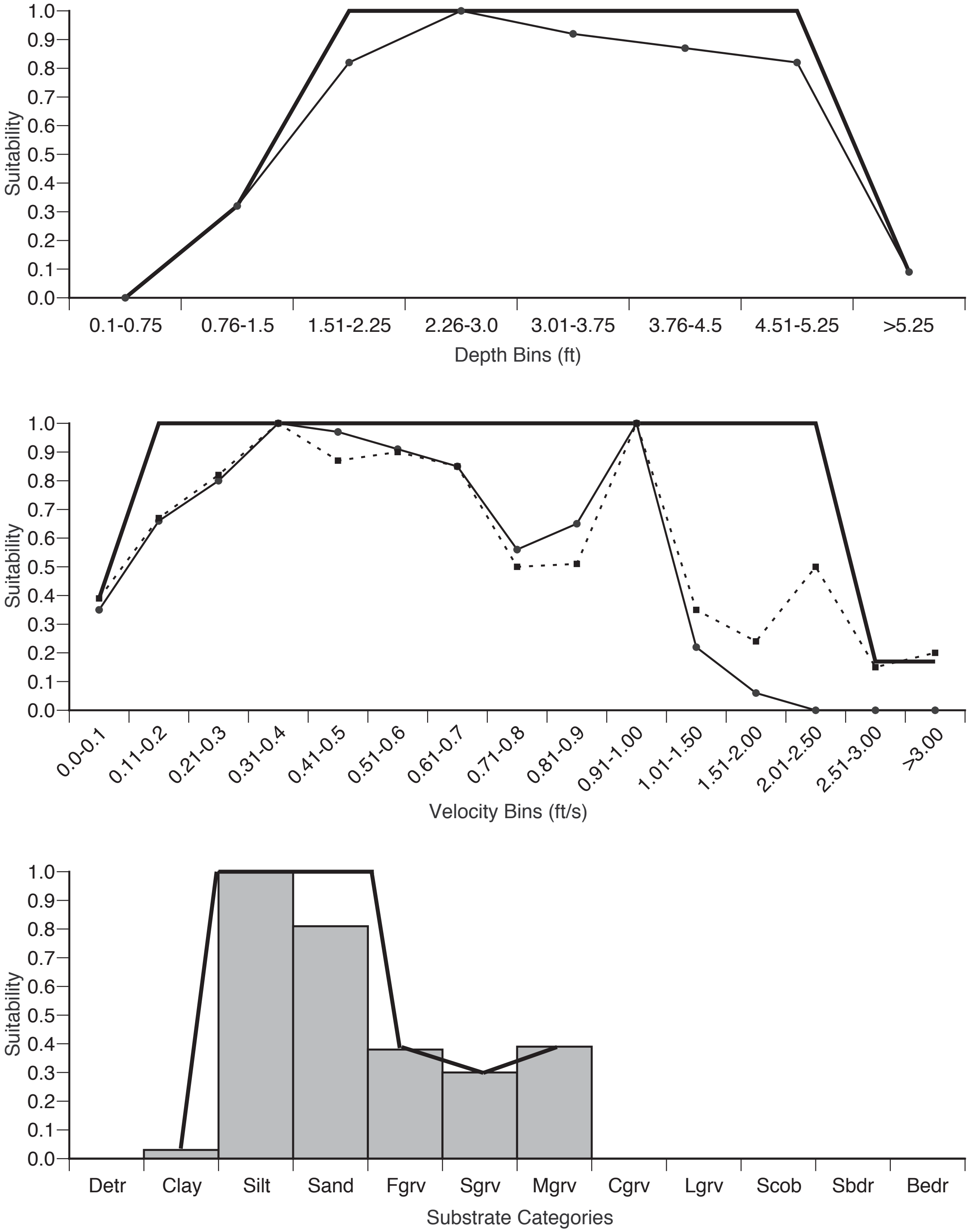
APPENDIX III: FIGURE 3.—Suitability criteria for *Heteranthera liebmannii* for depth, current velocity, and substrate in the upper San Marcos River. Preference indices are indicated by solid lines or bars (substrate) and supplemental velocity curves are represented by dashed lines. Idealized habitat utilization curves are represented by heavy lines. Refer to Table 2 for substrate classifications used in this study.



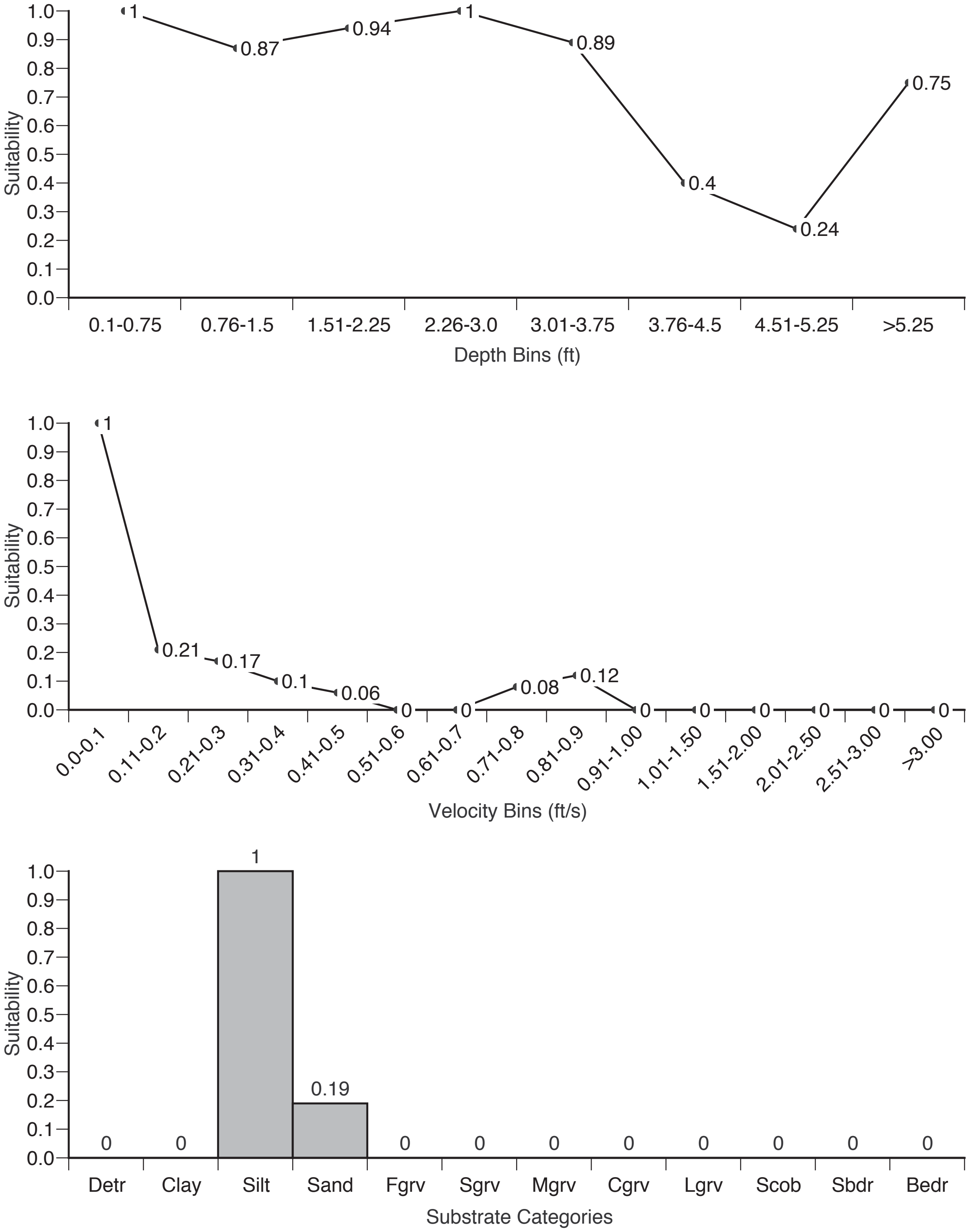
APPENDIX III: FIGURE 4.—Suitability criteria for *Vallisneria americana* for depth, current velocity, and substrate in the upper San Marcos River. Preference indices are indicated by solid lines or bars (substrate) and supplemental velocity curves are represented by dashed lines. Idealized habitat utilization curves are represented by heavy lines. Refer to Table 2 for substrate classifications used in this study.



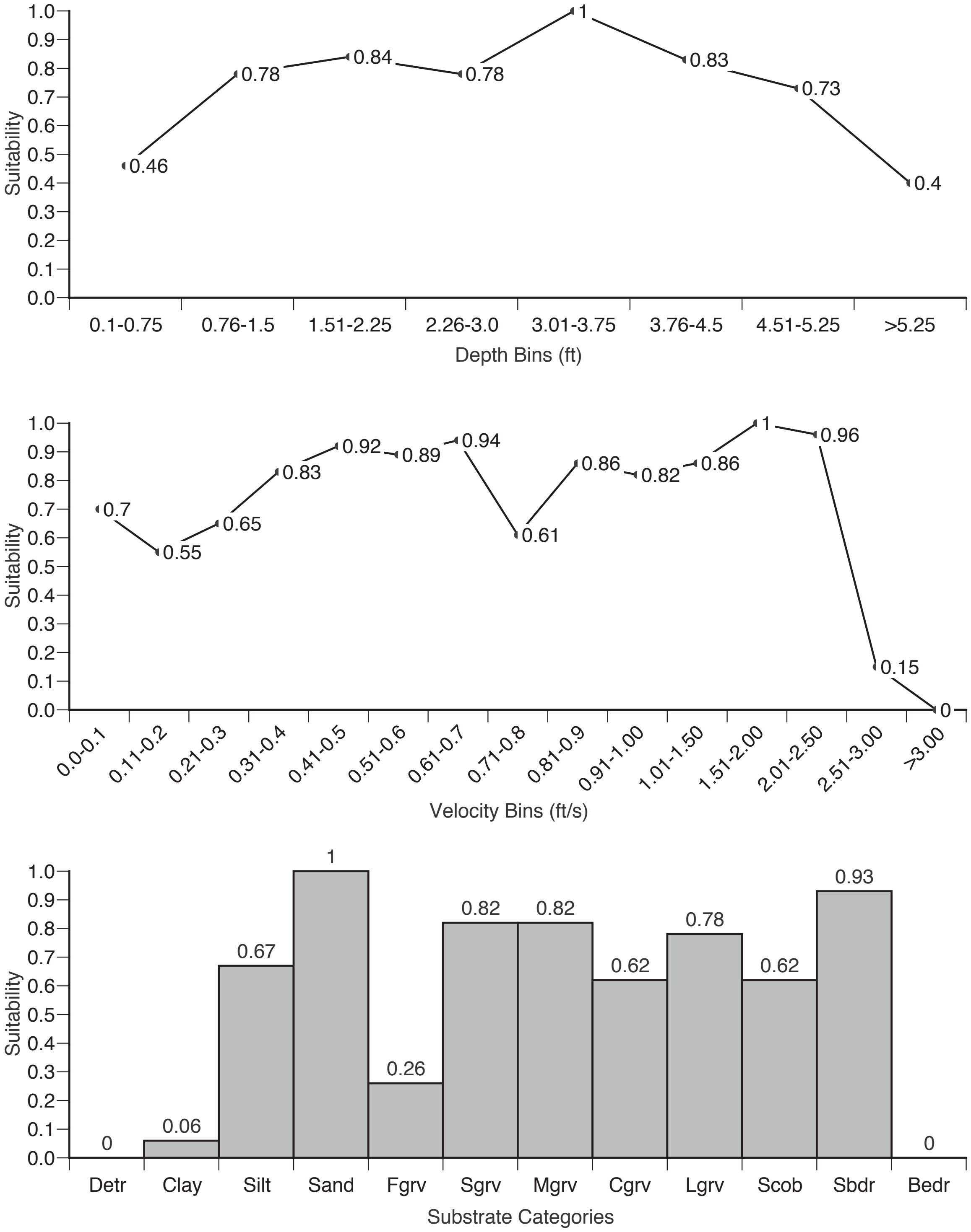
Appendix III: Figure 5.—Suitability criteria for *Sagittaria platyphylla* for depth, current velocity, and substrate in the upper San Marcos River. Preference indices are indicated by solid lines or bars (substrate) and supplemental velocity curves are represented by dashed lines. Idealized habitat utilization curves are represented by heavy lines. Refer to Table 2 for substrate classifications used in this study.



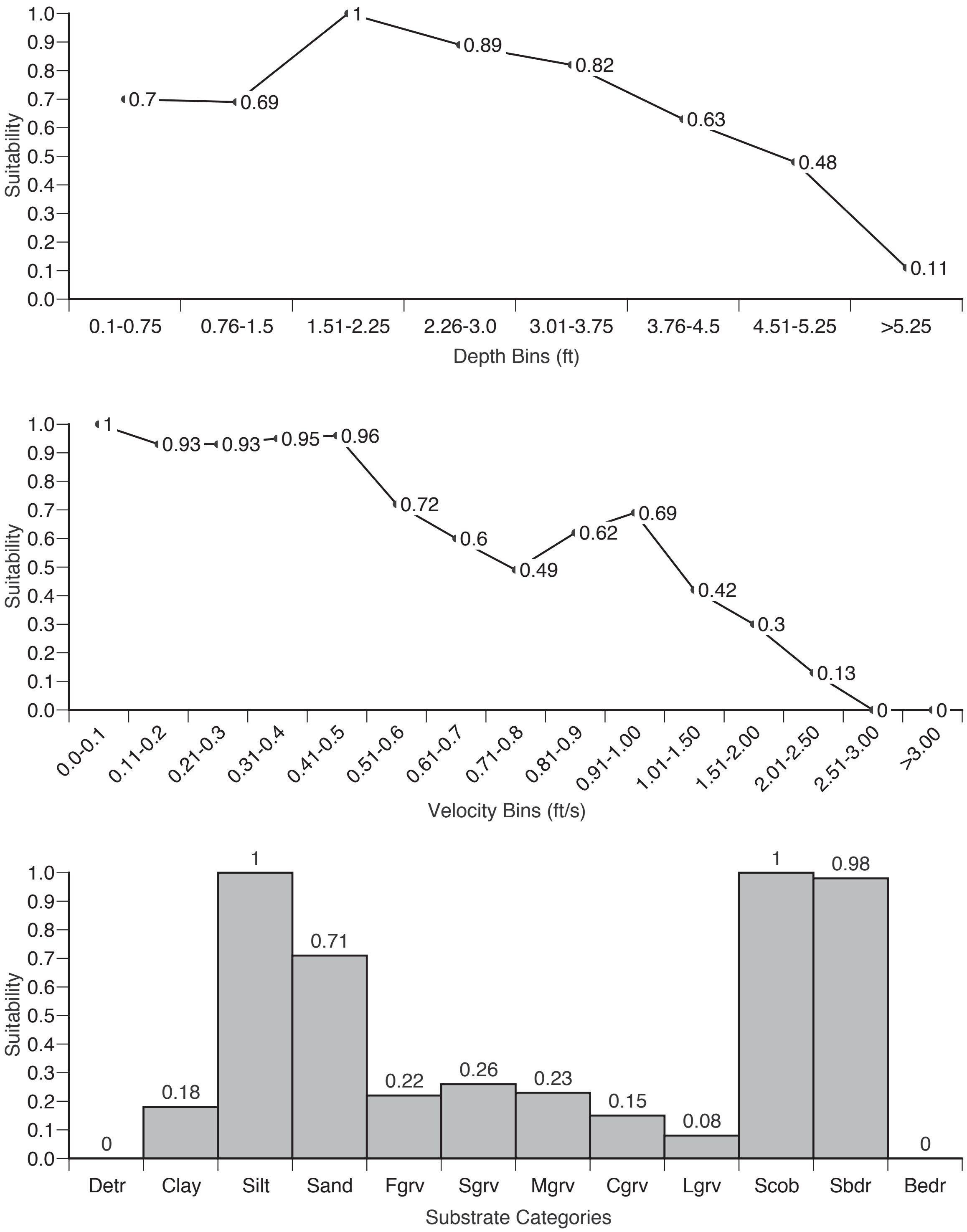
APPENDIX III: FIGURE 6.—Suitability criteria for *Potamogeton illinoensis* for depth, current velocity, and substrate in the upper San Marcos River. Preference indices are indicated by solid lines or bars (substrate) and supplemental velocity curves are represented by dashed lines. Idealized habitat utilization curves are represented by heavy lines. Refer to Table 2 for substrate classifications used in this study.



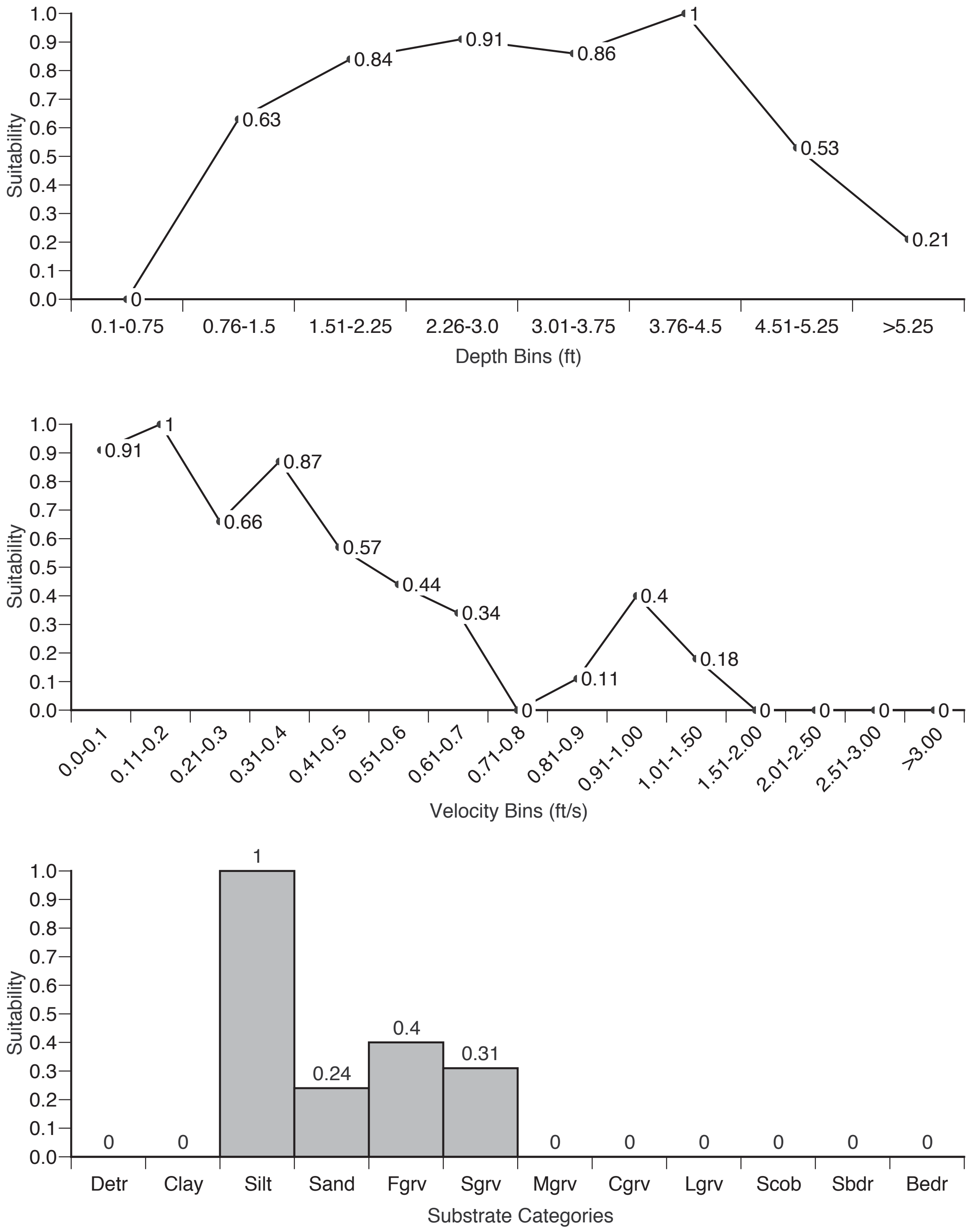
APPENDIX III: FIGURE 7.—Suitability criteria for *Cabomba caroliniana* (n=143) for depth, current velocity, and substrate in the upper San Marcos River. Refer to Table 2 for substrate classifications used in this study.



APPENDIX III: FIGURE 8.—Suitability criteria for *Hydrilla verticillata* (n=730) for depth, current velocity, and substrate in the upper San Marcos River. Refer to Table 2 for substrate classifications used in this study.

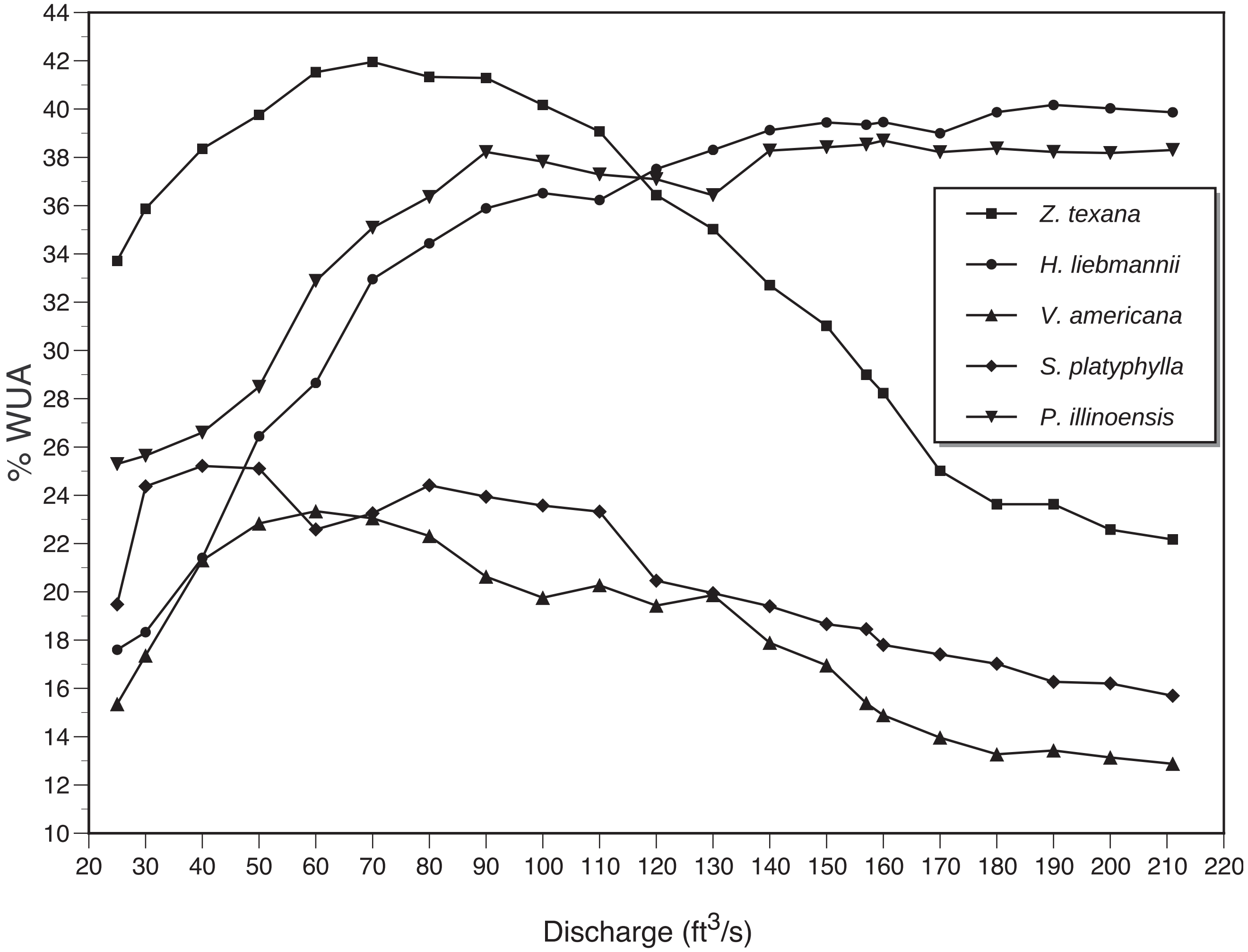


APPENDIX III: FIGURE 9.—Suitability criteria for *Hygrophila polysperma* (n=815) for depth, current velocity, and substrate in the upper San Marcos River. Refer to Table 2 for substrate classifications used in this study.

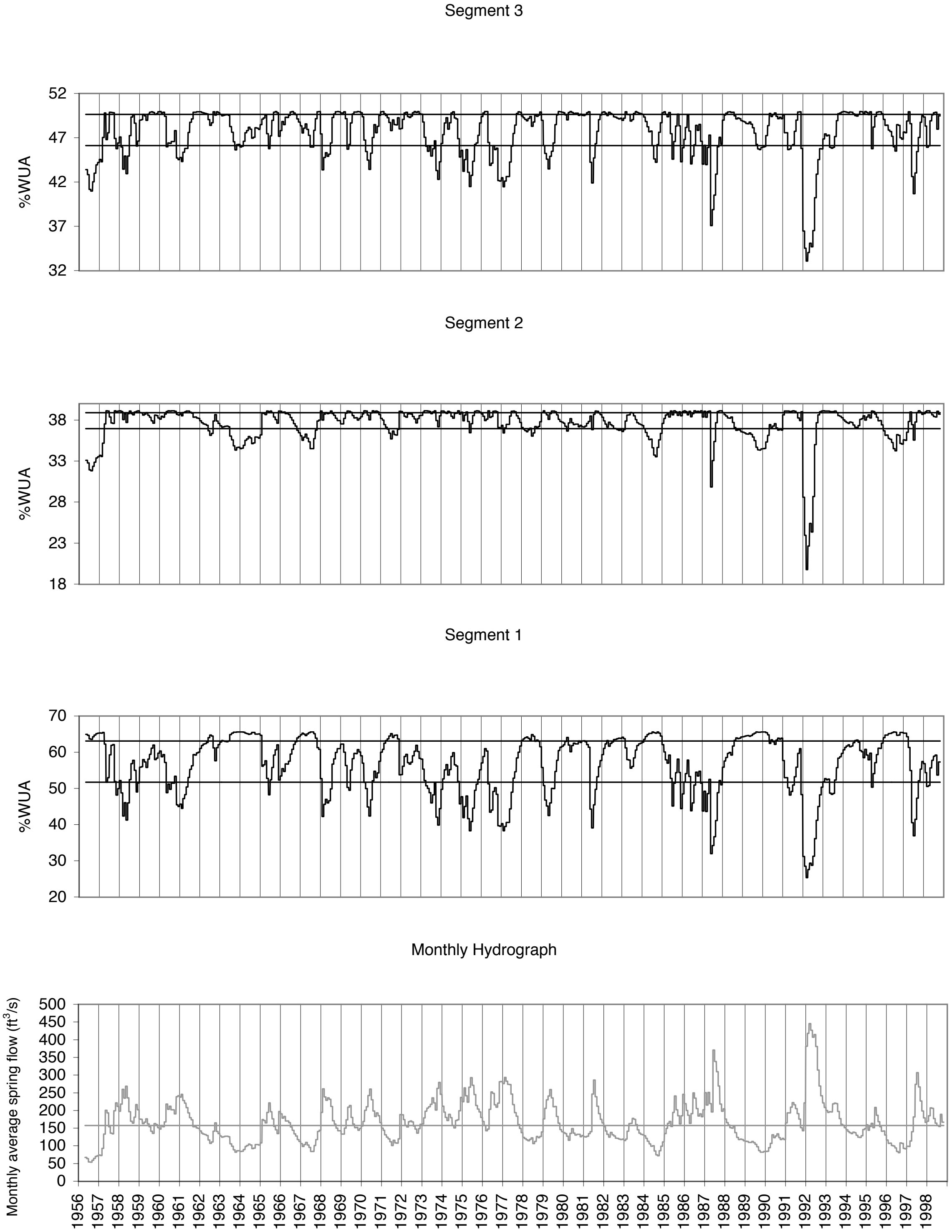


Appendix III: Figure 10.—Suitability criteria for *Egeria densa* (n=289) for depth, current velocity, and substrate in the upper San Marcos River. Refer to Table 2 for substrate classifications used in this study.

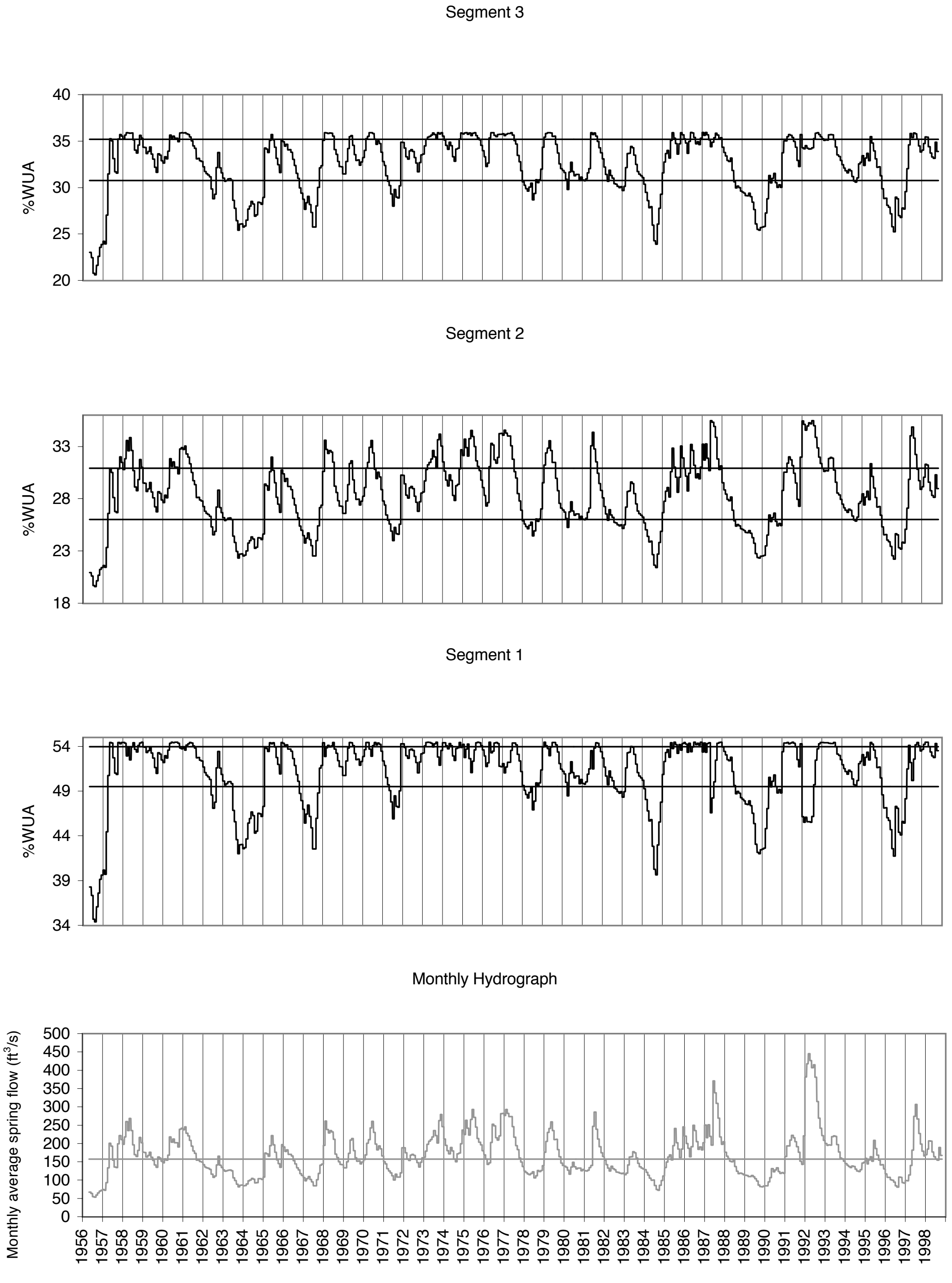
Appendix IV
Instream Habitat Model Output



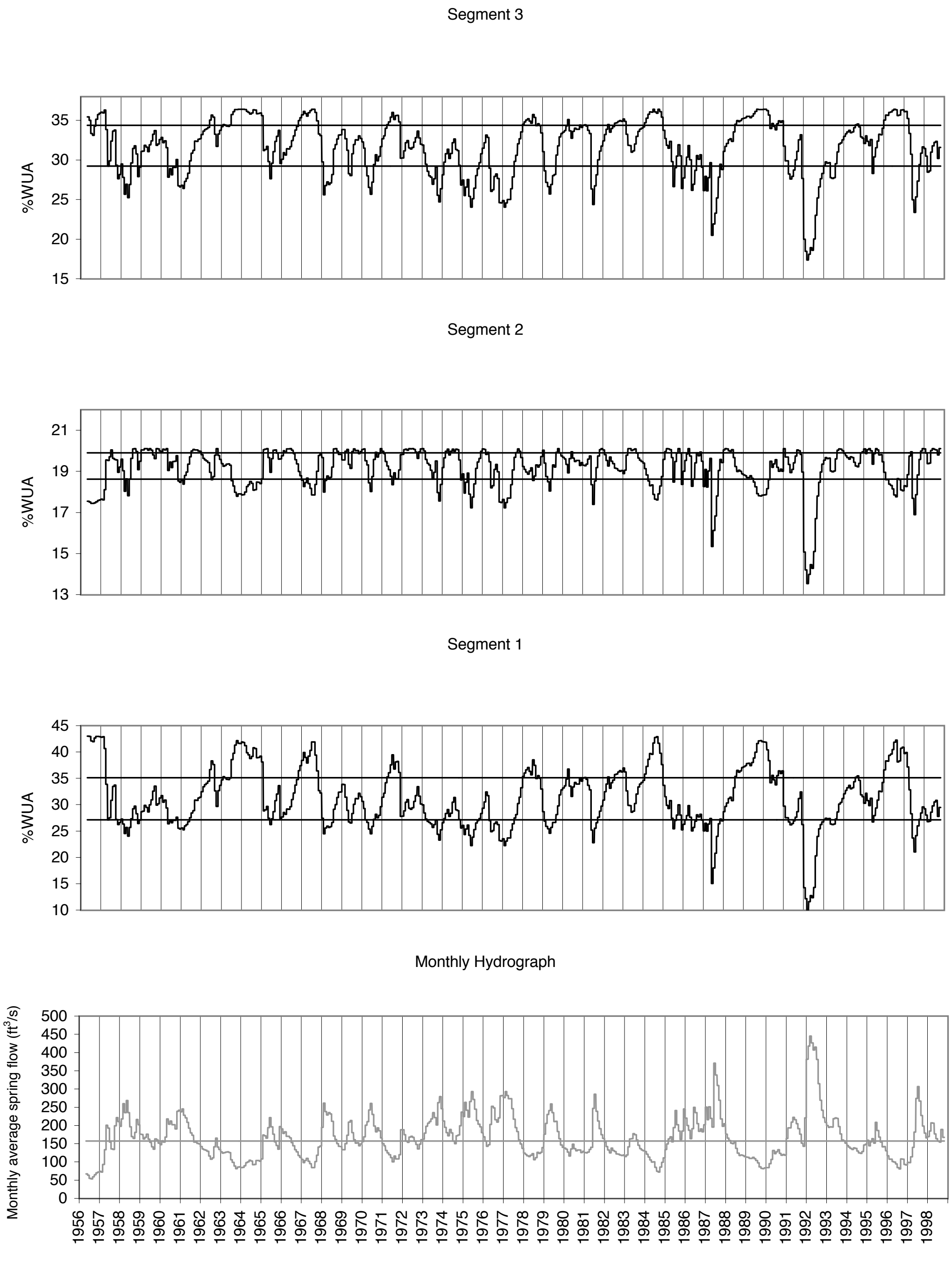
APPENDIX IV: FIGURE 1.—Percent weighted usable area (% WUA) in relation to discharge in the natural channel of the upper San Marcos River for the five target species.



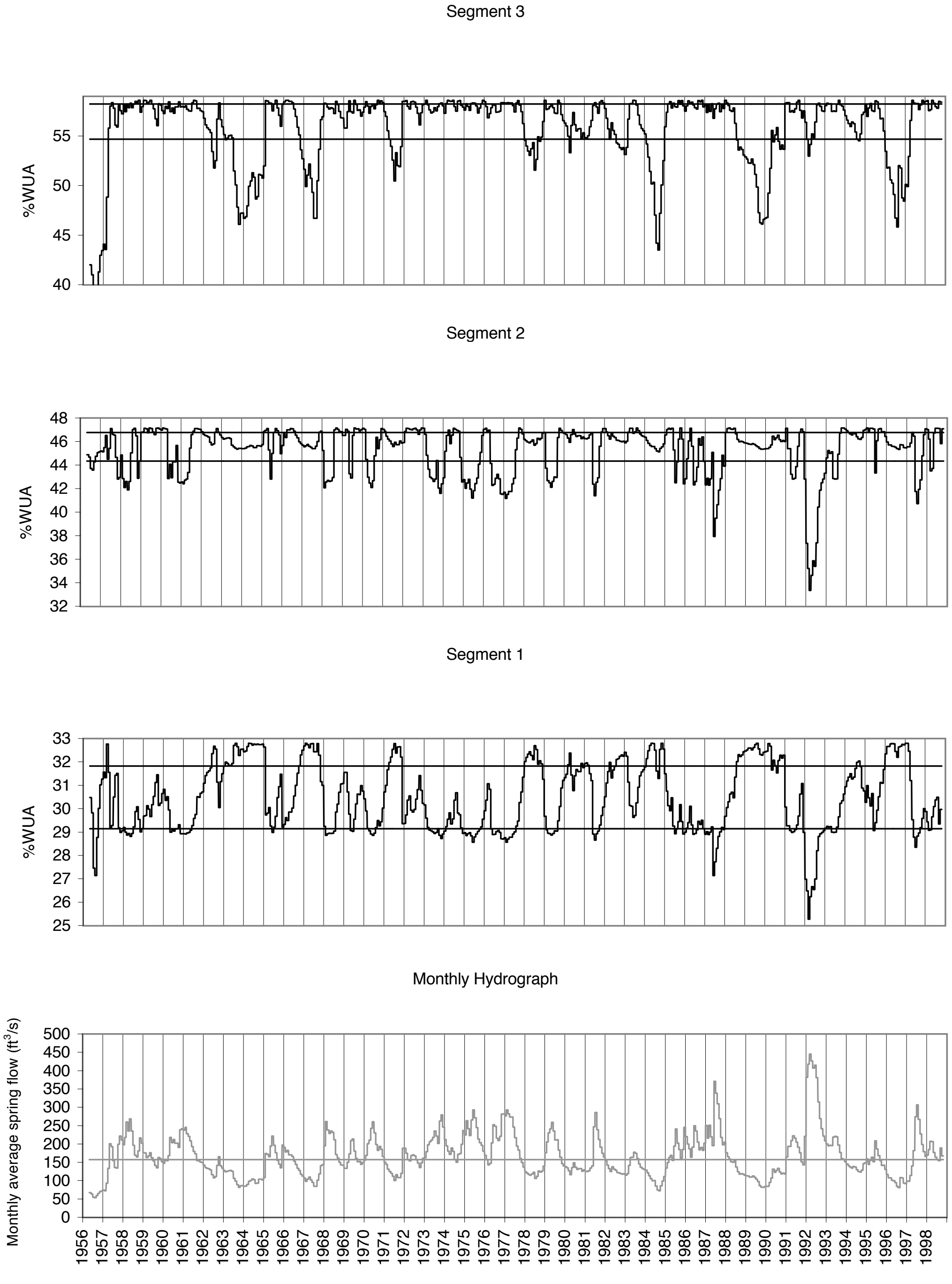
APPENDIX IV: FIGURE 2.—Habitat time series for *Zizania texana*. Upper horizontal black lines represent the 75th percentile % weighted usable area (WUA). Lower horizontal black lines represent the 25th percentile %WUA. Horizontal gray line on hydrograph represents monthly mean spring flow based upon the period from 26 May 1956 – 30 September 1998 (USGS Gage #08170000).



APPENDIX IV: FIGURE 3.—Habitat time series for *Heteranthera liebmannii*. Upper horizontal black lines represent the 75th percentile % weighted usable area (WUA). Lower horizontal black lines represent the 25th percentile %WUA. Horizontal gray line on hydrograph represents monthly mean spring flow based upon the period from 26 May 1956 – 30 September 1998 (USGS Gage #08170000).



APPENDIX IV: FIGURE 4.—Habitat time series for *Vallisneria americana*. Upper horizontal black lines represent the 75th percentile % weighted usable area (WUA). Lower horizontal black lines represent the 25th percentile %WUA. Horizontal gray line on hydrograph represents monthly mean spring flow based upon the period from 26 May 1956 – 30 September 1998 (USGS Gage #08170000).



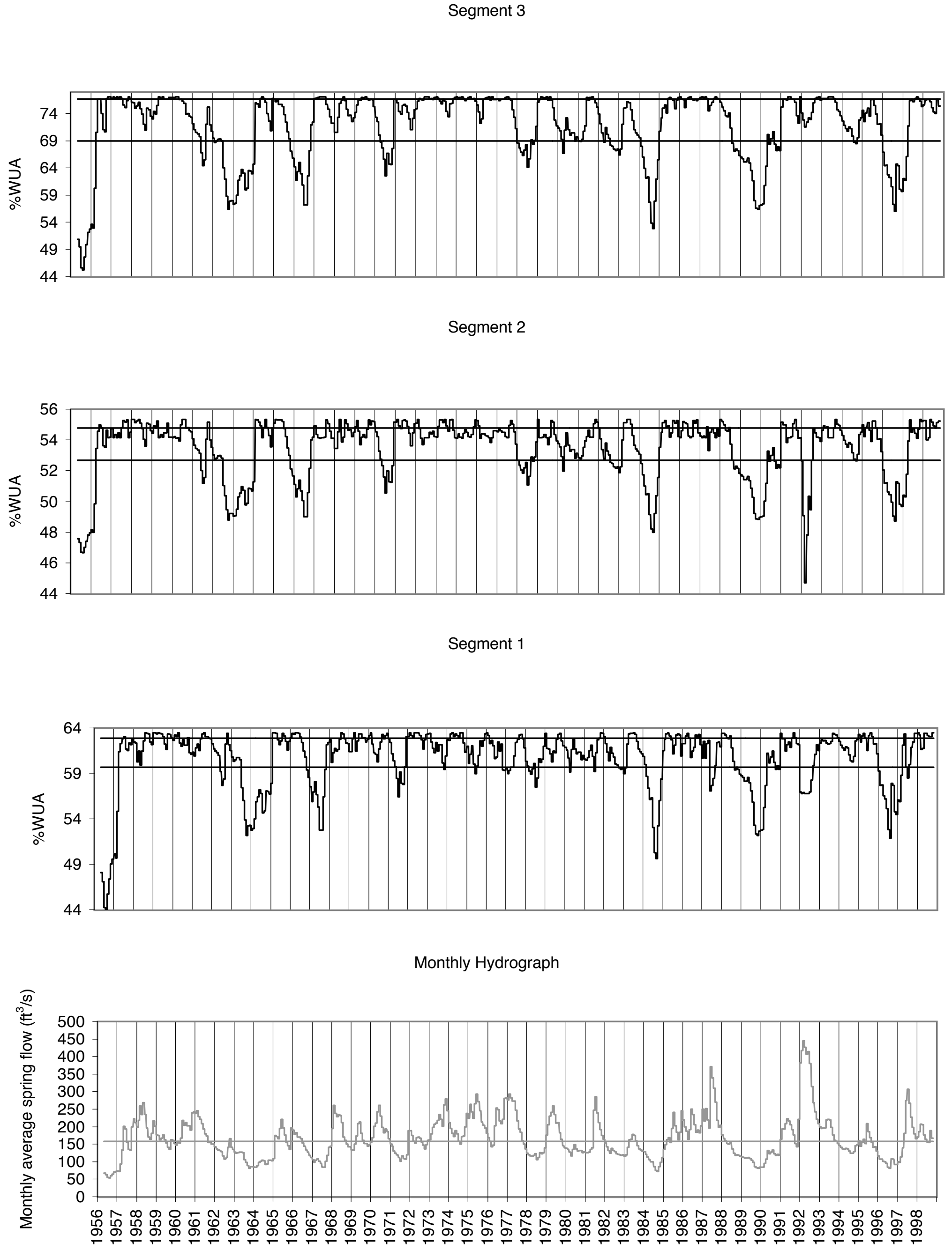
Segment 3

Segment 2

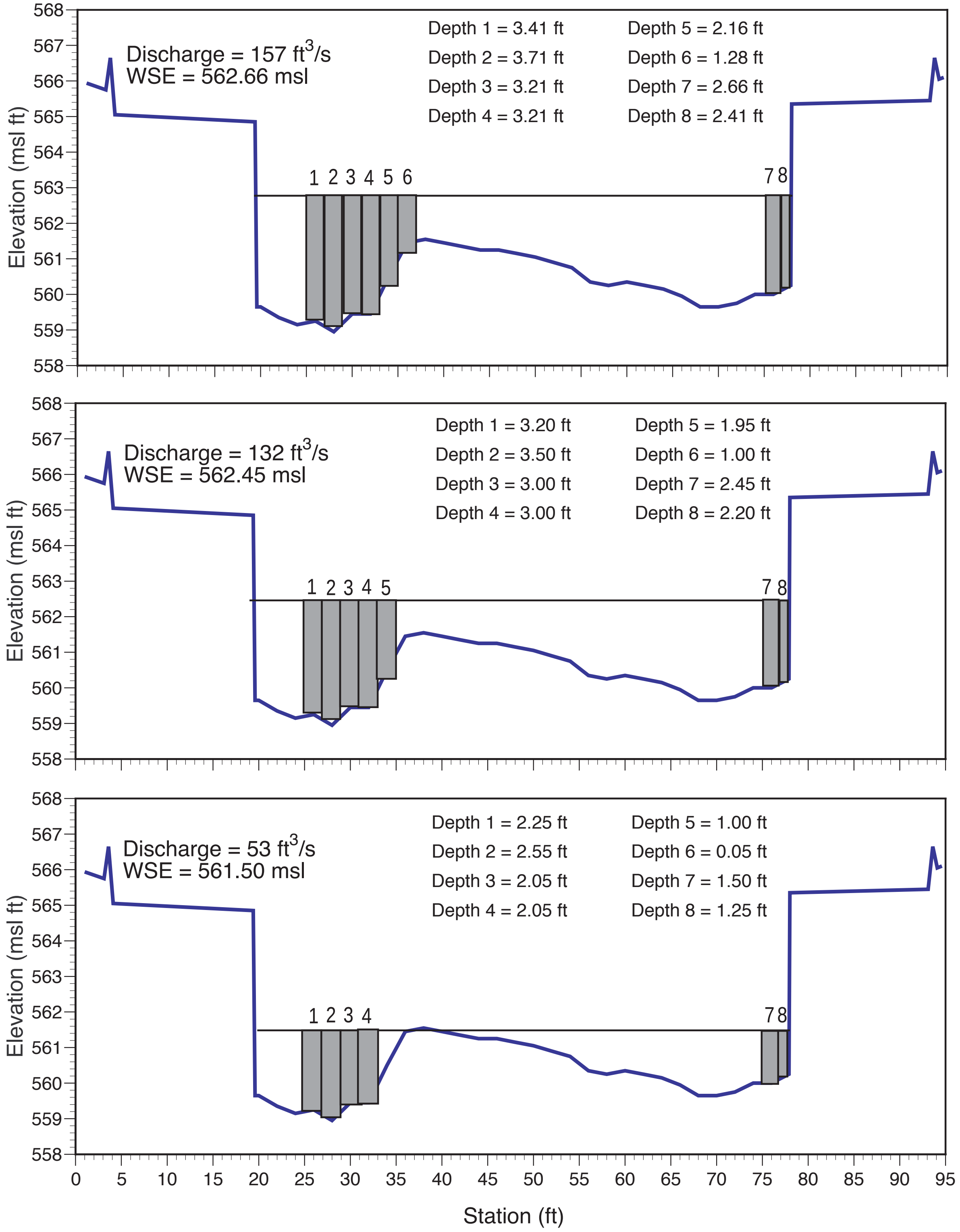
Segment 1

Monthly Hydrograph

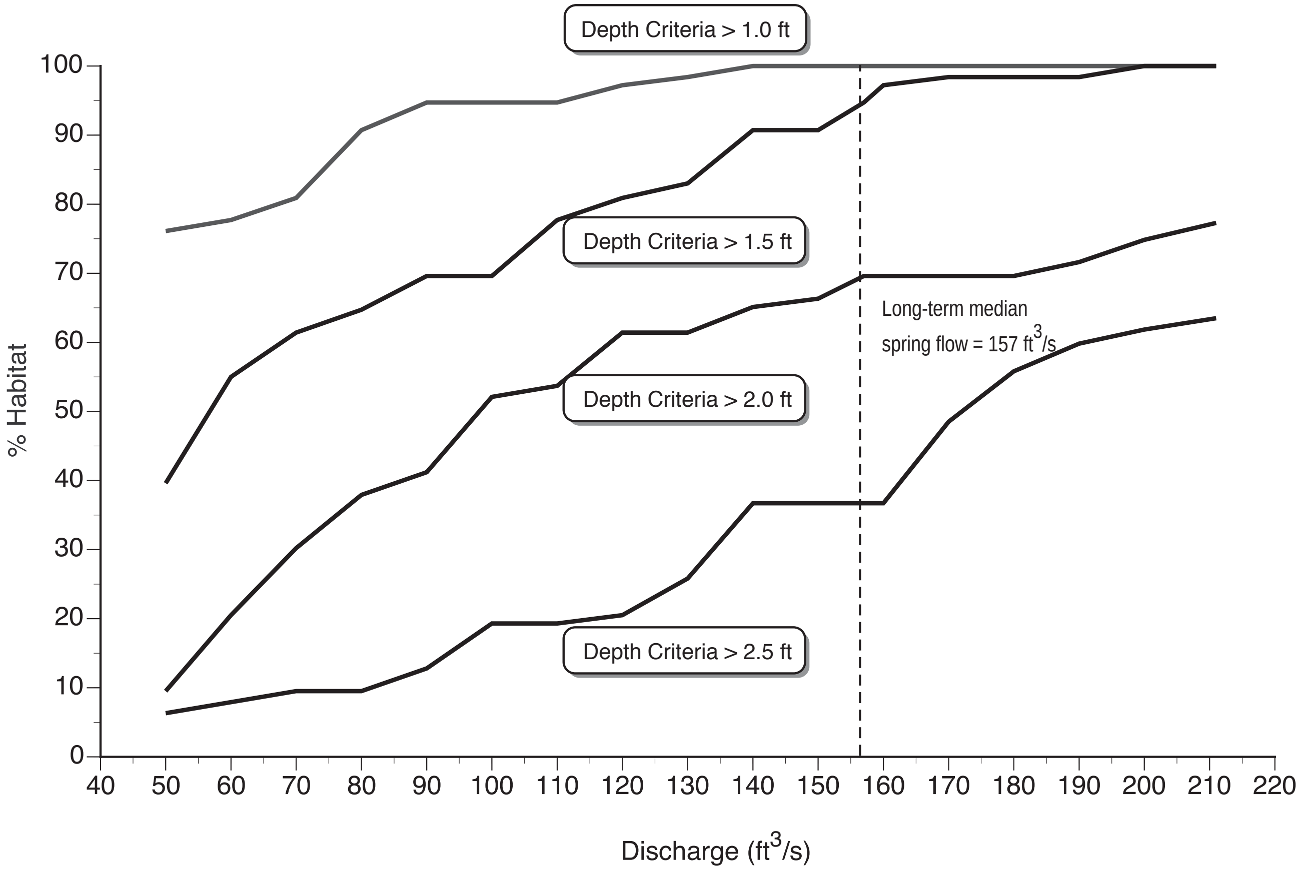
APPENDIX IV: FIGURE 5.—Habitat time series for *Sagitteria platyphylla*. Upper horizontal black lines represent the 75th percentile % weighted usable area (WUA). Lower horizontal black lines represent the 25th percentile %WUA. Horizontal gray line on hydrograph represents monthly mean spring flow based upon the period from 26 May 1956 – 30 September 1998 (USGS Gage #08170000).



APPENDIX IV: FIGURE 6.—Habitat time series for *Potamogeton illinoensis*. Upper horizontal black lines represent the 75th percentile % weighted usable area (WUA). Lower horizontal black lines represent the 25th percentile %WUA. Horizontal gray line on hydrograph represents monthly mean spring flow based upon the period from 26 May 1956 – 30 September 1998 (USGS Gage #08170000).



Appendix IV: Figure 7.—Depths at *Z. texana* verticals on cross-section 24, representative of run mesohabitat. Using a depth criteria of 1.0 ft, *Z. texana* vertical 6 (13.4% of *Z. texana* habitat) was eliminated at 132 ft^3/s and verticals 5 and 6 (26.8%) were eliminated at 53 ft^3/s.



APPENDIX IV: FIGURE 8.—Percentage of *Z. texana* habitat meeting depth criterias in relation to discharge in the upper San Marcos River. Data based on all habitat cross-sections in the main channel with *Z. texana* present. Long-term median spring flow based on water years 1956-1998.

Appendix V
Water Quality

APPENDIX V: TABLE 1.—San Marcos River, hourly water temperature data, by station and month.

Month	Station	Temperature (°C)				
		N	Mean	Std Dev	Minimum	Maximum
Nov-94	1	712	21.6	0.48	20.5	22.8
Nov-94	2	638	21.2	0.77	19.5	23.1
Nov-94	5	712	21.3	0.94	19.0	23.2
Dec-94	1	741	21.2	0.54	18.5	22.7
Dec-94	2	739	20.5	0.98	14.7	22.7
Dec-94	5	744	20.0	1.27	13.6	22.7
Jan-95	1	796	21.1	0.52	19.7	22.3
Jan-95	2	745	20.5	0.76	18.8	22.3
Jan-95	5	739	20.0	0.92	18.1	21.9
Feb-95	1	669	21.2	0.52	20.1	22.8
Feb-95	2	669	20.7	0.80	19.0	23.0
Feb-95	3	538	20.6	0.86	18.6	22.9
Feb-95	4	538	20.6	1.11	18.5	23.9
Feb-95	5	441	20.0	0.86	18.3	22.1
Mar-95	1	692	21.5	0.72	19.7	23.6
Mar-95	2	678	21.2	1.14	18.2	24.2
Mar-95	3	691	21.1	1.18	18.0	24.1
Mar-95	4	203	20.9	0.85	18.6	23.9
Mar-95	5	679	21.0	1.33	17.2	24.1
Mar-95	6	677	19.9	2.04	15.4	24.3
Apr-95	1	720	21.9	0.60	20.0	23.4
Apr-95	3	492	21.8	0.96	18.8	23.9
Apr-95	4	720	21.9	1.06	18.5	24.4
Apr-95	5	720	21.9	1.06	18.5	24.3
Apr-95	6	720	21.6	1.36	18.3	24.1
May-95	1	712	22.2	0.50	20.9	23.5
May-95	2	705	22.5	0.81	20.0	24.4
May-95	3	58	22.0	0.64	20.9	23.1
May-95	4	202	22.4	0.77	20.1	23.9
May-95	5	712	22.9	0.85	20.3	25.2
May-95	6	742	24.3	1.11	22.1	27.6
Jun-95	1	642	22.3	0.46	21.6	23.3
Jun-95	2	516	22.6	0.80	21.3	24.3
Jun-95	3	237	22.4	0.79	21.2	23.9
Jun-95	4	502	22.9	0.81	21.6	25.0
Jun-95	5	642	23.0	0.81	21.5	24.7
Jun-95	6	635	25.6	1.02	23.2	28.0
Jul-95	1	620	22.5	0.51	21.8	23.6
Jul-95	2	409	23.0	0.82	21.9	24.7
Jul-95	3	590	22.6	0.82	21.4	24.3
Jul-95	4	602	23.5	0.86	22.2	25.3
Jul-95	5	612	23.5	0.82	22.1	25.2
Jul-95	6	720	26.6	0.67	24.8	28.3
Aug-95	1	643	22.6	0.53	21.9	24.3
Aug-95	2	744	23.0	0.81	21.8	25.0
Aug-95	3	738	23.0	0.82	21.6	25.0
Aug-95	4	739	23.3	0.79	22.0	25.0
Aug-95	5	644	23.6	0.76	22.4	25.1
Aug-95	6	739	26.0	0.77	23.7	28.1
Sep-95	1	666	22.4	0.58	21.0	23.8
Sep-95	2	655	22.7	0.89	20.2	24.7
Sep-95	3	667	22.7	0.89	20.3	24.7
Sep-95	4	675	22.8	0.93	20.2	25.6
Sep-95	5	596	23.0	1.00	20.2	25.4
Sep-95	6	675	24.3	1.22	20.6	26.5
Oct-95	1	647	21.8	0.55	19.1	23.3
Oct-95	2	681	21.7	0.83	18.6	23.9
Oct-95	3	716	21.8	0.85	18.8	24.0
Oct-95	4	735	21.7	0.92	18.9	25.1
Oct-95	5	689	21.8	0.90	19.2	23.9
Oct-95	6	736	22.0	1.00	19.9	26.0
Nov-95	1	578	21.4	0.50	19.8	22.4
Nov-95	2	581	20.9	0.78	18.6	22.5
Nov-95	3	720	20.8	0.81	18.7	22.6
Nov-95	4	720	20.5	0.86	18.6	22.5
Nov-95	5	581	20.5	0.89	18.2	22.5
Nov-95	6	720	19.8	0.90	17.7	21.6
Dec-95	1	644	21.0	0.67	19.6	22.8
Dec-95	2	646	20.3	1.06	17.9	22.9
Dec-95	3	671	20.3	1.13	17.7	24.1

Appendix V: TABLE 1. Continued.—San Marcos River, hourly water temperature data, by station and month.

		Temperature (°C)				
Month	Station	N	Mean	Std Dev	Minimum	Maximum
Dec-95	4	672	19.9	1.19	17.1	22.7
Dec-95	5	646	19.7	1.32	16.8	22.6
Dec-95	6	670	18.8	1.62	16.1	21.9
Dec-95	7	564	18.4	1.55	16.0	21.6
Jan-96	1	637	20.7	0.74	19.1	22.4
Jan-96	2	688	19.9	1.14	17.2	22.2
Jan-96	3	744	19.7	1.12	17.1	22.1
Jan-96	4	744	19.4	1.22	16.3	21.8
Jan-96	5	694	19.2	1.32	15.9	21.7
Jan-96	6	744	18.0	1.45	14.5	21.1
Jan-96	7	693	17.9	1.46	14.4	20.6
Feb-96	1	571	21.0	1.05	18.8	23.4
Feb-96	2	572	20.4	1.64	17.1	23.7
Feb-96	3	659	20.3	1.57	16.9	23.5
Feb-96	4	663	20.0	1.81	16.0	23.2
Feb-96	5	572	19.8	2.02	15.5	23.1
Feb-96	6	659	19.2	2.38	14.0	23.2
Feb-96	7	573	19.1	2.54	13.9	22.7
Mar-96	1	622	21.0	0.95	18.7	23.4
Mar-96	2	546	20.5	1.49	16.4	23.8
Mar-96	3	768	20.4	1.53	16.3	24.0
Mar-96	4	768	20.2	1.63	16.2	23.7
Mar-96	5	624	19.9	1.68	16.0	23.2
Mar-96	6	768	19.5	1.94	15.4	23.4
Mar-96	7	492	19.2	2.06	15.5	22.9
Apr-96	1	496	22.2	0.75	20.7	24.1
Apr-96	2	497	22.3	1.17	19.7	25.0
Apr-96	3	720	21.8	1.47	15.8	24.8
Apr-96	4	720	21.8	1.55	15.2	24.9
Apr-96	5	497	22.3	1.13	19.4	24.7
Apr-96	6	720	22.0	1.68	16.4	25.0
Apr-96	7	481	22.6	1.03	19.9	25.0
May-96	1	681	22.9	0.65	21.9	24.4
May-96	2	681	23.4	1.00	21.7	25.8
May-96	3	736	23.4	0.97	21.4	25.5
May-96	4	736	23.6	0.95	21.2	25.9
May-96	5	681	23.8	0.91	22.1	26.0
May-96	6	736	24.5	0.94	21.4	26.9
May-96	7	681	24.5	0.86	22.6	26.5
Jun-96	1	651	23.2	0.71	21.7	24.7
Jun-96	2	603	23.8	1.08	21.5	26.1
Jun-96	3	720	23.8	1.03	21.6	26.0
Jun-96	4	720	24.2	0.92	22.0	26.1
Jun-96	5	650	24.4	0.87	22.0	26.2
Jun-96	6	720	25.6	0.80	23.2	27.4
Jun-96	7	420	25.4	0.91	23.3	27.3
Jul-96	1	650	23.3	0.70	22.3	24.8
Jul-96	2	651	24.1	0.97	22.5	26.0
Jul-96	3	667	24.1	0.92	22.6	25.9
Jul-96	4	667	24.6	0.77	23.0	25.9
Jul-96	5	652	25.0	0.66	23.6	26.2
Jul-96	6	666	26.3	0.64	25.0	27.9
Jul-96	7	547	26.1	0.50	25.0	27.3
Aug-96	1	439	23.3	0.75	22.1	24.8
Aug-96	3	744	23.8	0.94	22.1	25.9
Aug-96	4	744	24.2	0.78	22.7	25.9
Aug-96	5	706	24.7	0.78	22.9	26.2
Aug-96	6	744	25.6	0.98	23.2	27.6
Aug-96	7	706	25.5	0.87	23.5	27.3
Sep-96	1	584	22.6	0.64	21.0	24.1
Sep-96	2	584	22.9	1.01	20.0	24.9
Sep-96	3	82	23.2	0.87	22.1	25.0
Sep-96	4	720	23.2	0.96	20.0	25.1
Sep-96	5	665	23.4	1.02	20.0	25.4
Sep-96	6	719	24.2	1.01	20.4	25.6
Sep-96	7	652	24.0	1.00	20.4	25.4
Oct-96	1	608	22.1	0.59	20.5	23.6
Oct-96	2	324	22.1	0.90	20.1	24.1
Oct-96	3	542	21.9	0.96	19.2	24.0

Appendix V: TABLE 1. Continued.—San Marcos River, hourly water temperature data, by station and month.

		Temperature (°C)				
Month	Station	N	Mean	Std Dev	Minimum	Maximum
Oct-96	4	744	22.0	0.96	19.1	24.0
Oct-96	5	607	22.1	1.01	19.1	24.1
Oct-96	6	745	22.3	1.04	19.1	24.3
Oct-96	7	563	22.2	1.14	19.0	24.4
Nov-96	1	645	21.2	0.77	19.3	22.8
Nov-96	2	561	20.6	1.27	16.7	22.7
Nov-96	3	719	20.6	1.29	16.4	22.9
Nov-96	4	720	20.4	1.43	16.3	23.2
Nov-96	5	647	20.3	1.47	16.4	23.2
Nov-96	6	719	20.1	1.75	15.8	23.1
Nov-96	7	647	19.9	1.80	15.6	23.1
Dec-96	1	641	20.7	0.91	18.6	22.6
Dec-96	2	642	20.0	1.40	15.9	22.4
Dec-96	3	744	19.8	1.36	15.8	22.3
Dec-96	4	743	19.4	1.53	15.4	22.0
Dec-96	5	642	19.3	1.69	15.5	21.9
Dec-96	6	744	18.4	1.83	14.2	21.6
Dec-96	7	643	18.2	1.96	14.0	21.2
Jan-97	1	538	20.4	1.03	18.4	22.5
Jan-97	2	527	19.4	1.55	16.6	22.3
Jan-97	3	744	19.3	1.61	16.3	22.8
Jan-97	4	744	18.9	1.80	15.4	22.7
Jan-97	5	540	18.5	1.88	14.9	21.7
Jan-97	6	744	17.5	2.39	12.8	21.9
Jan-97	7	541	17.0	2.33	12.6	20.9
Feb-97	1	537	20.7	0.63	18.3	22.3
Feb-97	2	537	19.8	1.08	16.0	22.2
Feb-97	3	672	19.8	1.15	16.1	22.6
Feb-97	4	672	19.5	1.29	15.1	22.3
Feb-97	5	420	19.0	1.34	15.1	21.4
Feb-97	6	672	18.3	1.54	14.5	21.9
Feb-97	7	537	17.2	1.21	14.4	20.6
Mar-97	1	679	21.7	0.63	20.3	23.5
Mar-97	2	676	21.4	1.03	19.2	24.3
Mar-97	3	729	21.2	1.02	19.0	24.1
Mar-97	4	733	21.2	1.06	18.9	24.0
Mar-97	5	12	20.7	0.29	20.2	21.0
Mar-97	6	729	21.1	1.42	18.5	24.1
Mar-97	7	679	19.9	1.27	17.4	22.5
Apr-97	1	705	21.7	0.60	18.8	23.5
Apr-97	2	705	21.5	1.05	17.4	24.4
Apr-97	7	705	19.6	1.67	16.3	23.6
May-97	1	32	22.2	0.46	21.6	23.1
May-97	2	33	22.2	0.70	21.5	23.7
May-97	7	110	22.6	0.94	19.9	24.0

APPENDIX V: TABLE 2.—San Marcos River, dissolved oxygen by station and month. All data are from the first four days following data sonde calibration.

		Dissolved Oxygen (mg/L)				
Month	Station	N	Mean	Std Dev	Minimum	Maximum
Nov-94	1	96	6.3	0.61	5.4	7.7
Nov-94	2	96	7.4	0.81	6.3	9.1
Nov-94	5	96	5.3	0.34	4.6	6.2
Feb-95	1	96	7.5	0.73	6.6	9.0
Feb-95	2	96	7.7	1.28	6.2	10.4
Feb-95	5	96	7.1	0.78	6.0	9.1
Mar-95	1	96	7.0	0.68	6.1	8.6
Mar-95	2	96	8.1	1.19	6.9	10.9
Mar-95	5	96	7.3	0.71	6.2	8.9
Apr-95	1	96	7.5	0.79	6.7	9.8
Apr-95	5	96	6.9	0.63	5.8	8.9
May-95	1	96	8.5	1.09	7.2	10.6
May-95	2	96	6.9	1.22	5.4	9.8
May-95	5	96	6.2	0.55	5.2	7.4
Jun-95	1	96	7.6	0.81	6.6	8.9
Jun-95	2	96	7.7	1.08	6.3	9.7
Jun-95	5	96	8.2	0.49	7.6	9.3
Jul-95	1	96	7.8	0.85	6.7	9.3
Jul-95	2	96	7.9	1.41	6.3	10.5
Jul-95	5	96	8.7	0.64	8.0	9.9
Aug-95	1	96	7.5	0.76	6.7	9.0
Aug-95	2	96	5.5	1.22	4.2	8.5
Aug-95	5	96	7.7	0.53	7.0	8.9
Sep-95	1	96	7.4	0.82	6.4	9.2
Sep-95	2	96	7.2	1.35	5.6	10.2
Sep-95	5	96	7.7	0.70	6.8	9.2
Oct-95	1	96	8.2	0.87	7.3	9.7
Oct-95	2	95	8.0	1.07	7.0	10.2
Oct-95	5	96	7.4	0.46	6.8	8.3
Nov-95	1	95	7.5	0.68	6.7	9.0
Nov-95	2	96	7.4	0.87	6.3	9.3
Nov-95	5	96	7.2	0.46	6.0	8.1
Dec-95	1	96	8.1	0.71	7.3	9.6
Dec-95	2	96	8.1	1.22	6.7	10.8
Dec-95	5	96	8.1	0.69	7.2	9.6
Dec-95	7	96	9.3	0.27	8.8	9.8
Jan-96	1	96	8.1	0.66	7.3	9.4
Jan-96	2	96	8.3	1.12	6.9	10.7
Jan-96	5	96	8.6	0.76	7.7	10.1
Jan-96	7	96	9.8	0.25	9.2	10.3
Feb-96	1	96	8.4	1.00	7.3	10.2
Feb-96	2	96	8.8	1.76	6.8	12.2
Feb-96	5	96	8.4	1.24	7.0	10.8
Feb-96	7	96	9.4	0.34	8.7	10.0
Mar-96	1	96	7.9	1.00	6.2	9.6
Mar-96	2	96	6.9	1.45	4.7	10.4
Mar-96	5	96	8.1	1.26	6.4	10.4
Mar-96	7	96	8.9	0.34	8.3	9.6
Apr-96	1	96	8.5	1.20	7.1	10.5
Apr-96	2	96	6.5	1.58	4.1	9.9
Apr-96	5	96	7.1	1.02	5.6	9.3
Apr-96	7	96	7.6	0.36	6.7	8.4
May-96	1	96	7.6	1.04	6.4	10.0
May-96	2	96	7.6	1.33	5.3	11.1
May-96	5	96	6.7	0.76	5.8	8.7
May-96	7	96	7.2	0.53	6.1	8.2
Jun-96	1	96	8.0	1.18	6.6	9.9
Jun-96	2	96	5.7	1.13	3.2	8.4
Jun-96	5	96	6.4	0.60	5.5	7.7
Jun-96	7	96	7.6	0.32	6.6	8.2
Jul-96	1	95	8.2	1.17	6.8	10.1
Jul-96	2	96	7.5	1.68	5.1	10.7
Jul-96	5	96	6.4	0.71	5.2	7.9
Jul-96	7	96	6.9	1.06	5.1	8.6
Aug-96	1	96	8.1	1.12	6.7	10.0
Aug-96	5	96	7.8	1.39	5.5	10.6
Aug-96	7	96	6.3	0.97	5.1	8.7
Sep-96	1	96	7.6	0.91	6.6	9.3
Sep-96	2	96	7.0	0.93	5.7	9.0

APPENDIX V: TABLE 2. Continued. —San Marcos River, dissolved oxygen by station and month. All data are from the first four days following data sonde calibration.

		Dissolved Oxygen (mg/L)				
Month	Station	N	Mean	Std Dev	Minimum	Maximum
Sep-96	5	96	8.8	0.73	7.5	10.3
Sep-96	7	96	7.5	0.20	6.9	7.9
Oct-96	1	96	7.8	0.92	6.7	9.5
Oct-96	2	96	7.3	1.53	5.6	10.6
Oct-96	5	96	6.2	0.85	4.8	8.2
Oct-96	7	37	6.6	0.42	5.7	7.3
Nov-96	1	96	7.8	0.80	6.9	9.4
Nov-96	2	96	6.9	1.00	5.5	8.9
Nov-96	5	96	8.2	0.50	7.5	9.2
Nov-96	7	96	7.6	0.38	6.6	8.4
Dec-96	1	96	7.7	0.79	6.7	9.2
Dec-96	2	96	8.1	1.17	6.4	10.5
Dec-96	5	96	7.7	0.61	6.7	9.0
Dec-96	7	96	8.0	0.40	7.2	8.8
Jan-97	1	96	6.5	0.43	5.6	7.6
Jan-97	2	96	8.5	0.80	7.4	10.8
Jan-97	5	96	7.8	0.50	6.7	8.9
Jan-97	7	96	9.6	0.30	8.8	10.1
Feb-97	1	96	7.6	0.65	6.8	9.0
Feb-97	2	96	7.8	1.12	6.5	10.4
Feb-97	5	96	8.7	0.91	6.9	10.8
Feb-97	7	96	8.7	0.29	8.0	9.4
Mar-97	1	96	7.4	0.58	6.4	8.9
Mar-97	7	96	8.3	0.22	7.8	8.8
Apr-97	1	96	7.4	0.51	6.2	8.8
Apr-97	7	96	9.0	0.80	7.0	10.5

APPENDIX V: TABLE 3.—San Marcos River, pH by station and month.

		pH (standard units)				
Month	Station	N	Mean	Std Dev	Minimum	Maximum
Nov-94	1	712	7.5	0.07	7.4	7.7
Nov-94	2	638	7.7	0.12	7.5	8.1
Nov-94	5	712	7.8	0.06	7.7	8.0
Dec-94	1	741	7.5	0.06	7.3	7.6
Dec-94	2	739	7.8	0.15	7.4	8.1
Dec-94	5	744	7.8	0.08	7.6	8.0
Jan-95	1	796	7.5	0.08	7.4	7.8
Jan-95	2	745	7.8	0.13	7.6	8.2
Jan-95	5	739	7.8	0.09	7.6	8.1
Feb-95	1	669	7.3	0.07	7.2	7.6
Feb-95	2	669	7.7	0.11	7.5	8.0
Feb-95	5	441	7.6	0.09	7.5	8.0
Mar-95	1	692	7.5	0.07	7.3	7.7
Mar-95	2	678	7.6	0.12	7.3	7.9
Mar-95	5	678	7.8	0.09	7.6	8.0
Apr-95	1	720	7.4	0.07	7.3	7.6
Apr-95	5	720	7.6	0.10	7.4	7.9
May-95	1	712	7.5	0.08	7.3	7.7
May-95	2	705	8.0	0.16	7.7	8.4
May-95	5	712	7.8	0.09	7.6	8.1
Jun-95	1	642	7.4	0.08	7.3	7.6
Jun-95	2	516	7.7	0.25	7.4	8.3
Jun-95	5	642	7.7	0.10	7.5	8.0
Jul-95	1	620	7.5	0.06	7.4	7.6
Jul-95	2	409	7.7	0.10	7.5	7.9
Jul-95	5	612	7.8	0.08	7.7	8.2
Aug-95	1	643	7.6	0.07	7.5	7.8
Aug-95	2	744	7.8	0.13	7.6	8.2
Aug-95	5	644	7.9	0.08	7.7	8.1
Sep-95	1	666	7.5	0.14	7.3	7.8
Sep-95	2	655	7.7	0.18	7.4	8.2
Sep-95	5	596	7.9	0.10	7.6	8.2
Oct-95	1	647	7.5	0.11	7.2	7.7
Oct-95	2	682	7.7	0.09	7.6	8.0
Oct-95	5	689	8.0	0.08	7.8	8.2
Nov-95	1	578	7.6	0.06	7.4	7.7
Nov-95	2	581	7.8	0.09	7.6	8.0
Nov-95	5	581	8.0	0.08	7.8	8.2
Dec-95	1	644	7.5	0.08	7.4	7.7
Dec-95	2	646	7.7	0.11	7.5	8.0
Dec-95	5	646	7.9	0.11	7.7	8.2
Dec-95	7	564	8.0	0.05	7.9	8.1
Jan-96	1	637	7.5	0.07	7.4	7.7
Jan-96	2	688	7.7	0.11	7.5	8.0
Jan-96	5	694	7.9	0.09	7.7	8.1
Jan-96	7	693	8.1	0.04	8.0	8.2
Feb-96	1	571	7.6	0.07	7.5	7.9
Feb-96	2	572	7.8	0.12	7.5	8.1
Feb-96	5	572	8.0	0.09	7.8	8.2
Feb-96	7	572	8.2	0.07	8.0	8.3
Mar-96	1	622	7.6	0.10	7.4	7.8
Mar-96	2	546	7.7	0.14	7.5	8.1
Mar-96	5	624	7.9	0.09	7.7	8.2
Mar-96	7	492	8.1	0.13	7.9	8.4
Apr-96	1	496	7.5	0.08	7.3	7.7
Apr-96	2	497	7.5	0.13	7.3	7.8
Apr-96	5	497	8.0	0.08	7.8	8.2
Apr-96	7	481	8.1	0.07	7.9	8.2
May-96	1	681	7.5	0.09	7.3	7.7
May-96	2	681	7.8	0.11	7.5	8.0
May-96	5	681	8.0	0.11	7.7	8.2
May-96	7	681	8.0	0.07	7.8	8.1
Jun-96	1	651	7.6	0.08	7.4	7.7
Jun-96	2	603	7.8	0.11	7.5	8.1
Jun-96	5	650	8.0	0.09	7.7	8.2
Jun-96	7	420	8.1	0.09	7.9	8.3
Jul-96	1	650	7.5	0.09	7.3	7.7
Jul-96	2	651	7.7	0.11	7.5	8.0
Jul-96	5	652	7.8	0.06	7.7	8.2
Jul-96	7	535	8.0	0.08	7.9	8.2

Appendix V: Table 3. Continued. —San Marcos River, pH by station and month.

		pH (standard units)				
Month	Station	N	Mean	Std Dev	Minimum	Maximum
Aug-96	1	429	7.5	0.07	7.4	7.7
Aug-96	5	706	7.7	0.07	7.4	8.0
Aug-96	7	706	7.9	0.07	7.6	8.0
Sep-96	1	584	7.7	0.11	7.4	7.9
Sep-96	2	584	7.8	0.14	7.5	8.2
Sep-96	5	665	7.9	0.08	7.7	8.1
Sep-96	7	652	8.1	0.09	7.9	8.3
Oct-96	1	608	7.6	0.14	7.4	8.0
Oct-96	2	324	7.8	0.22	7.5	8.3
Oct-96	5	607	7.8	0.12	7.6	8.1
Oct-96	7	563	8.0	0.20	7.8	8.4
Nov-96	1	645	7.6	0.12	7.4	7.9
Nov-96	2	561	8.0	0.16	7.7	8.4
Nov-96	5	86	7.9	0.05	7.8	7.9
Nov-96	7	647	8.1	0.09	7.9	8.3
Dec-96	1	641	7.6	0.09	7.4	7.9
Dec-96	2	642	7.8	0.15	7.6	8.4
Dec-96	7	643	8.0	0.11	7.8	8.4
Jan-97	1	538	7.6	0.07	7.5	7.9
Jan-97	2	527	8.0	0.13	7.7	8.3
Jan-97	5	502	8.1	0.08	7.9	8.4
Jan-97	7	541	8.2	0.07	8.0	8.4
Feb-97	1	537	7.4	0.06	7.3	7.6
Feb-97	2	537	7.7	0.11	7.5	8.0
Feb-97	5	420	7.8	0.07	7.7	8.0
Feb-97	7	537	7.9	0.06	7.8	8.1
Mar-97	1	679	7.5	0.06	7.4	7.7
Mar-97	2	676	7.8	0.13	7.6	8.2
Mar-97	7	679	8.1	0.10	7.9	8.4
Apr-97	1	705	7.5	0.10	7.3	7.7
Apr-97	2	705	7.7	0.13	7.4	8.0
Apr-97	7	705	8.1	0.14	7.7	8.4
May-97	1	32	7.6	0.05	7.5	7.7
May-97	2	33	7.7	0.09	7.7	7.9
May-97	7	24	8.3	0.02	8.3	8.3

APPENDIX V: TABLE 4.—San Marcos River, specific conductance by station and month.

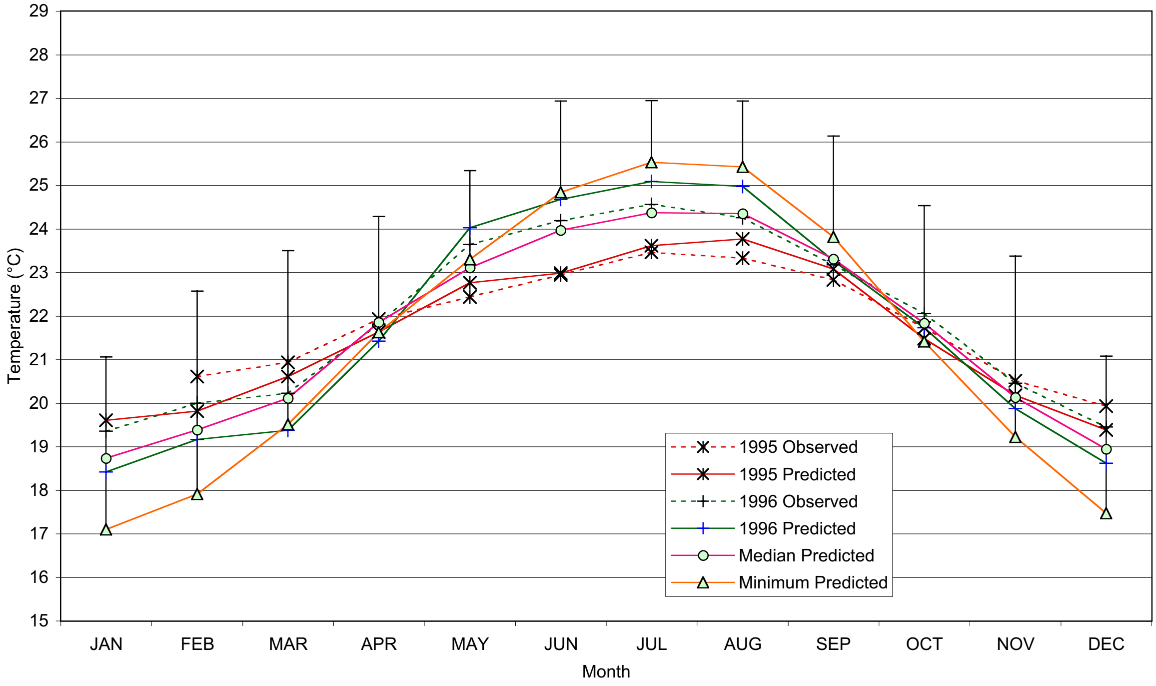
		Specific Conductance (μS/cm)				
Month	Station	N	Mean	Std Dev	Minimum	Maximum
Nov-94	1	712	618	6.9	511	637
Nov-94	2	638	591	12.1	415	599
Nov-94	5	712	629	16.7	451	653
Dec-94	1	741	595	9.5	542	637
Dec-94	2	739	576	28.7	352	596
Dec-94	5	744	595	41.4	355	637
Jan-95	1	796	556	38.2	323	608
Jan-95	2	745	585	2.4	573	590
Jan-95	5	739	599	5.3	532	612
Feb-95	1	669	597	11.0	537	604
Feb-95	2	669	597	13.1	473	619
Feb-95	5	441	618	6.4	569	629
Mar-95	1	692	612	6.5	507	618
Mar-95	2	678	619	22.4	340	628
Mar-95	5	678	565	30.6	255	622
Apr-95	1	720	599	6.9	493	608
Apr-95	5	720	613	28.9	341	635
May-95	1	712	620	13.6	385	629
May-95	2	705	624	44.6	182	640
May-95	5	712	633	53.5	230	665
Jun-95	1	642	604	6.1	555	620
Jun-95	2	516	603	20.9	457	641
Jun-95	5	642	600	18.1	454	641
Jul-95	1	620	589	7.6	536	602
Jul-95	2	409	587	4.5	567	592
Jul-95	5	612	596	8.7	506	609
Aug-95	1	643	584	9.6	385	590
Aug-95	2	731	578	20.6	281	585
Aug-95	5	643	591	20.2	336	606
Sep-95	1	666	618	23.9	290	633
Sep-95	2	655	614	40.5	170	633
Sep-95	5	596	598	46.8	169	625
Oct-95	1	647	591	12.2	335	629
Oct-95	2	682	592	22.7	291	630
Oct-95	5	689	609	18.9	356	640
Nov-95	1	578	592	10.6	365	596
Nov-95	2	581	587	30.3	213	599
Nov-95	5	581	601	38.5	244	638
Dec-95	1	644	609	6.2	592	615
Dec-95	2	646	587	4.0	552	593
Dec-95	5	646	597	7.3	562	621
Dec-95	7	564	629	5.2	607	644
Jan-96	1	636	604	2.1	582	608
Jan-96	2	688	599	4.2	582	604
Jan-96	5	694	609	6.4	590	624
Jan-96	7	693	624	5.1	612	636
Feb-96	1	571	599	2.4	572	603
Feb-96	2	572	586	5.6	574	598
Feb-96	5	572	609	5.7	594	627
Feb-96	7	572	608	9.6	593	634
Mar-96	1	622	612	8.1	558	619
Mar-96	2	546	591	10.5	503	603
Mar-96	5	624	610	10.1	543	632
Mar-96	7	492	605	10.3	553	624
Apr-96	1	496	591	6.8	503	598
Apr-96	2	497	603	18.2	391	612
Apr-96	5	497	594	19.5	397	613
Apr-96	7	481	611	18.0	484	629
May-96	1	681	595	4.4	499	599
May-96	2	681	599	9.4	543	612
May-96	5	680	603	9.8	545	626
May-96	7	681	589	7.0	558	605
Jun-96	1	651	553	21.5	339	596
Jun-96	2	603	551	36.2	242	609
Jun-96	5	649	590	35.6	299	623
Jun-96	7	420	582	43.5	364	603
Jul-96	1	650	587	12.6	470	595
Jul-96	2	651	589	4.4	557	594
Jul-96	5	652	632	10.9	572	653
Jul-96	7	535	609	5.3	591	621

APPENDIX V: TABLE 4. Continued.—San Marcos River, specific conductance by station and month.

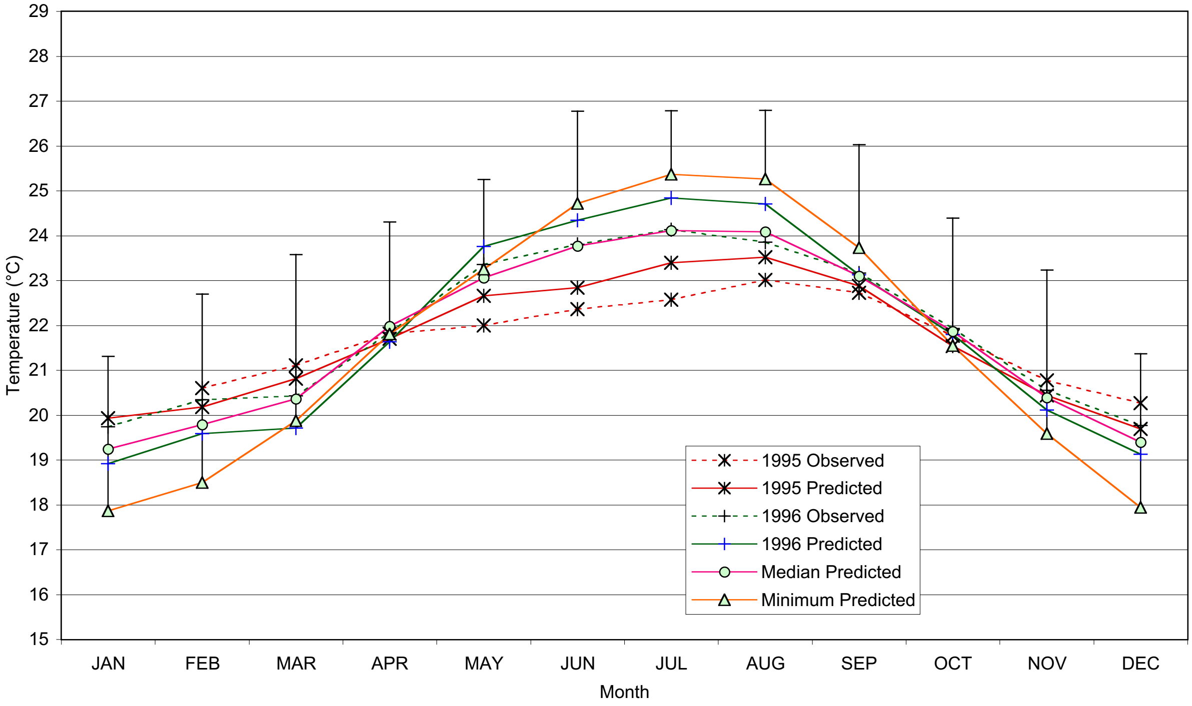
		Specific Conductance (µS/cm)				
Month	Station	N	Mean	Std Dev	Minimum	Maximum
Aug-96	1	429	596	15.3	335	603
Aug-96	5	706	588	82.7	165	664
Aug-96	7	706	567	91.5	203	622
Sep-96	1	584	585	10.8	498	593
Sep-96	2	584	583	21.9	407	593
Sep-96	5	665	601	28.1	436	632
Sep-96	7	652	590	27.2	472	615
Oct-96	1	608	591	10.4	515	598
Oct-96	2	324	588	4.7	552	593
Oct-96	5	607	611	8.7	569	632
Oct-96	7	563	604	5.9	577	616
Nov-96	1	645	591	8.3	513	596
Nov-96	2	561	597	23.2	370	605
Nov-96	5	647	607	25.8	409	632
Nov-96	7	647	600	26.2	430	621
Dec-96	1	641	595	7.2	515	600
Dec-96	2	642	594	23.1	350	603
Dec-96	5	641	608	27.8	371	641
Dec-96	7	643	591	27.3	400	614
Jan-97	1	538	585	4.0	573	597
Jan-97	2	527	596	7.8	432	605
Jan-97	5	540	612	6.7	596	630
Jan-97	7	541	600	4.2	590	611
Feb-97	1	537	583	18.0	430	595
Feb-97	2	537	589	22.4	402	605
Feb-97	5	420	609	32.0	431	633
Feb-97	7	537	573	28.7	455	615
Mar-97	1	679	597	7.9	511	605
Mar-97	2	676	605	7.1	550	611
Mar-97	7	679	563	10.4	535	590
Apr-97	1	705	598	13.6	356	605
Apr-97	2	705	593	42.2	238	614
Apr-97	7	705	499	55.3	273	575
May-97	1	32	601	1.2	599	603
May-97	2	33	609	1.0	607	611
May-97	7	34	523	3.1	518	528

APPENDIX V: TABLE 5.—San Marcos River turbidity measured at water quality stations 1, 2, 5, and 7. Results are in nephelometric turbidity units (NTU).

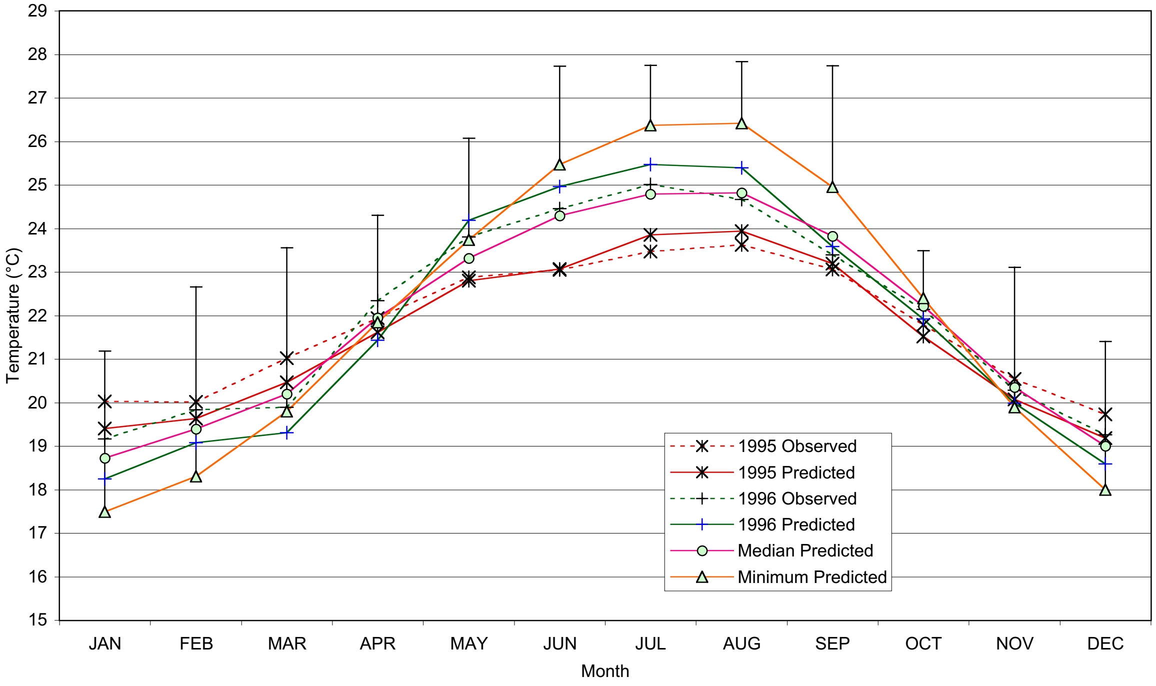
	Station			
Date	1	2	5	7
11/15/94	1.95	1.56	3.57	—
12/01/94	1.13	0.97	3.48	—
12/15/94	1.86	3.37	6.04	—
01/03/95	0.42	0.98	4.30	—
01/18/95	0.75	1.04	3.73	—
02/03/95	0.44	1.25	2.86	—
02/15/95	0.54	1.41	5.05	—
03/01/95	1.15	0.85	1.91	—
03/15/95	0.66	1.61	3.27	—
03/31/95	0.63	1.63	1.93	—
04/19/95	0.60	2.11	5.98	—
05/01/95	0.75	1.70	5.03	—
05/16/95	0.83	1.20	6.64	—
06/05/95	0.56	1.54	8.14	—
06/21/95	0.64	1.31	5.01	—
07/06/95	0.81	1.44	6.98	—
08/08/95	0.58	0.86	3.69	—
08/17/95	0.36	0.51	3.12	—
09/06/95	0.31	0.62	1.63	—
09/21/95	5.75	6.13	12.3	—
10/03/95	0.71	1.28	3.92	—
10/16/95	0.95	1.55	4.81	—
11/02/95	1.71	2.38	3.23	—
11/15/95	1.51	1.47	4.37	—
12/04/95	0.83	1.38	2.68	—
12/18/95	1.21	1.60	3.88	—
01/03/96	0.51	0.82	1.68	6.48
01/16/96	0.57	0.70	1.12	1.52
02/05/96	0.47	0.70	1.12	2.63
02/09/96	1.09	1.78	2.53	7.10
03/04/96	1.66	1.76	4.88	10.6
03/21/96	0.83	1.97	2.90	9.97
03/29/96	1.35	1.54	1.96	2.34
04/15/96	0.61	1.80	3.71	7.40
04/30/96	0.57	1.47	2.20	4.36
05/13/96	0.82	1.86	4.63	9.46
06/03/96	2.95	3.51	8.98	9.78
06/19/96	1.62	2.55	4.63	7.11
07/01/96	1.04	1.23	6.53	8.04
07/15/96	1.26	2.38	5.28	13.4
07/31/96	2.34	5.23	3.00	4.67
08/16/96	1.75	1.80	1.30	0.82
09/04/96	2.62	3.12	5.02	6.20
10/09/96	1.59	3.11	2.73	4.75
10/17/96	1.13	1.80	4.73	6.36
11/04/96	2.26	2.36	3.02	3.16
11/07/96	1.46	1.78	4.69	4.97
12/02/96	1.30	2.24	2.56	2.43
12/17/96	1.23	1.61	—	8.73
01/02/97	1.17	1.08	1.51	2.64
01/16/97	2.02	0.50	0.47	0.77
01/31/97	0.42	0.90	1.50	0.57
02/18/97	1.51	1.32	2.68	3.82
03/04/97	0.97	0.90	1.48	3.00
03/21/97	0.26	0.61	1.08	1.64
03/31/97	1.13	1.49	4.01	7.76
04/15/97	1.03	2.06	7.36	12.6
05/02/97	0.48	0.73	0.40	1.19
N	58	58	57	32
Mean	1.17	1.70	3.81	5.51
Std Dev	0.86	1.03	2.24	3.58
Minimum	0.26	0.50	0.40	0.57
Maximum	5.75	6.13	12.3	13.4



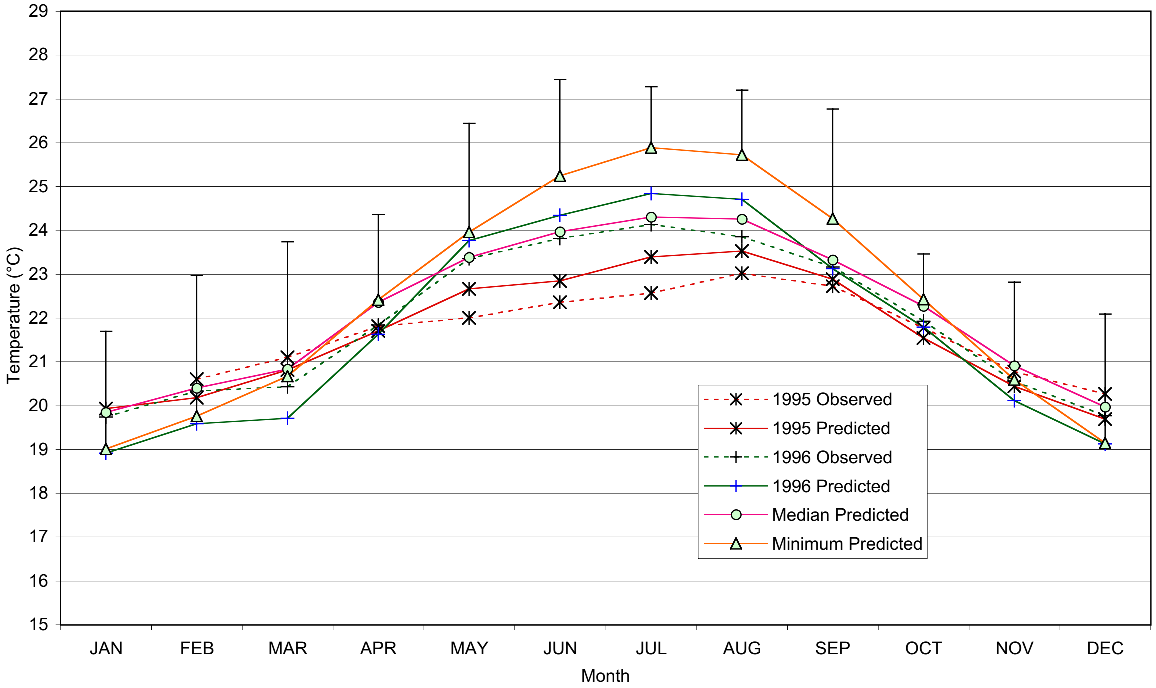
APPENDIX V: FIGURE 1.—Observed and predicted temperature for water quality station 3: temperature sonde 1 assuming normal air temperature. Bars represent maximum daily temperature for the minimum flow scenario.



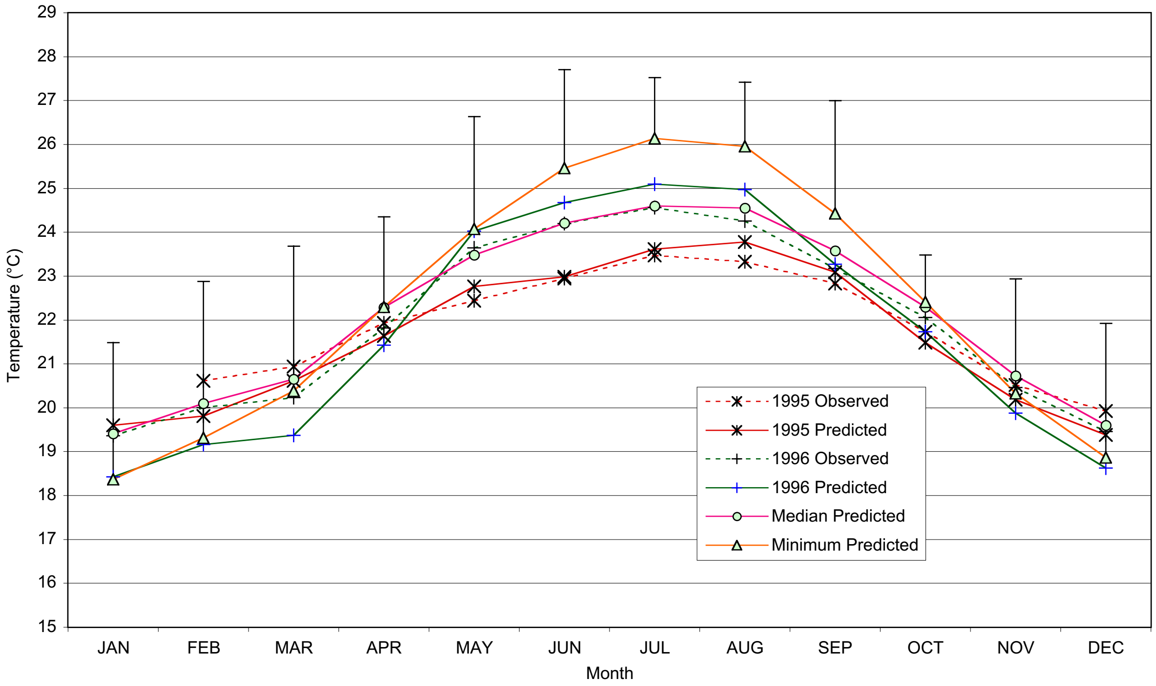
APPENDIX V: FIGURE 2.—Observed and predicted temperature for water quality station 4: temperature sonde 2 assuming normal air temperature. Bars represent maximum daily temperature for the minimum flow scenario.



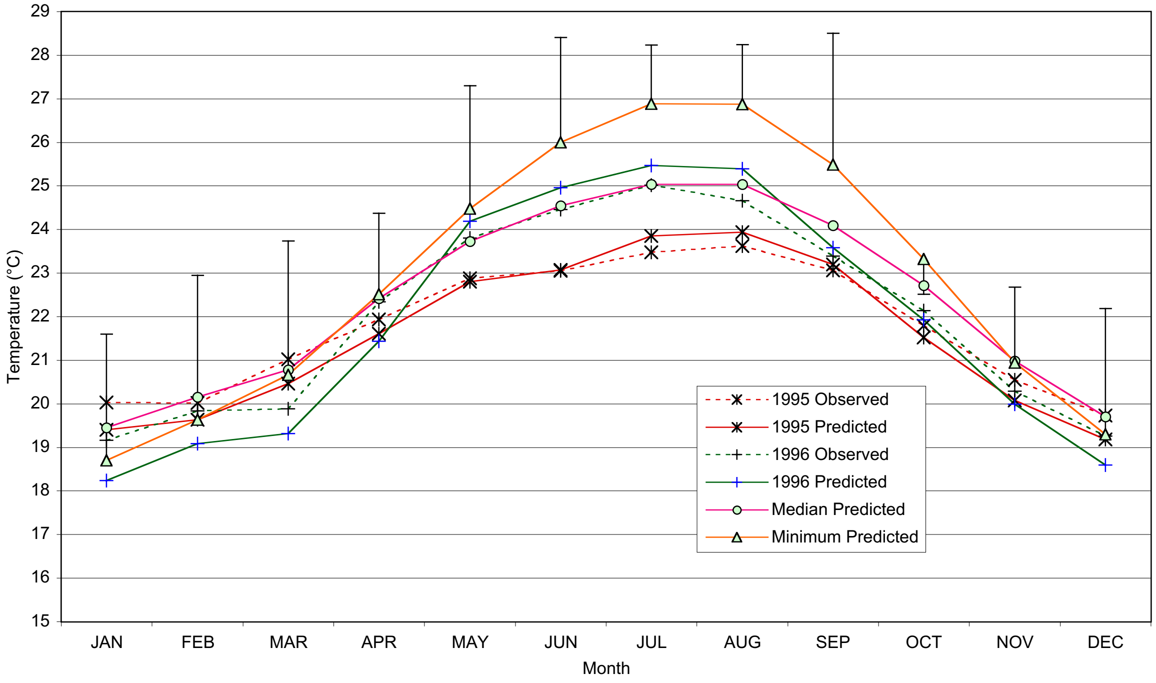
APPENDIX V: FIGURE 3.—Observed and predicted temperature for water quality station 5: hydrolab 3 assuming normal air temperature. Bars represent maximum daily temperature for the minimum flow scenario.



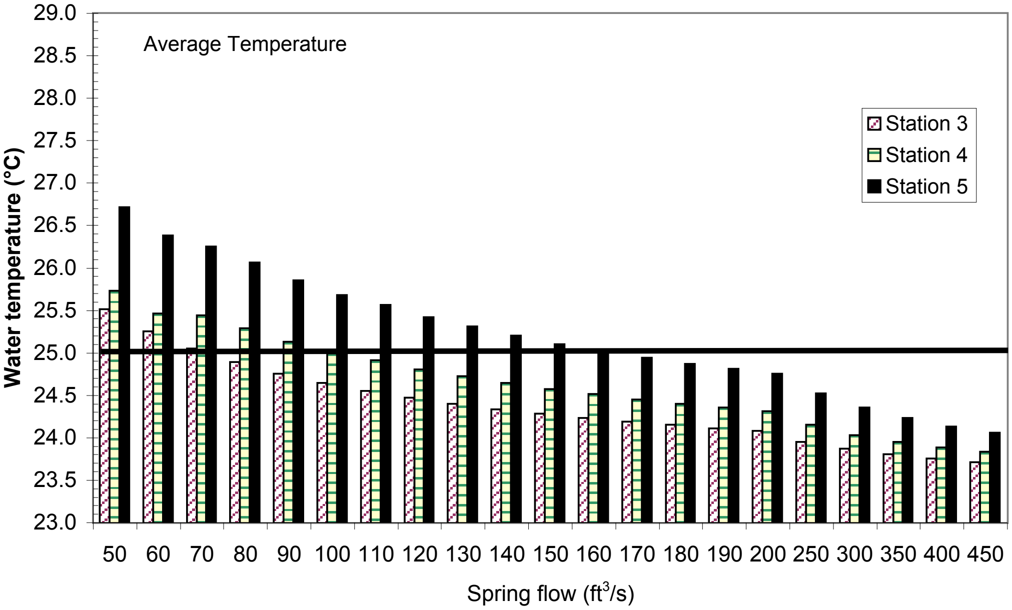
APPENDIX V: FIGURE 4.—Observed and predicted temperature for water quality station 3: temperature sonde 1 assuming 85th percentile air temperature. Bars represent maximum daily temperature for the minimum flow scenario.

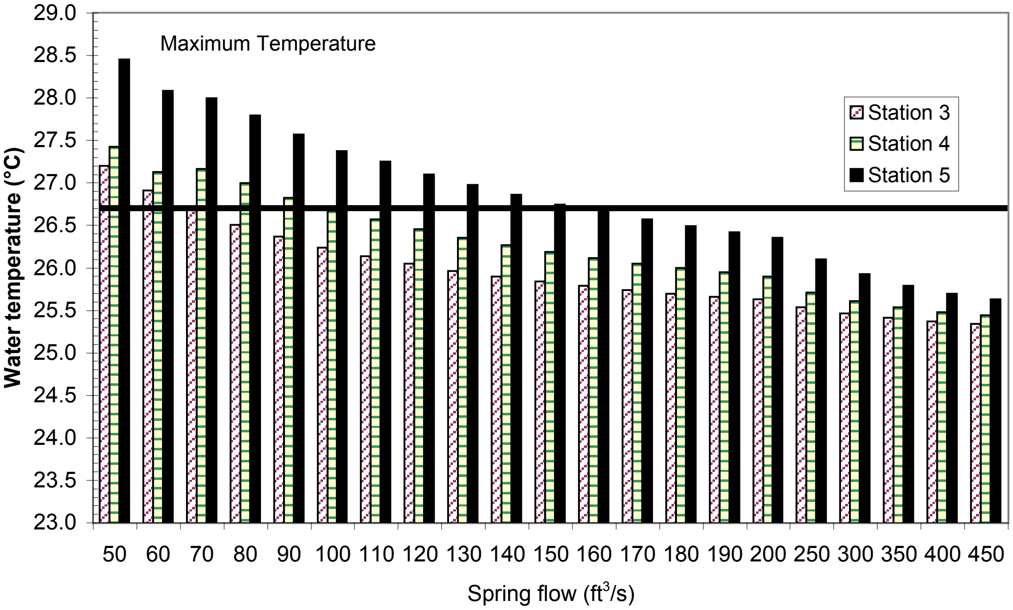


APPENDIX V: FIGURE 5.—Observed and predicted temperature for water quality station 4: temperature sonde 2 assuming 85th percentile air temperature. Bars represent maximum daily temperature for the minimum flow scenario.



APPENDIX V: FIGURE 6.—Observed and predicted temperature for water quality station 5: hydrolab 3 assuming 85th percentile air temperature. Bars represent maximum daily temperature for the minimum flow scenario.





APPENDIX V: FIGURE 7.—Average (upper) and maximum (lower) daily temperatures modeled at water quality stations 3, 4 and 5 for a flow range of 50 to 450 ft^3/s. Horizontal bars represent temperature criteria. Average temperature criteria equals 25°C and maximum temperature criteria equals 26.7°C.