FISH AND INVERTEBRATE ABUNDANCE IN RELATION TO ABIOTIC FACTORS IN THE MISSOURI RIVER

by

Christopher H. Hay

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Christopher H. Hay, Ph.D.

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Advisors: Thomas G. Franti and David B. Marx

Changes in flow management of the Missouri River Mainstem Reservoir System have been proposed to restore more of the ecological functions of the Missouri River. However, uncertainty exists about how the biota will respond to flow management changes. This dissertation explored relationships between three components of the biota and abiotic factors. The dissertation is divided into three studies corresponding to the biota studied: 1) aquatic macroinvertebrates; 2) larval fish; and 3) age-0 and age-1 fish. The objectives of each study were to estimate the relative importance or probability of an effect for key abiotic predictor variables to biotic response variables and to compare the results among reaches of the river. A multi-year, multi-location database of biological sampling was used to develop statistical models relating biotic responses to variables representing discharge, temperature, and turbidity in the Missouri River from Fort Randall Dam, SD to Rulo, NE. The results of the aquatic macroinvertebrate modeling varied by river reach. Greater macroinvertbrate drift densities were related to high flows out of Fort Randall Dam and low flows and reduced turbidity below Gavins Point Dam. The results below Gavins Point Dam suggest that increased macroinvertebrate drift densities are a response to reduced habitat and food availability. Results of the larval fish modeling indicated that water temperature was the most important predictor variable. Greater temperatures or degree days consistently increased the probability of finding larval fish and the resulting

drift densities. Discharge-related variables were the most important predictors for age-0 and age-1 fish. Greater catch per unit effort of age-0 or age-1 fish was generally related to less variable discharge in the unchannelized reaches and to greater, rising discharge in the channelized reaches. Overall, the results suggest that more natural discharge, temperature, and turbidity regimes would benefit native fish and invertebrate species in the Missouri River.

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Chapter 1

General Introduction

1.1 Introduction

The Missouri River basin (Figure 1.1) has a drainage area of 137,000,000 ha, which makes it the second largest river basin in the United States (Kammerer, 1990). Only the Mississippi River, of which the Missouri River is a tributary, has a larger drainage basin. The Missouri River is 4,090 km long from the headwaters of its source streams in Montana to its mouth near St. Louis, Missouri, making it the longest river in the United States (Kammerer, 1990). The river can be conveniently divided into three zones based on present geomorphology and hydrology (Galat et al., 2005*b*). The upper, least-altered zone extends from the origin to Fort Peck Lake, is unchannelized, and mostly free-flowing. The middle, inter-reservoir zone extends from Fort Peck Lake to Sioux City, Iowa, is unchannelized, and features six large impoundments that were constructed and are operated by the U. S. Army Corps of Engineers. The lower, channelized zone, which extends from Sioux City to the mouth near St. Louis, Missouri, is channelized along its entire length.

Human activities in the Missouri River basin have caused considerable change to the Missouri River ecosystem (National Research Council, 2002). Impoundments, flow regulation, and channelization have resulted in a loss of natural flood pulses, loss of natural low flows, reduction in water temperature variation, reduction in sediment transport, and loss of channel complexity. Agricultural development and urbanization in the floodplain have resulted in the loss of natural riparian vegetation and a reduction in the amount of organic matter entering the river.

Flow regulation has greatly altered the flow regime of the Missouri River (Figure 1.2). The historic Missouri River hydrograph was characterized by a bimodal spring rise (Hesse et al., 1989; Galat and Lipkin, 2000; Galat et al., 2005*a*). The first peak occurred in March to April following ice-out in the channel and prairie snowmelt. The second, larger peak occurred in June from Rocky Mountain snowmelt and rainfall on the plains and associated river valleys. Overbank flooding was common during the historic spring rises (Hesse et al., 1989; Galat et al., 2005*a*). Galat and Lipkin (2000) found that flow regulation of the Missouri River has resulted in a reduction in magnitude and duration of the annual flood pulse, an increase in the magnitude and duration of annual discharge minima, and a reduction in the rate of change of river flows. Pegg et al. (2003) found that daily mean flows are greater and flow variability has been reduced because of flow regulation. The impacts of flow regulation are greatest in the middle portion of the river from Lake Sakakawea to St. Joseph, Missouri (Galat and Lipkin, 2000; Pegg et al., 2003). Galat et al. (2001) found temperature depressions caused by hypolimnetic reservoir releases in the inter-reservoir reach of the river, but found that Gavins Point releases had no significant effects on

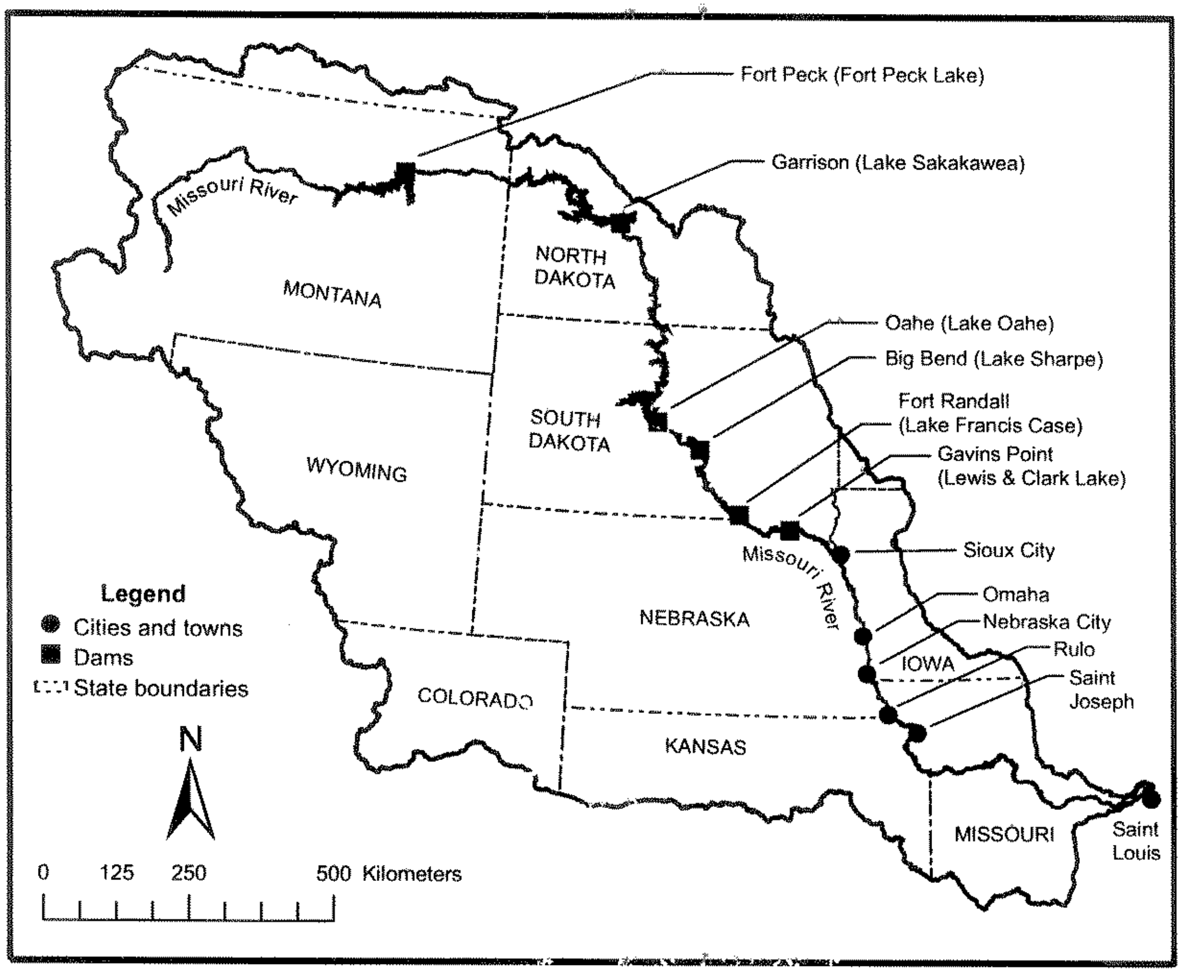

Figure 1.1. Map of the Missouri River basin, which shows the six large mainstem impoundments and other locations along the river.

water temperature. Large reductions in suspended sediment and turbidity resulting from the reservoir system have also been reported (Morris et al., 1968; Whitley and Campbell, 1974; Slizeski et al., 1982; Pflieger and Grace, 1987; Schmulbach et al., 1992; Galat et al., 2001).

Along with the loss of native habitat, the Missouri River ecosystem has experienced a significant loss of abundance of native species and communities (National Research Council, 2002). Three native species (pallid sturgeon, least tern, and piping plover) are on the federal Endangered Species List. Galat et al. (2005*b*), the most recent Missouri River fishery review, lists 24 fish species as declining in abundance of which 96% are native. Of the 17 species thought to be increasing, 53% are introduced. Eleven species are listed by two or more states as imperiled. Mestl and Hesse (1993) estimated that secondary production of aquatic insects decreased 61% between 1963 and 1980 in an unchannelized reach downstream of the mainstem dams.

Changes in environmental and resource values have resulted in increased interest in restoring some portion of the Missouri River's ecological function that has been lost. Habitat restoration and changes in flow management have both been proposed as ways to benefit ecological services of the Missouri River. A number of habitat restoration efforts to increase channel complexity and reconnect portions of the river to the floodplain are underway in the channelized portion of the river, but few of these have included explicit ecological objectives and performance evaluations (Galat et al., 2005*b*). Flow normalization has been more controversial and the subject of litigation. The National Research Council (2002) concluded that "the most significant scientific unknowns in the Missouri River ecosystem are how the ecosystem will respond to management actions designed to improve ecological conditions".

This study used biological sampling data from the Missouri River Historical Database

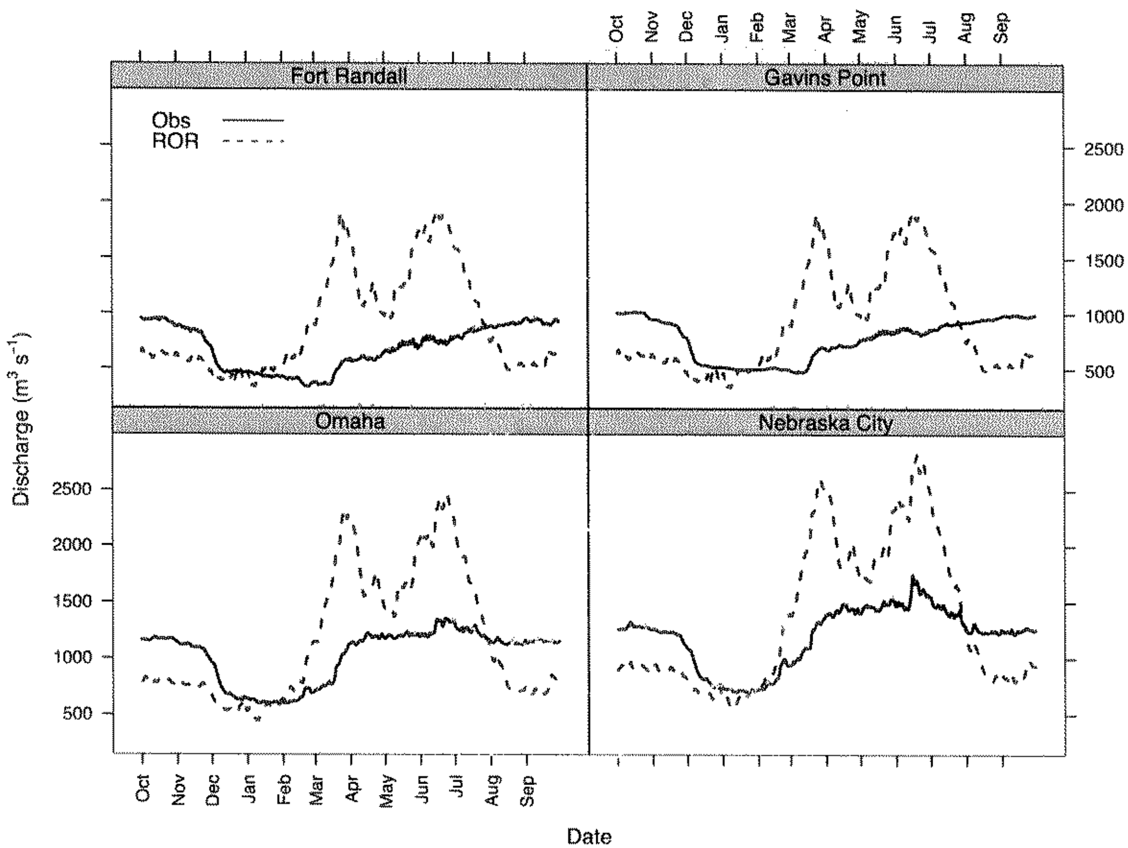

Figure 1.2. Comparison between observed (Obs) regulated and unregulated, run-of-the-river (ROR), mean daily discharge at four locations on the Missouri River. Regulated discharges are means of the actual observed daily discharges at Fort Randall Dam, Gavins Point Dam and the USGS Omaha and Nebraska City gauging stations from 1977 to 2004. Unregulated discharges are means of daily modeled discharges from 1977 to 1997 from the U. S. Army Corps of Engineers Daily Routing Model run-of-the-river scenario that is designed to remove the effects of flow regulation (U. S. Army Corps of Engineers, 1998).

(MRHD) (Hesse, 2001) to investigate the relationships between abiotic factors and Missouri River biota. The MRHD is a multi-year, multi-location database of macroinvertebrate and fish sampling that covers the portion of the Missouri River from Fort Randall Dam, SD to St. Joseph, MO. The data in the MRHD have been compiled from a variety of previous studies and projects. In addition, the physical data used were those readily available from public sources and may not completely reflect conditions at each of the individual sampling sites. Therefore, this study was an exploratory investigation.

1.2 Objectives

The overall goal of this research was to investigate relationships between native fish and invertebrate abundance and the hydrologic, thermal, and turbidity regimes. There are many other factors that influence fish and invertebrate abundance (e.g., habitat loss because of channelization and land use changes, fishing, nonnative species, and climatic effects). However, this research was focused on the impacts of specific abiotic factors.

To accomplish the research goal, the following objectives were pursued:

1. For the following response variables, develop sets of statistical models that relate the response to variables representing discharge, temperature, and turbidity for Missouri River reaches between Fort Randall Dam and Rulo, Nebraska.

   (a) Aquatic macroinvertebrate drift density

   (b) Larval fish presence and drift density

   (c) Age-0 and age-1 fish catch per unit effort

2. For each set of models, estimate the relative importance of the predictor variables or effect probabilities and develop model averaged parameter estimates.

3. Compare the results among species and reaches of the river.

1.3 Dissertation Organization

This dissertation is comprised of a general introduction, three manuscripts, and a general summary and conclusions. Each manuscript covers a different segment of the Missouri River biota and its relation to discharge, temperature and turbidity. The first manuscript titled " Macroinvertebrate Drift Density in Relation to Abiotic Factors in the Missouri River" focuses on drift of aquatic macroinvertebrates. The second manuscript, "Relationships Between Larval Fish Drift and Abiotic Factors in the Missouri River", covers the presence/absence and drift density of larval freshwater drum and catostomids. The final manuscript, "Catch of Age-0 and Age-1 Fish in Relation to Abiotic Factors in the Missouri River", examines catch per unit of effort of several cyprinid and a catostomid species.

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Chapter 2

Macroinvertebrate drift density in relation to abiotic factors in the Missouri River

2.1 Abstract

Changes in flow management of the Missouri River Mainstem Reservoir System have been proposed to restore more of the ecological functions of the Missouri River. However, uncertainty exists about how the biota will respond to flow management changes. The objectives of this study were to estimate the relative importance of key abiotic predictor variables to aquatic macroinvertebrate drift densities and to compare these results among reaches of the river. A multi-year, multi-location database of spring macroinvertebrate drift net sampling was used to develop relations between drift density and variables representing discharge, temperature, and turbidity in the Missouri River from Fort Randall Dam, SD to the mouth of the Little Nemaha River, NE. Multimodel inference using generalized linear mixed models and an information theoretic approach were used to estimate the relative importance of the predictor variables and the parameters. The results varied by reach. Discharge related factors were more important at the upstream end of the study area, and turbidity was more important

at the downstream end of the study area. Water temperature or degree days were also important predictors in the upstream reaches. The results below Gavins Point Dam suggest that increased macroinvertebrate drift densities are a response to reduced habitat and food availability. Since macroinvertebrates are an important food source for native fish, they should be included in biological monitoring protocols of flow management changes.

2.2 Introduction

Like many large rivers, the Missouri River has been greatly altered by human actions. Storage reservoirs, channelization, flood control structures, and other human developments have provided a number of economic benefits, but these have come at an ecological cost (National Research Council, 2002). Changes in environmental attitudes have led to an increased interest in restoring some portion of the Missouri River's lost ecological function. Habitat restoration and changes in flow management have both been proposed as ways to restore some of the ecological functions of the Missouri River system. Habitat restoration via backwater and side channel creation has been occurring in the channelized portion of the river. However, changes in flow management have been very controversial and the subject of litigation. There is considerable uncertainty as to how the Missouri River biota will respond to changes in flow management (National Research Council, 2002).

Changes in the flow regime resulting from the Missouri River Mainstem Reservoir System have been well documented (Hesse and Mestl, 1993; Galat and Lipkin, 2000; Pegg et al., 2003). These changes include reductions in the magnitude and duration of high flows, increases in the magnitude of low flows, and reduced flow variability (Galat and Lipkin, 2000; Pegg et al., 2003). Galat et al. (2001) found temperature depressions caused by hypolimnetic reservoir releases from Fort Randall Dam (Figure 2.1) in the inter-reservoir reach of the river. However, Gavins Point Dam releases had no significant effects on water temperature (Galat et al., 2001). Large reductions in suspended sediment and turbidity resulting from the reservoir system have also been well documented (Morris et al., 1968; Whitley and Campbell, 1974; Slizeski et al., 1982; Pflieger and Grace, 1987; Schmulbach et al., 1992; Galat et al., 2001). The ecological impacts caused by the reservoirs, flow regulation, channelization, and other human impacts are well reported (Hesse et al., 1989; Schmulbach et al., 1992; Hesse, 1996; National Research Council, 2002). These impacts have considerably altered the extent and characteristics of macroinvertebrate production (Patrick, 1998).

As intermediate trophic level consumers, macroinvertebrates play an influential role in nutrient cycling and are the primary link between their food sources (detritus, algae, macrophytes, and microorganisms) and higher trophic level consumers including fish and birds (Merritt et al., 1984; Allan, 1995; Wallace and Webster, 1996; Rader, 1997). Most native Missouri River fishes, including the endangered pallid sturgeon, feed on macroinvertebrates at some time in their lives (Hesse, 1996). Macroinvertebrates are also an important food source for the threatened piping plover and endangered least tern (Haig, 1992; Thompson et al., 1997). Drift is the primary mechanism for redistribution of aquatic macroinvertebrates and a measure of emigration and immigration (Minshall and Petersen, 1985) and is, therefore, important to understanding of aquatic ecosystems.

This study used macroinvertebrate sampling data from the Missouri River Historical Database (MRHD) (Hesse, 2001) to investigate the relationships between abiotic factors and the density of drifting macroinvertebrates. The MRHD is a multi-year, multi-location database of macroinvertebrate and fish sampling that covers the portion of the Missouri River from Fort Randall Dam, SD to St. Joseph, MO. The data in the MRHD have been compiled from a variety of previous studies and projects. In addition, the physical data used were those readily available from public sources and may not completely reflect conditions at each of the individual sampling sites. Therefore, this study was an exploratory investigation. There were three objectives for this study. The first objective was to estimate the relative importance of the predictor variables representing discharge, temperature, and turbidity to macroinvertebrate drift density for Missouri River reaches between Fort Randall Dam, SD and the mouth of the Little Nemaha River, NE. The second objective was to develop statistical models that relate macroinvertebrate drift density to these predictor variables. The third objective was to compare these results among different reaches of the study area.

2.3 Methods

2.3.1 Study area

Our study area included approximately 566 river kilometers (RK) of the mainstem of the Missouri River from Fort Randall Dam, SD (RK 1416) to the mouth of the Little Nemaha River, NE (RK 850). This portion of the 4,090 km Missouri River is the transition from the unchannelized inter-reservoir zone to the lower channelized zone. Channelization in the study area occurred from 1933 to 1981 (Schneiders, 1999). Discharge in the study area is regulated by Fort Randall Dam (closed in 1952) and Gavins Point Dam (closed in 1955). The 62 km segment between Fort Randall Dam and Lewis and Clark Lake and a 94 km segment immediately below Gavins Point Dam are designated as the Missouri National Recreational River as part of the National Wild and Scenic Rivers System (Berry and Young, 2004).

The study area was subdivided into four reaches with several sampling sites within each reach (Table 2.1, Figure 2.1). The first reach, a remnant unchannelized segment, is isolated between Fort Randall Dam, SD (RK 1416) and Gavins Point Dam, NE (RK 1305). Flow in this reach is primarily controlled by releases from Fort Randall Dam. However, the Niobrara River enters the Missouri River at RK 1359 near the headwaters of Lewis and Clark Lake, which is impounded behind Gavins Point Dam. The second reach extends from Gavins Point Dam to the mouth of the Big Sioux River (RK 1181) at Sioux City, IA. This reach is mostly unchannelized, but is stabilized near Sioux City. The James and Vermillion rivers enter the Missouri River in this reach below Yankton, SD. The third reach is from the Big Sioux River to the mouth of the Platte River (RK 957) near Plattsmouth, NE and is entirely channelized. The Floyd, Little Sioux, Soldier, and Boyer rivers enter the Missouri River in this reach. Reach four is from the Platte River to the mouth of the Little Nemaha River (RK 850) near Nemaha, NE. The entire reach is channelized, but flow variability and turbidity increase in this reach because of inflows from the Platte and Nishnabotna rivers.

2.3.2 Macroinvertebrate sampling data

The macroinvertebrate sampling data for this study came from drift net sample data contained in the Missouri River Historical Database (MRHD) (Hesse, 2001), developed by Rivers Corporation, Inc. (Nebraska nonprofit, Larry W. Hesse, Founder and Principal Scientist, Crofton, NE). All of the macroinvertebrate data in the MRHD were collected by scientists from the Nebraska Game and Parks Commission and Rivers Corporation, Inc. from 1983 to 2002. Drift net samples were collected using 560 μm nylon (nitex) mesh, conical nets attached to a stainless steel or fiberglass ring and rope towing bridle. Several different net dimensions (1 m diameter, 3 m long; 0.75 m diameter, 2.25 m long; and 0.5 m diameter, 1.5 m long) were used. A mechan-

Table 2.1. Macroinvertebrate sampling locations. Adapted from Hesse (2001).

Reach	Site Name	Code	Upper River km	Lower River km
Fort Randall	Boyd County	FR1	1408	1371
	Verdel	FR2	1369	1358
	Niobrara	FR3	1358	1344
	Lewis and Clark Lake	FR4	1342	1305
Gavins Point	Gavins Point Tailwater	GP1	1305	1297
	St. Helena	GP2	1297	1279
	Brooky Bottom	GP3	1279	1255
	Maskel	GP4	1255	1229
	Ponca	GP5	1229	1212
Sioux City	Sioux City	SC1	1181	1168
	Decatur	SC2	1112	1083
	Tekamah	SC3	1083	1043
	Blair	SC4	1043	1009
	Bellevue	SC5	978	973
Plattsmouth	Plattsmouth	PL1	973	916
	Nebraska City	PL2	916	883
	Brownville	PL3	872	850

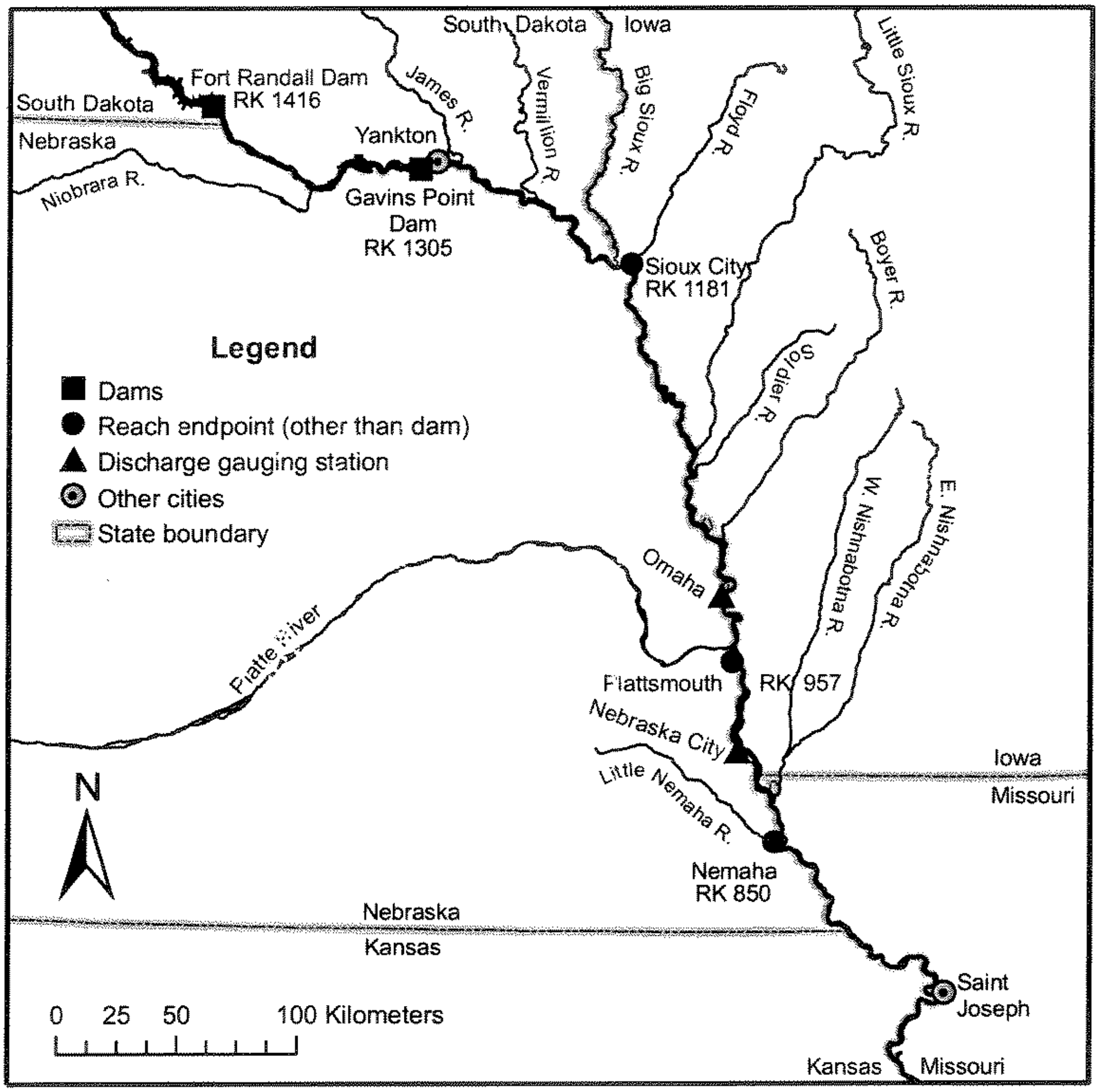

Figure 2.1. Map of the study area showing study reach boundaries and gaging station locations.

ical flowmeter (General Oceanics Model 2030R) was suspended in each net mouth to quantify the volume of water passing through the net. The codend of the drift nets was 0.09 m in diameter and fitted with a Dolphin Net Bucket assembly. Drift nets were towed in pairs near the surface behind a survey boat and recovered on steel cables with a hydraulic winch. The duration of a tow sample was dependent on water conditions. During periods of low turbidity, nets were towed for 12 minutes or more before clogging reduced filtering capacity, whereas a minimum tow was 3 minutes during periods of high turbidity. Samples were typically obtained from three locations, the cutting bank, filling bank, and mid-channel. River sites were generally sampled biweekly between April 15 and July 15 during daylight hours. Samples were preserved with formalin to 10% concentration, and macroinvertebrates were identified to the lowest practicable taxon.

Drift densities, as defined by Britton and Greeson (1987), were calculated from drift net samples contained in the MRHD and used as the response variable in the statistical modeling. For each sample, the number of individuals and volume of water sampled were extracted from the MRHD. Drift densities were then calculated by dividing the number of individuals captured by the volume of water that passed through the nets and standardizing to a volume of 100 m^3. The dates of drift sampling recorded in the MRHD varied from year to year but, for most years, samples were collected in May and June. Therefore, to minimize the seasonal variation among years, only macroinvertebrate drift samples collected in May and June were used for modeling.

There was considerable variation in the number of drift net samples by site and by year (Table 2.2). The Fort Randall and Gavins Point reaches were each sampled for 14 years, the Sioux City reach was sampled for 10 years, and the Plattsmouth reach was sampled for 8 years. The drift net samples include both aquatic and terrestrial insects. Since terrestrial insects are incidental to the drift, they were excluded from the drift density calculations. Only aquatic insects were used for the statistical modeling. Because all but one of the predictor variables (discussed later) were measured on a daily basis, days were used as the unit of analysis for the statistical modeling. For days with multiple drift net samples, the samples were pooled, and a mean drift density was calculated as the sum of the number of individuals divided by the sum of the volume sampled. This has the effect of weighting the samples by the volume sampled, so samples with larger volumes of water sampled were weighted more heavily.

Table 2.2. Number of days (D) that macroinvertebrate drift net samples were collected during May and June and total number of samples (S) collected by site and year. See Table 2.1 for descriptions of the reaches and sites.

Year	D	S	D	S	D	S	D	S	D	S
	Fort Randall									
	FR1		FR2		FR3		FR4			
1983	1	1	—	—	2	2	1	1		
1984	2	2	—	—	2	3	5	5		
1985	1	1	—	—	8	23	—	—		
1986	—	—	—	—	1	2	—	—		
1988	1	1	—	—	2	2	—	—		
1989	1	1	—	—	1	1	—	—		
1990	—	—	—	—	5	18	2	3		
1991	—	—	5	33	9	135	—	—		
1993	—	—	—	—	7	20	—	—		
1998	3	9	—	—	5	14	—	—		
1999	3	11	—	—	5	20	—	—		
2000	4	14	3	8	5	23	—	—		
2001	1	3	4	18	4	19	—	—		
2002	—	—	5	18	5	24	—	—		
Total	17	43	17	77	61	306	8	9		
	Gavins Point									
	GP1		GP2		GP3		GP4		GP5	
1983	2	2	2	2	4	25	—	—	2	2
1984	7	18	7	9	6	6	—	—	4	14
1985	8	18	6	6	5	5	—	—	7	16

continued on next page

Table 2.2. *continued.*

Year	D	S	D	S	D	S	D	S	D	S
1986	—	—	—	—	1	16	—	—	—	—
1988	3	3	3	5	1	1	—	—	2	2
1989	—	—	1	1	—	—	—	—	2	2
1990	3	13	5	20	—	—	—	—	—	—
1991	2	13	5	60	—	—	—	—	3	48
1993	—	—	—	—	—	—	—	—	6	20
1998	—	—	5	15	—	—	—	—	3	9
1999	—	—	5	17	—	—	—	—	4	18
2000	—	—	5	21	—	—	1	2	4	19
2001	—	—	4	20	—	—	2	11	4	22
2002	—	—	4	20	—	—	5	25	—	—
Total	25	67	52	196	17	53	8	38	41	172
					Sioux City					
	SC1		SC2		SC3		SC4		SC5	
1988	1	1	3	3	2	2	2	2	—	—
1989	2	2	1	1	1	1	1	1	—	—
1990	—	—	5	29	—	—	—	—	—	—
1991	5	63	4	60	—	—	—	—	—	—
1993	—	—	—	—	—	—	6	20	—	—
1998	—	—	5	13	—	—	5	14	—	—
1999	—	—	5	22	—	—	5	27	—	—
2000	—	—	5	27	—	—	5	24	—	—
2001	—	—	5	30	1	6	5	30	2	12
2002	—	—	5	23	—	—	5	28	—	—
Total	8	66	38	208	4	9	34	146	2	12
					Plattsmouth					
	PL1		PL2		PL3					
1988	—	—	2	2	1	1				
1989	—	—	1	1	2	2				
1993	—	—	—	—	6	18				
1998	—	—	—	—	4	12				
1999	—	—	—	—	4	24				
2000	—	—	—	—	6	26				
2001	1	5	1	6	4	26				
2002	—	—	5	26	5	30				
Total	1	5	9	35	32	139				

2.3.3 Statistical modeling

Predictor variables were chosen from among the abiotic variables cited as influencing invertebrate drift (Brittain and Eikeland, 1988; Ward and Stanford, 1982) (Table 2.3). The variables were chosen based on the availability of continuous data during the study period. Daily discharge and water temperature records were obtained from the U. S. Army Corps of Engineers for Fort Randall Dam and Gavins Point Dam. Daily discharge records for the Omaha, NE and Nebraska City, NE gaging stations were obtained from the U. S. Geological Survey National Water Information System. Records of mean monthly turbidity were obtained from the Omaha Metropolitan Utilities District for turbidity of Missouri River water at the District's intakes (RK 1007). High flow events were defined as any time the discharge exceeded the 67th percentile of all pre-alteration daily discharges, and low flow events were defined as discharges less than the 33rd percentile. The pre-alteration period was defined as 1929–1948, which was used previously by Hesse and Mestl (1993) and Galat and Lipkin (2000). Pre-alteration discharge records from the U. S. Geological Survey Yankton, SD gaging station were used to determine the high flow thresholds for Fort Randall and Gavins Point discharges. The Fort Randall Dam discharge and temperature data were used in the modeling of the Fort Randall reach. Discharge data from Gavins Point Dam, Omaha, and Nebraska City were used for the Gavins Point, Sioux City, and Plattsmouth reaches, respectively. Gavins Point Dam water temperature and Omaha turbidity data were used for all three reaches below Gavins Point Dam.

Based on visual inspection and Shapiro-Wilk normality tests, the daily drift densities did not follow a normal distribution . Therefore, the drift densities were modeled using generalized linear mixed models (GLMMs). GLMMs are a generalization of

Table 2.3. Description of the predictor variables used to model daily macroinvertebrate drift density.

Predictor	Description	Units
Discharge	Mean daily discharge at the Fort Randall Dam; Gavins Point Dam; Omaha, NE; or Nebraska City, NE gage	m^3s^{-1}
24 hr change in discharge	Change in discharge from the previous day	m^3s^{-1}
Days since a reversal	Days since a hydrograph reversal	d
Days since low flow	Days since a low flow event (discharge less than the 33rd percentile of the pre-impact daily discharges)	d
Days since high flow	Days since a high flow event (discharge greater than the 67th percentile of the pre-impact daily discharges)	d
Temperature	Mean daily water temperature of Fort Randall Dam or Gavins Point Dam discharges	°C
Degree days	Cumulative daily water temperature above a base of 0 °C	°C
Turbidity	Mean monthly turbidity measured at the Omaha MUD intakes	NTU

linear mixed models that do not require the assumption of normally distributed data (McCulloch and Searle, 2001). The gamma distribution was chosen because the data were continuous, positive, positively skewed and the distribution fit the data reasonably well based on visual inspection (Eqn. 2.1). The log link function was used to ensure positive predictions (Eqns. 2.2 and 2.3). Random effects for year and site were included to account for correlations between observations within the same year and at the same site, respectively (Eqns. 2.3, 2.4, and 2.5). The form of the models that were fit was as follows:

$$y_{ijk} \sim \text{indep.} \quad \text{Gamma}(\mu, \nu) \tag{2.1}$$

$$\text{E}[y_{ijk}] = \mu_{ijk} \tag{2.2}$$

$$\log(\mu_{ijk}) = a_i + b_j + \beta_0 + \sum_{m=1}^{p} x_{ikm}\beta_m \tag{2.3}$$

$$a_i \sim \text{N}(0, \sigma_a^2) \tag{2.4}$$

$$b_j \sim \text{N}(0, \sigma_b^2) \tag{2.5}$$

where y is the response variable, a is the year effect for the ith year, b is the site effect for the jth site, p is the number of predictor variables, x_{ikm} is the mth predictor variable for the kth day in the ith year, and β is a model parameter.

Because of the exploratory nature of this research, an all-subsets approach was used to fit all of the possible generalized linear mixed models for each reach. With the large number of predictor variables (7–8) relative to the number of data points (42–150), model selection uncertainty was expected to be high. Therefore, a multimodel inference technique described by Burnham and Anderson (2002) was used to rank the models and develop model averaged estimates that account for the model selection uncertainty.

The generalized linear mixed models were fit using the GLMM function in the lme4 package (Bates and Sarkar, 2005) of R (R Development Core Team, 2004). The individual models were ranked using a second-order variant of Akaike's information criterion (AIC_c). AIC_c was used because of the small number of observations relative to the number of predictor variables. An AIC_c difference (Δ) was calculated as the difference in AIC_c between each model and the top ranked model (the model with the lowest AIC_c). An Akaike weight (Burnham and Anderson, 2002),

$$w_i = \frac{\exp(-\frac{1}{2}\Delta_i)}{\sum_{r=1}^{R} \exp(-\frac{1}{2}\Delta_r)} \tag{2.6}$$

was then calculated for each model r within the set of R models. The Akaike weights are an estimate of the likelihood of the model being the best model based on the data. The relative variable importance (RVI) of each of the predictor variables was calculated by summing the Akaike weights for each of the models in which the predictor was included. Model averaged parameter estimates and unconditional standard errors were calculated as described in Burnham and Anderson (2002).

RVI values can range from 0 to 1 with 1 being most important. A cutoff value of 0.5 was used to classify whether a variable was important or not in each set of models. Selection of this value was arbitrary. However, since the modeling procedure represents a weight of evidence approach, it was assumed that a RVI of at least 0.5 was needed to classify a predictor variable as important. Also, the 0.5 level generally corresponded to the level at which a 95% confidence interval for the parameter estimates no longer contained zero. RVI values between 0.5 and 0.75 were considered to be moderate support, and RVI values of at least 0.75 were considered to be strong support for the importance of that predictor variable.

2.4 Results

The taxonomic composition of drifting macroinvertebrates varied by reach (Table 2.4). Diptera were prevalent in the Fort Randall and Gavins Point reaches (54.9 and 69.3%, respectively). The Fort Randall reach also had a relatively large proportion of terrestrial Hemiptera (20.7%). Trichoptera (34.1%), and Diptera (31.7%) were equally prevalent in the Sioux City reach. The most prevalent taxa in the Plattsmouth reach

Table 2.4. Percentage of the total (aquatic and terrestrial) catch of macroinvertebrate orders and families in the four reaches of the study area. Only orders and families representing at least one percent of the total catch are listed.

Taxon	Fort Randall to Gavins Point	Gavins Point to Sioux City	Sioux City to Plattsmouth	Plattsmouth to Little Nemaha
Ephemeroptera				
Baetidae	2.2	—	2.5	4.6
Isonychiidae	—	1.1	4.3	3.9
Heptageniidae	—	—	2.7	6.8
Caenidae	1.9	1.8	4.3	5.7
Ephemeridae	1.8	—	—	—
Polymitarcyidae	—	—	1.1	—
Other Ephemeroptera	2.6	1.8	2.1	3.5
Total	6.7	6.5	17.0	24.5
Plecoptera				
Total	1.3	—	1.0	2.0
Hemiptera				
Corixidae	1.2	—	1.2	1.1
Aphididae	13.0	4.0	5.0	5.6
Cicadellidae	1.6	—	1.0	1.9
Other Hemiptera	4.9	3.1	1.0	1.4
Total	20.7	7.1	8.2	10.0
Trichoptera				
Polycentropodidae	—	1.5	—	—
Hydropsychidae	2.3	7.4	31.3	23.8
Other Trichoptera	1.2	1.3	1.3	2.4
Total	3.5	8.7	34.1	26.2
Coleoptera				

continued on next page

Table 2.4. *continued.*

Taxon	Fort Randall to Gavins Point	Gavins Point to Sioux City	Sioux City to Plattsmouth	Plattsmouth to Little Nemaha
Total	4.7	3.1	2.2	2.5
Hymenoptera				
Total	3.5	1.6	2.3	2.5
Diptera				
Ceratopogonidae	1.1	—	1.1	1.4
Chironomidae	16.7	35.4	15.7	16.3
Culicidae	—	2.1	—	—
Psychodidae	—	—	—	1.3
Simuliidae	13.0	8.2	4.1	1.0
Other Diptera	24.1	23.6	10.8	9.4
Total	54.9	69.3	31.7	29.4
Hymenoptera				
Total	3.5	1.6	2.3	2.5
Other				
Total	4.7	3.7	3.5	2.9
Total no. of individuals	50,948	89,561	139,094	55,909

were Diptera (29.4%), Trichoptera (26.2%), and Ephemeroptera (24.5%). Trichoptera were primarily from the family Hydropsychidae. Chironomidae were generally the most abundant Diptera.

There was wide variation in the observed drift densities of aquatic macroinvertebrates (Table 2.5). Although there was variation among years, drift densities generally increased downstream. Overall mean drift densities were 16.4 individuals $100^{-1}\,m^{-3}$ in the Fort Randall reach, 36.6 individuals $100^{-1}\,m^{-3}$ in the Gavins Point reach, 86.1 individuals $100^{-1}\,m^{-3}$ in the Sioux City reach, and 125.3 individuals $100^{-1}\,m^{-3}$ in the Plattsmouth reach. Bootstrap calculated 95% confidence intervals for the means based on 1000 replicates and the bias corrected and accelerated (BCa) method were as follows: (13.0, 21.2) for the Fort Randall reach, (30.7, 44.9) for the Gavins Point reach, (68.8, 109.0) for the Sioux City reach, and (92.6, 177.4) for the Plattsmouth reach. Because of the skewness of the drift density data, the confidence intervals are not symmetric about the means. The confidence intervals provide strong evidence that drift densities in the Gavins Point reach are greater than those in the Fort Randall reach, and drift densities in the Sioux City and Plattsmouth reaches are greater than those in both the Gavins Point and Fort Randall reaches.

Discharge, days since a low flow event, temperature, and degree days all increased in the downstream direction (Table 2.6). Days since a high flow event decreased in the downstream direction. In contrast, there was no downstream trend for 24 hr change in discharge or days since a hydrograph reversal. During the study period, mean daily discharge varied over a range of 85–1000 m^3s^{-1} at Fort Randall Dam to 892–2,498 m^3s^{-1} at Nebraska City, NE. 24 hr change in discharge was highly variable at Fort Randall Dam. There were many hydrograph reversals (a change from increasing discharge to decreasing discharge or *vice versa*) in May and June during

Table 2.5. Summary of aquatic macroinvertebrate drift density by year in the four sampling reaches where n is the number of data points (days) followed by the mean and range of drift densities (no. of individuals per 100 m^3), respectively.

	Reach											
	Fort Randall			Gavins Point			Sioux City			Plattsmouth		
Year	n	Mean	Range	n	Mean	Range	n	Mean	Range	n	Mean	Range
1983	4	23.8	(2.9, 46.9)	10	81.2	(0.9, 244.6)		—			—	
1984	9	6.8	(1.1, 35.5)	24	32.0	(1.2, 132.4)		—			—	
1985	9	4.9	(0.9, 14.1)	26	14.8	(1.6, 53.8)		—			—	
1986	1	4.2	(4.2, 4.2)	1	6.9	(6.9, 6.9)		—			—	
1987		—			—			—			—	
1988	3	38.7	(25.5, 53.6)	9	87.4	(27.5, 158.3)	8	252.3	(59.9, 417.8)	3	313.2	(195.4, 394.0)
1989	2	32.7	(6.9, 58.5)	3	74.5	(52.1, 89.6)	5	57.9	(2.1, 104.3)	3	79.9	(53.2, 119.2)
1990	9	1.2	(0.0, 5.5)	15	2.5	(0.0, 13.7)	13	2.4	(0.0, 11.6)		—	
1991	14	14.7	(1.5, 64.3)	10	12.8	(3.5, 19.1)	9	33.7	(18.9, 55.5)		—	
1992		—			—			—			—	
1993	7	10.4	(0.5, 21.0)	6	6.2	(0.7, 13.4)	6	14.8	(2.4, 45.2)	6	10.7	(2.3, 23.4)
1994		—			—			—			—	
1995		—			—			—			—	
1996		—			—			—			—	
1997		—			—			—			—	
1998	8	22.1	(9.0, 56.0)	8	44.3	(7.9, 92.6)	10	55.9	(30.8, 91.6)	4	52.8	(23.6, 75.4)
1999	8	56.6	(24.3, 125.9)	9	67.8	(20.2, 117.2)	10	118.1	(47.6, 335.9)	4	119.3	(39.1, 222.5)
2000	12	21.5	(7.7, 62.7)	10	65.4	(29.3, 135.9)	10	191.8	(56.1, 421.3)	6	259.4	(98.5, 683.5)
2001	9	7.5	(1.2, 25.3)	10	46.1	(12.7, 97.3)	13	77.7	(38.8, 206.8)	6	71.9	(53.5, 100.6)
2002	10	9.2	(0.8, 21.8)	9	25.6	(4.0, 65.1)	10	69.8	(33.4, 159.2)	10	134.4	(72.4, 383.0)
Total	105	16.4	(0.0, 125.9)	150	36.6	(0.0, 244.6)	94	86.1	(0.0, 421.3)	42	125.3	(2.3, 683.5)

the study period at all four gage locations, so values for days since a flow reversal were generally small. There were two periods of relatively high discharge during the study period. The first was during the mid-1980s, and the second was during the mid-1990s. Therefore, there were some large values for days since a low flow event, particularly below Gavins Point Dam. However, the values for days since a high flow event were much smaller than those for low flow events. Water temperatures were lower at Fort Randall Dam because of hypolimnetic releases. Galat et al. (2001) found that temperature increased predictably downstream from Gavins Point Dam. The only continuous turbidity data available were at Omaha, NE and only on a monthly basis. Therefore, there were a maximum of two values per year (May and June) depending on whether or not macroinvertebrate sampling occurred in both months. The monthly averages likely obscure daily variations in turbidity from storm events. Because turbidity in the Missouri River below Gavins Point Dam is greatly influenced by tributary sediment inputs, the relationship between turbidity at Omaha and turbidity at the individual sampling sites should weaken with increasing distance from Omaha.

The important predictor variables for predicting drift densities of aquatic macroinvertebrates varied by reach (Table 2.7). In the Fort Randall reach, days since a high flow and temperature had moderate support as important predictor variables (RVI = 0.74 and 0.56, respectively). Drift density increased near the time of high flow events as evidenced by the negative correlation with days since a high flow event. Temperature was positively correlated with drift density. Prediction R^2 for the model averaged predictions was 0.55 in the Fort Randall Reach (Figure 2.2). In the Gavins Point reach, degree days and discharge had strong support as important predictor variables (RVI = 0.86 and 0.85, respectively). Drift density was positively correlated

Table 2.6. Summary of data for the predictor variables by location over the entire study period, where n is the number of data points (days) corresponding to the macroinvertebrate drift density data points followed by the minimum, mean, maximum and standard deviation, respectively. See Table 2.3 for definitions of the predictor variables.

Predictor	n	Min.	Mean	Max.	SD
Discharge (m^3s^{-1})					
Fort Randall Dam	105	85	600	1000	186
Gavins Point Dam	150	170	694	1028	196
Omaha	94	688	913	1396	174
Nebraska City	42	892	1324	2498	371
Discharge change (m^3s^{-1})					
Fort Randall Dam	105	−487	−9	535	120
Gavins Point Dam	150	−232	6	257	71
Omaha	94	−167	−1	116	55
Nebraska City	42	−390	−10	252	104
Days since reversal (d)					
Fort Randall Dam	105	0	1	6	1
Gavins Point Dam	150	0	4	33	6
Omaha	94	0	1	5	1
Nebraska City	42	0	2	7	2
Days since low flow (d)					
Fort Randall Dam	105	0	103	758	186
Gavins Point Dam	150	0	429	1884	592
Omaha	94	44	451	1622	563
Nebraska City	42	88	518	1620	572
Days since high flow (d)					
Fort Randall Dam	105	0	37	216	68
Gavins Point Dam	150	0	36	263	72
Omaha	94	0	9	196	28
Nebraska City	42	0	0	3	1
Temperature (°C)					
Fort Randall Dam	105	5.0	12.9	22.2	4.0
Gavins Point Dam	150	7.2	18.7	26.1	3.7
Degree days (°C)					
Fort Randall Dam	105	232	652	1294	240
Gavins Point Dam	150	282	997	1579	326
Turbidity (NTU)					
Omaha	26	31	157	385	110

with degree days and negatively correlated with discharge. Days since a low flow event had moderate support as an important predictor variable (RVI = 0.67) and was positively correlated with drift density. Model averaged predictions were weakest in the Gavins Point reach with a prediction R^2 of 0.49. Degree days and turbidity had moderate support as important predictor variables in the Sioux City reach (RVI = 0.58 and 0.56, respectively). Drift density was positively correlated with degree days and negatively correlated with turbidity. Model averaged predictions improved in the Sioux City reach with a prediction R^2 of 0.64. Turbidity was the only important predictor variable in the Plattsmouth reach with an RVI of 0.56 and was negatively correlated with drift density. Prediction R^2 was greatest in the Plattsmouth reach (0.67), but was reduced by a single large, highly influential drift density observation (Figure 2.2). The model averaged prediction equations for the four reaches are included in Table 2.8.

Table 2.7. Relative variable importance (RVI) and direction of the effect (sign of the parameter estimate) based on multi-model inference for each predictor variable by sampling reach. RVI values greater than 0.5 are indicated by an asterisk. See Table 2.3 for definitions of the predictor variables.

	Reach			
Predictor	Fort Randall	Gavins Point	Sioux City	Plattsmouth
Discharge	0.27 (+)	*0.85 (−)	0.25 (−)	0.19 (+)
24 hr change in discharge	0.25 (−)	0.30 (+)	0.26 (−)	0.24 (−)
Days since reversal	0.24 (−)	0.24 (−)	0.25 (+)	0.19 (−)
Days since low flow	0.27 (+)	*0.67 (+)	0.45 (+)	0.41 (+)
Days since high flow	*0.74 (−)	0.25 (−)	0.25 (−)	0.16 (+)
Temperature	*0.56 (+)	0.36 (+)	0.37 (+)	0.32 (+)
Degree days	0.41 (+)	*0.86 (+)	*0.58 (+)	0.42 (+)
Turbidity	—	0.37 (−)	*0.56 (−)	*0.56 (−)

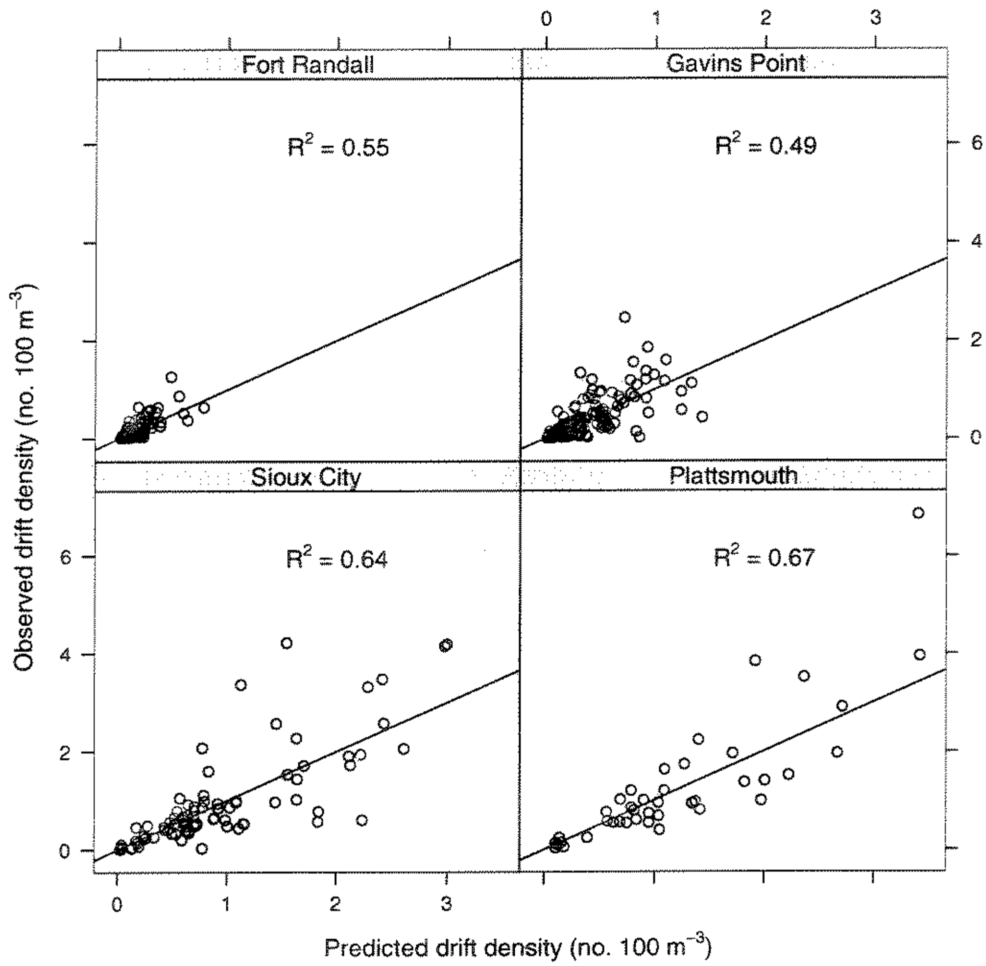

Figure 2.2. Observed versus predicted mean daily drift densities (no. 100^{-1} m^{-3}) of aquatic macroinvertebrates in the four reaches of the study area. The plotted lines represent a 1:1 relationship. A model averaged prediction R^2 is included for each reach.

Table 2.8. Model averaged parameter estimates for aquatic macroinvertebrate drift density prediction based on multi-model inference for each predictor variable by sampling reach. Parameter values are multiplied by 1000. Important predictor variables (RVI > 0.5) are indicated by an asterisk. See Table 2.3 for definitions of the predictor variables.

	Reach			
Predictor	Fort Randall	Gavins Point	Sioux City	Plattsmouth
Intercept	−2850	−1480	−1100	−670
Discharge	0.14	*−1.93	−0.09	0.01
24 hr change in discharge	−0.04	0.46	−0.31	−0.25
Days since reversal	−7.59	−0.13	17.50	−5.25
Days since low flow	0.22	*0.52	0.41	0.27
Days since high flow	*−4.69	−0.15	−0.17	34.40
Temperature	*45.00	17.00	9.54	22.60
Degree days	0.33	*0.99	*0.39	0.42
Turbidity	—	−0.43	*−1.69	*−3.91

2.5 Discussion

Fort Randall Dam is operated for hydropower production and flood control which results in substantial fluctuations in discharge (Patrick, 1998). Fort Randall discharge data during the study period showed large daily fluctuations as evidenced by the large variability in 24 hr change in discharge (Table 2.6). Water temperatures from hypolimnetic releases from Fort Randall Dam also occur in this reach (Galat et al., 2001). Overall densities of drifting macroinvertebrates were the smallest in this reach. The most prevalent aquatic macroinvertebrate taxa were Chironomidae and Simuliidae. In a study of macroinvertebrate communities below Fort Randall and Gavins Point Dams, Troelstrup and Hergenrader (1990) found that Chironomidae were more tolerant of discharge fluctuations from hydropower peaking operations. Chironomidae and Simuliidae use drift as a relocating mechanism to recolonize disturbed areas especially after spates or washouts (Mackay, 1992). Days since a high flow event was the most important predictor variable in this reach and was negatively correlated with drift density, which suggests that aquatic macroinvertebrates are drifting in greater number to recolonize following scouring flows. Temperature plays an important role in invertebrate ecology (Ward and Stanford, 1982) and may influence drift density as well (Pearson and Franklin, 1968; Brittain and Eikeland, 1988). Temperature also tends to covary with photoperiod (Williams and Feltmate, 1992), which Brittain and Eikeland (1988) state may also influence drift density. Temperature was the other important predictor variable in this reach, and drift densities increased with greater water temperatures.

Gavins Point Dam is operated as a re-regulating dam that evens out the flow fluctuations from Fort Randall Dam and releases uniform discharges for the navigation channel (Patrick, 1998). Daily fluctuations in Gavins Point discharge were less than those from Fort Randall Dam. Overall drift density in the Gavins Point reach was greater than in the Fort Randall reach. Invertebrate development may respond to degree days as well as absolute temperature (Ward, 1992), and degree days was the most important predictor variable in the Gavins Point reach. Discharge had strong support as an important predictor variable and was negatively correlated with drift density. Petts (1984) states that drops in discharge can cause a 'drought reaction' where the reduction in habitat encourages entry into the drift. Several studies have shown increases in drift following reductions in discharge (Minshall and Winger, 1968; Gore, 1977; Perry and Perry, 1986; Poff and Ward, 1991). Chironomidae were the most prevalent aquatic macroinvertebrates. Kerby et al. (1995) found that non-drifting Chironomids were more likely to have full or nearly full guts and suggested that hungrier individuals may enter the drift to search for food. Several other laboratory and field studies (Warren et al., 1964; Otto, 1976; Kohler, 1985; Richardson, 1991; Hinterleitner-Anderson et al., 1992; Siler et al., 2001) have indicated that macroinvertebrate drift increases when food resources are less abundant. The results of this study are consistent with these findings. Reduced discharge dewaters the more productive backwater and marsh habitats in this reach, much of which have already been lost because of channel degradation (Hesse et al., 1989; Mestl and Hesse, 1993). Therefore, reduced discharge may lead to increased drift densities as macroinvertebrates follow the retreating water from the backwaters and marshes towards the main channel. Reduced discharge from Gavins Point Dam also results in reduced plankton discharge, which has become an important food source in this reach (Patrick, 1998). Days since a low flow event also had moderate support as an important predictor variable and was positively correlated with drift density. Greater values of days since a low flow event and greater drift densities generally occurred in periods of average to low discharge, which followed the periods of greater discharge in the mid-1980s and mid-1990s. This further supports the idea that aquatic macroinvertebrates are entering the drift to search for food and new habitats.

Drift densities were greatest in the channelized Sioux City and Plattsmouth reaches, and Hydropsychidae became the most prevalent aquatic macroinvertebrates. Hydropsychidae are net-spinning filter feeders (Wiggins, 1996) that prefer large, stable substrates and high water velocities (Georgian and Thorp, 1992). The Hydropsychidae nets collect small algae, detrital seston, and small drifting animals (Fairchild and Holomuzki, 2002). Trapping of organic matter behind Fort Randall and Gavins Point Dams results in low particulate organic matter (POM) concentrations below the dams (Patrick, 1998), but tributary inputs and surface runoff increase organic matter concentrations longitudinally below Gavins Point Dam (Patrick, 1998). Several studies have indicated that Hydropsychidae emigrate through the drift from areas of low food abundance (Fuller and Mackay, 1980; Williams and Levens, 1988; Matczak and Mackay, 1990; Fairchild and Holomuzki, 2002). The results of this study are consistent with these studies because turbidity was an important predictor variable and was negatively correlated with drift density in the channelized reaches. Over 80% of the organic carbon in the Missouri River is transported in the suspended sediments (Galat et al., 2005). Malcolm and Durum (1976) found that particulate organic carbon was positively correlated with suspended sediments, and Carr (1988) found a positive correlation between particulate organic matter and turbidity. Therefore, reduced turbidity in the Missouri River likely means less particulate organic matter is readily available for filter feeders. Hesse et al. (1988) estimated that the 725 million kg of organic carbon transported to the Mississippi River represented less than 20% of historic levels. Degree days was again an important predictor variable in the Sioux City reach, but was not in the Plattsmouth reach. Since temperature increases predictably downstream of Gavins Point Dam (Galat et al., 2001), greater temperatures in the Plattsmouth reach may be less of a limitation to macroinvertebrate activity, and therefore, less important.

Because of the exploratory nature of this study and large sampling variability, model selection uncertainty was high, as expected. The models developed were based on data from May and June and are probably not useful outside of those months without further testing. However, the multi-model inference procedure has identified important predictor variables that could be used to predict macroinvertebrate drift density while accounting for model selection uncertainty. Results for the Fort Randall reach were different than for the other reaches probably because Fort Randall Dam is operated for hydropower production and releases hypolimnetic water, whereas Gavins Point Dam is a shallow, wind mixed, re-regulating reservoir. Below Gavins Point Dam, the results of the modeling were consistent with other studies that suggest that macroinvertebrate drift increases in response to reduced food and habitat availability. Discharge was the most important predictor variable in the Gavins

Point reach, and turbidity was an important predictor variable in the Sioux City and Plattsmouth reaches. Temperature or degree days were important predictors of macroinvertebrate drift density in the upstream reaches. Increased spring discharges, movement of sediment through the reservoirs, and habitat diversity restoration have all been proposed to help restore native species (Hesse et al., 1989; Galat and Lipkin, 2000; National Research Council, 2002). Since it appears drift increases in response to reduced food and habitat availability, these proposed changes should generally help improve macroinvertebrate production and increase the food availability for native fish and birds. In addition, the results of this study suggest future avenues of research for confirmatory studies under an adaptive management framework, as suggested by the the National Research Council (2002).

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Chapter 3

Relationships between larval fish drift and abiotic factors in the Missouri River

3.1 Abstract

Changes in reservoir operations have been proposed to improve ecological conditions in the Missouri River. However, uncertainty exists about how the biota will respond to flow management changes. Production and survival of larval fish are important factors in determining the strength of new fish generations. The objectives of this study were to estimate the relative importance of key abiotic variables to predict larval drift and to compare these results among fish species and reaches of the river. A multi-year, multi-location database of spring larval fish drift net sampling was used to develop relationships between larval freshwater drum and catostomid presence/absence and drift density and variables representing discharge, temperature, and turbidity in the Missouri River from Fort Randall Dam, SD to the mouth of the Little Nemaha River, NE. Multimodel inference using linear mixed models and an information theoretic approach along with classification trees were used to estimate the relative importance of the predictor variables. Temperature-related variables were consistently the

most important predictors of the presence and density of larval freshwater drum and catostomids. Results for the other predictor variables were inconsistent and difficult from which to draw conclusions.

3.2 Introduction

For over a century, the Missouri River has been greatly modified through the construction of storage reservoirs, channelization, and flood control structures (Galat et al., 1996). These developments have provided a number of economic benefits but at a considerable ecological cost (National Research Council, 2002). The impacts these changes have had on the natural flow regime have been well documented (Hesse and Mestl, 1993; Galat and Lipkin, 2000; Pegg et al., 2003). The most significant alterations to the flow regime include a reduction in the magnitude and duration of high flows, an increase in the magnitude of low flows, and reduced flow variability (Galat and Lipkin, 2000; Pegg et al., 2003). Water temperature depressions from hypolimnetic reservoir releases occur below the mainstem reservoirs, with the exception of Gavins Point Dam releases, which have no significant effects on water temperature (Galat et al., 2001). Suspended sediment concentrations and turbidity have also been greatly reduced as a result of the reservoir system (Morris et al., 1968; Whitley and Campbell, 1974; Slizeski et al., 1982; Pflieger and Grace, 1987; Schmulbach et al., 1992; Galat et al., 2001). The ecological impacts resulting from human alteration of the Missouri River ecosystem have been well documented and include declines in the abundance of many native fish species (Hesse et al., 1989; Schmulbach et al., 1992; Galat et al., 1996; Hesse, 1996; National Research Council, 2002). These impacts have considerably altered the extent and characteristics of fish production (Pflieger and Grace, 1987; Hesse et al., 1989; Hesse, 1996; Galat et al., 1996; Patrick, 1998).

Changes in environmental attitudes have led to an increased interest in restoring some portion of the Missouri River's ecological function that has been lost. Habitat restoration and changes in flow management have both been proposed as ways to restore some of the ecological functions of the Missouri River system. Habitat restoration through backwater and side channel creation has been occurring in the channelized portion of the river. However, changes in flow management have been very controversial and the subject of litigation. The Draft 2006 Annual Operating Plan for the Missouri River Mainstem Reservoir System includes the implementation of a spring rise in response to the U. S. Fish and Wildlife Service's 2003 Amended Biological Opinion. The proposed spring rise would consist of two pulses, one in March and one in May. There is considerable uncertainty as to how the Missouri River biota will respond to changes in flow management (National Research Council, 2002).

Survival during early life stages generally determines the strength of the next generation of fishes (Hergenrader et al., 1982; Humphries et al., 2002). Since larval and juvenile fish are more susceptible to environmental and anthropogenic disturbances, they can serve as a sensitive tool for monitoring the impacts of flow regulation (Humphries et al., 2002). Most temperate zone fish have seasonal reproductive cycles that are designed to produce young when environmental conditions are more favorable for survival (Bye, 1984). Light and temperature commonly initiate and control sexual development. Other environmental, physiological, and behavioral conditions are important during the periods leading up to and during spawning. The factors that serve as cues or controls may be different for each phase of the reproductive cycle. Because temperate regions have pronounced seasonal climatic variability, spawning is generally confined to a brief and specific time of year. Cues which initiate gonadal development must anticipate the suitable spawning season. Day length, temperature and food availability are the predominate cues in temperate regions (Bye, 1984).

A number of abiotic and biotic factors may influence spawning, hatching, and larval development and survival (Werner, 2002). Abiotic factors include temperature, photoperiod, discharge, and turbidity. The eggs and larvae of many species of fish are transported via drift from upstream spawning areas to downstream nursery areas (Hergenrader et al., 1982; Braaten, 2000). Fish larval drift may be influenced by behavioral and/or physical factors (Hergenrader et al., 1982). However, the factors causing larval drift are poorly understood (Hergenrader et al., 1982; Brown and Armstrong, 1985). Patterns of downstream juvenile recruitment may be related to upstream spawning success, and larval delivery and survival success (Braaten, 2000).

This study used larval fish sampling data from the Missouri River Historical Database (MRHD) (Hesse, 2001) to investigate the relationships between abiotic factors and the presence or absence of larval fish in the drift. The MRHD is a multi-year, multi-location database of macroinvertebrate and fish sampling that covers the portion of the Missouri River from Fort Randall Dam, SD to St. Joseph, MO. The data in the MRHD are a compilation of data from a variety of previous studies and projects. In addition, the physical data used were those readily available from public sources and may not completely reflect conditions at each of the individual sampling sites. Therefore, this study was an exploratory investigation. There were three objectives for this study. The first objective was to develop statistical models that relate larval fish presence/absence and drift density to variables representing discharge, temperature, and turbidity for the Missouri River between Fort Randall Dam, SD and the mouth of the Little Nemaha River, NE. The second objective was to estimate the relative importance of the predictor variables to larval fish presence/absence and drift density, and the third objective was to compare these results among different reaches of the study area and among different species or groups of fish.

3.3 Methods

3.3.1 Study area

Our study area included approximately 566 river kilometers (RK) of the mainstem of the Missouri River from Fort Randall Dam, SD (RK 1416) to Rulo, NE (RK 797). This portion of the 4,090 km Missouri River is the transition from the unchannelized inter-reservoir zone to the lower channelized zone. Channelization in the study area occurred from 1933 to 1981 (Schneiders, 1999). Discharge in the study area is regulated by Fort Randall Dam (closed in 1952) and Gavins Point Dam (closed in 1955). The 62 km segment between Fort Randall Dam and Lewis and Clark Lake and a 94 km segment immediately below Gavins Point Dam are designated as the Missouri National Recreational River as part of the National Wild and Scenic Rivers System (Berry and Young, 2004).

The study area was subdivided into four reaches with smaller sampling sites within each reach (Table 3.1, Figure 3.1). The first reach is isolated between Fort Randall Dam, SD (RK 1416) and Gavins Point Dam, NE (RK 1305). This reach is a remnant unchannelized segment. Flow in this reach is primarily controlled by releases from Fort Randall Dam. However, the Niobrara River enters the Missouri River at the downstream end of this reach at the headwaters of Lewis and Clark Lake, which is impounded behind Gavins Point Dam. The second reach stretches from Gavins Point Dam to the mouth of the Big Sioux River (RK 1181) at Sioux City, IA. This reach is mostly unchannelized, but is stabilized near Sioux City. The James and Vermillion rivers enter the Missouri River in this reach below Yankton, SD. The third reach was from the Big Sioux River to the mouth of the Platte River (RK 957) near Plattsmouth, NE. This entire reach is channelized. The Floyd, Little Sioux, Soldier, and Boyer rivers enter the Missouri River in this reach. The fourth reach was from the Platte River to Rulo, NE (RK 797). The entire reach is channelized, and the Nishnabotna River enters the Missouri River in this reach. Flow variability and turbidity increase in this reach because of inflows from the Platte and Nishnabotna rivers.

Table 3.1. Larval fish sampling locations. Adapted from Hesse (2001).

Reach	Sampling Site Name	Code	Upper River km	Lower River km
Fort Randall	Boyd County	FR1	1408	1371
	Verdel	FR2	1369	1358
	Niobrara	FR3	1358	1344
	Lewis and Clark Lake	FR4	1342	1305
Gavins Point	Gavins Point Tailwater	GP1	1305	1297
	St. Helena	GP2	1297	1279
	Brooky Bottom	GP3	1279	1255
	Maskel	GP4	1255	1229
	Ponca	GP5	1229	1212
Sioux City	Sioux City	SC1	1181	1168
	Decatur	SC2	1112	1083
	Tekamah	SC3	1083	1043
	Blair	SC4	1043	1009
	Bellevue	SC5	978	973
Plattsmouth	Plattsmouth	PL1	973	916
	Nebraska City	PL2	916	883
	Brownville	PL3	872	830
	Rulo	PL4	830	797

3.3.2 Larval fish sampling data

The larval fish sampling data for this study came from drift net sample data contained in the Missouri River Historical Database (MRHD) (Hesse, 2001), developed by Rivers Corporation, Inc. (Nebraska nonprofit, Larry W. Hesse, Founder and Prin-

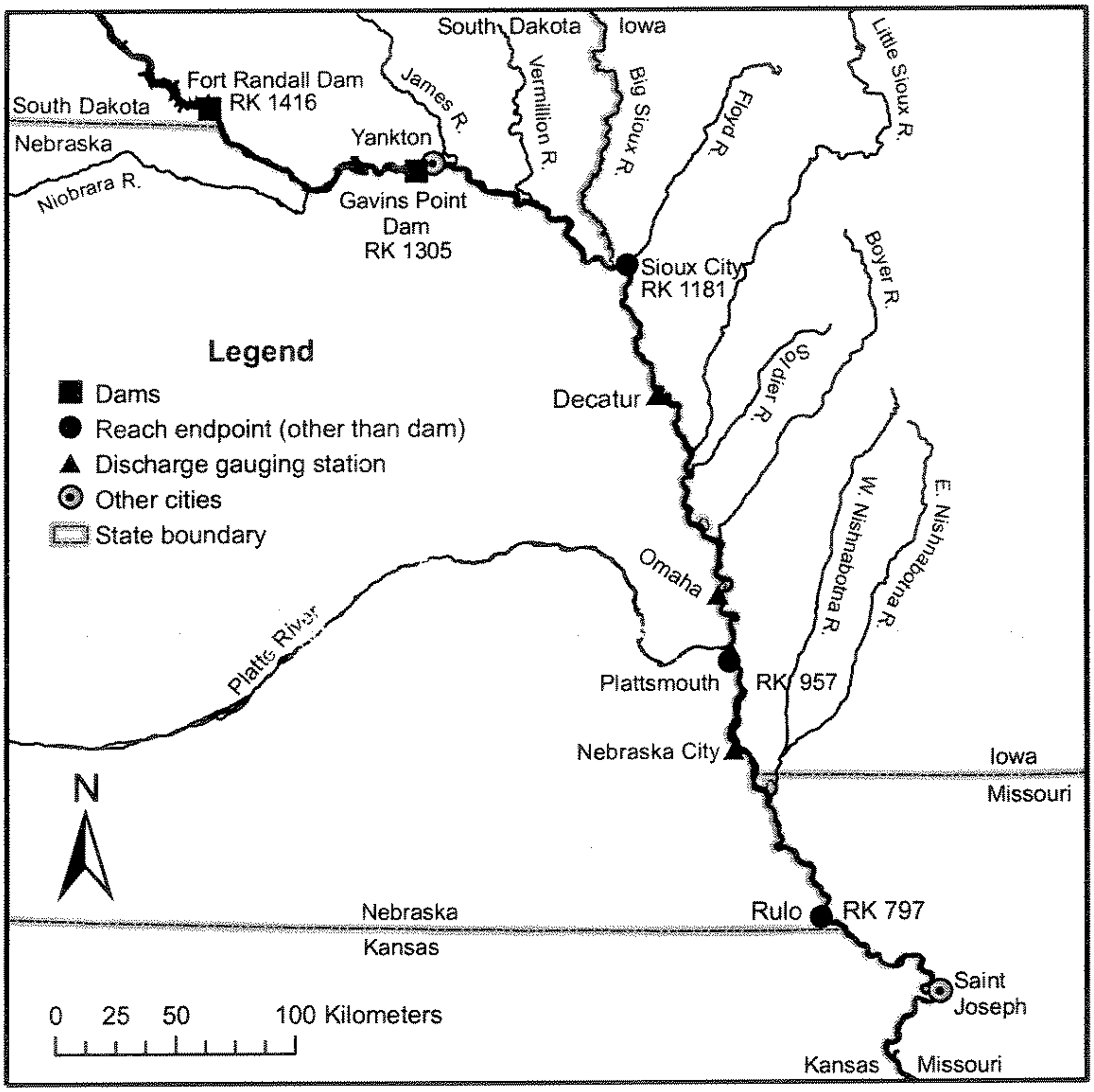

Figure 3.1. Map of the study area showing study reach boundaries and gaging station locations.

cipal Scientist, Crofton, NE). All of the larval fish data in the MRHD were collected by scientists from the Nebraska Game and Parks Commission and Rivers Corporation, Inc. from 1983 to 2004. Drift net samples were collected using 560 μm nylon (nitex) mesh, conical nets attached to a stainless steel or fiberglass ring and rope towing bridle. Several different net dimensions (1 m diameter, 3 m long; 0.75 m diameter, 2.25 m long; and 0.5 m diameter, 1.5 m long) were used. A mechanical flowmeter (General Oceanics Model 2030R) was suspended in each net mouth to quantify the volume of water passing through the net. The codend of the drift nets was 0.09 m in diameter and fitted with a Dolphin Net Bucket assembly. Drift nets were towed in pairs near the surface behind a survey boat and recovered on steel cables with a hydraulic winch. The duration of a tow sample was dependent on water conditions. During periods of low turbidity, nets were towed for 12 minutes or more before clogging reduced their filtering capacity, whereas a minimum tow was 3 minutes during periods of high turbidity. Samples were typically obtained from three locations, the cutting bank, filling bank, and mid-channel. River sites were generally sampled fortnightly between April 15 and July 15 during daylight hours. Samples were preserved with formalin to 10% concentration.

The timing of drift samples contained in the MRHD varied from year to year. However, all years contained samples collected in May or June. Therefore, to minimize the seasonal variation among years, only larval fish drift samples collected in May or June were used for modeling. There was considerable variation in the number of samples by site and by year (Table 3.2). The larval fish drift density data were characterized by a large number of zeroes and a small number of very large densities that greatly skewed the data. To deal with the skewed data, two different response variables were used in the statistical models. The first response variable used was the presence or absence of larval fish from individual drift net samples contained in the MRHD. For each sample, the response variable was coded as a 1 if a larval fish of the species being modeled was present or 0 if it was absent from the sample. The second response variable used was the monthly mean of transformed drift densities (number of individuals per 100 m^3). The drift densities from each individual sample were transformed using an eighth root transformation based on a Box-Cox procedure. Monthly means of the transformed sample drift densities were calculated for May and June. Many species were not present in enough samples to be useful for the statistical modeling. Freshwater drum (*Aplodinotus grunniens*) and a combined group of Catostomids, river carpsucker (*Carpiodes carpio*), smallmouth buffalo (*Ictiobus bubalus*), and bigmouth buffalo (*I. cyprinellus*), were chosen because they were among the most commonly collected species.

Table 3.2. Number of larval fish drift net samples by reach, year, and month Values are the sum of samples from all sites within each reach.

	Fort Randall		Gavins Point		Sioux City		Plattsmouth	
Year	May	June	May	June	May	June	May	June
1983	—	4	—	31	—	—	—	—
1984	5	5	11	35	—	—	—	—
1985	6	17	7	33	—	1	—	—
1986	5	—	14	33	3	9	—	—
1987	4	2	6	3	4	2	3	3
1990	—	3	5	32	5	29	—	—
1991	60	139	68	82	40	110	—	—
1993	12	9	12	8	12	8	12	5
1998	6	18	6	18	12	16	6	6
1999	16	18	16	22	22	32	12	12
2000	26	19	23	19	30	22	14	12
2001	18	23	28	26	36	42	12	26
2002	30	16	27	17	30	22	38	18
2003	10	18	16	13	24	24	18	12
2004	16	24	18	24	34	30	10	12
Total	214	315	257	396	252	347	125	106

3.3.3 Statistical modeling

Predictor variables for the presence/absence models were chosen from among those thought to have biological significance (Werner, 2002) and for which data were readily available (Table 3.3). The variables chosen were those for which continuous data were available covering the study period. Daily discharge and water temperature records were obtained from the U. S. Army Corps of Engineers for Fort Randall Dam and Gavins Point Dam. Daily discharge records for the Omaha, NE and Nebraska City, NE gaging stations were obtained from the U. S. Geological Survey. Records of mean monthly turbidity were obtained from the Omaha Metropolitan Utilities District for turbidity of Missouri River water at the District's intakes (RK 1007). The Fort Randall Dam discharge and temperature data were used in the modeling of the Fort Randall reach. Discharge data from Gavins Point Dam, Omaha, and Nebraska City were used for the Gavins Point, Sioux City, and Plattsmouth reaches, respectively. Gavins Point Dam water temperature and Omaha turbidity data were used for all three reaches below Gavins Point Dam. In addition to the above predictor variables, the volume filtered for each sample was included as a predictor variable to account for differences in sample sizes.

Classification trees (Breiman et al., 1984) were used to estimate the relative importance of the predictor variables and to develop classification models for the presence/absence data. The construction of classification trees is analogous to variable selection in regression models (Venables and Ripley, 2002). The inclusion of a variable and the level of its inclusion are indicators of the importance of the variable for classification. Classification trees were developed using the rpart package (Therneau and Atkinson, 2004) of R (R Development Core Team, 2004). Splitting was done using the Gini index, and pruning was done using 10-fold cross-validation and the

Table 3.3. Description of the predictor variables used to model presence/absence of larval fish.

Predictor	Description	Units
Discharge	Mean daily discharge at the Fort Randall Dam; Gavins Point Dam; Omaha, NE; or Nebraska City, NE gage	m^3s^{-1}
24 hr change in discharge	Change in discharge from the previous day	m^3s^{-1}
Temperature	Mean daily water temperature of Fort Randall Dam or Gavins Point Dam discharges	°C
Degree days	Cumulative daily water temperature above a base of 0 °C	°C
Turbidity	Mean monthly turbidity measured at the Omaha MUD intakes	NTU
Volume filtered	Volume of water passing through the net	m^3

1-SE rule (Venables and Ripley, 2002).

Predictor variables for the monthly means of the transformed drift densities were the monthly mean and coefficient of variation (CV) of discharge, monthly mean and CV of water temperature and monthly mean turbidity. In addition to the Omaha discharge records, discharge data from the USGS gaging stations at Sioux City and Decatur were also used in the Sioux City reach (Table 3.1). Sioux City discharge records were used for the Sioux City site. Decatur discharge records were used for the Decatur, Tekamah, and Blair sites. The Omaha discharge records were used for the Bellevue site. The monthly drift density models were fit using linear mixed models (LMMs). Random effects for year and site were included to account for correlations between observations within the same year and at the same site, respectively. The form of the models that were fit was as follows:

$$
\begin{aligned}
y_{ijk} &\sim \text{indep.} \quad \mathrm{N}(\mu, \sigma^2) && (3.1)\\
y_{ijk} &= a_i + b_j + \beta_0 + \sum_{m=1}^{p} x_{ikm}\beta_m && (3.2)\\
a_i &\sim \mathrm{N}(0, \sigma_a^2) && (3.3)\\
b_j &\sim \mathrm{N}(0, \sigma_b^2) && (3.4)
\end{aligned}
$$

where y is the response variable, a is the year effect for the ith year, b is the site effect for the jth site, p is the number of predictor variables, x_{ikm} is the mth predictor variable for the kth day in the ith year, and β is a model parameter.

Because of the exploratory nature of this research, an all-subsets approach was used to fit all of the possible linear mixed models. With the large number of predictor variables relative to the number of data points, model selection uncertainty was expected to be high. Therefore, a multimodel inference technique described by Burnham and Anderson (2002) was used to rank the models and develop model averaged estimates that account for the model selection uncertainty.

The linear mixed models were fit using the lmer function in the Matrix package (Bates and Maechler, 2006) of R (R Development Core Team, 2004). The individual models were ranked using a second-order variant of Akaike's information criterion (AIC_c). AIC_c was used because of the small number of observations relative to the number of predictor variables. An AIC_c difference (Δ) was calculated as the difference in AIC_c between each model and the top ranked model (the model with the lowest AIC_c). An Akaike weight (Burnham and Anderson, 2002),

$$
w_i = \frac{\exp(-\frac{1}{2}\Delta_i)}{\sum_{r=1}^{R}\exp(-\frac{1}{2}\Delta_r)} \qquad (3.5)
$$

was then calculated for each model r within the set of R models. The Akaike weights are an estimate of the likelihood of the model being the best model based on the data. The relative variable importance (RVI) of each of the predictor variables was calculated by summing the Akaike weights for each of the models in which the predictor was included. Model averaged parameter estimates and unconditional standard errors were calculated as described in Burnham and Anderson (2002).

RVI values can range from 0 to 1 with 1 being most important. A cutoff value of 0.5 was used to classify whether a variable was important or not in each set of models. Selection of this value was arbitrary. However, since the modeling procedure represents a weight of evidence approach, it was assumed that a combined weight of at least 0.5 was needed to classify a predictor variable as important. Also, the 0.5 level generally corresponded to the level at which the magnitude of the parameter estimates exceeded the standard error. RVI values between 0.5 and 0.75 were considered to be moderate support, and RVI values of at least 0.75 were considered to be strong support for the importance of that predictor variable.

3.4 Results

The taxonomic composition of larval fish that were collected in the May and June drift net samples contained in the MRHD varied by reach (Table 3.4). The most prevalent species overall was freshwater drum, which was the predominant species below Gavins Point Dam (35.1–78.9%). The second most prevalent species was river carpsucker, which was the predominant species between Fort Randall Dam and Gavins Point Dam (49.2%). Together, freshwater drum and river carpsucker accounted for 72.4% of the total catch of larval fish contained in the MRHD. Five species accounted for 80% of the remaining larvae captured. These species were gizzard shad, smallmouth buffalo, red shiner, emerald shiner, and common carp. Gizzard shad were prevalent in the Gavins Point reach (15.6%). Smallmouth buffalo were prevalent in the Fort Randall and Plattsmouth reaches (14.6 and 11.4%, respectively). Red and emerald shiners were prevalent in the Plattsmouth reach (18.8 and 15.2%, respectively). Common carp were not prevalent in any reach in particular, but were captured fairly consistently throughout the study area.

Table 3.4. Relative abundance (% of total) of larval fish taxa in the four reaches of the study area for species representing at least 0.1% of the total.

		Reach			
Common Name	Scientific Name	1	2	3	4
Goldeye	*Hiodon alosoides*	< 0.1	< 0.1	0.1	1.8
Skipjack herring	*Alosa chrysochloris*	—	0.2	2.0	—
Gizzard shad	*Dorosoma cepedianum*	2.3	15.6	2.0	0.2
Red shiner	*Cyprinella lutrensis*	0.2	0.1	0.1	18.8
Emerald shiner	*Notropis atherinoides*	2.2	1.7	0.5	15.2
River shiner	*Notropis blennius*	—	—	—	0.6
Sand shiner	*Notropis stramineus*	0.2	0.1	< 0.1	0.7
Common carp	*Cyprinus carpio*	5.8	3.7	1.7	1.6
River carpsucker	*Carpiodes carpio*	49.2	5.9	11.5	13.0
Blue sucker	*Cycleptus elongatus*	0.2	0.2	0.1	< 0.1
Smallmouth buffalo	*Ictiobus bubalus*	14.6	2.8	0.9	11.4
Bigmouth buffalo	*Ictiobus cyprinellus*	11.2	0.7	0.6	0.8
Shorthead redhorse	*Moxostoma macrolepidotum*	0.4	0.3	0.1	< 0.1
White bass	*Morone chrysops*	0.3	2.9	0.3	0.2
Bluegill	*Lepomis macrochirus*	0.2	0.2	0.1	< 0.1
Black crappie	*Pomoxis nigromaculatus*	0.3	0.1	0.2	< 0.1
Sauger	*Sander canadensis*	1.3	0.6	0.4	0.1
Freshwater drum	*Aplodinotus grunniens*	9.5	64.4	78.9	35.1
Total no. of individuals		5,971	61,030	64,198	38,423

Observed larval fish presence and drift densities varied in both space and time (Tables 3.5 and 3.6). Freshwater drum were more common below Gavins Point Dam than in the Fort Randall reach. Freshwater drum larvae were present in only 8% of the samples in the Fort Randall reach. Below Gavins Point Dam, freshwater drum larvae were present in June samples much more than in May samples. Drift densities were also greater in June than in May. June drift densities were greatest in the Sioux City reach, least in the Fort Randall reach, and approximately equal in the Gavins Point and Plattsmouth reaches. Catostomid larvae occurred less frequently in drift net samples in the Fort Randall reach, but occurred more frequently than did freshwater drum, occurring in 49% of the samples in the Fort Randall reach. Catostomids also occurred more frequently in June samples than in May, but occurred much more frequently in May samples than freshwater drum. Drift densities of Catostomid larvae increased downstream.

3.4.1 Presence/absence models

Discharge, temperature, and degree days all increased in the downstream direction (Table 3.7). In contrast, there was no downstream trend for 24 hr change in discharge. Mean daily discharge varied over a range of 85–1000 m^3s^{-1} at Fort Randall Dam to 892–2,498 m^3s^{-1} at Nebraska City, NE during the study period. Discharge changes were most variable at Fort Randall Dam. There were only two locations where continuous temperature data were available. Water temperatures were lower at Fort Randall Dam because of hypolimnetic releases. Galat et al. (2001) found that temperature predictably increased downstream from Gavins Point Dam. The only continuous turbidity data available were at Omaha, NE and only on a monthly basis. Therefore, there were a maximum of two values per year (May and June) depending on whether or not larval fish sampling occurred in both months. The monthly averages are likely obscuring daily variations in turbidity from storm events. Because turbidity in the Missouri River below Gavins Point Dam is greatly influenced by tributary sediment inputs, the relationship between turbidity at Omaha and turbidity at

Table 3.5. **Freshwater drum:** Summary of the percentage of samples in which larval fish were present (P, %) and mean larval drift density (D, no. of individuals per $100\,m^3$) by year and month in the four sampling reaches. Bootstrapped 95% confidence intervals (based on at least 1000 replicates and the bias corrected and accelerated method (BCa) method) are included for the overall means.

	Reach																
	Fort Randall				Gavins Point				Sioux City				Plattsmouth			
	May		June		May		June		May		June		May		June	
Year	P	D	P	D	P	D	P	D	P	D	P	D	P	D	P	D
1983	—	—	0	0.00	—	—	77	136.60	—	—	—	—	—	—	—	—
1984	0	0.00	0	0.00	0	0.00	37	13.08	—	—	—	—	—	—	—	—
1985	0	0.00	0	0.00	0	0.00	33	33.07	—	—	0	0.00	—	—	—	—
1986	0	0.00	—	—	14	0.37	73	56.97	67	0.51	100	377.32	—	—	—	—
1987	25	0.04	0	0.00	0	0.00	100	56.84	50	0.46	100	66.64	67	0.20	100	74.68
1990	—	—	100	2.26	0	0.00	100	27.07	80	3.44	100	53.60	—	—	—	—
1991	5	0.06	5	0.07	62	3.50	76	81.24	45	2.17	81	116.19	—	—	—	—
1993	0	0.00	22	7.45	17	0.08	88	3.03	8	0.03	75	3.36	33	0.24	80	1.15
1998	0	0.00	22	0.15	0	0.00	56	29.39	8	0.09	38	36.60	0	0.00	50	73.52
1999	0	0.00	22	0.28	0	0.00	77	20.27	0	0.00	69	20.05	0	0.00	100	15.42
2000	4	0.10	42	0.38	9	0.09	100	61.29	19	0.11	100	30.08	7	0.04	100	45.14
2001	0	0.00	13	0.13	21	0.26	88	19.34	11	0.09	83	93.07	25	0.45	96	119.59
2002	0	0.00	13	0.10	0	0.00	94	34.39	3	0.02	95	53.56	3	0.03	100	56.85
2003	0	0.00	6	0.02	0	0.00	92	31.36	13	0.11	71	77.28	0	0.00	75	41.30
2004	6	0.03	21	0.10	22	0.37	63	1.56	38	0.49	83	53.90	0	0.00	92	19.86
Total	3	0.03	12	0.34	23	1.01	73	48.13	21	0.54	82	81.67	9	0.08	92	59.10
95% CI		(0.0, 0.1)		(0.1, 1)		(0.6, 2)		(39, 62)		(0.3, 1)		(68, 102)		(0.0, 0.2)		(46, 74)

Table 3.6. **Catostomids** (river carpsucker, smallmouth buffalo, and bigmouth buffalo): Summary of the percentage of samples in which larval fish were present (P, %) and mean larval drift density (D, no. of individuals per 100 m^3) by year and month in the four sampling reaches. Bootstrapped 95% confidence intervals (based on at least 1000 replicates and the bias corrected and accelerated method (BCa) method) are included for the overall means.

	Reach															
	Fort Randall				Gavins Point				Sioux City				Plattsmouth			
	May		June		May		June		May		June		May		June	
Year	P	D	P	D	P	D	P	D	P	D	P	D	P	D	P	D
1983	—	—	75	3.58	—	—	81	14.50	—	—	—	—	—	—	—	—
1984	0	0.00	20	0.04	18	0.38	83	3.76	—	—	—	—	—	—	—	—
1985	0	0.00	59	1.08	14	0.03	85	24.22	—	—	100	1.07	—	—	—	—
1986	0	0.00	—	—	79	2.69	58	6.84	100	2.36	100	97.72	—	—	—	—
1987	50	11.41	100	67.61	50	7.14	67	5.53	100	17.96	100	16.91	100	15.81	100	27.06
1990	—	—	100	1.04	80	0.45	75	0.88	100	1.99	97	2.86	—	—	—	—
1991	48	1.08	65	2.89	75	8.38	62	3.30	85	11.73	77	7.43	—	—	—	—
1993	0	0.00	33	0.28	17	0.39	25	0.06	8	0.07	25	0.11	33	0.33	20	0.02
1998	0	0.00	67	5.62	50	0.40	89	2.26	42	4.50	88	2.52	83	1.44	67	10.64
1999	0	0.00	22	0.63	6	0.06	50	1.10	0	0.00	47	2.59	8	0.10	42	3.85
2000	27	0.37	95	17.49	74	10.67	95	3.53	77	4.80	100	16.40	86	3.64	92	763.24
2001	6	0.04	61	1.32	89	19.04	92	1.85	64	10.17	98	7.67	92	8.00	85	13.87
2002	3	0.03	81	1.38	41	2.42	76	1.36	43	1.98	91	5.01	29	1.41	72	6.77
2003	60	0.88	100	5.42	50	0.65	92	3.06	54	1.62	100	13.70	28	0.96	100	12.49
2004	6	0.02	100	4.20	61	1.89	79	1.50	79	6.12	100	12.23	50	2.94	100	26.72
Total	22	0.61	69	4.03	58	6.04	74	5.56	60	5.67	84	9.88	46	2.47	78	97.20
95% CI		(0.5, 1)		(3, 6)		(5, 8)		(4, 9)		(5, 7)		(8, 13)		(2, 4)		(38, 225)

the individual sampling sites should weaken with increasing distance from Omaha.

Degree days was consistently the most important predictor variable for predicting larval fish presence (Table 3.8). Classification and regression trees always selected degree days as the first variable chosen for discriminating between the presence and absence of fish larvae, as indicated by the values of one in Table 3.8. Temperature and volume of water filtered were generally the second most important predictors. The other predictor variables were used infrequently and at lower levels of the trees. The most complex classification trees were for the Gavins Point reach where there were six levels in each tree (Figure 3.2). Classification errors (percentage of misclassified observations) for the classification trees were generally a considerable improvement on the naive error rates (percentage of misclassified observations from assuming observations were either all present or all absent) with the exception of freshwater drum in the Fort Randall reach where they were not very abundant (Table 3.9).

3.4.2 Drift density models

With only one exception, temperature and variation in temperature were the most important predictor variables for the monthly means of the transformed drift densities in the drift density models (Table 3.10). The exception was for catostomids in the Sioux City reach where variation in discharge was the most important predictor variable. Variation in discharge reached the 0.5 level of importance in two other cases but was much less important than one or both of the temperature variables. Mean discharge and turbidity were not important in any of the models. Model predictions were generally very good except for freshwater drum in the Fort Randall reach (where a single extreme point exaggerates the prediction R^2) and catostomids in the Gavins Point reach where they were not prevalent.

Table 3.7. Summary of data for the predictor variables by location over the study period, where n is the number of unique data points corresponding to the fish larvae presence or absence samples followed by the minimum, mean, maximum and standard deviation, respectively. See Table 3.3 for definitions of the predictor variables.

Predictor	n	Min.	Mean	Max.	SD
Discharge (m^3s^{-1})					
Fort Randall Dam	115	85	619	1000	184
Gavins Point Dam	161	170	696	1028	196
Omaha	110	779	1147	1931	259
Nebraska City	51	892	1314	2498	341
Discharge change (m^3s^{-1})					
Fort Randall Dam	115	–487	–5	535	115
Gavins Point Dam	161	–232	–1	226	68
Omaha	110	–458	1	292	110
Nebraska City	51	–390	–13	252	103
Temperature (°C)					
Fort Randall Dam	115	5.0	13.0	22.2	4.1
Gavins Point Dam	161	7.2	18.7	26.1	3.8
Degree days (°C)					
Fort Randall Dam	115	234	654	1300	254
Gavins Point Dam	161	284	1009	1585	341
Turbidity (NTU)					
Omaha	28	36	156	385	101
Volume filtered (m^3)					
Fort Randall Reach	539	1	310	4490	289
Gavins Point Reach	653	4	291	1647	253
Sioux City Reach	599	38	196	1496	137
Plattsmouth Reach	231	35	181	1048	135

Table 3.8. Summary of the predictor variables used for classification using classification and regression trees. Numbers indicate the levels of each tree in which the predictor variables were used. Results for freshwater drum in the Fort Randall reach are not included because the model did not improve on the naive error rate.

	Reach			
Predictor	Fort Randall	Gavins Point	Sioux City	Plattsmouth
Discharge				
Freshwater drum	—	—	3	—
Catostomids	4	—	—	—
24 hr change in discharge				
Freshwater drum	—	3,4	—	—
Catostomids	—	4,6	—	—
Temperature				
Freshwater drum	—	5	—	—
Catostomids	—	2	2	—
Degree days				
Freshwater drum	—	1,3	1,2	1
Catostomids	1,3	1,3	1	1
Turbidity				
Freshwater drum	—	2	—	—
Catostomids	—	3,5	—	—
Volume filtered				
Freshwater drum	—	6	—	—
Catostomids	2	2	2	—

Table 3.9. Summary of classification errors (percentage of misclassified observations) by species and reach for the classification tree models as compared to no model (naive).

	Reach			
Species	Fort Randall	Gavins Point	Sioux City	Plattsmouth
Freshwater drum				
Naive	8%	53%	56%	47%
Tree	7%	15%	13%	9%
Catostomids				
Naive	42%	43%	32%	43%
Tree	20%	19%	12%	18%

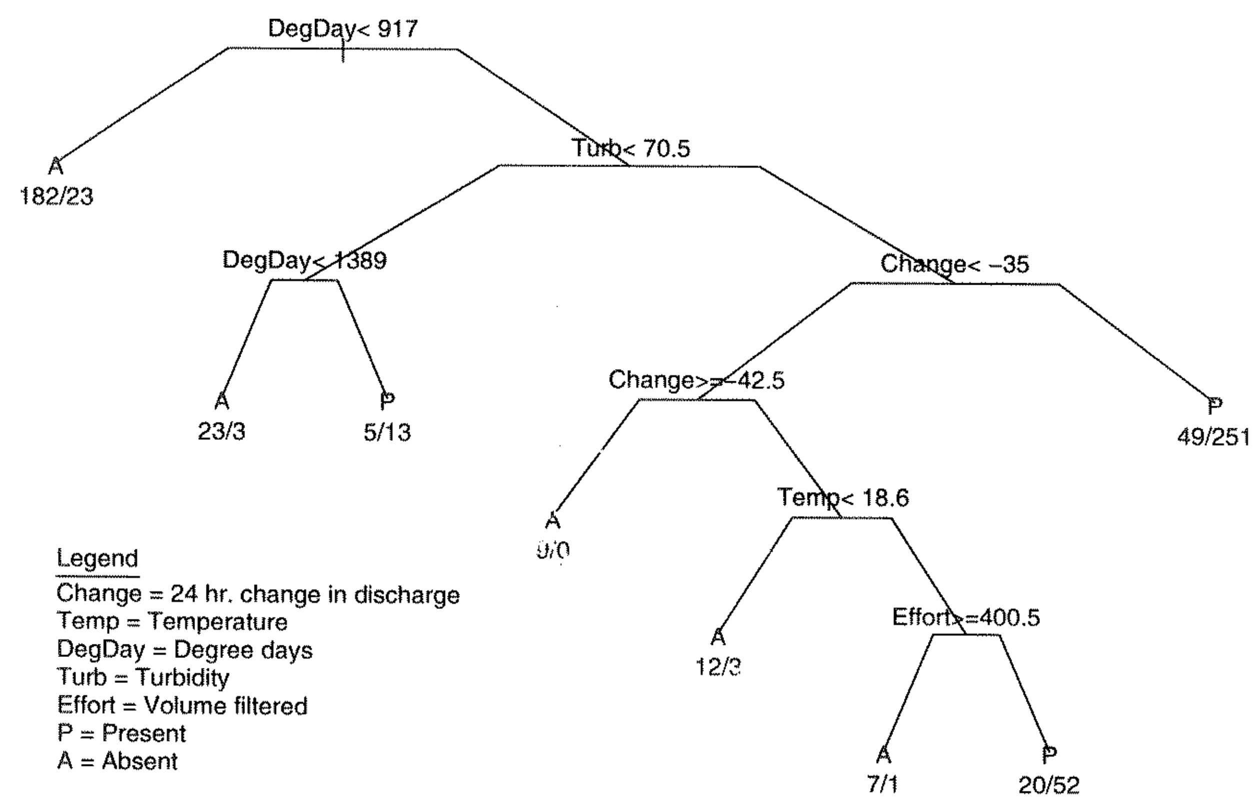

Figure 3.2. Classification tree for freshwater drum larvae between Gavins Point Dam and Sioux City, IA. At each node, if the condition is met, the left branch is followed. Otherwise, the right branch is followed. Numbers at the terminal nodes are the observed absence/presence data.

Table 3.10. Relative variable importance (RVI) and direction of the effect (sign of the parameter estimate) based on multi-model inference for each predictor variable by sampling reach and species or group. RVI values greater than 0.5 are indicated by an asterisk. Results are only shown for models with a prediction R^2 greater than 0.65.

	Reach			
Predictor	Fort Randall	Gavins Point	Sioux City	Plattsmouth
Mean discharge				
Freshwater drum	—	0.00 (+)	0.00 (−)	0.00 (−)
Catostomids	0.00 (−)	—	0.00 (−)	0.00 (−)
CV Discharge				
Freshwater drum	—	0.27 (−)	*0.51 (−)	0.36 (−)
Catostomids	0.18 (−)	—	*0.68 (−)	*0.50 (−)
Mean temperature				
Freshwater drum	—	*1.00 (+)	*1.00 (+)	*1.00 (+)
Catostomids	*1.00 (+)	—	*0.62 (+)	0.07 (+)
CV Temperature				
Freshwater drum	—	*1.00 (+)	*0.73 (+)	*0.68 (+)
Catostomids	*0.63 (+)	—	*0.58 (−)	*0.98 (−)
Turbidity				
Freshwater drum	—	0.00 (−)	0.00 (+)	0.00 (+)
Catostomids	—	—	0.00 (+)	0.00 (+)
Prediction R^2				
Freshwater drum	0.65	0.84	0.66	0.88
Catostomids	0.80	0.36	0.87	0.70

3.5 Discussion

The taxonomic composition of the larval fish in this study was similar to that reported by Hergenrader et al. (1982). Hergenrader et al. (1982) studied larval fish in relation to potential impacts of two nuclear power stations. They found that the larval fish assemblage was composed primarily of freshwater drum, catostomids, cyprinids, and carp. Gizzard shad, goldeye, and *Stizostedion* sp. were also common. They also found that the relative abundance of larval fish generally did not match that of adult fish. Freshwater drum represented 70–90% of the larval fish but only approximately 5% of adult fish. Relative abundance patterns of larval fish were relatively similar except within the influence of the Platte River. Similarly, in this study, the relative abundance patterns were generally similar except for the Plattsmouth reach which is below the Platte River. In particular, red and emerald shiners were much more prevalent in the Plattsmouth reach than in the other reaches. Freshwater drum and emerald shiners are pelagic spawners, which explains their prevalence in the drift (Balon, 1975; Hergenrader et al., 1982). Freshwater drum eggs and larvae are near the surface during both day and night (Hergenrader et al., 1982; Holland, 1986). Suckers (Catostomidae) are not negatively phototropic and are abundant in surface waters (Holland, 1986).

The timing patterns of larval fish in the drift were also similar to those found by Hergenrader et al. (1982). They found that larval fish were commonly found in the drift from early May through July and peaked from mid-June through early July. Catostomidae (primarily *Ictiobus* sp.) were prevalent in May, and freshwater drum and Catostomidae (primarily *Carpiodes* sp.) were prevalent from June through July. In this study, freshwater drum occurred much more frequently in June samples and Catostomids occured more frequently in May samples than did freshwater drum. Wolf and Willis (1996) found that larval fish diversity was less than expected and larvae appeared later than expected below Garrison Dam on the Missouri River, which was attributed to hypolimnetic releases. Similarly, the results of this study suggest that the occurrence and densities of larval fish in the drift below Fort Randall dam are negatively affected by hypolimnial releases.

In a study of small fish discharged through Gavins Point Dam, Walburg (1971) estimated that up to 10 million freshwater drum and 800,000 emerald shiner larvae were washed out of Lewis and Clark Lake during 24 h periods. Walburg (1971) also states that few if any small fish are lost from Lake Francis Case because water is drawn from near the reservoir bottom. Therefore, larval fish in the Fort Randall reach must come from sources primarily within the reach, whereas larval fish in the Gavins Point reach may be supplemented by Gavins Point discharges. This along with the reduced water temperatures in the Fort Randall reach help explain the smaller drift densities in Fort Randall Reach as compared to the Gavins Point reach from this study. Hergenrader et al. (1982) found that drift densities were greater at a transect 130 km downstream of Gavins Point Dam than they were at the dam outlet, and there were statistically significant increases between transects, which indicates that recruitment was coming from other sources in addition to Gavins Point Dam. The results indicated that many larvae were produced in the unchannelized section below Gavins Point Dam. The Platte River was also an important source of larvae.

Drift densities of catostomids increased downstream in this study, which suggests that catostomid larvae are being added to the drift along the entire length of the study area. The densities of freshwater drum increased through the Sioux City reach, which indicates that larvae are being added to the drift from sources in the unchannelized and channelized river in addition to larvae released from Lewis and Clark Lake. The density decreased in the Plattsmouth reach, which may be because of increased flow from tributary inputs and larval fish leaving the drift through settlement or mortality processes. Hergenrader et al. (1982) suggested that recruitment appears to be complex with input and output mechanisms taking place along the river.

The results of the statistical modeling indicate that temperature is the most important of predictor of the occurrence and density of freshwater drum and catostomid larvae. Several other studies have indicated relationships between temperature and recruitment of fish (Busch et al., 1975; Crecco and Savoy, 1987*b*,*a*; Uphoff, 1989; Cambray et al., 1997; King et al., 1998). Harvey et al. (2002) found that water temperature dominated relationships between physical variables and densities of age 0 Sacramento pikeminnow, steelhead, California roach, and Sacramento sucker. Other studies have found relationships between discharge and/or sediment and fish larvae (Lubinski et al., 1986; Crecco and Savoy, 1987*b*,*a*; Johnston et al., 1995; Cambray et al., 1997; King et al., 1998; Mion et al., 1998). Discharge and turbidity, within the ranges observed, were generally of minor importance for predicting larval fish presence and density in drift net samples in this study. It may be that discharge is more important to post-spawning recruitment than to spawning success for the studied species as suggested by Humphries and Lake (2000); Humphries et al. (2002).

Overall, the results of this study reaffirm the importance of temperature to fish reproduction. Greater temperatures or degree days consistently increased the probability of finding larval fish and the resulting drift densities of the studied species in the drift during May and June. Discharge was of minor or no importance in predicting presence/absence or drift densities. The models were developed within the range of discharges observed during the study period, which is reduced from what historically occurred (Hesse and Mestl, 1993; Galat and Lipkin, 2000; Pegg et al., 2003), and are probably not useful outside those ranges without further testing. Since larval fish drift densities were not related to discharge within the range of observed values, discharge experimentation within this same range is unlikely to affect larval fish densities.

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Chapter 4

Catch of age-0 and age-1 fish in relation to abiotic factors in the Missouri River

4.1 Abstract

Restoration of a more natural hydrologic regime has been proposed as part of Missouri River recovery plans. However, uncertainty exists about how the biota will respond to changes in flow management. The objectives of this study were to examine relationships between spawning season abiotic variables and catch per unit effort of age-0 and age-1 fish and to compare these results among species and reaches of the river. A multi-year, multi-location database of fish seining data was used to develop statistical models relating catch per unit effort of several cyprinid and one catostomid species and variables representing discharge, temperature, and turbidity in the Missouri River from Fort Randall Dam, SD to Rulo, NE. Bayesian model averaging using multiple linear regression models was used to estimate the posterior effect probabilities for each of the predictor variables. In most cases, there was evidence of an effect for one or more of the discharge related variables. Greater catch per unit effort was generally related to less variable discharge in the unchannelized reaches and to greater and

rising discharge in the channelized reaches. The results suggest that greater spring discharges below Gavins Point Dam would benefit fish populations in the Missouri River.

4.2 Introduction

As with many large rivers in the world, the natural flow regime of the Missouri River has been altered by impoundment, flow regulation, and channelization. The natural flow regime is considered by many to be the primary driver of river ecosystem processes (Richter et al., 1996; Poff et al., 1997). Alterations in the Missouri River's flow regime have coincided with reductions in many native fish species that were adapted to the natural flow regime (Cross and Moss, 1987; Pflieger and Grace, 1987; Hesse et al., 1993; Hesse, 1994, 1996; Galat et al., 2005*a*). The most significant alterations to the flow regime include a reduction in the magnitude and duration of high flows, an increase in the magnitude of low flows, and reduced flow variability (Galat and Lipkin, 2000; Pegg et al., 2003). In addition, water temperature depressions from hypolimnetic reservoir releases occur below the mainstem reservoirs above Gavins Point Dam (Galat et al., 2001) and sediment trapping in the reservoirs has greatly reduced suspended sediment loads and turbidity in the river (Morris et al., 1968; Whitley and Campbell, 1974; Slizeski et al., 1982; Pflieger and Grace, 1987; Schmulbach et al., 1992; Galat et al., 2001).

The historic Missouri River hydrograph was characterized by a bimodal spring rise (Hesse et al., 1989; Galat and Lipkin, 2000; Galat et al., 2005*b*). The first peak occured in March to April following ice-out in the channel and prairie snowmelt. The second, larger peak occurred in June from Rocky Mountain snowmelt and rainfall on the plains and associated river valleys. Overbank flooding was common during the historic spring rises (Hesse et al., 1989; Galat et al., 2005*b*). Many native Missouri River fish species are thought to time their spawning to take advantage of the increased discharge and flooding (Cross and Moss, 1987; Fausch and Bestgen, 1997). The spring rise is most effective at influencing fish reproduction when it is coupled with increasing water temperature (Junk et al., 1989; Galat et al., 1996; Tockner et al., 2000).

With shifting environmental and resource values has come increased interest in naturalizing some portions of the Missouri River system. Habitat restoration through backwater and side channel creation and floodplain acquistion has been occurring in the channelized portion of the river. The goal of these projects is to increase channel habitat complexity and restore some river-floodplain connectivity (Galat et al., 2005*a*). Restoring more natural flows has been much more controversial and the subject of litigation. An experimental spring rise through reservoir releases from Gavins Point Dam was conducted for the first time in 2006, but there is considerable uncertainty as to how the Missouri River biota will respond to changes in flow management (National Research Council, 2002).

This study used bag seine sampling data from the Missouri River Historical Database (MRHD) (Hesse, 2001) to investigate the relationships between abiotic factors and interannual variation in mean catch per unit effort (C/E) of age-0 and age-1 fish. The MRHD is a multi-year, multi-location database of macroinvertebrate and fish sampling that covers the portion of the Missouri River from Fort Randall Dam, SD to St. Joseph, MO. The data in the MRHD are a compilation of data from a variety of previous studies and projects. In addition, the physical data used were those readily available from public sources and may not always accurately reflect conditions at each of the individual sampling sites. Therefore, this study was an exploratory investigation. There were three objectives for this study. The first objective was to develop statistical models that relate C/E of age-0 and age-1 fish to variables representing discharge, temperature, and turbidity during the historic spring rise/spawning season for the Missouri River between Fort Randall Dam, SD and the mouth of the Rulo, NE. The second objective was to estimate the probability of an effect for each of the predictor variables, and the third objective was to compare these results among different reaches of the study area and among different species or groups of fish.

4.3 Methods

4.3.1 Study area

Our study area included approximately 566 river kilometers (RK) of the mainstem of the Missouri River from Fort Randall Dam, SD (RK 1416) to the mouth of the Little Nemaha River, NE (RK 850). This portion of the 4,090 km Missouri River is the transition from the unchannelized inter-reservoir zone to the lower channelized zone. Channelization in the study area occurred from 1933 to 1981 (Schneiders, 1999). Discharge in the study area is regulated by Fort Randall Dam (closed in 1952) and Gavins Point Dam (closed in 1955). The 62 km segment between Fort Randall Dam and Lewis and Clark Lake and a 94 km segment immediately below Gavins Point Dam are designated as the Missouri National Recreational River as part of the National Wild and Scenic Rivers System (Berry and Young, 2004).

The study area was subdivided into four reaches with several sampling sites within each reach (Table 4.1, Figure 4.1). The first reach, a remnant unchannelized segment, is isolated between Fort Randall Dam, SD (RK 1416) and Gavins Point Dam, NE (RK 1305). Flow in this reach is primarily controlled by releases from Fort Randall Dam. However, the Niobrara River enters the Missouri River at RK 1359 near the headwaters of Lewis and Clark Lake, which is impounded behind Gavins Point Dam. The second reach extends from Gavins Point Dam to the mouth of the Big Sioux River

(RK 1181) at Sioux City, IA. This reach is mostly unchannelized, but is stabilized near Sioux City. The James and Vermillion rivers enter the Missouri River in this reach below Yankton, SD. The third reach is from the Big Sioux River to the mouth of the Platte River (RK 957) near Plattsmouth, NE and is entirely channelized. The Floyd, Little Sioux, Soldier, and Boyer rivers enter the Missouri River in this reach. Reach four is from the Platte River to the mouth of the Little Nemaha River (RK 850) near Nemaha, NE. The entire reach is channelized, but flow variability and turbidity increase in this reach because of inflows from the Platte and Nishnabotna rivers.

Table 4.1. Fish sampling locations, number of years sampled between 1978 and 2004, and total sampling effort. Adapted from Hesse (2001).

Reach	Site Name	Upper River km	Lower River km	No. Years Sampled	Effort (m^2)
Fort Randall (FR)	Boyd County	1408	1371	8	39,776
	Verdel	1369	1358	6	15,312
	Niobrara	1358	1344	14	49,632
Gavins Point (GP)	Gavins Point Tailwater	1305	1297	5	25,520
	St. Helena	1297	1279	11	20,768
	Brooky Bottom	1279	1255	2	3,696
	Maskel	1255	1229	4	6,336
	Ponca	1229	1212	5	11,440
Upper Channelized (UC)	Sioux City	1181	1168	1	2,464
	Dakota City	1168	1112	4	4,400
	Decatur	1112	1083	9	24,816
	Tekamah	1083	1043	4	3,520
	Blair	1043	1009	10	29,270
	Bellevue	978	973	4	4,224
Lower Channelized (LC)	Plattsmouth	973	916	1	1,056
	Nebraska City	916	883	5	3,552
	Brownville	872	830	7	6,688
	Rulo	830	797	1	880

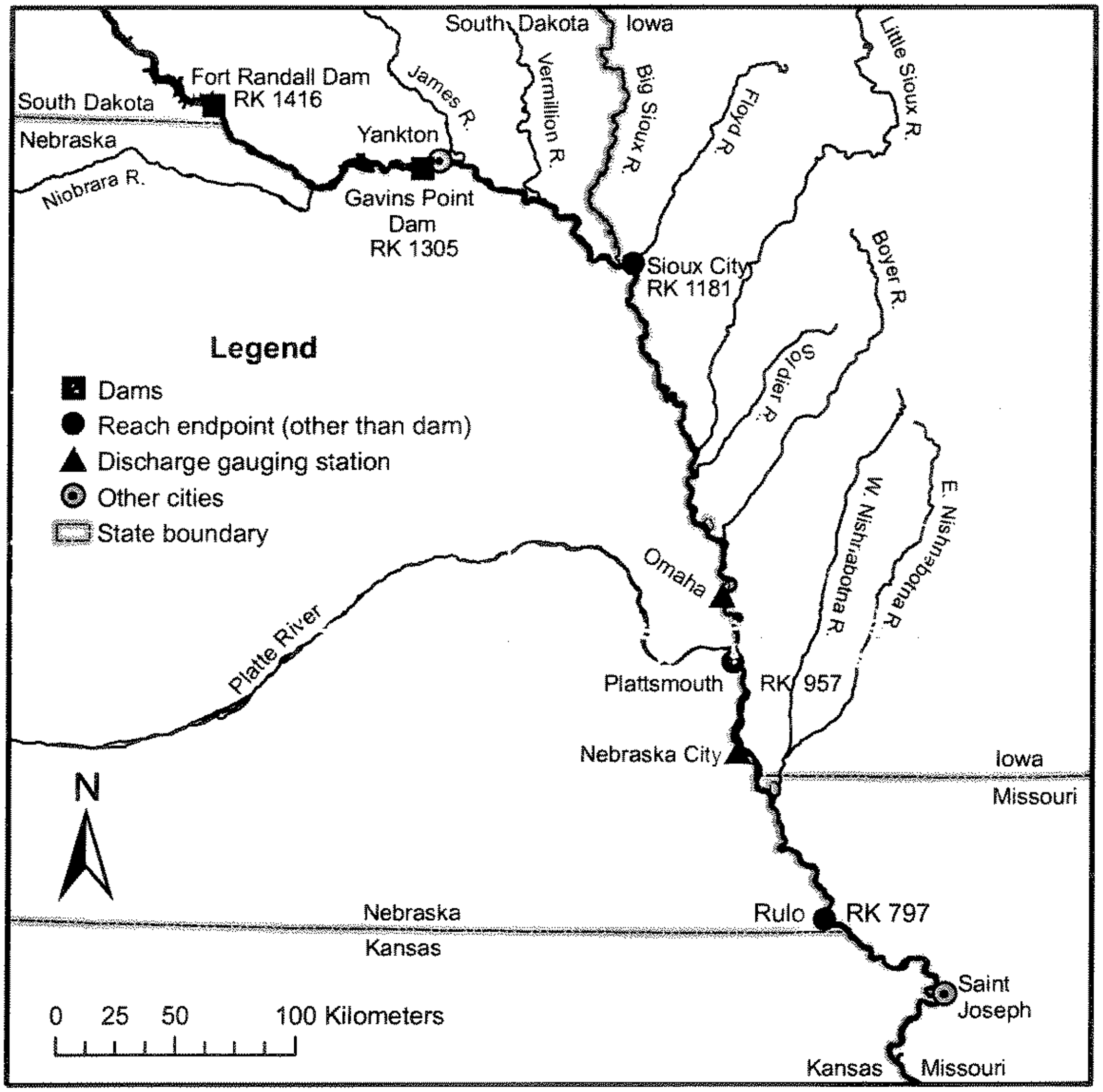

Figure 4.1. Map of the study area showing study reach boundaries and gaging station locations.

4.3.2 Fish sampling data

The fish sampling data for this study came from bag seine sample data contained in the Missouri River Historical Database (MRHD) (Hesse, 2001), developed by Rivers Corporation, Inc. (Nebraska nonprofit, Larry W. Hesse, Founder and Principal Scientist, Crofton, NE). Seining data in the MRHD were collected by scientists from the Nebraska Game and Parks Commission and Rivers Corporation, Inc. from 1978 to 2004. Additional years of data, in which individual lengths were not recorded in the database, were not included in the analyses. Seine samples were collected with a 15.2x1.8 m bag seine with 6.1 mm mesh. A standard seine haul was a quarter circle turn beginning with the seine perpendicular to the shore with one end anchored to the shore followed by an extended drag to the shore (Hesse et al., 1993; Hesse, 1994). Level of effort was defined as the area of the quarter circle sampled. Varying depths and substrate conditions made the seining effort difficult to replicate. However, the same method has been used consistently over time. Seined fish were preserved in the field with formalin for identification in the laboratory.

The species chosen for modeling were those which were numerically prevalent and additional cyprinid species of interest that were present in enough numbers to be modeled. Modeled species were red shiner (*Cyprinella lutrensis*), silver chub (*Macrohybopsis storeriana*), emerald shiner (*Notropis atherinoides*), river shiner (*N. blennius*), bigmouth shiner (*N. dorsalis*), sand shiner (*N. stramineus*), and river carpsucker (*Carpiodes carpio*). River shiners, bigmouth shiners, and sand shiners were combined into a group, hereinafter referred to as fluvial shiners, to ensure adequate numbers to be modeled. Fish from these species were classified into age groups using a length-frequency analysis (DeVries and Frie, 1996). MCLUST (Banfield and Raftery, 1993; Fraley and Raftery, 1999, 2002*b*,*a*, 2003) was used to fit a parameterized Gaussian mixture model to the length data and classify the lengths into age groups using model based clustering. For species captured in large enough numbers or whose lengths changed dramatically throughout the season (emerald shiner, river carpsucker, red shiner, and silver chub), clustering was performed using monthly or bimonthly data over all reaches. For species captured in lesser numbers (river shiner, sand shiner, and bigmouth shiner), the clustering was done using seasonal data over all reaches. Months for which the lengths could not be readily discriminated into separate age groups were not included in the analyses. Individual fish were then classified into age classes based on these results. Parameters for the Gaussian mixture models used for classification are shown in Table 4.2.

Catch per unit effort (C/E) (no. $1000^{-1}\,m^{-2}$) of age-0 or age-1 fish was used as the response variable in the statistical modeling. The individual sites were sampled with varying frequencies and most species were not captured in sufficient numbers to perform a site by site analysis. Therefore, data from the individual sites were pooled together by reach. The number of fish classified as age-0 or age-1 captured and the sampling effort by reach and by year were used to calculate C/E to use as the response variable. The C/E data were positively skewed and could not be reasonably assumed to follow a normal distribution. A maximum likelihood analysis of the Box-Cox family of power transformations was performed on the C/E data for each species with an appropriate constant added where necessary to ensure positive values. In each case, the log transformation was within the 95% confidence interval of the maximum likelihood for the Box-Cox parameter.

4.3.3 Statistical modeling

Predictor variables were chosen from among the abiotic variables thought to influence spawning of fishes in the Missouri River (Table 4.3). The variables were chosen based

Table 4.2. Summary of parameters from the Gaussian mixture models used to classify fish into age groups based on length. Values are in mm.

	Age-0		Age-1		Age-2	
Month	Mean	SD	Mean	SD	Mean	SD
Emerald shiner						
Aug	22	4	42	10	64	11
Sep	26	7	54	7	74	7
River carpsucker						
Aug	35	10	66	13		
Sep	38	9	73	15		
Oct	44	9	71	17		
Red shiner						
Jul-Aug	26	6	47	6	59	9
Sep-Oct	33	7	44	7	60	7
River shiner						
Aug-Oct	45	8	61	8		
Sand shiner						
Aug-Oct	30	7	42	4	53	4
Bigmouth shiner						
Aug-Oct	34	10	50	5		
Silver chub						
Jul	29	7	91	16		
Aug	45	7	99	16		
Sep	60	14	117	7		
Oct	59	11	124	11		

on the availability of continuous data during the period covered by the seining data. Daily discharge and water temperature records were obtained from the U. S. Army Corps of Engineers for Fort Randall Dam and Gavins Point Dam. Daily discharge records for the Omaha, NE and Nebraska City, NE gaging stations were obtained from the U. S. Geological Survey National Water Information System. Records of mean monthly water temperature and turbidity were obtained from the Omaha Metropolitan Utilities District (MUD) for the Missouri River water at the District's intakes (RK 1007). The Fort Randall Dam discharge and temperature data were used in the modeling of the Fort Randall reach. Discharge data from Gavins Point Dam, Omaha, and Nebraska City were used for the Gavins Point, Sioux City, and Plattsmouth reaches, respectively. Gavins Point Dam water temperature and Omaha turbidity data were used for the Gavins Point reach. Omaha water temperature and turbidity were used for the Sioux City and Plattsmouth reaches. The date of maximum discharge, rate of rise, and number of hydrographic reversals were calculated using the Indicators of Hydrologic Alteration (IHA) software (The Nature Conservancy, 2005).

A multiple linear regression approach was used to assess the the relationships between the response and the predictors. Because of the considerable variations in sampling effort, weighted least squares was used with weights proportional to sampling effort. Age-0 models related the response to predictors from the same year as the reponse, and age-1 models related the response to predictors from the previous year. The form of the models that were fit was as follows:

$$\log(y_i + C)w_i^{1/2} = w_i^{1/2}\beta_0 + \sum_{k=1}^{p} w_i^{1/2}x_{jk}\beta_k \tag{4.1}$$

where y is C/E for the ith year; C is a constant added where necessary to ensure positive values of the response; w is the weight, proportional to the sampling effort,

Table 4.3. Description of the predictor variables used to model C/E of age-0 and age-1 fish. Predictors were measured over the period from March 1 to July 31 to correspond with the historic spring rise period and the beginning of the spawning season.

Predictor	Description	Units
Discharge	Mean discharge at the Fort Randall Dam, Gavins Point Dam; Omaha, NE; or Nebraska City, NE gage	m^3s^{-1}
CV Discharge	Coefficient of variation of discharge	
Date Max. Discharge	Ordinal date of the maximum daily discharge	
Rate of Rise	Mean of all positive differences in daily discharge values	$m^3s^{-1}d^{-1}$
Reversals	Number of hydrograph reversals (change from increasing to decreasing discharge or *vice versa*	
Temperature	Mean water temperature at Fort Randall Dam, Gavins Point Dam, or the Omaha MUD intakes	°C
Turbidity	Mean monthly turbidity measured at the Omaha MUD intakes	NTU

for the ith year; p is the number of predictor variables; x_{jk} is the kth predictor variable for the jth year (either i or $i-1$); and β is a model parameter.

With the large number of predictor variables relative to the number of response data points, model selection uncertainty was expected to be high. Therefore, Bayesian model averaging (BMA) was used to account for the model selection uncertainty inherent in variable selection problems (Hoeting et al., 1999; Raftery, 1995). BMA accounts for model selection uncertainty by averaging over all possible sets of predictors or a subset of models supported by the data. Posterior effect probabilities, parameter estimates, and standard deviations are calculated as an average of the posterior distributions weighted by their posterior model probability (Hoeting et al., 1999). The bicreg function in the BMA package (Raftery et al., 2005) of R (R Development Core Team, 2004) was used to perform the Bayesian model averaging analysis using linear regression models. Grades of evidence as defined by Raftery (1995), were used to classify the strength of evidence for an effect for the predictor variables. These grades of evidence for the posterior effect probabilities were: > 99% was very strong evidence, 95–99% was strong evidence, 75–95% was positive evidence, and 50–75% was weak evidence. Because BMA is not yet in widespread use, P-values were calculated for variables included in models with the greatest posterior probabilities for comparison with more traditional variable selection procedures.

4.4 Results

The taxonomic composition of fish captured in July–October bag seine samples contained in the MRHD varied by reach (Table 4.4). Emerald shiners were the most prevalent species overall and were the predominant species in the Fort Randall reach. River carpsucker was the second most prevalent species overall and was particularly prevalent in the Gavins Point reach. Combined, emerald shiners and river carpsucker accounted for 56% of the total catch in the seine samples. In each reach, emerald shiners and one or two additional species made up greater than half of the catch. The remaining species captured were primarily from the family Cyprinidae. Emerald shiners were over twice as abundant as all other cyprinids combined in the Fort Randall and Gavins Point reaches, but there was more species evenness among the cyprinids in the channelized reach.

The C/E data of the assumed age-0 and age-1 fish used for the statistical modeling were highly variable (Table 4.5). Because of the the variability, confidence intervals for the means were generally wide and definite differences were difficult to distinguish. Among reaches, C/E of river carpsucker was greatest in the Gavins Point reach.

Table 4.4. Relative abundance (% of total) of fish species (all ages) captured between 1978 and 2004 in July–October bag seine samples in the four reaches of the study area for species representing at least 1% of the total. Species are listed in order of overall relative abundance. Reaches are Fort Randall (FR), Gavins Point (GP), upper channelized (UC), and lower channelized (LC).

		Reach				
Common name	Scientific name	FR	GP	UC	LC	Total
Emerald shiner	*Notropis atherinoides*	63	39	24	34	43
River carpsucker	*Carpiodes carpio*	6	23	9	2	13
Red shiner	*Cyprinella lutrensis*	3	4	16	8	7
Spotfin shiner	*Cyprinella spiloptera*	9	1	6	< 1	5
Gizzard shad	*Dorosoma cepedianum*	1	8	5	5	5
Sand shiner	*Notropis stramineus*	1	6	5	4	4
Channel catfish	*Ictalurus punctatus*	< 1	1	14	7	4
River shiner	*Notropis blennius*	< 1	2	7	9	3
White bass	*Morone chrysops*	2	3	1	1	2
Bigmouth shiner	*Notropis dorsalis*	< 1	3	3	1	2
Yellow perch	*Perca flavescens*	5	< 1	< 1	0	2
Plains minnow	*Hybognathus placitus*	< 1	< 1	1	16	1
Silver chub	*Macrhybopsis storeriana*	< 1	< 1	3	4	1
Smallmouth buffalo	*Ictiobus bubalus*	1	1	< 1	1	1
Common carp	*Cyprinus carpio*	< 1	1	< 1	< 1	1
Shorthead redhorse	*Moxostoma macrolepidotum*	< 1	1	1	0	1
Fathead minnow	*Pimephales promelas*	1	< 1	1	< 1	1
Johnny darter	*Etheostoma nigrum*	1	< 1	< 1	0	1
Smallmouth bass	*Micropterus dolomieu*	1	< 1	< 1	0	1
Total no. individuals		18,440	21,343	12,449	2,314	54,546

Within the Gavins Point reach, mean C/E was greater for emerald shiner and river carpsucker than for red shiner and fluvial shiner. In the upper channelized reach, emerald and red shiners were most abundant. Because of the smaller sample size and lesser effort in the lower channelized reach, confidence intervals were very wide, but emerald shiners were the most abundant.

For the predictor variables, mean discharge and temperature increased downstream (Table 4.5). Conversely, the date of maximum discharge decreased in the downstream direction. Variation in discharge was greatest in the Fort Randall reach and similar in the Gavins Point reach and below. Mean rate of rise was least in the Gavins Point, slightly greater with a wider range in the Fort Randall reach, and increased from the upper to the lower channelized reach. The number of hydrograph reversals was greatest in the Fort Randall reach, least in the Gavins Point reach, and similar in the channelized reaches.

Of the two species modeled in the Fort Randall reach, only red shiner C/E was modeled well by the predictor variables, with a model averaged weighted prediction R^2 of 0.84 (Table 4.6). For red shiner C/E, there was very strong evidence of effects for discharge, CV of discharge, and reversals (100% each) and weak evidence (59%) of an effect for date of maximum discharge. There was a negative relationship between all four predictors and red shiner C/E. For river carpsucker, the intercept only model had the greatest posterior model probability, and none of the other top models fit the data well.

River carpsucker was modeled well by the predictors in the Gavins Point reach, with a model averaged weighted prediction R^2 of 0.79 (Table 4.7). There was strong evidence for an effect for CV of discharge (96%) and positive evidence of an effect for reversals (82%) with negative and positive relationships with the response, respec-

Table 4.5. Summary of the response and predictor variable data used in multiple linear regression models. Means for the response variables (C/E) are weighted by sampling effort and bootstrapped 95% confidence intervals for the weighted means (based on 10,000 replicates and the bias corrected and accelerated (BCa) method) are included below the mean values. See Table 4.3 for a description and units of the predictor variables.

	Reach							
	Fort Randall ($n = 14$)		Gavins Point ($n = 14$)		Upper Channelized ($n = 11$)		Lower Channelized ($n = 10$)	
Variable	Mean	Range	Mean	Range	Mean	Range	Mean	Range
C/E (no. 1000 m^{-2})								
Emerald shiner	—	—	66	1–216	37	10–108	68	1–139
(Age-1)			(39, 98)		(21, 74)		(15, 221)	
River carpsucker	5	0–49	35	2–321	11	1–25	6	0–17
(Age-1)	(3, 7)		(20, 74)		(6, 18)		(2, 20)	
Red Shiner	5	0–26	10	0–47	20	3–61	9	0–41
(Age-1)	(2, 14)		(4, 19)		(12, 34)		(4, 20)	
Fluvial shiners	—	—	14	0–81	10	3–38	—	—
(Age-1)			(9, 22)		(6, 17)			
Silver chub	—	—	—	—	4	0–28	7	0–30
(Age-0)					(2, 8)		(4, 12)	
Predictors								
Discharge (m^3s^{-1})	656	247–1362	766	375–1511	1208	775–2171	1433	901–2305
CV Discharge	0.35	0.18–0.83	0.23	0.12–0.40	0.21	0.13–0.37	0.24	0.14–0.45
Date Max. Discharge	183	129–213	179	120–213	157	79–197	145	67–207
Rate of Rise ($m^3s^{-1}d^{-1}$)	47	16–127	42	20–111	56	24–117	76	29–176
Reversals	62	22–81	24	10–50	51	39–61	47	35–59
Temperature (°C)	9.9	7.8–12.4	13.9	12.8–15.1	16.4	14.6–18.0	16.3	14.6–18.0
Turbidity (NTU)	—	—	125	39–217	117	39–217	109	39–217

Table 4.6. **Fort Randall Reach:** Summary of Bayesian model averaging results of C/E of age-1 fish with estimates of the posterior probabilities of an effect given the data (D), model averaged parameter estimates (β) and standard errors given the data, and P-values from the model with greatest posterior model probability. Estimates for models with a model averaged weighted prediction $R^2 < 0.5$ are not shown.

Variable	$P(\beta \neq 0 \mid D)$ (%)	Mean $\beta \mid D$	SD $\beta \mid D$	P-value
	River Carpsucker ($R^2 = 0.22$)			
	Red Shiner ($R^2 = 0.84$)			
Intercept	100	14.8070	3.4055	0.0005
Discharge	100	-0.0075	0.0013	0.0001
CV Discharge	100	-4.7141	1.1887	0.0012
Date Max. Discharge	59	-0.0070	0.0084	0.1510
Rate of Rise	27	0.0015	0.0053	
Reversals	100	-0.0980	0.0211	0.0004
Temperature	21	0.0004	0.1029	

tively. For red shiners, there was very strong evidence of an effect for mean discharge (99%) and weak evidence for CV of discharge and turbidity (64 and 58%, respectively). Mean discharge and turbidity were positively related to red shiner C/E and CV of discharge was negatively related. CV of discharge had positive evidence of an effect (93%) for the fluvial shiners and was negatively related to C/E. There was weak evidence of an effect for turbidity and reversals (69 and 61%, respectively) and both were negatively related to fluvial shiner C/E. Emerald shiners were not modeled well by the predictors in the Gavins Point reach.

In the channelized reaches, there was strong evidence of an effect for CV of discharge (98%), and weak evidence of effects for the upper channelized reach (58%) and date of maximum discharge (56%) (Table 4.8). All were positively related to emerald shiner C/E. The positive upper channelized reach effect indicates that C/E was greater in the upper channelized reach as compared to the lower channelized reach.

Table 4.7. **Gavins Point Reach:** Summary of Bayesian model averaging results of C/E of age-1 fish with estimates of the posterior probabilities of an effect given the data (D), model averaged parameter estimates (β) and standard errors given the data, and P-values from the model with greatest posterior model probability. Estimates for models with a model averaged weighted prediction $R^2 < 0.5$ are not shown.

Variable	$P(\beta \neq 0 \mid D)$ (%)	Mean $\beta \mid D$	SD $\beta \mid D$	P-value
Emerald Shiner ($R^2 = 0.23$)				
River Carpsucker ($R^2 = 0.79$)				
Intercept	100	7.2970	4.4611	0.0000
Discharge	21	0.0000	0.0005	
CV Discharge	96	-11.8800	4.8181	0.0002
Date Max. Discharge	17	-0.0001	0.0035	
Rate of Rise	26	0.0028	0.0105	
Reversals	82	0.0476	0.0333	0.0338
Temperature	37	-0.1460	0.2865	
Turbidity	47	-0.0051	0.0077	
Red Shiner ($R^2 = 0.70$)				
Intercept	100	-4.8992	7.7126	0.5976
Discharge	99	0.0032	0.0012	0.0095
CV Discharge	64	-5.6781	6.1679	0.0585
Date Max. Discharge	43	0.0065	0.0111	
Rate of Rise	37	0.0100	0.0209	
Reversals	25	-0.0066	0.0247	
Temperature	37	0.1907	0.4059	
Turbidity	58	0.0090	0.0105	0.0733
Fluvial Shiners ($R^2 = 0.62$)				
Intercept	100	2.5350	4.5511	0.0071
Discharge	33	-0.0004	0.0009	
CV Discharge	93	-14.2800	7.4007	0.0095
Date Max. Discharge	45	0.0064	0.0104	
Rate of Rise	30	0.0051	0.0152	
Reversals	61	0.0364	0.0409	0.1141
Temperature	20	-0.0291	0.2496	
Turbidity	69	0.0117	0.0114	0.0846

There was very strong evidence of an effect for discharge (100%) in the prediction of river carpsucker C/E, positive evidence of an effect for the upper channelized reach (91%), and weak evidence for temperature and CV of discharge (71 and 55%, respectively). All four variables were positively related to carpsucker C/E. For red shiners, there was very strong evidence of a upper channelized reach effect (100%) and strong evidence for discharge and temperature (96% each) all of which had a positive relationship with C/E of red shiner. The best fitting model was for the fluvial shiners in which there was very strong evidence of an effect for rate of rise and turbidity (100% each and positive and negative relationships, respectively). In addition, there was positive evidence for a negative CV of discharge effect (75%) and weak evidence of a positive temperature effect (55%). For silver chubs, there was positive evidence for a CV of discharge effect (82%) and weak evidence of a turbidity effect (68%). Both relationships were positive. As with the Gavins Point reach, emerald shiner C/E could not be predicted well by the set of predictor variables.

Table 4.8. **Channelized Reaches:** Summary of Bayesian model averaging results of C/E of age-0 or age-1 fish with estimates of the posterior probabilities of an effect given the data (D), model averaged parameter estimates (β) and standard errors given the data, and P-values from the model with greatest posterior model probability.

Variable	$P(\beta \neq 0 \mid D)$ (%)	Mean $\beta \mid D$	SD $\beta \mid D$	P-value
	Emerald Shiner ($R^2 = 0.64$)			
Intercept	100	-0.1325	2.1291	0.6168
Reach UC	58	0.4529	0.5423	0.1013
Discharge	11	0.0000	0.0002	
CV Discharge	98	7.3220	2.6773	0.0012
Date Max. Discharge	56	0.0048	0.0059	0.0998
Rate of Rise	18	0.0004	0.0061	
Reversals	25	0.0088	0.0224	
Temperature	12	0.0093	0.0786	
Turbidity	17	-0.0006	0.0028	

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Table 4.8. *continued.*

Variable	$P(\beta \neq 0 \mid D)$ (%)	Mean $\beta \mid D$	SD $\beta \mid D$	P-value
	River Carpsucker ($R^2 = 0.61$)			
Intercept	100	-10.4900	8.4066	0.0157
Reach UC	91	1.3860	0.7287	0.0053
Discharge	100	0.0024	0.0009	0.0014
CV Discharge	55	2.9500	3.6643	0.1146
Date Max. Discharge	15	0.0002	0.0026	
Rate of Rise	26	-0.0002	0.0095	
Reversals	15	-0.0004	0.0135	
Temperature	71	0.4831	0.4191	0.0219
Turbidity	34	-0.0025	0.0050	
	Red Shiner ($R^2 = 0.58$)			
Intercept	100	-14.7800	6.2067	0.0041
Reach UC	100	1.5320	0.4818	0.0018
Discharge	96	0.0020	0.0008	0.0043
CV Discharge	15	-0.0781	0.9692	
Date Max. Discharge	18	-0.0005	0.0026	
Rate of Rise	16	-0.0004	0.0033	
Reversals	26	0.0081	0.0213	
Temperature	96	0.8202	0.3294	0.0021
Turbidity	17	-0.0003	0.0019	
	Fluvial Shiners ($R^2 = 0.86$) (Upper channelized reach only)			
Intercept	100	-1.8240	4.4220	0.3742
Discharge	32	0.0001	0.0004	
CV Discharge	75	-4.0530	3.6849	0.0851
Date Max. Discharge	35	0.0014	0.0039	
Rate of Rise	100	0.0709	0.0214	0.0032
Reversals	36	0.0079	0.0194	
Temperature	55	0.1614	0.2413	0.1721
Turbidity	100	-0.0234	0.0068	0.0049
	Silver Chub (Age-0) ($R^2 = 0.59$)			
Intercept	100	-0.7267	1.7264	0.0512
Reach UC	24	-0.1208	0.3114	
Discharge	9	0.0000	0.0001	
CV Discharge	82	5.0800	3.5923	0.0481
Date Max. Discharge	35	-0.0019	0.0036	

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Table 4.8. *continued.*

Variable	$P(\beta \neq 0 \mid D)$ (%)	Mean $\beta \mid D$	SD $\beta \mid D$	P-value
Rate of Rise	34	0.0054	0.0107	
Reversals	10	-0.0006	0.0127	
Temperature	13	0.0130	0.0790	
Turbidity	68	0.0068	0.0062	0.0327

4.5 Discussion

The Missouri River was historically a turbid river with a shifting, braided channel and seasonal flooding in the spring (Hesse et al., 1989; Galat et al., 2005*b*). Many native Missouri River species have specialized morphologic and behavioral adaptations for these conditions (Cross and Moss, 1987; Pflieger and Grace, 1987; Galat et al., 2005*a*). Populations of species most adapted to turbid, fluctuating rivers have declined dramaticly (Cross and Moss, 1987; Pflieger and Grace, 1987; Hesse et al., 1993; Hesse, 1994, 1996; Galat et al., 2005*a*). A similar pattern has occured in other plains streams that have been subjected to impoundment and flow regulation (Cross and Moss, 1987; Bonner and Wilde, 2002; Quist et al., 2004). Cyprinid species that have experienced the greatest declines in the Missouri River (*Hybognathus* spp. and chubs) have been replaced by sight feeding planktivores (Cross and Moss, 1987; Pflieger and Grace, 1987; Hesse, 1994; Galat et al., 2005*a*). These changes are reflected in the taxonomic composition presented here (Table 4.4). Emerald shiners and red shiners, sight feeding planktivores and omnivores, respectively (Pflieger, 1975; Sigler and Sigler, 1996; Bergstedt et al., 2004), were the most prevalent cyprinids collected in the seine samples. Spotfin shiners, which associate with clear water and submergent vegetation characteristic of reservoir deltas (Galat et al., 2005*a*), were common in the

Fort Randall reach. Other native cyprinids less specifically adapted to turbid rivers (river shiners, bigmouth shiners, and sand shiners) (Cross and Moss, 1987; Pflieger, 1975; Galat et al., 2005*a*) were also consistently collected. Of the large bodied fishes commonly captured in the seine samples, river carpsucker are listed as stable to decreasing, gizzard shad as increasing, and channel catfish as stable to increasing (Galat et al., 2005*a*).

Characteristic Missouri River species of concern (Cross and Moss, 1987; Pflieger and Grace, 1987; Hesse, 1994; Berry and Young, 2004; Galat et al., 2005*a*) were less common or rare. Plains minnows were the only *Hybognathus* species caught in any abundance. Of the 539 plains minnows captured, 59% (319) were captured in either 1997 (226) and 1998 (93) and primarily in the lower channelized reach, which suggests that flooding during 1997 (the year of greatest discharge during the study period) may have been important for plains minnow recruitment. Western silvery minnow (*H. argyritis*) were rare (23 individuals). Silver chubs, which are less specifically adapted to turbid rivers and have a more developed sense of sight than the other chubs (Pflieger, 1975; Cross and Moss, 1987; Hesse, 1994), were not captured in great numbers, but were caught relatively consistently in the channelized reaches. Speckled chubs (*Macrhybopsis aestivalis*), sturgeon chubs (*M. gelida*), sicklefin chubs (*M. meeki*), and flathead chubs (*Platygobio gracilis*) were rare (36, 2, 1, and 44 individuals, respectively).

The results of the statistical modeling suggest that a hydrologic regime characteristic of the historic spring rise/spawning season flow regime is important to the recruitment of native cyprinids and catostomids. There was at least positive evidence of a discharge-related effect for all of the modeled species except for river carpsucker in the Fort Randall reach and emerald shiners in the Gavins Point reach. River carpsuckers and emerald shiners are macrohabitat generalists that also do well in reservoirs (Pflieger, 1975; Galat et al., 2005*a*). The lack of a relationship to discharge in those reaches suggest that emerald shiners and river carpsucker may be less affected by the altered hydrologic regime below the dams which may partly explain their greater relative abundance. The discharge effects among the modeled species differed somewhat depending on the reach (Tables 4.6–4.8). The important predictor variables differed somewhat by species; however, they were generally similar within the reaches as discussed below.

Results were different between the two unchannelized reaches. In the Fort Randall reach, C/E of red shiners was related to reduced discharge with less variation and fewer hydrograph reversals. Fort Randall Dam is operated to generate hydroelectric power, which can result in large diurnal changes in discharge as evidenced by the greater means and ranges of CV of discharge and hydrograph reversals (Table 4.5). Because the Fort Randall reach retains some of the braided channel characteristics of the pre-dam geomorphology, these discharge fluctuations can result in large shifts in available aquatic habitat and may negatively impact spawning and recruitment. These results are consistent with other studies that have found reduced abundance below hydropower dams of small-bodied riverine fish that rely on shallow-water habitat (Bain et al., 1988; Kinsolving and Bain, 1993; Freeman et al., 2001).

In the Gavins Point reach, C/E of the modeled species was generally related to greater and less variable discharge. Red shiners were positively related to mean discharge, and river carpsucker and the fluvial shiners were negatively related to CV of discharge. Mean discharge and CV of discharge were negatively correlated in the Gavins Point reach, so greater discharge was generally less variable. There was also evidence of a reversals effect for river carpsucker and the fluvial shiners. Gavins Point Dam re-regulates the variable Fort Randall discharges to provide more constant flows for the navigation channel and hydrograph reversals were least in this reach. Rate of rise and hydrograph reversals were strongly correlated in the Gavins Point reach, so the positive relationship with reversals is another indication that greater spring discharges are important in the Gavins Point reach.

River carpsucker and cyprinid C/E were related to greater and increasing discharge in the channelized reaches. Mean discharge, CV of discharge, rate of rise, and turbidity were all positively correlated in the channelized reaches. River carpsuckers, red shiners, and silver chubs were all positively related to one or more of these predictors. Interpretation for the fluvial shiners is more difficult because, while there was a positive relationship with rate of rise, there were negative relationships with CV of discharge and turbidity. Closer inspection of the fluvial shiner models indicates that the relative strength of the rise effect is greater than that of the CV of discharge and turbidity effects. There was also evidence of a temperature effect for all but the silver chubs. Temperature and mean discharge were strongly negatively correlated in the channelized reaches.

Flow regime and temperature are thought to be the abiotic factors most important in regulating ecosystem processes in large floodplain rivers (Ward, 1985; Poff et al., 1997; Richter et al., 1997; Tockner et al., 2000). The flood pulse concept suggests that the predictable annual flood pulse was the most important hydrologic feature of river-floodplain systems and that the biotic communities are adapted to these pulses (Junk et al., 1989). Many native species of the Missouri River and other turbid, fluctuating, plains rivers are thought to time their reproductive cycles to correspond to these spring flooding events (Cross and Moss, 1987; Fausch and Bestgen, 1997). The results of this study support the concept that greater spring flows below Gavins Point Dam are important for fish spawning and recruitment. Reduced magnitudes of spring discharges are one of the most altered component of the flow regime in the middle portion of the Missouri River (Galat and Lipkin, 2000; Pegg et al., 2003). Similar studies on other rivers have also documented relationships between native fish abundance and greater spring discharge (Brown and Ford, 2002; Koel and Sparks, 2002). A study on the San Juan River found increases in native fish densities following reservoir releases of elevated spring discharges to mimic the natural flow regime (Propst and Gido, 2004). Results from this study combined with those of other studies add to the weight of evidence that a more natural flow regime would benefit native fish species in the Missouri River. Ideally, the results of this study could be combined with future sampling in combination with flow managment experimentation in an adaptive management framework to validate and extend the models.

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Chapter 5

Conclusions

Flow regulation and channelization have greatly altered the Missouri River. It has been transformed from what was historically a highly turbid river with a complex, shifting, braided channel that experienced frequent flooding (Pflieger and Grace, 1987; Hesse et al., 1989; Galat et al., 2005*a*). The pre-control spring flood pulses have been dampened, and overbank flooding has been largely eliminated from the middle river. Turbidity and sediment transport have been greatly reduced, temperatures have been altered, and the lower river has been confined to a single deep, narrow, high velocity channel. Coincident with these changes have been declines in a number of native species (Pflieger and Grace, 1987; Hesse et al., 1993; Hesse, 1996; Galat et al., 2005*b*). Conservation efforts are shifting from documenting human impacts on the river's ecosystem to the design and implementation of restoration and recovery efforts (Galat et al., 2005*a*). Proposals to restore more natural flows are being considered but have been the subject of much controversy. There is substantial uncertainty as to how the biota will respond to changes in flow management (National Research Council, 2002). This dissertation utilized a long term biological monitoring database to explore via statistical modeling how three different Missouri River biota have historically responded to discharge, temperature, and turbidity.

The first component of the biota studied was drifting aquatic macroinvertebrates. Colonizing species were prevelant in the river reach below Fort Randall Dam and the results indicated that their density in the drift is related to recolonization after high flows. Results below Gavins Point Dam suggest that aquatic macroinvertebrate densities in the drift increase in response to reduced food and habitat availibility. Greater drift densities in the unchannelizd reach below Gavins Point Dam were related to reduced discharge out of Gavins Point Dam, which dewaters productive backwater habitats and discharges less plankton. In the channelized reaches, drift densities increased with reduced turbidity suggesting that drift increases when organic matter transported in the suspended sediment is less. Drift densities were also often related to water temperature.

The results of statistical modeling of larval fish drift presence and densities indicated that water temperature was the most important predictor variable. Greater temperatures or degree days consistently increased the probability of finding larval fish and the resulting drift densities. The results suggested that the occurrence and densities of larval fish in the drift below Fort Randall dam are negatively affected by hypolimnetic releases. Discharge was generally of minor or no importance in predicting larval fish presence and drift density.

The results of the statistical modeling of age 0 and age 1 fish suggest that the hydrologic regime during the historic spring rise/spawning season is important to the recruitment of native cyprinids and catostomids. Fort Randall Dam is operated to generate hydroelectric power, which results in large discharge fluctuations. Greater catch per unit effort in the Fort Randall reach was related to reductions in discharge fluctuations. Below Gavins Point Dam, greater catch per unit effort of cyprinid and catostomid species was generally related to greater, rising spring discharge. The results of this study support the concept that greater spring flows below Gavins Point Dam are important for fish spawning and recruitment.

Several authors have recommended the restoration of more natural discharge, temperature, and turbidity regimes to improve conditions for native species in the Missouri River (Hesse et al., 1989, 1993; Galat et al., 1996; Galat and Lipkin, 2000; National Research Council, 2002). The results of this research generally support these recommendations. Among the recommendations to benefit native species suggested by these results are as follows: 1) adaptive management experimentation of spring discharges from Gavins Point Dam that emulate historic spring rises should be implemented, 2) discharge fluctuations from Fort Randall and Gavins Point Dams should be reduced, 3) Fort Randall releases should be modified to reduce water temperature depressions, and 4) measures to bypass sediment through the reservoirs should be implemented. Greater spring discharge with a greater rate of rise in discharge from Gavins Point Dam should lead to greater recruitment of native fish in the lower Missouri River. Reducing discharge variability from hydropower operations at Fort Randall Dam and fluctuating discharges from Gavins Point Dam would stabilize habitat availability in these unchannelized reaches. Discharge modifications to reduce temperature depressions of Fort Randall Dam releases would help mitigate delays in spawning and reduced fish and macroinvertebrate densities. Finally, increased sediment transport from sediment bypass would increase organic matter transport to benefit macroinvertebrates, increase energy flow, and benefit turbid-river fishes in their competitive interactions with sight-feeding fishes. In addition, moving sediment that is accumulating in the reservoirs would reduce channel degradation, extend the life of the reservoirs, and reduce flooding concerns from delta formation in the reservoir headwaters.

The results of these studies are important to Missouri River ecology, and large river ecology in general, because they further elucidate linkages between biotic relationships to abiotic factors in large rivers. This dissertation presents predictive models for aquatic macroinvertebrates, larval fish, and age-0 and age-1 fish that can be tested, expanded, and validated through adaptive management experimentation of Missouri River reservoir operations. The results also add to the weight of evidence that restoration of more natural discharge, temperature, and turbidity regimes would benefit native species in the Missouri River.

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Appendix A

Supporting data and results for aquatic macroinvertebrate models

A.1 Model input data

Table A.1. **Fort Randall Reach – Aquatic Macroinvertebrates:** Summary of aquatic macroinvertebrate drift density by year, day of year, and site where n is the number of samples followed by the pooled drift densities (no. of individuals per $100\,m^3$).

		FR1		FR2		FR3		FR4	
Year	Day	n	Density	n	Density	n	Density	n	Density
1983	165	1	41.67	—	—	1	46.94	—	—
1983	166	—	—	—	—	—	—	1	3.51
1983	173	—	—	—	—	1	2.91	—	—
1984	123	—	—	—	—	—	—	1	1.18
1984	136	—	—	—	—	—	—	1	2.31
1984	143	—	—	—	—	—	—	1	1.49
1984	144	1	2.91	—	—	1	2.83	—	—
1984	156	1	4.70	—	—	2	9.01	—	—
1984	157	—	—	—	—	—	—	1	1.12
1984	164	—	—	—	—	—	—	1	35.51
1985	133	—	—	—	—	1	4.54	—	—
1985	136	—	—	—	—	5	6.58	—	—
1985	143	—	—	—	—	1	5.85	—	—
1985	154	—	—	—	—	1	2.95	—	—
1985	155	1	0.94	—	—	—	—	—	—
1985	157	—	—	—	—	7	2.04	—	—
1985	162	—	—	—	—	1	4.85	—	—
1985	175	—	—	—	—	1	2.18	—	—
1985	178	—	—	—	—	6	14.05	—	—
1986	125	—	—	—	—	2	4.21	—	—
1988	144	1	37.15	—	—	—	—	—	—
1988	153	—	—	—	—	1	53.56	—	—
1988	158	—	—	—	—	1	25.48	—	—
1989	141	1	6.88	—	—	—	—	—	—
1989	151	—	—	—	—	1	58.54	—	—
1990	134	—	—	—	—	16	1.44	8	0.32
1990	141	—	—	—	—	14	0.66	8	0.08
1990	149	—	—	—	—	14	1.91	8	0.00
1990	162	—	—	—	—	14	1.24	—	—
1990	169	—	—	—	—	14	5.51	8	0.00
1991	144	—	—	—	—	20	18.45	—	—
1991	148	—	—	—	—	20	12.71	—	—
1991	151	—	—	—	—	20	38.04	—	—
1991	154	—	—	—	—	19	23.95	—	—

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Table A.1. *continued.*

Year	Day	FR1 n	FR1 Density	FR2 n	FR2 Density	FR3 n	FR3 Density	FR4 n	FR4 Density
1991	158	—	—	12	1.45	14	13.32	—	—
1991	162	—	—	8	4.29	18	64.32	—	—
1991	164	—	—	8	1.99	16	11.47	—	—
1991	168	—	—	8	3.08	14	2.79	—	—
1991	175	—	—	8	2.98	14	6.98	—	—
1993	124	—	—	—	—	4	0.50	—	—
1993	131	—	—	—	—	4	1.08	—	—
1993	145	—	—	—	—	4	7.28	—	—
1993	158	—	—	—	—	2	20.99	—	—
1993	165	—	—	—	—	4	20.37	—	—
1993	173	—	—	—	—	1	17.03	—	—
1993	180	—	—	—	—	2	5.73	—	—
1998	125	—	—	—	—	3	9.56	—	—
1998	138	—	—	—	—	3	23.76	—	—
1998	152	3	14.43	—	—	3	17.05	—	—
1998	168	3	10.09	—	—	3	36.54	—	—
1998	177	3	9.04	—	—	3	55.98	—	—
1999	125	—	—	—	—	4	24.26	—	—
1999	132	5	31.02	—	—	5	33.65	—	—
1999	153	—	—	—	—	4	86.65	—	—
1999	168	4	125.91	—	—	3	51.29	—	—
1999	180	2	37.00	—	—	4	62.97	—	—
2000	123	2	9.43	2	7.71	5	7.90	—	—
2000	136	—	—	4	17.33	4	31.00	—	—
2000	151	2	11.40	2	12.70	5	36.17	—	—
2000	164	6	10.18	—	—	4	29.56	—	—
2000	177	4	21.67	—	—	—	—	—	—
2000	178	—	—	—	—	5	62.70	—	—
2001	138	—	—	4	1.81	6	1.19	—	—
2001	149	—	—	4	16.52	4	3.26	—	—
2001	162	—	—	6	3.04	6	3.03	—	—
2001	176	3	25.34	4	7.07	4	6.34	—	—
2002	123	—	—	6	0.85	6	1.22	—	—
2002	136	—	—	4	3.11	5	4.52	—	—
2002	148	—	—	4	21.84	6	17.57	—	—
2002	164	—	—	4	12.32	4	14.84	—	—
2002	175	—	—	4	6.55	4	9.53	—	—

Table A.2. **Fort Randall Reach – Predictors:** Summary of predictor variable data corresponding to macroinvertebrate sampling days.

Year	Day	Disch. (m^3s^{-1})	Change in disch. (m^3s^{-1})	Days since reversal (d)	Days since low flow (d)	Days since high flow (d)	Temp. (°C)	Degree days (°C)
1983	165	470	-130	3	38	4	12.8	606
1983	166	413	-57	4	39	5	10.0	616
1983	173	147	-9	2	0	12	12.2	705
1984	123	294	-46	2	0	149	5.0	273
1984	136	368	-14	1	6	162	6.7	345
1984	143	535	85	1	13	169	8.3	394
1984	144	521	-14	0	14	170	7.8	401
1984	156	748	80	3	4	0	11.1	522
1984	157	654	-94	0	5	1	11.1	534
1984	164	241	-155	0	0	8	11.1	601
1985	133	640	-113	0	14	1	11.1	472
1985	136	490	-14	3	17	4	11.7	506
1985	143	776	6	2	24	0	13.3	592
1985	154	787	-29	0	35	0	18.3	756
1985	155	736	-51	1	36	0	15.6	772
1985	157	790	91	0	38	0	15.6	802
1985	162	776	-25	0	43	0	17.2	885
1985	175	827	6	4	56	0	17.3	1100
1985	178	753	-60	1	59	0	18.3	1155
1986	125	459	74	0	4	154	7.8	351
1988	144	648	-108	1	71	1	12.8	486
1988	153	759	40	6	80	0	13.3	604
1988	158	784	28	1	85	0	13.9	676
1989	141	739	-14	5	58	0	11.1	480
1989	151	770	-37	0	68	0	14.4	618
1990	134	753	22	1	51	0	10.0	536
1990	141	552	-60	0	58	7	10.0	607
1990	149	685	226	0	66	6	11.7	694
1990	162	629	-76	0	79	4	13.9	862
1990	169	445	40	0	86	5	13.3	963
1991	144	544	-232	0	61	1	10.0	447
1991	148	552	-17	1	65	2	20.6	502
1991	151	422	-65	1	68	2	16.7	552
1991	154	544	156	0	71	5	17.2	603
1991	158	408	-113	0	75	9	18.3	675
1991	162	677	213	1	79	13	18.9	749
1991	164	498	-9	1	81	15	18.3	787

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Table A.2. *continued.*

Year	Day	Disch. (m^3s^{-1})	Change in disch. (m^3s^{-1})	Days since reversal (d)	Days since low flow (d)	Days since high flow (d)	Temp. (°C)	Degree days (°C)
1991	168	663	201	1	85	19	20.0	866
1991	175	501	-198	0	92	26	22.2	1021
1993	124	266	-45	3	0	209	5.6	318
1993	131	85	-23	2	0	216	7.2	366
1993	145	241	-3	1	0	2	8.3	487
1993	158	736	535	1	1	0	11.1	616
1993	165	263	-473	0	0	1	12.2	694
1993	173	229	5	0	0	3	11.7	795
1993	180	193	-487	0	0	10	12.2	890
1998	125	606	-23	0	706	62	8.9	294
1998	138	790	65	1	719	0	8.9	419
1998	152	759	6	0	733	0	11.1	572
1998	168	464	8	1	749	9	12.2	781
1998	177	651	5	6	758	18	14.4	912
1999	125	479	-260	0	13	1	8.3	421
1999	132	583	45	4	20	8	9.4	475
1999	153	765	-116	1	41	0	13.3	734
1999	168	722	-94	1	56	0	13.3	960
1999	180	558	-51	3	68	2	18.9	1169
2000	123	773	23	1	64	0	9.4	459
2000	136	1000	51	2	77	0	12.8	605
2000	151	869	19	1	92	0	15.0	817
2000	164	892	3	0	105	0	16.1	1030
2000	177	903	3	0	118	0	20.6	1274
2000	178	852	-51	0	119	0	20.0	1294
2001	138	396	17	2	3	175	6.7	273
2001	149	490	-6	1	14	186	10.0	385
2001	162	544	-3	0	27	199	11.1	526
2001	176	513	-11	0	41	213	12.2	697
2002	123	521	-34	3	48	25	7.8	232
2002	136	481	25	1	61	38	8.9	339
2002	148	685	28	1	73	50	11.1	464
2002	164	671	-9	0	89	66	16.1	664
2002	175	711	23	1	100	0	15.6	836

Table A.3. **Gavins Point Reach – Aquatic Macroinvertebrates:** Summary of aquatic macroinvertebrate drift density by year, day of year, and site where n is the number of samples followed by the pooled drift densities (no. of individuals per 100 m^3).

		GP1		GP2		GP3		GP4		GP5	
Year	Day	n	Density	n	Density	n	Density	n	Density	n	Density
1983	166	1	9.21	1	38.46	1	1.47	—	—	1	5.88
1983	173	1	154.55	1	56.48	—	—	—	—	1	0.93
1983	178	—	—	—	—	7	244.55	—	—	—	—
1983	179	—	—	—	—	5	184.48	—	—	—	—
1983	180	—	—	—	—	12	115.65	—	—	—	—
1984	122	—	—	1	24.44	1	4.02	—	—	—	—
1984	123	1	3.96	1	2.15	—	—	—	—	—	—
1984	136	2	2.10	—	—	—	—	—	—	—	—
1984	137	—	—	1	5.68	1	18.64	—	—	—	—
1984	142	—	—	2	60.08	1	11.70	—	—	—	—
1984	143	1	2.37	—	—	—	—	—	—	—	—
1984	157	1	1.25	1	6.60	1	8.44	—	—	—	—
1984	158	—	—	—	—	—	—	—	—	1	1.26
1984	163	—	—	2	79.20	1	22.83	—	—	—	—
1984	164	1	41.72	—	—	—	—	—	—	—	—
1984	170	3	132.43	—	—	—	—	—	—	—	—
1984	171	9	79.01	—	—	—	—	—	—	—	—
1984	172	—	—	—	—	—	—	—	—	5	86.92
1984	173	—	—	—	—	—	—	—	—	7	119.30
1984	179	—	—	1	12.56	1	18.57	—	—	1	23.11
1985	123	1	6.59	1	2.11	1	6.86	—	—	1	9.34
1985	134	1	4.74	—	—	—	—	—	—	—	—
1985	135	—	—	1	26.22	—	—	—	—	—	—
1985	140	—	—	1	13.43	—	—	—	—	—	—
1985	143	1	3.42	—	—	1	53.84	—	—	1	10.47
1985	155	1	1.57	—	—	—	—	—	—	—	—
1985	156	—	—	1	33.37	1	3.51	—	—	1	6.65
1985	161	—	—	1	27.52	—	—	—	—	—	—
1985	162	1	2.20	—	—	1	13.01	—	—	1	7.84
1985	168	3	43.33	—	—	—	—	—	—	—	—
1985	169	9	29.38	—	—	—	—	—	—	1	3.57
1985	170	—	—	—	—	—	—	—	—	2	24.29
1985	171	—	—	—	—	—	—	—	—	9	16.12
1985	176	1	2.63	—	—	—	—	—	—	—	—
1985	177	—	—	1	26.26	1	7.45	—	—	—	—
1986	177	—	—	—	—	15	6.87	—	—	—	—
1988	144	1	27.50	—	—	1	58.42	—	—	1	95.54
1988	152	—	—	3	119.17	—	—	—	—	—	—
1988	158	1	76.90	—	—	—	—	—	—	—	—
1988	159	—	—	1	158.33	—	—	—	—	—	—
1988	172	1	80.44	1	41.50	—	—	—	—	1	128.34
1989	151	—	—	—	—	—	—	—	—	1	81.82
1989	164	—	—	—	—	—	—	—	—	1	52.09
1989	165	—	—	1	89.63	—	—	—	—	—	—

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Table A.3. *continued.*

Year	Day	GP1 n	GP1 Density	GP2 n	GP2 Density	GP3 n	GP3 Density	GP4 n	GP4 Density	GP5 n	GP5 Density
1990	130	—	—	14	7.06	—	—	—	—	—	—
1990	134	14	0.89	—	—	—	—	—	—	—	—
1990	135	—	—	14	4.83	14	0.00	—	—	14	0.00
1990	141	14	1.37	—	—	—	—	—	—	—	—
1990	149	14	0.66	—	—	—	—	—	—	—	—
1990	150	—	—	14	13.65	14	0.00	—	—	—	—
1990	162	14	0.00	14	5.60	—	—	—	—	—	—
1990	163	—	—	—	—	14	0.00	—	—	14	0.00
1990	169	14	0.00	13	3.50	—	—	—	—	—	—
1991	144	—	—	18	16.25	—	—	—	—	—	—
1991	148	—	—	20	12.59	—	—	—	—	20	18.67
1991	151	10	15.32	—	—	—	—	—	—	—	—
1991	154	—	—	20	19.09	—	—	—	—	20	11.09
1991	162	—	—	10	11.35	—	—	—	—	—	—
1991	163	—	—	—	—	—	—	—	—	14	8.25
1991	168	8	12.04	10	3.52	—	—	—	—	—	—
1993	124	—	—	—	—	—	—	—	—	4	6.96
1993	131	—	—	—	—	—	—	—	—	4	1.46
1993	145	—	—	—	—	—	—	—	—	4	0.65
1993	158	—	—	—	—	—	—	—	—	4	6.77
1993	165	—	—	—	—	—	—	—	—	2	13.42
1993	180	—	—	—	—	—	—	—	—	2	7.63
1998	125	—	—	3	7.94	—	—	—	—	—	—
1998	138	—	—	3	36.84	—	—	—	—	—	—
1998	152	—	—	3	20.19	—	—	—	—	3	16.82
1998	167	—	—	3	70.91	—	—	—	—	3	92.57
1998	177	—	—	3	64.02	—	—	—	—	3	45.02
1999	123	—	—	—	—	—	—	—	—	4	34.75
1999	125	—	—	1	20.18	—	—	—	—	—	—
1999	133	—	—	4	50.94	—	—	—	—	4	51.06
1999	153	—	—	4	92.41	—	—	—	—	—	—
1999	167	—	—	4	108.28	—	—	—	—	—	—
1999	168	—	—	—	—	—	—	—	—	4	40.88
1999	180	—	—	4	94.07	—	—	—	—	—	—
1999	181	—	—	—	—	—	—	—	—	6	117.19
2000	123	—	—	4	43.91	—	—	—	—	—	—
2000	124	—	—	—	—	—	—	2	40.85	—	—
2000	136	—	—	4	49.47	—	—	—	—	5	42.10
2000	152	—	—	4	84.63	—	—	—	—	4	65.87
2000	164	—	—	5	135.93	—	—	—	—	6	29.25
2000	179	—	—	4	111.36	—	—	—	—	—	—
2000	180	—	—	—	—	—	—	—	—	4	50.89
2001	122	—	—	—	—	—	—	—	—	6	12.74
2001	137	—	—	—	—	—	—	—	—	6	28.84
2001	138	—	—	6	52.02	—	—	—	—	—	—
2001	149	—	—	4	97.34	—	—	—	—	—	—

continued on next page

Table A.3. *continued.*

		GP1		GP2		GP3		GP4		GP5	
Year	Day	n	Density	n	Density	n	Density	n	Density	n	Density
2001	151	—	—	—	—	—	—	—	—	6	40.16
2001	162	—	—	6	54.59	—	—	—	—	—	—
2001	164	—	—	—	—	—	—	6	30.29	—	—
2001	176	—	—	4	82.89	—	—	5	36.64	—	—
2001	178	—	—	—	—	—	—	—	—	4	25.48
2002	122	—	—	—	—	—	—	4	3.96	—	—
2002	135	—	—	—	—	—	—	6	24.14	—	—
2002	136	—	—	6	26.07	—	—	—	—	—	—
2002	148	—	—	6	65.11	—	—	—	—	—	—
2002	149	—	—	—	—	—	—	6	18.08	—	—
2002	161	—	—	4	35.71	—	—	4	15.98	—	—
2002	176	—	—	4	24.34	—	—	5	17.12	—	—

Table A.4. **Gavins Point Reach – Predictors:** Summary of predictor variable data corresponding to macroinvertebrate sampling days.

Year	Day	Disch. (m^3s^{-1})	Change in disch. (m^3s^{-1})	Days since reversal (d)	Days since low flow (d)	Days since high flow (d)	Temp. (°C)	Degree days (°C)	Turb. (NTU)
1983	166	566	-74	5	58	2	19.4	1084	115
1983	167	566	0	6	59	3	19.4	1103	115
1983	173	170	-91	4	0	9	21.1	1220	115
1983	178	340	-28	0	0	14	20.0	1330	115
1983	179	215	-125	1	0	15	22.2	1352	115
1983	180	170	-45	2	0	16	22.8	1375	115
1984	122	510	-25	1	303	38	10.0	368	70
1984	123	510	0	2	304	39	10.0	378	70
1984	136	425	-56	1	317	52	13.9	522	70
1984	137	538	113	0	318	53	15.0	537	70
1984	142	595	0	5	323	58	18.3	624	70
1984	143	595	0	6	324	59	18.3	643	70
1984	157	765	0	6	338	0	18.9	886	315
1984	158	722	-43	0	339	0	20.0	906	315
1984	163	510	57	0	344	5	19.4	1003	315
1984	164	428	-82	0	345	6	19.4	1023	315
1984	170	453	-11	0	5	12	22.8	1145	315
1984	171	411	-42	1	6	13	22.8	1168	315
1984	172	368	-43	2	7	14	22.2	1190	315
1984	173	385	17	0	8	15	22.8	1213	315
1984	179	340	57	0	0	21	26.1	1355	315
1985	123	651	14	4	5	11	15.0	544	113
1985	134	784	-34	1	16	0	17.2	731	113
1985	135	731	-53	2	17	0	17.2	748	113
1985	140	779	14	3	22	0	15.6	825	113
1985	143	821	28	6	25	0	18.3	876	113
1985	155	779	-42	1	37	0	17.8	1108	70
1985	156	793	14	0	38	0	17.2	1125	70
1985	161	850	0	5	43	0	19.4	1225	70
1985	162	850	0	6	44	0	20.0	1245	70
1985	168	850	-14	1	50	0	20.0	1360	70
1985	169	864	14	0	51	0	18.9	1379	70
1985	170	864	0	1	52	0	18.9	1397	70
1985	171	878	14	2	53	0	19.4	1417	70
1985	176	878	0	7	58	0	21.7	1520	70
1985	177	878	0	8	59	0	21.7	1541	70
1988	144	878	-5	1	1121	0	17.8	790	45
1988	152	878	0	6	1129	0	21.1	949	65
1988	158	878	0	12	1135	0	22.8	1085	65
1988	159	878	0	13	1136	0	22.8	1108	65
1988	172	906	0	1	1149	0	23.9	1404	65
1989	151	906	28	0	69	0	17.2	1020	77
1989	164	878	-17	2	82	0	18.9	1269	31

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Table A.4. *continued.*

Year	Day	Disch. (m^3s^{-1})	Change in disch. (m^3s^{-1})	Days since reversal (d)	Days since low flow (d)	Days since high flow (d)	Temp. (°C)	Degree days (°C)	Turb. (NTU)
1989	165	903	25	0	83	0	18.3	1287	31
1990	130	654	-48	9	47	2	14.4	668	309
1990	134	694	3	0	51	2	12.8	722	309
1990	135	850	156	1	52	0	13.3	735	309
1990	141	852	257	0	58	0	13.3	814	309
1990	149	665	5	0	66	2	17.2	944	309
1990	150	850	185	1	67	0	18.3	963	309
1990	162	850	170	0	79	0	20.6	1186	385
1990	163	680	-170	0	80	1	21.7	1208	385
1990	169	651	-3	0	86	4	22.2	1343	385
1991	144	821	170	1	61	0	19.4	891	123
1991	148	651	-170	0	65	1	21.7	973	123
1991	151	651	-133	0	68	1	20.6	1036	123
1991	154	688	-20	0	71	4	21.1	1100	369
1991	162	597	2	0	79	2	22.8	1274	369
1991	163	779	182	1	80	0	22.8	1297	369
1991	168	580	0	1	85	2	23.3	1412	369
1993	124	467	-29	2	12	207	12.2	362	122
1993	131	340	-31	2	0	214	14.4	460	122
1993	145	425	-232	0	12	228	17.8	696	122
1993	158	425	0	1	25	241	17.2	920	160
1993	165	651	226	0	32	248	20.0	1048	160
1993	180	425	0	2	47	263	22.2	1366	160
1998	125	736	0	5	1099	0	14.4	452	106
1998	138	906	56	18	1112	0	19.4	661	106
1998	152	906	0	7	1126	0	19.4	914	275
1998	167	623	-23	4	1141	2	18.3	1166	275
1998	177	850	77	3	1151	0	23.9	1382	275
1999	123	821	28	3	1462	0	12.2	490	81
1999	125	776	-45	0	1464	0	13.3	517	81
1999	133	736	0	2	1472	0	13.9	619	81
1999	153	915	-113	1	1492	0	17.8	941	175
1999	167	963	113	0	1506	0	18.9	1223	175
1999	168	1028	65	1	1507	0	18.3	1241	175
1999	180	881	-28	2	1519	0	21.7	1478	175
1999	181	966	85	0	1520	0	21.1	1499	175
2000	123	807	0	21	1827	0	12.8	560	57
2000	124	807	0	22	1828	0	13.3	574	57
2000	136	943	-17	0	1840	0	14.4	765	57
2000	152	963	0	8	1856	0	16.7	1021	71
2000	164	963	0	3	1868	0	21.7	1249	71
2000	179	934	0	3	1883	0	22.2	1557	71
2000	180	934	0	4	1884	0	22.2	1579	71
2001	122	453	0	9	5	158	15.0	282	114

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Table A.4. *continued.*

Year	Day	Disch. (m^3s^{-1})	Change in disch. (m^3s^{-1})	Days since reversal (d)	Days since low flow (d)	Days since high flow (d)	Temp. (°C)	Degree days (°C)	Turb. (NTU)
2001	137	453	0	8	20	173	18.9	523	114
2001	138	453	0	9	21	174	19.4	542	114
2001	149	538	0	20	32	185	13.9	718	114
2001	151	538	0	22	34	187	15.0	747	114
2001	162	609	0	33	45	198	18.9	937	163
2001	164	609	-14	0	47	200	19.4	976	163
2001	176	544	20	4	59	212	22.2	1234	163
2001	178	552	0	6	61	214	22.2	1278	163
2002	122	629	-8	21	370	160	7.2	405	36
2002	135	597	17	0	383	173	12.2	553	36
2002	136	609	12	1	384	174	11.7	565	36
2002	148	688	14	13	396	186	16.7	738	36
2002	149	685	-3	0	397	187	19.4	757	36
2002	161	694	0	11	409	199	20.6	994	78
2002	176	722	6	26	424	0	24.4	1322	78

Table A.5. **Sioux City Reach – Aquatic Macroinvertebrates:** Summary of aquatic macroinvertebrate drift density by year, day of year, and site where n is the number of samples followed by the pooled drift densities (no. of individuals per 100 m^3).

		SC1		SC2		SC3		SC4		SC5	
Year	Day	n	Density	n	Density	n	Density	n	Density	n	Density
1988	145	—	—	1	59.88	1	170.24	1	193.26	—	—
1988	160	—	—	1	204.75	—	—	—	—	—	—
1988	172	1	226.71	—	—	—	—	—	—	—	—
1988	173	—	—	1	417.78	1	331.23	1	413.86	—	—
1989	143	1	46.23	—	—	—	—	—	—	—	—
1989	144	—	—	1	85.64	—	—	1	2.09	—	—
1989	150	—	—	—	—	1	104.34	—	—	—	—
1989	164	1	51.38	—	—	—	—	—	—	—	—
1990	137	14	0.00	14	3.98	14	0.00	—	—	—	—
1990	142	14	0.00	14	9.01	—	—	—	—	—	—
1990	151	14	0.00	14	3.45	—	—	—	—	—	—
1990	163	14	0.00	—	—	—	—	—	—	—	—
1990	165	—	—	14	3.74	14	0.00	—	—	—	—
1990	170	14	0.00	—	—	—	—	—	—	—	—
1990	171	—	—	14	11.55	16	0.00	—	—	—	—
1991	129	1	21.88	—	—	—	—	—	—	—	—
1991	149	19	25.15	20	18.94	—	—	—	—	—	—
1991	157	20	28.27	20	39.78	—	—	—	—	—	—
1991	163	20	25.21	20	39.73	—	—	—	—	—	—
1991	176	17	48.72	12	55.53	—	—	—	—	—	—
1993	125	—	—	—	—	—	—	4	3.80	—	—
1993	131	—	—	—	—	—	—	4	2.35	—	—
1993	147	—	—	—	—	—	—	4	17.81	—	—
1993	159	—	—	—	—	—	—	4	45.18	—	—
1993	167	—	—	—	—	—	—	2	13.24	—	—
1993	180	—	—	—	—	—	—	2	6.43	—	—
1998	126	—	—	3	54.36	—	—	—	—	—	—
1998	127	—	—	—	—	—	—	3	78.05	—	—
1998	140	—	—	3	52.48	—	—	3	54.67	—	—
1998	153	—	—	3	31.98	—	—	—	—	—	—
1998	154	—	—	—	—	—	—	3	42.84	—	—
1998	166	—	—	3	30.77	—	—	3	53.27	—	—
1998	180	—	—	2	91.57	—	—	2	69.38	—	—
1999	123	—	—	1	47.58	—	—	—	—	—	—
1999	126	—	—	—	—	—	—	5	60.37	—	—
1999	137	—	—	—	—	—	—	6	335.88	—	—
1999	138	—	—	6	95.40	—	—	—	—	—	—
1999	153	—	—	6	85.93	—	—	—	—	—	—

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Table A.5. *continued.*

Year	Day	SC1 n	SC1 Density	SC2 n	SC2 Density	SC3 n	SC3 Density	SC4 n	SC4 Density	SC5 n	SC5 Density
1999	159	—	—	—	—	—	—	6	99.01	—	—
1999	169	—	—	4	51.63	—	—	4	52.44	—	—
1999	181	—	—	5	256.64	—	—	6	96.35	—	—
2000	124	—	—	5	152.82	—	—	3	421.25	—	—
2000	136	—	—	6	101.64	—	—	—	—	—	—
2000	137	—	—	—	—	—	—	6	142.81	—	—
2000	151	—	—	—	—	—	—	4	56.11	—	—
2000	152	—	—	6	77.50	—	—	—	—	—	—
2000	165	—	—	6	171.55	—	—	6	190.32	—	—
2000	180	—	—	4	257.14	—	—	6	347.16	—	—
2001	122	—	—	6	47.01	—	—	6	38.79	—	—
2001	123	—	—	—	—	—	—	—	—	6	206.84
2001	134	—	—	6	46.99	—	—	6	50.57	—	—
2001	149	—	—	—	—	—	—	6	52.70	—	—
2001	152	—	—	6	49.66	—	—	—	—	—	—
2001	164	—	—	6	98.09	—	—	6	110.70	—	—
2001	177	—	—	—	—	—	—	—	—	6	42.74
2001	178	—	—	6	83.84	6	87.94	6	93.84	—	—
2002	121	—	—	—	—	—	—	6	65.15	—	—
2002	135	—	—	6	60.31	—	—	6	67.08	—	—
2002	149	—	—	6	33.44	—	—	6	37.39	—	—
2002	162	—	—	6	79.92	—	—	6	68.01	—	—
2002	176	—	—	4	64.49	—	—	4	62.48	—	—
2002	177	—	—	2	159.18	—	—	—	—	—	—

Table A.6. **Sioux City Reach – Predictors:** Summary of predictor variable data corresponding to macroinvertebrate sampling days.

Year	Day	Disch. (m^3s^{-1})	Change in disch. (m^3s^{-1})	Days since reversal (d)	Days since low flow (d)	Days since high flow (d)	Temp. (°C)	Degree days (°C)	Turb. (NTU)
1988	145	886	-20	2	139	0	17.8	808	45
1988	160	898	-11	3	154	0	22.2	1130	65
1988	172	923	-3	1	166	0	23.9	1404	65
1988	173	920	-3	2	167	0	26.1	1430	65
1989	143	920	-3	4	60	0	17.2	872	77
1989	144	912	-8	5	61	0	18.9	891	77
1989	150	855	-34	0	67	0	17.8	1003	77
1989	164	909	-17	0	81	0	18.9	1269	31
1990	137	759	-51	0	52	1	13.3	761	309
1990	142	770	116	0	57	2	13.3	828	309
1990	151	818	102	0	66	0	18.3	981	309
1990	163	796	94	0	78	0	21.7	1208	385
1990	165	694	-71	1	80	2	22.2	1254	385
1990	170	787	-82	0	85	1	23.3	1366	385
1990	171	838	51	0	86	0	23.9	1390	385
1991	129	688	-6	0	44	196	10.0	638	123
1991	149	756	-26	0	64	4	21.1	994	123
1991	157	733	-54	1	72	2	21.7	1164	369
1991	163	705	-74	1	78	2	22.8	1297	369
1991	176	810	111	0	91	0	22.8	1595	369
1993	125	807	11	4	59	0	11.7	374	122
1993	131	1065	105	0	65	0	14.4	460	122
1993	147	773	-110	1	81	1	18.3	732	122
1993	159	895	-167	1	93	0	16.7	936	160
1993	167	816	0	1	101	0	21.1	1088	160
1993	180	1345	-28	0	114	0	22.2	1366	160
1998	126	903	-9	2	838	0	15.6	468	106
1998	127	898	-5	3	839	0	14.4	482	106
1998	140	1022	3	2	852	0	19.4	699	106
1998	153	1022	0	1	865	0	18.9	933	275
1998	154	1028	6	0	866	0	17.8	951	275
1998	166	963	6	0	878	0	18.9	1148	275
1998	180	971	-3	0	892	0	25.6	1458	275
1999	123	1019	8	2	1200	0	12.2	490	81
1999	126	1008	-28	0	1203	0	11.7	529	81
1999	137	1110	54	4	1214	0	15.6	665	81
1999	138	1099	-11	0	1215	0	15.6	680	81
1999	153	1359	-3	0	1230	0	17.8	941	175
1999	159	1297	71	0	1236	0	21.1	1056	175
1999	169	1297	108	1	1246	0	17.8	1259	175
1999	181	1053	-133	1	1258	0	21.1	1499	175
2000	124	886	-3	1	1566	0	13.3	574	57
2000	136	1082	6	0	1578	0	14.4	765	57

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Table A.6. *continued.*

Year	Day	Disch. (m^3s^{-1})	Change in disch. (m^3s^{-1})	Days since reversal (d)	Days since low flow (d)	Days since high flow (d)	Temp. (°C)	Degree days (°C)	Turb. (NTU)
2000	137	1068	-14	0	1579	0	13.9	779	57
2000	151	1042	11	0	1593	0	16.1	1004	57
2000	152	1034	-8	0	1594	0	16.7	1021	71
2000	165	1051	17	0	1607	0	22.2	1271	71
2000	180	1022	5	0	1622	0	22.2	1579	71
2001	122	1396	-37	3	50	0	15.0	282	114
2001	123	1308	-88	4	51	0	14.4	297	114
2001	134	1028	-45	2	62	0	16.7	465	114
2001	149	816	9	0	77	0	13.9	718	114
2001	152	801	-20	1	80	0	16.1	763	163
2001	164	824	14	0	92	0	19.4	976	163
2001	177	787	-12	1	105	1	22.2	1256	163
2001	178	807	20	0	106	0	22.2	1278	163
2002	121	739	8	0	52	28	8.9	397	36
2002	135	697	-25	2	66	42	12.2	553	36
2002	149	773	79	0	80	56	19.4	757	36
2002	162	770	25	0	93	69	21.7	1015	78
2002	176	739	0	4	107	83	24.4	1322	78
2002	177	756	17	0	108	84	25.0	1347	78

Table A.7. **Plattsmouth Reach – Aquatic Macroinvertebrates:** Summary of aquatic macroinvertebrate drift density by year, day of year, and site where n is the number of samples followed by the pooled drift densities (no. of individuals per $100\,m^3$).

		PL1		PL2		PL3	
Year	Day	n	Density	n	Density	n	Density
1988	162	—	—	—	—	1	195.41
1988	174	—	—	1	393.95	—	—
1989	150	—	—	1	119.17	1	53.24
1989	163	—	—	—	—	1	67.28
1993	125	—	—	—	—	4	2.26
1993	131	—	—	—	—	4	12.07
1993	147	—	—	—	—	4	23.43
1993	159	—	—	—	—	2	8.09
1993	167	—	—	—	—	2	13.41
1993	180	—	—	—	—	2	4.85
1998	127	—	—	—	—	3	75.41
1998	140	—	—	—	—	3	55.08
1998	153	—	—	—	—	3	23.63
1998	180	—	—	—	—	3	57.08
1999	126	—	—	—	—	6	53.92
1999	137	—	—	—	—	6	161.89
1999	168	—	—	—	—	6	39.05
1999	181	—	—	—	—	6	222.49
2000	124	—	—	—	—	4	194.70
2000	138	—	—	—	—	1	98.51
2000	139	—	—	—	—	4	139.49
2000	151	—	—	—	—	5	150.40
2000	165	—	—	—	—	6	289.60
2000	180	—	—	—	—	6	683.50
2001	134	—	—	—	—	6	53.49
2001	149	—	—	—	—	6	54.70
2001	165	—	—	—	—	8	100.55
2001	177	5	78.76	6	59.83	6	84.16
2002	121	—	—	6	72.40	6	99.10
2002	134	—	—	6	118.69	8	94.11
2002	150	—	—	6	79.57	6	92.68
2002	162	—	—	6	96.43	—	—
2002	163	—	—	—	—	6	172.48
2002	177	—	—	2	382.96	4	135.85

Table A.8. **Plattsmouth Reach – Predictors:** Summary of predictor variable data corresponding to macroinvertebrate sampling days.

Year	Day	Disch. (m^3s^{-1})	Change in disch. (m^3s^{-1})	Days since reversal (d)	Days since low flow (d)	Days since high flow (d)	Temp. (°C)	Degree days (°C)	Turb. (NTU)
1988	146	1260	-45	1	138	0	17.8	826	45
1988	162	1133	-31	0	154	0	22.2	1174	65
1988	174	988	0	1	166	0	26.1	1456	65
1989	150	1099	68	0	112	0	17.8	1003	77
1989	163	997	-3	2	125	0	19.4	1250	31
1993	125	1271	-3	1	120	0	11.7	374	122
1993	131	1934	252	4	126	0	14.4	460	122
1993	147	1359	73	0	142	0	18.3	732	122
1993	159	1730	79	0	154	0	16.7	936	160
1993	167	1676	-97	1	162	0	21.1	1088	160
1993	180	2257	-79	0	175	0	22.2	1366	160
1998	127	1274	-40	2	837	0	14.4	482	106
1998	140	1325	48	0	850	0	19.4	699	106
1998	153	1472	-20	2	863	0	18.9	933	275
1998	180	1566	-63	3	890	0	25.6	1458	275
1999	126	1574	17	3	1201	0	11.7	529	81
1999	137	1923	71	2	1212	0	15.6	665	81
1999	168	1917	37	1	1243	0	18.3	1241	175
1999	181	2498	-390	0	1256	0	21.1	1499	175
2000	124	1053	0	3	1564	0	13.3	574	57
2000	138	1215	-11	0	1578	0	14.4	793	57
2000	139	1218	3	0	1579	0	15	808	57
2000	151	1294	-9	2	1591	0	16.1	1004	57
2000	165	1172	8	1	1605	0	22.2	1271	71
2000	180	1529	-329	0	1620	0	22.2	1579	71
2001	134	1733	-88	2	143	0	16.7	465	114
2001	149	1243	-31	7	158	0	13.9	718	114
2001	165	1294	122	0	174	0	21.1	997	163
2001	177	1144	-17	6	186	0	22.2	1256	163
2002	121	951	-17	0	88	0	8.9	397	36
2002	134	1119	-59	0	101	0	11.7	541	36
2002	150	1022	5	2	117	0	20	777	36
2002	162	951	25	2	129	0	21.7	1015	78
2002	163	1138	187	3	130	0	22.2	1037	78
2002	177	892	-11	2	144	3	25	1347	78

A.2 Results

Table A.9. **Fort Randall Reach:** Summary of multimodel inference results of aquatic macroinvertebrate drift density. Column two contains the relative variable importances (RVI). Columns three and four are the model averaged parameter estimates conditional on the variable being included in the model and their standard errors. Column five contains the bias corrected model averaged estimates. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, AIC_c values, and Akaike weights (w_i).

Variable	RVI	Conditional Estimate	Std. Error Estimate	Bias Adj. Estimate	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.00	-2.84977	0.63037	-2.84977	-2.95000	-2.57015	-1.88838	-3.40506	-2.99022
Year	1.00	0.00000	0.98726	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Site	1.00	0.00000	0.29646	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Discharge	0.28	0.00052	0.00073	0.00014	—	—	—	—	—
Change in discharge	0.25	-0.00016	0.00075	-0.00004	—	—	—	—	—
Days since reversal	0.24	-0.03199	0.06382	-0.00759	—	—	—	—	—
Days since low flow	0.27	0.00082	0.00126	0.00022	—	—	—	—	0.00075
Days since high flow	0.74	-0.00634	0.00206	-0.00469	-0.00599	-0.00638	-0.00747	—	-0.00592
Temperature	0.56	0.08081	0.03866	0.04496	0.08036	—	—	0.10093	0.07769
Degree days	0.41	0.00080	0.00063	0.00032	—	0.00101	—	—	—
No. Variables					2	2	1	1	3
AIC_c					98.53	99.24	100.02	100.30	100.59
w_i					0.09	0.07	0.04	0.04	0.03

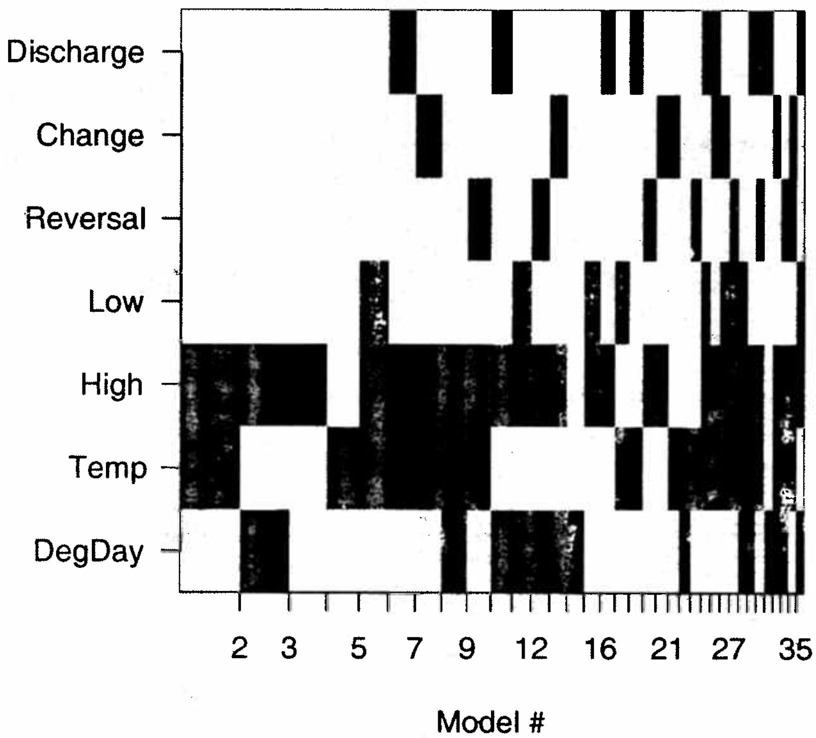

Figure A.1. **Fort Randall Reach:** Visual summary of multi-model inference. Rows correspond to the predictor variables. Columns correspond to the subset of models whose Akaike weights sum to at least 0.75. For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's Akaike weight.

Table A.10. **Gavins Point Reach:** Summary of multimodel inference results of aquatic macroinvertebrate drift density. Column two contains the relative variable importances (RVI). Columns three and four are the model averaged parameter estimates conditional on the variable being included in the model and their standard errors. Column five contains the bias corrected model averaged estimates. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, AIC_c values, and Akaike weights (w_i).

Variable	RVI	Conditional Estimate	Std. Error Estimate	Bias Adj. Estimate	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.00	-1.48305	0.76218	-1.48305	-1.36137	-1.21288	-1.24497	-1.04730	-1.55768
Year	1.00	0.00000	0.95777	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Site	1.00	0.00000	0.27538	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Discharge	0.85	-0.00228	0.00076	-0.00193	-0.00221	-0.00238	-0.00177	-0.00271	-0.00219
Change in discharge	0.30	0.00151	0.00123	0.00046	—	—	—	0.00163	—
Days since reversal	0.24	-0.00054	0.01478	-0.00013	—	—	—	—	—
Days since low flow	0.67	0.00078	0.00039	0.00052	0.00078	0.00083	—	0.00084	0.00079
Days since high flow	0.25	-0.00058	0.00232	-0.00015	—	—	—	—	—
Temperature	0.36	0.04757	0.04900	0.01698	—	—	—	—	0.01871
Degree days	0.86	0.00114	0.00032	0.00099	0.00118	0.00134	0.00112	0.00117	0.00101
Turbidity	0.37	-0.00118	0.00124	-0.00043	—	-0.00138	—	—	—
No. variables					3	4	2	4	4
AIC_c					148.41	149.11	150.02	150.03	150.57
w_i					0.09	0.06	0.04	0.04	0.03

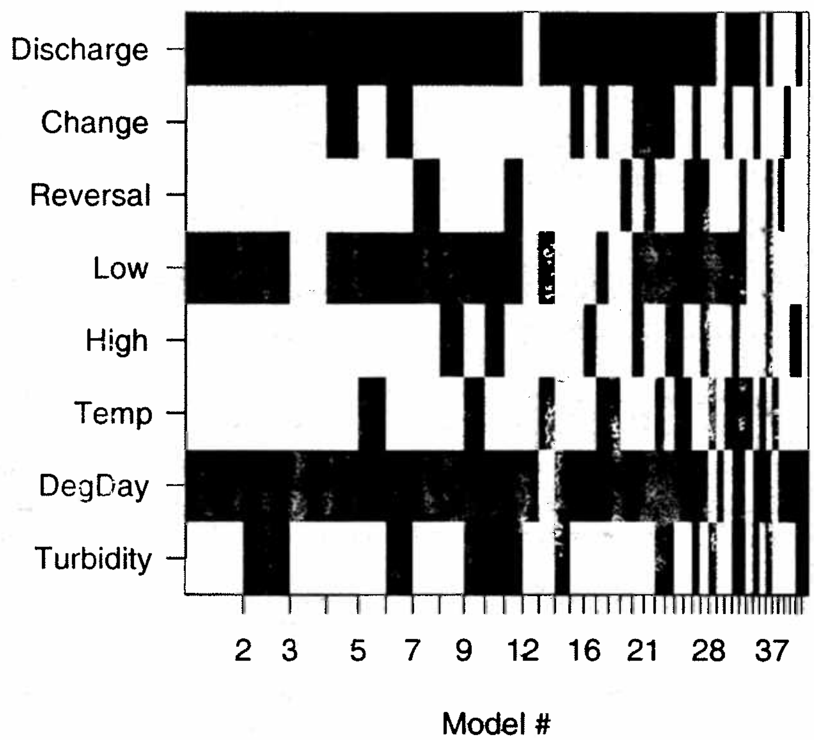

Figure A.2. **Gavins Point Reach:** Visual summary of multi-model inference. Rows correspond to the predictor variables. Columns correspond to the subset of models whose Akaike weights sum to at least 0.75. For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's Akaike weight.

Table A.11. **Sioux City Reach:** Summary of multimodel inference results of aquatic macroinvertebrate drift density. Column two contains the relative variable importances (RVI). Columns three and four are the model averaged parameter estimates conditional on the variable being included in the model and their standard errors. Column five contains the bias corrected model averaged estimates. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, AIC$_c$ values, and Akaike weights (w_i).

Variable	RVI	Conditional Estimate	Std. Error Estimate	Bias Adj. Estimate	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.00	-1.10177	0.61644	-1.10177	-0.90645	-1.18179	-1.08962	-1.14101	-1.24475
Year	1.00	0.00000	1.52614	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Site	1.00	0.00000	0.51690	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Discharge	0.25	-0.00035	0.00062	-0.00009	—	—	—	—	—
Change in discharge	0.26	-0.00117	0.00133	-0.00031	—	—	—	—	—
Days since reversal	0.25	0.06892	0.06866	0.01750	—	—	—	—	—
Days since low flow	0.45	0.00092	0.00059	0.00041	—	0.00075	—	0.00109	—
Days since high flow	0.25	-0.00068	0.00375	-0.00017	—	—	—	—	—
Temperature	0.37	0.02577	0.03366	0.00954	—	—	—	—	0.04897
Degreee days	0.58	0.00067	0.00036	0.00039	0.00076	0.00072	0.00042	—	—
Turbidity	0.56	-0.00299	0.00174	-0.00169	-0.00341	-0.00344	—	—	-0.00235
No. variables					2	3	1	1	2
AIC$_c$					82.32	83.13	83.70	84.05	84.27
w_i					0.06	0.04	0.03	0.02	0.02

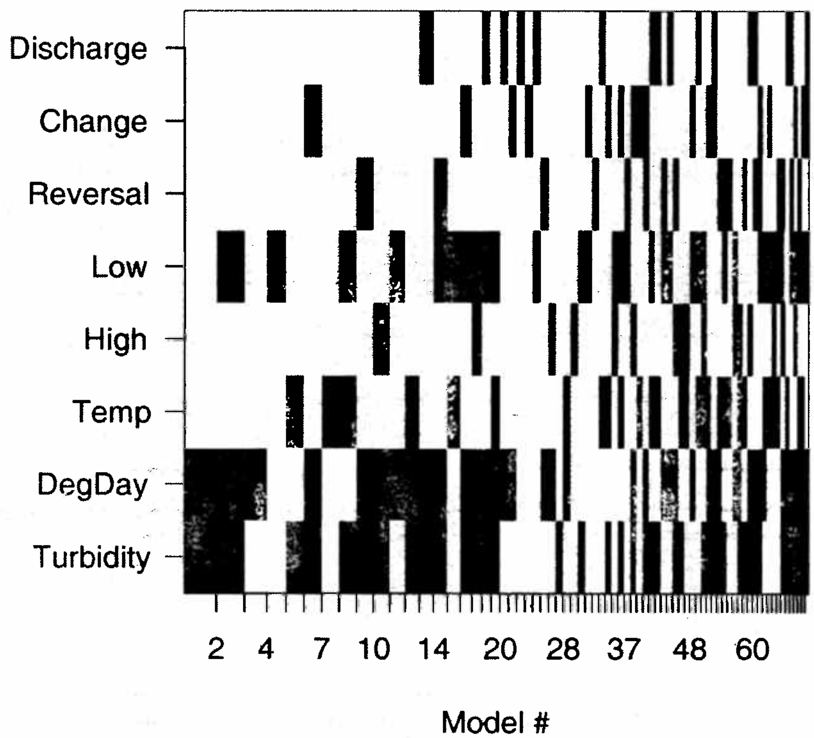

Figure A.3. **Sioux City Reach:** Visual summary of multi-model inference. Rows correspond to the predictor variables. Columns correspond to the subset of models whose Akaike weights sum to at least 0.75. For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's Akaike weight.

Table A.12. **Plattsmouth Reach:** Summary of multimodel inference results of aquatic macroinvertebrate drift density. Column two contains the relative variable importances (RVI). Columns three and four are the model averaged parameter estimates conditional on the variable being included in the model and their standard errors. Column five contains the bias corrected model averaged estimates. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, AIC_c values, and Akaike weights (w_i).

Variable	RVI	Conditional Estimate	Std. Error Estimate	Bias Adj. Estimate	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.00	-0.66978	0.62633	-0.66978	-0.47686	-0.72803	-0.48187	-1.39398	-1.08259
Year	1.00	0.00000	1.48076	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Site	1.00	0.00000	0.11062	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Discharge	0.19	0.00004	0.00045	0.00001	—	—	—	—	—
Change in discharge	0.24	-0.00105	0.00098	-0.00025	—	—	—	—	—
Days since reversal	0.19	-0.02787	0.05857	-0.00525	—	—	—	—	—
Days since low flow	0.41	0.00067	0.00049	0.00027	—	0.00058	0.00079	0.00075	—
Days since high flow	0.16	0.21322	0.16473	0.03438	—	—	—	—	—
Temperature	0.32	0.07058	0.03129	0.02263	—	—	—	0.09058	0.08971
Degree days	0.42	0.00101	0.00047	0.00042	0.00131	0.00129	—	—	—
Turbidity	0.56	-0.00696	0.00341	-0.00391	-0.00868	-0.00898	—	-0.00755	-0.00671
No. variables					2	3	1	3	2
AIC_c					43.49	44.07	44.45	44.46	45.03
w_i					0.07	0.05	0.04	0.04	0.03

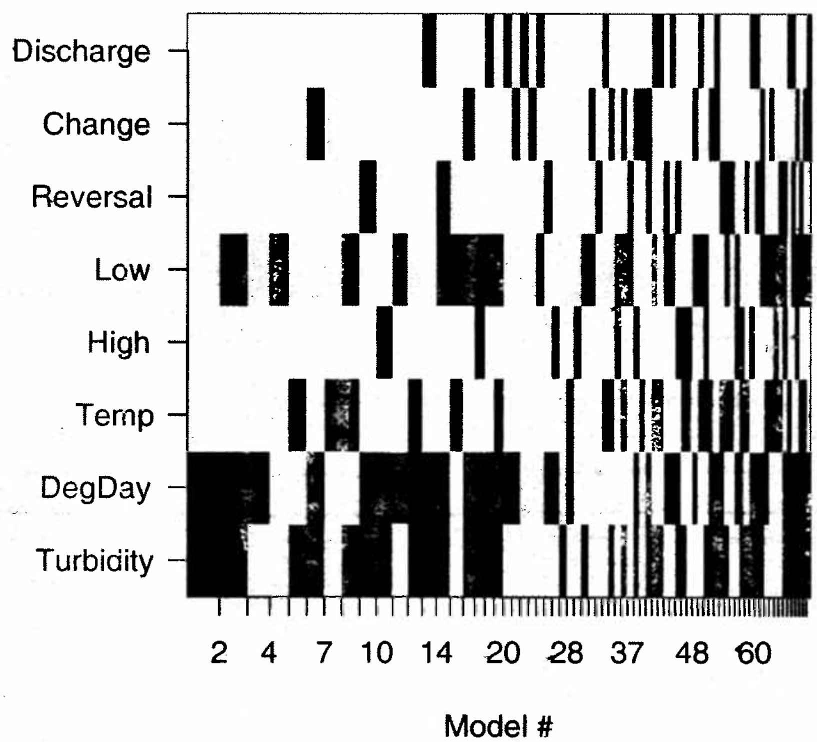

Figure A.4. **Plattsmouth Reach:** Visual summary of multi-model inference. Rows correspond to the predictor variables. Columns correspond to the subset of models whose Akaike weights sum to at least 0.75. For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's Akaike weight.

Appendix B

Supporting data and results for larval fish models

B.1 Model input data

Table B.1. **Fort Randall Reach – Freshwater Drum:** Summary of the number of samples (n), number of samples in which larval fish were present (P, %) and mean larval drift density (D, no. of individuals per 100 m^3) by year and month.

		FR1			FR2			FR3			FR4		
Year	Month	n	P	D	n	P	D	n	P	D	n	P	D
1983	6	1	0	0.00	—	—	—	2	0	0.00	1	0	0.00
1984	5	1	0	0.00	—	—	—	1	0	0.00	3	0	0.00
1984	6	1	0	0.00	—	—	—	2	0	0.00	2	0	0.00
1985	5	—	—	—	—	—	—	6	0	0.00	—	—	—
1985	6	—	—	—	—	—	—	17	0	0.00	—	—	—
1986	5	1	0	0.00	—	—	—	4	0	0.00	—	—	—
1987	5	2	1	0.08	—	—	—	2	0	0.00	—	—	—
1987	6	1	0	0.00	—	—	—	1	0	0.00	—	—	—
1990	6	—	—	—	—	—	—	—	—	—	3	3	2.26
1991	5	—	—	—	—	—	—	60	3	0.06	—	—	—
1991	6	—	—	—	44	4	0.14	95	3	0.04	—	—	—
1993	5	—	—	—	—	—	—	12	0	0.00	—	—	—
1993	6	—	—	—	—	—	—	9	2	7.45	—	—	—
1998	5	—	—	—	—	—	—	6	0	0.00	—	—	—
1998	6	9	1	0.03	—	—	—	9	3	0.28	—	—	—
1999	5	6	0	0.00	—	—	—	10	0	0.00	—	—	—
1999	6	6	2	0.25	—	—	—	12	2	0.29	—	—	—
2000	5	4	0	0.00	8	0	0.00	14	1	0.19	—	—	—
2000	6	10	4	0.46	—	—	—	9	4	0.29	—	—	—
2001	5	—	—	—	8	0	0.00	10	0	0.00	—	—	—
2001	6	3	1	0.67	10	0	0.00	10	2	0.10	—	—	—
2002	5	—	—	—	14	0	0.00	16	0	0.00	—	—	—
2002	6	—	—	—	8	1	0.06	8	1	0.14	—	—	—
2003	5	—	—	—	8	0	0.00	12	0	0.00	—	—	—
2003	6	—	—	—	8	1	0.04	10	0	0.00	—	—	—
2004	5	—	—	—	6	0	0.00	10	1	0.05	—	—	—
2004	6	—	—	—	14	4	0.13	10	1	0.05	—	—	—

Table B.2. **Fort Randall Reach – Catostomids** (river carpsucker, smallmouth buffalo, and bigmouth buffalo): Summary of the number of samples (n), number of samples in which larval fish were present (P, %) and mean larval drift density (D, no. of individuals per 100 m^3) by year and month.

		FR1			FR2			FR3			FR4		
Year	Month	n	P	D	n	P	D	n	P	D	n	P	D
1983	6	1	1	2.78	—	—	—	2	1	4.90	1	1	1.75
1984	5	1	0	0.00	—	—	—	1	0	0.00	3	0	0.00
1984	6	1	0	0.00	—	—	—	2	0	0.00	2	1	0.11
1985	5	—	—	—	—	—	—	6	0	0.00	—	—	—
1985	6	—	—	—	—	—	—	17	10	1.08	—	—	—
1986	5	1	0	0.00	—	—	—	4	0	0.00	—	—	—
1987	5	2	1	22.35	—	—	—	2	1	0.47	—	—	—
1987	6	1	1	7.39	—	—	—	1	1	127.82	—	—	—
1990	6	—	—	—	—	—	—	—	—	—	3	3	1.04
1991	5	—	—	—	—	—	—	60	29	1.08	—	—	—
1991	6	—	—	—	44	28	1.47	95	63	3.55	—	—	—
1993	5	—	—	—	—	—	—	12	0	0.00	—	—	—
1993	6	—	—	—	—	—	—	9	3	0.28	—	—	—
1998	5	—	—	—	—	—	—	6	0	0.00	—	—	—
1998	6	9	6	4.84	—	—	—	9	6	6.39	—	—	—
1999	5	6	0	0.00	—	—	—	10	0	0.00	—	—	—
1999	6	6	3	0.95	—	—	—	12	1	0.47	—	—	—
2000	5	4	1	0.26	8	2	0.16	14	4	0.51	—	—	—
2000	6	10	10	28.86	—	—	—	9	8	4.84	—	—	—
2001	5	—	—	—	8	0	0.00	10	1	0.07	—	—	—
2001	6	3	0	0.00	10	7	1.16	10	7	1.88	—	—	—
2002	5	—	—	—	14	0	0.00	16	1	0.05	—	—	—
2002	6	—	—	—	8	6	0.82	8	7	1.94	—	—	—
2003	5	—	—	—	8	0	0.00	12	6	0.73	—	—	—
2003	6	—	—	—	8	8	3.84	10	10	6.68	—	—	—
2004	5	—	—	—	6	0	0.00	10	1	0.02	—	—	—
2004	6	—	—	—	14	14	4.87	10	10	3.26	—	—	—

Table B.3. **Fort Randall Reach – Predictors:** Summary of predictor variable data corresponding to larval fish sampling months.

Year	Month	Disch. (m^3s^{-1})	CV Disch.	Temp. (°C)	CV Temp.
1983	6	443	0.56	11.9	0.12
1984	5	400	0.24	7.1	0.23
1984	6	295	0.69	10.8	0.10
1985	5	670	0.16	11.4	0.22
1985	6	784	0.05	17.4	0.06
1986	5	707	0.30	9.9	0.19
1987	5	676	0.17	9.5	0.25
1987	6	746	0.08	17.2	0.13
1990	6	617	0.15	15.2	0.15
1991	5	592	0.15	10.5	0.30
1991	6	538	0.18	18.8	0.13
1993	5	376	0.53	8.0	0.21
1993	6	393	0.58	12.0	0.17
1998	5	686	0.10	9.9	0.17
1998	6	629	0.21	14.1	0.19
1999	5	723	0.29	10.8	0.22
1999	6	831	0.13	16.1	0.12
2000	5	827	0.10	12.6	0.17
2000	6	877	0.02	18.1	0.12
2001	5	360	0.30	7.8	0.30
2001	6	500	0.13	11.9	0.09
2002	5	583	0.12	9.3	0.16
2002	6	681	0.04	14.7	0.14
2003	5	674	0.04	10.1	0.17
2003	6	691	0.05	15.1	0.10
2004	5	728	0.10	11.9	0.13
2004	6	754	0.08	16.4	0.07

Table B.4. **Gavins Point Reach – Freshwater Drum:** Summary of the number of samples (n), number of samples in which larval fish were present (P, %) and mean larval drift density (D, no. of individuals per 100 m^3) by year and month.

		GP1			GP2			GP3			GP4			GP5		
Year	Month	n	P	D	n	P	D	n	P	D	n	P	D	n	P	D
1983	6	2	1	1.32	2	2	53.73	25	19	161.14	—	—	—	2	2	48.01
1984	5	3	0	0.00	5	0	0.00	3	0	0.00	—	—	—	—	—	—
1984	6	14	0	0.00	4	3	39.49	3	2	7.00	—	—	—	14	8	19.91
1985	5	2	0	0.00	3	0	0.00	1	0	0.00	—	—	—	1	0	0.00
1985	6	14	0	0.00	2	1	50.26	3	1	31.82	—	—	—	14	9	63.96
1986	5	6	0	0.00	2	1	2.28	6	1	0.10	—	—	—	—	—	—
1986	6	7	3	0.66	6	6	237.66	—	—	—	—	—	—	—	—	—
1987	5	2	0	0.00	2	0	0.00	—	—	—	—	—	—	2	0	0.00
1987	6	1	1	7.72	1	1	124.09	—	—	—	—	—	—	1	1	38.72
1990	5	—	—	—	3	0	0.00	2	0	0.00	—	—	—	—	—	—
1990	6	13	13	31.57	11	11	34.04	5	5	11.03	—	—	—	3	3	8.77
1991	5	10	8	3.38	38	19	1.47	—	—	—	—	—	—	20	15	7.41
1991	6	8	5	41.84	40	27	126.41	—	—	—	—	—	—	34	30	37.37
1993	5	—	—	—	—	—	—	—	—	—	—	—	—	12	2	0.08
1993	6	—	—	—	—	—	—	—	—	—	—	—	—	8	7	3.03
1998	5	—	—	—	6	0	0.00	—	—	—	—	—	—	—	—	—
1998	6	—	—	—	9	6	8.65	—	—	—	—	—	—	9	4	50.13
1999	5	—	—	—	8	0	0.00	—	—	—	—	—	—	8	0	0.00
1999	6	—	—	—	12	8	4.35	—	—	—	—	—	—	10	9	39.37
2000	5	—	—	—	12	2	0.17	—	—	—	2	0	0.00	9	0	0.00
2000	6	—	—	—	9	9	76.32	—	—	—	—	—	—	10	10	47.76
2001	5	—	—	—	10	4	0.44	—	—	—	—	—	—	18	2	0.16
2001	6	—	—	—	10	8	7.11	—	—	—	12	11	20.92	4	4	45.19
2002	5	—	—	—	11	0	0.00	—	—	—	16	0	0.00	—	—	—
2002	6	—	—	—	8	8	13.81	—	—	—	9	8	52.68	—	—	—
2003	5	—	—	—	8	0	0.00	—	—	—	8	0	0.00	—	—	—
2003	6	—	—	—	8	8	50.36	—	—	—	11	10	83.21	—	—	—
2004	5	—	—	—	8	1	0.26	—	—	—	10	3	0.45	—	—	—
2004	6	—	—	—	12	9	2.06	—	—	—	12	6	1.07	—	—	—

Table B.5. **Gavins Point Reach – Catostomids** (river carpsucker, smallmouth buffalo, and bigmouth buffalo): Summary of the number of samples (n), number of samples in which larval fish were present (P, %) and mean larval drift density (D, no. of individuals per 100 m^3) by year and month.

		GP1			GP2			GP3			GP4			GP5		
Year	Month	n	P	D	n	P	D	n	P	D	n	P	D	n	P	D
1983	6	2	2	10.41	2	2	2.62	25	19	14.66	—	—	—	2	2	28.51
1984	5	3	0	0.00	5	0	0.00	3	2	1.38	—	—	—	—	—	—
1984	6	14	10	2.24	4	3	0.66	3	3	3.01	—	—	—	14	13	6.34
1985	5	2	0	0.00	3	0	0.00	1	0	0.00	—	—	—	1	1	0.20
1985	6	14	9	47.88	2	2	2.07	3	3	0.72	—	—	—	14	14	8.77
1986	5	6	5	4.10	2	1	0.35	6	5	2.07	—	—	—	—	—	—
1986	6	7	7	22.84	6	6	8.71	—	—	—	—	—	—	—	—	—
1987	5	2	1	0.89	2	1	12.01	—	—	—	—	—	—	2	1	8.53
1987	6	1	0	0.00	1	1	9.15	—	—	—	—	—	—	1	1	7.45
1990	5	—	—	—	3	2	0.30	2	2	0.66	—	—	—	—	—	—
1990	6	13	9	0.73	11	7	0.69	5	5	1.65	—	—	—	3	3	0.98
1991	5	10	3	0.16	38	30	9.34	—	—	—	—	—	—	20	18	10.65
1991	6	8	3	3.57	40	26	2.21	—	—	—	—	—	—	34	22	4.52
1993	5	—	—	—	—	—	—	—	—	—	—	—	—	12	2	0.39
1993	6	—	—	—	—	—	—	—	—	—	—	—	—	8	2	0.06
1998	5	—	—	—	6	3	0.40	—	—	—	—	—	—	—	—	—
1998	6	—	—	—	9	9	2.20	—	—	—	—	—	—	9	7	2.32
1999	5	—	—	—	8	1	0.11	—	—	—	—	—	—	8	0	0.00
1999	6	—	—	—	12	7	1.40	—	—	—	—	—	—	10	4	0.74
2000	5	—	—	—	12	8	4.66	—	—	—	2	0	0.00	9	9	21.06
2000	6	—	—	—	9	8	2.86	—	—	—	—	—	—	10	10	4.14
2001	5	—	—	—	10	10	27.55	—	—	—	—	—	—	18	15	14.31
2001	6	—	—	—	10	9	2.34	—	—	—	12	12	1.75	4	3	0.93
2002	5	—	—	—	11	5	4.57	—	—	—	16	6	0.95	—	—	—
2002	6	—	—	—	8	7	2.22	—	—	—	9	6	0.59	—	—	—
2003	5	—	—	—	8	4	0.48	—	—	—	8	4	0.82	—	—	—
2003	6	—	—	—	8	7	2.05	—	—	—	11	11	5.56	—	—	—
2004	5	—	—	—	8	5	2.45	—	—	—	10	6	1.43	—	—	—
2004	6	—	—	—	12	9	1.10	—	—	—	12	10	1.90	—	—	—

Table B.6. **Gavins Point Reach – Predictors:** Summary of predictor variable data corresponding to larval fish sampling months.

Year	Month	Disch. (m^3s^{-1})	CV Disch.	Temp. (°C)	CV Temp.	Turb. (NTU)
1983	6	573	0.43	19.3	0.12	315
1984	5	558	0.09	14.2	0.24	146
1984	6	473	0.33	21.1	0.12	531
1985	5	779	0.09	17.2	0.11	113
1985	6	858	0.03	19.7	0.06	70
1986	5	825	0.24	16.2	0.09	95
1986	6	977	0.03	21.3	0.09	104
1987	5	799	0.12	17.1	0.08	117
1987	6	825	0.07	22.6	0.08	52
1990	5	729	0.10	14.1	0.16	309
1990	6	712	0.12	21.6	0.12	385
1991	5	696	0.10	15.8	0.28	123
1991	6	657	0.13	22.3	0.04	369
1993	5	500	0.22	15.8	0.14	122
1993	6	482	0.21	19.5	0.11	160
1998	5	823	0.09	16.4	0.13	106
1998	6	792	0.15	19.6	0.17	275
1999	5	871	0.14	15.0	0.16	81
1999	6	994	0.08	19.8	0.09	175
2000	5	911	0.08	15.7	0.09	57
2000	6	957	0.01	20.1	0.08	71
2001	5	463	0.09	16.0	0.12	114
2001	6	545	0.10	20.1	0.13	163
2002	5	642	0.04	13.2	0.23	36
2002	6	705	0.02	21.6	0.10	78
2003	5	762	0.19	14.3	0.16	94
2003	6	778	0.30	19.9	0.11	201
2004	5	765	0.07	15.6	0.12	203
2004	6	810	0.05	20.3	0.08	180

Table B.7. **Sioux City Reach – Freshwater Drum:** Summary of the number of samples (n), number of samples in which larval fish were present (P, %) and mean larval drift density (D, no. of individuals per 100 m^3) by year and month.

		SC1			SC2			SC3			SC4			SC5		
Year	Month	n	P	D	n	P	D	n	P	D	n	P	D	n	P	D
1985	6	1	0	0.00	—	—	—	—	—	—	—	—	—	—	—	—
1986	5	1	0	0.00	—	—	—	1	1	0.73	1	1	0.79	—	—	—
1986	6	1	1	1692.31	—	—	—	7	7	141.86	—	—	—	—	—	—
1987	5	2	0	0.00	—	—	—	—	—	—	1	1	0.20	—	—	—
1987	6	—	—	—	—	—	—	1	1	28.43	1	1	104.85	—	—	—
1990	5	2	2	2.38	—	—	—	—	—	—	—	—	—	—	—	—
1990	6	9	9	45.61	—	—	—	10	10	67.03	—	—	—	—	—	—
1991	5	20	8	3.30	—	—	—	—	—	—	—	—	—	—	—	—
1991	6	58	49	103.43	—	—	—	—	—	—	—	—	—	—	—	—
1993	5	—	—	—	—	—	—	—	—	—	12	1	0.03	—	—	—
1993	6	—	—	—	—	—	—	—	—	—	8	6	3.36	—	—	—
1998	5	—	—	—	—	—	—	—	—	—	6	0	0.00	—	—	—
1998	6	—	—	—	—	—	—	—	—	—	8	3	33.29	—	—	—
1999	5	—	—	—	—	—	—	—	—	—	12	0	0.00	—	—	—
1999	6	—	—	—	—	—	—	—	—	—	16	12	23.56	—	—	—
2000	5	—	—	—	—	—	—	—	—	—	13	2	0.19	—	—	—
2000	6	—	—	—	—	—	—	—	—	—	12	12	29.58	—	—	—
2001	5	—	—	—	—	—	—	—	—	—	18	4	0.19	6	0	0.00
2001	6	—	—	—	—	—	—	6	6	121.02	12	12	66.88	6	6	324.13
2002	5	—	—	—	—	—	—	—	—	—	18	1	0.04	—	—	—
2002	6	—	—	—	—	—	—	—	—	—	10	10	82.74	—	—	—
2003	5	—	—	—	6	1	0.16	—	—	—	12	2	0.13	—	—	—
2003	6	—	—	—	12	7	41.04	—	—	—	12	10	113.53	—	—	—
2004	5	—	—	—	—	—	—	—	—	—	14	3	0.29	12	8	0.99
2004	6	—	—	—	—	—	—	—	—	—	12	12	114.09	—	—	—

Table B.8. **Sioux City Reach – Catostomids** (river carpsucker, smallmouth buffalo, and bigmouth buffalo): Summary of the number of samples (n), number of samples in which larval fish were present (P, %) and mean larval drift density (D, no. of individuals per 100 m^3) by year and month.

		SC1			SC2			SC3			SC4			SC5		
Year	Month	n	P	D	n	P	D	n	P	D	n	P	D	n	P	D
1985	6	1	1	1.07	—	—	—	—	—	—	—	—	—	—	—	—
1986	5	1	1	5.56	—	—	—	1	1	0.73	1	1	0.79	—	—	—
1986	6	1	1	64.10	—	—	—	7	7	70.05	—	—	—	—	—	—
1987	5	2	2	4.77	—	—	—	—	—	—	1	1	11.90	—	—	—
1987	6	—	—	—	—	—	—	1	1	17.06	1	1	16.77	—	—	—
1990	5	2	2	2.80	—	—	—	—	—	—	—	—	—	—	—	—
1990	6	9	9	3.18	—	—	—	10	9	1.74	—	—	—	—	—	—
1991	5	20	16	6.41	—	—	—	—	—	—	—	—	—	—	—	—
1991	6	58	42	4.83	—	—	—	—	—	—	—	—	—	—	—	—
1993	5	—	—	—	—	—	—	—	—	—	12	1	0.07	—	—	—
1993	6	—	—	—	—	—	—	—	—	—	8	2	0.11	—	—	—
1998	5	—	—	—	—	—	—	—	—	—	6	3	7.15	—	—	—
1998	6	—	—	—	—	—	—	—	—	—	8	6	2.16	—	—	—
1999	5	—	—	—	—	—	—	—	—	—	12	0	0.00	—	—	—
1999	6	—	—	—	—	—	—	—	—	—	16	7	2.40	—	—	—
2000	5	—	—	—	—	—	—	—	—	—	13	10	5.79	—	—	—
2000	6	—	—	—	—	—	—	—	—	—	12	12	16.15	—	—	—
2001	5	—	—	—	—	—	—	—	—	—	18	14	9.68	6	3	2.32
2001	6	—	—	—	—	—	—	6	6	10.54	12	12	9.23	6	6	12.76
2002	5	—	—	—	—	—	—	—	—	—	18	6	1.53	—	—	—
2002	6	—	—	—	—	—	—	—	—	—	10	9	5.35	—	—	—
2003	5	—	—	—	6	5	2.22	—	—	—	12	7	2.08	—	—	—
2003	6	—	—	—	12	12	9.61	—	—	—	12	12	17.78	—	—	—
2004	5	—	—	—	—	—	—	—	—	—	14	12	6.92	12	10	4.31
2004	6	—	—	—	—	—	—	—	—	—	12	12	19.25	—	—	—

Table B.9. **Sioux City Reach – Sioux City Predictors:** Summary of predictor variable data corresponding to larval fish sampling months.

Year	Month	Disch. (m^3s^{-1})	CV Disch.	Temp. (°C)	CV Temp.	Turb. (NTU)
1985	6	963	0.04	19.7	0.06	70
1986	5	1310	0.12	16.2	0.09	95
1986	6	1244	0.05	21.3	0.09	104
1987	5	903	0.10	17.1	0.08	117
1990	5	771	0.10	14.1	0.16	309
1990	6	784	0.07	21.6	0.12	385
1991	5	731	0.07	15.8	0.28	123
1991	6	784	0.07	22.6	0.04	369
2003	5	823	0.03	14.3	0.16	94
2003	6	821	0.07	19.9	0.11	201

Table B.10. **Sioux City Reach – Decatur Predictors:** Summary of predictor variable data corresponding to larval fish sampling months.

Year	Month	Disch. (m^3s^{-1})	CV Disch.	Temp. (°C)	CV Temp.	Turb. (NTU)
1987	5	903	0.10	17.1	0.08	117
1987	6	863	0.06	22.6	0.08	52
1987	6	863	0.06	22.6	0.08	52
1990	6	800	0.09	21.6	0.12	385
1993	5	955	0.18	15.8	0.14	122
1993	6	1064	0.15	19.5	0.11	160
1998	5	972	0.06	16.4	0.13	106
1998	6	998	0.09	19.6	0.17	275
1999	5	1125	0.11	15.0	0.16	81
1999	6	1314	0.07	19.8	0.09	175
2000	5	1035	0.09	15.7	0.09	57
2000	6	1060	0.05	20.1	0.08	71
2001	5	1050	0.18	16.0	0.12	114
2001	6	865	0.09	20.1	0.13	163
2001	6	865	0.09	20.1	0.13	163
2002	5	738	0.03	13.2	0.23	36
2002	6	765	0.02	21.6	0.10	78
2003	5	843	0.03	14.3	0.16	94
2003	6	849	0.08	19.9	0.11	201
2004	5	878	0.12	15.6	0.12	203
2004	6	995	0.08	20.3	0.08	180

Table B.11. **Sioux City Reach – Omaha Predictors:** Summary of predictor variable dataw corresponding to larval fish sampling months.

Year	Month	Disch. (m^3s^{-1})	CV Disch.	Temp. (°C)	CV Temp.	Turb. (NTU)
1997	6	2156	0.03	19.6	0.12	63
2001	5	1319	0.21	16.0	0.12	114
2001	6	1047	0.12	20.1	0.13	163
2004	5	963	0.20	15.6	0.12	203

Table B.12. **Plattsmouth Reach – Freshwater Drum:** Summary of the number of samples (n), number of samples in which larval fish were present (P, %) and mean larval drift density (D, no. of individuals per 100 m^3) by year and month.

		PL1			PL2			PL3			PL4		
Year	Month	n	P	D	n	P	D	n	P	D	n	P	D
1987	5	—	—	—	1	0	0.00	1	1	0.32	1	1	0.29
1987	6	—	—	—	1	1	131.51	1	1	54.46	1	1	38.09
1993	5	—	—	—	—	—	—	12	4	0.24	—	—	—
1993	6	—	—	—	—	—	—	5	4	1.15	—	—	—
1998	5	—	—	—	—	—	—	6	0	0.00	—	—	—
1998	6	—	—	—	—	—	—	6	3	73.52	—	—	—
1999	5	—	—	—	—	—	—	12	0	0.00	—	—	—
1999	6	—	—	—	—	—	—	12	12	15.42	—	—	—
2000	5	—	—	—	—	—	—	14	1	0.04	—	—	—
2000	6	—	—	—	—	—	—	12	12	45.14	—	—	—
2001	5	6	6	171.53	6	6	143.50	12	3	0.45	—	—	—
2001	6	—	—	—	—	—	—	14	13	87.07	—	—	—
2002	5	—	—	—	18	1	0.06	20	0	0.00	—	—	—
2002	6	—	—	—	8	8	31.36	10	10	77.23	—	—	—
2003	5	—	—	—	12	0	0.00	6	0	0.00	—	—	—
2003	6	—	—	—	6	6	79.12	12	9	44.75	—	—	—
2004	5	—	—	—	4	0	0.00	6	0	0.00	—	—	—
2004	6	—	—	—	—	—	—	12	11	19.86	—	—	—

Table B.13. **Plattsmouth Reach – Catostomids** (river carpsucker, smallmouth buffalo, and bigmouth buffalo): Summary of the number of samples (n), number of samples in which larval fish were present (P, %) and mean larval drift density (D, no. of individuals per 100 m^3) by year and month.

		PL1			PL2			PL3			PL4		
Year	Month	n	P	D	n	P	D	n	P	D	n	P	D
1987	5	—	—	—	1	1	10.28	1	1	12.01	1	1	25.14
1987	6	—	—	—	1	1	46.58	1	1	19.57	1	1	15.04
1993	5	—	—	—	—	—	—	12	4	0.33	—	—	—
1993	6	—	—	—	—	—	—	5	1	0.02	—	—	—
1998	5	—	—	—	—	—	—	6	5	1.44	—	—	—
1998	6	—	—	—	—	—	—	6	4	10.64	—	—	—
1999	5	—	—	—	—	—	—	12	1	0.10	—	—	—
1999	6	—	—	—	—	—	—	12	5	3.85	—	—	—
2000	5	—	—	—	—	—	—	14	12	3.64	—	—	—
2000	6	—	—	—	—	—	—	12	11	763.24	—	—	—
2001	5	6	6	12.26	6	6	18.84	12	11	8.00	—	—	—
2001	6	—	—	—	—	—	—	14	10	12.42	—	—	—
2002	5	—	—	—	18	5	0.64	20	6	2.11	—	—	—
2002	6	—	—	—	8	4	5.05	10	9	8.14	—	—	—
2003	5	—	—	—	12	3	1.28	6	2	0.31	—	—	—
2003	6	—	—	—	6	6	10.63	12	12	17.14	—	—	—
2004	5	—	—	—	4	4	7.27	6	1	0.05	—	—	—
2004	6	—	—	—	—	—	—	12	12	26.72	—	—	—

Table B.14. **Plattsmouth Reach – Predictors:** Summary of predictor variable data corresponding to larval fish sampling months.

Year	Month	Disch. (m^3s^{-1})	CV Disch.	Temp. (°C)	CV Temp.	Turb. (NTU)
1987	5	1514	0.22	17.1	0.08	117
1987	6	1318	0.07	22.6	0.08	52
1993	5	1556	0.23	15.8	0.14	122
1993	6	1834	0.16	19.5	0.11	160
1998	5	1383	0.12	16.4	0.13	106
1998	6	1771	0.19	19.6	0.17	275
1999	5	1724	0.08	15.0	0.16	81
1999	6	2048	0.14	19.8	0.09	175
2000	5	1191	0.09	15.7	0.09	57
2000	6	1262	0.12	20.1	0.08	71
2001	5	1746	0.24	16.0	0.12	114
2001	6	1286	0.12	20.1	0.13	163
2002	5	997	0.06	13.2	0.23	36
2002	6	976	0.13	21.6	0.10	78
2003	5	1216	0.13	14.3	0.16	94
2003	6	1104	0.13	19.9	0.11	201
2004	5	1185	0.33	15.6	0.12	203
2004	6	1333	0.08	20.3	0.08	180

B.2 Results

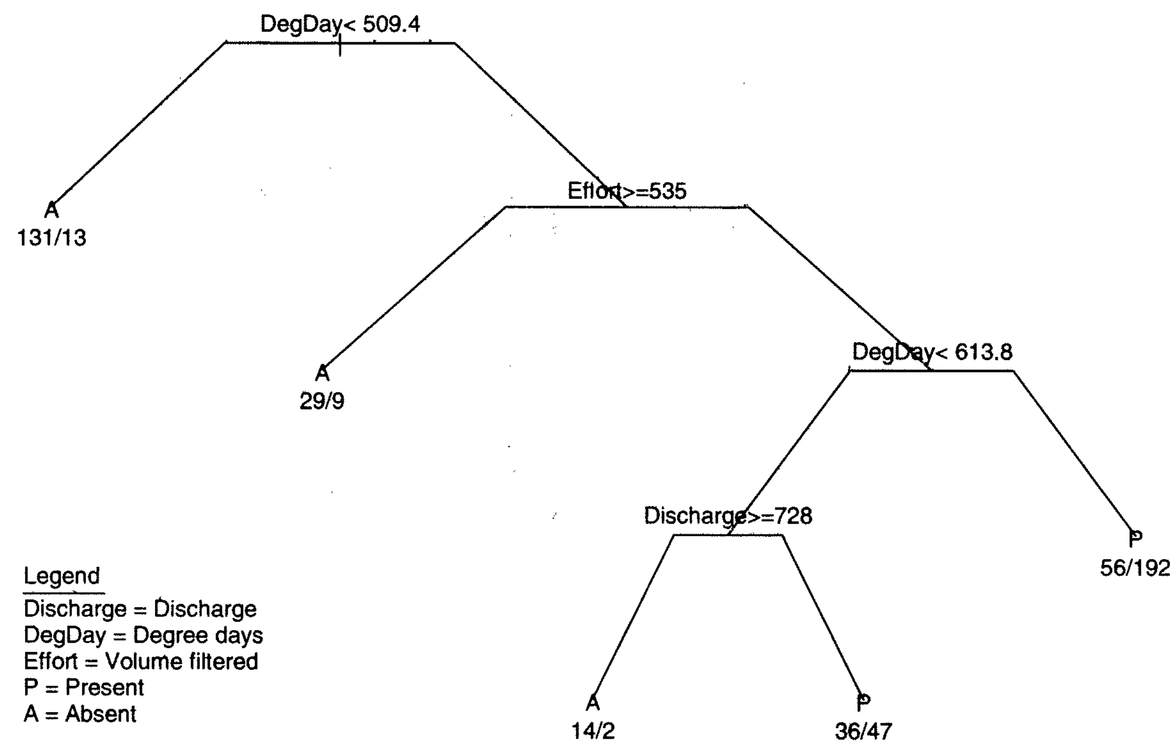

Figure B.1. **Fort Randall Reach – Catostomids** (river carpsucker, smallmouth buffalo, bigmouth buffalo): Classification tree for larval fish presence or absence. At each node, if the condition is met, the left branch is followed. Numbers at the terminal nodes are the observed absence/presence data.

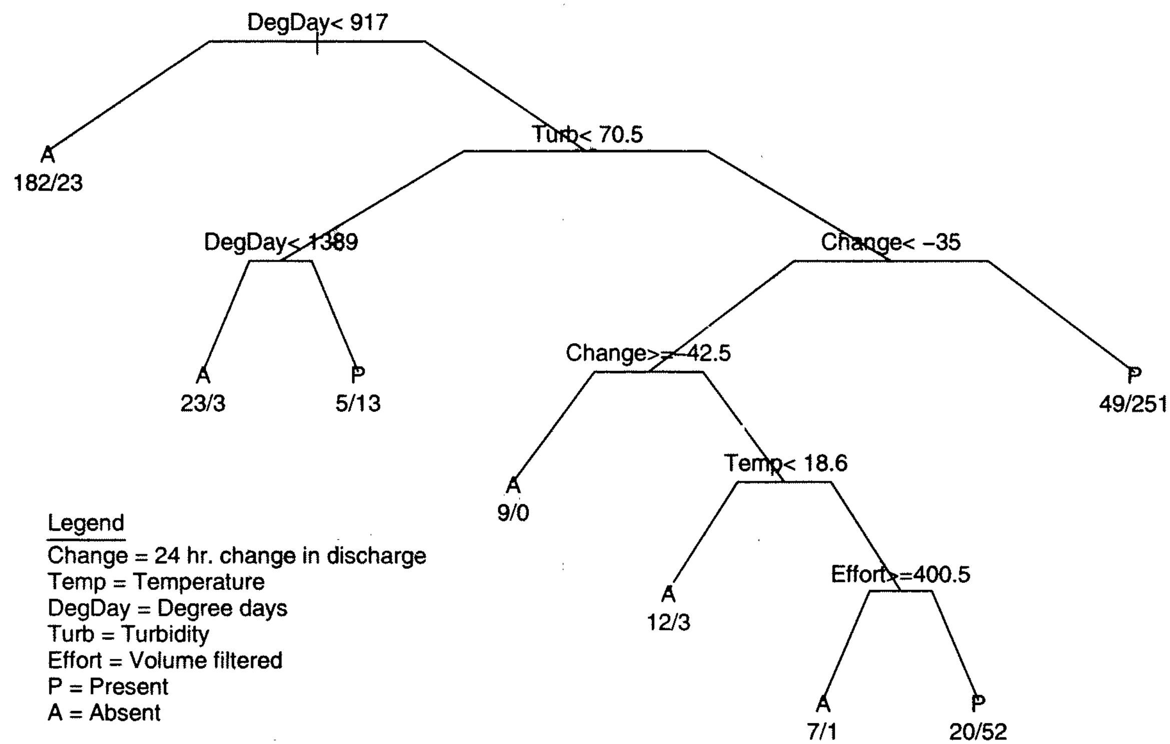

Figure B.2. **Gavins Point Reach – Freshwater Drum:** Classification tree for larval fish presence or absence. At each node, if the condition is met, the left branch is followed. Numbers at the terminal nodes are the observed absence/presence data.

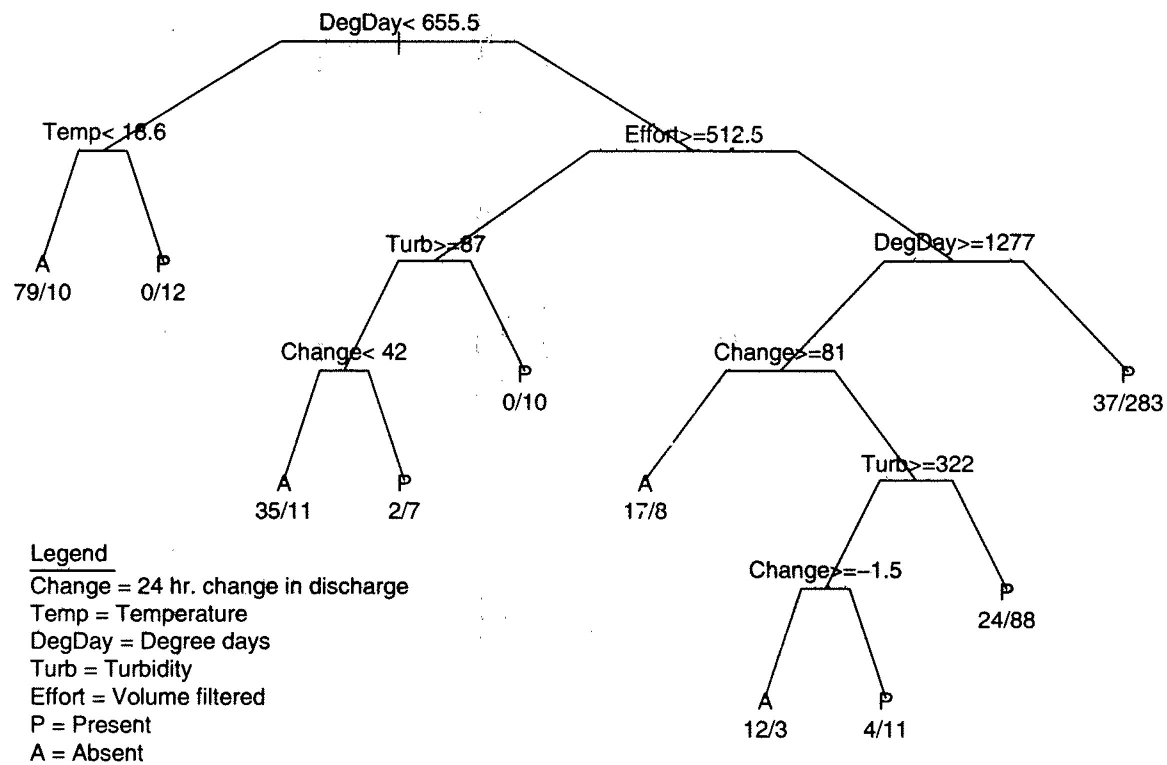

Figure B.3. **Gavins Point Reach – Catostomids** (river carpsucker, smallmouth buffalo, bigmouth buffalo): Classification tree for larval fish presence or absence. At each node, if the condition is met, the left branch is followed. Numbers at the terminal nodes are the observed absence/presence data.

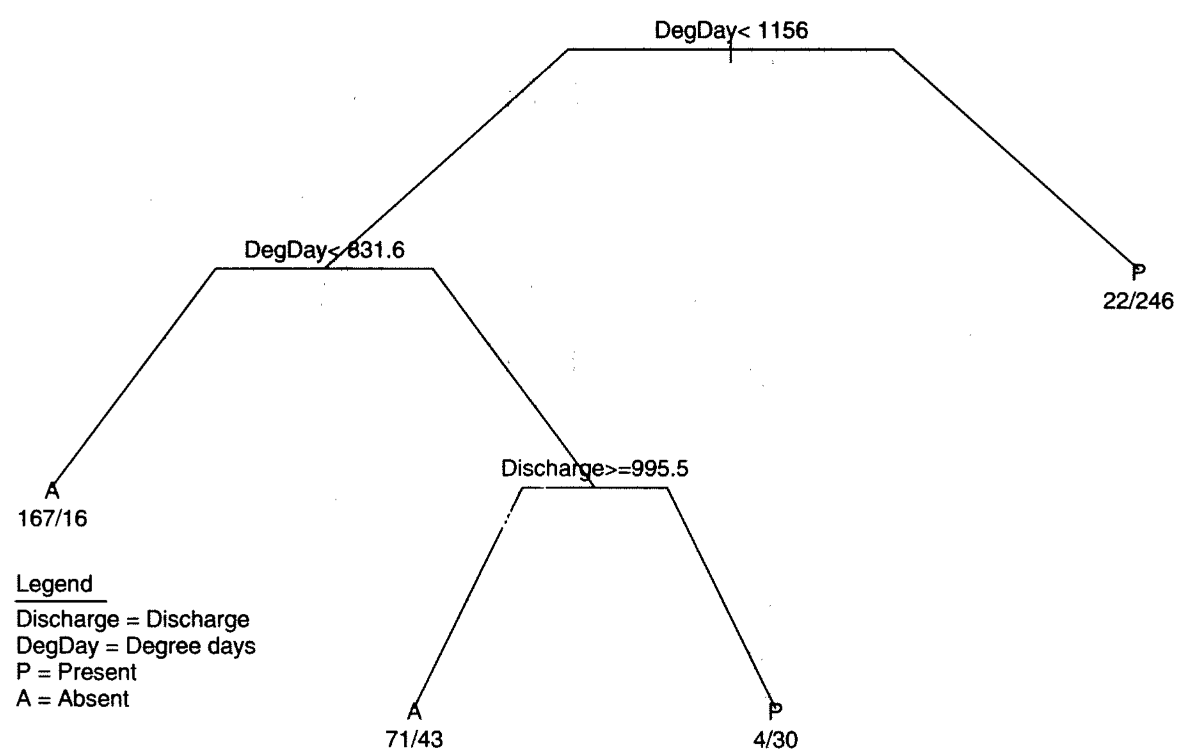

Figure B.4. **Sioux City Reach – Freshwater Drum:** Classification tree for larval fish presence or absence. At each node, if the condition is met, the left branch is followed. Numbers at the terminal nodes are the observed absence/presence data.

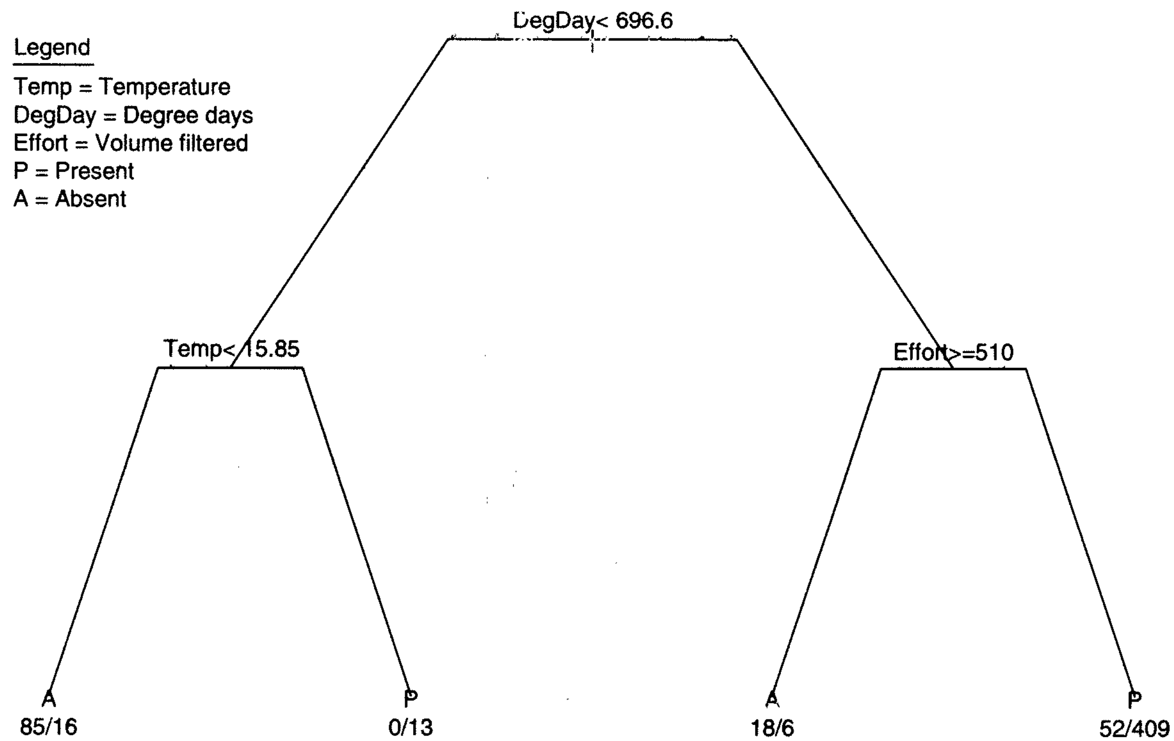

Figure B.5. **Sioux City Reach – Catostomids** (river carpsucker, smallmouth buffalo, bigmouth buffalo): Classification tree for larval fish presence or absence. At each node, if the condition is met, the left branch is followed. Numbers at the terminal nodes are the observed absence/presence data.

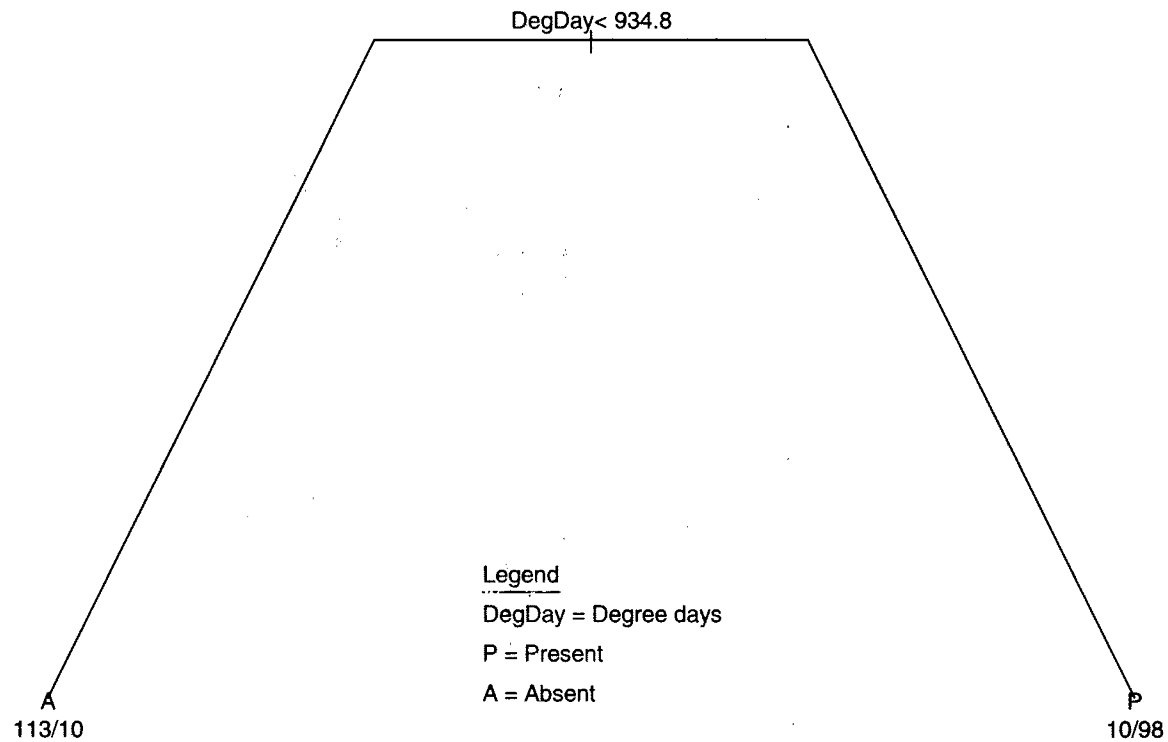

Figure B.6. **Plattsmouth Reach – Freshwater Drum:** Classification tree for larval fish presence or absence. At each node, if the condition is met, the left branch is followed. Numbers at the terminal nodes are the observed absence/presence data.

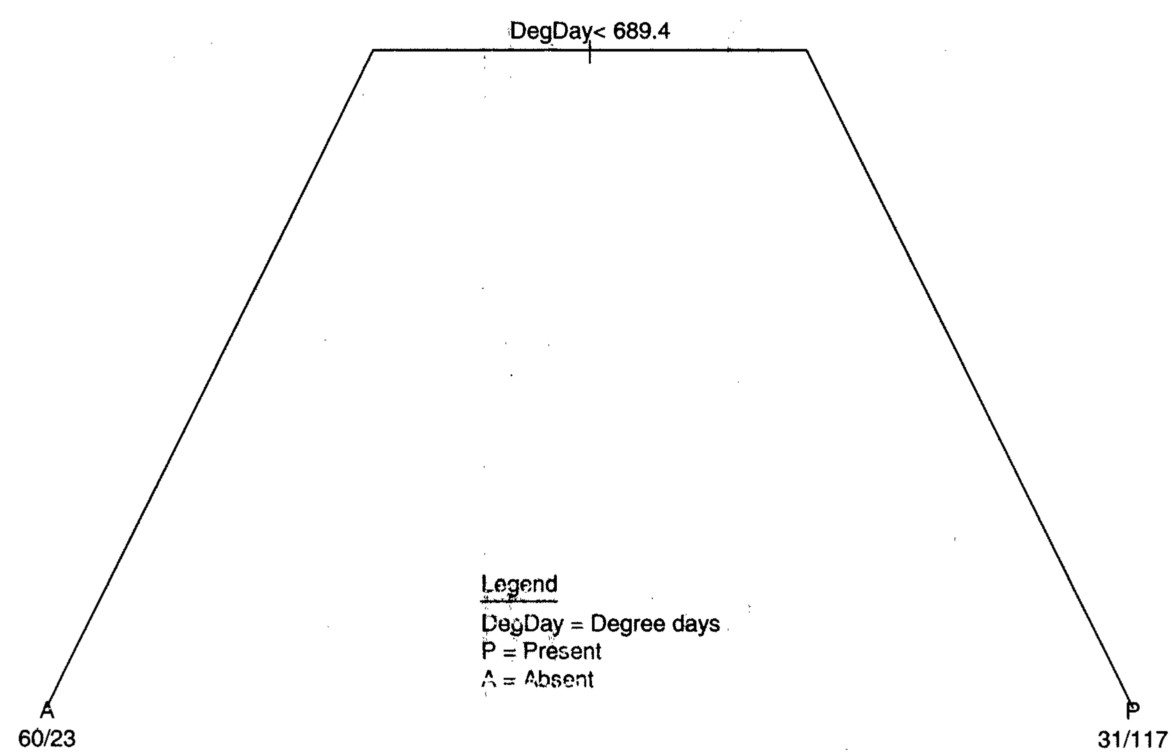

Figure B.7. **Plattsmouth Reach – Catostomids** (river carpsucker, smallmouth buffalo, bigmouth buffalo): Classification tree for larval fish presence or absence. At each node, if the condition is met, the left branch is followed. Numbers at the terminal nodes are the observed absence/presence data.

Table B.15. **Fort Randall Reach – Catostomids** (river carpsucker, smallmouth buffalo, bigmouth buffalo): Summary of multimodel inference results of larval fish drift density. Column two contains the relative variable importances (RVI). Columns three and four are the model averaged parameter estimates conditional on the variable being included in the model and their standard errors. Column five contains the bias corrected model averaged estimates. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, AIC_c values, and Akaike weights (w_i).

Variable	RVI	Conditional Estimate	Std. Error Estimate	Bias Adj. Estimate	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.00	-1.27500	0.43681	-1.27500	-1.47920	-0.94061	-1.45824	-0.90415	-1.36143
Year	1.00	0.00000	0.26179	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Site	1.00	0.00000	0.00001	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Discharge	0.00	-0.00041	0.00061	0.00000	—	—	—	—	-0.00028
CV Discharge	0.18	-0.07623	0.32020	-0.01372	—	—	-0.04877	-0.11927	—
Temperature	1.00	0.13015	0.02208	0.13014	0.13925	0.11495	0.13868	0.11411	0.14299
CV Temperature	0.63	1.44911	1.01271	0.91314	1.45274	—	1.43298	—	1.49621
No. variables					2	1	3	2	3
AIC_c					44.42	45.51	47.51	48.45	60.16
w_i					0.52	0.30	0.11	0.07	0.00

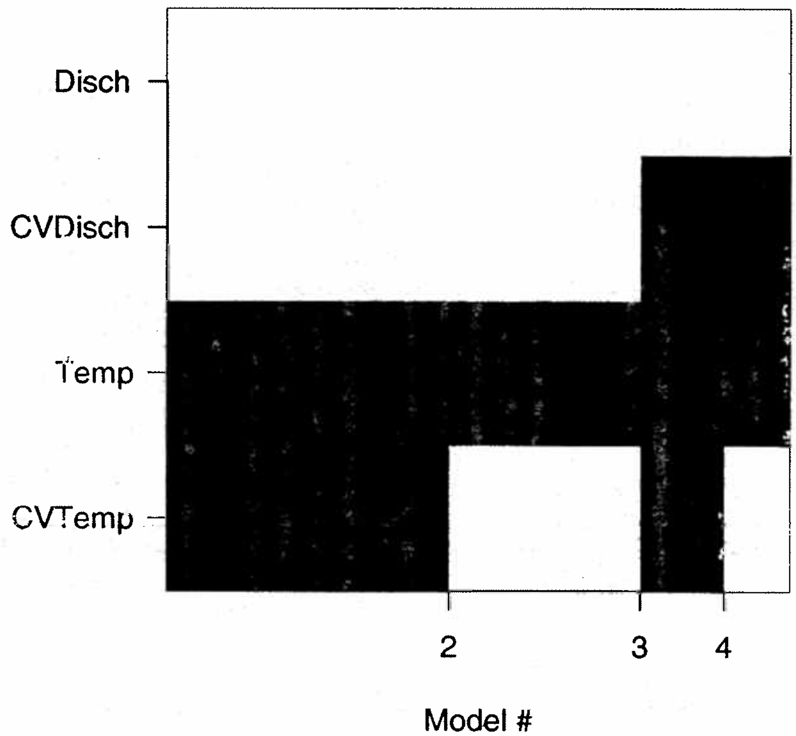

Figure B.8. **Fort Randall Reach – Catostomids** (river carpsucker, smallmouth buffalo, bigmouth buffalo): Visual summary of multi-model inference. Rows correspond to the predictor variables. Columns correspond to the subset of models whose Akaike weights sum to at least 0.99. For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's Akaike weight.

Table B.16. **Gavins Point Reach – Freshwater Drum:** Summary of multimodel inference results of larval fish drift density. Column two contains the relative variable importances (RVI). Columns three and four are the model averaged parameter estimates conditional on the variable being included in the model and their standard errors. Column five contains the bias corrected model averaged estimates. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, AIC_c values, and Akaike weights (w_i).

Variable	RVI	Conditional Estimate	Std. Error Estimate	Bias Adj. Estimate	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.00	-4.18568	0.41916	-4.18568	-4.18849	-4.17365	-4.43720	-4.24635	-4.61612
Year	1.00	0.00000	0.20551	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Site	1.00	0.00000	0.15599	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Discharge	0.00	0.00057	0.00044	0.00000	—	—	—	—	0.00054
CV Discharge	0.27	-0.17951	0.48770	-0.04916	—	-0.19468	0.92757	—	—
Temperature	1.00	0.23326	0.01711	0.23326	0.23298	0.23357	0.25567	0.24733	0.23363
CV Temperature	1.00	4.69467	0.98400	4.69408	4.69208	4.70701	4.45137	4.42055	4.88462
Turbidity	0.01	-0.00126	0.00056	-0.00001	—	—	-0.00149	-0.00096	—
No. variables					2	3	4	3	3
AIC_c					64.90	66.87	75.50	76.10	79.43
w_i					0.72	0.27	0.00	0.00	0.00

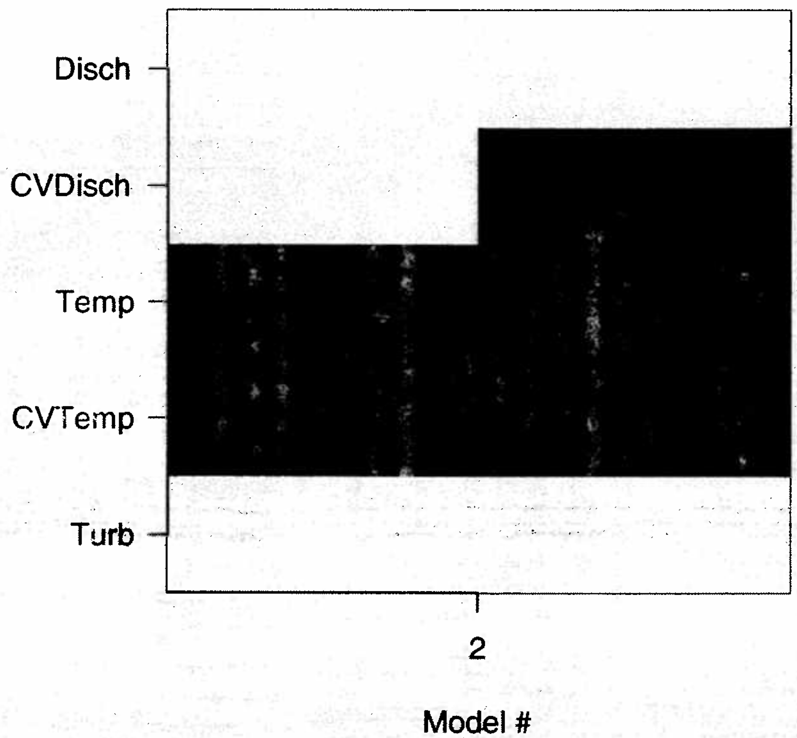

Figure B.9. **Gavins Point Reach – Freshwater Drum:** Visual summary of multi-model inference. Rows correspond to the predictor variables. Columns correspond to the subset of models whose Akaike weights sum to at least 0.99. For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's Akaike weight.

Table B.17. **Sioux City Reach – Freshwater Drum:** Summary of multimodel inference results of larval fish drift density. Column two contains the relative variable importances (RVI). Columns three and four are the model averaged parameter estimates conditional on the variable being included in the model and their standard errors. Column five contains the bias corrected model averaged estimates. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, AIC_c values, and Akaike weights (w_i).

Variable	RVI	Conditional Estimate	Std. Error Estimate	Bias Adj. Estimate	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.00	-3.44624	0.92888	-3.44624	-3.70263	-3.67583	-2.77357	-2.83402	-2.81721
Year	1.00	0.00000	0.14577	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Site	1.00	0.00000	0.00001	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Discharge	0.00	-0.00072	0.00032	0.00000	—	—	—	—	-0.00070
CV Discharge	0.51	-0.20392	1.98485	-0.10379	-0.06197	—	-0.56854	—	—
Temperature	1.00	0.21971	0.03730	0.21967	0.22767	0.22681	0.19879	0.20035	0.22253
CV Temperature	0.73	2.87191	2.29416	2.09236	2.90752	2.84202	—	—	2.06985
Turbidity	0.00	0.00094	0.00103	0.00000	—	—	—	—	—
No. variables					3	2	2	1	3
AIC_c					63.95	63.99	65.86	66.03	76.83
w_I					0.37	0.36	0.14	0.13	0.00

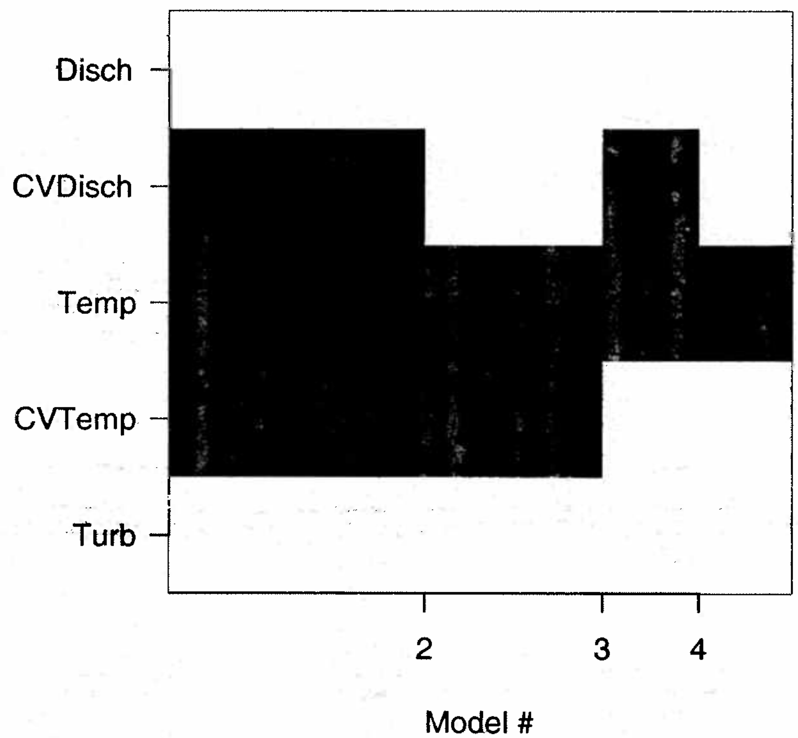

Figure B.10. **Sioux City Reach – Freshwater Drum:** Visual summary of multi-model inference. Rows correspond to the predictor variables. Columns correspond to the subset of models whose Akaike weights sum to at least 0.99. For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's Akaike weight.

Table B.18. **Sioux City Reach – Catostomids** (river carpsucker, smallmouth buffalo, bigmouth buffalo): Summary of multimodel inference results of larval fish drift density. Column two contains the relative variable importances (RVI). Columns three and four are the model averaged parameter estimates conditional on the variable being included in the model and their standard errors. Column five contains the bias corrected model averaged estimates. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, AIC_c values, and Akaike weights (w_i).

Variable	RVI	Conditional Estimate	Std. Error Estimate	Bias Adj. Estimate	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.00	0.38116	0.78388	0.38116	1.37620	0.05117	-0.18604	-0.51306	-0.16273
Year	1.00	0.00000	0.40800	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Site	1.00	0.00000	0.00888	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Discharge	0.00	-0.00071	0.00026	0.00000	—	—	—	—	—
CV Discharge	0.68	-2.12601	1.48330	-1.43777	-2.93613	-1.34904	—	—	-1.14678
Temperature	0.62	0.05857	0.01616	0.03654	—	0.05151	0.05843	0.06870	0.05807
CV Temperature	0.58	-0.62727	1.84267	-0.36361	-2.01890	—	—	1.08039	0.64031
Turbidity	0.00	0.00088	0.00099	0.00000	—	—	—	—	—
No. variables					2	2	1	2	3
AIC_c					34.78	35.41	35.95	36.00	36.08
w_i					0.26	0.19	0.15	0.14	0.14

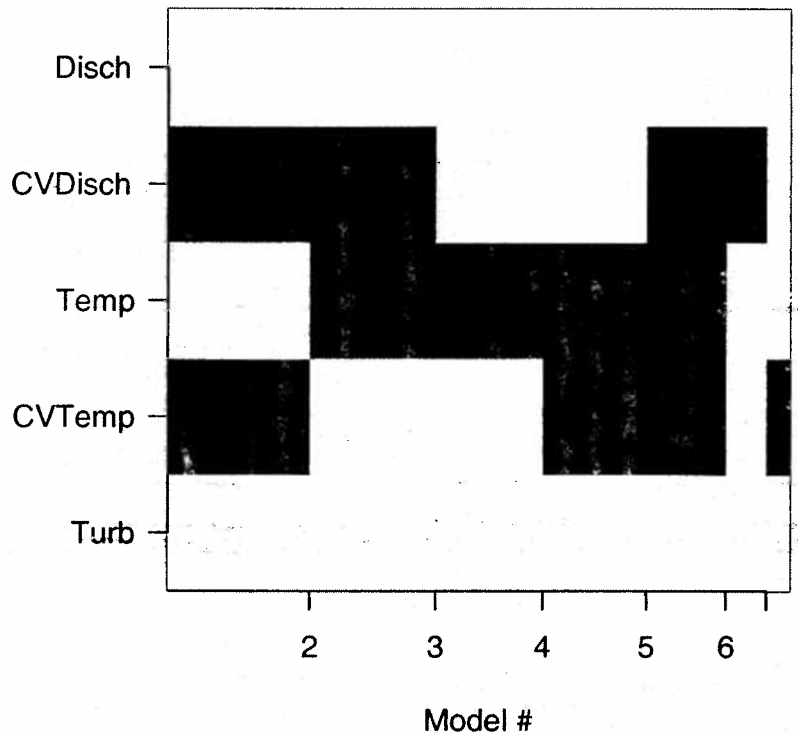

Figure B.11. **Sioux City Reach – Catostomids** (river carpsucker, smallmouth buffalo, bigmouth buffalo): Visual summary of multi-model inference. Rows correspond to the predictor variables. Columns correspond to the subset of models whose Akaike weights sum to at least 0.99. For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's Akaike weight.

Table B.19. **Plattsmouth Reach – Freshwater Drum:** Summary of multimodel inference results of larval fish drift density. Column two contains the relative variable importances (RVI). Columns three and four are the model averaged parameter estimates conditional on the variable being included in the model and their standard errors. Column five contains the bias corrected model averaged estimates. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, AIC_c values, and Akaike weights (w_i).

Variable	RVI	Conditional Estimate	Std. Error Estimate	Bias Adj. Estimate	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.00	-3.67711	0.69273	-3.67711	-4.00726	-3.72565	-3.28308	-3.01018	-4.02056
Year	1.00	0.00000	0.11500	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Site	1.00	0.00000	0.00467	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Discharge	0.00	-0.00018	0.00023	0.00000	—	—	—	—	—
CV Discharge	0.36	-0.69174	0.90354	-0.24611	—	-0.51137	—	-0.96332	—
Temperature	1.00	0.23885	0.02587	0.23885	0.24858	0.24078	0.22635	0.21956	0.24730
CV Temperature	0.68	2.49132	1.90873	1.69627	2.65769	2.12909	—	—	2.67251
Turbidity	0.00	0.00068	0.00125	0.00000	—	—	—	—	0.00026
No. variables					2	3	1	2	3
AIC_c					28.82	30.38	30.76	31.21	44.26
w_i					0.47	0.21	0.18	0.14	0.00

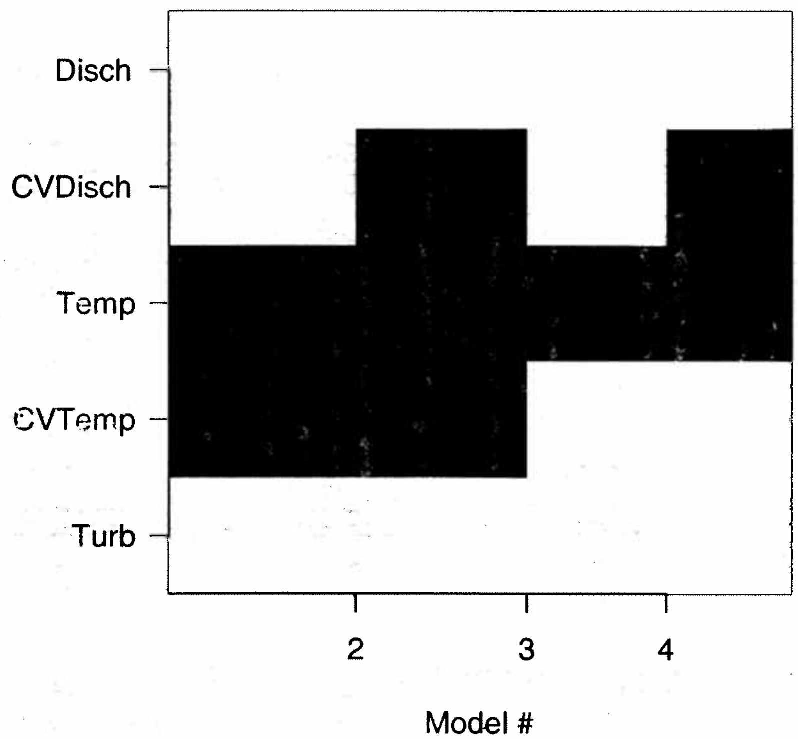

Figure B.12. **Plattsmouth Reach – Freshwater Drum:** Visual summary of multi-model inference. Rows correspond to the predictor variables. Columns correspond to the subset of models whose Akaike weights sum to at least 0.99. For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's Akaike weight.

Table B.20. **Plattsmouth Reach – Catostomids** (river carpsucker, smallmouth buffalo, bigmouth buffalo): Summary of multimodel inference results of larval fish drift density. Column two contains the relative variable importances (RVI). Columns three and four are the model averaged parameter estimates conditional on the variable being included in the model and their standard errors. Column five contains the bias corrected model averaged estimates. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, AIC_c values, and Akaike weights (w_i).

Intercept	1.00	1.76138	0.42503	1.76138	1.98737	1.77355	0.38660	0.57864	-0.64696
Year	1.00	0.00000	0.27041	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Site	1.00	0.00000	0.00001	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Discharge	0.00	-0.00047	0.00032	0.00000	—	—	—	—	—
CV Discharge	0.50	-1.17294	1.02091	-0.59227	-1.22701	—	—	-0.32275	—
Temperature	0.07	0.06008	0.03181	0.00444	—	—	0.05548	0.05020	0.08569
CV Temperature	0.98	-7.07912	2.00568	-6.97293	-7.40190	-7.13108	-3.97753	-4.37501	—
Turbidity	0.00	0.00158	0.00159	0.00000	—	—	—	—	—
No. variables					2	1	2	3	1
AIC_c					36.22	36.36	41.21	42.55	44.19
w_i					0.48	0.45	0.04	0.02	0.01

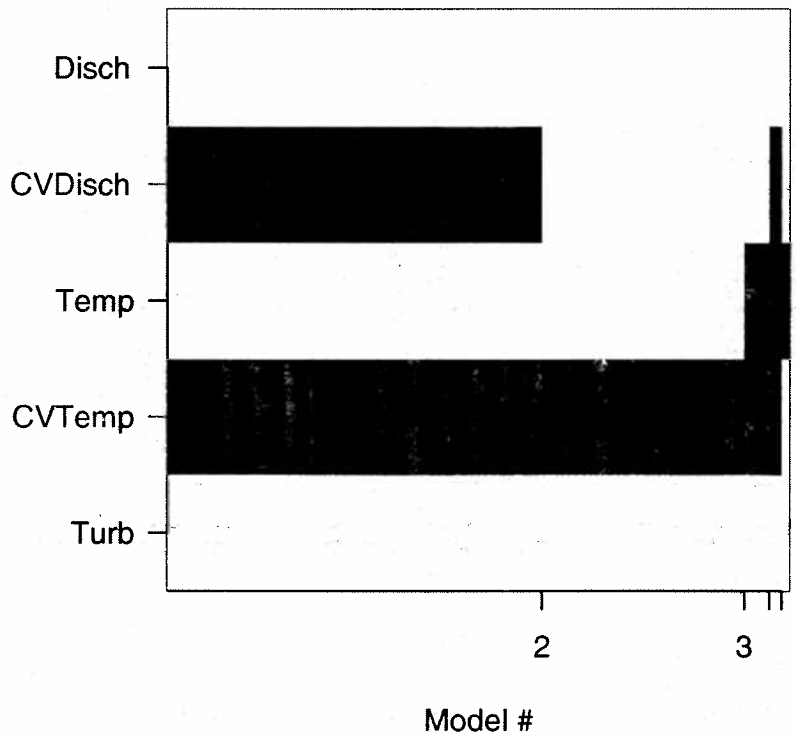

Figure B.13. **Plattsmouth Reach – Catostomids** (river carpsucker, smallmouth buffalo, bigmouth buffalo): Visual summary of multi-model inference. Rows correspond to the predictor variables. Columns correspond to the subset of models whose Akaike weights sum to at least 0.99. For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's Akaike weight.

Appendix C

Supporting data and results for age 0 and age 1 fish models

C.1 Model input data

Table C.1. **Emerald Shiner:** Summary of sampling effort (m^2) and catch per unit effort (C/E) (no. $1000\,m^{-2}$) of fish from August and September seine samples in the MRHD classified as age 1 by reach.

	Gavins Point		Upper Channelized		Lower Channelized	
Year	Effort	C/E	Effort	C/E	Effort	C/E
1978	—	—	—	—	266	139.10
1983	3168	70.71	—	—	—	—
1984	2640	1.14	—	—	—	—
1985	7040	47.30	—	—	—	—
1986	4224	39.06	2464	13.80	—	—
1994	1760	139.20	4224	108.19	4048	99.56
1997	1056	4.73	2992	30.08	1056	75.76
1998	4048	34.09	3222	11.48	176	5.68
1999	704	11.36	4576	10.49	—	—
2000	1408	165.48	2816	37.64	352	8.52
2001	1936	21.69	2992	31.42	528	7.58
2002	2112	215.91	5280	41.67	704	42.61
2003	704	113.64	2464	22.32	—	—
2004	2112	107.95	2464	34.09	1056	0.95

Table C.2. **River Carpsucker:** Summary of sampling effort (m^2) and catch per unit effort (C/E) (no. $1000\,m^{-2}$) of fish from August–October seine samples in the MRHD classified as age 1 by reach.

Year	Fort Randall Effort	Fort Randall C/E	Gavins Point Effort	Gavins Point C/E	Upper Channelized Effort	Upper Channelized C/E	Lower Channelized Effort	Lower Channelized C/E
1978	—	—	—	—	—	—	435	0.00
1983	8448	0.59	5808	6.03	—	—	—	—
1984	13200	0.68	2640	7.58	—	—	—	—
1985	16368	3.60	10208	1.96	—	—	—	—
1986	3168	6.31	4224	8.05	2464	2.44	—	—
1993	1936	20.14	1408	43.32	3344	4.49	—	—
1994	4224	5.68	1760	6.82	4224	3.08	4048	9.14
1997	528	49.24	1056	90.91	5456	14.11	1056	10.42
1998	4752	0.21	5808	46.14	5510	24.86	176	17.05
1999	3168	21.78	2112	70.55	7040	2.13	—	—
2000	4752	10.94	1760	321.02	3520	24.15	352	0.00
2001	2992	0.67	1936	41.84	4400	19.55	528	9.47
2002	3168	4.10	2464	46.27	5632	19.53	1056	1.89
2003	2112	8.52	1760	52.27	6864	1.17	1056	0.00
2004	4576	0.00	2112	19.89	2464	4.46	1056	0.00

Table C.3. **Red Shiner:** Summary of sampling effort (m^2) and catch per unit effort (C/E) (no. $1000\,m^{-2}$) of fish from July–October seine samples in the MRHD classified as age 1 by reach.

Year	Fort Randall Effort	Fort Randall C/E	Gavins Point Effort	Gavins Point C/E	Upper Channelized Effort	Upper Channelized C/E	Lower Channelized Effort	Lower Channelized C/E
1978	—	—	—	—	—	—	560	41.07
1983	12144	0.49	6864	1.75	—	—	—	—
1984	18480	14.61	5632	3.20	—	—	—	—
1985	22704	1.06	13376	0.67	—	—	—	—
1986	5280	1.89	7392	17.05	3520	13.35	—	—
1993	1936	2.58	1408	0.00	3344	10.77	—	—
1994	4224	0.47	1760	2.84	4224	6.87	4048	1.98
1997	1584	1.89	3520	47.16	6864	9.03	1584	15.15
1998	5984	0.17	7920	25.76	7798	21.54	880	4.55
1999	5104	5.09	3696	15.15	7920	10.73	352	0.00
2000	7568	1.19	4048	15.07	7744	32.41	352	0.00
2001	5984	3.68	4400	0.68	6512	61.27	1232	38.15
2002	4224	26.04	3168	0.95	7392	29.36	1056	1.89
2003	2816	0.00	2464	0.00	8976	9.47	1056	0.95
2004	6688	1.50	2112	0.00	4400	3.18	1056	4.73

Table C.4. **Fluvial Shiners** (river shiner, sand shiner, and bigmouth shiner): Summary of sampling effort (m^2) and catch per unit effort (C/E) (no. $1000\,m^{-2}$) of fish from August–October seine samples in the MRHD classified as age 1 by reach.

	Gavins Point		Upper Channelized	
Year	Effort	C/E	Effort	C/E
1983	5808	15.32	—	—
1984	2640	0.00	—	—
1985	10208	3.53	—	—
1986	4224	11.84	2464	4.46
1993	1408	8.52	3344	5.08
1994	1760	21.59	4224	18.94
1997	1056	70.08	5456	21.08
1998	5808	5.17	5510	5.99
1999	2112	22.73	7040	2.70
2000	1760	81.25	3520	37.50
2001	1936	0.52	4400	7.27
2002	2464	8.12	5632	4.62
2003	1760	38.07	6864	4.37
2004	2112	9.94	2464	4.06

Table C.5. **Silver Chub:** Summary of sampling effort (m^2) and catch per unit effort (C/E) (no. $1000\,m^{-2}$) of fish from July–October seine samples in the MRHD classified as age 0 by reach.

	Upper Channelized		Lower Channelized	
Year	Effort	C/E	Effort	C/E
1978	—	—	560	30.357
1986	3520	9.943	—	—
1993	3344	28.409	—	—
1994	4224	5.445	4048	3.458
1997	6864	1.166	1584	9.470
1998	7798	2.437	880	10.227
1999	7920	0.379	352	11.364
2000	7744	1.291	352	0.000
2001	6512	5.068	1232	21.916
2002	7392	0.947	1056	0.947
2003	8976	1.560	1056	1.894
2004	4400	7.045	1056	0.947

Table C.6. **Predictors – Fort Randall Reach:** Summary of predictor variables measured over the historic Missouri River spring rise period (March–July). Years correspond to sampling years minus one for the Fort Randall reach.

Year	Discharge (m^3s^{-1})	CV Discharge	Date Max. Discharge (ordinal date)	Rate of Rise ($m^3s^{-1}d^{-1}$)	Reversals	Temperature (°C)
1982	647	0.30	182	49	74	10.0
1983	499	0.48	209	57	50	8.1
1984	479	0.69	202	51	60	8.4
1985	652	0.29	199	37	56	11.4
1992	567	0.31	129	76	81	11.0
1993	247	0.83	147	127	80	8.0
1996	994	0.26	209	51	49	10.3
1997	1362	0.24	188	40	22	10.1
1998	630	0.18	199	28	59	9.7
1999	746	0.25	213	51	61	11.4
2000	767	0.19	136	24	67	12.4
2001	362	0.51	205	25	58	7.8
2002	606	0.20	185	21	77	10.1
2003	625	0.19	154	16	70	10.4

Table C.7. **Predictors – Gavins Point Reach:** Summary of predictor variables measured over the historic Missouri River spring rise period (March–July). Years correspond to sampling years minus one for the Gavins Point reach.

Year	Discharge (m^3s^{-1})	CV Discharge	Date Max. Discharge (ordinal date)	Rate of Rise ($m^3s^{-1}d^{-1}$)	Reversals	Temperature (°C)	Turbidity (NTU)
1982	742	0.22	212	27	19	13.8	152
1983	623	0.32	201	37	19	13.3	149
1984	619	0.40	197	42	32	13.6	209
1985	745	0.20	200	25	14	15.1	120
1992	636	0.25	130	90	50	14.3	109
1993	375	0.38	148	111	42	13.5	217
1996	1129	0.20	198	49	24	12.9	123
1997	1511	0.20	190	39	22	12.8	94
1998	782	0.12	139	35	12	14.3	149
1999	912	0.17	207	41	44	14.4	113
2000	848	0.17	141	28	13	15.1	43
2001	478	0.26	203	27	18	13.9	132
2002	645	0.16	213	20	10	13.5	39
2003	676	0.17	120	21	16	14.2	106

Table C.8. **Predictors – Upper Channelized Reach:** Summary of predictor variables measured over the historic Missouri River spring rise period (March–July). Years correspond to sampling years and sampling years minus one for the upper channelized reach.

Year	Discharge (m^3s^{-1})	CV Discharge	Date Max. Discharge (ordinal date)	Rate of Rise ($m^3s^{-1}d^{-1}$)	Reversals	Temperature (°C)	Turbidity (NTU)
1985	1102	0.13	115	51	50	16.5	120
1986	1424	0.20	79	81	50	16.7	149
1992	899	0.20	197	46	61	16.1	109
1993	1473	0.37	192	117	53	15.0	217
1994	1209	0.15	179	44	52	16.5	112
1996	1540	0.26	175	83	39	14.7	123
1997	2171	0.19	107	51	51	14.6	94
1998	1126	0.15	177	54	46	16.4	149
1999	1376	0.16	185	62	51	16.3	113
2000	1004	0.18	179	26	58	18.0	43
2001	1071	0.31	120	61	50	16.8	132
2002	775	0.16	164	24	53	17.2	39
2003	859	0.24	193	47	45	16.8	106
2004	881	0.26	132	42	53	17.8	126

Table C.9. **Predictors – Lower Channelized Reach:** Summary of predictor variables measured over the historic Missouri River spring rise period (March–July). Years correspond to sampling years and sampling years minus one for the upper channelized reach.

Year	Discharge (m^3s^{-1})	CV Discharge	Date Max. Discharge (ordinal date)	Rate of Rise ($m^3s^{-1}d^{-1}$)	Reversals	Temperature (°C)	Turbidity (NTU)
1977	1055	0.14	150	36	57	17.2	63
1978	1475	0.35	82	102	35	14.6	104
1993	1973	0.45	207	176	55	15.0	217
1994	1395	0.17	67	81	49	16.5	112
1996	1754	0.28	176	102	44	14.7	123
1997	2305	0.17	109	55	37	14.6	94
1998	1476	0.22	167	97	41	16.4	149
1999	1703	0.20	181	79	49	16.3	113
2000	1123	0.15	179	37	59	18.0	43
2001	1382	0.30	127	79	39	16.8	132
2002	901	0.15	165	29	47	17.2	39
2003	1018	0.22	127	64	45	16.8	106
2004	1074	0.27	146	57	48	17.8	126

C.2 Results

Table C.10. **Fort Randall Reach – River Carpsucker:** Summary of BMA results of C/E of Age 1 fish. Columns two–four are the posterior effect probabilities, mean parameter estimates, and standard deviations given the data (D), respectively. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, R^2 values, BIC values, and posterior model probalities (PMP).

Variable	$P(\beta \neq 0 \mid D)$ (%)	Mean $\beta \mid D$	SD $\beta \mid D$	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	100.0	-0.2660	3.1040	1.2548	0.1209	1.8194	0.8876	1.0363
Discharge	26.0	-0.0003	0.0009	—	—	-0.0009	—	—
CV Discharge	14.6	0.1588	0.8200	—	—	—	—	0.5059
Date Max. Disch.	24.3	0.0027	0.0083	—	—	—	—	—
Rate of Rise	19.4	0.0016	0.0064	—	—	—	0.0074	—
Reversals	31.0	0.0068	0.0167	—	0.0189	—	—	—
Temperature	28.4	0.0668	0.1887	—	—	—	—	—
No. Variables				0	1	1	1	1
R^2				0.00	0.08	0.06	0.04	0.01
BIC				0.00	1.49	1.79	2.12	2.46
PMP				0.18	0.09	0.07	0.06	0.05

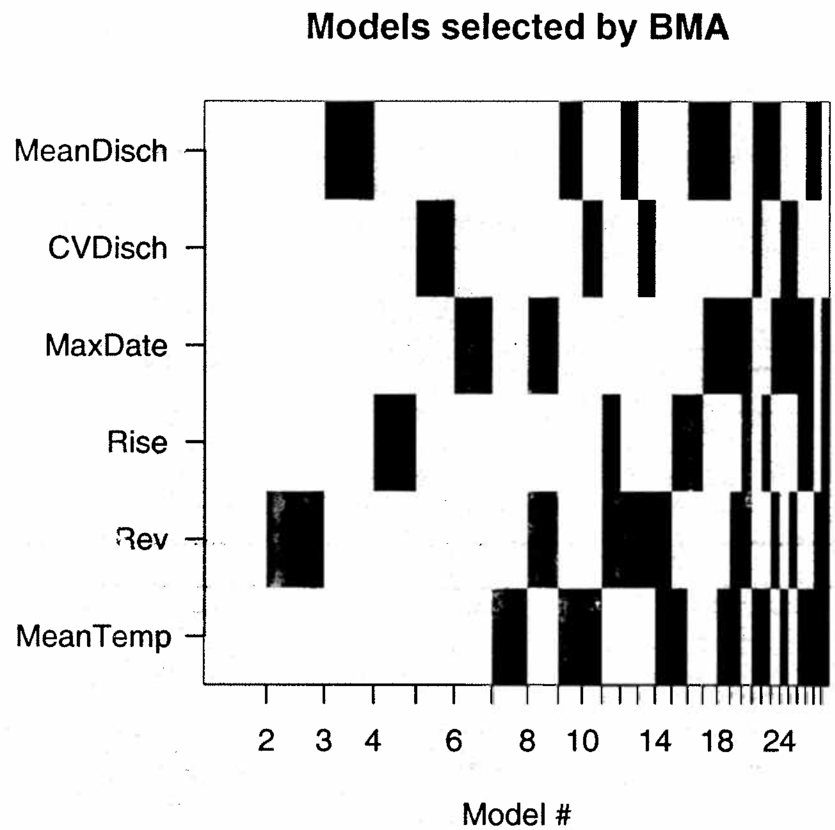

Figure C.1. **Fort Randall Reach – River Carpsucker:** Visual summary of BMA. Rows correspond to the predictor variables. Columns correspond to the subset of models supported by the data using the Occam's window method of Madigan and Raftery (1994). For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's posterior probability.

Table C.11. **Fort Randall Reach – Red Shiner:** Summary of BMA results of C/E of Age 1 fish. Columns two–four are the posterior effect probabilities, mean parameter estimates, and standard deviations given the data (D), respectively. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, R^2 values, BIC values, and posterior model probalities (PMP).

Variable	$P(\beta \neq 0 \mid D)$ (%)	Mean $\beta \mid D$	SD $\beta \mid D$	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	100.0	14.8070	3.4055	16.4112	12.4075	16.4905	16.4820	12.6423
Discharge	100.0	-0.0075	0.0013	-0.0077	-0.0069	-0.0079	-0.0077	-0.0071
CV Discharge	100.0	-4.7141	1.1887	-4.6592	-4.4855	-5.0992	-4.6929	-5.0156
Date Max. Disch.	59.0	-0.0070	0.0084	-0.0120	—	-0.0117	-0.0121	—
Rate of Rise	26.6	0.0015	0.0053	—	—	0.0051	—	0.0061
Reversals	100.0	-0.0980	0.0211	-0.1051	-0.0860	-0.1071	-0.1045	-0.0891
Temperature	21.1	0.0004	0.1029	—	—	—	-0.0115	—
No. Variables				4	3	5	5	4
R^2				0.84	0.80	0.85	0.84	0.81
BIC				-15.06	-14.31	-13.00	-12.42	-12.32
PMP				0.34	0.24	0.12	0.09	0.09

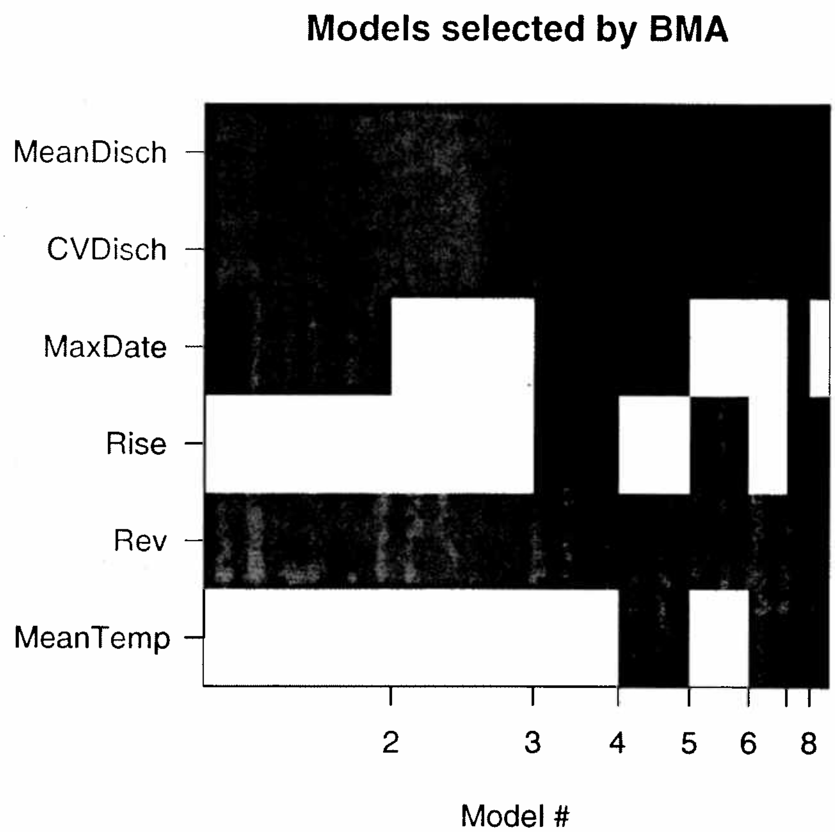

Figure C.2. **Fort Randall Reach – Red Shiner:** Visual summary of BMA. Rows correspond to the predictor variables. Columns correspond to the subset of models supported by the data using the Occam's window method of Madigan and Raftery (1994). For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's posterior probability.

Table C.12. **Gavins Point Reach – Emerald Shiner:** Summary of BMA results of C/E of Age 1 fish. Columns two–four are the posterior effect probabilities, mean parameter estimates, and standard deviations given the data (D), respectively. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, R^2 values, BIC values, and posterior model probalities (PMP).

Variable	$P(\beta \neq 0\|D)$ (%)	Mean $\beta\|D$	SD $\beta\|D$	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	100.0	1.7833	5.5387	3.6617	2.8170	-1.5766	4.2028	4.5795
Discharge	15.1	-0.0001	0.0006	—	—	—	-0.0007	—
CV Discharge	19.4	-0.9619	3.5575	—	—	—	—	—
Date Max. Disch.	10.1	-0.0005	0.0049	—	—	—	—	-0.0049
Rate of Rise	12.6	-0.0002	0.0097	—	—	—	—	—
Reversals	41.3	0.0236	0.0443	—	0.0367	—	—	—
Temperature	25.1	0.1258	0.3617	—	—	0.3781	—	—
Turbidity	15.6	0.0002	0.0052	—	—	—	—	—
No. Variables				0	1	1	1	1
R^2				0.00	0.07	0.05	0.03	0.01
BIC				0.00	1.65	1.97	2.22	2.43
PMP				0.18	0.08	0.07	0.06	0.05

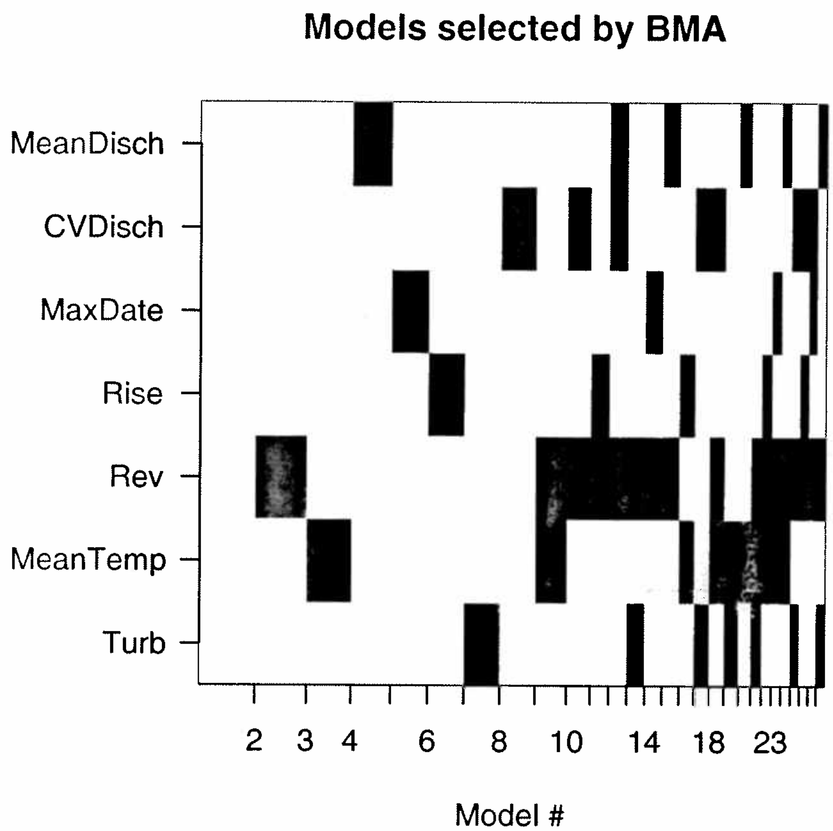

Figure C.3. **Gavins Point Reach – Emerald Shiner:** Visual summary of BMA. Rows correspond to the predictor variables. Columns correspond to the subset of models supported by the data using the Occam's window method of Madigan and Raftery (1994). For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's posterior probability.

Table C.13. **Gavins Point Reach – River Carpsucker:** Summary of BMA results of C/E of Age 1 fish. Columns two–four are the posterior effect probabilities, mean parameter estimates, and standard deviations given the data (D), respectively. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, R^2 values, BIC values, and posterior model probalities (PMP).

Variable	$P(\beta \neq 0 \mid D)$ (%)	Mean $\beta \mid D$	SD $\beta \mid D$	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	100.0	7.2970	4.4611	5.0560	5.2700	10.6000	10.0200	4.5770
Discharge	20.8	0.0000	0.0005	—	—	—	—	0.0004
CV Discharge	96.1	-11.8800	4.8181	-14.4700	-9.9570	-15.2300	-11.0900	-13.7100
Date Max. Disch.	17.0	-0.0001	0.0035	—	—	—	—	—
Rate of Rise	26.4	0.0028	0.0105	—	—	—	—	—
Reversals	81.9	0.0476	0.0333	0.0591	0.0610	0.0578	0.0597	0.0571
Temperature	37.3	-0.1460	0.2865	—	—	-0.3852	-0.3316	—
Turbidity	47.4	-0.0051	0.0077	—	-0.0101	—	-0.0090	—
No. Variables				2	3	3	4	3
R^2				0.74	0.78	0.77	0.81	0.74
BIC				-13.29	-13.28	-12.70	-12.42	-11.05
PMP				0.11	0.11	0.09	0.07	0.04

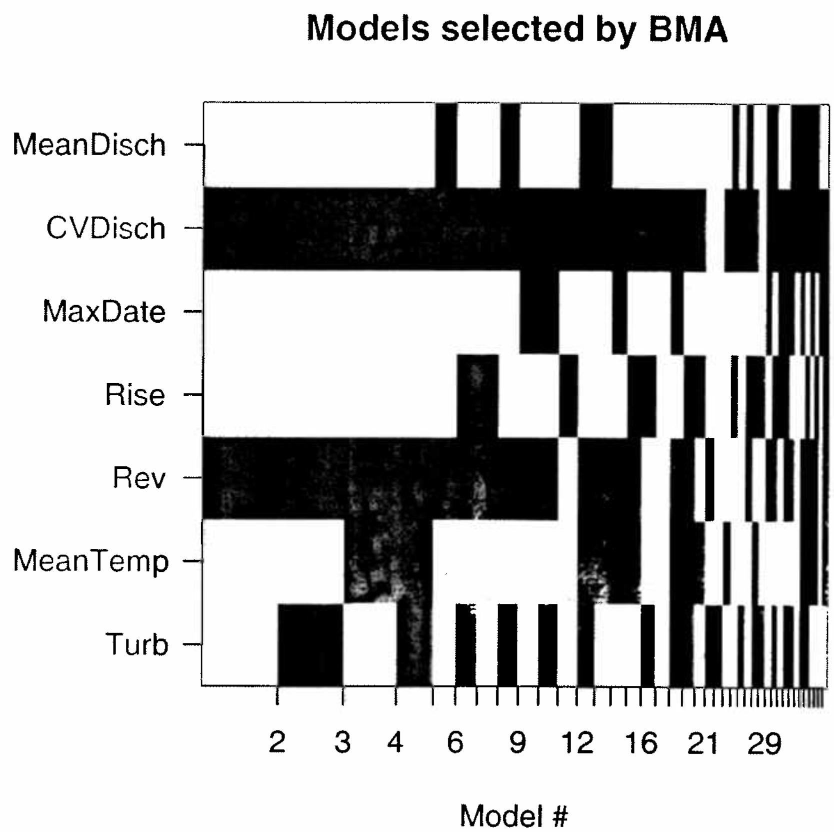

Figure C.4. **Gavins Point Reach – River Carpsucker:** Visual summary of BMA. Rows correspond to the predictor variables. Columns correspond to the subset of models supported by the data using the Occam's window method of Madigan and Raftery (1994). For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's posterior probability.

Table C.14. **Gavins Point Reach – Red Shiner:** Summary of BMA results of C/E of Age 1 fish. Columns two–four are the posterior effect probabilities, mean parameter estimates, and standard deviations given the data (D), respectively. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, R^2 values, BIC values, and posterior model probalities (PMP).

Variable	$P(\beta \neq 0 \mid D)$ (%)	Mean $\beta \mid D$	SD $\beta \mid D$	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	100.0	-4.8992	7.7126	-0.7548	-0.9178	-16.9286	-2.1381	-3.1432
Discharge	99.4	0.0032	0.0012	0.0031	0.0031	0.0039	0.0029	0.0026
CV Discharge	63.9	-5.6781	6.1679	-10.0732	—	-9.1336	-10.8459	-12.3817
Date Max. Disch.	42.7	0.0065	0.0111	—	—	0.0238	0.0093	0.0151
Rate of Rise	36.6	0.0100	0.0209	—	—	0.0502	—	0.0210
Reversals	24.7	-0.0066	0.0247	—	—	-0.0536	—	—
Temperature	37.1	0.1907	0.4059	—	—	0.7356	—	—
Turbidity	58.3	0.0090	0.0105	0.0174	—	0.0171	0.0170	0.0152
No. Variables				3	1	7	4	5
R^2				0.65	0.48	0.83	0.68	0.73
BIC				-6.79	-6.50	-5.94	-5.49	-4.96
PMP				0.10	0.09	0.07	0.06	0.04

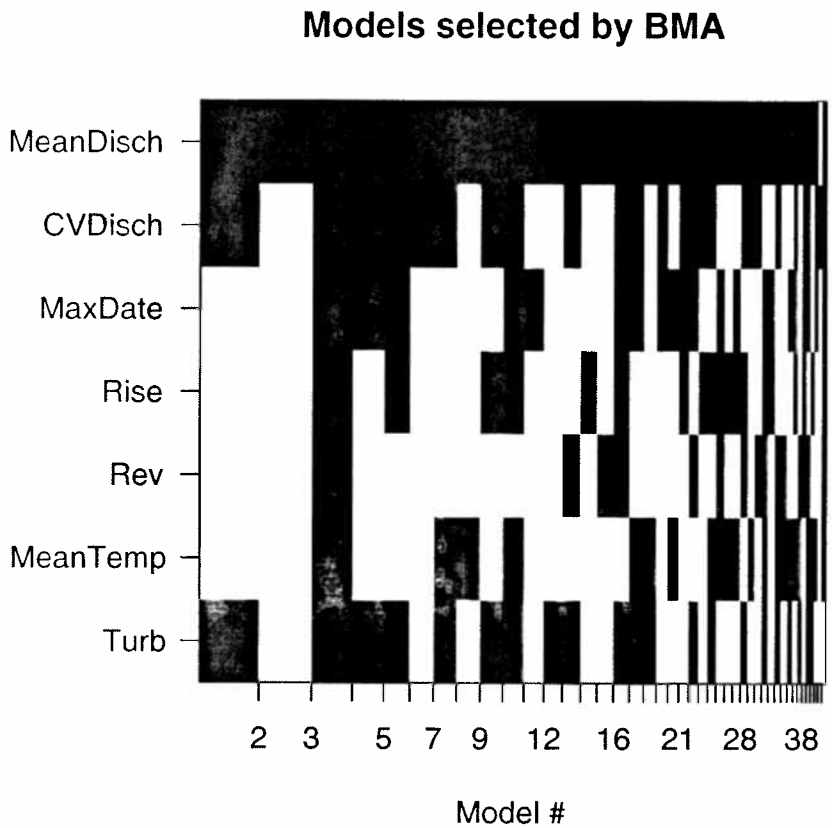

Figure C.5. **Gavins Point Reach – Red Shiner:** Visual summary of BMA. Rows correspond to the predictor variables. Columns correspond to the subset of models supported by the data using the Occam's window method of Madigan and Raftery (1994). For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's posterior probability.

Table C.15. **Gavins Point Reach – Fluvial Shiners** (river shiner, sand shiner, bigmouth shiner): Summary of BMA results of C/E of Age 1 fish. Columns two–four are the posterior effect probabilities, mean parameter estimates, and standard deviations given the data (D), respectively. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, R^2 values, BIC values, and posterior model probalities (PMP).

Variable	$P(\beta \neq 0 \mid D)$ (%)	Mean $\beta \mid D$	SD $\beta \mid D$	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	100.0	2.5350	4.5511	2.6986	0.5741	1.3939	3.0680	-0.3177
Discharge	32.9	-0.0004	0.0009	—	—	-0.0010	—	—
CV Discharge	93.4	-14.2800	7.4007	-16.9594	-18.4081	-19.4428	-14.0266	-17.4352
Date Max. Disch.	44.7	0.0064	0.0104	—	0.0120	0.0144	—	0.0171
Rate of Rise	29.9	0.0051	0.0152	—	—	—	—	0.0297
Reversals	61.2	0.0364	0.0409	0.0530	0.0626	0.0700	—	—
Temperature	19.9	-0.0291	0.2496	—	—	—	—	—
Turbidity	68.7	0.0117	0.0114	0.0177	0.0178	0.0152	0.0186	0.0180
No. Variables				3	4	5	2	4
R^2				0.53	0.60	0.65	0.39	0.56
BIC				-2.59	-2.31	-1.61	-1.56	-1.03
PMP				0.09	0.08	0.06	0.05	0.04

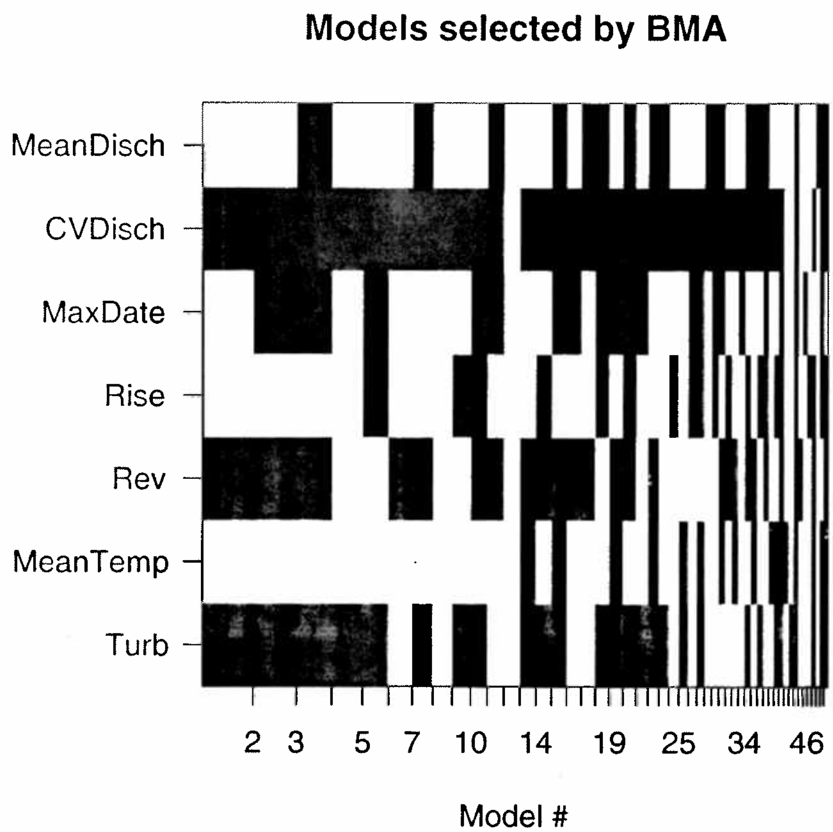

Figure C.6. **Gavins Point Reach – Fluvial Shiners** (river shiner, sand shiner, bigmouth shiner): Visual summary of BMA. Rows correspond to the predictor variables. Columns correspond to the subset of models supported by the data using the Occam's window method of Madigan and Raftery (1994). For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's posterior probability.

Table C.16. **Channelized Reaches – Emerald Shiner:** Summary of BMA results of C/E of Age 1 fish. Columns two–four are the posterior effect probabilities, mean parameter estimates, and standard deviations given the data (D), respectively. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, R^2 values, BIC values, and posterior model probalities (PMP).

Variable	$P(\beta \neq 0 \mid D)$ (%)	Mean $\beta \mid D$	SD $\beta \mid D$	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	100.0	-0.1325	2.1291	-0.5134	1.6453	0.5691	0.7657	-1.9999
ReachUC	57.6	0.4529	0.5423	0.7718	—	—	0.6989	0.7683
Discharge	11.2	0.0000	0.0002	—	—	—	—	—
CV Discharge	98.3	7.3220	2.6773	7.4030	6.9839	6.0819	8.2645	7.1764
Date Max. Disch.	55.8	0.0048	0.0059	0.0088	—	0.0080	—	0.0082
Rate of Rise	18.1	0.0004	0.0061	—	—	—	—	—
Reversals	25.4	0.0088	0.0224	—	—	—	—	0.0328
Temperature	12.0	0.0093	0.0786	—	—	—	—	—
Turbidity	16.7	-0.0006	0.0028	—	—	—	—	—
No. Variables				3	1	2	2	4
R^2				0.65	0.50	0.57	0.57	0.67
BIC				-9.99	-9.66	-9.30	-9.27	-8.61
PMP				0.10	0.09	0.07	0.07	0.05

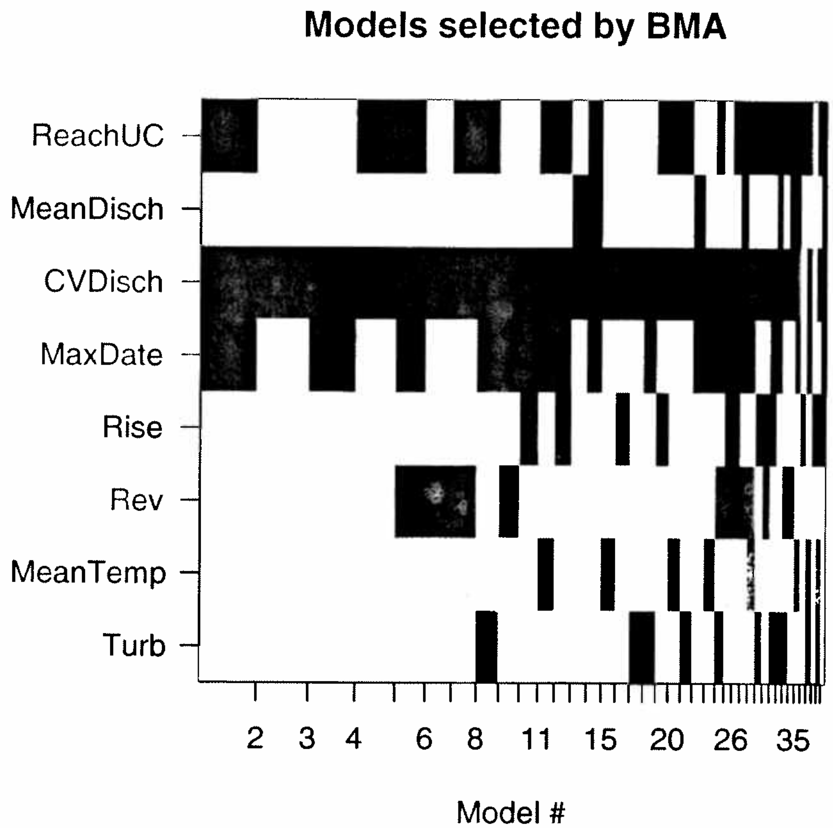

Figure C.7. **Channelized Reaches – Emerald Shiner:** Visual summary of BMA. Rows correspond to the predictor variables. Columns correspond to the subset of models supported by the data using the Occam's window method of Madigan and Raftery (1994). For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's posterior probability.

Table C.17. **Channelized Reaches – River Carpsucker:** Summary of BMA results of C/E of Age 1 fish. Columns two–four are the posterior effect probabilities, mean parameter estimates, and standard deviations given the data (D), respectively. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, R^2 values, BIC values, and posterior model probalities (PMP).

Variable	$P(\beta \neq 0 \mid D)$ (%)	Mean $\beta \mid D$	SD $\beta \mid D$	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	100.0	-10.4900	8.4066	-16.4860	-12.4347	-13.4657	-0.7788	-14.4049
ReachUC	91.4	1.3860	0.7287	1.7031	1.3384	1.7136	1.0702	1.4747
Discharge	100.0	0.0024	0.0009	0.0029	0.0028	0.0027	0.0015	0.0029
CV Discharge	55.3	2.9500	3.6643	3.7555	—	6.0723	—	6.3701
Date Max. Disch.	14.7	0.0002	0.0026	—	—	—	—	—
Rate of Rise	26.0	-0.0002	0.0095	—	—	—	—	-0.0097
Reversals	14.8	-0.0004	0.0135	—	—	—	—	—
Temperature	71.2	0.4831	0.4191	0.7717	0.6020	0.6118	—	0.6565
Turbidity	34.1	-0.0025	0.0050	—	—	-0.0065	—	—
No. Variables				4	3	5	2	5
R^2				0.60	0.53	0.65	0.41	0.62
BIC				-6.47	-6.04	-5.92	-4.54	-4.38
PMP				0.13	0.10	0.10	0.05	0.04

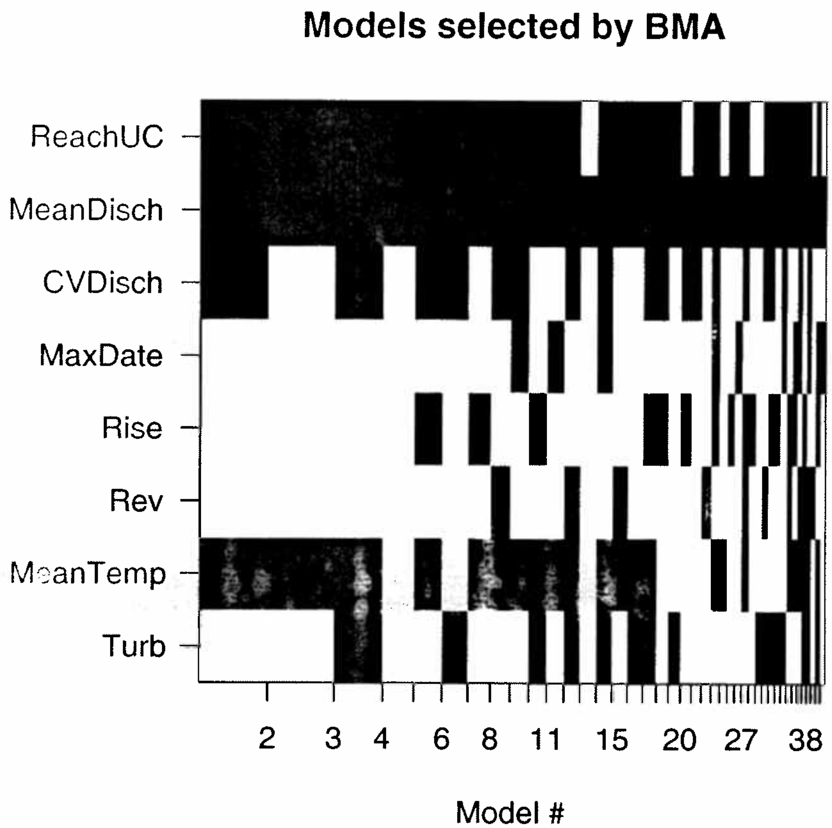

Figure C.8. **Channelized Reaches – River Carpsucker:** Visual summary of BMA. Rows correspond to the predictor variables. Columns correspond to the subset of models supported by the data using the Occam's window method of Madigan and Raftery (1994). For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's posterior probability.

Table C.18. **Channelized Reaches – Red Shiner:** Summary of BMA results of C/E of Age 1 fish. Columns two–four are the posterior effect probabilities, mean parameter estimates, and standard deviations given the data (D), respectively. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, R^2 values, BIC values, and posterior model probalities (PMP).

Variable	$P(\beta \neq 0 \mid D)$ (%)	Mean $\beta \mid D$	SD $\beta \mid D$	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	100.0	-14.7800	6.2067	-16.3018	-15.5750	-14.7188	-15.0254	-15.3901
ReachUC	100.0	1.5320	0.4818	1.6053	1.5598	1.5525	1.4933	1.5609
Discharge	95.9	0.0020	0.0008	0.0021	0.0020	0.0021	0.0021	0.0020
CV Discharge	15.3	-0.0781	0.9692	—	—	—	—	—
Date Max. Disch.	17.9	-0.0005	0.0026	—	—	—	—	-0.0019
Rate of Rise	15.9	-0.0004	0.0033	—	—	—	-0.0025	—
Reversals	26.4	0.0081	0.0213	—	0.0235	—	—	—
Temperature	95.9	0.8202	0.3294	0.9122	0.8099	0.8368	0.8520	0.8856
Turbidity	16.7	-0.0003	0.0019	—	—	-0.0019	—	—
No. Variables				3	4	4	4	4
R^2				0.56	0.58	0.57	0.56	0.56
BIC				-8.11	-5.92	-5.40	-5.27	-5.25
PMP				0.32	0.11	0.08	0.08	0.08

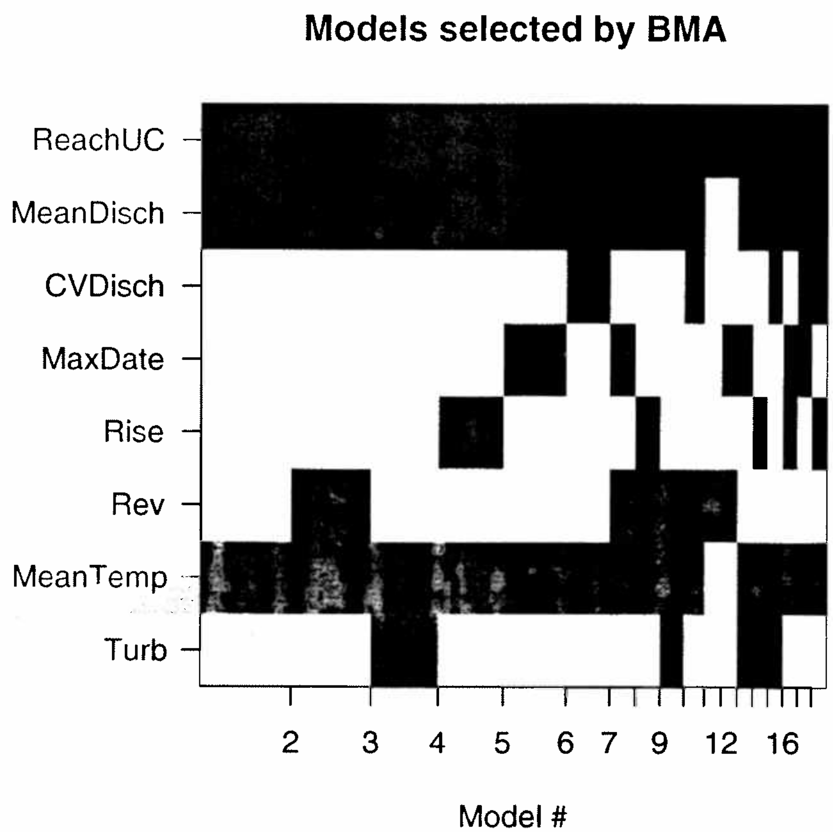

Figure C.9. **Channelized Reaches – Red Shiner:** Visual summary of BMA. Rows correspond to the predictor variables. Columns correspond to the subset of models supported by the data using the Occam's window method of Madigan and Raftery (1994). For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's posterior probability.

Table C.19. **Upper Channelized Reach – Fluvial Shiners** (river shiner, sand shiner, bigmouth shiner): Summary of BMA results of C/E of Age 1 fish. Columns two–four are the posterior effect probabilities, mean parameter estimates, and standard deviations given the data (D), respectively. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, R^2 values, BIC values, and posterior model probalities (PMP).

Variable	$P(\beta \neq 0\|D)$ (%)	Mean $\beta\|D$	SD $\beta\|D$	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	100.0	-1.8240	4.4220	-2.9500	-3.7060	1.7720	-5.9410	1.3570
Discharge	31.6	0.0001	0.0004	—	—	—	0.0004	—
CV Discharge	74.9	-4.0530	3.6849	-5.9440	-6.5660	-4.0650	-5.8820	—
Date Max. Disch.	35.1	0.0014	0.0039	—	—	—	—	—
Rate of Rise	100.0	0.0709	0.0214	0.0825	0.0858	0.0645	0.0831	0.0525
Reversals	36.1	0.0079	0.0194	—	0.0229	—	—	—
Temperature	54.5	0.1614	0.2413	0.2774	0.2525	—	0.4259	—
Turbidity	100.0	-0.0234	0.0068	-0.0257	-0.0260	-0.0223	-0.0252	-0.0203
No. Variables				4	5	3	5	2
R^2				0.85	0.87	0.78	0.86	0.72
BIC				-10.96	-10.36	-9.66	-9.53	-9.28
PMP				0.13	0.10	0.07	0.06	0.06

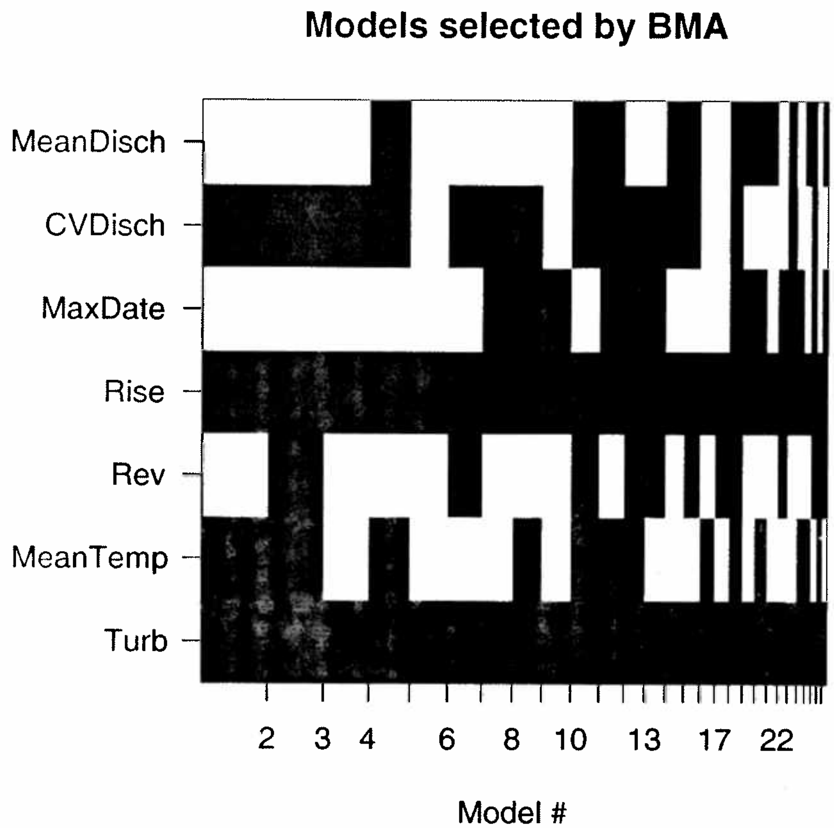

Figure C.10. **Upper Channelized Reach – Fluvial Shiners** (river shiner, sand shiner, bigmouth shiner): Visual summary of BMA. Rows correspond to the predictor variables. Columns correspond to the subset of models supported by the data using the Occam's window method of Madigan and Raftery (1994). For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's posterior probability.

Table C.20. **Channelized Reaches – Silver Chub:** Summary of BMA results of C/E of Age 0 fish. Columns two–four are the posterior effect probabilities, mean parameter estimates, and standard deviations given the data (D), respectively. The following five columns show the parameter estimates for the five top ranked models along with the numbers of predictor variables included, R^2 values, BIC values, and posterior model probalities (PMP).

Variable	$P(\beta \neq 0 \mid D)$ (%)	Mean $\beta \mid D$	SD $\beta \mid D$	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	100.0	-0.7267	1.7264	-1.1322	-0.1636	-1.0915	-0.6573	-0.3714
ReachUC	24.2	-0.1208	0.3114	—	—	—	-0.5635	—
Discharge	8.7	0.0000	0.0001	—	—	—	—	—
CV Discharge	82.4	5.0800	3.5923	5.9919	5.6804	6.0971	5.9687	—
Date Max. Disch.	34.8	-0.0019	0.0036	—	-0.0058	—	—	—
Rate of Rise	34.1	0.0054	0.0107	—	—	0.0177	—	—
Reversals	10.0	-0.0006	0.0127	—	—	—	—	—
Temperature	12.9	0.0130	0.0790	—	—	—	—	—
Turbidity	68.1	0.0068	0.0062	0.0095	0.0093	—	0.0095	0.0139
No. Variables				2	3	2	3	1
R^2				0.53	0.59	0.52	0.58	0.41
BIC				-9.69	-9.50	-9.42	-8.94	-8.06
PMP				0.10	0.09	0.08	0.07	0.04

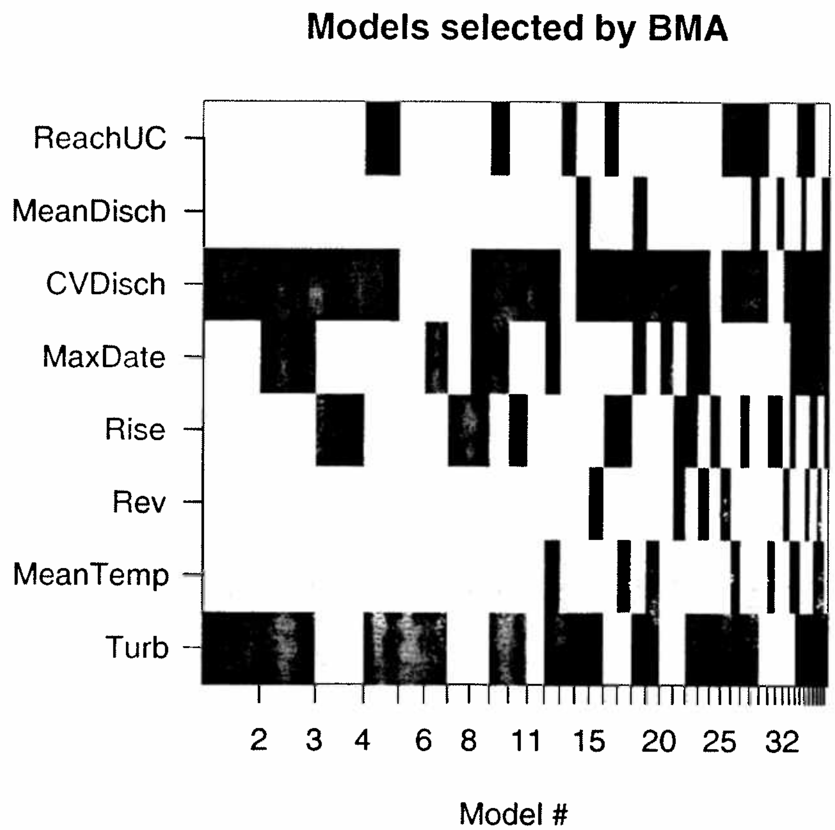

Figure C.11. **Channelized Reaches – Silver Chub:** Visual summary of BMA. Rows correspond to the predictor variables. Columns correspond to the subset of models supported by the data using the Occam's window method of Madigan and Raftery (1994). For each row-column combination, the corresponding rectangle is black if the predictor variable was included in the model and white otherwise. The width of each column is proportional to the model's posterior probability.