EVALUATION OF THE LAGRANGIAN SCHEME FOR SAMPLING THE MISSISSIPPI RIVER DURING 1987-90

by John A. Moody

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CONVERSION FACTORS

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer
	Velocity	
mile per hour (mi/h)	0.447	meter per second
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

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ABSTRACT

The ideal Lagrangian scheme for sampling rivers is to collect an initial sample of the water, to follow this water downstream, and to collect additional samples from the same water at later times. The scheme is evaluated for six sampling cruises that were conducted during July 1987 to March 1990 along a 1,120-mile reach of the Mississippi River from near St. Louis, Missouri, to below New Orleans, Louisiana. The additional samples collected downstream were not from the same water but sometimes upstream and sometimes downstream from the initial water sample. The collective water mass is bounded by the sample that is farthest downstream and by the sample that is farthest upstream. The length of this collective water mass is determined for each cruise by using a one-dimensional routing method. The relative location of each sample in the collective water mass is listed in tables for each day of each cruise.

The greatest length of the collective water mass occurred during high-water conditions in June 1989, when the length of the collective water mass reached 531 miles as a result of delays owing to ship repairs, crew changes, and tributary sampling. The samples collected during low-water conditions in May and June of 1988, were closest to the ideal Lagrangian scheme, having a collective water mass length that was about 137 miles.

The estimated length of the collective water mass for all six cruises ranged from 12 to 30 percent of the total flow past a fixed point for a period equal to the length of each cruise. Estimates of the error in the evaluation method indicate that these estimates of the length of the collective water mass are a maximum and that the actual length was probably less than those listed in this report.

INTRODUCTION

The ideal Lagrangian scheme for sampling rivers is to collect an initial sample of the water, to follow this same mass of water in the river, and to collect additional samples in a downstream spatial sequence so that chemical, physical, and hydrologic processes altering the characteristics of the water mass can be investigated. The additional samples collected at sites downstream define individual water masses that, in practice, do not coincide with the initial water mass but are sometimes upstream and sometimes downstream from the initial water mass. The individual water masses have an approximate length equal to the product of the time required to collect the water sample (1 to 6 hours centered around noon; Moody and Meade, 1992) and the mean cross-sectional velocity (1 to 4 mi/h; Moody and Meade, 1992, 1993) or about 1 to 24 mi. The water within and between these individual water masses is defined as the collective water mass. The length of the collective water mass is the distance between the midpoint of the individual water mass that is farthest downstream in the Mississippi River and the midpoint of the individual water mass that is farthest upstream in the Mississippi River and is shown schematically in figure 1. The length does not include those individual water masses still in tributaries. The Lagrangian sampling scheme has an advantage over the traditional Eulerian sampling scheme in

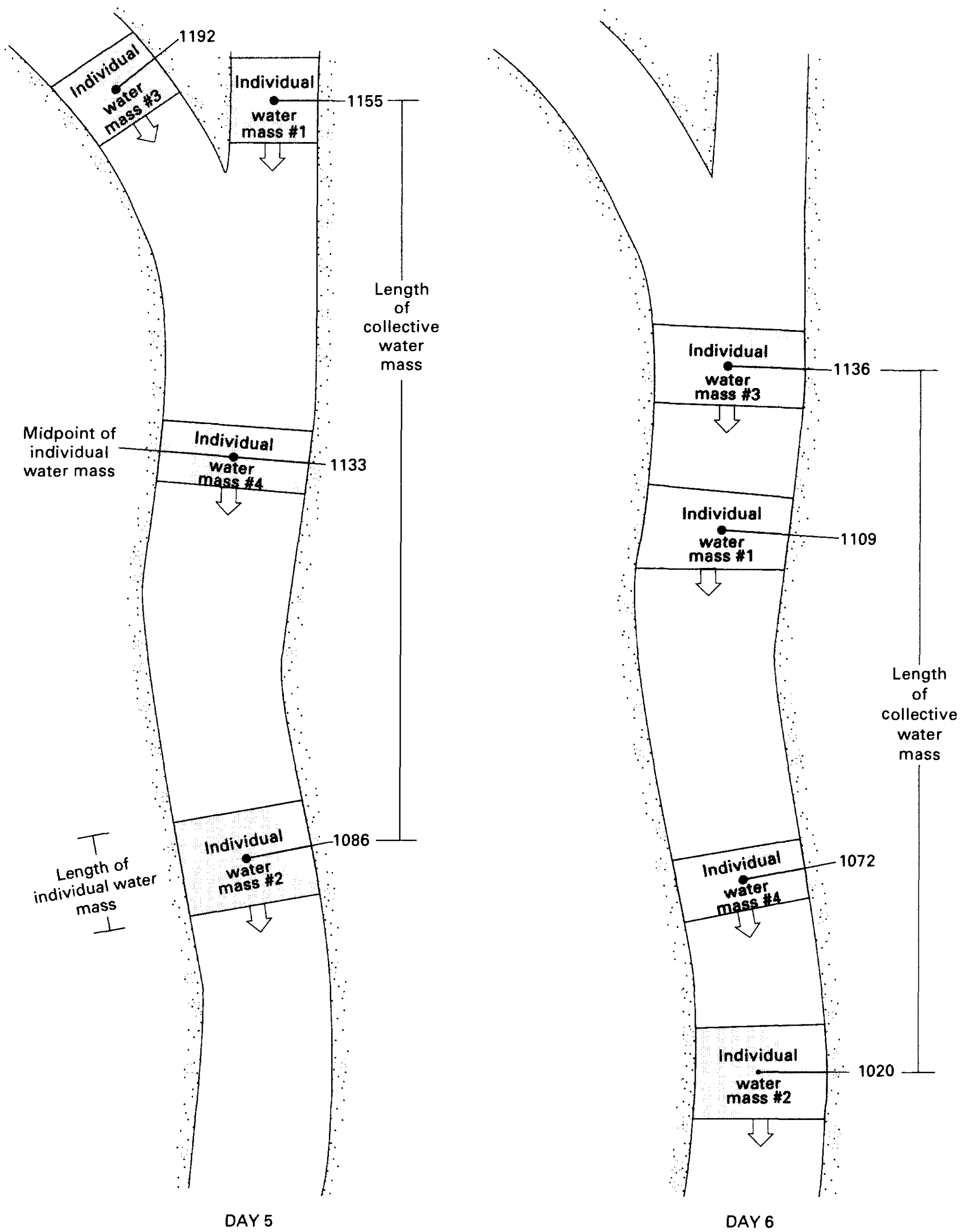

Figure 1.--Conceptual diagram showing the individual and collective water masses. The individual water masses are numbered in the order in which they were collected. Number 1 (#1) is the initial sample and number 2 (#2), 3 (#3), and 4 (#4) are additional samples. The numbers along the left descending bank are the river miles (upstream from a reference point) of the midpoint of each individual water mass. On day 5, individual water mass #3, at mile 1192, is still in a tributary and not part of the collective water mass, so that the length of the collective water mass is the distance between the midpoint of the individual water mass that is farthest downstream (#2) and the midpoint of the individual water mass that is farthest upstream (# 1) or 69 miles. On day 6, the individual water mass #3 has joined the mainstem and is the farthest upstream so that it becomes the upper bound and the length of the collective water mass is 116 miles.

which samples are collected in a time sequence at a fixed point, in that the data can be used to construct transport models of dissolved chemicals, suspended sediment, and the chemicals associated with suspended sediment (Meade and Stevens, 1990). The Lagrangian scheme has been used in two large rivers (Orinoco and Amazon) of South America (Meade and others, 1983; Nordin and others, 1983; Meade, 1985; Meade and others, 1985; Hedges and others, 1986; and Richey and others, 1986) where the typical annual graph of river stage is basically a sinusoidal-shaped curve with only very small variations about a monthly mean (fig. 2A). Sample collection that deviates from the ideal Lagrangian scheme on these rivers probably is of little consequence because the spatial variability of dissolved chemicals or suspended sediment in the river probably is small -- similar to the annual variability in river stage. The Orinoco and Amazon Rivers are still virtually natural rivers in contrast to some of the large regulated rivers of North America like the Mississippi River. An annual graph of river stage for the Mississippi River is also basically a sinusoidal-shaped curve but has large amplitude variations that occur about every 3 to 4 weeks (fig. 2B), and reflect the narrowing of the flood plain with manmade levees and the periodic occurrence of temperate cyclonic storms.

To interpret chemical data derived from Lagrangian sampling of the Mississippi and similar rivers, it is important to know (1) how far the individual water masses are from the center of the initial water mass, and (2) the natural spatial variability of dissolved chemicals in the rivers (Moody and Goolsby, 1993). Small deviations in distance of the individual water masses from the center of the initial water mass can produce large changes in concentrations that are caused by spatial variability and not by chemical, physical, or hydrological processes.

The U.S. Geological Survey used the Lagrangian sampling scheme on a 320-mi reach of the Mississippi River upstream from its mouth between 1983 and 1985 to study transport of suspended sediment and associated chemicals (Demas and Curwick, 1987; 1988). Later, the U.S. Geological Survey did a study of sediment-transported contaminants by using the Lagrangian sampling scheme along the lower 1,120 mi of the Mississippi River (Pereira and others, 1990; 1992; Leenheer and others, 1989; Rees and Ranville, 1990; and Taylor and others, 1990). This study used the 57-ft research vessel ACADIANA (owned and operated by the Louisiana Universities' Marine Consortium) to follow and sample the water downstream.

Purpose and Scope

This report evaluates the Lagrangian scheme for collecting water samples during six sampling cruises on the Mississippi River and some of its tributaries in July-August 1987; November-December 1987; May-June 1988; March-April 1989; June 1989; and March 1990. During these cruises water samples were collected from 24 sites along a 1,120-mi reach of the Mississippi River starting about 60 mi north of St. Louis, Missouri, and ending about 70 mi north of the mouth of the Mississippi River. Water samples also were collected from sites within 100 mi of the mouth of the following tributaries: Illinois, Missouri, Ohio, White, Arkansas and Yazoo Rivers. The Lagrangian sampling sites are shown in figure 3 and listed in table 1. Ideally, the Lagrangian sampling scheme would result in the midpoint of all individual water masses being at the same location as the initial water sample and the length of the collective water mass would be zero. Therefore, the Lagrangian scheme is evaluated by estimating the relative location of each individual water mass inside the collective water mass and the length of the collective water mass. This information is provided so that it can be combined with data on spatial variability to aid in the interpretation of Lagrangian data sets, especially those involving chemical data, and to aid in planning future Lagrangian sampling of other rivers.

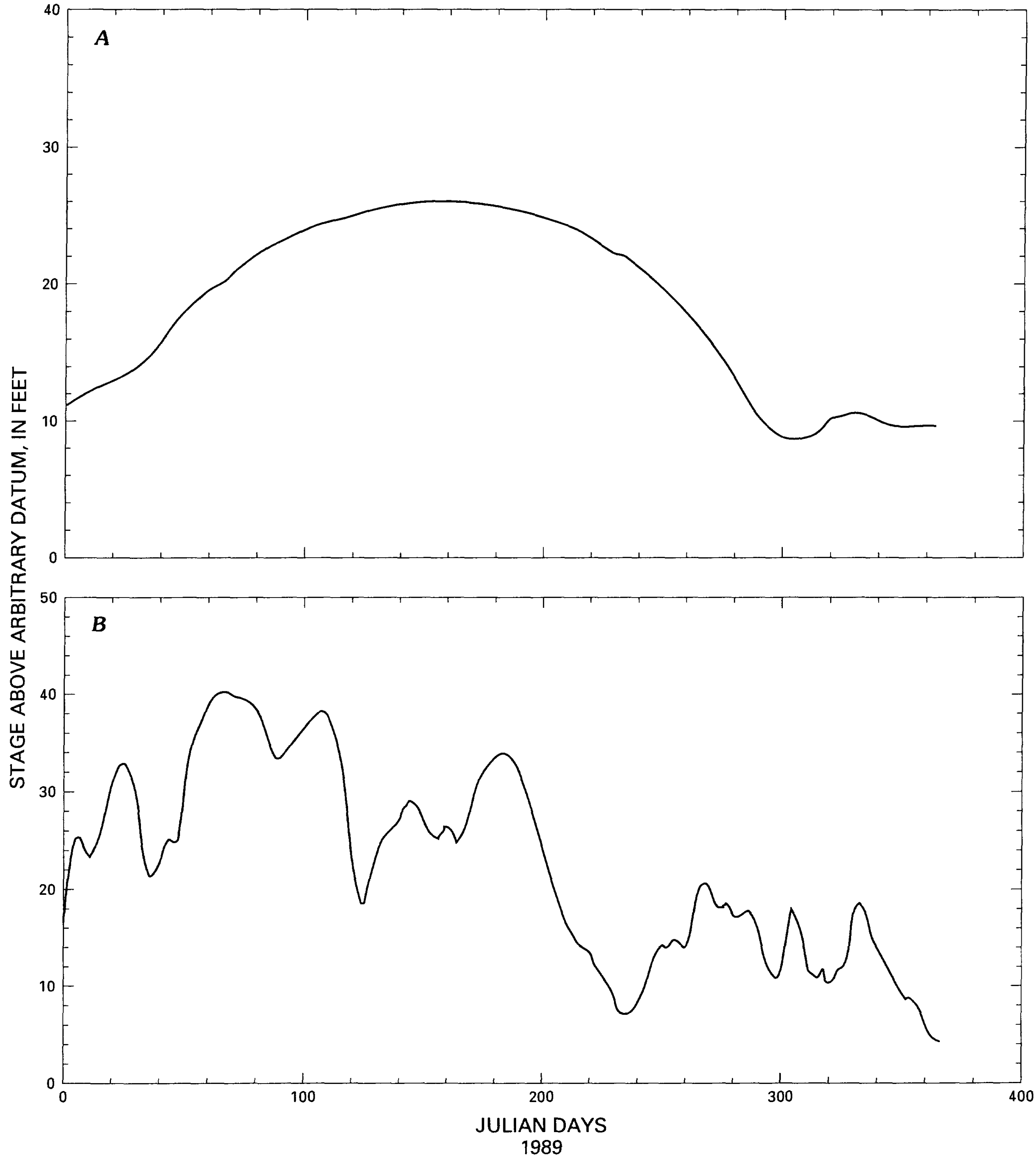

Figure 2. Daily stages for 1989 in the A. Amazon River at Obidos, Brazil (data supplied by Companhia de Pesquisas de Recursos Minerais, Belém), and B. Mississippi River at Vicksburg, Mississippi, U.S.A. (data supplied by U.S. Army Corps of Engineers, Vicksburg District).

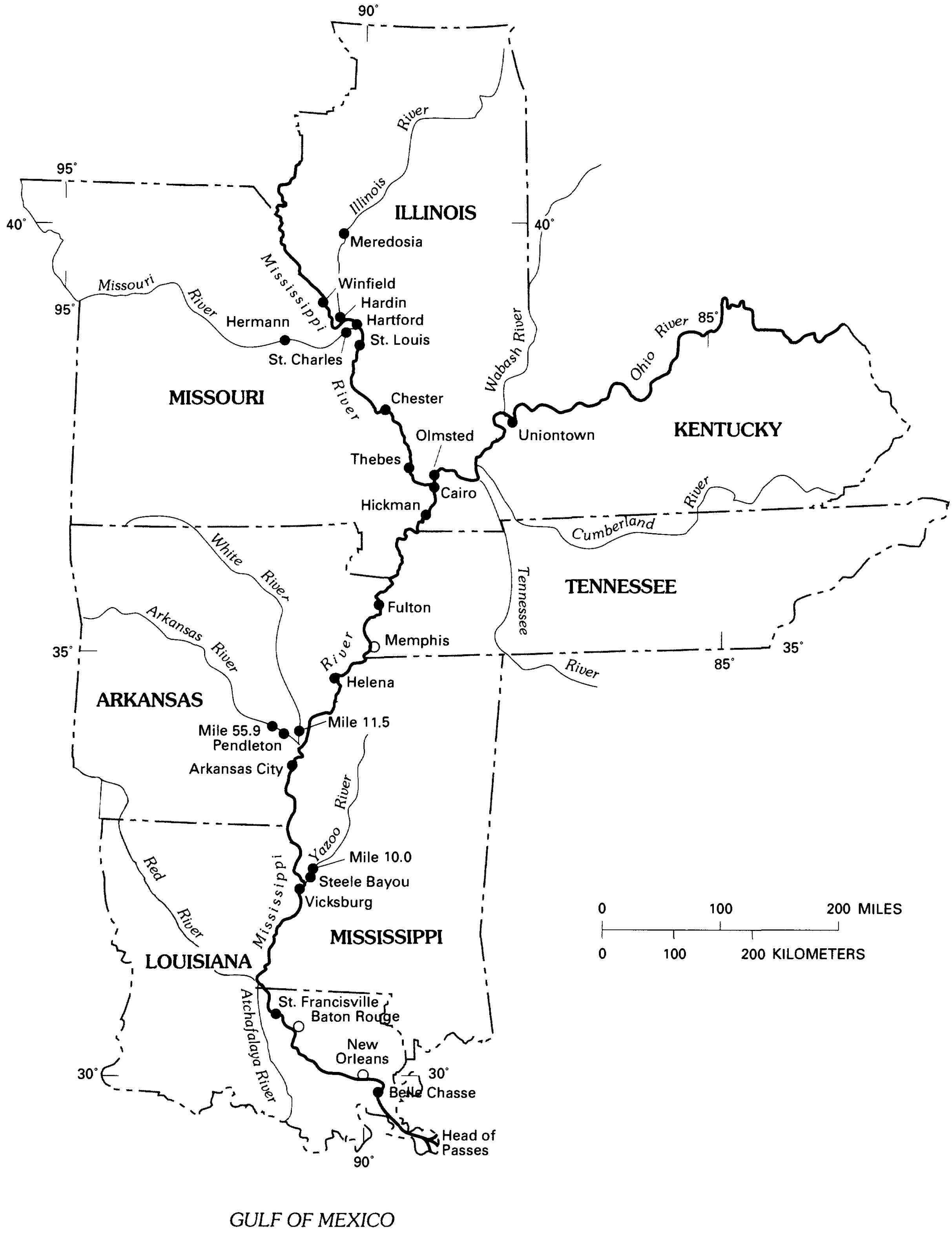

Figure 3.--Lagrangian sampling sites on the Mississippi River and some of its tributaries. Sampling sites are shown as solid circles and other geographical locations are shown as open circles.

Table 1.--Lagrangian sampling sites and dates for six sampling cruises

[X indicates the site was sampled]

Sampling site	Abbreviation	Distance upriver from mouth of Mississippi River at Head of Passes (river miles)	Lagrangian cruises					
			July-Aug. 1987	Nov.-Dec. 1987	May-June 1988	Mar.-Apr. 1989	June 1989	March 1990
Mississippi R. near Winfield, Mo.	WIN	1193.0	X	X	X	X		
Illinois R. below Meredosia, Ill.	ILL	1245.3	X	X	X			
Illinois R. at Hardin, Ill.	ILL	1199.9				X	X	
Mississippi R. at Hartford, Ill.	HAR	1151.5	X					
Missouri R. at Hermann, Mo.	HER	1247.0	X		X	X	X	
Missouri R. at St. Charles, Mo.	STC	1177.2		X				
Mississippi R. at St. Louis, Mo.	STL	1133.1	X	X	X	X	X	
Mississippi R. at Chester, Ill.	CHE	1062.7	X					
Mississippi R. at Thebes, Ill.	THE	997.7		X	X	X	X	
Ohio R. at Uniontown, Ky.	UNI	1092.9						X
Ohio R. at Olmsted, Ill.	OLM	970.3	X	X	X	X	X	X
Mississippi R. below Hickman, Ky.	HIC	916.8	X	X	X	X	X	X
Mississippi R. at Fulton, Tenn.	FUL	777.3		X	X		X	
Mississippi R. below Fulton, Tenn.	FUL	773.4				X		X
Mississippi R. at Helena, Ark.	HEL	663.9	X	X	X	X	X	X
White R. at Mile 11.5, Ark.	WHI	610.3	X	X	X	X	X	
Arkansas R. at Mile 55.9, Ark.	55.	637.4	X					
Arkansas R. at Pendleton, Ark.	PEN	603.9				X	X	
Mississippi R. above Arkansas City, Ark.	ARK	566.0	X	X	X	X	X	X
Yazoo R. at Mile 10.0, Miss.	YAZ	447.2		X	X			
Yazoo R. below Steele Bayou, Miss.	YAZ	446.2				X	X	
Mississippi R. below Vicksburg, Miss.	VIC	433.4	X	X	X	X	X	X
Mississippi R. near St. Francisville, La.	STF	266.4	X	X	X	X	X	X
Mississippi R. below Belle Chasse, La.	BEL	73.1	X	X	X	X	X	X

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WATER ROUTING METHOD USED FOR EVALUATION OF LAGRANGIAN SAMPLING SCHEME

Description

Many flow-routing models have been developed to solve unsteady flow problems (Lawler, 1964; Keefer, 1974; Fread, 1978; Dunne and Leopold, 1978; Schaffranek and others, 1981; Doyle and others, 1983; Barkau, 1985; Hoos and others, 1989; Jobson, 1989; and Morel-Seytoux and others, 1993). All these models are predictive by design. In order to evaluate the Lagrangian sampling scheme (after sampling has been completed) it is not necessary to use one of these numerical predictive velocity models, which require extensive calibration. In fact, smaller errors will be incurred if the water velocities are interpolated directly from velocity versus stage or discharge relations using the measured river stages for each day during the sampling cruise.

A simple, one-dimensional routing method (see Appendix for the BASIC program listing) was devised to route the water masses down the tributaries and then down the Mississippi River. This method is based on the following assumptions:

1. The mean velocity in a regularly gaged cross section is representative of a reach of the river ranging in length from 6 to 234 mi.

2. The mean velocity in a cross section can be determined by use of a linear regression relation based on either the stage or discharge measured at the same cross section.

3. The mean velocity within a reach of the river remains constant for 24 hours--from noon of one day to the noon of the next day.

4. All individual water masses within a reach of the river move at the same mean velocity.

5. The center of an individual water mass is sampled at noon.

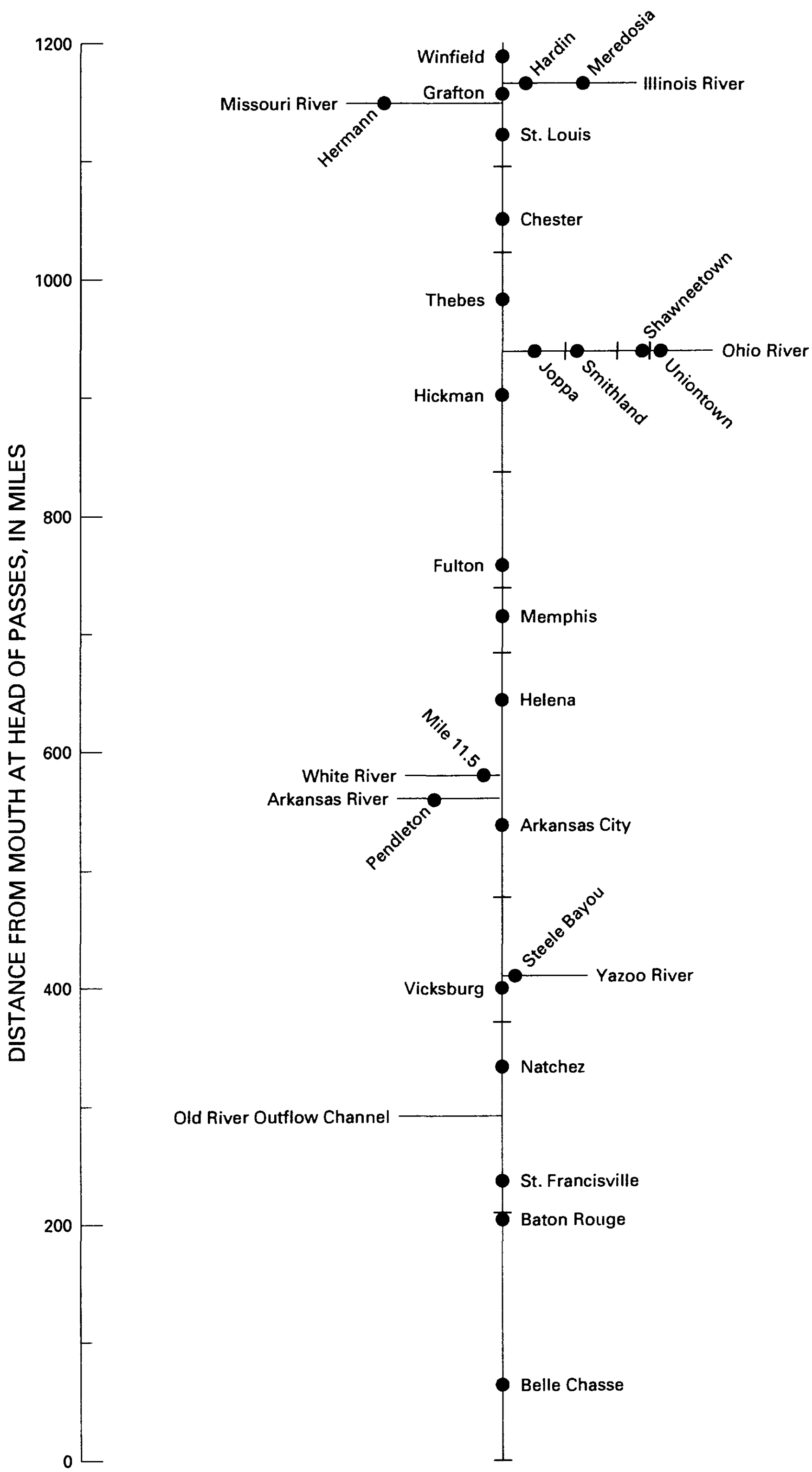

Figure 4. Schematic diagram for a one-dimensional, water-mass routing method used to evaluate the Lagrangian sampling scheme. Sites where velocity was determined are shown as solid circles. Boundaries of some reaches are shown as short lines perpendicular to the line representing each river. The other boundaries are the points where tributaries meet the Mississippi River.

Table 2.--Sites at which velocity was calculated, reaches of the Mississippi River and its tributaries and method of calculating the velocity

[V, velocity in miles per hour; S, stage in feet; Q, water discharge in 1,000 cubic feet per second; R^2, coefficient of determination]

Name of velocity site	Length of reach (miles)	Distance upriver from the mouth of Mississippi River at Head of Passes in river miles			Method of calculating velocity	R^2
		Start of reach	End of reach	Velocity site		
MISSISSIPPI RIVER						
Mississippi R.:						
near Winfield, Mo.	14.9	1193.0	1178.1	1193.0	Direct measurement	
at Grafton, Ill.	29.0	1178.1	1149.1	1168.4	V=0.012 Q + 0.022	0.99
at St. Louis, Mo.	51.1	1149.1	1098.0	1133.1	V=0.084 S + 1.8	0.95
at Chester, Ill.	67.7	1098.0	1030.3	1062.7	V=0.083 S + 2.0	0.92
at Thebes, Ill.	76.5	1030.3	953.8	997.7	V=0.068 S + 1.6	0.94
at Hickman, Ky.	106.8	953.8	847.0	918.4	V=0.069 S + 1.6	0.91
at Fulton, Tenn.	91.0	847.0	756.0	777.3	Direct measurement	
at Memphis, Tenn.	56.5	756.0	699.5	735.2	V=0.097 S + 2.6	0.93
at Helena, Ark.	118.0	699.5	581.5	663.9	V=0.090 S + 1.5	0.92
above Arkansas City, Ark.	82.0	581.5	499.5	566.0	V=0.090 S + 1.5	0.96
at Vicksburg, Miss.	102.0	499.5	397.5	435.2	V=0.078 S + 2.0	0.93
at Natchez, Miss.	83.0	397.5	314.5	362.4	V=0.070 S + 0.8	0.96
near St. Francisville, La.	80.5	314.5	234.0	266.4	Direct measurement	
at Baton Rouge, La.	234.0	234.0	0.0	233.8	V=0.098 S + 0.4	0.87
or below Belle Chasse, La.	234.0	234.0	0.0	73.1	Direct measurement	
TRIBUTARIES						
Illinois R. below Meredosia, Ill.	74.2	1246.0	1171.8	1245.3	Direct measurement[2]	
or at Hardin, Ill.				1199.9		
Missouri R. at Hermann, Mo.	97.9	1247.0	1149.1	1247.0	V=0.083 S + 1.7	0.91
Ohio R.:						
at Uniontown, Ky.	6.0	1093.0	1087.0	1092.9	NWS[1]	
at Shawneetown, Ill.	40.0	1087.0	1047.0	1077.0	NWS[1]	
at Smithland, Ky.	35.0	1047.0	1012.0	1016.8	NWS[1]	
at Joppa, Ill.	58.2	1012.0	953.8	984.3	NWS[1]	
White R. at Mile 11.5, Ark.	11.2	611.0	598.8	610.3	Direct measurement	
Arkansas R. at Pendleton, Ark.	56.5	638.0	581.5	603.9	Direct measurement	
Yazoo R. below Steele Bayou, Miss.	10.8	448.0	437.2	446.2	Direct measurement	

[1]National Weather Service, Ohio River Forecast Center, Flow and Velocity Program, Cincinnati, Ohio.

[2]Or Stall and Hiestand, 1969.

The Mississippi River and its tributaries were divided into 24 reaches (fig. 4 and table 2). Distances given in this report are river miles measured upstream from the mouth of the Mississippi River at Head of Passes, Louisiana. In this report, distances are listed in miles to facilitate location of water masses on published navigation charts that show each river mile. The navigation lights and day markers located on the banks of the river also have their locations in miles painted on them.

The boundary between some reaches is the point where a tributary meets the Mississippi River; this occurs at confluences with the Illinois River (river mile 1171.8), Missouri River (river mile 1149.1), Ohio River (river mile 953.8), White River (river mile 598.8), Arkansas River (river mile 581.5), and Yazoo River (river mile 437.2). The estimate of velocity within each reach and for each day of the cruise was determined: (1) from linear regressions of discharge measurements made by either the U.S. Geological Survey or the U.S. Army Corps of Engineers (fig. 5 and table 2), (2) by direct measurements while collecting water samples, (3) from a National Weather Service model predicting flow in the Ohio River or (4) from published reports. In order not to unduly bias the linear regression for stages which occur more frequently, the data points for the linear regression were selected to provide a nearly uniform distribution of stages between the minimum and maximum stage (fig. 5).

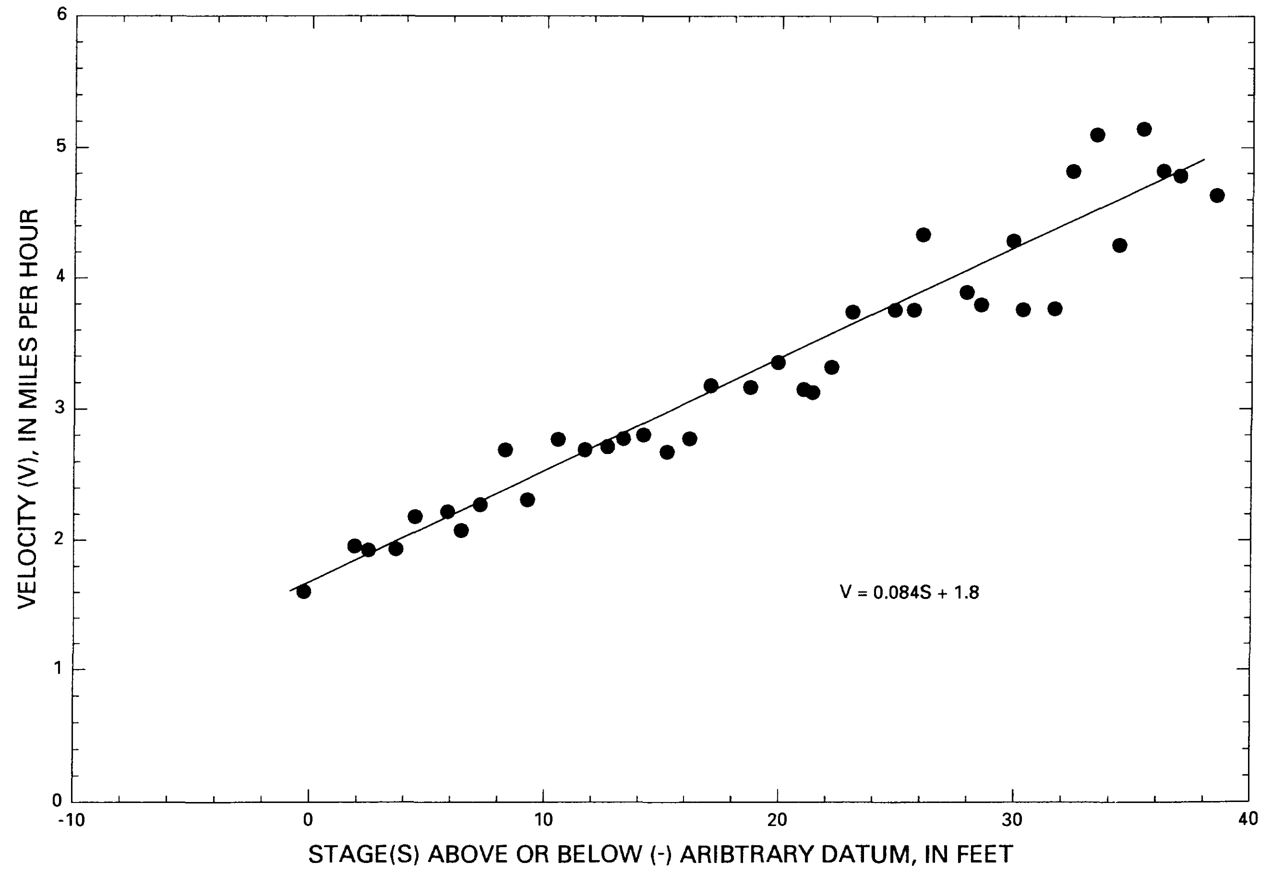

Figure 5. Relation between velocity and stage for the Mississippi River at St. Louis, Missouri. Data points were selected from measurements made from 1982 through 1987 to give a nearly uniform distribution of stages. The equation for the linear regression line is listed in table 2 along with the regression equations for the other velocity sites.

Errors and Verification

The gaging sites where velocities are measured are almost always located at narrow, stable cross sections of the river or tributary; therefore, the measured velocity can be slightly higher than the reach-averaged velocity. The magnitude of this bias error is unknown without measuring several cross-sectional mean velocities within a reach and comparing them with the velocity at the gaging site. An approach to estimating this variability, however, is to determine the variability in a composite reach of the Mississippi River that includes several of the smaller reaches in figure 4. On the basis of the velocities calculated from stage and discharge relations in table 2 for 11 reaches from St. Louis to St. Francisville (river mile 1149.1 to river mile 234.0) the mean velocity at low water (May 28, 1988) was 2.4 mi/h with a standard deviation of 0.3 mi/h or 13 percent, and the mean velocity at high water (March 19, 1989) was 3.8 mi/h with a standard deviation of 0.9 mi/h or 22 percent. Thus, the velocities at the measuring sites could be 13 to 22 percent higher than the reach-averaged velocities.

The error associated with the velocities predicted by the regression equations listed in table 2 was determined by comparing them with measurements made at the same sites during sampling cruises (St. Louis, Thebes, Hickman, Helena, Arkansas City, and Vicksburg in tables 1 and 2). There were 33 comparisons for the 6 cruises, and the predicted velocities averaged about 6 percent greater than the measured velocities with standard deviation of 13 percent.

A verification of the one-dimensional routing method's ability to predict the location of individual water masses was obtained in May-June 1988 when 100-300 surface drift cards (total 5,000 cards; see Moody and Meade, 1992, for details) were released at each sampling site. About 1 percent (41 cards) were recovered downstream while floating in the river. The distance that the cards had moved on the surface was not equal to the distance that water traveling with the cross-sectional mean velocity would have moved, so that the surface distances were adjusted by multiplying by the ratio (0.85) of the depth-averaged velocity to the surface velocity based on results given by Savini and Bodhaine (1971) and Rantz and others (1982). These adjusted surface distances were compared to the routing distances predicted by the one-dimensional routing method. For 18 of the recovered drift cards, the routing distance was much larger than the adjusted surface distance, indicating that the cards had been detained for a considerable length of time, perhaps in an eddy (one was actually found in an eddy, recovered, released again, but never found a second time) or perhaps washed ashore and refloated -- these cards were not used to verify the routing method. Of the 23 remaining cards, 19 were recovered in the same reach of river (maximum adjusted surface distance was 56 river miles) in which they were released and were used to verify the reach-average velocity by computing the distance traveled. The average difference (absolute value) between the routing and adjusted surface distance was 17 percent and, in general, the routing method overestimated the distance traveled by about 7 percent. The 4 drift cards that had traveled more than one reach were used to verify routing through successive reaches (maximum adjusted surface distance was 165 river miles). The average difference (absolute value) between the routing and adjusted surface distance was 27 percent and again, in general, the routing method overestimated the distance traveled by about 16 percent. Certainly, the recovery of more cards would have improved this verification, but this independent verification agrees with the error estimated in the previous paragraphs and suggest that this routing method probably overestimates the length of the collective water mass and the separation between individual water masses.

RESULTS OF ROUTING METHOD

Location of Individual Water Masses

The location (river miles above the mouth of the Mississippi River at Head of Passes) of each individual water mass was calculated for noon of each day of each cruise using the routing method described above. The midpoint of an individual water mass was moved in distance increments of 1 mi assuming that the velocity was constant within each reach and that the velocity changed in a step-like manner as the individual water mass crossed the boundary separating reaches. The increment of time to move a distance of 1 mi was added to the elapsed time (measured from noon) until the elapsed time exceeded 24 hours. The location at noon was then calculated by interpolating between the last location at an elapsed time greater than 24 hours and the previous location at an elapsed time less than 24 hours. The locations are given in tables 3-8 for the midpoint of each individual water mass, and the individual water masses that are still in a tributary and not in the Mississippi River are identified by an asterisk.

Length of Collective Water Mass

In general, the length of the collective water mass (tables 3-8) will increase with time as practical limitations (fuel stops, crew changes, equipment malfunctions, and so forth) dictate that sampling sites are sometimes downstream or upstream from water that was previously sampled. The length of the collective water mass is not necessarily the maximum minus minimum river mile listed in tables 3-8. For example in table 3 the Illinois River water mass (ILL in table 3) at noon on July 21, 1987 is at river mile 1181, which is in the Illinois River (mouth of Illinois River is at river mile 1171.8) and the Missouri River water mass (HER in table 3) is at river mile 1194, which is in the Missouri River. The length of the collective water mass for July 21, 1987 is, therefore, 1150 mi (which is not the maximum distance) minus 1145 mi (which is the minimum distance) or 5 mi. The Illinois River water mass enters the Mississippi River and becomes part of the collective water mass sometime during the afternoon of July 21, 1987 so that the length of the collective water mass on July 22, 1987 is the distance between the maximum (1162 mi) and minimum (1082 mi) distances listed for the individual water masses or 80 mi.

The length of the collective water mass might decrease as the leading individual water mass enters a reach where velocities are less than the velocities of the reach in which the trailing individual water mass is located. This happened during the first cruise (table 3) between August 6 and 7 when the Winfield water mass entered the Belle Chasse reach (river mile 234.0 to river mile 0.0, table 2) just before noon on August 6, 1987 and slowed down to about 1.0 mi/h; while the Arkansas River water mass (identified as 55. in table 3) was still in the Vicksburg reach (river mile 499.5 to river mile 397.5, table 2) where the velocity was about 2.5 mi/h. The net effect was that the length of the collective water mass decreased from 226 mi to 190 mi. Total water volume or mass was still conserved because the mean depth of the river in the Belle Chasse reach is about twice the mean depth in the Vicksburg reach.

The length of the collective water mass is not listed in tables 3-8 if the leading individual water mass reached the Gulf of Mexico (noon location less than river mile 0.0) before the end of the cruise. This occurred for the last three cruises made during high water when water velocities were often 3-5 mi/h in some reaches of the Lower Mississippi River (river mile 953.8 to river mile 0.0).

Table 3.--Noon location of individual water masses and length of collective water mass from July 18 through August 9, 1987

[Locations are given in river miles upriver from the mouth of the Mississippi River at Head of Passes. Abbreviations are the first three letters of the river or sampling site name listed in table 1; 55. is Arkansas River at Mile 55.9, Ark; *, individual water mass is in the tributary]

Day	ILL	WIN	HER	HAR	STL	CHE	OLM	HIC	HEL	WHI	55.	ARK	VIC	STF	BEL	Length of collective water mass (miles)
July 1987																
18		1239														0
19	*1220	1193														0
20	*1201	1166	*1247													0
21	*1181	1145	*1194	1150												5
22	1162	1082	1140	1091	1133											80
23	1133	1014	1080	1022	1071	1062										119
24	1070	952	1012	960	1004	996										118
25	1005	897	952	904	945	938										108
26	945	841	897	849	890	882										104
27	890	786	842	794	834	827	970									104
28	837	732	789	740	782	774	942	917								210
29	785	668	733	676	724	716	889	864								221
30	728	600	668	609	659	650	836	811	664							236
31	664	547	603	554	594	585	786	761	599	*610						239
August 1987																
1	599	502	551	508	544	538	730	702	548	565	*673					228
2	548	438	506	447	499	490	666	637	503	520	*637	566				228
3	503	380	444	386	434	425	601	575	440	464	*601	520				221
4	442	332	385	338	377	370	550	529	382	401	561	466	433			229
5	384	283	339	290	332	325	504	478	336	355	515	403	378			232
6	338	233	292	240	283	276	444	416	288	309	459	356	332			226
7	290	206	241	211	233	229	386	365	238	258	396	310	284	267		190
8	240	180	211	184	207	203	340	319	209	220	351	260	233	224		171
9	210	154	185	158	180	176	292	269	183	194	304	221	207	198	73	231

Table 4.--Noon location of individual water masses and length of collective water mass from November 29 through December 20, 1987.

[Locations are given in river miles upriver from the mouth of the Mississippi River at Head of Passes. Abbreviations are the first three letters of the river or sampling site name listed in table 1; *, individual water mass is in the tributary]

Day	ILL	WIN	STC	STL	THE	OLM	HIC	FUL	HEL	WHI	ARK	YAZ	VIC	STF	BEL	Length of collective water mass (miles)
Nov. 1987																
29		1239														0
30	*1220	1193														0
Dec. 1987																
1	*1201	1164														0
2	*1181	1132	*1176													0
3	1160	1066	1114	1133												94
4	1118	997	1044	1066												121
5	1050	933	978	998	998											117
6	983	871	915	934	934	970										112
7	920	808	852	871	872	931	917									123
8	860	745	790	810	810	871	857	777								126
9	798	673	723	746	747	809	795	708								136
10	733	604	653	675	675	746	729	638								142
11	662	544	583	606	606	674	658	571	664							130
12	595	486	528	546	546	607	591	516	597	*610						124
13	539	414	466	491	491	549	536	450	541	566	566					152
14	482	357	397	422	422	495	478	385	484	514	513	*447				157
15	413	305	346	364	364	426	409	334	415	449	448	409	433			145
16	358	248	293	314	314	367	355	280	359	384	384	355	373			136
17	307	204	236	256	256	317	303	226	308	334	333	303	322			130
18	252	168	199	212	212	262	248	190	253	280	280	248	268	267		112
19	209	132	163	176	176	216	207	154	210	228	228	207	220	219		96
20	173	96	127	140	140	180	171	118	174	192	192	171	184	183	73	119

Table 5.--Noon location of individual water masses and length of collective water mass from May 16 through June 7, 1988

[Locations are given in river miles upriver from the mouth of the Mississippi River at Head of Passes. Abbreviations are the first three letters of the river or sampling site name listed in table 1; *, individual water mass is in the tributary]

Day	ILL	WIN	HER	STL	THE	OLM	HIC	FUL	MEM[1]	HEL	WHI	ARK	YAZ	VIC	STF	BEL	Length of collective water mass (miles)
May 1988																	
16	*1239																0
17	*1217	1193															0
18	*1196	1166															0
19	*1174	1145	*1247														0
20	1155	1086	*1192	1133													69
21	1109	1020	1136	1072													116
22	1044	960	1075	1007	998												115
23	982	906	1010	948	940	970											104
24	925	851	951	893	885	933	917										100
25	870	793	895	837	829	878	862										102
26	813	734	840	779	771	822	805	777									106
27	755	669	782	718	708	764	746	715	735								113
28	691	605	721	653	643	701	681	650	670	664							115
29	623	551	655	586	578	634	614	583	603	597	*610						104
30	564	506	587	538	532	571	558	537	550	546	565	566					81
31	519	446	540	490	482	525	512	488	505	500	519	520					94
June 1988																	
1	464	386	493	428	420	472	455	426	445	438	464	466	*447				107
2	401	338	430	373	366	410	393	371	385	381	402	403	437	433			99
3	352	289	375	325	318	359	345	323	337	333	353	354	384	377			95
4	304	239	327	275	268	311	297	273	288	284	304	306	336	329			97
5	253	210	277	229	225	261	246	228	238	233	254	255	287	279	267		77
6	218	184	231	202	199	222	214	201	210	207	218	219	239	232	225		55
7	192	157	205	176	172	196	187	175	183	180	192	192	210	206	199	73	137

[1]Represents a sewage spill into the Mississippi River at Memphis, Tenn., on May 27, 1988.

Table 6.--Noon location of individual water masses and length of collective water mass from March 9 through April 1, 1989

[Locations are given in river miles upriver from the mouth of the Mississippi River at Head of Passes. Abbreviations are the first three letters of the river or sampling site name listed in table 1; *, individual water mass is in the tributary; --, part of the collective water mass is in the Gulf of Mexico]

Day	ILL	WIN	HER	STL	THE	OLM	HIC	FUL	HEL	WHI	PEN	ARK	YAZ	VIC	STF	BEL	Length of collective water mass (miles)
March 1989																	
9	*1194																0
10	*1175	1193															0
11	1160	1179															19
12	1136	1164	*1247														28
13	1077	1146	*1192	1133													69
14	1012	1086	1136	1071													124
15	954	1019	1075	1006	998												121
16	866	956	1008	940	928	970											142
17	764	869	942	851	838	884	917										178
18	648	767	853	745	729	786	825										205
19	535	652	747	629	615	672	714	775									240
20	420	542	633	520	507	561	601	664									244
21	320	429	526	404	390	451	496	555	663								343
22	237	327	412	308	297	345	382	445	562	*610							325
23	190	246	316	231	224	261	292	344	456	537	*638						347
24	144	195	236	185	179	204	222	260	353	430	*600	566					422
25	63	114	155	103	97	122	140	180	270	332	537	474					474
26		34	76	24	18	43	61	101	192	252	438	369	*447				--
27								21	113	174	343	286	362	433			--
28									36	98	258	206	275	333			--
29										21	180	129	195	249			--
30											105	55	121	174	267		--
31											31		47	99	190		--
April 1989																	
1														25	116	73	--

Table 7.--Noon location of individual water masses and length of collective water mass from June 4 through June 28, 1989.

[Locations are given in river miles upriver from the mouth of the Mississippi River at Head of Passes. Abbreviations are the first three letters of the river or sampling site name listed in table 1; *, individual water mass is in the tributary; --, part of the collective water mass is in the Gulf of Mexico]

Day	ILL	WIN	HER	STL	THE	OLM	HIC	FUL	HEL	WHI	PEN	ARK	YAZ	VIC	STF	BEL	Length of collective water mass (miles)
June 1989																	
4	*1194																0
5	1160	1193															33
6	1112	1160															48
7	1042	1108	*1247														66
8	976	1038	*1180	1133													157
9	905	972	1120	1066													215
10	827	899	1051	998	998												224
11	742	820	984	929	930	970											242
12	653	734	913	853	853	902	917										264
13	568	645	835	767	767	823	839										271
14	492	562	748	675	675	734	753	777									285
15	399	482	656	586	586	643	660	684									285
16	322	390	569	509	509	558	572	595									273
17	247	313	488	415	415	474	492	514	664								417
18	177	239	391	332	332	380	394	419	574	*610							397
19	107	169	312	258	259	302	315	335	488	562	*638						455
20	35	97	237	186	186	228	240	259	389	472	565	566					531
21		25	165	114	114	156	168	186	308	374	475	476					--
22			91	39	39	81	94	112	234	295	377	378	*447				--
23			16			7	19	38	159	220	295	296	367	433			--
24									85	146	221	222	286	342			--
25									8	69	144	145	209	262			--
26											67	68	133	185	267		--
27													56	108	190		--
28														29	110	73	--

Table 8.--Noon location of individual water masses and length of collective water mass from March 1 through March 14, 1990.

[Locations are given in river miles upriver from the mouth of the Mississippi River at Head of Passes. Abbreviations are the first three letters of the river or sampling site name listed in table 1; --, part of the collective water mass is in the Gulf of Mexico]

Day	UNI	OLM	HIC	FUL	HEL	ARK	VIC	STF	BEL	Length of collective water mass (miles)
March 1990										
1	1092									0
2	1025									0
3	960	965								5
4	877	884	917							40
5	798	805	838	773						65
6	698	709	759	662						97
7	585	596	645	551	664					113
8	477	488	538	437	557	566				129
9	364	374	424	331	446	457				126
10	273	281	321	245	339	348	433			188
11	183	193	236	152	252	259	330			178
12	92	101	145	61	162	170	244	266		205
13	1	10	54		71	79	154	178		--
14							63	86	73	--

There were increases in the length of the collective water mass during some cruises as a result of days spent at a dock changing crews or in a shipyard making repairs. One such increase occurred between July 27-28, 1987 (elapsed day 10-11 in fig. 6) and another between June 16-17, 1989 (elapsed day 13-14 in fig. 7) when the length of the collective water mass increased about 100-150 mi in 24 hours.

Time spent going up and sampling a tributary was an advantage to the Lagrangian sampling scheme of the Mississippi River when the river was low and moving slowly but a disadvantage when the river was high and moving fast. An example of this disadvantage was in March-April 1989 (fig. 6) when the river was high (typical velocities in the Lower Mississippi River were 3-5 mi/h) and 2 days were spent sampling the White River on March 22 and the Arkansas River on March 23 (elapsed day 14-15 in fig. 6). The length of the collective water mass on March 24, when the Mississippi River was sampled above Arkansas City, was 422 mi (table 6); however, if the tributaries had not been sampled and the Mississippi River above Arkansas City had been sampled on March 22 the length of the collective water mass would have been about 100 mi shorter. For this reason, during the March 1990 cruise, no tributaries were sampled so that the first spring runoff from the Ohio River could be sampled in a Lagrangian sequence just upstream from the confluence of the Ohio and Wabash Rivers near Uniontown, Kentucky (tables 1 and 2 and fig. 3), to Belle Chasse, Louisiana. This cruise was during high-water conditions and the maximum length of the collective water mass was 205 mi-- much less than the maximum lengths of 474 and 531 mi for the high-water sampling cruises of March-April 1989 and June 1989. Given the errors associated with the velocities predicted by the regression equations, the lengths of the collective water masses (shown in figure 6 and 7) are most likely a maximum, and the actual length or maximum separation between individual water masses is smaller.

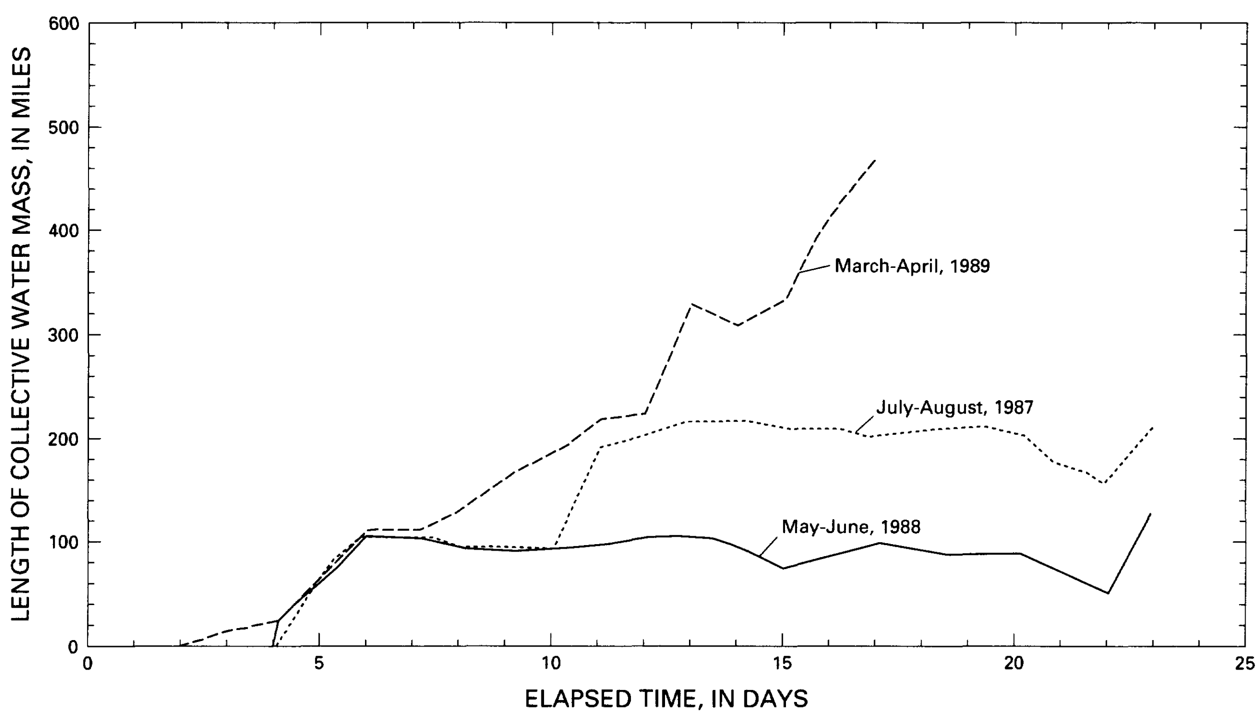

Figure 6. Length of collective water mass in the Mississippi River: July-August 1987; May-June 1988; and March-April 1989.

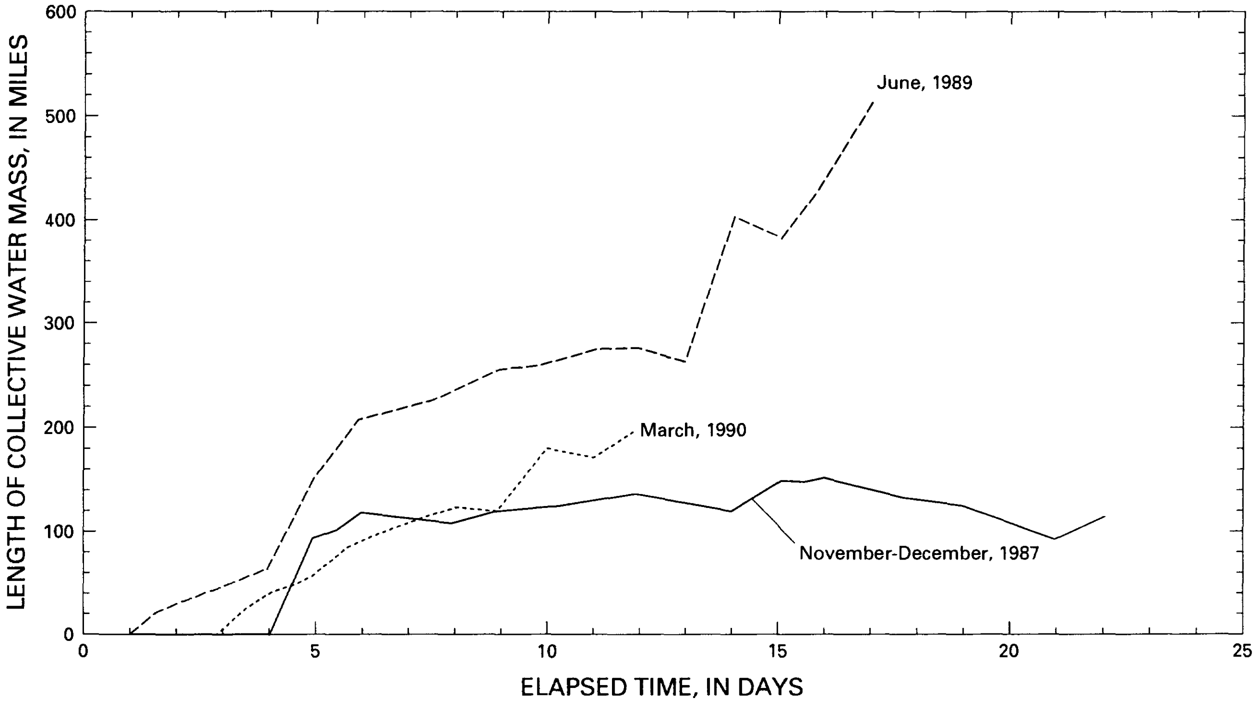

Figure 7. Length of collective water mass in the Mississippi River; November-December 1987; June 1989; and March 1990.

A time line for each cruise is drawn in figure 8. This line connects dots representing the location and time of each sample of an individual water mass in the Mississippi River. The rectangle represents the length of the collective water mass and includes all the water previously sampled at upriver sites (see tables 3-8 for the exact location of individual water masses).

Samples collected during the May-June 1988 cruise were the closest to ideal Lagrangian scheme. The maximum length of the collective water mass (which occurred on the last day) was 137 mi (table 5) but was usually about 100 mi. The samples from the other low-water cruise in November-December 1987 formed a collective water mass that had a maximum length of 157 mi (table 4), and the samples collected during the cruise that followed the Ohio River spring runoff in March 1990 had a length of the collective water mass that was equal to or less than 205 mi (table 8). The first cruise had the fourth longest collective water mass (239 mi) -- owing partly to time spent in a shipyard, changing crews, and sampling tributaries (table 3). The other two high-water cruises had the largest length of the collective water mass of 474 and 531 mi -- a combined result of shipyard time, crew changing, sampling tributaries, and the inability to operate the research vessel 24 hours per day, which would have allowed the vessel to catch up to the individual water masses moving downstream (tables 6 and 7).

If the average river velocities at low and high water were 2 and 3 mi/h, respectively, the total length of water flowing past a fixed point during the period of each cruise was about 1,100 mi for the three cruises during low-water conditions, about 1,750 mi for the first two cruises during high-

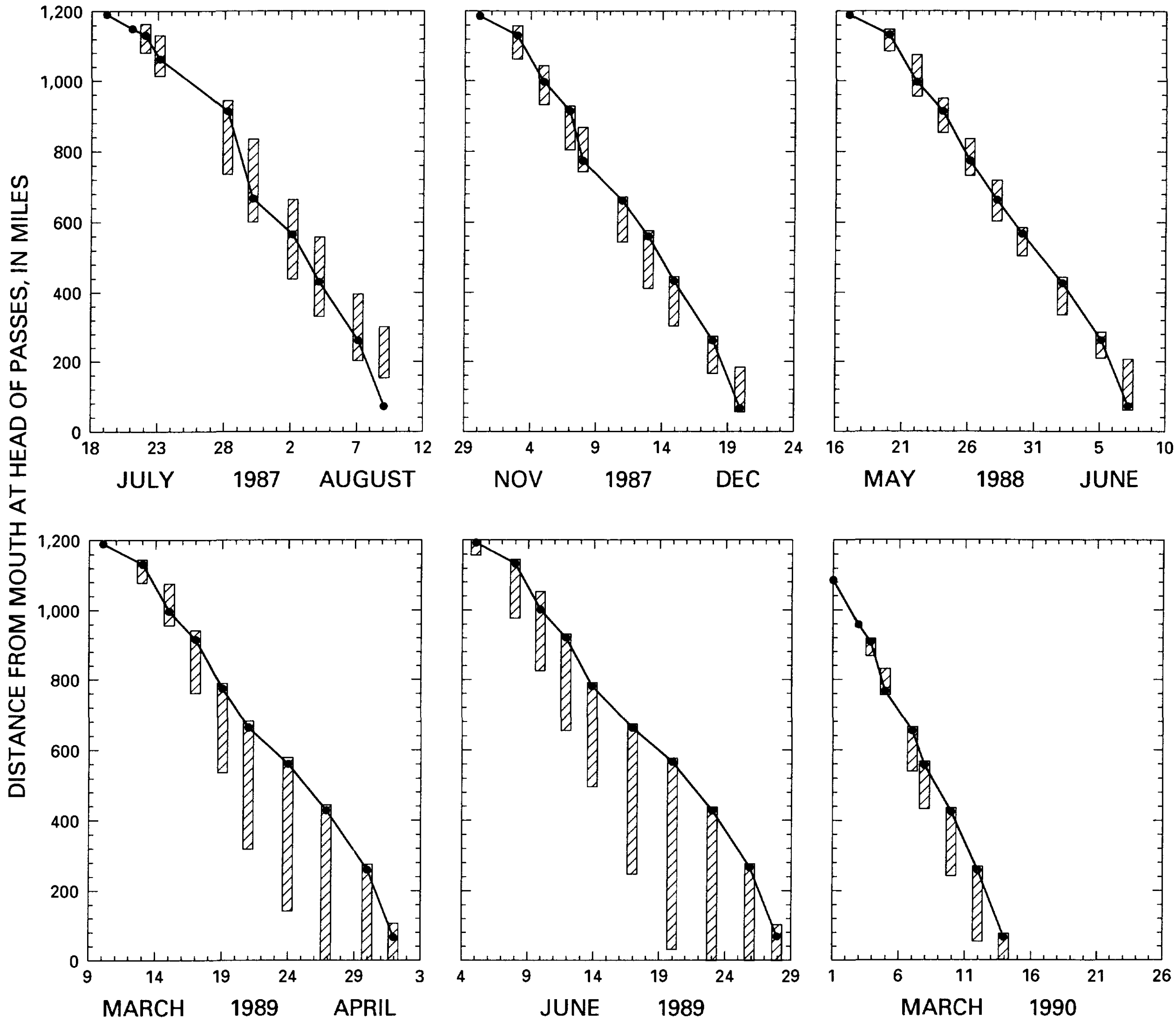

Figure 8. Time lines for six cruises showing the time and location of each Lagrangian sample (solid circle) and its relative location within the collective water mass (cross-hatched rectangle). The three cruises at the top were made during low-water conditions and the three cruises at the bottom were made during high-water conditions. The last cruise (lower right) specifically was designed to follow the Ohio River water mass.

water conditions, and about 1,000 mi for the last cruise that followed the Ohio River spring runoff. The length of the collective water masses expressed as a percentage of the total length of water per cruise are: 22 percent (July-August 1987), 15 percent (November-December 1987), 12 percent (May-June 1988), 27 percent (March-April 1989), 30 percent (June 1989), and 20 percent (March 1990). Expressing the length of the collective water mass as a percentage of the total water flowing past a point per water year would make even the collective water mass with the largest length (June 1989) less than 3 percent of the total annual flow.

SUMMARY

The Lagrangian scheme that was used to follow the same water downstream and to collect additional samples from the same water was evaluated for three sampling cruises during low-water conditions and three sampling cruises during high-water conditions along a 1,120-mi reach of the Mississippi River. The collective water mass increased in length as the additional samples were sometimes collected downstream and sometimes upstream from previously sampled water owing to ship repairs, changing crews, operating the research vessel only during daylight, and taking time to sample tributaries of the Mississippi River. The length of the collective water mass ranged from 137 mi for a cruise during low-water conditions in May-June 1988 to 531 mi for a cruise during high-water conditions in June 1989. By eliminating the sampling of tributaries and using only 1 day for a crew change, the cruise during high-water conditions, which was designed to follow the Ohio River spring runoff in 1990, resulted in the collection of Lagrangian samples that reduced the length of the collective water mass, compared to the other two cruises during high-water conditions, by about 40 percent.

REFERENCES CITED

Barkau, R.L., 1985, A mathematical model of flow through a dendritic network: Ph.D. Dissertation, Colorado State University, Ft. Collins, Colorado.

Demas, C.R. and Curwick, P.B., 1987, Suspended-sediment, bottom-material, and associated chemical data from the lower Mississippi River, Louisiana: Baton Rouge, Louisiana Department of Transportation and Development Water-Resources Basic Records Report No. 14, 117 p.

_____, 1988, Suspended-sediment and associated chemical transport characteristics of the lower Mississippi River, Louisiana: Baton Rouge, Louisiana Department of Transportation and Development, Technical Report No. 45, 44 p.

Doyle, W.H., Jr., Shearman, J.O., Stiltner, G.J., and Krog, W.E., 1983, A digital model for streamflow routing by convolution methods: U.S. Geological Survey Water-Resources Investigations Report 83-4160, 50 p.

Dunne, T., and Leopold, L.B., 1978, Water in Environmental Planning, Chapter 10, Channel routing: W.H. Freeman, San Francisco, p. 356-391.

Fread, D.L., 1978, NWS operational dynamic wave model: Proceedings of 26th Annual ASCE Hydraulics Division Specialty Conference, University of Maryland, College Park, Maryland, p. 455-464.

Hedges, J.I., Clark, W.A., Quay, P.D., Richey, J.E., Devol, A.H., and Santos, U. de M., 1986, Compositions and fluxes of particulate organic material in the Amazon River: Limnology and Oceanography: v. 31, p. 717-738.

Hoos, A.B., Koussis, A.D., and Beale, G.O., 1989, A channel dynamics model for real-time flood forecasting: Water Resources Research, v. 25, No. 4, p. 691-705.

Jobson, H.E., 1989, Users manual for an open-channel stream-flow model based on the diffusion analogy: U.S. Geological Survey Water-Resources Investigations Report 89-4133, 73 p.

Keefer, T.N., 1974, Desktop computer flow routing: Journal of the Hydraulics Division, ASCE, v. 100, No. HY7, p. 1047-1058.

Lawler, E.A., 1964, Hydrology of flow control, Part II, Flood routing, in Chow, V.T., ed., Handbook of Applied Hydrology, McGraw-Hill, New York, Chapter 25, p. 34-59.

Leenheer, J.A., Meade, R.H., Taylor, H.E., and Pereira, W.E., 1989, Sampling, fractionation, and dewatering of suspended sediment from the Mississippi River for geochemical and trace-contaminant analysis, in Mallard, G.E. and Ragone, S.E., eds., U.S. Geological Survey Toxic Substances Hydrology Program-proceedings of the technical meeting, Phoenix, Arizona: September 26-30, 1988: U.S. Geological Survey Water-Resources Investigations Report 88-4220, p. 501-511.

Meade, R.H., 1985, Suspended sediment in the Amazon River and its tributaries in Brazil during 1982-84: U.S. Geological Survey Open-File Report 85-492, 33 p.

Meade, R.H., Dunne, T., Richey, J.E., Santos, U. de M., and Salati, E., 1985, Storage and remobilization of suspended sediment in the lower Amazon River of Brazil: Science, v. 228, p. 488-490.

Meade, R.H., Nordin, C.F., Jr., Pérez-Hernández, D., Mejía-B., A., and Pérez-Godoy, J.M., 1983, Sediment and water discharge in Rio Orinoco, Venezuela and Colombia, in Proceedings of the Second International Symposium on River Sedimentation, Nanjing, China: Beijing, Water Resources and Electric Power Press, p. 1134-1144.

Meade, R.H., and Stevens, H.H., Jr., 1990, Strategies and equipment for sampling suspended sediment and associated toxic chemicals in large rivers - with emphasis on the Mississippi River: Science of the Total Environment, v. 97/98, p. 125-135.

Moody, J.A., and Goolsby, D.A., 1993, Spatial variability of triazine herbicides in the Lower Mississippi River: Environmental Science and Technology, October.

Moody, J.A., and Meade, R.H., 1992, Hydrologic and sedimentologic data collected during three cruises at low water on the Mississippi River and some of its tributaries, July 1987-June 1988: U.S. Geological Survey Open-File Report 91-485, 143 p.

_____, 1993, Hydrologic and sedimentologic data collected during four cruises at high water on the Mississippi River and some of its tributaries, March 1989-June 1990: U.S. Geological Survey Open-File Report 92-651, 227p.

Morel-Seytoux, H.J., Fahmy, H., and Lamagat, J., 1993, A composite hydraulic and statistical flow-routing method: Water Resources Research, v. 29, no. 2, p. 413-418.

National Weather Service, Ohio River Forecast Center, 1987-1990, Ohio River Flow and Velocity Program: Cincinnati, Ohio, unpublished.

Nordin, C.F. Jr., Cranston, C.C. and Mejía-B., Abel, 1983, New technology for measuring water and suspended-sediment discharge of large rivers, in Proceedings of the Second International Symposium on River Sedimentation, Nanjing, China: Beijing, Water Resources and Electric Power Press, p. 1145-1158.

Pereira, W.E., Rostad, C.E., and Leiker, T.J., 1990, Distributions of agrochemicals in the lower Mississippi River and its tributaries: Science of the Total Environment, v. 97/98, p. 41-53.

_____, 1992, Synthetic organic agrochemicals in the lower Mississippi River and its major tributaries: Distribution, transport and fate: Journal of Contaminant Hydrology, v. 9, p. 175-188.

Rantz, S.E. and others, 1982, Measurement and computation of streamflow: Volume 1. Measurement of stage and discharge: U.S. Geological Survey Water-Supply Paper 2175, 284 p.

Rees, T.F., and Ranville, J.F., 1990, Collection and analysis of colloidal particles transported in the Mississippi River, U.S.A.: Journal of Contaminant Hydrology, v. 6, p. 241-250.

Richey, J.E., Meade, R.H., Salati, E., Devol, A.H., Nordin, C.F., and Santos, U. de M., 1986, Water discharge and suspended sediment concentrations in the Amazon River, 1982-1984: Water Resources Research, v. 22, p. 756-764.

Savini, J., and Bodhaine, G.L., 1971, Analysis of current-meter data at Columbia River gaging stations, Washington and Oregon: U.S. Geological Survey Water-Supply Paper 1869-F, 59 p.

Schaffranek, R.W., Baltzer, R.A., and Goldberg, D.E., 1981, A model for simulation of flow in singular and interconnected channels: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 7, Chapter C3, 110p.

Stall, J.B., and Hiestand, D.W., 1969, Provisional time-of-travel for Illinois streams: Urbana, Illinois State Water Survey Report of Investigations 63, 31 p.

Taylor, H.E., Garbarino, J.R., and Brinton, T.I., 1990, The occurrence and distribution of trace metals in the Mississippi River and its tributaries: Science of the Total Environment, v. 97/98, p. 369-384.

APPENDIX

BASIC Program for calculating the position of water masses every 24 hours. The program includes reaches of the Mississippi River and tributaries upriver from river mile 1193.0 at Winfield, Missouri, tributaries to the Wabash and Ohio Rivers, as well as the tributaries and Mississippi River shown in figure 4.

```
10 LPRINT CHR$(15);
20 REM PROGRAM WMASSC.BAS
30 WIDTH "LPT1:",132 : OPEN "LPT1:" FOR OUTPUT AS #1
40 REM CALCULATES NOON LOCATION OF UP TO 50 WATER MASSES
50 REM FOR CEDAR, IOWA, IROQUOIS, KANKAKEE, ILLINOIS, WHITE , WABASH
60 REM OHIO, TENN., CUMBERLAND, MISSOURI, AND MISSISSIPPI RIVERS.
70 DEFINT I-N
80 DEFSTR S
90 DIM U(100,40),X(100,50),T(300),TM(300),XLOC(50),SMASS(50),MDAY(50)
100 INPUT "ENTER FILE NAME WITH NAME AND LOCATION OF WATER MASS-->",SFILE
110 OPEN "I",#3,SFILE
120 INPUT #3,NUM
130 FOR I=1 TO NUM : INPUT #3,SMASS(I),XLOC(I),MDAY(I) : NEXT I
140 CLOSE #3
150 INPUT "ENTER FILE NAME WITH VELOCITY AND STARTING DAY-->",SFILE,KDATE
160 OPEN "I",#2,SFILE
170 INPUT #2,NUMV,NDAY
180 FOR I=1 TO NUMV
190 FOR K=1 TO NDAY : INPUT #2,U(I,K) : NEXT K
200 NEXT I
210 PRINT #1, "DAY    ";
220 CLOSE #2
230 FOR L=1 TO NUM
240 PRINT #1, SMASS(L)"   "; : NEXT L
250 PRINT #1, " "
260 PRINT #1, USING "##      ";(KDATE);
270 PRINT #1, USING "#### ";XLOC(1)
280 TIME=0
290 FOR M=1 TO NUM : X(MDAY(M),M)=XLOC(M) : NEXT M
300 FOR K=1 TO NDAY
310 PRINT #1, USING "##      ";(K+KDATE);
320 FOR J=1 TO NUM
330 IF K>=MDAY(J) THEN 340 ELSE 2350
340 FOR I=1 TO 300
350 IF SMASS(J)="CED" OR SMASS(J)="DES" THEN 360 ELSE 560
360 IF SMASS(J)="CED" AND X(K,J)>1493 THEN 480 ELSE 370
370 IF SMASS(J)="CED" AND X(K,J)>1417 THEN 510 ELSE 380
380 IF SMASS(J)="CED" AND X(K,J)>1388 THEN 540 ELSE 390
390 IF SMASS(J)="DES" AND X(K,J)>1315 THEN 410 ELSE 440
```

```
400 REM KEOSAUQUA TO DES MOINES--MISS. CONFLUENCE
410  DT=1/U(36,K)
420 GOTO 2180
430 REM IOWA--MISS. CONFLUENCE TO ILLINOIS--MILE 1295
440 IF X(K,J)>1295 AND X(K,J)<1388 THEN 450 ELSE 1130
450  DT=1/U(35,K)
460 GOTO 2180


470 REM  WATERLOO--CEDAR RAPIDS  TO  CEDAR RAPIDS--CONESVILLE
480  DT=1/U(32,K)
490 GOTO 2180
500 REM  CEDAR RAPIDS--CONESVILLE  TO  IOWA--CEDAR CONFLUENCE
510  DT=1/U(33,K)
520 GOTO 2180
530 REM  IOWA--CEDAR CONFLUENCE  TO  IOWA--MISS. CONFLUENCE
540  DT=1/U(34,K)
550 GOTO 2180
560 IF SMASS(J)="UNI" AND X(K,J)>953.8 THEN 1290 ELSE 570
570 IF SMASS(J)="NOR" AND X(K,J)>1338 THEN 590 ELSE 610
580 REM  WHITE R. AT NORA  TO  CENTERTON--NEWBERRY
590  DT=1/U(37,K)
600 GOTO 2180
610 IF SMASS(J)="NOR" AND X(K,J)>1232.1 THEN 630 ELSE 650
620 REM  CENTERTON--NEWBERRY   TO   WHITE--E. FORK WHITE CONFLUENCE
630  DT=1/U(38,K)
640 GOTO 2180
650 IF SMASS(J)="BED" AND X(K,J)>1232.1 THEN 670 ELSE 690
660 REM   BEDFORD   TO  WHITE--E.FORK WHITE CONFLUENCE
670  DT=1/U(39,K)
680 GOTO 2180
690 IF SMASS(J)="NOR" OR SMASS(J)="BED" THEN 700 ELSE 740
700 IF X(K,J)>1182.6 AND X(K,J)<1232.1 THEN 720 ELSE 1290
710 REM   WHITE--E.FORK WHITE CONFL.   TO  WHITE--WABASH CONFLUENCE
720  DT=1/U(40,K)
730 GOTO 2180
740 IF SMASS(J)="WAB" AND X(K,J)>953.8 THEN 1290 ELSE 750
750 IF SMASS(J)="SMI" AND X(K,J)>953.8 THEN 1290 ELSE 760
760 IF SMASS(J)="CUM" AND X(K,J)>953.8 THEN 1290 ELSE 770
770 IF SMASS(J)="TEN" AND X(K,J)>953.8 THEN 1290 ELSE 780
780 IF SMASS(J)="YAZ" AND X(K,J)>437.1 THEN 1990 ELSE 790
790 IF SMASS(J)="HER" THEN 1170 ELSE 800
800 IF SMASS(J)="IRO" AND X(K,J)>1489 THEN 870 ELSE 810
810 IF SMASS(J)="IRO" AND X(K,J)>1452 THEN 900 ELSE 820
820 IF SMASS(J)="IRO" AND X(K,J)>1178.1 THEN 930 ELSE 830
830 IF SMASS(J)="ILL" AND X(K,J)>1178.1 THEN 930 ELSE 840
840 IF SMASS(J)="WIN" AND X(K,J)>1178.1 THEN 1130 ELSE 1090
850 IF X(K,J)<=1239! AND X(K,J)>1178.1 THEN 1070 ELSE 1090
860 REM CHEBANSE  TO  IROQUOIS--KANKAKEE CONFLUENCE
870  DT=1/U(27,K)
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880 GOTO 2180
890 REM  KANKAKEE--IROQUOIS CONFLUENCE  TO  ILLINOIS--KANKAKEE CONF.
900  DT=1/U(28,K)
910 GOTO 2180
920 REM MEREDOSIA TO IL--MISS CONFLUENCE
930 IF X(K,J)<=1452 AND X(K,J)>1400 THEN 950 ELSE 970
940 REM  ILLINOIS--KANKAKEE CONF.  TO  MARSEILLES--HENRY
950  DT=1/U(29,K)
960 GOTO 2180
970 IF X(K,J)<=1400 AND X(K,J)>1348 THEN 990 ELSE 1010
980 REM  MARSEILLES--HENRY  TO HENRY--KINGSTON MINES
990  DT=1/U(30,K)
1000 GOTO 2180
1010 IF X(K,J)<=1348 AND X(K,J)>1281 THEN 1030 ELSE 1050
1020 REM  HENRY--KINGSTON MINES  TO KINGSTON MINES--VALLEY CITY

1030  DT=1/U(31,K)
1040 GOTO 2180
1050 IF X(K,J)<=1281 AND X(K,J)>1171.8 THEN 1070 ELSE 1090
1060 REM  KINGSTON MINES--VALLEY CITY  TO  ILLINOIS--MISS. CONFLUENCE
1070  DT=1/U(14,K)
1080 GOTO 2180
1090 IF X(K,J)<=1171.8 AND X(K,J)>1149.1 THEN 1110 ELSE 1210
1100 REM IL--MISS CONFLUENCE TO MO--MISS CONFLUENCE
1110 DT=1/U(15,K)
1120 GOTO 2180
1130 IF X(K,J)<=1295! AND X(K,J)>1171.8 THEN 1150 ELSE 1090
1140 REM WINFIELD TO IL--MISS CONFLUENCE
1150  DT=1/U(16,K)
1160 GOTO 2180
1170 IF X(K,J)<=1247! AND X(K,J)>1149.1 THEN 1190 ELSE 1210
1180 REM HERMANN TO MO--MISS CONFLUENCE
1190  DT=1/U(1,K)
1200 GOTO 2180
1210 IF X(K,J)<=1149.1 AND X(K,J)>1098! THEN 1230 ELSE 1250
1220 REM MO--MISS CONFLUENCE TO ST. LOUIS--CHESTER
1230  DT=1/U(2,K)
1240 GOTO 2180
1250 IF X(K,J)<=1098! AND X(K,J)>1030.3 THEN 1270 ELSE 1560
1260 REM ST. LOUIS--CHESTER TO CHESTER--THEBES
1270  DT=1/U(3,K)
1280 GOTO 2180
1290 IF X(K,J)<=1182.6 AND X(K,J)>1087! THEN 1300 ELSE 1380
1300 IF SMASS(J)="WAB" OR SMASS(J)="NOR" OR SMASS(J)="BED" THEN 1310 ELSE
1360
1310 IF X(K,J)>1087 THEN 1330 ELSE 1360
1320 REM WABASH TO WABASH--OHIO CONFLUENCE
1330 DT=1/U(25,K)
1340 GOTO 2180
1350 REM UNIONTOWN TO SHAWNEETOWN
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1360 DT=1/U(26,K)
1370 GOTO 2180
1380 IF X(K,J)<=1087! AND X(K,J)>1047! THEN 1400 ELSE 1420
1390 REM SHAWNEETOWN TO SMITHLAND DAM
1400 DT=1/U(24,K)
1410 GOTO 2180
1420 IF X(K,J)<=1047! AND X(K,J)>1012! THEN 1530 ELSE 1430
1430 IF X(K,J)<=1012! AND X(K,J)>953.8 THEN 1440 ELSE 1660
1440 IF SMASS(J)="CUM" AND X(K,J)>1012! THEN 1460 ELSE 1480
1450 REM CUMBERLAND TO CUMBERLAND--OHIO CONFLUENCE
1460 DT=1/U(22,K)
1470 GOTO 2180
1480 IF SMASS(J)="TEN" AND X(K,J)>1000! THEN 1500 ELSE 1590
1490 REM TENNESSEE TO TENNESSEE--OHIO CONFLUENCE
1500 DT=1/U(21,K)
1510 GOTO 2180
1520 REM SMITHLAND DAM TO CUMBERLAND--OHIO CONFLUENCE
1530 DT=1/U(23,K)
1540 GOTO 2180
1550 IF X(K,J)<=1012! AND X(K,J)>953.8 THEN 1590 ELSE 1660
1560 IF X(K,J)<=1030.3 AND X(K,J)>953.8 THEN 1570 ELSE 1640
1570 IF SMASS(J)="OLM" THEN 1590 ELSE 1620

1580 REM OLMSTED TO OHIO--MISS CONFLUENCE
1590  DT=1/U(17,K)
1600 GOTO 2180
1610 REM CHESTER--THEBES TO MISS--OHIO CONFLUENCE
1620  DT=1/U(4,K)
1630 GOTO 2180
1640 IF X(K,J)<=953.8 AND X(K,J)>847! THEN 1660 ELSE 1680
1650 REM MISS--OHIO CONFLUENCE TO HICKMAN--FULTON
1660  DT=1/U(5,K)
1670 GOTO 2180
1680 IF X(K,J)<=847! AND X(K,J)>756! THEN 1700 ELSE 1720
1690 REM HICKMAN--FULTON TO FULTON--MEMPHIS
1700  DT=1/U(6,K)
1710 GOTO 2180
1720 IF X(K,J)<=756! AND X(K,J)>699.5 THEN 1740 ELSE 1760
1730 REM FULTON--MEMPHIS TO MEMPHIS--HELENA
1740 DT=1/U(7,K)
1750 GOTO 2180
1760 IF X(K,J)<=699.5 AND X(K,J)>581.5 THEN 1770 ELSE 1900
1770 IF SMASS(J)="WHI" AND X(K,J)<598.8 THEN 1790 ELSE 1810
1780 REM WHITE TO WHITE--MISS CONFLUENCE
1790  DT=1/U(18,K)
1800 GOTO 2180
1810 IF SMASS(J)="PEN" THEN 1830 ELSE 1870
1820 REM ARKANSAS TO ARKANSAS--MISS CONFLUENCE
1830 IF X(K,J)<=700! AND X(K,J)>581.5 THEN 1850 ELSE 1940
1840 REM ARKANSAS R. TO ARKANSAS--MISS CONFLUENCE
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1850  DT=1/U(19,K)
1860 GOTO 2180
1870 REM MEMPHIS--HELENA TO MISS--ARKANSAS CONFLUENCE
1880  DT=1/U(8,K)
1890 GOTO 2180
1900 IF X(K,J)<=599! AND X(K,J)>581.5 THEN 1920 ELSE 1940
1910 REM MISS--WHITE CONFLUENCE TO MISS--ARKANSAS CONFLUENCE
1920  DT=1/U(8,K)
1930 GOTO 2180
1940 IF X(K,J)<=581.5 AND X(K,J)>499.5 THEN 1960 ELSE 2010
1950 REM MISS--ARKANSAS CONFLUENCE TO ARK.CITY--VICKSBURG
1960  DT=1/U(9,K)
1970 GOTO 2180
1980 REM IN YAZOO CANAL
1990 DT=1/U(20,K)
2000 GOTO 2180
2010 IF X(K,J)<=499.5 AND X(K,J)>397.5 THEN 2030 ELSE 2050
2020 REM ARK.CITY--VICKSBURG TO VICKSBURG--NATCHEZ
2030  DT=1/U(10,K)
2040 GOTO 2180
2050 IF X(K,J)<=397.5 AND X(K,J)>314.5 THEN 2070 ELSE 2090
2060 REM VICKSBURG--NATCHEZ TO OLDRIVER OUTFLOW CHANNEL
2070  DT=1/U(11,K)
2080 GOTO 2180
2090 IF X(K,J)<=314.5 AND X(K,J)>234! THEN 2110 ELSE 2130
2100 REM OLDRIVER OUTFLOW CHANNEL TO BATON ROUGE
2110  DT=1/U(12,K)
2120 GOTO 2180
2130 IF X(K,J)<=234! AND X(K,J)>0! THEN 2150 ELSE 2170

2140 REM BATON ROUGE TO HEAD OF PASSES
2150  DT=1/U(13,K)
2160 GOTO 2180
2170 GOTO 2180
2180 IF I>1 GOTO 2220
2190 T(1)=TIME
2200 TM(1)=TIME
2210 IF I=1 GOTO 2280
2220 T(I)=T(I-1)+DT
2230 REM PRINT #1, USING "####.##";T(I),X(K,J),DT
2240 TM(I)=T(I) MOD 24
2250 X(K,J)=X(K,J)-1!
2260 IF I=1 GOTO 2280
2270 IF TM(I-1)>TM(I) THEN 2290 ELSE 2280
2280 NEXT I
2290 X(K,J)=((X(K,J)+1!)*(T(I)-24!)+X(K,J)*(24!-T(I-1)))/(T(I)-T(I-1))
2300 IF X(K,J)>=0! THEN 2330
2310 PRINT #1, "     ";
2320 X(K+1,J)=X(K,J) : GOTO 2340
2330 PRINT #1, USING "####  ";X(K,J); : X(K+1,J)=X(K,J)
```

```
2340 NEXT J
2350 PRINT #1, USING "####  ";X(MDAY(J),J);
2360 PRINT #1, "     ";
2370 PRINT #1,
2380 NEXT K
2390 END
```

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