Technical Report M2

# NAVIGATION STUDY AT THE APPROACH TO LOCK AND DAM 24, UPPER MISSISSIPPI RIVER

# HYDRAULIC MICRO MODEL INVESTIGATION

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# INTRODUCTION

A physical hydraulic sedimentation and flow study was initiated in order to evaluate a number of design alternatives and modifications to alleviate outdraft experienced by downbound tows entering the lock chamber at Lock and Dam 24. The study area consisted of a 6.5-Mile reach of the Upper Mississippi River, between Mile 277.5 and Mile 271.0 near Clarksville, Missouri. The study was sponsored by the St. Louis District Lock and Dam 24 Major Rehabilitation Project .

The study was conducted during the period between September 1996 and July 1997. The study was performed by Mr. David Gordon and Mr. Robert Hetrick, Hydraulic Engineers, under direct supervision of Mr. Robert Davinroy, District Potamologist for the St. Louis District.

Personnel from the St. Louis District also involved in the study included: Mr. Claude Strauser, Chief, Potamology Section; Mr. Steve Redington, Chief, River Engineering Unit; Mr. Tom Lovelace, Chief, Hydrologic and Hydraulics Branch; Mr. Ken Koller, Project Manager of the Study; Mr. Wally Feld, Assistant Chief of the Construction-Operations Readiness Division; Mr. Chris Morgan, Lockmaster at Lock and Dam 24; Mr. Stan Ebersohl, Rivers Project Manager; Mr. Mike Kruckeberg, Civil Engineer; and Mr. Tom Johnson, Mechanical Engineer.

Navigation industry representatives from River Industry Action Committee (RIAC) and the Lower Mississippi River Action Committee (LOMRC) included Messrs. Raymond Hopkins, Sherman Henson, Bob Aldrich, Tommy Seals, Gary Lewis, Bruce Engert, Tim Robinson, Ed Herleben, Dick Burke, Billy Moore, Kevin Kelly, Mike Flanagan, Red Buchhold, and Rick Sadtler.

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# BACKGROUND

This report details the investigation of a sedimentation and flow study of the Upper Mississippi River using a physical hydraulic micro model. The micro model methodology was used to evaluate detrimental flow conditions experienced at the downbound navigation approach to Lock and Dam 24, Mile 273.5R, at Clarksville, Missouri. Plate 1 displays the vicinity map and USGS quad sheet of the study reach. Plate 2 is a photograph of Lock and Dam 24.

## 1. Problem Description

### *A. Outdraft*

Outdraft has been defined as the condition whereby natural or man-induced crosscurrents developed in the river adversely affect a vessel while in a low-powered state. Outdraft at Lock and Dam 24 on the Upper Mississippi River has existed since 1940 at the beginning of project operation.

Downbound vessels (tows) approaching Lock 24 may experience detrimental crosscurrent patterns near the upper end of the lock chamber. These currents tend to pull boats toward the riverwall and adjacent gate openings. Numerous accidents and near catastrophic events have occurred from this historic problem.

Outdraft becomes prevalent when there is at least 30 feet of total gate opening on the dam. The greater the gate opening, the greater the outdraft. Outdraft becomes most severe during high flow and open river conditions when the gates are completely out of the water. Flows equal to or exceeding this condition have occurred approximately 48 percent of the time.
Outdraft is experienced at all lock chambers on the Mississippi River. The degree and severity of outdraft is different at each project location. Generally,

outdraft is caused by the lock chamber acting as an obstruction to flow in the river, causing current patterns to detour around the chamber and head through the adjacent gate openings. However, outdraft at Lock 24 is greatly exaggerated. As discovered by the findings of this study, outdraft at Lock 24 is magnified due to a combination of the existing river alignment and localized geology. A protruding rock bluff (marked “The Pinnacle” on the USGS Quad) extends along the right descending bankline from the lock chamber to river Mile 274.1 (Plate 1). River currents subtly strike and deflect off this protrusion and are directed toward the gate openings.

Another contributing factor to the severity of the outdraft is the fact that the lock and dam was built in a moderate river crossing. Currents on the right descending bankline generally have a tendency to head away from the lock chamber and toward the thalweg in the crossing.

### *B. Navigation Procedure*

Downbound tows frequently require the services of a helper boat during most river conditions to enter the lock chamber. A helper boat assists the tow by pushing its “head-of-tow” against the landwall while the tow pilot positions the stern towards the right descending bankline. Plate 3 is a plan view aerial diagram describing the process of a tow entering the lock chamber with the assistance of a helper boat. Plates 4, 5, and 6 are photographs displaying the sequence of events. If the towing company chooses not to use the helper boat, the tow pilot must align or check his “head-of-tow” into the landwall several times with the help of lock personnel. If the tow strikes the riverwall, barges may become separated and carried into the gate openings (Plate7).

### *C. Waiting Areas*

In 1969, a perpendicular stone dike was constructed in the Mississippi River on the right descending bank at river Mile 274.0R (Plate 3). This dike was extended in 1971. The dike was constructed in an attempt to alleviate outdraft conditions and create a waiting or holding area for downbound tows. The downstream eddy or flow shadow of the structure maintains a low velocity region. Most tows approaching the lock will travel downstream of the dike and then back up into the dike before making their final approach into the lock chamber. This allows the pilot to properly align the tow before entering the lock chamber. While within the dike shadow, the next maneuver consists of turning the tow at a skewed angle. The stern is positioned in the slack water near the bankline and the bow is positioned out in the faster current. The pilot then proceeds toward the lock. Plates 3 through 6 show the sequence of events that most pilots use to enter the lock chamber. Model test results discussed later in this report indicate that this dike is crucial in the overall solution to the outdraft problem.

### *D. Economic Impacts*

Lock records have indicated that through the period between 1980 and 1991, 55 percent of downbound tows experienced outdraft of which 36 accidents occurred. Of these accidents, 23 involved damage to the lock or dam (1). The economic and safety impacts of this navigation problem are of great concern. In 1993, a detailed economic analysis study was conducted by the St. Louis District as part of the Lock and Dam 24 Major Rehabilitation Report (Appendix B, Economics). In this report, three economic costs were specified as being incurred by the outdraft problem. The first and most important cost was the increased transportation costs imposed by traffic delays on downbound tows waiting to enter the lock. The second was the costs associated with the prevention of tow accidents, while the third was the increased accident costs incurred when outdraft was present relative to the accident costs incurred when outdraft was not present.

The impacts of reducing delay times by eliminating outdraft was estimated at approximately $1,020,000 annually. Cost reductions associated with the prevention of tow accidents were estimated to be $33,500 annually. Total costs associated with the outdraft problem were thus estimated to be $1,053,000 annually. For the twelve year period in this study, the average cost for the repair of damages to the lock and dam as a result of outdraft was $12,877 per accident, while the cost per accident without outdraft was $1,841.

Another cost associated with the outdraft problem was transportation delays caused by the closure of the lock due to repair of the miter gates from collisions. Plate 7 shows the consequences of an outdraft induced accident at Lock and Dam 24. An unscheduled half-day lock closure for repairing a leaf gate was estimated to increase transportation costs approximately $220,000. A two-day unscheduled lock closure for repair was estimated to increase transportation costs approximately $2,760,000. The greatest cost would result from an accident that causes major damages to the miter or tainter gates, resulting in a loss of pool. The minimum closure due to this occurrence was estimated to be 14 days with navigation delays estimated at approximately $82,163,000.

## 2. Study Purpose and Goals

The purpose of this study was to develop possible remedial measures to improve navigation conditions at Lock and Dam 24. This was accomplished by the utilization of a hydraulic micro model.

The goals of this study were to:

a. Further investigate the flow mechanics causing the outdraft problem.

b. Evaluate a variety of remedial measures in the micro model with the objective of identifying the most positive, economical, and environmentally friendly plan to alleviate the outdraft problem.

c.  Communicate to other engineers, lockmasters, river industry personnel, biologists, and environmentalists the results of the micro model tests and the plans for improvements.

# FIELD INVESTIGATION OF OUTDRAFT VELOCITY PATTERNS

Historically, a somewhat modest amount of velocity data had been collected near Lock and Dam 24. Traditional velocity measuring systems were used in an attempt to study outdraft. Unfortunately, the resolution of this data had limited the depiction or visualization of the outdraft. With the more recent advancements of data collection and remote sensing methodologies, the opportunity existed in this study to obtain additional velocity data with greater resolution. The following section is a description of the velocity data used for this model study. Observations and conclusions made from this data are then discussed:

## 1. Historic Velocity Data

Plates 8, 9, and 10 show velocity vectors surveyed upstream of the lock during three consecutive days in April of 1982. The density or resolution of the data points was limited. The surveys tended to show that velocities in front of the lock chamber were directed toward the gate openings. The most severe skewed angles of velocity occurred just upstream of the riverwall. However, reliable velocity patterns describing the outdraft could not fully be determined from this data alone.

## 2. Acoustic Doppler Current Profile (ADCP) Data

Plates 11 and 12 display velocity vectors and velocity contours at the downbound approach to Lock and Dam 24. This data was collected using ADCP equipment in March of 1997 during open river conditions. The data was collected to allow engineers to better visualize the outdraft. Since the resolution of the historical data was limited, this data further enhanced the perception of velocity patterns. Results indicated that currents actually deflected off the right descending bankline (near the apex of the rock bluff protrusion) approximately 600 feet upstream of the end of the landwall. This discovery served a vital role in the eventual calibration of the micro model.

## 3. Remote Sensing Data

The use of remote sensing software and standard image processing software was used to analyze aerial photography for river current pattern recognition in the vicinity of Lock and Dam 24. Since there has been a lack of velocity data in the immediate vicinity of the lock chamber, a remote sensing technique was developed at AREC to identify the flow patterns (5). A color aerial photo from December 1993, which contained color differences on the water surface, was selected for the application of this technique. The effects of sediment load (turbidity), surface roughness, and turbulence were expected to affect the spectral reflectance characteristics of the water, which could possibly lead to an analysis of current patterns on the river. The scanned aerial photo was imported into a standard image processing software package and a multispectral classification scheme. The flow patterns near the lock chamber were then analyzed by enhancing the color variations on the water surface.

Most of the color variations occurred as a result of a major influx of suspended sediment from an upstream tributary (Salt River). The Salt River enters the Mississippi River approximately 10 Miles upstream of Lock and Dam 24 (Plate 13). The tributary supplied the study area with a seeding mechanism of suspended sediment that failed to thoroughly mix into the water column before reaching Lock 24. This caused distinct color separation on the water surface which lead to the possibility of determining flow patterns.

Plate 14 shows the original color aerial and the color-enhanced aerial from a standard image processing software package. Visual comparison between the two images showed a distinct variance in color. This represented the effects of surface roughness and suspended sediment.

The remote sensing analysis revealed two important trends. First, it could be seen that currents deflected off the tip of dike 274.0R, as expected. Second, however, it could be visualized that both the deflected currents off the dike tip and the currents within the downstream shadow of the dike were pulled toward and then away from the apex point of the rock bluff protrusion. This visualization of current deflection at the bluff was verified by observations from the ADCP data (Plate 11).

The remote sensing technique, combined with the ADCP data and the historic velocity data, enabled engineers to determine how, why, and where outdraft was occurring in the river. It was apparent that the rock bluff protrusion, located approximately 600 feet above the lock chamber, was the primary influence to the development of exaggerated outdraft conditions upon downbound approaching tows. This observation was later verified by flow visualization of the micro model base test (Plate 26).

# MICRO MODEL SETUP

## 1. Scales and Bed Materials

Plate 15 is a photograph of the Lock and Dam 24 hydraulic micro model used in this study. The scales of the model were 1 inch = 800 feet, or 1:9600 horizontal and 1 inch = 50 feet, or 1:600 vertical for a 16:1 distortion ratio. This distortion supplied the necessary forces required for the simulation of sediment transport conditions similar to the prototype (2). The bed material used was granular plastic urea, Type II, with a specific gravity of 1.23.

## 2. Apperturences

The model was constructed according to 1994 aerial photography of the study reach. The physical lock chamber was fabricated out of sheet metal, while the dam was constructed out of oil based clay. The tainter gates were not placed in the model because the study only examined open river conditions. Stage was monitored by a staff gage and a three-dimensional digitizer. Resultant bed configurations (bathymetry) were measured and recorded with a three-dimensional digitizer with a computer interface.

Surface current patterns were captured using a flow visualization technique developed at AREC. This technique was performed for the base test and all design alternative tests.

# MICRO MODEL TESTS

## 1. Calibration and Verification

The calibration and verification of the micro model involved the adjustment of water discharge, sediment load, and floodplain slope. These parameters were refined until the measured bed response of the model was similar to the prototype. Only open river conditions were used to calibrate the model. This condition was simulated in the model as steady-state flow.

Several historic hydrographic surveys were used to determine the general bed characteristics that existed in the prototype. Plate 16 shows an 1880-bankline survey of the study reach overlaid on a 1994 aerial photograph. The comparison indicates that the bankline in this area has remained relatively unchanged for the past 115 years. This suggests that bedrock, clay deposits, and/or other non-erodables are predominant in this area. Plate 17 shows pre-construction (1939) and post-construction (1947) prototype surveys of the riverbed. Plates 18 through 24 show prototype surveys during 1968, 1977, 1982, 1987, 1993, 1995, and 1997. These surveys indicate that the bathymetry through the study reach has remained primarily unchanged since the construction of the lock and dam.

Once a favorable comparison of these prototype surveys was made with model surveys, the model was considered calibrated. The resultant bathymetry of this bed response served as both the verification and the base test of the micro model (2).

## 2. Base Test

Plate 25 shows the resultant bed configuration of the micro model base test. This survey served as the comparison survey for all future design alternative model tests. The base test was developed by simulating steady flow or open river conditions until bed stability was reached.

The bathymetric trends of the base test were as follows:

- Between Miles 277.5 and 275.3, the thalweg followed the right descending bankline through the bend near Pharrs Island.
- A crossing developed near Mile 275. The thalweg crossed toward Middleton Island and remained on the left descending bankline side of the channel.
- The depths in the secondary channel on the Illinois side of Pharrs and Middleton Islands were relatively shallow as compared with the main channel.
- Downstream of the dam, a shallow crossing developed between Miles 273 and 272.
- The thalweg remained off the Missouri right descending bankline through the rest of the study reach.

Generally, the bathymetric trends established in the micro model were very similar to the trends observed in the historical prototype surveys. The only major noted difference was the location of the scour hole pattern below the dam. The scour had a tendency to occur further downstream in the model as compared to the prototype.

Plate 26 is a flow visualization of the micro model base test. Results indicated that the currents deflected off dike 274.0R, curved back towards the right descending bank, and then deflected off the rock bluff protrusion toward the gate openings. These trends were similar to what was observed from the ADCP and remote sensing prototype data (Plates 11 and 14).

## 3.  Alternative Plans

Thirty alternative design plans were tested in this study in an attempt to improve flow conditions at Lock and Dam 24.  The effectiveness of each plan was compared to base test conditions.  Impacts or changes of each alternative were evaluated by analyzing both the flow (using flow visualization) and sediment response of the model.   A qualitative evaluation of the ramifications of each plan to both downbound and upbound tows was made during team participation meetings at AREC.  Engineers and navigation industry port captains and pilots carefully examined and discussed each alternative.  Plate 27 is a photo of AREC engineers working with river industry personnel from RIAC and LOMRC on the micro model.

All of the alternative tests conducted in the model study are categorized in alphabetical order, followed by a bulleted design description.  A brief description of the changes to the bathymetry and changes to the flow patterns compared to the base test is then summarized.  The alternative tests are as follows:

**Alternative A**

- 400-foot trail added to existing dike 274.0R
- 800-foot dike with a 600 foot trail added at Mile 274.2R

Alternative A was founded on a test conducted on a previous hydraulic model study of Lock and Dam 22 at Saverton, Missouri (conducted at the Waterways Experiment Station, Vicksburg, MS).   Plates 28 and 29 show the resultant bed configuration and flow visualization of Alternative A.  Test results indicated that the bed response in the main channel remained essentially unchanged except for increased deposition upstream of the dike field.  Flow visualization revealed that outdraft was similar to conditions observed in the base test.

**Alternative B**

- 250-foot dike added at  Mile 273.9R

- 800-foot dike added at Mile 274.2R
- 700-foot dike added at Mile 274.4R

Alternative B was also founded on a test conducted on a previous model of Lock and Dam 22. Plates 30 and 31 show the resultant bed configuration and flow visualization of Alternative B. Test results indicated that the bed response in the main channel remained essentially unchanged except for increased deposition upstream of the dike field. Flow visualization revealed that outdraft was similar to conditions observed in the base test.

**Alternative C**

- 250-foot dike with a 250-foot trail added at Mile 273.9R
- 400-foot trail added to existing dike 274.0R
- 800-foot dike with a 600-foot trail added at Mile 274.2R
- 700-foot dike with a 700-foot trail added at Mile 274.4R

Alternative C included trails added to all the dikes described in Alternative B. Plates 32 and 33 show the resultant bed configuration and flow visualization of Alternative C. Test results indicated that the bed response in the main channel remained essentially unchanged. Flow visualization showed that outdraft was reduced slightly by pulling currents off the rock bluff.

**Alternative D**

- 1950-foot dike built at –5-feet LWRP at Mile 274.0L
- 2200-foot dike built at –5-feet LWRP at Mile 274.3L
- 1650-foot dike built at –5-feet LWRP at Mile 275.0L

Alternative D included three long, low-elevation dikes, which extended from the SNY Levy on the Illinois bankline. Plates 34 and 35 show the resultant bed configuration and flow visualization of Alternative D. Test results indicated that the dike field directed most of the flow from the Illinois side to the Missouri side of the channel. The dikes deepened and widened the thalweg considerably while causing deposition in the side channel. However, the location of the thalweg remained essentially unchanged.  Flow visualization showed that the outdraft problem remained unchanged as compared to the base test.

**Alternative E**

- 3500-foot longitudinal dike placed parallel to the lock chamber and tangent to the river alignment between Miles 273.6R and 274.4R

Plates 36 and 37 show the resultant bed configuration and flow visualization of Alternative E.  Test results indicated that the bed response in the main channel remained essentially unchanged except for increased deposition upstream of the dike.  Flow visualization showed that currents were pulled considerably off the rock bluff thereby reducing the outdraft.

**Alternative F**

- 150-foot dike with a 200-foot trail added at Mile 273.8R
- 400-foot dike with a 400-foot trail added at Mile 273.9R
- 175-foot extension and a 300-foot trail added to existing dike 274.0R
- 1000-foot dike with a 600-foot trail added at Mile 274.2R
- 900-foot dike with a 500-foot trail added at Mile 274.4R

Alternative F included extensions of all dikes described in Alternative C.  Plates 38 and 39 show the resultant bed configuration and flow visualization of Alternative F.  Test results indicated that the bed response in the main channel remained essentially unchanged except for increased deposition upstream of the dike field.  Flow visualization showed currents were pulled away from the rock bluff thereby reducing the outdraft.

**Alternative G**

*Bendway Weirs Built at –15-feet LWRP and Added in Two Sets of Weir Fields*:

- 7 bendway weirs located near the downstream end of Pharrs Island on the right descending bankline between Miles 275.6R and 276.1R
- 4 bendway weirs located on the downstream end of Middleton Island on the left descending bankline between Miles 274.4L and 275.0L

Plates 40 and 41 show the resultant bed configuration and flow visualization of Alternative G.  Tests results indicated that the thalweg shifted from the left descending bank to the right descending bank near the end of Middleton Island. Flow visualization showed that by moving the thalweg towards the right descending bank, currents were directed at dike 274.0R.  This made the dike more effective.  Currents were pulled away from the rock bluff thereby reducing the outdraft.

**<u>Alternative H</u>**

- 11 bendway weirs described in Alternative G
- Existing dike 274.0R removed

Plates 42 and 43 show the resultant bed configuration and flow visualization of Alternative H.  Test results indicated that the thalweg moved from the left descending bank toward the right descending bank as in Alternative G.  Flow visualization showed that without the existing dike, currents deflected more severely off the rock bluff protrusion as compared to the base test thereby increasing outdraft.

**<u>Alternative I</u>**

- 11 bendway weirs described in Alternative G
- 400-foot trail added to existing dike 274.0R

Plates 44 and 45 show the resultant bed configuration and flow visualization of Alternative I.  Test results indicated a similar bed response and flow pattern as observed in Alternative G.

**<u>Alternative J</u>**

- 4 downstream bendway weirs described in Alternative G located between Miles 274.4L and 275.0L

In Alternative J, 7 of the 11 bendway weirs in Alternative G were eliminated. Plates 46 and 47 show the resultant bed configuration and flow visualization of Alternative J.  Test results indicated that the thalweg moved toward the right descending bank but not quite as severe as observed in Alternative G.  Flow visualization showed that with only four bendway weirs, the dike at 274.0R still became more effective. Currents were pulled away from the rock bluff reducing the outdraft, but to a lesser degree than observed in Alternative G.

**Alternative K**

- 1800 foot longitudinal dike placed parallel to the lock chamber and tangent to the river alignment between Miles 273.6R and 274.0R

Alternative K was a modification of the dike in Alternative E. Plates 48 and 49 show the resultant bed configuration and flow visualization of Alternative K. Test results indicated that the bed response in the main channel remained essentially unchanged except for increased deposition upstream of the dike. Flow visualization showed that the longitudinal dike plan pulled currents substantially away from the rock bluff thereby reducing the outdraft.

**Alternative L**

- 3500-foot longitudinal dike built at –5-feet LWRP, placed parallel to the lock chamber and tangent to the river alignment between Miles 273.6R and 274.4R
- Existing dike 274.0R removed

Alternative L was a modification of the dike in Alternative E. Plates 50 and 51 show the resultant bed configuration and flow visualization of Alternative L. Test results indicated that the bed response in the main channel remained essentially unchanged except for increased deposition upstream of the dike. Flow visualization showed that outdraft was reduced as compared to the base test.

**Alternative M**

- 4 downstream bendway weirs described in Alternative G implemented between Miles 274.4L and 275.0L
- 400-foot trail added to existing dike 274.0R

Plates 52 and 53 show the resultant bed configuration and flow visualization of Alternative M. Test results indicated a similar bed response and flow pattern comparable to Alternative J.  Flow visualization showed that outdraft was reduced by pulling currents away from the rock bluff.

**<u>Alternative N</u>**

- 4 downstream bendway weirs described in Alternative G implemented between Miles 274.4L and 275.0L
- 1700-foot longitudinal dike extending upstream from the middle of the existing dike 274.0R between Miles 274.0R and 274.3R

Plates 54 and 55 show the resultant bed configuration and flow visualization of Alternative N.  Test results indicated that the thalweg moved towards the right descending bankline.  Flow visualization showed that the addition of the longitudinal dike plan caused a decrease in the effectiveness of dike 274.0.R. The outdraft condition remained similar to conditions observed in the base test.

**<u>Alternative O</u>**

- 4 downstream bendway weirs described in Alternative G implemented between Miles 274.4L and 275.0L
- Existing dike 274.0R removed
- 800-foot dike added at Mile 274.2R

Plates 56 and 57 show the resultant bed configuration and flow visualization of Alternative O.  Test results indicated that the thalweg moved toward the right descending bankline near the dike plan.  Flow visualization showed that the outdraft conditions remained essentially the same as observed in the base test.

**<u>Alternative P</u>**

- Existing dike 274.0R removed
- 800-foot dike added at Mile 274.2R

Plates 58 and 59 show the resultant bed configuration and flow visualization of Alternative P.  Test results indicated that the main channel remained relatively unchanged.  Flow visualization showed that outdraft conditions remained the same as observed in the base test.

**Alternative Q**

- 950-foot dike added on the downstream end of Middleton Island at Mile 274.7L

Plates 60 and 61 show the resultant bed configuration and flow visualization of Alternative Q.  Test results indicated that the end of the dike created a deep scour hole and the thalweg moved toward the right descending bankline downstream of the dike.  Flow visualization showed that currents were slightly pulled away from the rock bluff.

**Alternative R**

- 225-foot extension added to existing dike 274.0R

Plates 62 and 63 show the resultant bed configuration and flow visualization of Alternative R.  Test results indicated that the main channel remained relatively unchanged except for increased deposition upstream of the dike.  Flow visualization showed that the outdraft was reduced as compared to the base test.

**Alternative S**

- Existing dike 274.0R removed

Alternative S was implemented to simulate flow conditions before the existing dike was built.  Plates 64 and 65 show the resultant bed configuration and flow visualization of Alternative S.  Test results indicated that the main channel remained relatively unchanged except for increased deposition in the area where the existing dike was removed.  Flow visualization showed that the outdraft condition was greatly exaggerated.  Deflection currents off the rock bluff were much more pronounced than observed in the base test.

**Alternative T**

- 4 weirs angled perpendicular to flow at –15-feet LWRP, located on the downstream end of Middleton Island on the left descending bankline between Miles 274.4L and 275.0L

Plates 66 and 67 show the resultant bed configuration and flow visualization of Alternative T. Test results indicated that the thalweg remained relatively unchanged through the weir field. From the lower end of the weir field to the lock chamber, the channel became shallow. Flow visualization showed that the outdraft was similar to what was observed in the base test.

*(Construction Sequencing: Alternatives U, V, W, X, and Y were tested to evaluate the best order of construction of the 4 downstream bendway weirs described in Alternative G.)*

**Alternative U**

- 2 uppermost weirs of the downstream weir field described in Alternative G implemented between Miles 274.8L and 275.0L

Plates 68 and 69 show the resultant bed configuration and flow visualization of Alternative U. Test results indicated that the main channel remained relatively unchanged. Flow visualization showed that the outdraft was similar to what was observed in the base test.

**Alternative V**

- 3 uppermost weirs of the downstream weir field described in Alternative G implemented between Miles 274.6L and 275.0L

Plates 70 and 71 show the resultant bed configuration and flow visualization of Alternative V. Test results indicated that the thalweg moved toward the right descending bankline upstream of the existing dike. Flow visualization showed that outdraft was reduced as compared to the base test.

**Alternative W**

- 2 lowermost weirs of the downstream weir field described in Alternative G implemented between Miles 274.4L and 274.6L

Plates 72 and 73 show the resultant bed configuration and flow visualization of Alternative W. Test results indicated that the thalweg moved toward the right descending bankline upstream of the existing dike. Flow visualization showed that outdraft was reduced as compared to the base test.

**Alternative X**

- 3 lowermost weirs of the downstream weir field described in Alternative G implemented between Miles 274.4L and 274.8L

Plates 74 and 75 show the resultant bed configuration and flow visualization of Alternative X. Test results indicated that the thalweg was moved toward the right descending bankline upstream of the existing dike. Flow visualization showed that the outdraft was reduced as compared to the base test.

**Alternative Y**

- 2 uppermost weirs of the downstream weir field described in Alternative G implemented between Miles 274.8L and 275.0L
- 225-foot extension added to existing dike 274.0R

Plates 76 and 77 show the resultant bed configuration and flow visualization of Alternative Y. Test results indicated that the thalweg moved slightly toward the right descending bankline near the existing dike. Flow visualization showed that outdraft was reduced as compared with the base test.

**Alternative Z0**

- 4 downstream bendway weirs described in Alternative G implemented between Miles 274.4L and 275.0L; effective lengths shortened approximately 50%.

Plates 78 and 79 show the resultant bed configuration and flow visualization of Alternative Z0. Test results indicated that the thalweg moved slightly toward the right descending bankline downstream of the last weir. Flow visualization showed that outdraft was slightly reduced as compared to the base test.

**Alternative Z1**

- 2 weirs angled about 30 degrees downstream to flow at –15-feet LWRP and located on the downstream end of Middleton Island on the left descending bankline between Miles 274.4L and 274.6L

Plates 80 and 81 show the resultant bed configuration and flow visualization of Alternative Z1. Test results indicated that the thalweg moved toward the left descending bankline downstream of the weirs. Deposition occurred near the right descending bank and in the main navigation channel adjacent to the existing dike. Flow visualization showed that outdraft was reduced as compared to the base test.

**Alternative Z2**

- 275-foot extension added to existing dike 274.0R
- 1050-foot dike added at Mile 274.2R
- 850-foot dike added at Mile 274.4R

Plates 82 and 83 show the resultant bed configuration and flow visualization of Alternative Z2. Test results indicated that the thalweg remained essentially unchanged except for large scour holes that formed off the end of the two uppermost dikes. Flow visualization showed outdraft was reduced as compared to the base test.

**Alternative Z3**

- 275-foot extension added to existing dike 274.0R
- 1050-foot dike added at Mile 274.2R

Plates 84 and 85 show the resultant bed configuration and flow visualization of Alternative Z3. Test results indicated that the thalweg remained essentially unchanged except for a large scour hole that formed off the end of the uppermost dike. Flow visualization showed that outdraft was slightly reduced as compared to the base test.

**<u>Alternative Z4</u>**

- 4 downstream bendway weirs described in Alternative G implemented between Miles 274.4L and 275.0L
- 200-foot extension added to existing dike 274.0R

Plates 86 and 87 show the resultant bed configuration and flow visualization of Alternative Z4. Test results indicated that the thalweg moved toward the right descending bankline downstream of the weir field. Flow visualization showed that the outdraft was reduced as compared to the base test.

# RESULTS AND CONCLUSIONS

## 1. Summary of Model Tests

In evaluating and summarizing the impacts of all alternative model tests, it was found that two principles were most effective at reducing or eliminating the outdraft problem. The first principle involved moving or directing the thalweg towards the right descending bank upstream of Lock and Dam 24. This redirection of flow generally caused the existing dike at Mile 274.0R to become more efficient at reducing outdraft.

Placing bendway weirs in the channel off the left descending bank upstream of the existing dike proved to be very effective at following this first principle. Eleven weirs in two separate weir fields (Alternatives G & I) achieved this goal. Four weirs in a single field (Alternatives J, M & Z-4) also proved effective, although to a slightly lesser extent. Economically, Alternative J was much more attractive than Alternative G.

Adding dikes on the left descending bankline just upstream of the lock chamber (Alternatives D & Q) proved ineffective at reducing outdraft. Although these dikes shifted the thalweg slightly toward the right descending bankline, the structures had minimal effect on outdraft. These alternatives also proved to be very costly.

The second principle consisted of reducing outdraft without shifting the thalweg. Extending existing dike 274.0R (Alternatives R, Y & Z-4) produced positive effects at reducing outdraft following this second principle. However, these plans had a tendency to create shoaling effects near the entrance to the port facility at Mile 274.5R. Downstream of the dike, no shoaling effects were observed.

Other alternatives (E, K, and L) involving the placement of longitudinal structures off the right descending bank upstream of the lock chamber showed some promise in reducing outdraft. Unfortunately, the high construction costs, increased deposition near the port facility, and possible environmental impacts of these solutions made them somewhat undesirable.

Alternatives that involved adding dikes on the right descending bank (A, B, C, F, Z-2 and Z-3) proved to be minimally effective at reducing the outdraft problem. Again, the construction costs, increased deposition, and environmental impacts of these solutions made them unattractive.

Moving the existing dike upstream (Alternatives P & O) had no effect at eliminating outdraft. These plans also created shoaling problems.

## 2. Recommended Solution

Using the model study test results as a guide, team representatives from the St. Louis District and river industry determined the most efficient, economical, and practical solutions to the outdraft at Lock and Dam 24. The team concluded that four bendway weirs upstream of the lock chamber off the left descending bank and an extension of the existing dike at Mile 274.0R would be the best possible measure at reducing or eliminating the outdraft problem.

By comparing the alternative plans of the eleven weirs versus the four weirs, model tests suggested that the eleven weirs plan would shift the thalweg too aggressively towards the right descending bank. Flow visualization showed that most of the flow would be concentrated off the end of dike 274.0R. Although effective at eliminating outdraft, this design would possibly create strong velocities between the dike and lock chamber outside of the riverwall. The team was concerned about the development of dangerous flow patterns for upbound tows leaving the lock chamber. It was decided that the four-weir plan, combined with the dike extension, would make for much safer conditions for upbound navigation.

A 200-foot extension on dike 274.0R combined with the four weirs would create increased slack water between the dike and the lock chamber. Alternative Z-4 incorporated both these solutions. The resultant bathymetry indicated that the thalweg was shifted toward the right descending bankline. Flow visualization showed that this plan reduced outdraft. This design would provide favorable flow conditions for both upbound and downbound tows.

## 3. Construction

The team decided that the river training structures described in Alternative Z-4 should be constructed in three phases. Each phase would be spaced approximately six months apart, which would create moderate changes in the bathymetry and the flow patterns. This would enable tow pilots to assimilate to the changing flow patterns gradually. Alternatives U, V, W, X, and Y were tested to evaluate the best order in which to construct each phase. After careful consultation among team members, it was determined that the safest construction sequencing was as follows:

- Phase 1. Construct the extension at dike 274.0R
- Phase 2. Construct the two uppermost weirs
- Phase 3. Construct the two lowermost weirs

## 4. Interpretation of Model Test Results

In the interpretation and evaluation of the results of the tests conducted, it should be remembered that the results of these model tests were qualitative in nature.

Any hydraulic model, whether physical or numerical, is subject to biases introduced as a result of the inherent complexities that exist in the prototype. Anomalies in actual hydrographic events, such as prolonged periods of high or low flows, are not reflected in these results, nor are complex physical phenomena, such as the existence of underlying rock formations or other non-erodible variables.

Finally, it should be noted that the innovative ideas set forth in this study were developed as a result of a cooperative effort. “Hands on” group plan formulation, discussions, model experimentation, and professional experience enabled both river pilots and engineers to understand and solve the historic outdraft problem at Lock and Dam 24.

# BIBLIOGRAPHY


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2. Davinroy, Robert D., Physical Sediment Modeling of the Mississippi River on a Micro Scale, University of Missouri-Rolla Thesis, Rolla, Missouri, October 1994.

3. Davinroy, Robert D., Micro Scale Sediment Modeling (Micro Modeling) of Inland Waterways, Proceedings of the Sixth Federal Interagency Sedimentation Conference, Las Vegas, Nevada, 1996.

4. Leopold, Luna B., A View of the River, Harvard University Press, Cambridge, Massachusetts, London, England, 1995.

5. Davinroy, Robert D., Gordon, David C., and Kreighbaum David W., Remote Sensing of Detrimental Flow Conditions at the Downstream Approach to Lock and Dam 24, Upper Mississippi River, ASCE Hydrology Conference, Las Vegas, Nevada, April 1998.

# FOR MORE INFORMATION

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Fax:  (314) 263-4166

e-mail:  davinroy@smtp.mvs.usace.army.mil

gordon@smtp.mvs.usace.army.mil


Or you can visit us on the World Wide Web at:

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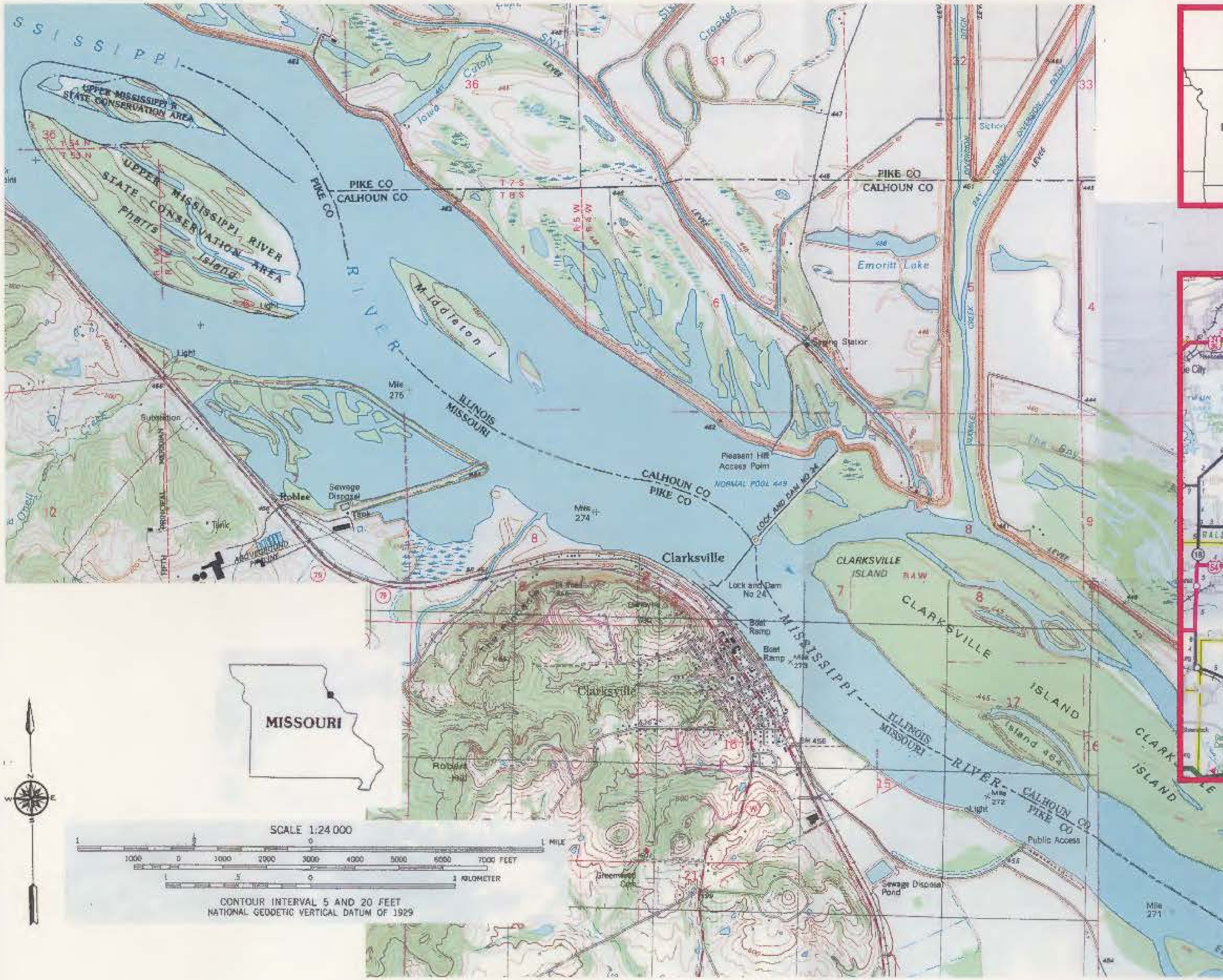
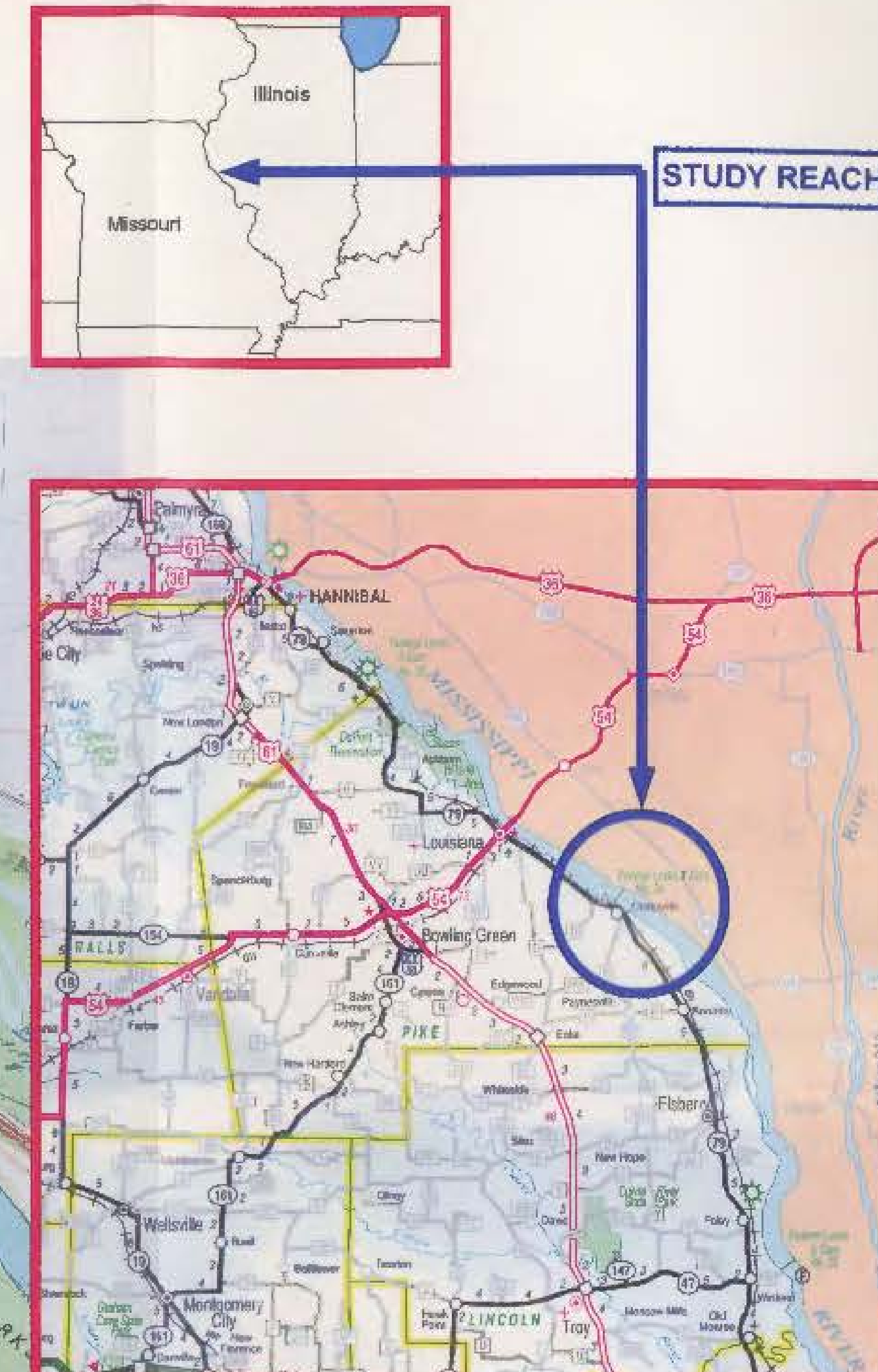
# APPENDIX

Plates #'s 1 through 86 follow:

1. Vicinity Map and USGS Quad Sheet of the Study Area
2. Photograph of Lock & Dam 24 – Looking Upstream
3. Simulation of a Downbound Tow Entering Lock & Dam 24
4. 15 Barge Tow Preparing to Enter Lock & Dam 24 with Aid of a Helper Boat
5. 15 Barge Tow Preparing to Enter Lock & Dam 24 with Aid of a Helper Boat
6. 15 Barge Tow Preparing to Enter Lock & Dam 24 with Aid of a Helper Boat
7. Accident Aftermath Due to Outdraft – Several Barges Against the Dam and Damage to the Miter Gates
8. Velocity Vectors at Lock and Dam 24, Surveyed April 6, 1982
9. Velocity Vectors at Lock and Dam 24, Surveyed April 7, 1982
10. Velocity Vectors at Lock and Dam 24, Surveyed April 8, 1982
11. ADCP Survey Data, Velocity Vectors, March 4, 1997
12. ADCP Survey Data, Velocity Contours, March 4, 1997
13. Salt River Tributary Entering the Mississippi River 10 Miles Upstream of Lock & Dam 24
14. Remote Sensing Flow Data at the Downbound Approach to Lock & Dam 24
15. Lock & Dam 24 Micro Model
16. 1880 Prototype Survey of the Bankline
17. 1939 Prototype Survey Upstream of the Dam and 1947 Prototype Survey Downstream of the Dam
18. 1968 Prototype Survey
19. 1977 Prototype Survey
20. 1982 Prototype Survey
21. 1987 Prototype Survey
22. 1993 Prototype Survey
23. 1995 Prototype Survey
24. 1997 Prototype Survey

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Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Vicinity Map and USGS Quad Sheet of the Study Area

PLATE NO. 1

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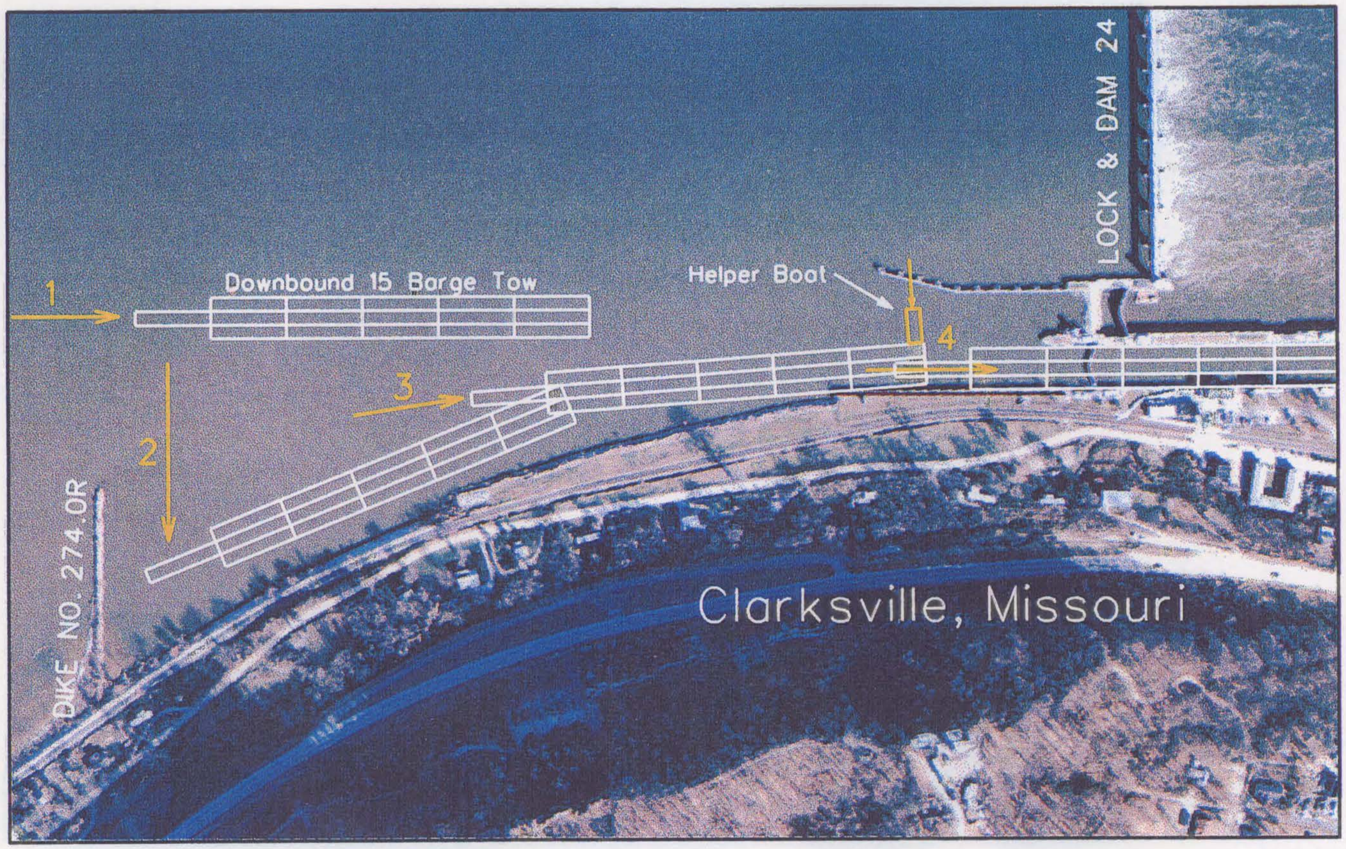
Mississippi River Miles 271 - 277

Photograph of Lock and Dam 24 - Looking Upstream

PLATE NO. 2




1. Downbound tow prepares to enter Lock 24 below Dike 274.0R.

2. The tow moves against the bankline behind the shadow provided by the dike.

3. A helper boat helps the tow manuver its bow against the land wall while the stern is held towards the shore line.

4. The tow enters the lock chamber while keeping its stern tightly against the land wall.

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Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

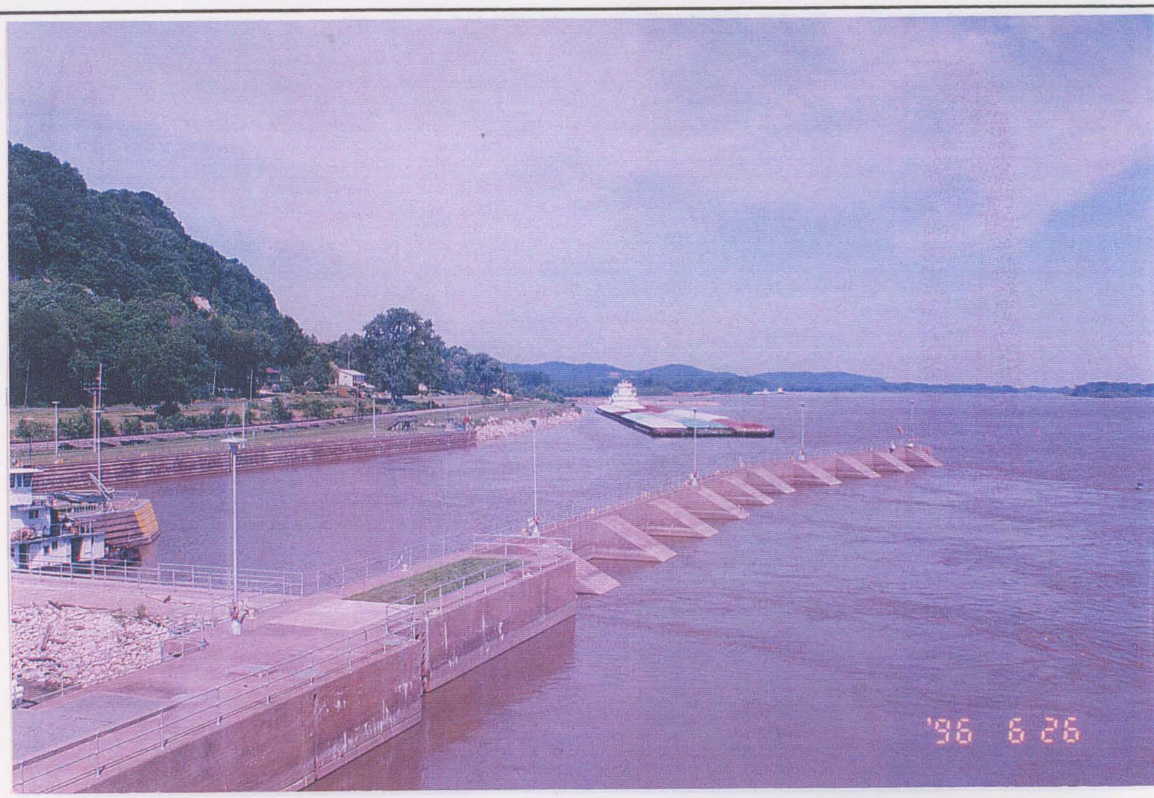
Simulation of a Downbound Tow Entering Lock and Dam 24

500' 400' 300' 200' 100' 0 500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\

PLOT SCALE: 1" = 500'

PLATE NO. 3





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Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

15 Barge Tow Preparing to Enter Lock and Dam 24
With the Aid of a Helper Boat

PLATE NO **4**



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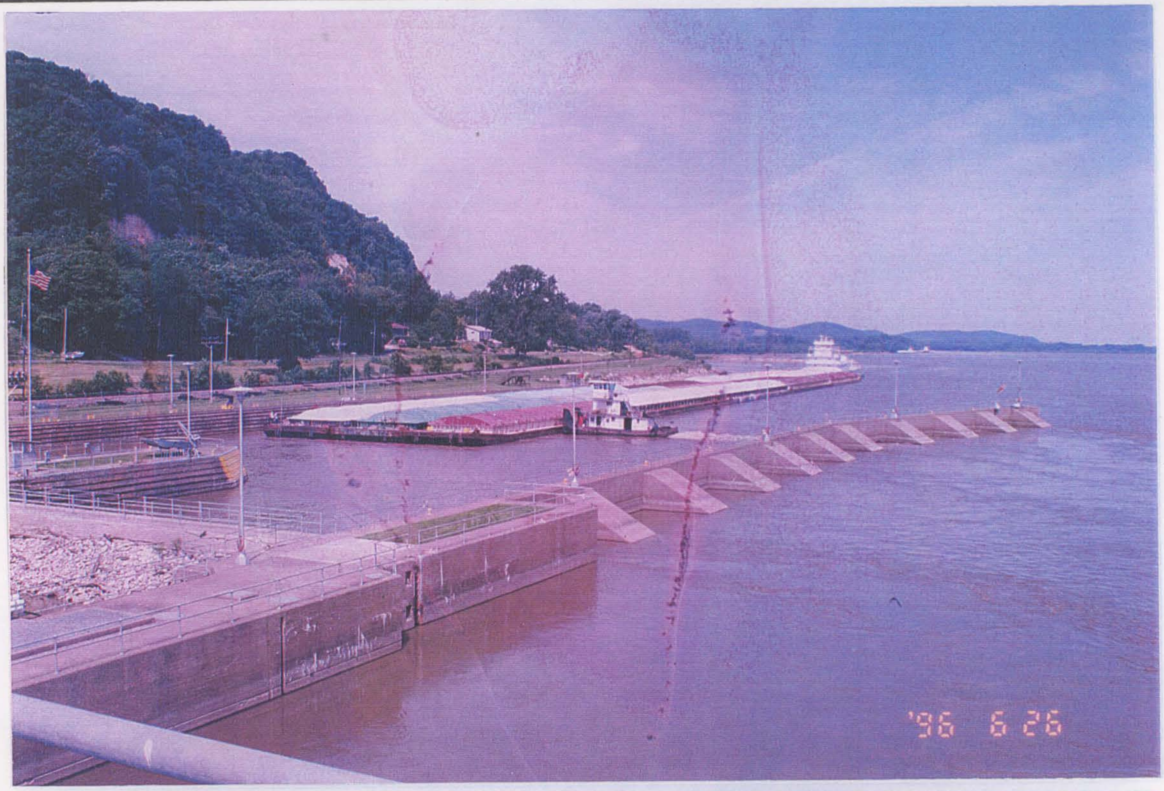
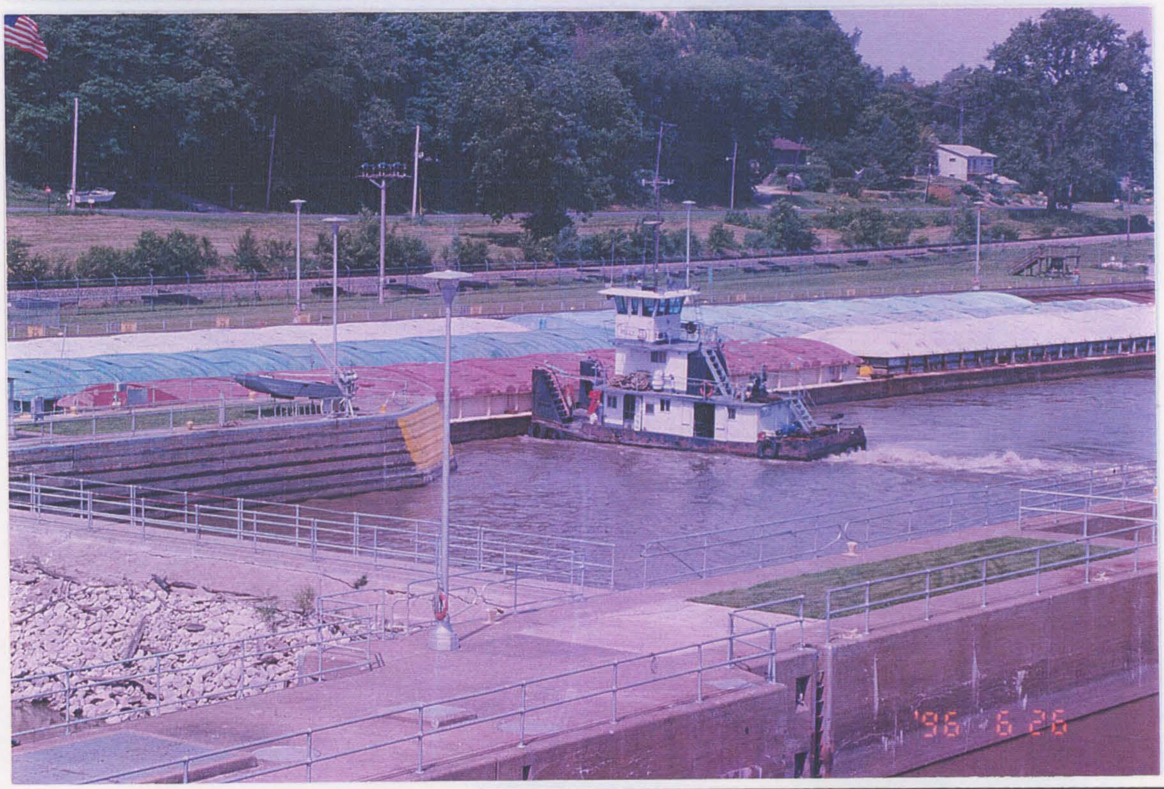
Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

15 Barge Tow Preparing to Enter Lock and Dam 24
With the Aid of a Helper Boat

PLATE NO 5

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Mississippi River Miles 271 - 277

15 Barge Tow Preparing to Enter Lock and Dam 24
With the Aid of a Helper Boat

PLATE NO **6**



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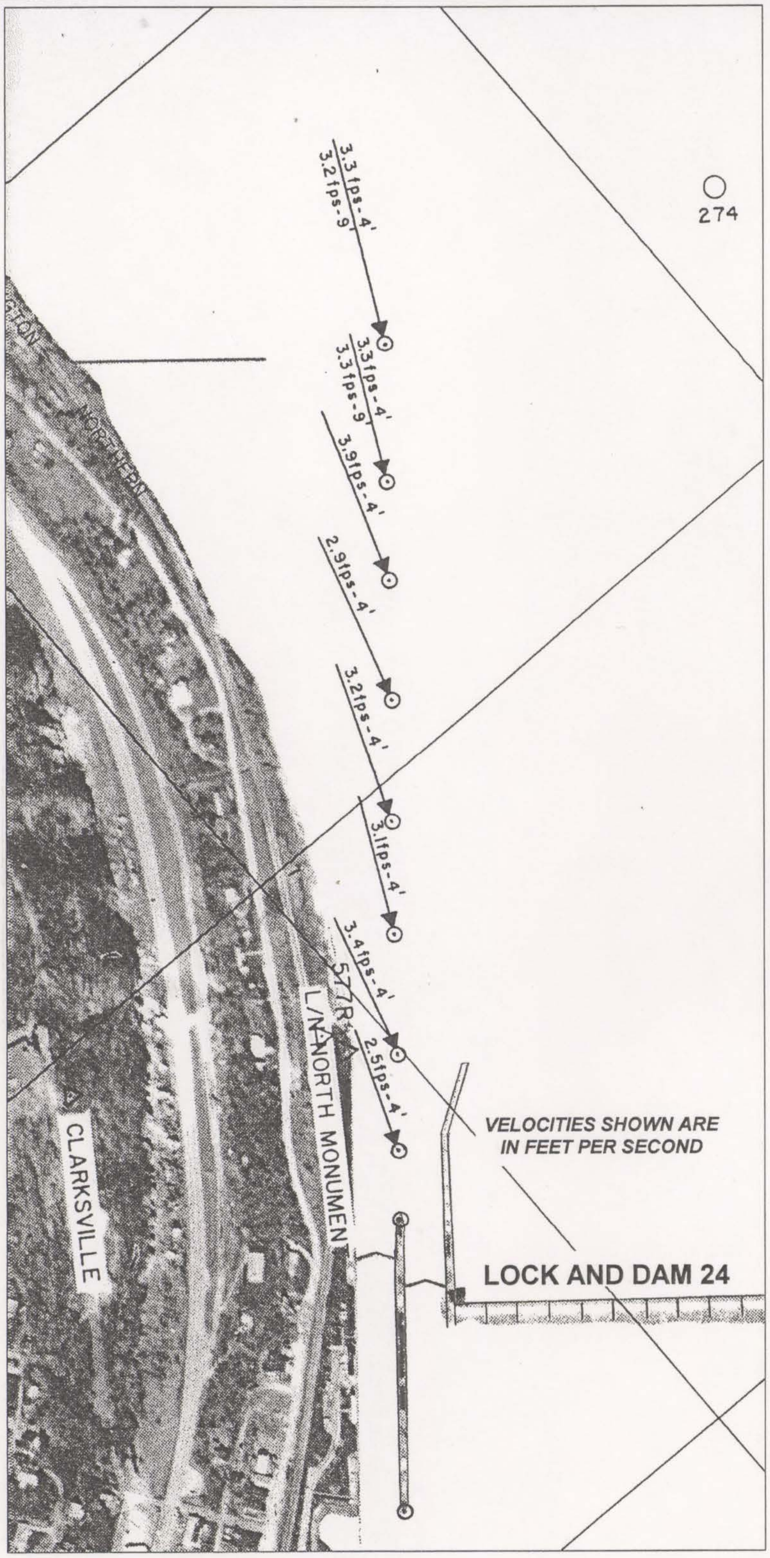
Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Accident Aftermath Due to Outdraft- Several Barges Against The Dam and Damage to the Miter Gates

PLATE NO. 7

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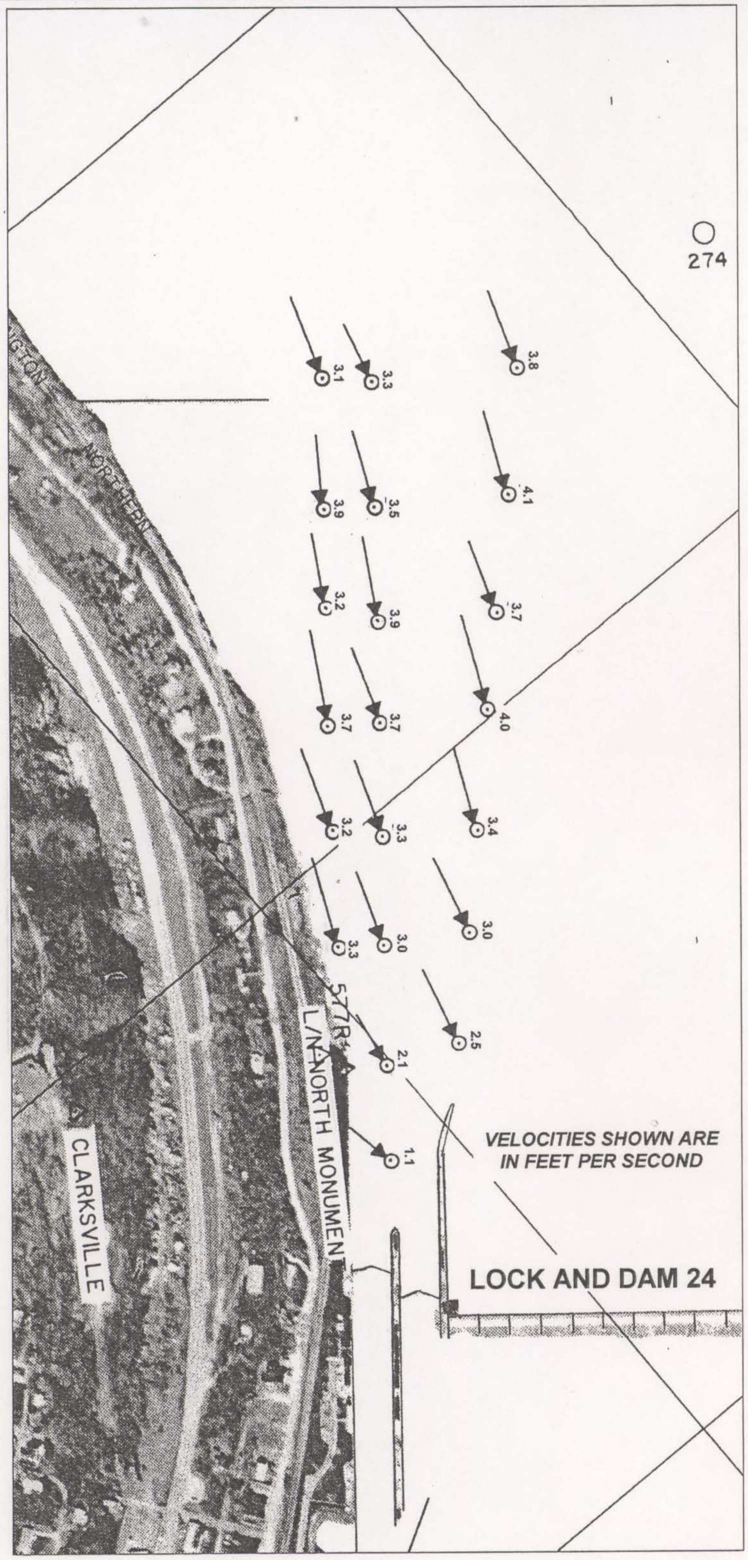
| PREPARED BY: D. Gordon<br>CHECKED BY: R. Davinroy | Lock and Dam 24 Micro Model Study<br>Mississippi River Miles 271 - 277<br><br>Velocity Vectors at Lock and Dam 24<br>Surveyed April 6, 1982 |
| | PLATE NO. **8** |

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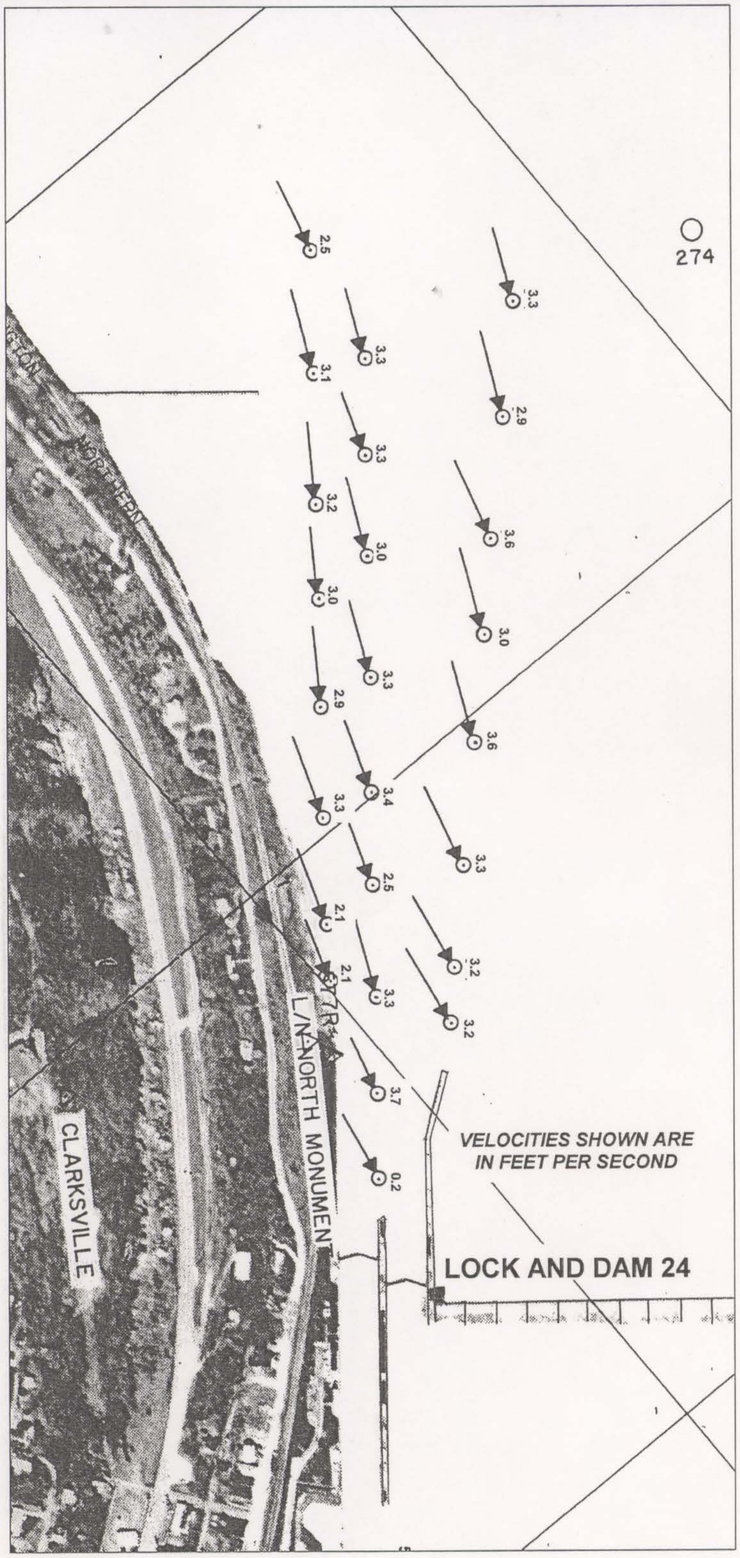
Mississippi River Miles 271 - 277

Velocity Vectors at Lock and Dam 24
Surveyed April 7, 1982

PLATE NO.
**9**

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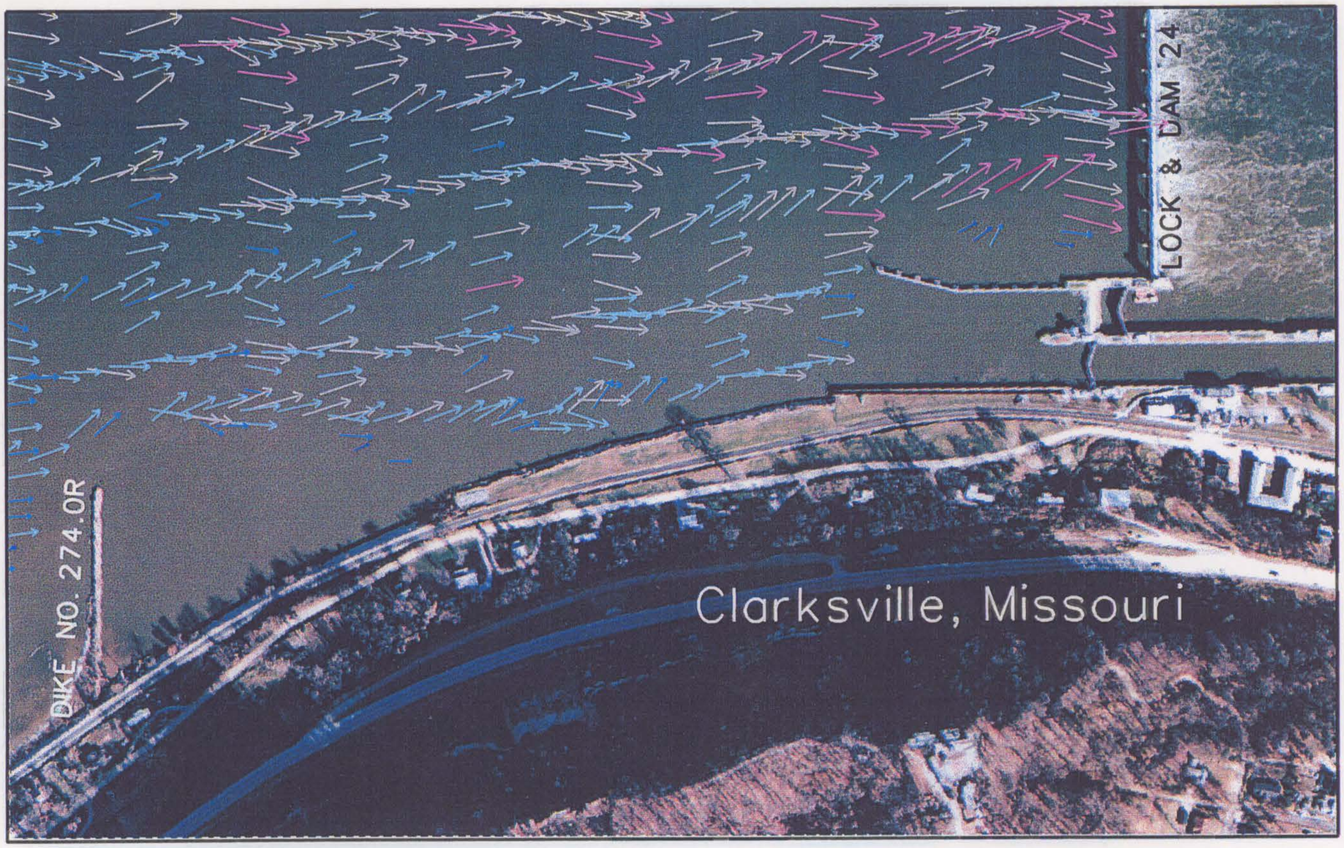
Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Velocity Vectors at Lock and Dam 24
Surveyed April 8, 1982

PLATE NO.
**10**




Velocity
(Feet per Second)

| |
|---|
| 0.0 |
| 1.0 |
| 2.0 |
| 3.0 |
| 4.0 |
| 5.0 |
| 6.0 |
| 7.0 |
| 8.0 |
| 9.0 |
| 10.0 |

Note: The Velocity Vectors Shown were Surveyed at a Depth of 7.7 Feet Below WSEL During Open River Conditions.

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Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

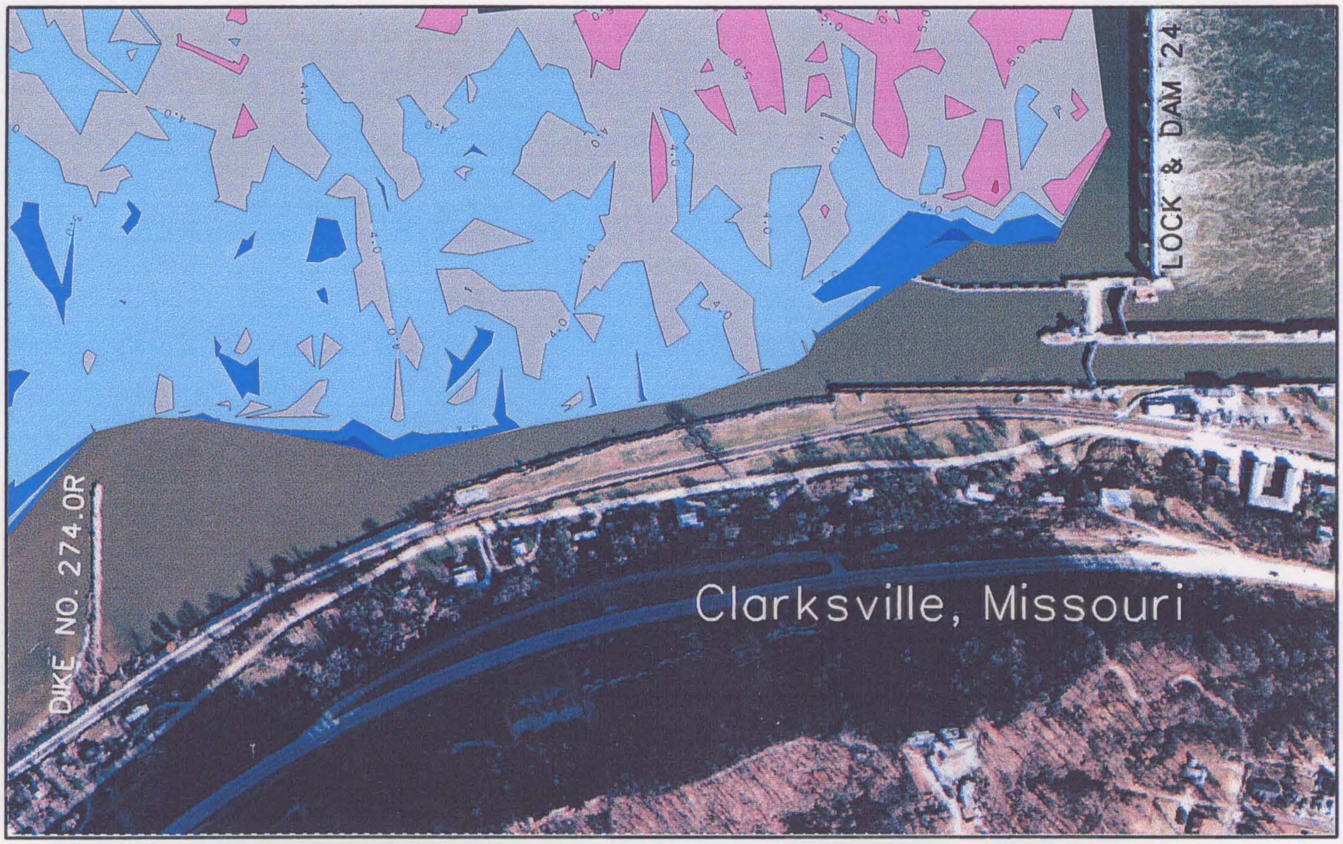
ADCP Survey Data - March 4, 1997

500' 400' 300' 200' 100' 0 500'

DESIGN FILE: D:\DGN\MODEL\L&D*24\

PLOT SCALE: 1" = 500'

PLATE NO. 11




Velocity
(Feet per Second)


Note: The Velocity Contours Shown were Surveyed at a Depth of 7.7 Feet Below WSEL During Open River Conditions.

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|---|---|
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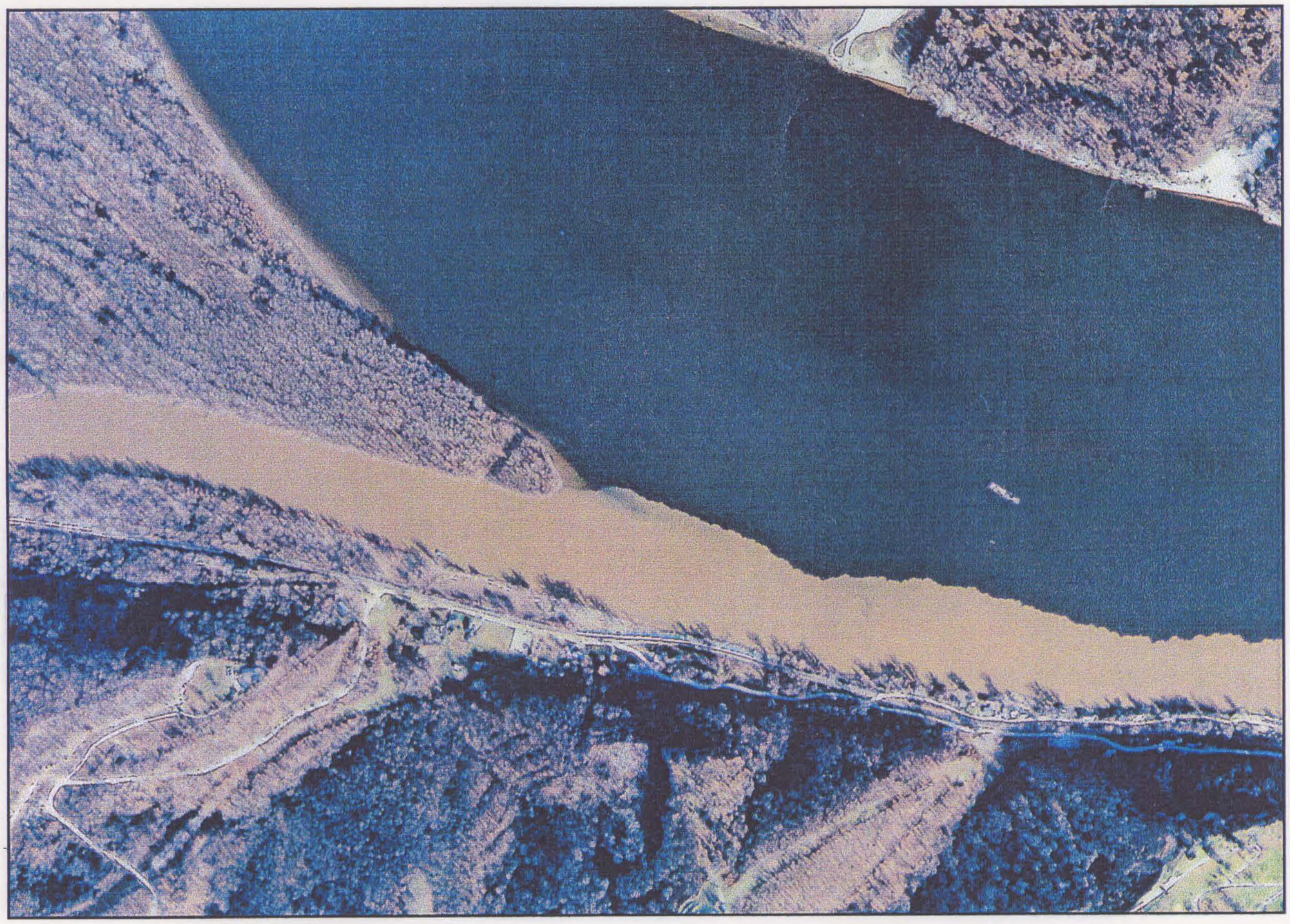
| | PLOT SCALE: 1" - 500' |
| | PLATE NO. 12 |



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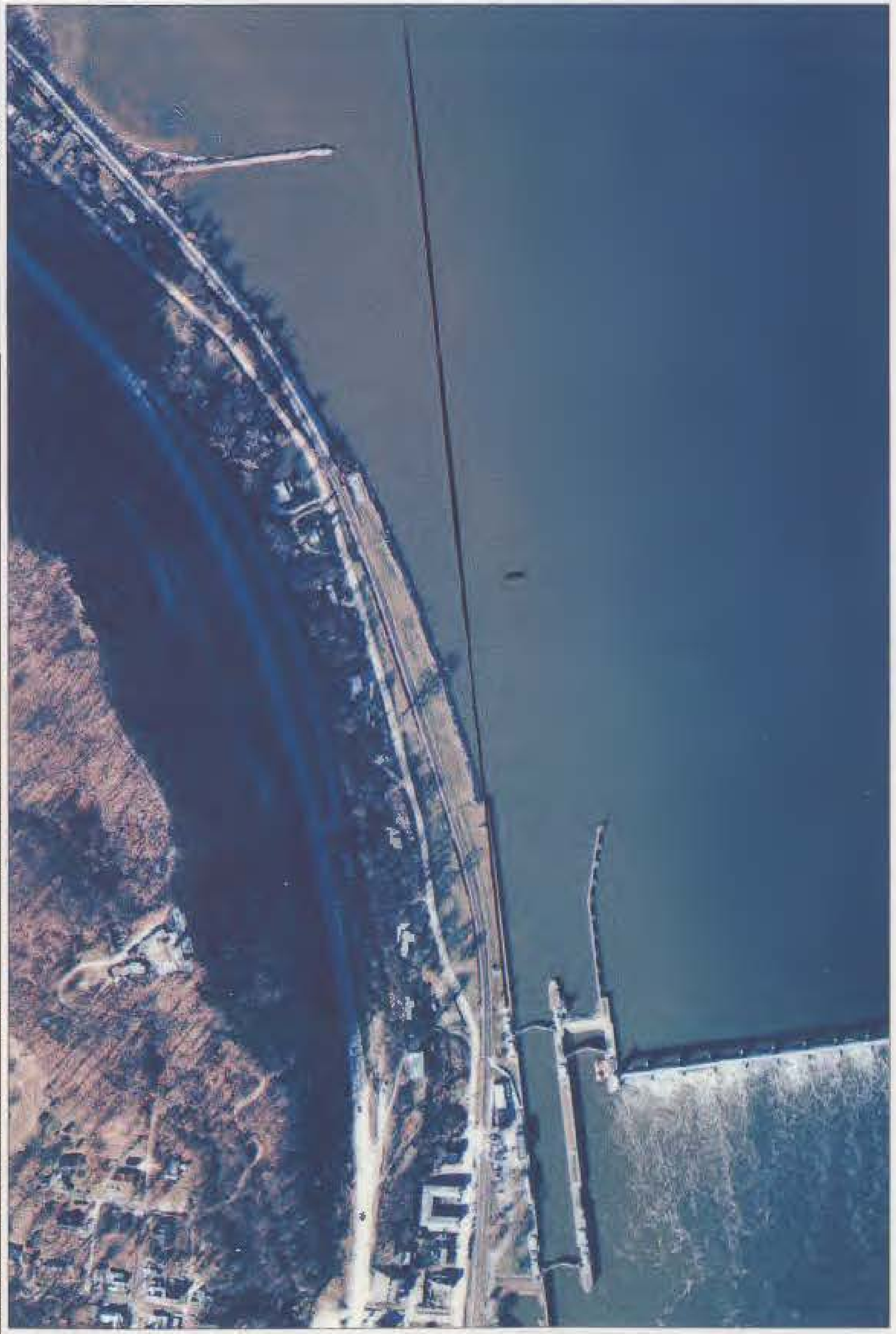
| | PLATE NO. **13** |



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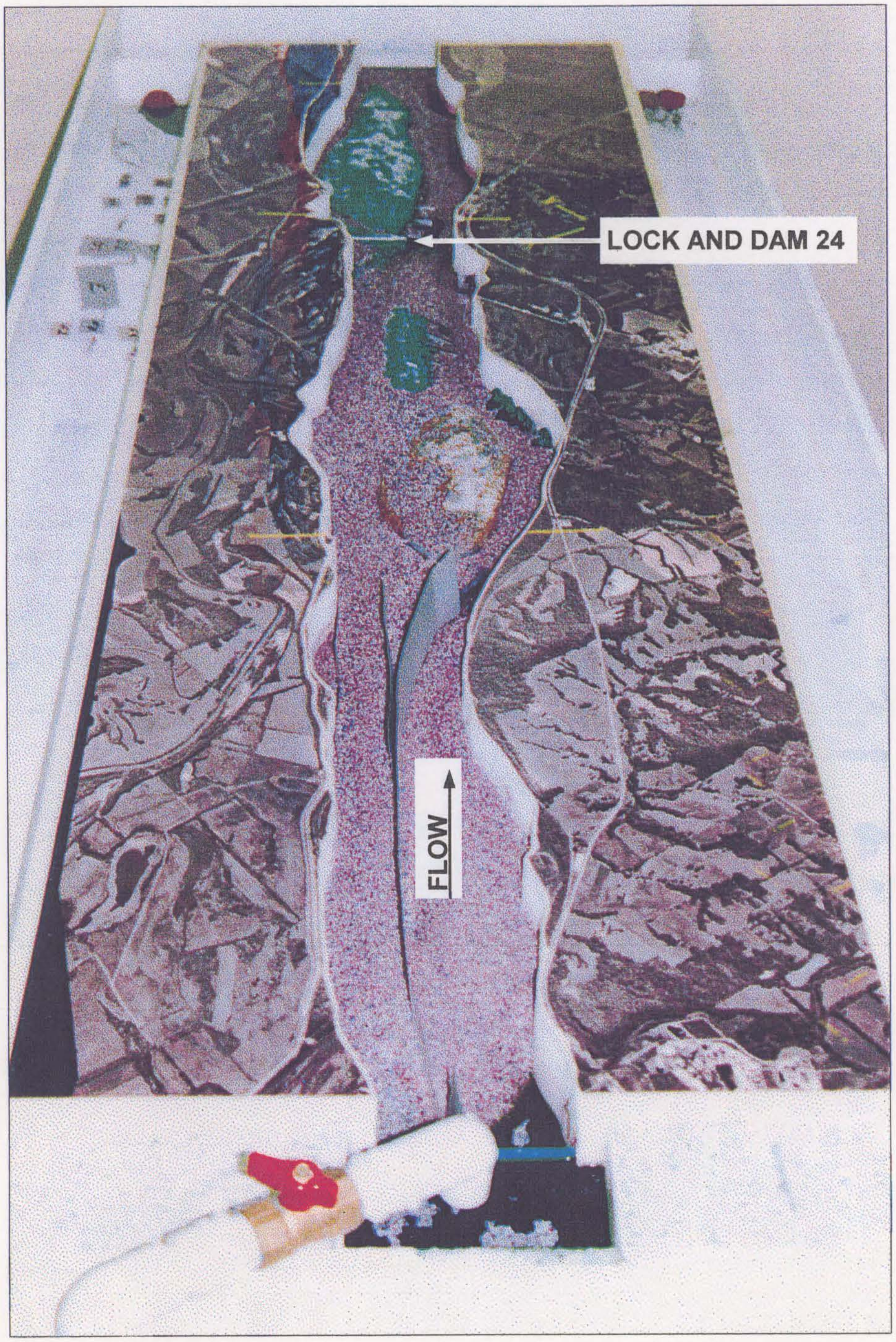
Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Remote Sensing Flow Data at the Downbound Approach to Lock and Dam 24

PLATE NO
14

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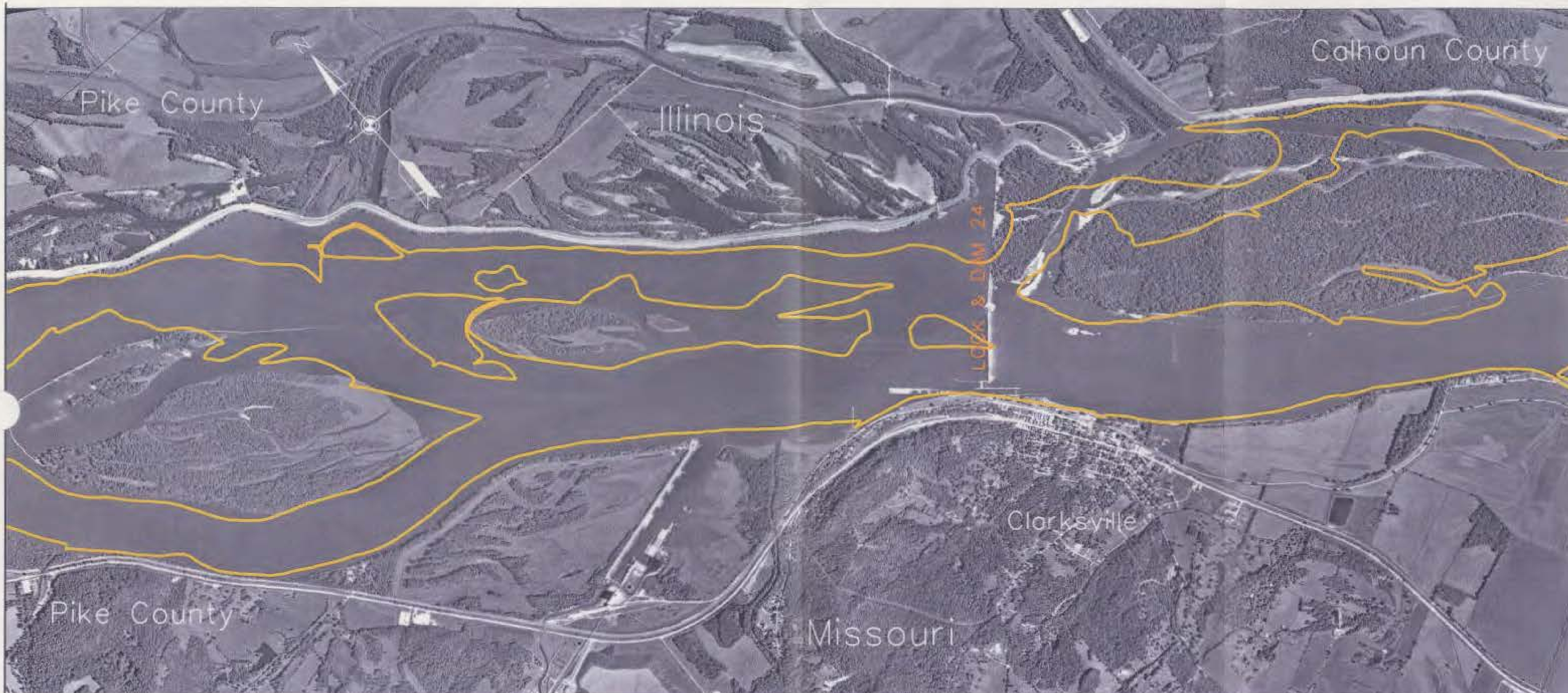
Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Lock and Dam 24 Micro Model

PLATE NO. 15

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Mississippi River Miles 271 - 277

1880 Prototype Survey of the Bankline

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\LBD*24\
PLOT SCALE: 1" = 2000'

PLATE NO. 16


Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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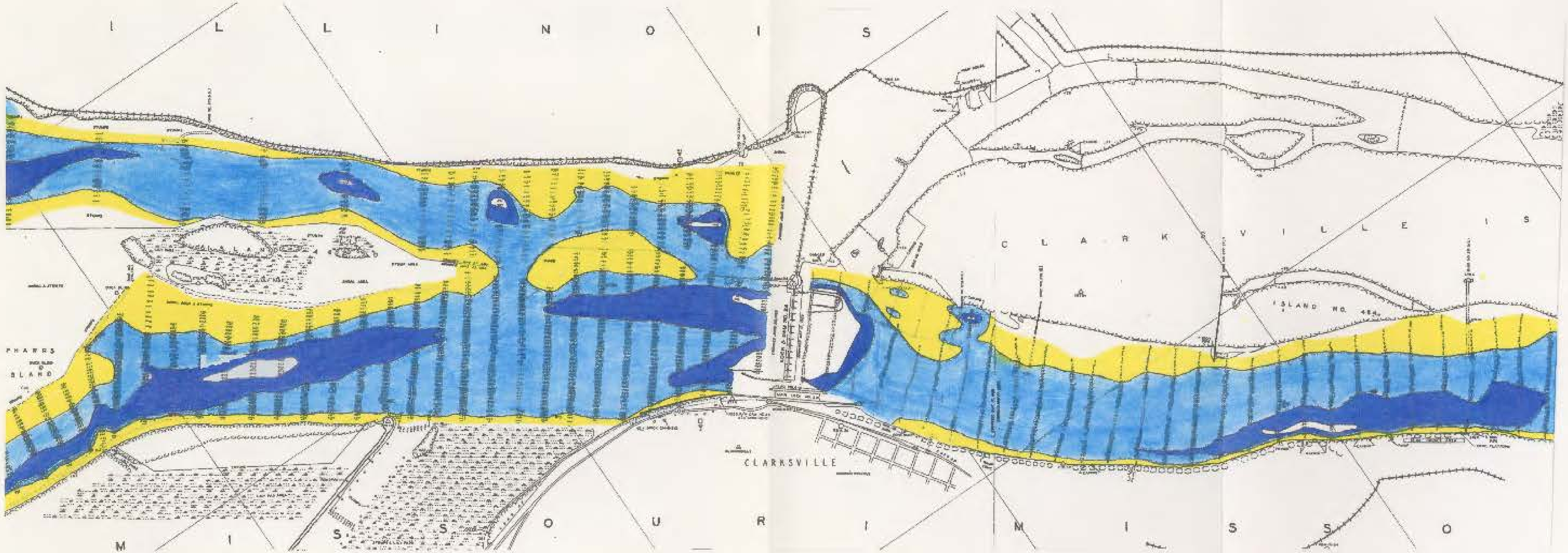
Lock and Dam *24 Micro Model Study
Mississippi River Miles 271 - 277

1939 Prototype Survey Upstream of the Dam
1947 Prototype Survey Downstream of the Dam

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\LAD-24\
PLOT SCALE: 1" - 1500'
PLATE NO. 17




Elevations Referenced to LWRP

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+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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Mississippi River Miles 271 - 277

1968 Prototype Survey

1500' 0 500' 1000' 1500'

PLATE NO. 18


Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

1977 Prototype Survey

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\

PLOT SCALE: 1" - 1500'

PLATE NO. 19

Elevations Referenced
to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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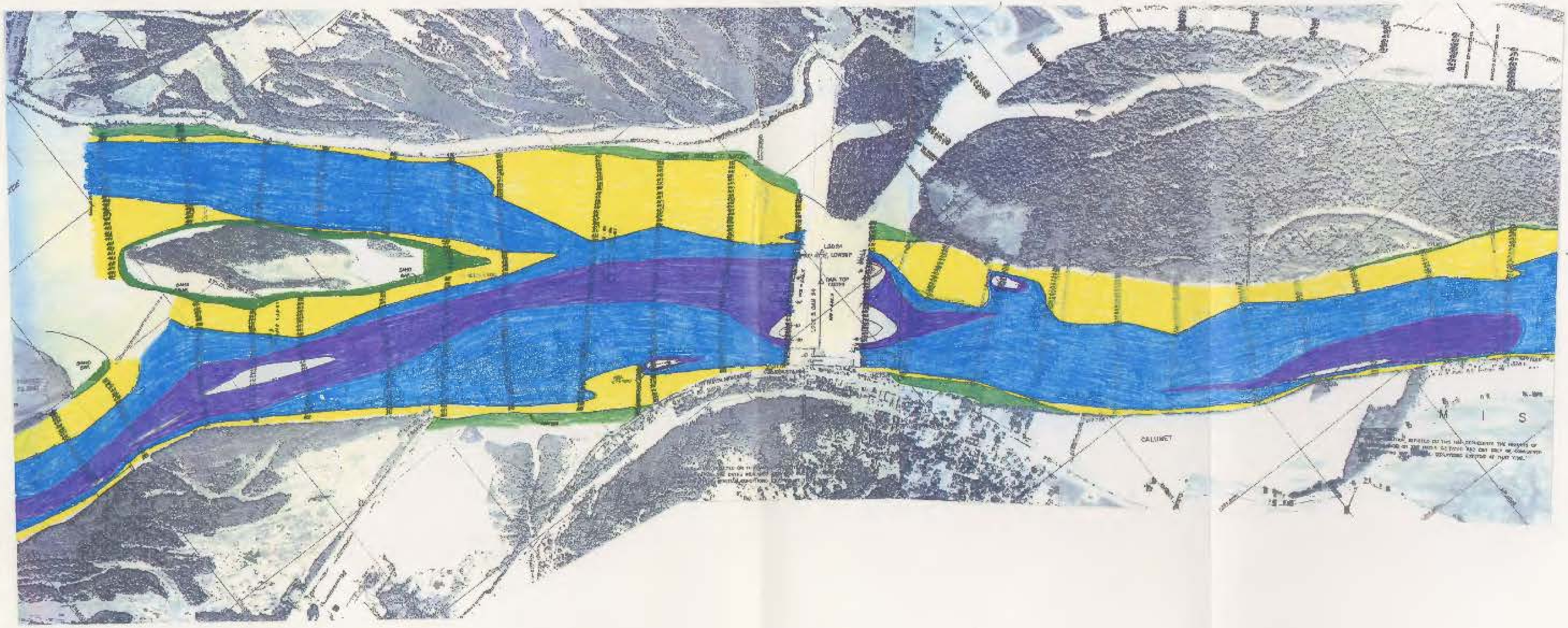
Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

1982 Prototype Survey

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D-24\
PLOT SCALE: 1" = 1500'

PLATE NO. 20




Elevations Referenced to LWRP

| | |
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| | +10 FT |
| | 0 FT |
| | -10 FT |
| | -20 FT |
| | -30 FT |
| | -40 FT |
| | -50 FT |

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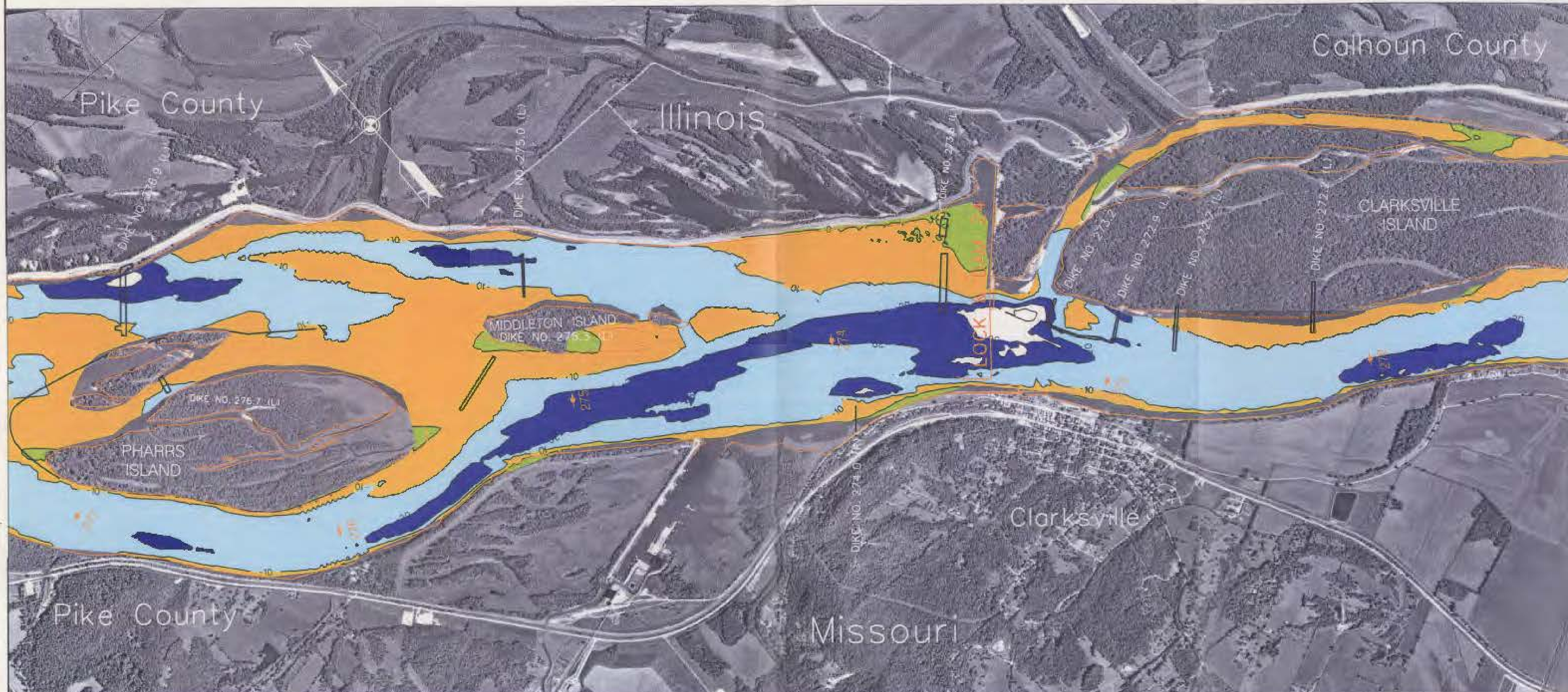
Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

1987 Prototype Survey

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\
PLOT SCALE: 1" - 1600'

PLATE NO. 21




Elevations Referenced to LWRP

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+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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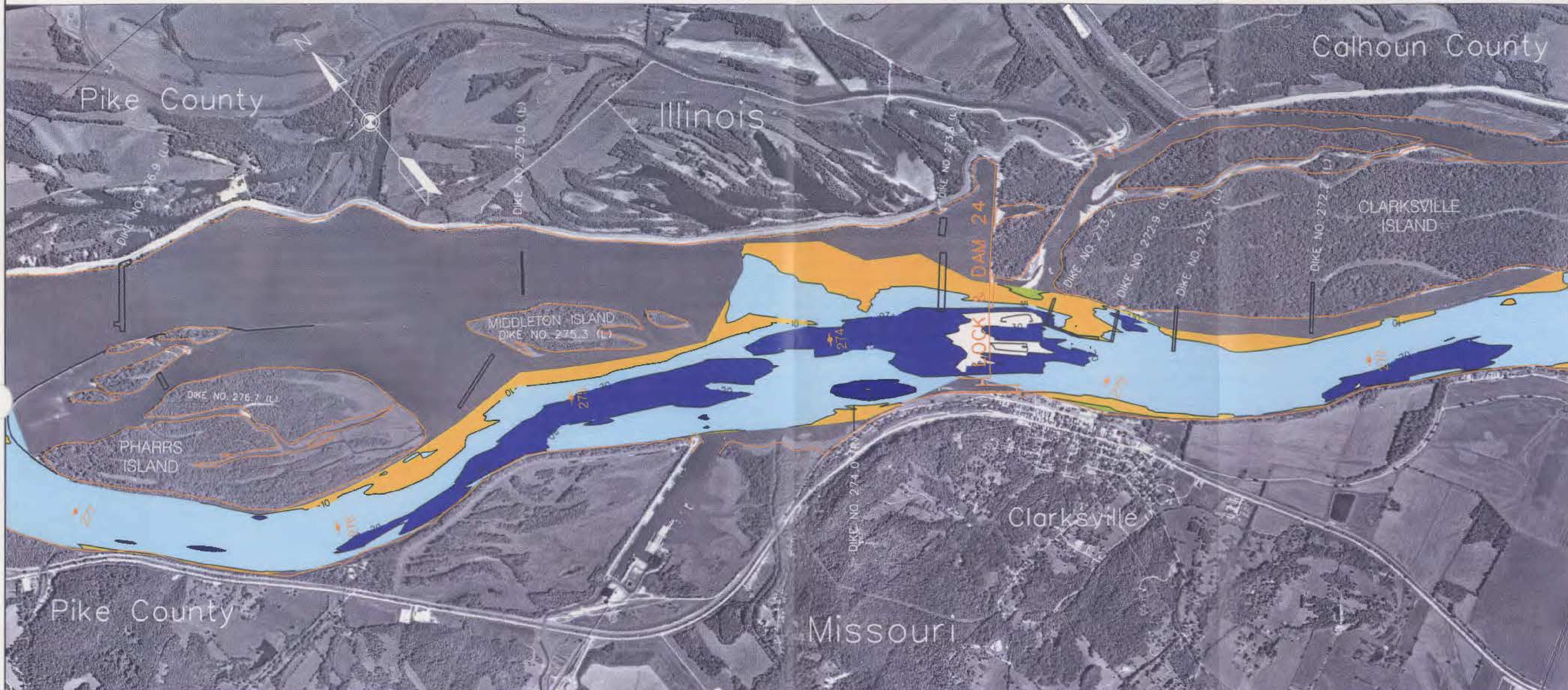
Lock and Dam *24 Micro Model Study
Mississippi River Miles 271 - 277

1993 Prototype Survey

1500' 0 500' 1000' 1500'

PLOT SCALE: 1" - 2000'

PLATE NO. 22




Elevations Referenced to LWRP

+20 FT
+10 FT
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-40 FT
-50 FT

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Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

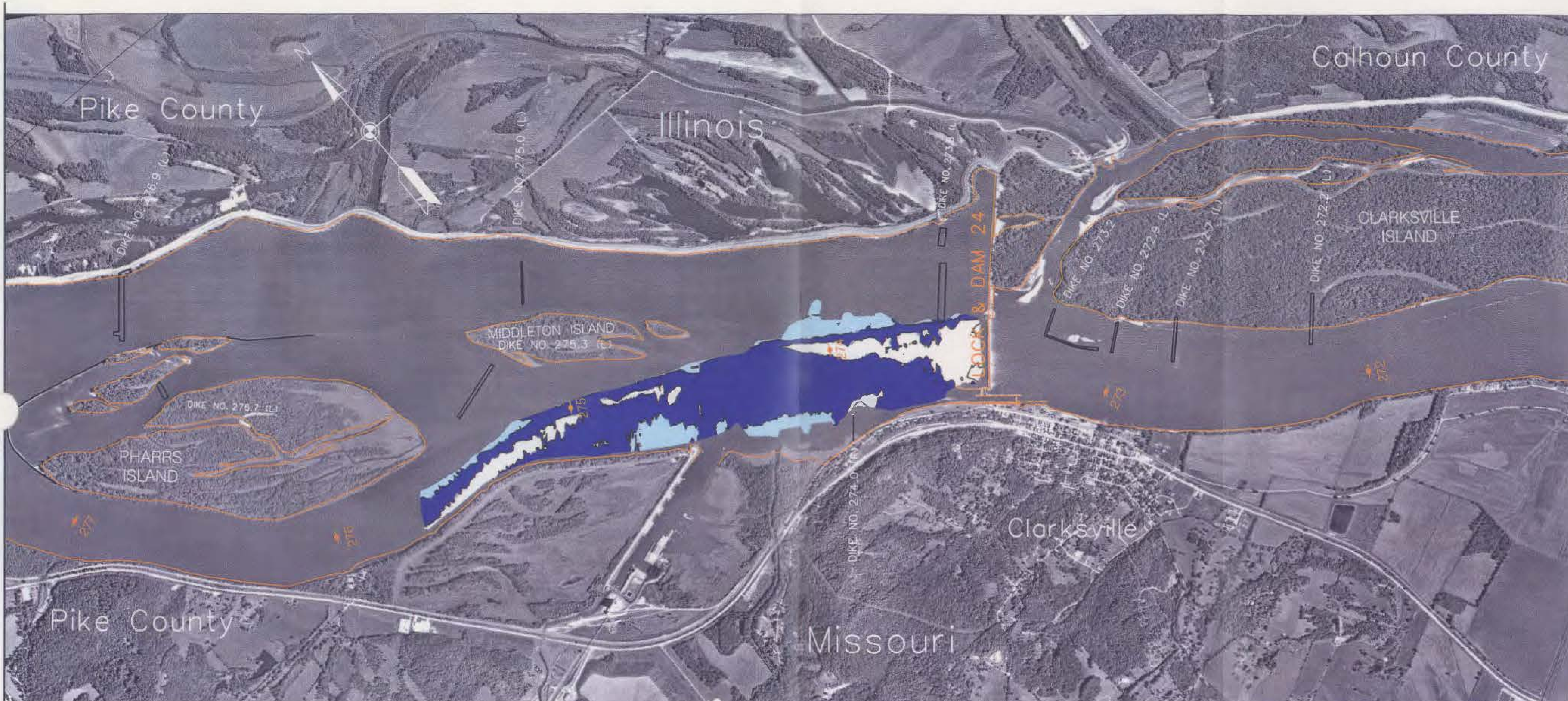
1995 Prototype Survey

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\

PLOT SCALE: 1" = 2000'

PLATE NO. 23




Elevations Referenced to LWRP

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+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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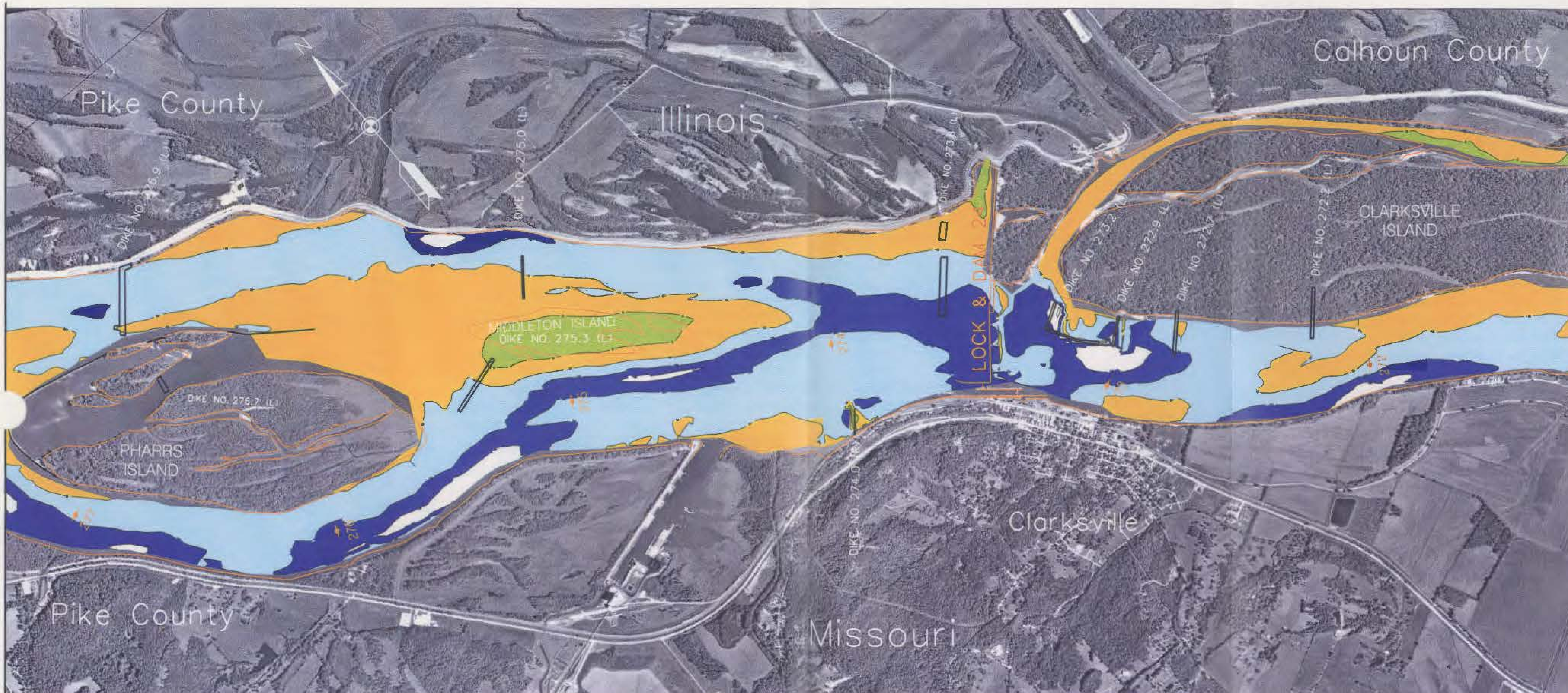
Mississippi River Miles 271 - 277

1997 Prototype Survey

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D*24\
PLOT SCALE: 1" = 2000'

PLATE NO. 24




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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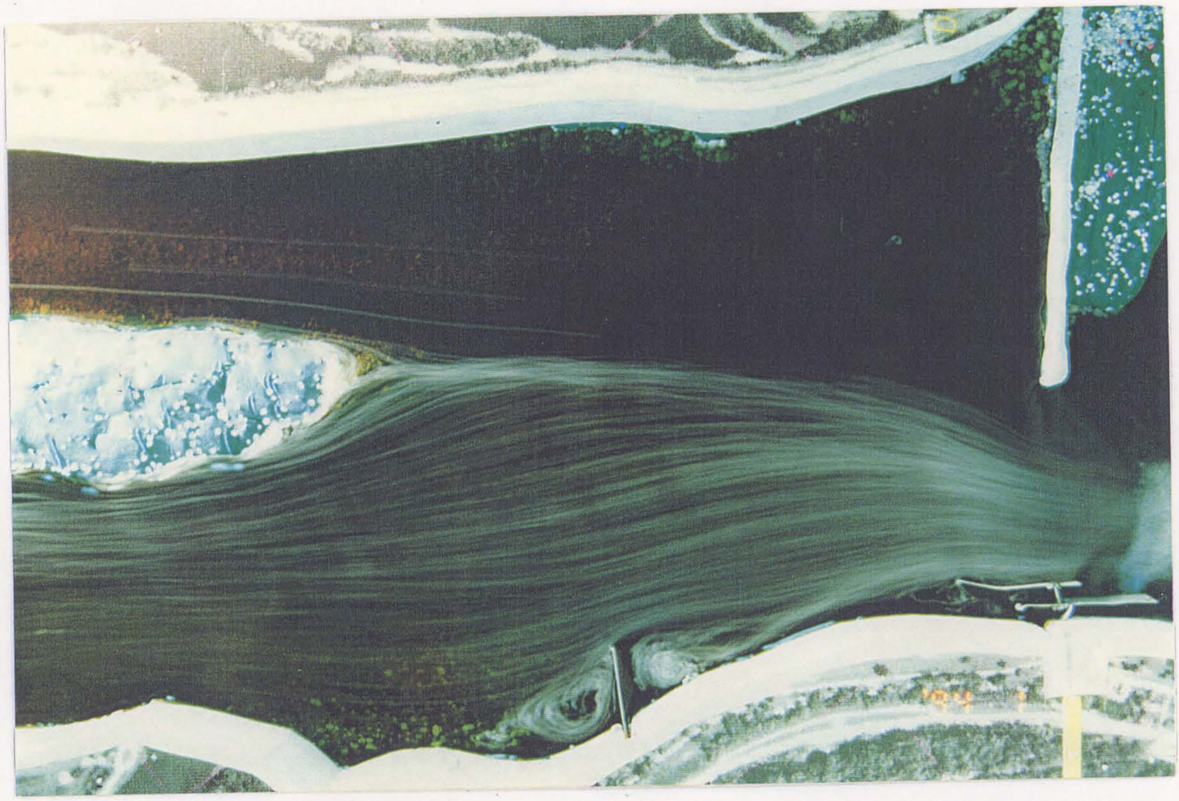
Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

Base Test

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D-24\
PLOT SCALE: 1" = 2000'
PLATE NO. 25



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Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Base Test

PLATE NO
26

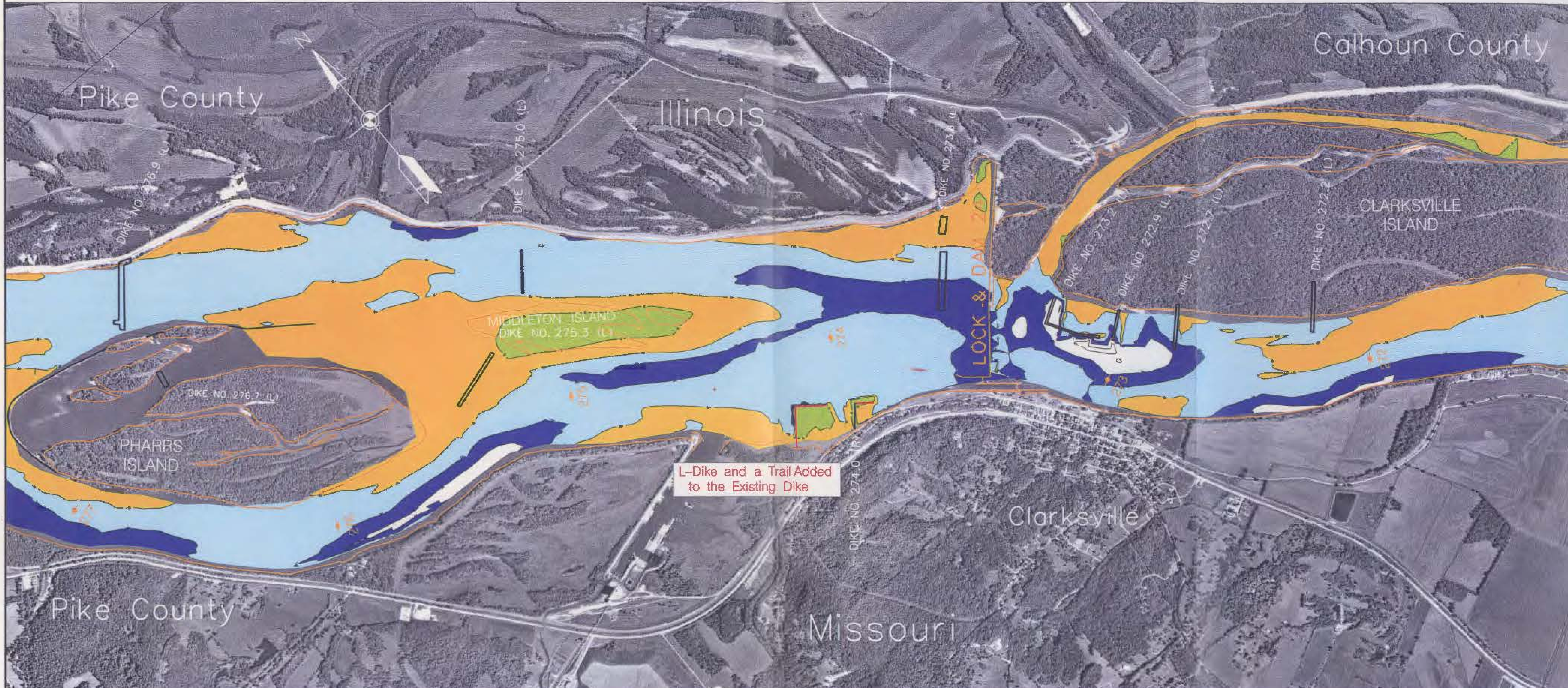
U.S ARMY ENGINEER DISTRICT, ST. LOUIS
CORPS OF ENGINEERS
ST. LOUIS, MISSOURI

PREPARED BY: D. Gordon
CHECKED BY: R. Davinroy

Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

River Pilots and Engineers Formulating Ideas at the Applied River Engineering Center

PLATE NO. 27




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

U.S. ARMY ENGINEER DISTRICT, ST. LOUIS
CORPS OF ENGINEERS
ST. LOUIS, MISSOURI

PREPARED BY: D. Gordon
DRAWN BY: D. Gordon
CHECKED BY: R. Davinroy

Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

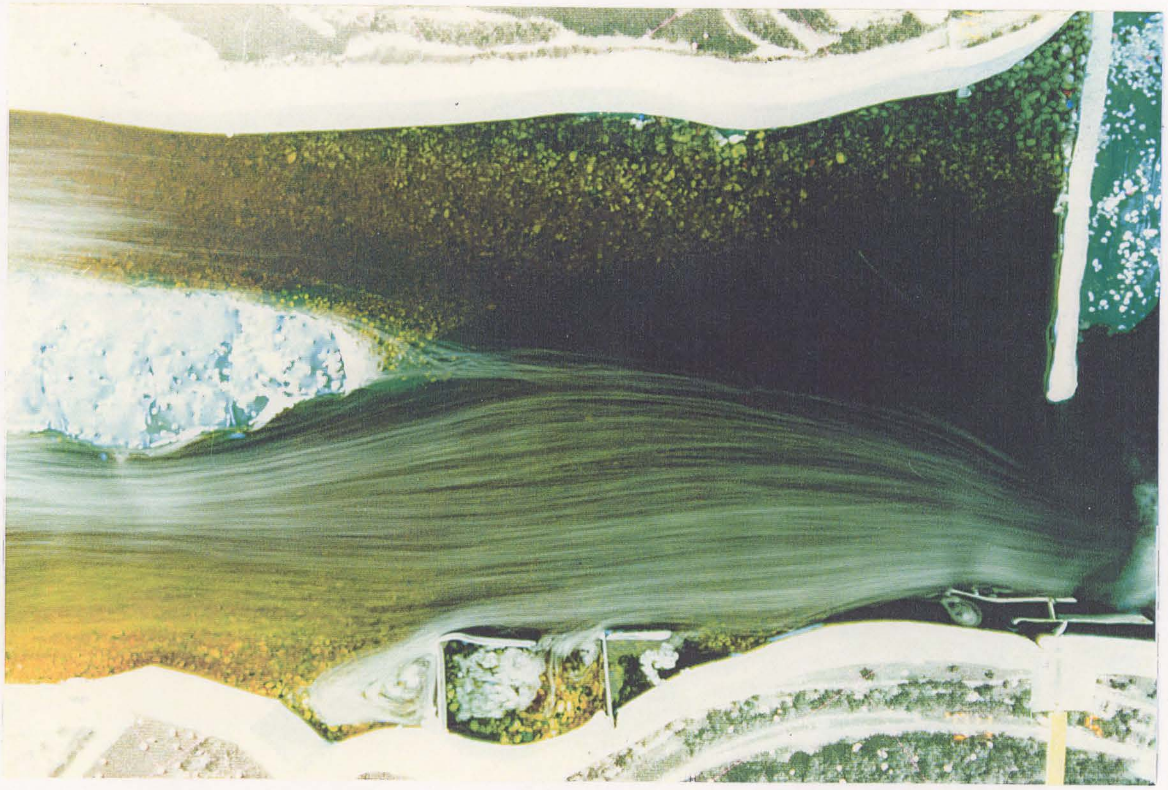
Alternative A

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\LBD-24\

PLOT SCALE: 1" = 2000'

PLATE NO. 28



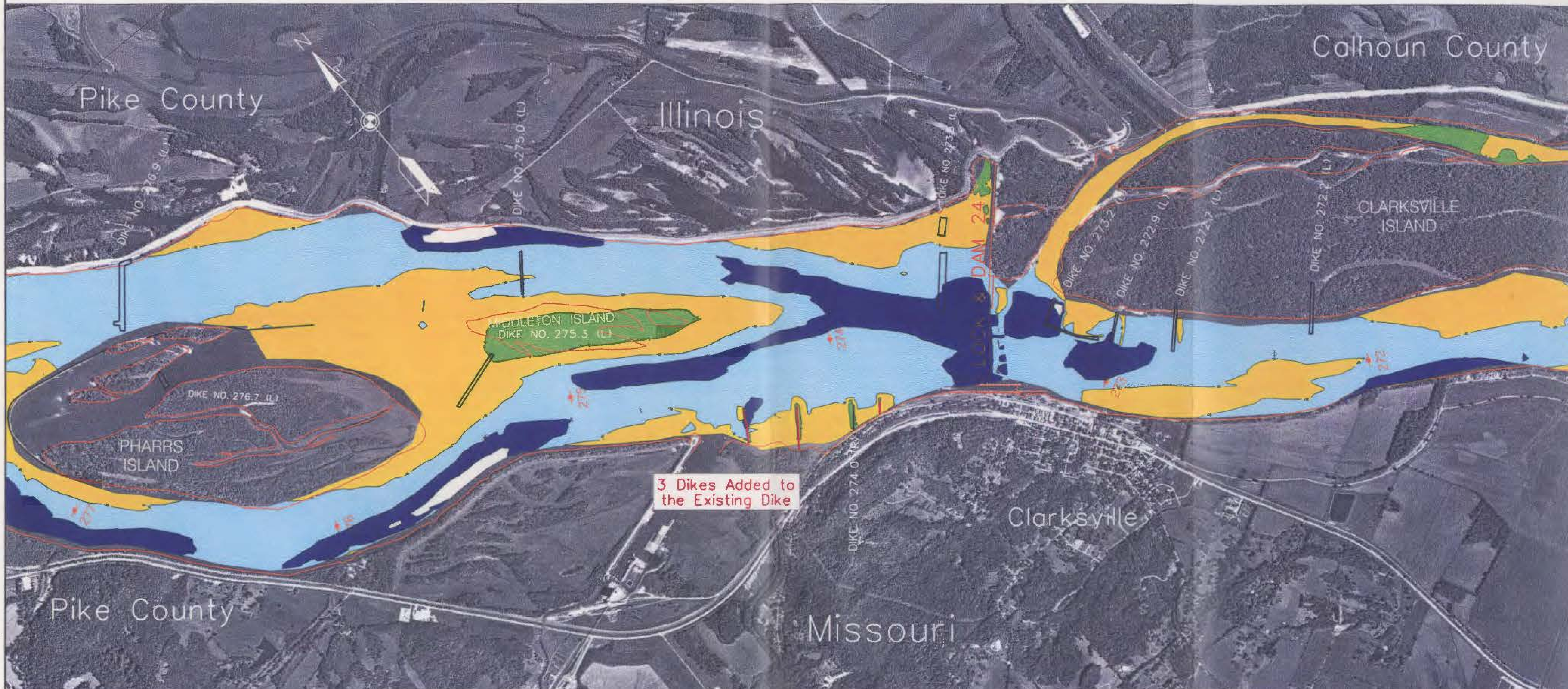
U.S ARMY ENGINEER DISTRICT, ST. LOUIS
CORPS OF ENGINEERS
ST. LOUIS, MISSOURI

PREPARED BY D Gordon
CHECKED BY: R. Davinroy

Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Alternative A

PLATE NO 29




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

U.S. ARMY ENGINEER DISTRICT, ST. LOUIS
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ST. LOUIS, MISSOURI

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Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

Alternative B

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\
PLOT SCALE: 1" = 2000'

PLATE NO. 30

**U.S ARMY ENGINEER DISTRICT, ST. LOUIS**
**CORPS OF ENGINEERS**
**ST. LOUIS, MISSOURI**

PREPARED BY: D Gordon
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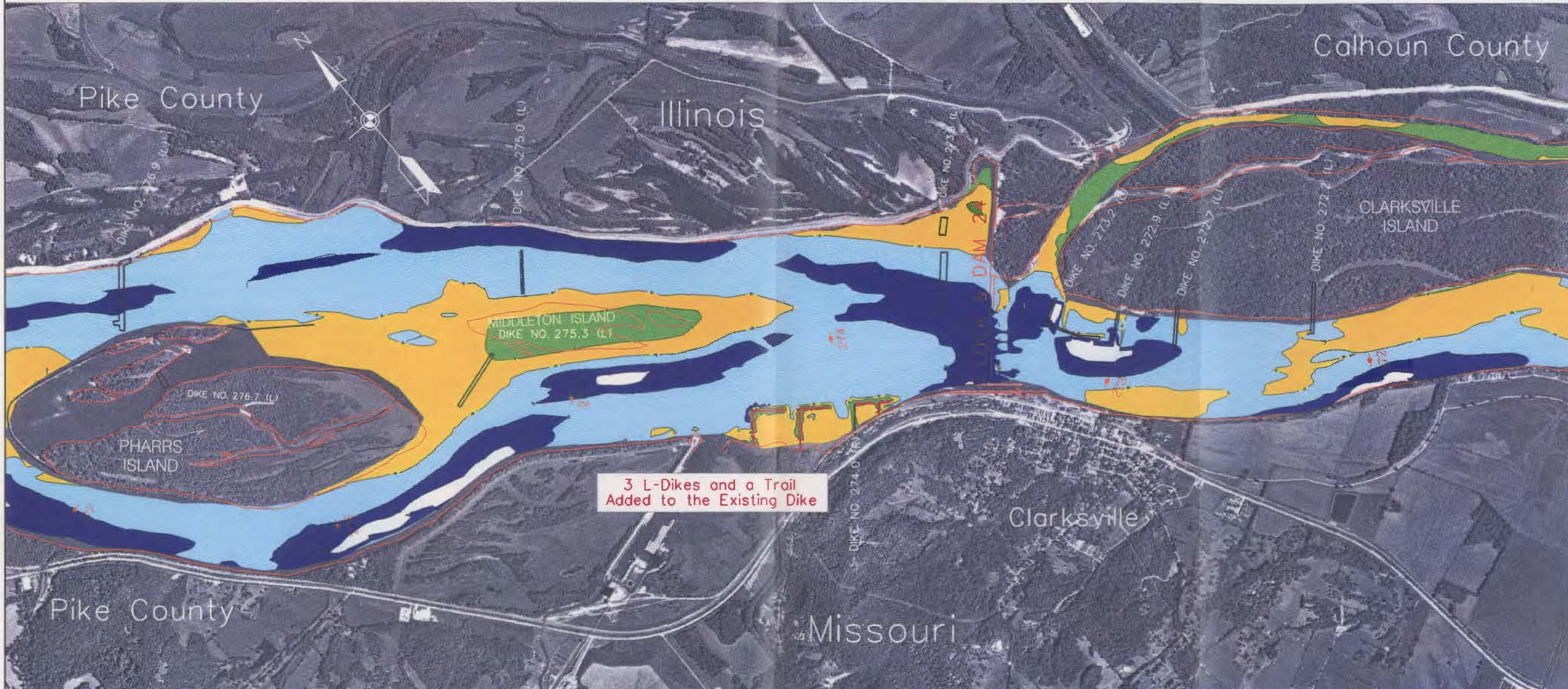
Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Alternative B

PLATE NO. **31**




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

U.S. ARMY ENGINEER DISTRICT, ST. LOUIS
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ST. LOUIS, MISSOURI

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DRAWN BY: D. Gordon
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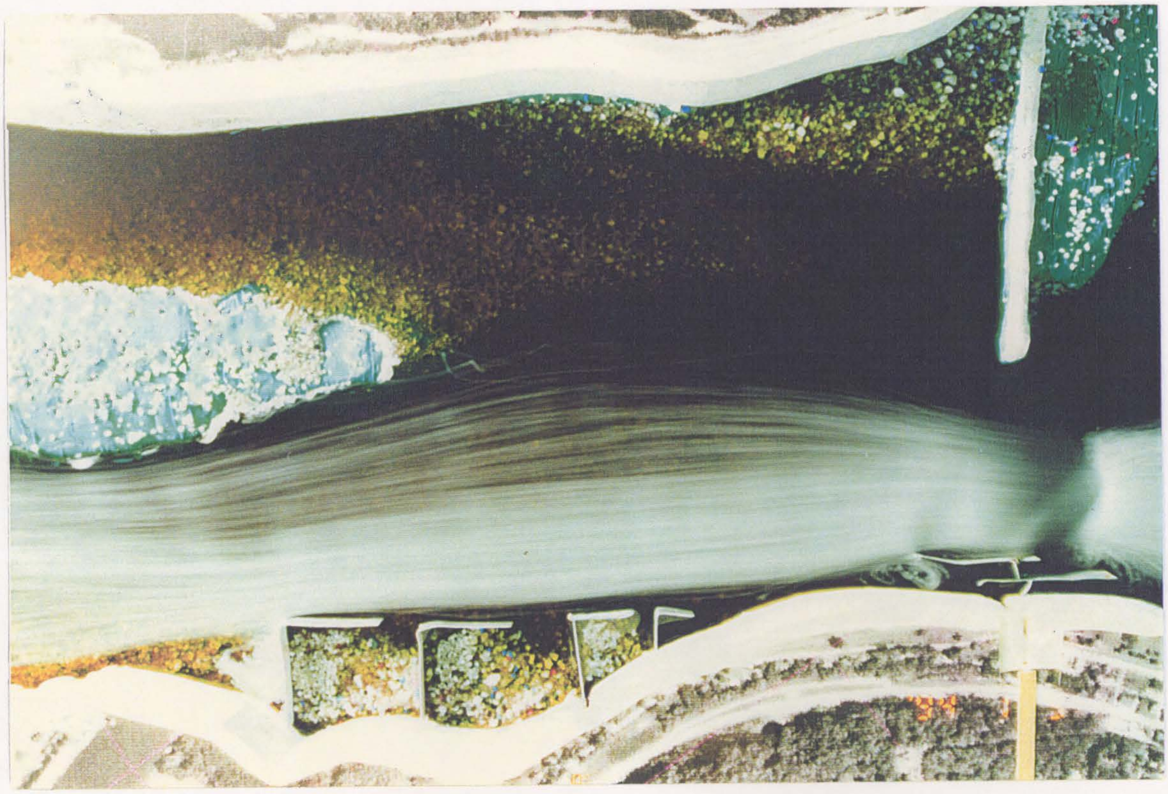
Lock and Dam *24 Micro Model Study
Mississippi River Miles 271 - 277

Alternative C

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D*24\
PLOT SCALE: 1" = 2000'

PLATE NO. 32



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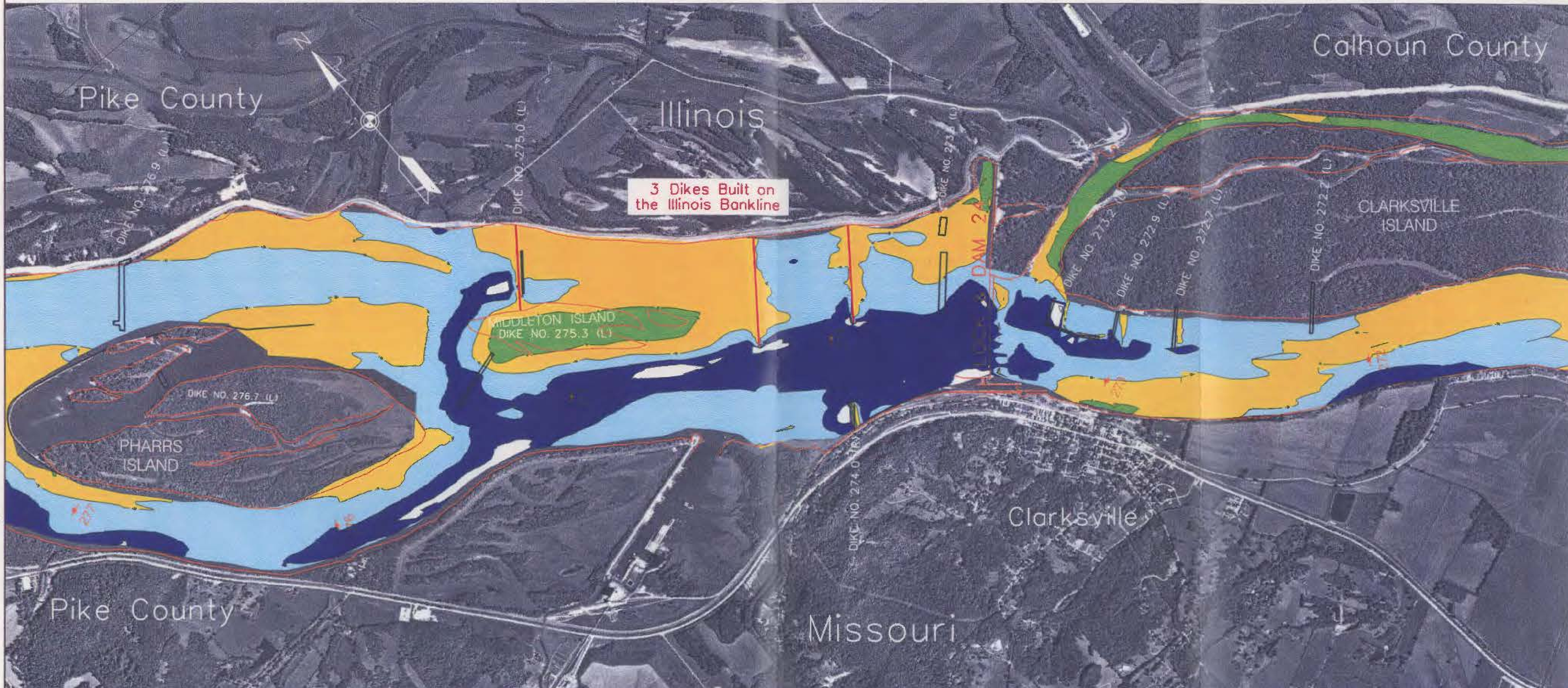
Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Alternative C

PLATE NO 33




Elevations Referenced to LWRP

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+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

U.S. ARMY ENGINEER DISTRICT, ST. LOUIS
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DRAWN BY: D. Gordon
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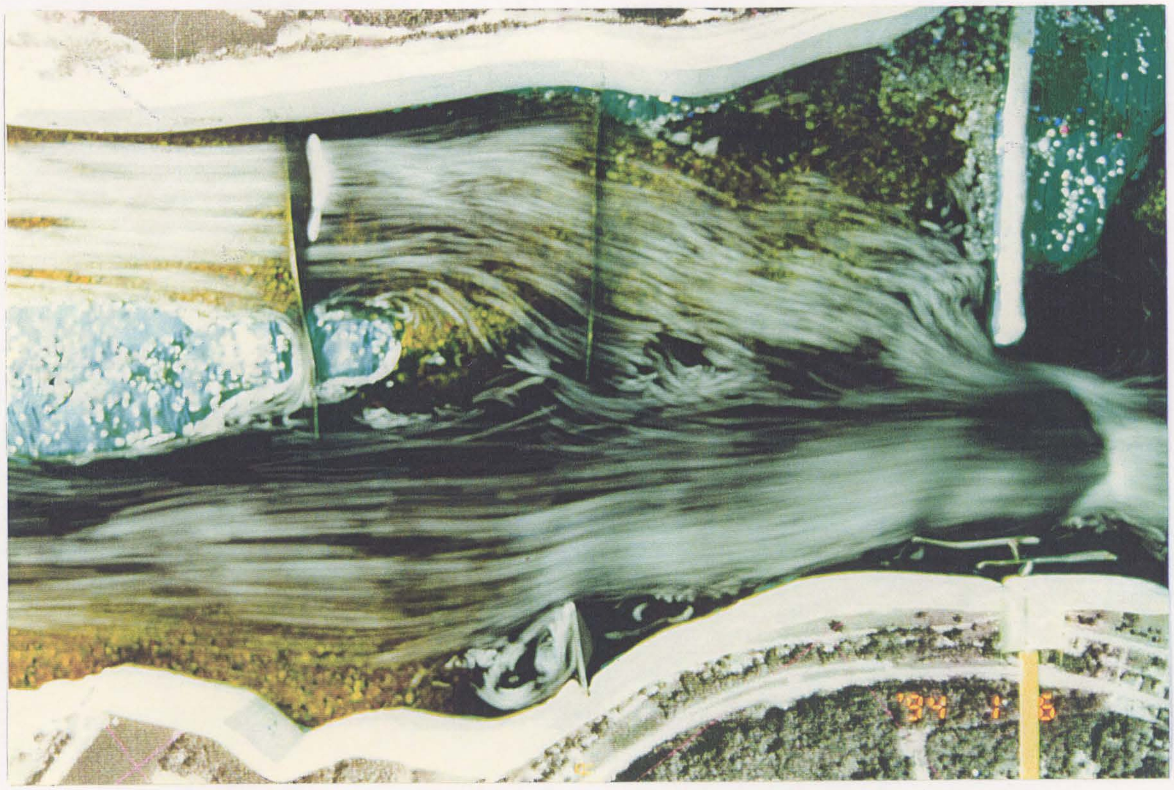
Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

Alternative D

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\
PLOT SCALE: 1" - 2000'

PLATE NO. 34



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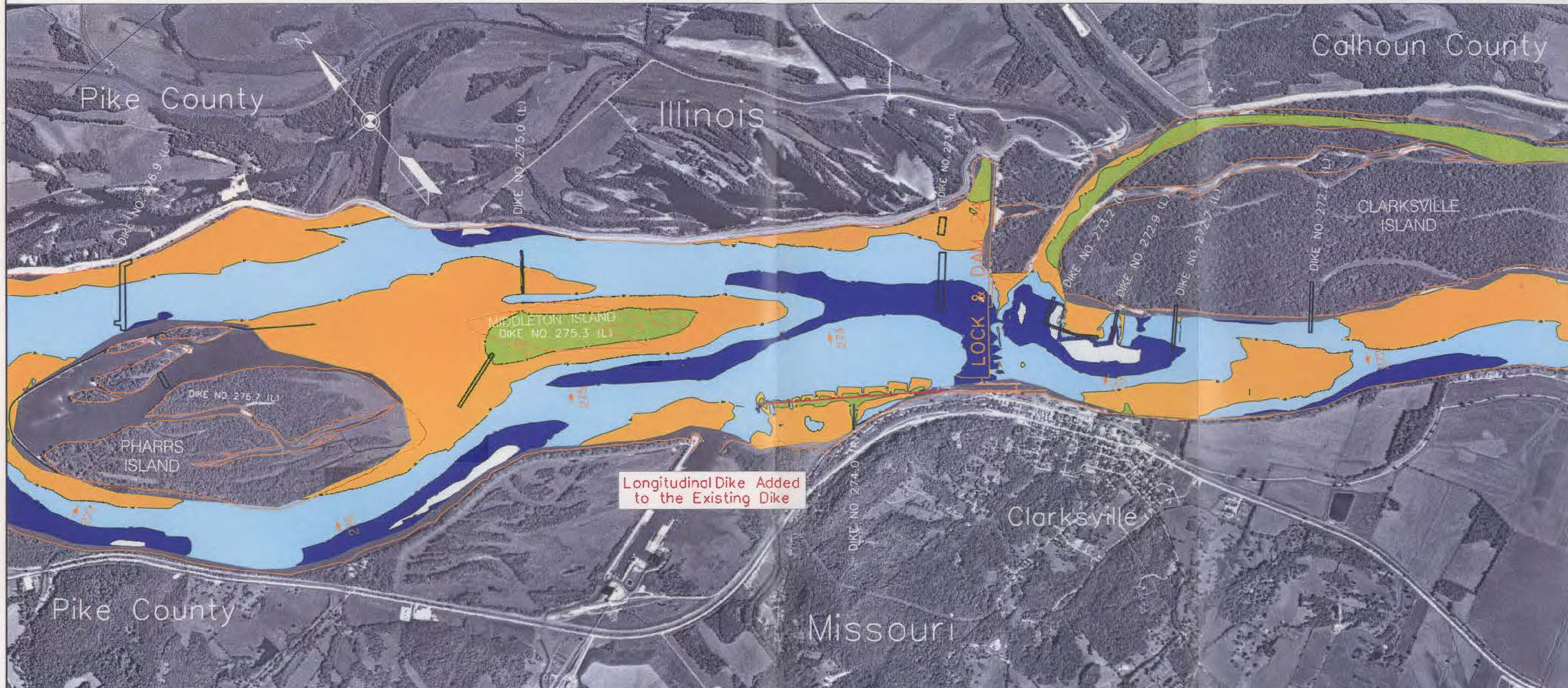
Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Alternative D

PLATE NO

35




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

U.S. ARMY ENGINEER DISTRICT, ST. LOUIS
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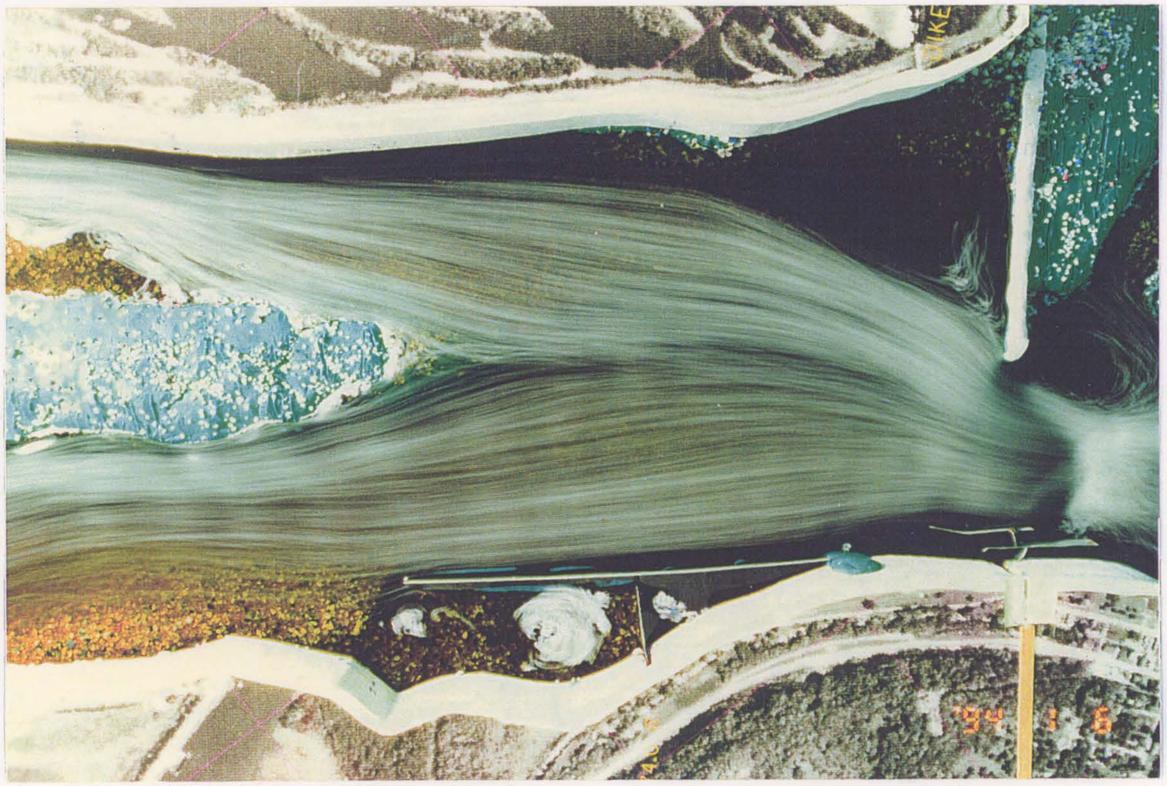
Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

Alternative E

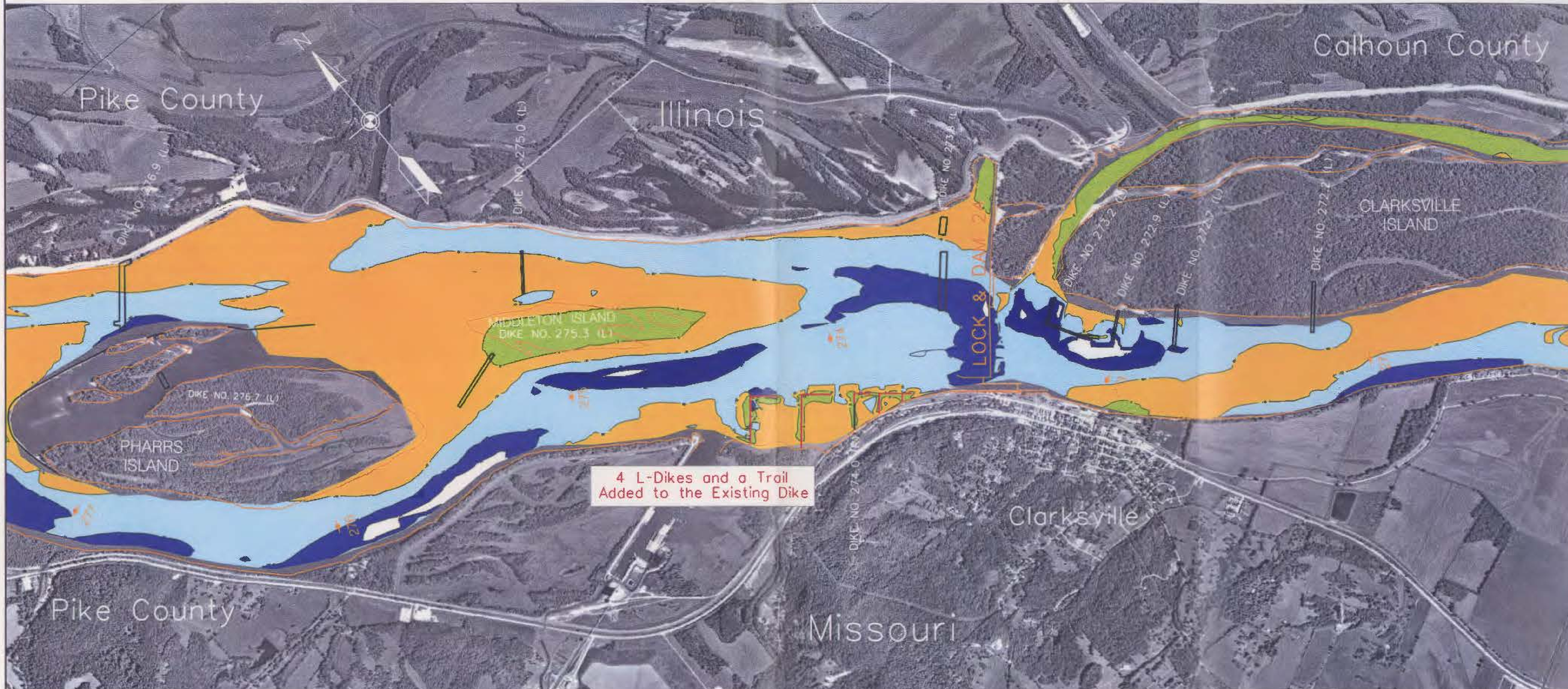
1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D-24\
PLOT SCALE: 1" = 2000'

PLATE NO. 36



| | |
|---|---|
| | **U.S ARMY ENGINEER DISTRICT, ST. LOUIS**<br>**CORPS OF ENGINEERS**<br>**ST. LOUIS, MISSOURI** |
| PREPARED BY: D. Gordon<br>CHECKED BY: R. Davinroy | Lock and Dam 24 Micro Model Study<br>Mississippi River Miles 271 - 277<br><br><u>Flow Visualization - Alternative E</u> |
| | PLATE NO **37** |




Elevations Referenced to LWRP

| |
|---|
| +20 FT |
| +10 FT |
| 0 FT |
| -10 FT |
| -20 FT |
| -30 FT |
| -40 FT |
| -50 FT |

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Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

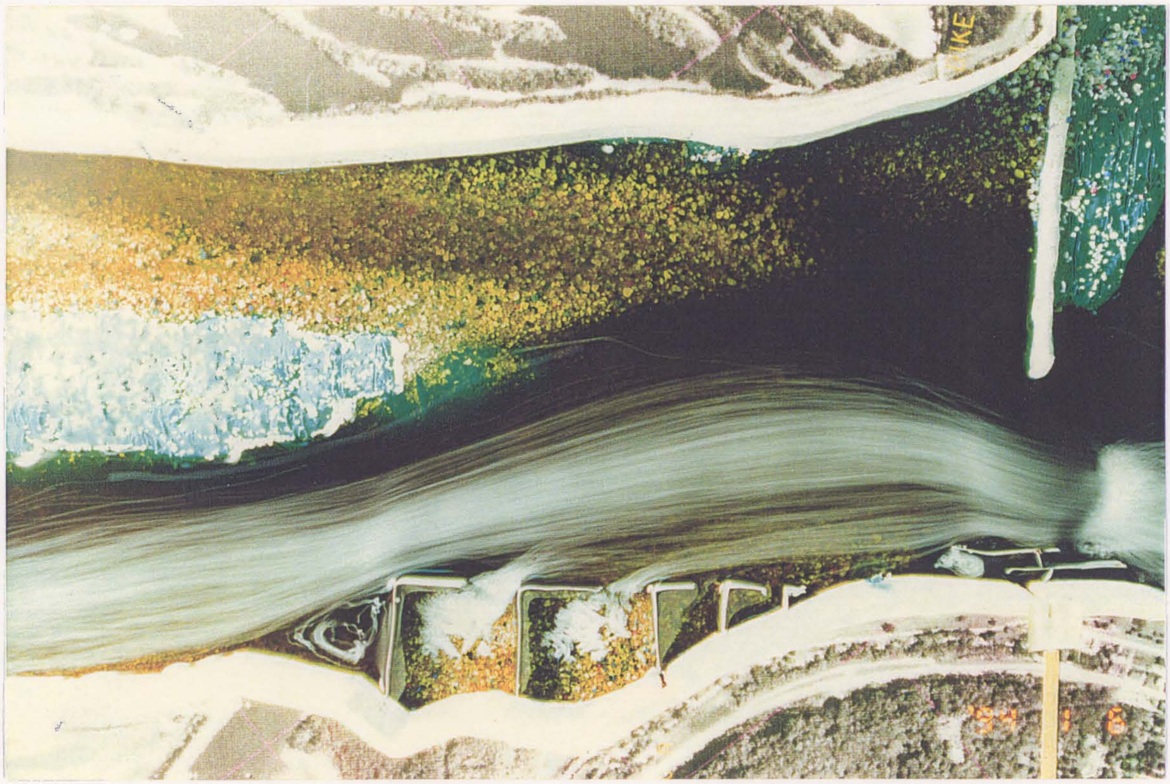
Alternative F

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\

PLOT SCALE: 1" - 2000'

PLATE NO. 38



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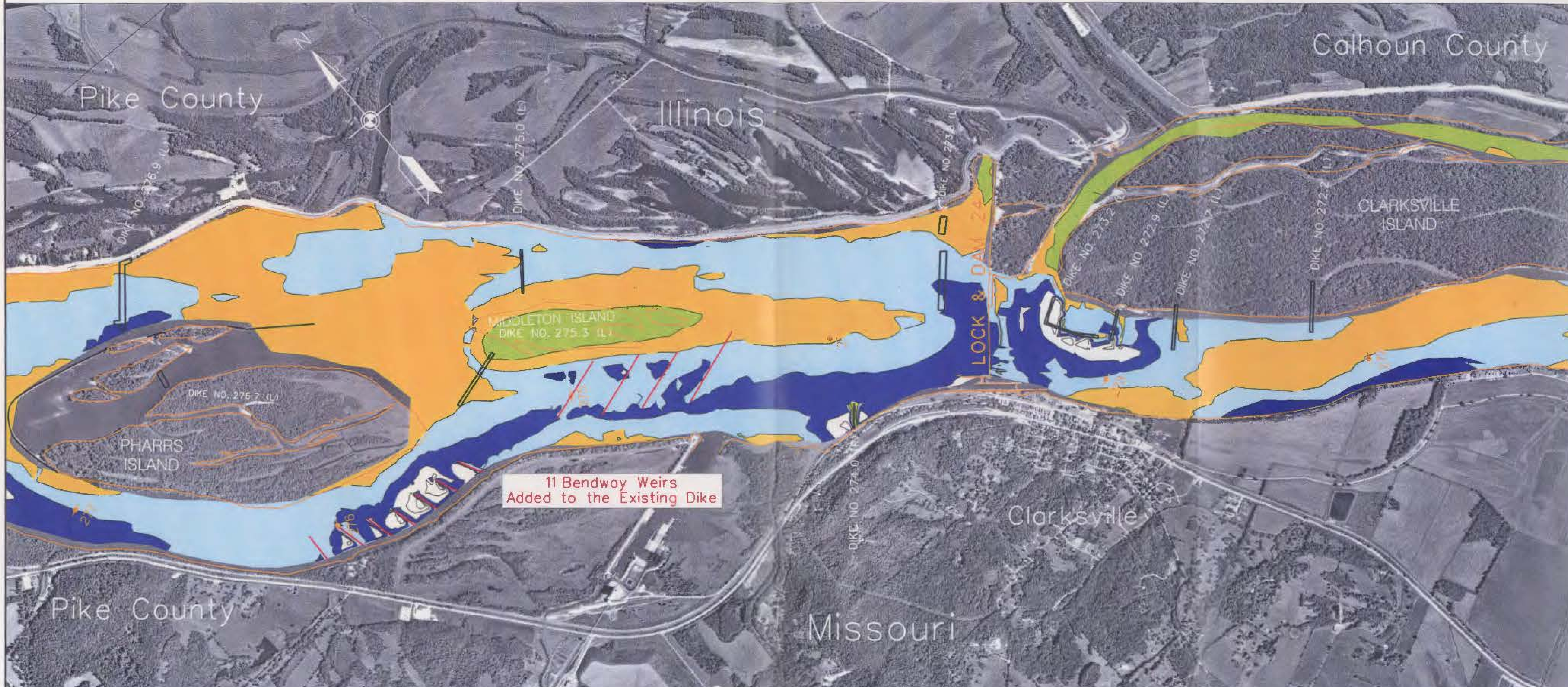
Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Alternative F

PLATE NO
39




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

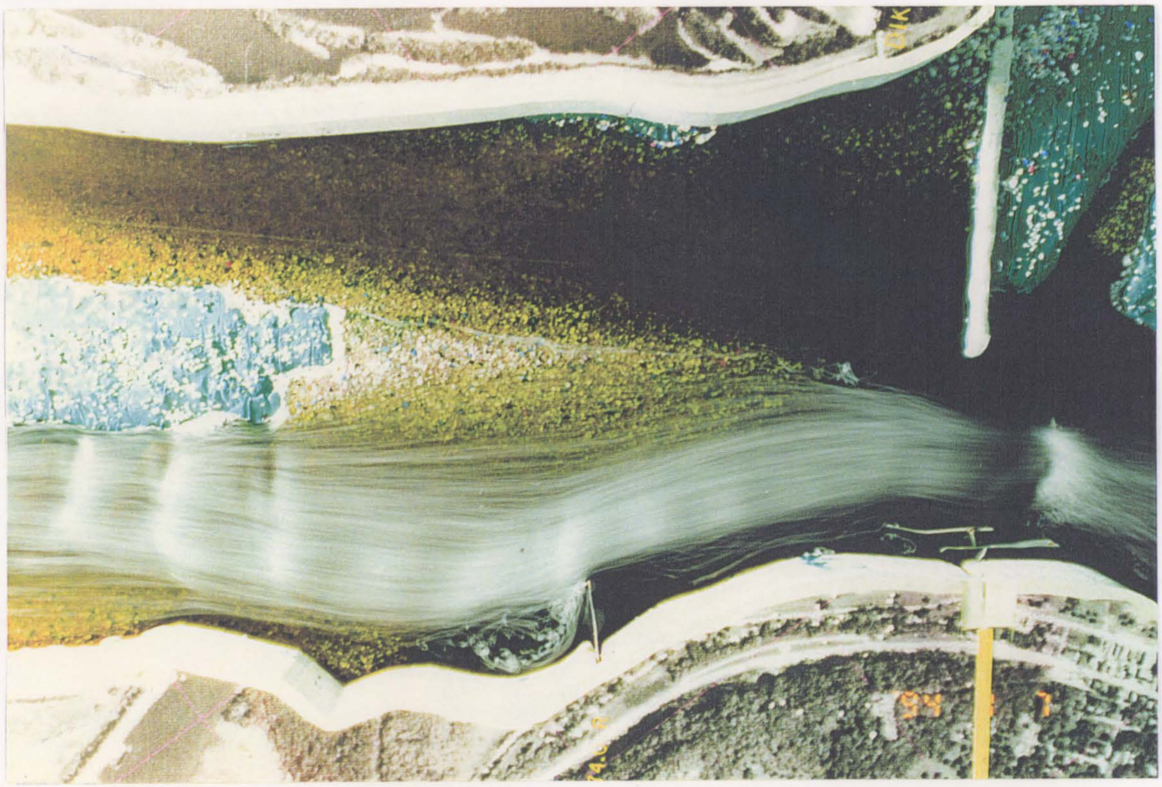
Alternative G

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\

PLOT SCALE: 1" = 2000'

PLATE NO. 40



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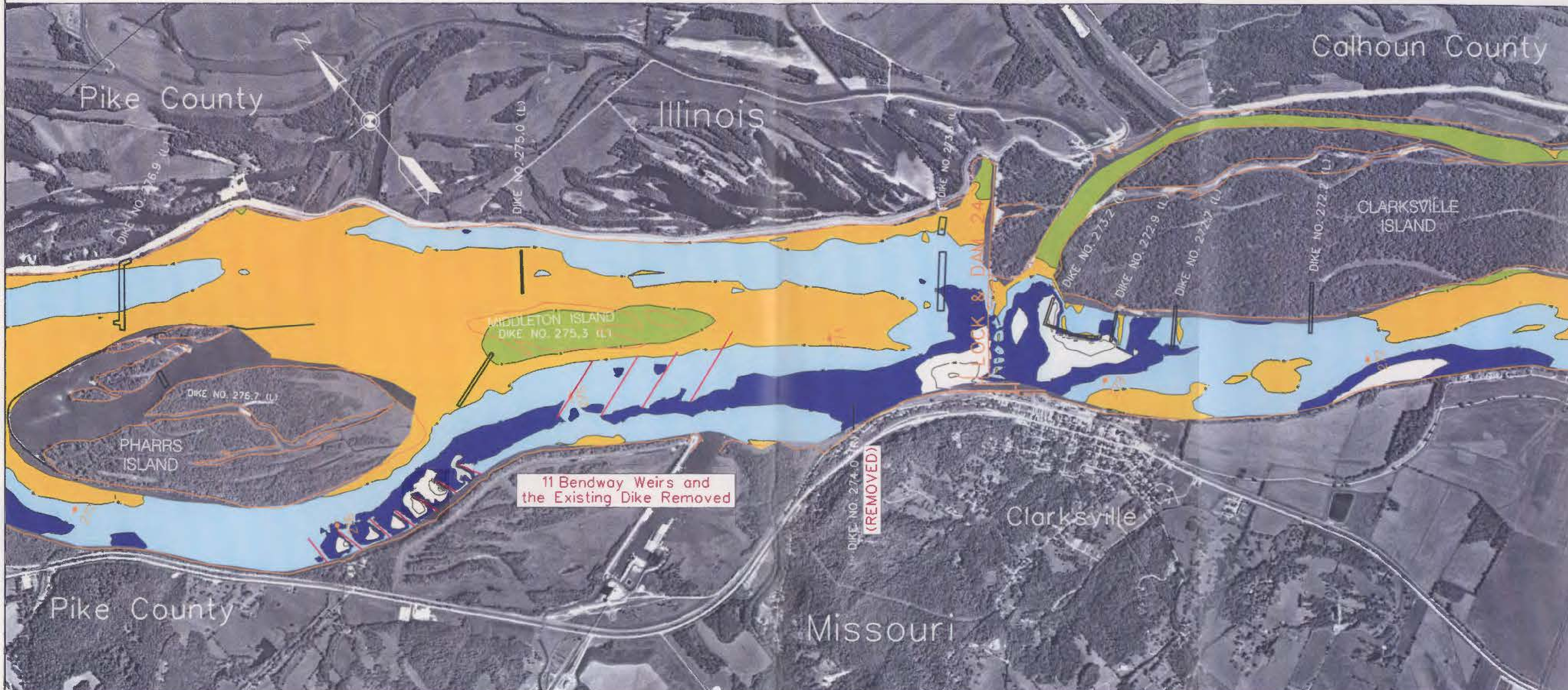
Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Alternative G

PLATE NO
41




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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PREPARED BY: D. Gordon
DRAWN BY: D. Gordon
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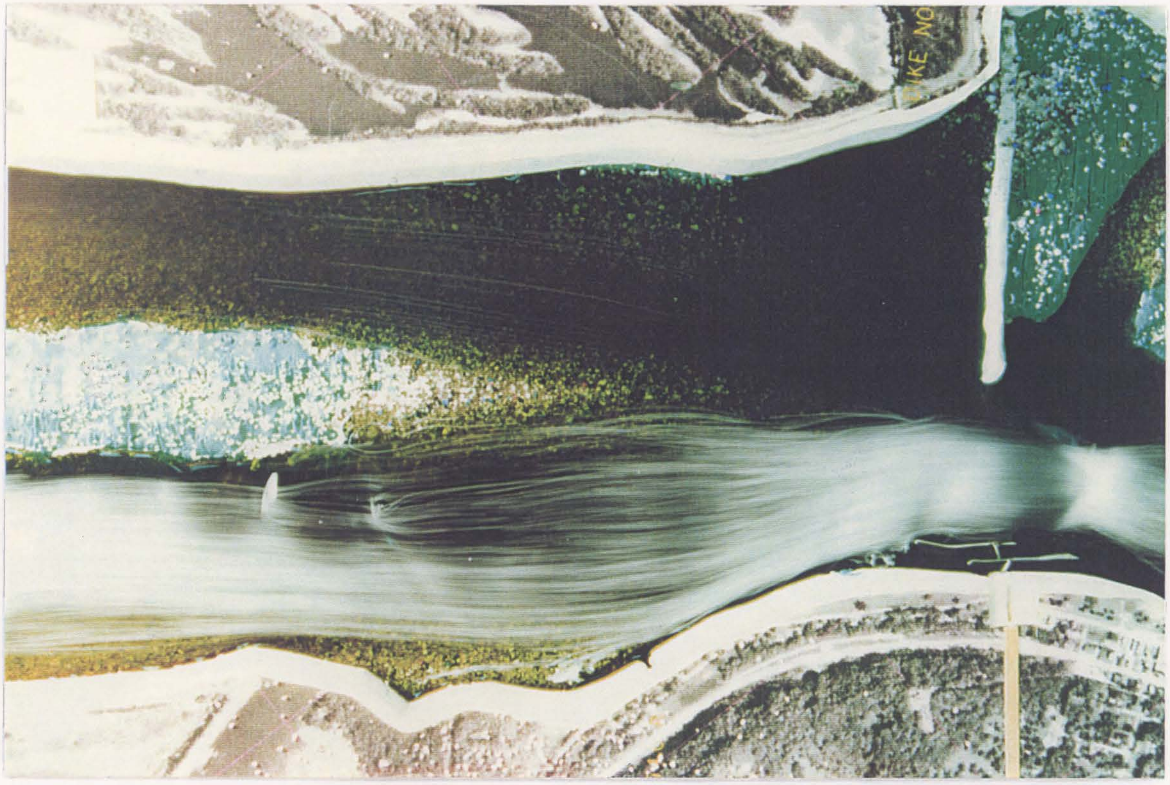
Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

Alternative H

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\
PLOT SCALE: 1" = 2000'
PLATE NO. 42



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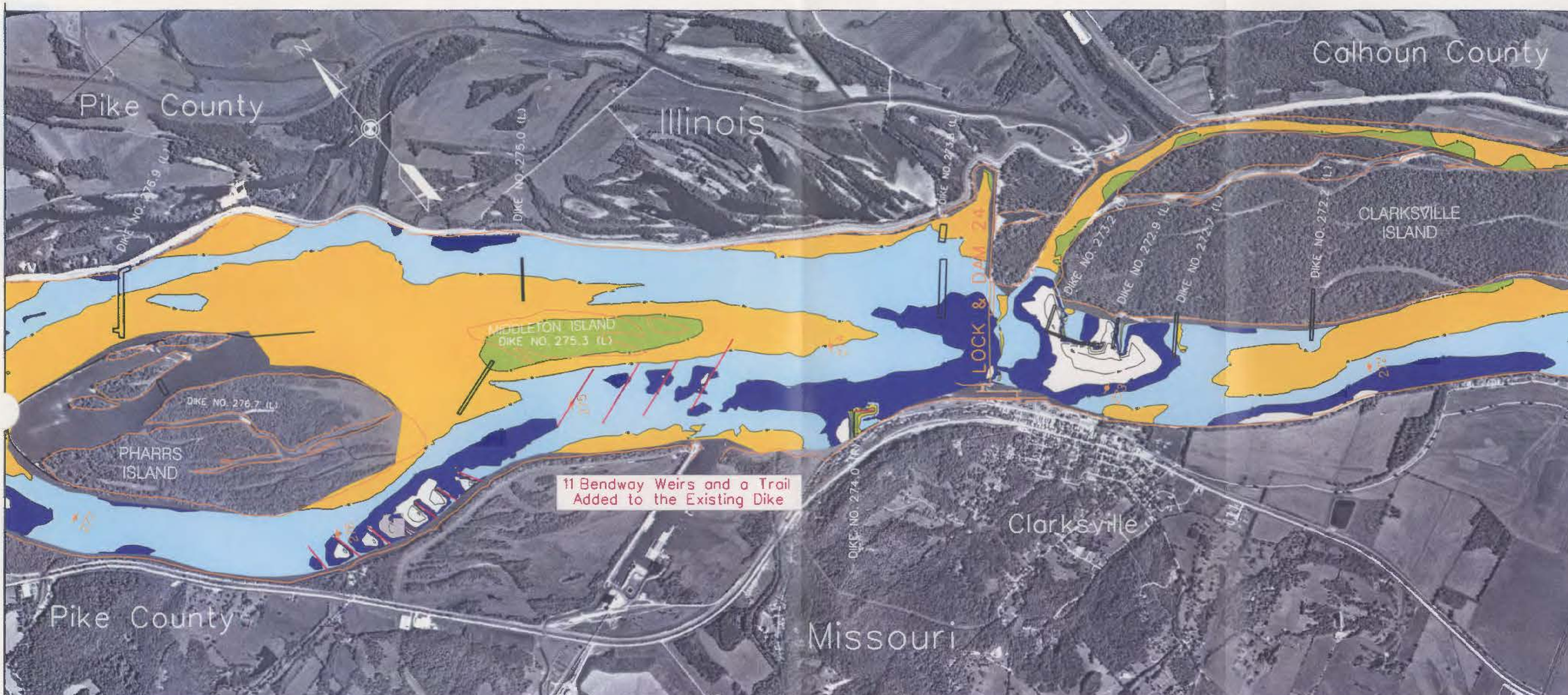
Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Alternative H

PLATE NO
43




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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DRAWN BY: D. Gordon
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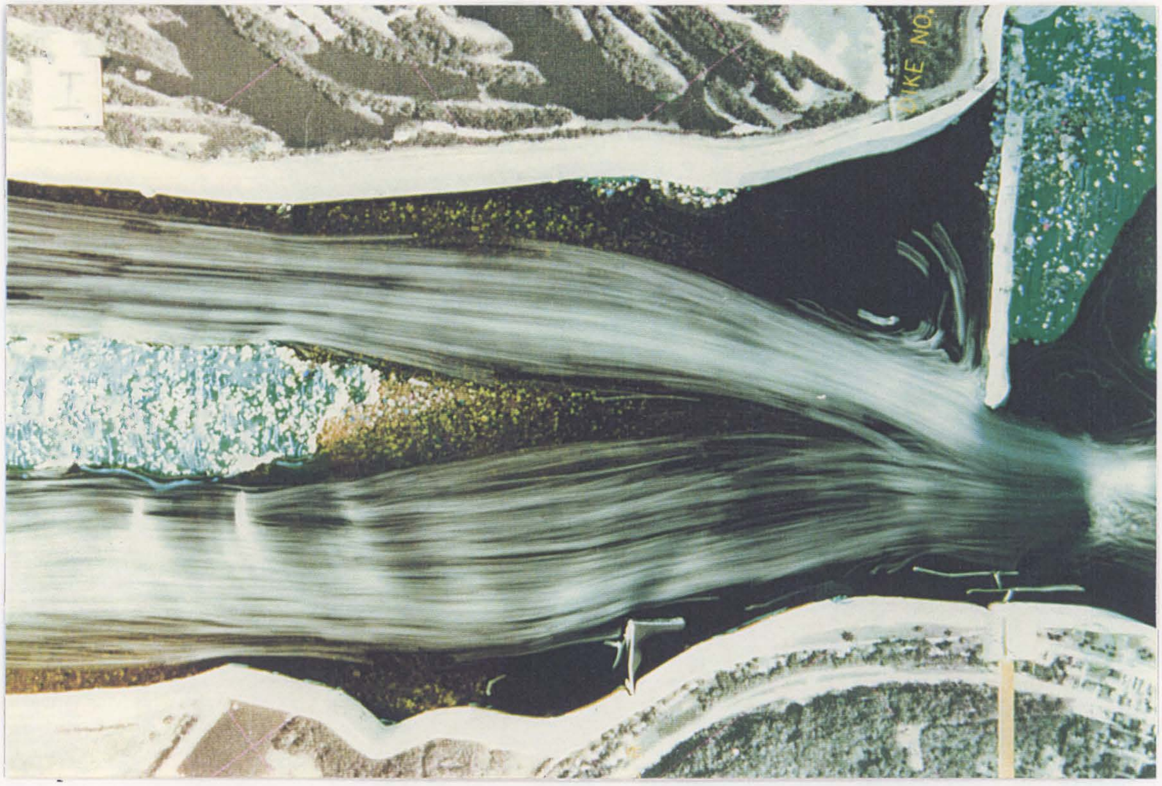
Lock and Dam •24 Micro Model Study
Mississippi River Miles 271 - 277

Alternative I

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D•24\
PLOT SCALE: 1" = 2000'

PLATE NO. 44



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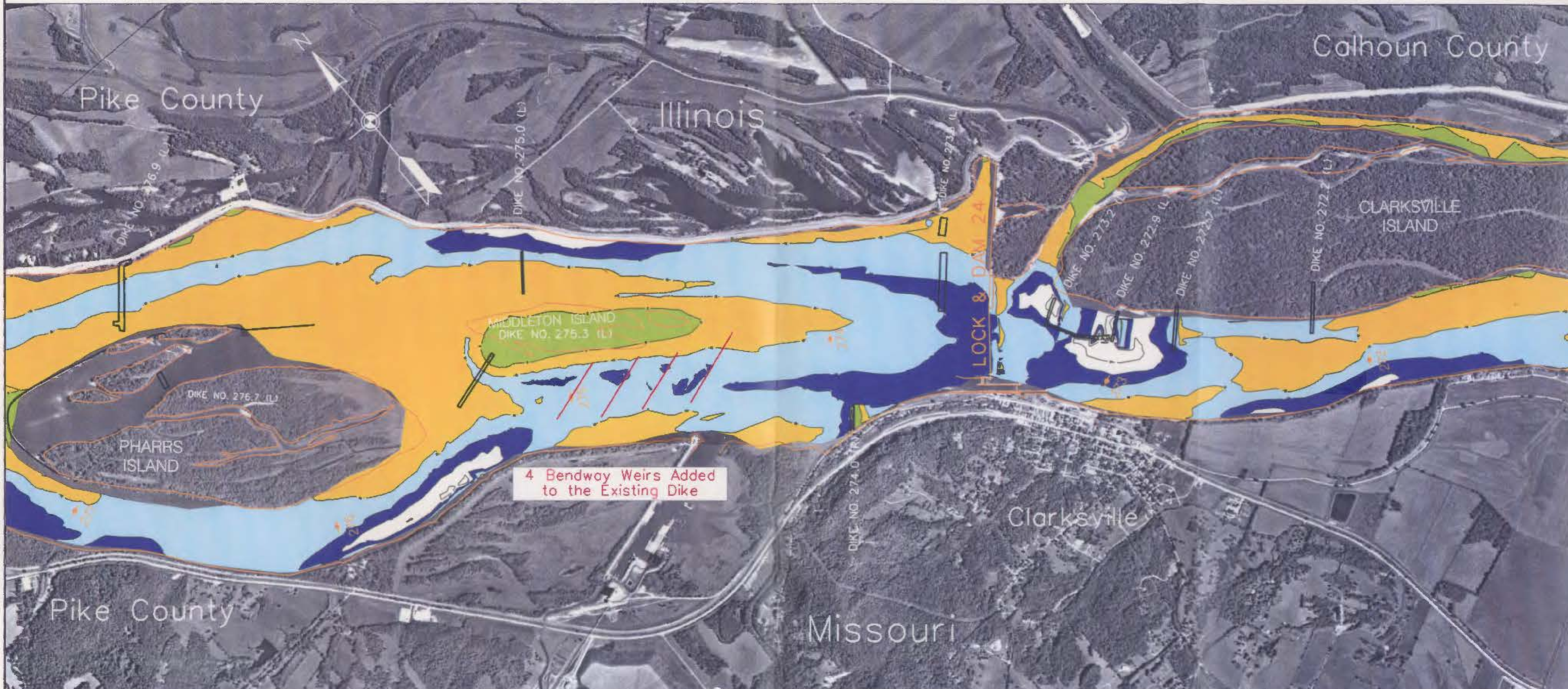
PREPARED BY: D. Gordon
CHECKED BY R. Davinroy

Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Alternative I

PLATE NO 45




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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DRAWN BY: D. Gordon
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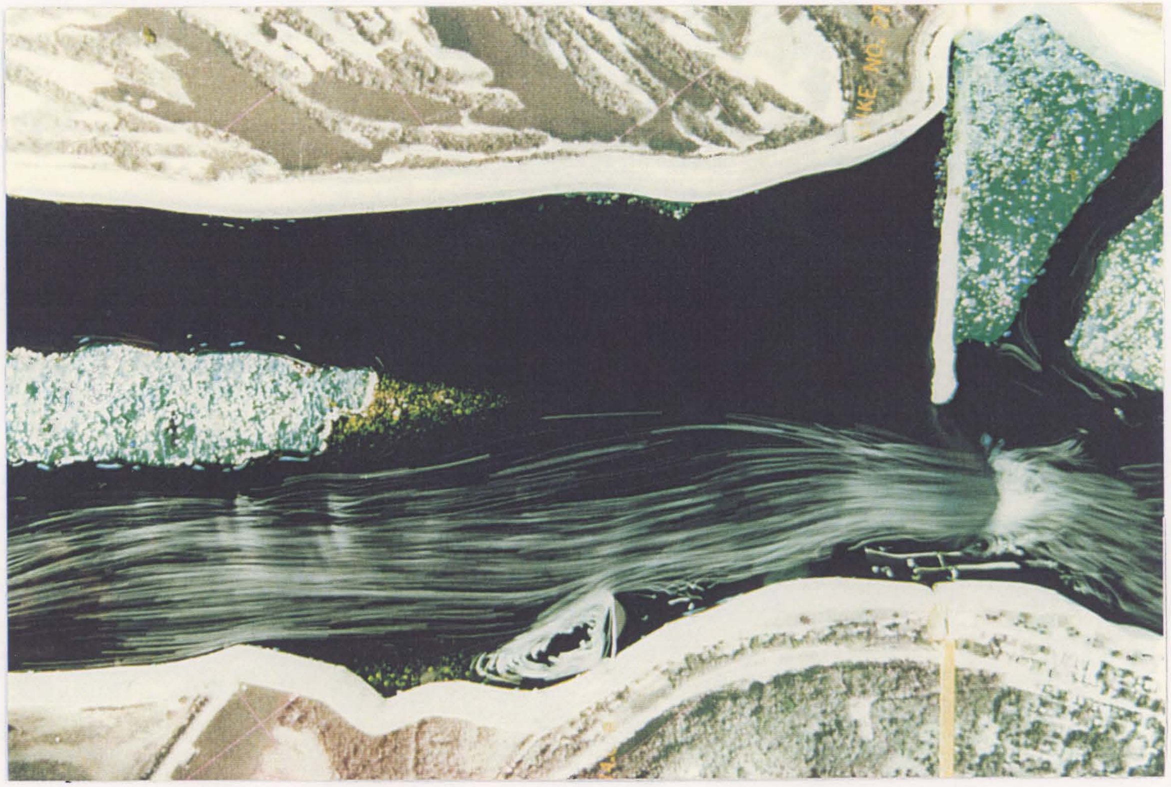
Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

Alternative J

1500' 0 500' 1000' 1500'

PLOT SCALE: 1" = 2000'

PLATE NO. 46



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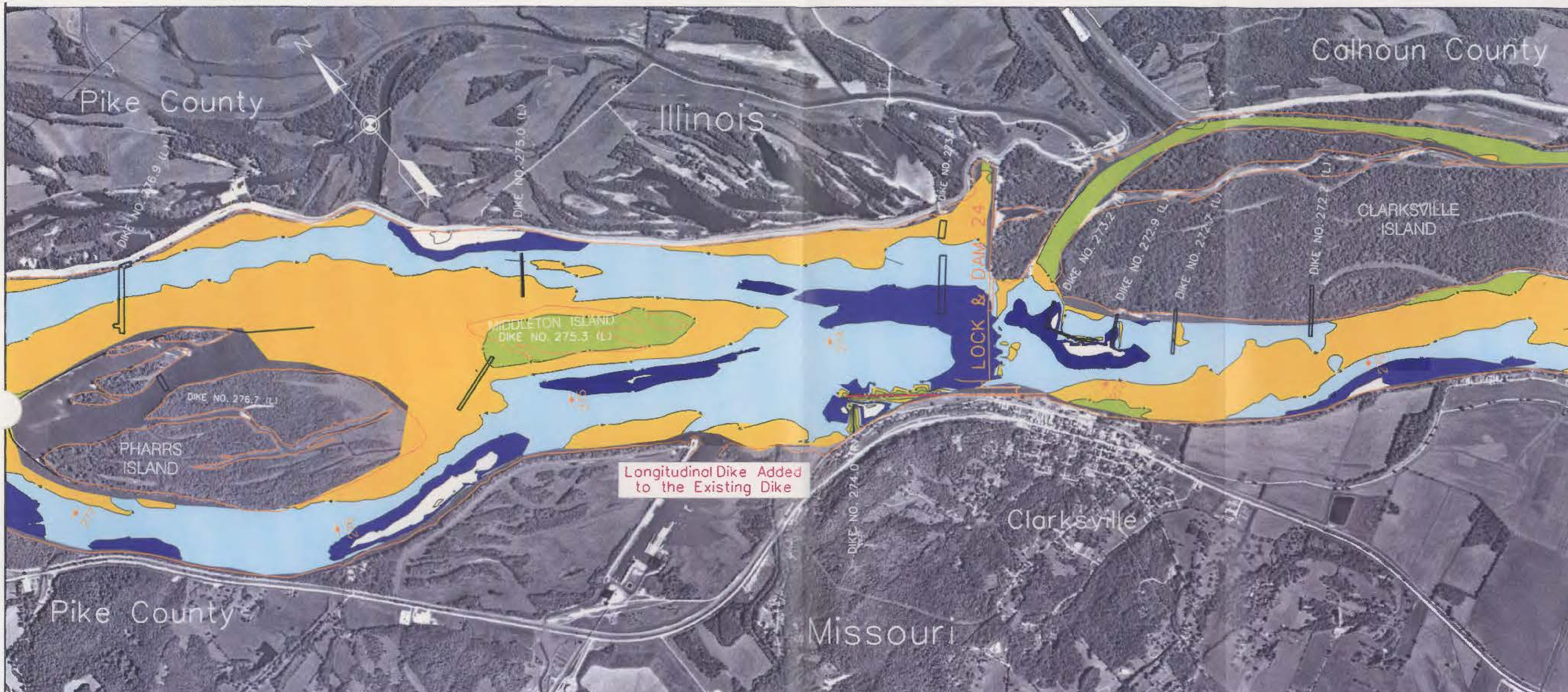
PREPARED BY: D. Gordon
CHECKED BY: R. Davinroy

Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Alternative J

PLATE NO
47




Elevations Referenced to LWRP

| | |
|---|---|
| +20 FT | |
| +10 FT | |
| 0 FT | |
| -10 FT | |
| -20 FT | |
| -30 FT | |
| -40 FT | |
| -50 FT | |

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ST. LOUIS, MISSOURI

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DRAWN BY: D. Gordon
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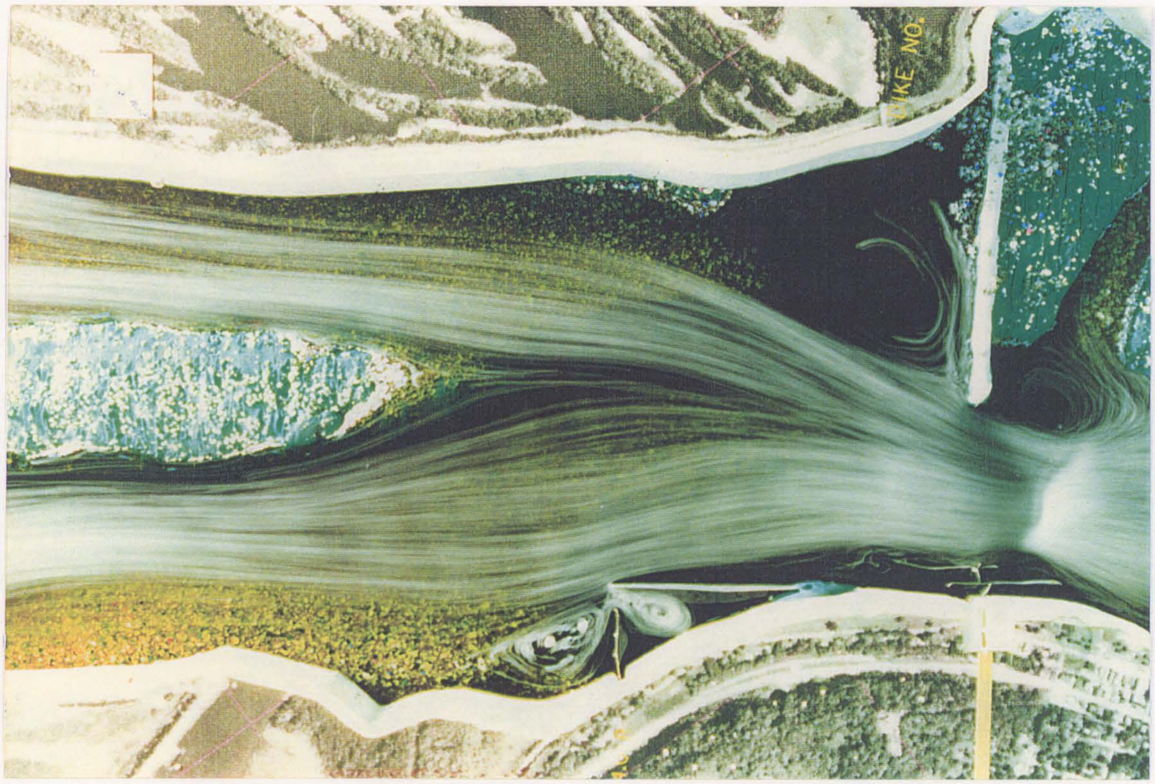
Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

Alternative K

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\
PLOT SCALE: 1" = 2000'

PLATE NO. 48



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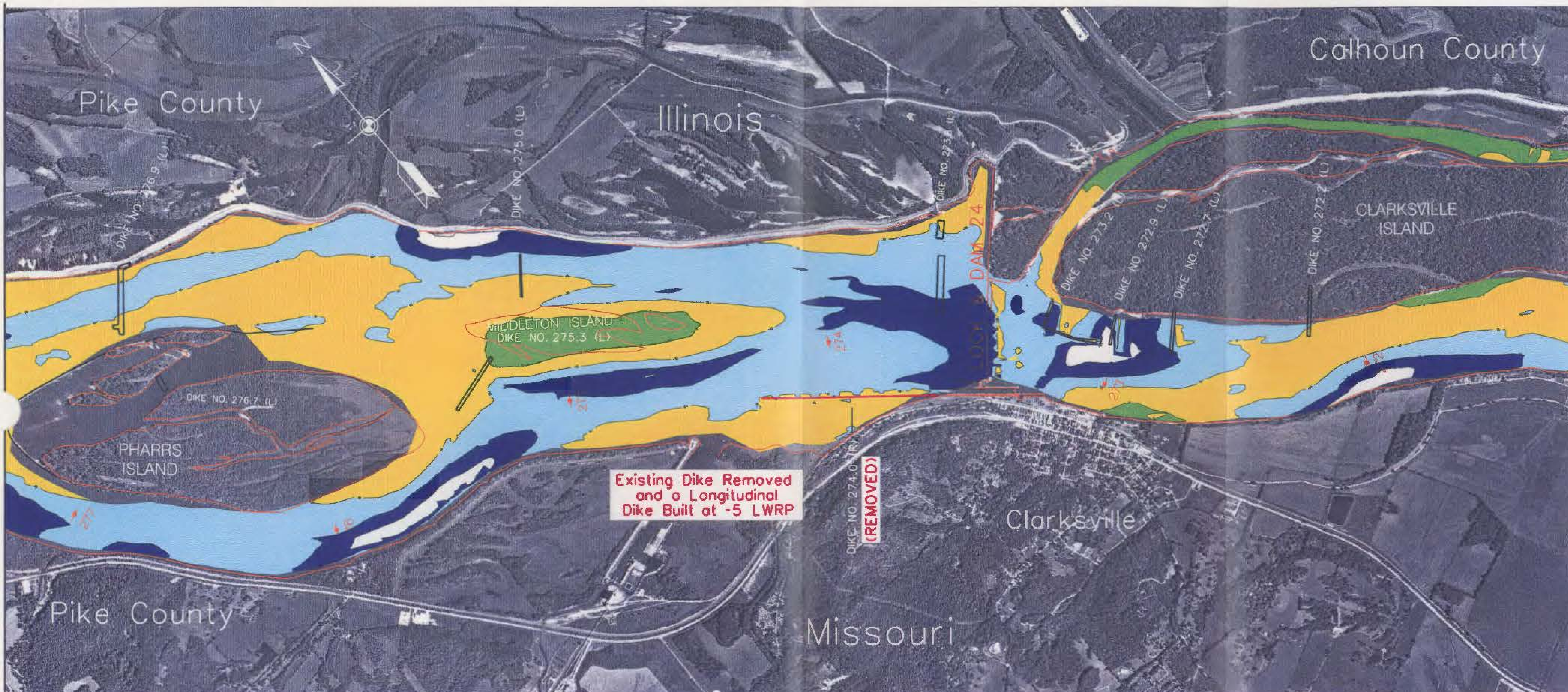
ST. LOUIS, MISSOURI

PREPARED BY: D. Gordon
CHECKED BY: R. Davinroy

Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Alternative K

PLATE NO 49




Elevations Referenced to LWRP

| |
|---|
| +20 FT |
| +10 FT |
| 0 FT |
| -10 FT |
| -20 FT |
| -30 FT |
| -40 FT |
| -50 FT |

U.S. ARMY ENGINEER DISTRICT, ST. LOUIS
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ST. LOUIS, MISSOURI

PREPARED BY: O. Gordon
DRAWN BY: D. Gordon
CHECKED BY: R. Davinroy

Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

Alternative L

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D-24\
PLOT SCALE: 1" = 2000'

PLATE NO. 50


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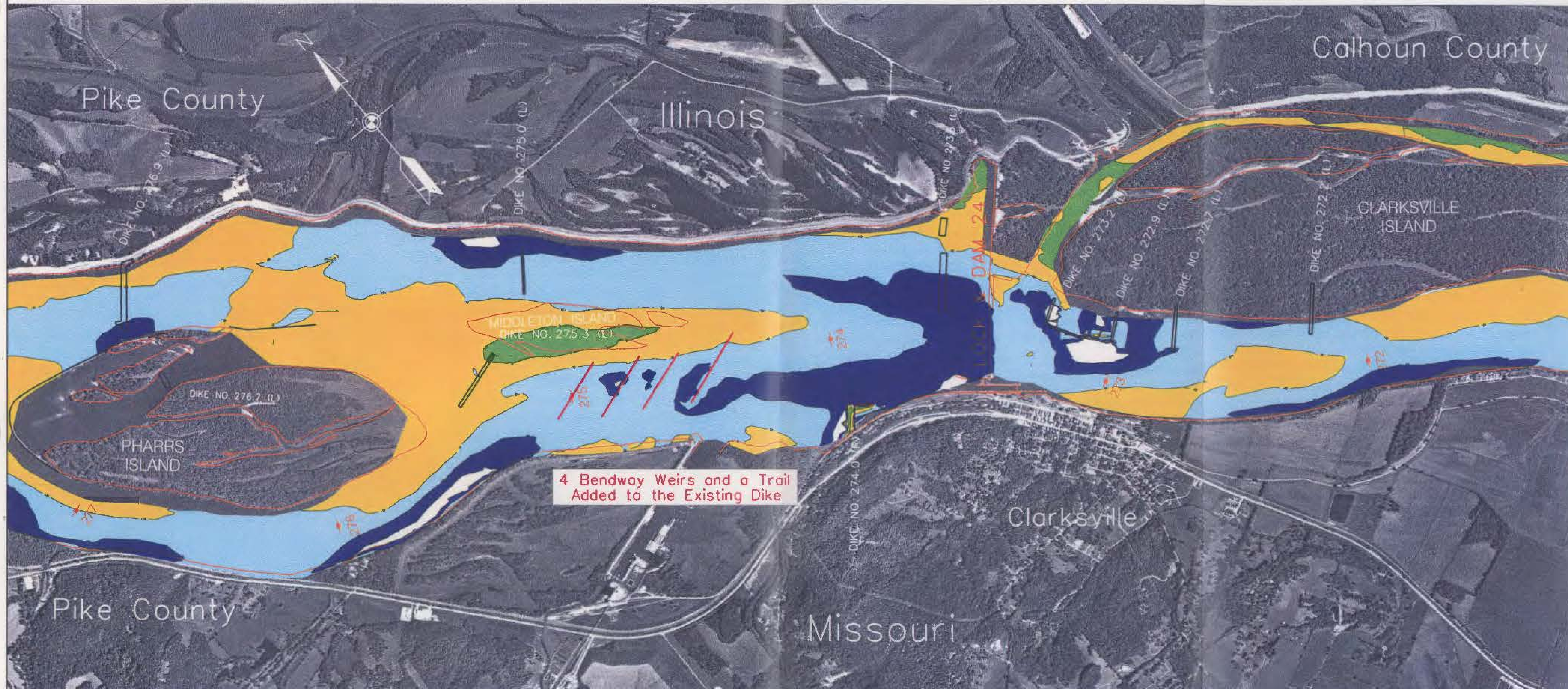
CORPS OF ENGINEERS
ST. LOUIS, MISSOURI

PREPARED BY: D. Gordon
CHECKED BY: R. Davinroy

Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Alternative L

PLATE NO
51




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

U.S. ARMY ENGINEER DISTRICT, ST. LOUIS
CORPS OF ENGINEERS
ST. LOUIS, MISSOURI

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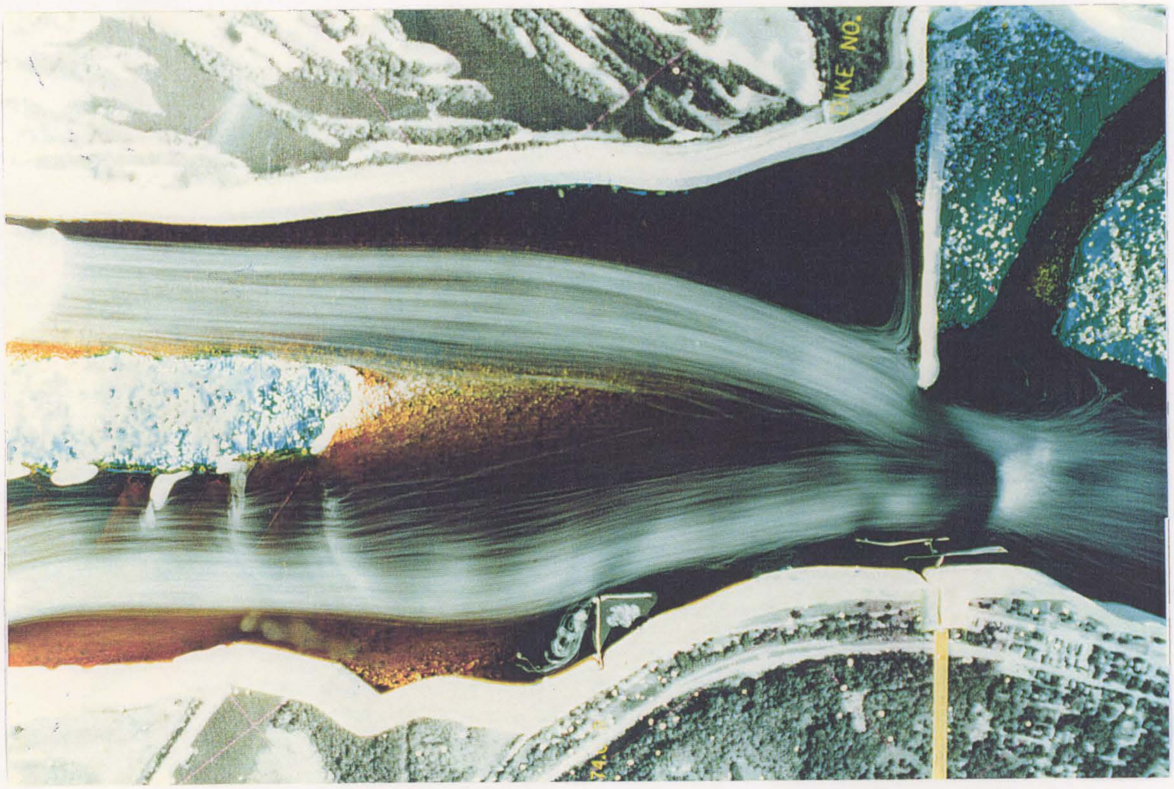
DRAWN BY: D. Gordon
CHECKED BY: R. Davinroy

Lock and Dam *24 Micro Model Study
Mississippi River Miles 271 - 277

Alternative M

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D*24\
PLOT SCALE: 1" = 2000'
PLATE NO. 52

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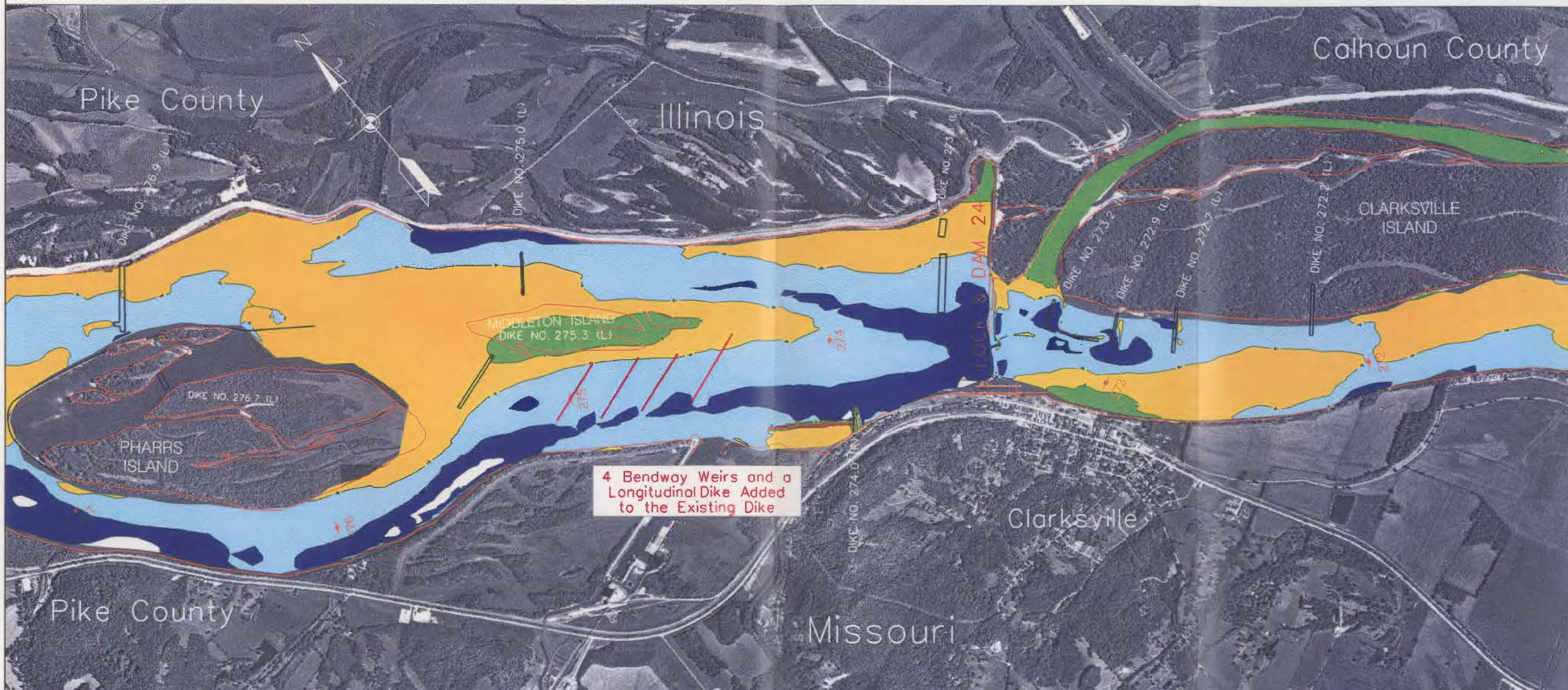
ST. LOUIS, MISSOURI

PREPARED BY: D. Gordon
CHECKED BY: R. Davinroy

Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Alternative M

PLATE NO
53




Elevations Referenced to LWRP

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+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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DRAWN BY: D. Gordon
CHECKED BY: R. Davinroy

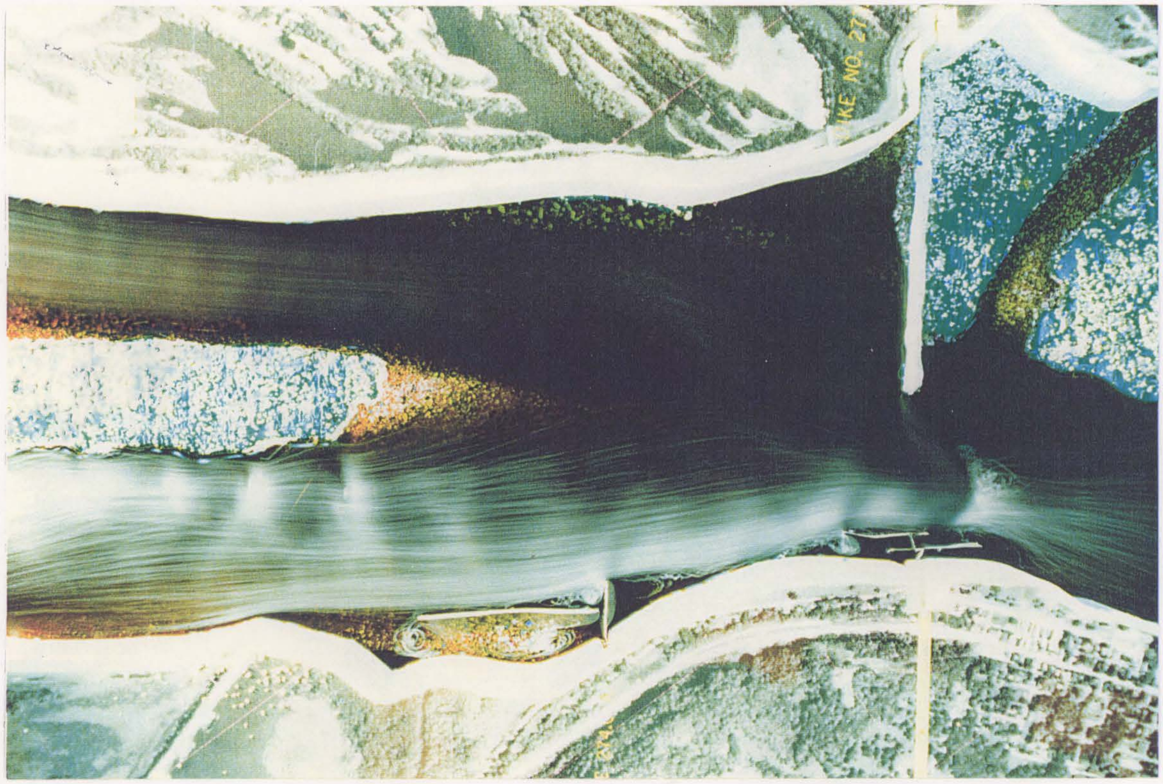
Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

Alternative N

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\
PLOT SCALE: 1" = 2000'

PLATE NO. 54



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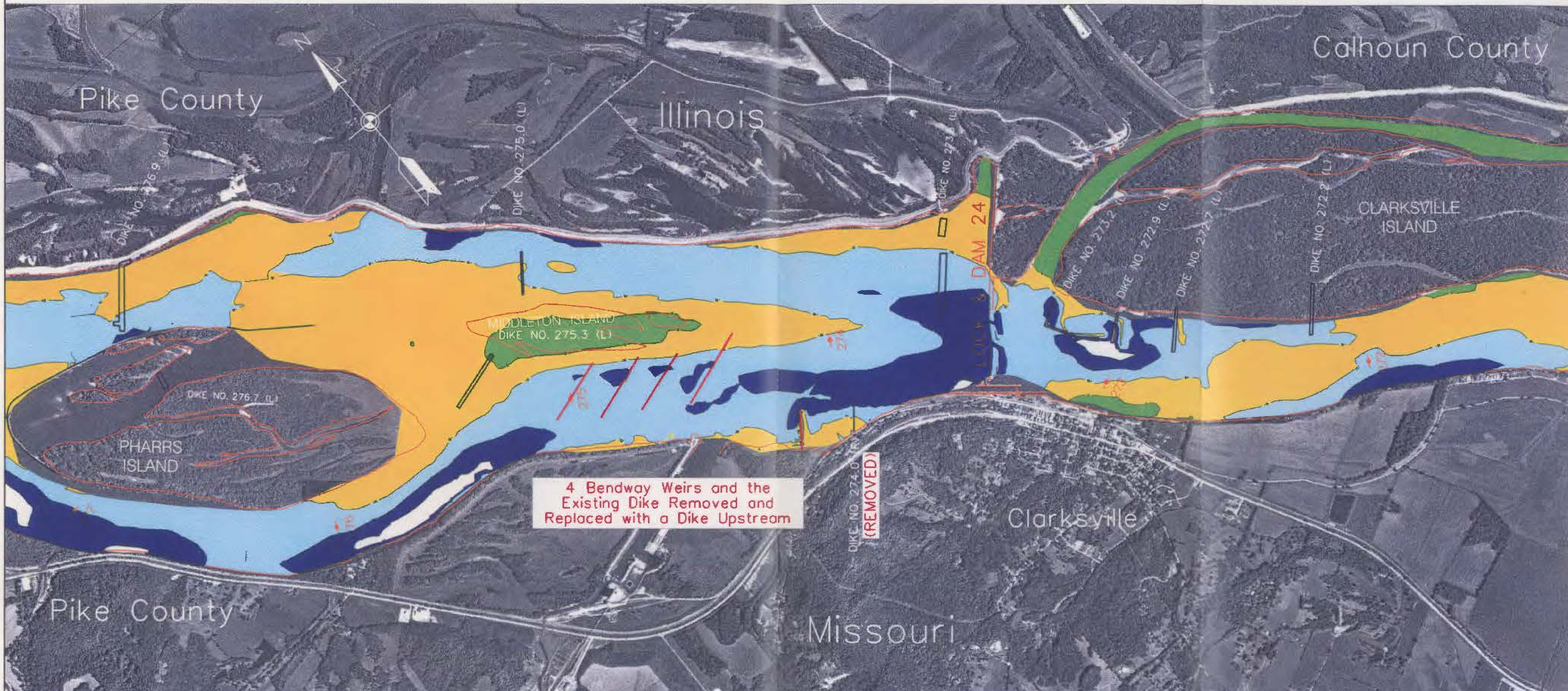
Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Alternative N

PLATE NO
55




Elevations Referenced
to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

U.S. ARMY ENGINEER DISTRICT, ST. LOUIS
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ST. LOUIS, MISSOURI

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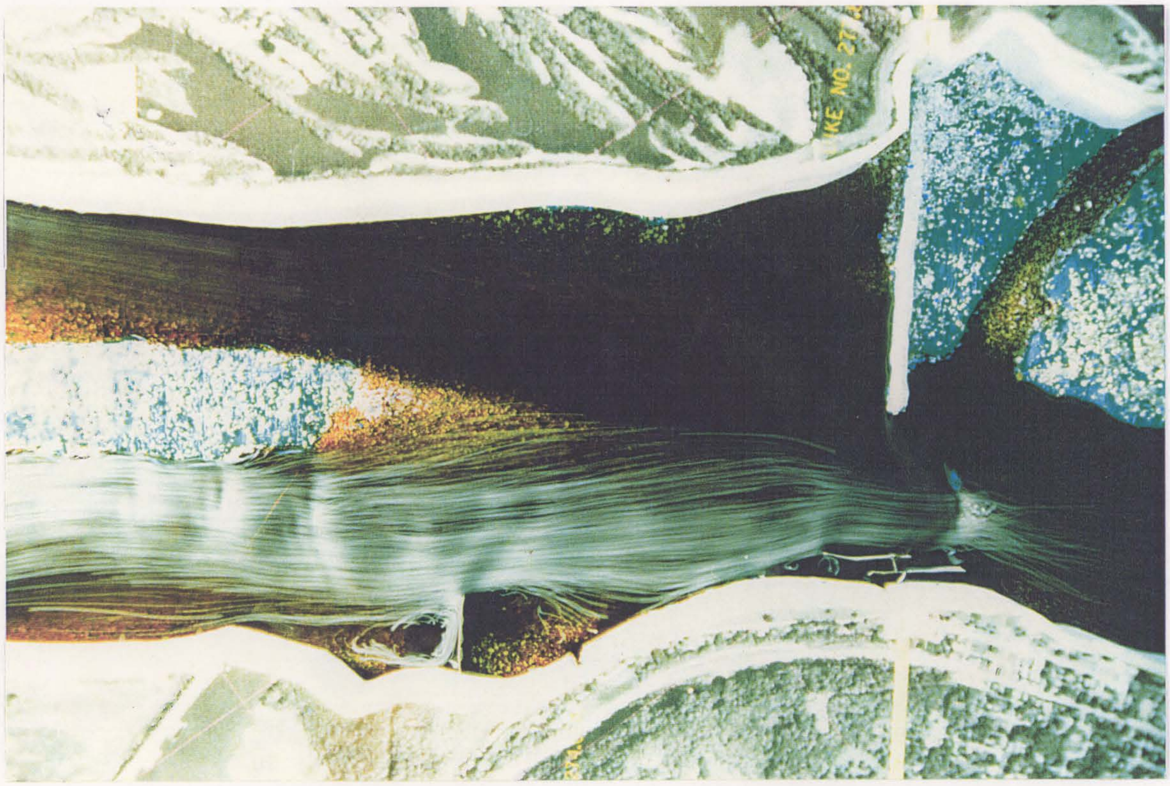
DRAWN BY: D. Gordon
CHECKED BY: R. Davinroy

Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

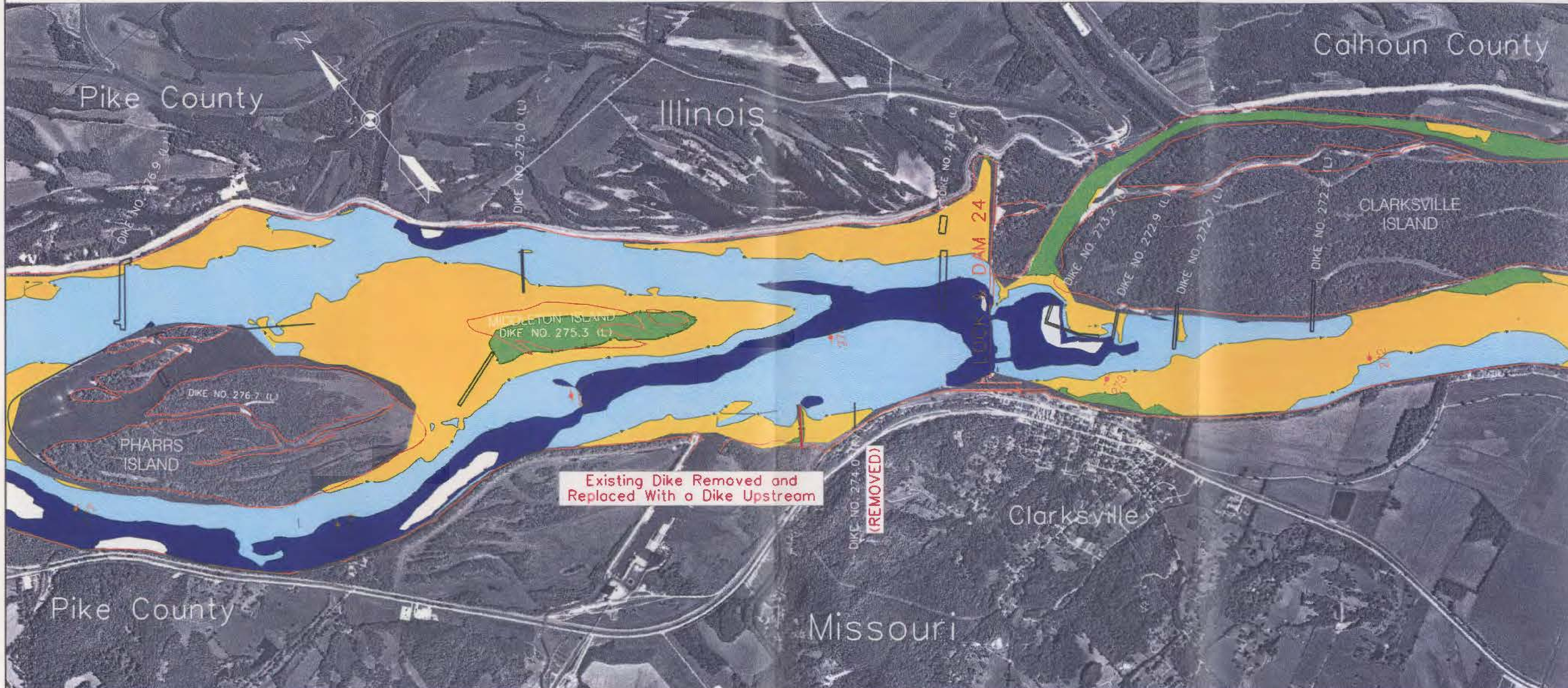
Alternative D

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DDR\MODEL\L&D#24\
PLOT SCALE: 1" = 2000'
PLATE NO. 56



| | |
|---|---|
| | **U.S ARMY ENGINEER DISTRICT, ST. LOUIS**<br>**CORPS OF ENGINEERS**<br>**ST. LOUIS, MISSOURI** |
| PREPARED BY: D. Gordon<br>CHECKED BY: R. Davinroy | Lock and Dam 24 Micro Model Study<br>Mississippi River Miles 271 - 277<br><br>Flow Visualization - Alternative O |
| | PLATE NO<br>**57** |




Elevations Referenced to LWRP

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+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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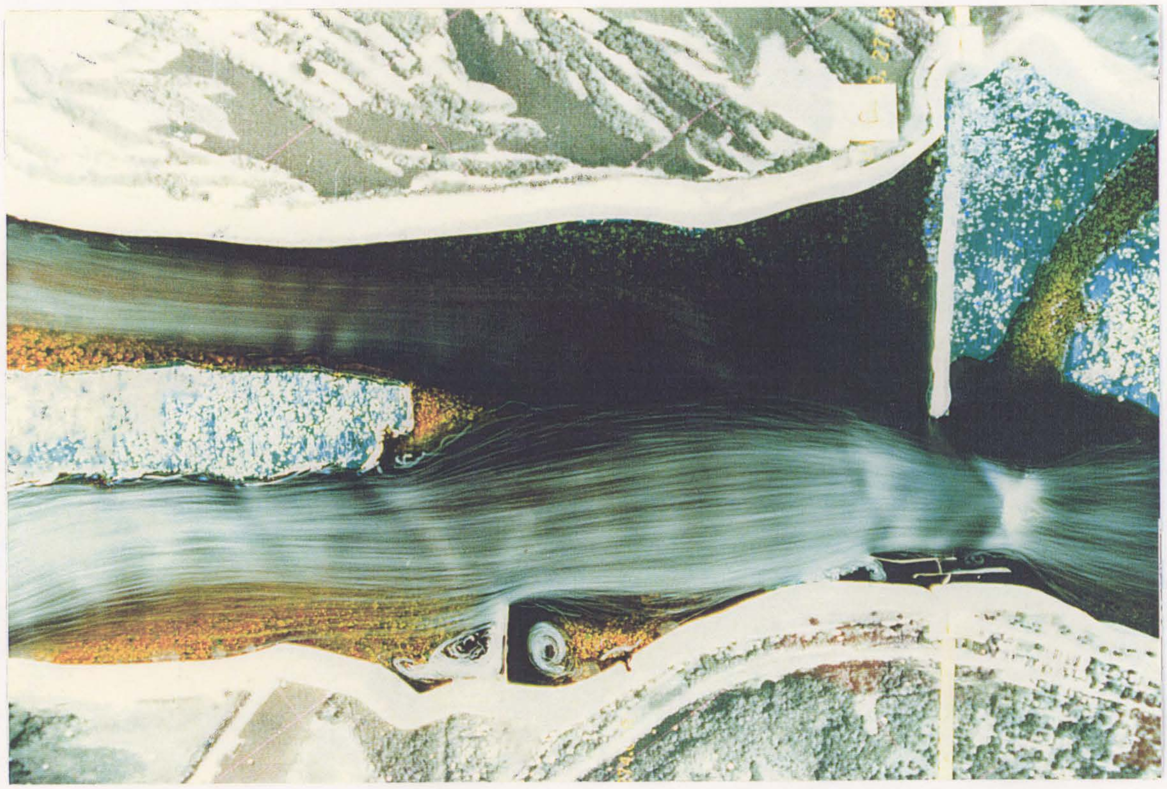
PREPARED BY: D. Gordon
DRAWN BY: D. Gordon
CHECKED BY: R. Denlaroy

Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

Alternative P

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\
PLOT SCALE: 1" = 2000'
PLATE NO. 58



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ST. LOUIS, MISSOURI

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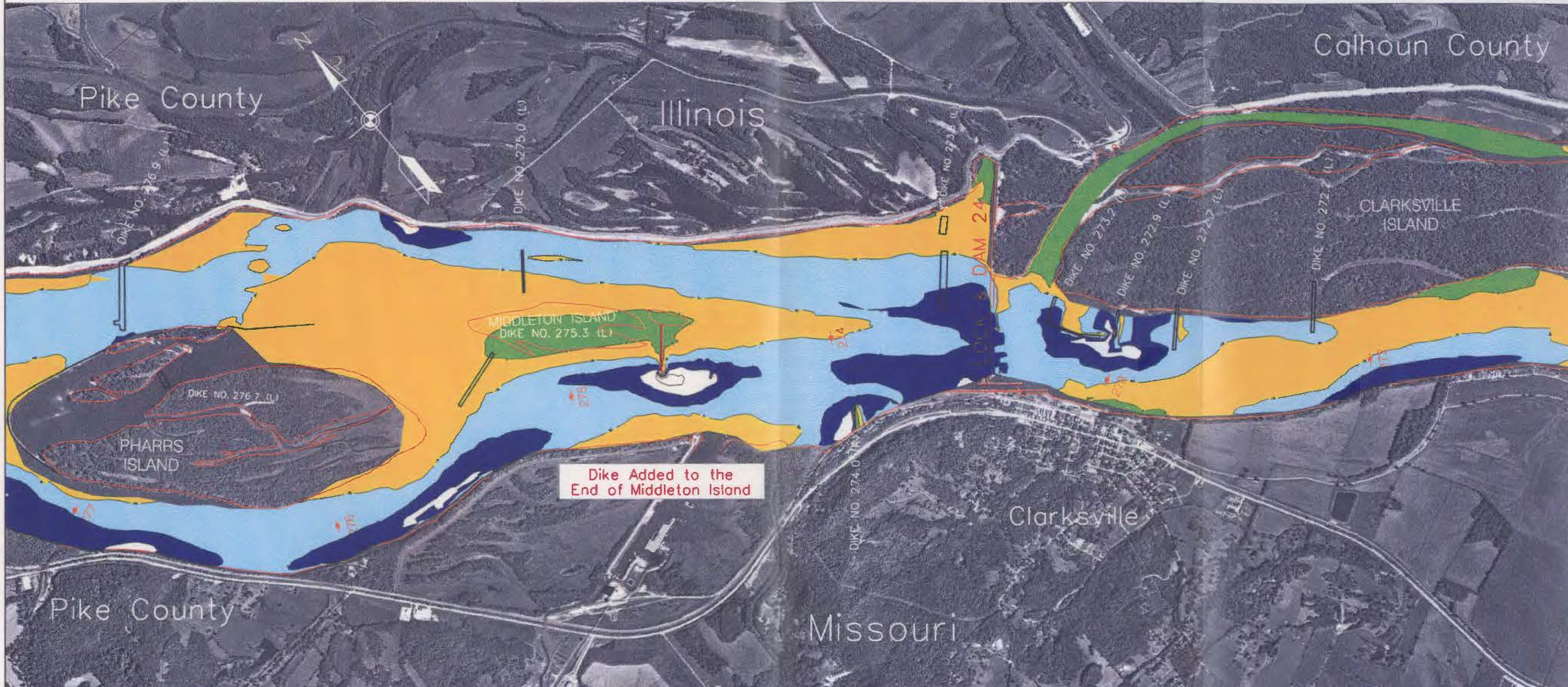
CHECKED BY: R Davinroy

Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Alternative P

PLATE NO
59




Elevations Referenced to LWRP

| | |
|---|---|
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| | +10 FT |
| | 0 FT |
| | -10 FT |
| | -20 FT |
| | -30 FT |
| | -40 FT |
| | -50 FT |

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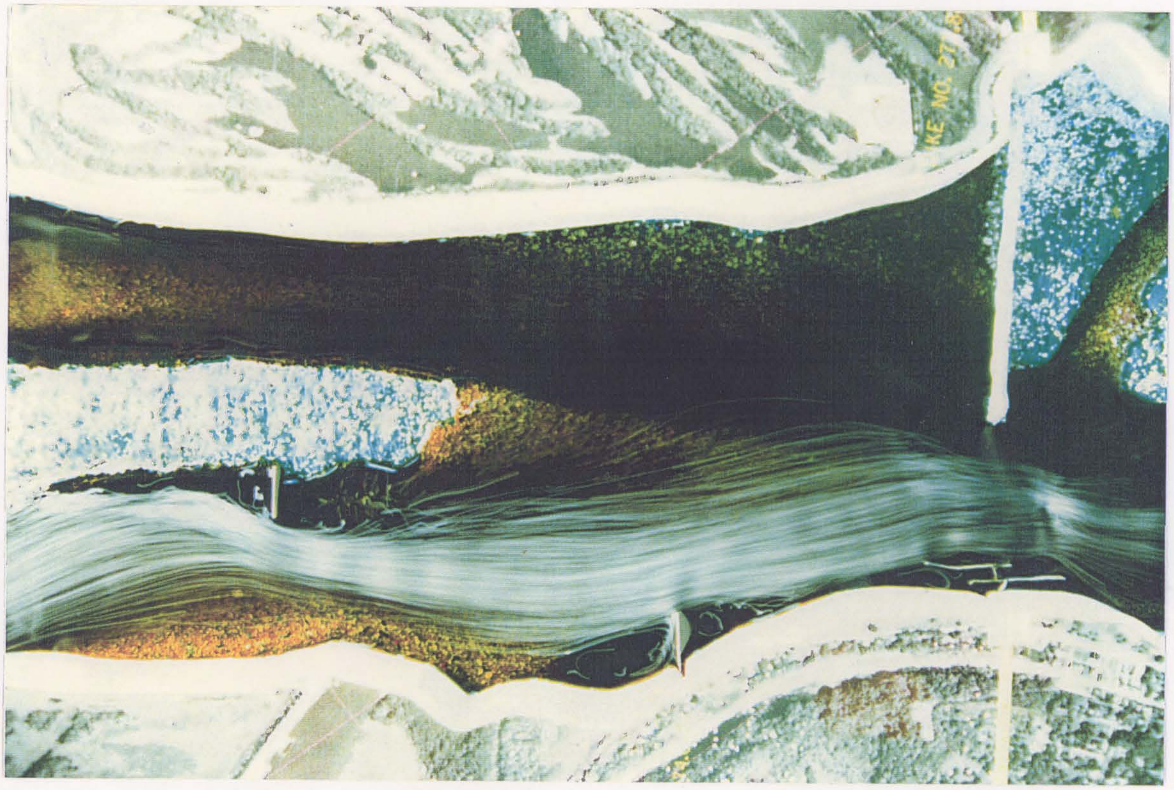
CHECKED BY: R. Davinroy

Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

Alternative Q

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D*24\
PLOT SCALE: 1" = 2000'
PLATE NO. 60



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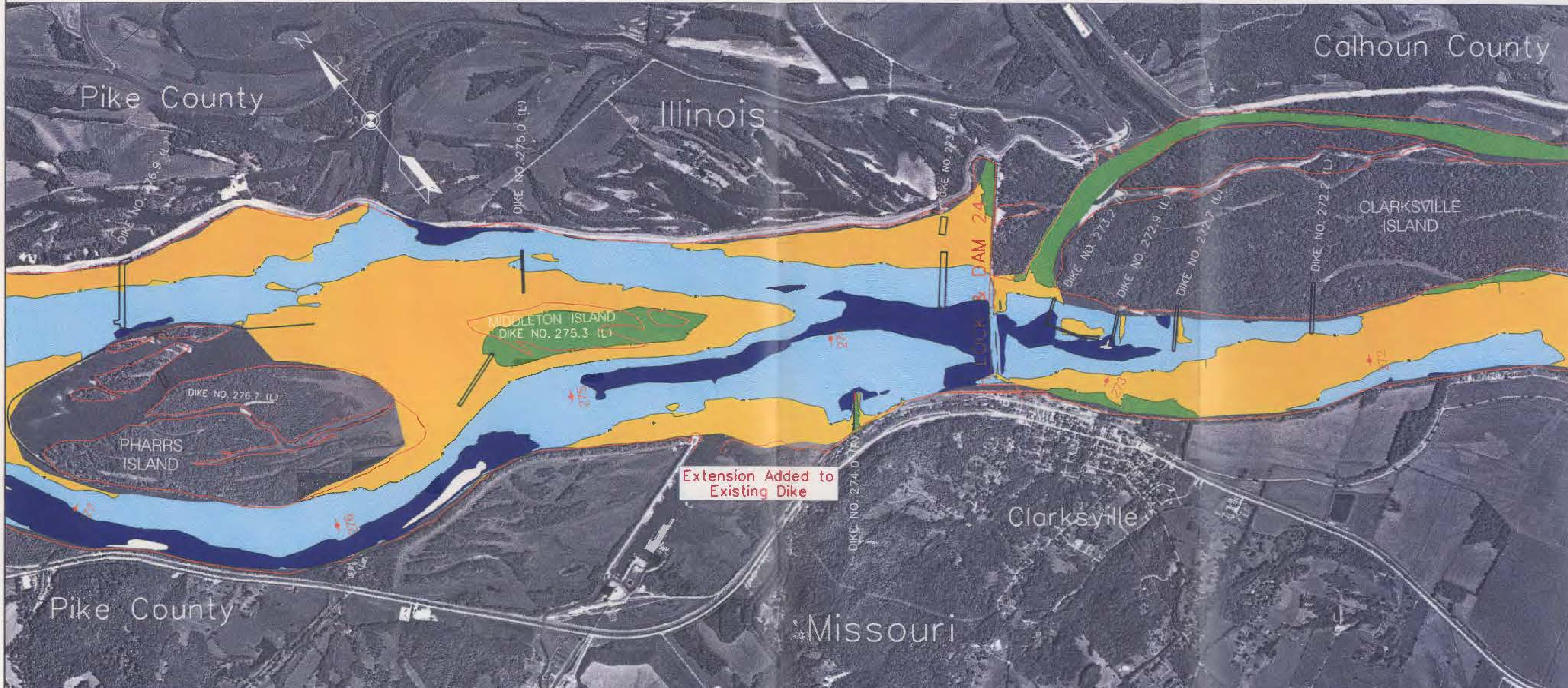
Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Alternative Q

PLATE NO
61




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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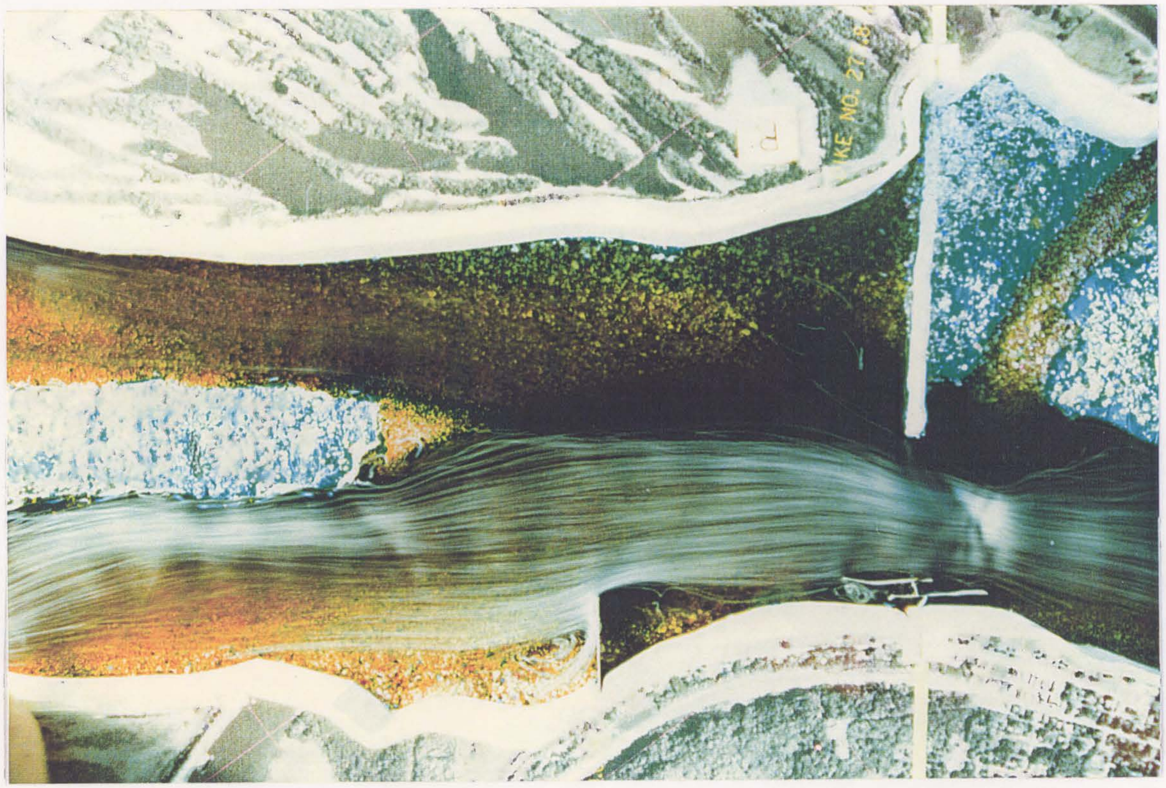
Mississippi River Miles 271 - 277

Alternative R

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DON\MODEL\L&D#24\
PLOT SCALE: 1" = 2000'
PLATE NO. 62



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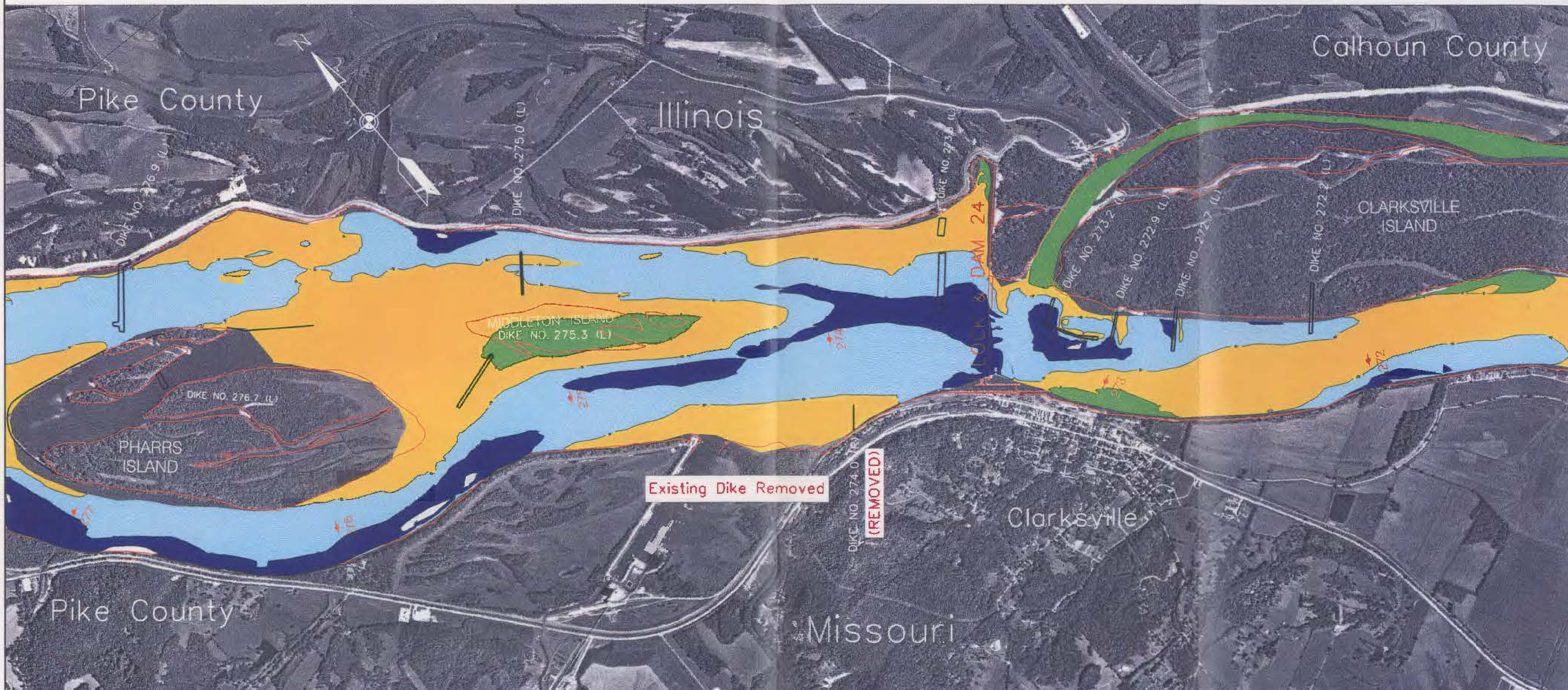
Mississippi River Miles 271 - 277

Flow Visualization - Alternative R

PLATE NO
63




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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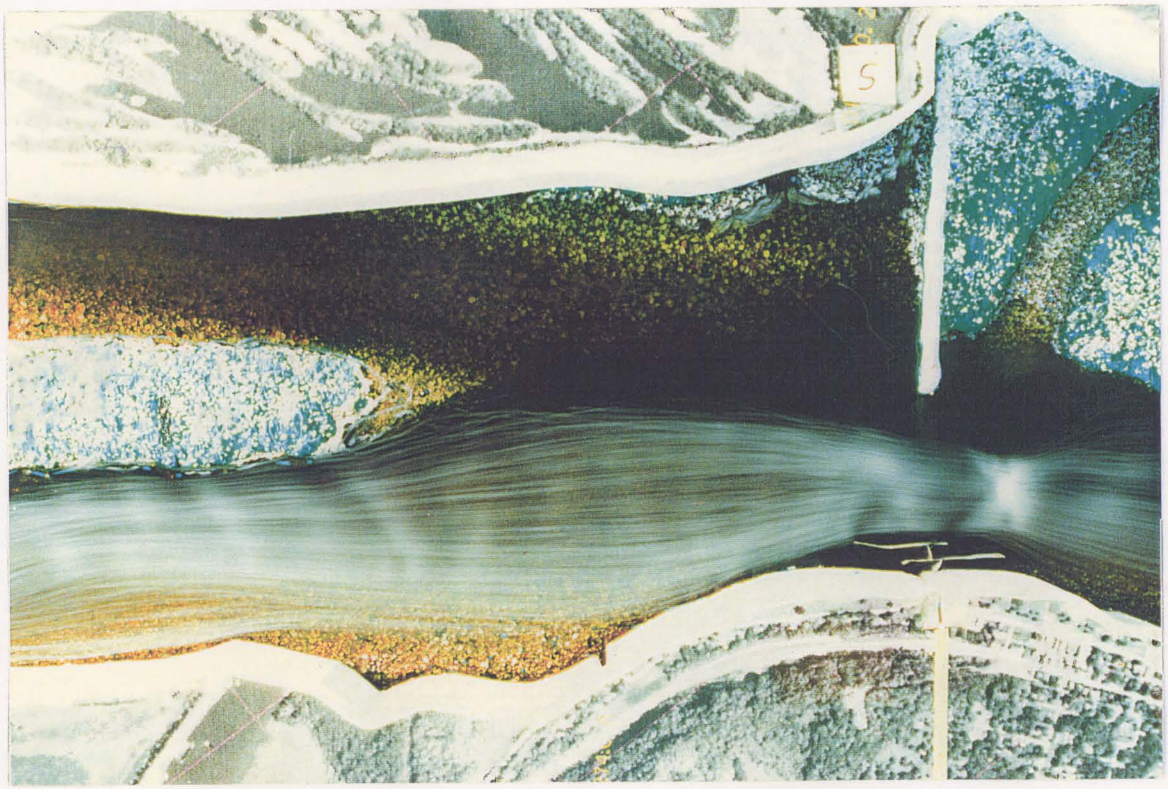
Mississippi River Miles 271 - 277

Alternative S

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\
PLOT SCALE: 1" = 2000'
PLATE NO. 64

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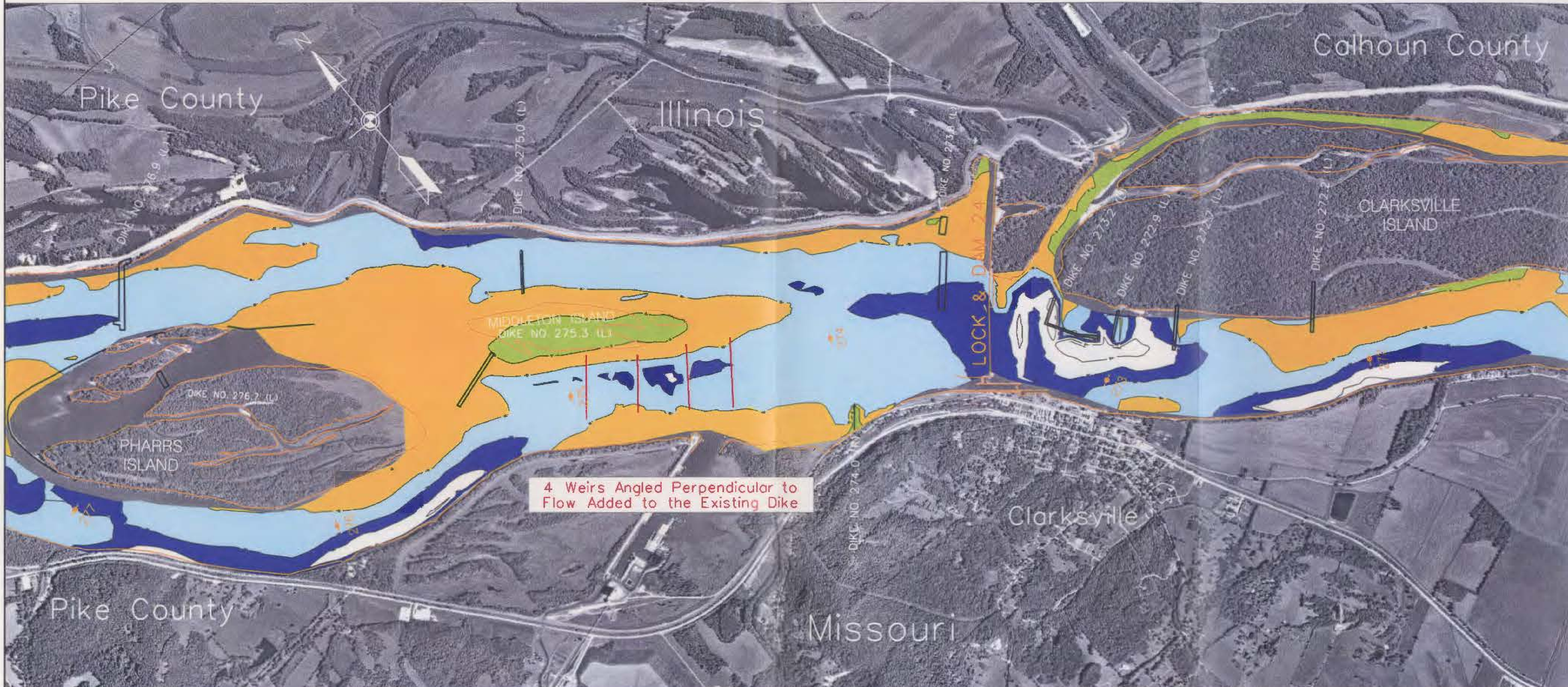
Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Alternative S

PLATE NO **65**




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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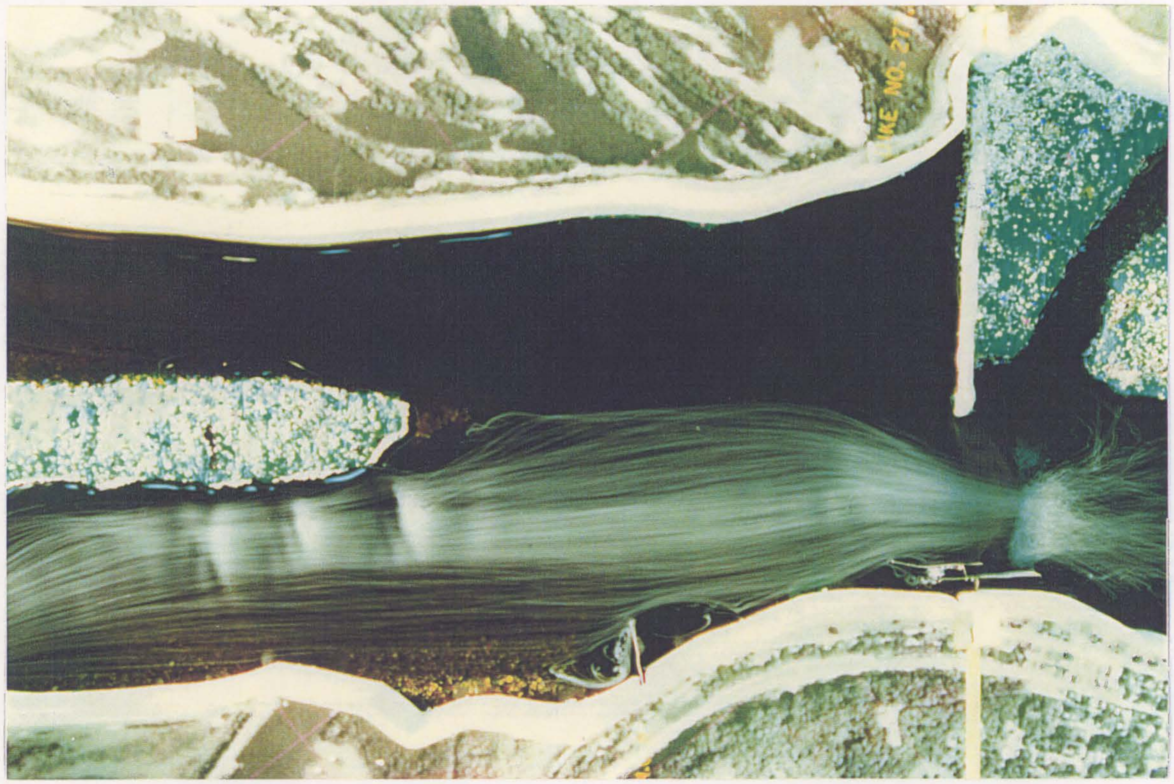
Mississippi River Miles 271 - 277

Alternative T

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\
PLOT SCALE: 1" = 2000'

PLATE NO. 66



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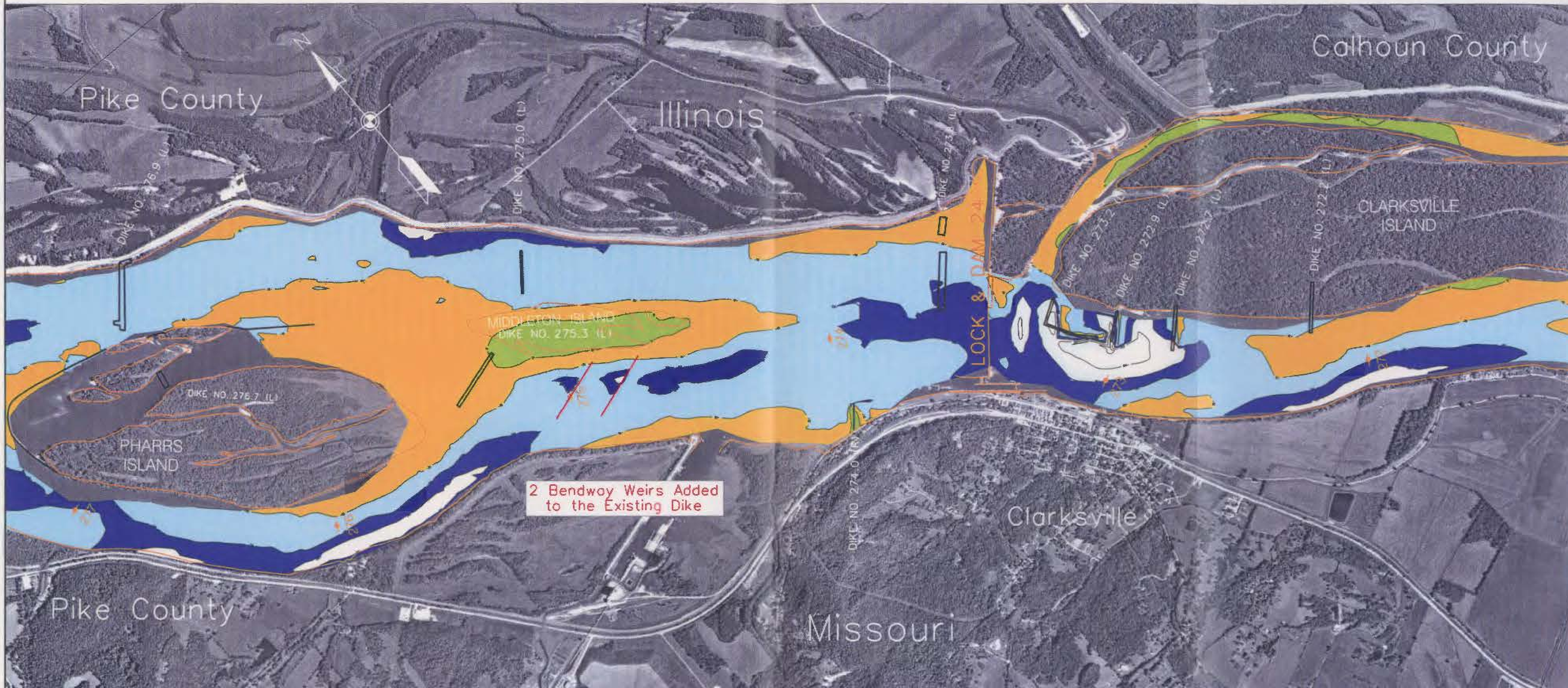
Mississippi River Miles 271 - 277

Flow Visualization - Alternative T

PLATE NO. 67




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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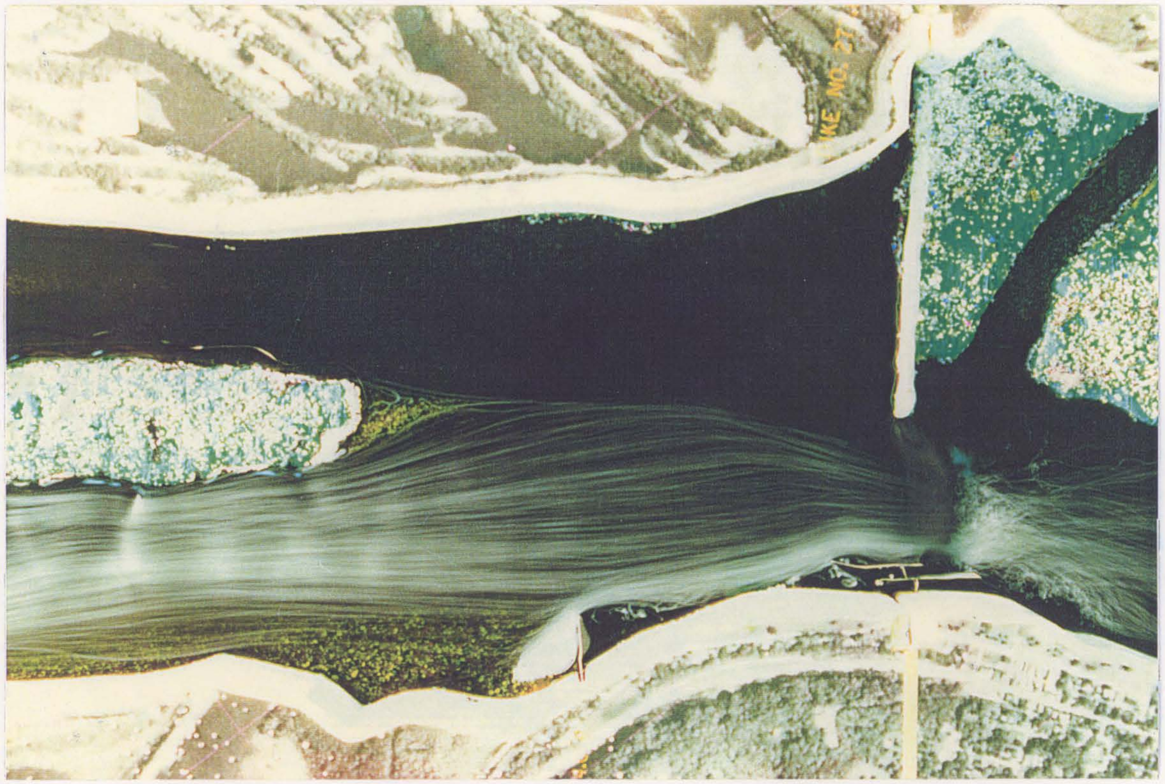
Mississippi River Miles 271 - 277

Alternative U

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\
PLOT SCALE: 1" = 2000'
PLATE NO. 68



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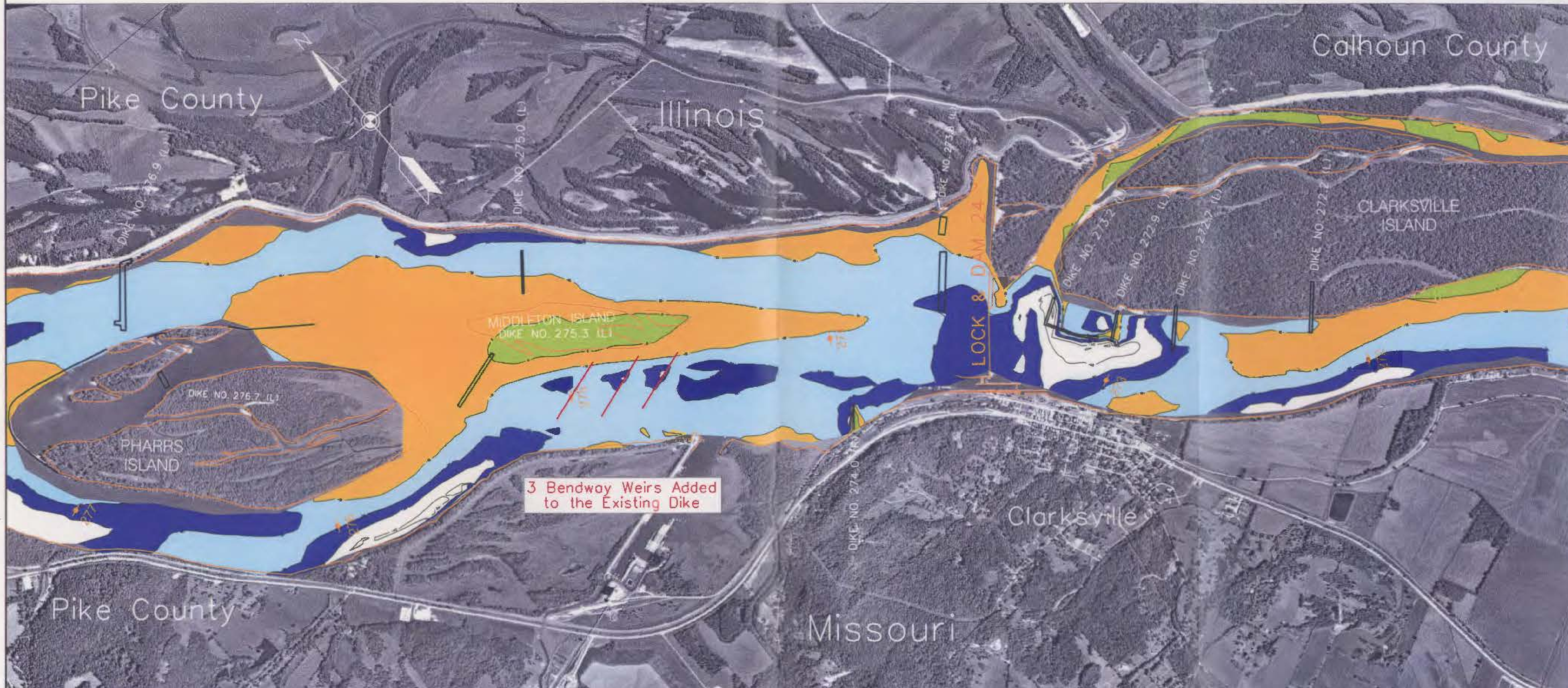
Mississippi River Miles 271 - 277

Flow Visualization - Alternative U

PLATE NO
69




Elevations Referenced to LWRP

- +20 FT
- +10 FT
- 0 FT
- -10 FT
- -20 FT
- -30 FT
- -40 FT
- -50 FT

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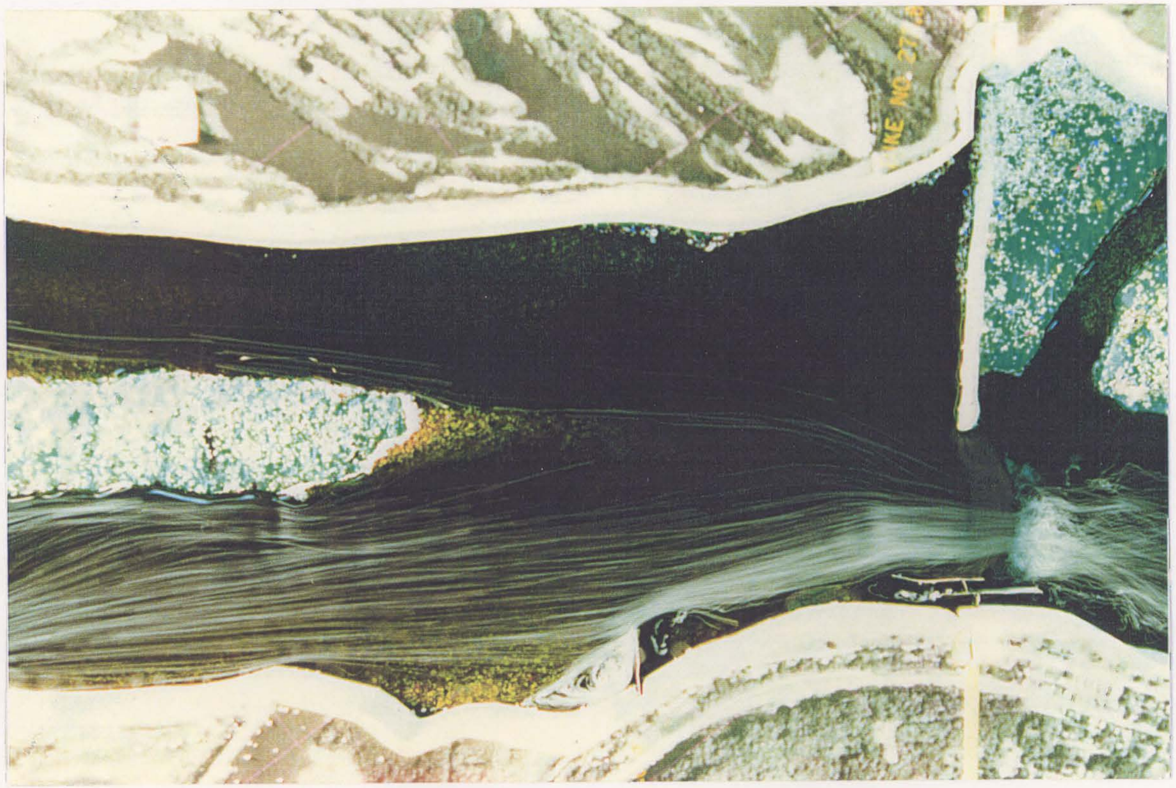
Mississippi River Miles 271 - 277

Alternative V

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D*24\
PLOT SCALE: 1" = 2000'

PLATE NO. 70



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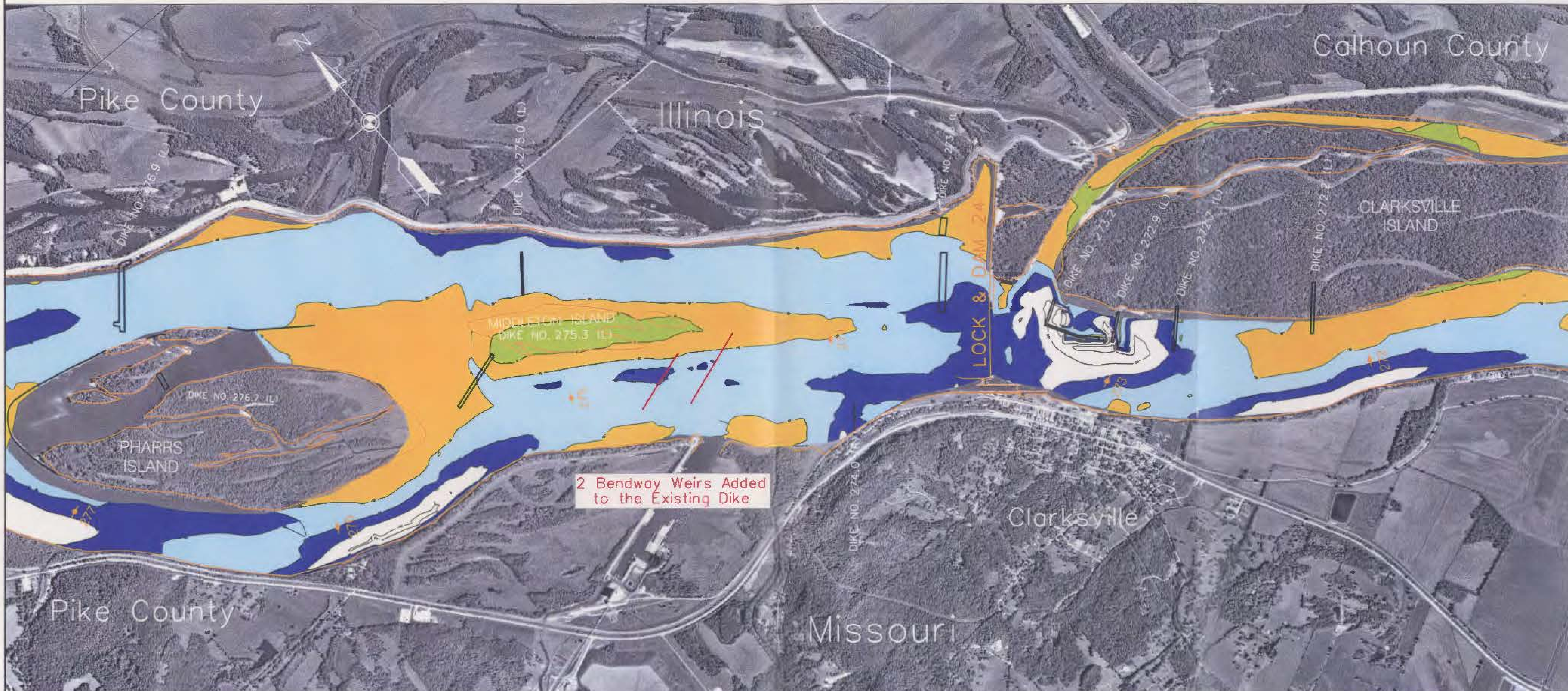
Mississippi River Miles 271 - 277

Flow Visualization - Alternative V

PLATE NO 71




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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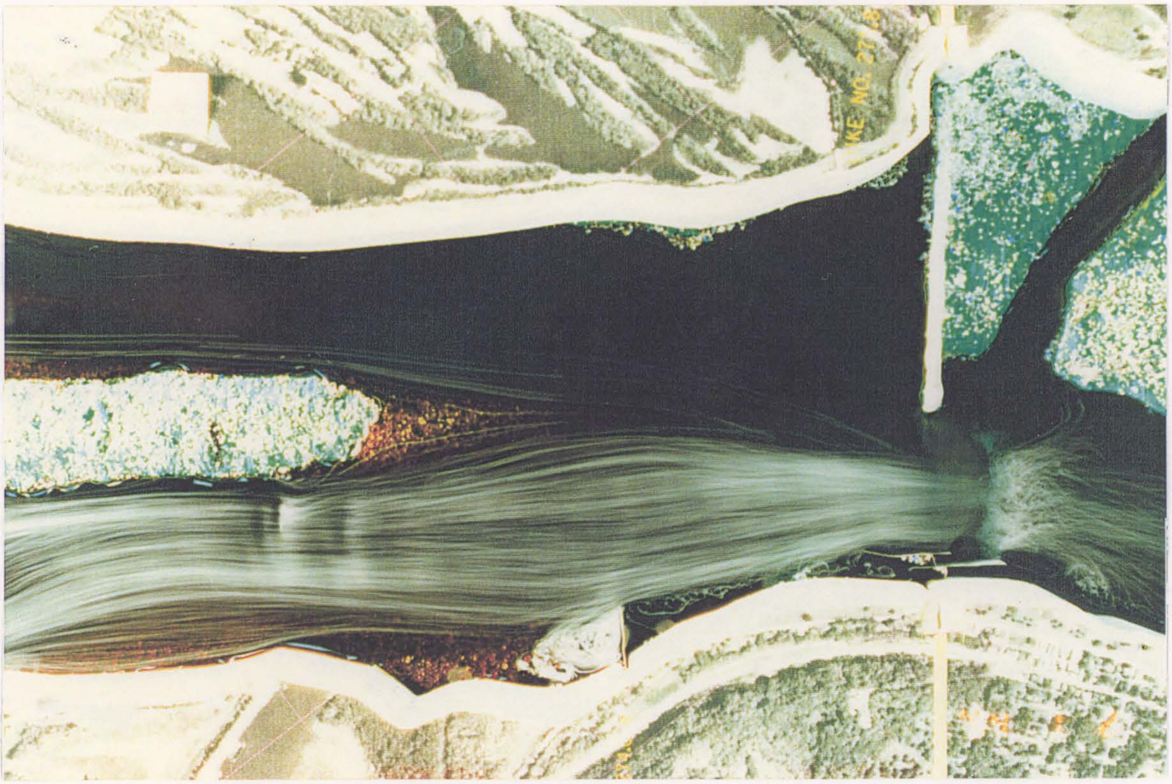
Mississippi River Miles 271 - 277

Alternative W

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\
PLOT SCALE: 1" = 2000'
PLATE NO. 72



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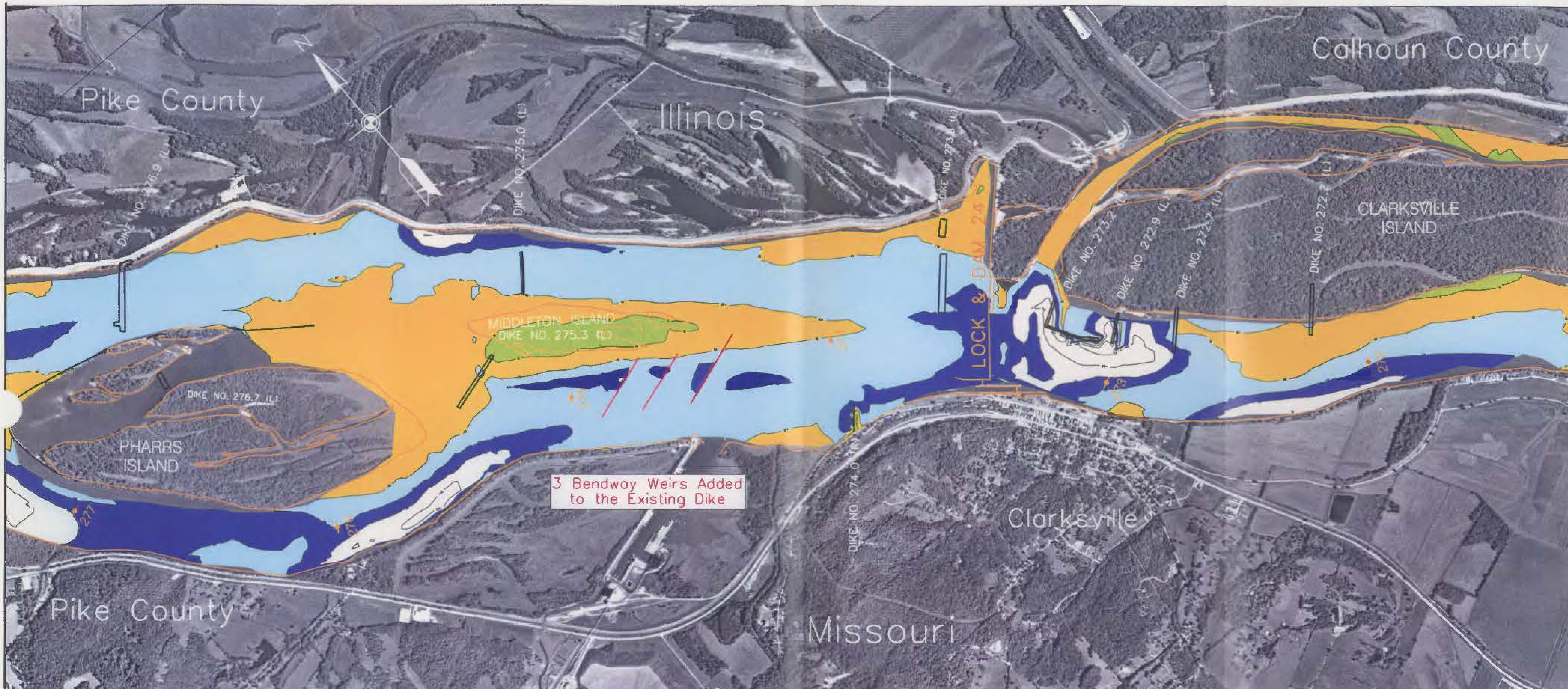
Mississippi River Miles 271 - 277

Flow Visualization - Alternative W

PLATE NO.
73




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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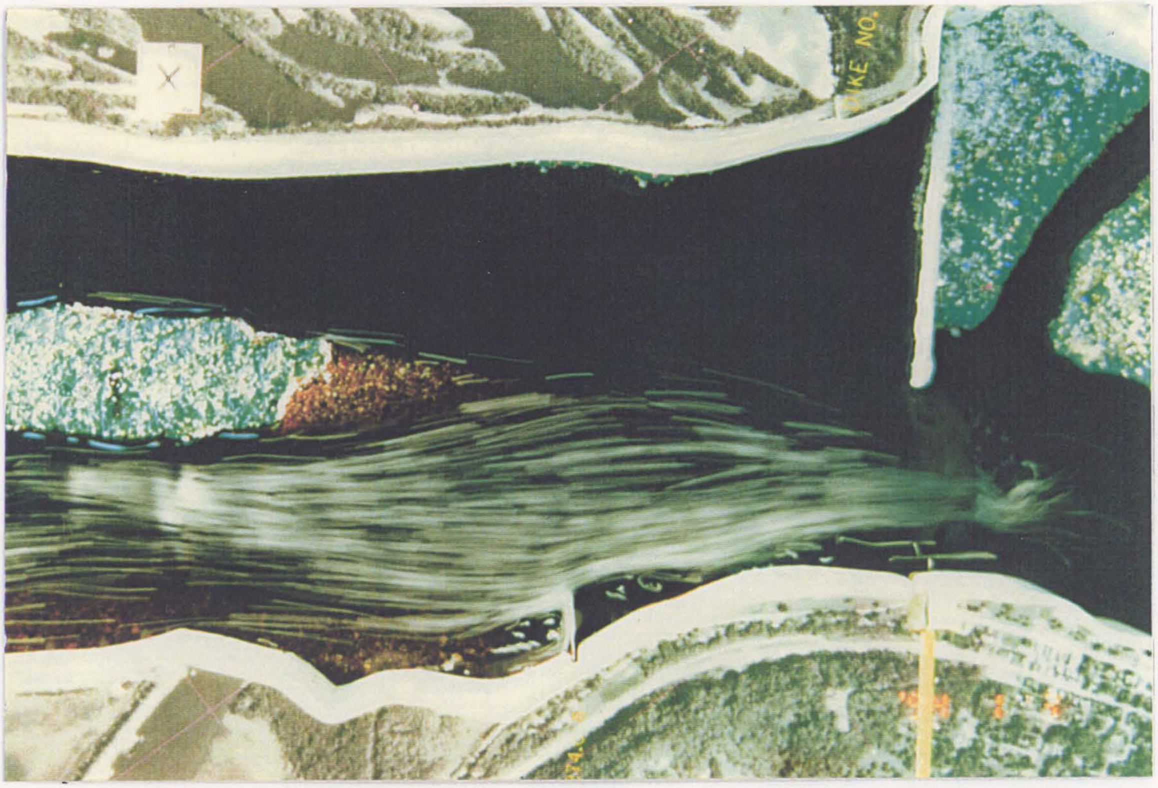
Mississippi River Miles 271 - 277

Alternative X

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\
PLOT SCALE: 1" = 2000'

PLATE NO. 74

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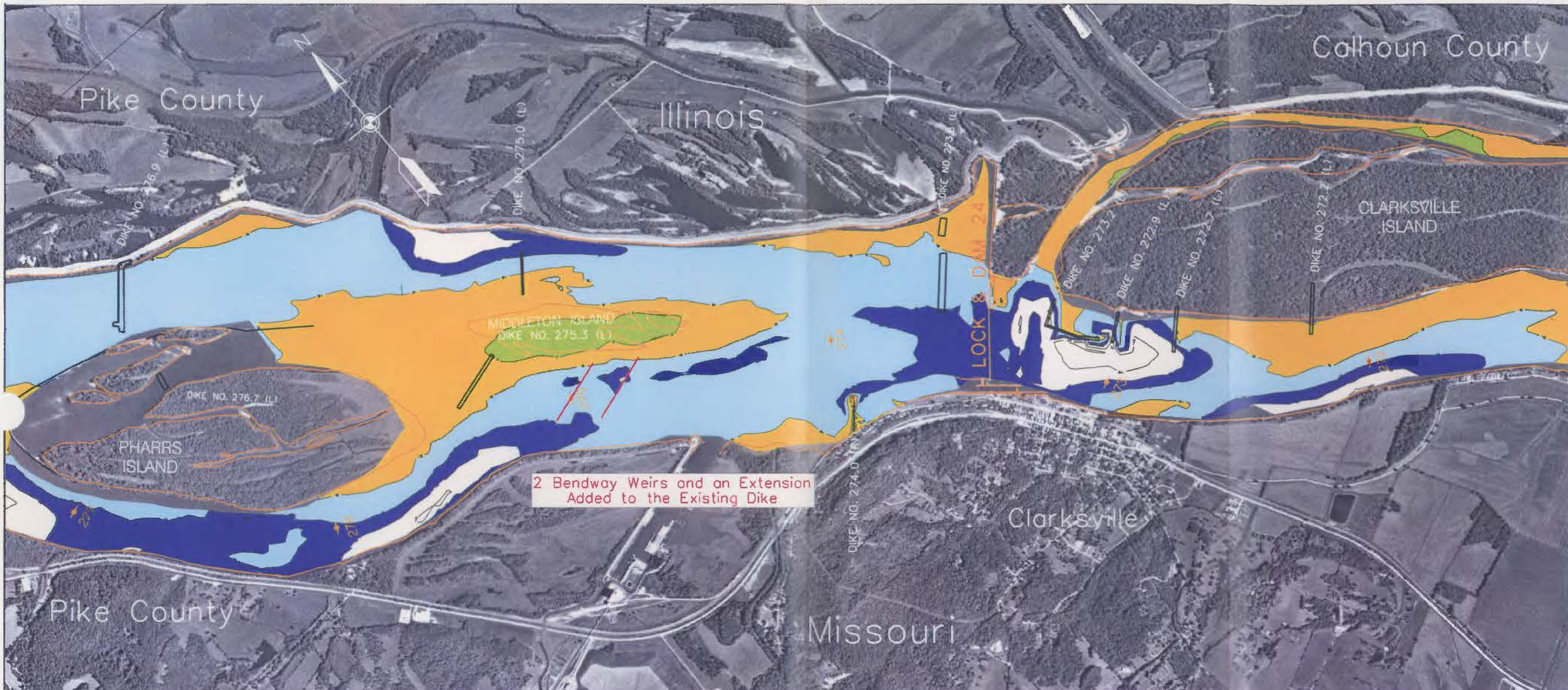
Mississippi River Miles 271 - 277

Flow Visualization - Alternative X

PLATE NO
75




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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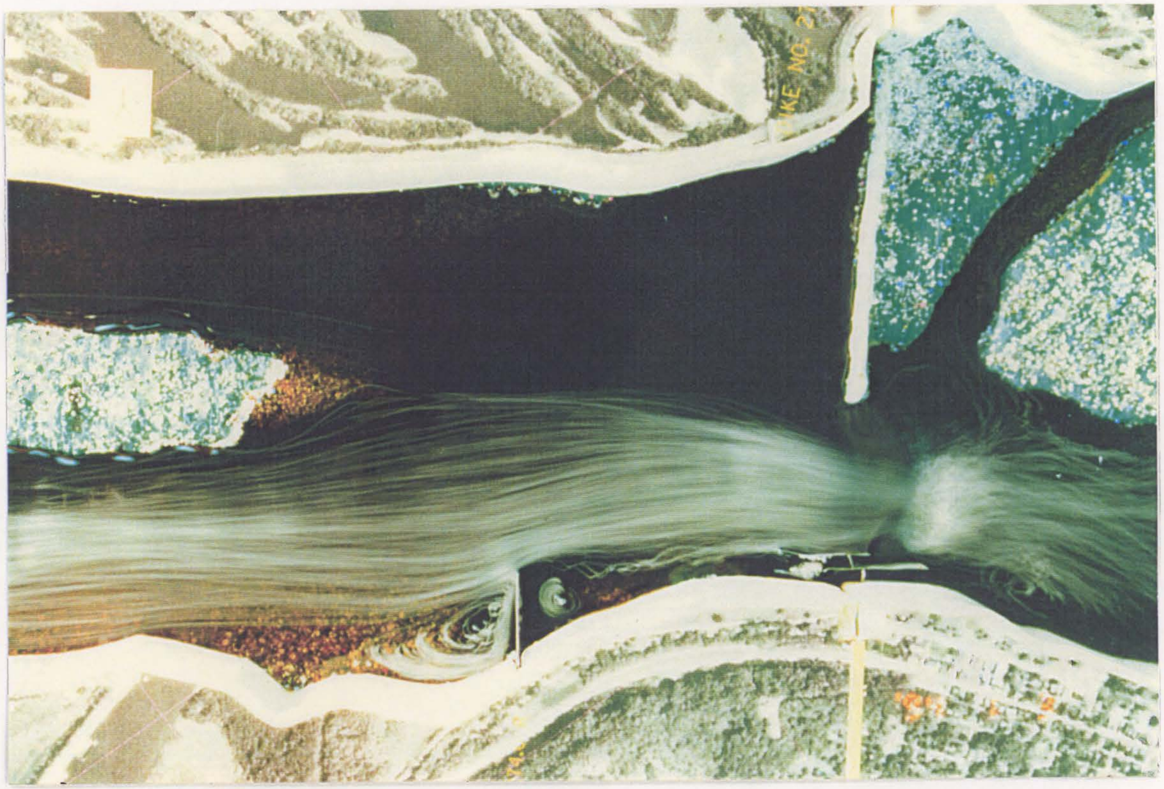
Mississippi River Miles 271 - 277

Alternative Y

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\
PLOT SCALE: 1" = 2000'
PLATE NO. 76



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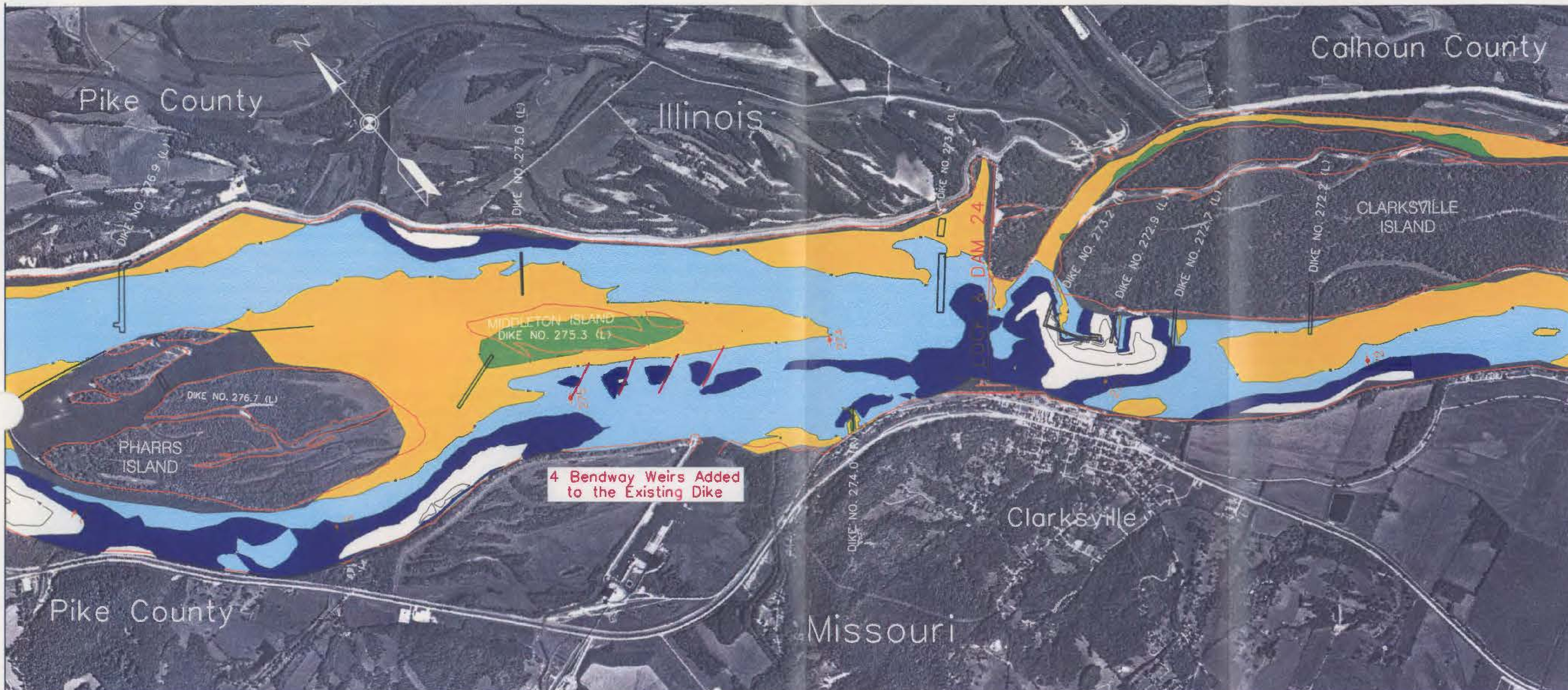
Mississippi River Miles 271 - 277

Flow Visualization - Alternative Y

PLATE NO
77




Elevations Referenced to LWRP

| | |
|---|---|
| | +20 FT |
| | +10 FT |
| | 0 FT |
| | -10 FT |
| | -20 FT |
| | -30 FT |
| | -40 FT |
| | -50 FT |

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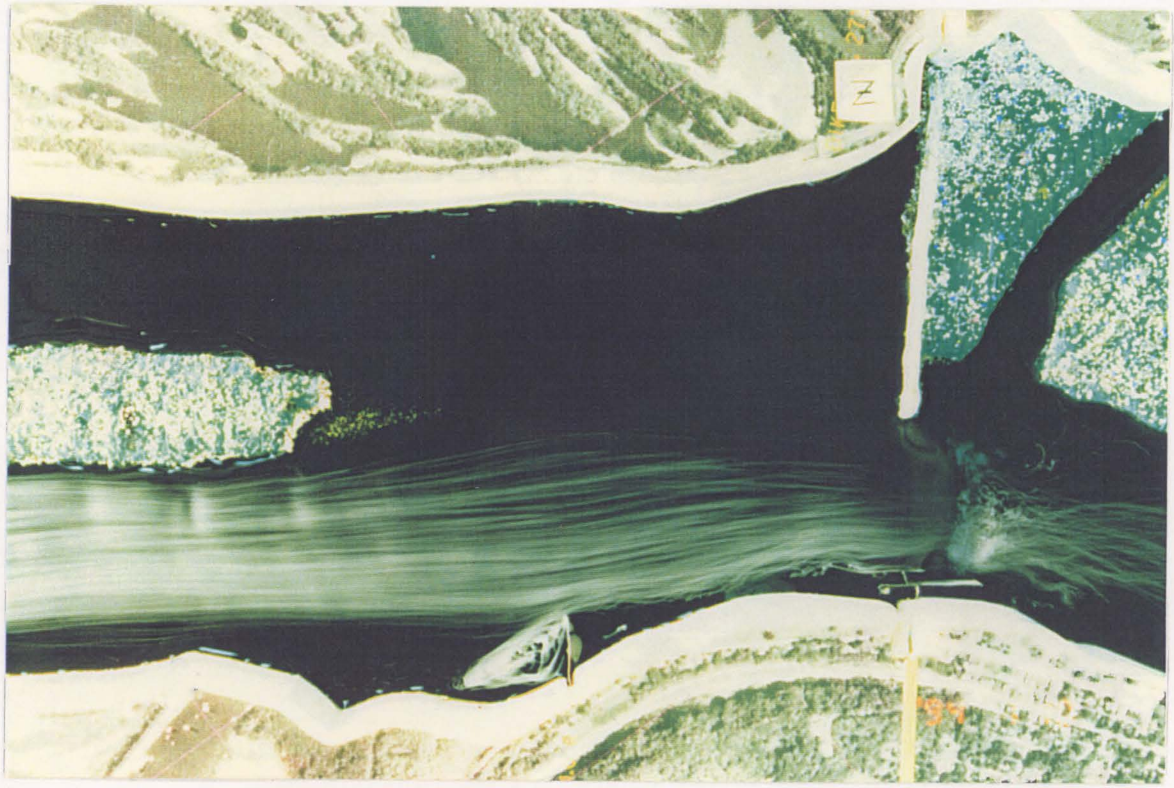
Lock and Dam #24 Micro Model Study
Mississippi River Miles 271 - 277

Alternative Z-D

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\
PLOT SCALE: 1" = 2000'
PLATE NO. 78



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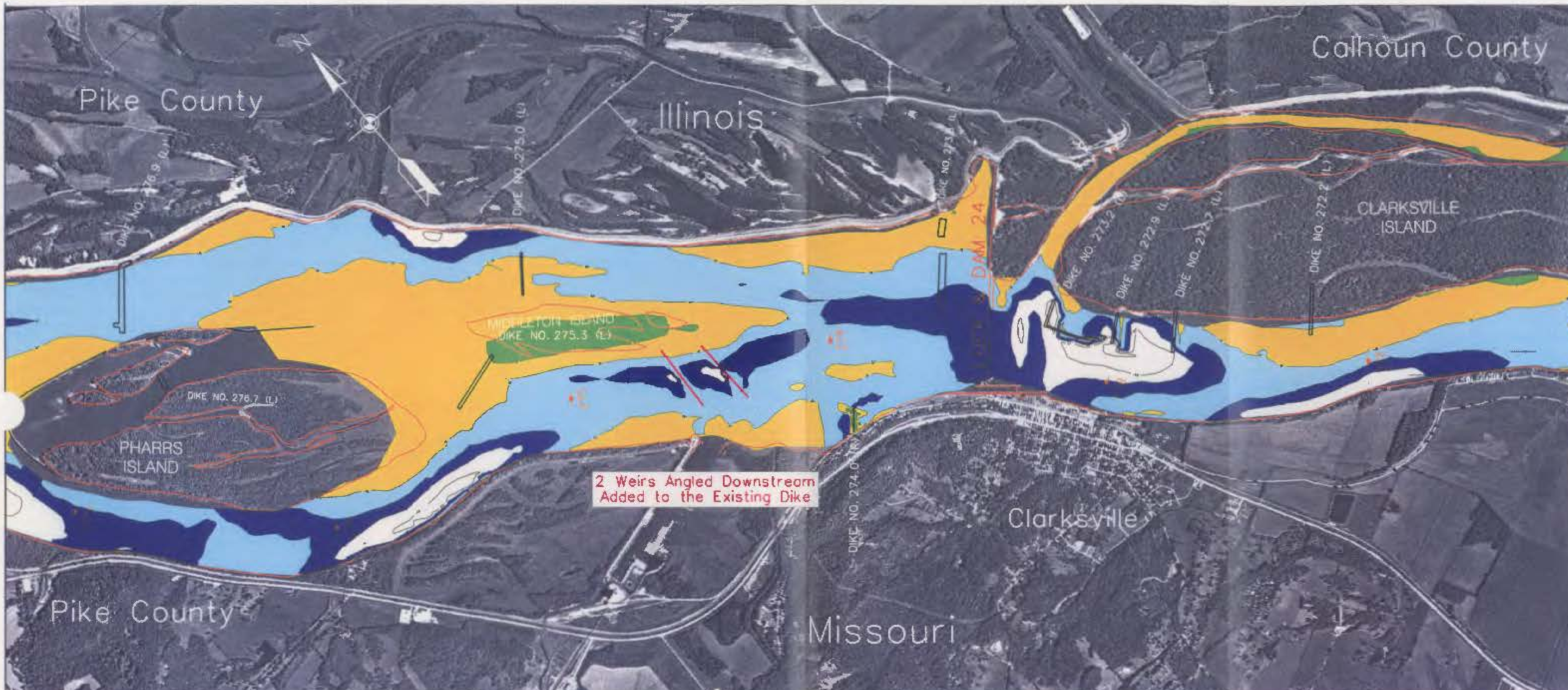
Mississippi River Miles 271 - 277

Flow Visualization - Alternative Z-0

PLATE NO.
79




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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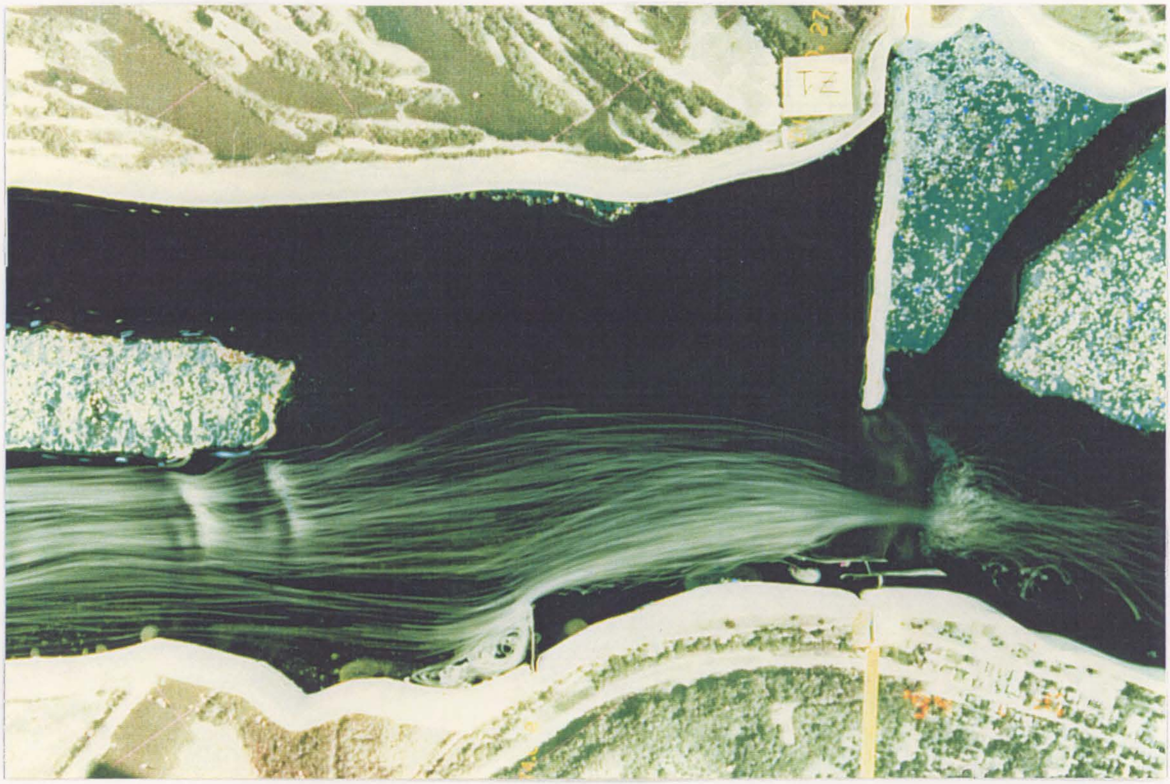
Mississippi River Miles 271 - 277

Alternative Z-1

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D-24\
PLOT SCALE: 1" = 2000'
PLATE NO. 80



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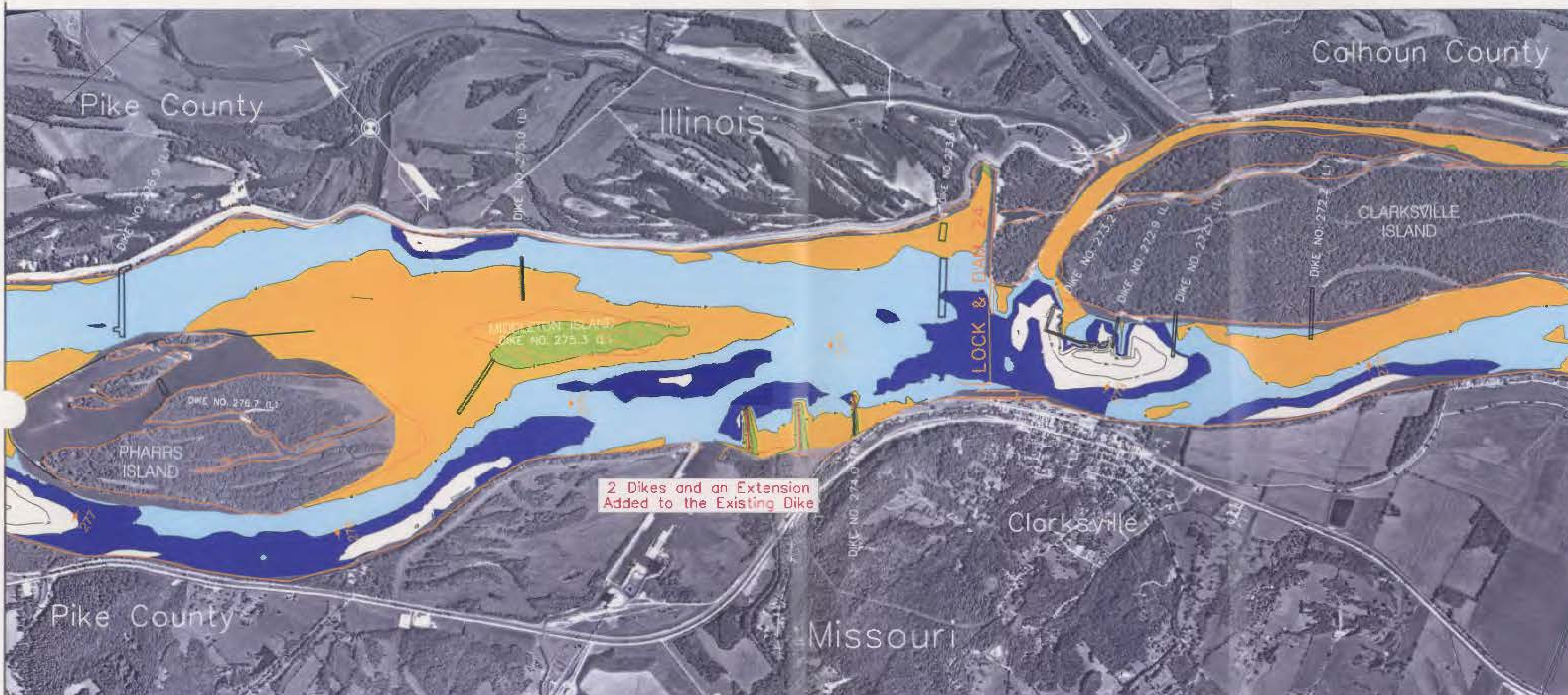
Lock and Dam 24 Micro Model Study
Mississippi River Miles 271 - 277

Flow Visualization - Alternative Z-1

PLATE NO
**81**




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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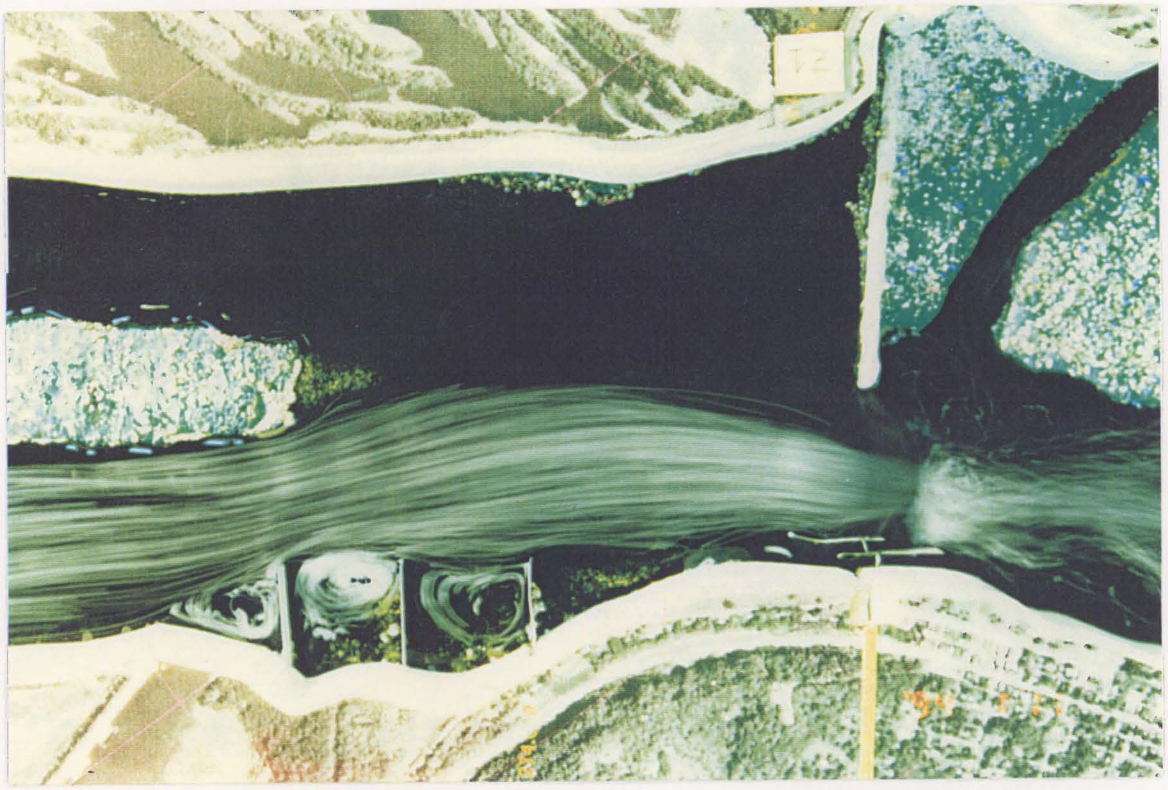
Mississippi River Miles 271 - 277

Alternative Z-2

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D#24\
PLOT SCALE: 1" = 2000'

PLATE NO. 82



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Mississippi River Miles 271 - 277

Flow Visualization - Alternative Z-2

PLATE NO
83


Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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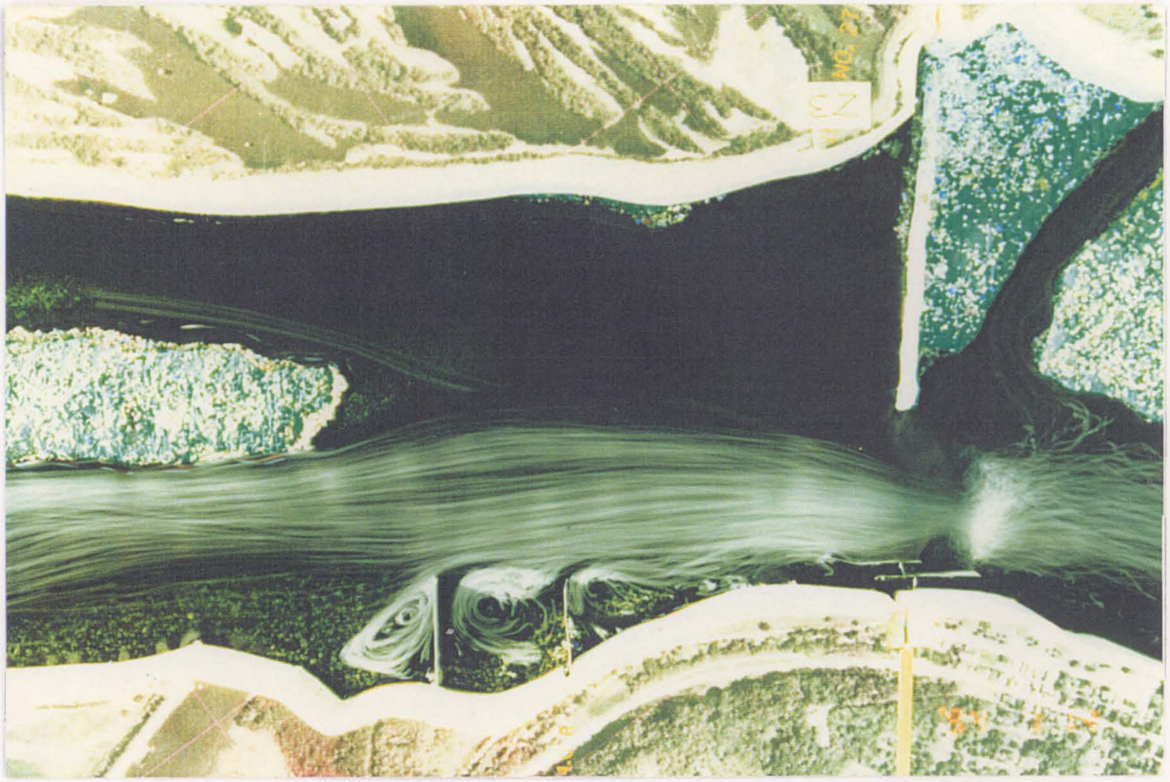
Mississippi River Miles 271 - 277

Alternative Z-3

1500' 0 500' 1000' 1500'

DESIGN FILE: D:\DGN\MODEL\L&D-24\
PLOT SCALE: 1" = 3000'
PLATE NO. 84



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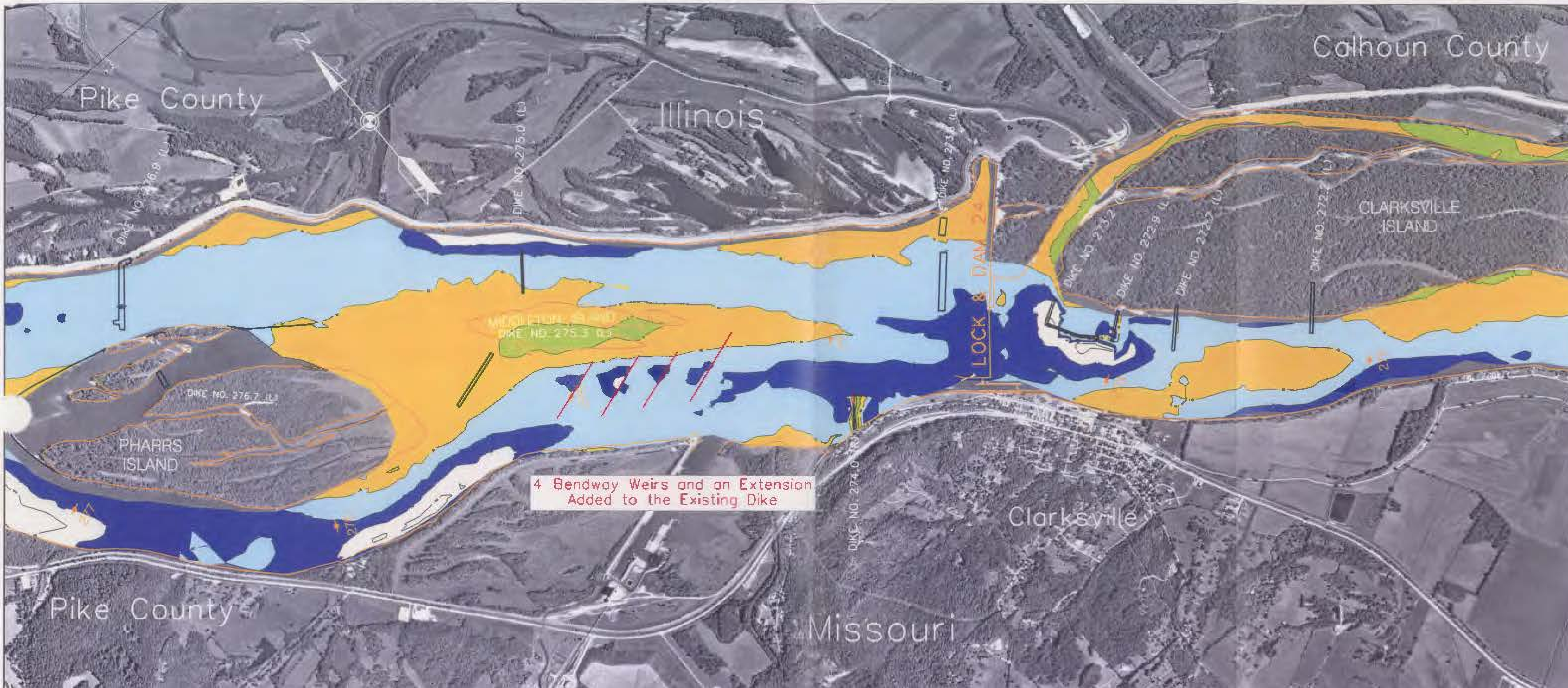
Mississippi River Miles 271 - 277

Flow Visualization - Alternative Z-3

PLATE NO 85




Elevations Referenced to LWRP

+20 FT
+10 FT
0 FT
-10 FT
-20 FT
-30 FT
-40 FT
-50 FT

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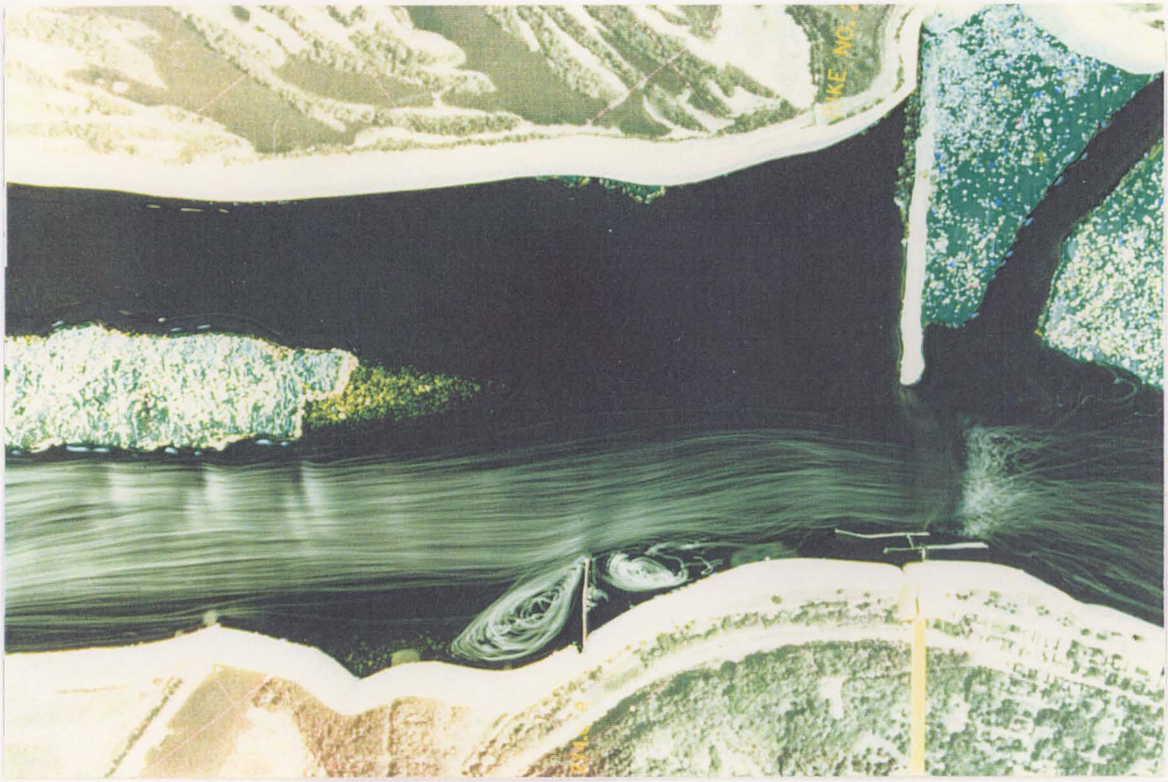
Mississippi River Miles 271 - 277

Alternative Z-4

1500' 0 500' 1000' 1500'

PLOT SCALE: 1" = 2000'

PLATE NO. 86



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Mississippi River Miles 271 - 277

Flow Visualization - Alternative Z-4

PLATE NO
**87**