USGS
science for a changing world

Initial-Phase Investigation of Multi-Dimensional Streamflow Simulations in the Colorado River, Moab Valley, Grand County, Utah, 2004

Scientific Investigations Report 2005–5022

Prepared in cooperation with the
Utah Department of Environmmental Quality, Division of Radiation Control;
and the U.S. Environmental Protection Agency

U.S. Department of the Interior
U.S. Geological Survey

Initial-Phase Investigation of Multi-Dimensional Streamflow Simulations in the Colorado River, Moab Valley, Grand County, Utah, 2004

By Terry A. Kenney

Prepared in cooperation with the

UTAH DEPARTMENT OF ENVIRONMENTAL QUALITY,
DIVISION OF RADIATION CONTROL; and the
U.S. ENVIRONMENTAL PROTECTION AGENCY

Scientific Investigations Report 2005-5022

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

U.S. Geological Survey, Reston, Virginia: 2005
For sale by U.S. Geological Survey, Information Services
Box 25286, Denver Federal Center
Denver, Colorado 80225

For more information about the USGS and its products:
Telephone: 1-888-ASK-USGS
World Wide Web: http://www.usgs.gov/

.

For additional information, write to:

District Chief
U.S. Geological Survey
2329 West Orton Circle
Salt Lake City, Utah 84119
http://ut.water.usgs.gov

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND DATUMS

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot (ft)	0.3048	meter (m)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per square second (ft/s^2)	0.3048	meter per square second (m/s^2)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
pound per square foot (lb/ft^2)	47.88	newton per square meter (N/m^2)
square foot per second (ft^2/s)	0.0929	square meter per second (m^2/s)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Initial-Phase Investigation of Multi-Dimensional Streamflow Simulations in the Colorado River, Moab Valley, Grand County, Utah, 2004

By Terry A. Kenney

ABSTRACT

A multi-dimensional hydrodynamic model was applied to aid in the assessment of the potential hazard posed to the uranium mill tailings near Moab, Utah, by flooding in the Colorado River as it flows through Moab Valley. Discharge estimates for the 100- and 500-year recurrence interval and for the Probable Maximum Flood (PMF) were evaluated with the model for the existing channel geometry. These discharges also were modeled for three other channel-deepening configurations representing hypothetical scour of the channel at the downstream portal of Moab Valley. Water-surface elevation, velocity distribution, and shear-stress distribution were predicted for each simulation.

The hydrodynamic model was developed from measured channel topography and over-bank topographic data acquired from several sources. A limited calibration of the hydrodynamic model was conducted. The extensive presence of tamarisk or salt cedar in the over-bank regions of the study reach presented challenges for determining roughness coefficients.

Predicted water-surface elevations for the current channel geometry indicated that the toe of the tailings pile would be inundated by about 4 feet by the 100-year discharge and 25 feet by the PMF discharge. A small area at the toe of the tailings pile was characterized by velocities of about 1 to 2 feet per second for the 100-year discharge. Predicted velocities near the toe for the PMF discharge increased to between 2 and 4 feet per second over a somewhat larger area. The manner to which velocities progress from the 100-year discharge to the PMF discharge in the area of the tailings pile indicates that the tailings pile obstructs the over-bank flow of flood discharges. The predicted path of flow for all simulations along the existing Colorado River channel indicates that the current distribution of tamarisk in the over-bank region affects how flood-flow velocities are spatially distributed. Shear-stress distributions were predicted throughout the study reach for each discharge and channel geometry examined. Material transport was evaluated by applying these shear-stress values to empirically determined critical shear-stress values for grain sizes ranging from very fine sands to very coarse gravels.

INTRODUCTION

The fate of the Moab uranium mill tailings adjacent to the Colorado River at the north end of Moab Valley, Utah (fig. 1), is a serious concern to Federal, State, and local resource managers. A consultant report entitled “Geomorphic, hydraulic, and lateral migration characteristics of the Colorado River, Moab, Utah, Reference No. 94-02” (Robert A. Mussetter and M.D. Harvey, Mussetter Engineering, Inc., written commun., 1994), along with the analyses presented in this report, indicate that the mill-tailings pile is situated within the 100-year recurrence-interval flood plain of the Colorado River. This position within the flood plain raises questions regarding the vulnerability of the tailings to extreme discharge events in the Colorado River. The stability of the tailings and the river are closely related because changes of the river channel location and morphology could possibly affect the long-term stability of the tailings pile. Although some investigation into the vulnerability of the tailings pile has been conducted (Robert A. Mussetter and M.D. Harvey, Mussetter Engineering, Inc., written commun., 1994; U.S. Department of Energy, 2003), questions remain as to whether it is

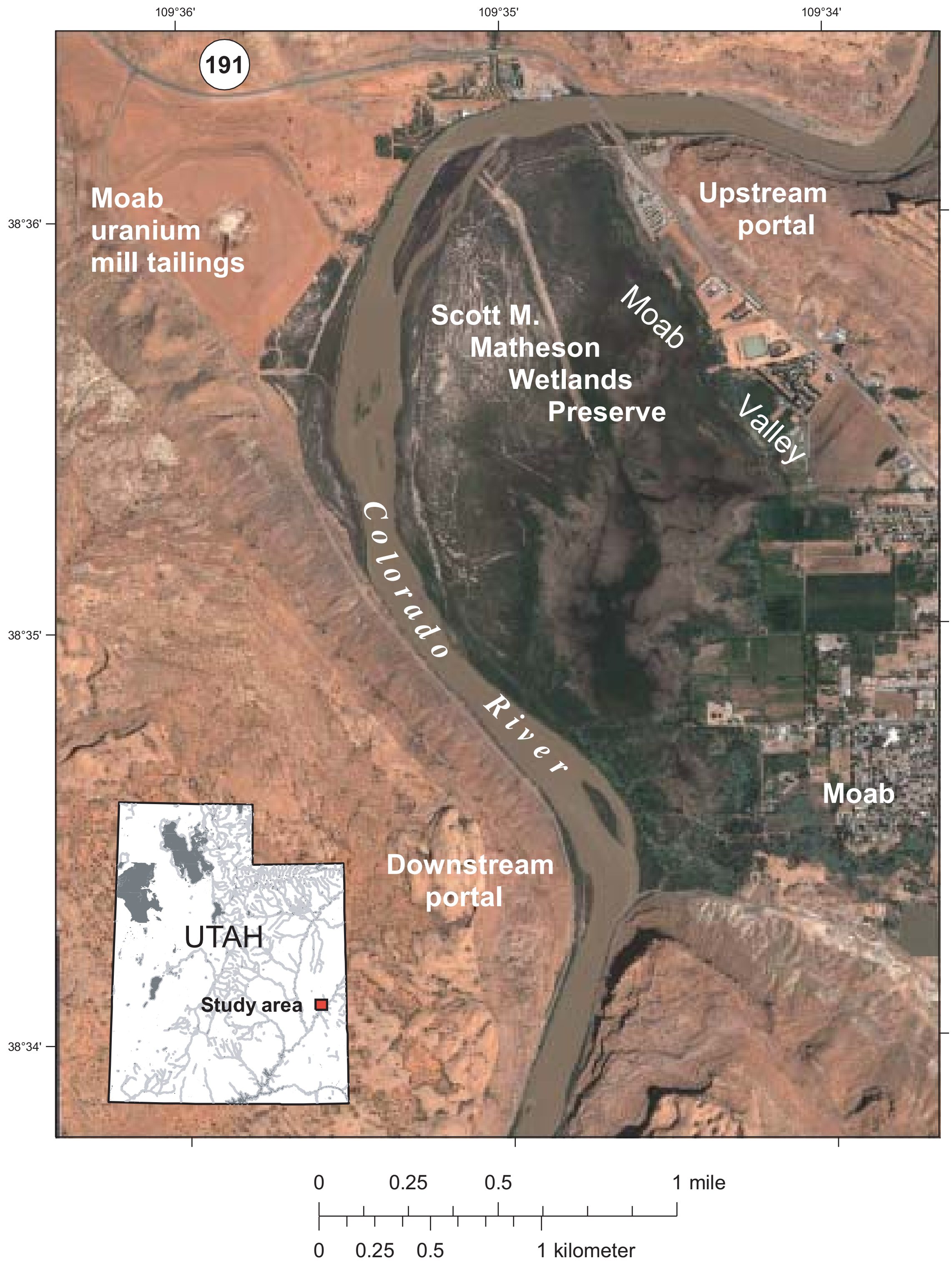


Figure 1. Location of Moab uranium mill tailings study area, Moab Valley, Grand County, Utah.

susceptible to scour during extreme discharge events in the Colorado River. The use of hydraulic models provides the best means to predict hydraulic characteristics throughout the study reach for potential extreme discharge events. A multi-dimensional hydrodynamic model was used to aid in this initial assessment of the potential hazard posed to the Moab uranium mill tailings by flooding in the Colorado River. The application of the model presented here is preliminary in that calibration with observed water-surface elevations and velocities was not conducted. This report was prepared in cooperation with the Utah Department of Environmental Quality, Division of Radiation Control, and the U.S. Environmental Protection Agency.

Peak streamflow discharges recorded during the period of record at the nearest U.S. Geological Survey (USGS) streamflow-gaging station 09180500, Colorado River near Cisco, Utah, may be exceeded during the designed lifespan of any remediation effort at the tailings site. For the purposes of determining statistically valid streamflow discharge estimates to evaluate with the hydrodynamic model, a flood-frequency analysis was conducted. Discharge estimates for the 100- and 500-year recurrence intervals for the Colorado River near Cisco, Utah, gage were computed. The largest likely discharge that can be expected to occur within a river system is commonly referred to as the Probable Maximum Flood (PMF). A PMF estimate for the Colorado River determined by the U.S. Nuclear Regulatory Commission (NRC) also was examined.

To improve the understanding of how these computed discharge estimates for the Colorado River may affect the Moab uranium mill tailings, an exploratory multi-dimensional hydrodynamic model was developed as part of an initial scoping effort, which is the initial phase of a multi-phase investigation of the hydraulic characteristics of the Colorado River near Moab, Utah. This initial phase of the effort explored the hydraulic conditions associated with the existing channel geometry. For experimental purposes, three other geometries representing hypothetical channel-scour extents of 10, 25, and 50 ft at the outlet of Moab Valley, locally known as the downstream portal, were examined.

The objective of this investigation was to develop a multi-dimensional hydrodynamic model for the Colorado River in Moab Valley, Utah, with existing data. Previous investigations and conceptual models discuss the presence of shallow, hydraulically controlling bedrock at the downstream portal. The existence of a nonerodible hydraulic control at the downstream portal was determined to limit velocities and shearing forces through the reach for large discharge events (Robert A. Mussetter and M.D. Harvey, Mussetter Engineering, Inc., written commun., 1994). Unfortunately, no data are available on the thickness of alluvial material at the portal. As part of this scoping assessment, hydraulic characteristics of the Colorado River related to three hypothetical channel geometries at the portal were examined along with the current channel configuration.

Average annual peak discharge at USGS streamflow-gaging station 09180500, Colorado River near Cisco, Utah, for the period of record is 36,300 ft^3/s. Since 1950, about the beginning of extensive flow regulation, average annual peak discharge is 29,400 ft^3/s. Observed water-surface elevation and velocity data from discharges of these magnitudes were not available, which limited calibration for this modeling assessment. With that limitation, the results presented here for this model provide local resource managers with an approximation of how extreme discharge events might affect the Moab uranium mill tailings under the existing and hypothetical boundary conditions examined. Future acquisition of other data including streamflow velocities and water-surface elevations from a large discharge event, in-channel and over-bank grain-size classification and distribution, and seismic profiles would allow for full model calibration and an improved understanding of the hydraulic characteristics of the Colorado River in Moab Valley, Utah.

Purpose and Scope

This report documents the initial scoping effort in the development of the multi-dimensional hydrodynamic model. Water-surface elevations, the distribution of two-dimensional streamflow velocities, and the distribution of shear stress throughout the study reach of the Colorado River in Moab Valley, Utah, are presented and described. These parameters were evaluated for the existing channel topography along with hypothetical scour depths of 10, 25, and 50 ft at the downstream portal. The potential for substantial channel change is large for the discharges examined in this study. These hypothetical channel geometries can be viewed as representations of developed scour-holes formed as a result of the constriction posed by the downstream portal. The methodologies used in data acquisition and model development are presented. Limitations and assumptions for the developed model are described in this report. Guidance pertaining to further model enhancements and the future utility of the developed model are outlined in this report as well.

Description of Study Reach

The Colorado River drains more than 24,500 mi^2 of Colorado and Utah prior to entering Moab Valley, Utah. The river upstream and downstream from Moab Valley is confined laterally by large consolidated sedimentary deposits of Jurassic and Cretaceous age that are prevalent within the Colorado Plateau region (Pitlick and Cress, 2002). Substantial salt dissolution and resulting collapse within the salt core of the Moab Valley anticline during the past 160 million years (Doelling and others, 2002; U.S. Department of Energy, 2003) has led to the topographic low known as Moab Valley in Utah. The Colorado River within Moab Valley is considered a fully alluvial river free to migrate laterally (Pitlick and Cress, 2002). The Moab uranium mill tailings are located on the northwest bank of the Colorado River roughly 1 mi downstream from the inlet to Moab Valley, locally known as the upstream portal. As the river crosses the valley it generally curves to the south-southeast toward the downstream portal where it is once again confined and flows toward the southwest. The study reach for this investigation extends roughly 1 mi upstream and 0.5 mi downstream from Moab Valley (fig. 1), for a total of approximately 3.5 mi.

Dominated by snowmelt runoff, annual peak-flow events in the Colorado River are of long duration and occur during late spring. USGS streamflow-gaging station 09180500, Colorado River near Cisco, Utah, is located about 33 mi upstream from the study reach. No significant inflows occur between the gage and Moab Valley. The maximum recorded discharge at the Cisco, Utah, gage of 76,800 ft^3/s occurred on June 19, 1917. A flood at Fruita, Colorado, on July 4, 1884, reached a peak discharge of about 125,000 ft^3/s (Tibbetts and others, 2003). Flow in the Colorado River drainage upstream from the study reach is regulated by reservoirs and other water-diversion structures.

The Colorado River within the study reach has been characterized as a relatively stable, meandering river in quasi-equilibrium (U.S. Department of Energy, 2003). The average slope of the study reach is 0.0002 ft/ft, and bed materials range from coarse gravels to silt. Depending upon river stage, a variable series of mid-channel bars and islands can be present, whereas one particular island located about 0.4 mi downstream from the entrance into Moab Valley is heavily vegetated, indicating long-term stability.

Dense stands of invasive tamarisk or salt cedar (*Tamarix chinensis*) exclusively occupy the over-bank areas of the study reach. Although introduced to the region in the 1800s, the spread of tamarisk to the study reach is believed to have occurred in the late 1940s. The expansive spread of tamarisk throughout the Colorado Plateau region is associated with the most dramatic change in the fluvial landscape during the past century (Graf, 1978). Substantial channel narrowing, attributed to flow regulation of the Colorado River and tamarisk occupation within the study reach, can be seen in historic and recent photographs (figs. 2 and 3). Many questions regarding the role tamarisk plays during over-bank flooding exist. As discussed later in this report, the dense colonization of tamarisk within the study reach presented challenges to the development of the model.

Flood-Frequency Analysis

Streamflow discharges of the magnitude used for this flood-hazard assessment have not been observed in the Colorado River since the USGS began computing discharge records at the Cisco, Utah, gage in 1895. For this reason a statistical frequency analysis was conducted to estimate the 100- and 500-year recurrence interval discharges for the Colorado River near Cisco, Utah, gage. The USGS PEAKFQ Version 4.1 computer program (W.O. Thomas, Jr., A.M. Lumb, K.M. Flynn, and W.H. Kirby, U.S. Geological Survey, written commun., 1998), which follows Bulletin 17B (Interagency Advisory Committee on Water Data, 1982) guidelines for determining flood-flow frequency, was used. The procedures outlined in Bulletin 17B do not cover watersheds where flood flows are appreciably altered by reservoir regulation (Interagency Advisory Committee on Water Data, 1982). Although flow in the Colorado River watershed is heavily regulated, employment of the methods outlined in Bulletin 17B

Figure 2. Colorado River upstream portal of Moab Valley, Utah, 1905.
Note lack of tamarisk presence. (Photograph by C.C. Whitman)

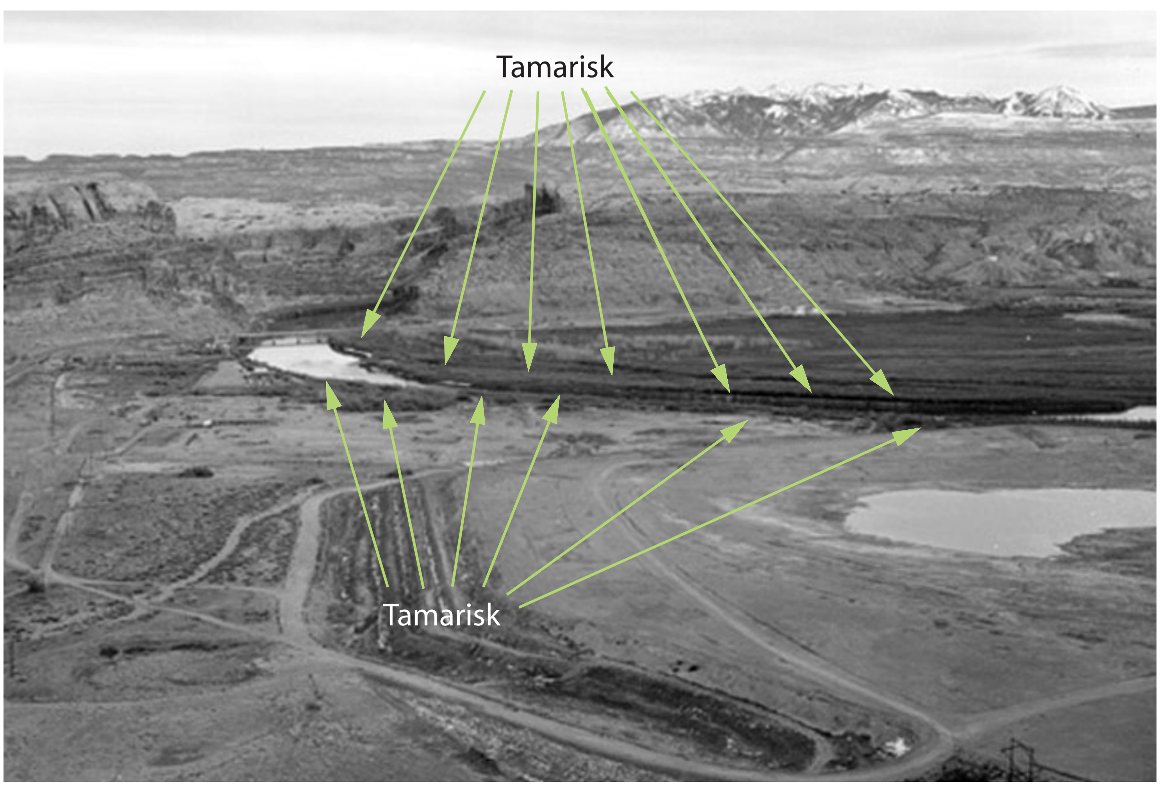


Figure 3. Colorado River upstream portal of Moab Valley, Utah, 1998.
Tamarisk presence is visible along river banks. The Moab uranium mill tailings can be seen in right forefront.

was considered reasonable for the acquisition of discharge estimates for model simulation.

For USGS streamflow-gaging station 09180500, Colorado River near Cisco, Utah, discharges of 97,600 ft^3/s and 120,000 ft^3/s were estimated to have a return frequency of 100- and 500-years, respectively, based on a dataset of 86 annual flood peaks. This dataset included the 1884 flood discharge of 125,000 ft^3/s documented in Fruita, Colorado, about 50 mi upstream of the Cisco, Utah, gage. It is likely that flow regulation during the past half century has caused peak magnitudes to be slightly lessened, which might explain why the 100- and 500-year discharge estimates are relatively similar. In using these flood-frequency estimates for a potential future event, it is assumed that the reservoirs of the Colorado River Basin will continue to be operated in much the same manner as in the past 50 years. A PMF discharge estimate for the Colorado River in Moab Valley of 300,000 ft^3/s is given in NRC Docket File No. 40-3453 (Dawn L. Jacoby and R.O. Gonzales, U.S. Nuclear Regulatory Commission, written commun., 1993).

MODEL DEVELOPMENT

Multi-dimensional hydrodynamic models provide a physically based method for simulating hydraulic characteristics in complicated flow environments for a range of discharges. The study reach of the Colorado River has a sophisticated morphology which includes a substantial bend occupied by various mid-channel bars and islands. The Moab uranium mill tailings are located approximately 650 ft from the main channel along the bend in the river (fig. 1). The main objectives of this preliminary modeling assessment include simulating water-surface elevation, two-dimensional velocity distribution, and shear-stress distribution throughout the study reach for three discharges and four downstream portal channel configurations. For this investigation the USGS Multi-Dimensional Surface Water Modeling System (MD_SWMS), which incorporates the Flow and Sediment Transport and Morphological Evolution of Channels (FASTMECH) 2- and 2.5-dimensional flow models, was used. This modeling system has been used in a number of alluvial environments to predict hydraulic and sediment transport characteristics (Andrews and Nelson, 1989; Nelson, 1997; Lisle and others, 2000; Conaway and Moran, 2004).

MD_SWMS is a finite-difference, steady-state surface-water computer modeling system that simulates vertically averaged two-dimensional streamflow velocities based upon input parameters and boundary conditions. Input parameters include surface topography, discharge, water-surface elevation at the downstream boundary, and surface-material roughness, input as nondimensional drag coefficients. The model boundary is defined by the creation of a curvilinear grid in which the number of streamwise and cross-stream points is defined by the user. MD_SWMS interpolates a continuous surface from the input topography with a triangular irregular network (TIN) for the grid-defined model boundary. Important for this study, MD_SWMS outputs shear-stress values from the two-dimensional velocity solution.

Data Acquisition Methods

Channel-topography data were collected from a moving boat on November 4 and 5, 2004, by using a real-time kinematic global positioning system (RTK-GPS) interfaced with a 200-kHz echo sounder. By referencing the RTK-GPS to known survey control points, real world horizontal and vertical positions were acquired continuously in real time. A GPS base station equipped with a radio receiver and transponder was set up above a survey control point. This GPS base station received a position correction and then broadcasted to a second GPS receiver that was acquiring positions. This second GPS receiver is often referred to as a rover.

The rover GPS antenna was mounted directly above the echo sounder fastened to a mast on the boat. The distance between the rover GPS antenna and echo sounder was measured. A digital data-collection grid of selected cross sections was developed for the study reach prior to data collection. This grid was followed by the motor boat operator equipped with a handheld GPS interfaced with a personal digital assistant (PDA). In addition to the selected cross sections, a series of longitudinal and near-channel-edge data-collection tracks were made to best define the topographic surface of the main channel.

Topographic Data

Multi-dimensional hydraulic models require accurate representation of the topographic surface over which discharges will be simulated. Discharges simulated in this study were large and well above the bank-full stage. To predict the hydraulic characteristics of the Colorado River in Moab Valley, an extensive high-resolution topographic dataset was necessary. Topographic data from multiple sources were acquired (fig. 4) and referenced to the same vertical and horizontal datums.

Collected river-channel data included depths recorded by the echo sounder, and horizontal and vertical positions of the rover GPS antenna. Following data collection, the measured vertical offset between the rover GPS antenna and the echo sounder, and the depth measured by the echo sounder, were added together and then subtracted from the recorded elevations of the rover GPS antenna for each acquired horizontal location. In this manner real-world vertical and horizontal positions of the channel bed were obtained, which allowed the natural slope of the study reach to be represented in the data.

The study reach of the Colorado River encompassed a vast over-bank region south and east of the river in the Scott M. Matheson Wetlands Preserve. For this area, data points from a survey conducted in 1994 for the U.S. Bureau of Reclamation (BOR) were obtained. The U.S. Department of Energy (DOE) provided two topographic datasets developed from high- and low-altitude aerial surveys conducted in 2001. Survey data of the channel banks upstream of the State Road 191 Colorado River Bridge in support of the Utah Department of Transportation (UDOT) were provided by Horrocks Engineers. After incorporating these datasets there was a region of the model domain east of the wetlands area missing topographic data. For this area, 10-meter digital elevation model (DEM) data were used. All horizontal coordinates from the various topographic datasets were converted to the Universal Trans-Mercator (UTM) system, North American Datum of 1983 (NAD 83), Zone 12. Elevations for each dataset were referenced to the North American Vertical Datum of 1988 (NAVD 88).

Hypothetical Channel Geometries

The study reach extends across Moab Valley, which was formed by subsidence caused by salt dissolution. Over time this topographic low has accumulated alluvial material. Doelling and others (2002) presented a diagrammatic cross section through Moab Valley of the alluvial material thickness developed from well logs (fig. 5). Currently (2004), there are no data on the thickness of alluvial material in the vicinity of the downstream portal. Past conceptual models related to the hydraulic characteristics of the Colorado River within Moab Valley have included the assumption that bedrock exists near the surface at the downstream portal. Under this assumption, a one-dimensional HEC 2 model indicated substantial backwater caused by the constriction at the rigid portal boundary that limited streamflow velocities, and thus shearing forces, within the study reach for flows greater than 30,000 ft^3/s. (Robert A. Mussetter and M.D. Harvey, Mussetter Engineering, Inc., written commun., 1994). As part of this initial modeling effort, hypothetical channel geometries for the downstream portal were created to represent scour depths of 10, 25, and 50 ft to simulate the effects of different channel geometries on velocities and shear stress. To create the hypothetical topography at the portal, the existing channel topography at the downstream portal was exported out of MD_SWMS and adjusted to meet the desired channel depths. The existing and three hypothetical channel geometries at the downstream portal that were input into the MD_SWMS model are shown in figures 6 through 9. The determined amounts of channel deepening were held constant from the downstream portal through the lower model boundary. These hypothetical scour extents were then interpolated upstream to the existing channel bed elevation about 1 mi above the downstream portal. Model simulations were conducted for each of these real and hypothetical geometries and the three discharge estimates. It is important to understand that the behavior of flow in open channels is heavily driven by the channel-bed slope in the absence of a hydraulic control. The degree of hypothetical modification made to the channel geometry at the portal as part of this scoping investigation substantially altered much of the underlying natural hydraulics of the study reach. These modifications were conducted in an effort to determine the type of hydraulic characteristics that could be

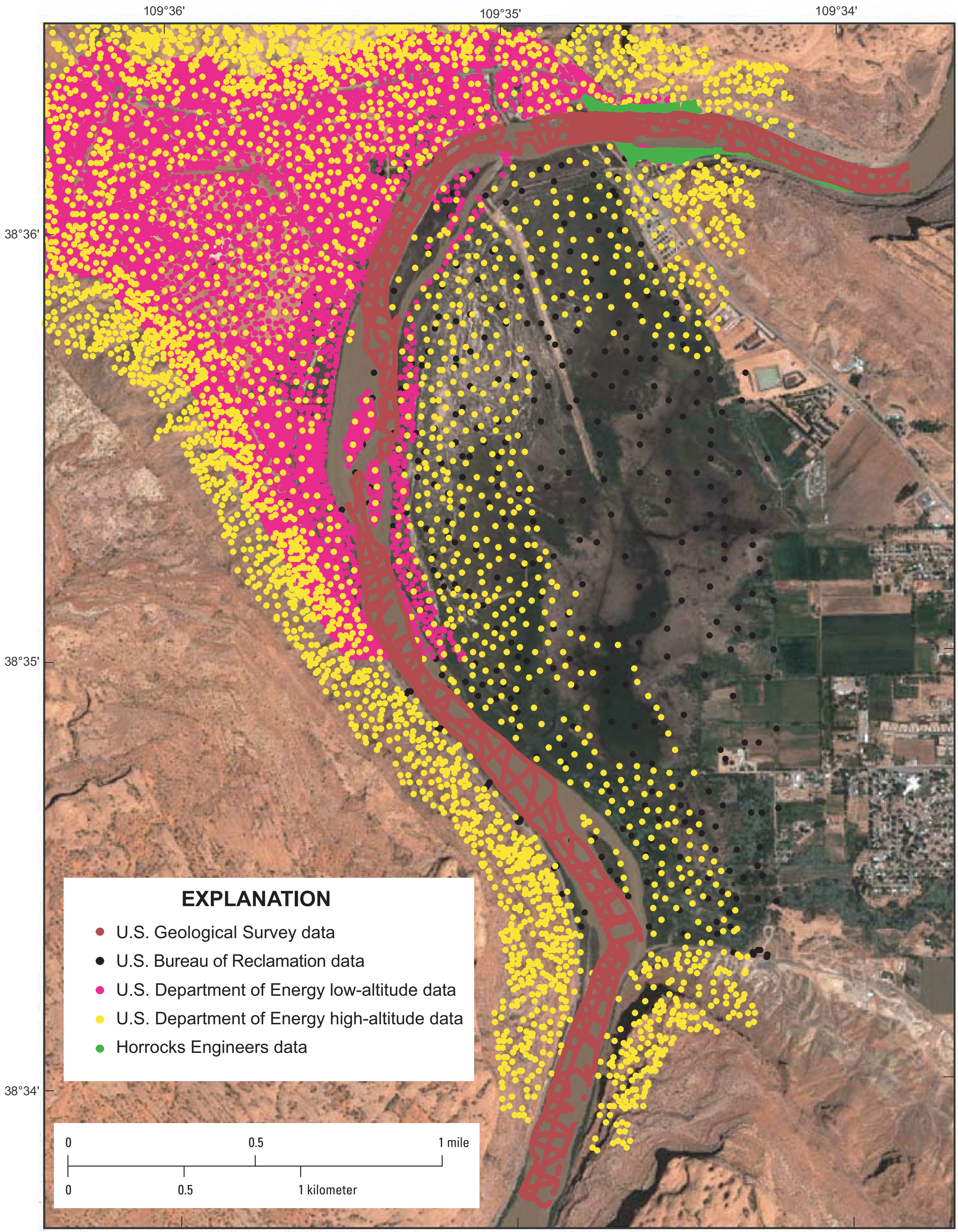
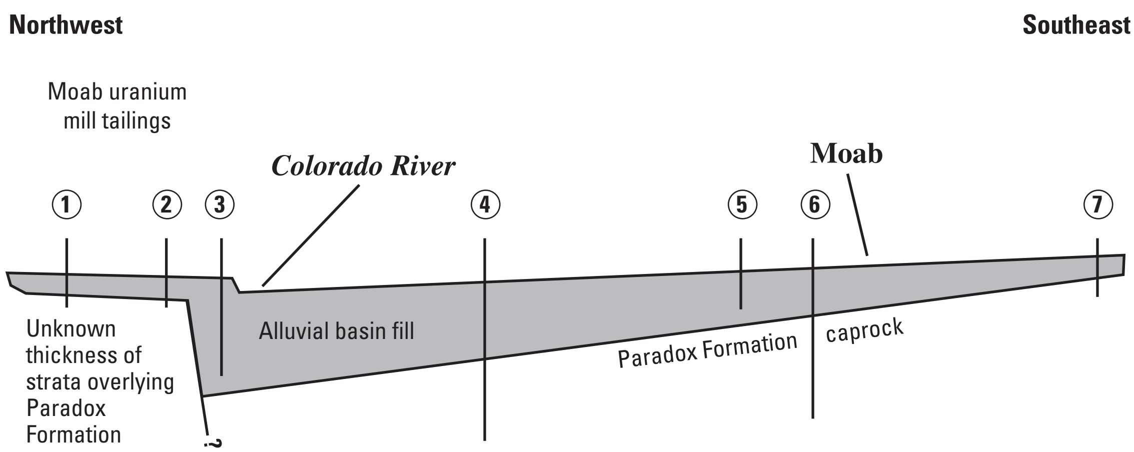


Figure 4. The Colorado River, Moab Valley, Utah, showing location of the topographic data points that were input into the model.



Well	Thickness, in feet
1. Atlas Minerals B-4 borehole	99
2. Atlas Minerals B-3 borehole	108
3. Atlas Minerals ATP-1 borehole	Greater than 406
4. Great Lakes Carbon Corporation brine disposal well	320
5. Water wells in section 1, T.26 S., R.21 E.	Greater than 100
6. Western Allied-Big Six Oil Companies oil & gas well	200
7. Several water wells in section 7, T.26 S., R.22 E.	56 to123

Figure 5. Diagramatic cross section of Moab Valley, Utah, indicating thickness of alluvial material. (Modified from Doelling and others, 2002, and U.S. Department of Energy, 2003)

expected in the presence of scour holes of various sizes at the downstream portal.

Model Boundary Conditions

Multi-dimensional streamflow simulations included the estimated 100- and 500-year recurrence interval discharges and the PMF discharge estimate computed by the NRC. These discharges were input for the existing downstream portal geometry along with three other hypothetical geometric configurations representing channel scour of 10, 25, and 50 ft. Three specific input parameters were needed for each simulation: discharge, downstream boundary water-surface elevation, and drag coefficients. Discharge estimates were determined through frequency analysis. Downstream boundary water-surface elevations were determined by using a one-dimensional hydraulic model. Drag coefficients were developed through model calibration methods and empirical data on vegetation-roughness values.

A curvilinear orthogonal grid that generally followed the direction of the main channel was developed for the study. The grid was defined with 310 cross-stream, and 450 stream-wise points. The cross-stream width of the grid was 1.74 mi, and the centerline stream-wise distance was about 3.6 mi. Cell size varied with the curvilinear grid, but the stream-wise increment along the centerline was 42.3 ft, and the cross-stream increment was 32.8 ft.

The downstream boundary water-surface elevation was computed with the one-dimensional U.S. Army Corps of Engineers' River Analysis System (HEC-RAS). Cross sections for each of the channel geometries were exported out of MD_SWMS and imported into HEC-RAS. The in-channel Manning's n value for the existing channel configuration HEC-RAS model was determined by iteratively adjusting the

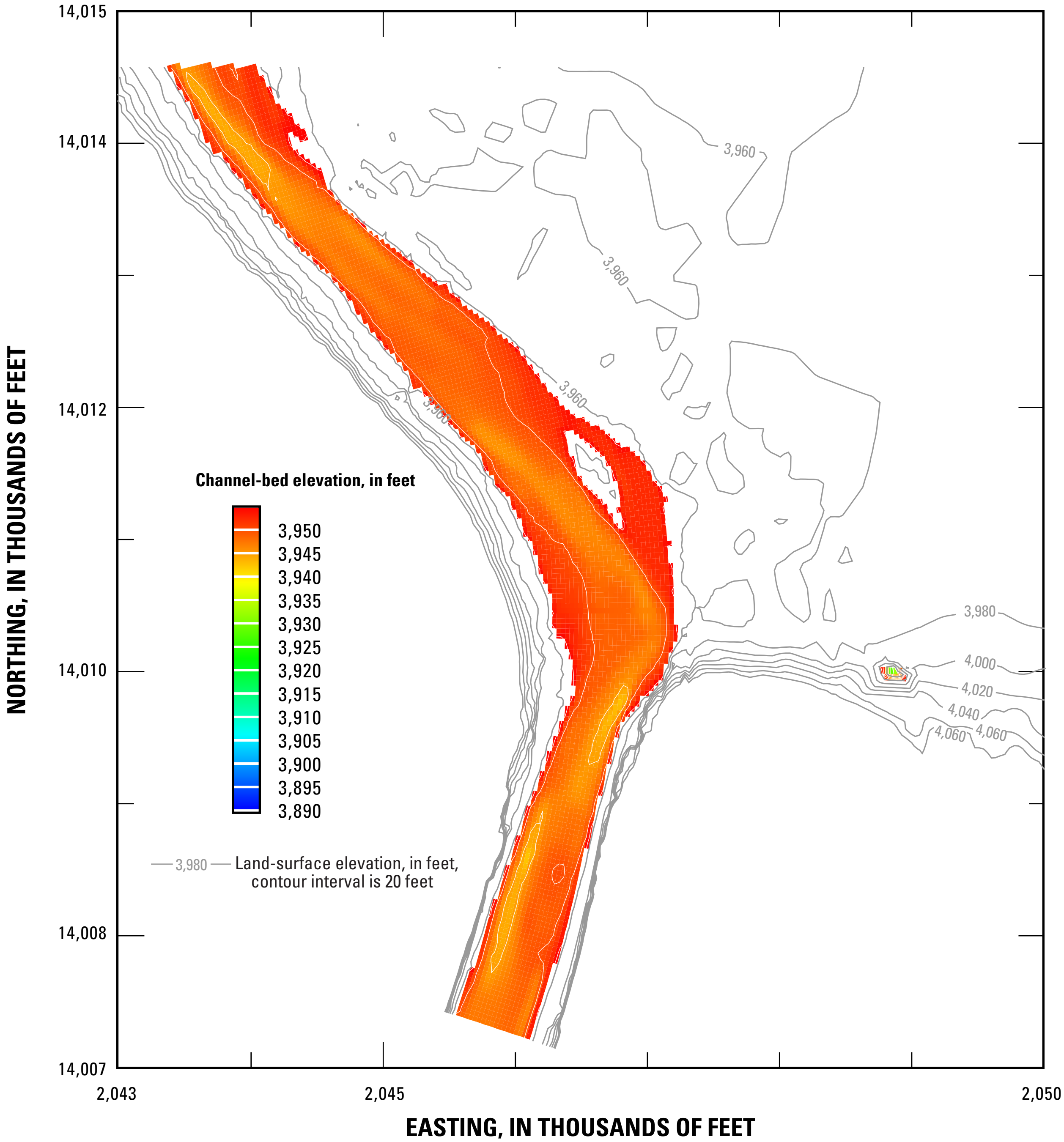


Figure 6. Existing channel geometry at downstream portal of Moab Valley, Utah.

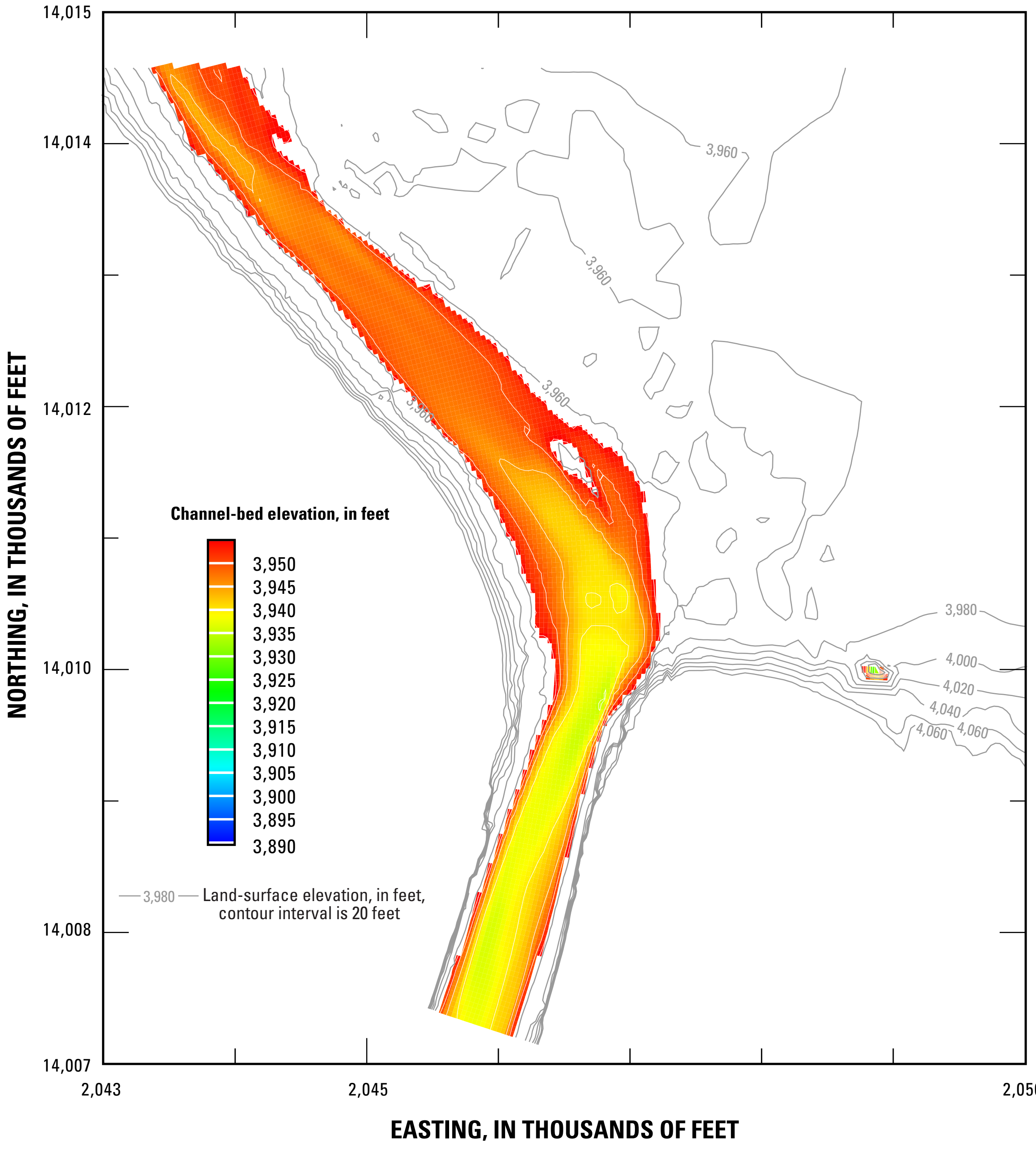


Figure 7. Hypothetical channel geometry representing 10-foot scour at downstream portal of Moab Valley, Utah.

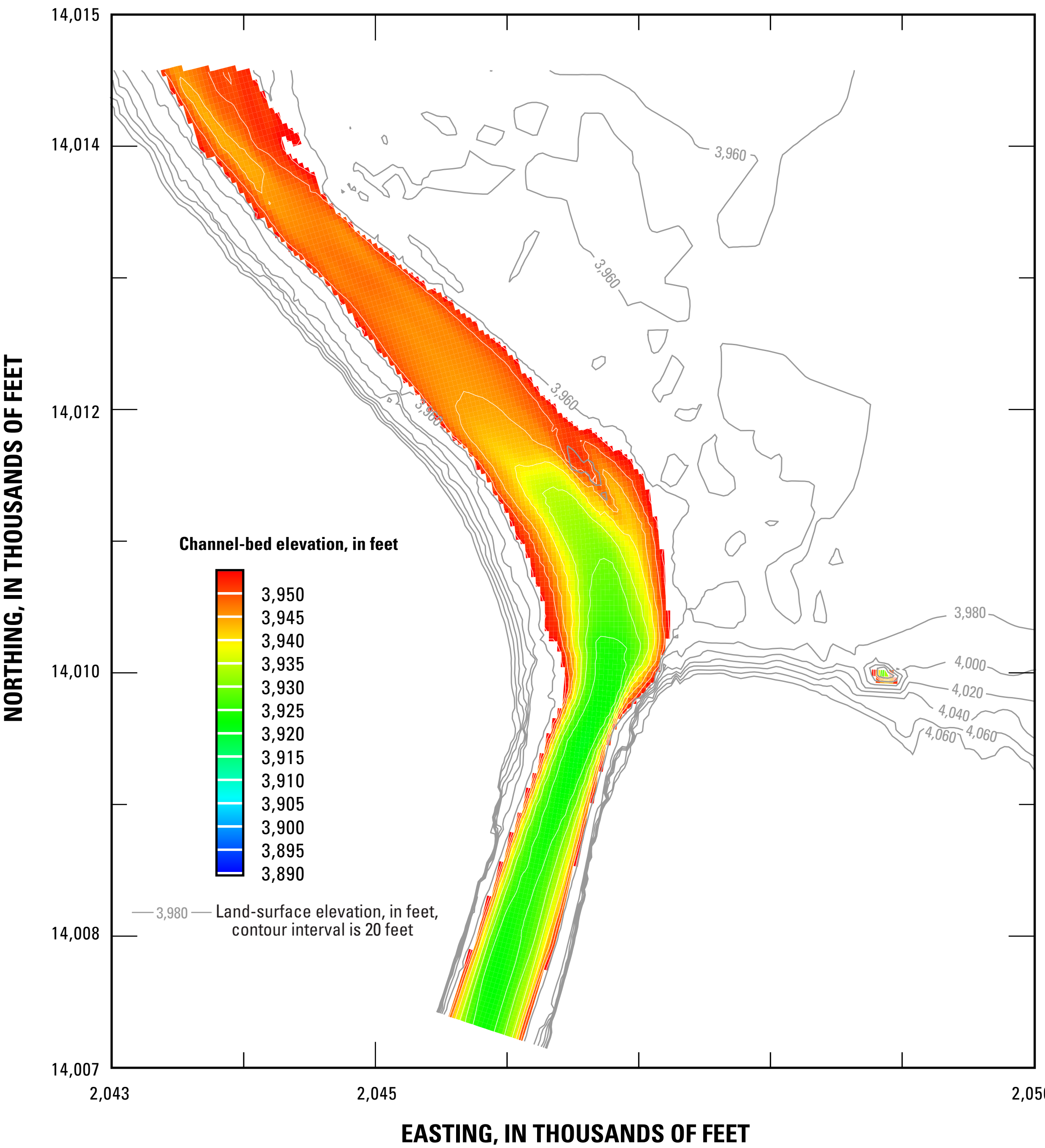


Figure 8. Hypothetical channel geometry representing 25-foot scour at downstream portal of Moab Valley, Utah.

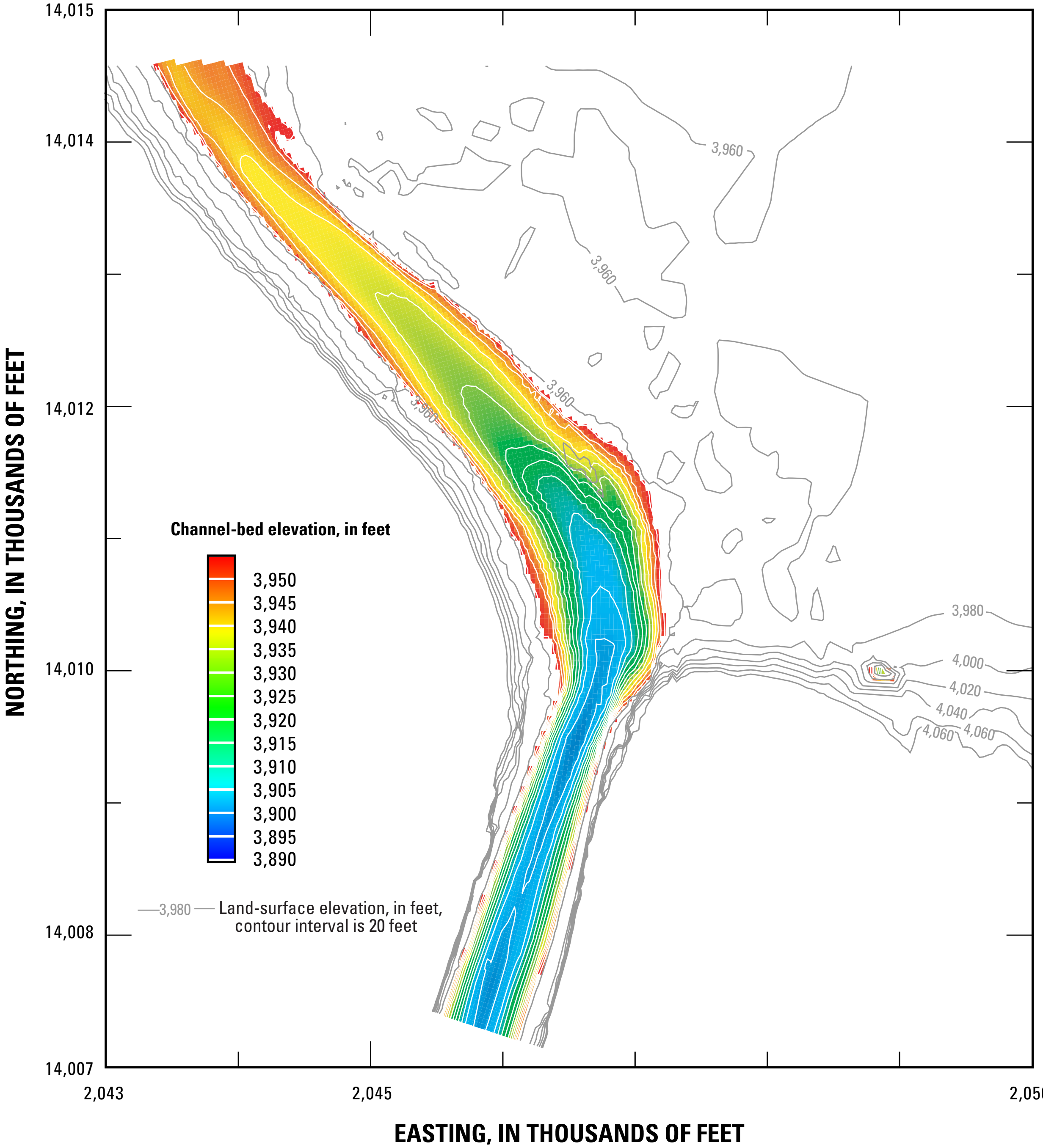


Figure 9. Hypothetical channel geometry representing 50-foot scour at downstream portal of Moab Valley, Utah.

Manning's n value until the predicted water-surface elevations for each cross section closely agreed with observed water-surface elevations measured when the channel topography was acquired at a discharge of 3,550 ft^3/s. This Manning's n value was then used for each of the channel geometry one-dimensional models. Computed downstream boundary water-surface elevations for each discharge and downstream portal configuration are shown in table 1.

Table 1. Discharge and corresponding downstream boundary water-surface elevation for each model simulation conducted

Discharge (cubic feet per second)	Downstream boundary water-surface elevation for downstream portal configuration (feet)			
	Existing geometry	10-foot scour configuration	25-foot scour configuration	50-foot scour configuration
97,600	3,971.06	3,965.44	3,955.44	3,936.21
120,000	3,973.88	3,968.59	3,958.75	3,939.89
300,000	3,991.33	3,987.03	3,978.77	3,960.82

Model Calibration

A graphical and statistical model-calibration module contained within the MD_SWMS interface allows for calibration with observed velocities and (or) water-surface elevations. Calibration is achieved by adjusting drag coefficients iteratively until computed values best represent observations (Conaway and Moran, 2004). Calibration for the model presented here was limited solely to the in-channel drag coefficient. This calibration was based upon water-surface elevations acquired throughout most of the reach when channel topography was acquired. The mean streamflow discharge during the 2 days of data collection that was used for model calibration was about 3,550 ft^3/s. By iteratively adjusting the in-channel drag coefficient and examining the predicted versus observed water-surface elevations, a drag coefficient of 0.00276 was determined to best represent the roughness of the in-channel materials for the calibration discharge. The observed and predicted water-surface elevations for the calibration discharge of 3,550 ft^3/s are shown in figure 10. Although results from the calibration of the in-channel drag coefficient are satisfactory (root mean square error = 0.084), this calibration should be considered limited and incomplete. The discharges simulated with this model are orders of magnitude greater than the measured discharge used for calibration, therefore calibration of the in-channel drag coefficient with larger discharges needs to be conducted. Velocity should also be calibrated with larger discharges.

Over-Bank Drag Coefficient

All discharges modeled in this investigation generated flow into the tamarisk-occupied over-bank regions. The roughness, or drag coefficient, associated with the in-channel materials was iteratively determined through a limited calibration procedure. Over-bank flow through the tamarisk in the study reach has not been quantified, making it difficult to assign it a drag coefficient. Many data exist on empirically determined Manning's n values for a range of materials. A Manning's n value in a heavy stand of timber with flood stage reaching the branches has been shown to range from 0.08 to 0.16 (Chow, 1959; Sturm, 2001). In Mussetter and Harvey's one-dimensional model of this study reach, stands of tamarisk greater than 1 ft tall were assigned a Manning's n value of 0.15 (Robert A. Mussetter and M.D. Harvey, Mussetter Engineering, Inc., written commun., 1994). The dimensionless drag coefficient used in MD_SWMS can be related mathematically to the commonly used Manning's roughness coefficient, or Manning's n, by the following equation:

$$C_d = \frac{\left(\frac{n_m}{1.515}\right)^2 g}{H^{1/3}} \qquad (1)$$

where:

C_d is the dimensionless drag coefficient,
n_m is the dimensionless Manning's roughness coefficient,
g is the acceleration of gravity, in ft/s^2, and
H is the mean depth of flow, in ft.

By using a range of potential Manning's n values of 0.08 to 0.15 for the thick stands of tamarisk in the study reach, drag coefficients were determined with equation 1. Assuming these Manning's n values represent flow within the branches of the tamarisk, the mean flow depth used in equation 1 was 6.5 ft, about the average height of tamarisk within the study reach. Drag coefficients for the areas vegetated with tamarisk were determined to range from 0.05 to 0.17.

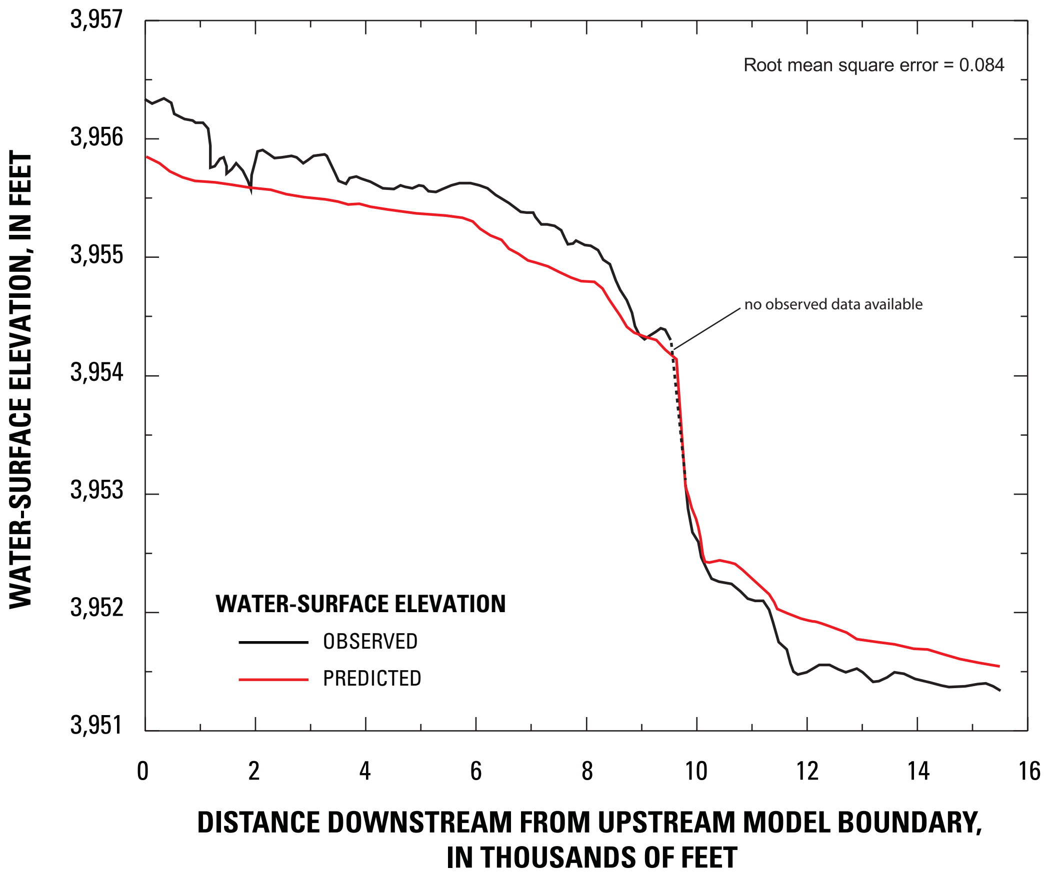


Figure 10. Relation of observed to predicted water-surface elevation for calibration discharge of 3,550 cubic feet per second.

Model sensitivity to drag-coefficient variations in the tamarisk-dominated areas was analyzed. All three discharge estimates, 97,600 ft^3/s, 120,000 ft^3/s, and 300,000 ft^3/s, were first simulated with the tamarisk region drag coefficient set to 0.05 and then 0.17. Modeled velocities for the drag coefficient equal to 0.05 were subtracted from those that were modeled with a drag coefficient of 0.17 (figs. 11-13). Generally, velocities associated with the 0.17 drag coefficient were faster within the main channel, slower on the south bank immediately downstream of the entrance portal, and slower on the upstream side of the large vegetated island. For the 100- and 500-year discharges, main-channel velocity differences were less than 2 ft/s. These differences occurred downstream from the tailings pile in the center of the main channel. The greatest difference in modeled in-channel velocities for the PMF discharge estimate was less than 3 ft/s. Spatially, this 2 to 3 ft/s difference was noted in three small areas: downstream from the tailings, along the east side of the vegetated island, and on the north side of the upstream portal. Differences from 1 to 2 ft/s were more extensive for the PMF discharge.

Velocity differences in discrete areas of the reach were substantial; however, the spatial extent of these areas was generally small. Velocity differences greater than 1 ft/s throughout the reach were minimal, specifically within the main channel adjacent to and upstream from the tailings pile for the discharges examined. This indicates that the model is not overly sensitive to the range of drag coefficients selected to represent dense, mature tamarisk stands roughly 6.5 ft tall. On the basis of these results, the literature cited previously, and the exploratory nature of this modeling

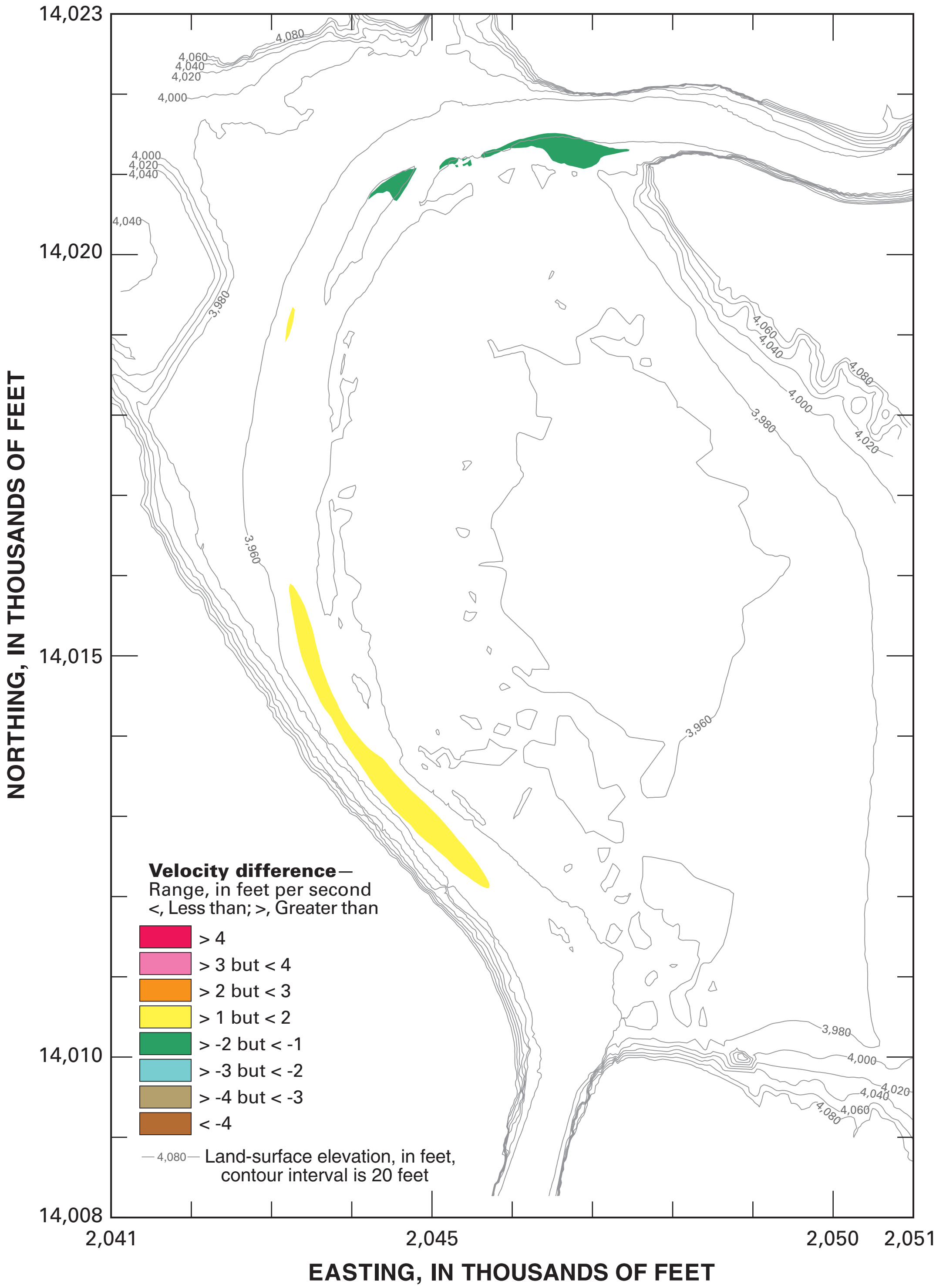


Figure 11. Predicted velocities for tamarisk drag coefficient equal to 0.17 minus predicted velocities from drag coefficient equal to 0.05 for 100-year discharge in the Colorado River, Moab Valley, Utah.

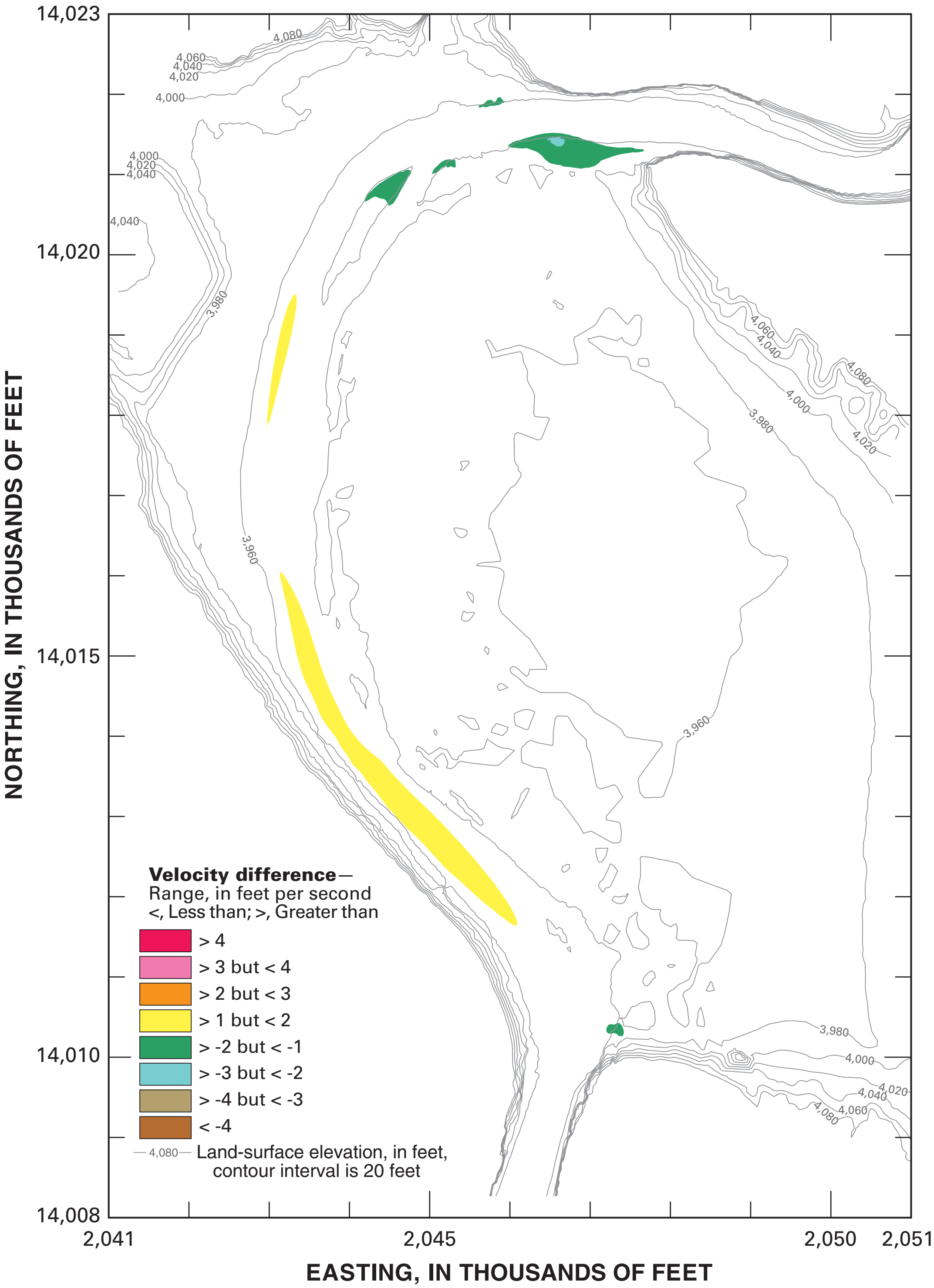


Figure 12. Predicted velocities for tamarisk drag coefficient equal to 0.17 minus predicted velocities from drag coefficient equal to 0.05 for 500-year discharge in the Colorado River, Moab Valley, Utah.

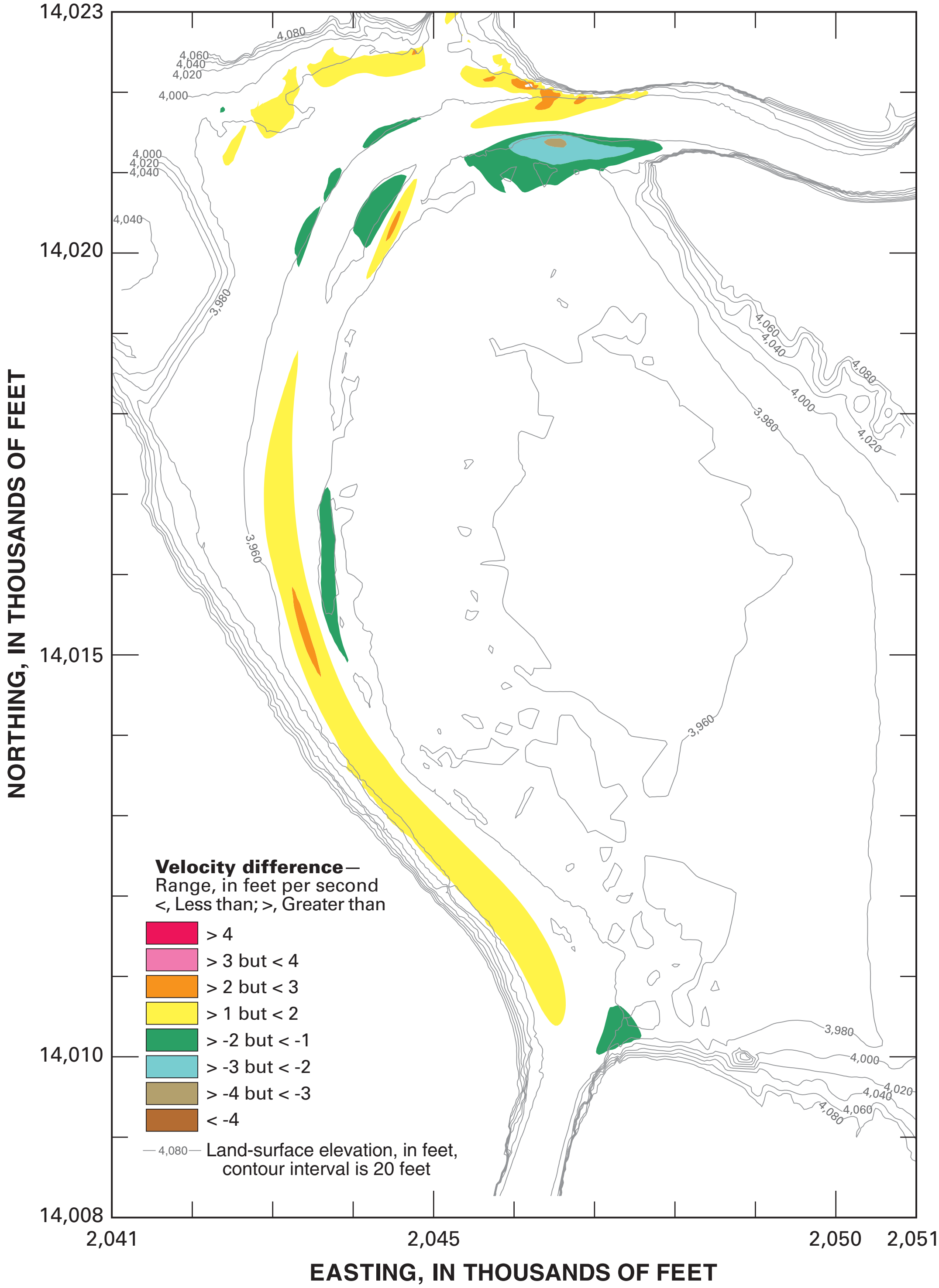


Figure 13. Predicted velocities for tamarisk drag coefficient equal to 0.17 minus predicted velocities from drag coefficient equal to 0.05 for Probable-Maximum-Flood discharge in the Colorado River, Moab Valley, Utah.

effort, a drag coefficient of 0.17 was selected to represent the areas occupied by tamarisk in the study reach (fig. 14). The remainder of the over-bank region was assigned the same drag coefficient as the main channel, 0.00276.

Model Limitations

Specific limitations of the developed model should be understood when interpreting the results presented in this report. The model used in this analysis is considered uncalibrated for the large discharges simulated in this investigation. The model is steady state in that duration of flow is not evaluated, and boundary conditions, including the topographic surface, remain fixed. The Colorado River Bridge at State Road 191 was not represented in the model.

Methods of handling flow through vegetation in two-dimensional models are not well developed. Vegetation extends from the surface with flow occurring around and through it. Drag coefficients are assigned to surface materials to represent their resistance characteristics. When modeling flow in two dimensions, flow resistance caused by vegetation has to be treated as a topographic surface with extremely high roughness. In order to estimate shear stress and material transport in areas occupied by vegetation, high roughness values need to be partitioned as resistance related to the plant form, form drag, and as resistance of the bed materials, skin friction. Without quantified observations of flow and sediment transport in vegetated areas, these simplifications increase the uncertainty of predicted parameters. Valid interpretation of the data presented in this report requires a clear understanding of these limitations.

SIMULATION RESULTS

The multi-dimensional hydrodynamic model simulations predicted flow characteristics for the 100- and 500-year discharge estimates as well as the estimated PMF discharge for all four downstream portal channel configurations. Water-surface elevations, velocity distributions, and shear-stress distributions were generated for the 12 model simulations. Below are brief discussions on each of these parameters along with graphical two-dimensional plots for each simulation. A labeled plot of the study reach (fig. 15) shows the location of elevation contours that are contained in the numerous two-dimensional plots of the parameters examined.

Water-Surface Elevation

Water-surface elevations within the study reach are an important aid in understanding the hydraulic regime for each discharge and downstream portal geometry simulation. Downstream distances of predicted water-surface elevations for each simulation conducted are shown in figure 16. In assessing the potential hazard posed to the Moab uranium mill tailings by flooding in the Colorado River, an important initial step is to determine the degree of inundation caused by each flow and channel geometry. The base, or toe, of the tailings pile is located roughly 650 ft from the current channel bank of the Colorado River at an elevation of about 3,970 ft.

Water-Surface Elevation for Existing Channel Geometry

Each discharge simulation with the existing channel geometry flooded a considerable part of the over-bank region (figs. 17-19). Water-surface elevations for the three discharge simulations at the toe of the tailings pile ranged from 3,974 to about 3,995 ft. The differences in water-surface elevations between the portals was about 3 to 4 ft for each simulation, a water-surface slope roughly equal to the main-channel slope of about 0.0002 ft/ft.

Water-Surface Elevation for Hypothetical Channel Geometries

As bed elevation at the portal was decreased, water-surface elevations within the study reach also decreased (figs. 20-28). The changes in channel configurations dramatically altered the slope of the reach, and consequently the water-surface slope. The 100- and 500-year recurrence interval discharges were nearly contained within the main channel when the portal bed was decreased 50 ft, eliminating most over-bank flow.

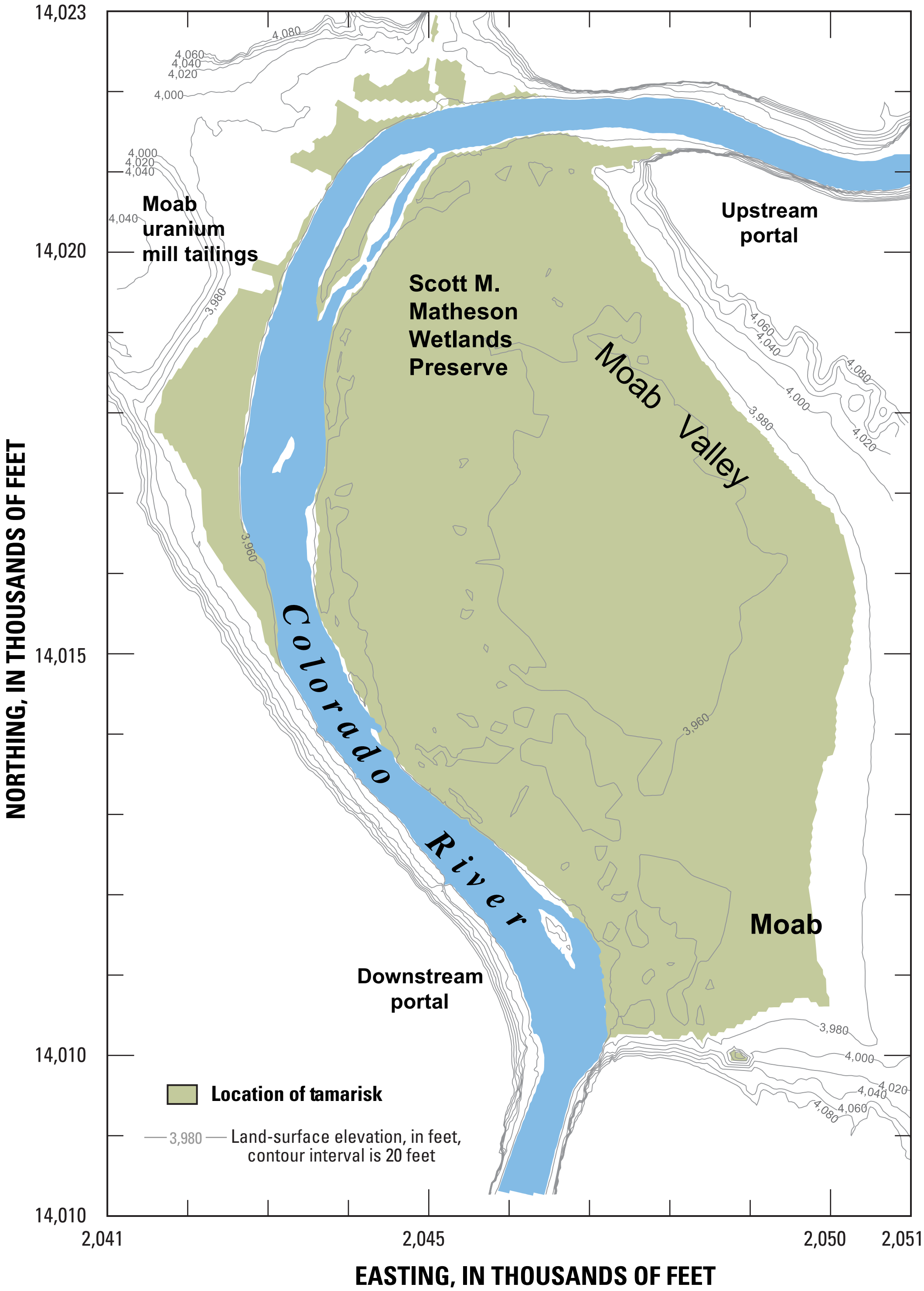


Figure 14. Location of tamarisk-occupied areas of the study area, Moab Valley, Utah.

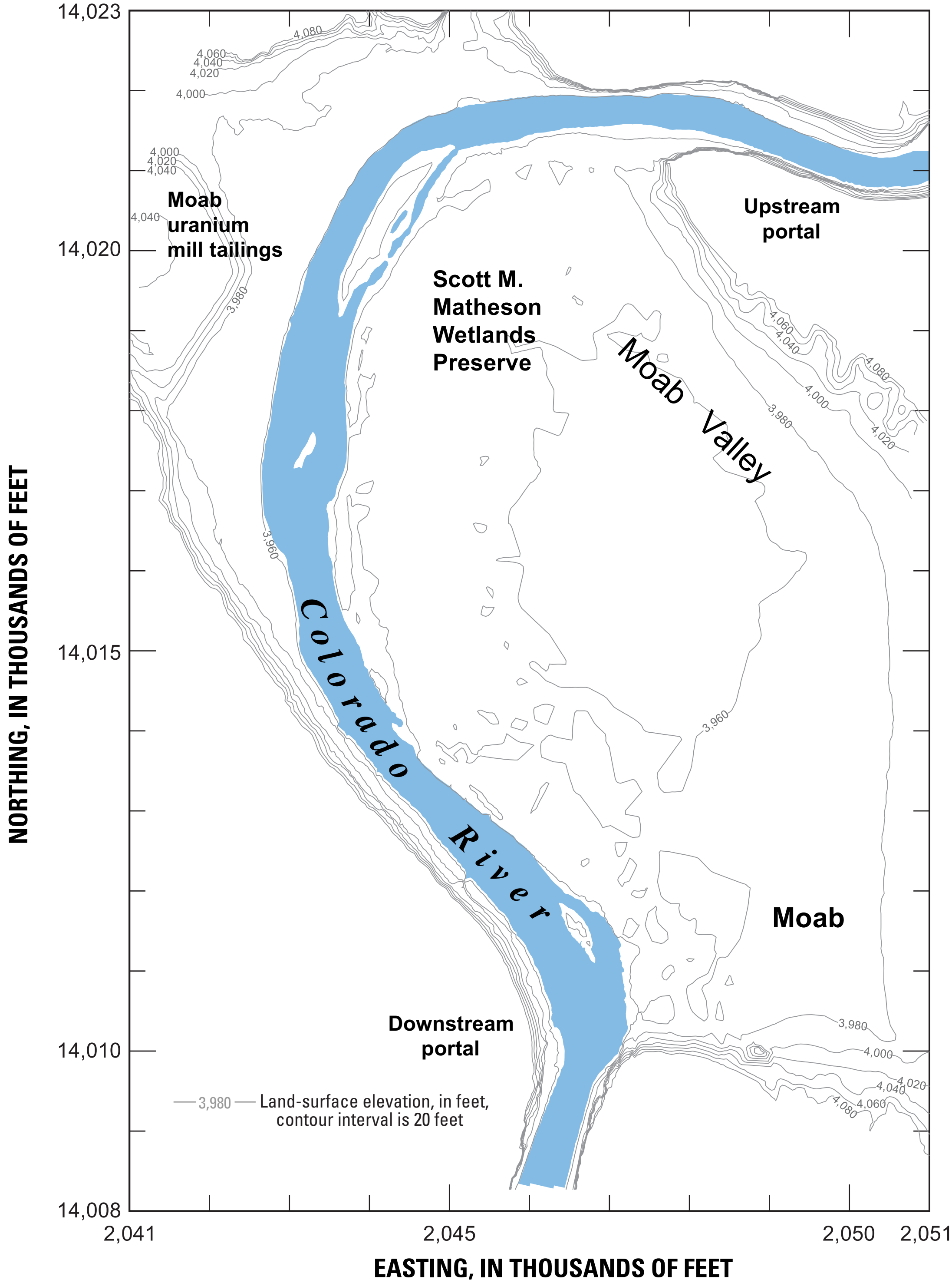


Figure 15. Topographic surface of the Moab uranium mill tailings study area, Moab Valley, Grand County, Utah.

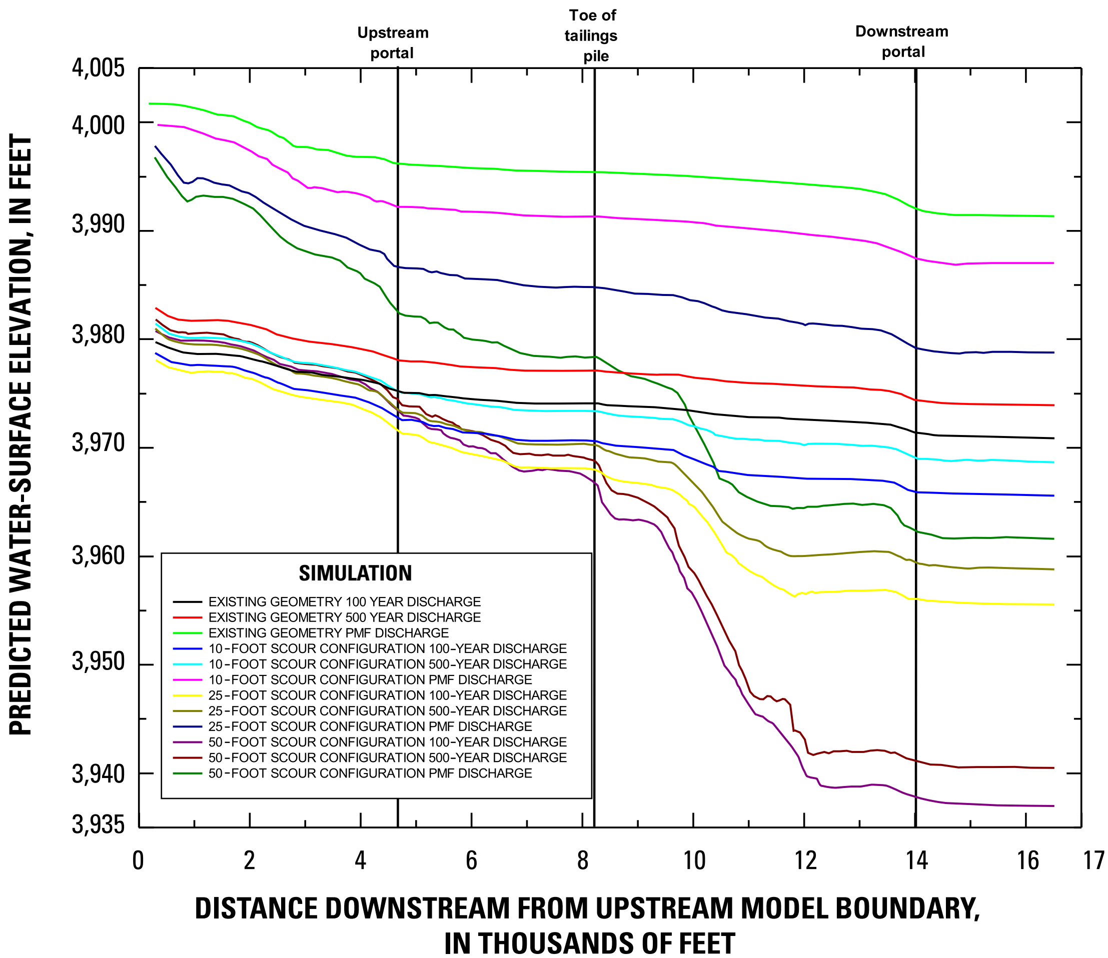


Figure 16. Predicted water-surface elevation and distance downstream from the upstream model boundary for all channel configurations and discharge simulations of the Colorado River in Moab Valley, Utah.

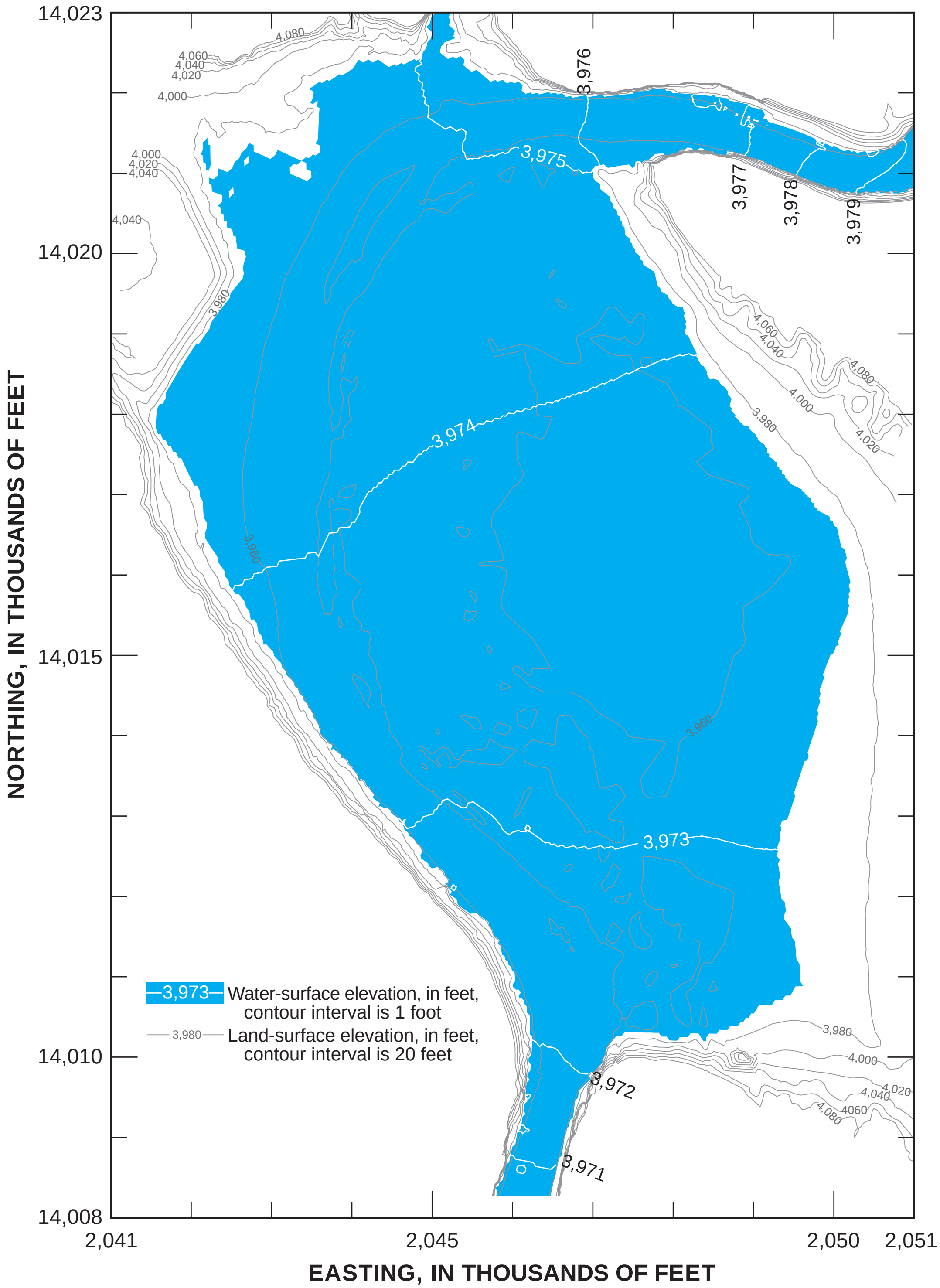


Figure 17. Predicted water-surface elevations for 100-year discharge and existing channel geometry configuration of the Colorado River in Moab Valley, Utah.

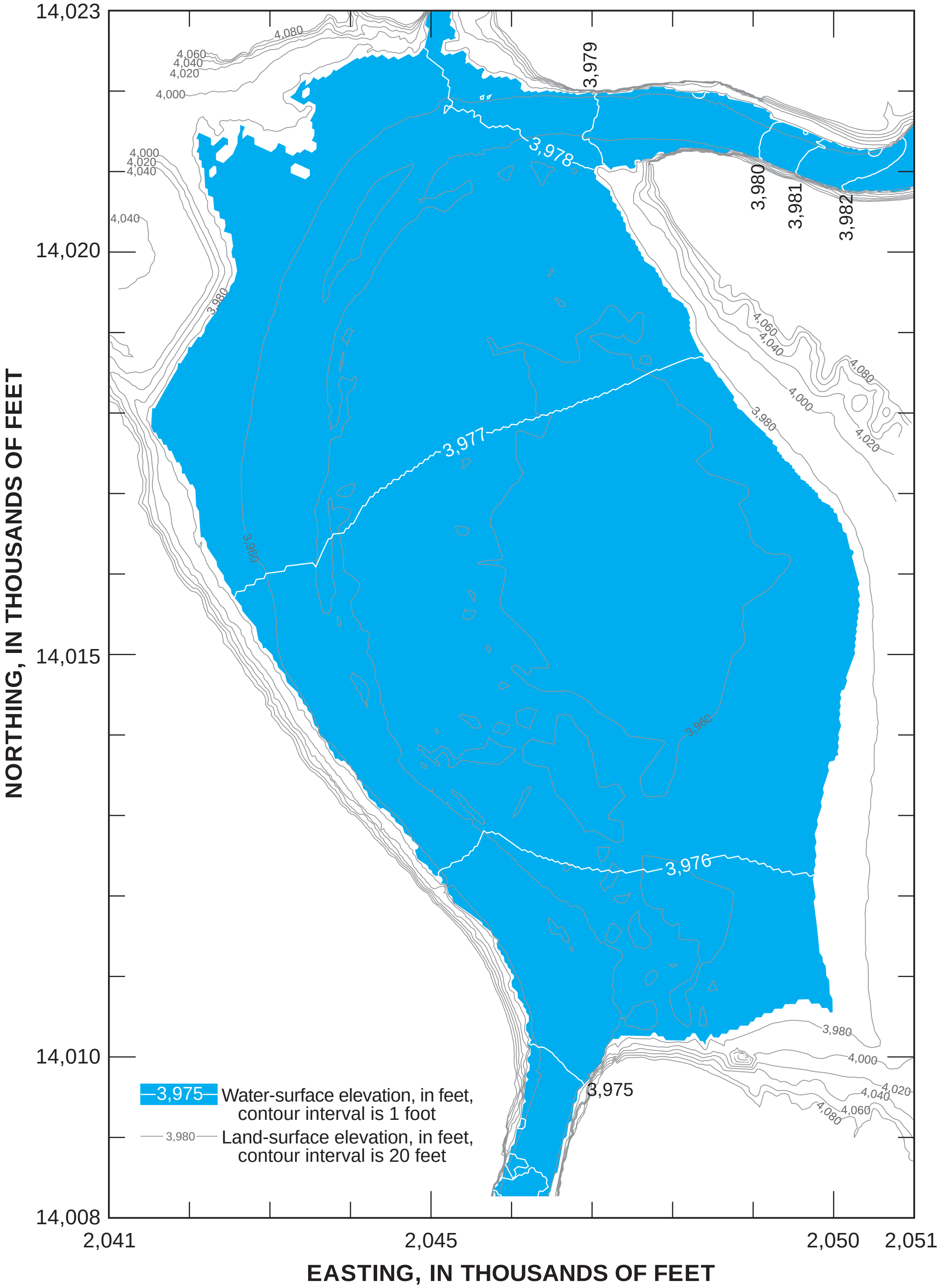


Figure 18. Predicted water-surface elevations for 500-year discharge and existing channel geometry configuration of the Colorado River in Moab Valley, Utah.

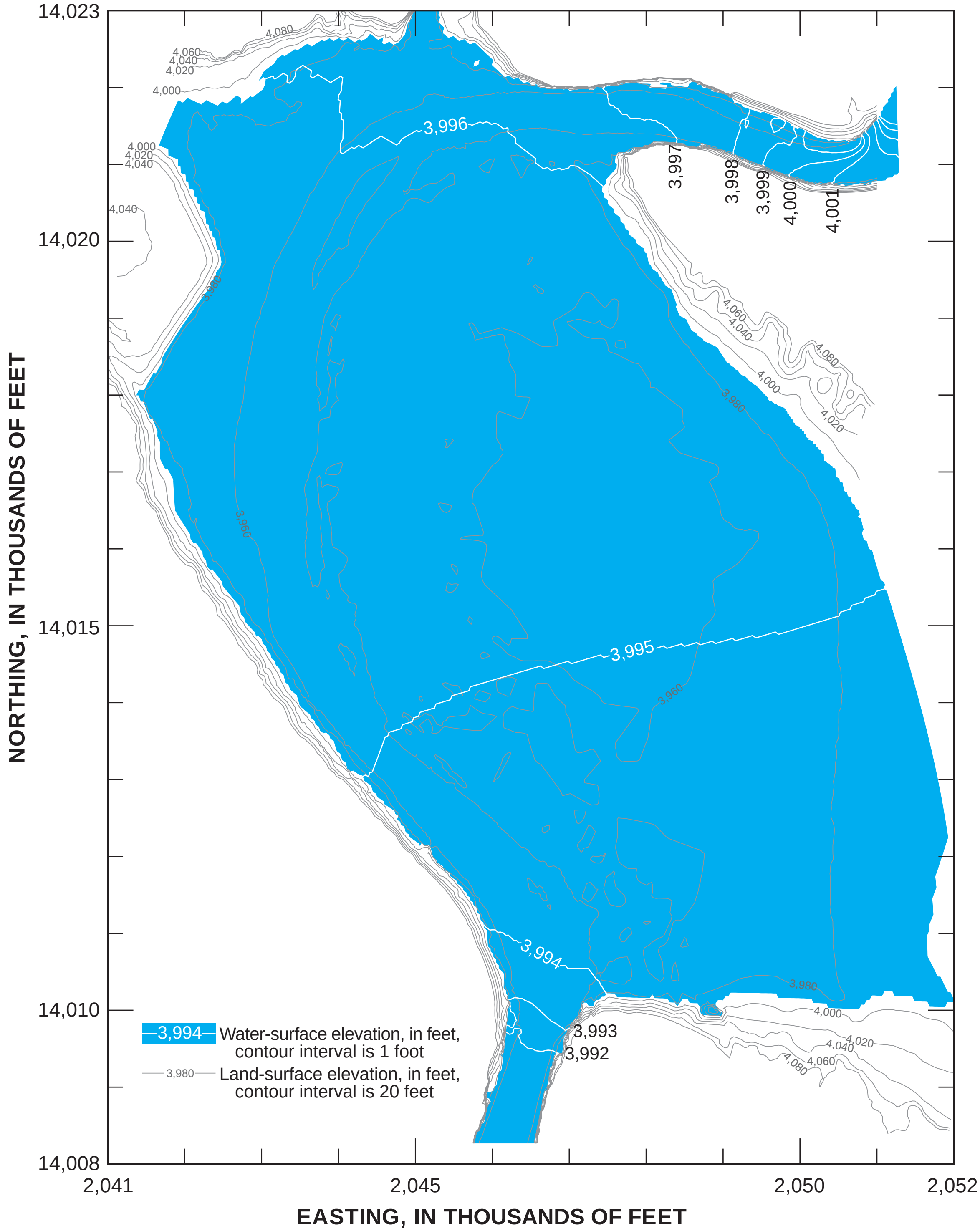


Figure 19. Predicted water-surface elevations for Probable-Maximum-Flood discharge and existing channel geometry configuration of the Colorado River in Moab Valley, Utah.

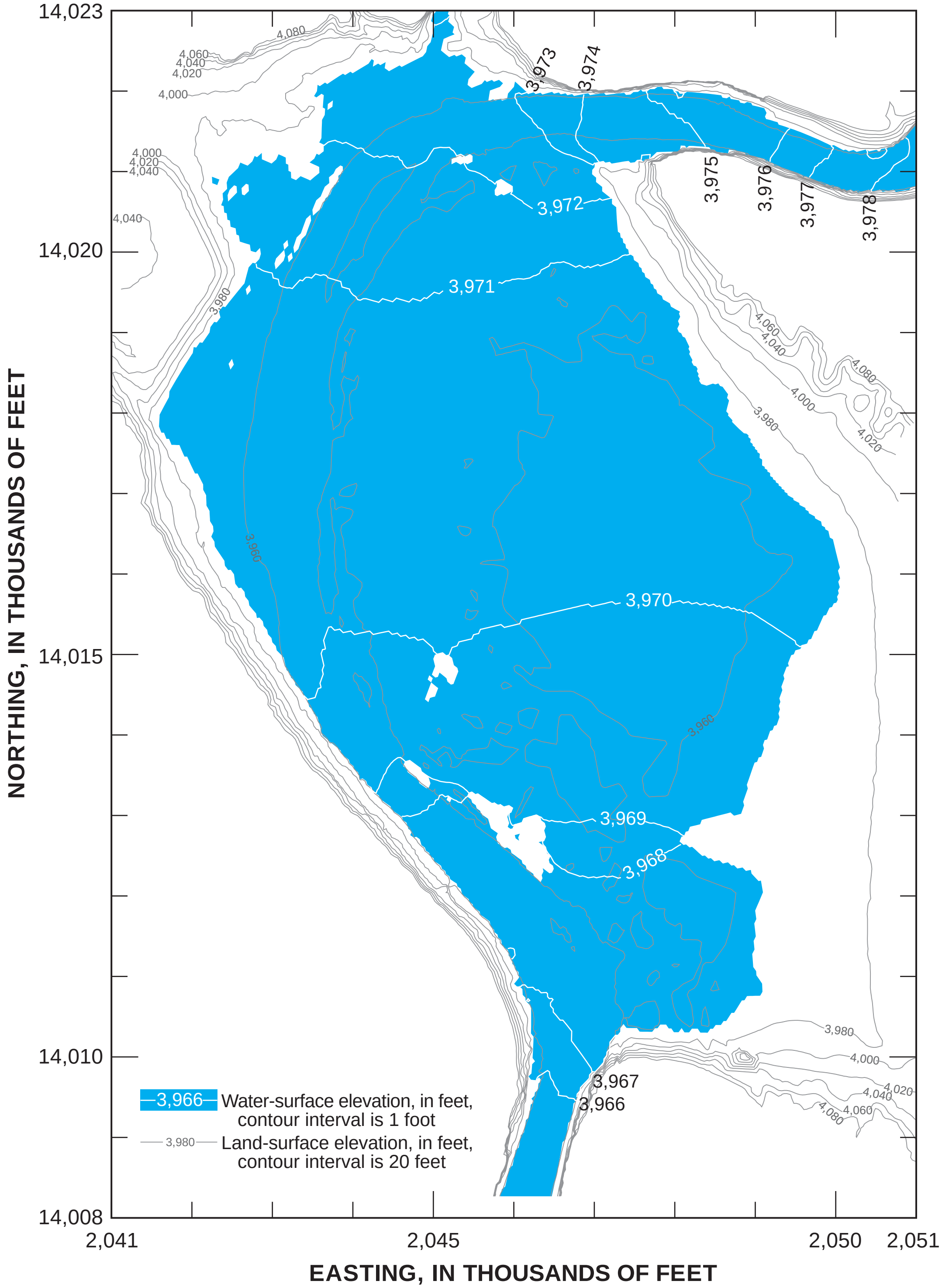


Figure 20. Predicted water-surface elevations for 100-year discharge and hypothetical 10-foot scour configuration of the Colorado River in Moab Valley, Utah.

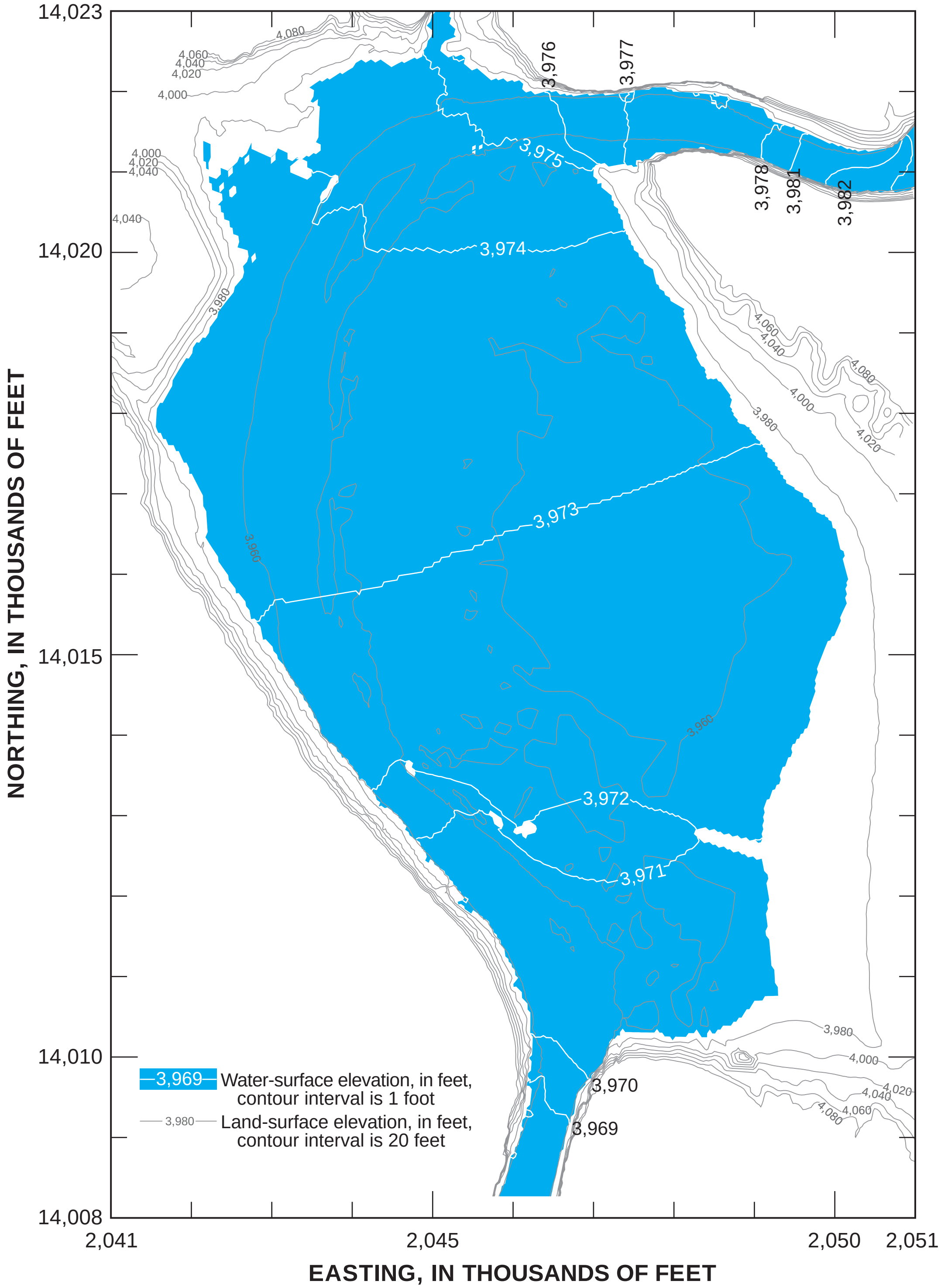


Figure 21. Predicted water-surface elevations for 500-year discharge and hypothetical 10-foot scour configuration of the Colorado River in Moab Valley, Utah.

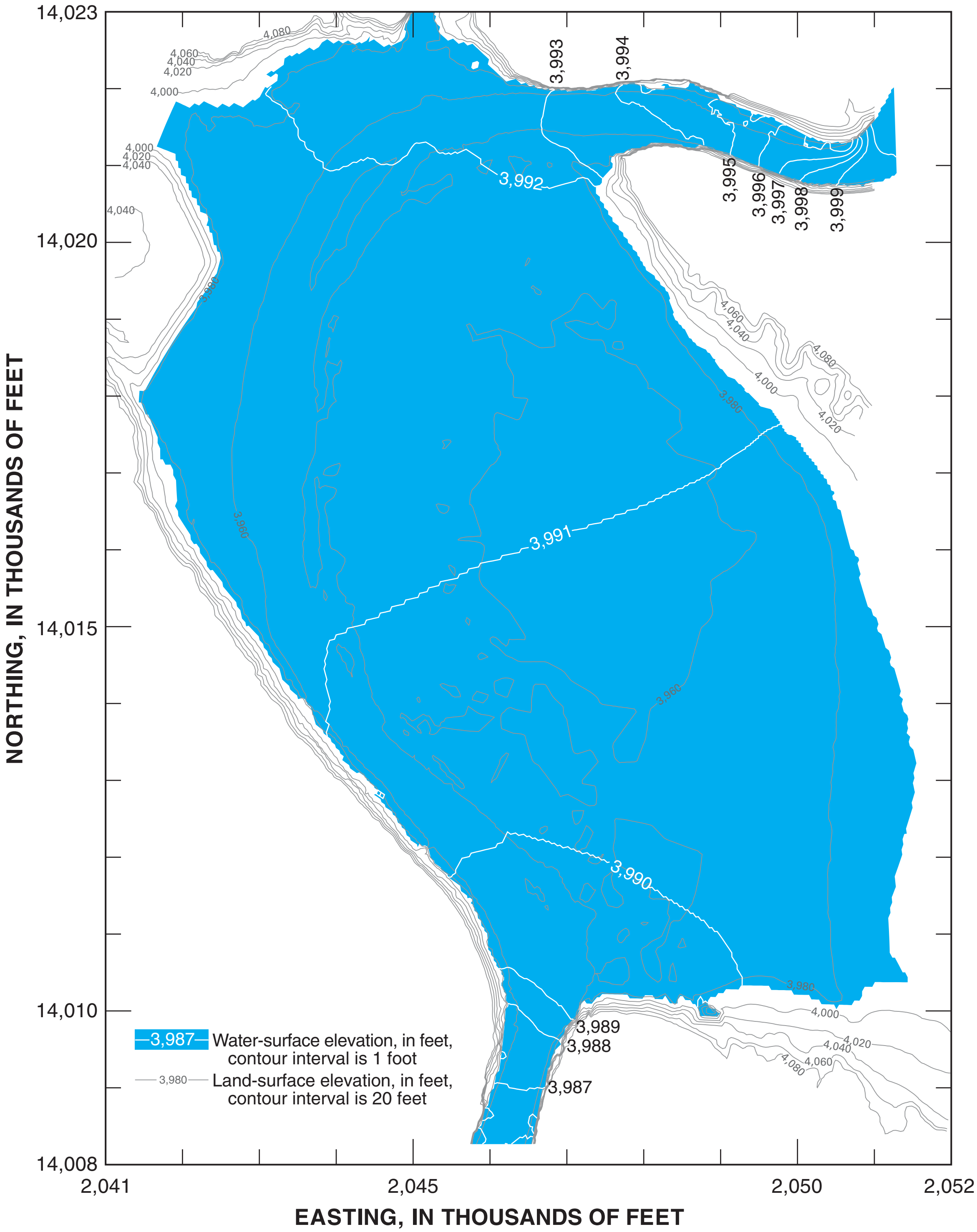


Figure 22. Predicted water-surface elevations for Probable-Maximum-Flood discharge and hypothetical 10-foot scour configuration of the Colorado River in Moab Valley, Utah.

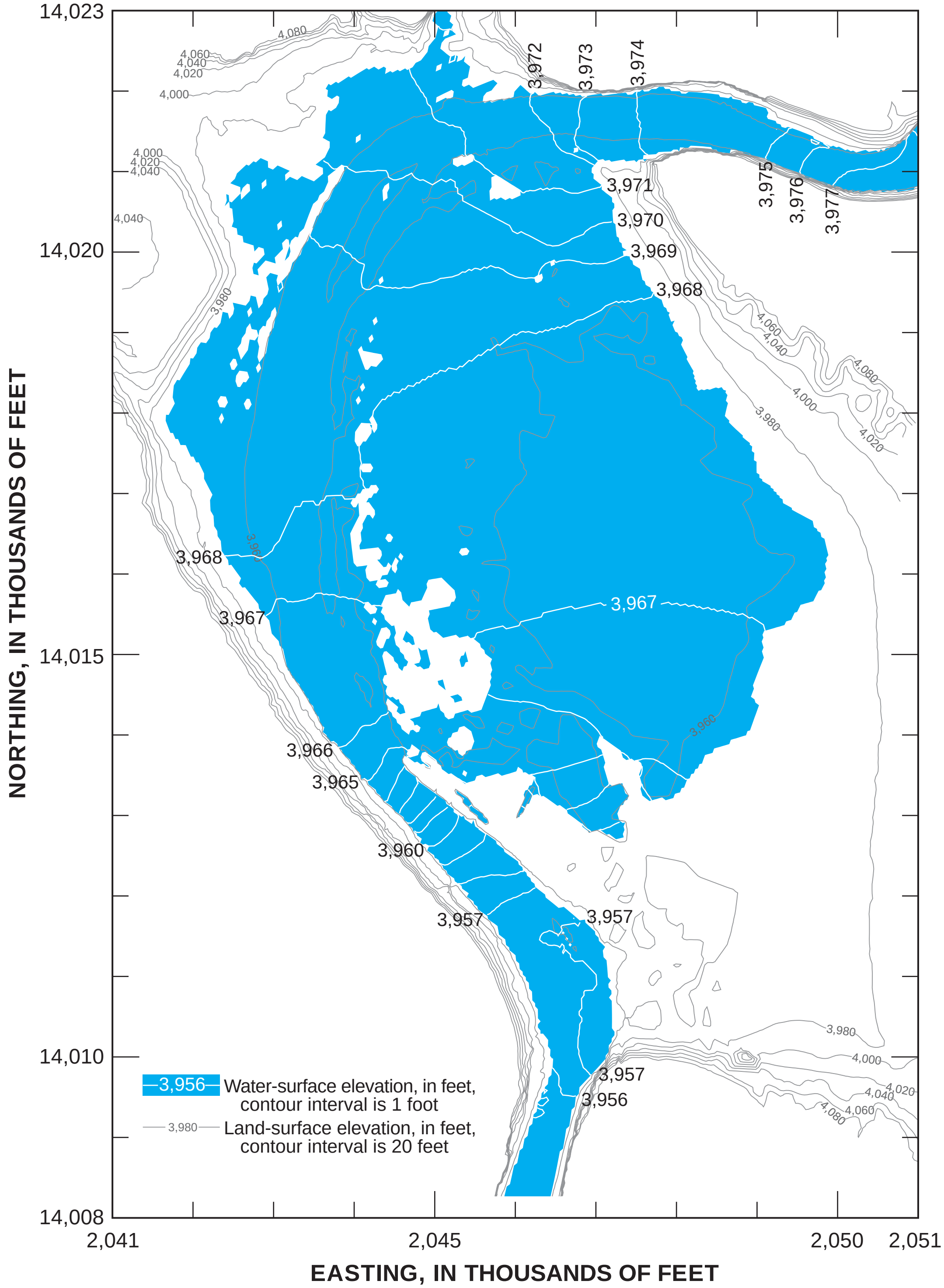


Figure 23. Predicted water-surface elevations for 100-year discharge and hypothetical 25-foot scour configuration of the Colorado River in Moab Valley, Utah.

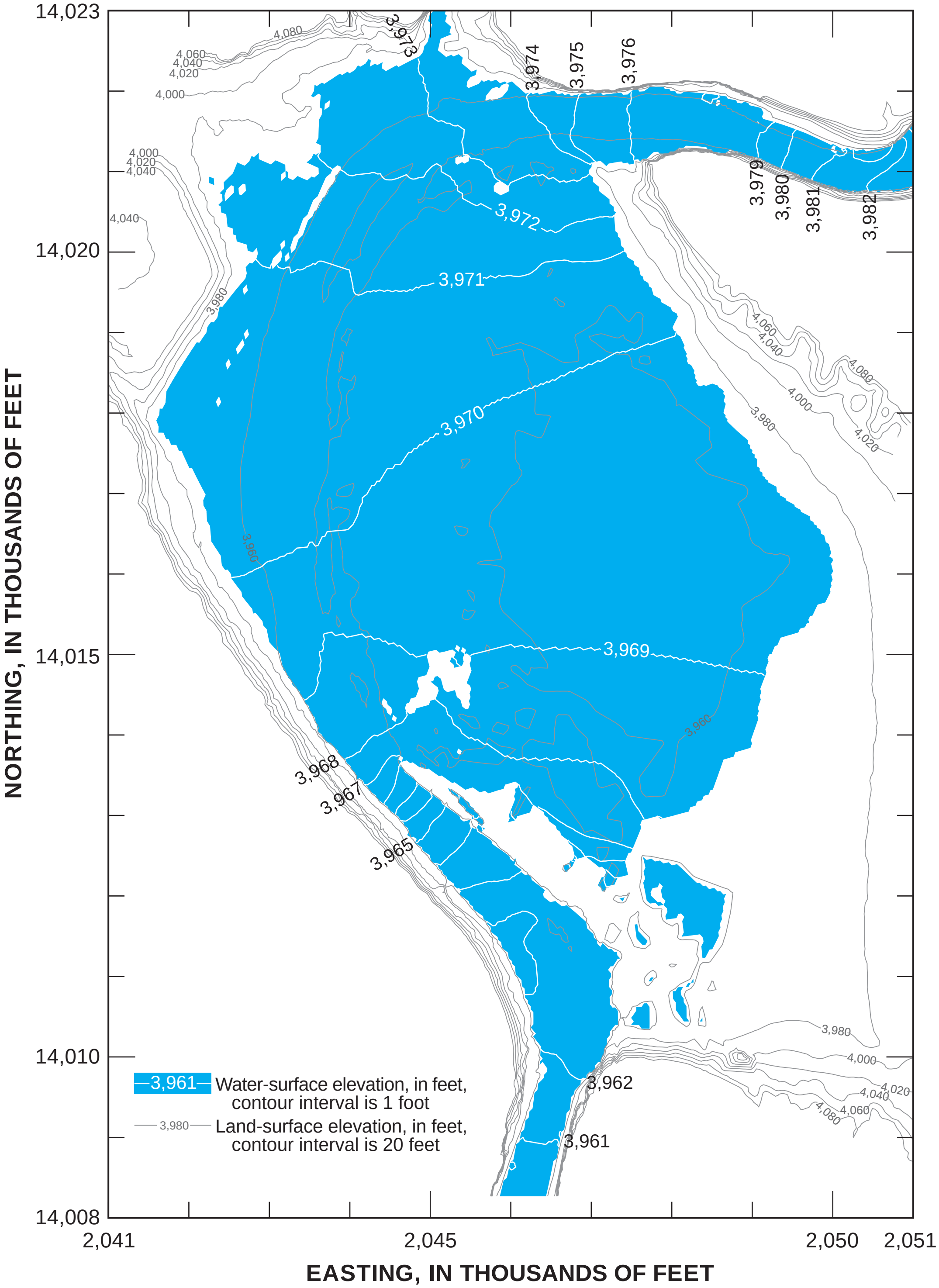


Figure 24. Predicted water-surface elevations for 500-year discharge and hypothetical 25-foot scour configuration of the Colorado River in Moab Valley, Utah.

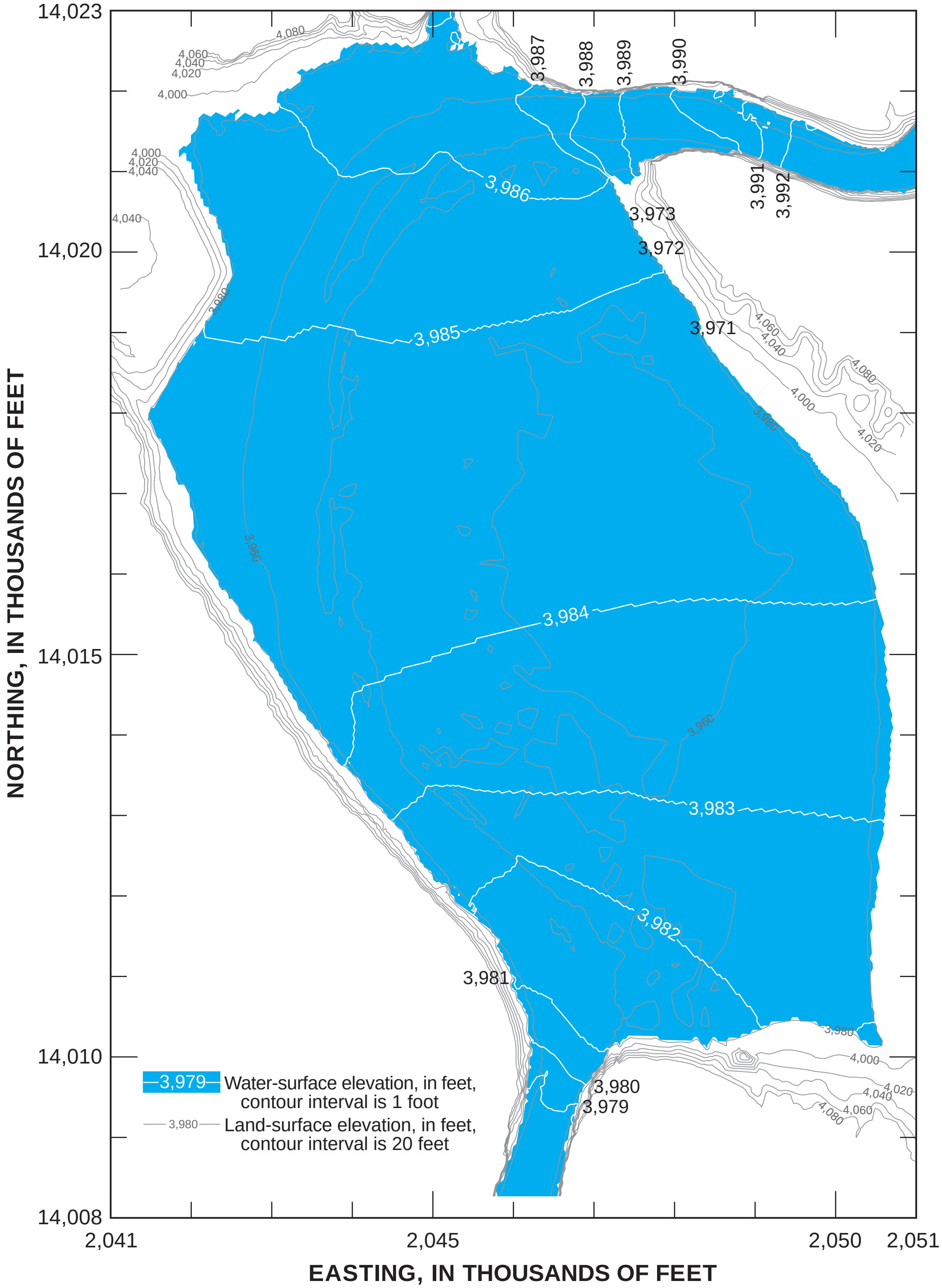


Figure 25. Predicted water-surface elevations for Probable-Maximum-Flood discharge and hypothetical 25-foot scour configuration of the Colorado River in Moab Valley, Utah.

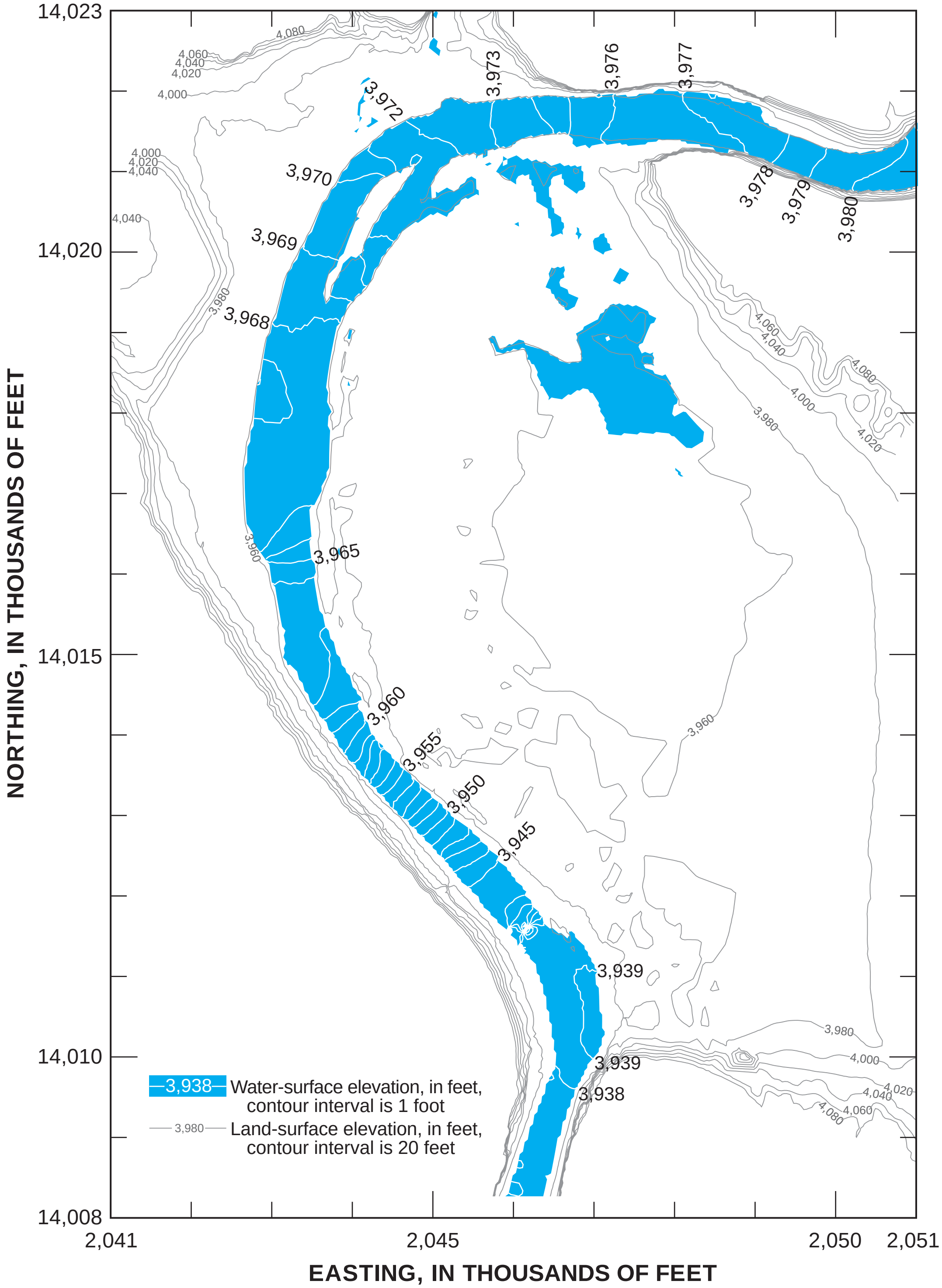


Figure 26. Predicted water-surface elevations for 100-year discharge and hypothetical 50-foot scour configuration of the Colorado River in Moab Valley, Utah.

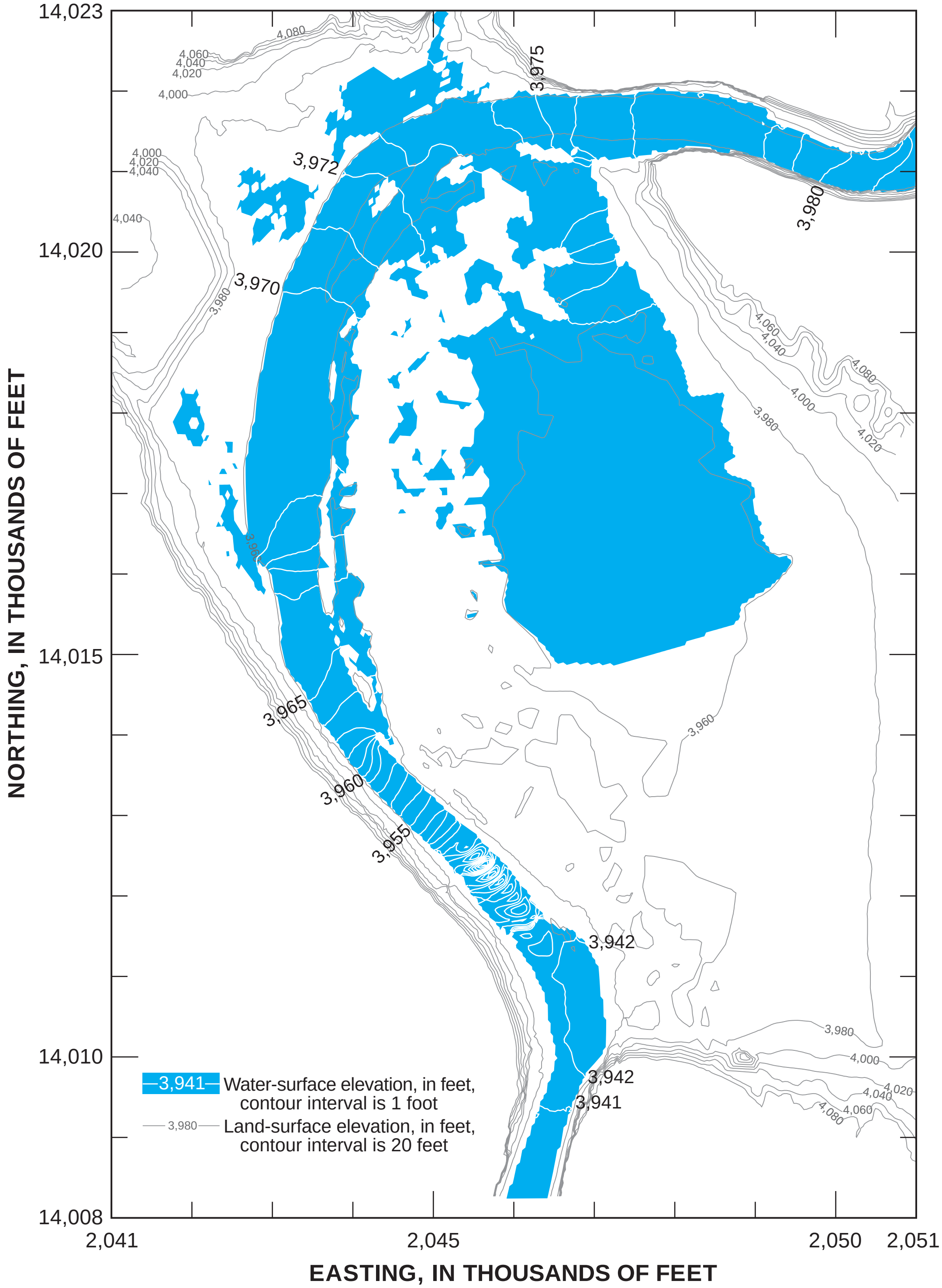


Figure 27. Predicted water-surface elevations for 500-year discharge and hypothetical 50-foot scour configuration of the Colorado River in Moab Valley, Utah.

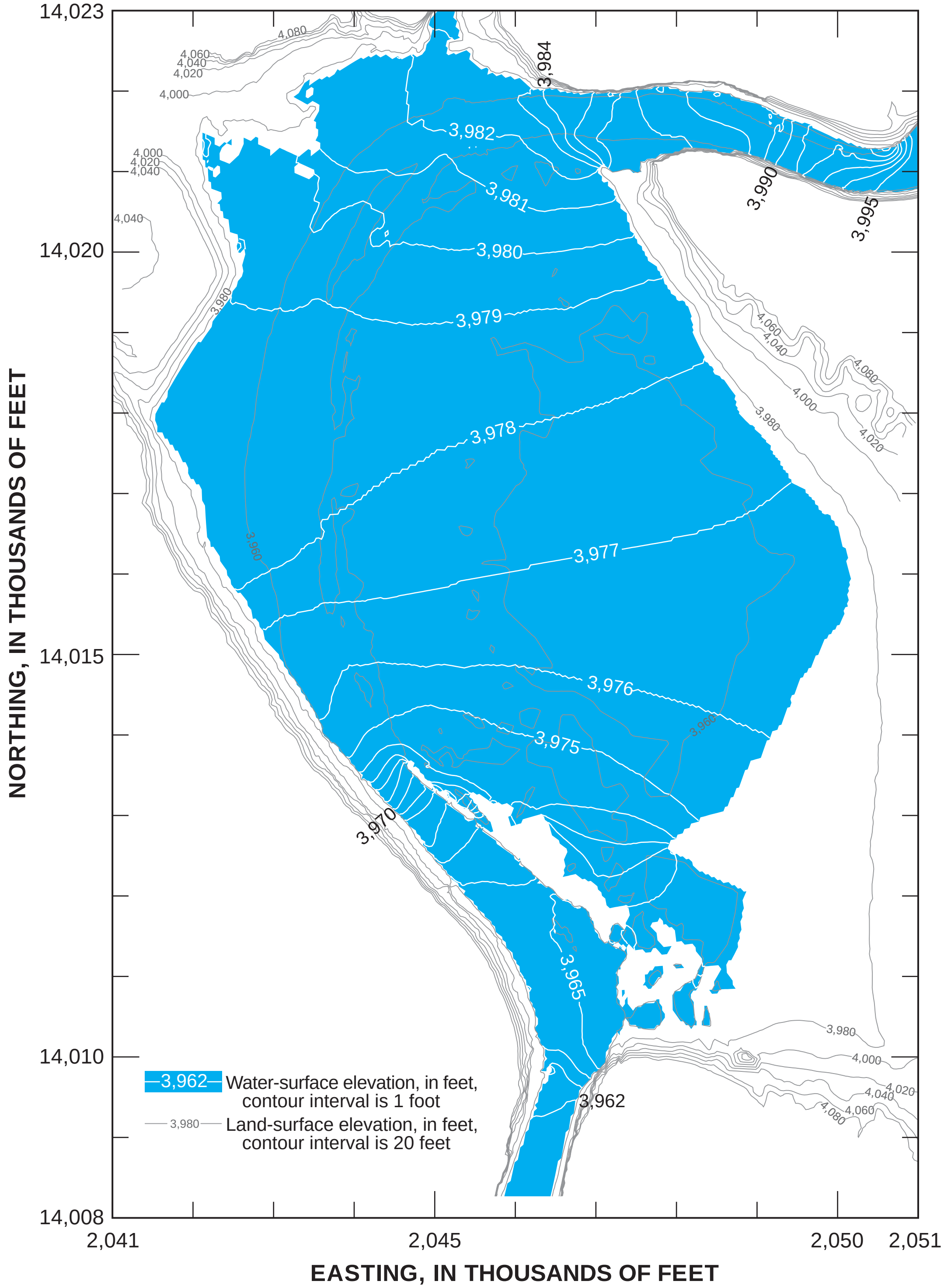


Figure 28. Predicted water-surface elevations for Probable-Maximum-Flood discharge and hypothetical 50-foot scour configuration of the Colorado River in Moab Valley, Utah.

Velocity Distribution

A main objective of this assessment was to model velocities within the Colorado River in Moab Valley. As shown by the water-surface elevation plots, all the discharges examined exceed the capacity of the main channel Colorado River. The velocity contour plots that follow indicate that flow conveyance is greatest within the main channel of the Colorado River through Moab Valley for all simulations conducted.

Velocity Distribution for Existing Channel Geometry

Main-channel velocities within Moab Valley for the three discharge simulations with the existing channel geometry reached a maximum of between 6 and 8 ft/s (figs. 29-31). Velocities of this magnitude were predicted as occurring within the main channel adjacent to the tailings pile. Velocities predicted at the upstream portal are generally equal to those at the downstream portal for each of the discharge simulations. Modeled velocities for the PMF simulation exceeded 12 ft/s at the portals outside Moab Valley. Over-bank flow velocity at the toe of the tailings increases as discharge increases. A small area at the toe of the tailings pile was characterized by velocities of about 1 to 2 ft/s for the 100-year discharge. Predicted velocities near the toe for the PMF discharge increased to between 2 and 4 ft/s over a somewhat larger area (figs. 29 and 31). This is likely a result of accumulating over-bank flow from upstream being forced around the front of the tailings pile. This progression of velocities near the toe of the tailings pile can be seen in the velocity vector plots (figs. 32 and 33). A back-eddy is visible in the over-bank area upstream of the tailings pile for the 100-year discharge. Predicted velocity vectors for the PMF discharge indicate that over-bank velocities are accelerated around the toe of the tailings pile.

To better compare the predicted velocities for the existing channel configuration, a series of difference plots were developed (figs. 34-36). There are no differences greater than 1 ft/s within Moab Valley among the modeled velocities for the 100- and 500-year discharges (fig. 36). Consequently, the differences among the PMF, and the 100- and 500-year discharges, are roughly equal. Main-channel flow velocities for the PMF increase toward the inside of the river bend downstream from the tailings pile and decrease toward the outside.

Velocity Distribution for Hypothetical Channel Geometries

Main channel velocities for all discharges throughout Moab Valley exceed 6 ft/s when the elevation of the channel bed at the downstream portal is decreased 10 ft (figs. 37-39). Compared with the PMF discharge, velocities in the secondary channel on the east side of the vegetated island are greater for the 100- and 500-year discharges.

Deepening the channel bed at the downstream portal by 25 and 50 ft resulted in substantial velocity increases throughout the main channel (figs. 40-45). With these configurations, the three discharge simulations produced maximum in-channel velocities adjacent to the tailings pile in excess of 12 ft/s, more than double the maximum velocities predicted under the existing geometric conditions. Over-bank flow velocities near the tailings and upstream portal for the PMF discharge with the 25- and 50-foot scour configuration of the downstream portal are higher than over-bank velocities associated with any of the other geometric configurations examined in this study. This may occur because increased conveyance at the downstream portal lessens the amount of slack water occupying the over-bank regions.

Shear-Stress Distribution

The capability of a river to move material is related to the shearing forces associated with flow, known as shear stress. The initiation of movement for noncohesive grains occurs as the boundary-threshold condition is exceeded (Sturm, 2001). This threshold condition is often referred to as the critical shear stress. MD_SWMS uses the following equation to calculate boundary shear stress:

$$\tau_b = \rho C_d(u^2 + v^2) \qquad (2)$$

where:

τ_b is the boundary shear stress, in lb/ft^2,
ρ is the fluid density, in lb/ft^3,
C_d is the nondimensional drag coefficient,
u is the vertically averaged x component of velocity, in ft/s, and
v is the vertically averaged y component of velocity, in ft/s.

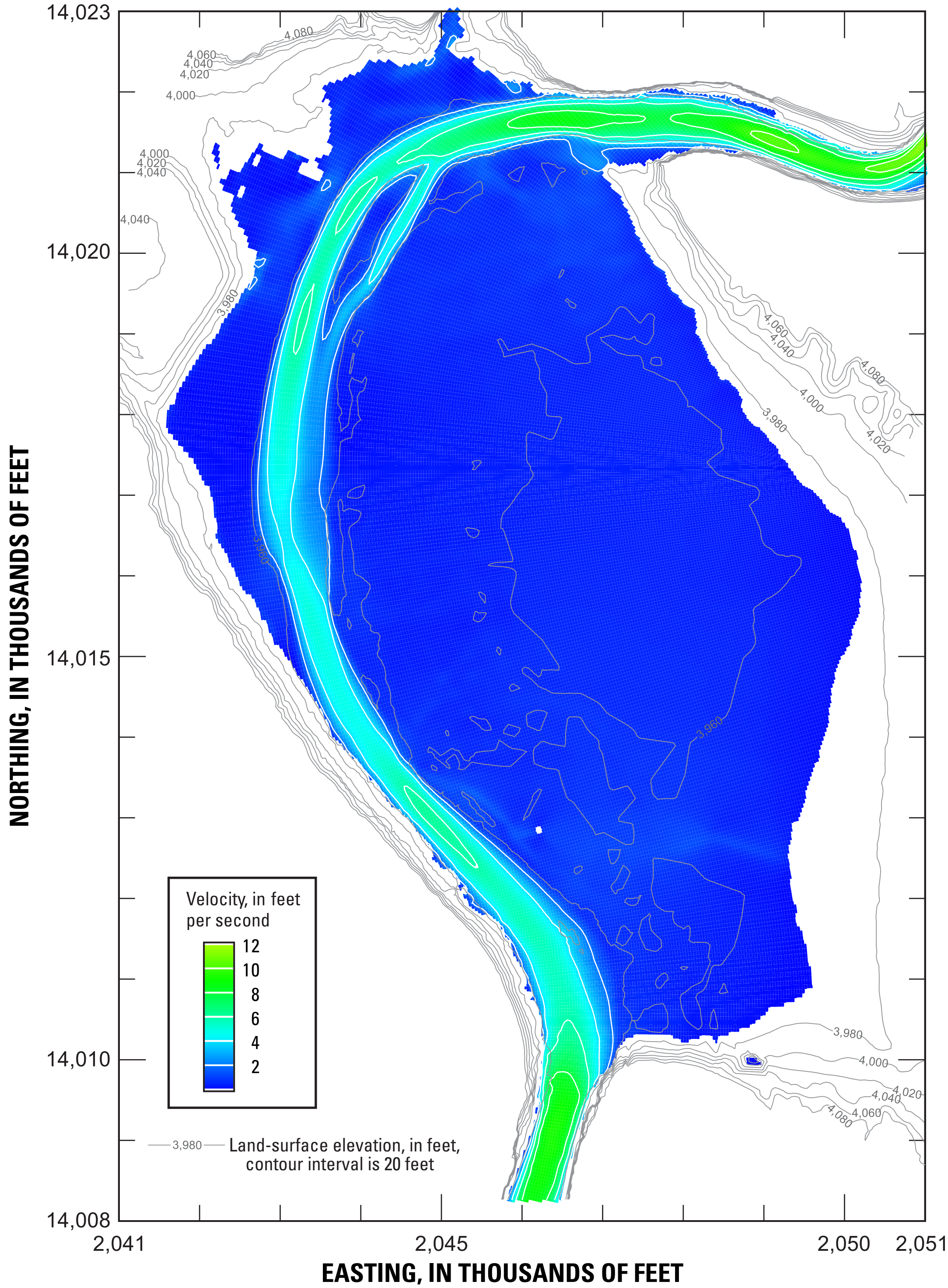


Figure 29. Predicted velocity distribution for 100-year discharge and existing channel geometry configuration of the Colorado River in Moab Valley, Utah.

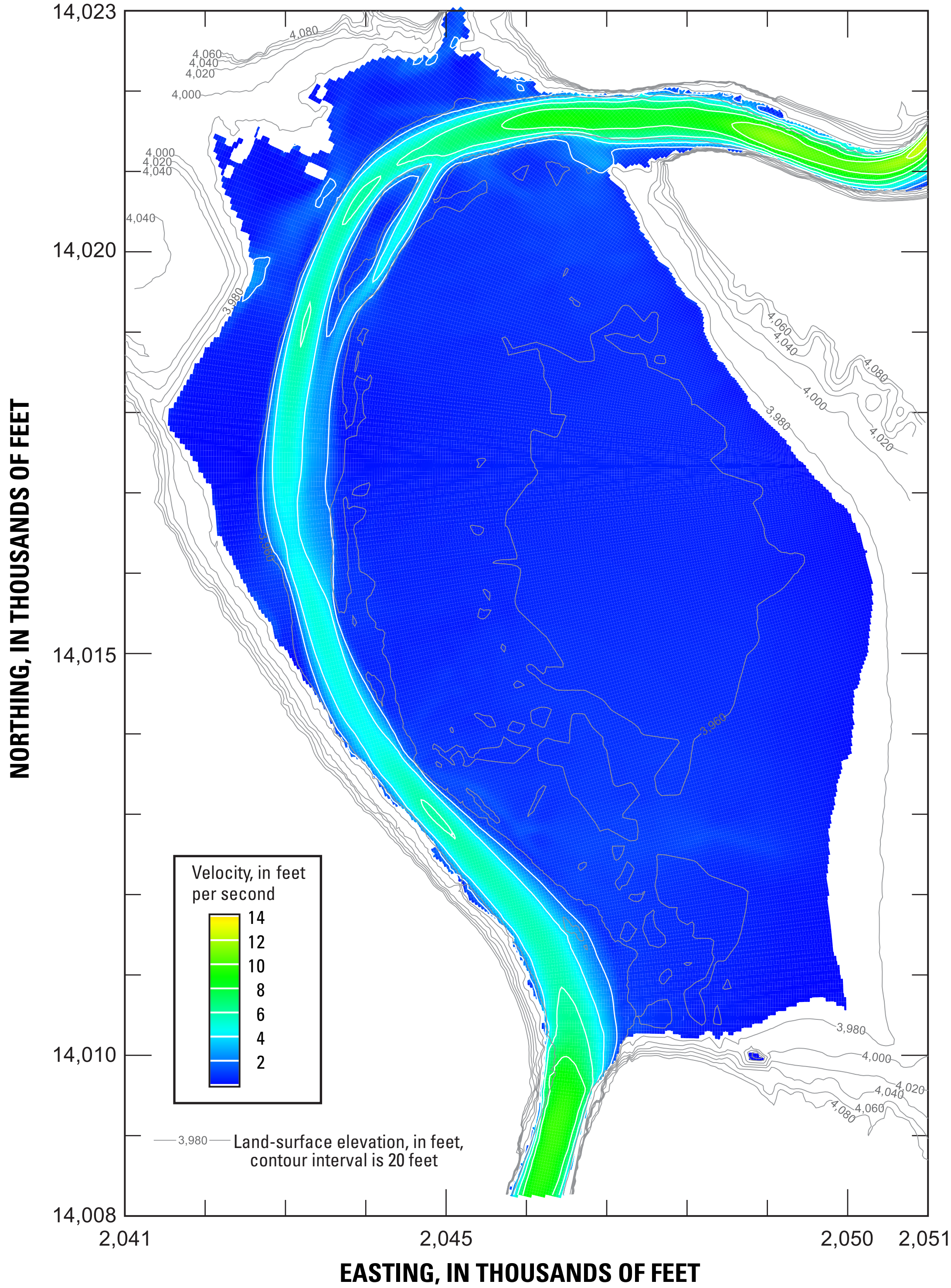


Figure 30. Predicted velocity distribution for 500-year discharge and existing channel geometry configuration of the Colorado River in Moab Valley, Utah.

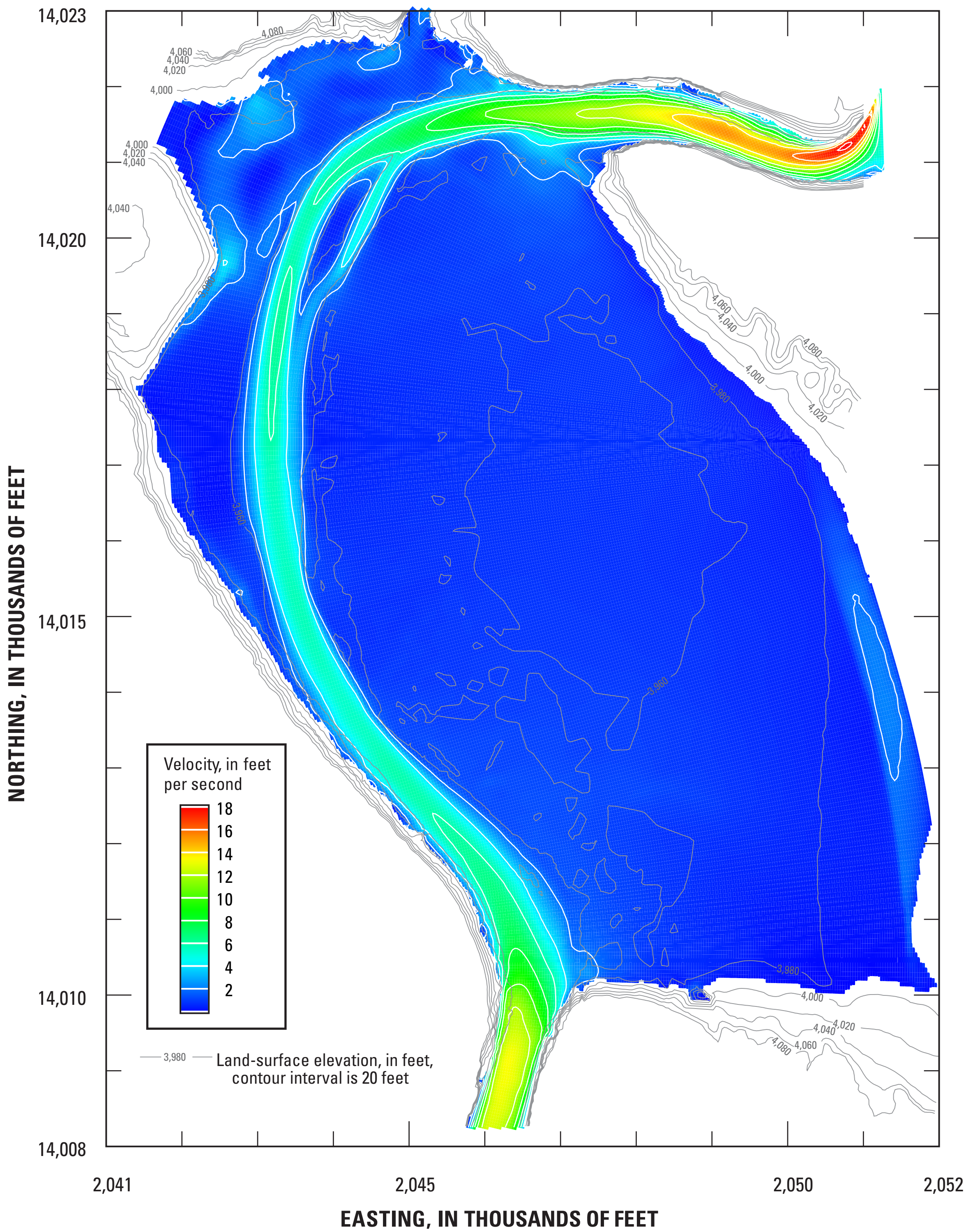


Figure 31. Predicted velocity distribution for Probable-Maximum-Flood discharge and existing channel geometry configuration of the Colorado River in Moab Valley, Utah.

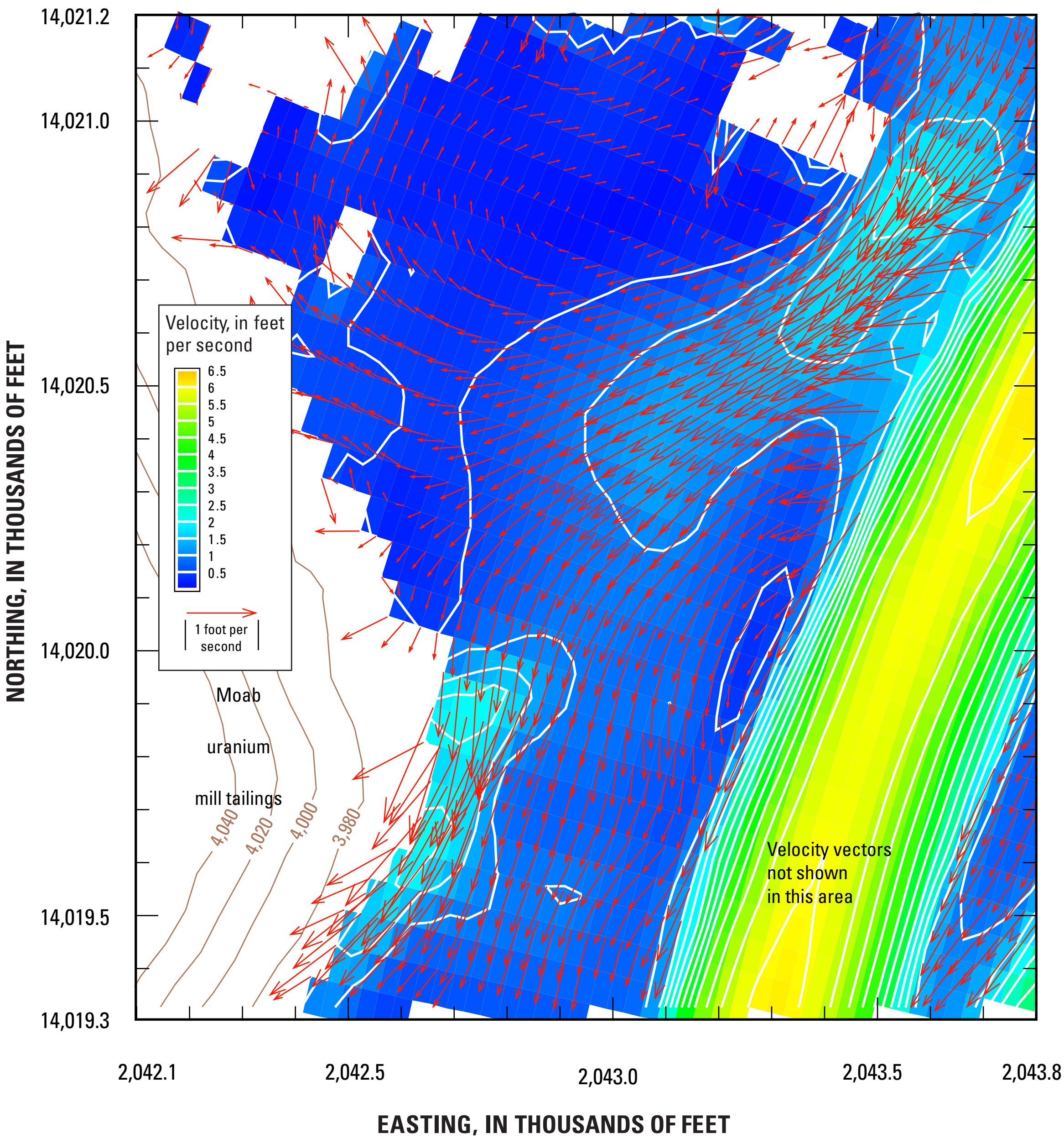


Figure 32. Predicted velocity vectors and contours near tailings pile for 100-year discharge and existing channel geometry configuration of the Colorado River in Moab Valley, Utah.

Predicted back-eddy is visible at the top center.

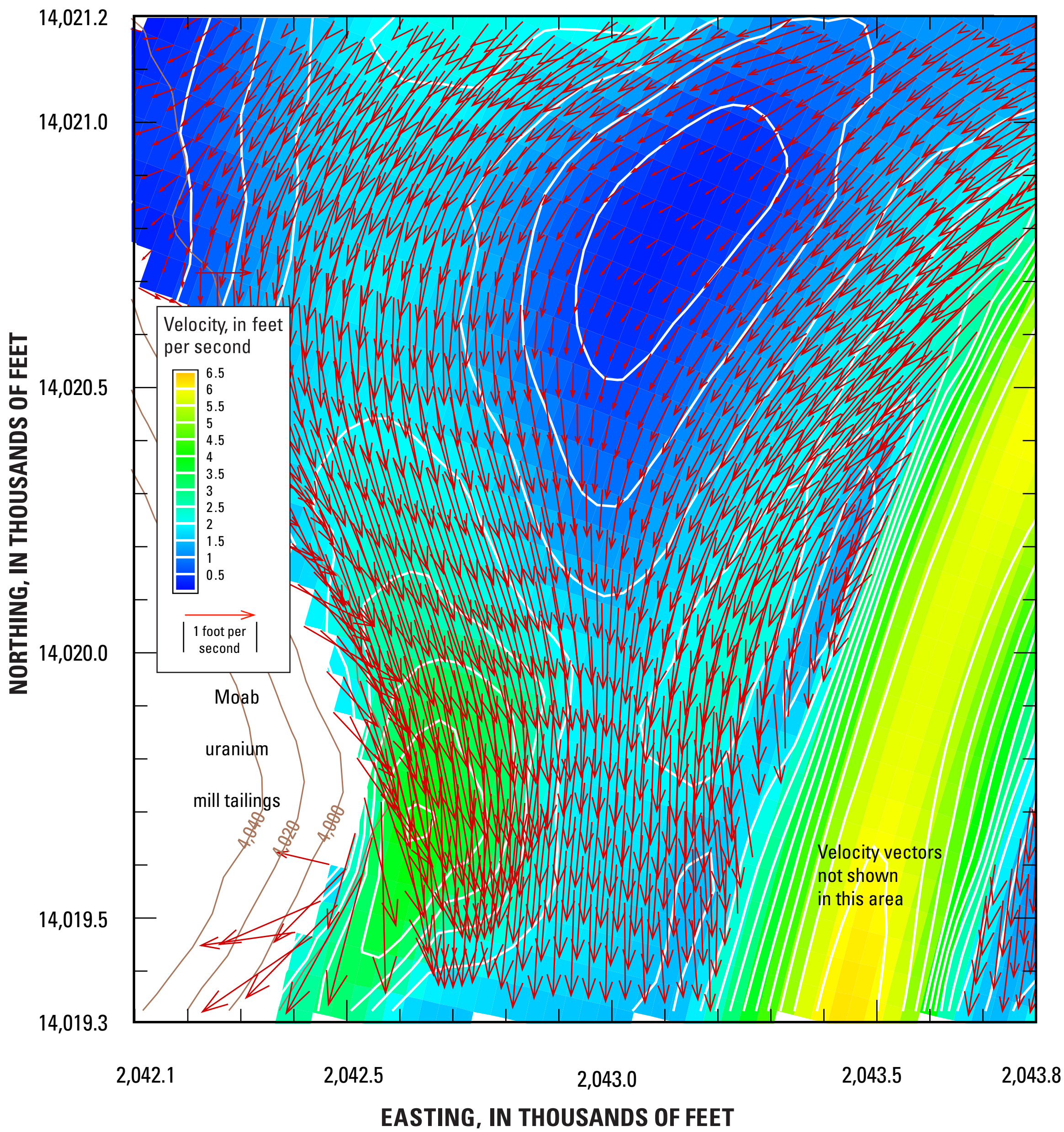


Figure 33. Predicted velocity vectors and contours near tailings pile for Probable-Maximum-Flood discharge and existing channel geometry configuration of the Colorado River in Moab Valley, Utah.

Predicted flow acceleration around the toe of the tailings pile can be seen.

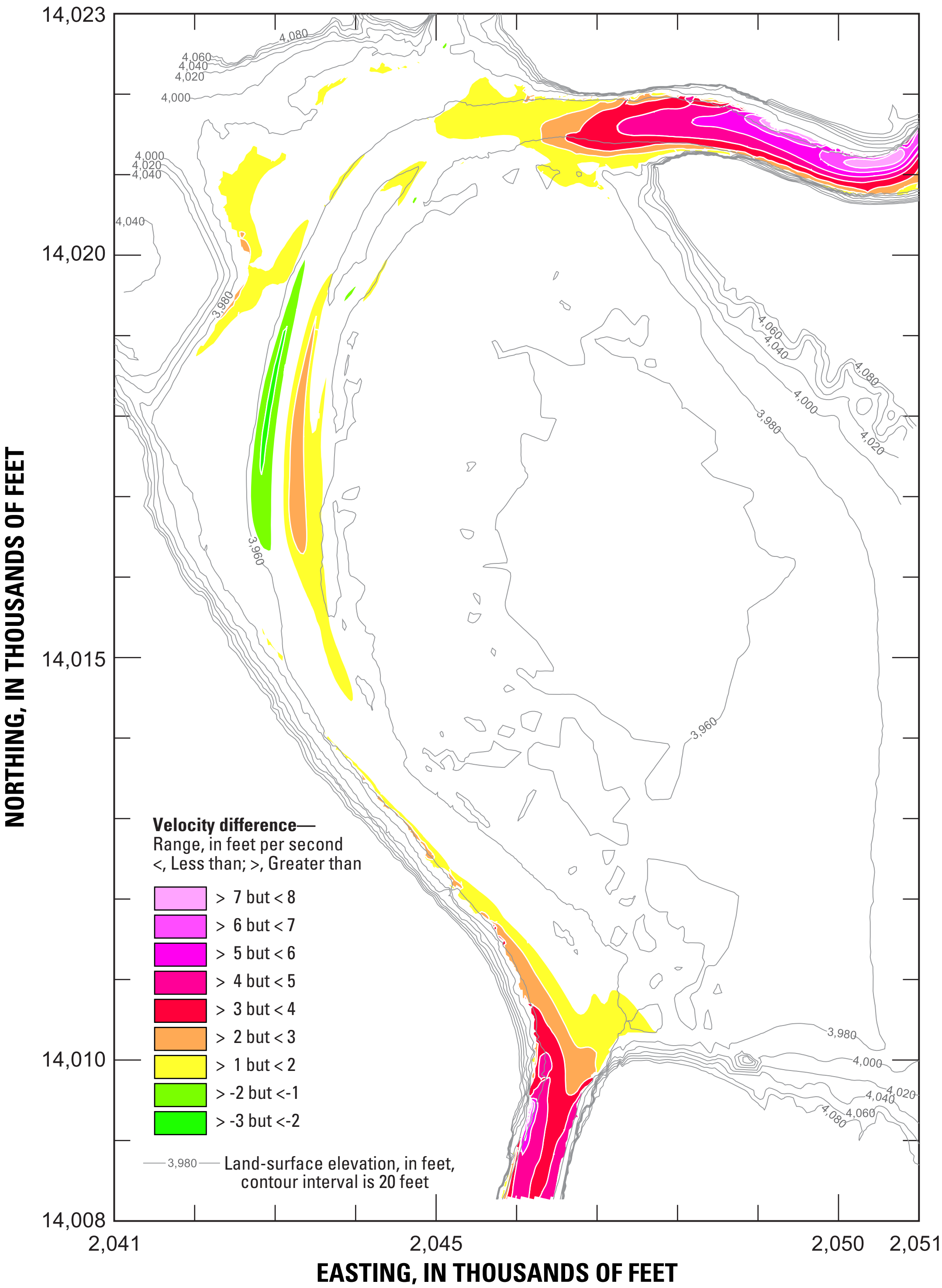


Figure 34. Predicted differences in velocity distributions for the Probable-Maximum-Flood discharge minus the 100-year discharge of the Colorado River in Moab Valley, Utah.

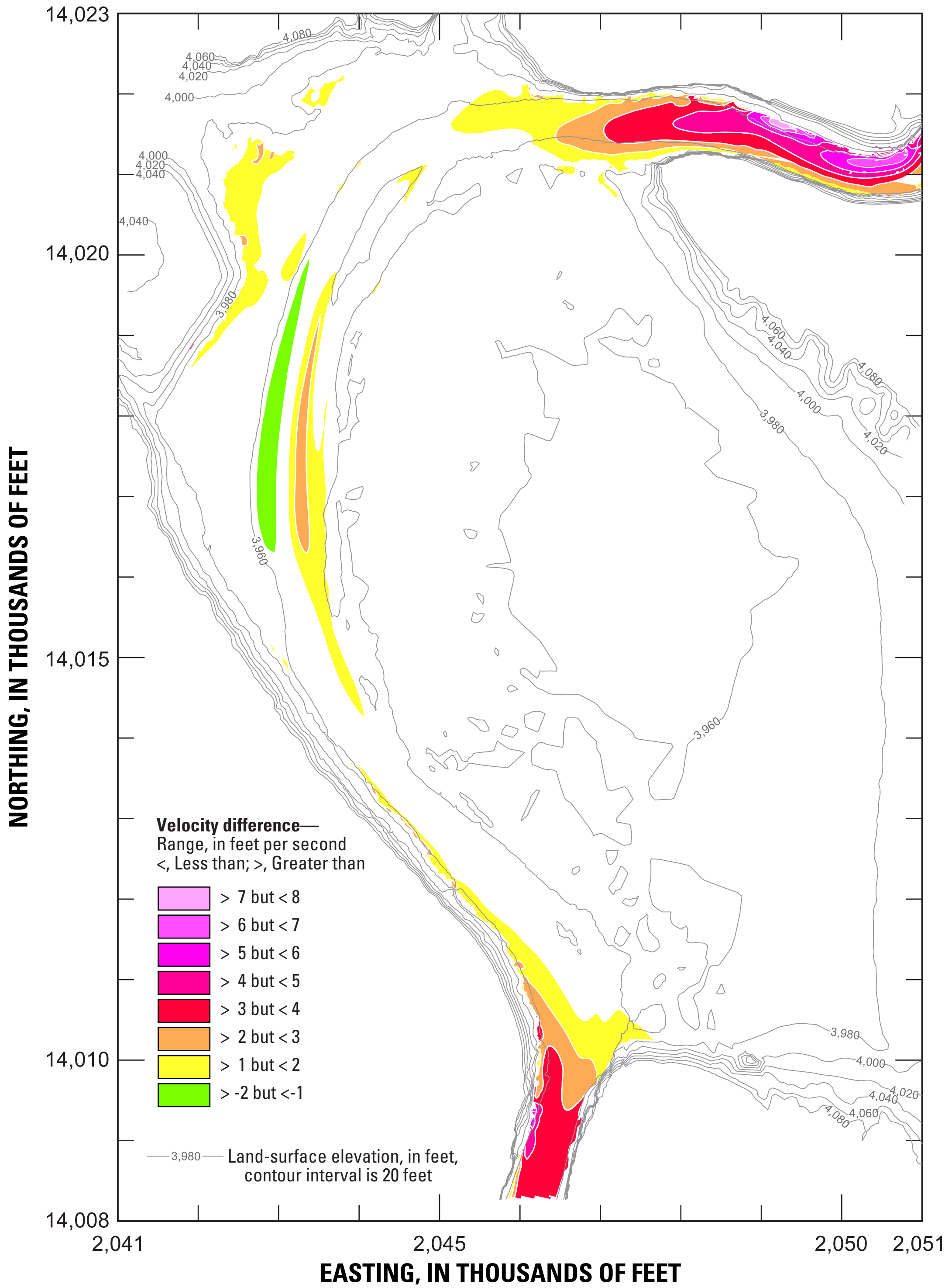


Figure 35. Predicted differences in velocity distributions for the Probable-Maximum-Flood discharge minus the 500-year discharge of the Colorado River in Moab Valley, Utah.

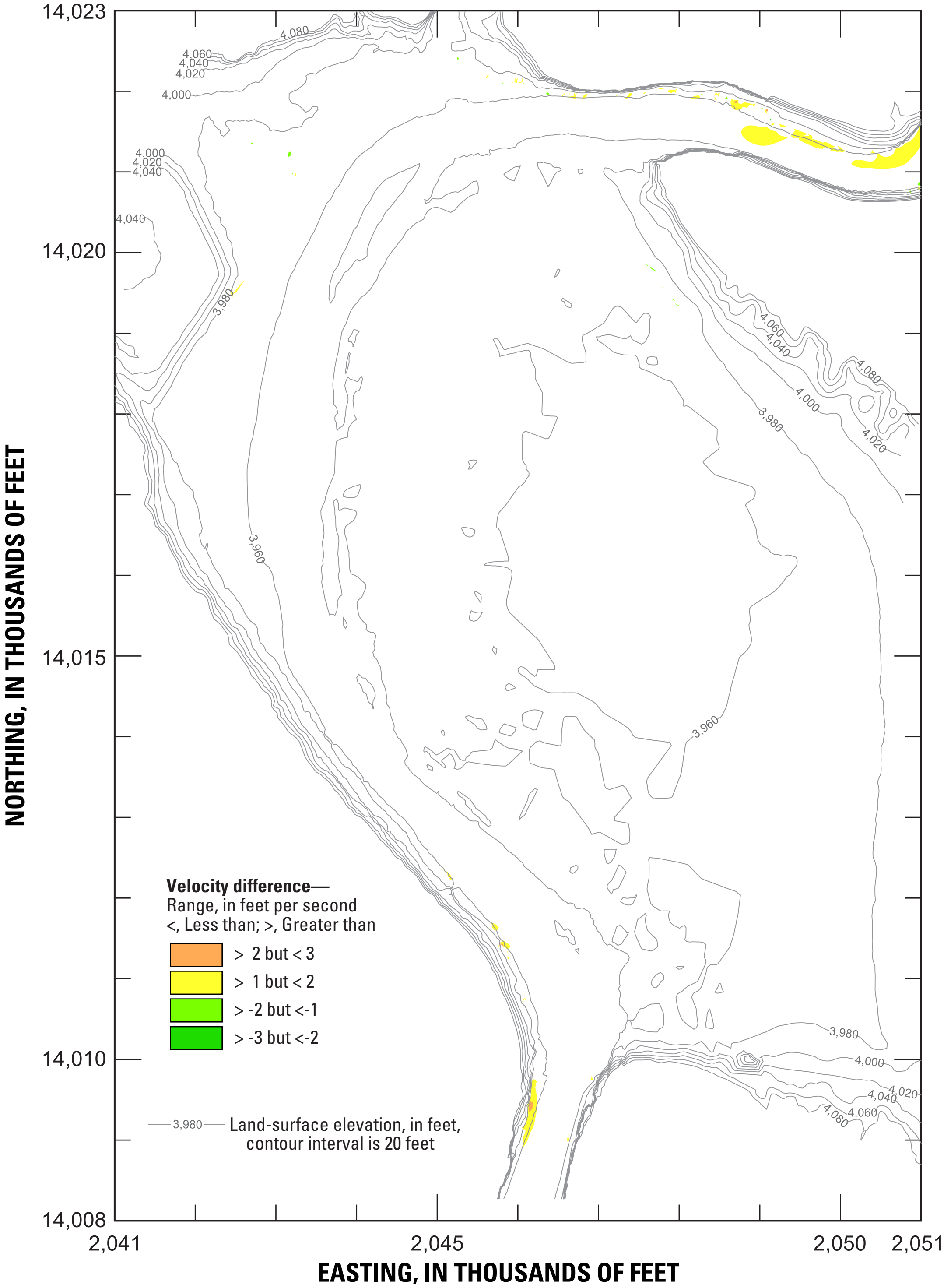


Figure 36. Predicted differences in velocity distributions for the 500-year discharge minus the 100-year discharge of the Colorado River in Moab Valley, Utah.

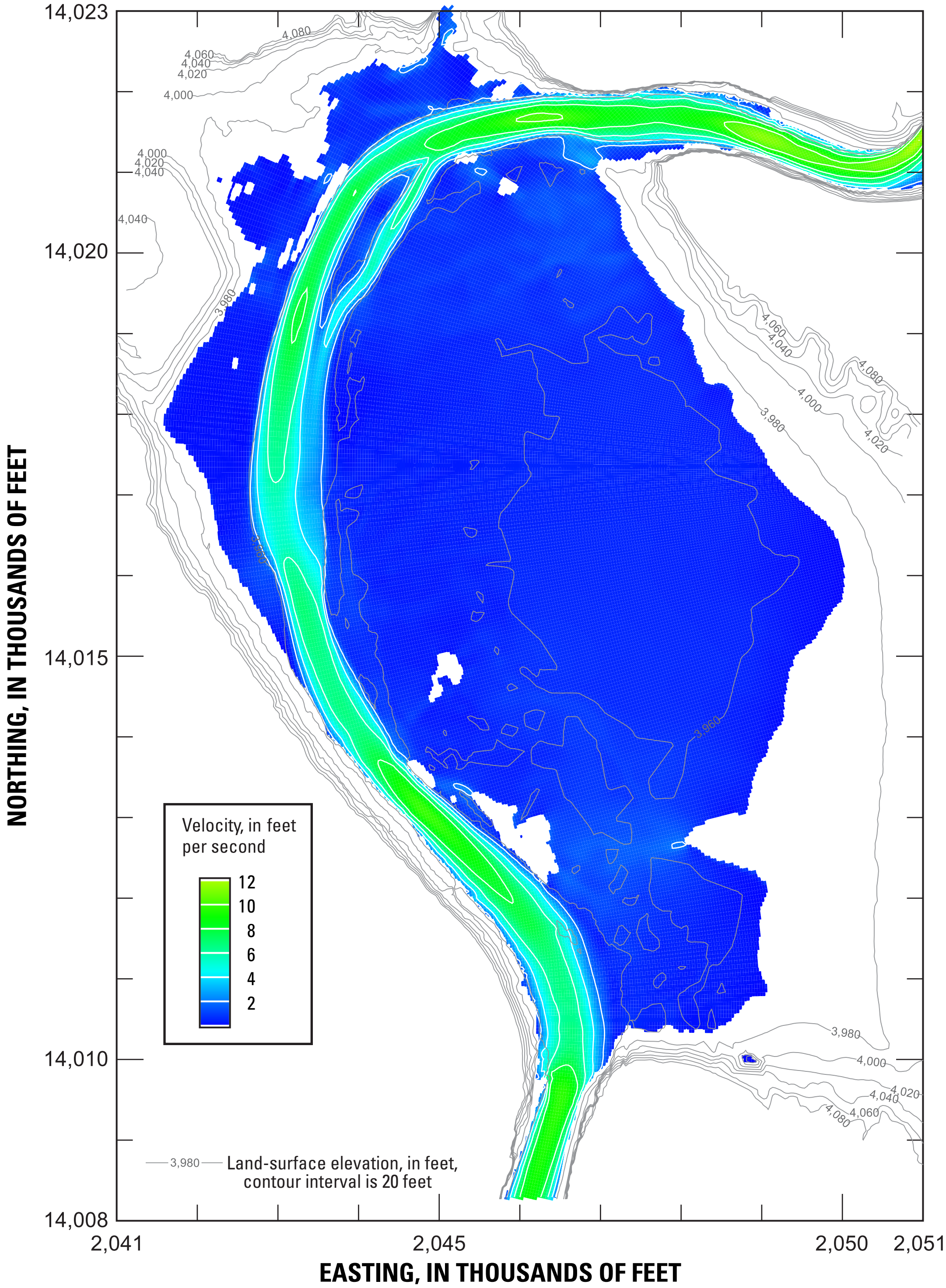


Figure 37. Predicted velocity distribution for 100-year discharge and hypothetical 10-foot scour configuration of the Colorado River in Moab Valley, Utah.

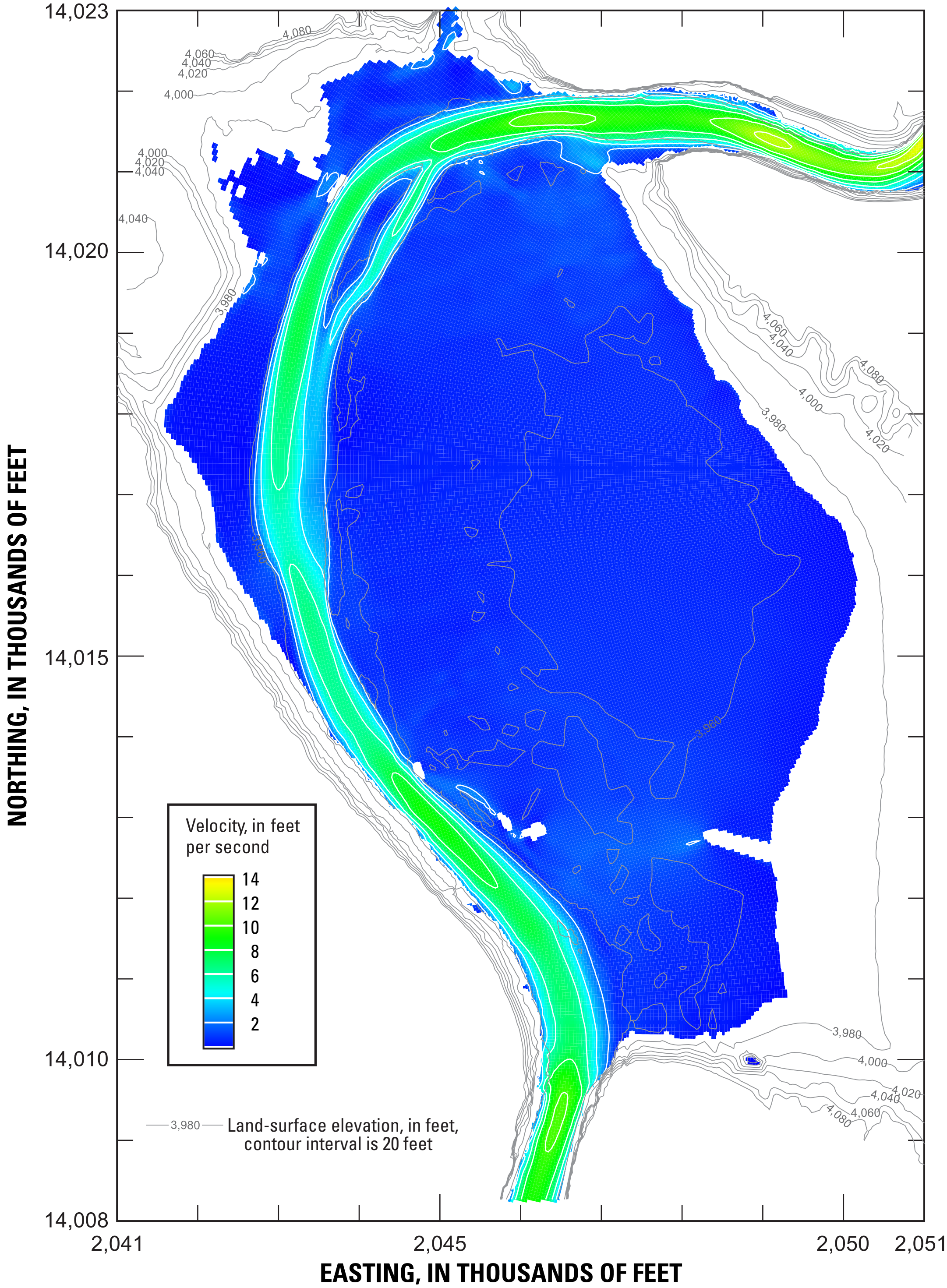


Figure 38. Predicted velocity distribution for 500-year discharge and hypothetical 10-foot scour configuration of the Colorado River in Moab Valley, Utah.

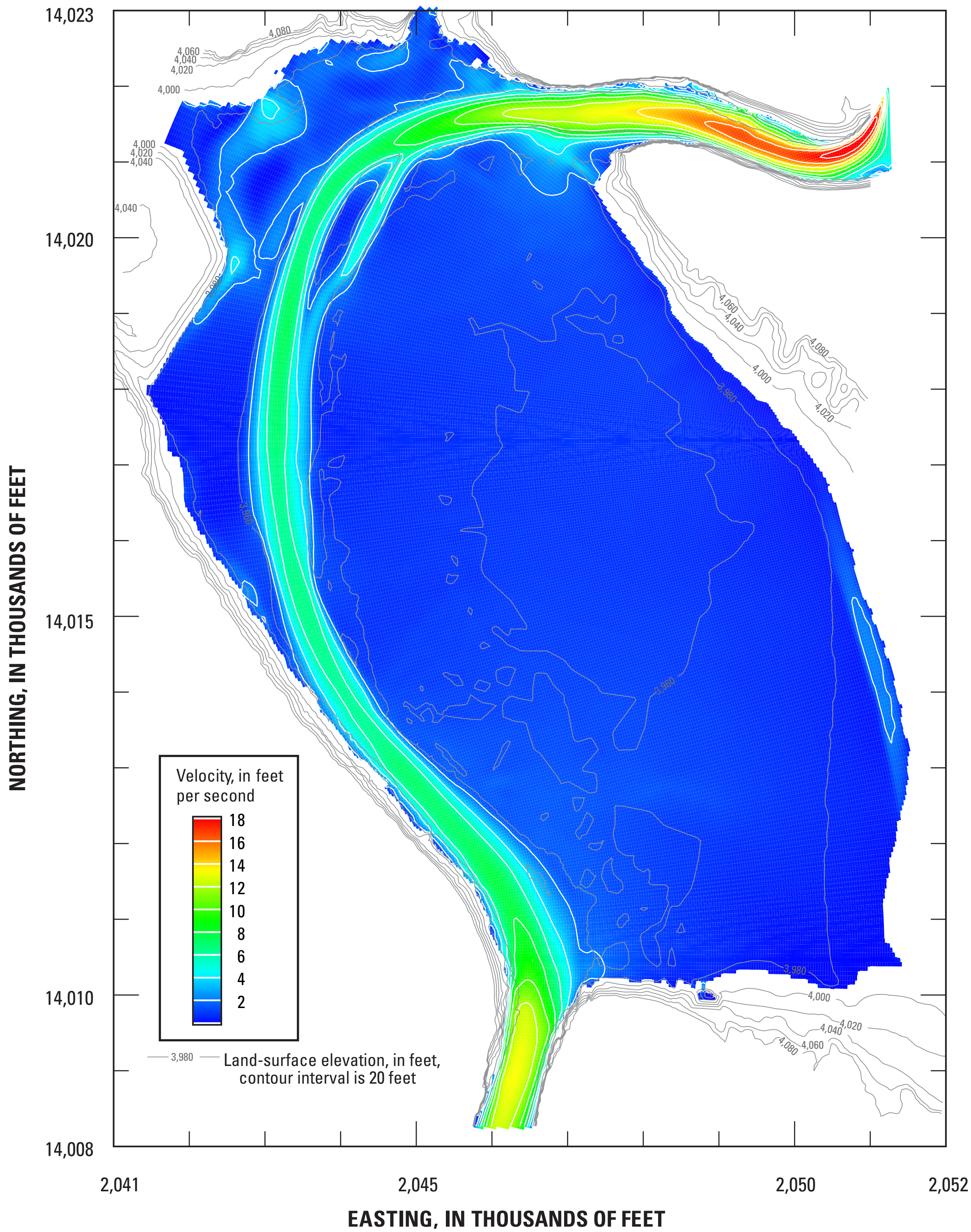


Figure 39. Predicted velocity distribution for Probable-Maximum-Flood discharge and hypothetical 10-foot scour configuration of the Colorado River in Moab Valley, Utah.

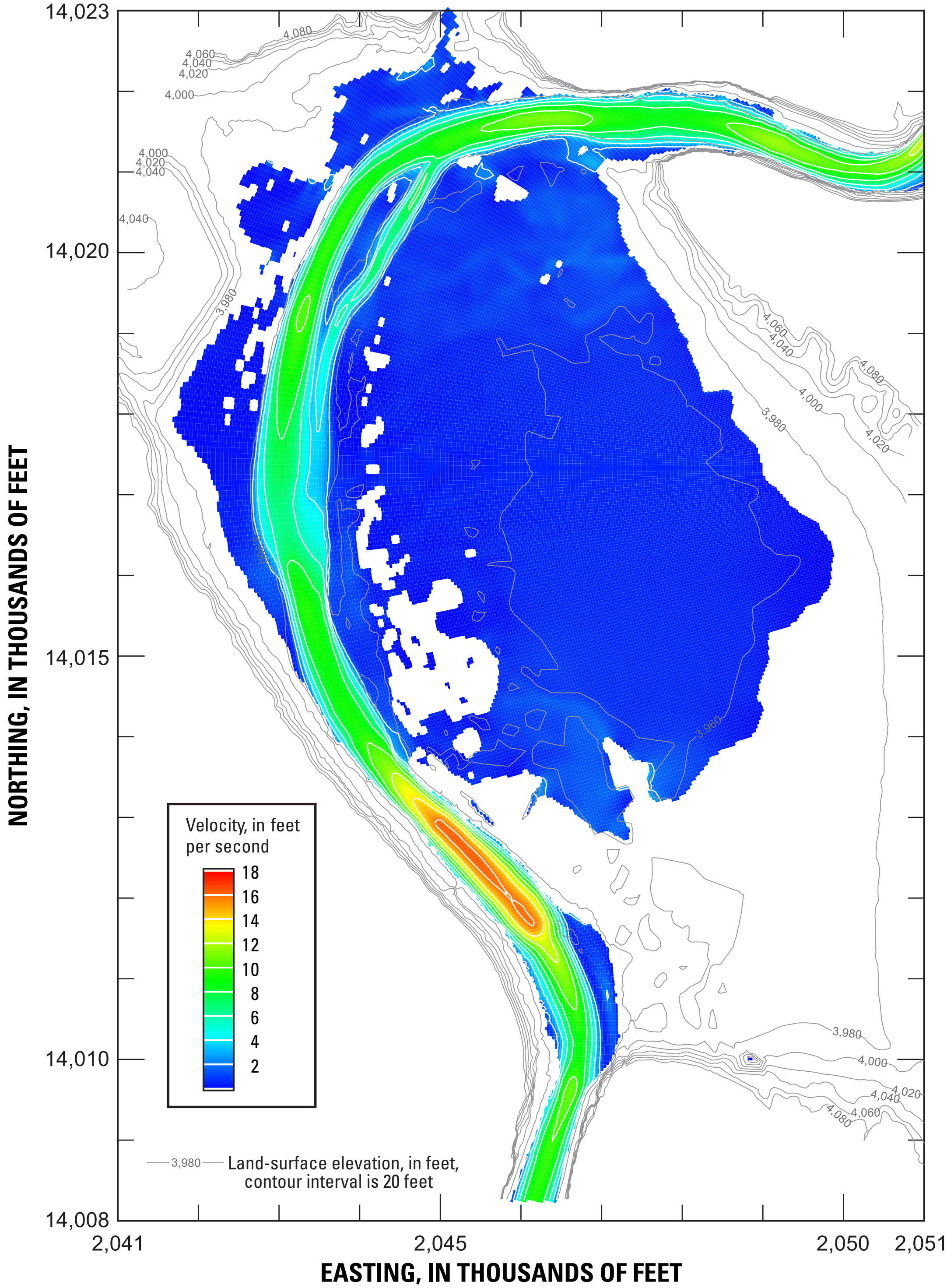


Figure 40. Predicted velocity distribution for 100-year discharge and hypothetical 25-foot scour configuration of the Colorado River in Moab Valley, Utah.

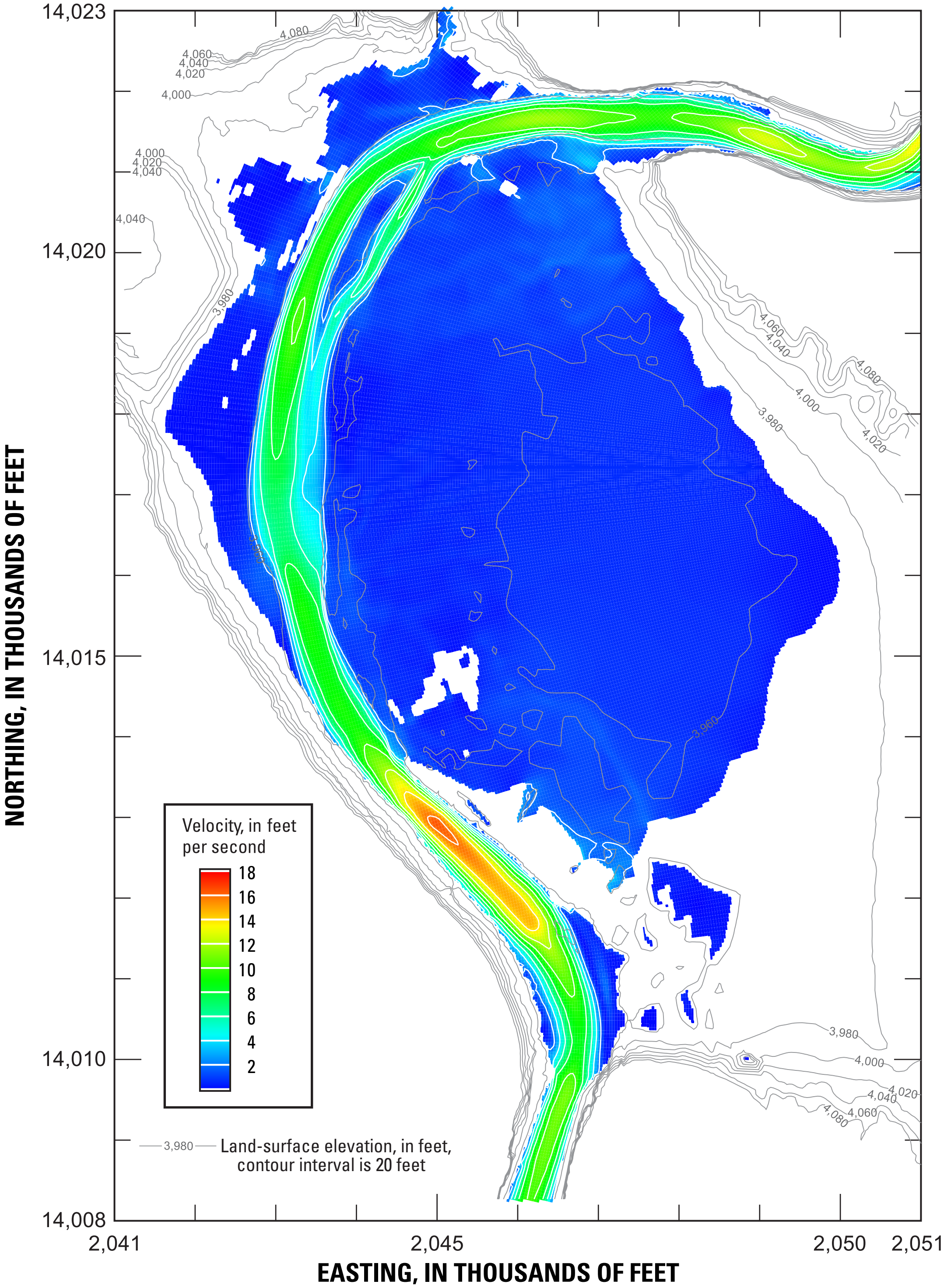


Figure 41. Predicted velocity distribution for 500-year discharge and hypothetical 25-foot scour configuration of the Colorado River in Moab Valley, Utah.

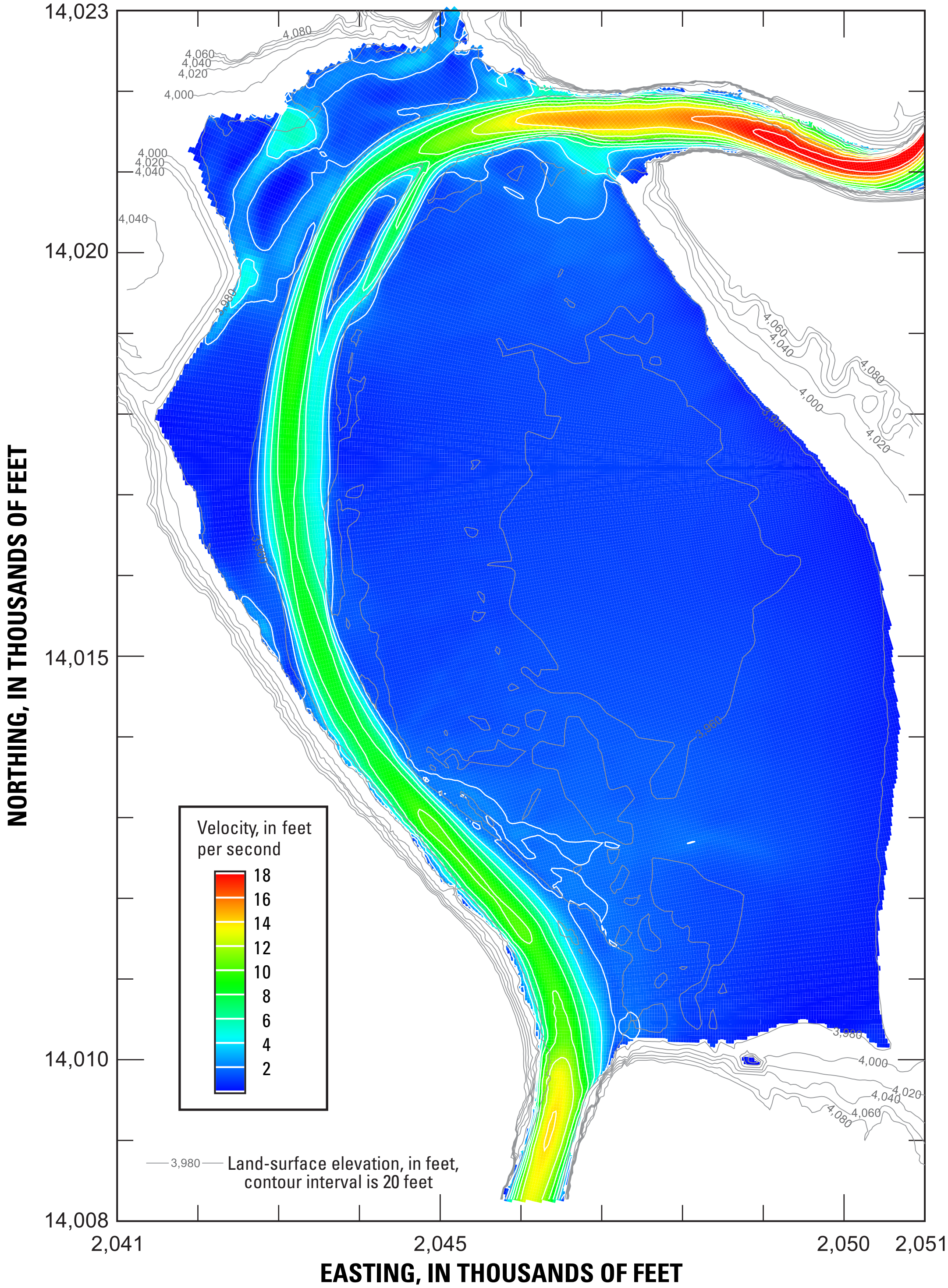


Figure 42. Predicted velocity distribution for Probable-Maximum-Flood discharge and hypothetical 25-foot scour configuration of the Colorado River in Moab Valley, Utah.

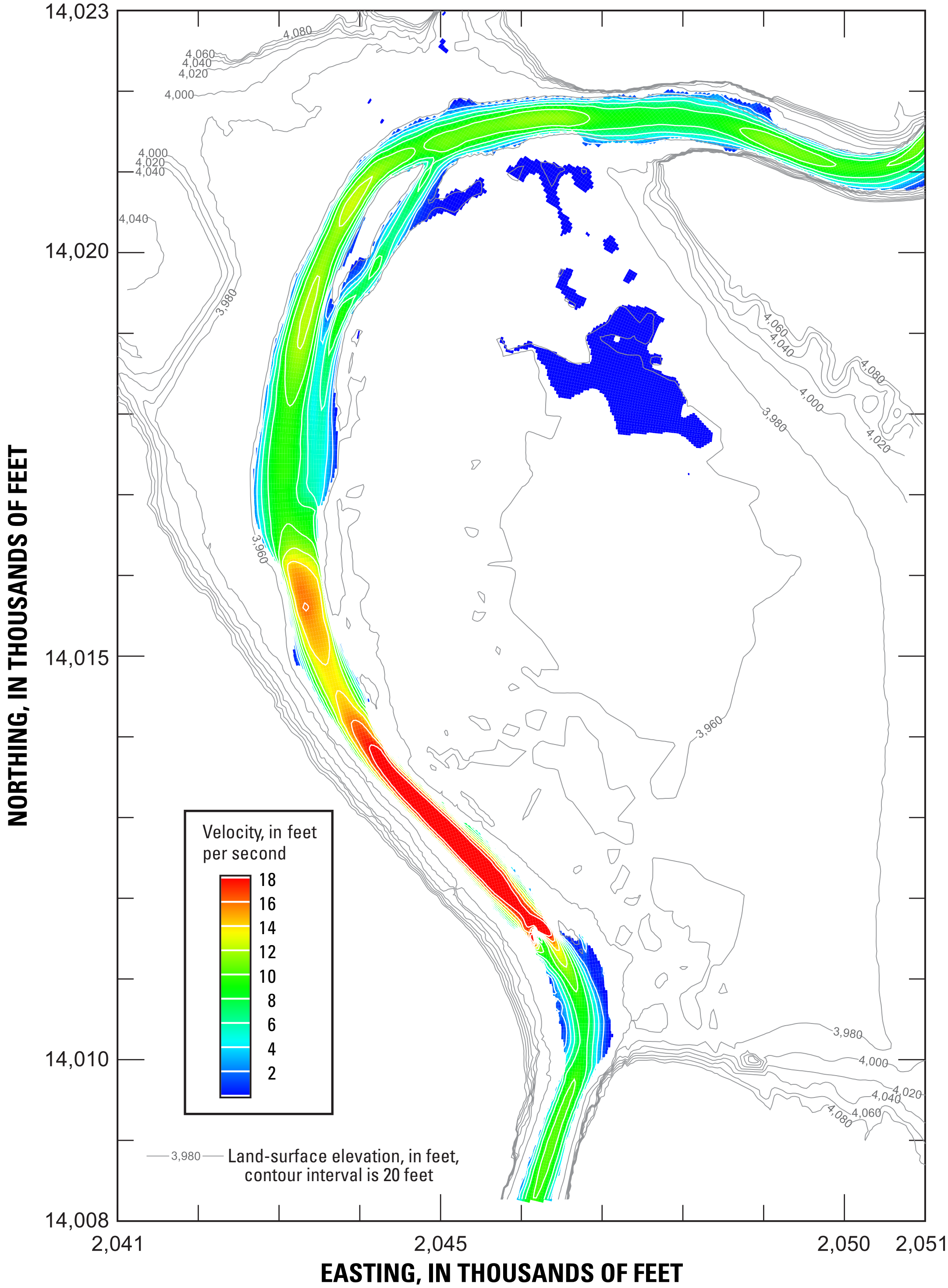


Figure 43. Predicted velocity distribution for 100-year discharge and hypothetical 50-foot scour configuration of the Colorado River in Moab Valley, Utah.

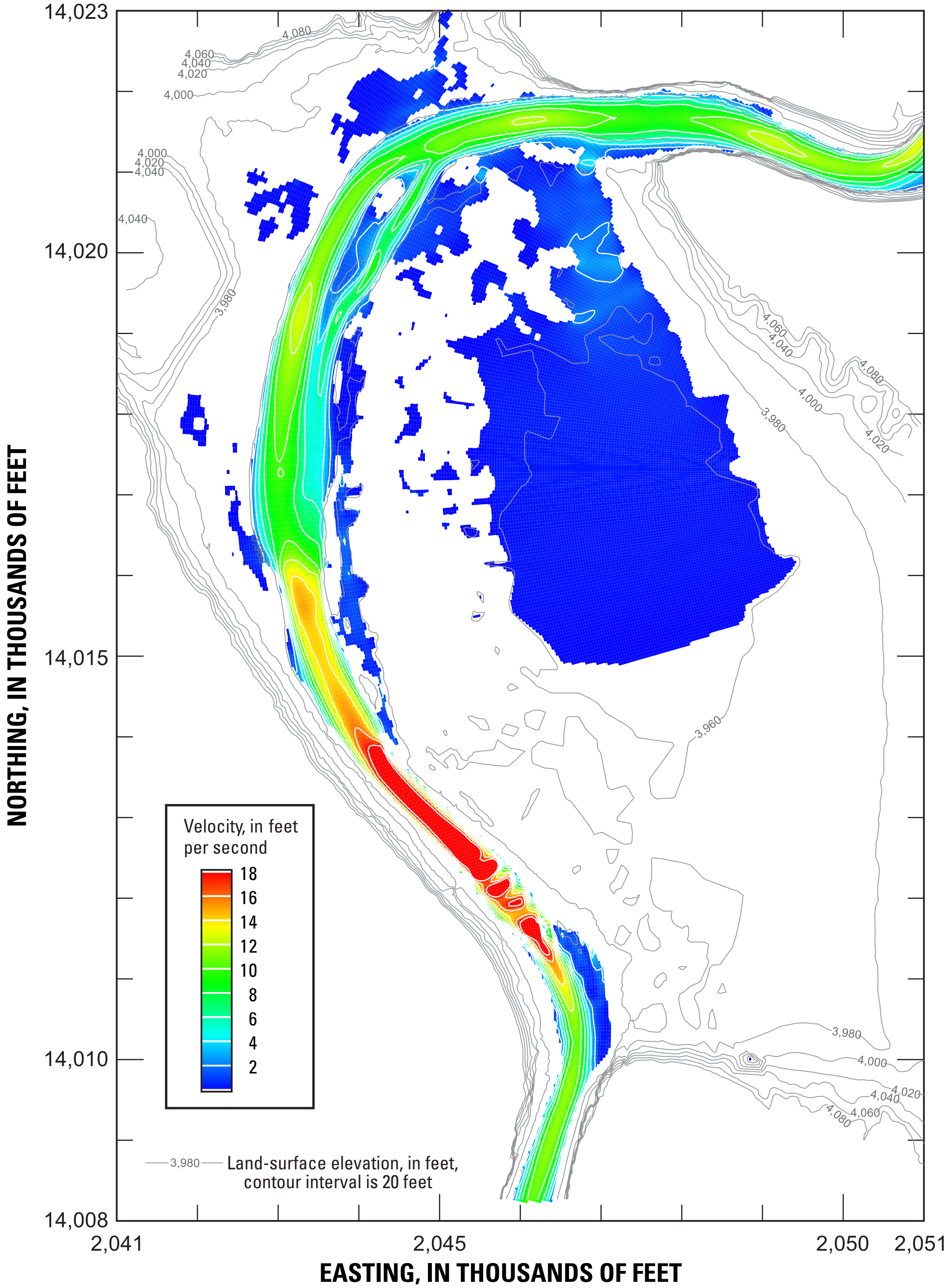


Figure 44. Predicted velocity distribution for 500-year discharge and hypothetical 50-foot scour configuration of the Colorado River in Moab Valley, Utah.

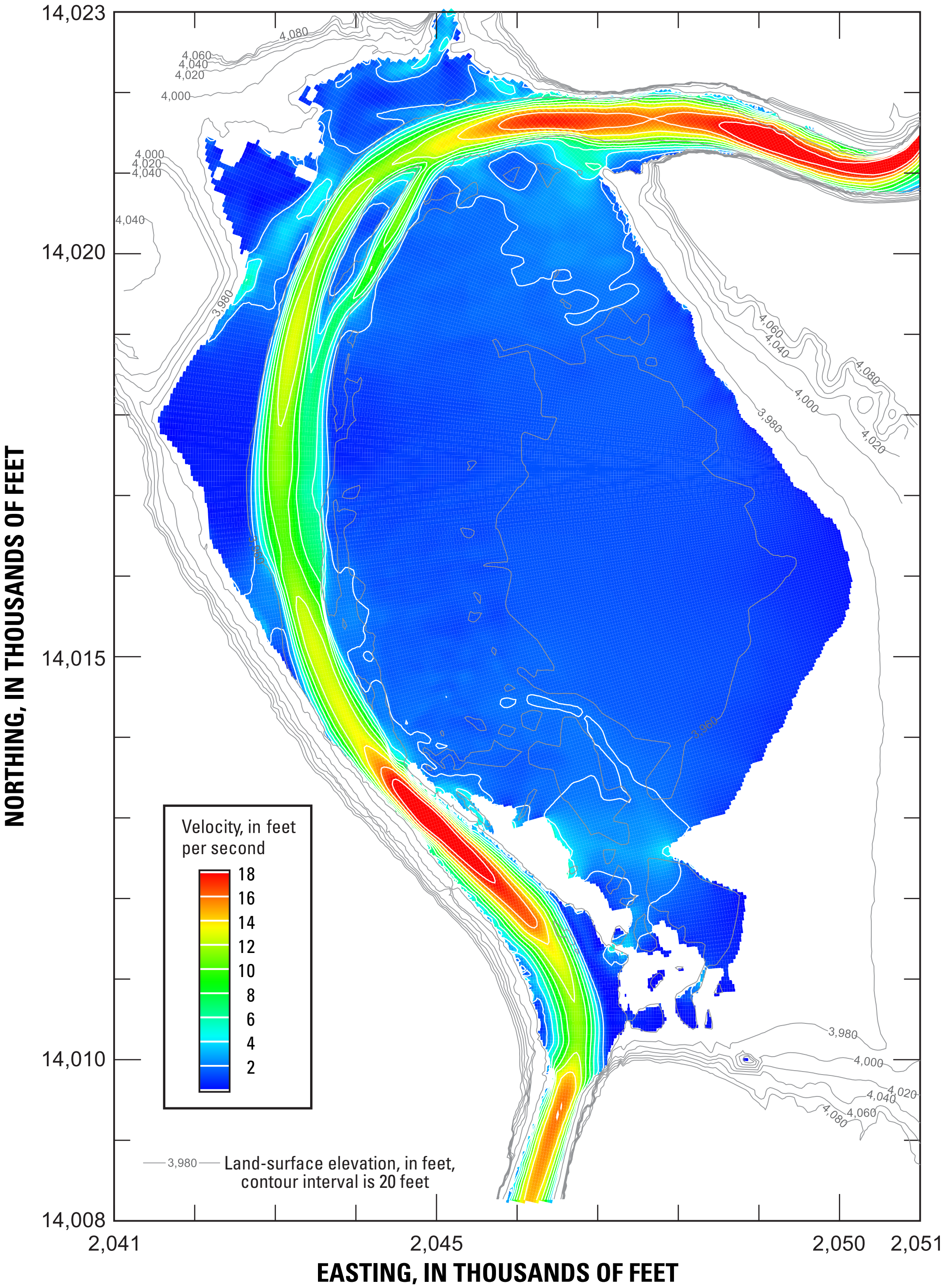


Figure 45. Predicted velocity distribution for Probable-Maximum-Flood discharge and hypothetical 50-foot scour configuration of the Colorado River in Moab Valley, Utah.

In solving boundary shear stress, equation 2 uses the drag coefficient for bottom stress closure (Nelson and others, 2003). In equation 2, increasing the drag coefficient for the same velocity will increase boundary shear stress by that same factor. For this investigation, a large drag coefficient was assigned to the over-bank areas occupied by tamarisk. This drag coefficient was representative of the flow-resistance characteristics of the tamarisk, specifically when flow occurs within the branches and leaves. When examining boundary sheer stress, it is important to distinguish between resistance related to form, described as form drag, and resistance associated specifically with bed materials, known as skin friction. For these reasons, the drag coefficient assigned to the areas occupied by tamarisk was partitioned into a skin-friction and a form-drag component prior to computing boundary shear-stress values by using the equation:

$$C_d = (C_{ds} + C_{df}) \quad (3)$$

where:

C_d is the nondimensional drag coefficient,
C_{ds} is the nondimensional skin friction, and
C_{df} is the nondimensional form drag.

Without quantified bed-resistance values for the over-bank region, a skin friction equal to the drag coefficient of the main channel was selected, 0.00276. Boundary shear-stress values for the areas occupied by tamarisk were computed by substituting C_{ds} for C_d in equation 2.

When modeling material transport, boundary shear-stress values are compared with empirically derived critical boundary shear-stress values for specific sediment grain sizes. Motion is assumed if the bed stress exceeds the critical shear stress. Boundary shear stress was predicted throughout the study reach for each of the simulated discharges and portal geometry configurations. To aid in the evaluation of these predicted stress values, plots were constructed with color levels developed from empirical critical shear-stress values of specific grain sizes. The sediment grade scale used in developing the color levels for the shear-stress plots is contained in table 2. Nondimensional critical shear-stress values for these grain sizes were obtained from the Shields diagram (fig. 46), after first computing nondimensional sediment grain sizes by using the equation:

$$d* = \left[\frac{\left(\left(\frac{\gamma_s}{\gamma}\right) - 1\right) g d^3}{v^2}\right] \quad (4)$$

where:

$d*$ is the nondimensional grain size,
γ_s is the specific weight of sediment, in lb/ft^3,
γ is the specific weight of water, in lb/ft^3,
g is the acceleration of gravity, in ft/s^2,
d is grain size, in ft, and
v is the kinematic viscosity of water, in ft^2/s.

Table 2. American Geophysical Union Sediment Grade Scale

[From Sturm, 2001]

Class name	Size range, in feet
Very coarse gravel	0.2100-0.1050
Coarse gravel	0.1050-0.0525
Medium gravel	0.0525-0.0262
Fine gravel	0.0262-0.0131
Very fine gravel	0.0131-0.0066
Very coarse sand	0.0066-0.0033
Coarse sand	0.0033-0.0016
Medium sand	0.0016-0.0008
Fine sand	0.0008-0.0004
Very fine sand	0.0004-0.0002

The nondimensional critical shear stress values acquired from the Shields diagram were then converted into dimensional critical shear-stress values by using the equation:

$$\tau_{bc} = \tau*_{bc}(\gamma_s/\gamma) - 1)\gamma d \quad (5)$$

where:

τ_{bc} is the dimensional critical boundary shear stress, in lb/ft^2,
$\tau*_{bc}$ is the nondimensional critical boundary shear stress,
γ_s is the specific weight of sediment, in lb/ft^3,
γ is the specific weight of water, in lb/ft^3, and
d is grain size, in ft.

Predicted boundary shear-stress values for each simulation were colored by the critical shear-stress values of specific grain sizes (figs. 47-58). Colors in these plots correspond to the largest predicted transportable grain size. The inundated areas occupied by tamarisk are delineated on the plots to convey the uncertainty that exists in these predicted shear-stress values.

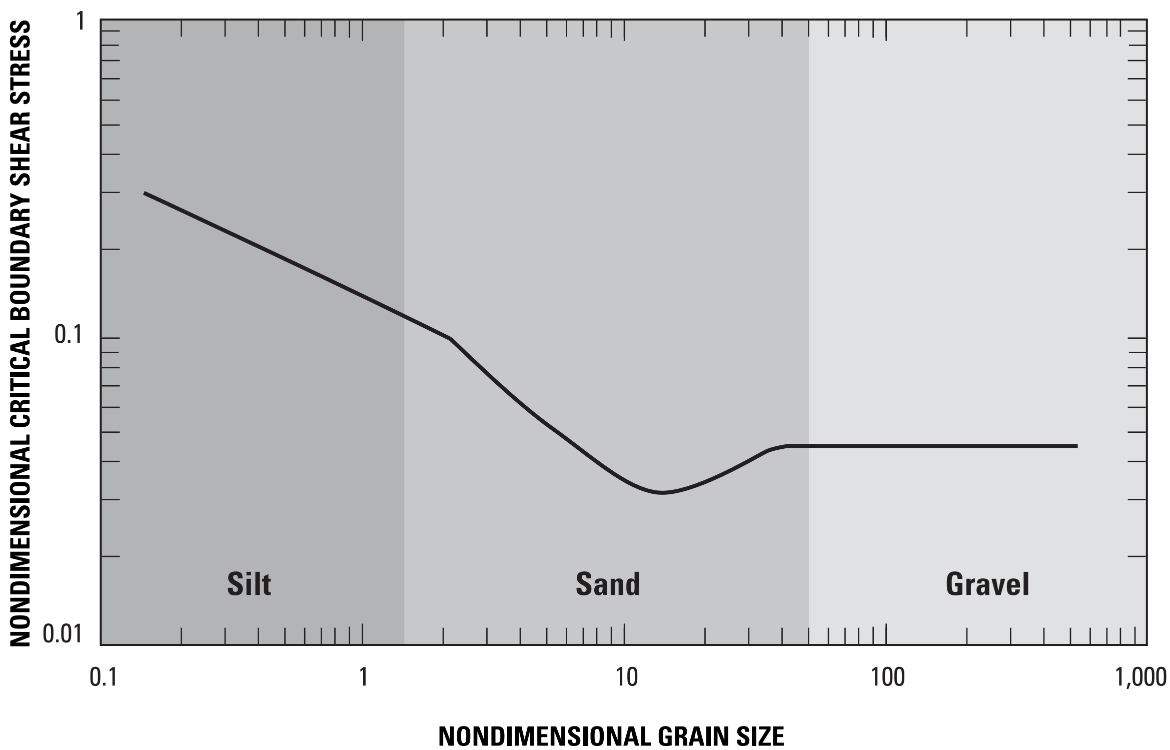


Figure 46. Alternate form of the Shields diagram for direct determination of critical shear stress. (Modified from Julien, 1995; and Sturm 2001)

Shear-Stress Distribution for Existing Channel Geometry

Predicted shear-stress distributions for the three discharges with existing channel configuration indicate stress levels in the main channel capable of transporting materials as large as medium-sized gravels throughout Moab Valley. The region unoccupied by tamarisk on the right bank upstream and adjacent to the tailings pile indicates predicted shear-stress values exceeding the critical shear stress of coarse sands for the 100-year discharge. Predicted shear stresses for the PMF discharge in this region increased in both magnitude and spatial extent. The simulated PMF discharge shows an overall amplification of shear-stress values predicted for the 100- and 500-year discharges.

Shear-Stress Distribution for Hypothetical Channel Geometries

Predicted shear-stress distributions for the hypothetical channel geometry simulations tend to show an increase in main-channel bed stress with the decrease in bed elevation at the downstream portal. The experimental channel adjustments substantially increased channel slope through the reach, which increased predicted flow velocities and shearing forces. Predicted shear-stress values within the over-bank area between the tailings pile and river channel do not appear to expand with the experimental deepening of the downstream portal for the 100- and 500-year discharges, likely as a result of less over-bank flow. Predicted shear-stress values in this area for the PMF discharge are greatest for the 25-foot scouring scenario.

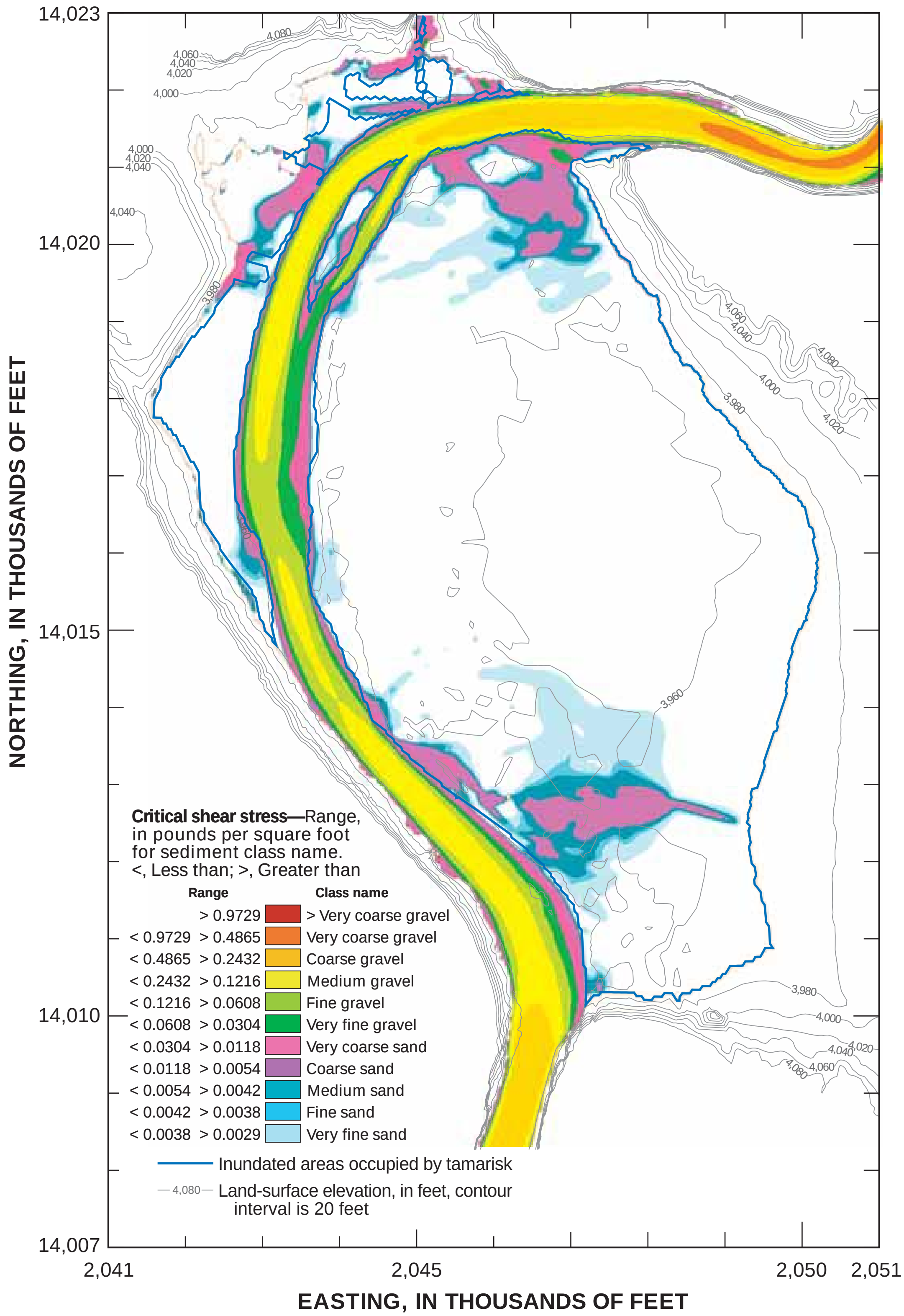


Figure 47. Predicted shear-stress distribution colored by grain-size critical shear-stress values for 100-year discharge and existing channel geometry configuration of the Colorado River in Moab Valley, Utah.

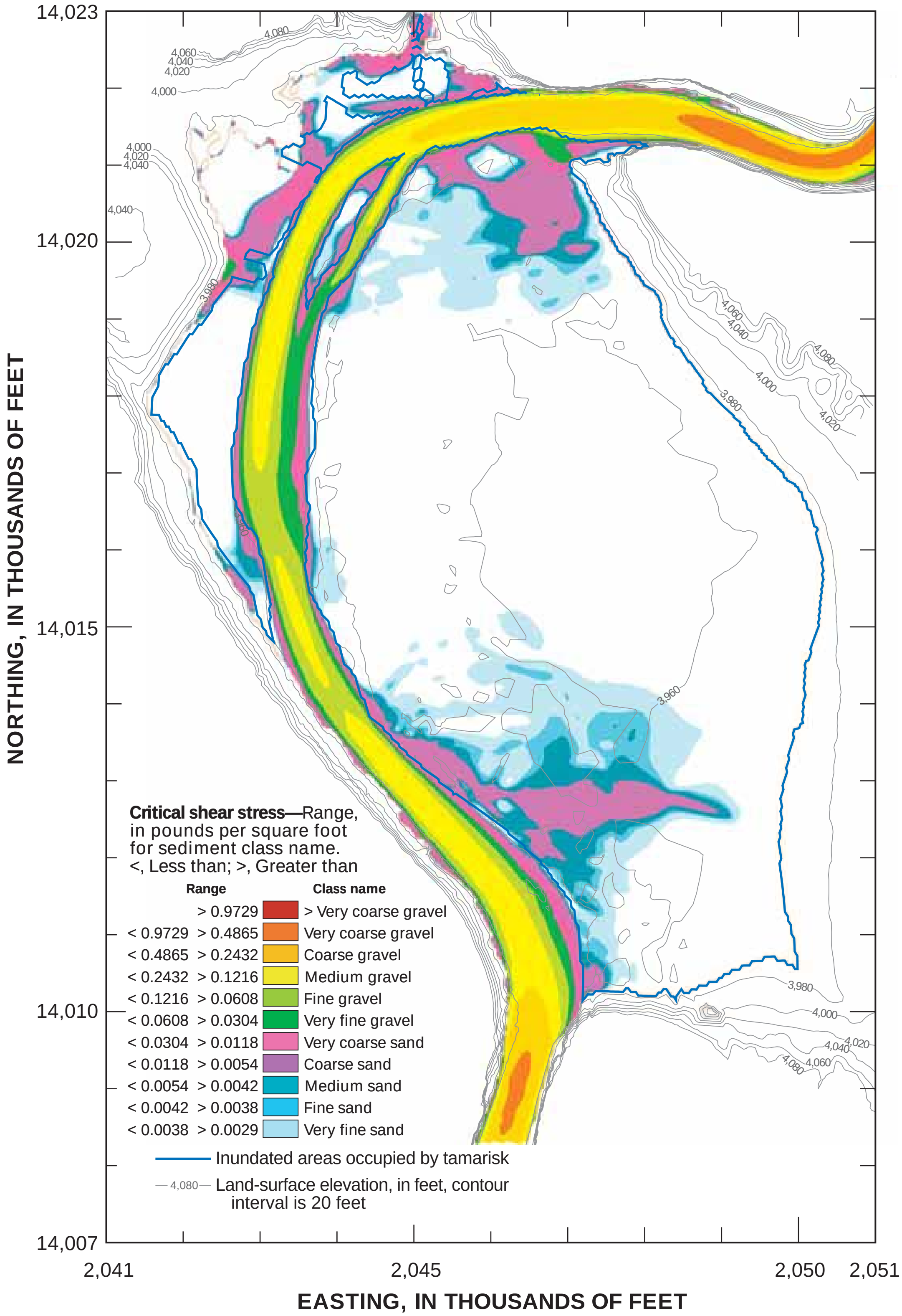


Figure 48. Predicted shear-stress distribution colored by grain-size critical shear-stress values for 500-year discharge and existing channel geometry configuration of the Colorado River in Moab Valley, Utah.

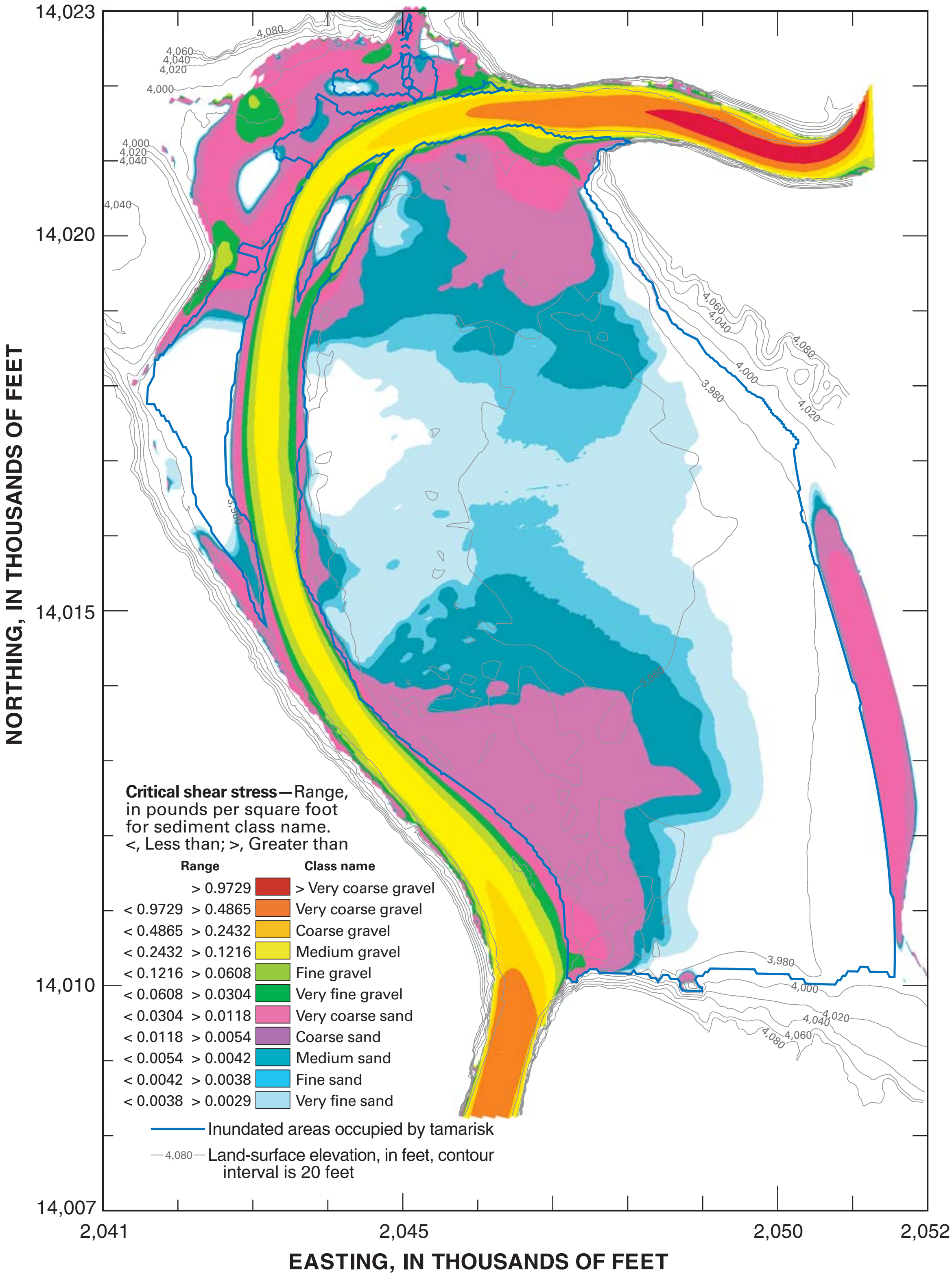


Figure 49. Predicted shear-stress distribution colored by grain-size critical shear-stress values for Probable-Maximum-Flood discharge and existing channel geometry configuration of the Colorado River in Moab Valley, Utah.

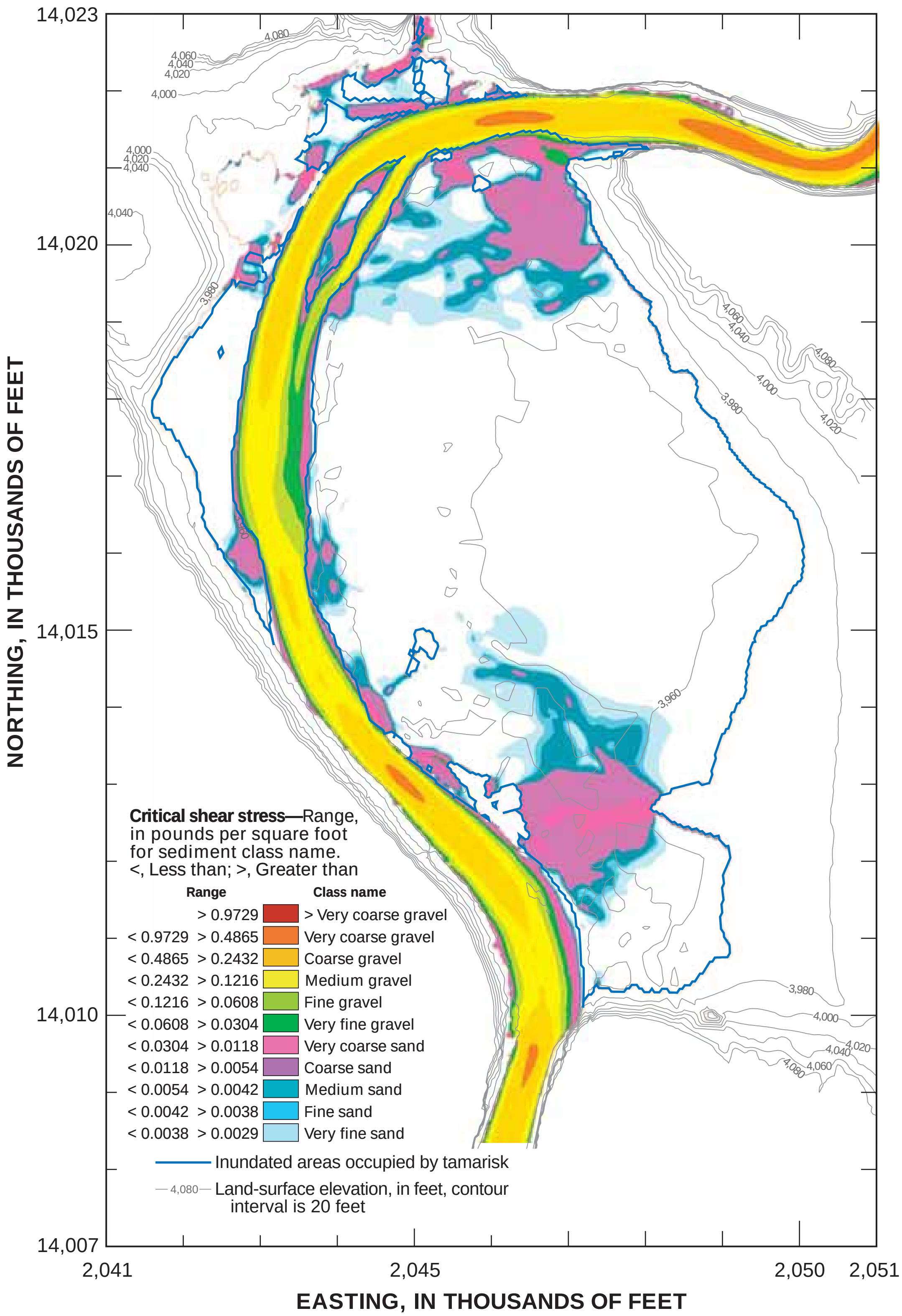


Figure 50. Predicted shear-stress distribution colored by grain-size critical shear-stress values for 100-year discharge and hypothetical 10-foot scour configuration of the Colorado River in Moab Valley, Utah.

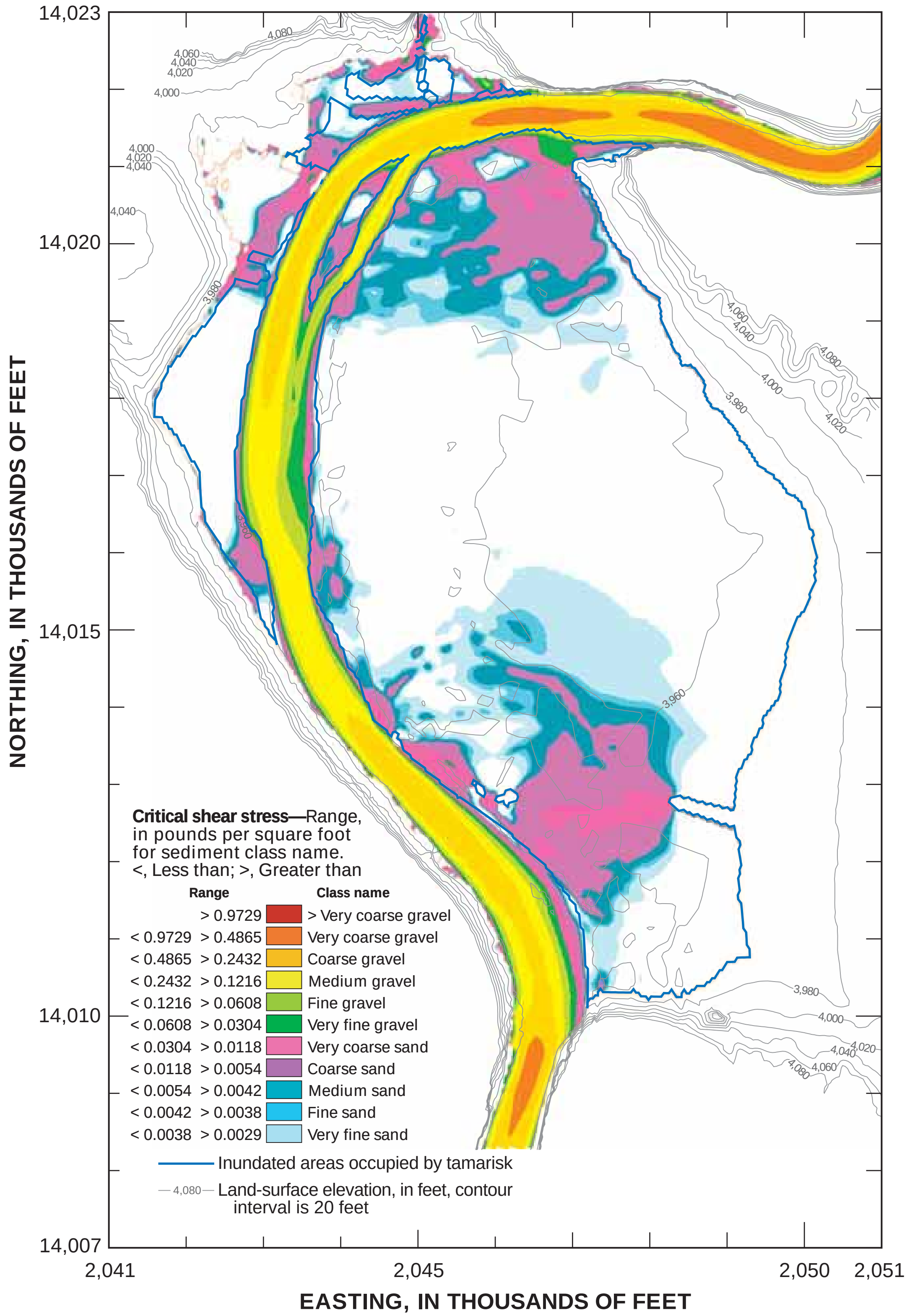


Figure 51. Predicted shear-stress distribution colored by grain-size critical shear-stress values for 500-year discharge and hypothetical 10-foot scour configuration of the Colorado River in Moab Valley, Utah.

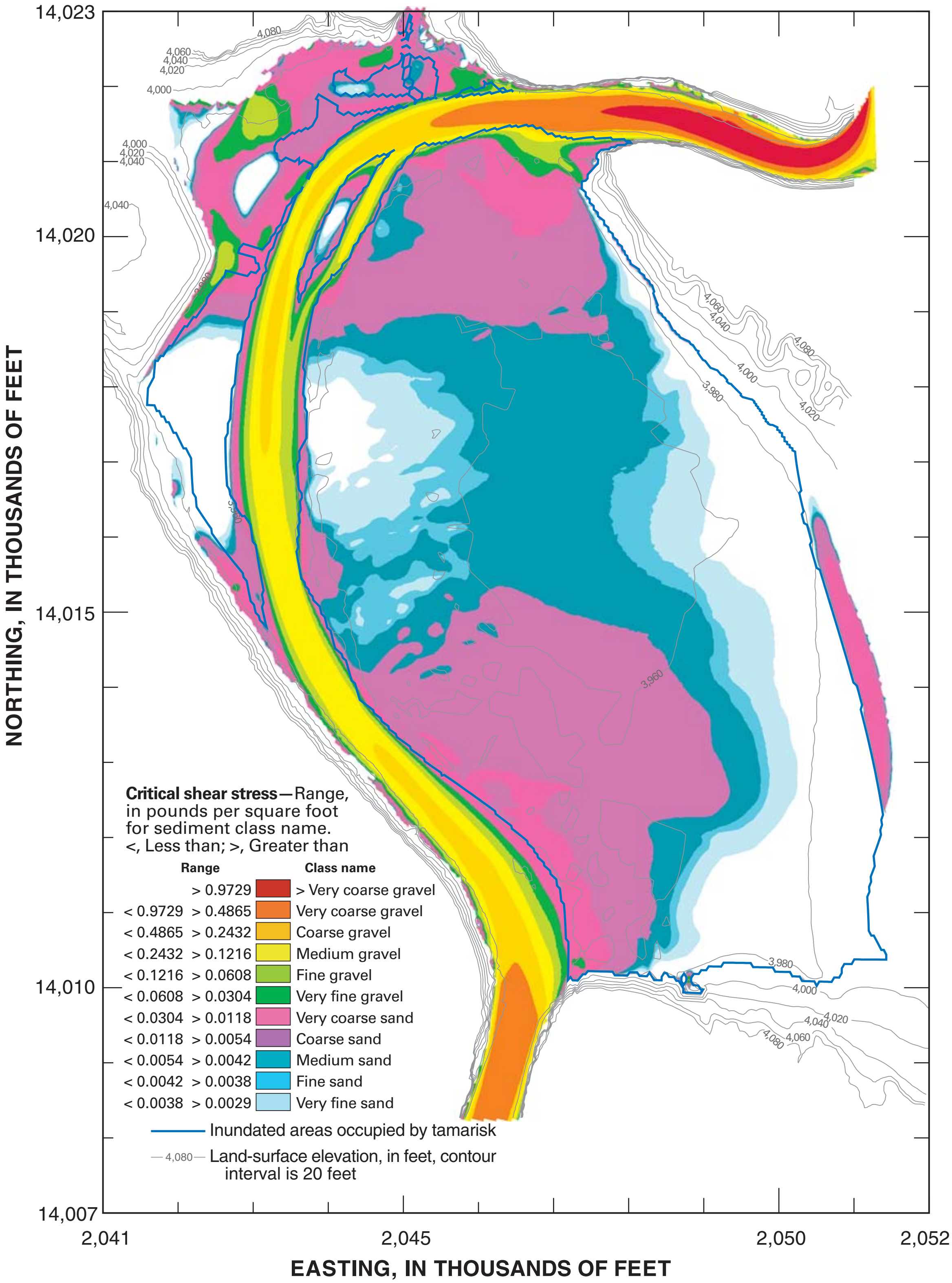


Figure 52. Predicted shear-stress distribution colored by grain-size critical shear-stress values for Probable-Maximum-Flood discharge and hypothetical 10-foot scour configuration of the Colorado River in Moab Valley, Utah.

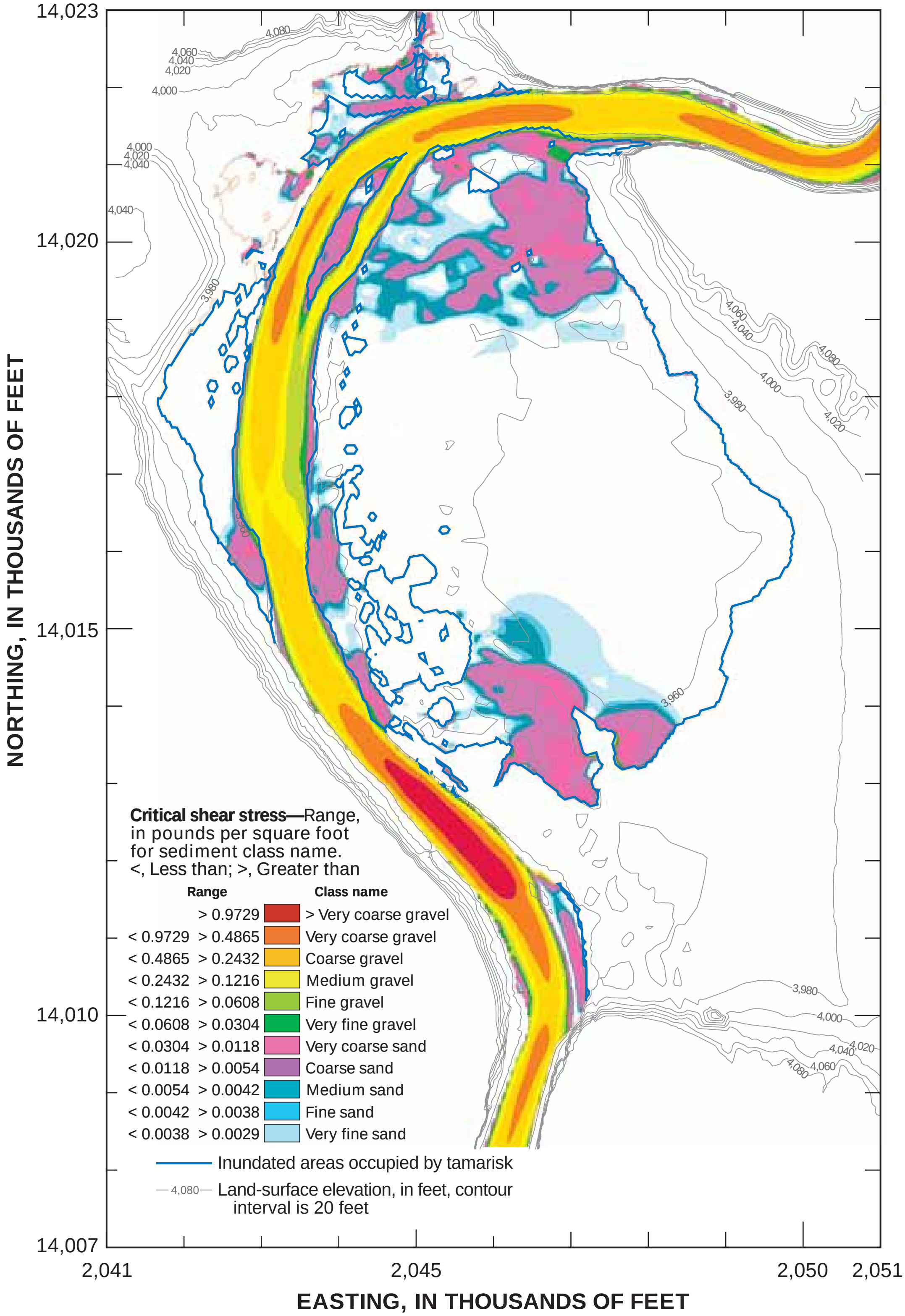


Figure 53. Predicted shear-stress distribution colored by grain-size critical shear-stress values for 100-year discharge and hypothetical 25-foot scour configuration of the Colorado River in Moab Valley, Utah.

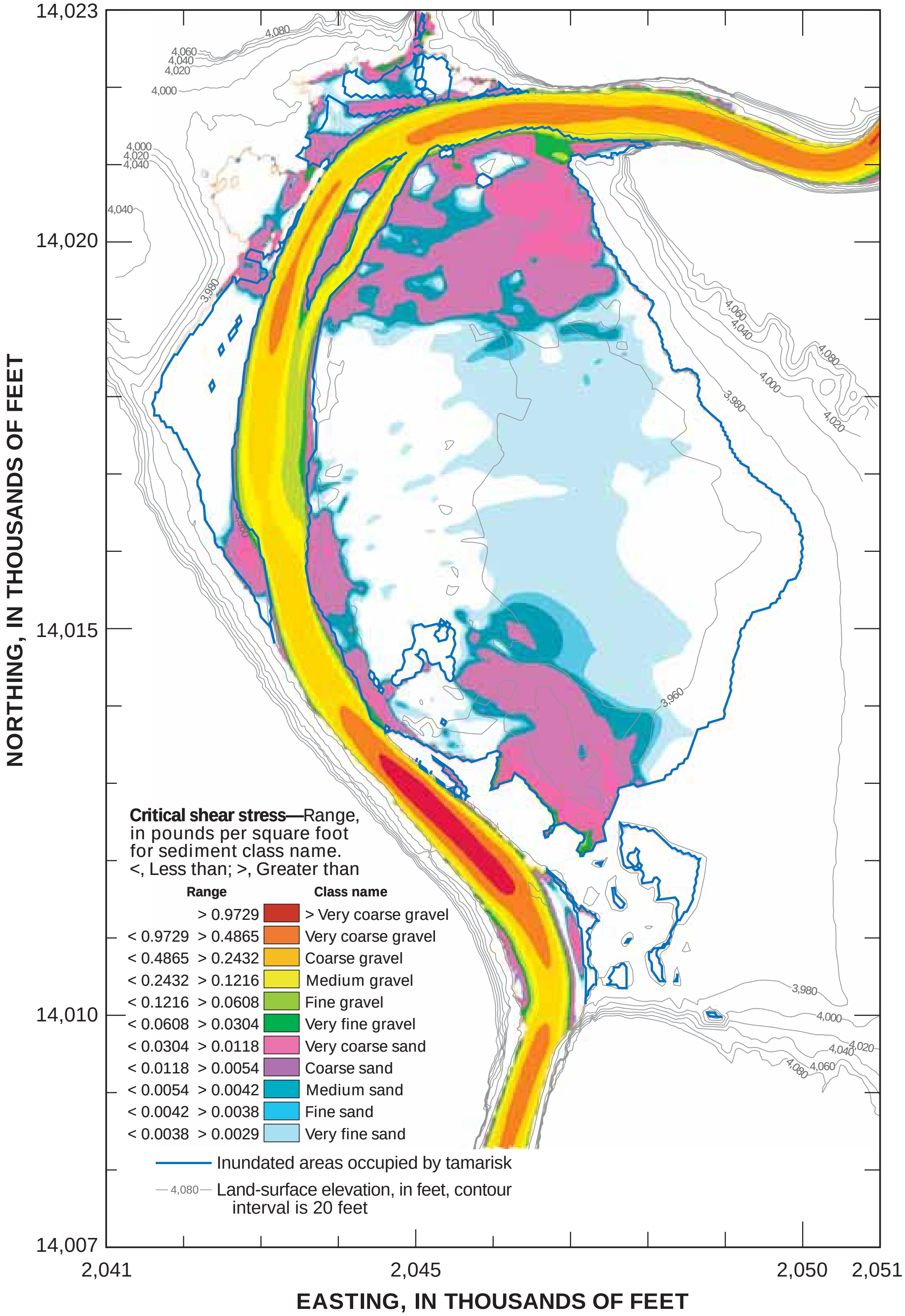


Figure 54. Predicted shear-stress distribution colored by grain-size critical shear-stress values for 500-year discharge and hypothetical 25-foot scour configuration of the Colorado River in Moab Valley, Utah.

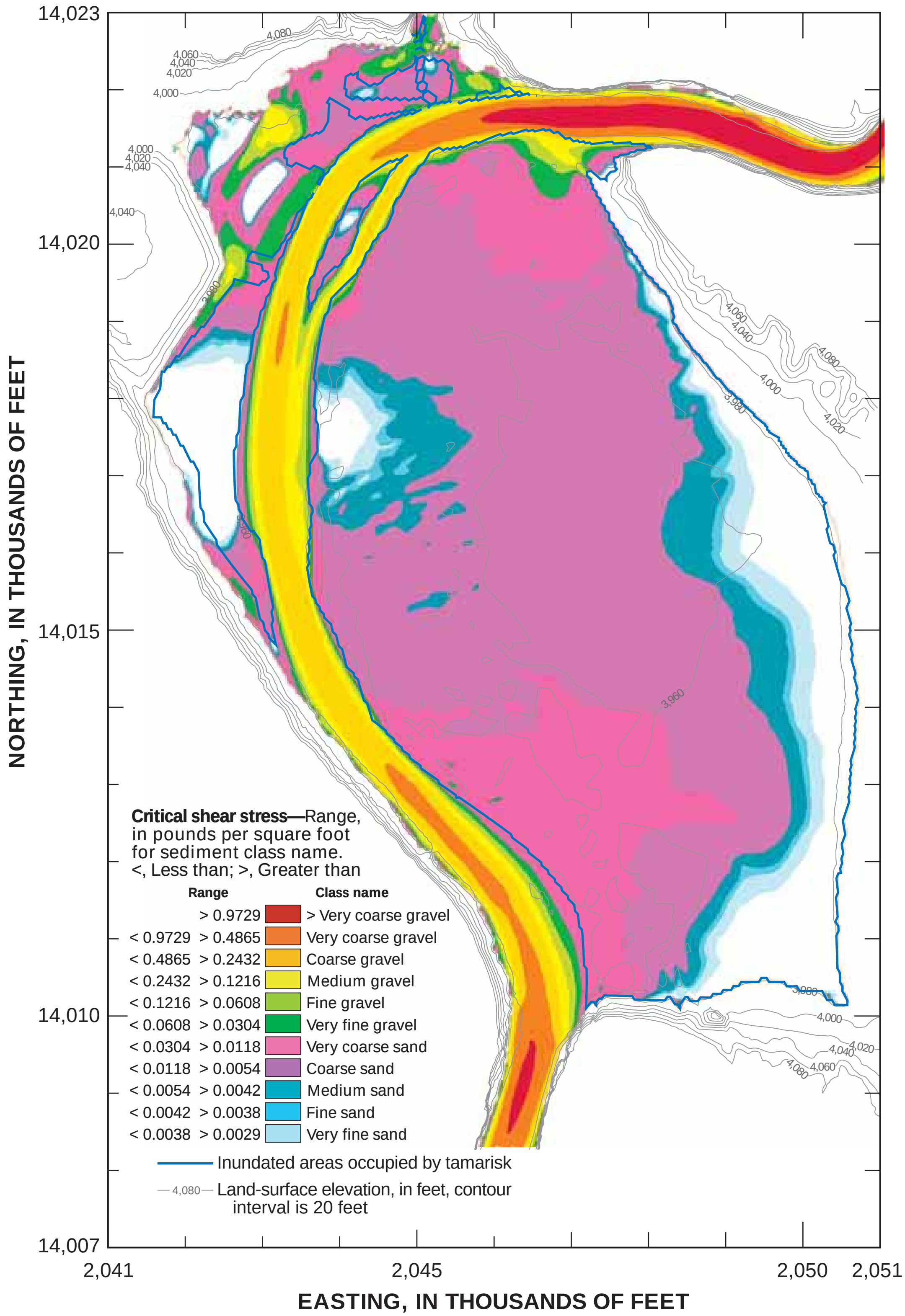


Figure 55. Predicted shear-stress distribution colored by grain-size critical shear-stress values for Probable-Maximum-Flood discharge and hypothetical 25-foot scour configuration of the Colorado River in Moab Valley, Utah.

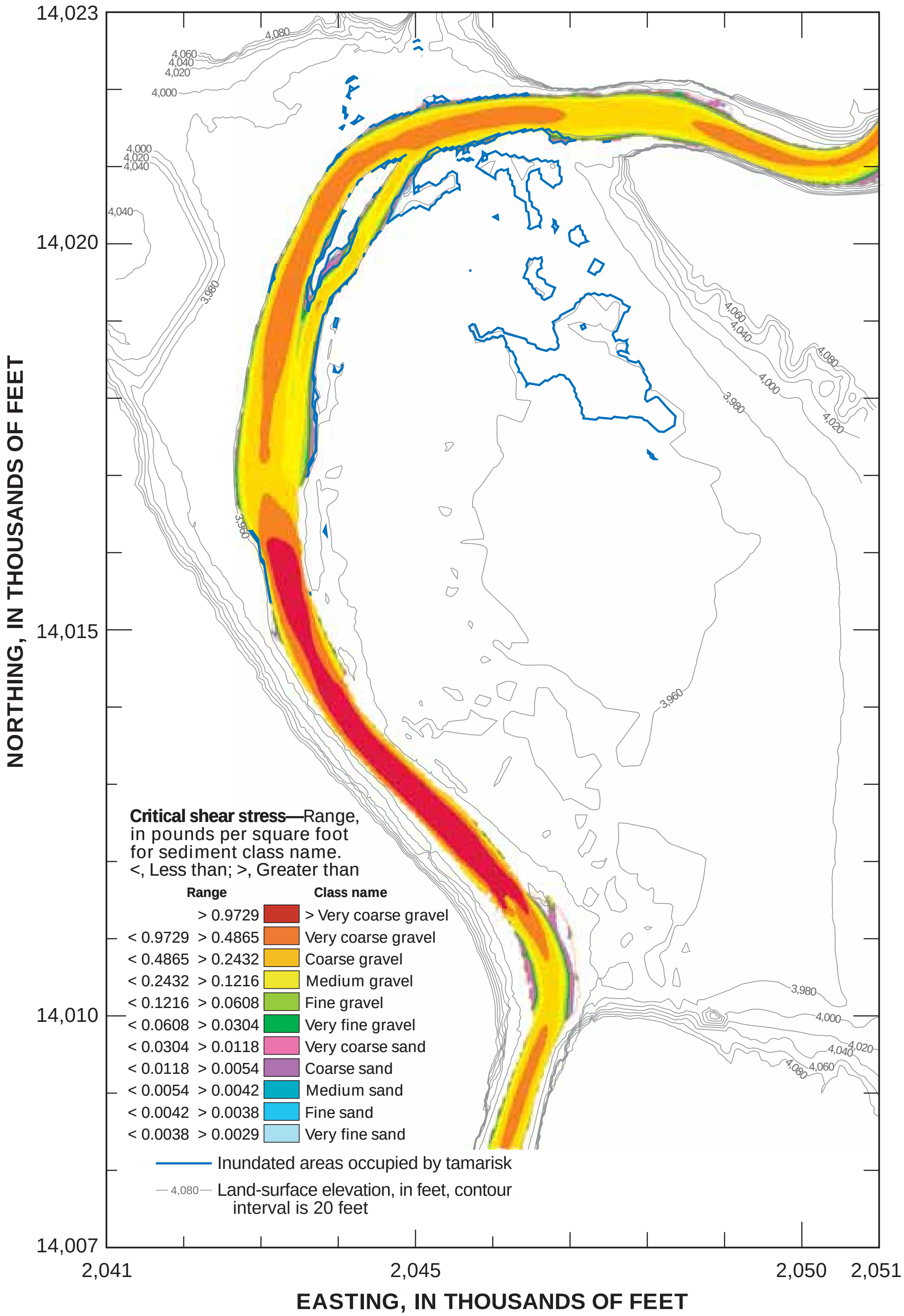


Figure 56. Predicted shear-stress distribution colored by grain-size critical shear-stress values for 100-year discharge and hypothetical 50-foot scour configuration of the Colorado River in Moab Valley, Utah.

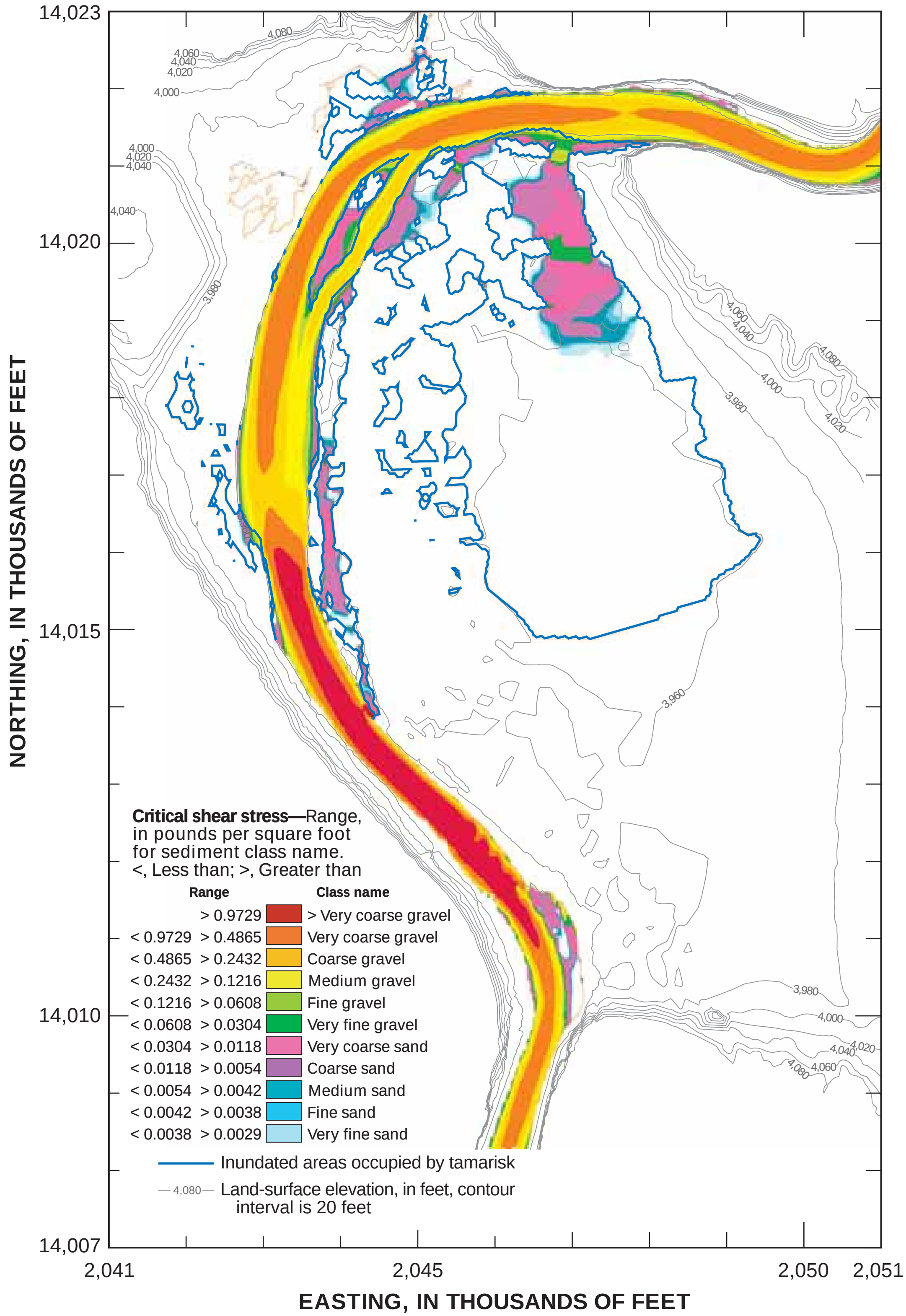


Figure 57. Predicted shear-stress distribution colored by grain-size critical shear-stress values for 500-year discharge and hypothetical 50-foot scour configuration of the Colorado River in Moab Valley, Utah.

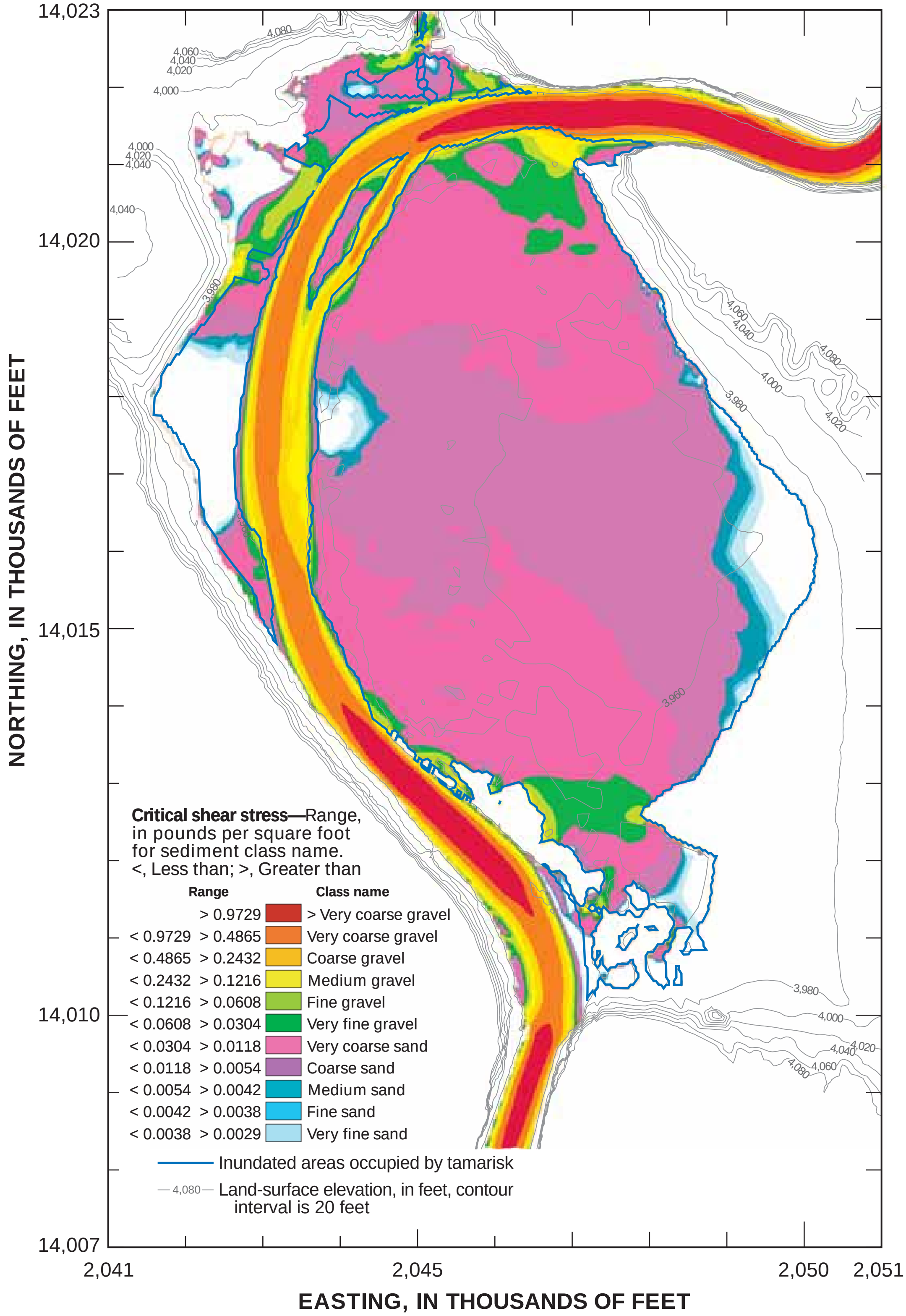


Figure 58. Predicted shear-stress distribution colored by grain-size critical shear-stress values for Probable-Maximum-Flood discharge and hypothetical 50-foot scour configuration of the Colorado River in Moab Valley, Utah.

FUTURE WORK

A tool has been developed to predict various hydraulic characteristics of the Colorado River in Moab Valley, Utah. This tool was used to evaluate the potential hazard posed to the Moab uranium mill tailings by flooding in the Colorado River. The future of the tailings pile is currently being decided. Two principal alternatives have been outlined by the DOE in the draft environmental impact statement for the Moab uranium mill tailings: on-site disposal and off-site disposal (U.S. Department of Energy, 2004). Regardless of the mitigation strategy selected, the developed multi-dimensional hydrodynamic model is capable of providing critical information in the future to those responsible for protecting the site.

If the on-site disposal alternative is selected, the model could provide information to the engineers tasked with designing the disposal cell structure. Proposed structure geometries could be input into the model and evaluated on how they affect the hydraulic characteristics of the Colorado River. Predicted shearing forces acting upon these geometries would aid in determining materials used to encapsulate the tailings pile. If the off-site disposal alternative is selected, the model could help guide the removal process. Scenarios related to the sequence in which portions of the pile are removed would ensure that the most susceptible areas would be eliminated first. As the pile is removed during the 3-year period estimated by the DOE (U.S. Department of Energy, 2004), the changing geometry of the pile could be updated in the model. This would allow for near real-time hazard evaluation during the removal period. The final contouring of the tailings site could be evaluated with the model. The model developed for this initial assessment could be used in a number of ways to help ensure that the flood hazard posed to the tailings pile throughout its mitigation is understood and accounted for.

The model developed in this investigation is a scoping model which is considered uncalibrated for large discharges. Refinement of the existing model would aid in expanding and enhancing its utility. A number of tasks are outlined that would advance the existing model:

1. Comprehensive model calibration needs to be conducted. Calibration of the existing model and any future models will be dependent upon acquisition of velocities and water-surface elevations throughout the reach for an event representative of the average annual peak streamflow.
2. Grain-size distributions along the channel bed and throughout the over-bank region should be acquired. Information on the location of specific grain sizes would allow for a more accurate prediction of material transport within the reach.
3. Information on the thickness of alluvial material at the downstream portal is needed. With this information, more realistic scenarios related to appreciable channel scour can be developed.
4. The complexity of flow through the tamarisk-occupied areas of the reach needs to be quantitatively evaluated. Scenarios related to changes in the tamarisk distribution within the reach should be conducted to examine how they influence the distribution of velocities.
5. To more thoroughly understand the velocities, boundary shear stresses, and channel evolution, a calibrated, transient, hydrodynamic model could be developed. Steady-state models, such as the one presented here, are unable to evaluate duration of flow upon materials. By incorporating time within the modeling domain, rates of change, and subsequently, channel evolution, can be evaluated.

SUMMARY

A multi-dimensional hydrodynamic model was applied to aid in the assessment of the potential hazard posed to the Moab uranium mill tailings by flooding in the Colorado River. Discharge estimates for the 100- and 500-year recurrence interval, and Potential Maximum Flood (PMF), were simulated for the current channel geometry and for three hypothetical channel configurations at the downstream portal of Moab Valley, Utah. Water-surface elevations, velocity distributions, and shear-stress distribution were predicted for each discharge and geometric configuration simulated.

Calibration was limited to water-surface elevations collected at a discharge of 3,550 ft^3/s. This calibration of the model should be considered limited. Calibration was based solely upon the in-channel characteristics, when all of the discharges simulated exceeded the capacity of the main channel, and were

orders of magnitude greater than the calibration discharge. The over-bank regions of the study area are dominated by dense stands of tamarisk. Because quantitative observations of flow within these regions were not available, drag coefficients assigned to the over-bank areas occupied by tamarisk were computed from empirical Manning's roughness values for vegetation.

Predicted water-surface elevations at the toe of the tailings pile for the current channel geometry ranged from about 3,974 to 3,995 ft, a predicted inundation of about 4 ft by the 100-year discharge and 25 ft by the PMF discharge. Water-surface slopes for all three simulated discharges under the existing channel configuration were roughly equal to the average channel slope. The experimental deepening of the channel at the downstream portal decreased water-surface elevations throughout the reach.

The main path of flow for all simulations followed the Colorado River channel throughout the reach. Velocities within Moab Valley for each discharge simulated under the current channel geometry reached a maximum of from 6 to 8 ft/s. Predicted velocity distribution for the 100- and 500-year discharges were nearly identical for the existing channel conditions. For the existing channel geometry, a small area at the toe of the tailings pile was characterized by velocities of about 1 to 2 ft/s for the 100-year discharge. Predicted velocities near the toe for the PMF discharge increased to between 2 and 4 ft/s over a somewhat larger area. The dramatically increased channel slope created by the 50-ft experimental channel deepening caused velocities in the main channel adjacent to the tailings to exceed 12 ft/s.

Shear-stress distributions were presented by grain-size critical shear-stress values. Predicted main-channel bed stress values indicate substantial transport of medium-size gravels for the simulations conducted with the existing channel geometry. Transport of coarse sands was predicted near the tailings pile for the 100-year discharge, and fine gravel transport was predicted in this region for the PMF discharge. Decreasing the downstream portal bed elevation generally increased main channel shear-stress values. The greatest over-bank shear stress was predicted for the PMF discharge under the 25-foot scour scenario.

Results generated from this scoping model should provide local resource managers with an approximation of hydraulic characteristics for extreme discharge events in the Colorado River in Moab Valley, Utah. The developed model is subject to two major limitations: a lack of calibration with large discharges, and simplifications made to represent tamarisk in the study reach. These limitations must be considered when using or interpreting these data.

From this initial modeling effort, some important observations regarding the relation between the Colorado River and the Moab uranium mill tailings can be made. The degree of inundation at the tailings pile together with the presence of a velocity structure around the toe indicates that the tailings pile plays a role in obstructing the natural flow of over-bank flood discharges through the reach. The predicted path of flow along the existing Colorado River channel indicates that the current distribution of tamarisk in the over-bank region may determine how flood-flow velocities are spatially distributed. In a sense, the tamarisk may play a role in constraining the highest velocities to within the main channel. Further examination of the study reach, particularly the items discussed previously, would allow for a better understanding of the complex hydraulics and fluvial setting that exist in Moab Valley, Utah.

REFERENCES CITED

Andrews, E.D., and Nelson, J.M., 1989, Topographic response of a bar in the Green River, Utah, to variation in discharge, *in* Ikeda, S., and Parker, G., eds., River Meandering: American Geophysical Union, Water Resources Monograph 12, p. 463-485.

Chow, Ven Te., 1959, Open channel hydraulics: New York: McGraw-Hill, 680 p.

Conaway, J.S., and Moran, E.H., 2004, Development and calibration of a two-dimensional hydrodynamic model of the Tanana River near Tok, Alaska: U.S. Geological Survey Open-File Report 2004-1225, 13 p.

Doelling, H.H., Ross, M.L., and Mulvey, W.E., 2002, Geologic map of the Moab quadrangle, Grand County, Utah, Map 181: Salt Lake City, Utah, Utah Geological Survey.

Graf, W.L., 1978, Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region: Geological Society of America Bulletin, v. 89, p. 1491-1501.

Interagency Advisory Committee on Water Data, 1982, Guidelines for determining flood flow frequency: Washington, D.C., Interagency Advisory Committee on Water Data, Hydrology Subcommittee Bulletin 17B, 183 p.

Julien, P.Y., 1995, Erosion and sedimentation: New York, Cambridge University Press, 280 p.

Lisle, T.E., Nelson, J.M., Pitlick, J., Madej, M.S., and Barkett, B.L., 2000, Variability of bed mobility in natural gravel-bed channels and adjustments to sediment load at local and reach scales, Water Resources Research, v. 36, p. 3743-3755.

Nelson, J.M., 1997, The role of floods in the development and maintenance of lateral separation deposits in the Colorado River in Grand Canyon, *in* Recent Trends of Floods and Their Preventive Measures: Hokkaido River Disaster Prevention Research Center, Sapporo, p. 175-189.

Nelson, J.M., Bennett, J.P., and Wiele, S.M., 2003, Flow and sediment transport modeling, *in* Kondolop, M., and Piegay, H., eds., Tools in Fluvial Geomorphology: Chichester, England, Wiley and Sons, p. 539-576.

Pitlick, John, and Cress, Robert, 2002, Downstream changes in the channel geometry of a large gravel bed river: Water Resources Research, v. 38, no. 10, 12 p.

Sturm, T.W., 2001, Open channel hydraulics: New York, McGraw-Hill, 493 p.

Tibbetts, J.R., Enright, Michael, and Wilberg, D.E., 2003, Water resources data, Utah: U.S. Geological Survey Water-Data Report UT-03-1, 458 p.

U.S. Department of Energy, 2003, Migration potential of the Colorado River channel adjacent to the Moab project site, Letter report, 12 p., accessed December 1, 2004, at http://gj.em.doe.gov/moab/documents/gs_water/characterization/ 2003_11migration_potential.pdf

U.S. Department of Energy, 2004, Remediation of the Moab uranium mill tailings, Grand and San Juan Counties, Utah, Draft Environmental Impact Statement, DOE/EIS-0355D, accessed January 13, 2005, at http://www.eh.doe.gov/nepa/docs/deis/eis0355d/toc.html

Terry A. Kenney—Initial-Phase Investigation of Multi-Dimensional Streamflow Simulations in the Colorado River, Moab Valley, Grand County, Utah, 2004—Scientific Investigations Report 2005–5022