Transient Simulation of Groundwater Levels within a Sandbar of the Colorado River, Marble Canyon, Arizona, 2004

By Thomas A. Sabol and Abraham E. Springer

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Cover: Eddy sandbar at river mile 30.7R after recession of the 2004 high-flow experiment, Colorado River, Marble Canyon, Arizona. Visible are piezometers in the bar face regions of the downstream part of the sandbar.

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
Flow rate		
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

SI to Inch/Pound

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
Area		
square meter (m^2)	0.0002471	acre
Flow rate		
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
Hydraulic conductivity		
meter per day (m/d)	3.281	foot per day (ft/d)

Vertical coordinate information is referenced in meters to height above the GRS80 ellipse defined by NAD83(1982).

Horizontal coordinate information is referenced to North American Datum of 1983, NAD83(1982).

Elevation, as used in this report, regers to distance above the vertical datum.

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Transient Simulation of Groundwater Levels within a Sandbar of the Colorado River, Marble Canyon, Arizona, 2004

By Thomas A. Sabol[1] and Abraham E. Springer[2]

Abstract

Seepage erosion and mass failure of emergent sandy deposits along the Colorado River in Grand Canyon National Park, Arizona, are a function of the elevation of groundwater in the sandbar, fluctuations in river stage, the exfiltration of water from the bar face, and the slope of the bar face. In this study, a generalized three-dimensional numerical model was developed to predict the time-varying groundwater level, within the bar face region of a freshly deposited eddy sandbar, as a function of river stage. Model verification from two transient simulations demonstrates the ability of the model to predict groundwater levels within the onshore portion of the sandbar face across a range of conditions. Use of this generalized model is applicable across a range of typical eddy sandbar deposits in diverse settings. The ability to predict the groundwater level at the onshore end of the sandbar face is essential for both physical and numerical modeling efforts focusing on the erosion and mass failure of eddy sandbars downstream of Glen Canyon Dam along the Colorado River.

Introduction and Background

Emergent sandy deposits along the Colorado River in Grand Canyon National Park, Arizona, are a key fixture of the ecosystem downstream of Glen Canyon Dam (fig. 1; Rubin and others, 1998, 2002; Topping and others, 2006). Closure of the dam in 1963 reduced the supply of sand-sized sediment in the Colorado River at the upstream boundary of Grand Canyon National Park, located at the mouth of the Paria River, by about 94 percent from a mean annual sediment load of about 60 million metric tons to about 3 million metric tons (Topping and others, 2000a, 2006, 2010; Draut and others, 2005); the remaining 6 percent of the post-dam sand supply is contributed almost exclusively by the Paria River (Topping and others, 2006, 2010). In addition to the reduction in the downstream supply of sand-sized sediment, operation of the dam has altered the natural seasonal hydrograph such that sediment no longer accumulates seasonally on the main-channel bed of the river during low-flow periods (pre-dam, July–March) and sediment is no longer redeposited seasonally in lateral recirculation eddy sandbars during high-flood-flow periods (pre-dam, April–June) (Howard and Dolan, 1981; Rubin and others, 2002; Topping and others, 2003, 2010; Hazel and others, 2006a). Although the post-dam seasonal hydrograph has been smoothed, operation of Glen Canyon Dam to provide peak on-demand hydroelectric power generation has caused large diurnal fluctuations in discharge that have increased the daily range in discharge 99.9 percent of the time relative to the pre-dam period of record (Topping and others, 2003). The combination of a reduced sediment supply, an increase in the frequency of floods with peak

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discharges between 523.6 and 820.7 m^3/s, and an increase in the daily range of discharge has facilitated the degradation of sediment storage along the Colorado River corridor through Marble and Grand Canyons (see, for example, Dolan and others, 1974; Laursen and others, 1976; Clark and others, 1991; Beus and others, 1992; Topping and others, 2000a, 2000b, 2003, 2010; Rubin and others, 2002; Hazel and others, 2006a).

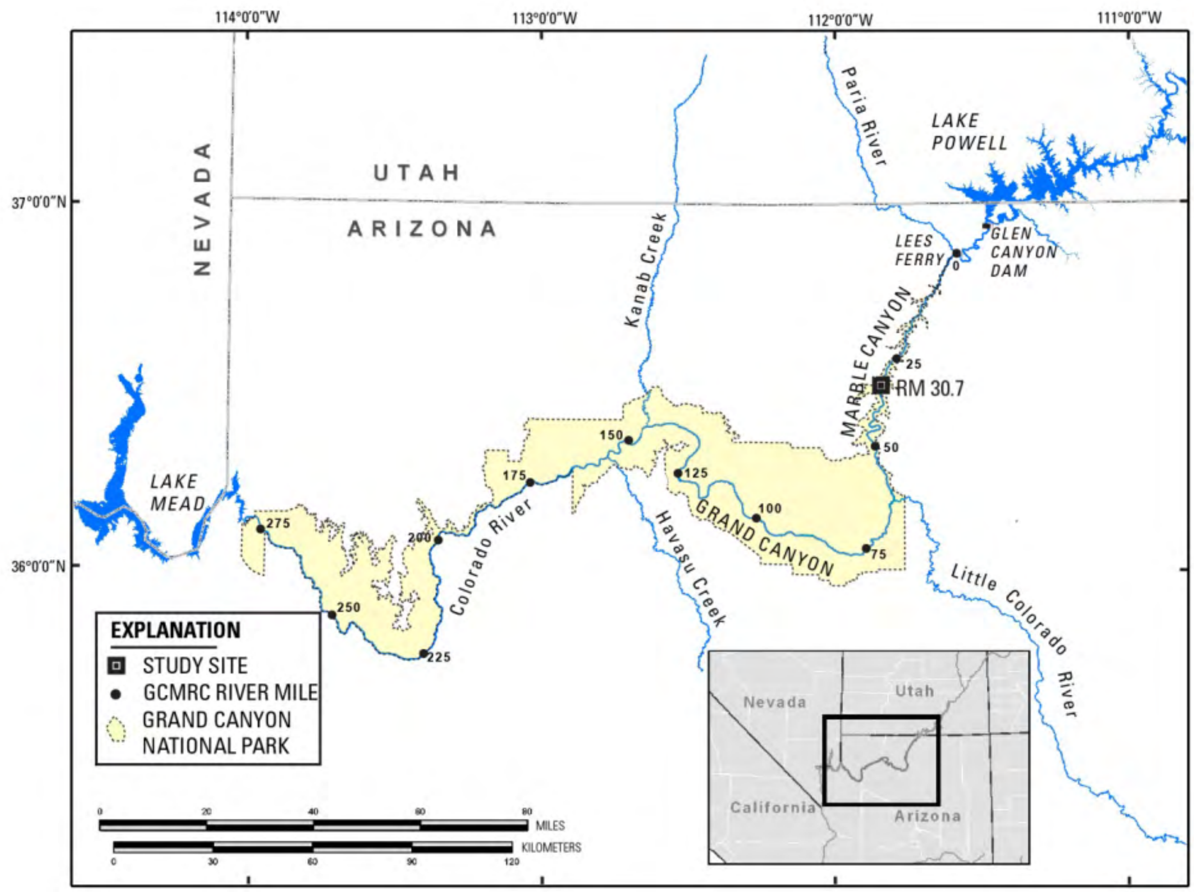

Figure 1. Map of the Colorado River in Glen, Marble and Grand Canyons, Arizona, showing the location of the Grand Canyon Monitoring and Research Center (GCMRC) river mile (RM) 30.7R study site. Horizontal coordinate information is referenced to North American Datum of 1983, NAD83(1982).

Sediment storage in the pre-dam Colorado River was driven seasonally by seasonal fluctuations in the main-stem discharge, with storage of sediment occurring in both the main-channel bed and the lateral recirculation eddy deposits. In the contemporary post-dam river, the predominant proportion of sediment in the river is stored mainly in eddies (see, for example, Schmidt, 1990; Rubin and others, 2002; Hazel and others, 2006a; Topping and others, 2010). For example, in Marble Canyon, in the 99-km reach beginning with km 0 at Lees Ferry, 51–94 percent of the sediment is stored within lateral recirculation eddies, despite the fact that eddies constitute only about 17 percent of the flow field surface area (Hazel and others, 2006a). These results indicate the importance of lateral recirculation eddy deposits as a resource for long-term storage of sediment along the Colorado River downstream of Glen Canyon Dam as the degradation of fine-sediment deposits progresses throughout the downstream ecosystem. Because of the infrequent inundation of the high-elevation eddy deposits (that is, parts of the deposit emergent above the 227 m^3/s river stage), these portions of the bar have a longer response time to typical diurnal dam operations. As a result, high-elevation eddy deposits potentially are the last bastion of storage in a system that is in a state of active scour during times when the bed of the channel is not enriched in fine sediment (Schmidt and others, 2004; Hazel and others, 2006a).

Emergent bars create terrestrial habitats for riparian vegetation and low-velocity aquatic habitats for fish and other benthos, act as a source of fine sediment for aeolian processes that may be integral in the preservation of archeological resources, and are used by boaters and other visitors for recreation (Rubin and others, 2002; Draut and others, 2005; Kaplinski and others, 2005; Topping and others; 2006; Behn and others, 2010; Ralston, 2010). Given the current decline in sediment storage of the post-dam Colorado River in both Marble and Grand Canyons, and the importance of eddy sandbars within the downstream ecosystem, efforts have been made to understand both the long-term stability of the eddy deposits upon emergence and the efficacy of high-flow experiments to rebuild and maintain the eddy deposits (Hazel and others, 2010; Schmidt and Grams, 2011a; Alvarez and Schmeeckle, 2012).

From 1966 to 1990, the Glen Canyon Dam hydropower plant was operated to deliver water to downstream users, as well as to optimally meet daily demand for electrical power by supplying electricity at peak times of the day (typically, midday in summer and midday and early evening in winter). During this time period, historical releases from the dam of as much as 892 m^3/s (power plant capacity), accompanied by unrestricted ramp rates, resulted in large fluctuations in river stage downstream of the dam (U.S. Department of the Interior, 1995; Alvarez and Schmeeckle, 2012). Scientific findings toward the end of this time period concluded that large stage fluctuations resulting from the unrestricted operation of Glen Canyon Dam were eroding sandbars and deteriorating the downstream ecosystem (U.S. Department of the Interior, 1988). As a partial response to these findings, the Grand Canyon Protection Act (GCPA) was passed in 1992; the "Operation of Glen Canyon Dam—Final Environmental Impact Statement" was prepared; and the Record of Decision for alternative dam-operation strategies for meeting the GCPA requirements was signed by the Secretary of the Interior in 1996 (U.S. Department of the Interior, 1996; Schmit and Schmidt; 2011; Alvarez and Schmeeckle, 2012). As a result of the 1996 Record of Decision, which imposes restrictions on fluctuating discharges from Glen Canyon Dam, a modified low fluctuating flow (MLFF) operation criteria was implemented that constrained minimum (141.5 m^3/s by night, 226.5 m^3/s by day) and maximum (707.5 m^3/s) releases, maximum daily fluctuations (226.5 m^3/s within 24 hours), and discharge ramp rates [113.2 $(m^3/s)/h$ rising limb, 42.5 $(m^3/s)/h$ falling limb] (U.S. Department of the Interior, 2008; Alvarez and Schmeeckle, 2012). Under the current MLFF operating regime of Glen Canyon Dam, typical diurnal fluctuations in discharge of the Colorado River result in daily stage changes of about 1.5 m in Marble Canyon (U.S. Department of the Interior, 1996; Hazel and others, 2006b; Alvarez and Schmeeckle, 2012).

The erosion of sandbars is thought to occur as a dynamic interplay between seepage erosion, mass failure, and tractive forces within the water column (such as turbulent flow and waves) acting on the toe of the bar and the submerged seepage face (Beus and others, 1992; Budhu, 1992; Cluer, 1992, 1995; Bauer and Schmidt, 1993; Budhu and Gobin, 1994, 1995; Alvarez and Schmeeckle, 2012). On the rising limb of the diurnal stage fluctuation, and during times of steady high flow, water infiltrates the sandbar and recharges the unsaturated and variably saturated pores of the sandbar aquifer skeleton. Conversely, during the downramp cycle, rapid decreases in stage lead to an elevated water table in emergent bars that, in turn, results in elevated pore water pressures and the exfiltration of water accompanying the drainage of water stored in the aquifer skeleton of the sandbar. Seepage erosion occurs when the exfiltration of water causes the entrainment and transport of unconsolidated sediment along the sandbar face; in some instances, seepage erosion initiates the process of mass failure (Beus and others, 1992; Cluer, 1992; Bauer and Schmidt, 1993; Budhu and Gobin, 1994, 1995; Fox and others, 2006; Alvarez and Schmeeckle, 2012).

Since the 1990s, considerable scientific research has focused on the restoration and preservation of eddy sandbar deposits throughout the Colorado River ecosystem in Marble and Grand Canyons (Schmidt and Grams, 2011a, 2011b; Alvarez and Schmeeckle, 2012). High-flow experiments (1996, 2004, 2008), with discharges about 50 percent greater than peak hydropower plant operating range, were conducted to increase the area and volume of eroded eddy sandbar resources (Schmidt and Grams, 2011a, 2011b); the response of the high-elevation eddy sandbars to these experiments was positive in both area and volume (Hazel and others, 2010). However, readjustment of the newly aggraded eddy sandbars to typical diurnal dam operation led to system-wide erosion as the equilibrium beach face slope evolved; equilibrium slope values for the subaerial part of a typical Grand Canyon eddy sandbar beach face range from 11 to 14 degrees (Schmidt and Graf, 1990; Budhu and Gobin, 1994; Hazel and others, 2010; Alvarez and Schmeeckle, 2012).

The evolution of subaerial beach face sediments, from a freshly deposited steep sandbar face to a shallower equilibrium slope within the zone of fluctuating river stage, is governed by an interplay between seepage erosion, mass failure, and turbulent sediment transport within the water column (Beus and others, 1992; Bauer and Schmidt, 1993; Budhu and Gobin, 1994, 1995; Alvarez and Schmeeckle, 2012). Seepage erosion and mass failure are primarily a function of the elevation of groundwater in the sandbar, the stage fluctuations along the sandbar face, the exfiltration of water from the sandbar face, and the slope of the sandbar face (Budhu and Gobin, 1994, 1995; Alvarez and Schmeeckle, 2012). Downstream of Glen Canyon Dam, the duration of Colorado River peak discharge typically is insufficient for groundwater levels in sandbars to equilibrate with peak river stage, resulting in an observed lag between groundwater fluctuations in sandbars and the hydrograph of the river (Cluer, 1992, 1995; Budhu and Gobin, 1995; Carpenter and others, 1995a, 1995b; Alvarez and Schmeeckle, 2012). Understanding the time-varying relation between groundwater levels in the sandbar, the regulated hydrograph of the river, and dam operations is critical for any model, numerical or physical, where the onshore, groundwater-level boundary condition is required.

Purpose and Scope

The purpose of this report is to develop a generalized numerical model for the prediction of time-varying groundwater levels, within the bar face region of a freshly deposited eddy sandbar, as a function of river stage. This report describes the development and calibration of a numerical model using an existing finite-element software package. The ability to predict the groundwater level at the onshore end of a sandbar face is essential for physical and numerical modeling efforts focusing on the erosion and mass failure of eddy sandbars downstream of Glen Canyon Dam along the Colorado River within Grand Canyon National Park (fig. 1). The model framework developed in this report was based on data collected from a single eddy sandbar (river mile [RM] 30.7R); however, use of this generalized model may be applicable across a range of typical eddy sandbar deposits at multiple study sites.

Study Sites

The study site is a reattachment-type sandbar (Schmidt and Graf, 1990) in an eddy of recirculating flow at RM 30.7R along the Colorado River in Marble Canyon within Grand Canyon National Park (GRCA) (fig. 1). By longstanding convention, locations along the Colorado River in GRCA are referenced to river miles. Marble Canyon extends from RM 0 to the mouth of the Little Colorado River near RM 62; Grand Canyon extends from the mouth of the Little Colorado River to the Grand Wash Cliffs near RM 277. Data used in this study were collected at the RM 30.7R eddy sandbar during two different discharge regimes regulated by Glen Canyon Dam, following a period of partial scour, reworking, and deposition of sediment during the Glen Canyon Dam high-flow experiment of November, 2004 (fig. 2; Topping and others, 2006; Melis and others, 2007, 2011; Melis, 2011; Melis and others, 2012).

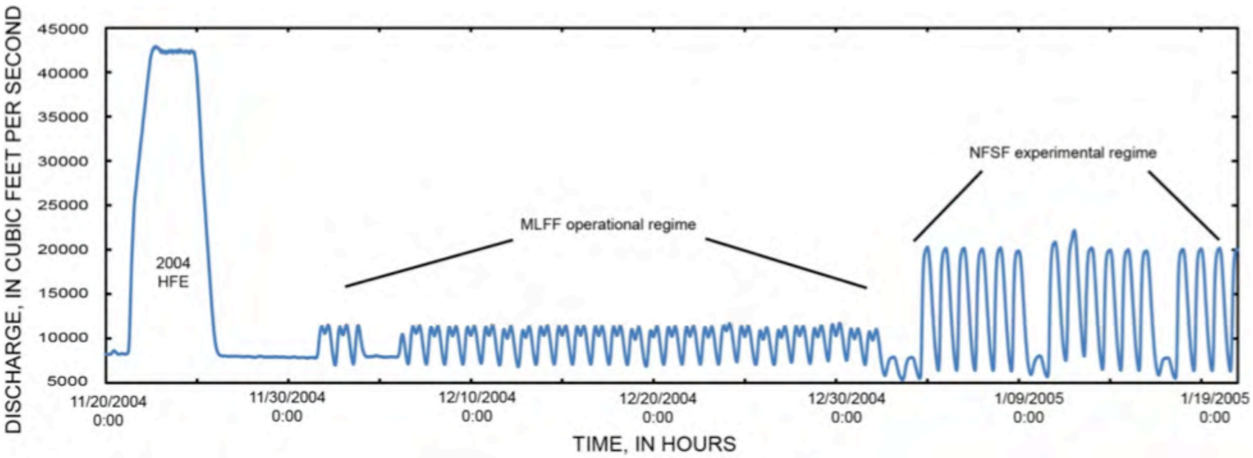

Figure 2. Continuous discharge record for the river mile 30.7 sandbar study site from November 20, 2004 through January 20, 2005. Shown is the discharge record during (1) the 2004 high-flow experiment (HFE), (2) the return to modified low fluctuating flow (MLFF) operation criteria, and (3) the beginning of nonnative fish suppression flows (NFSF). Throughout the 39-day period after the downramp of the 2004 HFE, the discharge of water moving past the river mile 30.7R study site was regulated by the MLFF operational criteria of Glen Canyon Dam. Beginning on January ,3 2005, through the end of the discharge record shown, the discharge of water moving past the river mile 30.7R study site was part of the NFSF experimental test release from Glen Canyon Dam. The period of NFSF discharge shown illustrates the typical diurnal weekday and week end operational flow releases from Glen Canyon Dam characteristic of the NFSF experimental test at the river mile 30.7R study site; maximum daily range in discharge during this time period (up to 424.5 cubic meters per second within a 24 hour period) exceeded the MLFF maximum daily fluctuation range of 226.5 cubic meters per second within 24 hours.

Data Collection

In November 2004, during the recession of a high-flow experiment release from Glen Canyon Dam, the emergent part of a freshly deposited high-elevation eddy sandbar at RM 30.7R was instrumented with transducers to measure changes in pressure head across the subaerial extent of the sandbar relative to fluctuations in river stage at the bar face (fig. 3, cover photo). A total of 16 15-PSI MiniTroll ™ (InSitu Corp, Fort Collins, Colorado) vented pressure transducers were individually deployed in 16 hand-driven, 1-¼-inch threaded black steel pipe piezometers. Each piezometer was fitted with Johnson model no. 813 (Johnson Screens, Saint Paul, Minnesota), 304 stainless steel, 0.006 slot wire wrap sand points; the screened interval of the sand point was 31.8 cm. Piezometers were developed to remove fines clogging the screened interval during late November 2004, and again on December 31, 2004, using a peristaltic pump.

Following recession of the high-flow experiment, the topography of the newly deposited high-elevation eddy sandbar and the top of each piezometer casing were surveyed with vertical heights referencing the ellipsoid on December 5, 2004; the survey again was conducted on March 8, 2005 (J. Hazel, Northern Arizona University, written commun., 2006). The level reference value for the transducers was set using the measured distance from the top of casing ellipsoid height to the water surface in the piezometer (table 1). On December 31, 2004 and January 1, 2005, slug tests were performed to measure hydraulic conductivity of the sediments recently deposited during the November 2004 high-flow experiment in the lateral recirculation eddy at RM 30.7R. Recovery data from displacement of the slug were recorded and analyzed using the Bouwer and Rice (1976) method.

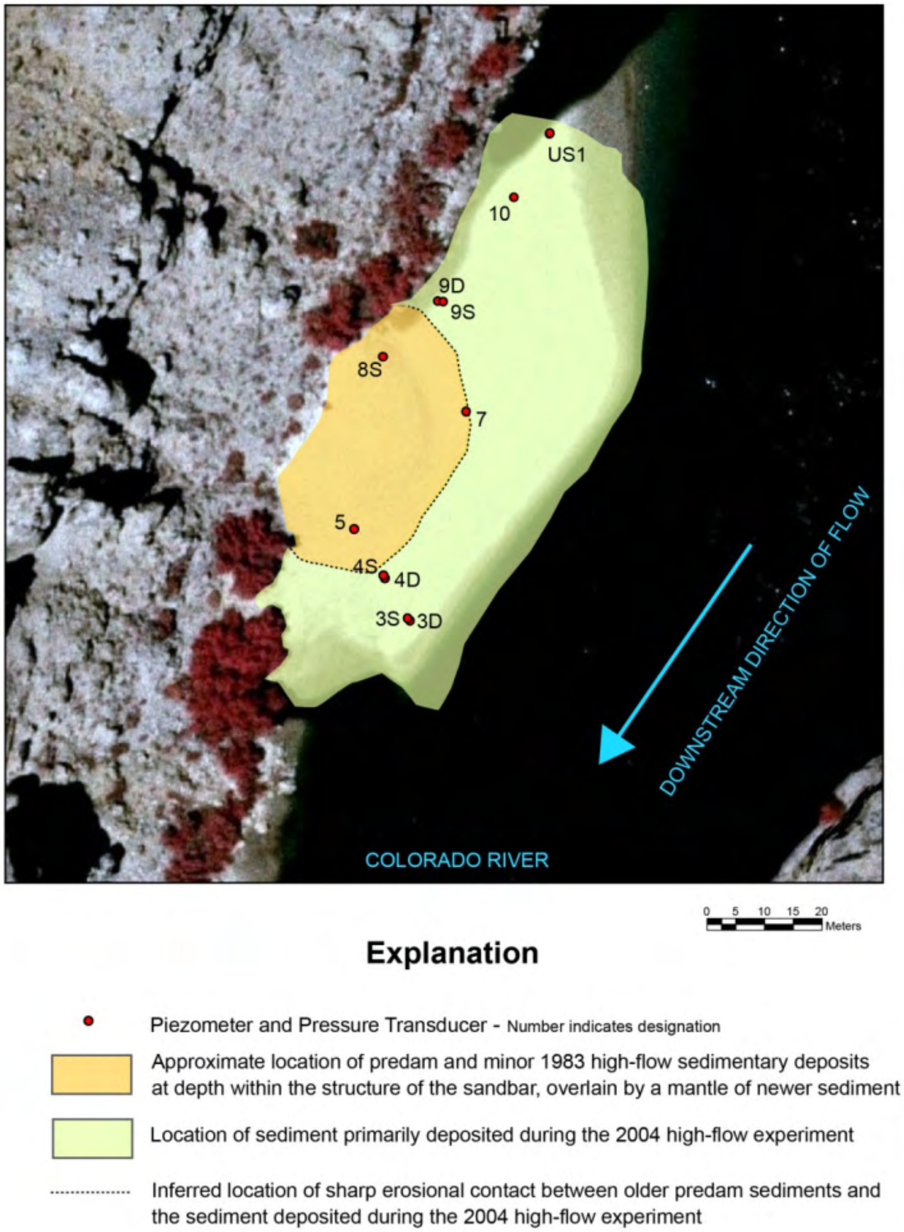

Figure 3. Plan view image of the river mile 30.7R, Colorado River in Marble Canyon, Arizona, eddy sandbar study site showing the approximate horizontal extent of pre-dam sediments within the structure of the sandbar at depth. Tan polygon depicts the extent of the sandbar presumed to be pre-dam sediment at depth. The pre-dam sediment within the structure of the bar is typically covered by a mantle of newer sediment ranging in thickness from 0.5 to several meters; mantle of younger sediment overlying the tan pre-dam deposit polygon is not shown in this figure. Green polygon depicts the subaerial extent of deposits, above the 141.5 cubic meters per second river stage elevation, from the 2004 high-flow experiment; the full thickness of the sandbar within the area delineated by the green polygon is thought to consist almost entirely of deposits form the 2004 high-flow experiment. Dashed line is the inferred location of the erosional contact between pre-dam sediments and the 2004 high-flow experiment deposits. Location of piezometers containing pressure transducers within the active model shown in red, number indicates the designation (table 1). Sedimentological data used for this figure is based off of trench and pit data collected in March, 2005 by David M. Rubin (D. Rubin, U.S. Geological Survey, written commun., 2005).

Table 1. Locations and selected construction data for piezometers installed in the eddy sandbar at river mile 30.7R, Colorado River in Marble Canyon, Arizona.

Well id	Well location		Top of casing	Screen elevation		Hydraulic conductivity	Screened interval
	Easting (m)	Northing (m)	Elevation (m)	Top (m)	Bottom (m)	Model (m/d)	Model layer
3D	219535.890	611732.214	858.865	852.635	852.318	0.08	2
3S	219535.486	611732.649	858.410	853.723	853.405	13.8	1
4D	219531.553	611739.648	859.594	853.386	853.068	6.8	1
4S	219531.287	611740.128	858.643	853.983	853.666	6.8	1
5	219526.182	611748.163	859.626	854.884	854.566	6.8	1
7	219545.636	611768.546	860.320	855.627	855.309	6.8	1
8S	219531.718	611778.616	860.201	855.492	855.175	6.8	1
9D	219540.767	611787.724	859.059	854.402	854.085	6.8	1
9S	219541.666	611787.661	859.228	856.086	855.769	13.8	1
10	219553.932	611805.708	858.602	855.466	855.149	13.8	1
US1	219560.145	611816.863	857.186	854.047	853.730	n/a	1

Groundwater Model

Two-dimensional numerical models have been used to predict changes in the phreatic surface in eddy sandbars, resulting from various transient dam discharge regimes along the Colorado River, with “good” results for an individual cross-section of the sandbar face (Budhu and Contractor, 1994; Budhu and Gobin, 1995). Potential spatial variations in crossbar topography and internal structural heterogeneity of the recirculating eddy sandbar deposits can be overlooked in two-dimensional analyses (Rubin and others, 1990; Schmidt, 1990; Springer and others, 1999; Alvarez and Schmeeckle, 2012). Therefore, in this study, we considered the response of the groundwater level in the sandbar across the entire three-dimensional bar face region. A finite-element model (FEFLOW 5.2, Institute for Water Resources Planning and Systems Research Inc. [WASY], Berlin, Germany) was used to develop a generalized three-dimensional model for predicting time-varying groundwater levels within the sandbar face as a function of river stage fluctuations. Model verification, using two transient simulations, against a range of groundwater levels observed during two different discharge regimes regulated by Glen Canyon Dam (fig. 2), demonstrates the ability of the model to predict the groundwater level in the sandbar face region for a wide range of soil parameters in fully saturated, variably saturated, and unsaturated conditions.

Model Framework

Model parameters were defined for saturated media with transient flow in an unconfined aquifer. The uppermost surface of the model was developed directly from topographic survey data collected on December 5, 2004 (J. Hazel, Northern Arizona University, written commun., 2006). The topographic response of the RM 30.7R sandbar to the 2004 high-flow experiment (HFE) is shown in figure 4, and the subsequent discharge regimes regulated by Glen Canyon Dam are shown in figure 2. The model framework was discretized into two, three-dimensional slices representative of the general hydrogeological structure of the RM 30.7R eddy sandbar study area; discretization of the model framework was based on soil properties determined during field data collection (fig. 5, table 1). The uppermost surface was set as free and movable, which allows the surface of the top layer (layer 1) to follow the groundwater surface using the BASD (Best-Adaptation-to-Stratigraphic -Data) moving grid technique (WASY, Berlin, Germany). The top of layer 2 was defined as unspecified which allows it to be distributed according to the moving groundwater surface and the hydraulic conductivity of the sediment. The bottom of the model was fixed and unmovable.

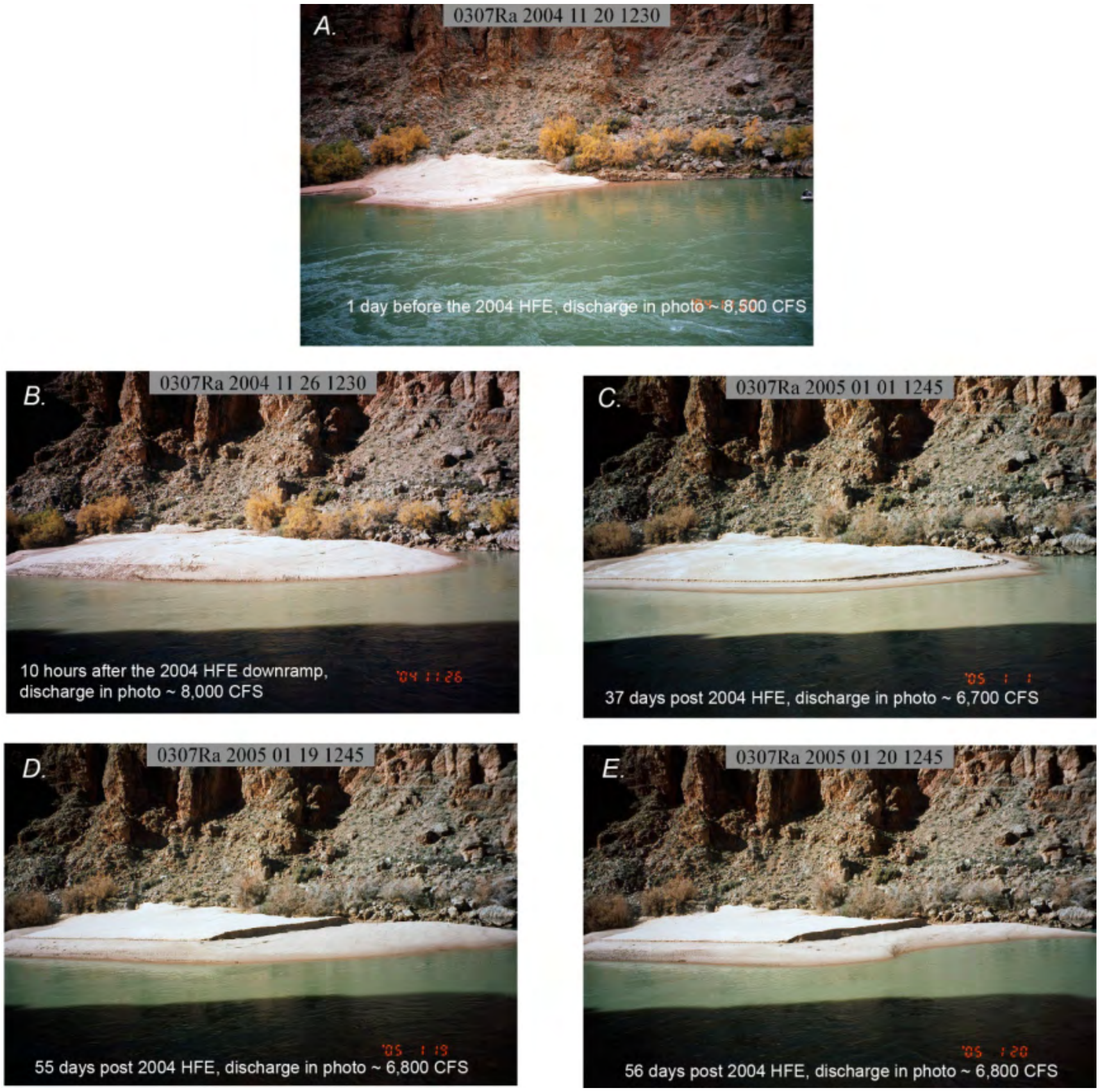

Figure 4. Matched oblique photographic views of the river mile 30.7R sandbar study site, Colorado River in Marble Canyon, Arizona, taken from left river bank illustrating the topographic condition of the study area (A) before the 2004 HFE, (B) 10-hours after the cessation of the 2004 HFE downramp, (C) 37-days post 2004 HFE downramp, (D) 55-days post 2004 HFE downramp, and (E) 57-days post 2004 HFE downramp. Direction of downstream flow is from right-to-left. Little change in the topographic condition of the RM 30.7R sandbar (B, C) is observed under modified low fluctuating flow (MLFF) operation criteria (fig. 2); however, during times of experimental nonnative fish suppression flows (NFSFs) (fig. 2), when maximum 24-hour range in discharge is increased above MLFF operational criteria, changes in the topographic condition of the sandbar become evident (D, E). During the NFSF experimental flows, a change in two dynamic variables occurred: (1) a nearly factor of 2X increase in the maximum 24-hour range of discharge at the study site (424.5 cubic meters per second per day versus 226.4 cubic meters per second per day), and (2) an increase in the subaqueous extent of the sandbar exposed to tractive forces as a result of the increase in the 24-hour discharge range. During this experiment, the hourly downramping rate for fluctuations was also increased by a factor of 2X, from 42.5 cubic meters per second per hour to 84.9 cubic meters per second per hour which also resulted in an increase in the time the river was held at peak flow each day through January, February and March, 2005.

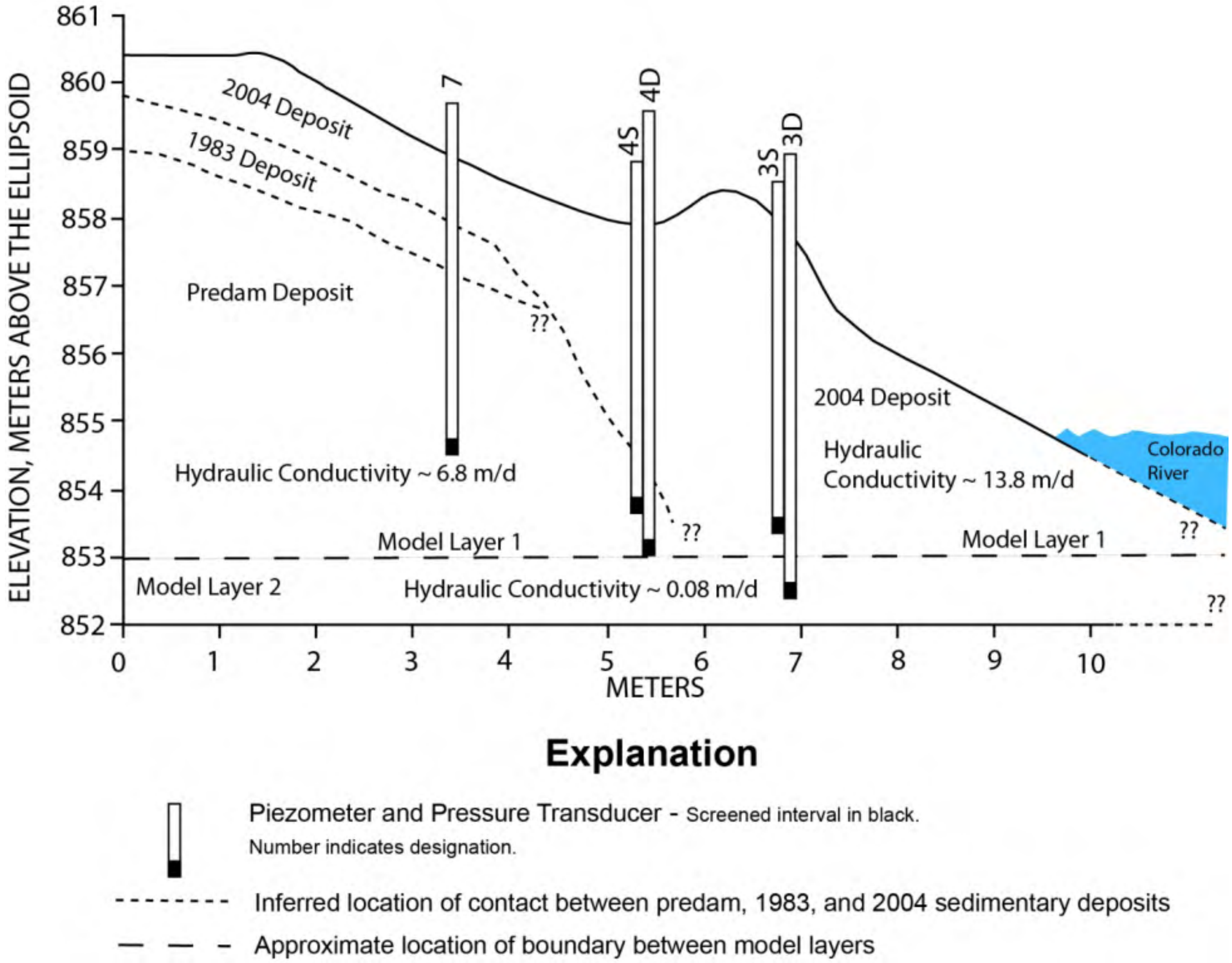

Figure 5. Idealized cross-section showing the eddy sandbar at river mile 30.7R, Colorado River in Marble Canyon, Arizona, view upstream. Diagram shows both the location of piezometers and the inferred location of pre-dam and younger deposits within the framework of the sandbar. Values of hydraulic conductivity used to simulate zones of pre-dam and 2004 deposits during the model runs are shown. See Table 1 for the values of hydraulic conductivity used at each target piezometer during development of the model framework. Sedimentological data used for this figure is based off of trench and pit data collected in March, 2005 by David M. Rubin (D. Rubin, U.S. Geological Survey, written commun., 2005).

Hydraulic Conductivity

Recovery data from the slug tests were analyzed, using the Bouwer and Rice (1976) method for unconfined aquifers with partially penetrating wells, to constrain the spatial distribution of hydraulic conductivity (K) in the model framework and to define the horizontal boundary between model layers (fig. 5, table 1). Throughout the calibration process, parameters of hydraulic conductivity were varied slightly to achieve model calibration. The hydraulic conductivity values at individual target locations in each layer were interpolated across the model layer to develop a best-fit approximation of the anisotropic and heterogeneous hydrogeologic framework that exists throughout the sandbar structure (fig. 6).

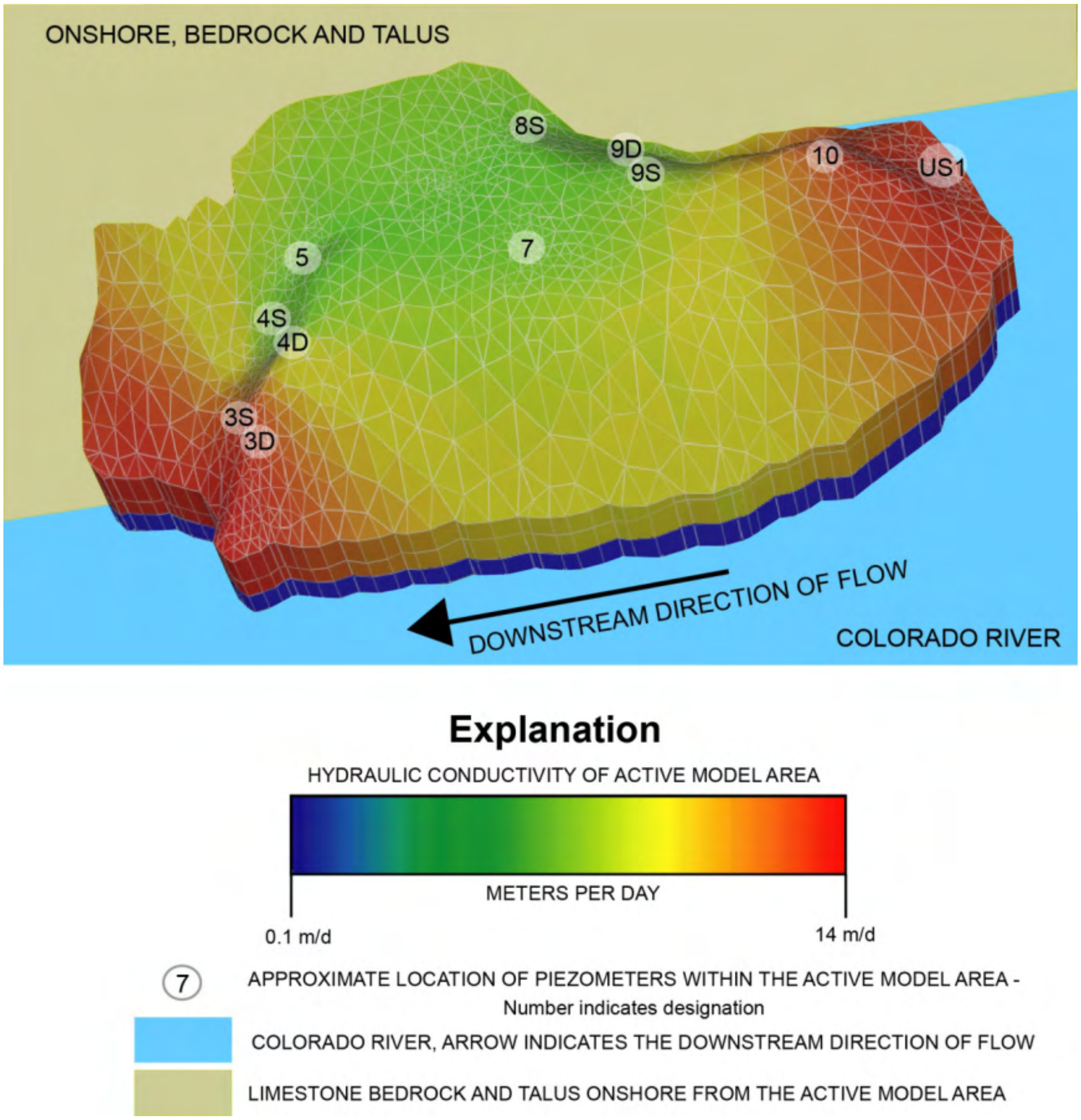

Figure 6. Hydraulic conductivity (K) of model layers 1 and 2 within the three-dimensional groundwater model framework developed for this study, river mile 30.7R, Colorado River in Marble Canyon, Arizona. Figure shows interpolation of hydraulic conductivity across model layer 1 between piezometers screened in pre-dam sediments (K~6.8 meters per day) and piezometers screened in post-dam sediment deposits from the 2004 high-flow experiment (K~13.8 meters per day). Hydraulic conductivity of 0.08 meters per day used throughout model layer 2. Finite element mesh shown in white.

The uppermost layer of the model, layer 1, contained 9 piezometers screened in sediment higher than the 852.9-m bottom boundary elevation of the layer. Analyses of the slug test data indicate the presence of two spatially discrete zones of hydraulic conductivity within the layer 1 framework (figs. 5–6, table 1). The interior area of the sandbar (about 800 m^2) is composed primarily of pre-dam lower hydraulic conductivity sediments, high in silt and clay content (30–40 percent silt and clay), and overlain by a thin mantle of sediment deposited during a 2,800 m^3/s release from Glen Canyon Dam in June 1983 (figs. 3, 5). Piezometers 5, 7, and 8S, screened in this zone of pre-dam sediment, had average hydraulic conductivity values of 6.8 m/d (table 1). A comparison of the horizontal position and the screened interval elevation of piezometers 5, 7, and 8S with a detailed examination of internal structures exposed in a 60 m long sequence of trenches and pits (D. Rubin, U.S. Geological Survey, written commun., 2005) confirmed that piezometers 5, 7, and 8S were all screened within the pre-dam low hydraulic conductivity zone of sediments in layer 1 (figs. 3, 5). An average hydraulic conductivity value of 6.8 m/d was also used for piezometers 4S, 4D, and 9D (fig. 6, table 1). Although trench and pit data (D. Rubin, U.S. Geological Survey, written commun., 2005) could not unequivocally confirm the locus of the screened interval of the piezometers (4S, 4D, 8S) within the pre-dam deposits at RM 30.7R, the nearness of these piezometers to the pre-dam deposits at depth and an analysis of field slug tests data confirmed the approximate hydraulic conductivity values used at piezometers 4S, 4D, and 8S (figs. 3, 6).

The exterior part of the model framework in layer 1 consists of a thick sequence of relatively high hydraulic conductivity fluvial sediments, deposited during the 1,160 m^3/s peak of the 2004 high-flow experiment, which overlay a sharp erosional contact with the low hydraulic conductivity pre-dam sediments in the onshore interior area of the sandbar (figs. 3, 5, 6). The high hydraulic conductivity sediments in the exterior part of the sandbar are bounded by a time-varying specified-head boundary (river stage) along the streamside edge of the active model area. Piezometers screened in this zone of freshly deposited sediment on the outer part of the bar (3S, 9S, 10) had hydraulic conductivity values of 13.8 m/d (figs. 3, 6, table 1). Only one piezometer, 3D, was screened within layer 2. The relatively low hydraulic conductivity value, 0.08 m/d, indicates the presence of silt- and clay-rich lenses at depth that shows the degree of variability that can occur within the already heterogeneous structure of the sandbar (table 1).

Storage Coefficient

Values of specific yield (S_y), storativity (S), and porosity (n) were defined for predictive transient modeling simulations. The storage coefficient (S) is the volume of water a permeable unit will absorb or expel per unit surface area per unit change in head. In most unconfined aquifers, storativity (S) is assumed to be nearly equal to the specific yield (S_y), that is, $S=S_y$ (Fetter, 1994). The conceptual distribution of specific yield ($S_y=n-S_r$) varied at RM 30.7R because the eddy sandbar consists of a core of older pre-dam and 1983 deposits at depth mantled by new deposits from the 2004 high-flow experiment around the perimeter (figs. 3, 5, 6). In places, pre-dam and 1983 deposits contain 30–40 percent silt and clay, which greatly increases the specific retention (S_r). Finer sand typically has a higher specific retention (S_r). As the percent of S_r relative to porosity (n) becomes greater, S_y becomes smaller. Using porosity values between 25 percent and 35 percent for model layer 1, the S_y of pre-dam deposits was estimated between 2 and 5 percent, while the S_y of newly deposited 2004 high-flow experiment sediment was greater than 10 percent. Through calibration, the sensitivity of the transient model to storage coefficient became apparent and a best-fit approximation for S_y of 2 percent was used across the model area in layer 1. The storage coefficient (S) for layer 2, considered confined by the model, was estimated at 0.0005 (Anderson and Wossener, 1992).

Initial Head Values

During the model calibration process, initial hydraulic head values across the model area were interpolated from water levels recorded at individual piezometers for a common time step. Initial head is the desired starting boundary condition for the model simulations. The initial head condition is taken from a time step when the groundwater level in all piezometers throughout the sandbar is best equilibrated with a particular peak or trough stage in the river hydrograph. For subsequent predictive modeling simulations, initial head was estimated using previously observed relations between river stage and groundwater elevation data in piezometers during analogous regulated flow regimes.

Boundary Conditions

The outer boundary of the active model area in contact with the Colorado River was delineated by the subaerial extent of the eddy bar higher than the 141.5 m^3/s stage elevation as surveyed on December 5, 2004 (Hazel and others, 2006b; J. Hazel, Northern Arizona University, written commun., 2006). A specified head, first type Dirichlet, boundary condition was used to describe the fixed potential head along the perimeter of the model that comes in contact with river (fig. 7). The temporal changes in river stage elevation along the river boundary were simulated with a time-varying function during the model run. The relation between stage and time was interpolated from the river stage piezometer US1 for the model calibration runs and from an ADVM at RM 30.3 for the predictive runs. Site-specific stage-discharge relations developed by Hazel and others (2006b) were used to facilitate this process.

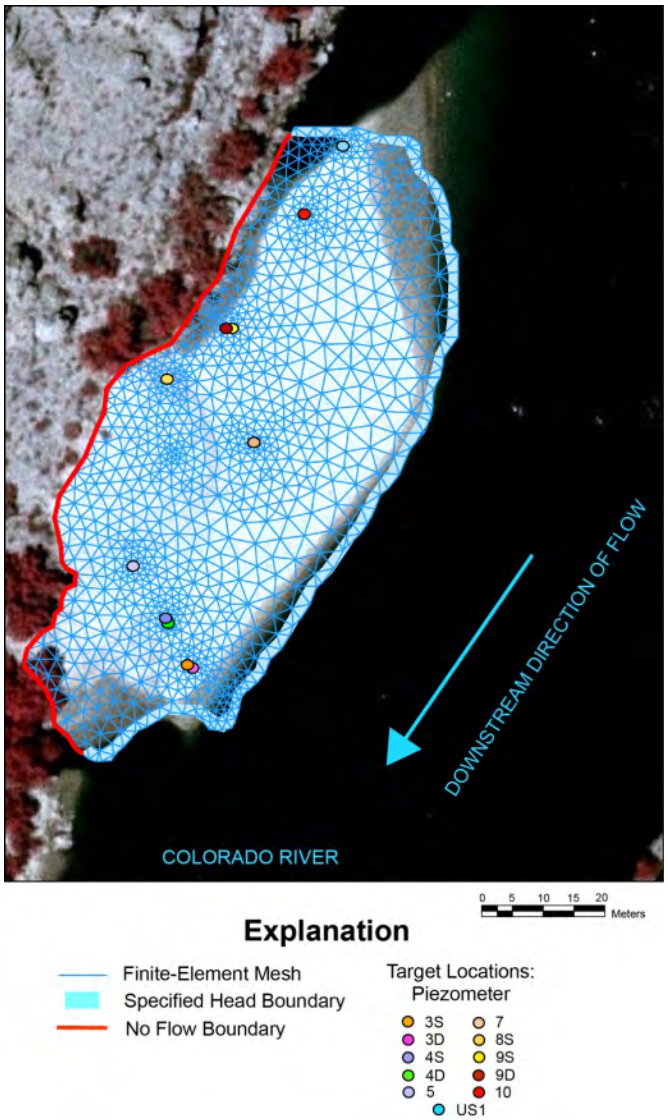

Figure 7. Plan view image of the river mile 30.7R eddy sandbar study site showing the location of piezometers used as targets for calibration and transient verification of the groundwater model developed for this study, river mile 30.7R, Colorado River in Marble Canyon, Arizona. Shown are the locations of the Specified Head Boundary and the No Flow Boundary around the perimeter of the Finite-Element Mesh within the active model area. Outer boundary of the active model area is delineated by the subaerial extent of the eddy sandbar above the 141.5 cubic meters per second river stage elevation.

Along the onshore model boundary between the contact of the sandbar with the bedrock and talus slope, a specified flux of zero was assigned to the boundary nodes (fig. 7). Recharge, another type of specified flux boundary condition, was not incorporated in the model. Despite its application during a period of above-average precipitation, the model was not sensitive to recharge; the specified head river stage boundary condition is the main control on the location of the phreatic surface in the model.

Model Calibration

Calibration Criteria and Model Error

A calibrated three-dimensional numerical model of Colorado River eddy sandbars can produce model outputs that replicate, although non-uniquely, observed changes in the phreatic surface of the sandbar as a function of river stage. Evaluation of the degree of calibration, or goodness-of-fit, is based on the residual differences between observed and simulated model results at target locations.

Calibration criteria were established so that the residual between the transient model simulation and the observed field condition should be no more than 15 percent of the variability in the total head change across the model domain, expressed as:

$$[h_m - h_s]/h_r \leq 15\% \,, \tag{1}$$

where h_m is measured head in meters, h_s is the modeled head in meters, and h_r is the range in measured head (h_m) across the model area in meters. Mean absolute error (MAE) and the root mean squared error (RMSE) combine individual residuals and quantify the average error across the model domain as:

$$MAE = 1/n \sum_{i=1}^{n} \left| (h_m - h_s) i \right| \,, \tag{2}$$

$$RMSE = \left[1/n \sum_{i=1}^{n} (h_m - h_s) i^2 \right]^{0.5} \,, \tag{3}$$

where n is the number of calibration values. Because MAE and RMSE provide an average error from specific target locations, they may be biased to these locations and may not necessarily represent the spatial distribution of error across the entire active model area.

The transient model was calibrated to water surface elevation data collected at 11 piezometers between January 3, 2005 and January 18, 2005 (fig. 8). Upon final download of the transducers, the mean absolute error of the residual between the measured depth to water in each piezometer and the value recorded by the transducer was 0.01 m for all targets. When all possible sources of systematic error associated with the measurement of the water surface elevation in each piezometer were accounted for, the error envelope for all target data used in the model calibration and verification was plus-or-minus 0.35 m, or 4 percent of the maximum range in head change across the sandbar at any given time step. The primary uncertainty stems from the precision of the optical survey measurements along the Colorado River in Grand Canyon, which is reported at “0.05 m or better” (Hazel and others, 2006b).

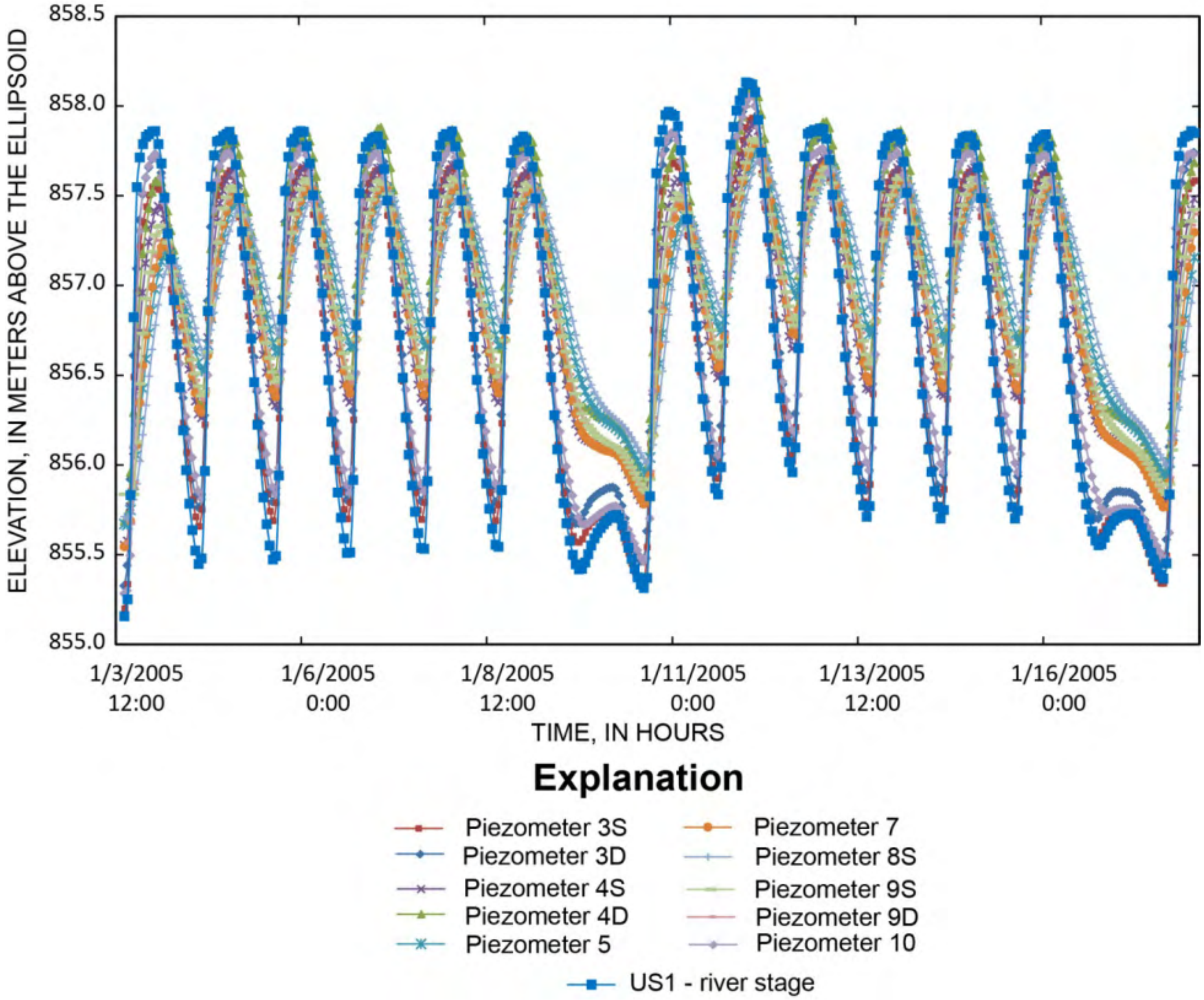

Figure 8. Measured elevation of groundwater level in all piezometers at river mile 30.7R eddy sandbar site relative to river stage (US1), Colorado River in Marble Canyon, Arizona, during the time period of calibration and transient verification of the model, January 3–18, 2005.

Model Results

The transient model for the entire eddy sandbar area at RM 30.7R was calibrated to water surface elevation data collected at 11 piezometers between January 3, 2005 and January 18, 2005 (fig. 8). The mean absolute error of the residual between the measured and modeled groundwater elevations at each target location, expressed as a percent of the total observed head change across the model area (1.66 m), was 14.6 percent among all 11 targets (table 2). The calibrated transient model is considered a good predictor of the phreatic surface across the entire three-dimensional domain of the RM 30.7R eddy sandbar model area.

Table 2. Root mean squared error (RMSE) and mean absolute error (MAE) residual differences between the measured groundwater level in piezometers and the simulated model results at target locations, Colorado River in Marble Canyon, Arizona, for transient model verification purposes, January 3–18, 2005 (see Table 1 for locations).

[RMSE and MAE are also presented as a percent of the total measured head change across the model domain at target locations].

Well id	RMSE of residual (m)	MAE of residual (m)	RMSE as % of total observed head change across model area[1]	MAE as % of total observed head change across model area[1]
3D	0.216	0.167	13.00%	10.01%
3S	0.164	0.117	9.88%	7.02%
4D	0.465	0.439	27.95%	26.39%
4S	0.305	0.269	18.35%	16.15%
5	0.343	0.313	20.60%	18.80%
7	0.297	0.228	17.86%	13.73%
8S	0.378	0.340	22.73%	20.47%
9D	0.399	0.298	23.97%	17.89%
9S	0.391	0.295	23.51%	17.72%
10	0.284	0.212	17.07%	12.75%
US1	0.000	0.000	0.02%	0.02%
Average	0.295	0.243	17.72%	14.60%

[1]Total head change across model area during simulation: 1.663 m

The sandbar face is the critical region affected by the processes of seepage erosion and mass failure in newly deposited eddy sandbars along the Colorado River. A major control on the exfiltration of groundwater from the sandbar and seepage erosion along the bar face is the elevation and location of the groundwater level within the sandbar, onshore from the bar face (Budhu and Contractor, 1994; Alvarez and Schmeeckle, 2012). To better emphasize the usefulness of the model within the sandbar face region conceptual refinement of the model was conducted to focus solely on the targets within the bar face area of critical concern for issues of seepage erosion and mass failure (piezometers 3S, 3D, and 10). In this usage, the boundary of sandbar face region is about10 meters onshore, horizontally, from the shoreline of the river at peak stage. The model provides an excellent simulation of the groundwater level within the bar face region that is continually affected by diurnal fluctuation in the hydrograph. The mean absolute error of the residual between the measured and modeled groundwater elevations at 3 piezometers (3S, 3D, and 10) within the sandbar face region is about10 percent; total observed head change across the model area is 1.663 m (fig. 9, table 2).

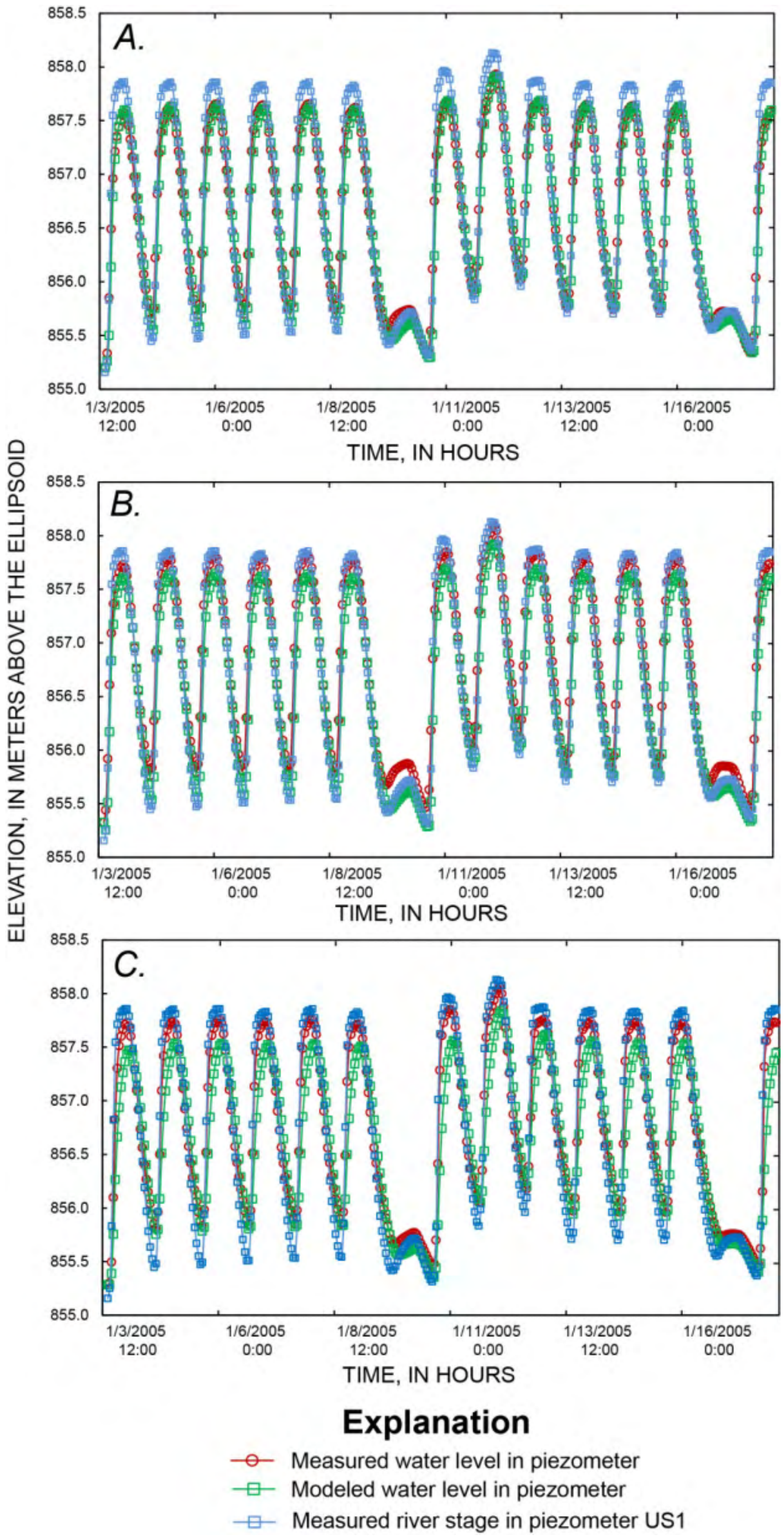

Figure 9. Graph plot showing measured and modeled groundwater level in piezometers (A) 3S, (B) 3D, and (C) 10, within the bar face region of the eddy sandbar at river mile 30.7R, Colorado River in Marble Canyon, Arizona, during transient verification of the model, January 3–18, 2005. Measured river stage at US1 is also shown.

Hydrologic data collected in piezometers at sandbar RM 30.7R were used to provide out-of-sample verification of the model as a predictive tool within the bar face region of the eddy sandbar. A time-varying function was used to simulate the river stage data observed at US1, from December 7, 2004 to December 20. 2004, at the specified head model boundary (fig. 10). The mean absolute error of the residual between the measured and modeled groundwater elevation during this simulation at piezometer 10, within the sandbar face region, is 8.67 percent (fig. 10, table 3). This out-of-sample goodness-of-fit confirms that the generalized three-dimensional model developed in this study accurately predicts time-varying groundwater levels, within the sandbar face of an eddy sandbar, as a function of highly variable fluctuations in river stage.

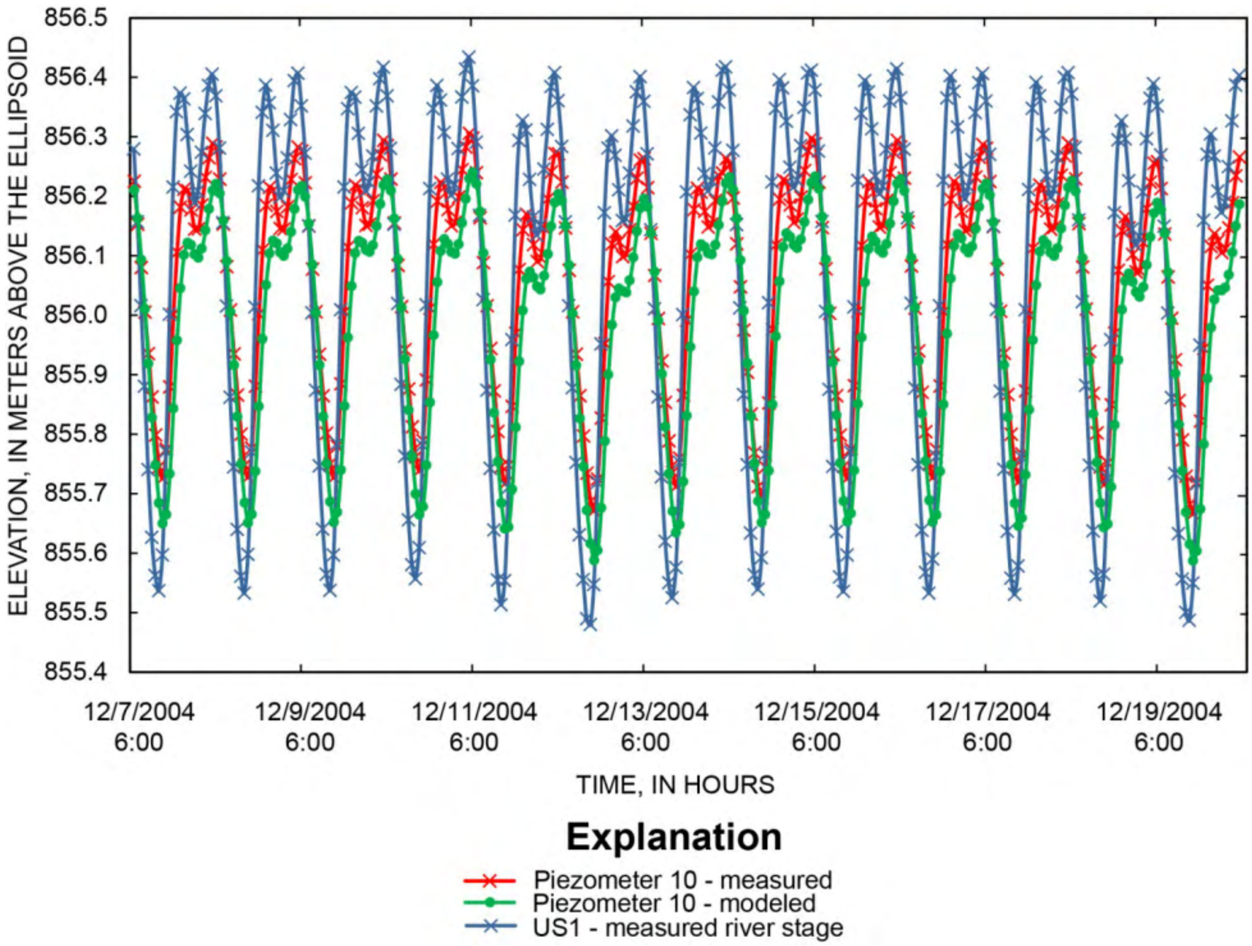

Figure 10. Graph plot showing measured and modeled groundwater level in piezometer 10, within the bar face region of the eddy sandbar at river mile 30.7R, Colorado River in Marble Canyon, Arizona, during transient verification of the model, December 7–20, 2004. Measured river stage at US1 is also shown.

Table 3. Root mean squared error (RMSE) and mean absolute error (MAE) for the measured groundwater level in piezometers and the simulated model results at piezometer 10, located within the river mile 30.7R sandbar face, during a transient model simulation, December 7–20, 2004.

Well ID	RMSE of Residual (m)	MAE of Residual (m)	RMSE as % of total observed head change across model area[1]	MAE as % of total observed head change across model area[1]
10	0.088	0.075	10.06%	8.67%
US1	0.000	0.000	0.03%	0.03%

[1]Total head change across model area during simulation: 0.87 m

As newly deposited sandbars evolve, temporal fluctuations in hydraulic conductivity, permeability, and effective stress can occur throughout the aquifer skeleton (Semmens, 1999; Springer and others, 1999). The two transient simulations (in-sample and out-of-sample) of the groundwater level in the bar face region yield mean absolute errors of less than 10 percent. During both simulations, the only model input parameter that was adjusted was the time-varying specified head boundary for river stage; all soil properties were kept constant. The two transient model runs demonstrate the ability of the model to simulate groundwater levels in the bar face region for observed data collected throughout a period where temporal fluctuations in soil properties were likely occurring, 14 and 40 days after the deposition of new 2004 high-flow sediments. Given (1) the likely temporal fluctuations in hydraulic conductivity and permeability as a function of effective stress during these transient model runs, and (2) that the model properly simulated (MAE < 10 percent) all observed bar face groundwater levels without any parameter adjustment, it reasonably may be concluded that the model developed in this study is not sensitive to small changes in soil parameters. Therefore, the model accurately simulates the groundwater level in the sandbar face under a range in hydrogeologic conditions at the sandbar throughout time.

Conclusion

A generalized numerical model was developed to predict groundwater levels within the bar face region of eddy sandbars, along the Colorado River downstream of Glen Canyon Dam, as a function of changes in river stage owing to unsteady dam releases. Two transient simulations (in-sample and out-of-sample) of the groundwater level in the bar face region, as a function of time-varying stage, yield mean absolute errors of less than 10 percent. The low mean absolute errors between the measured and modeled groundwater elevations in bar face piezometers are an indication of the model's ability to replicate observed changes in the groundwater level within the sandbar as a function of river stage. The model implemented in this study accurately simulates the groundwater level in the bar face region under a range in hydrogeologic conditions at the sandbar aquifer throughout time.

The generalized model developed during this study is applicable across a range of typical eddy sandbar deposits in diverse settings. The general predictive capability provided by this study meets the basic needs of researchers to estimate time-varying groundwater levels at the onshore end of a sandbar face for physical and numerical modeling of beach face stability, particularly during times of sandbar adjustment in response to seasonal, monthly, or weekly changes in diurnal fluctuating flow regimes.

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