Prepared in cooperation with the U.S. Department of State, the Mekong River Commission, Phnom Penh Autonomous Port, and the Cambodian Ministry of Water Resources and Meteorology

Hydrographic Survey of Chaktomuk, the Confluence of the Mekong, Tonlé Sap, and Bassac Rivers near Phnom Penh, Cambodia, 2012

Scientific Investigations Report 2014–5227

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

Cover photographs.
1. West bank of the Tonlé Sap River looking upstream, Phnom Penh, Cambodia, Februrary 8, 2011. Photograph by Benjamin J. Dietsch, U.S. Geological Survey (USGS).
2. Survey of a bench mark at Chroy Changvar, Phnom Penh, Cambodia, April 24, 2012. Photograph by Brenda K. Densmore, USGS.
3. View of the Mekong River near Phnom Penh, Cambodia, from the upper deck of the hydrographic survey boat, April 20, 2012. Photograph by Benjamin J. Dietsch, USGS.
4. Bank of the Mekong River near Kday Takoy Temple, Phnom Penh, Cambodia, April 21, 2012. Photograph by Benjamin J. Dietsch, USGS.
5. Survey of a bench mark at Kday Takoy Temple, Phnom Penh, Cambodia, March 28, 2012. Photograph by Richard C. Wilson, USGS.

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U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2015

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Conversion Factors and Datum

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
	Mass	
ton	1.102	ton, short (2,000 pounds)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)
	Ratio	
decibel (dB)	0.1	bel
	Frequency	
hertz (Hz)	1	cycle per second
kilohertz (kHz)	1,000	cycles per second
	Equivalent concentration terms	
gram per liter (g/L)	1	part per thousand

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Horizontal coordinate information is referenced to the World Geodetic System of 1984 (WGS 84).

Vertical coordinate information is referenced to Ha Tien 1960.

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

Hydrographic Survey of Chaktomuk, the Confluence of the Mekong, Tonlé Sap, and Bassac Rivers near Phnom Penh, Cambodia, 2012

By Benjamin J. Dietsch, Brenda K. Densmore, and Richard C. Wilson

Abstract

The U.S. Geological Survey, in cooperation with the U.S. Department of State, Mekong River Commission, Phnom Penh Autonomous Port, and the Cambodian Ministry of Water Resources and Meteorology, completed a hydrographic survey of Chaktomuk, which is the confluence of the Mekong, Tonlé Sap (also spelled Tônlé Sab), and Bassac Rivers near Phnom Penh, Cambodia. The hydrographic survey used a high-resolution multibeam echosounder mapping system to map the riverbed during April 21–May 2, 2012.

The multibeam echosounder mapping system was made up of several components: A RESON Seabat™ 7125 multibeam echosounder, an inertial measurement unit and navigation unit, data collection computers, and a Real-Time Kinematic (RTK) Global Navigation Satellite System (GNSS) base station. The survey area was divided into six survey subreaches and each subreach was surveyed within 3 days along survey lines oriented parallel to the flow direction. Complete coverage of the riverbed was the operational objective; however, to obtain broad spatial coverage, gaps between parallel swaths were permitted, especially in wide, shallow areas where multibeam swath widths were narrow.

The survey was referenced to two existing bench marks with known geographic coordinates by establishing a GNSS base station on the bench marks each day and using real-time corrections from the base station to correct boat navigation data. The World Geodetic System of 1984 (WGS 84) ellipsoid was used during data collection to reference height, and data were adjusted to the local datum, Ha Tien 1960, during postprocessing.

The quality of hydrographic surveys was described by an uncertainty estimate called total propagated uncertainty (TPU). Calculations of TPU were completed for the hydrographic survey data resulting in the maximum TPU of 0.33 meters. The mean and median TPUs were 0.18 meters, and 99.9 percent of TPU values were less than 0.25 meters.

Detailed hydrographic maps of Mekong, Tonlé Sap, and Bassac Rivers showing the riverbed elevations surveyed April 21–May 2, 2012, referenced to Ha Tien 1960 were produced. The surveyed area included a 2-km stretch of the Mekong River between the confluence with the Tonlé Sap and Bassac Rivers, and extended 4 km upstream and 3.6 km downstream from the 2,000-m confluence stretch of the Mekong River. In addition, 0.7 km of the Bassac River downstream and 3.5 km of the Tonlé Sap River (from the confluence to Chroy Changvar Bridge) upstream from their confluence with the Mekong River were surveyed. Riverbed features (such as dunes, shoals, and the effects of sediment mining, which were observed during data collection) are visible on the hydrographic maps. All surveys were completed at low annual water levels as referenced to nearby Mekong River Commission streamflow-gaging stations. Riverbed elevations surveyed ranged from 24.08 m below to 1.54 m above Ha Tien 1960.

Introduction

The Lower Mekong Basin (fig. 1) is home to more than 60,000,000 people with 11,600,000 people living in Cambodia (Mekong River Commission, 2011). Because of the basin's importance to this region, the Lower Mekong Initiative (LMI) was created as a result of a July 2009 meeting between the U.S. Secretary of State and the Foreign Ministers of the Kingdom of Cambodia, Lao People's Democratic Republic, Socialist Republic of Vietnam, and the Kingdom of Thailand. Myanmar (Burma) formally joined the LMI in July 2012 (Turnipseed, 2011). The People's Republic of China is not a formal member of the LMI, but is a stakeholder in the initiative. The purpose of the LMI is to create integrated regional cooperation among the five Lower Mekong countries. The LMI serves as a platform to address complex, transnational development and policy challenges in the Lower Mekong Basin region. The member countries agreed to enhance cooperation and build upon their common interests in the areas of environment and water, health, education, and infrastructure development (U.S. Department of State, 2014).

The LMI Environment and Water Pillar focuses on the development of a regional approach to sustainable environmental management and capacity development to manage shared natural and water resources. One element of the LMI environmental and water program is Forecast Mekong. Forecast Mekong is a project led by the U.S. Geological Survey (USGS) that provides data integration; predictive environmental, natural, and water resource models; and scientific visualization tools to help the LMI member countries make resource management decisions (Stefanov, 2012). Forecast Mekong provides planning tools to visualize and predict the consequences of water-resources development and river management. One Forecast Mekong project is the hydrographic survey of Chaktomuk, the confluence of the Mekong, Tonlé Sap (also spelled Tônlé Sab), and Bassac Rivers near Phnom Penh, Cambodia (fig. 1). The USGS, in cooperation with the U.S. Department of State, Mekong River Commission (MRC), Phnom Penh Autonomous Port, and the Cambodian Ministry of Water Resources and Meteorology, surveyed this area to collect data that could improve navigation and shipping safety and provide baseline scientific data to document natural and anthropogenic disturbances and geomorphic change in the confluence area. The hydrographic survey was completed in 2012 and supports the goals of Forecast Mekong by providing data to help visualize the confluence and aid the development of planning tools.

Purpose and Scope

The purpose of this report is to describe the methods and results of the 2012 hydrographic survey at Chaktomuk, the confluence of the Mekong, Tonlé Sap, and Bassac Rivers near Phnom Penh, Cambodia. The report includes background on the Mekong River Basin and a discussion of the objectives of the Forecast Mekong Project and the LMI.

Description of Study Area

The focus of the Forecast Mekong project includes the entire Lower Mekong River Basin (Lower Basin in fig. 1); however, the scope of the hydrographic survey is limited to the Chaktomuk area near Phnom Penh in southeast Cambodia (fig. 1). The Chaktomuk area was selected for this study because of the hydrologic importance of the location and its proximity to Phnom Penh, the capital city of Cambodia. The confluence of the Mekong, Tonlé Sap, and Bassac Rivers is known in the Khmer language as Chaktomuk, or "the four faces", signifying the four branches of the three rivers. The French named the confluence the Quatre Bras, or "the four arms." For most of the year, the Tonlé Sap River flows into the Chaktomuk, and the Bassac River flows out of the Chaktomuk to the South China Sea. During the wet season, the Tonlé Sap River flows away from the Chaktomuk and carries water from the Mekong River to the Tonlé Sap Lake, or the Great Lake, which is located northwest of Phnom Penh (fig. 1). The Tonlé Sap Lake serves as a flood- storage reservoir for the Mekong River and supports important wetlands, fisheries, and rice-growing areas (Campbell and others, 2006). Sedimentation or other alterations at Chaktomuk could alter this unique and important hydrologic system.

The confluence of the Mekong, Tonlé Sap and Bassac Rivers is ecologically and economically important to Cambodia. It serves as the primary source of drinking water for the approximately 1,500,000 citizens of Phnom Penh (U.S. Central Intelligence Agency, 2014), as well as a water supply for many industrial and commercial uses. Chaktomuk is the receiving water body for treated and untreated wastewater effluent. Chaktomuk serves as a transportation hub for the region. Vessels ranging from 5,000 deadweight tons sea-going cargo ships, to high-speed passenger boats, to small river-fishing boats can dock and transfer goods, materials, people, and food products at Phnom Penh Autonomous Port, which is an international port under the supervision of the Cambodian Ministry of Public Works and Transport and the Ministry of Economy and Finance. To facilitate shipping, Phnom Penh Autonomous Port maintains a continuous program of dredging Chaktomuk (Phnom Penh Autonomous Port, 2014). Typically, dredge spoils from the confluence are deposited near the head of the Bassac River creating reclamation land that has important economic value for commerce and industry within Phnom Penh (Chaktomuk Project Management Unit and DHI Water and Environment, 2002).

Mekong River Basin

The Mekong River begins in the Tibetan Plateau of China at an elevation of approximately 4,500 meters (m) above mean sea level (Mekong River Commission, 2005). The river flows southeast for approximately 4,800 kilometers (km) (Mekong River Commission, 2005) through the countries of China, Myanmar (Burma), Laos, Thailand, Cambodia, and Vietnam, where it discharges into the South China Sea. The river basin area is approximately 795,000 square kilometers (km^2), the mean annual discharge is approximately 14,500 cubic meters per second (m^3/s), and the annual runoff is approximately 457 cubic kilometers (Mekong River Commission, 2005). Based on mean annual discharge at its mouth, the Mekong River is the tenth largest river in the world (Mekong River Commission, 2005).

The Mekong River typifies large tropical rivers driven by the monsoonal cycle, with large mean annual discharge in conjunction with well-defined monsoonal wet and dry seasons (Adamson and others, 2009). The wet season typically lasts from May until early October, with the greatest precipitation usually falling in August and September (Mekong River Commission, 2005). The magnitude of discharges during the wet season can be 20 times larger than discharges during the dry season (fig. 2).

The Mekong Basin can be divided into two parts—the Upper Basin and Lower Basin (fig. 1). The Upper Mekong Basin, primarily located within the Chinese provinces (not shown) of Yunnan and Tibet, composes approximately 24 percent of the total Mekong Basin. In the Upper Basin, the Mekong River is called the Lancang Jiang, and generally

Base from Global Land Cover Facility: Shuttle Radar Topography Mission, 2004
Horizontal coordinate information referenced to the World Geodetic System 1984 (WGS 84) geographic projection
Vertical coordinate information referenced to the Earth Gravity Model, 1996

EXPLANATION

Mekong Basin
Upper Basin
Lower Basin

Major river
Other river
Capital city
City

Elevation, in meters
0 meters
3,495 meters

Figure 1. The Mekong River Basin and study area (modified from Turnipseed, 2011).

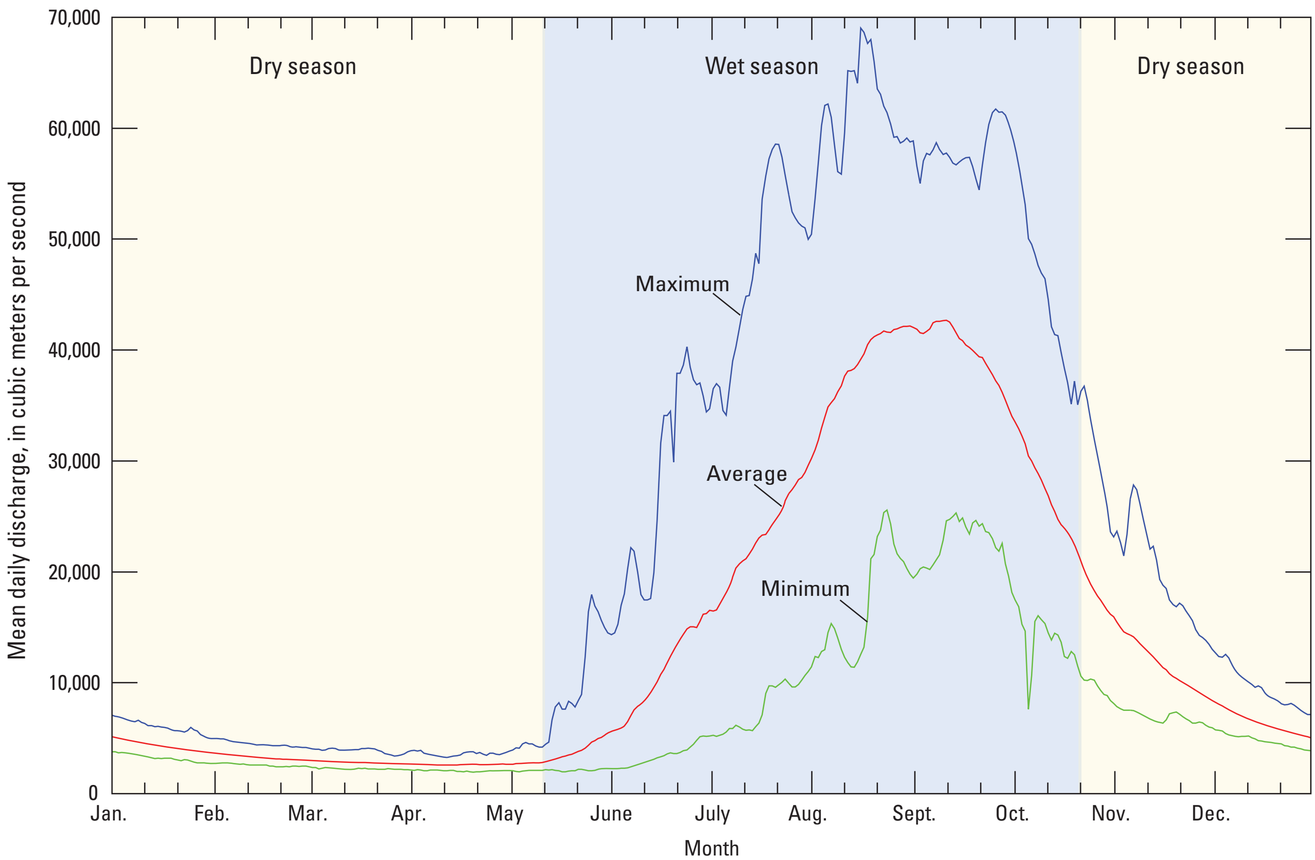

Figure 2. Average, maximum, and minimum mean daily discharge of Mekong River at Mekong River Commission streamflow-gaging station 019802 at Kompong Cham, Cambodia, 1960–2002 (Mekong River Commission, 2014b).

flows through narrow and deep canyons (Mekong River Commission, 2005). The Upper Basin has a monsoonal climate that varies with topography and elevation. The seasonal distribution of precipitation follows the monsoon cycle, but overall amounts generally decrease towards the north in Tibet (not shown). Snowmelt runoff at the higher elevations is a large source of water during the dry season, particularly in April through May. The Upper Basin contributes approximately 16 percent of the mean annual discharge, but more than 24 percent of the discharge during the dry season originates from snowmelt (Mekong River Commission, 2014a).

The Lower Mekong Basin approximately begins downstream from Yunnan Province (not shown), China. The Lower Basin widens in Thailand and Laos (fig. 1). The steep left-bank tropical tributaries (oriented looking downstream) in Laos contribute most of the flow of the Mekong during the wet season, whereas the low-relief right-bank tributaries in Thailand drain areas that generally receive less rainfall and contribute only 6 percent of the mean annual discharge (Mekong River Commission, 2005). At Kratie, in central Cambodia (fig. 1), the Mekong's mean discharge is more than 90 percent of the mean annual discharge at its mouth (Mekong River Commission, 2014a). In Cambodia, the Lower Basin is characterized by a wide and flat flood plain and contains the Tonlé Sap River and the Tonlé Sap Lake (also called the Great Lake). The Mekong, Tonlé Sap River, and Tonlé Sap Lake form a unique hydrologic system in which the Tonlé Sap River reverses flow twice a year depending on high or low stage of the Mekong River. When stage is low in the Mekong River, the Tonlé Sap River flows to the Mekong River. Conversely, when stage is high in the Mekong River, the Tonlé Sap River flows to Tonlé Sap Lake. Tonlé Sap Lake serves as a flood-storage reservoir for the Mekong River. The Tonlé Sap Basin has a drainage area of approximately 84,000 km² and Tonlé Sap Lake is the largest fresh- water lake in Southeast Asia (Kummu and Sarkkula, 2008). Tonlé Sap Lake serves as an important agricultural and fisheries production area for Cambodia. At Chaktomuk, the Tonlé Sap River joins the Mekong River, and then splits into two main distributary channels consisting of the Mekong and Bassac Rivers (fig. 1). Chaktomuk also marks the beginning of the Mekong Delta that extends from Cambodia through Vietnam into the South China Sea (fig. 1) (Mekong River Commission, 2005).

Hydrographic Survey of Chaktomuk

The Tonlé Sap and Mekong Rivers flow into the confluence from the northwest and north respectively, whereas the Mekong and Bassac Rivers flow out of the confluence to the southeast and south respectively (figs. 1 and 3). The confluence is located approximately 330 km upstream from the mouth of the Mekong River at the South China Sea, 3,870 km downstream from the headwaters of the Mekong River, and 140 km downstream from Tonlé Sap Lake, and it is the origin point of the Bassac River.

The climate conditions at Phnom Penh are determined by the monsoonal wet and dry cycle typical for the lowland plains of Cambodia. The wet season typically begins in May and ends in October. The dry season typically begins in November and ends in April with the least monthly average precipitation occurring in January. The average yearly rainfall at Phnom Penh is 1,470 millimeters (mm) (Mekong River Commission, 2014b) with the greatest average rainfall occurring in September. The hottest month is April, the coolest month is January, and the range of monthly mean temperatures is only 3.5 degrees Celsius (°C) (Mekong River Commission, 2014b). The mean annual temperature is 27.7 °C (Mekong River Commission, 2014b).

The Mekong River at Kompong Cham (streamflow-gaging station number 019802; Mekong River Commission, 2014c) is approximately 77 km upstream from Phnom Penh, making it the closest discharge measurement station to Chaktomuk (fig. 1). The mean daily hydrograph at Kompong Cham has a consistent seasonal pattern (fig. 2) that is similar to other Lower Mekong River streamflow-gaging stations at Kratie, Pakse, and Vientiane (fig. 1). The May–June increase in streamflow is representative of the monsoon-driven transition from dry to wet seasons.

The Mekong River at Kompong Cham streamflow-gaging station was started in 1960. The monthly mean discharge ranged from a minimum of 2,625 m^3/s in April to a maximum of 40,388 m^3/s in September. From 1960 to 2002, the lowest discharge on record was 1,947 m^3/s measured April 21, 1993, and the peak of record was 69,025 m^3/s measured on August 17, 1978 (Mekong River Commission, 2014b). Typically, the maximum water levels occur in August to October

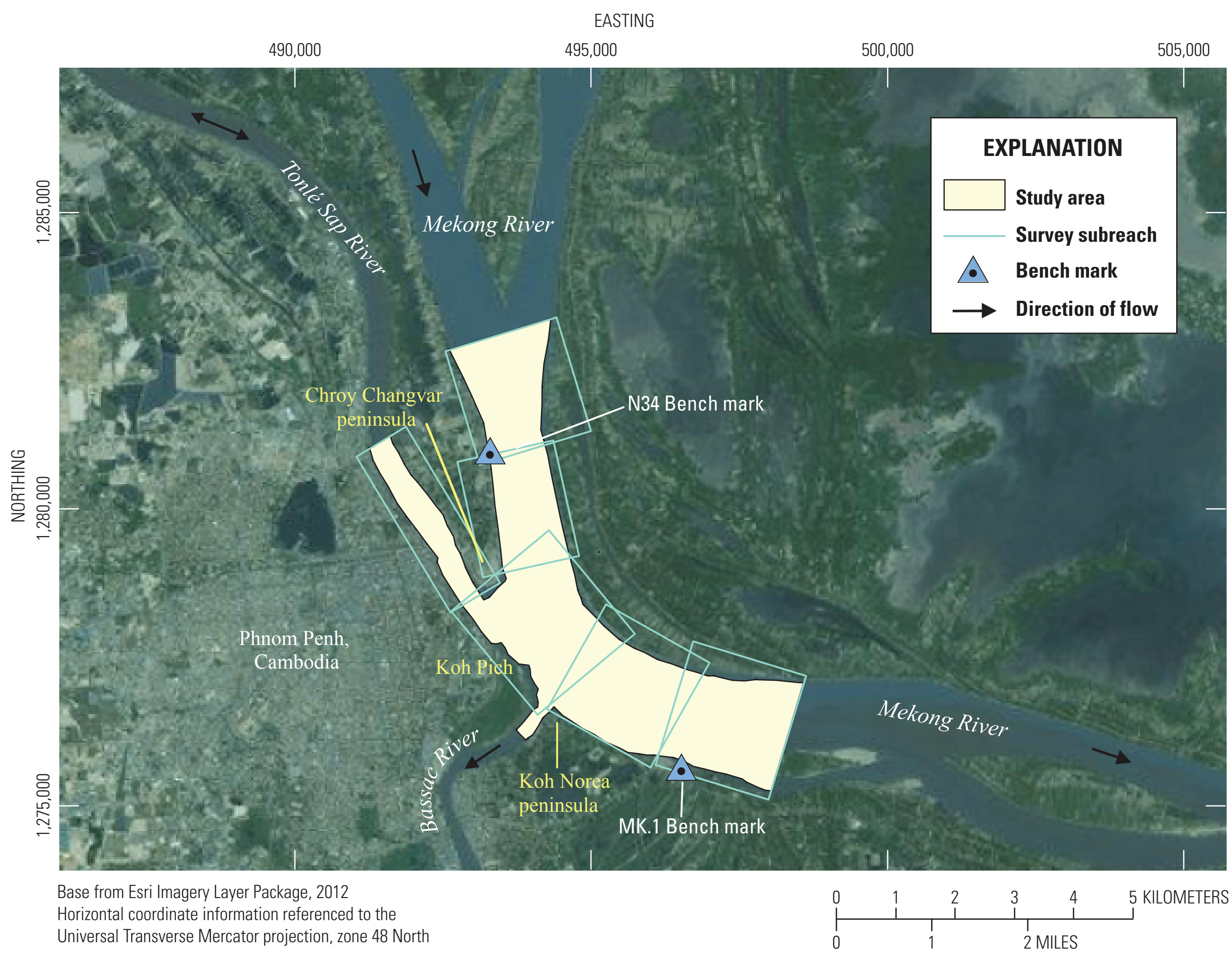

Figure 3. The confluence of the Mekong, Tonlé Sap, and Bassac Rivers.

and minimum water levels occur in April. The annual exceedance probability of occurrence of high water levels at Chaktomuk is shown in table 1.

The bed material of the Mekong River at Chaktomuk is predominantly sand. The median grain size is approximately 0.3 mm, which generally is classified as medium sand (Chaktomuk Project Management Unit and DHI Water and Environment, 2002). Upstream from the confluence, the bed of the Mekong River becomes more coarse grained (sand and gravel), whereas the bed of the Tonlé Sap River is composed primarily of silt and fine sand (Chaktomuk Project Management Unit and DHI Water and Environment, 2002). Suspended-sediment concentration varies in relation to streamflow, with the highest median values found typically in August at 0.48 gram/liter (g/L) in conjunction with the rising flows of the Mekong River and lowest median values found in December at 0.151 g/L corresponding to declining flows (Chaktomuk Project Management Unit and DHI Water and Environment, 2002). Sediment transport calculations indicated that bed material is transported mainly as bed load (Chaktomuk Project Management Unit and DHI Water and Environment, 2002).

The planform shape of the confluence is evolving by a process of continual migration towards the south as noted in previous studies (Chaktomuk Project Management Unit and DHI Water and Environment, 2002). The most pronounced feature is the extension of the Chroy Changvar (or Chruy Chanvar [Chaktomuk Project Management Unit and DHI Water and Environment, 2002]) peninsula, which separates the Mekong from the Tonlé Sap River on the northern side of the confluence (fig. 3). The elongation rate of the peninsula is estimated to be 10 m per year since 1876 (Chaktomuk Project Management Unit and DHI Water and Environment, 2002). The Tonlé Sap River flows into the northwestern side of the confluence and the right bank (west) of the Tonlé Sap River is armored with a concrete revetment that has stabilized the bank and prevents lateral channel migration. The entrance to the Bassac River is on the southern end of the confluence and it is bounded by Koh Norea peninsula and Koh Pich island (Chaktomuk Project Management Unit and DHI Water and Environment, 2002) (fig. 3). The northern tip of Koh Norea peninsula, located downstream from the entrance into the Bassac River, is eroding (Chaktomuk Project Management Unit and DHI Water and Environment, 2002). Koh Pich is an island that is expanding because of placement of dredging spoils. Channel dredging is required, because of the deposition of silt in the confluence (Phnom Penh Autonomous Port, 2014) that otherwise would obstruct the navigation of the confluence and Mekong River allowing large shipping vessels clear and safe access to dock at the Phnom Penh Autonomous Port. The riverbed at Chaktomuk is characterized by pock-marked patterns and deep excavation pits from dredging. The dredge spoils serve as an important source of material for land reclamation projects (Chaktomuk Project Management Unit and DHI Water and Environment, 2002). Typically, dredge spoils from the confluence are deposited near the head of the Bassac River on Koh Pich, creating reclamation land that has important economic value (Chaktomuk Project Management Unit and DHI Water and Environment, 2002).

Table 1. Annual exceedance probability of occurrence of water levels at Chaktomuk.[1]

Annual exceedance probability of occurrence, in percent	High water level, in meters above Ha Tien 1960
50	8.9
20	9.4
10	9.7
5	9.9
3.3	10.0
2	10.1

[1]Modified from Chaktomuk Project Management Unit and DHI Water and Environment, 2002.

Methods of Investigation

The Mekong, Tonlé Sap, and Bassac Rivers near Phnom Penh were surveyed by using a multibeam echosounder (MBES) mapping system. The study area was surveyed by a team of scientists, technicians, and engineers from the USGS, MRC, Phnom Penh Autonomous Port, and the Cambodian Ministry of Water Resources and Meteorology. Hydrographic surveys were completed during several weeks.

Description of Equipment

The MBES consists of several components including a projector, receiver, link-control unit (LCU), and sonar processor. The entire MBES mapping system includes these MBES components, an inertial measurement unit (IMU) and navigation unit, and data collection computers. The MBES mapping system and configuration used for the surveys was similar to the systems described in Densmore and others (2013), Huizinga (2010), and Huizinga and others (2010).

The MBES used was the RESON SeaBat™ 7125 manufactured in 2008 (RESON A/S, Slangerup, Denmark) operating at a frequency of 400 kilohertz (kHz). The SeaBat™ 7125 was operated in the equidistance mode during the survey. The equidistance mode collects 512 equally spaced depth readings each time the projector transmits one sound wave (a ping), which has been transformed into beams (table 2). In this mode, the beams cover a 128 degrees cross-track swath that is focused within a 1 degree along-track area (RESON, Inc., 2008). The maximum depth that this MBES can survey is 200 m (table 2); however, the depths observed during this survey never exceeded this limit. The typical minimum survey depth for the SeaBat™ 7125 is 0.5 m; however, the MBES was mounted for this survey such that depths of about 1.5 m or more were required for standard operation.

The boat used during the hydrographic survey was 15-m long with a 3-m beam width and 1-m draft (fig. 4) and was selected for its ability to accommodate a work area for several computer monitors; the boated needed to maintain a cruising speed of about 2 to 3 meters per second (m/s) during data collection. The MBES projector and receiver components were mounted on the starboard bow on a pole that allowed the MBES projector and receiver components to be rotated alongside the boat into the water and locked into surveying position about 1 m below the surface (fig. 4*C*). The MBES projector and receiver components were secured in surveying position for the duration of the survey. The projector and receiver are each an array of piezo-electric ceramics that transform the sound wave into beams through constructive and destructive interference. The speed of sound in the water at the sonar projector/receiver, as recorded by a sound velocity probe (RESON SVP-71) mounted near the projector and receiver components, was continuously monitored so depths could be accurately calculated for each sounding (RESON, Inc., 2008). A separate profiling-sound velocity probe was used to collect a speed-of-sound profile throughout the water column at multiple locations in the survey area, and these data were consistent with sound velocity data near the surface; therefore, a sound velocity profile was not applied to the data.

The SeaBat™ 7125 MBES is controlled by a sonar processor, which is a high-performance computer that manages data flow and signal attributes (transmitted power, ping rate, pulse length, and receiver gain). The transmitted power control setting increases or decreases the amount of acoustic energy transmitted into the water. During the surveys, the acoustic power was always set at 220 decibels (dB) and the ping rate was typically varied between upstream and downstream passes to collect a similar amount of data because the boat moves slowly upstream against the current and quickly downstream with the current. The ping rate was set to 10 pings per second (p/s) for upstream passes and 30 p/s for downstream passes. The pulse length controls the length of time the acoustic signal is transmitted. Pulse length on the RESON SeaBat™ 7125 can range from 33 microseconds (µs) to 300 µs (table 2). A narrow pulse length provides high resolution in shallow depths, but a wider pulse length provides maximum range with low resolution images. Pulse length was typically set from 40 µs to 60 µs for the rivers in the survey area. Receiver gain controls the increase in the amplitude applied to the returned sonar signal

Table 2. Specifications of multibeam-echosounder mapping system equipment.

[kHz, kilohertz; m, meters; °, degrees; Hz, hertz; CW, continuous wave; mm, millimeters; µs, microseconds; RTK, real-time kinematic; GNSS, Global Navigation Satellite System; m, meters; m/s, meters per second; ppm, part per million; RMS, root mean square]

RESON SeaBat™ 7125 specifications (RESON, Inc., 2008)	
Frequency	400 kHz
Maximum depth	200 m
Swath coverage	128°
Beam width	0.5° × 1°
Number of beams	256/512 Equi-angle or 512 equidistant
Maximum update rate	50 Hz
Wave form	Gated CW
Depth resolution	5 mm
Pulse length	33 to 300 µs
System control	7-P Processor unit
Mounting angle	20 to -20°
POS MV WaveMaster system (Applanix Corporation, 2006) with RTK GNSS corrections	
Pitch and roll accuracy	0.02°
Heave accuracy	0.05 m
Heading accuracy	0.06°
Positional accuracy	0.02–0.09 m
Velocity accuracy	0.05 m/s
Trimble® R8 GNSS receivers (Trimble® Navigation Limited, 2009)	
Horizontal accuracy	10 mm + 1 ppm RMS
Vertical accuracy	20 mm + 1 ppm RMS

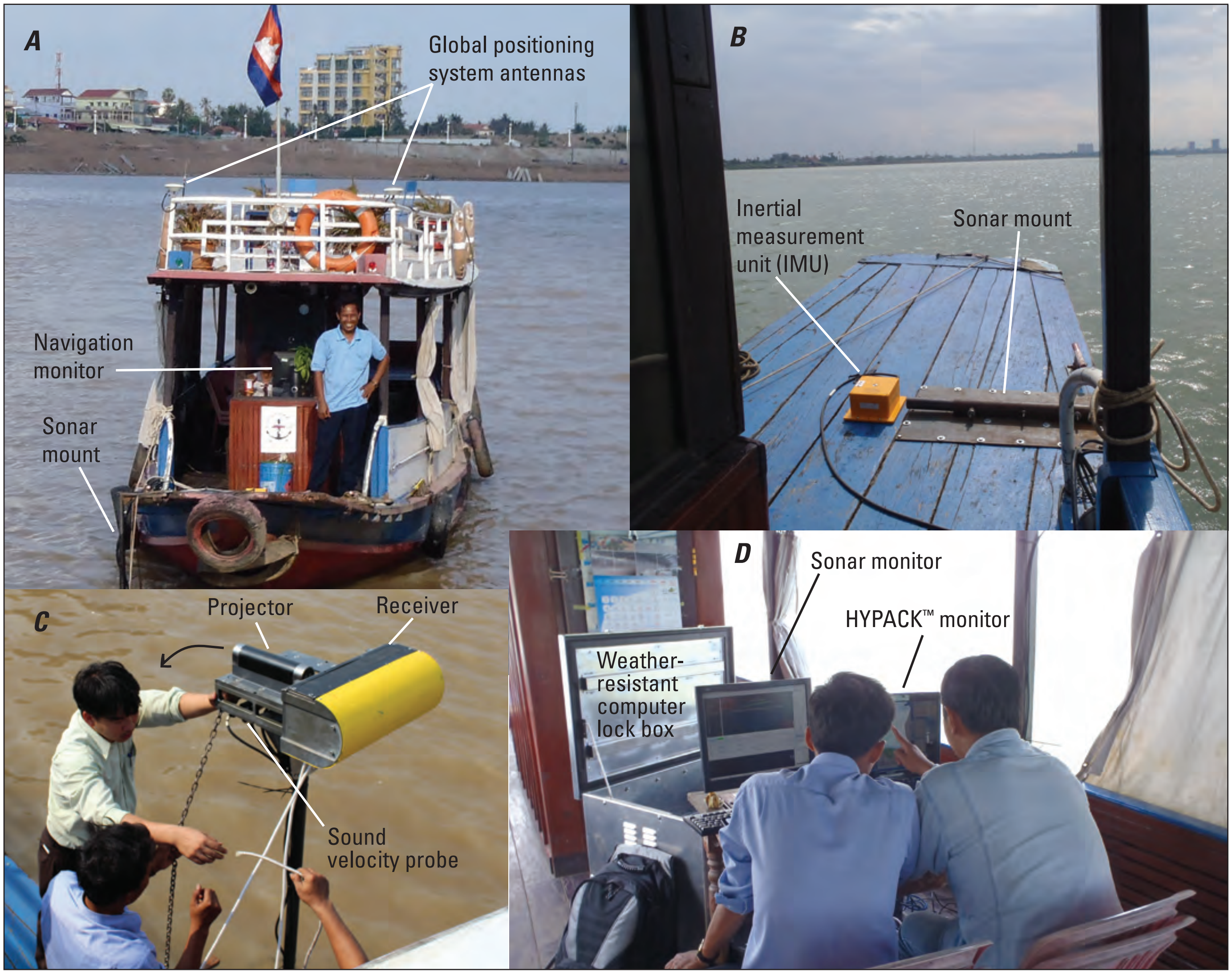

Figure 4. A multibeam-echosounder mapping system. *A*, View of front of boat with the global positioning system antennas, navigation monitor, and sonar mount. *B*, View forward from the bow with the inertial measurement unit (IMU) and sonar mount. *C*, View of the stowed sonar head (rotated approximately 180 degrees from deployed position) with the projector, receiver, and sound velocity probe. *D*, View of main cabin interior with the computer system setup including sonar and HYPACK® monitors and weather-resistant computer lock box.

in addition to the calculated time-varied gain (TVG). Receiver gain was typically set for 30 to 40 dB.

The IMU and navigation system used with the MBES (fig. 4*B*) was an Applanix Position Orientation Solution for Marine Vessels (POS MV™) WaveMaster system (Applanix Corp., Richmond Hill, Ontario, Canada). The POS MV™ system consists of two Trimble Zephyr Global Positioning System (GPS) antennas (Trimble Navigation, Ltd., Sunnyvale, Calif.), the IMU, and a POS Computer System that is configured and monitored through POSView Controller software. The GPS antennas were mounted on the rail of the observation deck about 4 m above the MBES projector and receiver (fig. 4*A*). The IMU consists of three linear accelerometers and three solid-state gyroscopes arranged in a triaxial orthogonal array to sense acceleration and angular motion in all three axes, and was located at the center of the bow of the boat about 7.5 m forward of the boat's center of gravity (fig. 4*B*). Data from the GPS antennas and from the IMU were combined by the POS MV™ system to provide position, roll and pitch angles, true heading, and real-time heave of the boat to enable correction of the MBES data. A Real-Time Kinematic (RTK) GPS/Global Navigation Satellite System (GPS/GNSS) radio link to a base station (Trimble® R8 GNSS receiver [Trimble® Navigation Limited, 2009]) located on a bench mark provided additional correction information. The GPS/GNSS Azimuth Measurement Subsystem (GAMS) algorithm of the POS MV™ and RTK solution was used during the hydrographic survey; therefore, the accuracy of the roll and pitch measured was 0.02°, heave was 0.05 m, heading was 0.06°, position was 0.02 to 0.09 m, and velocity was 0.05 m/s (Applanix Corporation, 2006) (table 2). When GPS/GNSS reception outages occurred, typically near shorelines and under bridges, the POS MV™ provided the sole source of boat position information, which caused a slight degradation of accuracy for those periods.

The high-resolution MBES system required detailed documentation of sensor locations, timing differences, and instrument calibrations to achieve a high level of precision and accuracy. The positions of each sensor were precisely measured in relation to all others using a total-station survey instrument. Timing between the MBES instruments was synchronized using a pulse-per-second message sent to the sonar from the POS MV™.

All the sounding, navigation, and motion data were combined, saved, and displayed using the HYPACK®/HYSWEEP® software (HYPACK, Inc., 2007a and 2007b) and were continuously monitored on a laptop computer during data collection (fig. 4*D*). An operator monitored data streams and oversaw navigation in real-time while concurrently refining sonar settings. A separate monitor, displaying the navigation software output, was positioned at the boat pilot's station so that survey lines could be followed and survey plan boundaries, orthophotographs, and charts could be viewed while data were collected (fig. 4*D*).

Hydrographic Survey Methods

The hydrographic survey was completed using a high-resolution MBES mapping system installed on a modified boat. A brief overview of the various component parts of the MBES are given in the "Description of Equipment" section of this report. The field procedures and data-processing procedures used to complete the survey are described in the following sections.

Field Procedures

The goal of the study was to survey the riverbed elevations at Chaktomuk to help develop visualization and modeling tools and to provide a dataset for comparison with previous and future surveys. To achieve this goal, the survey included as much of the region near the confluence as was practical in the time available. The survey area, generally centered on the confluence of the rivers, was divided into six survey subreaches (fig. 3). Each subreach was small enough to be surveyed within 3 days to minimize discontinuity in survey data caused by ongoing processes, such as water-level changes, bedform translation, and anthropogenic changes. The location and extent of each subreach were based on assumptions of boat speed, river width and depth, and distance to a survey-control bench mark (GNSS base station).

The first subreach to be surveyed was on the Mekong River at the downstream end of the study area. The orientation of the MBES sonar mount was not changed during surveying to avoid errors related to different mounting positions. The boat pilot followed streamwise (parallel to the direction of flow) survey lines that were projected onto a navigation display to obtain broad spatial coverage along each river. Gaps between parallel swaths were permitted, especially in wide, shallow areas where swath widths were limited by depth. MBES settings such as power, gain, and filter windows were adjusted based on depth, quality of received signal, and noise (random fluctuation in the signal).

At the beginning of each survey day, a GPS/GNSS base station was deployed on one of two bench marks (fig. 3) with known geographic coordinates. During data collection, the World Geodetic System of 1984 (WGS 84) ellipsoid was used to reference height because elevation referenced to the local vertical datum, Ha Tien 1960, was unknown for either of the bench marks. Although real-time corrections to GPS/GNSS positions were applied to data points obtained during the survey, the accuracy of the survey points was dependent on the accuracy of the assumed coordinates of the bench marks. After the survey was completed, the geodetic position of the bench marks was revised based on an average of National Geodetic Survey Online Positioning User Service (OPUS; National Geodetic Survey, 2014) solutions computed from data collected at each bench mark during the study (table 3). A correction based on the refinement of the bench mark location was applied to the survey data during post-processing. A bench mark, designated MK.1 located near the downstream end in the survey area, was used for the most downstream survey subreach, and the Chroy Changvar bench mark, designated N34, near the upstream end of the study area (fig. 3 and table 3) was used for the rest of the survey subreaches.

Data-Processing Procedures

Using MBES data required software and several steps that were capable of processing large datasets. The USGS used three different software packages to process the MBES data: (1) HYPACK®/HYSWEEP® software, primarily for data collection; (2) CARIS HIPS and SIPS™ and Bathy DataBASE: Base Editor™ software (CARIS, 2012a and 2012b), primarily for post-processing; and (3) Esri's ArcMap software (Esri, 2012) for additional post-processing, including elevation adjustments and visualization of mapping results.

First, all offset values (distances between MBES components used by the software) and calibration values were either determined or evaluated, and the values were applied to the dataset before it was edited. Calibration values were determined from processing data collected specifically for the calibration test. This process is described in the "Quality Assurance and Quality Control" section of this report. Offset values were determined for the configuration of the boat for data collection and did not change as long as mounting points remained unaltered; however, the surveyor verified that all offsets were entered correctly for each dataset.

Second, water-surface heights were reviewed to ensure that accurate corrections were applied to the depth measurements, which, in turn, were used to calculate the height of riverbed above the reference ellipsoid (WGS 84). If water-surface heights were not deemed to be sufficiently accurate (evaluated if a point was collected using fixed GPS/GNSS solution) throughout the dataset, then a time series of water-surface profiles were created by selecting representative upstream and downstream water-surface heights from each survey dataset. The water-surface profiles were used to spatially interpolate the water surface for successive intervals for the time of the survey.

After water-surface heights were determined and applied to the dataset, the bathymetric soundings were filtered to remove data that did not agree within 0.01 m of the riverbed height collected by adjacent beams. Filters removed spikes or narrow peaks likely caused by interference with the sonar signal. Data points flagged as poor quality because they were collected at low signal strength and (or) because they were not collinear in elevation/depth were removed. Data points from the extreme outside edges of the swath were removed because random fluctuations often are present in the outermost beams. After filters were applied, each swath was reviewed in graphic displays, and remaining values that were determined by a hydrographer to be erroneous were edited or deleted from the dataset.

The CARIS HIPS and SIPS™ implementation of the Combined Uncertainty and Bathymetry Estimator (CUBE) algorithm (Calder and Wells, 2007) was used to create a riverbed surface model based on the hydrographic dataset, which consisted of more than 53 million individual points. The CUBE algorithm uses a data reduction technique that estimates the depth and a confidence interval for each node of a gridded surface model based on the points in the dataset. Therefore, the gridded surface model is a “smoothed” representation of the bathymetric data points and contains less variance. The surface model was exported in a geospatial raster format—grids with 0.5-m by 0.5-m cells. Each cell value represents an estimate of the most likely riverbed height associated with the area inside the cell. On average, about 48 data points were used to estimate the most likely riverbed height in each cell.

Next, the coordinate values in the hydrographic dataset were measured in reference to the WGS 84 ellipsoid, but the local tidal datum used to reference elevation above mean sea level is Ha Tien 1960. The vertical separation between Ha Tien 1960 and WGS 84 ellipsoid is about 10 m in the Lower Mekong River Basin (Falke, 2009); however, the separation

Table 3. Location and location checks of bench marks used for hydrographic surveys of Chaktomuk near Phnom Penh, Cambodia, 2012.

[WGS 84, World Geodetic System of 1984; OPUS, Online Positioning User Service]

Date surveyed	Bench-mark identifier	Source of coordinates	Coordinates referenced to WGS 84		
			Longitude	Latitude	Ellipsoid height, in meters
1/6/2006	MK.1	Previous survey[1]	104°58′04.2665″	11°32′22.9218″	-1.333
3/27/2012	MK.1	OPUS solution	104°58′04.2858″	11°32′22.9164″	-1.625
4/20/2012	MK.1	OPUS solution	104°58′04.2879″	11°32′22.9167″	-1.705
4/21/2012	MK.1	OPUS solution	104°58′04.2862″	11°32′22.9174″	-1.747
4/23/2012	MK.1	OPUS solution	104°58′04.2863″	11°32′22.9166″	-1.756
3/27–4/23/2012	MK.1	OPUS average	104°58′04.2865″	11°32′22.9168″	-1.736
1993	N34	Previous survey[2]	104°56′18.4424″	11°35′16.5024″	5.774
4/24/2012	N34	OPUS solution	104°56′18.4602″	11°35′16.4968″	5.609
4/25/2012	N34	OPUS solution	104°56′18.4605″	11°35′16.4958″	5.619
4/26/2012	N34	OPUS solution	104°56′18.4608″	11°35′16.4958″	5.590
4/27/2012	N34	OPUS solution	104°56′18.4603″	11°35′16.4960″	5.606
4/28/2012	N34	OPUS solution	104°56′18.4610″	11°35′16.4958″	5.581
4/30/2012	N34	OPUS solution	104°56′18.4609″	11°35′16.4955″	5.648
5/1/2012	N34	OPUS solution	104°56′18.4623″	11°35′16.4954″	5.695
5/2/2012	N34	OPUS solution	104°56′18.4620″	11°35′16.4955″	5.642
4/24–5/2/2012	N34	OPUS average	104°56′18.4610″	11°35′16.4958″	5.624

[1]Cambodian Ministry of Public Works and Transport, written commun., 2006.

[2]Institut Géographique National Français, written commun., 1993.

between the two datums is poorly documented in the study area. Global geoid models of the earth such as the WGS 84 Earth Gravitational Model 2008 (EGM2008) are surfaces referenced to the global mean ocean surface elevation. In contrast, a local tidal datum is referenced to the long-term average of tides at a specific location (or locations). Heights referenced to the WGS 84 ellipsoid can be converted to elevations referenced to a local tidal datum through a two-step process if the separation of the local tidal datum from a geoid model is known.

For this hydrographic survey, conversion of the WGS 84 ellipsoid heights to elevations above Ha Tien 1960 was achieved by first converting the ellipsoid heights to orthometric heights referenced to EGM2008, and then from orthometric heights above EGM2008 to heights above Ha Tien 1960 based on separation between Ha Tien 1960 and EGM2008.

For the USGS hydrographic survey of Chaktomuk in 2012, heights above the WGS 84 ellipsoid were converted to orthometric heights referenced to EGM2008 using the following equation:

$$H = h - N \tag{1}$$

where

- H is the orthometric height, in meters;
- h is the WGS 84, ellipsoid height, in meters; and
- N is the EGM2008, geoid height, in meters.

Geoid heights were computed for each point on a 100-m by 100-m grid covering the entire study area using software developed by the National Geospatial-Intelligence Agency (National Geospatial-Intelligence Agency, 2013). In general, geoid heights trended from about -12.38 m in the southeast part of the survey to about -12.81 m in the northwest. The geoid grid then was subtracted from the hydrographic grids to convert the vertical reference from the WGS 84 ellipsoid to orthometric heights based on EGM2008. Previous GPS surveys of a second-order vertical control point in Phnom Penh (not used in this survey) indicated that Ha Tien 1960 is 0.76 m lower than EGM2008 (F.S. Seebacher, Mekong River Commission, written commun., 2014). Thus, a separation offset of 0.76 m was assumed to be valid for the study area and was subtracted from the orthographic grids referenced to EGM2008 to create hydrographic grids referenced to Ha Tien 1960.

Last, hydrographic maps of the survey subreaches in the Mekong, Tonlé Sap, and Bassac Rivers were produced from the 0.5-m by 0.5-m grids referenced to Ha Tien 1960. The riverbed elevation associated with the center of each grid cell was exported as an (x-y-z) text file for publication.

Quality Assurance and Quality Control

Two primary methods were used for quality assurance and quality control (QA/QC) during collection and processing of data with the MBES mapping system: operator QA/QC during data collection and patch tests. During collection of hydrographic data, the MBES system operator was continuously checking the data being logged for poor soundings (such as those that had low echo intensity or were not collinear with the surrounding data) and adjusting settings on the system to ensure that the best possible data were collected. The MBES operator also compared data collected from overlapping swaths and subreaches to ensure that the data being collected were well correlated with those from previous passes.

Patch tests are short survey lines located in specifically selected test areas, and when surveyed in parallel or perpendicular directions, the results allow timing and determination of orientation offsets of the MBES with respect to the IMU. Patch-test data were collected in HYPACK®/HYSWEEP® software following the same procedures that were used to collect data that were not used for patch tests, but data from these specific survey lines were further evaluated using HYPACK®/HYSWEEP® software to determine latency, or timing difference between the MBES and the POS MV™ positioning data, and angular offset values. In addition, patch tests were used to determine the angular offsets of the MBES projector/receiver with respect to the IMU. These angular offsets are referred to as roll, pitch, and yaw. Uncorrected latency, pitch, and yaw offsets appear as horizontal offsets in the collected data, whereas uncorrected roll offsets appear as vertical and horizontal offsets in the data. Further details of patch tests are documented in Densmore and others (2013) and HYPACK, Inc. (2007b).

The latency test was used to determine a timing offset (Δt) between the MBES mapping system and the positioning or GPS component of the POS MV™. Timing offsets were determined by collecting data on the same survey line over the riverbed slope or bedform feature in the same direction, but at two different speeds. The latency test completed for this survey determined that the latency (Δt) was zero.

A roll test was used to determine the angular offset of the sonar projector/receiver alignment with respect to the IMU orientation along the longitudinal axis of the boat. To determine the roll-angle offset (α), data were collected over a flat area on one survey line; data were collected twice while the boat moved in opposite directions. The results of these roll tests indicated that the roll-angle offset was 2.8 degrees (away from the boat).

The pitch test was used to determine the angular offset of the MBES transducer projector/receiver alignment with respect to the IMU orientation in the lateral axis or along the track direction of the boat. To determine the pitch-angle offset (β), one line was surveyed twice over a slope or bedform feature; data were collected while the boat traversed the line in opposite directions. The pitch test for this survey determined that the pitch-angle offset along the lateral axis of the boat was 12.8 degrees.

The yaw test was used to determine the angular offset of the MBES projector/receiver alignment with respect to the IMU orientation about the vertical axis. To determine the yaw-angle offset (δ), two parallel lines were surveyed while the boat moved in the same direction over a slope or bedform feature. The yaw test for this survey determined that the yaw-angle offset was 0.0 degrees.

Overall vertical accuracy of the hydrographic data presented in this report is estimated to be plus or minus 0.2 m. This estimate is based on equipment specifications, evaluation of overlap data, and previous data collection with this equipment. Accuracy of hydrographic survey data is typically challenging to evaluate because there are few underwater areas with known elevation. However, the quality of hydrographic surveys is often described by uncertainty estimates called total propagated uncertainty (TPU) (CARIS, 2011). Calculations of TPU were completed for the hydrographic survey data. The maximum TPU was 0.33 m, and the mean and median were 0.18 m (table 4). The percentage of bathymetry points with TPU values less than 0.25 m and 0.20 m was 99.9 percent and 94.2 percent, respectively.

Hydrographic Survey Maps

Using the fully processed 0.5-m resolution dataset, detailed hydrographic maps of the Mekong, Tonlé Sap, and Bassac Rivers were produced that document the riverbed elevations, as surveyed April 21–May 2, 2012, and referenced to Ha Tien 1960. The six subreaches of the study area (fig. 3) were combined into four sections (fig. 5) to show higher-resolution maps and to delineate areas for statistical summaries. Three of the four sections primarily depict the Mekong River (figs. 6–8), whereas the forth section includes the Tonlé Sap River from its mouth to the Chroy Changvar Bridge (fig. 9). Riverbed features (such as dunes, shoals, and the effects of sediment mining) observed during data collection are visible on the maps. Statistical summaries of the surveyed riverbed elevations are presented by section of the study area (table 5 and fig. 10). Riverbed elevations surveyed for the entire survey area ranged from 24.08 m below to 1.54 m above Ha Tien 1960.

All surveys were completed at relatively low water levels. Water-surface elevations during 2012 at selected streamflow-gaging stations ranged from 1.54–8.60 m on the Mekong River and 1.04–7.69 m on the Tonlé Sap River (table 5) (Mekong River Commission, 2014b). During the hydrographic surveys, the mean water-surface elevations ranged from 1.85–1.97 m on the Mekong River and the mean water-surface elevation on the Tonlé Sap River was 1.13 (table 5); these values are at the low end of the annual water-surface elevation range at these streamflow-gaging stations. No nearby streamflow-gaging stations were available for the Bassac River.

Table 4. Summary by section of study area of total propagated uncertainty for the hydrographic survey of Chaktomuk near Phnom Penh, Cambodia, April 21–May 2, 2012.

[TPU, total propagated uncertainty]

Section of study area	Maximum value of TPU, in meters	Mean TPU, in meters	Median value of TPU, in meters	Standard deviation of TPU values, in meters	Bathymetry points with TPU values less than indicated value, in percent			
					0.25 meter	0.20 meter	0.15 meter	0.10 meter
[1]Mekong River, upstream from confluence (fig. 6)	0.23	0.19	0.18	0.01	100.0	97.09	0.3	0
Mekong River, at confluence (fig. 7)	0.29	0.18	0.18	0.01	99.9	94.49	2.4	0.1
[1]Mekong River, downstream from confluence (fig. 8)	0.25	0.18	0.18	0.02	100.0	92.31	4.3	0.2
Tonlé Sap River (fig. 9)	0.33	0.18	0.18	0.02	99.5	92.84	4.2	0.7
	Entire survey area							
	0.33	0.18	0.18	0.01	99.9	94.2	2.2	0.1

[1]Subreaches were combined for these final 4 sections (figs. 3 and 5).

Mekong River

Three sections of the Mekong River (fig. 5) were surveyed April 21–May 2, 2012, and included the section extending upstream from the southern end of the Chroy Changvar peninsula (fig. 6), a section at the confluence of the Mekong, Tonlé Sap and Bassac Rivers (fig. 7), and a section downstream from the confluence (fig. 8).

The upstream section of the Mekong River was surveyed April 30–May 2 (fig. 6). The upstream section was about 4 km long and about 1,600 m wide at the most upstream part of the section and then narrowed to about 1,000 m in the downstream part of the section. Riverbed elevations were less than -18 m in the center of the channel for most of this section (fig. 6). Compared with the downstream section surveyed for this study (fig. 8), this upstream section is narrow and deep with 50 percent of the surveyed riverbed area at an elevation less than -12.5 m (fig. 10*A*).

The middle section at the confluence of the Mekong, Tonlé Sap, and Bassac Rivers was surveyed on April 24–25. The middle section was about 2 km long and the channel was approximately 1,500 m wide (fig. 7). The mouth of the Tonlé Sap River and the head of the Bassac River distributary were included in this section of the survey. Areas of sediment mining were present near the downstream end of Chroy Changvar peninsula and extended about 1,500 m downstream. Riverbed elevations where sediment was mined were as much as 8 m lower than the riverbed elevations in the channel immediately adjacent to areas that were not mined (fig. 7). The riverbed elevations in this section were not as deep as in the upstream section, with 50 percent of the riverbed area at an elevation less than -9 m (fig. 10*B*).

The Mekong River section downstream from the confluence was surveyed on April 21–23 and April 27–28. The downstream section was about 3.6 km long and the channel ranged from about 1,300 to 1,800 m wide (fig. 8). The effects of sediment mining are visible near the downstream end of the section, which is locally 12 m lower than the typical riverbed elevations adjacent to the mined area (fig. 8). Two scour holes near the right bank also were evident: (1) about 600 m downstream from the Bassac River was a smaller scour hole where the surveyed riverbed elevations were about 11 m less than typical riverbed elevations adjacent to the scour hole, and (2) downstream from a protrusion in the bank (about 2,000 m downstream from the Bassac River) was a larger scour hole where surveyed riverbed elevations were about 16 m less than

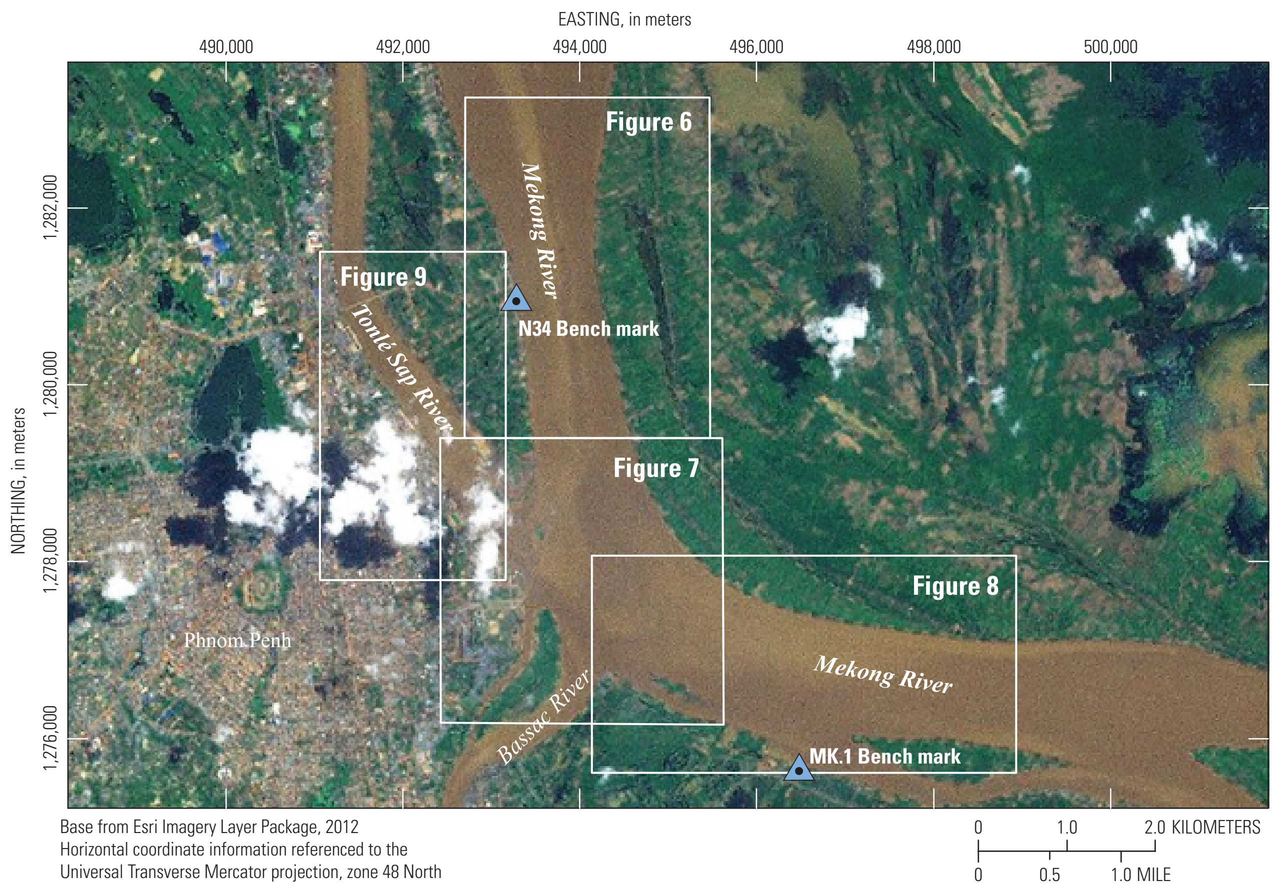

Figure 5. Hydrographic survey of Chaktomuk, the confluence of the Mekong, Tonlé Sap, and Bassac Rivers near Phnom Penh, Cambodia, April 21–May 2, 2012.

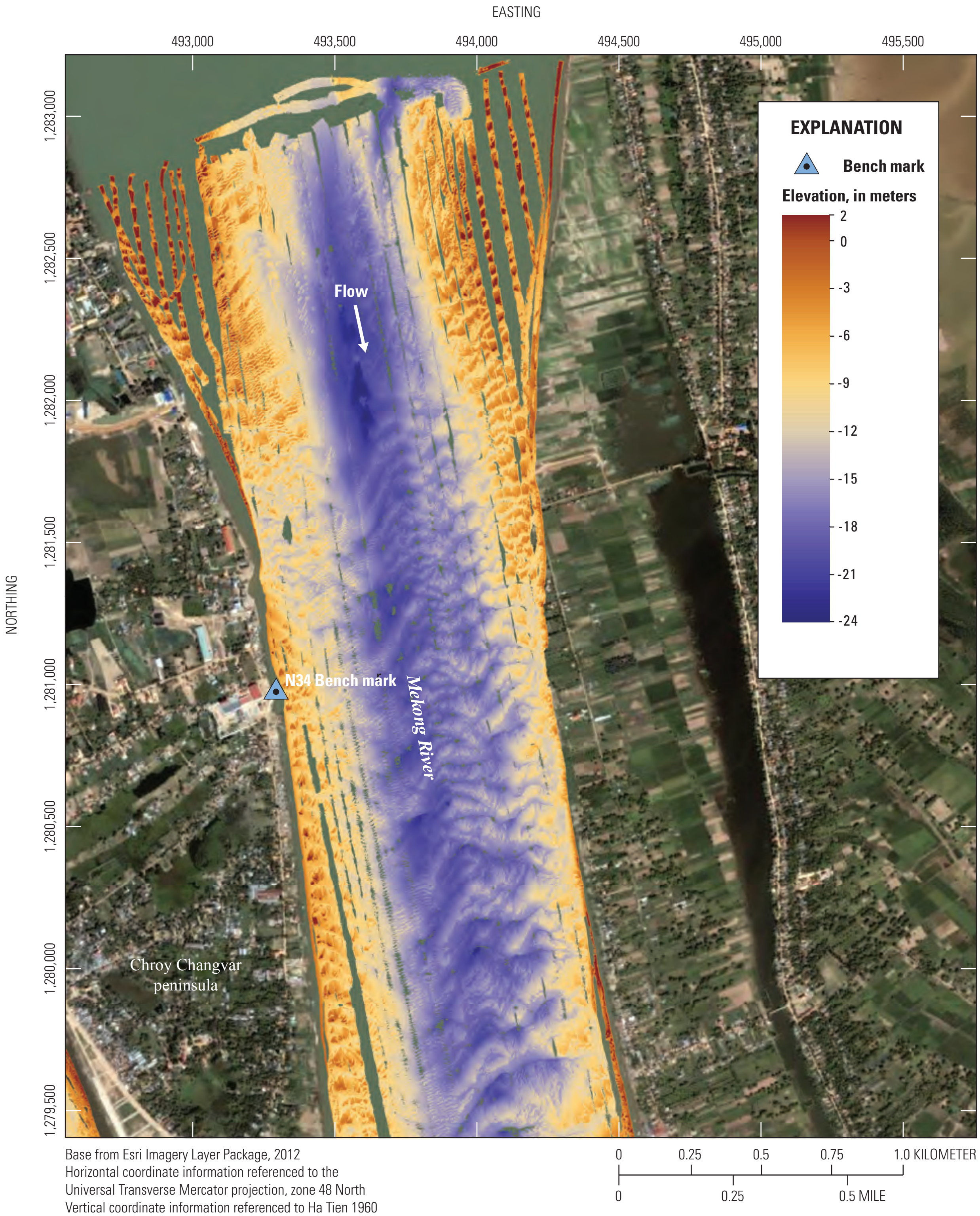

Figure 6. Hydrographic survey of the Mekong River upstream from the confluence of the Mekong, Tonlé Sap, and Bassac Rivers near Phnom Penh, Cambodia, April 30–May 2, 2012.

typical riverbed elevations adjacent to this scour hole (fig. 8). In general, the riverbed elevations in this third section of the Mekong River were the shallowest of all surveyed sections, with 50 percent of the riverbed area at an elevation less than -5 m (fig. 10*C*).

Bassac River

Approximately 700 m of the Bassac River was surveyed on May 2 on as part of the Mekong River middle-section survey (fig. 7). Water depths in the Mekong River were generally much shallower near the bifurcation at the head of the Bassac River; however, one area of deep water was present near the left bank of the Bassac River (at Koh Norea peninsula) near an area where active bank erosion was evident. At the time of the survey, construction was occurring on the west bank of the Mekong River at Koh Pich, and structures associated with that activity had diverted flow away from the Bassac River (fig. 7). About 100 m downstream from the head of the Bassac River, riverbed elevations in the Bassac River were typically about -9 m.

Tonlé Sap River

On April 26, 2012, the Tonlé Sap River was surveyed from its mouth to the Chroy Changvar Bridge; the section is about 3.5 km long and the channel was typically 300–400 m wide along the surveyed section (fig. 9). At the time of the survey, the Tonlé Sap River was flowing into the Mekong River. The hydrographic map shows that depths on the Tonlé Sap River were 2 to 3 times shallower than on the section of the Mekong River upstream from the confluence, with 50 percent of the riverbed area surveyed on the Tonlé Sap River at an elevation less than -5 m (fig. 10*C*).

Summary

Forecast Mekong is a project led by the U.S. Geological Survey (USGS) that provides data integration; predictive environmental, natural, and water resource models; and scientific visualization tools to help decision makers. A component of this effort was a hydrographic survey of Chaktomuk, the confluence of the Mekong, Tonlé Sap (also spelled Tônlé Sab), and Bassac Rivers near Phnom Penh, Cambodia. The USGS, in cooperation with the U.S. Department of State, Mekong River Commission (MRC), Phnom Penh Autonomous Port, and the Cambodian Ministry of Water Resources and Meteorology, surveyed this area to collect data that could improve navigation and shipping safety and provide baseline scientific data to document natural and anthropogenic disturbances and geomorphic change in the confluence area. The hydrographic survey was completed in 2012 and supports the goals of Forecast Mekong by providing data to help visualize the confluence and aid the development of planning tools.

The Mekong River begins in the Tibetan Plateau of China. The river flows southeast for approximately 4,800 kilometers through the countries of China, Myanmar (Burma), Laos, Thailand, Cambodia, and Vietnam, and discharges into the South China Sea. The river basin area is approximately 795,000 square kilometers. The mean annual discharge is approximately 14,500 cubic meters per second and the annual runoff is approximately 457 cubic kilometers. The Mekong River typifies large, tropical monsoonal rivers, with large mean annual discharge distributed in conjunction with well-defined wet and dry seasons. The wet season of the monsoon cycle typically lasts from May until early October, with the greatest precipitation usually falling in August and September.

The confluence of the Mekong, Tonlé Sap, and Bassac Rivers is known as Chaktomuk. For most of the year, the Tonlé Sap River flows into the Chaktomuk, and the Bassac River flows out of the Chaktomuk to the South China Sea. When stage is high in the Mekong River the Tonlé Sap River flows to Tonlé Sap Lake. Conversely, when stage is low in the Mekong River the Tonlé Sap River flows to Chaktomuk and the Mekong River. The Tonlé Sap Lake serves as a flood-storage reservoir for the Mekong River and supports important wetlands, fisheries, and rice-growing areas. Sedimentation or other geomorphic and hydrologic alterations at Chaktomuk could alter this unique and important hydrologic system.

The Mekong, Tonlé Sap, and Bassac Rivers near Phnom Penh were surveyed by using a multibeam echosounder (MBES) mapping system, composed of a RESON Seabat™ 7125 MBES, an inertial measurement and navigation unit, data collection computers, and a Real-Time Kinematic (RTK) Global Navigation Satellite System (GNSS) base station. The survey area was divided into subreaches, and each subreach was surveyed within 3 days to minimize discontinuity in survey data caused by ongoing processes, such as water-level changes, bedform translation, and anthropogenic changes.

The survey was referenced to two existing bench marks with known geographic coordinates by establishing a GNSS base station on the bench marks each day and using the real-time corrections from the base station to correct the boat navigation data. During data collection, the World Geodetic System of 1984 (WGS 84) ellipsoid was used as a to reference riverbed height. The hydrographic survey data were converted from WGS 84 ellipsoid heights to elevations above Ha Tien 1960 during postprocessing.

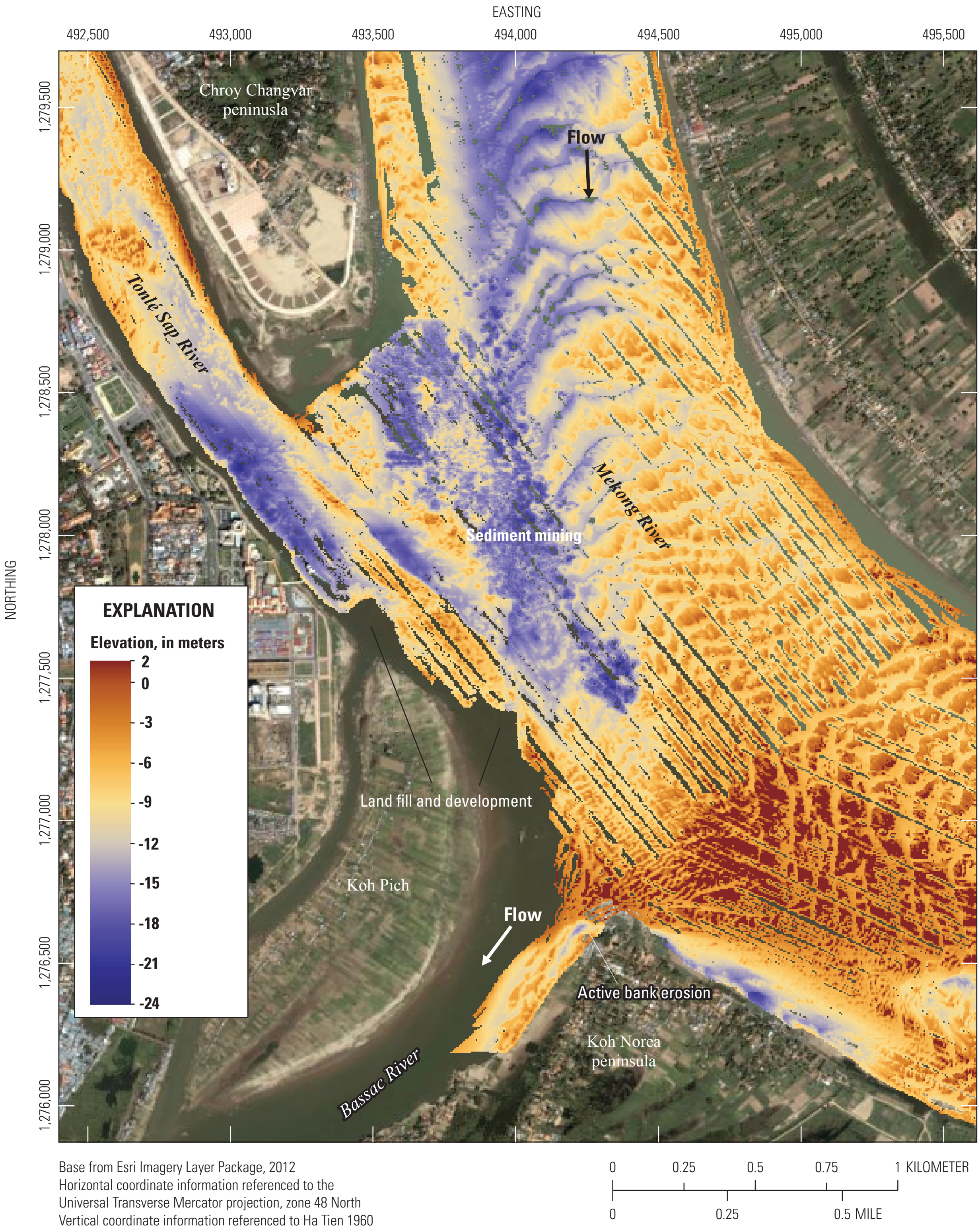

Figure 7. Hydrographic survey of the Mekong River at the confluence of the Mekong, Tonlé Sap, and Bassac Rivers near Phnom Penh, Cambodia, April 24–April 25, 2012.

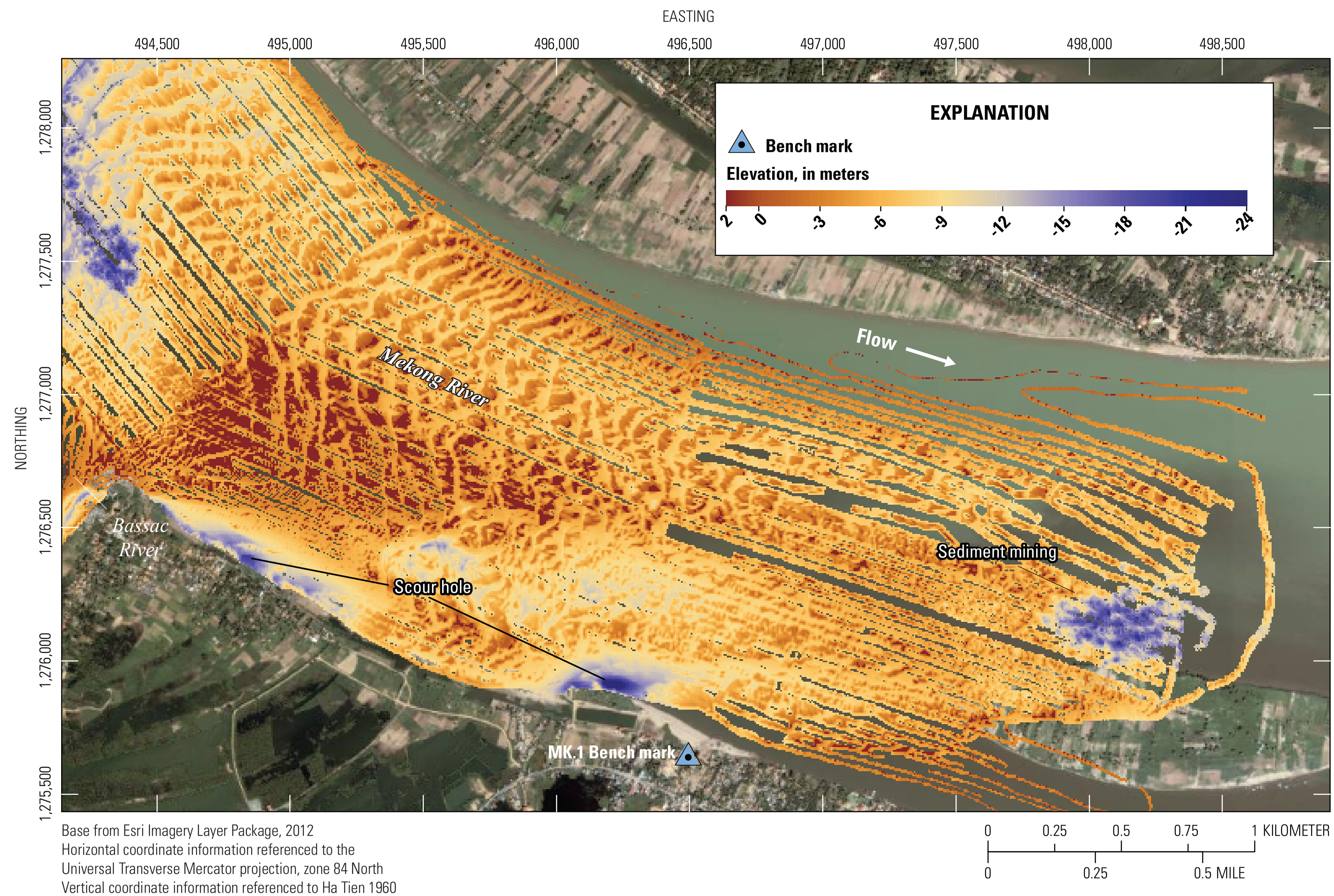

Figure 8. Hydrographic survey of the Mekong River downstream from the confluence of the Mekong, Tonlé Sap, and Bassac Rivers near Phnom Penh, Cambodia, April 21–April 23 and April 27–April 28, 2012.

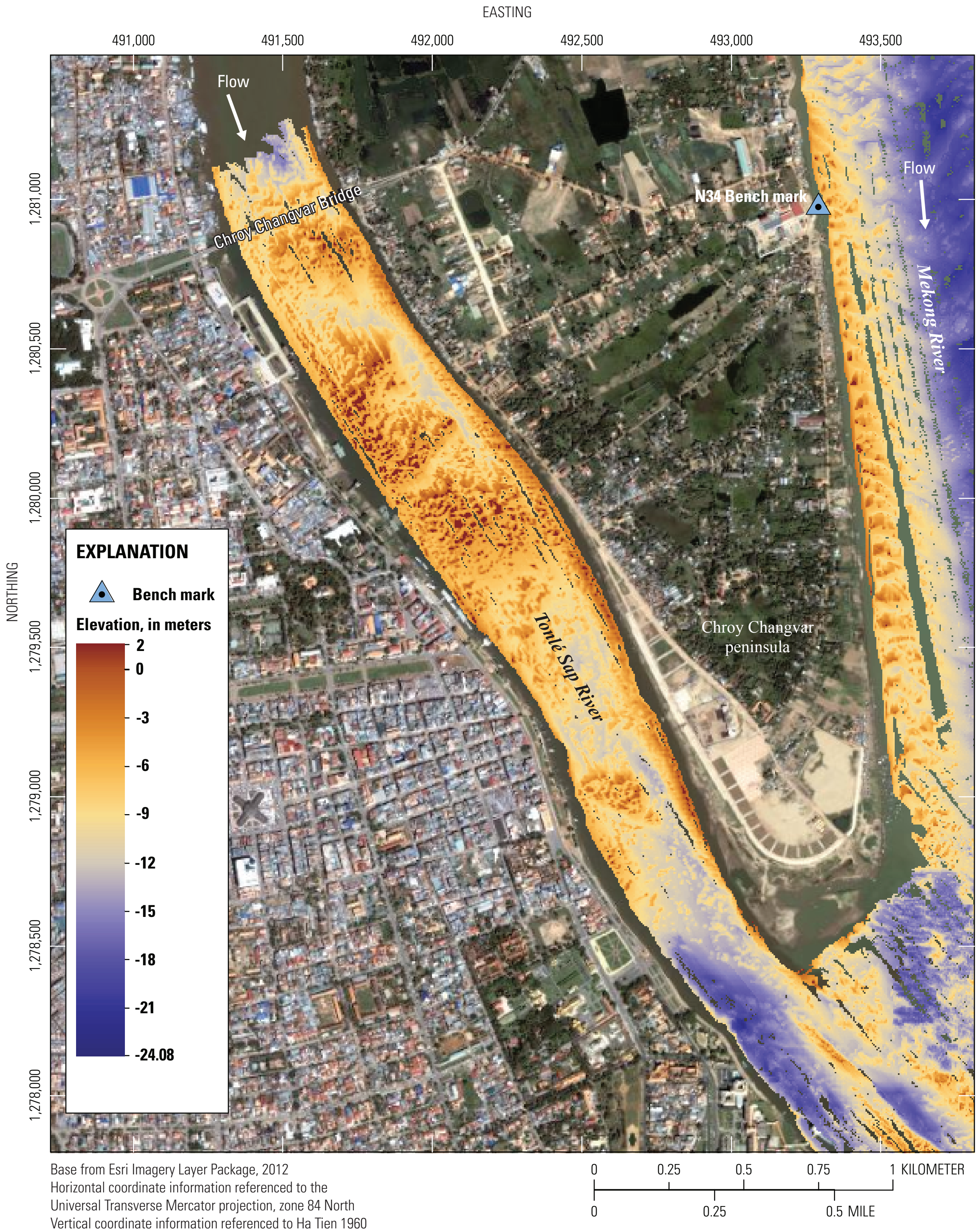

Figure 9. Hydrographic survey of the Tonlé Sap River upstream from the confluence of the Mekong, Tonlé Sap, and Bassac Rivers near Phnom Penh, Cambodia, April 26, 2012.

Table 5. Summary of riverbed elevations surveyed at Chaktomuk, Cambodia, April 21–May 2, 2012, and water-surface elevations at two streamflow-gaging stations.

[All elevations are referenced to Ha Tien 1960; km², square kilometers; m, meters; WSE, water surface elevation; km, kilometers]

Section of study area	Survey period	Area surveyed (km²)	Minimum riverbed elevation observed (m)	Maximum riverbed elevation observed (m)	Mean WSE (m)	Maximum WSE (m)	Minimum WSE (m)	Maximum WSE (m)	Minimum WSE (m)
					Survey period			January–December, 2012	
Mekong River, upstream from confluence (fig. 6)	April 30–May 2, 2012	3.70	-22.96	1.00	[1]1.89	[1]2.18	[1]1.55	[1]8.60	[1]1.54
Mekong River, at confluence (fig. 7)	April 24–25, 2012	3.51	-24.08	1.54	[1]1.97	[1]2.18	[1]1.77	[1]8.60	[1]1.54
Mekong River, downstream from confluence (fig. 8)	April 21–23; April 27–28, 2012	4.51	-23.27	1.51	[1]1.85	[1]2.41	[1]1.56	[1]8.60	[1]1.54
Tonlé Sap River (fig. 9)	April 26, 2012	1.15	-15.18	1.01	[2]1.13	[2]1.14	[2]1.12	[2]7.69	[2]1.04
	Entire survey area								
	April 21–May 2, 2012	12.87	-24.08	1.54	[1]1.89	[1]2.18	[1]1.55	[1]8.60	[1]1.54

[1]Water-surface elevation of the Mekong River observed at Mekong River Commission streamflow-gaging station 019802 at Kompong Cham, approximately 77 km upstream from the study area (Mekong River Commission, 2014b).

[2]Water-surface elevation of the Tonlé Sap River observed at Mekong River Commission streamflow-gaging station 020102 at Prek Kdam, approximately 30 km upstream from the study area (Mekong River Commission, 2014b).

The quality of hydrographic surveys was described by uncertainty estimates called total propagated uncertainty (TPU). Results of TPU calculated for the hydrographic survey data indicated that the maximum TPU was 0.33 m, the mean and median were 0.18 m, and 99.9 percent of TPU values were less than 0.25 m.

Detailed hydrographic maps of Mekong, Tonlé Sap, and Bassac Rivers were produced that document the riverbed elevations surveyed April 21–May 2, 2012. The surveyed area of the Mekong River included a 4-km reach upstream from the confluence, a 2-km reach at the confluence, and a 3.6-km reach downstream from the confluence. In addition, 0.7 km of the Bassac River and 3.5 km of the Tonlé Sap River (from the confluence to Chroy Changvar Bridge) were surveyed. Riverbed features (such as dunes, shoals, and the effects of sediment mining, which were observed during data collection) are visible on the hydrographic maps. All surveys were completed at low water levels during 2012, as indicated by selected Mekong River Commission streamflow-gaging stations. Riverbed elevations surveyed ranged from -24.08 m to 1.54 m above Ha Tien 1960.

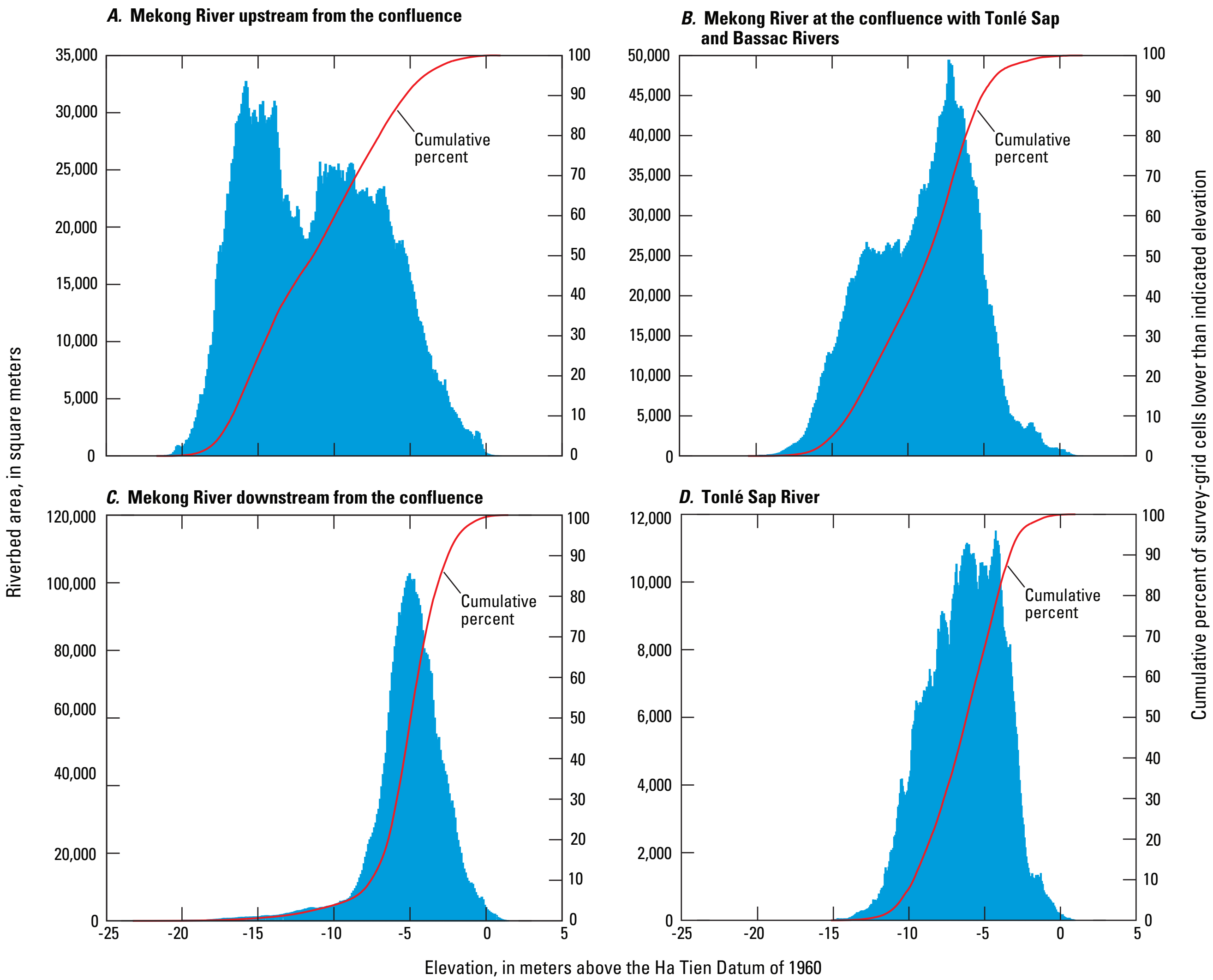

Figure 10. Frequency distributions of the areas of riverbed elevations surveyed at Chaktomuk, the confluence of the Mekong, Tonlé Sap, and Bassac Rivers near Phnom Penh, Cambodia, April 21–May 2, 2012. *A*, Mekong River upstream from the confluence. *B*, Mekong River at the confluence with the Tonlé Sap and Bassac Rivers. *C*, Mekong River downstream from the confluence. *D*, Tonlé Sap River.

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Glossary

display depth range Setting for the RESON SeaBat™ 7125 that sets the maximum distance that the sonar will display. Depth range partially controls ping rate by estimating time of return for one sonar ping before a second sonar ping can be transmitted. The setting for the RESON SeaBat™ 7125 has a range from 5 to 300 meters.

distributary A river branch flowing away from the main stream.

fixed Global Positioning System/Global Navigation Satellite System (GPS/GNSS) solution Position determined by the GPS/GNSS rover with information from five or more GNSS satellites and with base-station correction information with all carrier-phase ambiguities resolved and the estimated position error below a set tolerance.

latency The time lapse between two different datasets. In multibeam hydrographic surveying, this time lapse is typically the time offset between sounding data and positioning data.

maximum ping rate Setting for the RESON SeaBat™ 7125 that limits the number of pings per second (p/s), usually used to set it slower than the standard ping rate for that range setting. The setting for the RESON SeaBat™ 7125 has a range from OFF to 50 p/s. Maximum ping rate might be increased for additional data collection over areas of interest or decreased to limit redundant data.

monsoonal Relating to the seasonal prevailing wind of the Indian Ocean and southern Asia, blowing from the southwest and bringing rain from May through September and blowing from the northeast from October through April.

outer beams The acoustic beams that are formed by a sonar ping on the outer edge of the swath. The soundings from these beams are revised or deleted because of the tendency for these data to be inconsistent with adjacent or overlapping data as a result of the low angle of incidence and high energy loss from absorption and spreading over the greater distance.

piezo-electric ceramics Ceramic material with piezoelectric (electric resulting from pressure) characteristics as well as reverse piezoelectric effects (internal generation of a mechanical strain resulting from an applied electric field). Reverse piezoelectric effects are used to produce sound waves by applying a voltage to the ceramic that responds with oscillation. The frequency of this oscillation depends on the frequency of the input signal and the characteristics and design of the ceramic material. This oscillation causes a series of compressions and rare-factions in the surrounding water—a sound pressure wave (RESON, Inc., 2001).

ping rate The number of sonar signals transmitted per second.

pitch Rotation of the boat about the across-track axis.

pulse length Setting for the RESON SeaBat™ 7125 that controls the length of time the sonar signal is transmitted. Pulse length setting on the RESON SeaBat™ 7125 can range from 10 to 300 microseconds (µs). A narrow pulse length provides high resolution in shallow depths, but a wider pulse length provides maximum range but also low-resolution images.

receiver gain Setting for the RESON SeaBat™ 7125 that controls the increase in amplitude applied to the returned sonar signal (echo) in addition to the calculated time varied gain (TVG). The gain settings for the RESON SeaBat™ 7125 range from 0.0 to 83.0 decibels (dB).

roll Rotation of the boat about the along-track axis.

swath A contiguous area of the lake, river, or ocean bottom that is surveyed as the boat makes one pass and is made up of many sonar pings. This area extends perpendicularly from the track (or traverse) and its extent is dependent on multibeam echosounder settings and water depth; for the RESON SeaBat™ 7125 the angular swath width is 128 degrees, or approximately 4 times water depth.

transmitted power Setting for the RESON SeaBat™ 7125 that increases or decreases the amount of acoustic energy transmitted into the water. The RESON SeaBat™ 7125 has a range from OFF to 220 dB.

yaw Rotation of the boat about the vertical axis.

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