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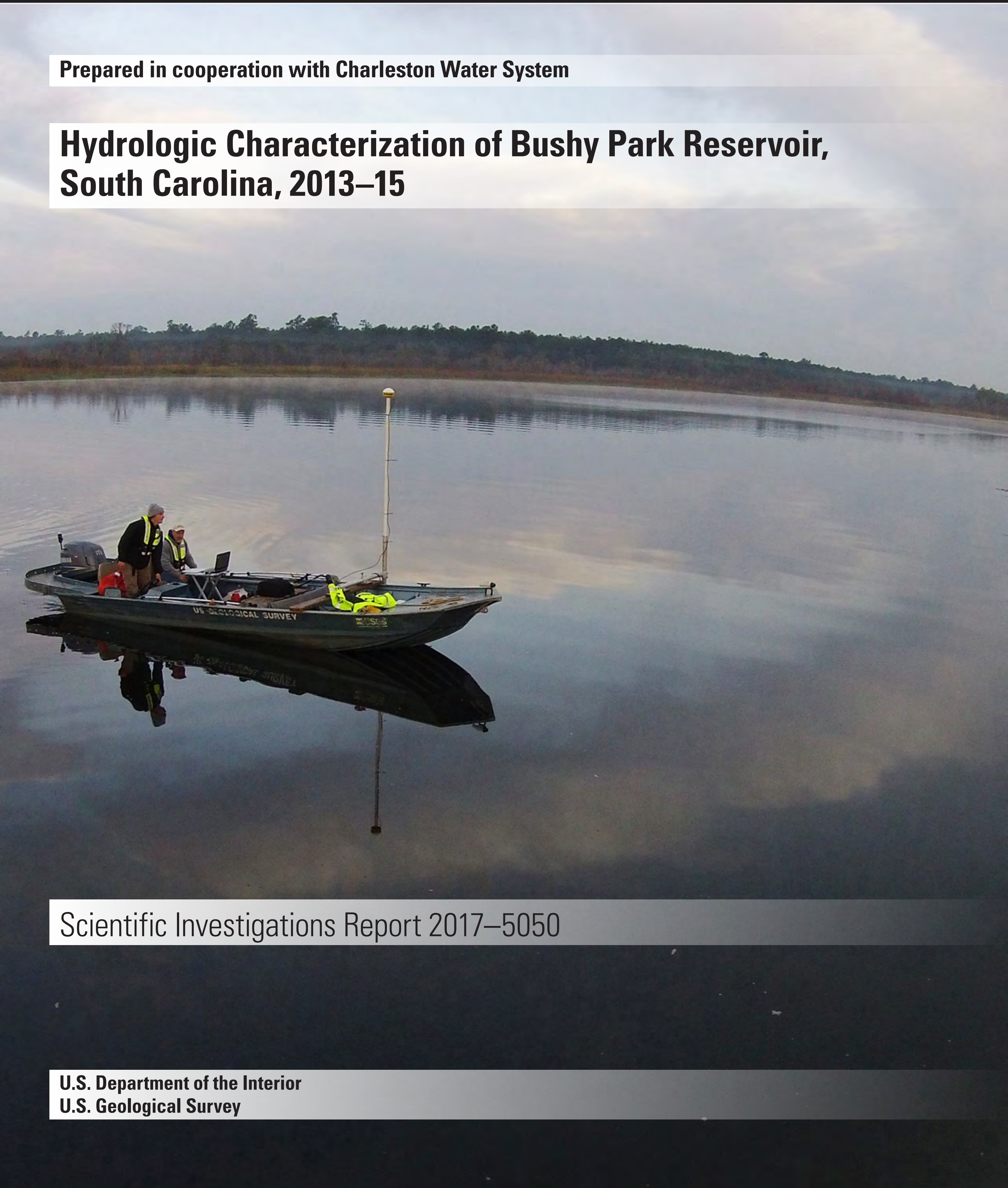
Hydrologic Characterization of Bushy Park Reservoir, South Carolina, 2013–15



Scientific Investigations Report 2017–5050

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

Cover. Bushy Park Reservoir, South Carolina. Photograph by Michael Hall, U.S. Geological Survey

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By Paul A. Conrads, Matthew D. Petkewich, W. Fred Falls, and Timothy H. Lanier

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U.S. Department of the Interior
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U.S. Geological Survey
William H. Werkheiser, Acting Director

U.S. Geological Survey, Reston, Virginia: 2017

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The authors also thank the U.S. Geological Survey (USGS) and CWS reviewers for their thoughtful reviews and constructive comments.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

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

$$°C = (°F - 32) / 1.8.$$

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

$$°F = (1.8 \times °C) + 32.$$

Datum

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

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

Abbreviations

ADAPS	Automated Data Processing System
ADCP	acoustic Doppler current profiler
ADVM	acoustic Doppler velocity meter
ASCII	American Standard Code for Information Interchange
AUV	autonomous underwater vehicle
BC	beam check
BGA	blue-green algae
CRP	Cooper River Partners
CWS	Charleston Water System
dGPS	digital Global Positioning System
GPS	Global Positioning System
kHz	kiloHertz
MIB	2-methylisoborneol
mph	mile per hour
NWIS	National Water Information System
PAR	photosynthetically active radiation
SCADA	Supervisory Control and Data Acquisition
SCDNR	South Carolina Department of Natural Resources
SCE&G	South Carolina Electric and Gas Company
SNR	signal-to-noise ratio
SWUDS	Site-Specific Water Use Data System
USACE	U.S. Corps of Engineers
USGS	U.S. Geological Survey
VMT	Velocity Mapping Tool
WAAS	Wide Area Augmentation System
3D	three dimensional

Hydrologic Characterization of Bushy Park Reservoir, South Carolina, 2013–15

By Paul A. Conrads, Matthew D. Petkewich, W. Fred Falls, and Timothy H. Lanier

Abstract

The Bushy Park Reservoir is a relatively shallow impoundment in a semi-tropical climate and is the principal water supply for the 400,000 people of the city of Charleston, South Carolina, and the surrounding areas including the Bushy Park Industrial Complex. Although there is an adequate supply of freshwater in the reservoir, taste-and-odor water-quality issues are a concern. The U.S. Geological Survey conducted an investigation in cooperation with the Charleston Water System to study the hydrology and hydrodynamics of the Bushy Park Reservoir to identify factors affecting water-quality conditions. Specifically, five areas for monitoring and (or) analysis were addressed: (1) hydrologic monitoring of the reservoir to establish a water budget, (2) flow monitoring in the tunnels to compute flow from Bushy Park Reservoir and at critical distribution junctions, (3) water-quality sampling, profiling, and continuous monitoring to identify the causes of taste-and-odor occurrence, (4) technical evaluation of appropriate hydrodynamic and water-quality simulation models for the reservoir, and (5) preliminary evaluation of alternative reservoir operations scenarios.

This report describes the hydrodynamic and hydrologic data collected from 2013 to 2015 to support the application and calibration of a three-dimensional hydrodynamic model and the water-quality monitoring and analysis to gain insight into the principal causes of the Bushy Park Reservoir taste-and-odor episodes. The existing U.S. Geological Survey real-time network on the West Branch of the Cooper River was augmented with a tidal flow gage on Durham Canal, Back River, and Foster Creek. The Charleston Water System intake structure was instrumented to collect water-level, water temperature (top and bottom probes), specific conductance (top and bottom probes), wind speed and direction, and photosynthetically active radiation data. In addition to the gages attached to fixed structures, four bottom-mounted velocity profilers were deployed at six locations over different periods. The deployment period for the velocity profilers ranged from 2 weeks to 4 months. During the investigation, tidal cycle (13-hour) streamflow measurements were made at 30-minute intervals at five locations.

The Williams Station is a coal-fired powerplant that withdraws water from Bushy Park Reservoir for cooling purposes. The magnitude of the withdrawal (approximately 550 million gallons per day) is the major factor controlling the circulation in the reservoir. The net flow in Durham Canal to the reservoir is comparable to the withdrawal rates of the powerplant. When the Williams Station is not withdrawing water, the net flow in Durham Canal quickly goes to zero or reverses with a net flow away from the reservoir and to the Cooper River. Plan views of the velocity vectors for the tidal cycle streamflow measurements and rose diagrams of the velocity profilers created with the Williams Station withdrawing and not withdrawing water show substantial effects of the distribution of magnitude and direction of the water velocities.

Introduction

The Charleston Water System (CWS) (formerly the Commissioners of Public Works of the City of Charleston, South Carolina) has been a leader in water-resource planning for the low country of South Carolina since its inception as Charleston Light and Water Company in 1902. Looking for an alternative water supply to the Goose Creek Reservoir and the Edisto River (fig. 1), CWS contributed to the construction of the Bushy Park Reservoir and Industrial Complex in the 1950s (Williams, 2010). In 1954, the Bushy Park Industrial Complex was established between the east bank of the Back River and the west bank of the Cooper River. To provide water to the industrial users, a freshwater reservoir was constructed by damming the Back River at the lower end near the confluence with the Cooper River (fig. 2). Durham Canal was constructed as a conduit between the upper reaches of the Back River and the freshwater part of the West Branch of the Cooper River. Aerial photographs of the Back River-Cooper River stream network from 1949 and 2016 are shown in figure 2. The construction of the Back River Dam did not raise the water surface above the high tide height of the river and thus did not inundate the flood plain that is typical of reservoir impoundments.

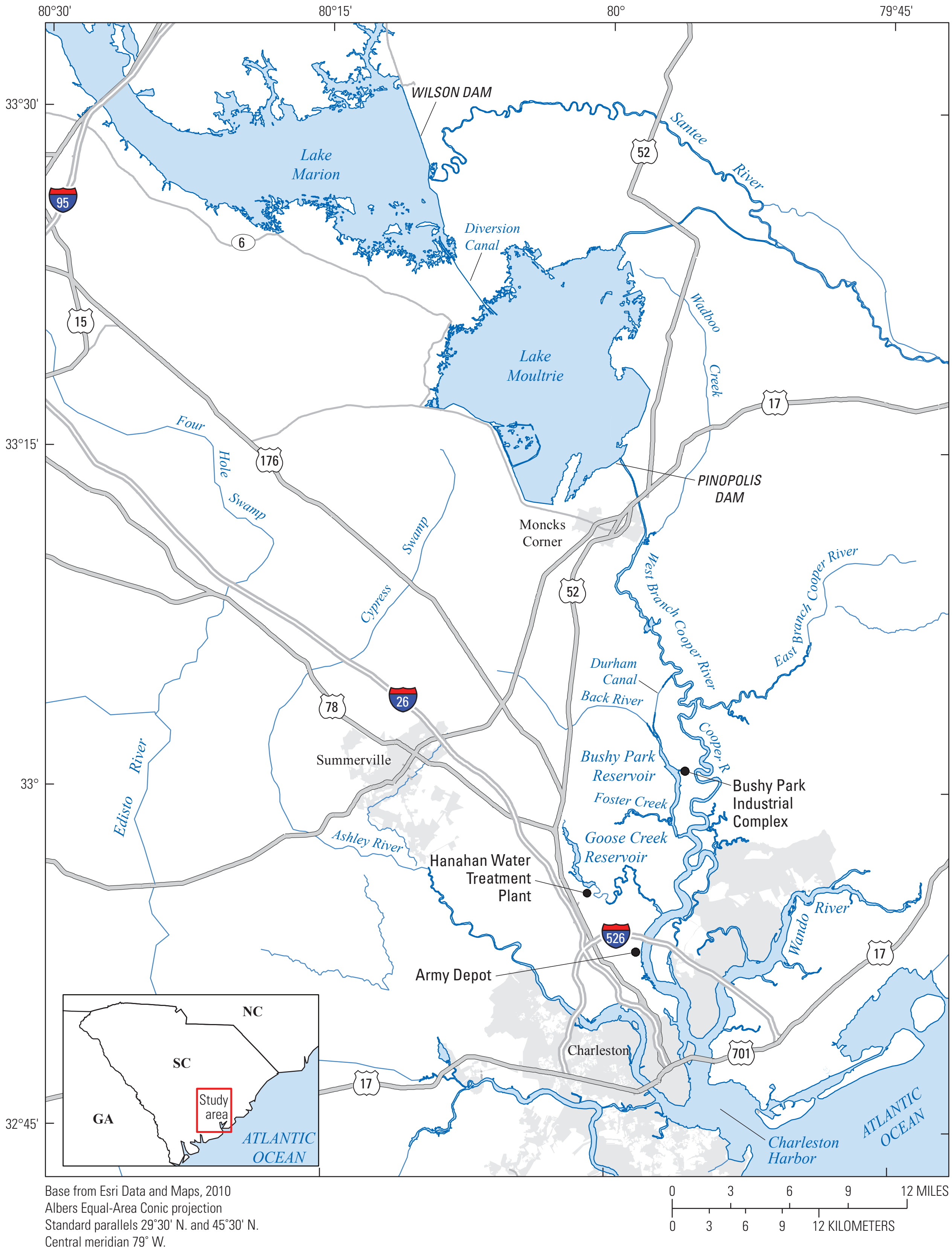


Figure 1. Study area of the Santee-Cooper River Basin, South Carolina.

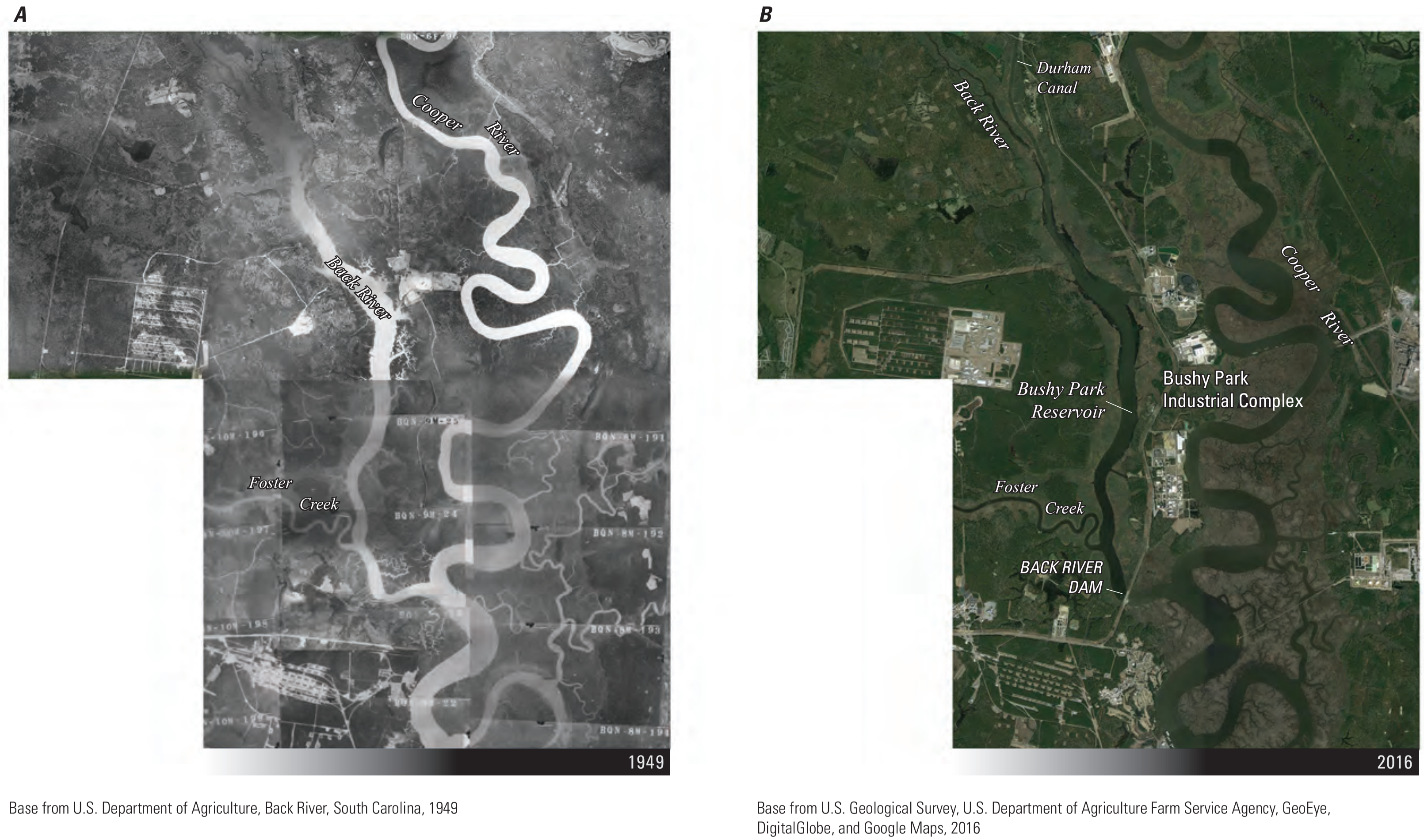


Figure 2. *A*, Aerial view of Back River in 1949 and *B*, satellite image of Bushy Park Reservoir in 2016.

Bushy Park Reservoir is a relatively shallow impoundment in a semi-tropical climate. Although the reservoir provides an adequate supply of freshwater, there are water-quality concerns related to taste and odor. In general, taste-and-odor episodes are common in reservoirs used for drinking water throughout the United States (Pearl and others, 2001; Taylor and others, 2006; Jüttner and Watson, 2007). The occurrence of trans-1, 10-dimethyl-trans-9-decalol (geosmin), and 2-methylisoborneol (MIB), which produce musty, earthy tastes and odors in drinking water, is one of the primary causes of taste-and-odor episodes (Suffet and others, 1996). Although not a human health problem, geosmin and MIB are problematic in drinking water because of the human ability to detect these compounds at low concentrations (10 nanograms per liter [ng/L]; Wnorowski, 1992; Young and others, 1996), and conventional water-treatment procedures (particle separation, oxidation, and adsorption) typically do not reduce concentrations below the threshold level (Suffet and others, 1996). Production and release of geosmin and MIB have been related to soil bacteria (actinomycetes; Jüttner and Watson, 2007) and certain species of cyanobacteria (also known as blue-green algae [BGA]). Geosmin- and MIB-producing BGA blooms are attributed to a range of environmental factors, including nutrient concentrations and ratios, light availability, water temperatures, water-column stability, and flushing rates (Downing and others, 2001; Pearl and others, 2001; Mau and others, 2004; Dzialowski and others, 2009). The complex interaction among the physical, chemical, and biological processes within lakes and reservoirs, however, often makes it difficult to identify primary environmental factors that cause the production and release of these cyanobacteria by-products. Nonetheless, understanding of the environmental factors that control cyanobacteria dominance in reservoirs has allowed water- resource and watershed managers to apply management strategies to prevent conditions under which cyanobacteria dominate (Downing and others, 2001; Taylor and others, 2006). Remediation efforts of reservoir conditions where cyanobacteria dominance occurred has hinged upon a strong scientific understanding of the mechanisms controlling the algal community (Downing and others, 2001; Taylor and others, 2006).

Currently (2016), the Bushy Park Reservoir is the principal water supply for the 400,000 people of the city of Charleston, S.C., and the surrounding areas and industries in the Bushy Park Industrial Complex. The South Carolina Surface Water Withdrawal, Permitting Use, and Reporting Act of 2011 (http://www.scstatehouse.gov/code/t49c004.php) had an effect on the permitting and operations of the Bushy Park Reservoir such that there was an immediate need for hydrologic, hydrodynamic, and water-quality data and analysis to inform water-resource planning for the Charleston area. This need would also address five areas of interest for CWS in their long-range planning process:

1. Hydrologic monitoring of the reservoir to establish a water budget and document reservoir circulation dynamics;
2. Flow monitoring in the water-supply tunnel to compute flow from Bushy Park Reservoir;
3. Water-quality sampling, profiling, and continuous monitoring to understand the causes of taste-and-odor occurrence;
4. Technical evaluation of an existing hydrodynamic and water-quality simulation model for the reservoir; and
5. Preliminary evaluation of alternative reservoir operations scenarios.

The U.S. Geological Survey (USGS) in collaboration with the CWS evaluated the circulation of Bushy Park Reservoir and its effects on water quality.

Purpose and Scope

This report presents the hydrologic and water velocity data collected to characterize the hydrology, flow, and water circulation of the Bushy Park Reservoir. Of the five areas of interest, the first two—reservoir water budget and circulation, and flow monitoring of the Bushy Park water-supply tunnel—are addressed in this report. The data-collection network was designed to provide data that describe the physical, chemical, and biological processes that influence (1) geosmin and MIB occurrence in this source-water reservoir, (2) cyanobacteria biovolumes, and (3) geosmin-producing and toxin-producing genera of cyanobacteria.

The data-collection effort, which began in the fall of 2013 and ended in the fall of 2015, included enhancements to the existing continuous monitoring network, such as water velocity profile measurements, water-quality surveys with an autonomous underwater vehicle (AUV), discrete sampling and profiling, and continuous monitoring of flow in one of the water-supply tunnels. The spatial extent of the study was the Bushy Park Reservoir from the Back River Dam to the confluence of Durham Canal and the West Branch of the Cooper River and the two tributaries that form the reservoir, the Back River and Foster Creek.

An important part of the USGS mission is to provide scientific information for the effective water-resources management of the Nation. To assess the quantity and quality of the Nation’s surface water, the USGS collects hydrologic and water-quality data from rivers, lakes, and estuaries, using standardized methods, and maintains the data in a national database. This investigation of water-quantity and water-quality conditions of the Bushy Park Reservoir supports two of the six USGS strategic science directions (U.S. Geological Survey, 1999, 2007).

- Understanding ecosystems and predicting ecosystem change—this science direction is designed to study “the causes and consequences of ecological change” and to monitor “biological and physical components of ecosystems.”

- A water census for the United States—the water census is designed to, among other things, provide information and forecasts "of likely outcomes for water availability, water quality and aquatic ecosystem health caused by changes in land use and land cover ...[and] natural and engineered infrastructure."

In support of the USGS Water Resources Mission (https://water.usgs.gov/mission.html), this study provided data and information to "protect and enhance water resources for human health, aquatic health, and environmental quality." Benefits of this investigation to the CWS and others included accurate data and analysis on the water quantity and water quality of Bushy Park Reservoir. These data will provide reference conditions of the available quantity of freshwater for the reservoir and will provide baseline conditions and understanding of the causes of taste-and-odor issues. Better understanding the environmental factors that control cyanobacteria dominance in Bushy Park Reservoir has the potential to allow water-resource managers to apply long-term management strategies to prevent conditions under which cyanobacteria dominate and to implement short-term treatment technologies to mitigate the taste-and-odor compounds.

Description of the Study Area

The Bushy Park Reservoir (fig. 1) is located in the lower part of the Santee-Cooper River Basin. This basin covers 21,700 square miles (mi^2) and is the second largest drainage basin on the East Coast. The construction of the Bushy Park Reservoir and Durham Canal is part of the long history of anthropogenic changes to the Santee and Cooper Rivers (Kjerfve, 1976). Because of the increased demand for electric power in the 1930s, two freshwater lakes were created as part of the Santee-Cooper Project by diverting flows from the Santee River, and the naturally high topographic relief adjacent to the Cooper River was used to generate hydroelectric power. The project was completed in 1941 by the construction of Wilson Dam across the Santee River that formed Lake Marion, and Pinopolis Dam near the headwaters of the West Branch of the Cooper River that formed Lake Moultrie (fig. 1).

To provide a convenient freshwater reservoir for industrial and municipal water use for the newly created Bushy Park Industrial Complex (1954), the Back River Dam and Durham Canal were built in 1955 and 1956, respectively, by the Bushy Park Authority (a legislative committee of city and county government officials and area utilities) to form Bushy Park Reservoir. The Back River was dammed at the downstream end near the confluence with the Cooper River to create the Bushy Park Reservoir, and Durham Canal was constructed as a conduit between the upper reaches of the Back River and the freshwater reaches of the West Branch of the Cooper River (figs. 2 and 3). The Back River part of Bushy Park Reservoir has a length of approximately 5.5 miles (mi), with widths ranging from 690 to 2,200 feet (ft) and depths ranging from 12 to 45 ft. The canal is approximately 3 mi long, 150 ft wide, and 17 ft deep (Bower and others, 1993). The Charleston Commissioners of Public Works (currently CWS) purchased the assets of the Bushy Park Authority in 1964 and controls use of the waters from the reservoir. Presently (2016) five facilities have water-withdrawal intakes located on Bushy Park Reservoir, including the South Carolina Electric and Gas Company (SCE&G) Williams Station, the CWS, DAK Americas, British Petroleum (BP) Amoco, and Cooper River Partners (CRP) (fig. 3).

In 1985, the U.S. Army Corps of Engineers (USACE) rediverted flows from Lake Moultrie back to the Santee River to alleviate a severe sedimentation problem in Charleston Harbor created by the diversion of freshwater flows. After the rediversion project, flows to the Cooper River were reduced from the annual mean flow of 15,600 cubic feet per second (ft^3/s) to a regulated weekly mean flow of 3,000 ft^3/s, a level that would alleviate sedimentation in the harbor while ensuring an adequate freshwater source to the Bushy Park Reservoir at the mouth of the Durham Canal (South Carolina Water Resources Commission, 1979).

The climate of the Bushy Park Reservoir watershed is classified as humid semi-tropical (Pidwirny, 2011). Annual mean precipitation from 1981 to 2010 for the weather station located at the Charleston International Airport was 51.03 inches (in.; National Oceanic and Atmospheric Administration, undated), and the corresponding mean temperature was 65.8 degrees Fahrenheit (°F). Monthly temperature and precipitation normals are shown in figure 4. There is a 33.8-degree range in monthly temperatures (January to July) and a 4.72-in. range in average monthly precipitation between August and November (fig. 4).

The land cover of Bushy Park Reservoir, Foster Creek, and Back River drainage basin (ending halfway up Durham Canal) is predominantly forested (36.2 percent), wetlands (35.5 percent), and developed (21.1 percent; table 1; Homer and others, 2015). The reservoir is eutrophic and is densely vegetated with aquatic plants that thrive only in freshwater, such as water hyacinth (*Eichhornia crassipes*), water primrose (*Ludwigia uruguayensis*), and hydrilla (*Hydrilla verticillata*) (South Carolina Department of Health and Environmental Control, 2005). The South Carolina Department of Natural Resources (SCDNR) routinely applies herbicides to the aquatic growth, requiring periodic interruption of municipal and industrial withdrawals.

The flow and circulation dynamics of the Bushy Park Reservoir are complex. The major natural tributaries to the Bushy Park Reservoir are the Back River (upstream from the confluence with Durham Canal) and Foster Creek, which contain approximately 12,900 acres (20.2 mi^2) of woody and emergent herbaceous wetland areas (table 1). Most of the flow into the Bushy Park Reservoir comes from Durham Canal. The reservoir is tidally affected and experiences semi-diurnal tides consisting of two high tides and two low tides in a 24.8-hour period. A 14-day periodic tidal cycle also occurs, resulting in spring and neap tides. Spring tides are periods of increased

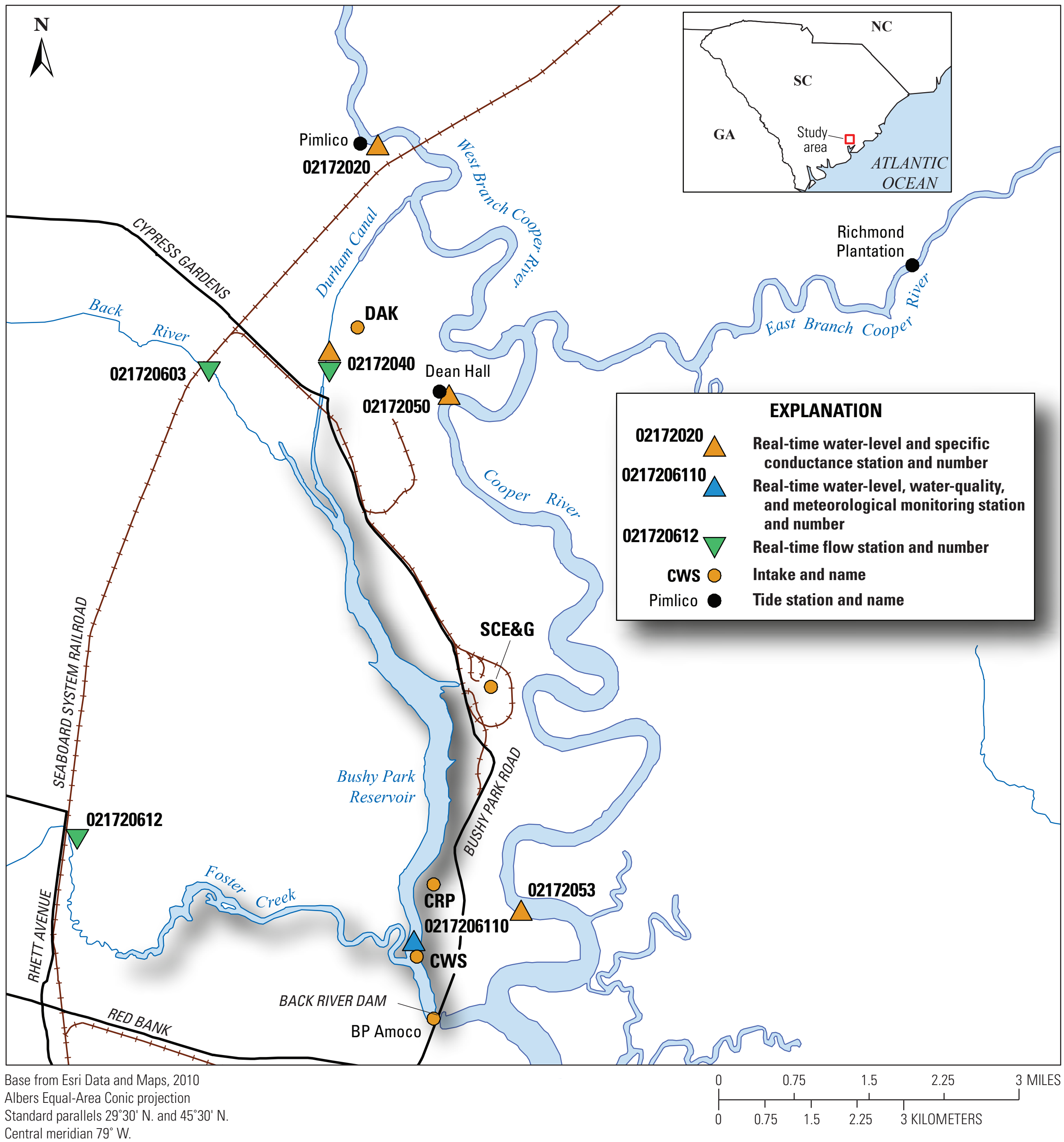


Figure 3. U.S. Geological Survey real-time gaging network near the Bushy Park Reservoir, real-time gages installed for the study, and water withdrawal intakes. [SCE&G, South Carolina Electric and Gas Company; CRP, Cooper River Partners; CWS, Charleston Water System]

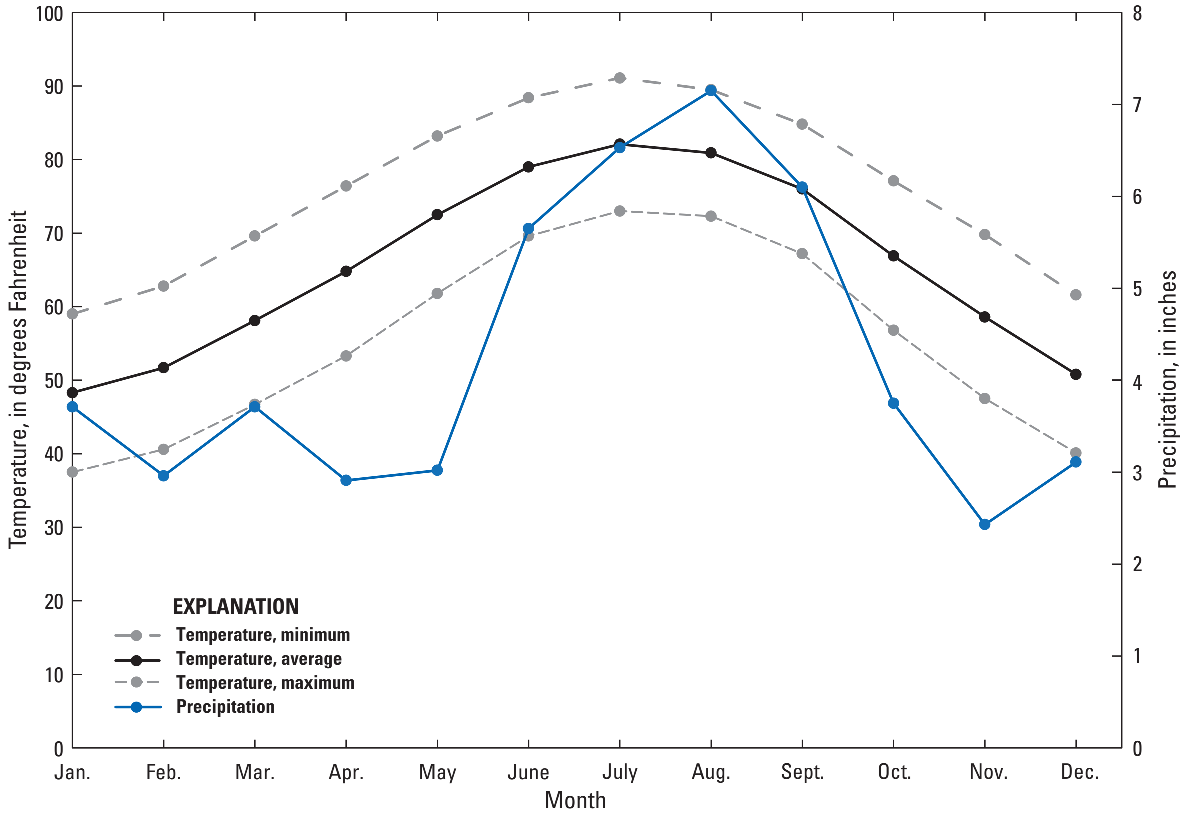


Figure 4. 1981 to 2010 average monthly temperature and precipitation normals at the Charleston International Airport, South Carolina National Weather Service station.

tidal range that occur during the time of full and new moons. Neap tides are periods of decreased tidal range that occur around the onset of waxing and waning moons. There are also seasonal and annual cycles to tides. As the tidal wave propagates upstream from Charleston Harbor, there is a small increase (0.19 ft) in the tidal range up to Army Depot on the Cooper River (table 2; fig. 1). Upstream from this location the tidal range decreases with the increased freshwater streamflow of the East and West Branches of the Cooper River (2.55 ft and 3.53 ft, respectively; fig. 3) and energy losses due to channel geometry. The tidal wave diminishes as it propagates through Durham Canal, into the reservoir and up the tributaries. The 15-minute water levels for Durham Canal and the CWS intake for October 1–15, 2014, are shown in figure 5. The average mean tidal range for that period for Durham Canal and the Bushy Park Reservoir is 1.31 and 0.86 ft, respectively. The phase shift (time delay) between the tides in Charleston Harbor and Pimlico is approximately 3.5 hours and from Durham Canal to the CWS intake is approximately 2.5 hours. The water levels on the upstream and downstream side of the Back River Dam are completely out of phase with high tide occurring on the reservoir side at approximately the same time as low tide occurring on the Cooper River side (Bower and others, 1993).

As with many estuarine systems, there may be large changes in flow and water level on the tidal time scale (<13 hours) but on the longer time scales (day to weeks) there may be only small changes in net (tidally averaged) flow and water level. The largest freshwater exchange to Bushy Park Reservoir is through Durham Canal. Although the tidal flows in Durham Canal are about +/– 4,000 ft^3/s (Bower and others, 1993), the net daily flow may be an order of magnitude less. Foster Creek and Back River are tidal sloughs with negligible daily mean streamflows and only contribute substantial freshwater flows following rainfall. Flows in Foster Creek can increase from background flows of less than 20 ft^3/s to more than 400 ft^3/s during a rain event (Campbell and Bower, 1996). Much of the circulation within the reservoir is due to water withdrawals by industrial users. The major withdrawal is by SCE&G and is approximately 800 ft^3/s for cooling water that discharges to the Cooper River (Horner, 2013).

Previous Studies

Over the years there have been a number of ecological and modeling studies of the Bushy Park Reservoir and its tributaries. In the 1970s, 1980s, and 1990s, there were a number of studies of Foster Creek generally addressing the effect of runoff

Table 1. Land-cover and land-use areas for the Back River, Foster Creek, and Bushy Park Reservoir.

[From Homer and others, 2015]

Land cover and land use	Back River (square miles)	Foster Creek (square miles)	Bushy Park Reservoir (square miles)	Bushy Park Reservoir with Back River and Foster Creek (square miles)
Open water	0.34	0.13	0.98	1.45
Developed, open space	4.35	2.09	1.52	7.96
Developed, low intensity	2.31	2.55	0.86	5.70
Developed, medium intensity	0.70	0.75	0.38	1.80
Developed, high intensity	0.32	0.18	0.16	0.66
Barren land	0.77	0.06	0.01	0.83
Deciduous forest	0.29	0.04	0.01	0.34
Evergreen forest	10.45	4.18	6.76	21.39
Mixed forest	0.66	0.27	0.13	1.06
Shrub/scrub	3.20	0.44	1.12	4.77
Grassland/herbaceous	0.78	0.18	0.17	1.13
Pasture/hay	1.49	0.16	0.12	1.78
Cultivated crops	0.27	0.00	0.01	0.30
Woody wetlands	15.01	3.52	5.09	23.64
Emergent herbaceous wetlands	0.99	0.68	1.72	3.39
Total area	**41.92**	**15.21**	**19.06**	**76.18**
	Back River (percent)	**Foster Creek (percent)**	**Bushy Park Reservoir (percent)**	**Bushy Park Reservoir with Back River and Foster Creek (percent)**
Open water	0.8	0.8	5.2	1.9
Developed	18.3	36.6	15.4	21.1
Barren land	1.8	0.4	0.0	1.1
Forest	34.8	32.3	42.1	36.2
Grassland/pasture/crop	6.1	2.2	1.6	4.2
Wetlands	38.2	27.6	35.7	35.5

Table 2. Mean tidal water levels, mean tidal range, and tidal epoch for selected sites on Charleston Harbor and the Cooper River, South Carolina.

[Data from National Oceanic and Atmospheric Administration, 2013. NAVD 88, North American Vertical Datum of 1988]

Location	Mean higher high water (feet above NAVD 88)	Mean high water (feet above NAVD 88)	Mean low water (feet above NAVD 88)	Mean lower low water (feet above NAVD 88)	Mean tide range (feet above NAVD 88)	Tidal epoch
Charleston Harbor	8.53	8.17	2.95	2.77	5.22	1983–2001
Charleston Harbor	8.29	7.95	2.68	2.49	5.27	1960–78
Cooper River at Army Depot	7.96	7.65	2.19	2	5.46	1960–78
Cooper River at Dean Hall	5.58	5.36	1.93	1.63	3.43	1960–78
East Branch Cooper River at Richmond Plantation	8.42	8.22	5.55	5.3	2.67	1983–2001
West Branch Cooper River at Pimlico	4.45	4.23	2.55	2.38	1.69	1983–2001

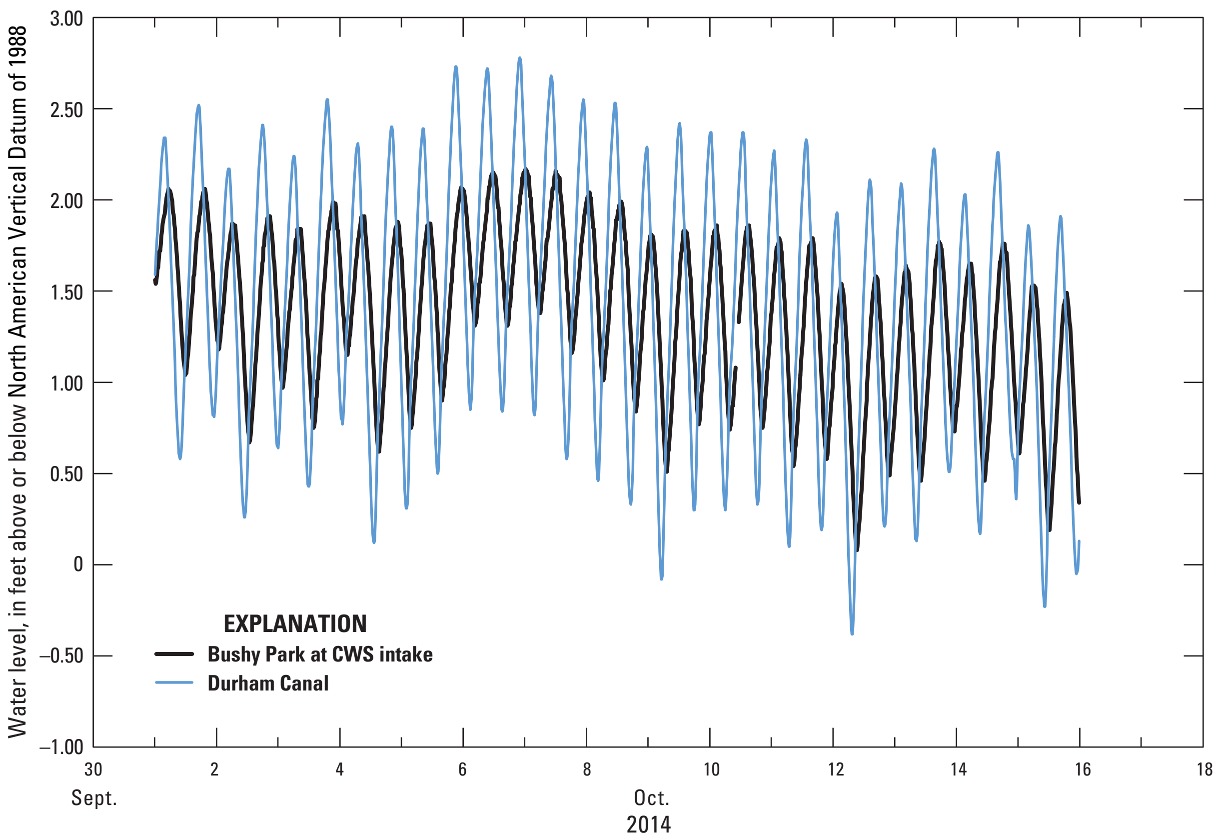


Figure 5. Water levels at the Charleston Water System (CWS) intake and the Durham Canal monitoring station for October 1–15, 2014.

from military, commercial, and residential areas. A summary of these studies can be found in Campbell and Bower (1996). Below are some of the highlights of these investigations that are of interest to the current study.

Jordan, Jones, and Goulding, Inc. (1988) investigated the cause of unpleasant taste and odors in municipal drinking water in the Charleston area and assessed the overall water quality in Foster Creek and Back River. The study arrived at four conclusions:

1. The entire Foster Creek, Bushy Park Reservoir, Durham Canal, and Back River system met South Carolina Department of Health and Environmental Control (SCDHEC) standards for Class B waters, with the exception of below standard dissolved-oxygen concentrations in Foster Creek and Back River.

2. Bushy Park Reservoir and its tributaries (including Foster Creek) were eutrophic and supported large amounts of aquatic vegetation.

3. Naturally occurring taste and odor compounds were found throughout the system but were highest in Foster Creek and the Back River.

4. Foster Creek samples had higher fecal coliform bacteria concentrations than Bushy Park Reservoir samples.

Overall, the water quality of Foster Creek and Bushy Park Reservoir has improved since the late 1970s, following elimination in 1983 of wastewater discharges into Foster Creek. Three investigations were conducted in the late 1980s and early 1990s to study the flow characteristics in Foster Creek. Results of the first investigation concluded that little circulation, flushing, or volume exchange was occurring between the upper reaches of Foster Creek and Bushy Park Reservoir on the basis of visual observations and measurements of low dissolved oxygen in the water column of Foster Creek (Jordan, Jones, and Goulding, Inc., 1988). The second investigation, conducted by SCDNR (de Kozlowski, 1990), included documentation of flow patterns in Foster Creek and determined that herbicide applications could be an effective method for controlling hydrilla. Bower and others (1993) simulated flow along the entire Back River-Cooper River flow system and demonstrated that Foster Creek is a tidally affected tributary to the Bushy Park Reservoir that remains stagnant without the hydrodynamic effects of either rainfall runoff (not studied) or municipal withdrawal. Flow characteristics of the Cooper River flow system also were simulated, as were the effects of simulated tide gates at Back River Dam on improving the quality of water in the Bushy Park Reservoir and Foster Creek. Operation of tide gates did not result in noticeable movement of water in the upper reaches of Foster Creek.

Models subsequent to Bower and others (1993) have included the Bushy Park Reservoir in the schematization of the models (Conrads and Smith, 1997; Yassuda and others, 2000; Rodriguez and Miller, 2007). These models were applied to evaluate the dissolved oxygen dynamic in the Ashley, Cooper, and Wando Rivers and Charleston Harbor (fig. 1). Although Bushy Park Reservoir was in the domain of these models, calibration of the flow and water-quality parameters for the reservoir was limited.

Approach

Temporal and spatial data were collected to analyze the convergence of environmental factors that occur among the physical, chemical, biological, and circulation processes within Bushy Park Reservoir to cause the production and release of the cyanobacteria by-products geosmin and MIB. To account for the water budget of the reservoir, the existing USGS real-time, data-collection network was augmented with continuous flow gages on Durham Canal, Back River, and Foster Creek; a water-level and meteorological gage at the CWS intake; and a flow gage in the water-supply tunnel from the reservoir to the Hanahan Water Treatment Plant (fig. 1). To understand the circulation in the reservoir, three to four up-looking acoustic velocity meters were deployed at various locations to record velocity profiles (at 15-minute intervals) for extended periods of time. To document the flow distribution across transects of the reservoir, with and without SCE&G withdrawals, flow measurements were made over a tidal cycle at five locations.

All the data used in this study are available online. The data from the USGS gaging network are available at the USGS National Water Information System (NWIS) web database U.S. Geological Survey (2016), and the velocity profile and velocity mapping data are available at Conrads and Lanier (2016).

Water Use

Five facilities have water-withdrawal intakes located on Bushy Park Reservoir (fig. 3): SCE&G Williams Station, CWS, DAK Americas, BP Amoco, and CRP. These five facilities withdrew a combined annual total of 182 billion gallons of raw water from the reservoir in 2014 (fig. 6). This volume of water was unevenly distributed in 2014, with approximately 88.5 percent withdrawn by SCE&G for power generation, 9.6 percent withdrawn by CWS for public supply, and 1.9 percent withdrawn by the other three facilities for industrial use.

Water-withdrawal records for the period January 1, 2007, to June 30, 2015, from each of the five facilities were compiled as daily values. Actual daily values were recorded and provided by SCE&G and CWS. Monthly data were recorded and provided by DAK Americas, BP Amoco, and CPR and were divided by the number of days per month to determine an estimated average daily value. During the data-compilation period, the Bushy Park Industrial Complex was operated by the Bayer Corporation from 2007 to 2009 and by CRP since 2010. Monthly water-use data were obtained from historical records maintained by South Carolina Department of Health and Environmental Control for the period when Bayer Corporation operated the Bushy Park Industrial Complex and directly from CRP for 2010 to June 30, 2015.

Williams Station, a thermoelectric powerplant built in 1973 and operated by SCE&G, is the largest water user of the five facilities withdrawing water from the reservoir. Water is diverted from the east side of the reservoir to the plant's intakes by a manmade, open channel. The plant withdraws water to circulate through its open-loop cooling system. The withdrawal rate ranged between 550 and 560 million gallons per day (Mgal/d) when operating at full capacity during the 8.5-year data-collection period. A withdrawal rate ranging from 15 to 19 Mgal/d generally is maintained by one of the three pumps even when the plant is not producing electricity. There were no periods of "zero" withdrawal during the study. Conversion of the plant's water circulation from an open-loop to a closed-loop cooling system has been discussed and could reduce the plant's daily raw water withdrawals by more than 90 percent, as seen during a similar conversion at the SCE&G Wateree Station (Horner, 2013).

The CWS uses the reservoir as a raw water source, and water is treated at the Hanahan Water Treatment Plant for drinking-water supply. The CWS intake is located in the reservoir north of the mouth of Foster Creek. The CWS withdrew raw water from the reservoir at an average daily rate of 52 Mgal/d during the data-compilation period. This average daily withdrawal rate includes nine short (1- to 3-day) periods of zero withdrawal in 2008, 2009, 2012, and 2013 and two extended periods of no withdrawals: January 3–31 and November 1–December 31, 2012. The withdrawals from 2007 to 2012 have a noticeable seasonal pattern of lower withdrawals during cooler periods from December to March and higher withdrawals during warmer periods from May to August. This pattern is not as distinct in the 2013 and 2015 withdrawal data and actually reverses in 2014 when withdrawals from mid-April through mid-August mostly are lower than the average withdrawal for 2014.

BP Amoco operates a chemical plant on the east side of the Cooper River. The freshwater intake structure is located near the earthen dam near the southern end of the reservoir more than 2 mi from the plant. BP Amoco has the largest raw water withdrawals of the three nonpower-generating industrial facilities with an estimated average daily withdrawal of 6.6 Mgal/d and withdrawals ranging from 3.1 to 8.7 Mgal/d during the modeling period. The three most noteworthy periods of low average daily withdrawals are 4 Mgal/d from October 2008 to September 2009, 3.6 Mgal/d in December 2013, and 4.3 Mgal/d from August 2014 to January 2015. The BP Amoco data had no months with zero withdrawals during the data-compilation period.

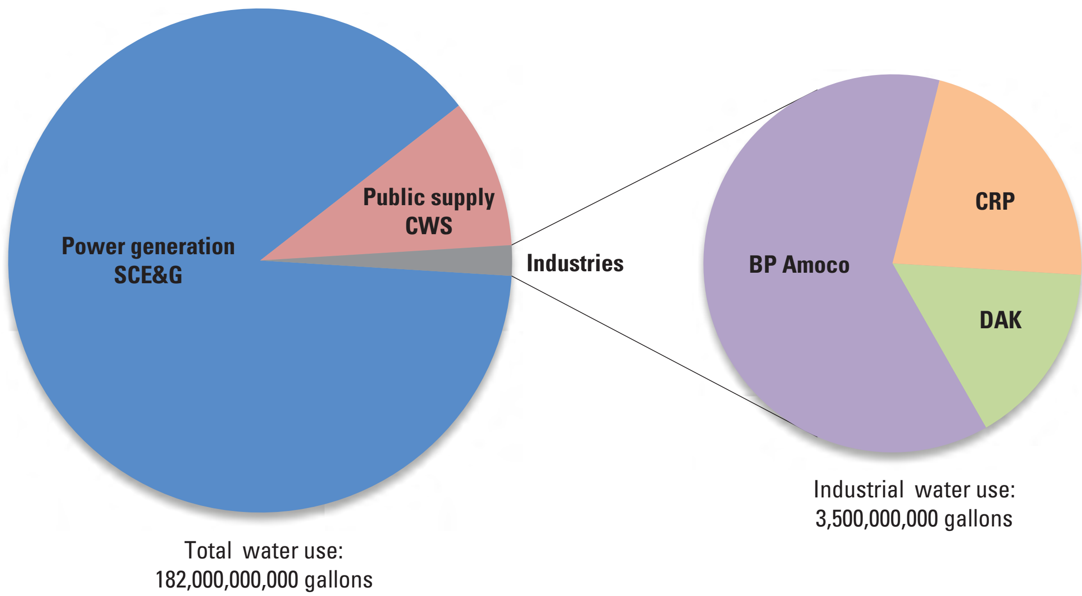


Figure 6. The total and industrial water use for 2014 for Bushy Park Reservoir.

The CRP operates the Bushy Park Industrial Complex located between the reservoir and the Cooper River. The intakes provide a raw water supply for multiple industries at the complex and are located on a 1,000-ft manmade channel that diverts water from the east edge of the reservoir to the intakes at the east end of the channel. The raw water withdrawals for the data-compilation period ranged from 1.9 to 2.8 Mgal/d and had an estimated average daily withdrawal rate of 2.2 Mgal/d. The Bushy Park Industrial Complex currently (2016) has sites available for industrial development and, therefore, has potential for increased water use. The CRP data had no months with zero withdrawals during the modeling period.

DAK Americas operates a chemical plant north of the reservoir and uses a 1,600-ft manmade channel to divert water from the Durham Canal to its intakes. The daily withdrawals have two distinct periods: January 2007 to January 2011 and February 2011 to June 30, 2015. Daily withdrawals for the period January 2007 to January 2011 ranged from approximately 3,500 to 210,000 gallons per day (gal/d) with an average withdrawal of 92,000 gal/d, excluding 5 months in 2010 for which daily withdrawals ranged from 0 to 135 gal/d. The daily withdrawals increased to an average of 1.0 Mgal/d from February 2011 to June 30, 2015, and ranged from 390,000 gal/d to 1.8 Mgal/d.

Monthly withdrawals provided by BP Amoco, CRP, and DAK Americas are stored in the USGS Site-Specific Water Use Data System (SWUDS). Daily withdrawals provided by SCE&G and CWS are stored in the USGS Automated Data Processing System (ADAPS).

Continuous Data-Collection Network

In the 1980s, the USGS established a real-time salinity alert network along the Cooper River, the West Branch of the Cooper River, and Durham Canal to continuously monitor the location of the freshwater-saltwater interface in the Cooper River. In the event that saltwater begins to move upstream toward the mouth of Durham Canal, the USGS notifies the operator of the hydroelectric facility, Santee-Cooper, and a prescribed amount of water is released into the West Branch of the Cooper River to maintain the freshwater availability in Durham Canal. In the 1990s, the network was augmented for a few years with additional gages to support studies by Bower and others (1993) and Campbell and Bower (1996). For the current study, the network was enhanced to collect additional meteorological, water-temperature, water-level, velocity, and flow data (fig. 3; table 3). The location of the real-time gaging stations in and near the Bushy Park Reservoir are shown in figure 3, and the parameters measured are listed in table 3. Photographs of the Durham Canal, CWS intake, Back River, and Foster Creek gages are shown in figure 7. The USGS gaging stations in the Bushy Park Reservoir Basin are part of the USGS National Water Information System (NWIS) database for storage and retrieval of water data collected at approximately 1.5 million sites around the country as part of the USGS program for disseminating water data to the public. The additions to the network for this investigation are described below.

Table 3. The U.S. Geological Survey continuous gaging network data for Bushy Park Reservoir.

[NAD, North American Datum of 1983; SC, South Carolina; Parameters measured: WL, water level; SC, specific conductance; WT, water temperature; Vel, velocity; Q, flow; DO, dissolved oxygen; pH, negative log of the hydrogen ion concentration; precip, precipitation; PAR, photosynthetically active radiation]

Station name	Station number	Name used in this report	Parameters measured	Period of record	Latitude (decimal degrees, NAD 83)	Longitude (decimal degrees, NAD 83)
Back River at Dupont Intake near Kittredge, SC	02172040	Durham Canal	WL, SC, WT	December 8, 1983–present	33°03'49"	79°57'26"
			Vel, Q	September 12, 2013–present		
			DO, pH	February 14, 1981–September 30, 1993		
Back River below S.C.Railroad Bridge near Kitterdge, SC	021720603	Back River	WL, Vel	November 11, 2013–June 9, 2015	33°03'39"	79°58'44"
			Q	June 1, 2014–June 9, 2015		
Bushy Park Reservoir above Foster Creek, Goose Creek, SC	0217206110	CWS Intake	WL, WT-top, WT-bottom, precip, wind speed and direction, PAR	August 29, 2013–December 31, 2016	32°58'47.6"	79°56'28.7"
Foster Creek at Goose Creek, SC	021720612	Foster Creek	WL	October 31, 2013–May 22, 2015	32°58'57"	80°00'02"
			Vel, Q	July 19, 2014–March 31, 2015		

Meteorological Data

A monitoring station was installed at the CWS intake (fig. 3) and instrumented to collect wind speed, wind direction, precipitation, and photosynthetically active radiation (PAR) in addition to water level and water temperature at the top and bottom of the intake structure (table 3). The wind speed, wind direction, and precipitation data from the intake were compared to the data collected at the Charleston Airport weather station (National Oceanic and Atmospheric Administration, undated).

Wind Speed and Direction

Wind vectors of velocity and direction were collected at 15-minute intervals. Rather than evaluating individual wind vectors, rose diagrams are often used to show the frequency of occurrence of winds with user-specified direction sectors (0 to 360 degrees or compass points) and speed (miles per hour, mph) intervals for a given location and time period. Wind rose diagrams for the Bushy Park Reservoir and Charleston Airport weather stations for the period September 2013 through June 2015 are shown in figure 8, and the data for the Bushy Park Reservoir rose diagram are listed in table 4. The rose diagrams used in this report were generated using the WRPLOT View Version 7.0.0 software by Lakes Environmental. The values for the 96 bins in table 4 are the percentage of the wind vectors that were measured for each bin over the 2-year data-collection period. The winds at Bushy Park Reservoir have a strong north-south orientation. The predominant winds blow from the north (N) and the north-northwest (NNW), 11.76 and 8.74 percent, respectively. The predominant southerly winds are from the south-southwest (SSW) and south (S), 8.57 and 7.25 percent, respectively. Calm winds are less than 1.0 mph and represent 12.18 percent of the record.

Similar to the orientation of the wind at the Bushy Park Reservoir, the predominant direction of wind at the Charleston Airport also has a strong north-northeast to south-southwest component (fig. 8). The airport winds have a major westerly component (7.2 percent, fig. 8*B*) that does not occur at the reservoir. The overall magnitudes of the winds at the two locations are similar, and Bushy Park Reservoir has a greater distribution of wind speeds of less than 4.0 mph.

Historic monthly wind direction data for the Charleston Airport station (1961–90) were compared to the monthly wind direction data for Bushy Park Reservoir (2014 and 2015). Monthly wind rose plots for these data are provided in appendix 1. Generally, the monthly wind directions at Bushy Park Reservoir follow the north-south alignment of the reservoir, and there is a westerly component with the winds at the airport that is not often seen in the rose diagrams for the reservoir. Many months show similar wind speed and direction or similarities in direction and differences in magnitude between the airport and reservoir stations, such as January, June, and July. Other months, such as February and March, show greater differences in the wind speed and direction at the two locations. Winds from the east and southeast were generally uncommon for both gages for the periods described above and constituted less than 10 percent of the total.

Figure 7. Gaging structures at *A*, Durham Canal, *B*, Charleston Water System intake, *C*, Back River, and *D*, Foster Creek. Photographs taken by Tim Lanier, U.S. Geological Survey, South Atlantic Water Science Center.

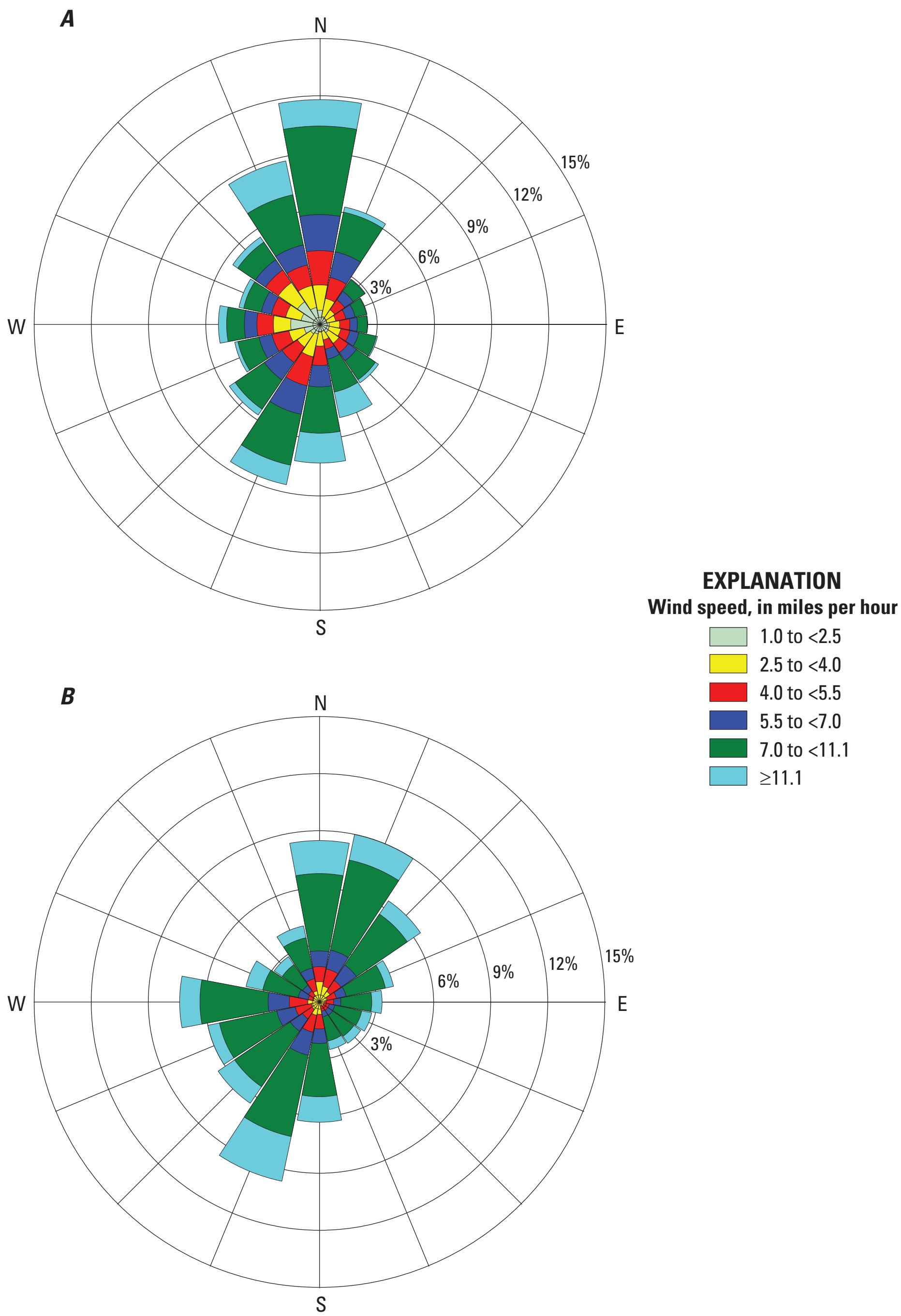


Figure 8. Wind rose diagrams for *A*, Bushy Park Reservoir and *B*, the Charleston International Airport for January 2014 through December 2015.

Table 4. Wind vectors organized by direction and speed intervals for Bushy Park Reservoir for the period January 1, 2014, to December 31, 2015.

[Wind direction is the direction from which the wind is blowing, in compass points: N, north; E, east; S, south; W, west; mph, miles per hour. Frequency of calm winds: 12.18 percent. Missing vectors: 0.09 percent. <, less than; ≥, greater than or equal to; >, greater than]

Wind direction	Percentage of vectors in bins						
	1 to <2.5 (mph)	2.5 to <4.0 (mph)	4.0 to <5.5 (mph)	5.5 to <7.0 (mph)	7.0 to <11.1 (mph)	≥11.1 (mph)	Total
N	0.74	1.33	1.79	1.89	4.63	1.38	11.76
NNE	0.43	0.95	1.13	1.37	2.12	0.27	6.27
NE	0.39	0.53	0.63	0.54	0.74	0.03	2.87
ENE	0.35	0.49	0.54	0.49	0.62	0.03	2.52
E	0.49	0.54	0.54	0.39	0.52	0.02	2.49
ESE	0.49	0.62	0.49	0.47	0.94	0.06	3.07
SE	0.53	0.68	0.58	0.52	1.21	0.19	3.70
SSE	0.37	0.47	0.50	0.54	1.75	1.37	4.99
S	0.41	0.74	1.01	1.12	2.43	1.56	7.25
SSW	0.51	1.22	1.55	1.53	2.72	1.05	8.57
SW	0.60	0.84	0.98	1.11	1.85	0.37	5.74
WSW	0.86	0.81	0.90	0.70	1.13	0.18	4.57
W	1.54	0.91	0.86	0.66	0.93	0.43	5.32
WNW	1.01	0.82	0.77	0.54	0.94	0.26	4.34
NW	1.43	1.22	0.81	0.65	1.11	0.32	5.53
NNW	0.90	1.18	1.10	1.07	2.68	1.82	8.74
Total	**11.05**	**13.33**	**14.15**	**13.59**	**26.29**	**9.32**	**87.73**

Precipitation

Precipitation data at the airport for the data-collection period (2014 to 2015) were similar to precipitation data for the period 1981 to 2010. Monthly precipitation at Bushy Park Reservoir was less than the precipitation at the airport for 15 of the 16 months of data collection in 2013 and 2014 and less than at the airport for 7 of the 12 months in 2015 (fig. 9*A*). During the historic rainfall event in October 2015 (Feaster and others, 2015), the airport recorded 18.91 in. of precipitation, which was 3.5 in. more than measured at Bushy Park Reservoir (15.34 in.). The similarities between the monthly totals at the airport for the data-collection period and the normals (average precipitation over a 30-year period) also are seen in the cumulative rainfall plots (fig. 9*B*) with the exception of the large rainfall amount for October 2015. Over the data-collection period from September 2013 to December 2015, rainfall measured at Bushy Park Reservoir was substantially less than at the airport.

Photosynthetically Active Radiation

Photosynthetically active radiation (PAR) defines the amount of light that is available for photosynthesis in plants such as blue-green algae. Whereas lumen is a measure of visible light to the human eye, PAR designates the spectral range between wavelengths of 400 to 700 nanometers that are photosynthetically useful to plants. A common adage in the plant growing community is “PAR is for plants, lumens are for humans.” The units for PAR are power per unit area or energy per second per unit area. Light quantity for plant growth involves discrete measures of quantum flux called photons. Photon flux is a direct measure of how much light energy is available for plants. Photon flux is commonly measured in units of micromoles per square meter per second, where 1 mole of photons = 6.022×10^{23} photons. Similar to solar radiation, PAR levels are dependent on the time of day and time of year because of the changing angle to the sun. Photosynthetically active radiation values for a 24-hour period (August 21, 2014) are shown in figure 10*A*. Values quickly increase after sunrise, reach a maximum around midday, and quickly decrease to zero at sunset. Although there is little change in the day-to-day values, there are differences during the day due to the degree of cloud cover (fig. 10*B*). There is a clear seasonal component to PAR because of the changing times of sunrise and sunset and solar intensities. Monthly PAR values for the data-collection period are shown in figure 10*C*. The highest annual monthly PAR values occurred in May in 2014 and June in 2015.

Water Temperature Data

Water temperatures were monitored at the top and bottom of the CWS intake structure. Temperature probes were set 13 ft apart with the top probe set at a gage height of –10 ft (North American Vertical Datum of 1988 [NAVD 88]) and the bottom probe set at a gage height of –23 ft (NAVD 88). The mean gage height at the intake over the data-collection period was 1 ft. The average daily water temperature and the temperature difference between the top and bottom probe are shown in figure 11*A*. The maximum average daily temperature was 86.4 °F (30.2 degrees Celsius [°C]) on July 25, 2015. The temperature stratified with differences of greater than 5.5 °F (3 °C) between the top and bottom water-temperature probes (fig. 11*A*). The temperature stratification began when the water temperatures were warming up in February and March and continued until August and September. The largest temperature difference between the top and bottom temperature probe occurred on June 21, 2015 (fig. 11*B*).

Streamflow Data

The computation of continuous streamflow data at the velocity sites is accomplished in three steps (Ruhl and Simpson, 2005; Lanier and Conrads, 2010; Levesque and Oberg, 2012). The first step is the development of a stage-area curve that establishes a relation between the river stage at each site and the cross-sectional area. The second step is to develop velocity ratings to convert the continuous velocity measurements (referred to as an “index-velocity” because it only measures the velocity in part of the channel cross section) to continuous mean velocity readings for the cross sections. The first two steps are accomplished by using the streamflow measurements and cross-sectional data collected at each site. The third and final step is to compute the streamflow by multiplying the mean velocity (computed using the velocity rating) by the cross-sectional area (determined by the stage-area curve).

Development of Stage-Area Curves

Stage-area curves that relate the continuous stage data to the cross-sectional area were computed from cross-sectional geometry data for each streamflow station. At Durham Canal, the channel geometry was determined by using an acoustic Doppler current profiler (ADCP) transect that was made at near peak stage during one of the tidal cycle flow measurements. A cross-sectional profile was computed by using the distance and depth data and the measured stage data collected at the site. For the Back River station, the channel geometry was surveyed with a digital level and a barcoded level rod. This cross section was further refined by using an ADCP transect collected at near peak stage. At Foster Creek, the channel geometry was defined by measuring down from the bridge deck at specific points along the downstream face of the railway bridge and surveying those points by using a digital level and barcoded level rod. The stage-area curves for the three velocity stations are shown in figure 12.

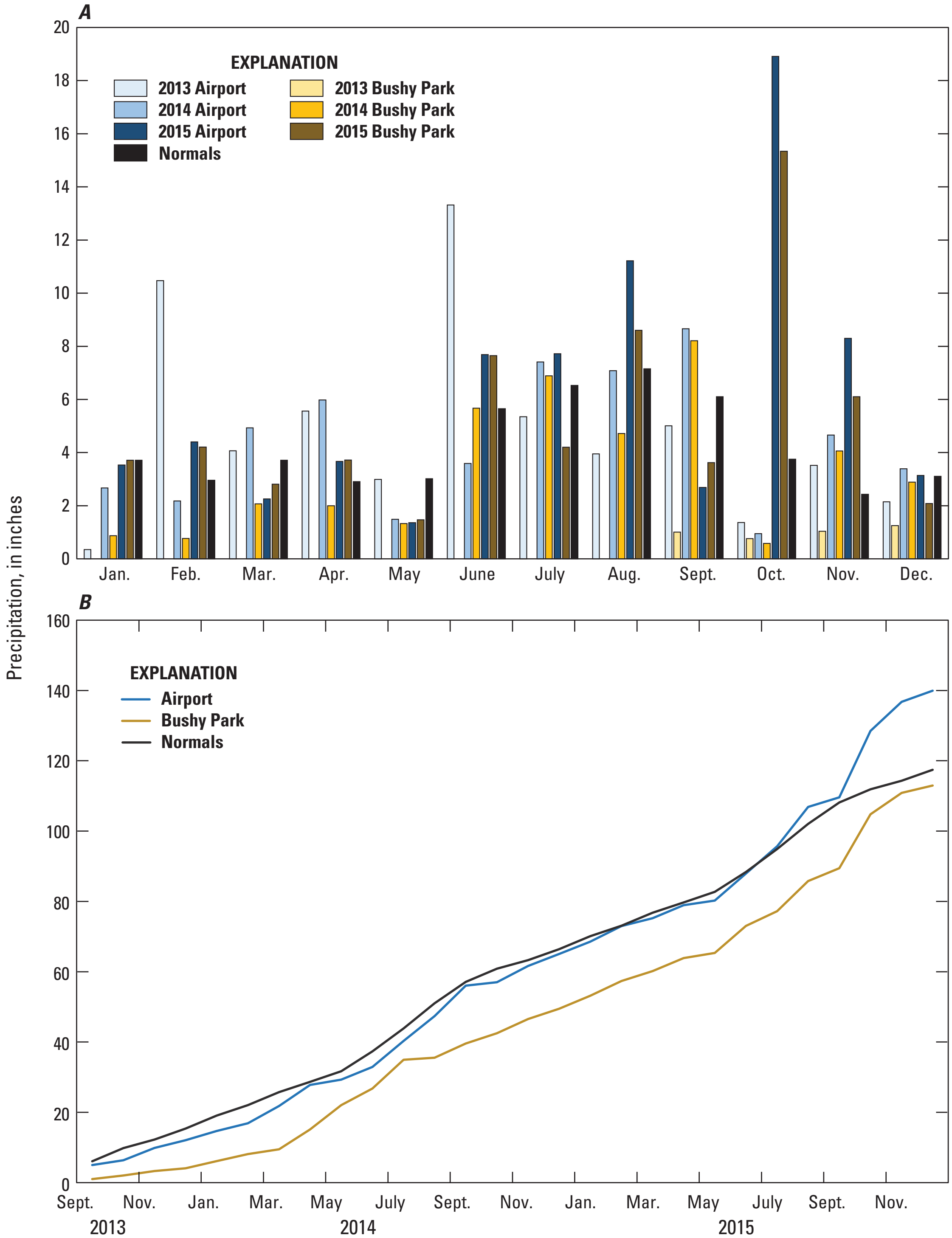


Figure 9. *A*, Monthly totals of precipitation for Bushy Park Reservoir and Charleston International Airport and normals (1965–2004). *B*, Cumulative amounts of precipitation for Bushy Park Reservoir, Charleston International Airport, and normals (1965–2004).

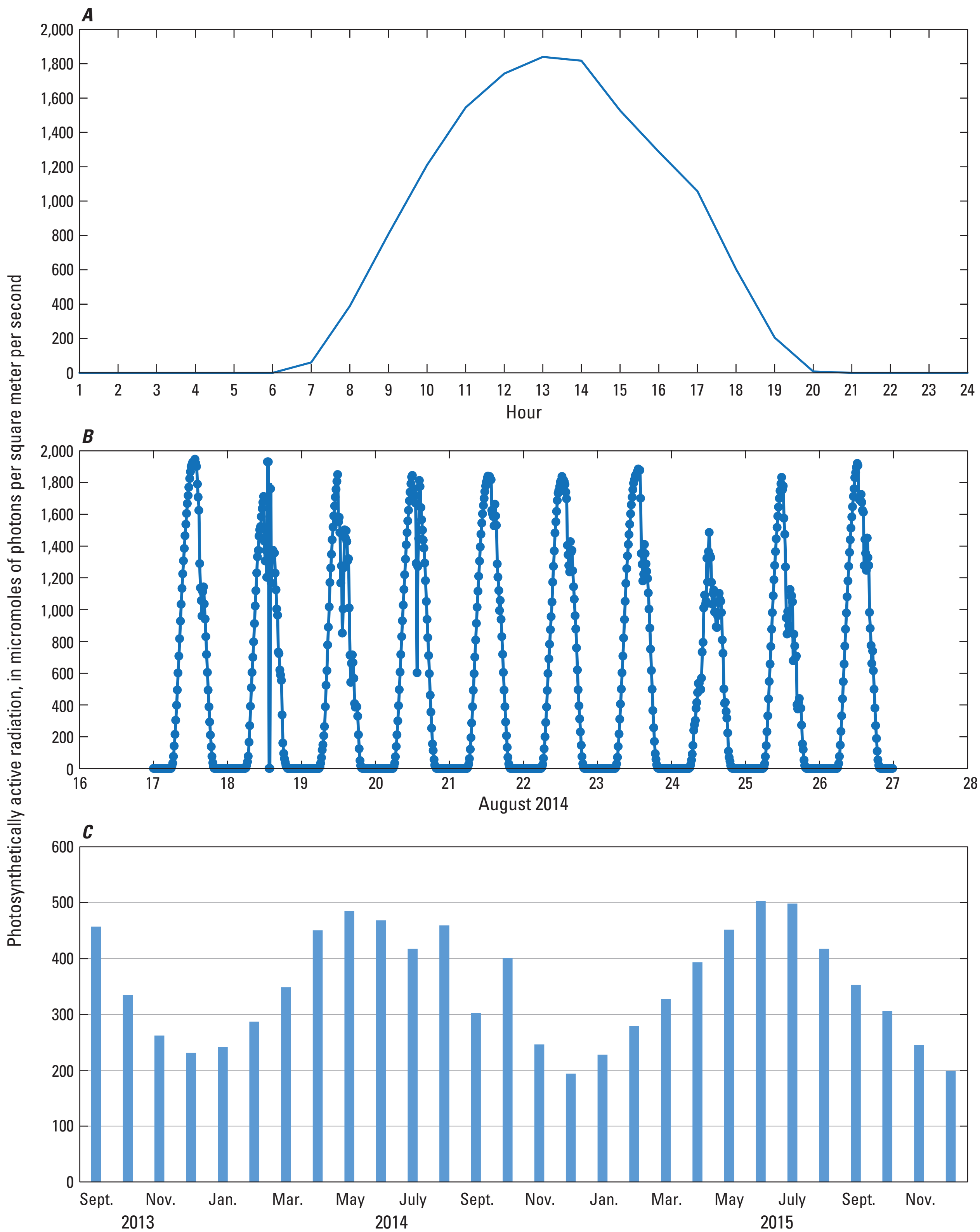


Figure 10. Photosynthetically active radiation *A*, hourly values for August 21, 2014, *B*, hourly values for August 17–24, 2014, and (*C*) monthly values for September 2013 to December 2015.

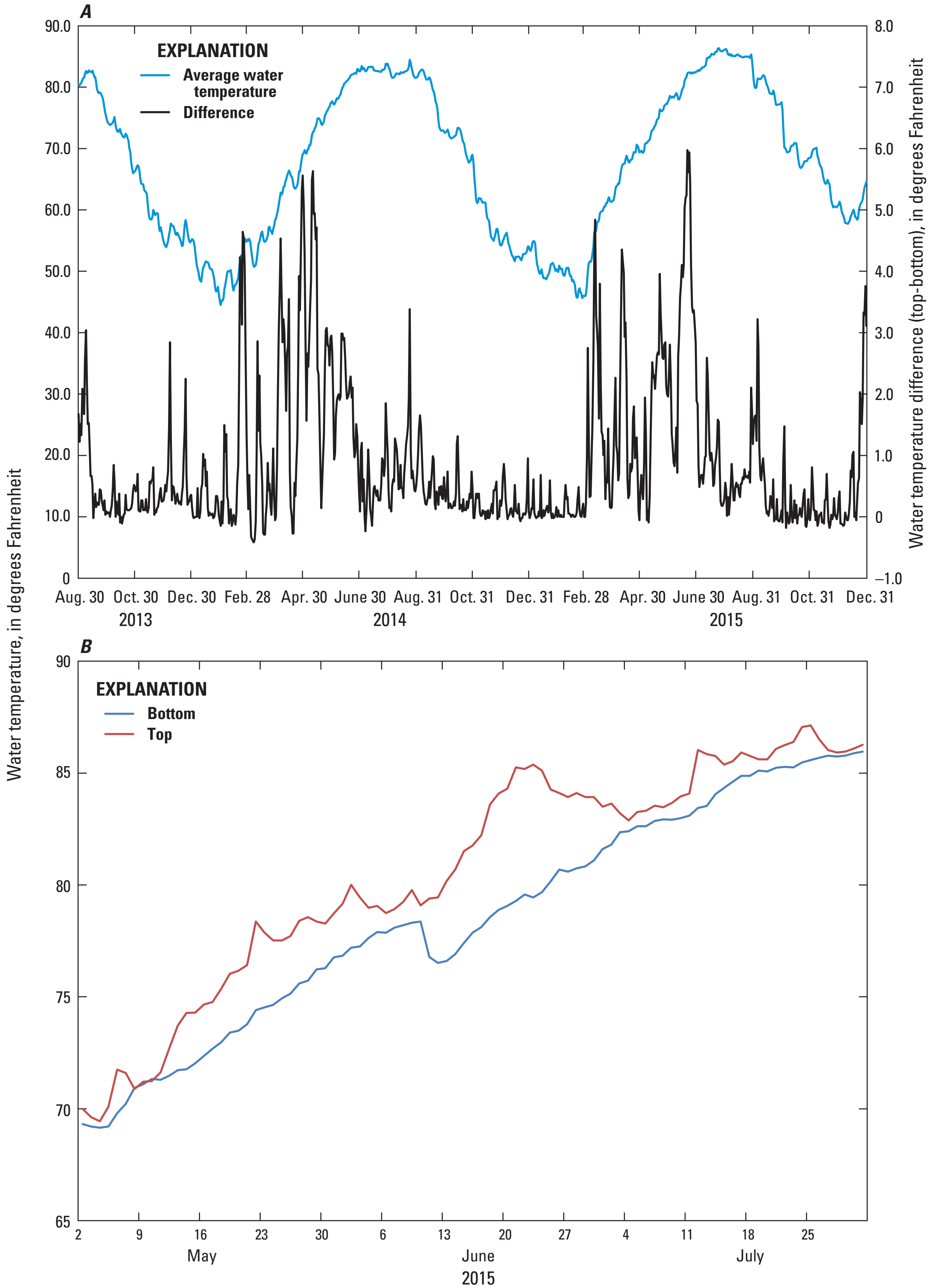


Figure 11. Water temperature from the Charleston Water System intake showing the *A*, average daily temperature and differences in top and bottom water temperature for the period August 30, 2013, to December 31, 2015, and *B*, top and bottom water temperatures for the period May 2, 2015, to July 31, 2015.

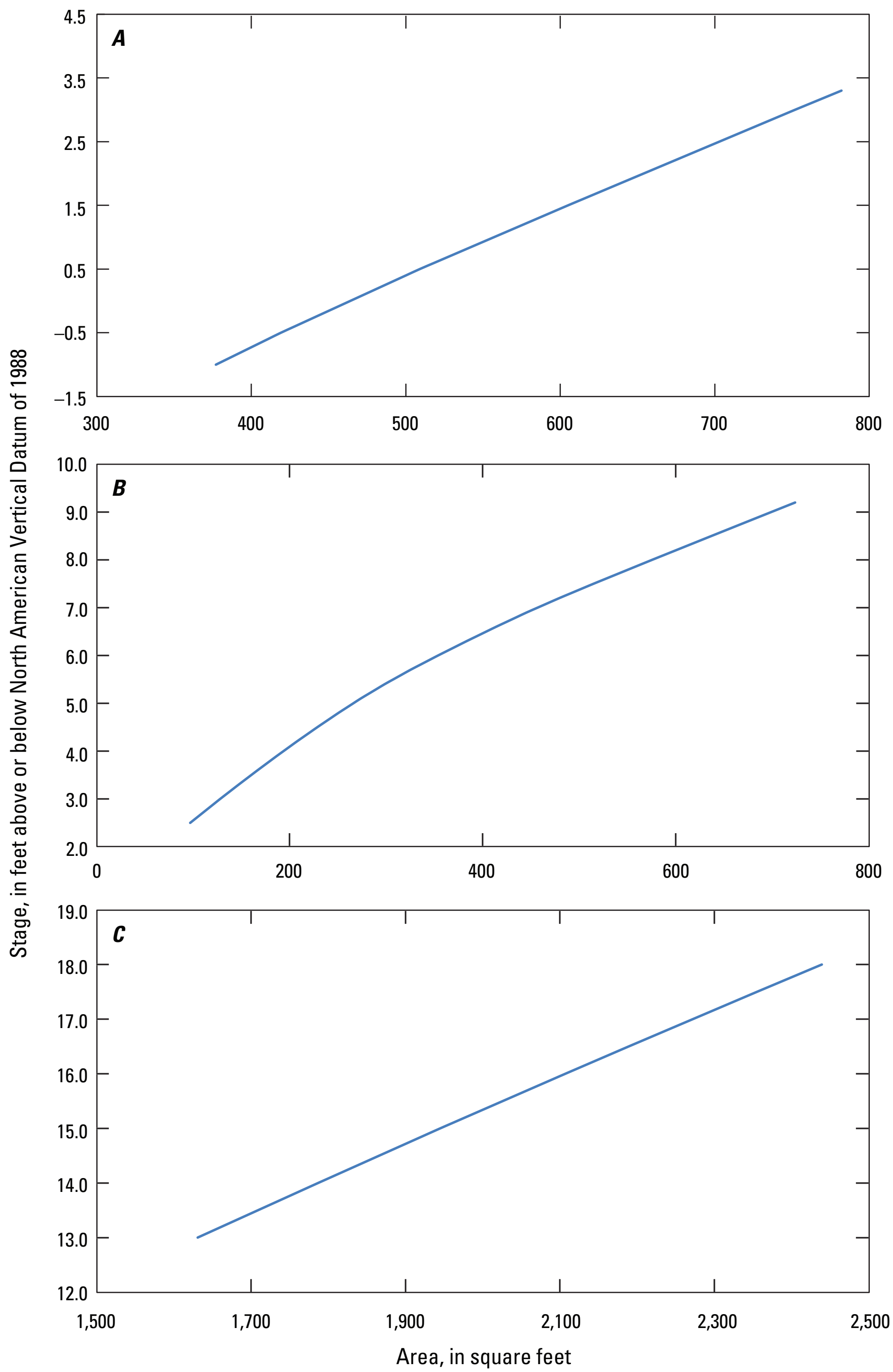


Figure 12. Stage-area curves for *A*, Back River (U.S. Geological Survey gaging station 021720603), *B*, Foster Creek (021720612), and C, Durham Canal (02172040), Bushy Park Reservoir, Charleston, South Carolina.

Development of Index-Velocity Ratings

The acoustic velocity meter is used to measure an integrated sample volume velocity (an "index-velocity") in a specific part of a channel cross section. In order to compute continuous streamflow by using the index-velocity readings, the index velocities must be converted to mean velocities for the cross section. Mean measured velocities were computed at each of the sites by dividing the measured flow by the area determined from the stage-area curve. The range of the measured velocities is listed in table 5 and shown in figure 13. For all three sites, the scatterplots of the mean measured velocity relative to rated index velocity show a similar slope for the ebb (outgoing) and flood (incoming) tides; therefore, the ebb and flood tides were analyzed together to compute the velocity ratings. Multiple linear regression was used to correlate the index velocity and stage to the mean measured velocity for each of the three stations. The importance of the stage (gage height) term in the multiple regression can be seen, especially at the Back River and Foster Creek sites, in the proximity of the rated velocity values (Vrated) to the one-to-one line as compared to the measured index velocity (Vi) values (fig. 13). The ratings for Back River and Foster Creek (fig. 13*A*, *B*), range from –0.2 to 1.7 foot per second (ft/s) with the higher positive velocities occurring during rainfall-runoff conditions. The velocities for the Durham Canal rating (fig. 13*C*) are symmetrically distributed around 0 ft/s (–2.0 to 2.0 ft/s), indicating a stronger tidal signal (influence) than the other two sites.

Computation of Continuous Streamflow

The continuous (15-minute interval) streamflow data computed for the three velocity stations are the product of the cross-sectional area and the mean velocity. The mean velocity is calculated by using the 15-minute index-velocity data and the relation developed between index-velocity and mean-velocity. The cross-sectional area is computed by using the 15-minute stage data and the relation developed between stage and cross-sectional area. The maximum tidal range and computed flood and ebb tide flows are listed in table 6. In tidally influenced environments, simple averaging of 15-minute values over a 24-hour period will not produce a true daily value. The tidal water-level and flow signals in the Charleston area are caused by a 24.8-hour lunar cycle, and using a 24-hour average of the data will introduce statistical biasing in the result. These variations are attributed to the changing 24-hour portion of the 24.8-hour tidal cycle being averaged, not to variations in the data. To remove the tidal effects, a Godin filter is used (Godin, 1972). This filter removes frequencies that have periods of less than 30 hours (astronomical tides have periods of approximately 12.4 and 24.8 hours). The filter uses at least 71 hours of data to create a filtered value at the 35th hour. Thus, approximately a day and a half is removed from the beginning and end of the tidally filtered dataset. The tidally filtered flow represents the net streamflow, either downstream or upstream.

The daily precipitation data from the Bushy Park Reservoir gage, the 60-minute computed flows for Foster Creek and Back River, and the streamflow and tidally filtered streamflow for Durham Canal are shown in figure 14 for the period September 1 to 30, 2014. The streamflow response to rainfall is clearly seen in the Foster Creek and Back River hydrographs (fig. 14*A*, *B*). The tidal signal remains in the Back River hydrograph following the rainfall but the tidal signal is greatly dampened in the Foster Creek hydrograph following the rainfall. The strong semi-diurnal tidal signal is clearly seen in the Durham Canal hydrograph (fig. 14*C*) with maximum positive and negative flows of greater than +/–4,000 ft^3/s. Although not seen as clearly as in the Foster Creek and Back River hydrographs, the flows in Durham Canal do respond to rainfall in the basin. The net flow in Durham Canal can be seen after removing the tidal signal by using the Godin filter (fig. 14*C*). The net flow is generally negative (toward the reservoir) except for a few days around September 22. During September 2014, SCE&G was withdrawing water at a rate of 857 ft^3/s (554 Mgal/d), which is approximately the net flow in the canal from September 1 to 13, 2014. The larger precipitation events (greater than 0.3 in.) and subsequent inflow from Foster Creek and Back River during the middle and end of the month (fig. 14*A*) had the effect of decreasing the negative flows in the canal and reversing flows on September 22 and 23.

Table 5. Instruments, sampling distance, averaging intervals, and maximum flood tide and ebb tide velocities and flows at the three index-velocity sites in the Bushy Park Reservoir.

[ft/s, foot per second; ft^3/s, cubic foot per second; R^2, coefficient of determination; ft, foot; m, meter; s, second]

Station	Instrument[1]	Sampling distance	Averaging interval[2]	Maximum index velocity (ft/s)		Maximum measured flow (ft^3/s)		Velocity rating	
				Flood tide	Ebb tide	Flood	Ebb tide	R^2	Standard error (ft/s)
Durham Canal	Argonaut-SL	9.8 to 59 ft (3 to18 m)	120 s	2.07	1.90	4,580	3,090	0.99	0.04
Back River	Argonaut-SL	6.6 to 23.0 ft (2 to 7 m)	120 s	0.16	1.09	43.4	555	0.97	0.02
Foster Creek	Argonaut-SL	1.6 to 5.9 ft (0.5 to 1.8 m)	180 s	0.14	1.70	15.0	457	0.96	0.01

[1]Argonaut-SL is firmware developed by SonTek.

[2]Made at the end of the 15-minute data-collection interval.

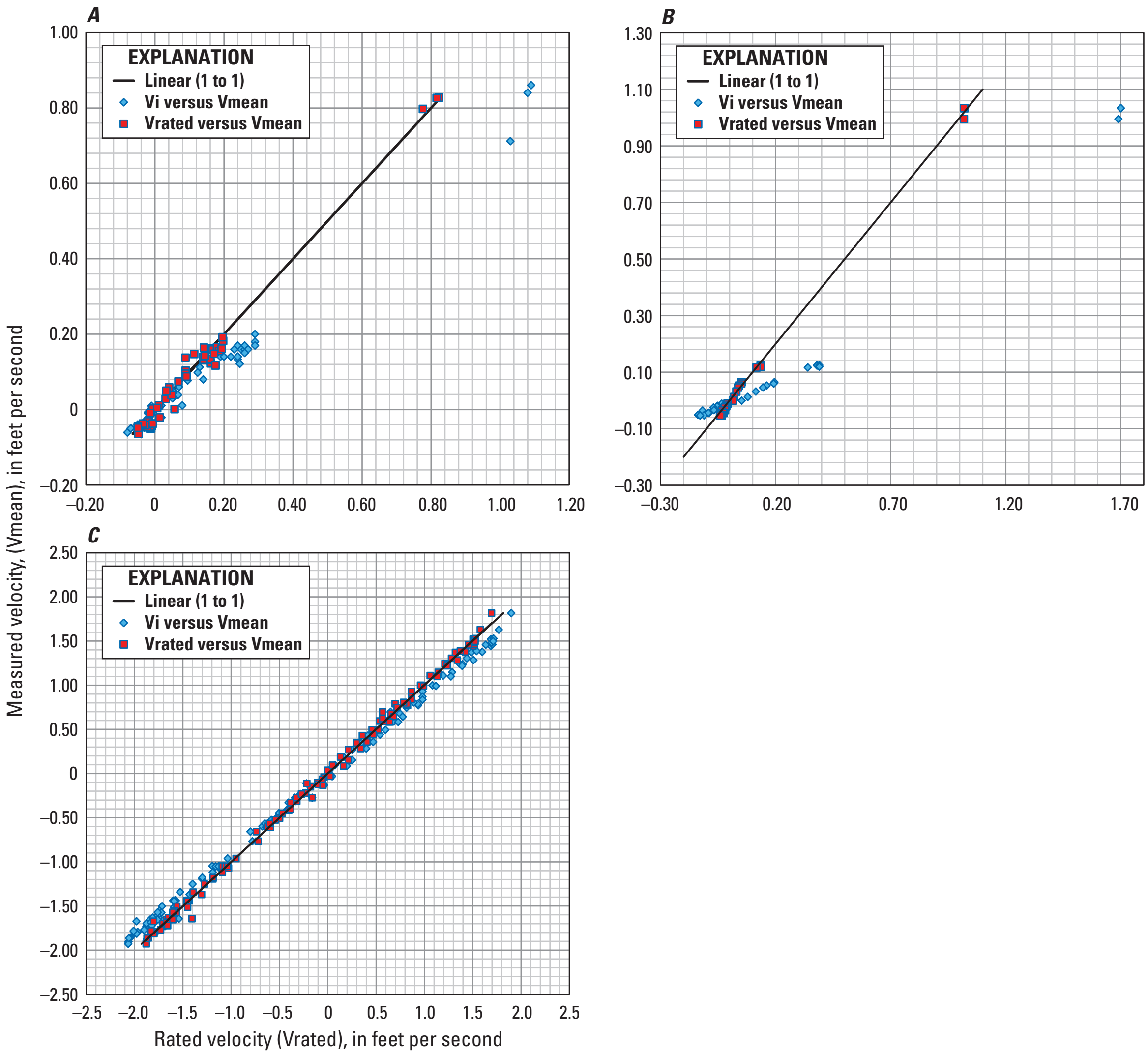


Figure 13. Index-velocity ratings for *A*, Back River (U.S. Geological Survey gaging station 021720603), *B*, Foster Creek (021720612), and *C*, Durham Canal (02172040), Bushy Park Reservoir, Charleston, South Carolina. The measured index velocities (Vi) are also shown.

Table 6. Tidal range and maximum velocity and flows for flood and ebb tides for the three index-velocity sites in the Bushy Park Reservoir.

[ft, foot; ft/s, foot per second; ft³/s, cubic foot per second]

Station	Tidal range (ft)	Maximum velocity (ft/s)		Maximum flow (ft³/s)	
		Flood tide	Ebb tide	Flood tide	Ebb tide
Durham Canal	3.0	2.07	1.90	5,820	5,190
Back River	2.0	0.16	1.09	27	815
Foster Creek	1.7	0.14	1.70	152	510

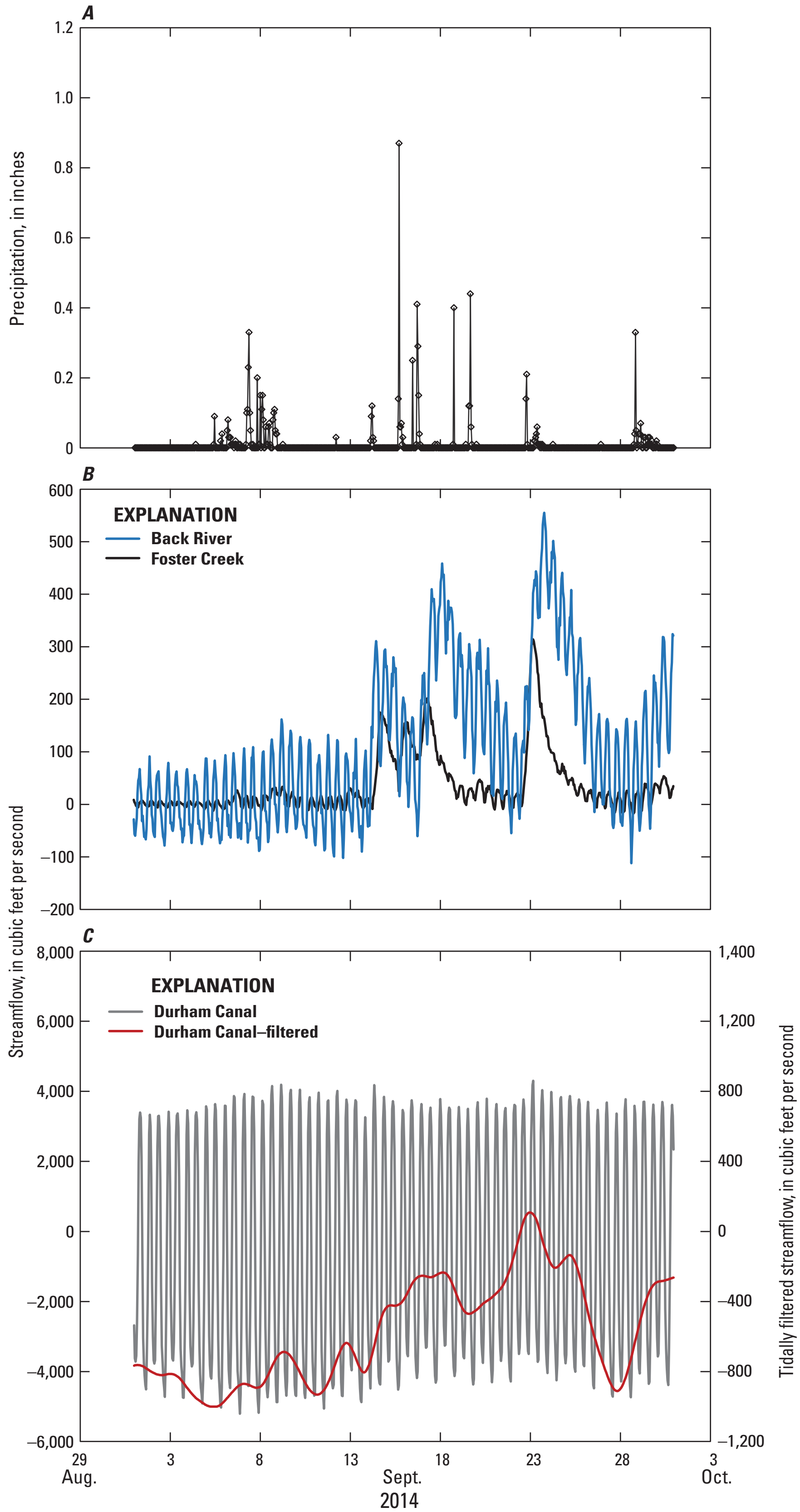


Figure 14. *A*, Precipitation at Bushy Park Reservoir. *B*, Streamflow in Foster Creek and Back River. *C*, Streamflow and tidally filtered streamflow for Durham Canal.

Water-Supply Tunnel Flow Data

In addition to flows measured at the three open-channel sites, flows also were measured in the Bushy Park water-supply tunnel, which conveys water approximately 13 mi from the reservoir to the Hanahan Water Treatment Plant (fig. 1). Installation of the velocity meters required close coordination of the Hanahan Water Treatment Plant staff, commercial divers, and USGS personnel. Because the dive depth was approximately 70 ft, dive times were limited to 48 minutes. For safety concerns, raw water and process pumps were turned off while the divers were in the tunnel. Only two dives per day were planned to minimize disruptions of water-plant operations. To install the velocity meters, divers descended down the access shaft (fig. 15*A*), entered the 8-ft-high water-supply tunnel, and installed a SonTek-IQ acoustic Doppler velocity meter (ADVM) to the tunnel ceiling approximately 250 ft from the access shaft (fig. 15*B*). A communication cable (fig. 15*C*) connects the ADVM to the telemetry equipment in the gage house at the land surface. The data are transmitted to the USGS Water Science Center in Columbia, S.C., and provided to the CWS Supervisory Control and Data Acquisition (SCADA) system.

A stage-area curve is not necessary to compute flow because the tunnel is full at all times and the cross-sectional flow area does not vary. The divers measured the dimensions of the arch-shaped tunnel at the location of the meter installation. The computation of the flow in the tunnel is the product of the average of the velocities recorded by the four beams of the ADVM and the cross-sectional area of the tunnel. The hydrograph for the tunnel for September 2014 is shown in figure 15*D*.

Velocity Profiles

To collect continuous velocity profiles within the reservoir, bottom-mounted ADCPs were deployed at six locations from the confluence of Back River to the mouth of Foster Creek (fig. 16) during the period December 2013 to May 2014. These upward-facing ADCPs are self-contained Sontek Argonaunt XRs with a frequency of either 1,500 or 3,000 kiloHertz (kHz). The ADCPs collect vertical profiles of three-dimensional (3D) water velocity as well as depth data of the water column above the sensor. In addition to the average velocity profile above the sensor, the ADCPs collect 3D water velocity data in as many as 10 predefined cells above the sensor.

Site Location and Pre-Deployment of Instruments

Velocity profiling sites were selected to measure a variety of velocities in the reservoir. As many as four sites were deployed concurrently depending on the number of available instruments. The deployment periods for each location are listed in table 7. Prior to deployment, the sites were located using the map coordinates and a hand-held Magellan global positioning system (GPS) unit. The reservoir depth at all locations was used to determine the frequency of the ADCP deployed at each site. For the deeper sites (greater than 25 ft), the 1,500-kHz frequency instruments were used. Depth data were used for an initial instrument setup and were programmed into the ADCP. Prior to deployment in the field, only minor adjustments to the instrument setup were required. The ADCPs were mounted on temporary platforms made of molded fiberglass grating and polyvinyl chloride (PVC) pipe. At one location, site VVP5, migration of a sand bar completely covered the instrumentation with approximately 6 ft of sand. Once covered with sand, the ADCP data collection stops. It was anticipated that similar conditions could affect the deployment at site VVP4; therefore, the same temporary platform used at the other sites was modified to include 2-ft-long legs at site VVP4 to prevent the ADCP from being buried in sand during the data-collection period (fig. 17).

All hardware used for the deployment of the bottom-mounted ADCPs was either brass or stainless steel to minimize compass interference. Each platform included an ADCP, power supply, tethering/communication cable, weights made of stainless steel shot, and a Teledyne Benthos transponder (location beacon). Prior to deployment, the internal compass on each of the ADCPs was calibrated to cancel out any magnetic interference that might occur at that location. The internal clock of the ADCP was reset to Eastern Standard Time and noted in the field book. Additionally, prior to the initial deployment, the instruments were placed on the reservoir bottom at the desired location but tethered to the surface by cable in order to communicate with the instrument directly to adjust the internal data-collection settings. Once the setup was finalized, a diver would disconnect the tethering cable and confirm the platform was level on the reservoir bottom.

At all locations except one, the height of the sampling volume above the sensor ranged from 4 ft above the reservoir floor to the water surface. Because the reservoir is tidally affected, the distance from the sensor to the surface was constantly changing, which could affect the number of vertical cells, or bins, collected in the water column. At site VVP4, the starting point above the reservoir floor was 3.5 ft because the instrument was mounted on a platform with legs due to the potential for sand bar movement in the area. The ADCP frequency, bin size, and blanking distance for each site are listed in table 8.

Instrument Deployment and Recovery

Once deployed, the ADCP instruments collect data for a predefined time interval. Data are collected for 120 seconds and averaged at the end of each 15-minute interval. The device then time tags the recorded average readings based on the device's internal clock. In addition, the instruments record the average 3D velocity within predefined cells beginning at the

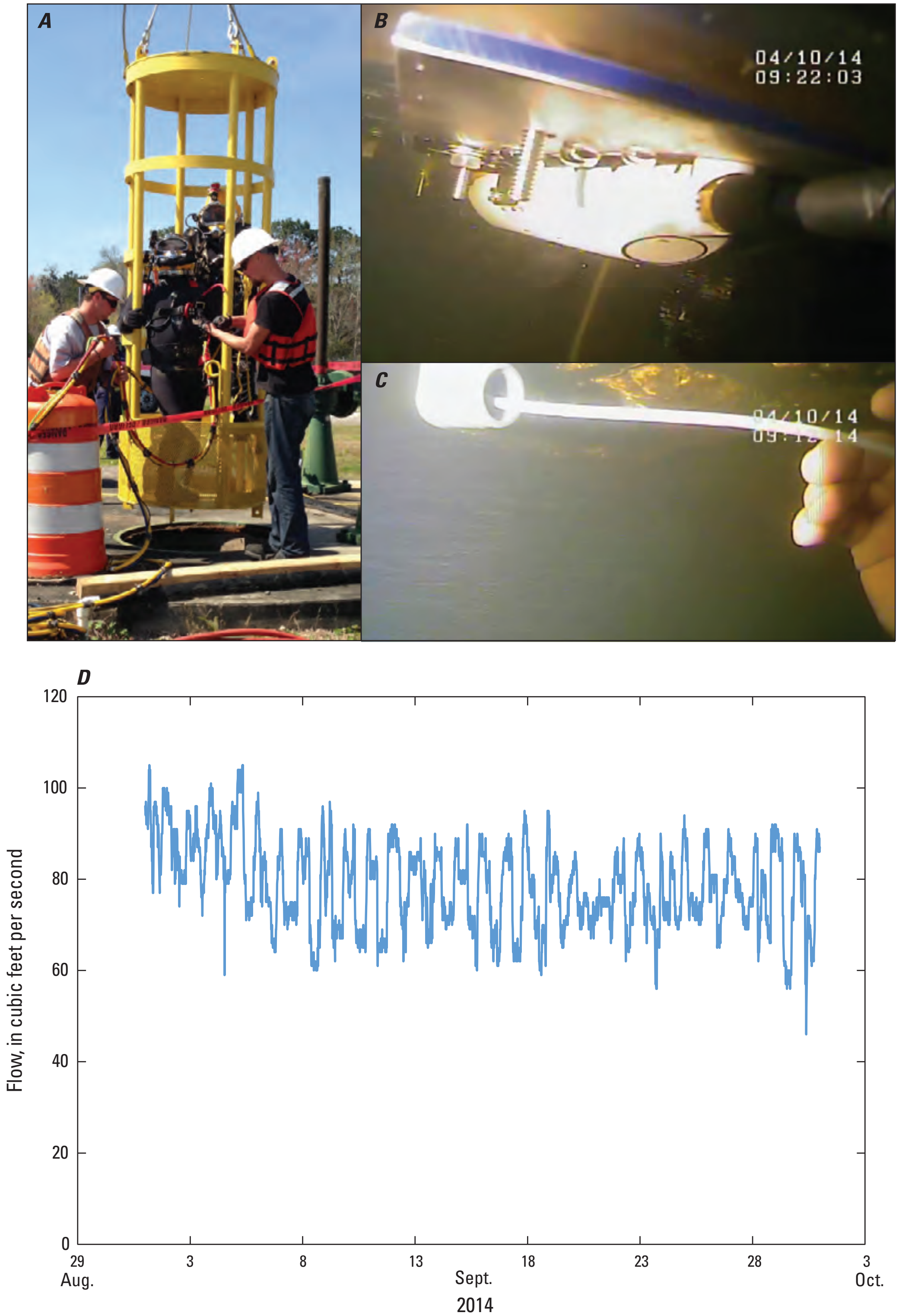


Figure 15. *A*, Divers being lowered into an access shaft to the Bushy Park water-supply tunnel. *B*, Velocity meter attached to the top of the water-supply tunnel. *C*, Communication cable being threaded into the conduit to the land surface. *D*, Flow in the water-supply tunnel for September 1–30, 2014.

Figure 16. Location of velocity profiling sites and velocity mapping transects on Foster Creek and Bushy Park Reservoir.

Table 7. Vertical profiling data-collection periods, dates of velocity mapping transects, and South Carolina Electric and Gas Company monthly average withdrawal rates.

[Cells with gradient shading indicate the meter was deployed or removed during that month on the date indicated. Mgal/d, million gallons per day]

Site	2013	2014												2015				
	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
VVP1				3/21											2/6			
VMT1									8/5			11/5						
VVP2	12/17			3/21											2/6			5/7
VMT2									8/5			11/5						
VVP3	12/17						6/22	7/9										5/7
VVP3-East															2/6			5/7
VMT3									8/5			11/5				3/26	4/23	
VVP4								7/9										5/7
VMT4									8/5			11/5				3/26	4/23	
VVP5	12/18	1/1																
VMT5									8/5			11/5						
SCE&G average monthly withdrawal rate (Mgal/d)	554	554	403	149	523	554	554	533	525	554	368	201	376	376	376	252	297	376
SCE&G outage dates			2/22 to 3/19								10/24 to 11/15					3/22 to 4/6		

Figure 17. Temporary platform used for the deployment of the vertical acoustic Doppler current profilers (ADCP). The ADCP is on the right and the power supply is on the left. The platform is supported off the bottom of the reservoir by three legs.

Table 8. Frequency, bin size, and blanking distances of the bottom-mounted acoustic Doppler current profilers at velocity profiling sites on Foster Creek and Bushy Park Reservoir.

Station	Frequency (kiloHertz)	Bin size (meter)	Blanking distance (meter)
VVP1	1,500	1	0.5
VVP2	1,500	[1]1.5, 2	0.5
VVP3	3,000	0.8	0.5
VVP3-East	3,000	0.8	0.5
VVP4	3,000	0.3	0.4
VVP5	3,000	0.8	0.2

[1]Bin size of 1.5 meters for the first deployment and 2.0 meters for the second deployment

previously mentioned heights above the reservoir floor to the water surface. The power supply for the ADCPs normally last 10 to 11 weeks. To minimize missing record within the collection period due to power loss, each location was revisited every 9 to 10 weeks. The general locations of the temporary platforms were located by using the latitude and longitude recorded during initial instrument deployment. The diver would locate the ADCP by a hand-held "listening" device that would communicate with the location beacon attached to the temporary platform. Once each platform was located, its location was temporarily marked on the reservoir floor to ensure proper redeployment placement. The platform was then brought to the surface by using inflatable lift bags and hoisted onto the boat. Once on deck, a number of steps were taken before redeploying the ADCP, including

- Quickly evaluating the data,
- Checking the ADCP clock against the laptop clock,
- Noting differences in time and resetting the ADCP clock,
- Cleaning the ADCP as necessary,
- Replacing the battery and the transponder used to locate the platform, and
- Recording the diver's comments on the conditions observed.

The diver would then redeploy the instrument at the same location by using the marks established during the recovery.

Velocity Profile Data Processing

The data were downloaded from the ADCP and processed using ViewArgonaut, a software package developed by SonTek, which allows the user to view the velocity data and quality-control parameters, such as signal-to-noise ratios (SNR) and beam checks (BC), which are recorded by the ADCP at regular intervals. These quality-control parameters can be used to identify intervals of the velocity data that are considered poor and should not be used. For example, when the data file was collected from site VVP3 on May 7, 2015, the diver noted that the sensor platform was completely covered by aquatic weeds. The data were evaluated by using ViewArgonaut, and on April 27, 2015, the SNR signal showed that the instrument was fouled by weeds. The BC on and after April 27 confirmed this finding. Thus, the data for April 27 to May 7 were deleted. This type of quality-control check was applied to all the data files prior to processing. Once the SNR filtering was completed, two date/time corrections were applied before the data were considered final. The first time correction was based on comparing the sampling start time to the sampling period. The second time correction was based on the ADCP clock inaccuracy.

An example of the 3D velocity vector data is shown in figure 18. During each 15-minute sampling period, the magnitude and direction of the water velocity are determined for each vertical cell (bin). Because of the changing water level with tides, the upper bins may be above the water surface and the velocity data would be erroneous and not used. Similar to the wind data, rather than evaluating individual water velocity vectors, rose diagrams can be used to show the frequency of the magnitude and direction of the water velocity user-specified direction sectors and speed intervals. One difference with the wind rose diagrams is that they show the direction from which the wind was blowing. The velocity vector rose diagrams show the direction that the currents are moving toward. One way of interpreting the current-velocity vector rose diagram is the frequency of the magnitude and direction of the movement of the water above the velocity meter. For example, vertical water velocity profiles were collected at the mouth of Foster Creek from March 21, 2014, to February 6, 2015 (site VVP1, table 7; fig. 16). The 15-minute average velocity vector was computed to create a current-velocity vector rose diagram of the data (fig. 19). The rose diagram shows that the velocity at site VVP1 is generally less than 0.4 ft/s, and the majority of the higher velocities (greater than 0.2 ft/s and 0.3 ft/s) move to the west toward the Back River Dam.

Velocity Mapping Transects

To understand the velocity magnitude and direction flow patterns in Bushy Park Reservoir with respect to the industrial withdrawals, a series of simultaneous tidal cycle flow measurements were made at five transects during low and high withdrawal periods to generate plan view velocity mapping transects (VMT). The flow measurement transects were located close to the velocity profiling sites in order to evaluate the VMTs and the continuous vertical profile data that were being collected concurrently (fig. 16). The times and dates of the measurements were scheduled for (1) daylight hours (for safety concerns), (2) slack tide occurring early in the morning to measure through a complete tidal cycle, and (3) days with SCE&G routine withdrawals and scheduled outages (August 5 and November 5, 2014, and March 26 and April 23, 2015 [sites VMT3 and VMT4 only]). The locations of the VMTs are shown in figure 16, and table 7 lists dates of transect measurements.

Water velocity and flow data were collected using a 1,200 kHz Teledyne RD Instruments (TRDI) Rio Grande ADCP in conjunction with a Trimble1 AG132 differential GPS (dGPS) receiver using the Wide Area Augmentation System (WAAS). The TRDI software package WinRiver was used for data collection and data integration. Position information was obtained from the dGPS. The ADCPs were temporarily mounted on the side of manned boats. The AG132 antenna was mounted directly above the ADCP. All data were collected with a vertical bin size of 0.82 ft (25 centimeters).

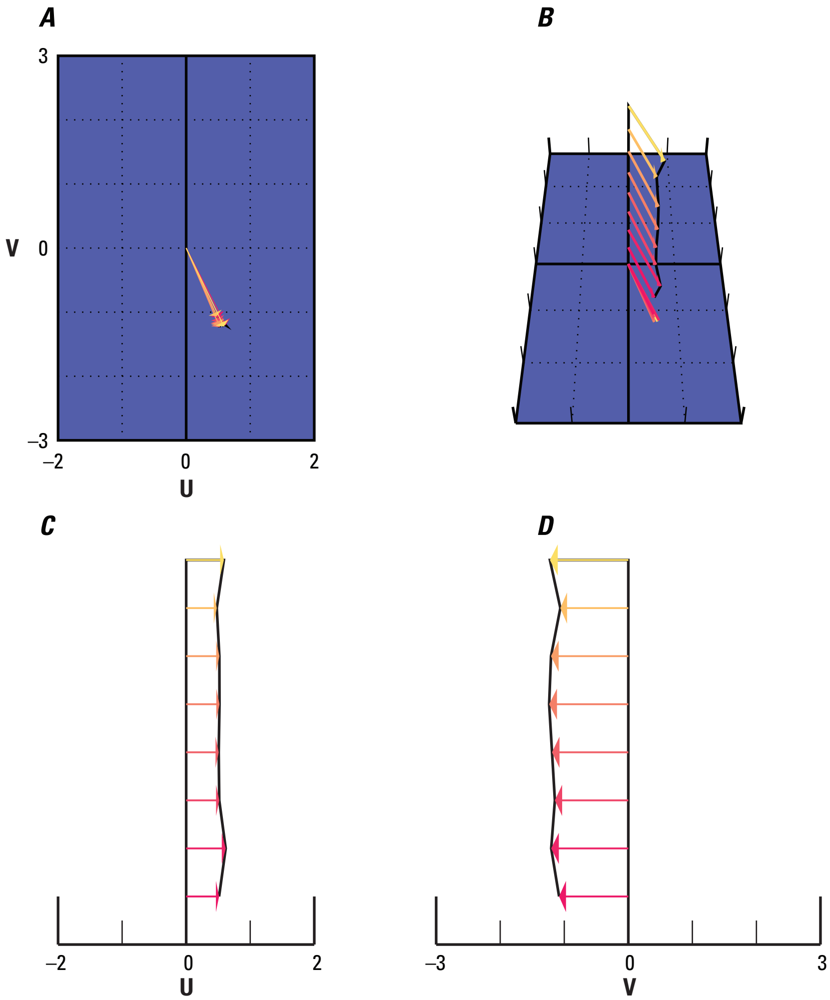


Figure 18. Examples of the velocity profile data displays for site VVP4 on August 14, 2014, at 12:06 a.m. *A*, plan view, *B*, profile view, *C*, velocity vectors in the U-direction, and *D*, velocity vectors in the V-direction. Units are in feet per second.

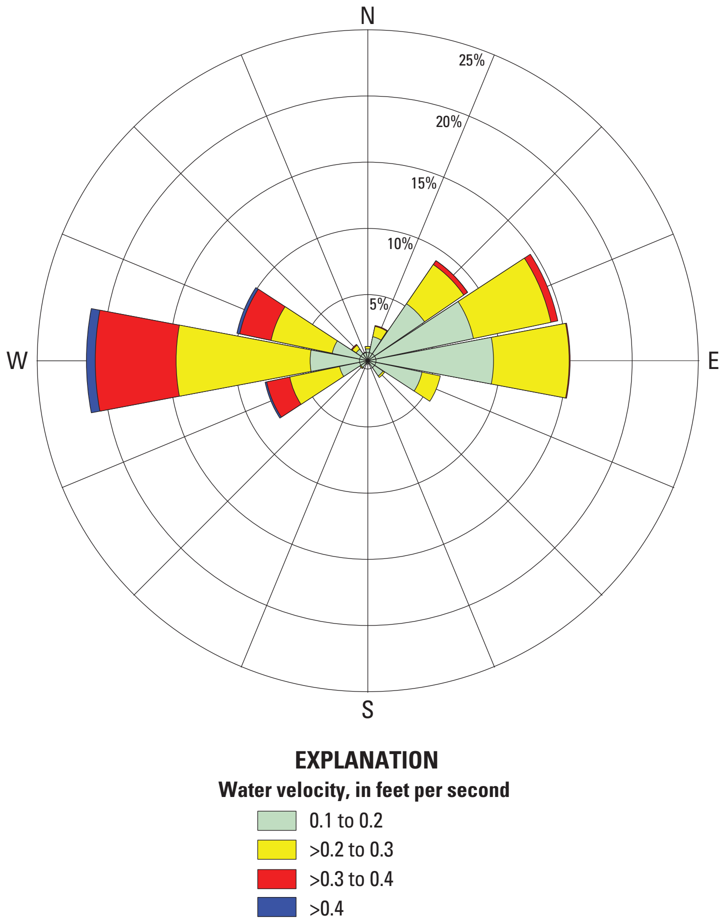


Figure 19. Velocity rose diagram for site VVP1 located at the confluence of Foster Creek and Bushy Park Reservoir.

The USGS guidance for flow measurements and velocity surveys was followed when possible (Oberg and others, 2005); however, deviations from guidance were required for two reasons: tides and transect widths. Because all five sites are affected by tides, measurements were synchronized and made simultaneously every half hour. These measurements required approximately 10 minutes to complete. Because of the difference in transect widths between the sites, boat-speed guidance at some transects were relaxed to accommodate the 10-minute measuring time interval. Six transects were possible at three of the sites, with reduced boat speed. It was decided to require only four transects in order to keep the hydrographer from being rushed and compromising the quality of the data. Due to the large transect width at the other two sites, only two transects were made per measurement. All boat paths for transects used the same general route but some drifting did occur due to wind. Moving-bed tests were made throughout the day, and compass calibrations were made prior to all measurements (Oberg and others, 2005).

Data Processing

Transect velocity and flow data were reviewed using the TRDI's WinRiver II software and output as ASCII text files after preprocessing. Preprocessing included review of each transect and the deletion of any ensembles that were adversely affected by aquatic growth along the reservoir banks. At all five VMT sites, the data were referenced to the depth profile measured during bank-to-bank transect. For further processing, the ASCII output files were loaded into the Velocity Mapping Toolbox (Parsons and others, 2013), which is a Matlab-based software package for visualizing ADCP data in rivers and other water bodies such as reservoirs. The VMT software facilitates the processing and visualization of a large number of ADCP datasets. In addition, the VMT software allows the user to generate primary and secondary flow maps from one transect, or if multiple transects are made, a mean velocity and flow for a transect. The VMT software allows the user to aggregate and average the horizontal and vertical velocity-vector ensembles and to output the data in several files formats. Similar to the vertical velocity cell data that were discussed in a previous section, the VMT software also plots cross-sectional views (fig. 20*A*) or plan views (fig. 20*B*).

The plan views of the depth average velocity transects generated by the VMT software can be integrated with aerial imagery from Google Earth to provide a geographic context for the streamflow measurements. Figure 21 shows velocity transects for sites VMT4, VMT3, and VMT2 (fig. 16) at approximately high ebb tide on August 5, 2014. At site VMT4, north of the SCE&G intake, the velocities range from 0.8 to 1.2 ft/s whereas at VMT2, just north of the CWS intake, the velocities are much lower and range between 0 and 0.2 ft/s. The plan views for each measurement at the five velocity mapping transects on August 5, 2014, November 5, 2014, March 23, 2015, and April 26, 2015 are shown in appendix 2.

Characterization of the Reservoir Hydrology and Circulation

The water level, water velocity, and flow direction in the Bushy Park Reservoir are constantly changing due to the tidal influence and flows from the Cooper River, industrial withdrawals, and meteorological conditions. The tidal effects on the reservoir are caused by orbital mechanics and are highly predictable. Historically, the Back River was a tidal slough (as was the Cooper River) with very little net flow. The Back River was dominated by the tidal exchange at the confluence with the Cooper River. After the construction of the Back River Dam and Durham Canal in the 1950s, the tidal exchange shifted to the confluence of the upper reaches of the Back River and Durham Canal, and net flow from the reservoir was through Durham Canal to the Cooper River. The Back River changed from a tidal brackish marsh to a fresh-water tidal marsh. In 1973, SCE&G constructed the Williams Station, a coal-fired powerplant that withdraws water from the reservoir for cooling and returns the water to the Cooper River. The flow patterns of the Bushy Park Reservoir are now (2016) dominated by the large withdrawal by SCE&G for cooling water for the Williams Station. The volume of the withdrawal, more than 500 Mgal/d, is the dominant factor in the water budget and circulation pattern of the reservoir. When the Williams Station is operating and water is being withdrawn, the net outflow from the reservoir is through the Williams Station and not through Durham Canal. Figure 22 shows daily precipitation, the tidally filtered daily flow for Durham Canal, the 7-day average flow in Durham Canal, and the withdrawal rates for the Williams Station (in cubic feet per second) for the period September 2013 to December 2015. (For data retrieved from the USGS website, positive flow in Durham Canal is to the Cooper River and negative flow is to the reservoir. Note that the sign for the Durham Canal flow for figure 22 has been reversed for plotting purposes.) The flows in Durham Canal and the withdrawals are of similar magnitudes. When the Williams Station has a planned or unplanned outage, the net flows in Durham Canal quickly change from into the reservoir to a small net flow into the Cooper River. Periods of extended rainfall can cause the net flow in Durham Canal to either decrease into the reservoir or to reverse to the Cooper River as in the case of the large rainfall in early October 2015.

The effect of the Williams Station withdrawal on the velocity in the lower part of the reservoir is not nearly as pronounced as in Durham Canal. Below the confluence with the Back River, the geometry of the reservoir expands, and as the cross-sectional area increases, the flow velocity decreases (fig. 21). The VMT transects for maximum ebb tide, slack tide, and maximum flood tide flows for site VMT3 are shown in figure 23. On August 5, 2014, the Williams Station was pumping 376 Mgal/d (fig. 23*A*, transects on the left), and on November 5, 2014, the Williams Station was pumping 16 Mgal/d (fig. 23*B*, transects on the right). The velocity distributions during ebb tide flows (fig. 23*B*) are more evenly distributed when the Williams Station is withdrawing in August than during the outage in November. The opposite occurs during the flood tide flow, with small velocity vector toward the east bank when the Williams Station is with-drawing in August and a more even distribution of velocity vectors during the outage.

Rose diagrams of the velocity profiles for sites VVP3 and VVP3-East for days in 2014 and 2015 when the Williams Station was withdrawing and during an outage show an increase in the magnitude of the vectors in the direction of the plant and a decrease in the velocity in the direction of Back River Dam (figs. 24–26). The days that the velocity meter at the site was deployed and the outage dates for the Williams Station are listed in table 7. In 2014 (fig. 24) when the Williams Station was withdrawing water, there were decreases in the number and magnitude of the velocity vectors in the north and south direction and an increase in the number and magnitude of velocity vectors in the north-northeast (NNE) direction. In 2015 there was a similar pattern at the VVP3 site (fig. 25) and at the VVP3-East site (fig. 26), but the increase in the NNE direction was not as large as in 2014. Velocity rose diagrams for the velocity profile sites that were deployed during outages at the Williams Station are shown in appendix 3.

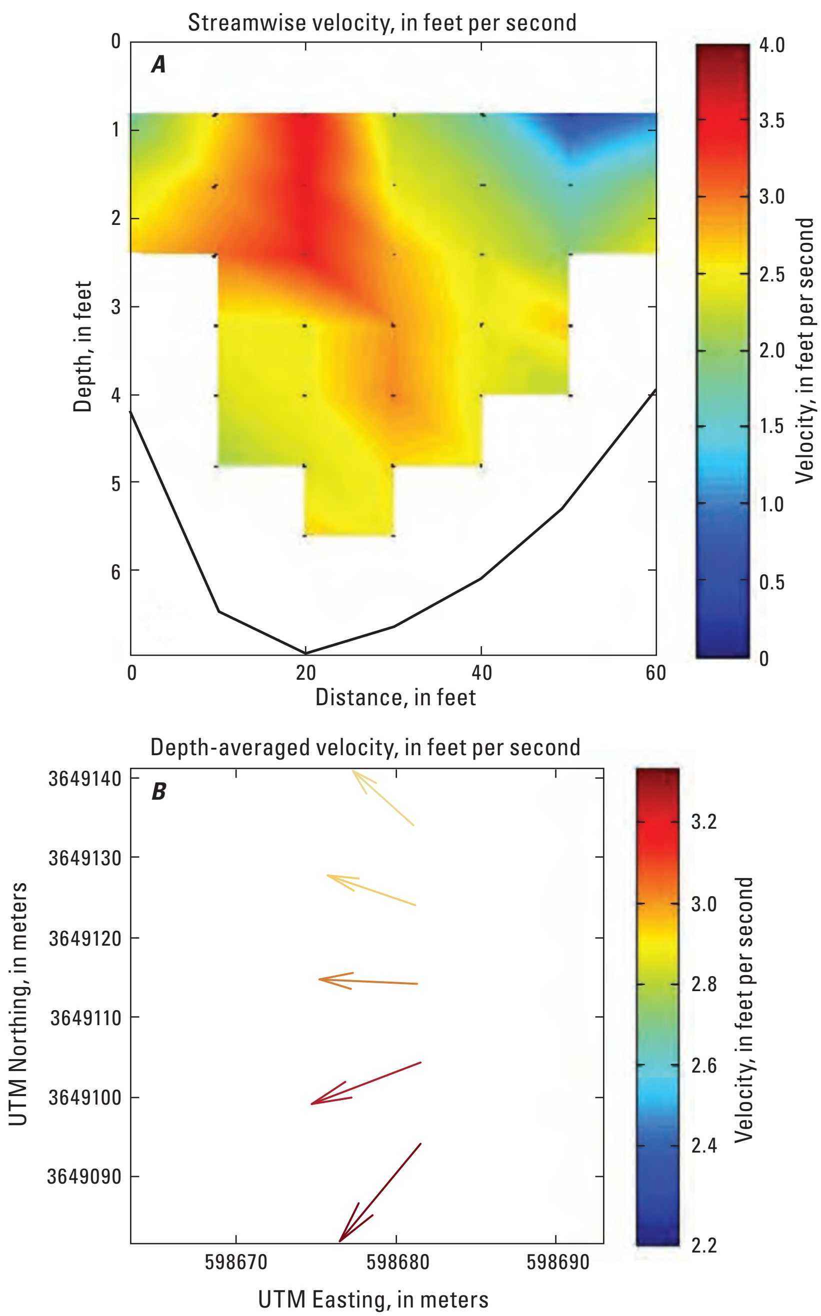
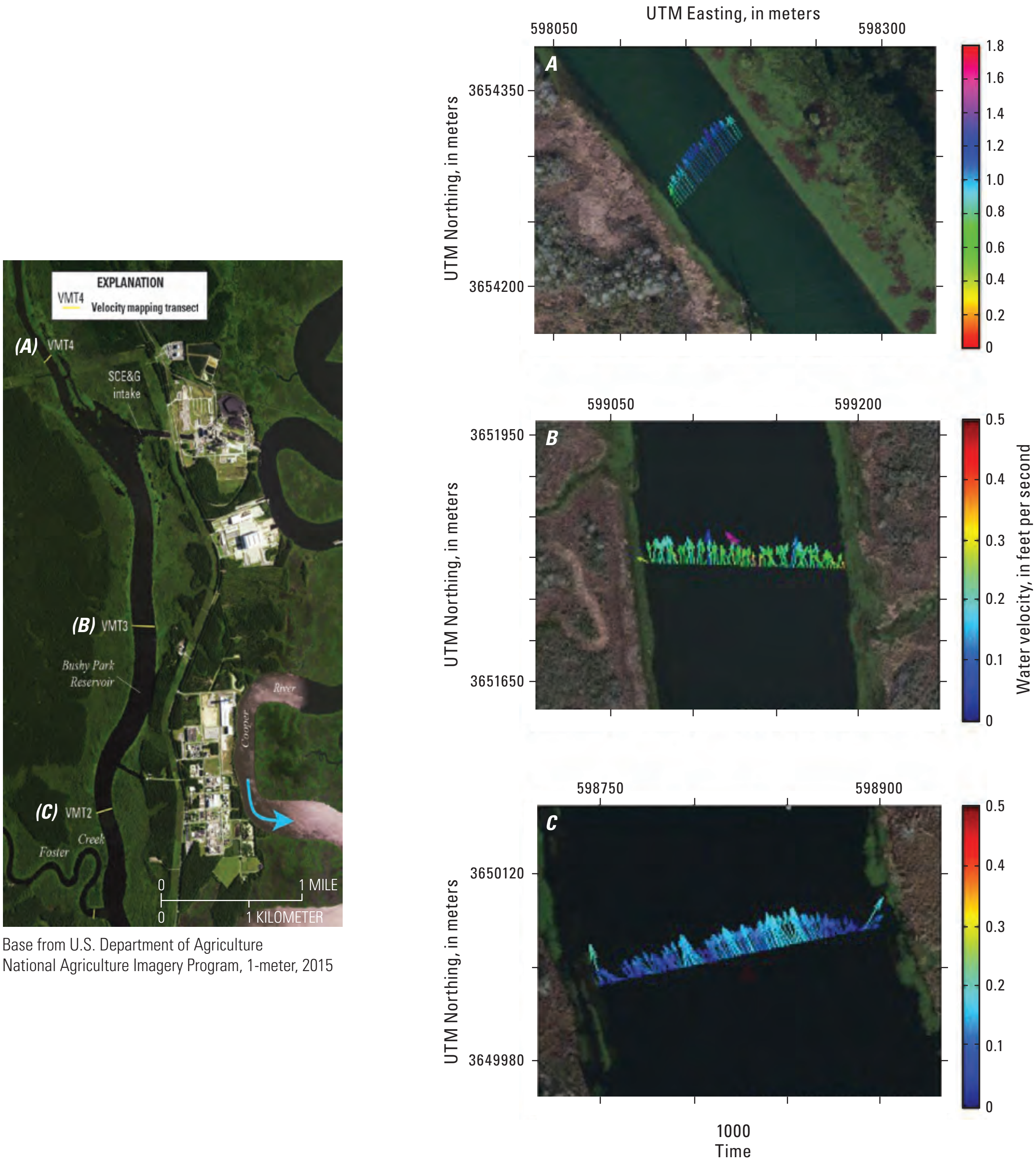


Figure 20. Examples of the *A*, cross-sectional view and *B*, plan view output from the Velocity Mapping Toolbox (modified from Parsons and others, 2013).



Base from U.S. Department of Agriculture
National Agriculture Imagery Program, 1-meter, 2015

Figure 21. Example of velocity mapping transects for sites *A,* VMT4, *B*, VMT3, and *C*, VMT2 for August 5, 2014, at 10:00 a.m.

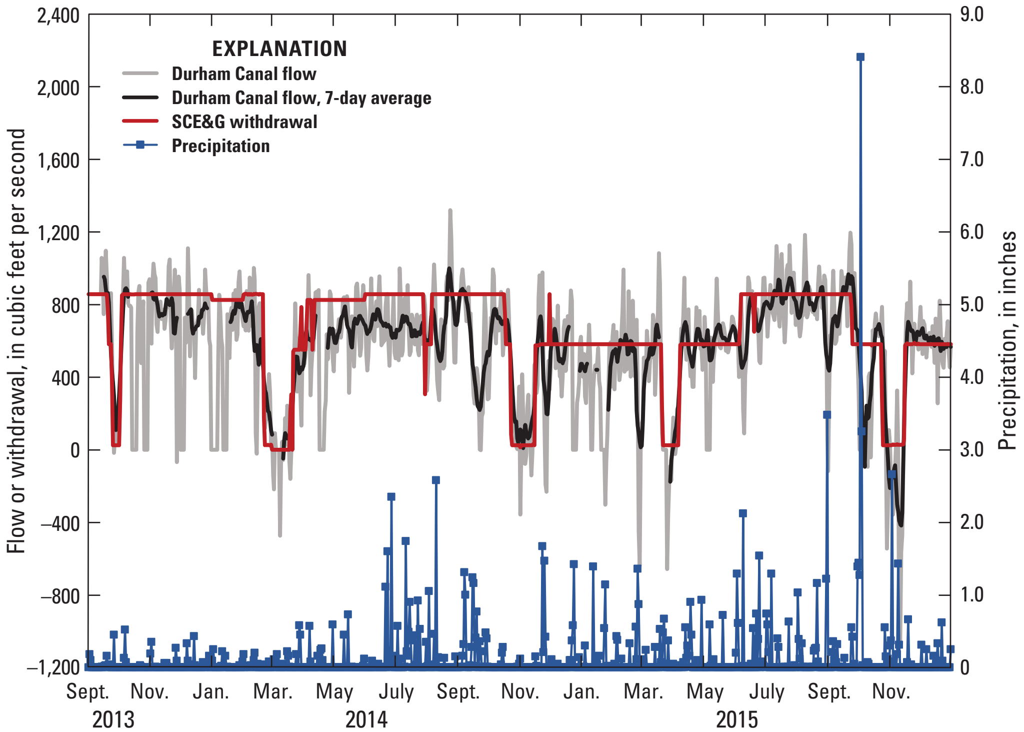


Figure 22. Precipitation at the Charleston Water Intake, daily flows and 7-day average flows in Durham Canal, and withdrawal rates from Bushy Park Reservoir by the Williams Station for the period September 1, 2013, to December 31, 2015. The sign of the Durham Canal flow was reversed (multiplied by negative one) for plotting purposes.

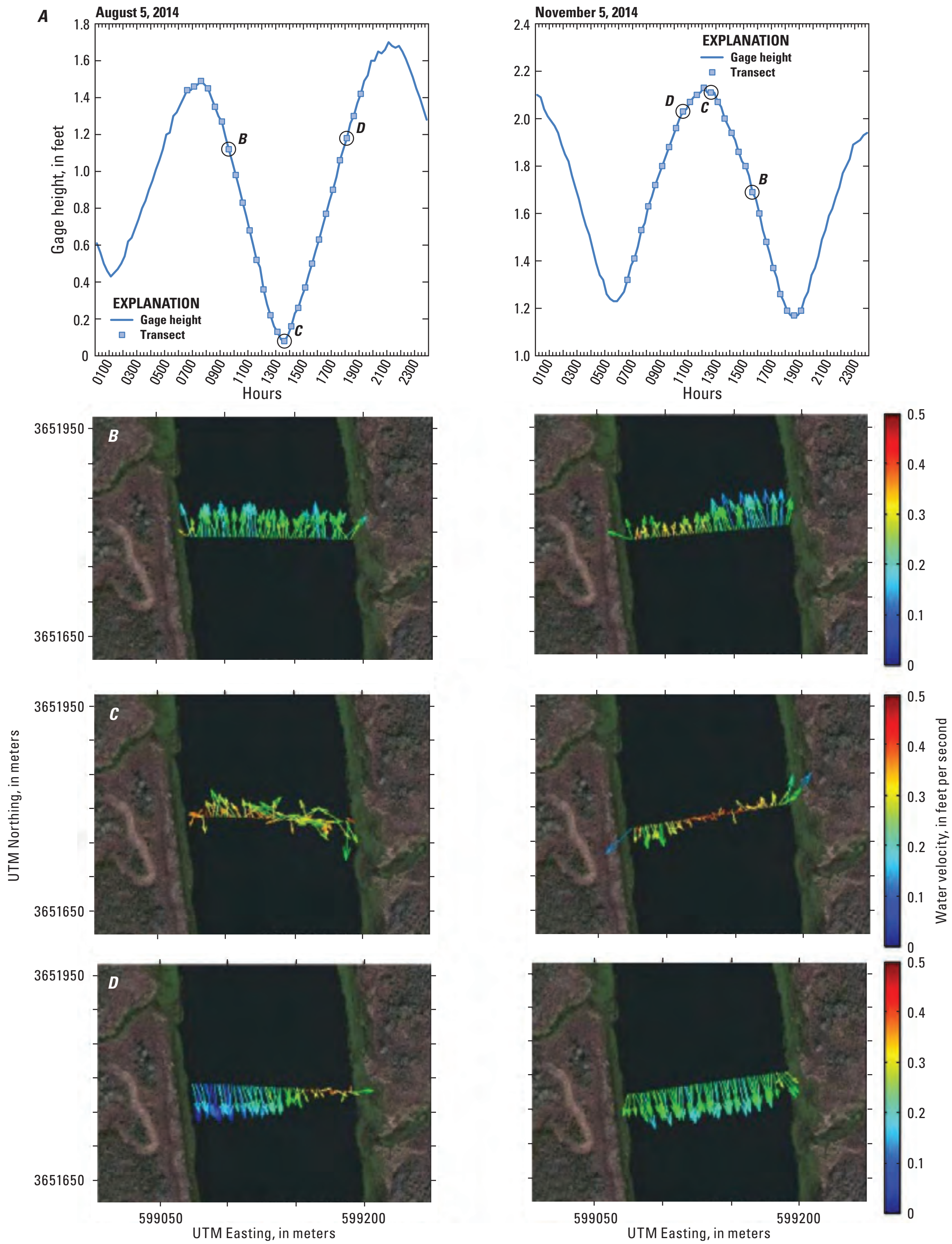


Figure 23. *A*, Stage hydrographs at the CWS intake for August 5 and November 5, 2014, and plan view of velocity mapping transects for site VMT3 for *B*, near maximum ebb tide, *C*, near slack tide, and *D*, near maximum flood tide for August 5, 2014, and November 5, 2014.

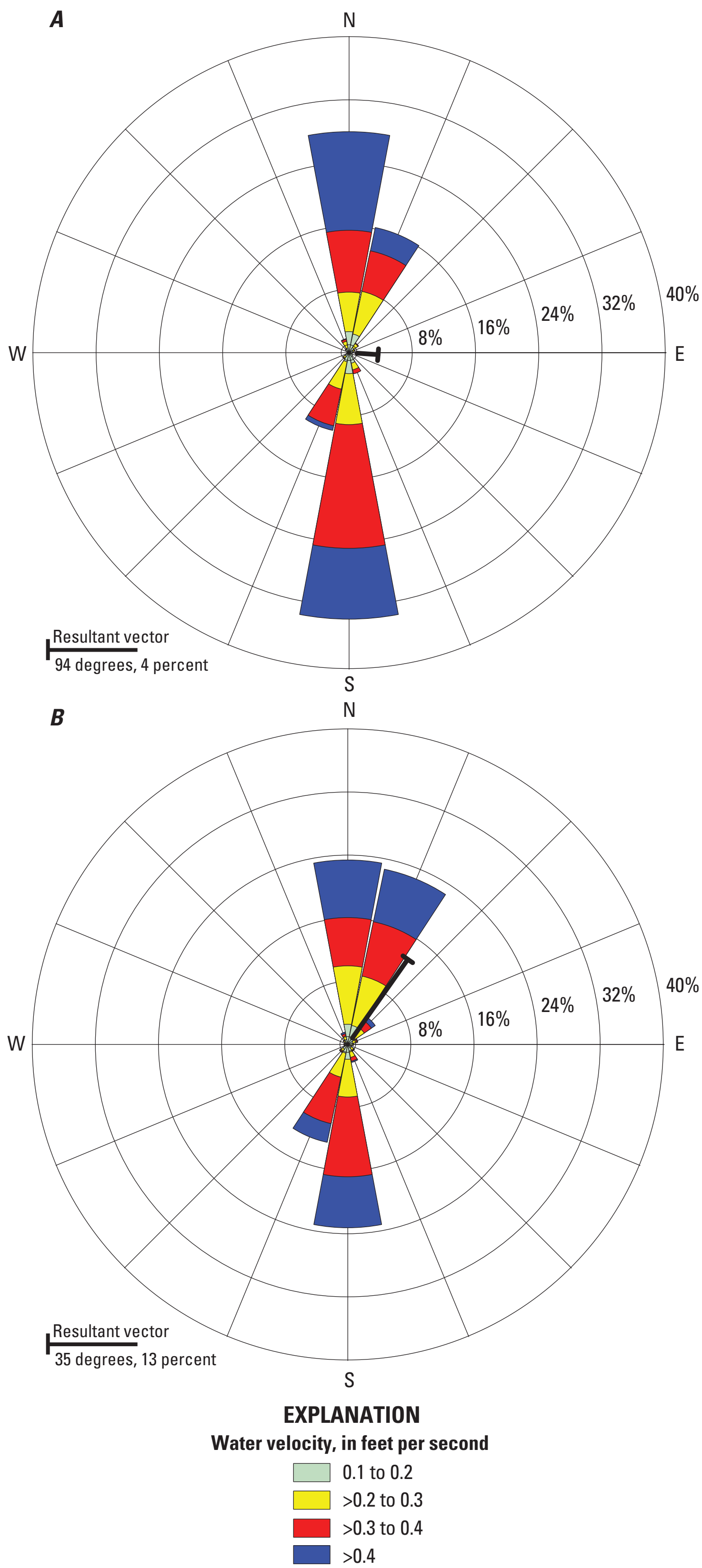


Figure 24. Rose diagrams of velocity vectors for site VVP3 for the days in 2014 that the Williams Station was *A*, not withdrawing water and *B*, withdrawing water. Vectors are for the direction that water is moving toward.

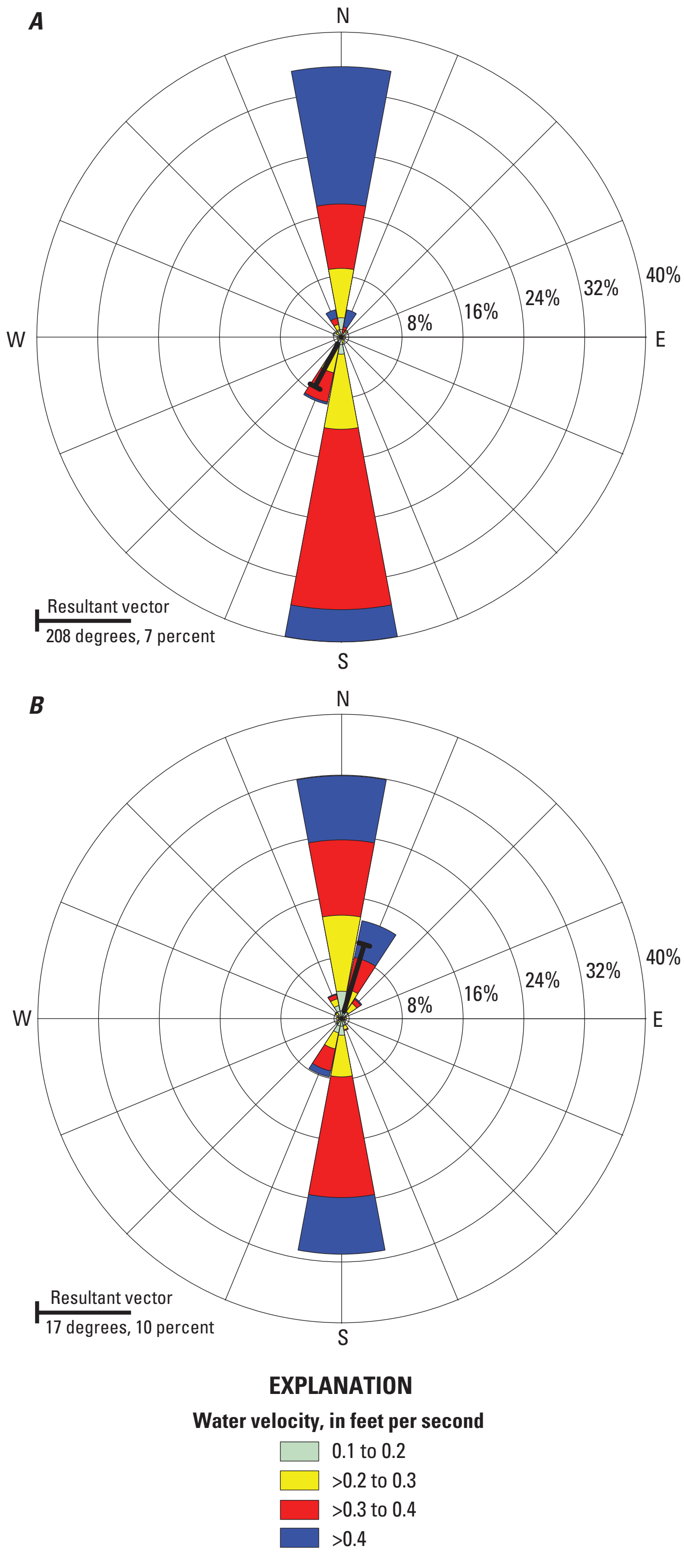


Figure 25. Rose diagrams of velocity vectors for site VVP3 for the days in 2015 that the Williams Station was *A*, not withdrawing water and *B*, withdrawing water. Vectors are for the direction that water is moving toward.

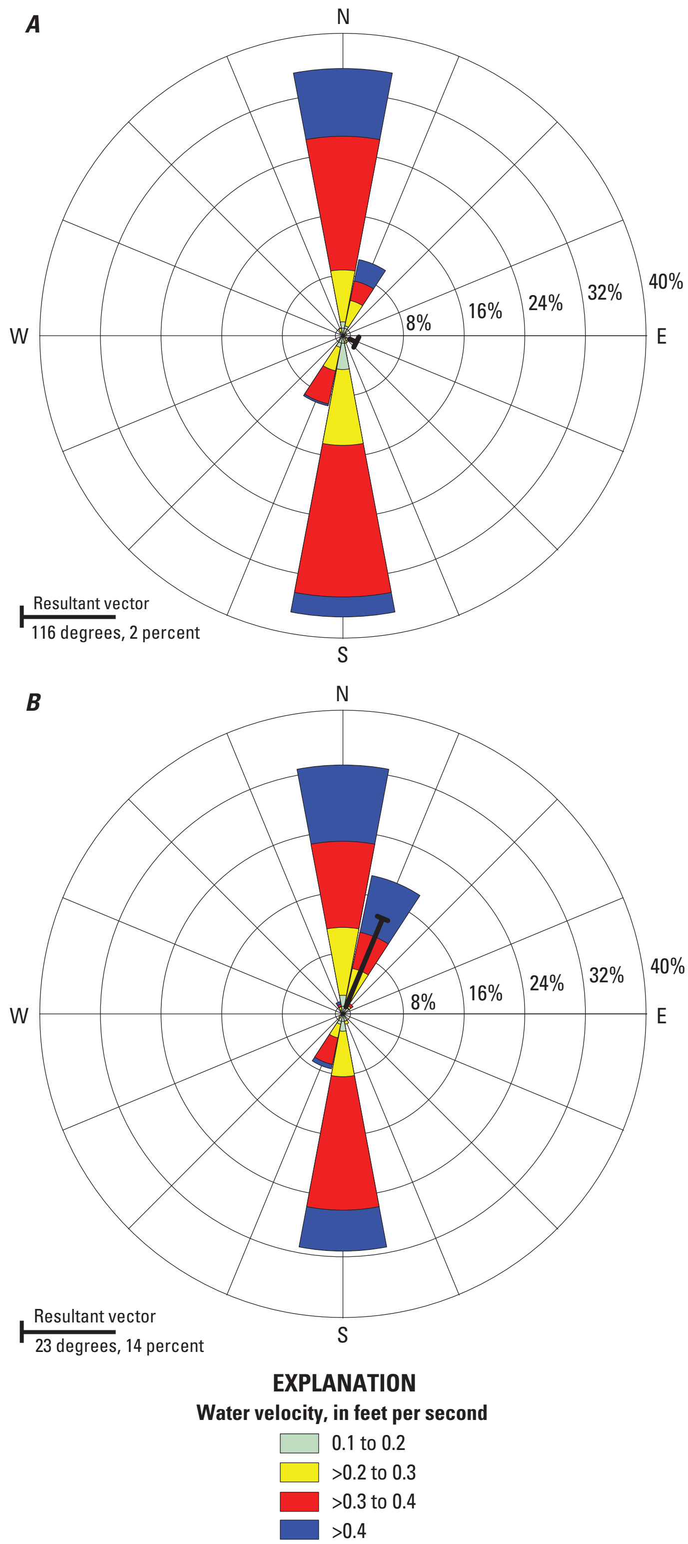


Figure 26. Rose diagrams of velocity vectors for site VVP3-East for the days in 2015 that the Williams Station was *A*, not withdrawing water and *B*, withdrawing water. Vectors are for the direction that water is moving toward.

Summary

The Bushy Park Reservoir is the principal water supply for the 400,000 people of the city of Charleston, South Carolina, and the surrounding areas and industries in the Bushy Park Industrial Complex. The U.S. Geological Survey (USGS), in cooperation with the Charleston Water System (CWS), evaluated the circulation of Bushy Park Reservoir and its effects on water quality. Hydrologic and water-velocity data were collected to characterize the hydrology, flow, and water circulation of the Bushy Park Reservoir.

The Bushy Park Industrial Complex was established in 1954 between the east bank of the Back River and the west bank of the Cooper River. A freshwater reservoir was constructed by damming the Back River at the lower end near the confluence with the Cooper River to provide water to the industrial users. Durham Canal was constructed as a conduit between the upper end of the Back River and the freshwater part of the West Branch of the Cooper River. The Williams Station, a coal-fired powerplant, accounts for 88 percent of the industrial water use and withdraws approximately 550 million gallons per day. Bushy Park Reservoir is a relatively shallow impoundment in a semi-tropical climate. Although the reservoir provides an adequate supply of freshwater, there are water-quality concerns related to taste and odor. In general, taste-and-odor episodes are common in reservoirs used for drinking water throughout the United States.

The approach to the data collection for the study was to collect temporal and spatial data to analyze the convergence of environmental factors that occur among the physical, chemical, biological, and circulation processes within Bushy Park Reservoir to cause the production and release of these taste-an-odor cyanobacteria by-products (trans-1, 10-dimethyl-trans-9-decalol [geosmin], and 2-methylisoborneol [MIB]). To account for the water budget of the reservoirs, the existing USGS real-time network was augmented with water-level and meteorological gages at the CWS intake; continuous flow gages on Durham Canal, Back River, and Foster Creek; and a flow gage in the water-supply tunnel to the Hanahan Water Treatment Plant from the reservoir. To understand the circulation in the reservoir, three to four up-looking acoustic velocity meters were deployed at various locations for extended periods (months) to collect vertical profiles of water velocities. To document the flow distribution across transects of the reservoir, tidal cycle (13-hour) streamflow measurements were made at five locations.

Historic monthly wind direction and precipitation data for the Charleston International Airport station (1961–90) were compared to the monthly wind and precipitation data for Bushy Park Reservoir (2014 and 2015). Generally, the monthly winds at Bushy Park follow the north-north alignment of the reservoir, and there is a westerly component with the winds at the airport that often is not seen at the reservoir. Monthly precipitation at Bushy Park Reservoir was less than at the airport for 22 of the 28 months of data collection.

Photosynthetically active radiation (PAR) defines the amount of light that is available for photosynthesis in plants such as blue-green algae. Although there is little change in the day-to-day values, there are differences during the day due to the degree of cloud cover and a clear seasonal component to PAR because of the changing times of sunrise and sunset and solar intensities. The highest monthly PAR values occurred in May in 2014 and June in 2015. Water temperatures were monitored at the top and bottom of the CWS intake structure. The water temperature stratified with differences in the warmer water at the surface of more than about 5.5 degrees Fahrenheit.

The tidal streamflows at Back River, Foster Creek, and Durham Canal were computed by using index-velocity methods. The streamflow response to rainfall is clearly seen in Foster Creek and Back River hydrographs. The tidal signal remains in the Back River hydrograph after rainfall, but the tidal signal is greatly dampened in the Foster Creek hydrograph after rainfall. The strong semi-diurnal tidal signal is clearly seen in the Durham Canal hydrograph with maximum positive and negative flows of greater than +/– 4,000 cubic feet per second. The net flow in Durham Canal to the reservoir is comparable to the Williams Station withdrawal rates (550 million gallons per day). When the plant is not withdrawing, the net flow in Durham Canal quickly goes to zero or reverses with a net flow away from the reservoir and back to the Cooper River.

Bottom-mounted acoustic Doppler current profilers were deployed at six locations to measure continuous velocity profiles within the reservoir. Rose diagrams of the velocity profiles for sites VVP3 and VVP3-East for days when the Williams Station was withdrawing water and during an outage show an increase in the magnitude of the vectors in the direction of the powerplant and a decrease in the velocity in the direction of Back River Dam. A series of simultaneous tidal cycle flow measurements were made at five transects to understand the velocity magnitude and direction flow patterns with respect to the major power generation withdrawal. The velocity distribution during ebb tide flows is more evenly distributed when the Williams Station is withdrawing water than during the outage. The opposite occurs during the flood tide flow with small velocity vector toward the east bank when the Williams Station is withdrawing water and a more even distribution of velocity vectors during the outage.

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Appendixes

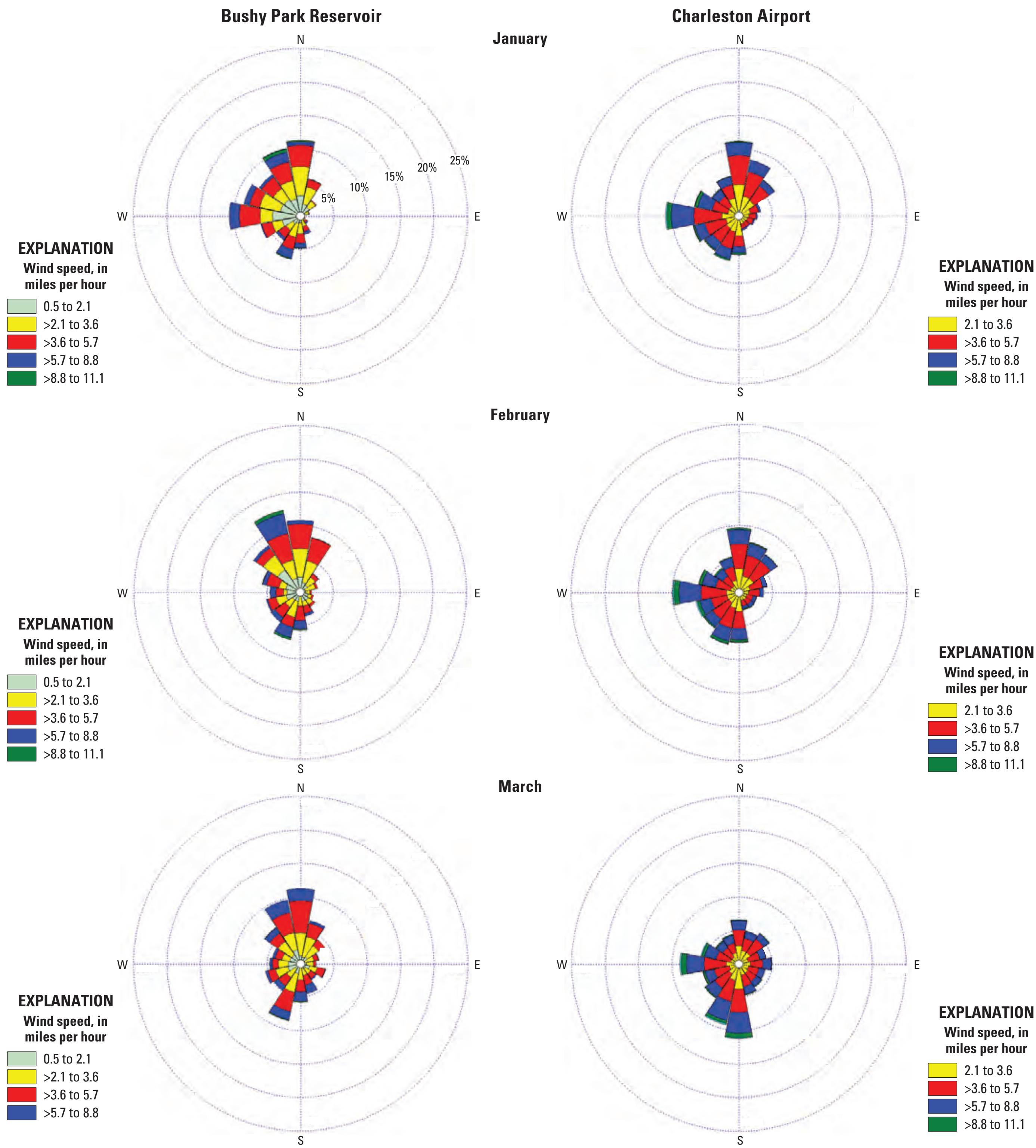


Figure 1–1. Wind rose diagrams for Bushy Park Reservoir and Charleston International Airport for *A*, January, *B*, February, and *C*, March. Data for Bushy Park Reservoir were based on the period January 1, 2014, to December 31, 2015. Data for the Charleston International Airport were based on January 1, 1961, to December 31, 1990.

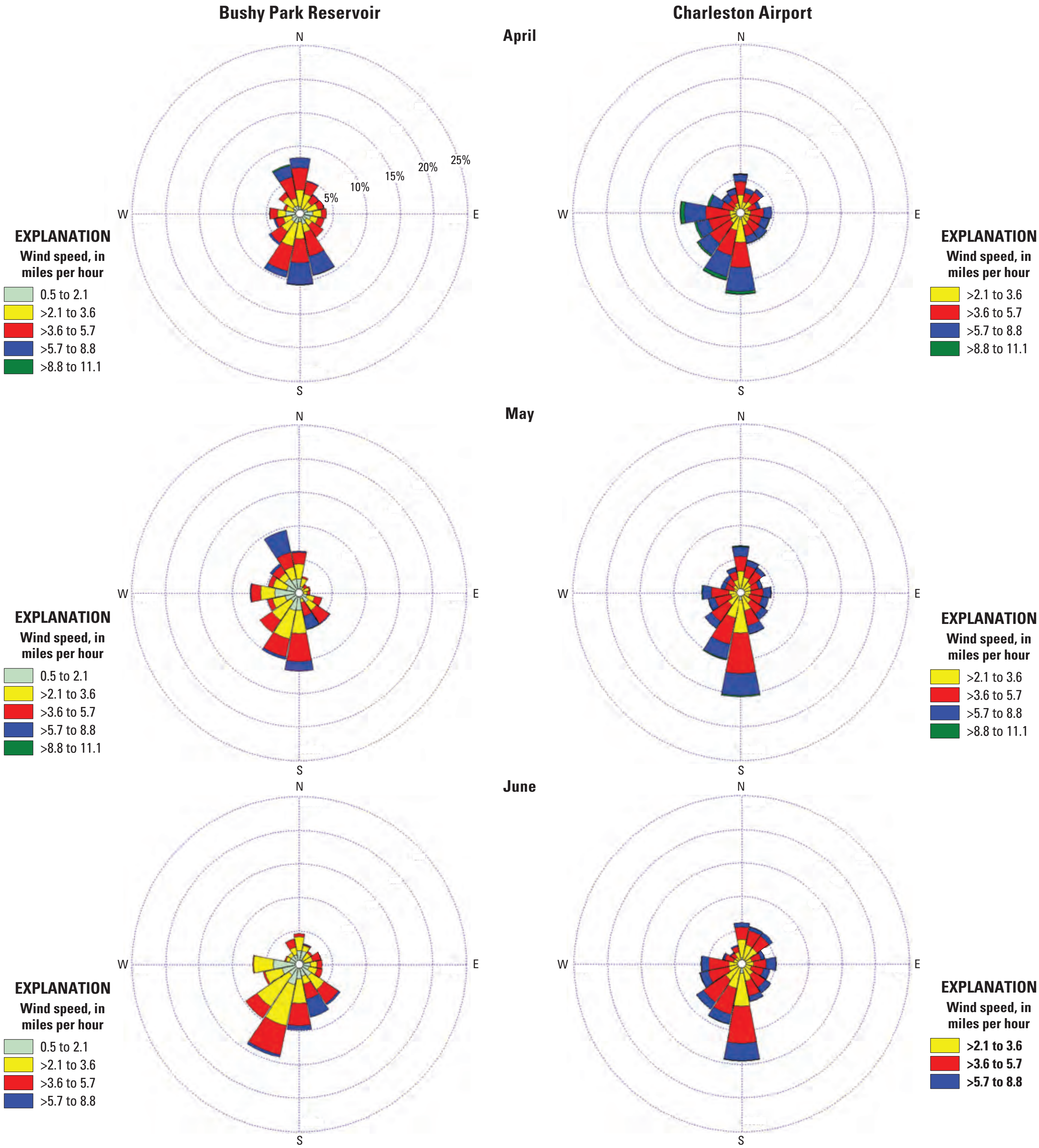


Figure 1–2. Wind rose diagrams for Bushy Park Reservoir and Charleston International Airport for *A*, April, *B*, May, and *C*, June. Data for Bushy Park Reservoir were based on the period January 1, 2014, to December 31, 2015. Data for the Charleston International Airport were based on January 1, 1961, to December 31, 1990.

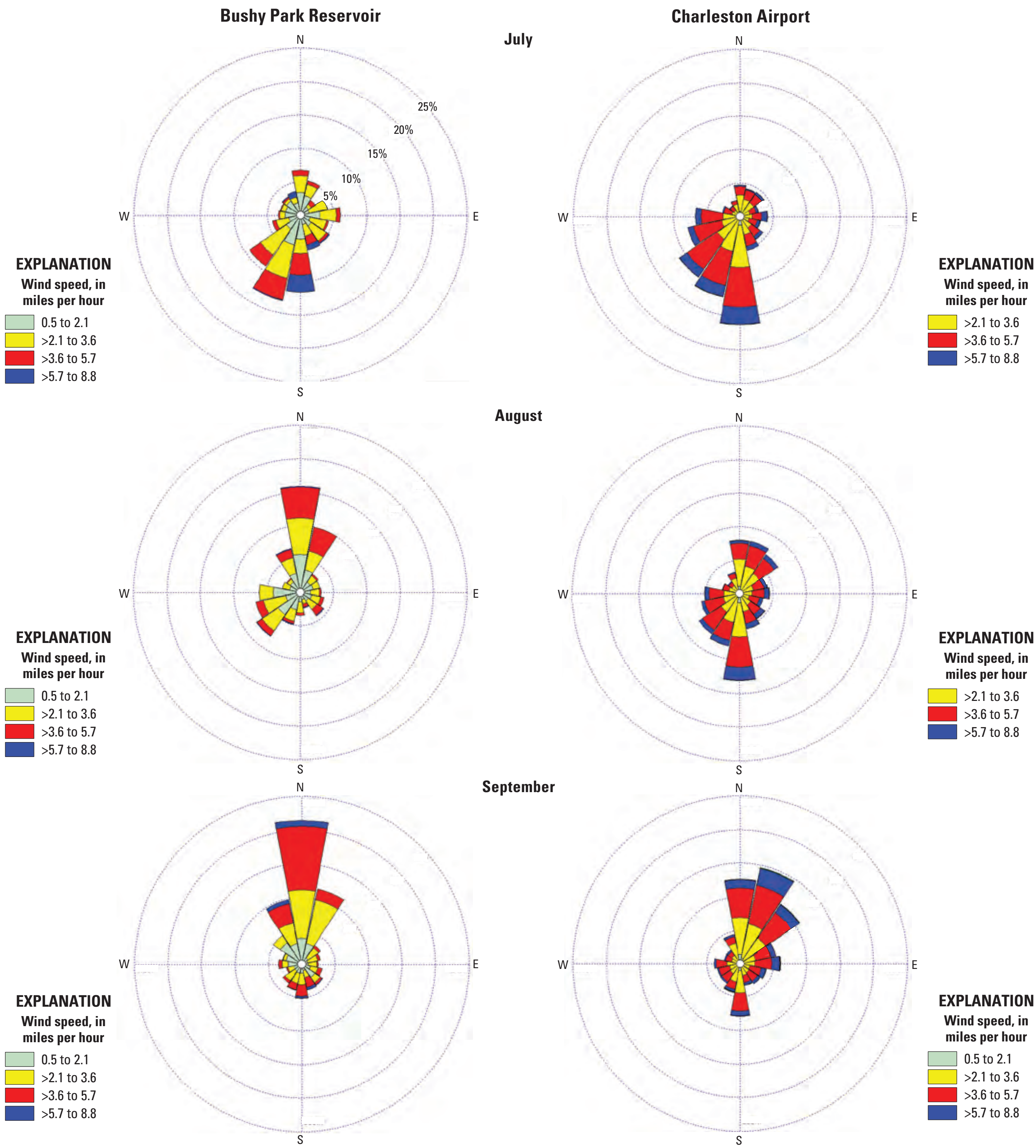


Figure 1–3. Wind rose diagrams for Bushy Park Reservoir and Charleston International Airport for *A*, July, *B*, August, and *C*, September. Data for Bushy Park Reservoir were based on the period January 1, 2014, to December 31, 2015. Data for the Charleston International Airport were based on January 1, 1961, to December 31, 1990.

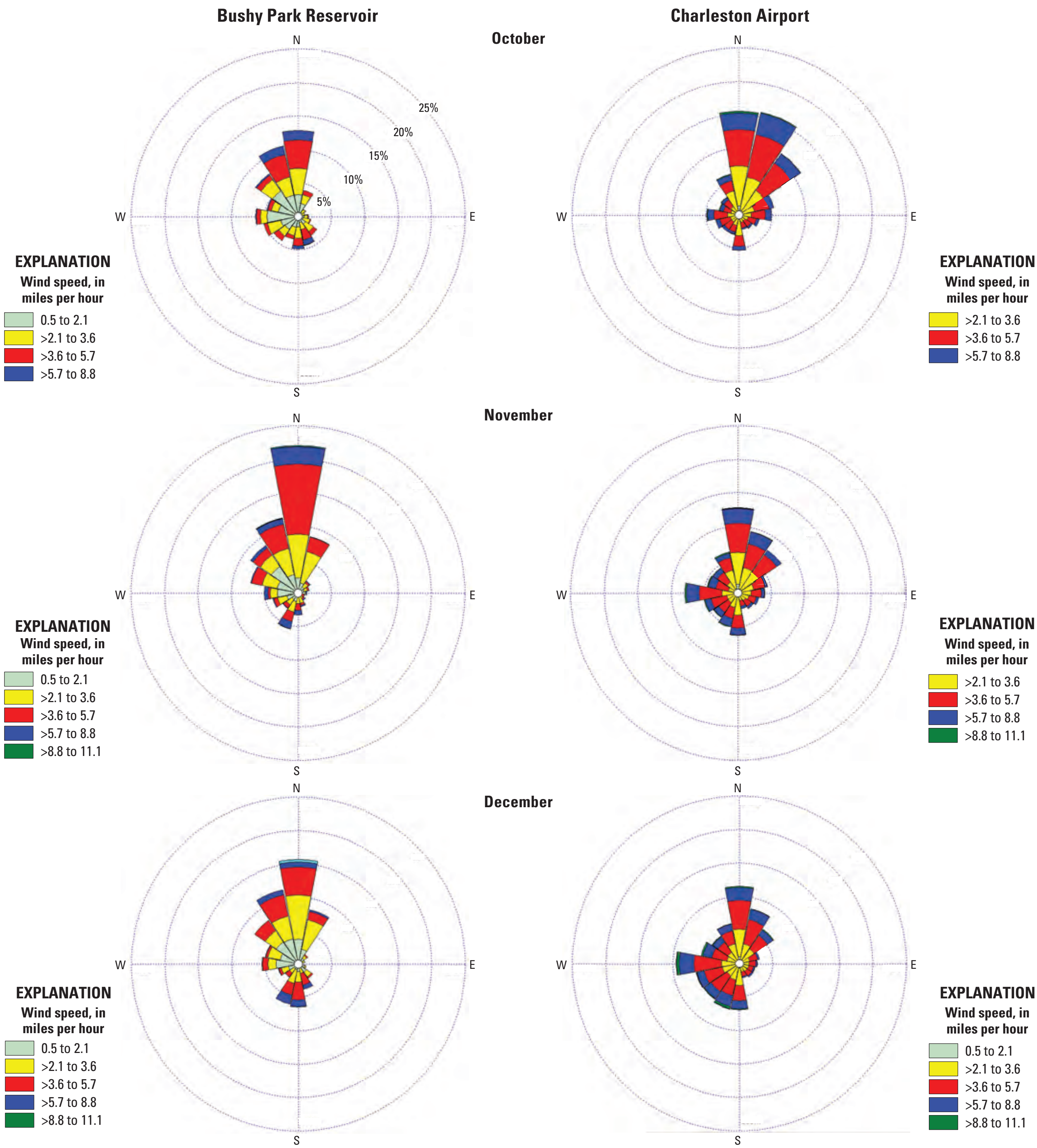


Figure 1–4. Wind rose diagrams for Bushy Park Reservoir and Charleston International Airport for *A*, October, *B*, November, and *C*, December. Data for Bushy Park Reservoir were based on the period January 1, 2014, to December 31, 2015. Data for the Charleston International Airport were based on January 1, 1961, to December 31, 1990.

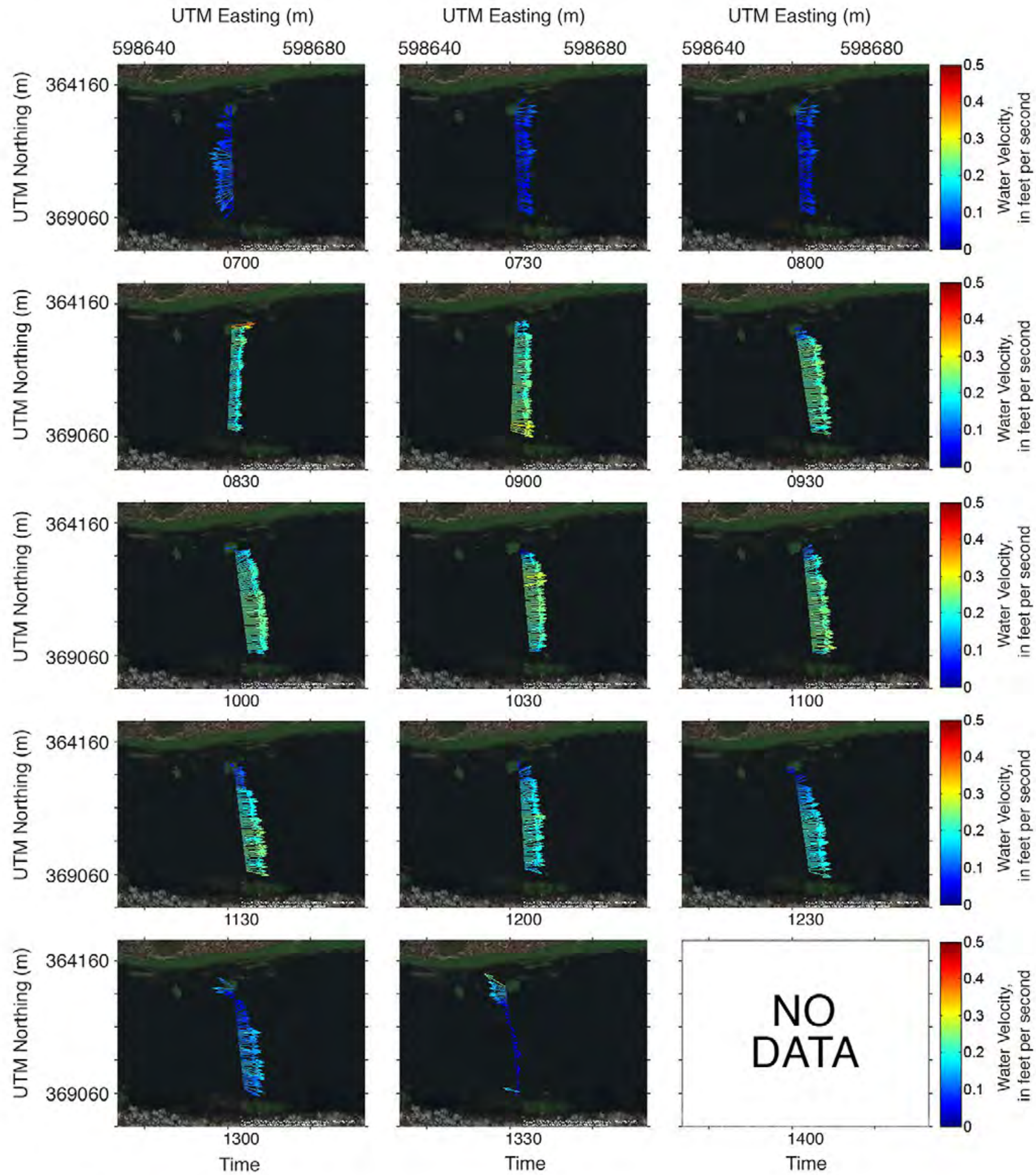


Figure 2–1. Plan views of average velocity vectors for site VMT1 for August 5, 2014.

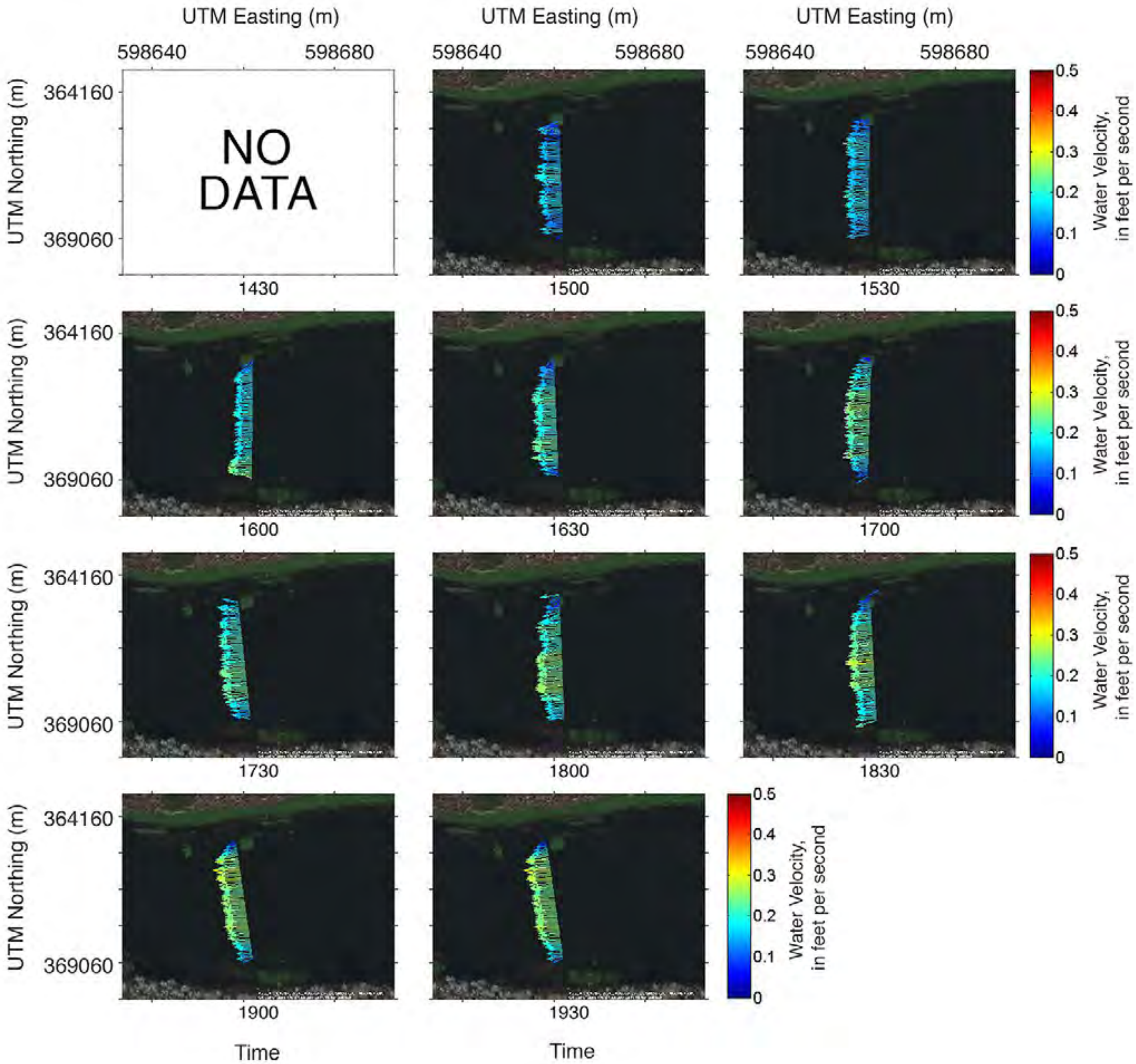


Figure 2–1. Plan views of average velocity vectors for site VMT1 for August 5, 2014.—Continued

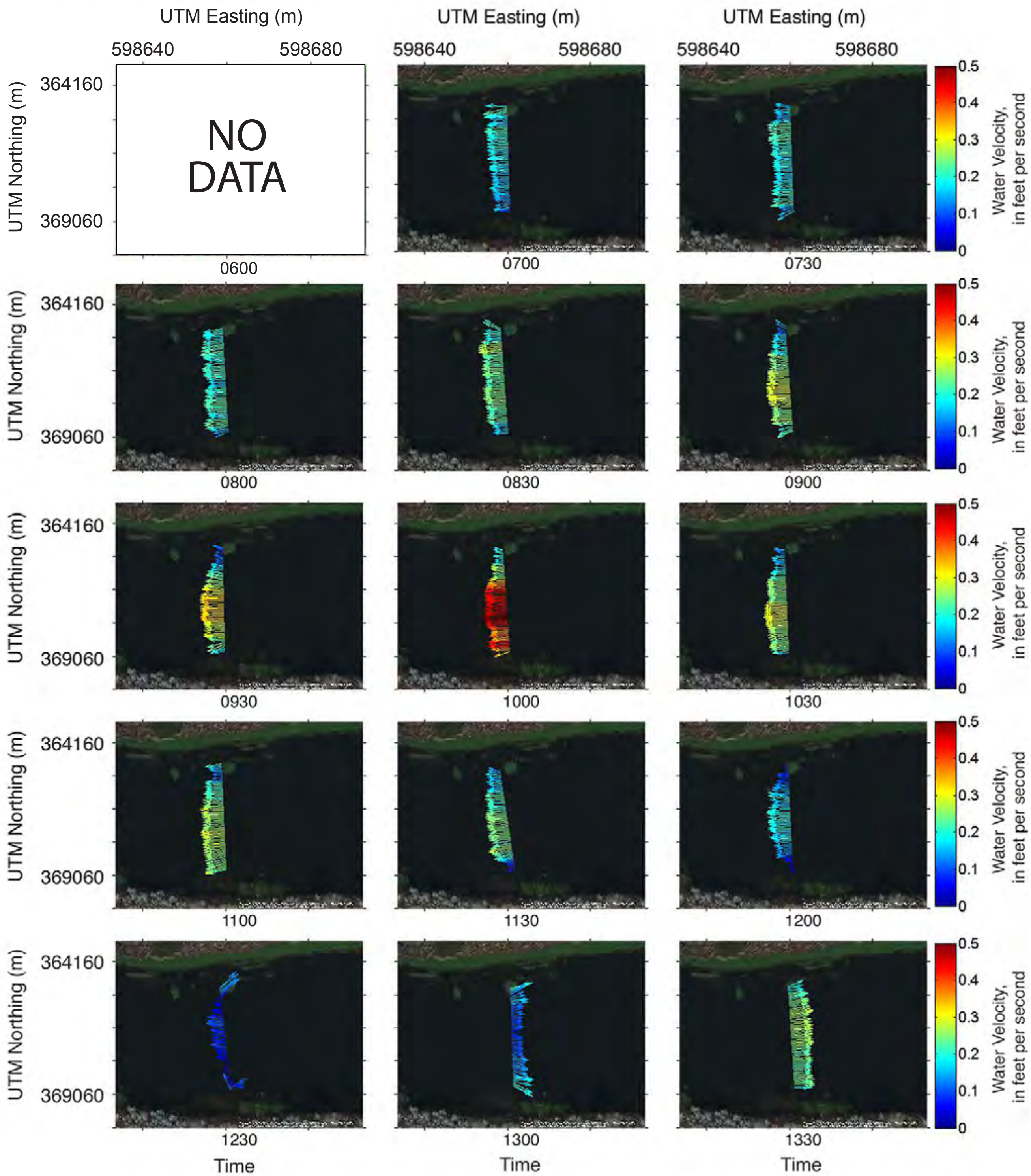


Figure 2–2. Plan views of average velocity vectors for site VMT1 for November 5, 2014.

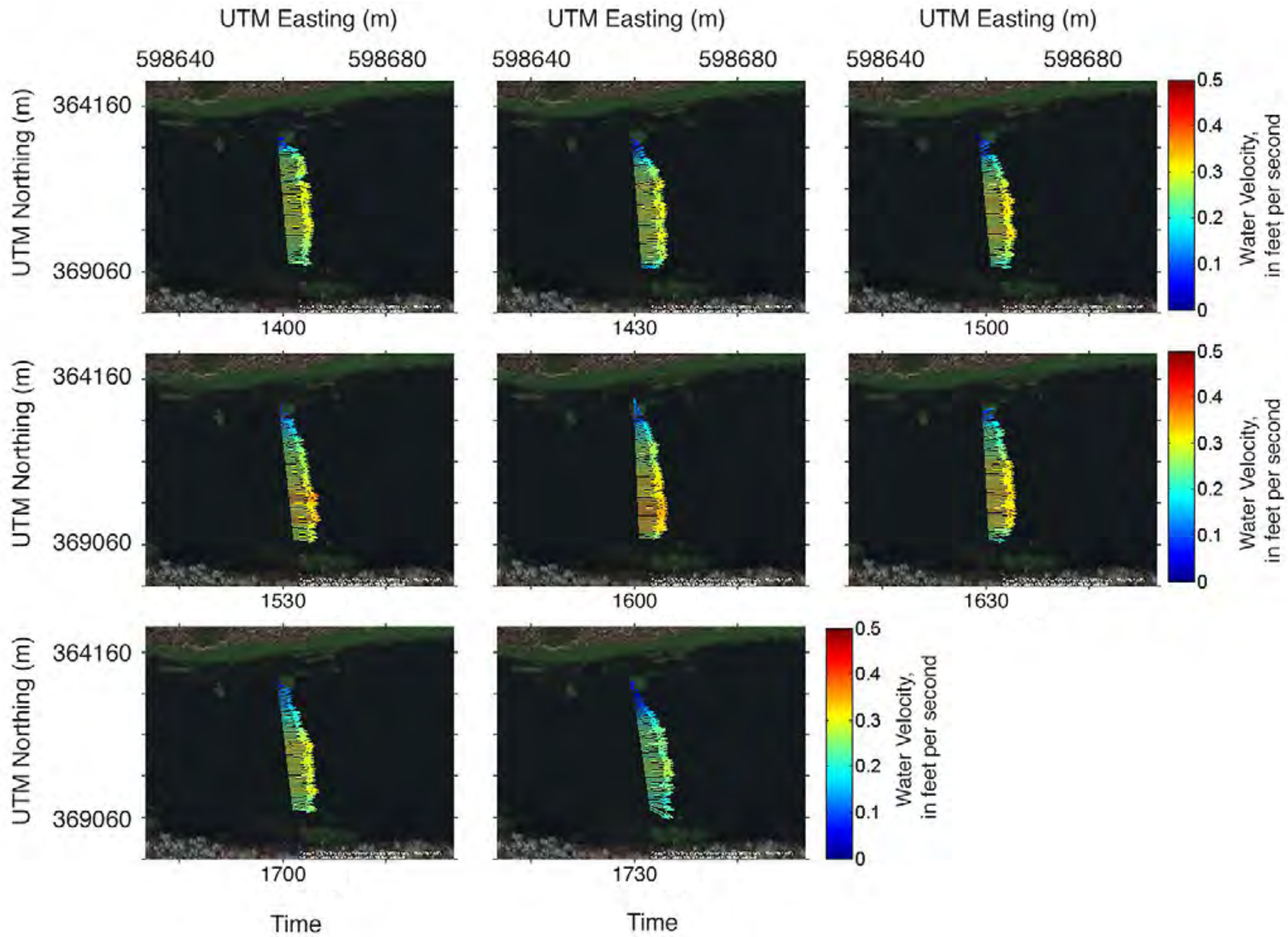


Figure 2–2. Plan views of average velocity vectors for site VMT1 for November 5, 2014.—Continued

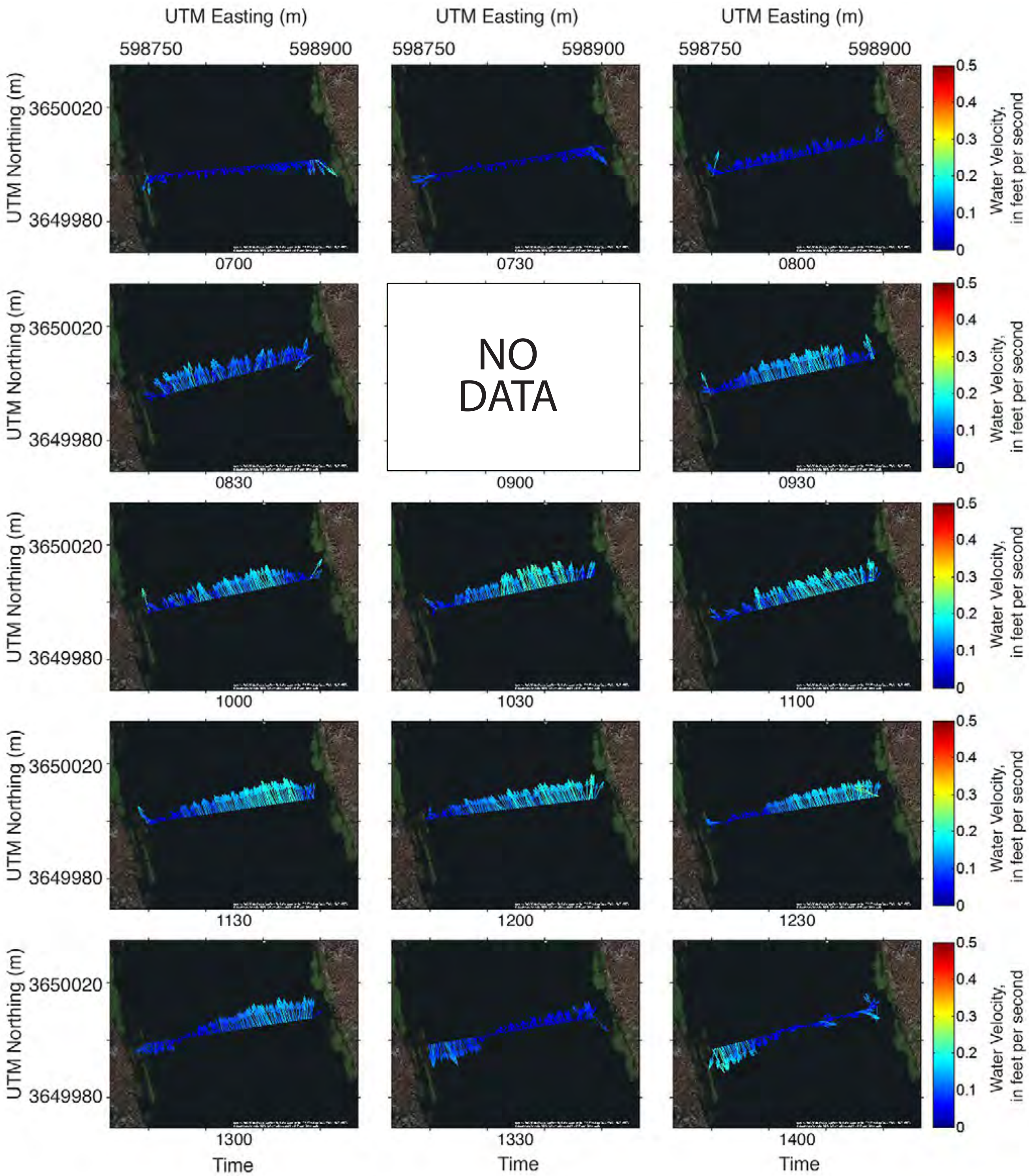


Figure 2–3. Plan views of average velocity vectors for site VMT2 for August 5, 2014.

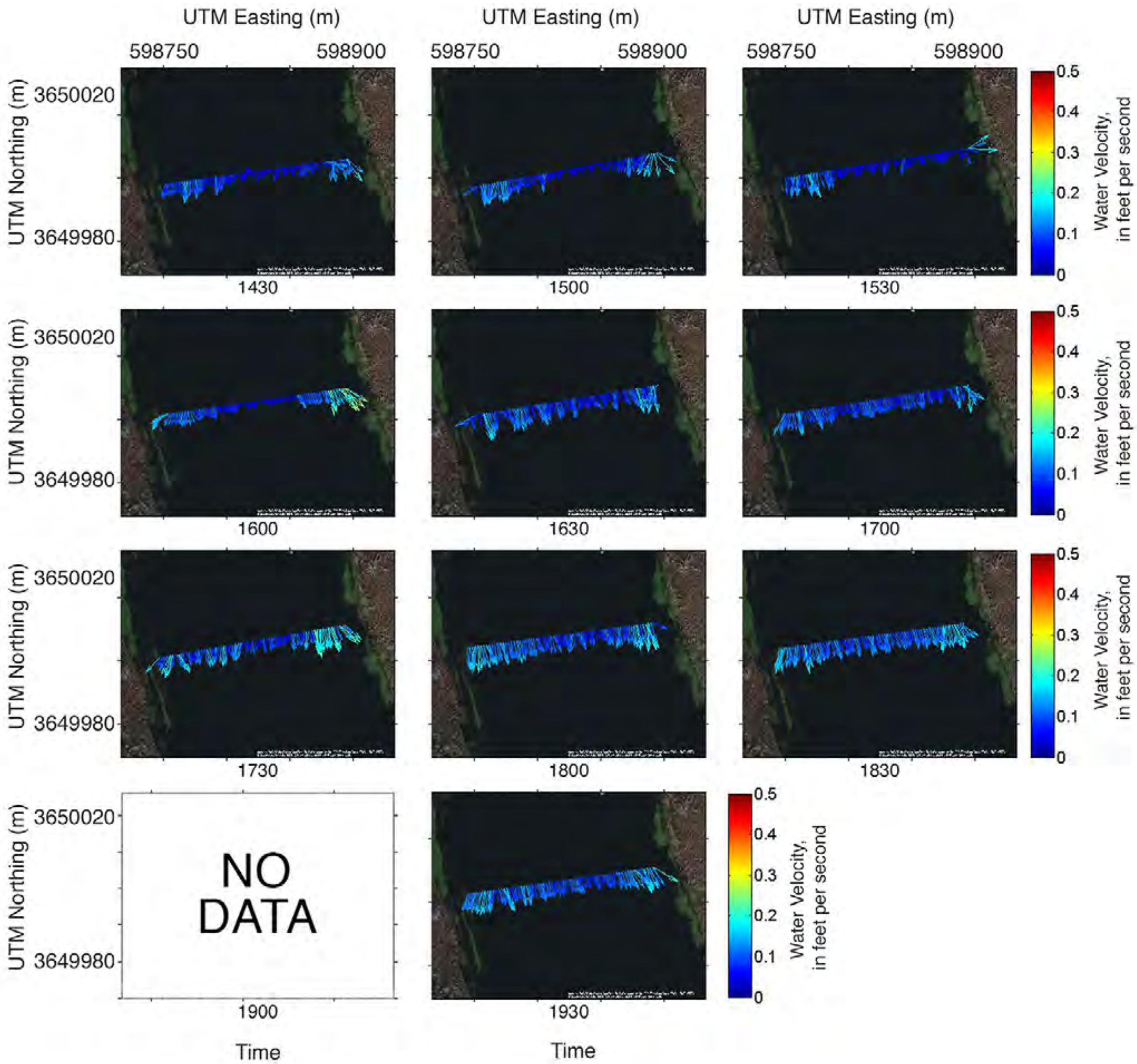


Figure 2–3. Plan views of average velocity vectors for site VMT2 for August 5, 2014.—Continued

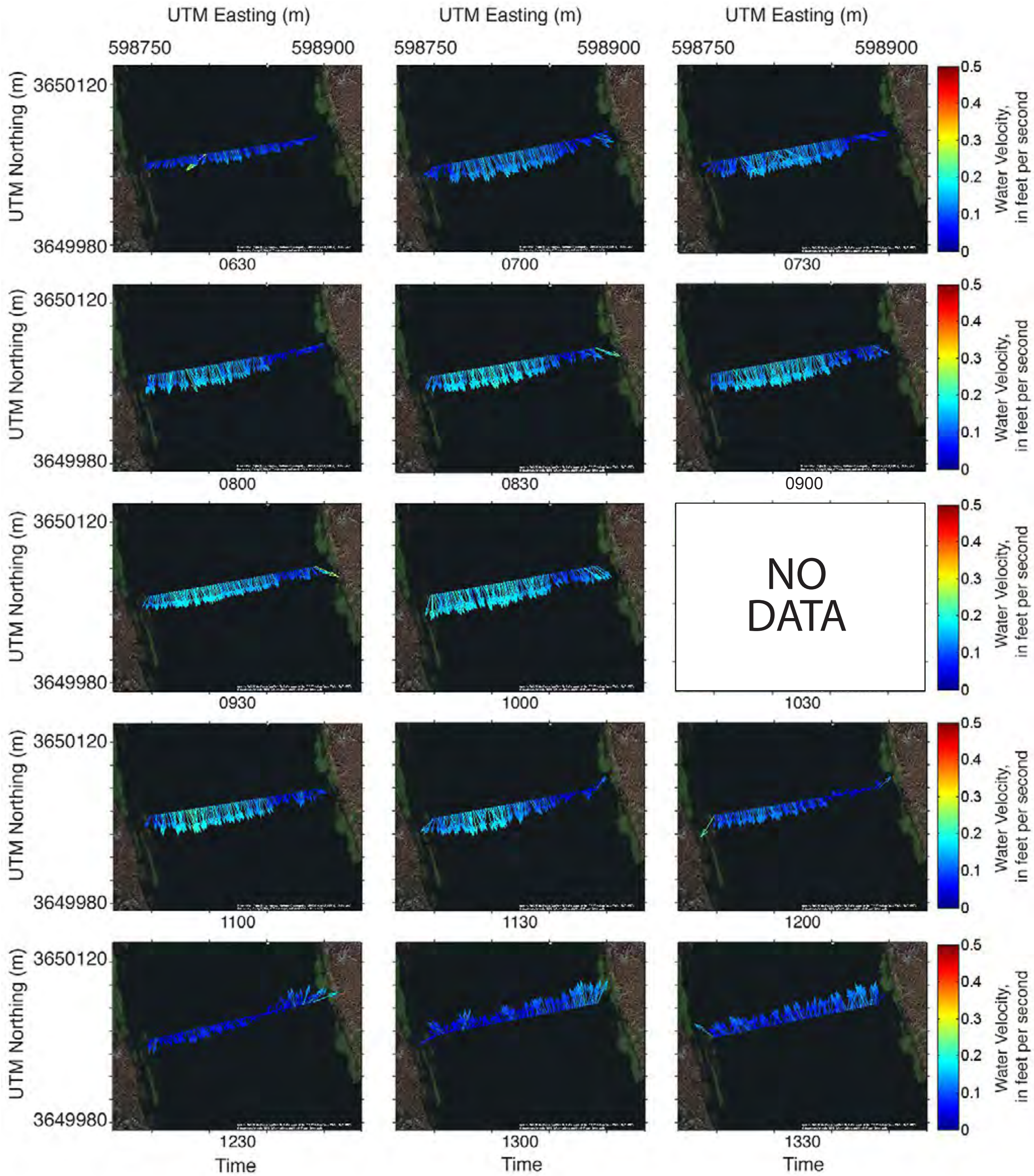


Figure 2–4. Plan views of average velocity vectors for site VMT2 for November 5, 2014.

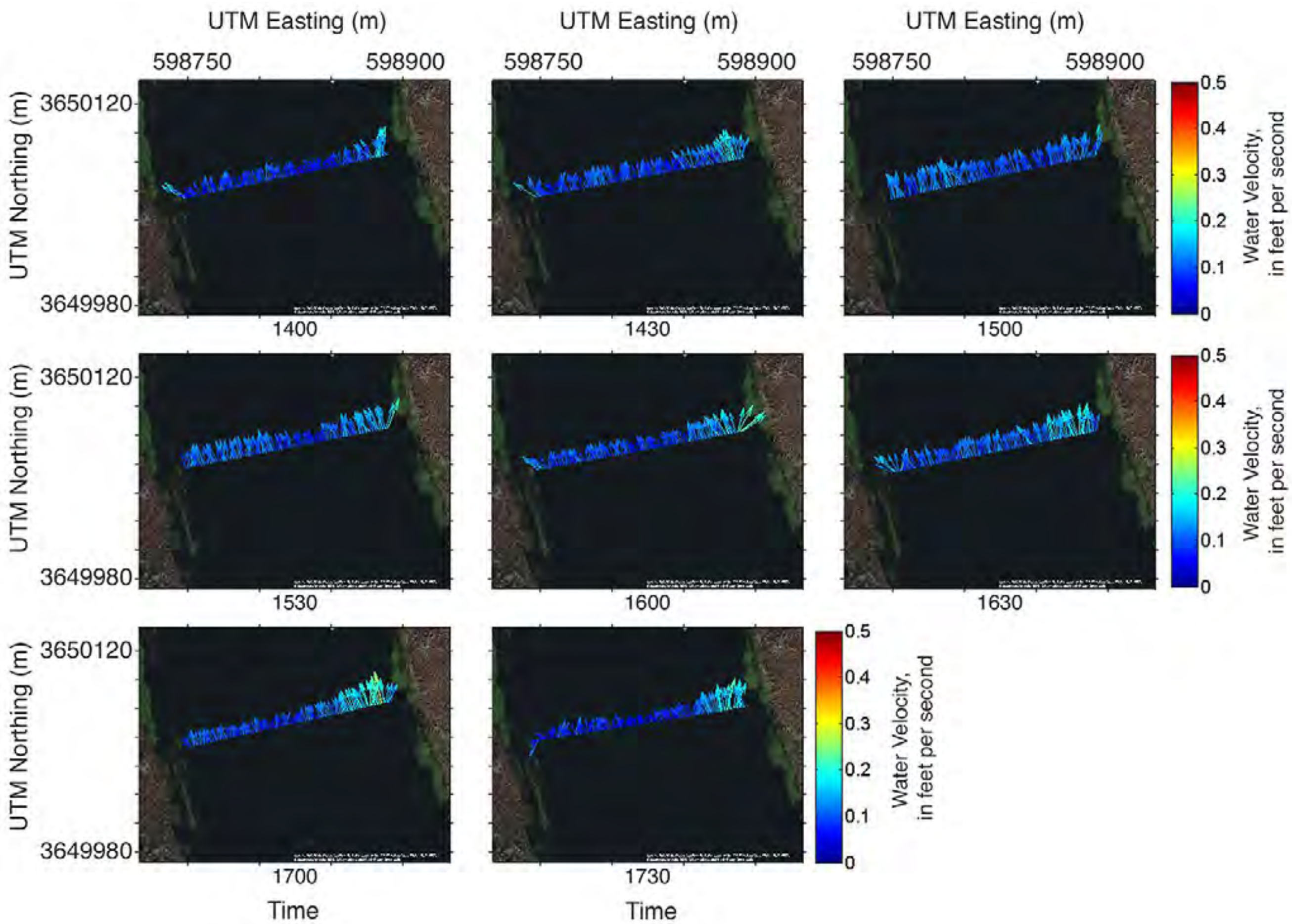


Figure 2–4. Plan views of average velocity vectors for site VMT2 for November 5, 2014.—Continued

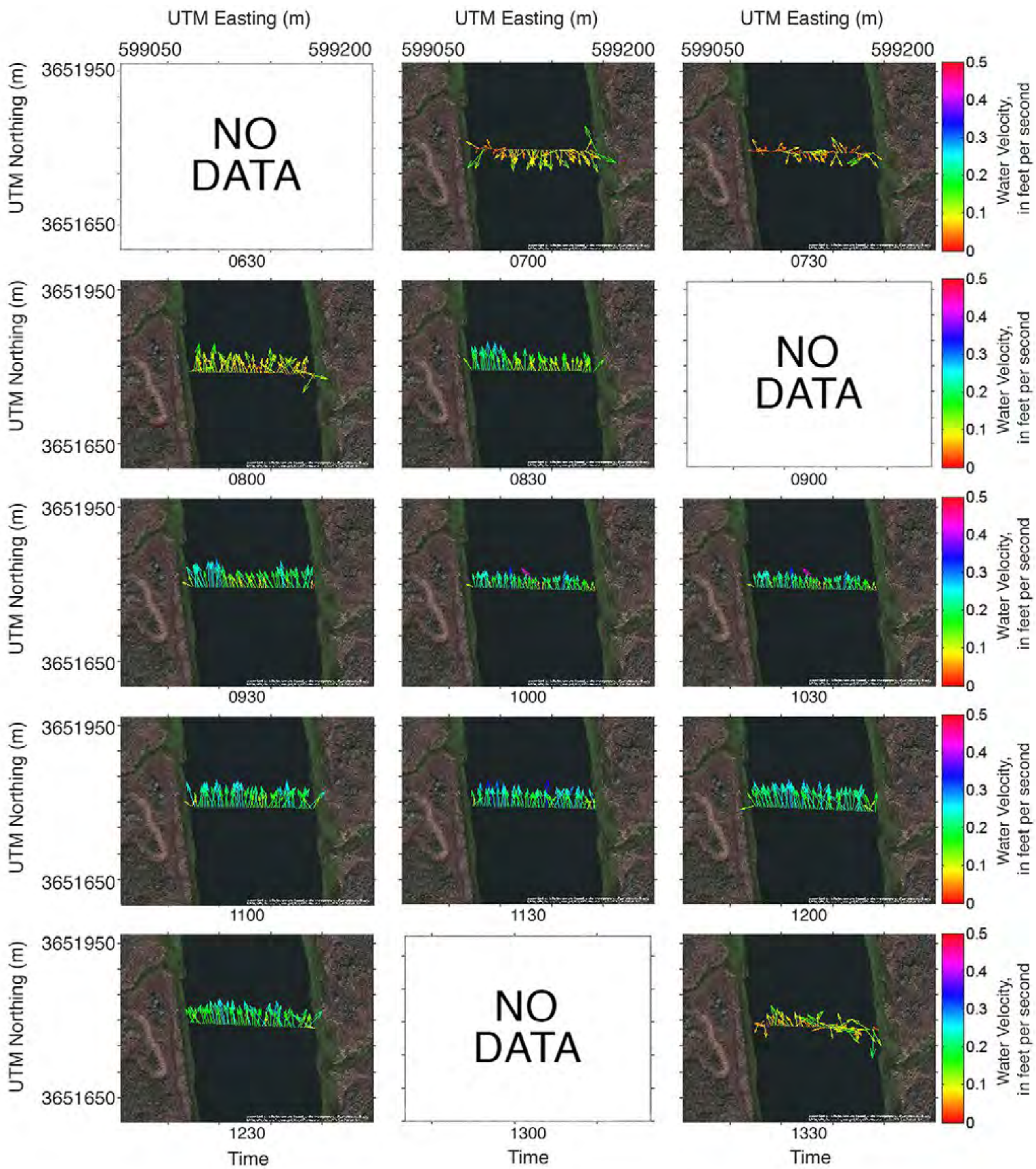


Figure 2–5. Plan views of average velocity vectors for site VMT3 for August 5, 2014.

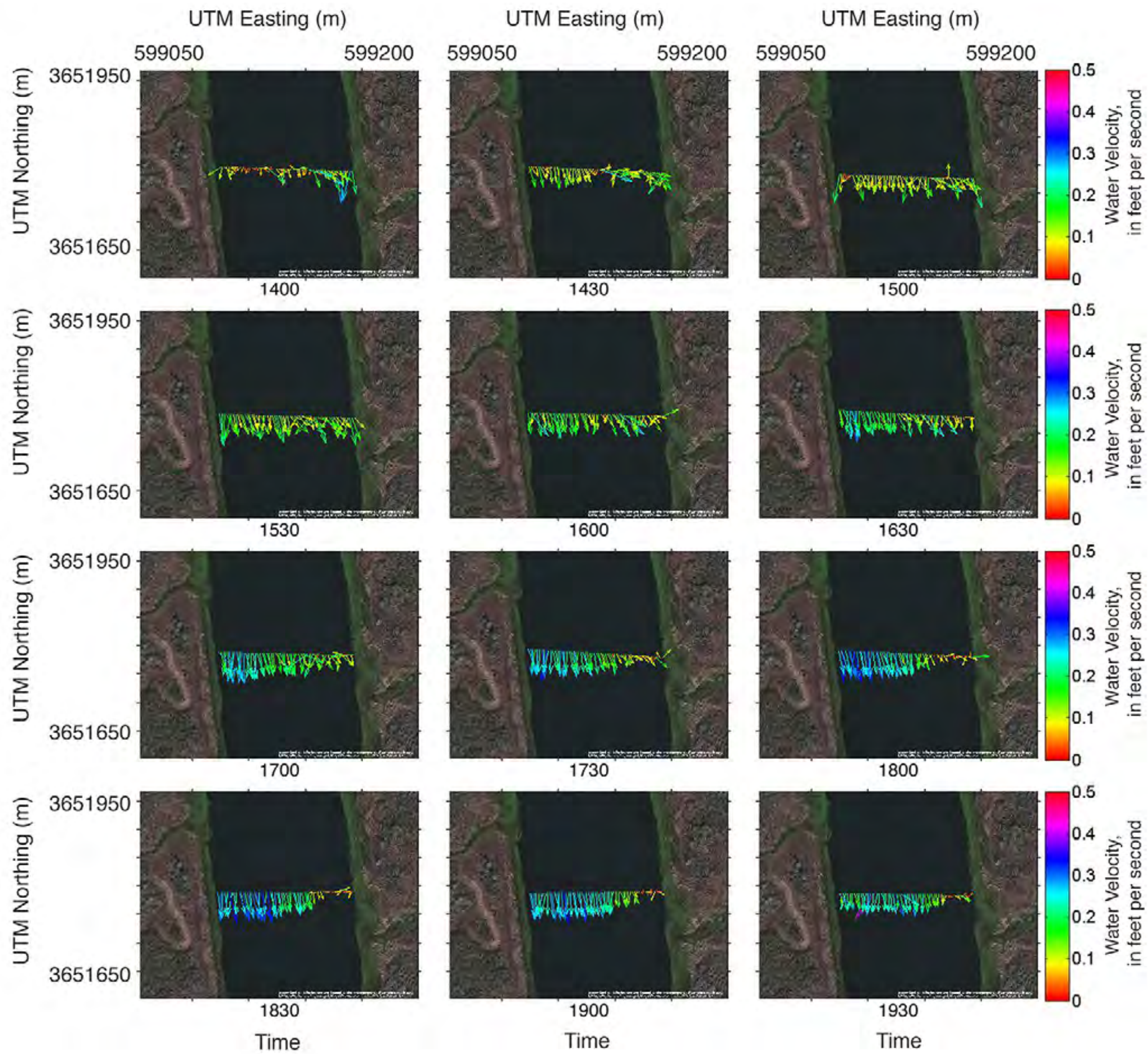


Figure 2–5. Plan views of average velocity vectors for site VMT3 for August 5, 2014.—Continued

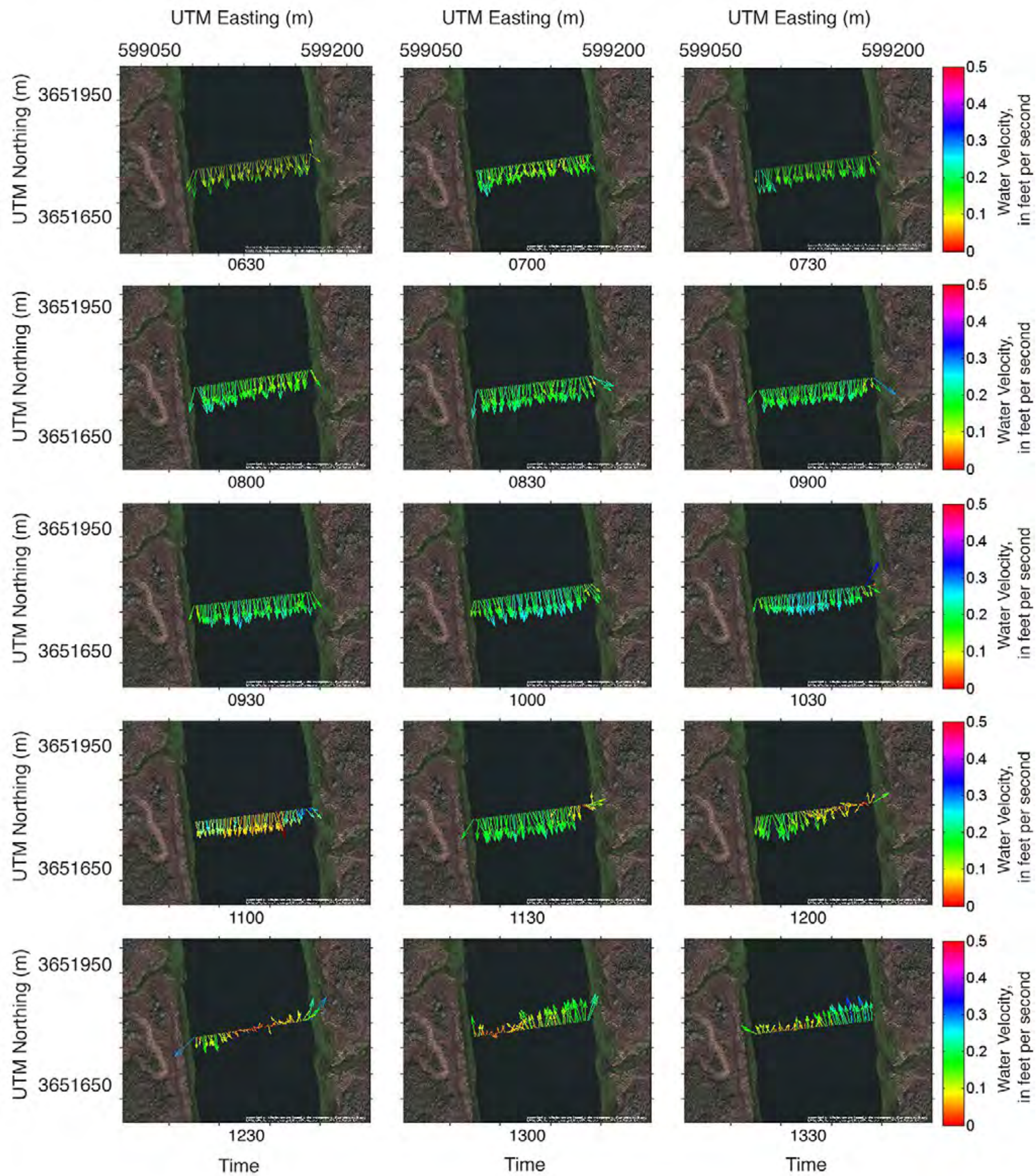


Figure 2–6. Plan views of average velocity vectors for site VMT3 for November 5, 2014.

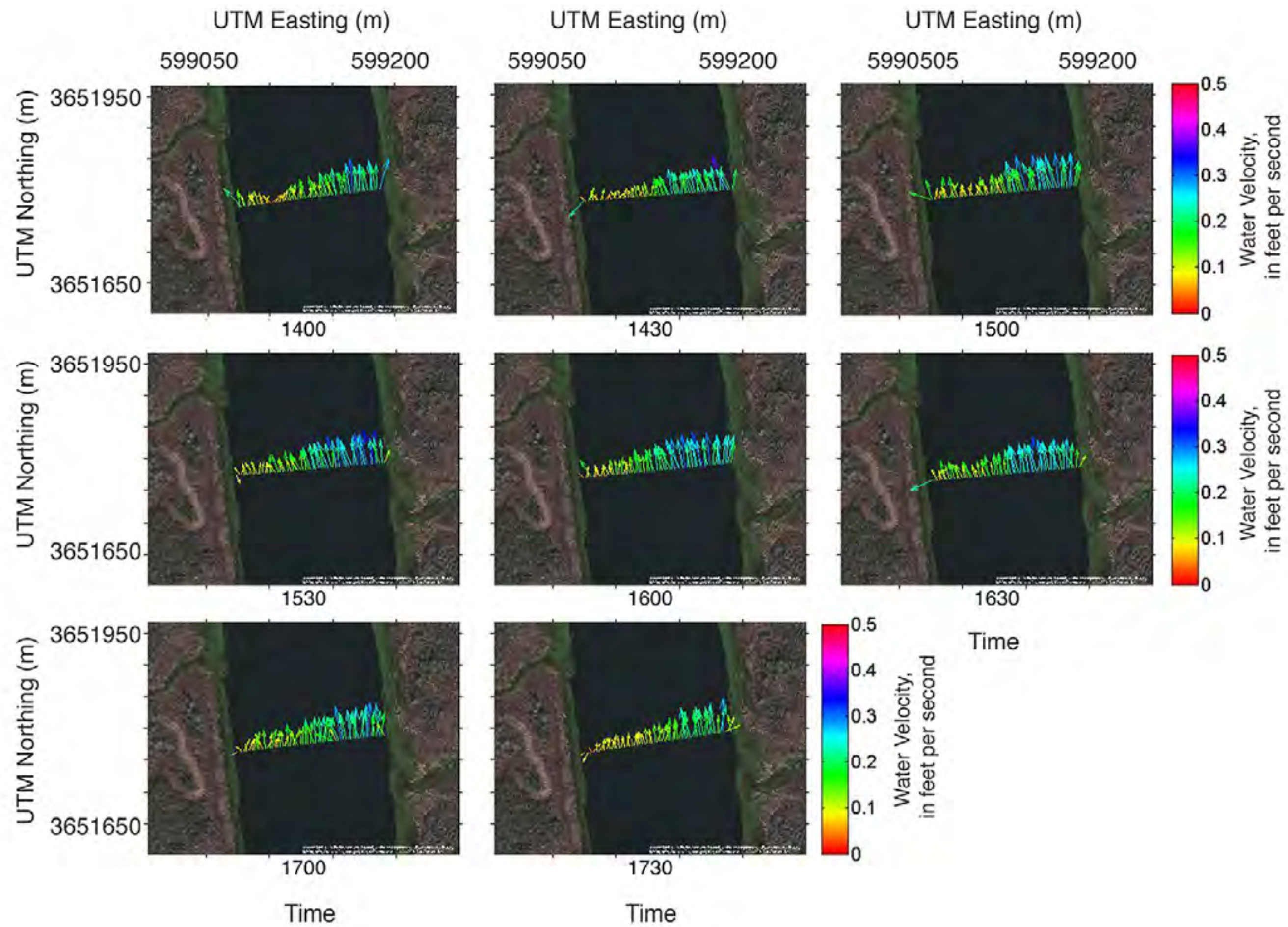


Figure 2–6. Plan views of average velocity vectors for site VMT3 for November 5, 2014..—Continued

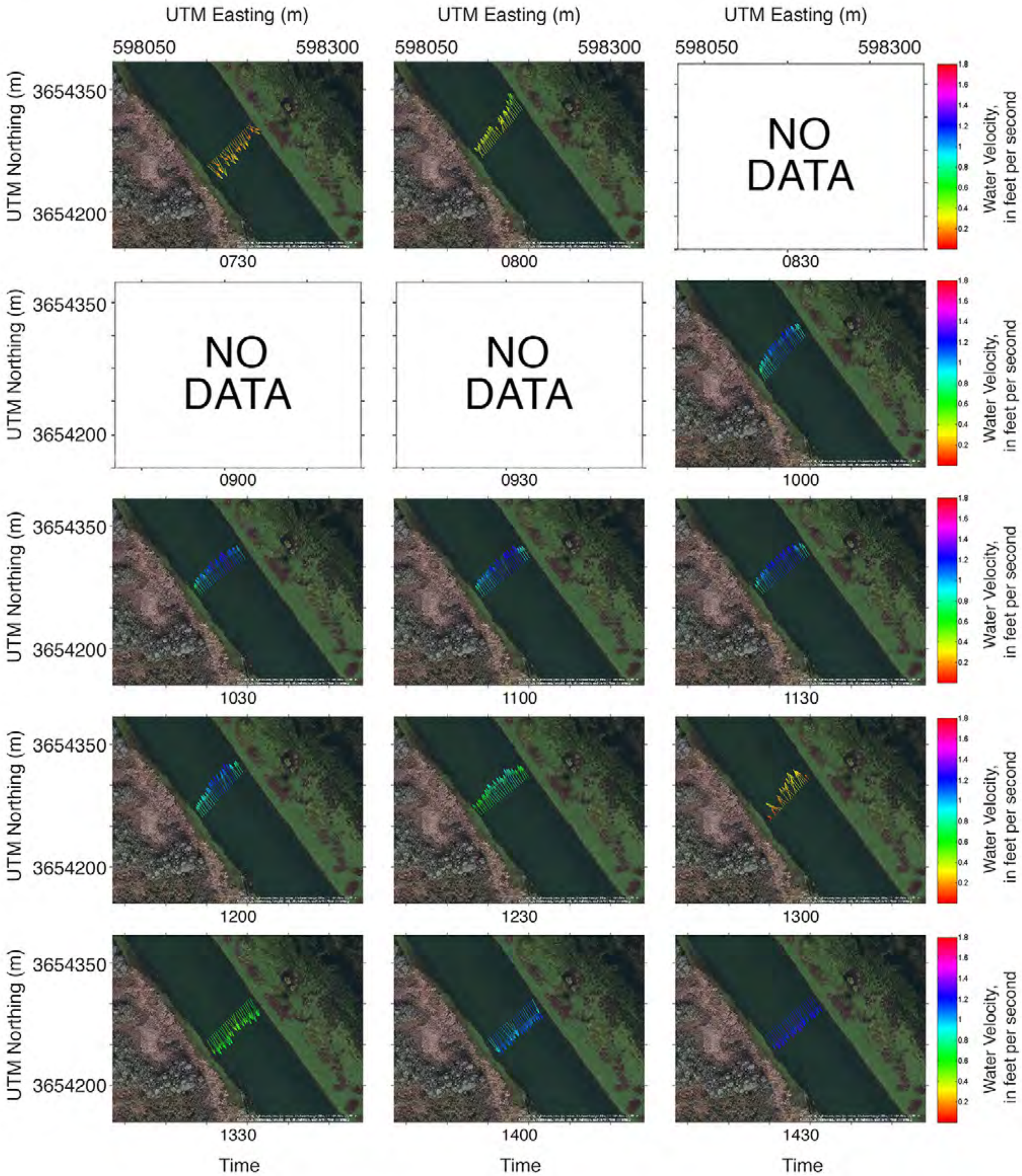


Figure 2–7. Plan views of average velocity vectors for site VMT4 for August 5, 2014.

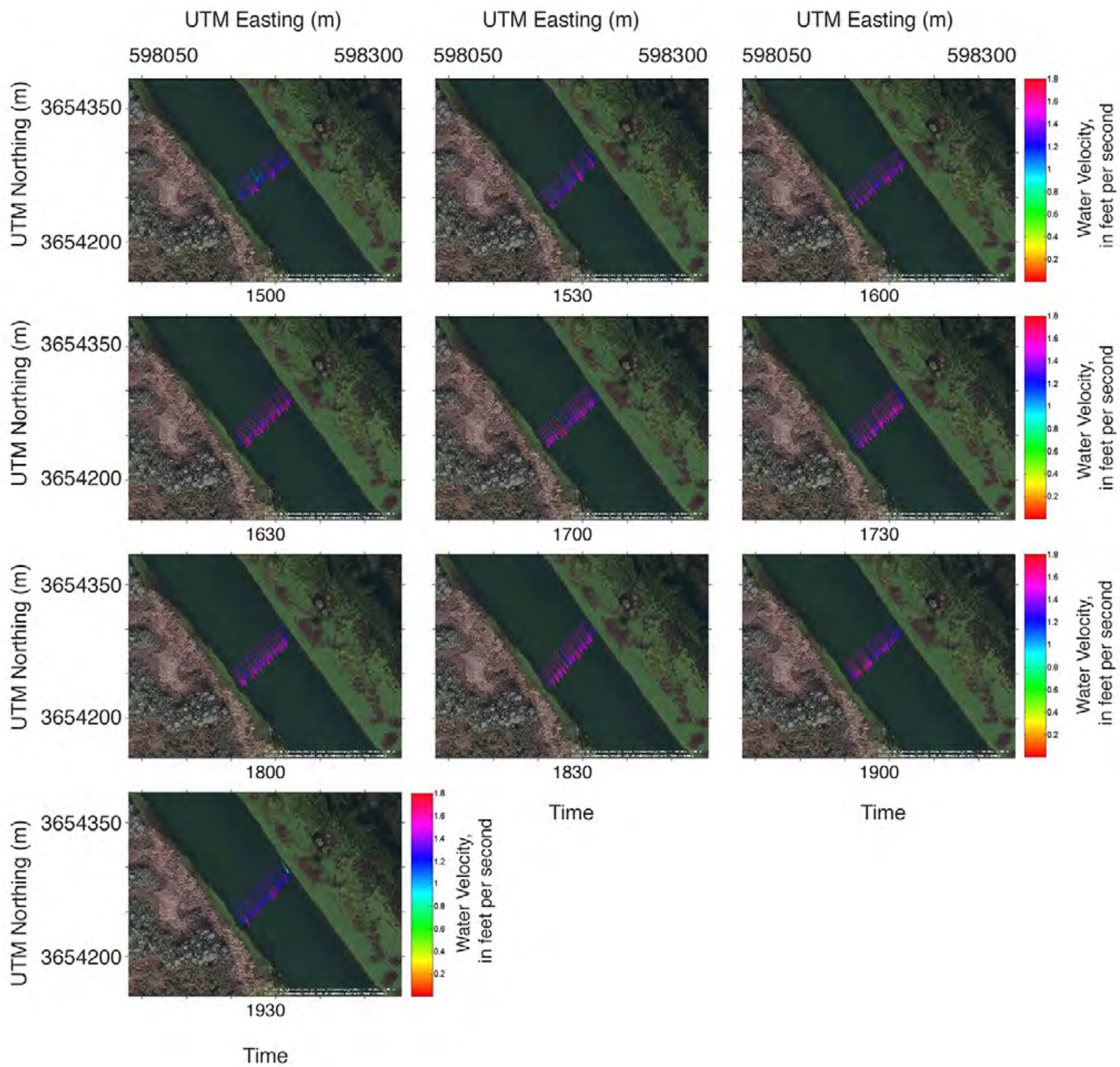


Figure 2–7. Plan views of average velocity vectors for site VMT4 for August 5, 2014.—Continued

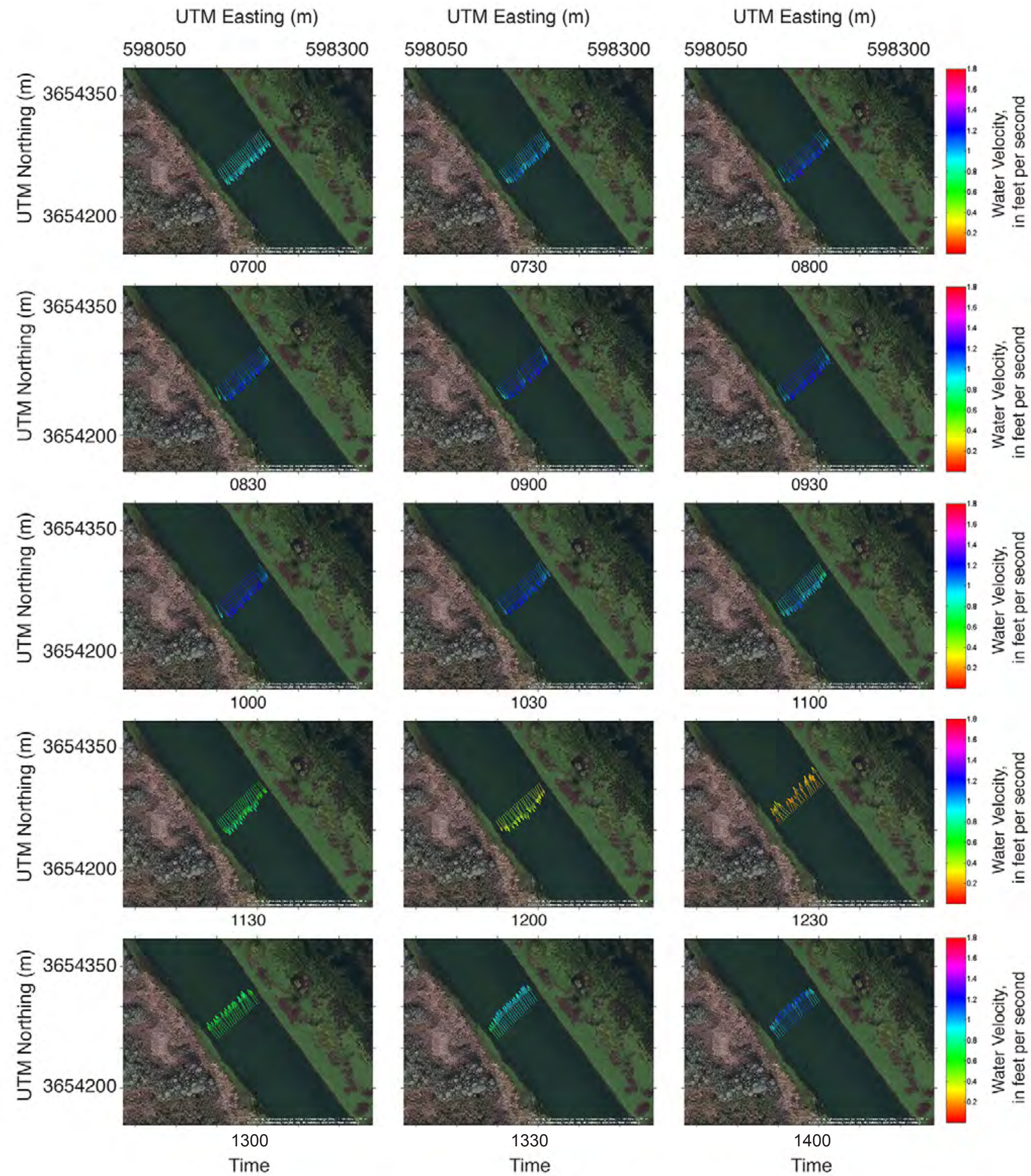
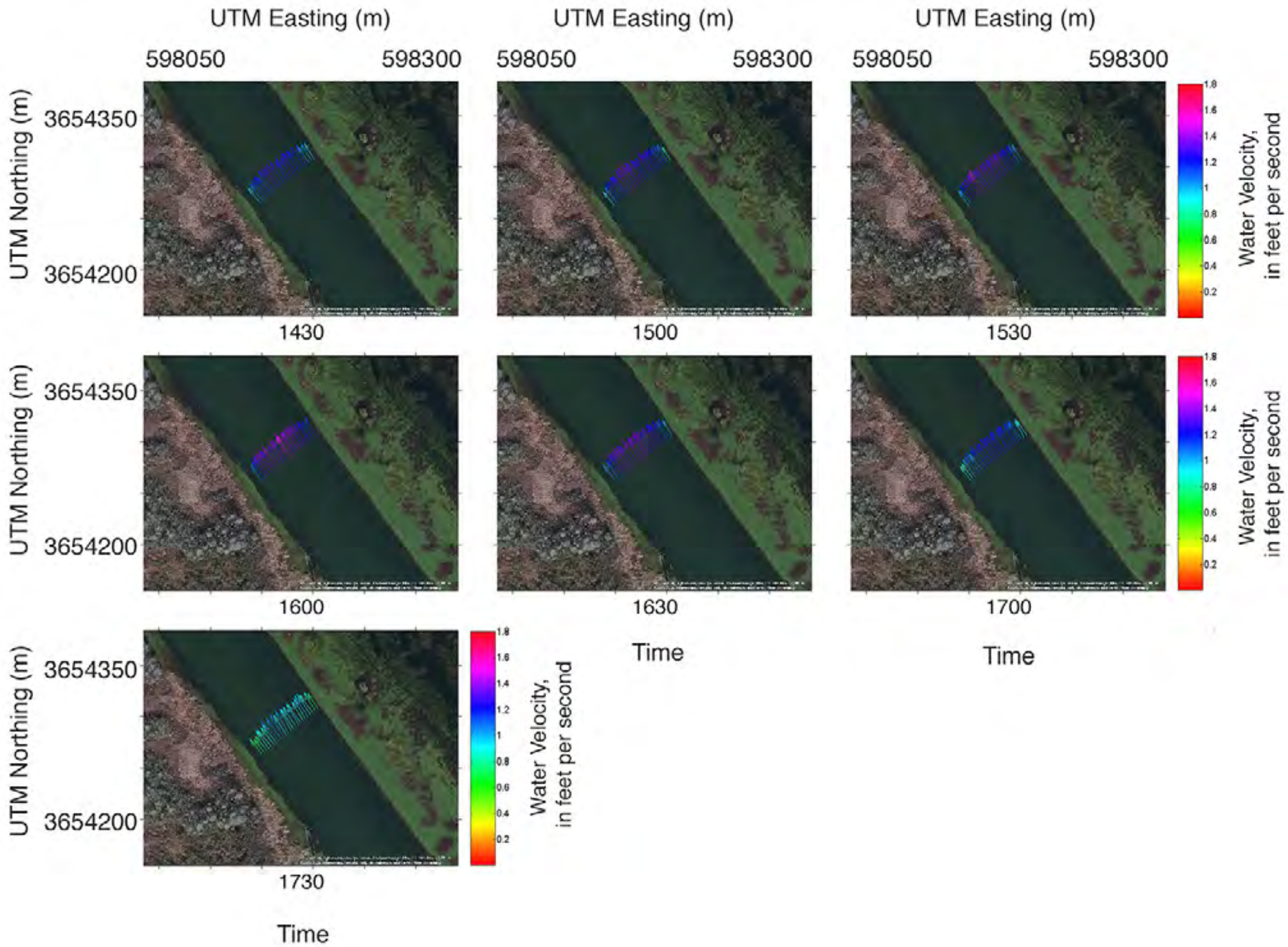


Figure 2–8. Plan views of average velocity vectors for site VMT4 for November 5, 2014.



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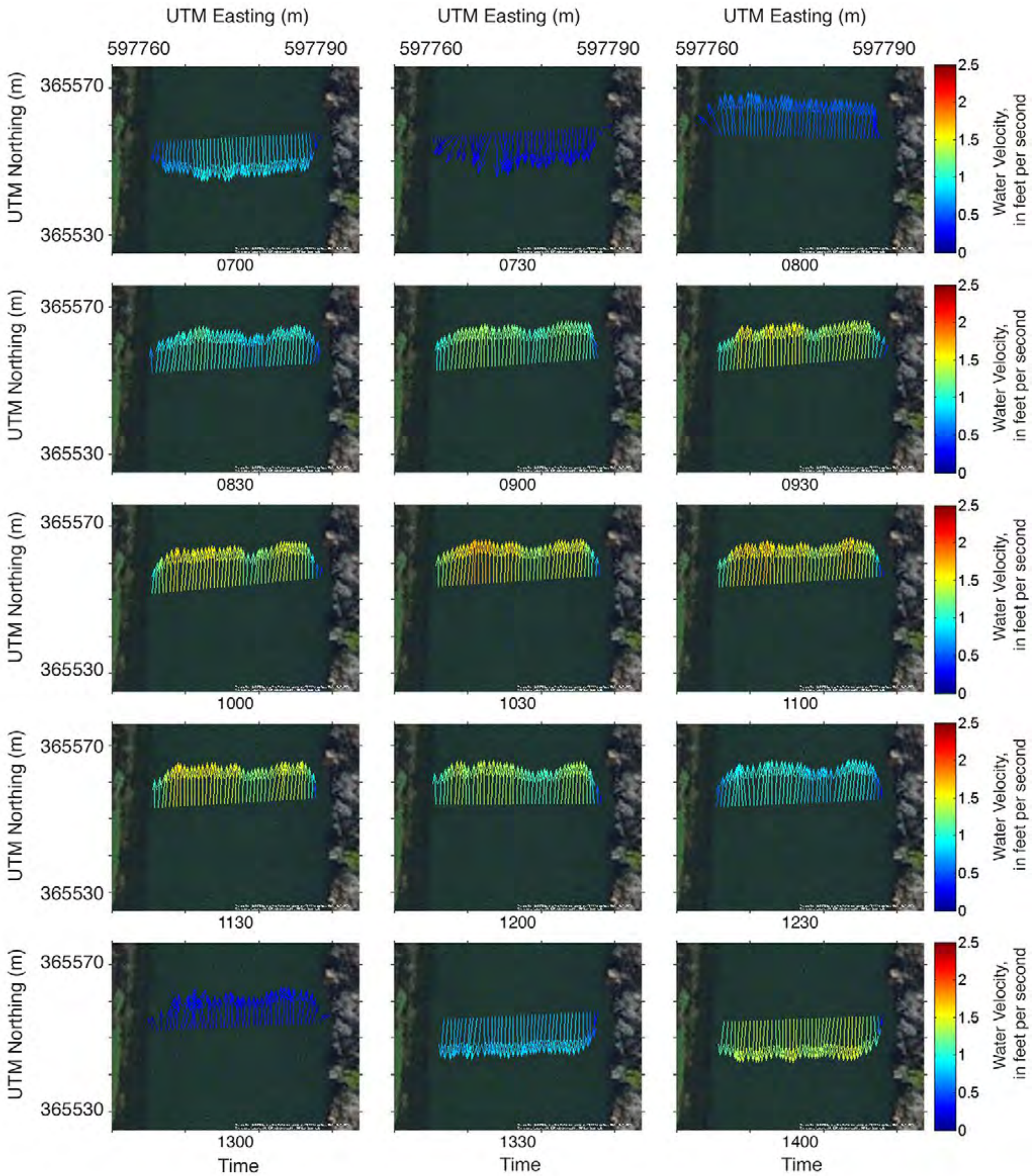


Figure 2–9. Plan views of average velocity vectors for site VMT5 for August 5, 2014.

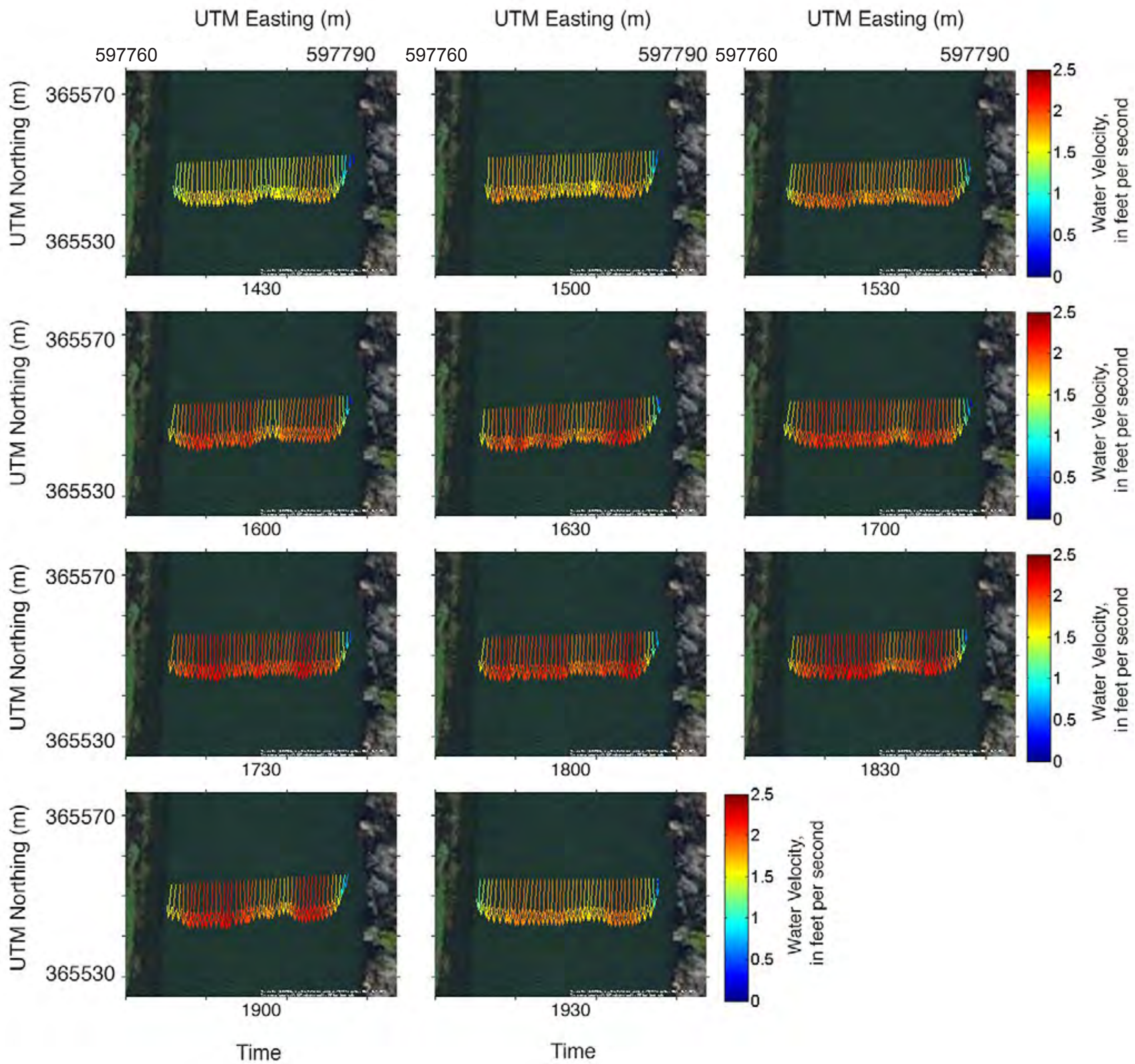


Figure 2–9. Plan views of average velocity vectors for site VMT5 for August 5, 2014.—Continued

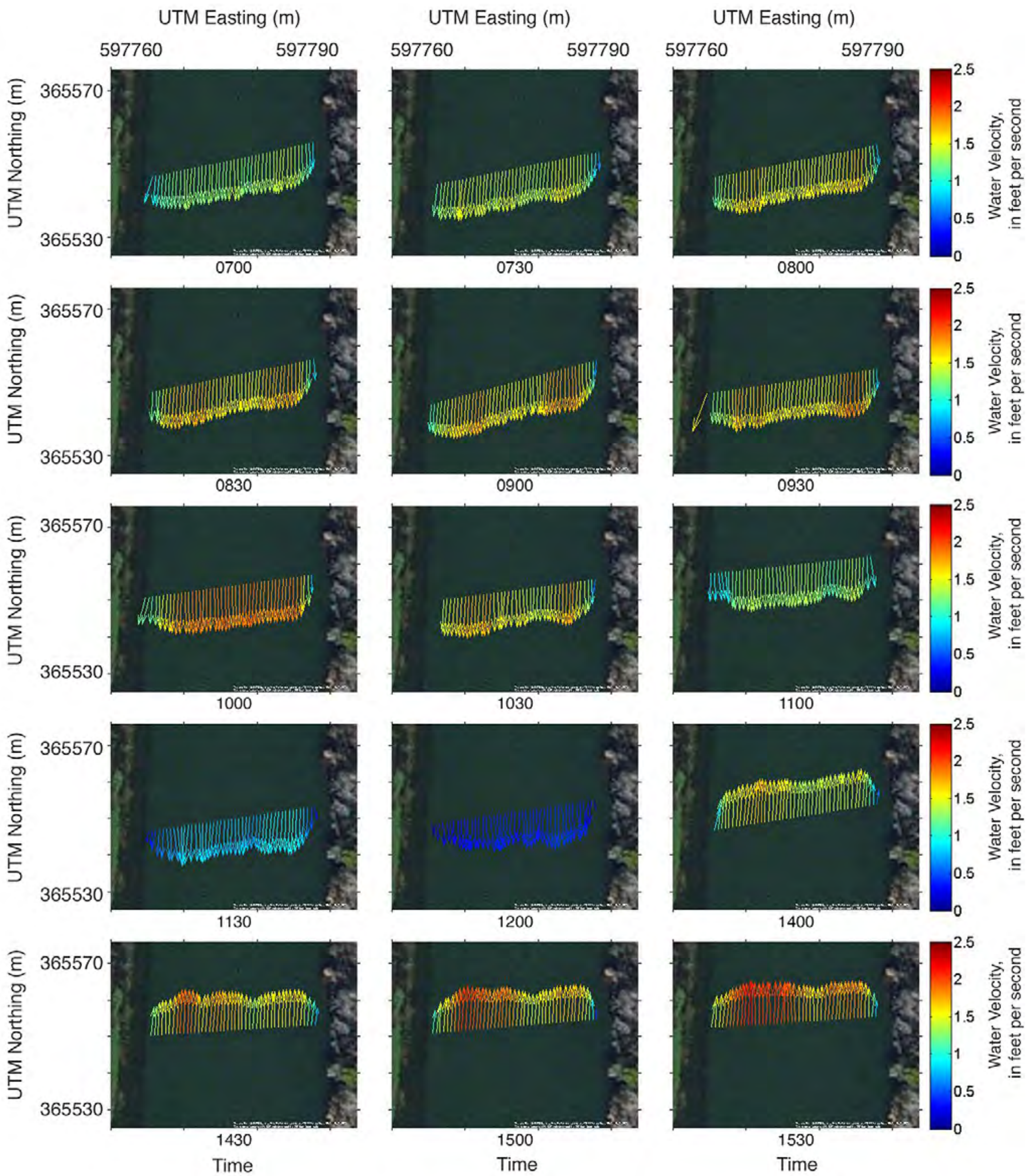


Figure 2–10. Plan views of average velocity vectors for site VMT5 for November 5, 2014.

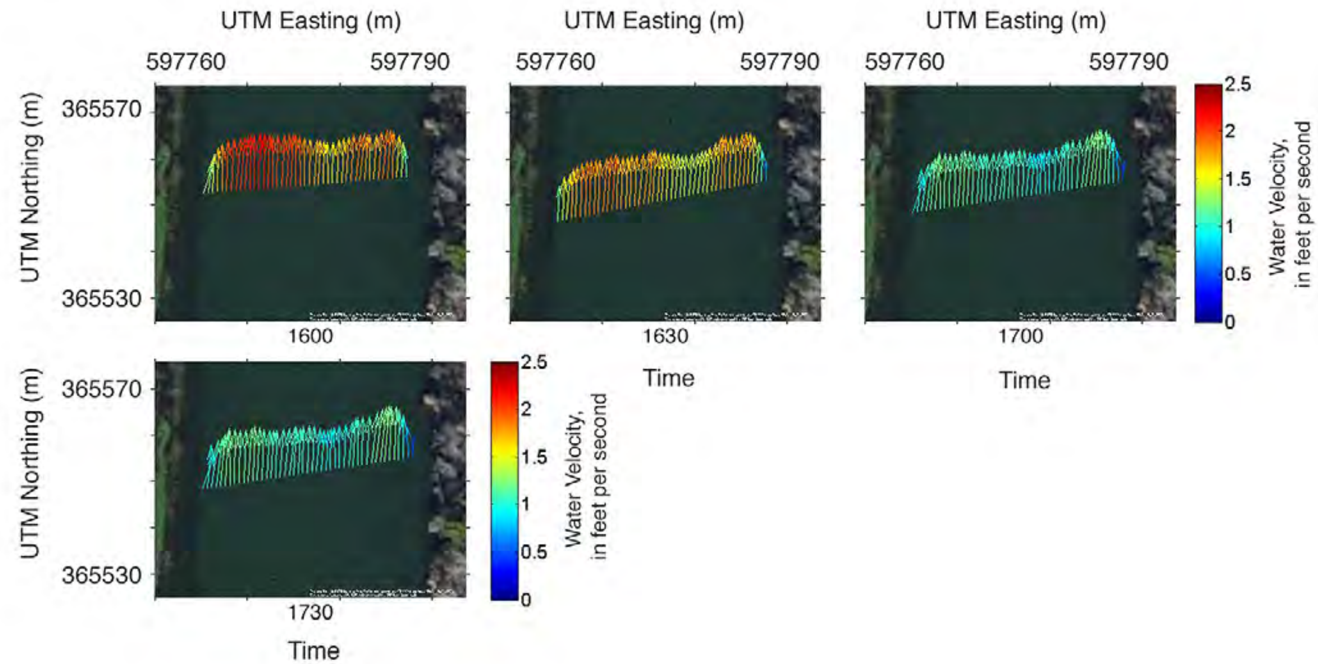


Figure 2–10. Plan views of average velocity vectors for site VMT5 for November 5, 2014.—Continued

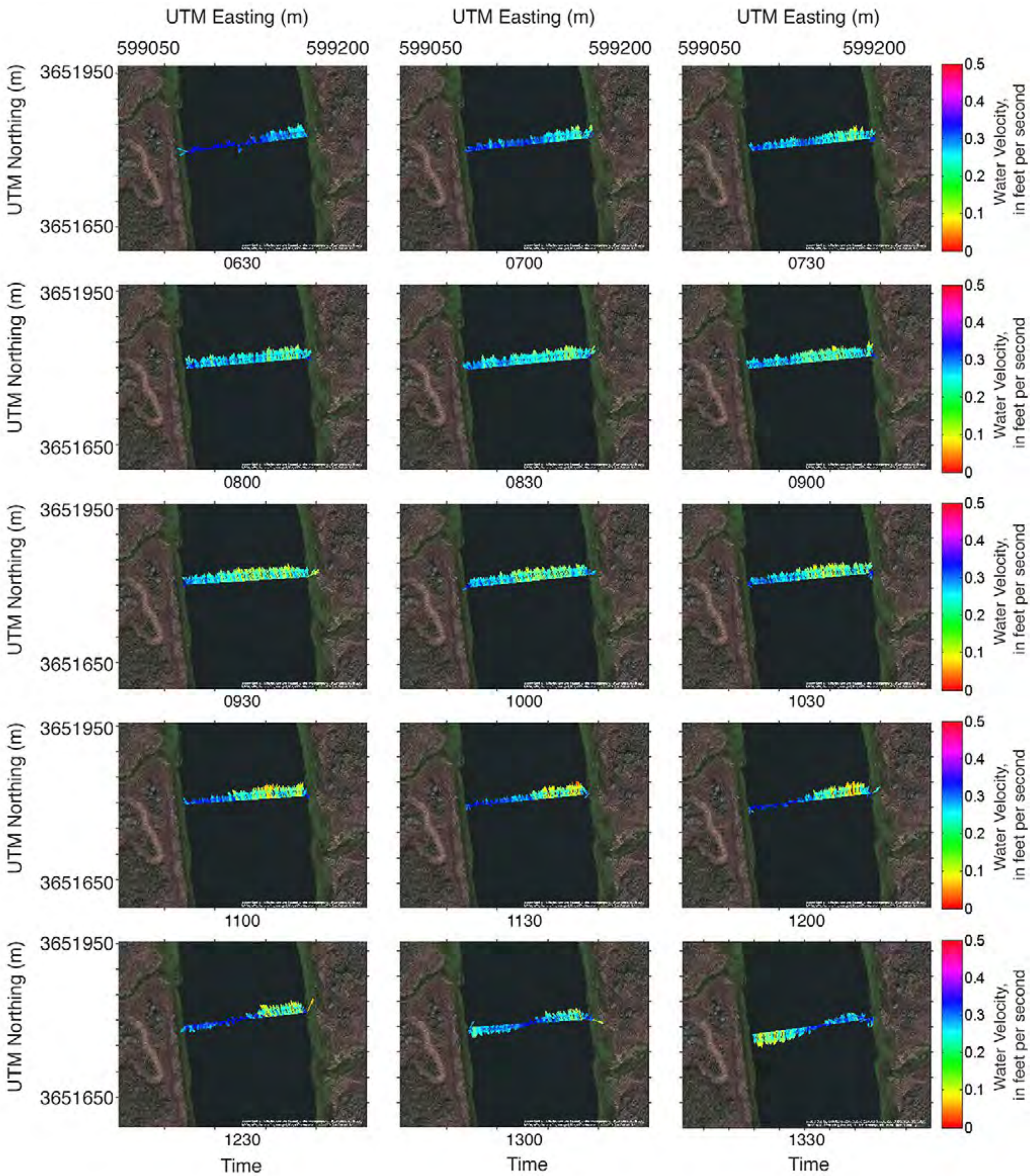


Figure 2–11. Plan views of average velocity vectors for site VMT3 for March 26, 2015.

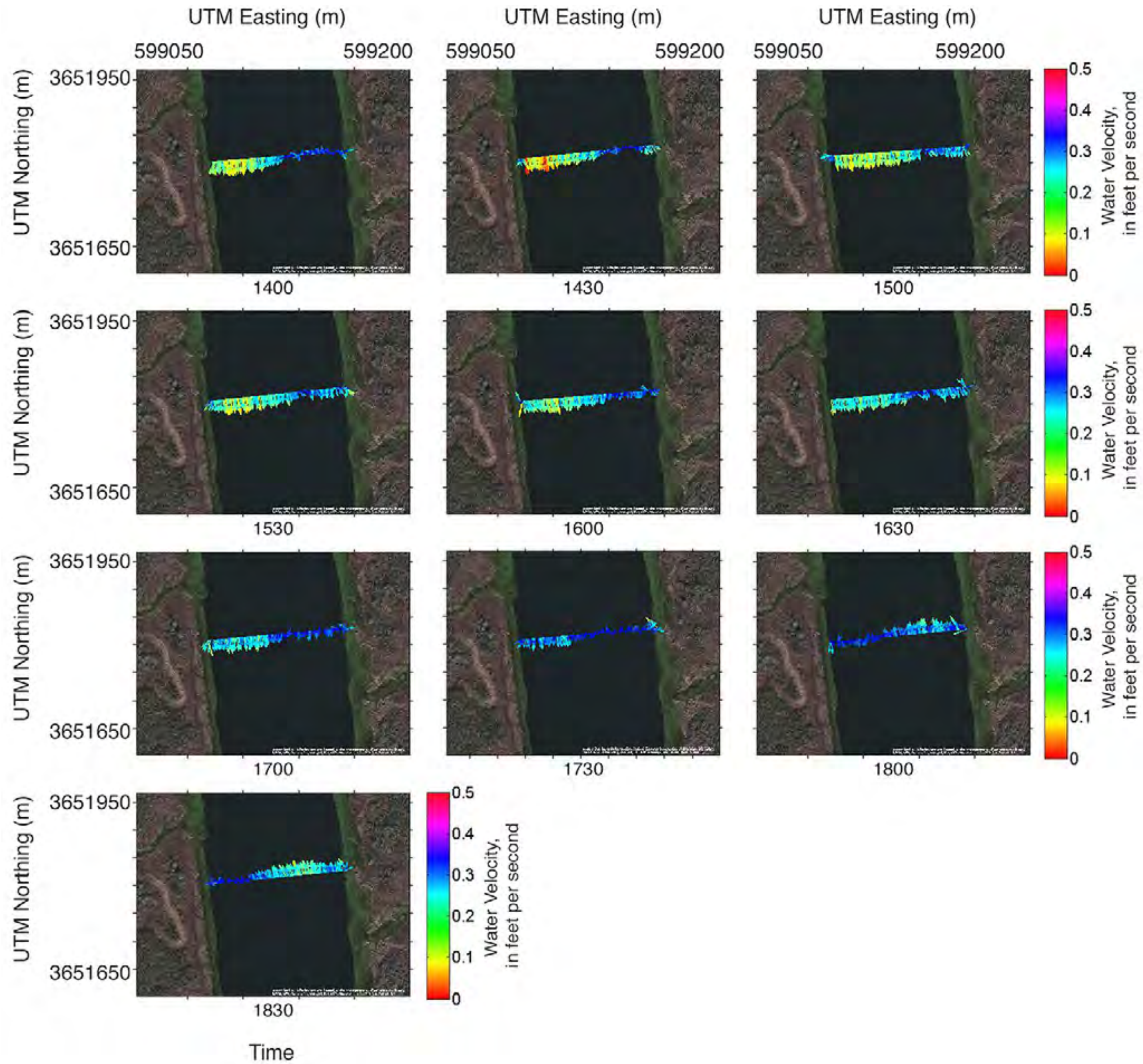


Figure 2–11. Plan views of average velocity vectors for site VMT3 for March 26, 2015.—Continued

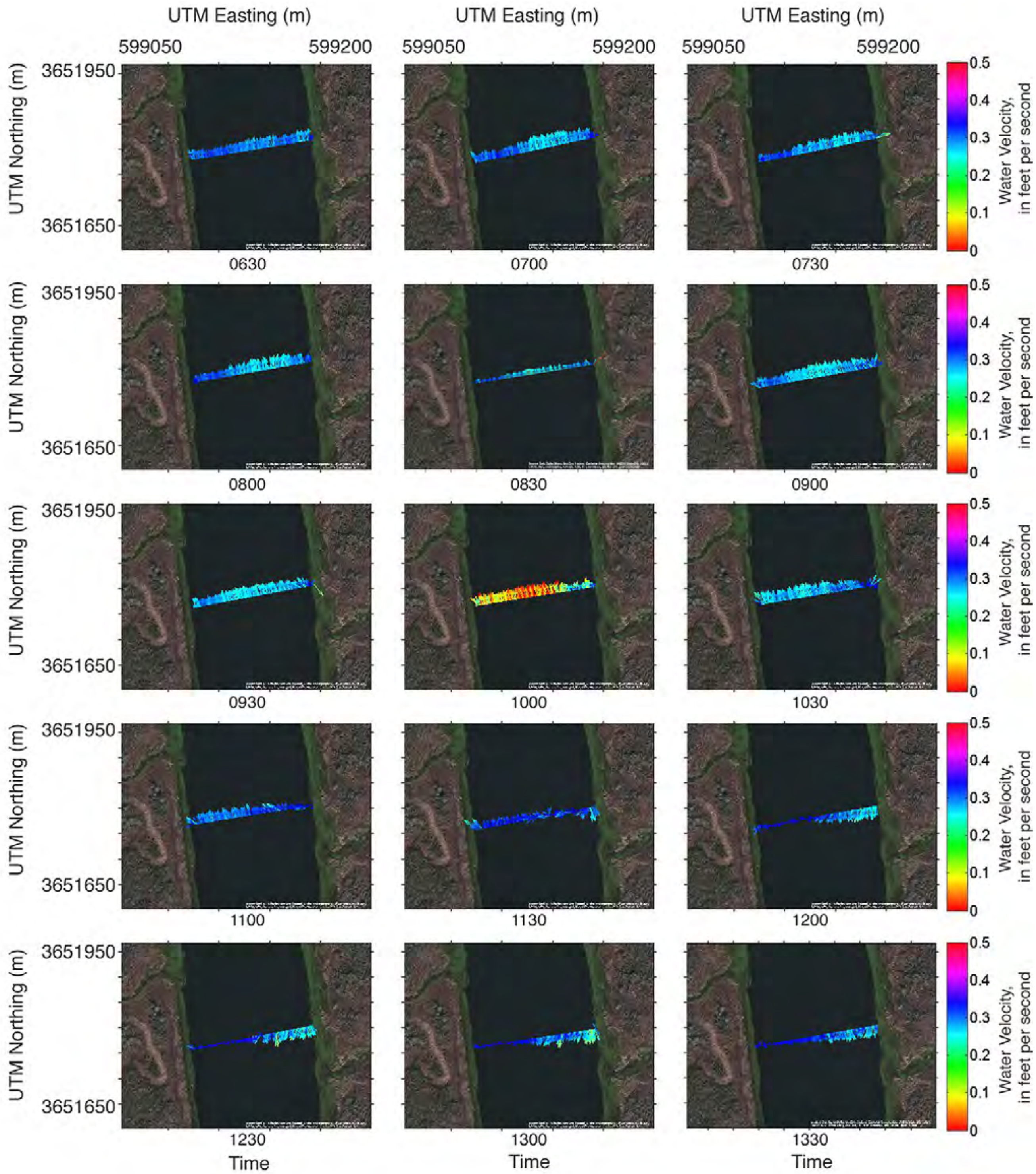


Figure 2–12. Plan views of average velocity vectors for site VMT3 for April 23, 2015.

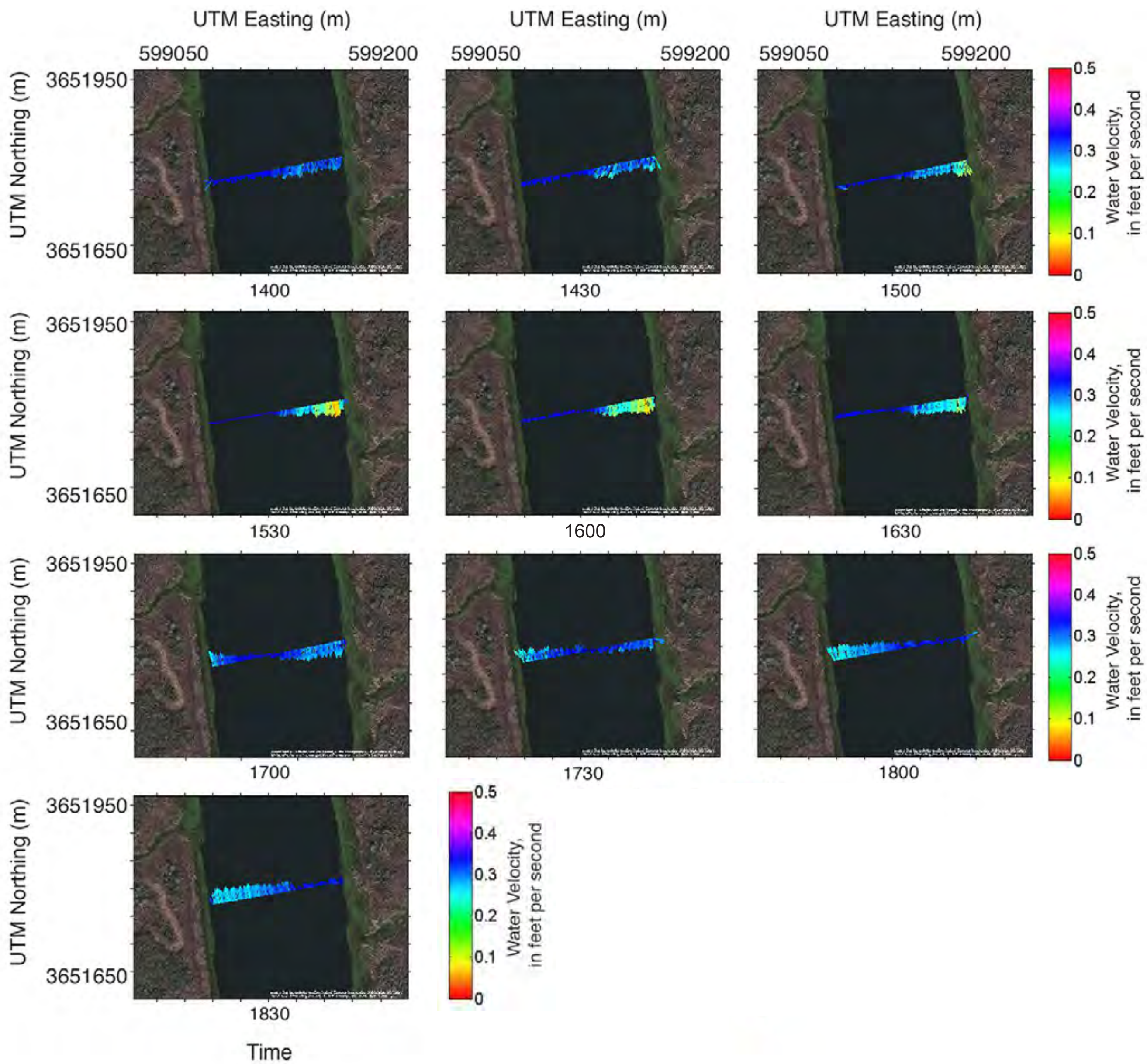


Figure 2–12. Plan views of average velocity vectors for site VMT3 for April 23, 2015.—Continued

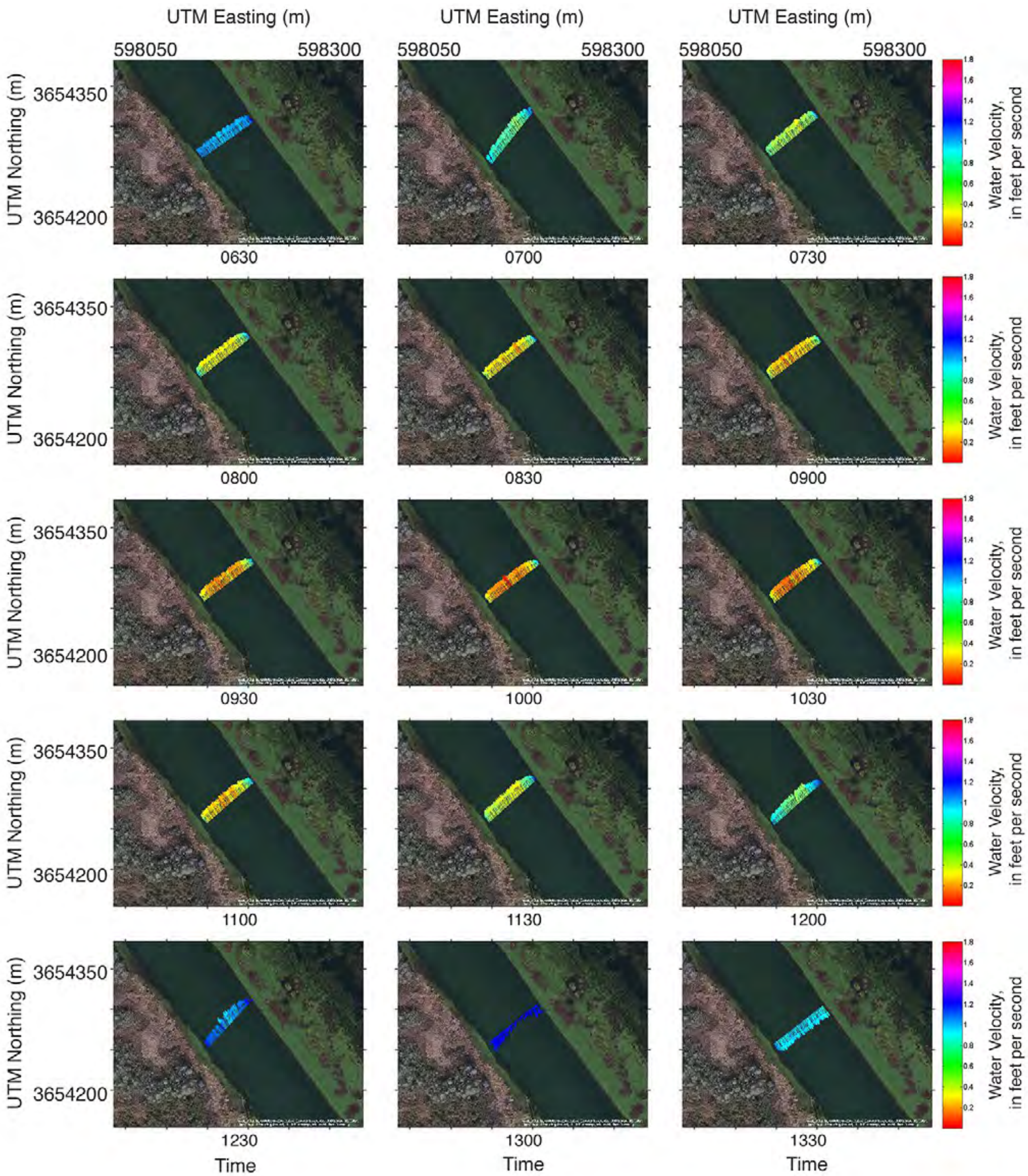


Figure 2–13. Plan views of average velocity vectors for site VMT4 for March 26, 2015.

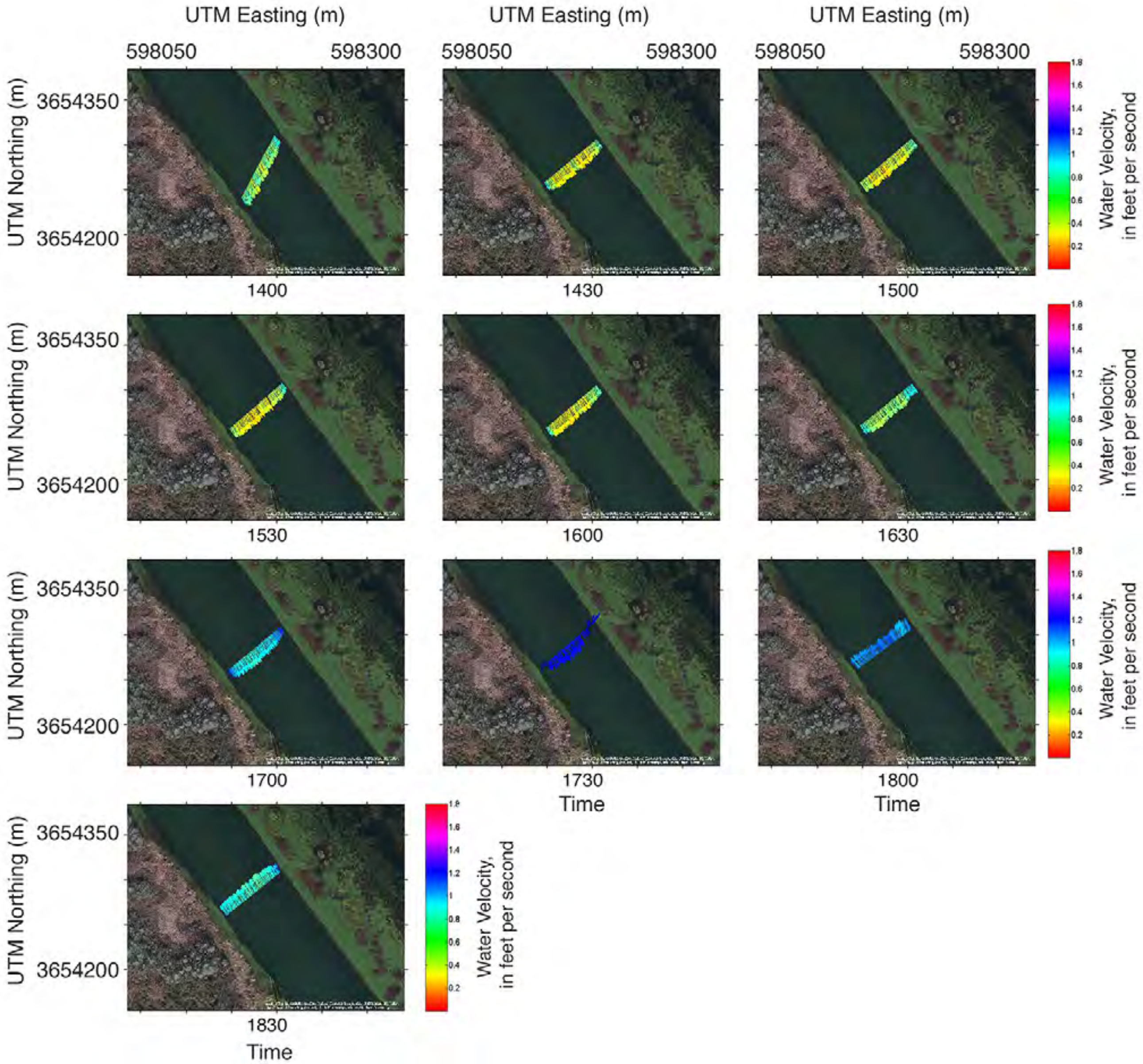


Figure 2–13. Plan views of average velocity vectors for site VMT4 for March 26, 2015.—Continued

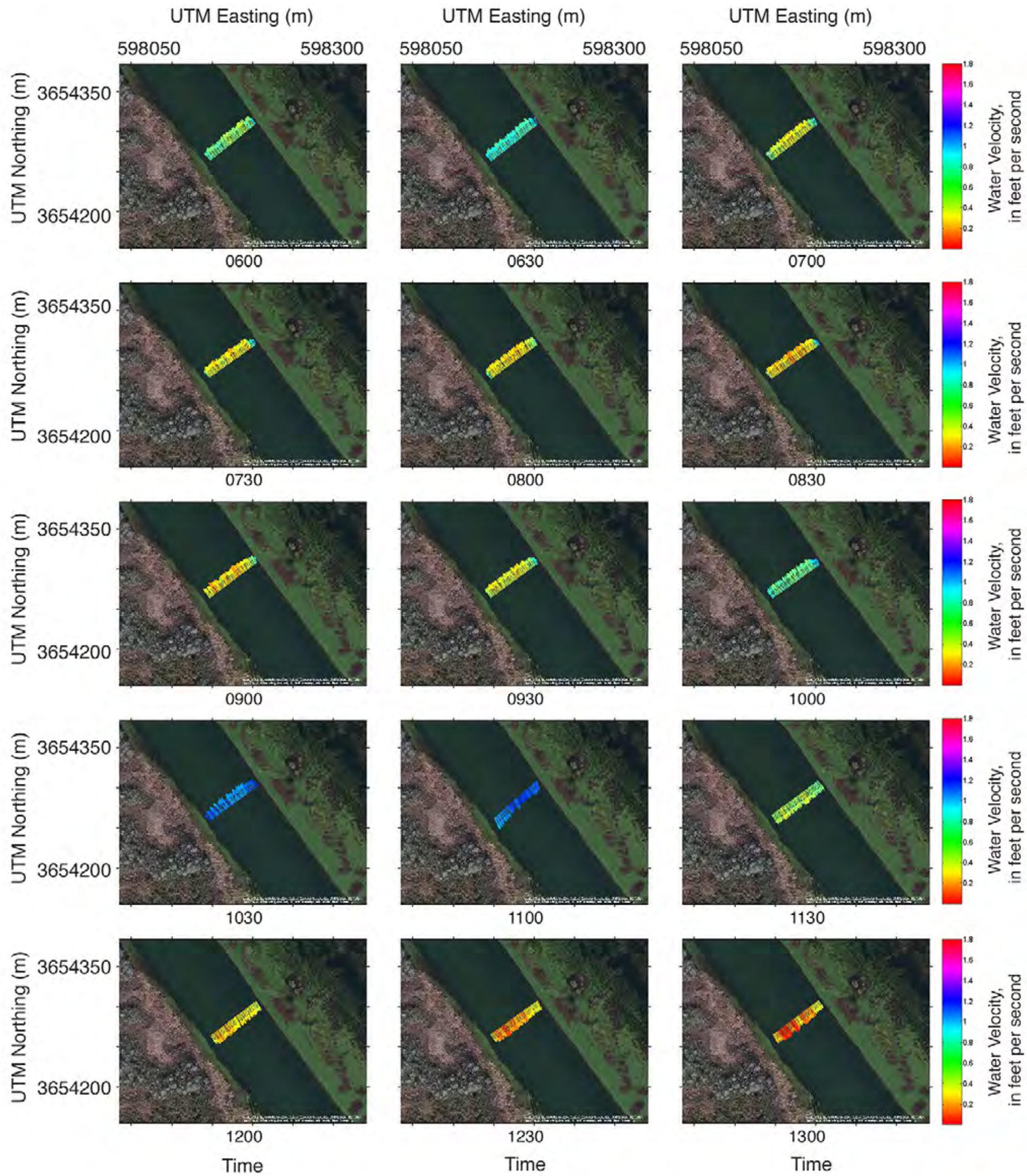


Figure 2–14. Plan views of average velocity vectors for site VMT4 for April 23, 2015.

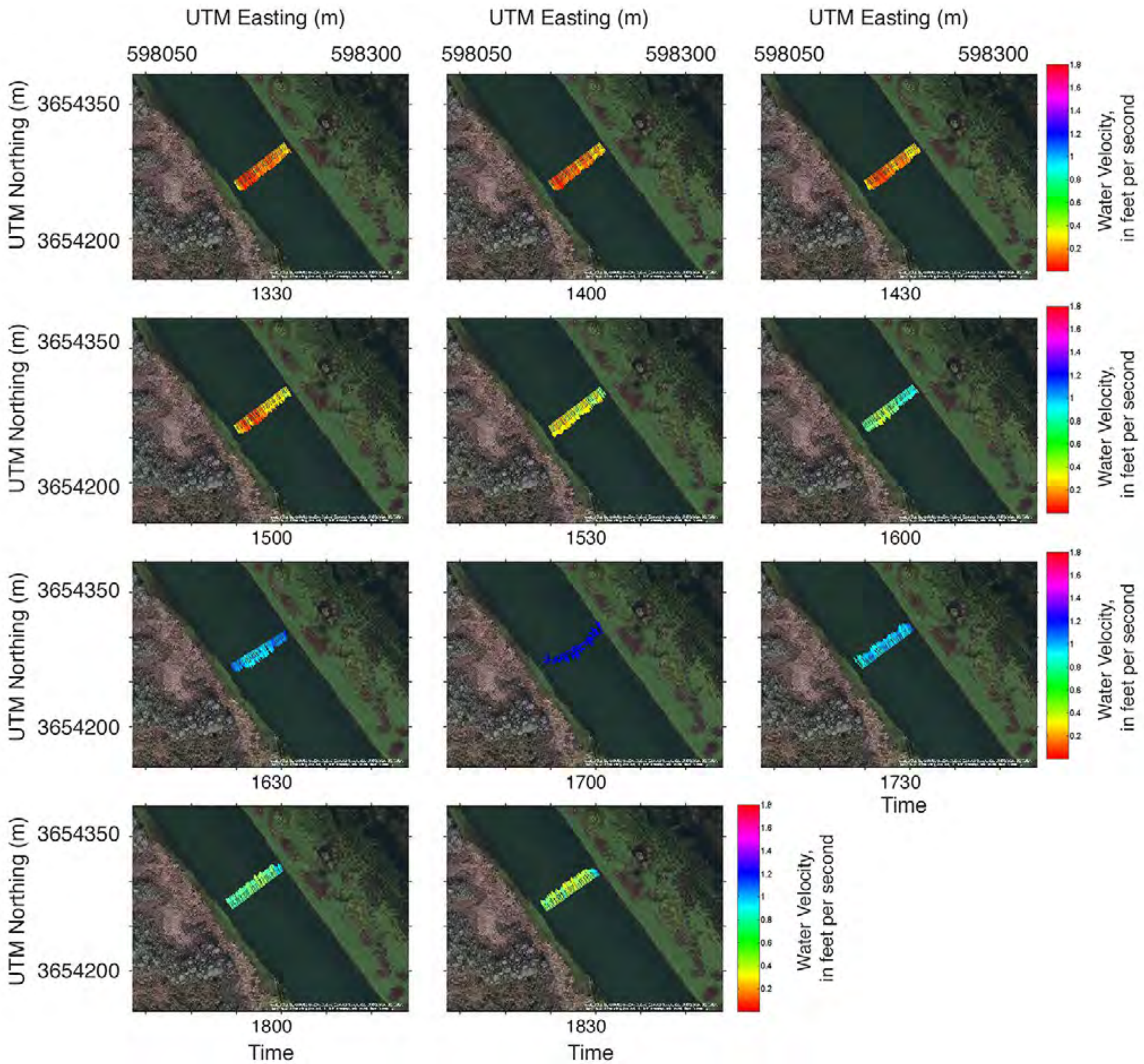


Figure 2–14. Plan views of average velocity vectors for site VMT4 for April 23, 2015.—Continued

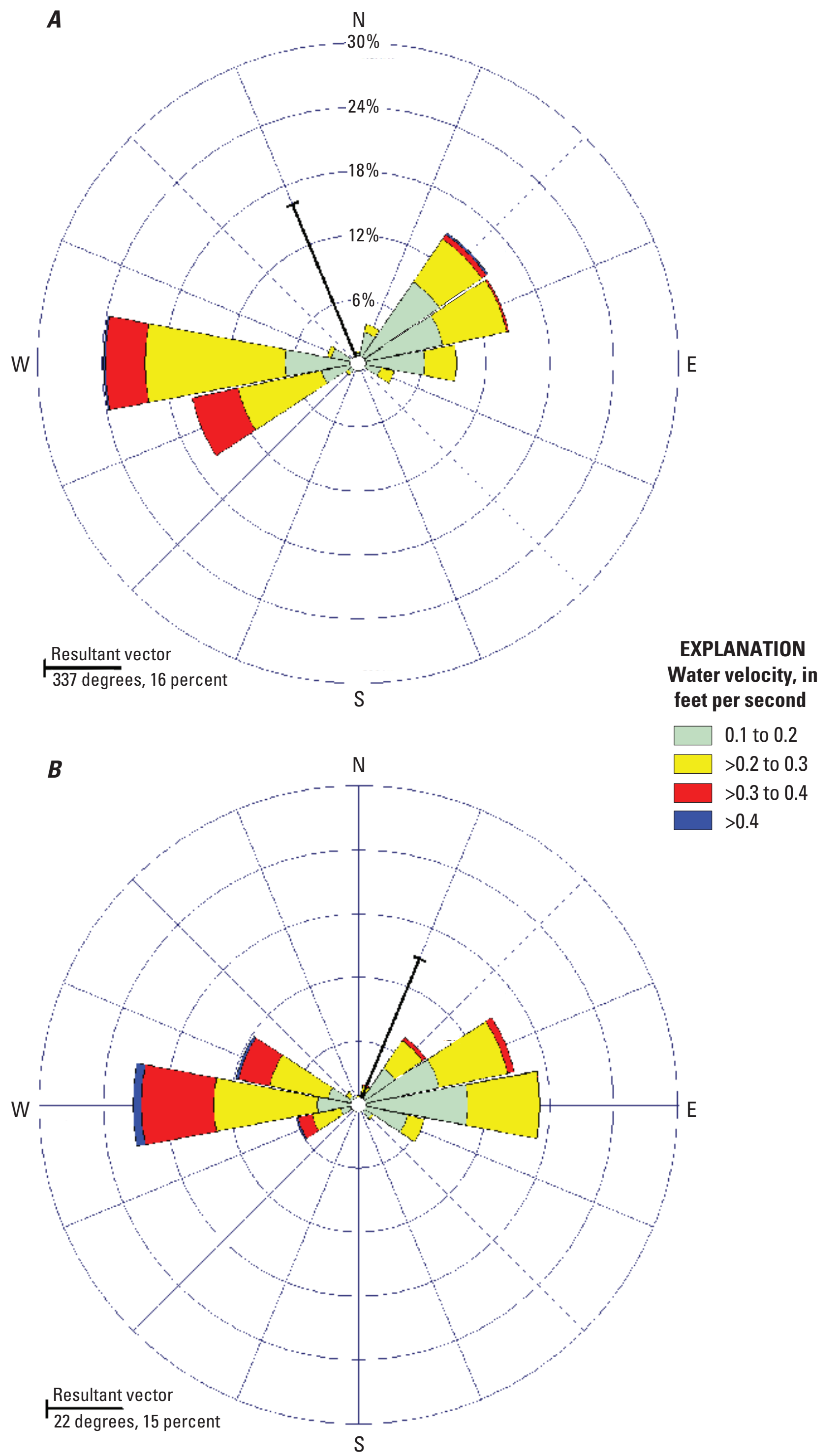


Figure 3–1. Rose diagram of velocity vectors for site VVP1 for the days in 2014 that the Williams Station was *A,* not withdrawing water and *B,* withdrawing water.

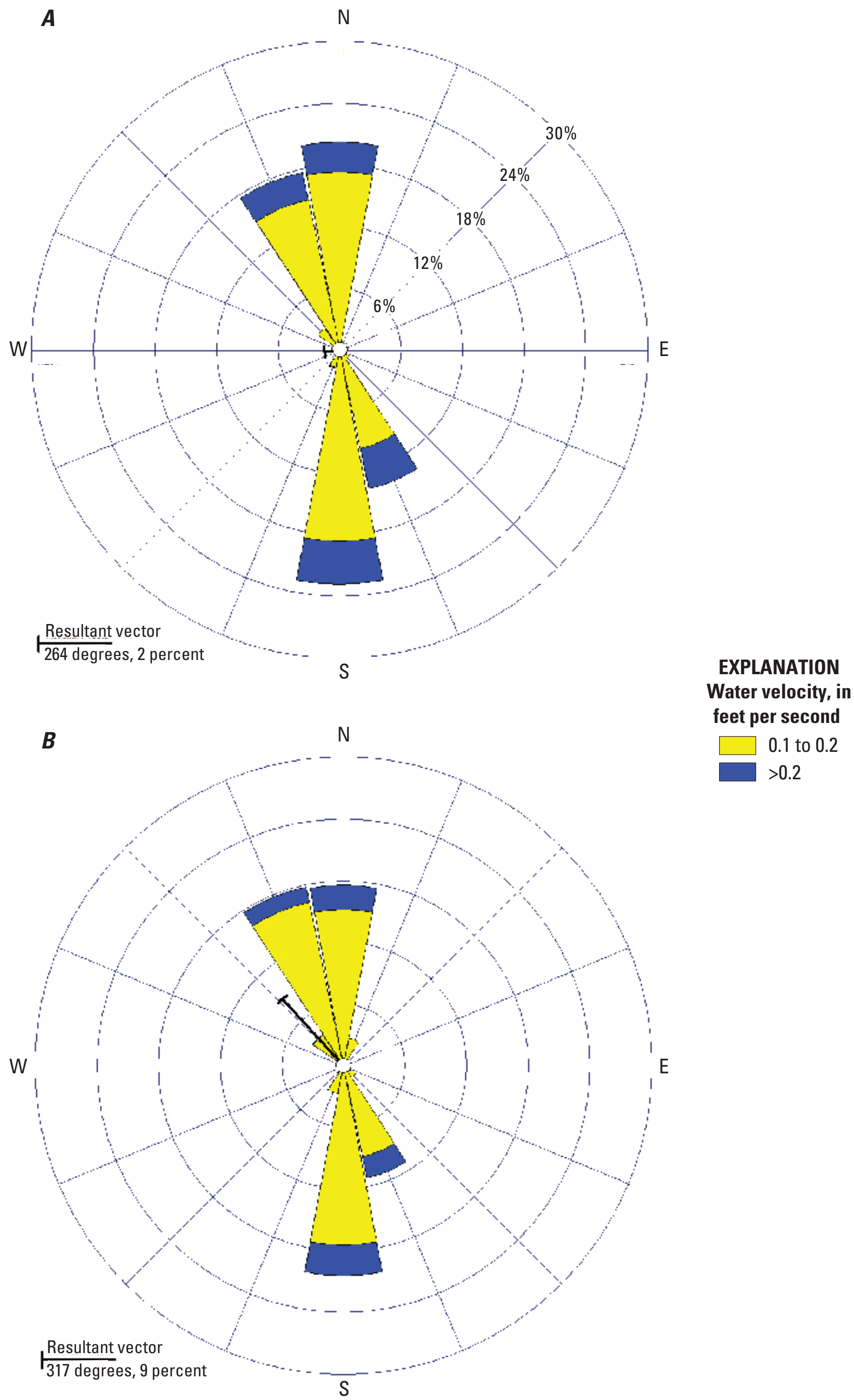


Figure 3–2. Rose diagram of velocity vectors for site VVP2 for the days in 2014 that the Williams Station was *A,* not withdrawing water and *B,* withdrawing water.

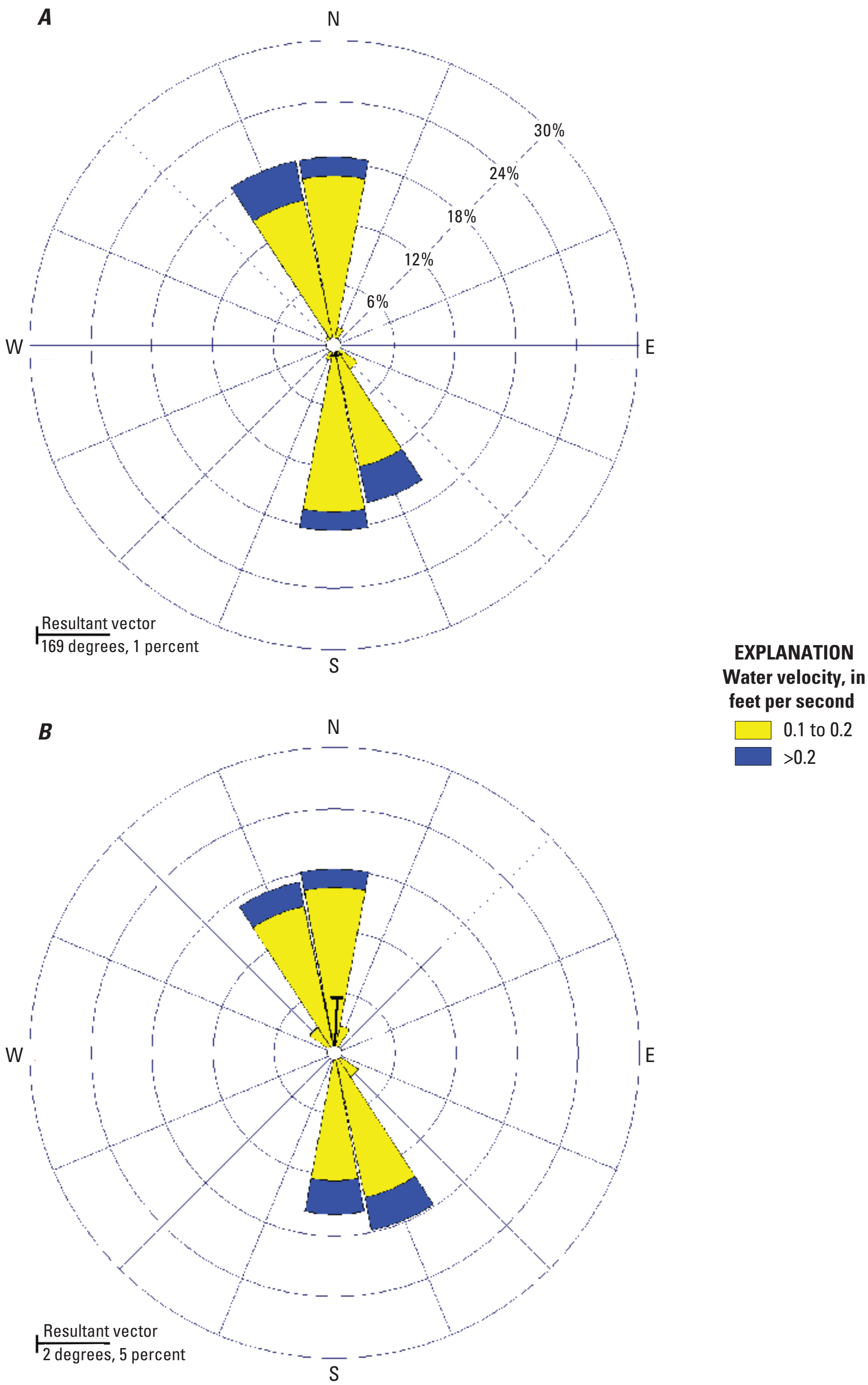


Figure 3–3. Rose diagram of velocity vectors for site VVP2 for the days in 2015 that the Williams Station was *A,* not withdrawing water and *B,* withdrawing water.

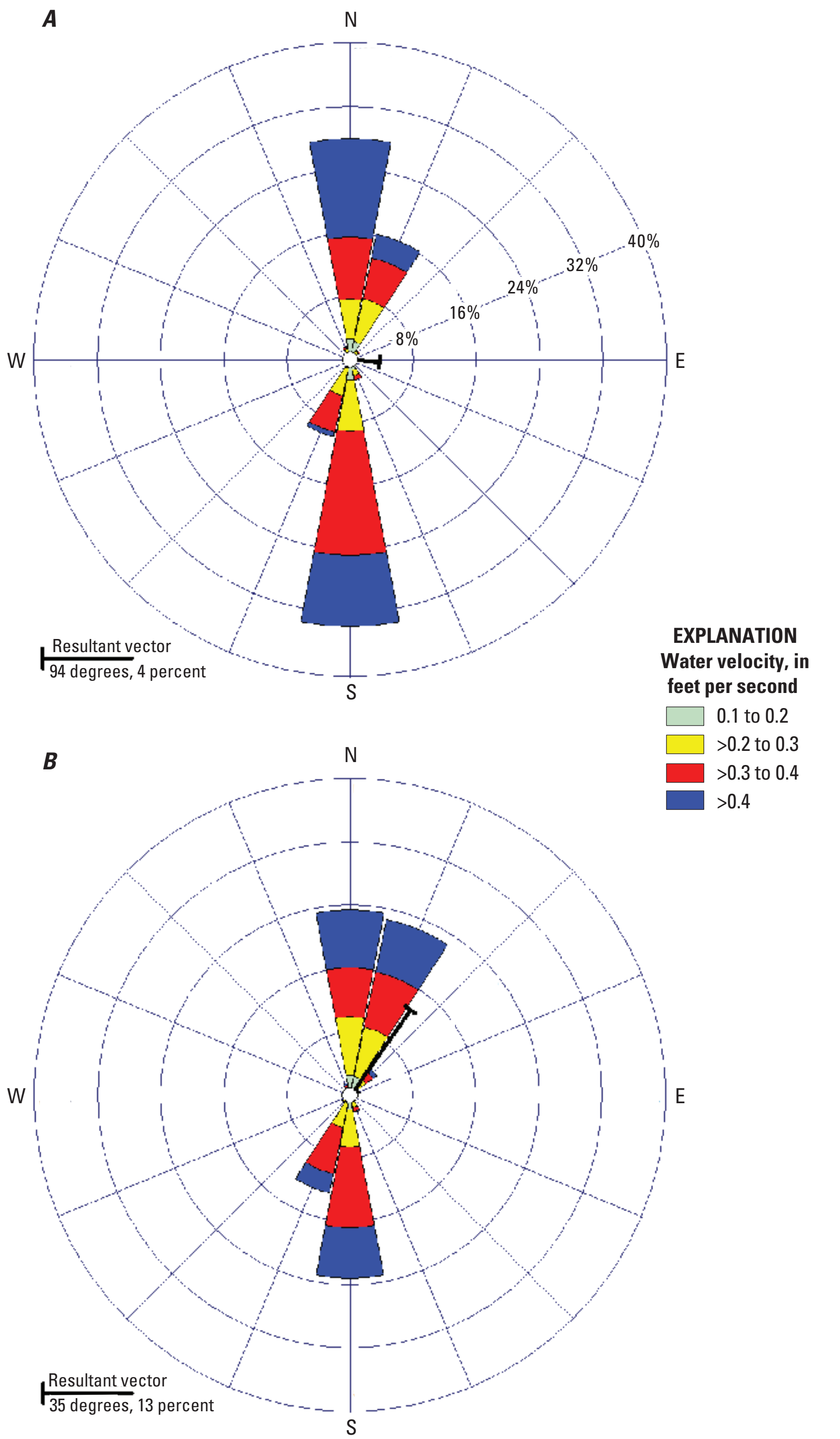


Figure 3–4. Rose diagram of velocity vectors for site VVP3 for the days in 2014 that the Williams Station was *A,* not withdrawing water and *B,* withdrawing water.

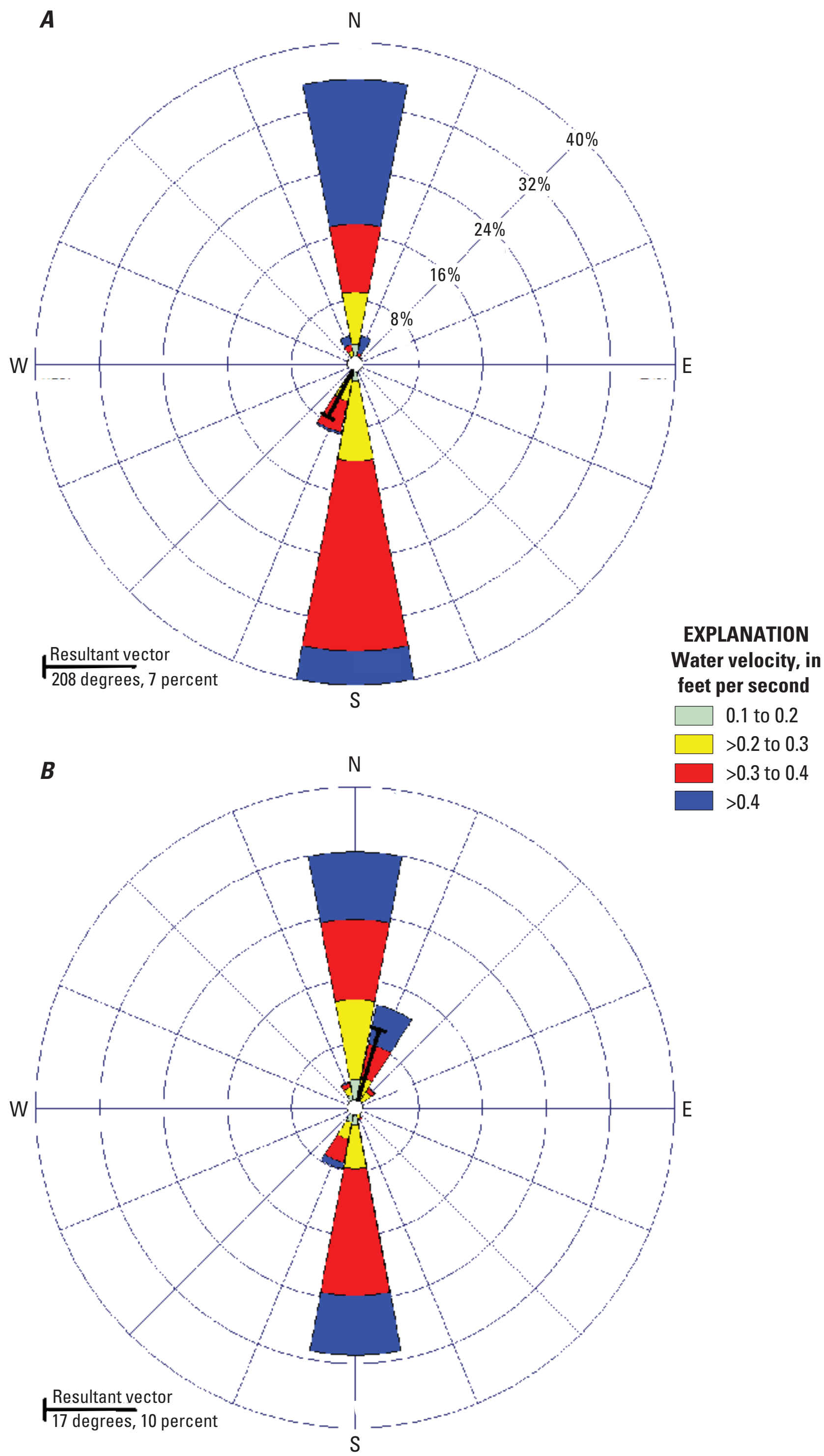


Figure 3–5. Rose diagram of velocity vectors for site VVP3 for the days in 2015 that the Williams Station was *A,* not withdrawing water and *B,* withdrawing water.

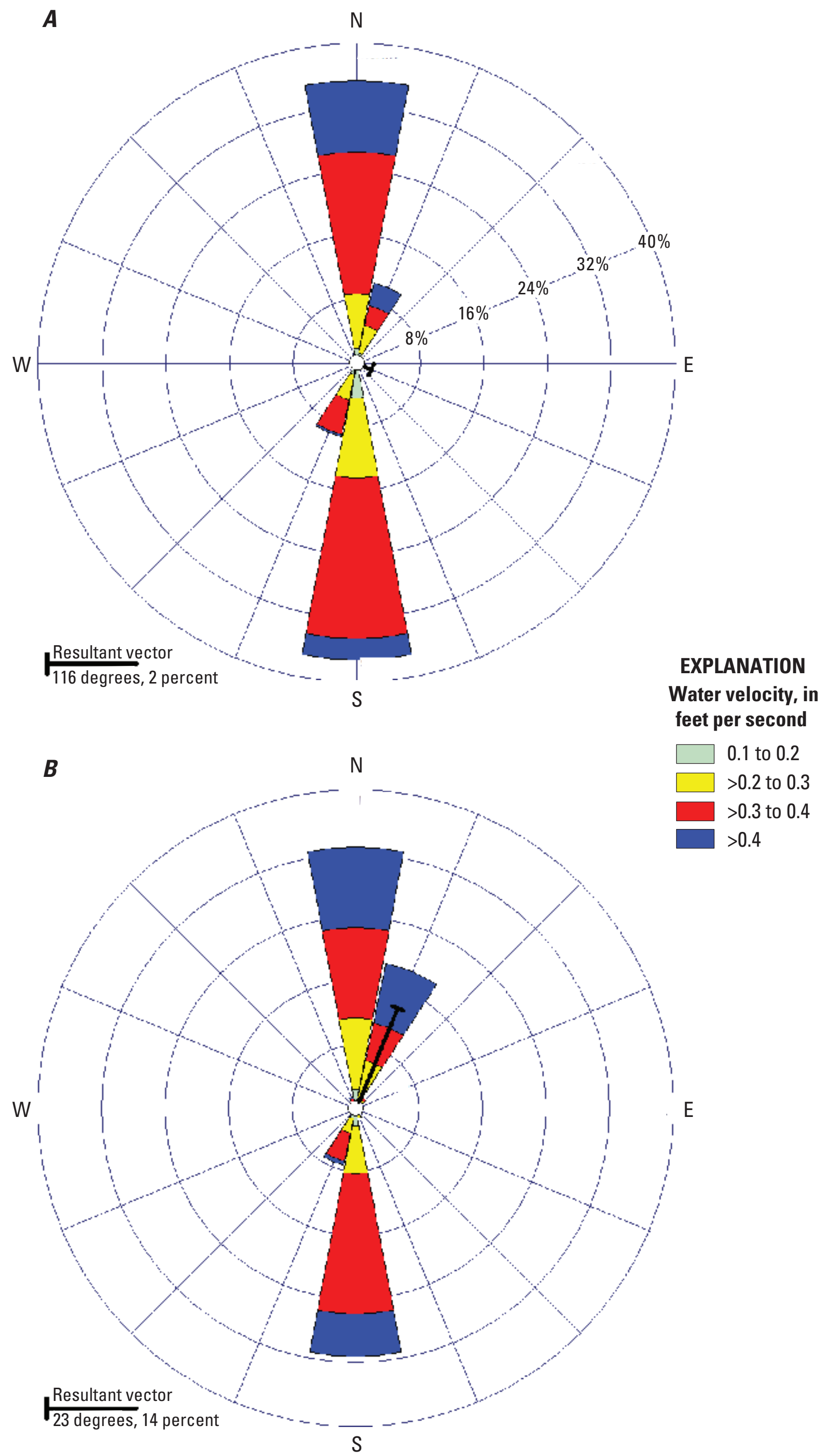
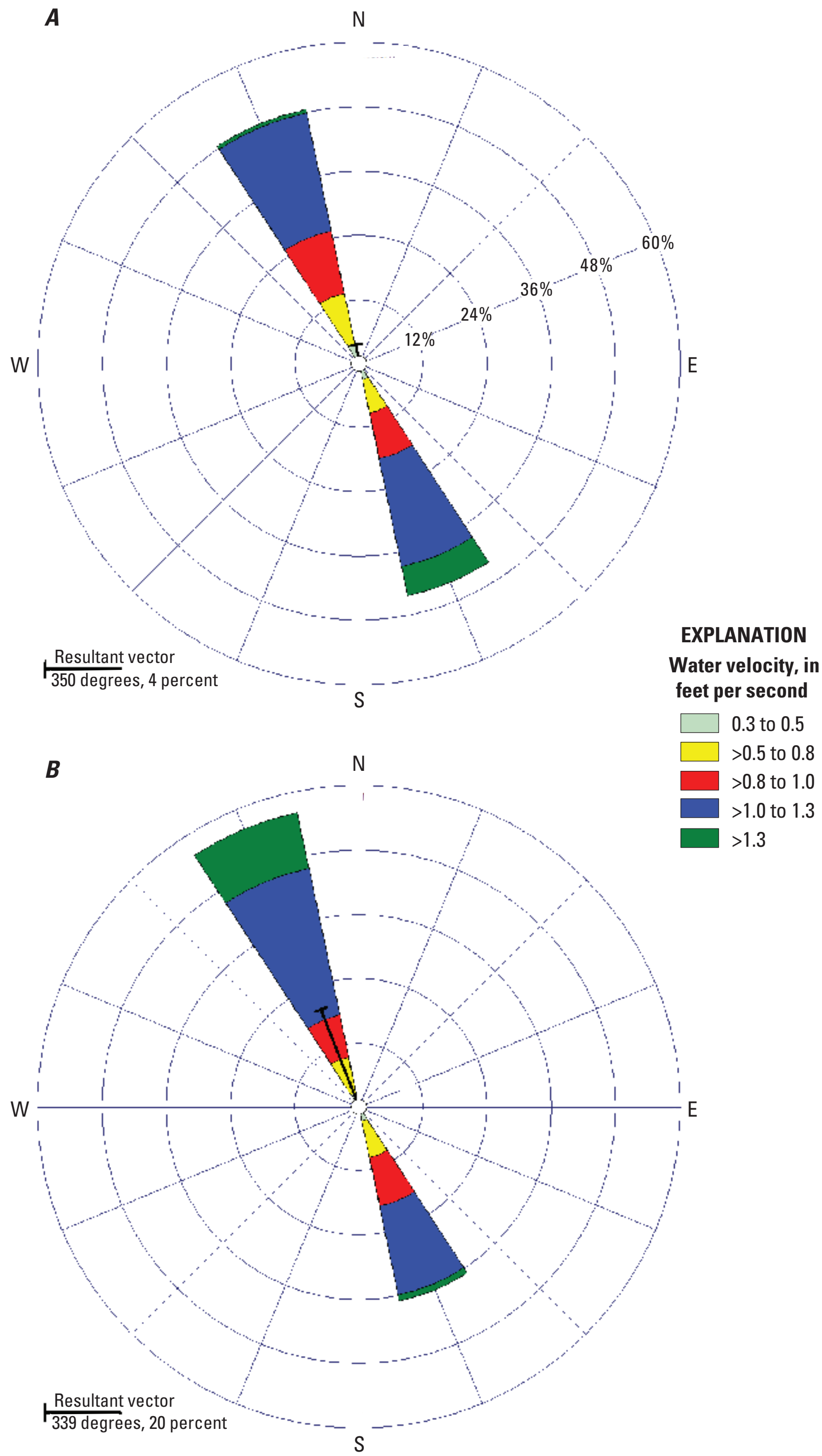


Figure 3–6. Rose diagram of velocity vectors for site VVP3-East for the days in 2014 that the Williams Station was *A,* not withdrawing water and *B,* withdrawing water.



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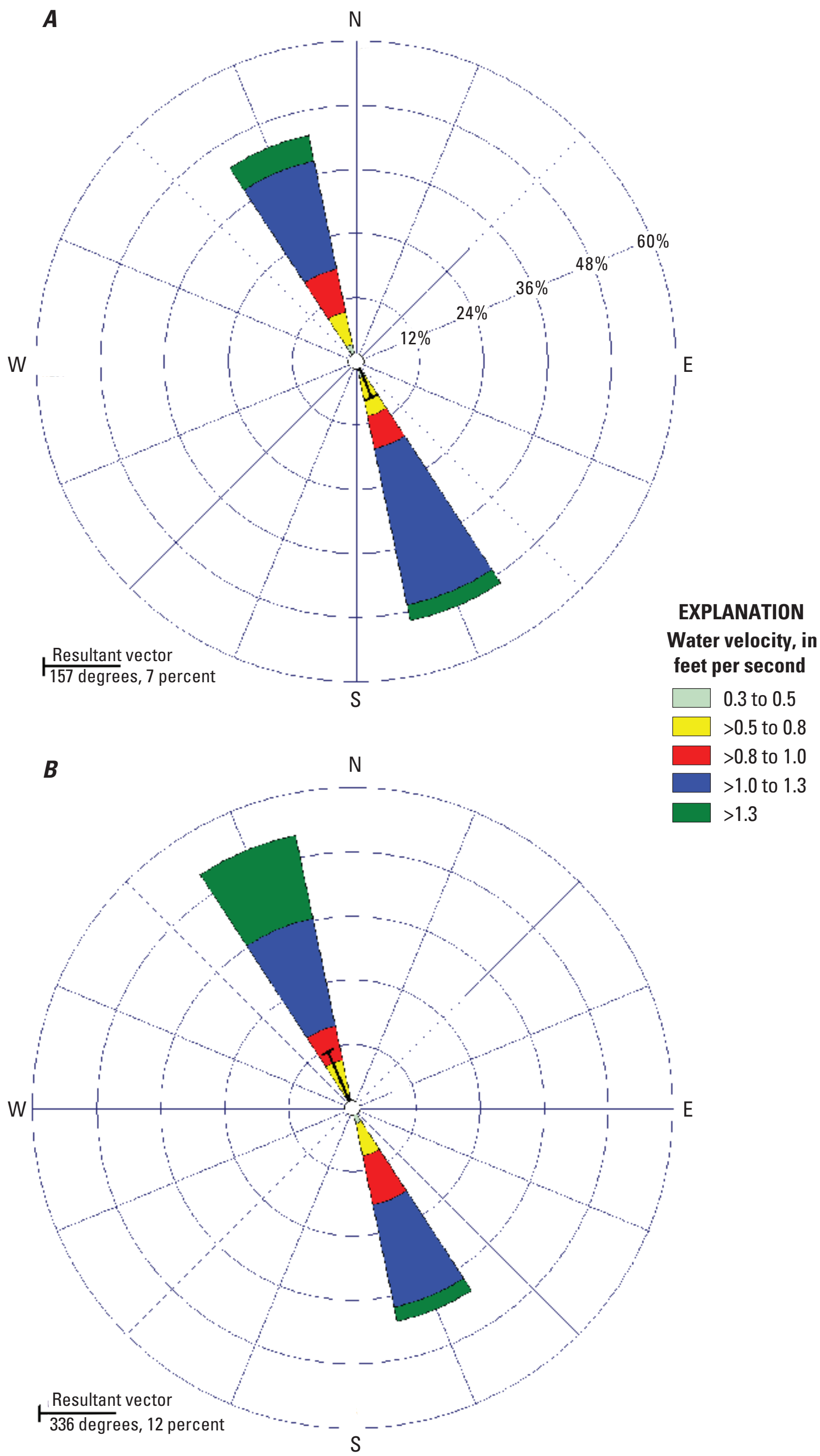

Figure 3–8. Rose diagram of velocity vectors for site VVP3 for the days in 2015 that the Williams Station was *A,* not withdrawing water and *B,* withdrawing water.

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