Prepared in cooperation with the Friends of Herring River

# Hydrogeology and Interactions of Groundwater and Surface Water Near Mill Creek and the Herring River, Wellfleet, Massachusetts, 2017–18

Scientific Investigations Report 2019–5145

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

**Cover.** Front: U.S. Geological Survey tide gage 011058798, Herring River at Chequessett Neck Road at Wellfleet, Massachusetts, December 2018. The tide gage measures water stage on the downstream side of the Herring River tide-control structure. Photograph by John Mullaney, U.S. Geological Survey. Back: Herring River and Mill Creek area, Wellfleet, Massachusetts, February 27, 2018. Image from Google, 2018.

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DAVID BERNHARDT, Secretary

**U.S. Geological Survey**
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## Tables

# Conversion Factors

U.S. customary units to International System of Units

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 2.54 | centimeter (cm) |
| inch (in.) | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | Area | |
| acre | 0.4047 | hectare (ha) |
| square mile ($mi^2$) | 259.0 | hectare (ha) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | Volume | |
| ounce, fluid (fl. oz) | 29.57 | milliliter (mL) |
| | Pressure | |
| pound per square inch ($lb/in^2$) | 6.895 | kilopascal (kPa) |
| | Precipitation | |
| inch per day (in/d) | 25.4 | millimeter per day (mm/d) |
| | Hydraulic conductivity | |
| foot per day (ft/d) | 0.3048 | meter per day (m/d) |
| | Transmissivity | |
| foot squared per day ($ft^2/d$) | 0.09290 | meter squared per day ($m^2/d$) |

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

$$°F = (1.8 \times °C) + 32.$$

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

$$°C = (°F – 32) / 1.8.$$

# 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).

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

# Abbreviations

| | |
|---|---|
| CYCC | Chequessett Yacht and Country Club |
| GOES | Geostationary Operational Environmental Satellite (National Oceanic and Atmospheric Administration) |
| lidar | light detection and ranging |
| NPS | National Park Service |
| NWIS | National Water Information System |
| NWS | National Weather Service |
| $R^2$ | coefficient of determination |
| USGS | U.S. Geological Survey |

# Hydrogeology and Interactions of Groundwater and Surface Water Near Mill Creek and the Herring River, Wellfleet, Massachusetts, 2017–18

By John R. Mullaney,[1] Janet R. Barclay,[1] Kaitlin L. Laabs,[1] and Katherine D. Lavallee[2]

## Abstract

Groundwater levels and stream stage were monitored by the U.S. Geological Survey, in cooperation with the Friends of Herring River, at 19 sites in the Mill Creek Basin, a tributary of the Herring River in Wellfleet, Massachusetts, on outer Cape Cod, to provide baseline data prior to a proposed restoration of tidal flow to the Herring River estuary at the Cape Cod National Seashore. Tidal flow in the Herring River has been restricted by a tide-control structure since 1909. Baseline data are necessary to understand current conditions and provide information on water levels for comparison to future water levels under the proposed Herring River restoration, which includes restoration of salt marshes by enhancing tidal flow to the Herring River and construction of a tide-control structure on Mill Creek to prevent the flooding of upstream private properties, including a golf course.

Analysis of data collected during monitoring-well installation at eight locations on or near the golf course and Mill Creek, along with analysis of existing information, determined that parts of the study area are underlain by salt marsh deposits up to 18 feet (ft) thick. These marsh deposits are directly underlain by estuarine sediments, and adjacent upland areas are underlain by medium to very coarse sand. The freshwater lens on the golf course is 70 ft thick or more.

Groundwater levels at individual wells in the study area fluctuated by 1.3 to 2.6 ft during the study period (June 1, 2017, to June 14, 2018). Total precipitation during this period was 60.8 inches, about 10 inches greater than the long-term (2000–17) annual average (50.3 inches). Groundwater levels on Cape Cod generally were normal to above normal during the study owing to the higher than normal precipitation. Tidal amplitudes of groundwater levels caused by daily fluctuations at nearby tidal waterbodies (M2 tidal harmonic) were as large as 0.12 ft at a well 105 ft from the tidally restricted Herring River and as large as 0.06 ft at a well 575 ft from Wellfleet Harbor. Tidal fluctuations in groundwater levels were generally limited to areas about 1,500 ft from the nearest tidal waterbody. Under the initial proposed restoration, where mean tides would be maintained similar to current conditions, tidal fluctuations would be restored to parts of Mill Creek, and subsequent tidal fluctuations in groundwater levels could increase at some of the areas closest to the proposed tide-control structure, but the fluctuations would be less than about 0.06 ft in magnitude.

Regression models were used to describe the variability of daily mean tidally filtered groundwater levels and daily maximum stream stage in Mill Creek. Significant independent variables for the groundwater-level model included daily tidally filtered Wellfleet Harbor stage with a lag time of zero to 2 days, 7-day precipitation, the growing degree days (50 degrees Fahrenheit), and the quartile of groundwater levels relative to a long period of record at a nearby observation well.

Significant independent variables to predict the Mill Creek stage included daily mean groundwater levels in nearby wells, 7-day precipitation, growing degree days (50 degrees Fahrenheit), and a binary indicator of either a flooded or non-flooded condition on the golf course near Mill Creek. Flooding in Mill Creek occurred primarily when groundwater levels at nearby wells reached certain thresholds, when the precipitation in the preceding 7 days was at least 0.92–1.04 inches, and during the nongrowing season.

## Introduction

The Herring River estuary is in the towns of Wellfleet and Truro, Massachusetts, on Cape Cod Bay (fig. 1). Prior to 1909, the Herring River estuary and flood plain was the largest tidal river and estuary complex on outer Cape Cod and included about 1,100 acres of salt marsh, intertidal flats, and open-water habitats (National Park Service and others, 2016). The natural tidal flow of the Herring River has been limited since the construction, in 1909, of a dike with tide gates (tide-control structure) near the mouth of the river at Chequessett Neck Road (fig. 2). Currently, the typical tide range on the upstream side of the Herring River tide-control structure is about 2.2 feet (ft), whereas on the downstream side of the tide-control structure (Wellfleet Harbor) it is about 10.3 ft. Consequently, the land in

[1]U.S. Geological Survey.

[2]National Park Service.

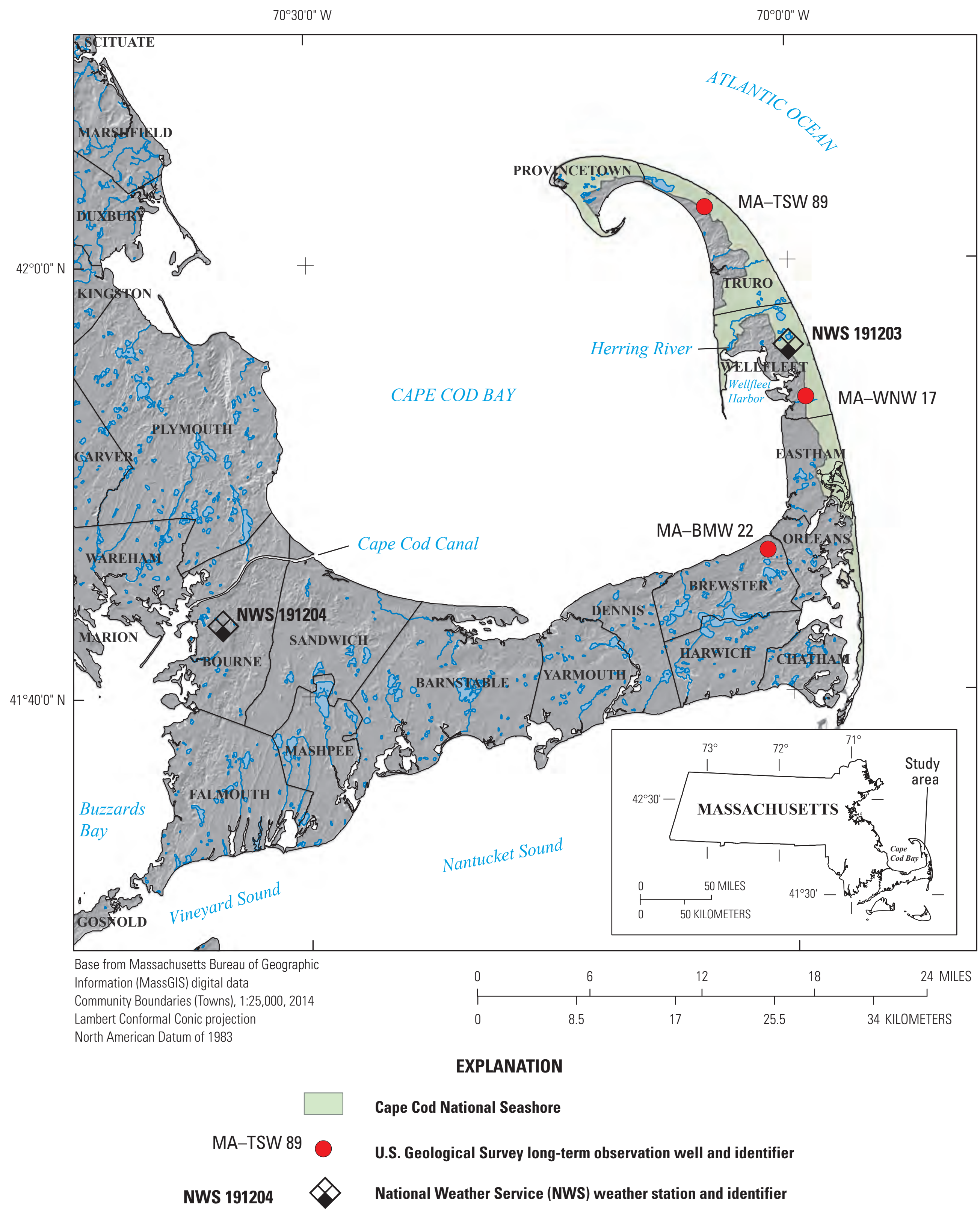


**Figure 1.** Location of the study area, Wellfleet, Massachusetts.

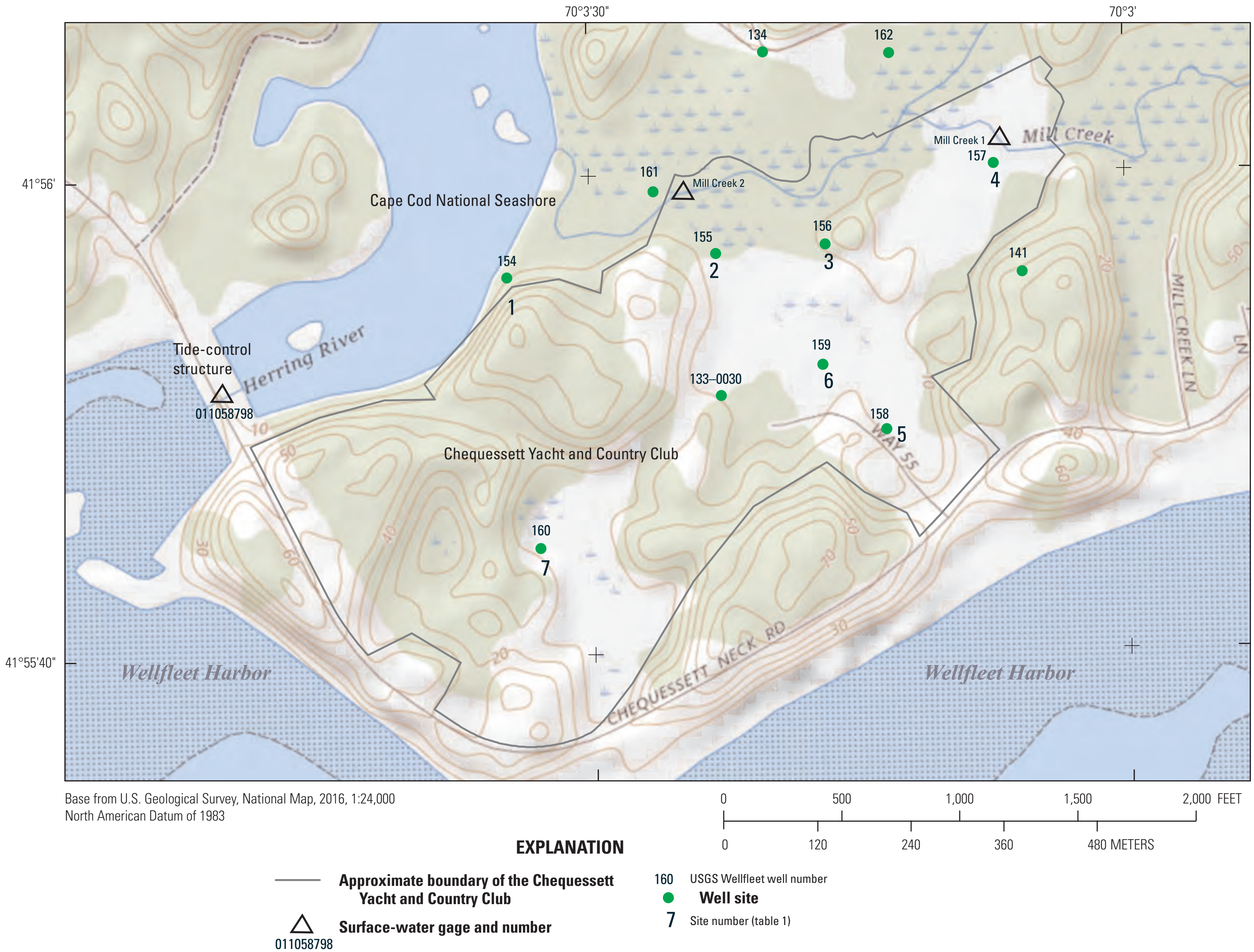


**Figure 2.** Data collection locations, in the Mill Creek study area, Wellfleet, Massachusetts.

some low-lying areas of the Herring River watershed that previously flooded at high tide was developed, including private homes and a golf course along the Mill Creek tributary.

The Herring River is separated from Wellfleet Harbor by the Chequessett Neck Road dike. The dike has three 6-ft-wide box culverts, each with an attached flow-control structure. One culvert has an adjustable sluice gate that is currently set partially open at 2 ft and allows limited bidirectional tidal flow. The remaining two culverts have tidal flap gates, designed to permit flow only during outgoing (ebbing) tides (National Park Service and others, 2016).

The restriction of the tide in the Herring River has had numerous effects upstream from the Herring River tide-control structure, including, but not limited to, plant community changes, loss of estuarine habitat, degradation of water quality, and alteration of natural sediment processes, leading to marsh subsidence, nuisance mosquito populations, restriction of river herring migration, lack of carbon storage and consequent increases in methane emissions. The lower Herring River Basin currently contains subtidal, riverine, vegetated wetland, and fringing upland flood plains. Habitat in the Mill Creek Basin is primarily *Phragmites* marsh and disturbed, wooded wetland (National Park Service and others, 2016).

To eventually eliminate many of these problems, research and planning to restore the habitats upstream from the Herring River tide-control structure have been ongoing for several decades. In the Environmental Impact Statement/Report completed for the project (National Park Service and others, 2016), the goals include restoration of tidal flow to a large part of the 1,100 acres of habitat that were degraded by the presence of the tide-control structure, with a minimal impact to private properties and cultural resources. Detailed restoration goals are described by the National Park Service and others (2016).

The current (2019) preferred restoration alternative in the Environmental Impact Statement/Report for the Herring River is identified as alternative D, which includes a new tide-control structure at Chequessett Neck Road and the installation of an additional tide-control structure on Mill Creek to prevent tidal flooding of the Chequessett Yacht and Country Club (CYCC) and some residential properties. The objective for alternative D is to fully open the new gates gradually to allow mean high water spring tides up to 5.6 ft above the North American Vertical Datum of 1988 (NAVD 88) and coastal storm-driven tides up to 7.5 ft above NAVD 88 in the Lower Herring River. Alternative D provides the highest possible altitudes of water surface at high tide, given the constraints of current land use in the flood plain (fig. 3). The gradual opening of the gates would allow for incremental evaluation of the effects of the higher tides on restoration objectives and private properties.

The tide-control structure to be constructed on Mill Creek would limit upstream movement of the tide, providing partial tidal restoration, while allowing freshwater to drain from the upstream Mill Creek Basin. To facilitate downstream movement of freshwater, a pumping system is being designed so that Mill Creek does not back up and cause nuisance flooding during high tides or during periods of high precipitation during storms.

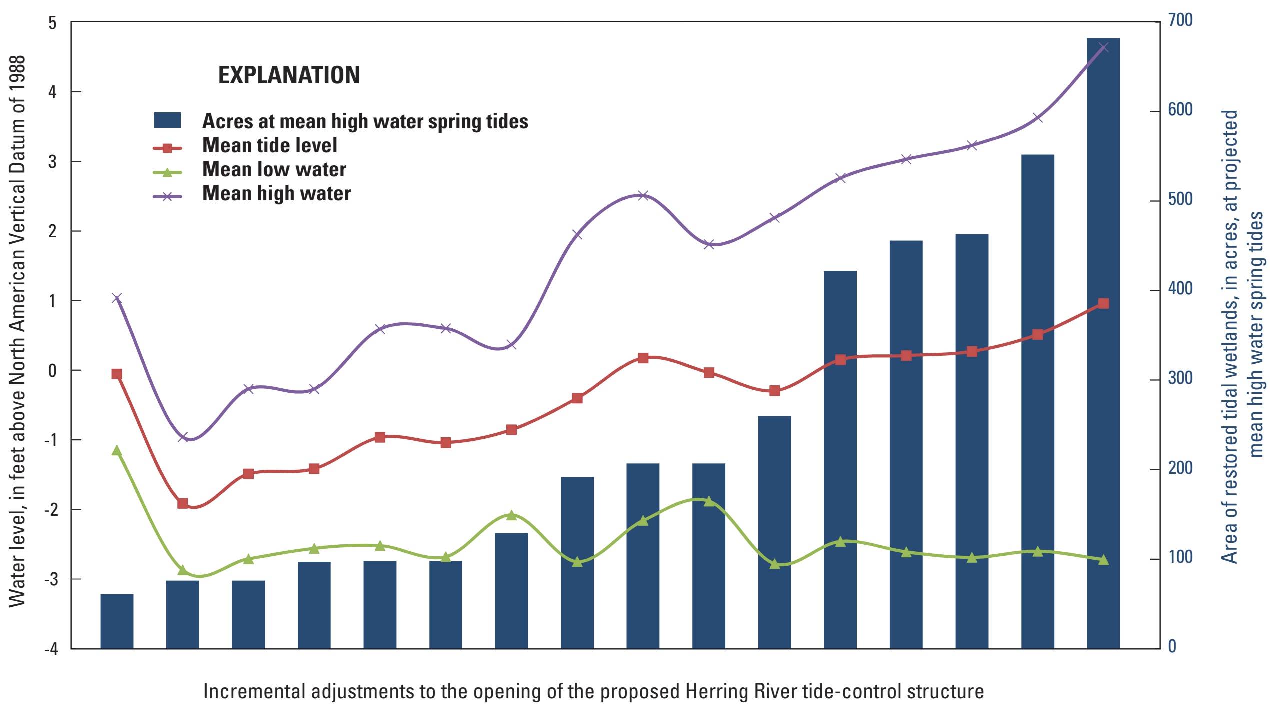


**Figure 3.** Tidal stage and acres of submerged wetlands at mean spring high tide for incrementally restoring tidal flow in the Herring River, Wellfleet, Massachusetts.

Parts of the CYCC currently flood periodically (fig. 4), affecting operations of the golf course during wet periods. Several of the fairways on the golf course are built on former low-lying salt marsh sediments that have compacted and caused land subsidence because of the loss of tidal flow to these areas. Although a mitigation plan that would elevate and regrade low parts of the golf course has been agreed to in concept, there is concern about increased flooding on the golf course caused by high groundwater levels or tidal flooding in Mill Creek.

To understand the hydrogeology of the Mill Creek/Herring River area, the U.S. Geological Survey (USGS) entered into a cooperative agreement with the Friends of Herring River in 2016 to conduct a study of the area from June 1, 2017, to June 14, 2018. The study provides baseline information prior to the beginning of the Herring River restoration. The objectives of this study were to (1) determine water-table conditions and stream-aquifer interaction during the prerestoration period and (2) acquire additional subsurface geologic and aquifer data to better define the hydrogeologic framework in the study area. This information can be used if new groundwater-flow models need to be developed, or if existing models need to be revised, to aid in adaptive management planning and further evaluation of the effects of restoration scenarios.

## Purpose and Scope

This report describes the hydrogeology of the Mill Creek area near the Herring River estuary on Cape Cod in Wellfleet, including the surficial geology, hydrologic properties of the aquifer, and fluctuations in groundwater and Mill Creek levels caused by precipitation and tidal fluctuations of the lower Herring River estuary upstream and downstream from a tide-control structure. The information in the report was collected from June 2017 to June 2018 and is intended to provide a baseline of the groundwater and surface-water levels in the study area prior to the restoration of the Herring River marsh.

**Figure 4.** Flooding at the Chequessett Yacht and Country Club in Wellfleet, Massachusetts, on May 1, 2018, when the daily maximum stage at the Mill Creek downstream site was 1.33 feet above the North American Vertical Datum of 1988. Photograph by Katherine Lavallee, National Park Service.

Information presented in this report may have applicability to similar geologic settings where the groundwater and tidal waterbodies interact. Data collected in this study are stored in the USGS National Water Information System (NWIS) database and publicly available (U.S. Geological Survey, 2018), or are reported in a USGS data release Mullaney and Barclay (2020).

## Site Description

The Herring River watershed is underlain by the Wellfleet plain glacial meltwater sediments described by Oldale (1992). These sediments were deposited by meltwater from the Cape Cod Bay and South Channel lobes of the glacial ice sheets that were retreating from Cape Cod about 15,000 years ago. The sediments were deposited as deltas in Glacial Lake Cape Cod, a lake that persisted in Cape Cod Bay when the ice from the retreating glacier blocked the northern part of the bay. The highest altitudes of the Wellfleet plain deposits near the mouth of the Herring River are currently about 80 ft above NAVD 88. The altitudes gradually increase to about 130 ft toward the east (Atlantic Ocean) side of lower Cape Cod. The lithology of the deposit is typically fine to coarse sand, with finer materials at depth (LeBlanc and others, 1986).

The Herring River and Mill Creek are in low-lying valleys thought to be created during deglaciation by the process of spring sapping, where a large volume of glacial meltwater was dammed by the outwash sediment, and a high volume of groundwater was forced through the sediments, causing erosion of these valleys (Oldale, 1992). The valleys now contain salt marsh sediments, the oldest of which were deposited more than 2,000 years before present (Oldale, 1992) as postglacial sea levels rose and inundated these low-lying coastal areas. The depth to bedrock in the area is about 490 ft based on information published by Lane and others (2008).

The Herring River drains parts of the towns of Wellfleet and Truro on lower Cape Cod to Wellfleet Harbor at the mouth, which is connected to Cape Cod Bay (fig. 1). The freshwater discharge in the Herring River system is dominated by groundwater flow; because of the permeable nature of sediments on lower Cape Cod, there is only a small amount of surface runoff. The Herring River drains a large part of the Chequessett groundwater-flow lens on Cape Cod as described by Masterson (2004). The estimated area contributing groundwater to the Herring River is about 7.4 square miles ($mi^2$), based on modeling described in Carlson and others (2017). Mill Creek is a subbasin of the Herring River that has a surface drainage area of about 0.5 $mi^2$; however, as is the case for the entire Herring River watershed, the discharge is dominated by groundwater flow and, because of the permeable nature of the sediments, the surface-water and groundwater basins are not coincident. The groundwater drainage divide between the Herring River and Mill Creek Basins and Wellfleet Harbor crosses the CYCC from east to west about 600–1,000 ft from Wellfleet Harbor (Carlson and others, 2017). The thickness of fresh groundwater (from the water table to salty groundwater) near the Herring River/CYCC study site ranges from 37 ft at USGS well MA–WNW 133 to 55 ft at USGS well MA–WNW 134 (shown on fig. 2) (Masterson, 2004; Martin, 2004, 2007).

Additional lithologic information for the study area is available from two recent studies. In March 2014, four borings were drilled at the site of a former dike (near the proposed future tide-control structure) on Mill Creek (Fuss and O'Neill, Inc., 2014). Borings were advanced to depths ranging from 41 to 71 ft. A piezometer was installed at one location (WNW 161, figs. 2 and 5) and screened at a depth of 8–18 ft, and slug tests were conducted to determine the hydraulic conductivity of aquifer materials. Hydraulic conductivity from these tests ranged from 5 to 14 feet per day (ft/d). A series of geotechnical tests were conducted on samples from these boring sites. Lithologic materials from these borings were typically fine to medium sand, but some silty and clayey layers were present.

A series of eight borings (fig. 5) was completed at the CYCC in 2009 (The Louis Berger Group, Inc., 2009). The purpose of the borings was to conduct geotechnical tests on the load-bearing properties of the soils in areas where filling and excavation have been proposed to eliminate flooding on the golf course under the preferred restoration alternative. A fine-grained silty organic layer 1–18 ft thick and containing peat (salt marsh deposits) was present at six of the eight locations. Beneath this layer was generally fine to medium sand, with some medium to coarse sand. The approximate area of the former salt marshes was determined through the use the information from the two studies described above, and from site visits to inspect the geology and landforms of the study area. The extent of former salt marsh was determined to be approximated by areas with altitudes less than 3.5 ft above NAVD 88 (fig. 5).

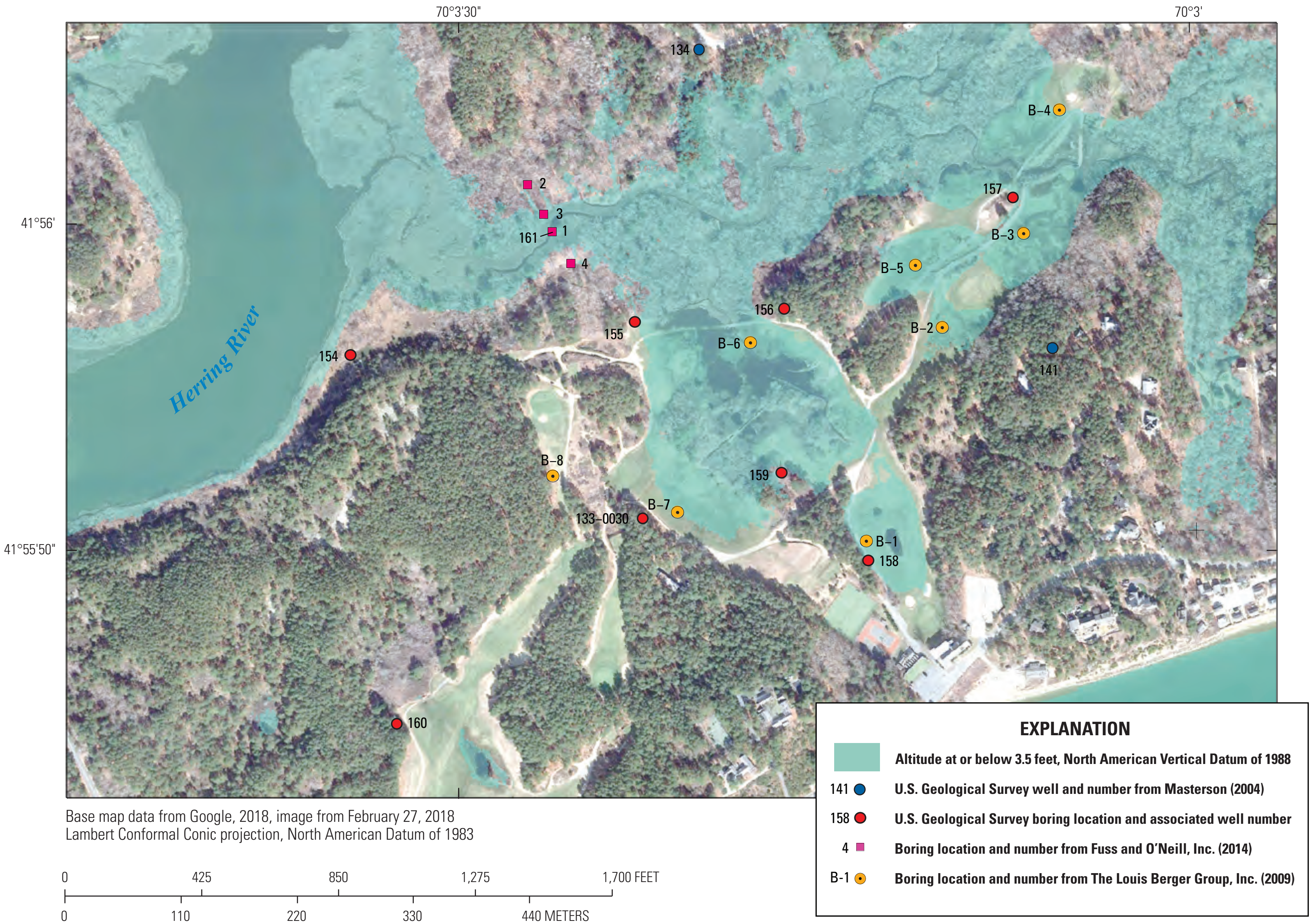


**Figure 5.** Approximate location of former salt marsh areas and locations with lithologic information collected during this study and previous investigations, Wellfleet, Massachusetts.

# Methods of Data Collection and Analysis

To establish a water-level network in the Herring River and Mill Creek study area, existing wells were inventoried. Four existing wells were located, including two USGS wells—MA–WNW 141 and MA–WNW 134—installed during a study by Masterson (2004) (figs. 2 and 5). These wells were originally installed to determine the depth to the freshwater/saltwater interface and were constructed with a deep sump and a shallow screen so that geophysical measurements could be made. In addition to the USGS wells, a well from a study of the subsurface of Mill Creek (Fuss and O'Neill, Inc., 2014, fig. 5) near the proposed Mill Creek tide-control structure and an additional well previously monitored by the National Park Service (NPS) on Old Chequessett Road (Martin and Medeiros, 2012) also were located (sites MA–WNW 161 and MA–WNW 162, respectively, fig. 2).

To collect lithologic information, and to establish baseline information on water-table altitudes, groundwater-level fluctuations, and fluctuations in stream stage in Mill Creek, new wells were installed at eight sites on the CYCC, including the replacement of one USGS well (MA–WNW 133) from a previous study, and sites were established to measure stream stage on Mill Creek at the CYCC and downstream from the golf course to improve understanding of the interaction between Mill Creek and groundwater levels.

## Drilling and Well Installation

Wells were installed at seven of the eight sites by use of a direct-push drilling technique during the week of May 15, 2017. At each location, a continuous core was collected to the approximate depth of the freshwater/saltwater transition zone. The core was logged, and subsamples were retained. To identify the top of the transition zone from freshwater to saltwater, specific conductance of pore water from each core was measured. In addition to measuring the specific conductance of the pore water, specific conductance also was measured in the field and in the laboratory by adding deionized water to subsamples of core material. The sample was prepared by adding 50 milliliters (mL) of sediment and adding enough deionized water so that the total volume was 150 mL. The specific conductance was then measured in the water/sediment slurry. Whereas the first method to measure specific conductance was done in situ and provided actual measurements of specific conductance of pore water, the second method was used to verify changes that might indicate the position of the top of the transition zone.

Following the collection of the continuous core, the direct-push drill rig was fitted with a temporary steel casing that was driven to the depth of interest for well installation. A 2-inch-diameter flush-jointed polyvinyl chloride casing and a 5-ft-long 0.010-inch-slot (number 10) screen were set in the temporary steel casing, which was then withdrawn from the boring.

Wells were installed at multiple depths at four sites (sites 2, 3, 4, and 6, fig. 2). At three of the sites (sites 2, 3, and 6, fig. 2), shallow and deep wells were installed, the former near the top of the saturated zone and the latter just above the transition zone from freshwater to saltwater. The depths of the well screens were selected based on the geology identified in the core samples. At site 4 (fig. 2), a third well was installed that penetrated through the transition zone to allow future electromagnetic borehole logging. This well was installed with a deep sump and screened at an intermediate depth to ensure that there was only freshwater in the well. Wells were completed by retrieving the temporary casing and allowing the formation to collapse around the well screens. A bentonite seal was emplaced near or at the water table, and the well was finished, depending on the location at the CYCC, with a standpipe or a flush-mounted well cover set in a concrete pad.

An additional well was installed near the Herring River (site 1, fig. 2) by using hand tools because the site was not accessible to vehicles. The well was installed with the use of a hand auger and was driven to additional depth by using a posthole driver. The well was constructed of 1.5-inch-diameter stainless steel casing and a 2.5-ft-long wire-wound 0.010-inch-slot (number 10) screen (site 1, fig. 2).

The altitude of the measuring point on each well installed at the CYCC or near the Herring River was determined by using a differential laser-level survey. The laser-level survey was tied to NAVD 88 by using altitudes established by the NPS at the existing Herring River tide-control structure. All wells were developed by pumping and monitoring recovery to verify if there was a connection to the aquifer, and therefore responsive to water-level change in the formation. Information on the well characteristics, well construction, and lithologic logs is presented in table 1.

## Mill Creek and Herring River Stage Monitoring

Two locations for monitoring stream stage were established on Mill Creek: an upstream site between two fairways at the CYCC (Mill Creek 1), and a downstream site in the Mill Creek Marsh about 800 ft upstream from the Herring River (Mill Creek 2, fig. 2). The upstream location was installed by using a standpipe that was attached to a bridge that is part of a golf cart path at the CYCC. At the downstream location, no fixed points were available to attach equipment to monitor water stage; therefore, a fixed point was established by driving two sections of angle iron to a depth of 10 ft, where firm sediment was encountered. A well screen was pushed into the sediment and attached to the angle iron as a housing to measure stage. Reference points were established at both locations for determining water-surface altitude. These points were tied to the survey of the measuring points for the wells installed for the study.

**Table 1.** Well characteristics, construction details, and general lithologic information for wells in the Mill Creek study area, Wellfleet, Massachusetts.

[Dates are given in year, month, and day (yyyymmdd). Latitude and longitude are given in degrees (°), minutes (′), and seconds (″) referenced to the North American Datum of 1983. no., number; USGS, U.S. Geological Survey; ft NAVD 88, foot above the North American Vertical Datum of 1988; ft rls, foot relative to land surface; ft bls, foot below land surface; MA, Massachusetts; na, not available]

| Site no. (fig. 2) | USGS local identifier | Station identifier | Date of construction | Latitude | Longitude | Altitude (ft NAVD 88) | | Height of measuring point (ft rls) | Depth of well (ft bls) | Screen internal (ft bls) | | Geologic materials in contact with the well screen |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Measuring point | Land surface | | | Top | Bottom | |
| 1 | MA–WNW 154 WELLFLEET, MA | 415556070033501 | 20170531 | 41°55′55.82″ | 70°03′34.65″ | 7.83 | 5.43 | 2.4 | 10.1 | 7.6 | 9.6 | Very coarse sand and gravel. |
| 2 | MA–WNW 155–0035 WELLFLEET, MA | 415557070032301 | 20170516 | 41°55′56.69″ | 70°03′22.95″ | 3.31 | 3.78 | −0.47 | 34.54 | 29.54 | 34.54 | Fine sand to silt. |
| | MA–WNW 155–0017 WELLFLEET, MA | 415557070032302 | 20170516 | 41°55′56.69″ | 70°03′22.95″ | 3.45 | 3.83 | −0.38 | 16.98 | 11.98 | 16.98 | Fine sand and silt, and peat over medium sand. |
| 3 | MA–WNW 156–0037 WELLFLEET, MA | 415557070031701 | 20170516 | 41°55′57.03″ | 70°03′16.8″ | 4.74 | 5.14 | −0.4 | 37.41 | 32.41 | 37.41 | Very coarse to fine sand. |
| | MA–WNW 156–0010 WELLFLEET, MA | 415557070031702 | 20170516 | 41°55′57.03″ | 70°03′16.8″ | 4.63 | 5.05 | −0.42 | 10.55 | 5.55 | 10.55 | Medium sand to very coarse sand, some granules over medium sand to very fine sand. |
| 4 | MA–WNW 157–0033 WELLFLEET, MA | 415600070030701 | 20170517 | 41°56′00.31″ | 70°03′07.31″ | 4.04 | 4.4 | −0.36 | 32.71 | 27.71 | 32.71 | Very coarse to fine sand with few pebbles. |
| | MA–WNW 157–0070 WELLFLEET, MA | 415600070030702 | 20170519 | 41°56′00.31″ | 70°03′07.31″ | 4.24 | 4.54 | −0.3 | 67.6 | 15 | 25 | Very coarse to fine sand with some granules. |
| | MA–WNW 157–0012 WELLFLEET, MA | 415600070030703 | 20170517 | 41°56′00.31″ | 70°03′07.31″ | 3.96 | 4.3 | −0.34 | 11.74 | 6.74 | 11.74 | Very coarse sand to fine sand, with some pebbles and granules. |
| 5 | MA–WNW 158 WELLFLEET, MA | 415549070031401 | 20170515 | 41°55′49.26″ | 70°03′13.52″ | 2.85 | 3.17 | −0.32 | 9.52 | 4.52 | 9.52 | Very coarse sand with some granules. |
| 6 | MA–WNW 159–0035 WELLFLEET, MA | 415552070031701 | 20170518 | 41°55′51.99″ | 70°03′17.03″ | 2.99 | 3.43 | −0.44 | 32.9 | 27.9 | 32.9 | Very fine to fine sand, and silt. |
| | MA–WNW 159–0012 WELLFLEET, MA | 415552070031702 | 20170518 | 41°55′51.99″ | 70°03′17.03″ | 6.44 | 3.34 | 3.1 | 11.79 | 6.79 | 11.79 | Medium to very coarse sand with some granules and few pebbles. |
| 7 | MA–WNW 160 WELLFLEET, MA | 415544070033301 | 20170515 | 41°55′44.49″ | 70°03′33.01″ | 5.33 | 5.74 | −0.41 | 12.18 | 7.18 | 12.18 | Coarse sand to very coarse sand with some granules and few pebbles over fine to medium sand. |

**Table 1.** Well characteristics, construction details, and general lithologic information for wells in the Mill Creek study area, Wellfleet, Massachusetts.—Continued

[Dates are given in year, month, and day (yyyymmdd). Latitude and longitude are given in degrees (°), minutes (′), and seconds (″) referenced to the North American Datum of 1983. no., number; USGS, U.S. Geological Survey; ft NAVD 88, foot above the North American Vertical Datum of 1988; ft rls, foot relative to land surface; ft bls, foot below land surface; MA, Massachusetts; na, not available]

| Site no. (fig. 2) | USGS local identifier | Station identifier | Date of construction | Latitude | Longitude | Altitude (ft NAVD 88) | | Height of measuring point (ft rls) | Depth of well (ft bls) | Screen internal (ft bls) | | Geologic materials in contact with the well screen |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Measuring point | Land surface | | | Top | Bottom | |
| na | MA–WNW 133–0030 WELLFLEET, MA | 415550070032202 | 20170518 | 41°55′50.67″ | 70°03′22.75″ | 12.81 | 13.15 | −0.34 | 29.62 | 24.62 | 29.62 | Medium to coarse sand, little fine sand. |
| na | MA–WNW 141 WELLFLEET, MA | 415556070030601 | 20040909 | 41°55′55.68″ | 70°03′05.8″ | 44.29 | 44.67 | −0.38 | 135.38 | 50.38 | 55.38 | na |
| na | MA–WNW 161 WELLFLEET, MA | 415559070032601 | 20140317 | 41°55′59.32″ | 70°03′26.38″ | 2.94 | 0.39 | 2.55 | 17.15 | 7.15 | 17.15 | na |
| na | MA–WNW 134 WELLFLEET, MA | 415605070032001 | 20030911 | 41°56′05.02″ | 70°03′20.12″ | 5.27 | 5.51 | −0.24 | 104.21 | 9.21 | 14.21 | Fine to very fine sand, some silt. |
| na | MA–WNW 162 WELLFLEET, MA | 415605070031301 | na | 41°56′04.98″ | 70°03′13.06″ | 3.99 | 3.51 | 0.48 | 4.87 | na | na | na |

Data for the Herring River stage (tidal gage 011058798, fig. 2) were collected by the USGS for another project to monitor water quality in the Herring River system. Stage data were collected from the upstream side of the Herring River tide-control structure (Herring River) at 5-minute intervals by using a pressure transducer and bubbler system. These data were available during the entire study. Data on Herring River stage downstream from the Herring River tide-control structure (Wellfleet Harbor) were collected beginning in September 2017 at 15-minute intervals by using a radar system over the water. The stage data were used in the analysis of the effects of the Herring River and Wellfleet Harbor tidal fluctuations on groundwater levels in the study area. Data were transmitted to the USGS National Water Information System (NWIS) database either by mobile phone modem or satellite transmitter and ground station to the National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellite (GOES).

## Measurement and Processing of Water-Level Data

Continuous water-level monitoring began at most groundwater sites as well as the two Mill Creek sites at the beginning of June 2017. Water levels were monitored using HOBO U20–001–04–TI unvented submersible pressure transducers, which measure the absolute pressure of the water and atmosphere. The typical error for this sensor for water levels is 0.01 ft (Onset Computer Corporation, 2019a). The transducers were suspended in the wells at set depths and programmed to measure pressure at 15-minute intervals. To correct for variations in atmospheric pressure, barometric pressure was monitored by using HOBO U20L–04 pressure transducers set to read at 15-minute intervals at two locations within the CYCC (sites 6 and 7, fig. 2). The maximum error for pressure for this sensor is 0.063 pound per square inch (Onset Computer Corporation, 2019b). To relate the pressure readings from the transducers to the groundwater levels, reference water-level measurements were made either by NPS or USGS personnel every 4 to 6 weeks by using a calibrated electric tape. Reference water levels (tape-down measurements to verify transducer calibration) were measured by using procedures outlined in Cunningham and Schalk (2011). The electric tapes used for the measurements were calibrated according to the guidance of the USGS tape calibration program (U.S. Geological Survey, 2013). Reference water levels were stored in the USGS program SVMobileAQ, which is an interface to the NWIS database. SVMobileAQ stores a copy of the database of groundwater-level measurements, as well as pertinent information regarding the measuring point of the well and the tape calibration adjustment for each water-level tape. It then provides a file output that is loaded directly into the NWIS database. All measurement data were uploaded within 1 week of each site visit.

Well MA–WNW 159-0012 (site 6, fig. 2) was instrumented with a vented transducer, which required no barometric correction. Data were transmitted directly to NWIS through transmission to the GOES satellite, and ground station. Data for this site were collected at 15-minute intervals and made available in near real time on the public web portal for NWIS.

Data from the HOBO loggers and the real-time site were downloaded in the field during each site visit. Data from the sites with HOBO loggers were corrected for barometric pressure, and then these time-series data were loaded into the USGS AQUARIUS database, analyzed, and approved by using the procedures outlined in U.S. Geological Survey (2017a). Time-series data were analyzed every 1–3 months, and any necessary corrections, based on field readings, were applied.

Reference water levels were collected at the two water-level stage sites on Mill Creek by measuring with an engineer's tape to the water surface from a reference point with a known altitude. Tape-down measurements were made just after a 15-minute time interval to correlate with the HOBO time-series data. Reference measurements at the Herring River tidal gages were made with a staff gage on the upstream side that was read at each site inspection on a 5-minute time interval. At the downstream site (harbor side), an engineer's tape and a 1-ft-long brass weight were used to tape down from a reference point to the water surface on a 15-minute time interval. Data collected at these sites were analyzed and approved by using the guidance in U.S. Geological Survey (2017b). Any corrections to time-series data were made based on field tape-down readings.

## Methods of Statistical Analysis of Groundwater-Level and Mill Creek Stage Data

As part of the data analysis, summary statistics were computed for the groundwater sites and the Herring River and Mill Creek monitoring sites. Summary statistics consist of the minimum, median, mean, and maximum water levels during the study period from June 1, 2017, through June 14, 2018 (table 2).

To analyze the daily tidal fluctuations in water levels at the wells and Herring River sites, a Godin filter (Godin, 1972) was applied to the 15-minute data for each site (Paul Work, U.S. Geological Survey, written commun., 2017). The filter removes the variation in the data caused by daily tidal fluctuations with three passes of 24, 24, and 25 hours. A record of the daily tidal fluctuations was created by subtracting the filtered result from the original unfiltered data. To determine the magnitude of daily tidal fluctuations on the groundwater levels, the daily fluctuations component for each well was regressed on five common tidal and solar harmonics (M2, principal lunar semidiurnal constituent; N2, larger lunar elliptic semidiurnal constituent; S2, principal solar semidiurnal constituent; O1, lunar diurnal constituent; and K1, lunar diurnal

**Table 2.** Groundwater, Mill Creek, and Herring River water-level statistics, June 1, 2017, to June 14, 2018, Mill Creek study area, Wellfleet and Truro, Massachusetts.

[no., number; USGS, U.S. Geological Survey; ft NAVD 88, foot above the North American Vertical Datum of 1988; ft bls, foot below land surface; Min, minimum; Med, median; Max, maximum; ft, foot; MA, Massachusetts; na, not available]

| Site no. (fig. 2) | USGS local identifier | Site type | Station identifier | Water-level altitude (ft NAVD 88) | | | | Depth (ft bls) | | | | Maximum range (ft) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Min | Mean | Med | Max | Min | Mean | Med | Max | |
| 1 | MA–WNW 154 WELLFLEET, MA | Well | 415556070033501 | −0.25 | 0.29 | 0.25 | 1.44 | 3.99 | 5.14 | 5.18 | 5.68 | 1.69 |
| 2 | MA–WNW 155–0035 WELLFLEET, MA | Well | 415557070032301 | 0.97 | 2.03 | 2.03 | 3.44 | 0.34 | 1.75 | 1.75 | 2.81 | 2.47 |
| | MA–WNW 155–0017 WELLFLEET, MA | Well | 415557070032302 | 0.92 | 2.09 | 2.09 | 3.56 | 0.27 | 1.74 | 1.74 | 2.91 | 2.64 |
| 3 | MA–WNW 156–0037 WELLFLEET, MA | Well | 415557070031701 | 1.21 | 1.73 | 1.7 | 2.72 | 2.42 | 3.41 | 3.44 | 3.93 | 1.51 |
| | MA–WNW 156–0010 WELLFLEET, MA | Well | 415557070031702 | 1.29 | 1.77 | 1.73 | 2.73 | 2.32 | 3.28 | 3.32 | 3.76 | 1.44 |
| 4 | MA–WNW 157–0033 WELLFLEET, MA | Well | 415600070030701 | 1.44 | 1.91 | 1.87 | 2.84 | 1.56 | 2.49 | 2.53 | 2.96 | 1.4 |
| | MA–WNW 157–0070 WELLFLEET, MA | Well | 415600070030702 | 1.44 | 1.90 | 1.87 | 2.82 | 1.72 | 2.64 | 2.67 | 3.1 | 1.38 |
| | MA–WNW 157–0012 WELLFLEET, MA | Well | 415600070030703 | 1.42 | 1.91 | 1.87 | 2.82 | 1.48 | 2.39 | 2.43 | 2.88 | 1.4 |
| 5 | MA–WNW 158 WELLFLEET, MA | Well | 415549070031401 | 0.95 | 1.66 | 1.64 | 2.88 | 0.29 | 1.51 | 1.53 | 2.22 | 1.93 |
| 6 | MA–WNW 159–0035 WELLFLEET, MA | Well | 415552070031701 | 1.06 | 1.67 | 1.64 | 2.76 | 0.67 | 1.76 | 1.79 | 2.37 | 1.7 |
| | MA–WNW 159–0012 WELLFLEET, MA | Well | 415552070031702 | 1.06 | 1.64 | 1.62 | 2.73 | 0.61 | 1.70 | 1.72 | 2.28 | 1.67 |
| 7 | MA–WNW 160 WELLFLEET, MA | Well | 415544070033301 | 0.53 | 1.17 | 1.15 | 2.38 | 3.36 | 4.57 | 4.59 | 5.21 | 1.85 |
| na | MA–WNW 133–0030 WELLFLEET, MA | Well | 415550070032202 | 0.98 | 1.52 | 1.49 | 2.65 | 10.5 | 11.63 | 11.66 | 12.17 | 1.67 |
| na | MA–WNW 141 WELLFLEET, MA | Well | 415556070030601 | 1.33 | 1.84 | 1.8 | 2.9 | 41.77 | 42.83 | 42.87 | 43.34 | 1.57 |
| na | MA–WNW 161 WELLFLEET, MA | Well | 415559070032601 | 0.2 | 1.14 | 1.19 | 1.98 | −1.59 | −0.75 | −0.8 | 0.19 | 1.78 |
| na | MA–WNW 162 WELLFLEET, MA | Well | 415605070031301 | 0.58 | 1.39 | 1.45 | 1.93 | 1.58 | 2.12 | 2.06 | 2.93 | 1.35 |
| na | MA–WNW 134 WELLFLEET, MA | Well | 415605070032001 | 1.15 | 1.58 | 1.55 | 2.49 | 3.02 | 3.93 | 3.96 | 4.36 | 1.34 |
| Mill Creek 1 | MILL CK AT CHEQUESSETT YT & GOLF WELLFLEET MA | Stream/ estuary | 415601070030701 | 0.39 | 1.28 | 1.37 | 2.06 | na | na | na | na | 1.67 |
| Mill Creek 2 | MILL CREEK US HERRING RIVER AT WELLFLEET MA | Stream/ estuary | 415560070032501 | 0.08 | 1.04 | 1.13 | 1.67 | na | na | na | na | 1.59 |
| Upstream | HERRING R AT CHEQUESSETT NECK RD AT WELLFLEET, MA | Estuary | 011058798 | −3.82 | −0.76 | −0.73 | 1.31 | na | na | na | na | 5.13 |
| Downstream[1] | HERRING R AT CHEQUESSETT NECK RD AT WELLFLEET, MA | Estuary | 011058798 | −3.71 | 0.27 | 0 | 9.76 | na | na | na | na | 13.47 |

[1]Data for downstream side of the Herring River tide-control structure only available from September 27, 2017, to June 14, 2018.

constituent) (Foreman and Henry, 1989; National Oceanic and Atmospheric Administration, 2018) by using the TideHarmonics package for R statistical software (Stephenson, 2016).

An additional analysis was done to examine the factors that affect groundwater-level fluctuations at time periods longer than the daily tidal fluctuations in the study area. Regression models were created for each well to describe the variability in water levels. Groundwater-level and water-level data from the Herring River were filtered by using the Godin filter described above. The dependent variable for each model was daily mean tidally filtered water level at each well. The independent variables included daily mean tidally filtered water levels in the Herring River downstream (Wellfleet Harbor) and upstream from the Herring River tide-control structure (Herring River), precipitation, the growing degree days (50 degrees Fahrenheit [°F], the base temperature), and the quartile of groundwater levels in nearby long-term USGS observation wells. Precipitation data and other weather characteristics were downloaded from the Western Regional Climate Center (2018). Data in this database were downloaded for the Wellfleet weather station (National Weather Service [NWS] 191203) and were supplemented with data from the Cape Cod site at Camp Edwards (NWS 191204) (fig. 1) if there were missing or erroneous values for any days (fig. 6) (Mullaney and Barclay, 2020). Data from nearby USGS long-term monitoring sites were downloaded from NWIS (U.S. Geological Survey, 2019).

To determine which variables in the regression models were the most important, the standardized coefficients for each model also were determined. Standardization was done using the lm.beta package in R (Behrendt, 2014). Standardized coefficients were calculated by subtracting the mean of each variable from each observed value and then dividing by the standard deviation of the variable. This allowed for the absolute values of the coefficients of each variable to be directly compared.

Additional regression models were developed to describe the variability in daily maximum water levels at the upstream and downstream sites on Mill Creek. The regression models were designed to identify factors that may be affecting water levels and the frequency of flooding at these sites. The independent variables tested included groundwater levels at nearby wells, precipitation, the growing degree days, and indicators of a flooded condition at each site. Standardized coefficients also were calculated as described above.

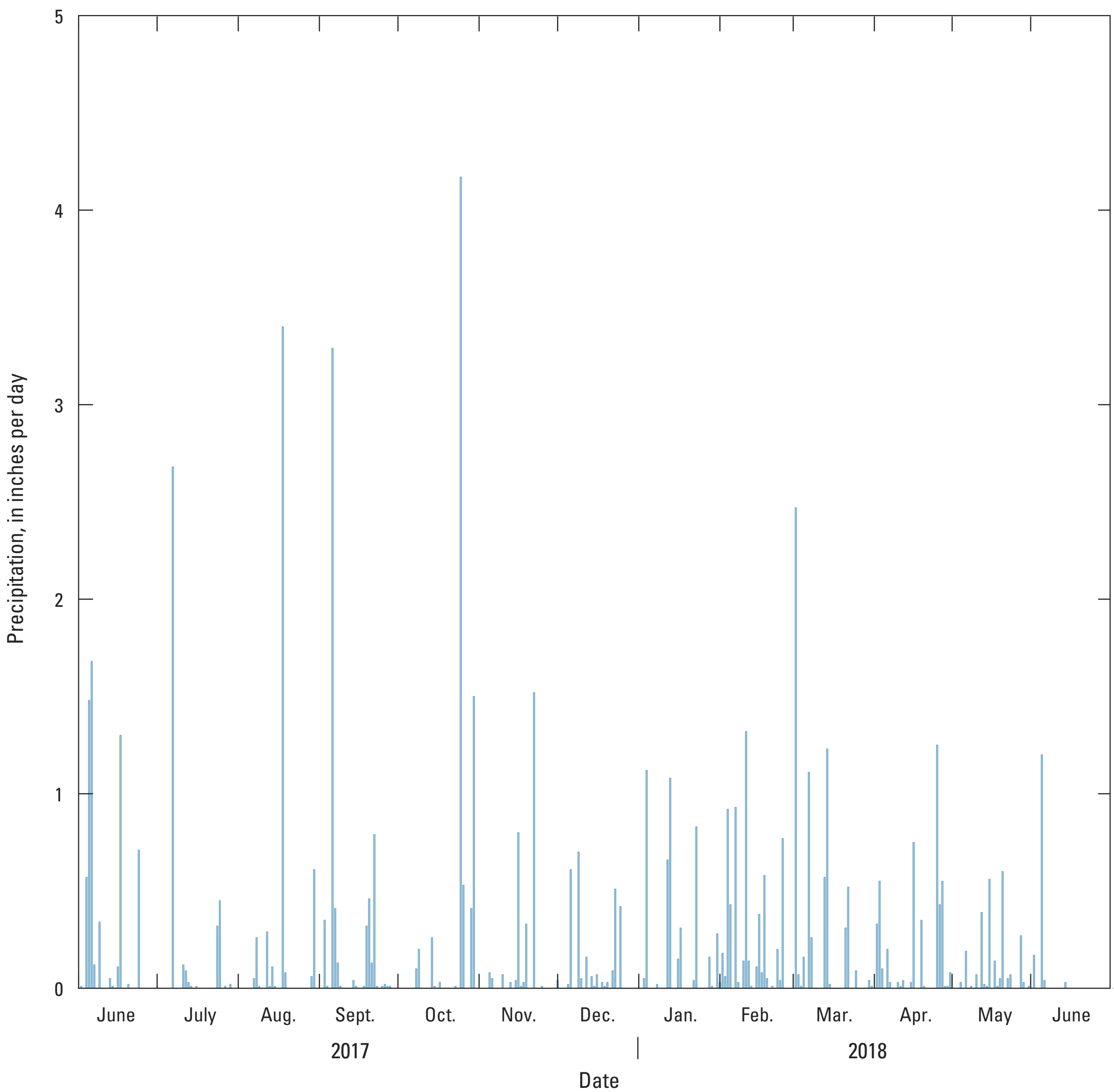


**Figure 6.** Precipitation data for Cape Cod, Massachusetts, compiled from National Weather Service stations (NWS) 191203, at Wellfleet, supplemented with data from station NWS 191204 at Camp Edwards, June 1, 2017, to June 14, 2018.

# Lithologic and Water-Level Data at the Mill Creek Study Area

The following sections summarize new and existing data on lithology, hydrologic conditions, and groundwater and surface-water levels in the study area. Statistical models relating fluctuations in groundwater levels over daily tidal cycles and longer periods to ancillary data are described. Statistical models relating ancillary data to water levels and flooding in Mill Creek also are discussed.

## Description of Site Geology

Data collected from the coring and well installation and from previous geotechnical studies of the subsurface at the CYCC were used to delineate the areas that were formerly salt marshes, show the lithology of the glacial deposits, and indicate the approximate depth to the top of the transition zone from fresh to saline groundwater (table 3). Of the new locations cored for this investigation, only the core at site 2 (well cluster MA–WNW 155, figs. 2 and 5) fully penetrated 15 ft of salt marsh deposits. The salt marsh deposits at this location contain organic material (peat) as well as clay. Additional data on the thickness of the salt marsh deposits were collected during a geotechnical investigation done as part of a study to

**Table 3.** Information on lithology, thickness of marsh deposits, and estimated depth to the transition zone between fresh groundwater and saline groundwater, Mill Creek study area, Wellfleet, Massachusetts.

[ft, foot; na, not applicable]

| Site identifier (fig. 5) | General description of site lithology | Thickness of salt marsh sediments (ft) | Approximate depth to top of the transition zone to saltwater (ft) | Source |
|---|---|---|---|---|
| Fuss and O'Neill boring 2 | Fine to medium sand, silt and clay | 0 | na | Fuss and O'Neill, Inc. (2014). |
| Fuss and O'Neill boring 3 | Fine sand, silt and clay | 0 | na | Fuss and O'Neill, Inc. (2014). |
| Fuss and O'Neill boring 4 | Fine sand, silt and clay | 0 | na | Fuss and O'Neill, Inc. (2014). |
| Louis Berger Group B–1 | Marsh deposits over medium sand | 4 | na | The Louis Berger Group, Inc. (2009). |
| Louis Berger Group B–2 | Marsh deposits over fine sand | 4 | na | The Louis Berger Group, Inc. (2009). |
| Louis Berger Group B–3 | Marsh deposits over fine to medium sand | 13 | na | The Louis Berger Group, Inc. (2009). |
| Louis Berger Group B–4 | Fine to medium sand over coarse sand | 0 | na | The Louis Berger Group, Inc. (2009). |
| Louis Berger Group B–5 | Marsh deposits over medium sand | 18 | na | The Louis Berger Group, Inc. (2009). |
| Louis Berger Group B–6 | Marsh deposits over fine to medium sand | 18 | na | The Louis Berger Group, Inc. (2009). |
| Louis Berger Group B–7 | Fill over marsh deposits over fine sand | 7 | na | The Louis Berger Group, Inc. (2009). |
| Louis Berger Group B–8 | Medium to fine sand | 0 | na | The Louis Berger Group, Inc. (2009). |
| MA–WNW 133 | Medium to coarse sand | 0 | 43 | Well was redrilled for this study, depth to transition zone from Masterson (2004). |
| MA–WNW 134 | Fine to very fine sand | 0 | 59 | Masterson (2004). |
| MA–WNW 141 | na | 0 | 95 | Masterson (2004). |
| MA–WNW 155 (site 2) | Marsh deposits over very fine to medium sand | 15 | 60 | na |
| MA–WNW 156 (site 3) | Medium to coarse sand | 0 | >65 | na |
| MA–WNW 157 (site 4) | Very coarse sand | 0 | >70 | na |
| MA–WNW 158 (site 5) | Medium to very coarse sand | 0 | 40 | na |
| MA–WNW 159 (site 6) | Fine to coarse sand | 0 | >45 | na |
| MA–WNW 160 (site 7) | Medium to very coarse sand | 0 | 40 | na |
| MA–WNW 161 | Marsh deposits over fine sand | 2 | 15 | Information from Fuss and O'Neill boring 1. |

determine whether fairways and other parts of the golf course could be filled to raise the land-surface altitude to mitigate flooding following the proposed restoration of tidal flow to the Herring River (The Louis Berger Group, Inc., 2009). The study indicated that salt marsh deposits are as much as 18 ft thick at other locations at the CYCC. The area at the CYCC that is underlain by former salt marsh deposits is roughly coincident with the area where the land-surface altitude is less than about 3.5 ft (fig. 5). Deposits directly underlying the marsh sediments are typically finer grained than the sediments in the adjacent upland areas. These underlying sediments are likely estuarine sediments (alluvium and mudflats) that predate the marsh sediments. The sediments in the upland areas are typically coarse grained and represent collapsed facies of the Wellfleet plain deposits.

The estimated depths to the transition zone at the CYCC, based on the drilling information collected in 2017, ranged from 40 ft at site 5 (MA–WNW 158, figs. 2 and 5) to greater than 70 ft at site 4 (MA–WNW 157–0070, figs. 2 and 5). The range in the depths to the transition zone from new and existing data was from 15 to 95 ft below land surface (table 3).

## Hydrologic Conditions Near the Mill Creek Study Area, June 1, 2017, Through June 14, 2018

The hydrologic conditions during the study period were characterized by several large precipitation events during the summer of 2017, with three events exceeding 2 inches and two of these events exceeding 3 inches of precipitation (fig. 6). During the fall, a large storm on Cape Cod on October 25–26 produced 4.8 inches of rainfall. This storm was followed by a strong coastal storm on October 29–30 that produced an additional 1.9 inches of precipitation. The winter of 2017–18 had several powerful coastal storms in January, February, and March. In addition to substantial precipitation, these coastal storms caused higher than normal tides in Wellfleet Harbor. The total precipitation for the period of the study from June 1, 2017, through June 14, 2018, was about 60.8 inches, based on data from the Wellfleet weather station and supplemented with data from the Camp Edwards station (data downloaded from the Western Regional Climate Center [2018]). The total study precipitation compares with an average annual precipitation of 50.3 inches for the period of 2000–17.

During the study, three long-term USGS monitoring wells on this part of Cape Cod (Wellfleet, MA–WNW 17; Truro, MA–TSW 89; and, Brewster, MA–BMW 22, fig. 1) had groundwater levels that were generally in the normal to above normal range during the summer of 2017. Because of the large amount of precipitation during the study period, groundwater levels ranged from above normal to much higher than normal during the spring of 2018, with record high monthly groundwater levels documented at the Brewster site during March and April (figs. 7*A*–*C*).

## Groundwater and Mill Creek Water Levels, June 1, 2017, Through June 14, 2018

Data on depth to groundwater, groundwater altitude, and Mill Creek water-level altitude from June 1, 2017, through June 14, 2018, are summarized in table 2. The highest groundwater levels were measured near Mill Creek in the shallowest well at site 2 (fig. 2), with water levels as high as 3.56 ft above NAVD 88 in March 2018. The range in groundwater levels during the study period observed at individual wells in the Mill Creek study area was smallest—1.34 ft—at well MA–WNW 134 on the north side of Mill Creek and largest—2.64 ft—at site 2 (MA–WNW 155–0017; fig. 2, table 2). The depth to water in most of the wells near the CYCC was typically 1–4 ft below land surface, except in wells drilled at higher altitudes in the study area (table 2). Graphs of the water levels for all sites monitored during the study are shown in appendix 1. The analysis of short-term tidal fluctuations is given in the next section of this report.

Generalized contour maps were created to show the altitude of the water table, the depth to groundwater, and the direction of groundwater flow under both dry and wet conditions (figs. 8*A*–*B*). Data for both conditions were analyzed for a specific time of day, and not daily means; therefore, water levels may be affected by the tidal fluctuation. The dry period was analyzed by using data from August 18, 2017, during one of the driest periods in the study. Data from February 27, 2018, were used for the wet period. Although water levels were not the highest on this date, February 27 was selected because of the availability of satellite imagery showing the extent of surface flooding at the CYCC.

The configuration of the water table for these two periods indicates that the directions of groundwater flow generally were to the west toward the Herring River, northwest toward Mill Creek, and southwest toward Wellfleet Harbor. The altitude of the water table at wells measured for the periods shown in figures 8*A* and 8*B* was from −0.13 to 1.48 ft above NAVD 88 during the dry period and from 0.44 to 2.52 ft above NAVD 88 during the wet period. During wet periods, the highest groundwater levels were measured in the shallow well at site 2 (MA–WNW 155–0017, fig. 2), indicating a local area of high groundwater levels. The high groundwater levels in this area may indicate that groundwater is flowing laterally from a high point in some of the adjacent upland deposits. It is possible that groundwater levels are higher in some of the coarse-grained deposits that make up the uplands on the CYCC because of higher recharge rates in these well-drained materials. The configuration of the water table under these deposits is difficult to determine because of the lack of measurement points in these upland areas.

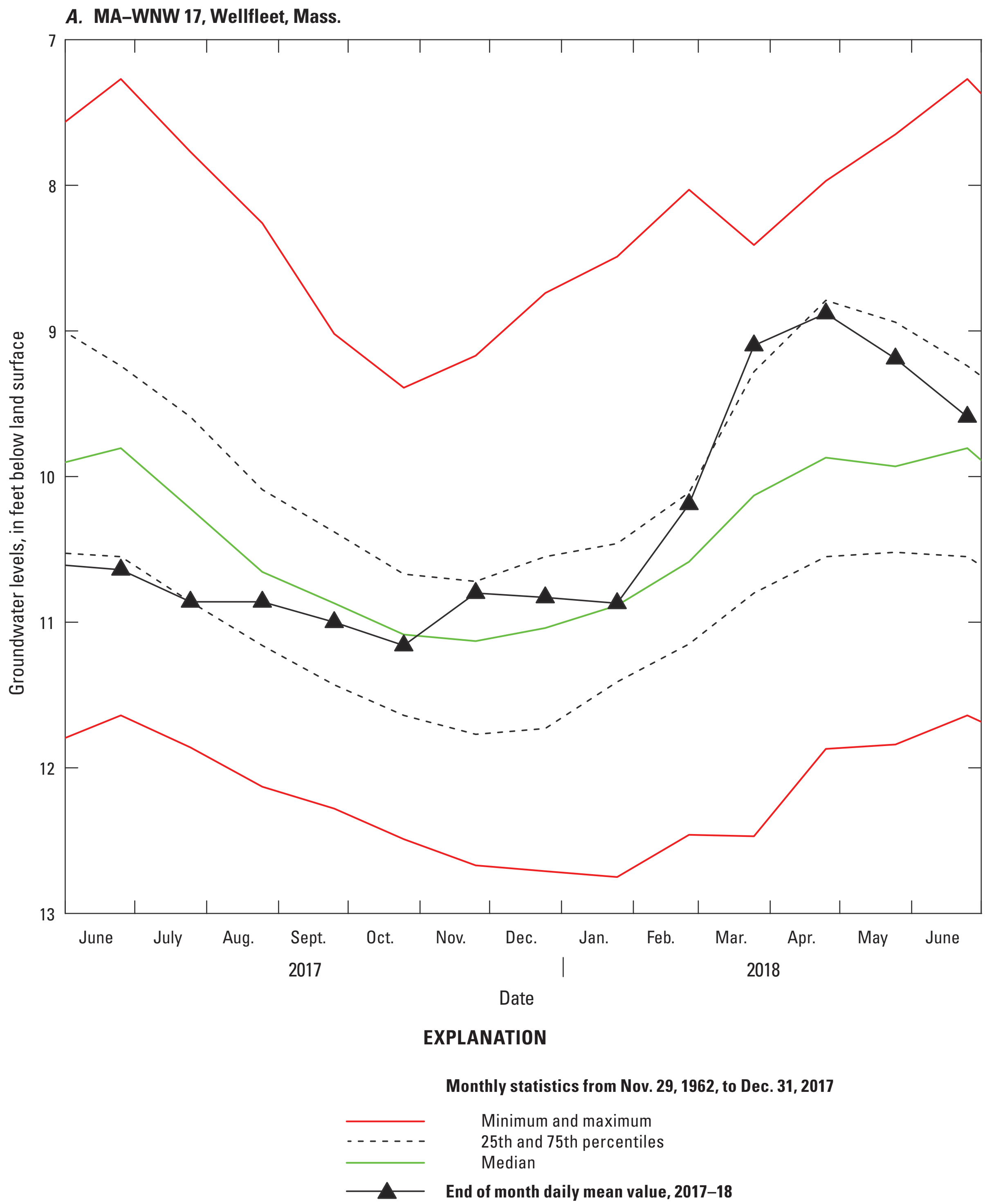


**Figure 7.** Groundwater levels at U.S. Geological Survey monitoring sites relative to long-term statistics, near the Mill Creek study area, Cape Cod, Massachusetts, 2017 to 2018: *A*, Wellfleet, *B*, Truro, *C*, Brewster.

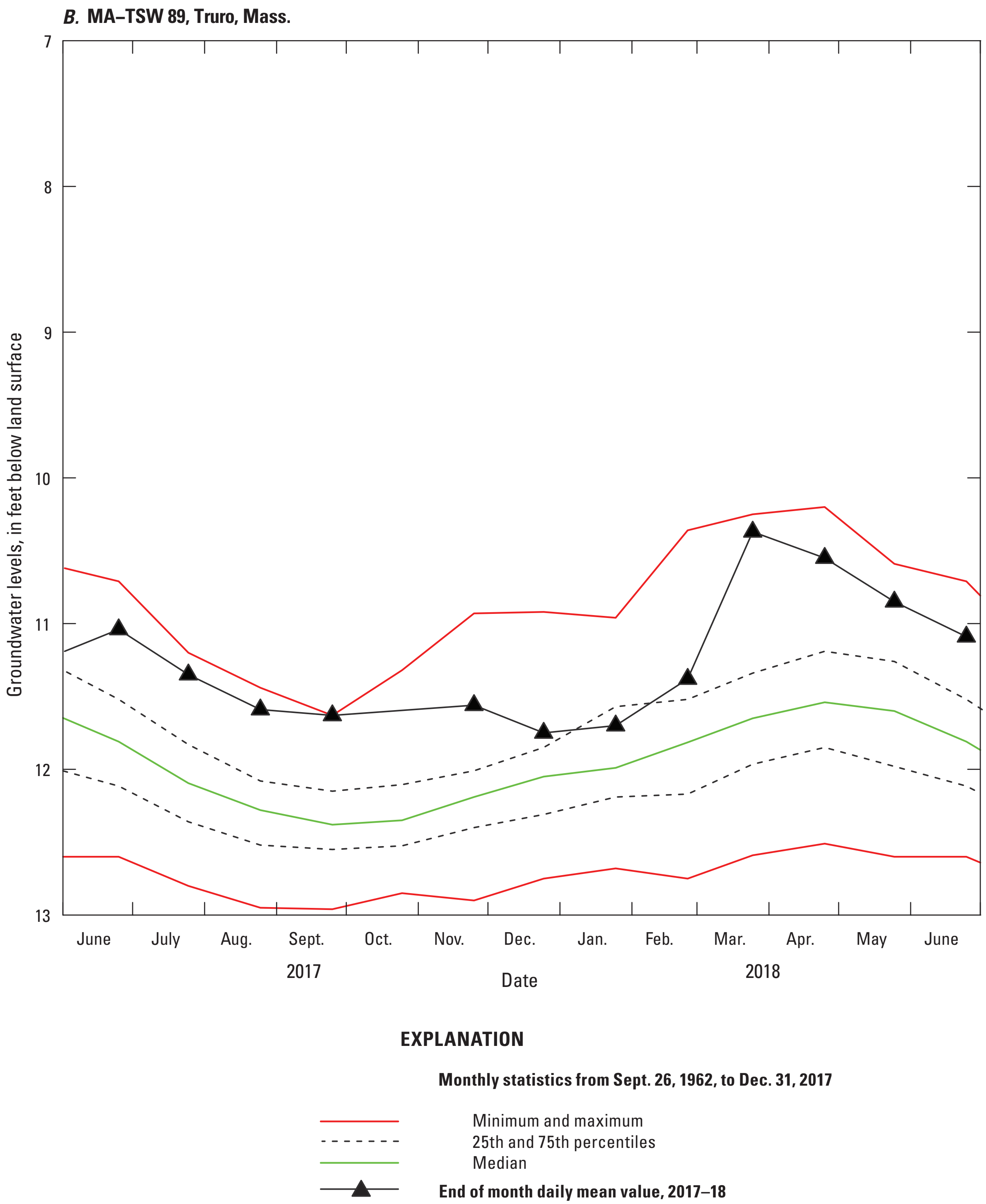


**Figure 7.** Groundwater levels at U.S. Geological Survey monitoring sites relative to long-term statistics, near the Mill Creek study area, Cape Cod, Massachusetts, 2017 to 2018: *A*, Wellfleet, *B*, Truro, *C*, Brewster. —Continued

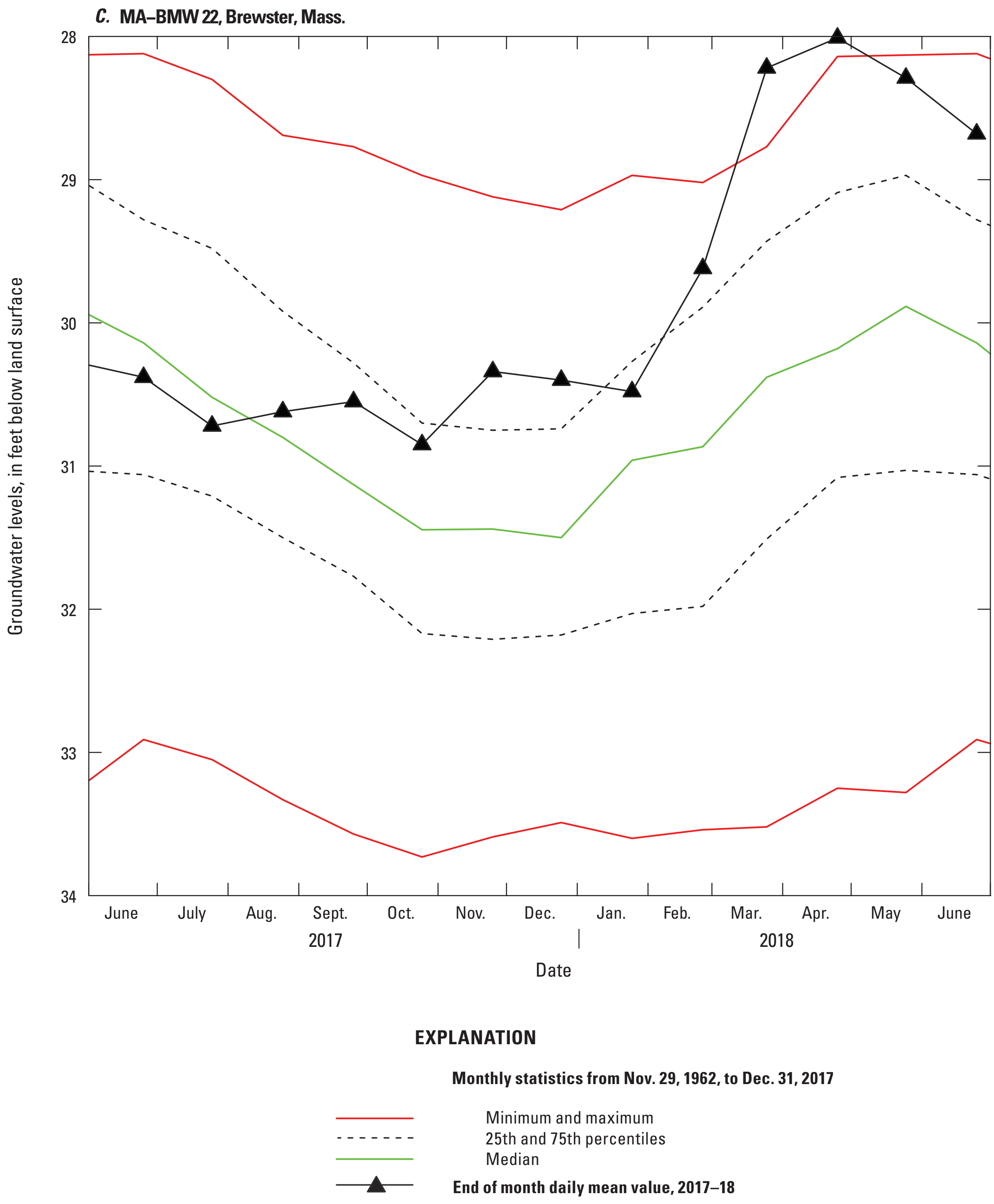


**Figure 7.** Groundwater levels at U.S. Geological Survey monitoring sites relative to long-term statistics, near the Mill Creek study area, Cape Cod, Massachusetts, 2017 to 2018: *A*, Wellfleet, *B*, Truro, *C*, Brewster. —Continued

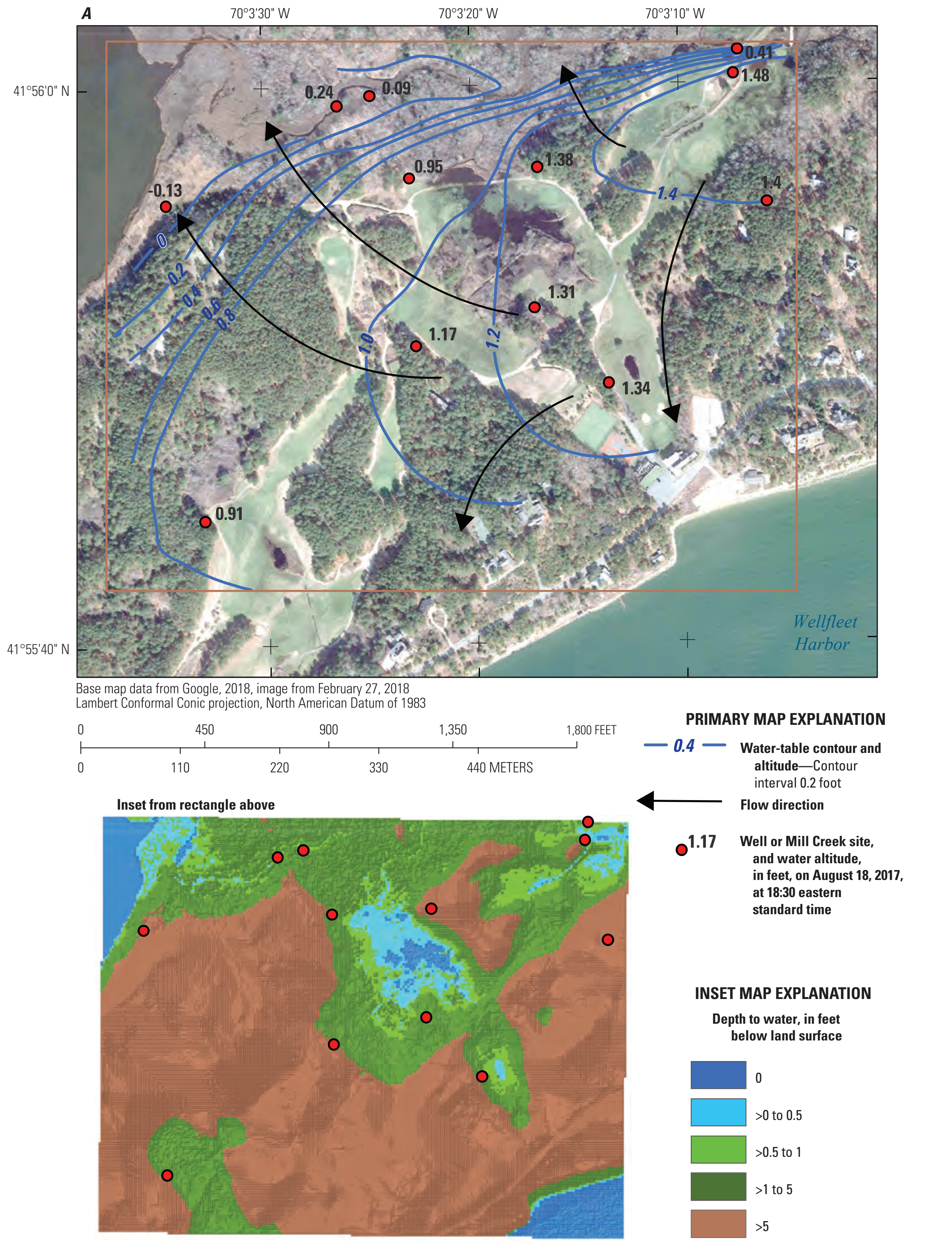


**Figure 8.** Water-table altitude, depth to groundwater, and generalized flow direction at the Mill Creek study area, Wellfleet, Massachusetts, *A*, during a dry period, August 18, 2017, and *B*, during a wet period, February 27, 2018.

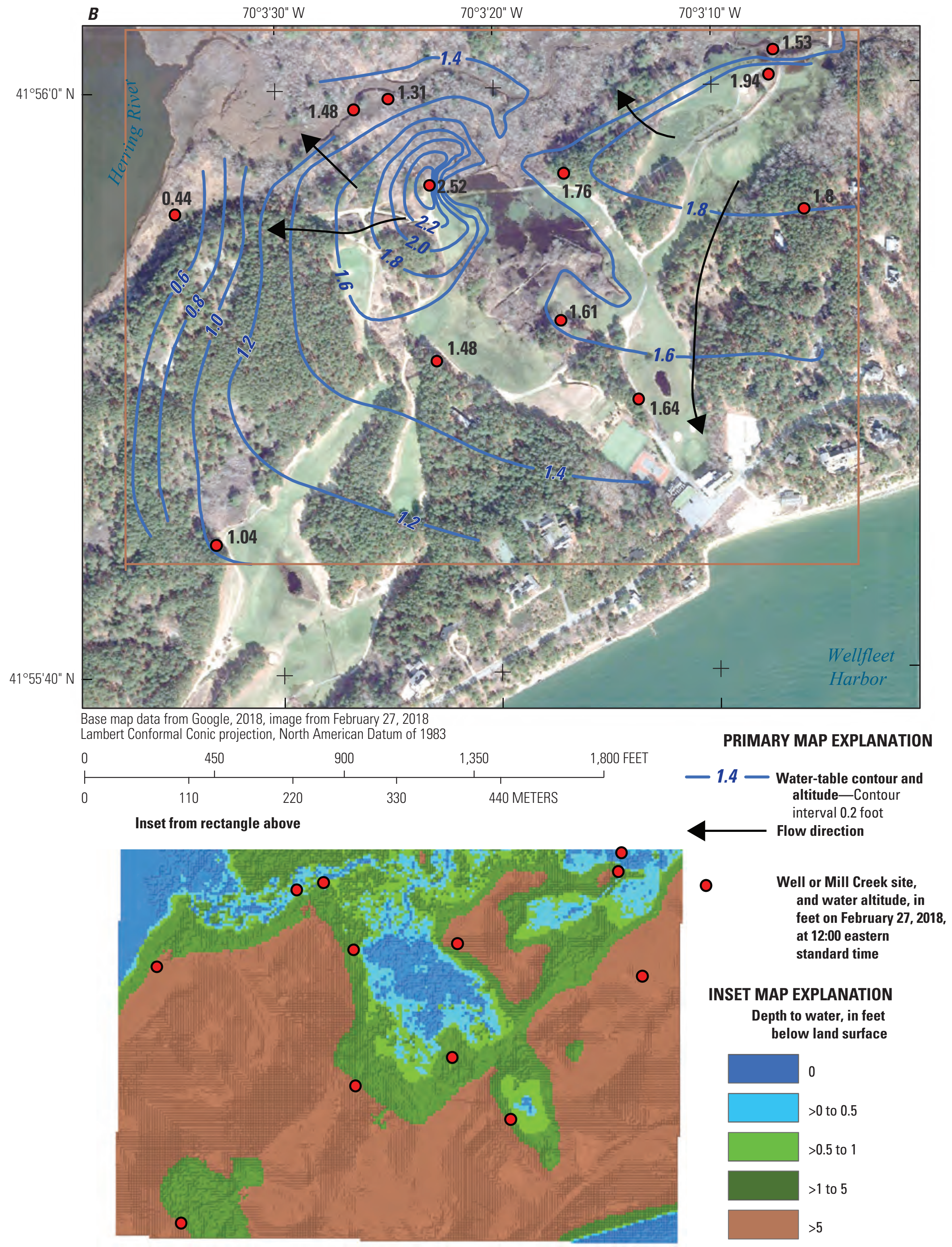


**Figure 8.** Water-table altitude, depth to groundwater, and generalized flow direction at the Mill Creek study area, Wellfleet, Massachusetts, *A*, during a dry period, August 18, 2017, and *B*, during a wet period, February 27, 2018.—Continued

## Short-Term Tidal Fluctuations in Groundwater Levels

Daily tidal fluctuations were observed in water levels at most of the wells monitored for this study, because they are near tidal waterbodies, including Wellfleet Harbor and the Herring River. Groundwater levels in the wells exhibited daily fluctuations as well as longer term fluctuations related to lunar tidal cycles and to other ocean, harbor, and Herring River water-level fluctuations.

The amplitudes of the tidal signals for the five common tidal and solar harmonics at the wells and sites on the Herring River monitored for this study are shown in table 4 and figures 9 and 10. The tidal amplitude is the “half range” from the low to the high tide. The coefficient of determination ($R^2$) (table 4) is a measure of how much of the variability in water level is explained by the statistical models using the five different tidal harmonics. For sites with a very low $R^2$, either (1) the wells are too distant from the tidal waterbody for water levels to be affected by ocean tides, (2) interactions between tides from the Herring River and tides from Wellfleet Harbor affect the periodicity of the tidal harmonics, (3) the tidal signal is of a similar order of magnitude to the noise in the data and instrument accuracy (less than 0.01 ft), or (4) water-level fluctuations are affected by other unidentified processes.

Amplitudes of the M2 harmonic (the largest tidal signal in the data) generally decreased with increasing distance from the tidal source (fig. 10). The strongest tidal signal was observed at MA–WNW 154 (site 1; amplitude=0.12 ft), which is about 105 ft from the Herring River. Water levels in wells at sites MA–WNW 161, MA–WNW 141 (shown only on fig. 9), and at MA–WNW 155 (both shallow and deep wells; site 2) showed less tidal influence than expected based on their proximity to tidal waterbodies (fig. 10). In contrast, the tidal response in the deep well at site 3 (MA–WNW 156–0035) was greater than expected, given the relation between distance from a tidal waterbody and M2 tidal amplitude shown in figure 10. Water levels in wells at site 2 (fig. 2), and the water levels at the nearby downstream monitoring site on Mill Creek showed little tidal influence. The greater response in some wells is likely related to the degree of hydraulic connection between the tidal waterbody and the aquifer and to the degree of confinement in the aquifer.

In the study area around the CYCC and Mill Creek, the tidally influenced water-level fluctuations in the wells were effectively limited to the area within about 1,500 ft from tidal waterbodies. The influence of the tidal fluctuations in the Herring River (upstream from the tide-control structure) were observed at site 1 (MA–WNW 154) and MA–WNW 134. Tidal fluctuations in water levels in wells likely caused by the Herring River tide also were observed at site MA–WNW 161 and at site 2 (MA–WNW 155, both shallow and deep wells), but the regressions on the tide harmonics had a low $R^2$ of less than 0.3 (fig. 10). The fluctuation in groundwater levels caused by tidal fluctuations in the Herring River was limited to short distances from the river, with the exception of well MA–WNW 134. Possible causes include the smaller average tidal amplitude of the Herring River (1.08 ft) than Wellfleet Harbor (4.04 ft) (table 2) and the hydraulic properties of the marsh deposits and fine-grained estuarine sediments underlying the Herring River and Mill Creek. The amplitude of the tidal fluctuations at MA–WNW 134 was greater than expected based on the general relation shown in figure 10. This amplitude may indicate locally confined conditions in the aquifer at this location, which would allow the effects of the tidal fluctuations to propagate further inland.

Under the proposed initial restoration scenario (fig. 3) (little to no change in mean tide, about zero ft above NAVD 88), the amplitude of the tidal fluctuation in the Herring River upstream from the control structure would increase to about 2.5 ft. The increased tidal fluctuations would be as much as 700 ft closer to the areas on the CYCC that presently flood and would also extend to the downstream side of a proposed tide-control structure on Mill Creek. Under these conditions, the daily tidal fluctuations in groundwater levels on parts of the CYCC nearest to the river could increase, depending on the degree to which the underlying lithology facilitates the interaction with the tides. Because the maximum observed tidal amplitude in well MA–WNW 158 at site 5 was about 0.06 ft in response to a tidal amplitude of 4.04 ft in Wellfleet Harbor 575 ft from the site, the future daily average groundwater tidal amplitude under the restoration scenario on the CYCC would likely be less than 0.06 ft. However, if the proposed tide-control structure is adjusted to allow the mean tide of the Herring River to an altitude greater than the current mean tide (about zero ft above NAVD 88, fig. 3), groundwater levels could rise at the locations nearest to the proposed tide-control structure on Mill Creek, as the water level in the aquifer adjusts to the new equilibrium between Herring River and Wellfleet Harbor tides.

## Groundwater-Level Fluctuations Over Periods Longer Than Daily Tidal Cycles

Water levels in the aquifer in the study area respond to daily tidal fluctuations and longer-term variations in the stage of Wellfleet Harbor that are associated with the recurrence and magnitude of the spring and neap tides. In addition, they are affected by other fluctuations in Wellfleet Harbor stage caused by short-term (storm surges) and long-term weather patterns, variations in barometric pressure, and the direction and strength of prevailing winds. The groundwater levels also are affected by precipitation, resulting in groundwater recharge, as well as evapotranspiration.

Tidally filtered water levels at MA–WNW 158 (site 5, fig. 2) follow the general pattern of tidally filtered Wellfleet Harbor water levels, with an apparent time lag. The effect of the Wellfleet Harbor stage on groundwater levels is difficult to separate from aquifer recharge events because precipitation often occurs during times of high mean Wellfleet Harbor stage.

**Table 4.** Tidal amplitudes of five tidal harmonics from regression using data from each well and the Herring River, Mill Creek study area, Wellfleet, Massachusetts.

[ft, foot; $R^2$, coefficient of determination; M2, principal lunar semidiurnal constituent; N2, larger lunar elliptic semidiurnal constituent; S2, principal solar semidiurnal constituent; O1, lunar diurnal constituent; K1, lunar diurnal constituent]

| Site (fig. 2) | Distance from nearest or tidal waterbody affecting groundwater levels | Harmonic | Amplitude (ft), rounded to nearest 0.01 ft | Phase (degree) | Adjusted $R^2$ |
|---|---|---|---|---|---|
| Herring River upstream 011058098 | 0 | M2 | 1.08 | 58.15 | 0.94 |
| | | N2 | 0.16 | 31.83 | |
| | | S2 | 0.1 | 96.81 | |
| | | O1 | 0.09 | 179.83 | |
| | | K1 | 0.12 | 196.91 | |
| Herring River downstream 011058098 | 0 | M2 | 4.04 | 353.88 | 0.95 |
| | | N2 | 0.78 | 326 | |
| | | S2 | 0.57 | 25.09 | |
| | | O1 | 0.32 | 149.48 | |
| | | K1 | 0.39 | 152.04 | |
| MA–WNW 133–0030 | 1,140 | M2 | 0.02 | 135.29 | 0.31 |
| | | N2 | 0 | 108.87 | |
| | | S2 | 0 | 219.5 | |
| | | O1 | 0.01 | 286.71 | |
| | | K1 | 0 | 252.7 | |
| MA–WNW 134 | 980 | M2 | 0.04 | 106.5 | 0.57 |
| | | N2 | 0.01 | 83.72 | |
| | | S2 | 0 | 165.53 | |
| | | O1 | 0.01 | 262.75 | |
| | | K1 | 0.01 | 262.42 | |
| MA–WNW 154 Site 1 | 105 | M2 | 0.12 | 91.05 | 0.87 |
| | | N2 | 0.02 | 62.01 | |
| | | S2 | 0.01 | 133.11 | |
| | | O1 | 0.01 | 232.94 | |
| | | K1 | 0.02 | 239.84 | |
| MA–WNW 155–0017 Site 2 (shallow well) | 910 | M2 | 0.01 | 110.84 | 0.06 |
| | | N2 | 0 | 107.13 | |
| | | S2 | 0 | 182.71 | |
| | | O1 | 0 | 277.66 | |
| | | K1 | 0.01 | 277.43 | |
| MA–WNW 155–0035 Site 2 (deep well) | 910 | M2 | 0.02 | 117.38 | 0.11 |
| | | N2 | 0 | 103.67 | |
| | | S2 | 0 | 184.14 | |
| | | O1 | 0.01 | 275.65 | |
| | | K1 | 0.01 | 284.25 | |
| MA–WNW 156–0010 Site 3 (shallow well) | 1,400 | M2 | 0.01 | 141.15 | 0.1 |
| | | N2 | 0 | 124.05 | |
| | | S2 | 0 | 220.32 | |
| | | O1 | 0 | 301.62 | |
| | | K1 | 0.01 | 288.13 | |
| MA–WNW 156–0035 Site 3 (deep well) | 1,400 | M2 | 0.04 | 96.3 | 0.62 |
| | | N2 | 0.01 | 72.44 | |
| | | S2 | 0 | 150.95 | |
| | | O1 | 0.01 | 258.47 | |
| | | K1 | 0.01 | 255.73 | |

**Table 4.** Tidal amplitudes of five tidal harmonics from regression using data from each well and the Herring River, Mill Creek study area, Wellfleet, Massachusetts.—Continued

[ft, foot; $R^2$, coefficient of determination; M2, principal lunar semidiurnal constituent; N2, larger lunar elliptic semidiurnal constituent; S2, principal solar semidiurnal constituent; O1, lunar diurnal constituent; K1, lunar diurnal constituent]

| Site (fig. 2) | Distance from nearest or tidal waterbody affecting groundwater levels | Harmonic | Amplitude (ft), rounded to nearest 0.01 ft | Phase (degree) | Adjusted $R^2$ |
|---|---|---|---|---|---|
| MA–WNW 157–0012 Site 4 (shallow well) | 1,520 | M2 | 0.01 | 147.64 | 0.07 |
| | | N2 | 0 | 137.27 | |
| | | S2 | 0 | 194.52 | |
| | | O1 | 0 | 294.24 | |
| | | K1 | 0 | 276.59 | |
| MA–WNW 157–0033 Site 4 (intermediate well) | 1,520 | M2 | 0.01 | 146.46 | 0.08 |
| | | N2 | 0 | 136.46 | |
| | | S2 | 0 | 192.32 | |
| | | O1 | 0 | 296.6 | |
| | | K1 | 0 | 278.71 | |
| MA–WNW 157–0070 Site 4 (deep well) | 1,520 | M2 | 0.01 | 147.09 | 0.08 |
| | | N2 | 0 | 147.2 | |
| | | S2 | 0 | 212.29 | |
| | | O1 | 0 | 297.79 | |
| | | K1 | 0 | 293.31 | |
| MA–WNW 158 Site 5 | 570 | M2 | 0.06 | 88.78 | 0.75 |
| | | N2 | 0.01 | 56.49 | |
| | | S2 | 0.01 | 137.59 | |
| | | O1 | 0.01 | 259.06 | |
| | | K1 | 0.01 | 259.48 | |
| MA–WNW 159–0012 Site 6 (shallow well) | 945 | M2 | 0.03 | 108.41 | 0.68 |
| | | N2 | 0.01 | 81.01 | |
| | | S2 | 0 | 147.76 | |
| | | O1 | 0.01 | 263.16 | |
| | | K1 | 0.01 | 257.67 | |
| MA–WNW 159–0035 Site 6 (deep well) | 945 | M2 | 0.03 | 103.12 | 0.59 |
| | | N2 | 0.01 | 75.6 | |
| | | S2 | 0 | 162.4 | |
| | | O1 | 0.01 | 267.49 | |
| | | K1 | 0.01 | 261.51 | |
| MA–WNW 160 Site 7 | 1,000 | M2 | 0.02 | 118.41 | 0.46 |
| | | N2 | 0 | 93.81 | |
| | | S2 | 0 | 184.05 | |
| | | O1 | 0.01 | 281.3 | |
| | | K1 | 0.01 | 277.53 | |
| MA–WNW 161 | 560 | M2 | 0.02 | 116.94 | 0.15 |
| | | N2 | 0 | 100.25 | |
| | | S2 | 0 | 173.47 | |
| | | O1 | 0 | 255.69 | |
| | | K1 | 0.01 | 264.29 | |

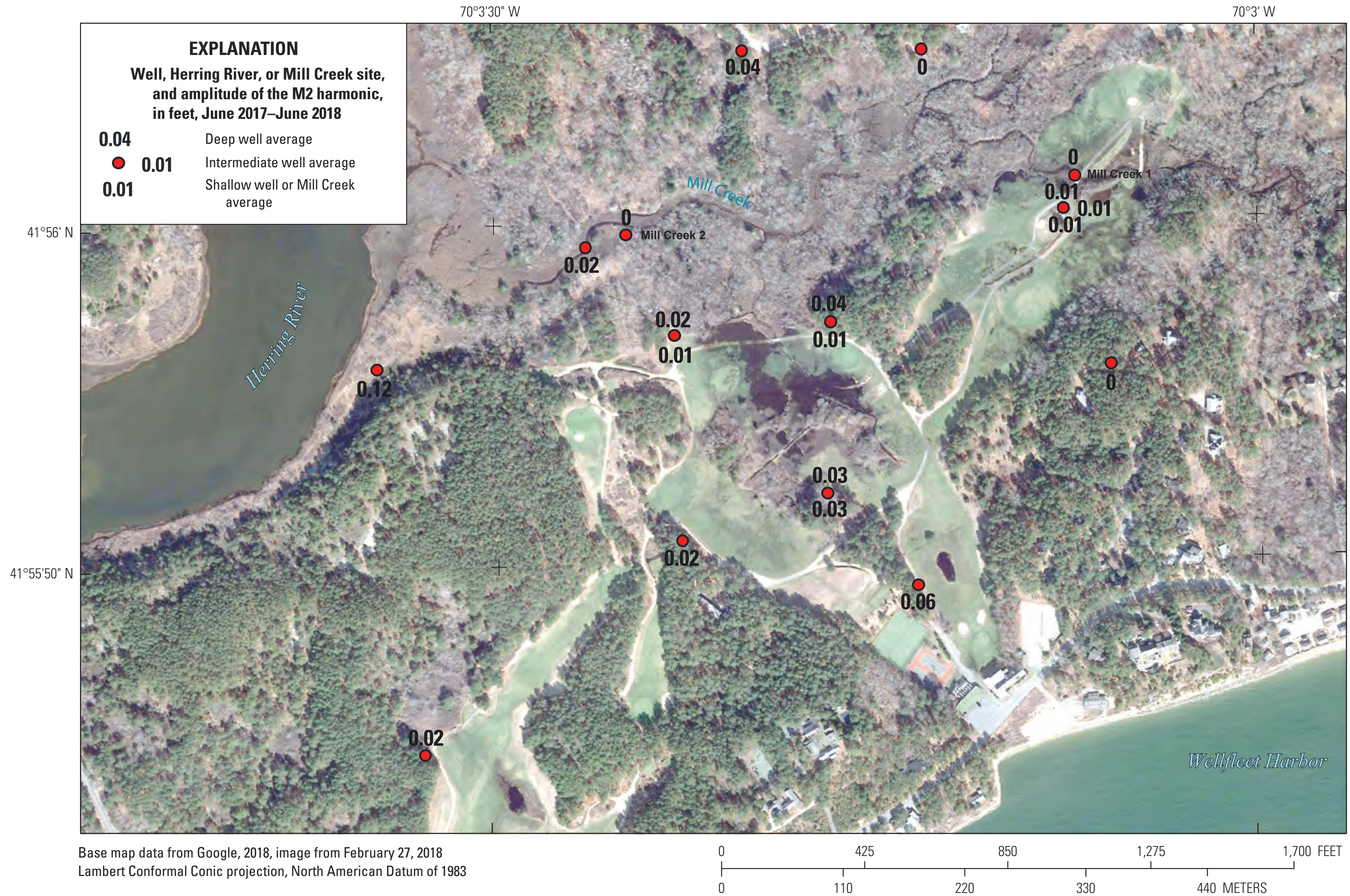


**Figure 9.** Average amplitude of the M2 tidal harmonic for wells and rivers in the study area, Wellfleet, Massachusetts, June 1, 2017, through June 14, 2018.

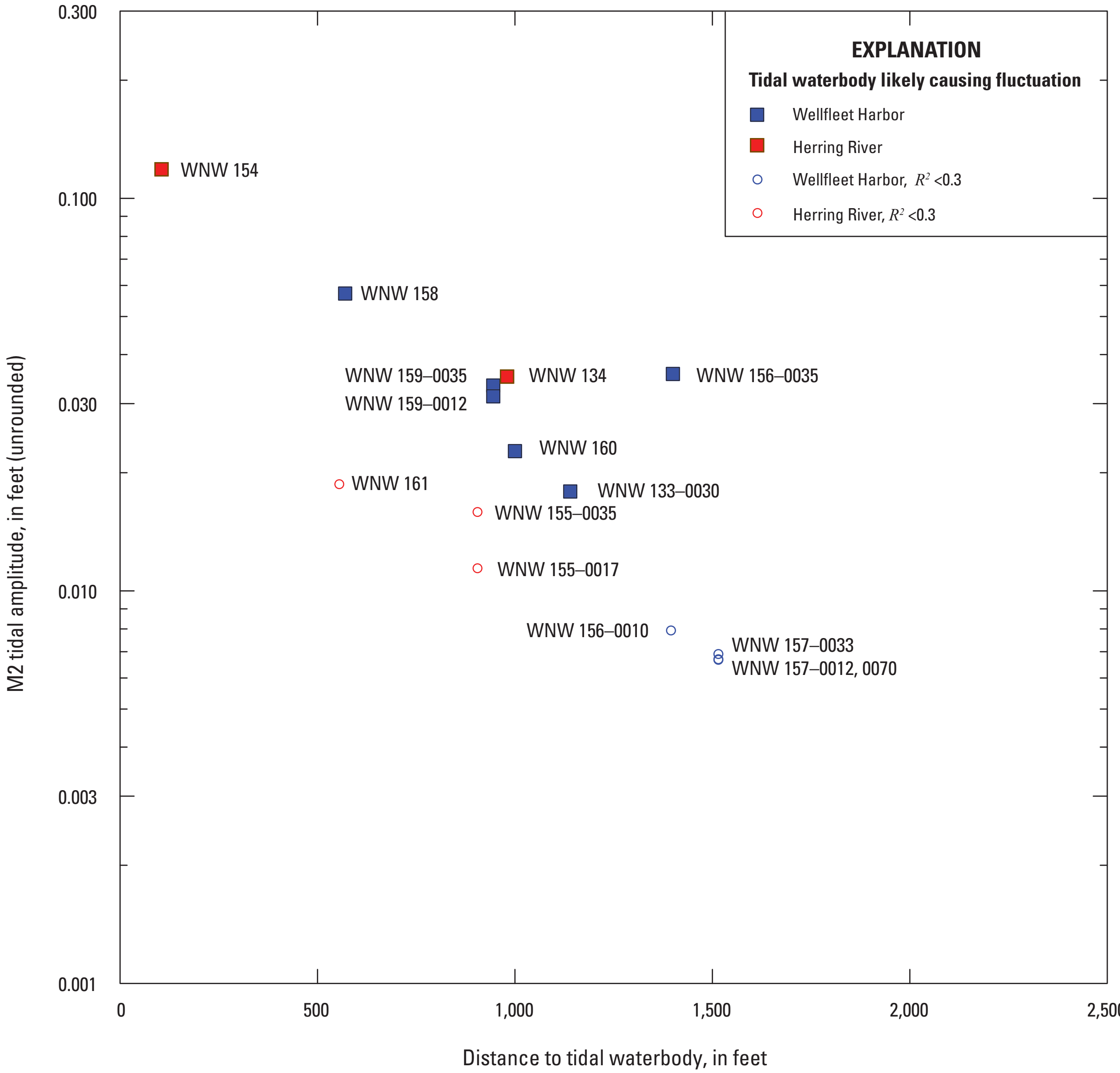


**Figure 10.** Relation of the amplitude of the M2 tidal harmonic to distance of the well from the nearest tidal waterbody, June 1, 2017, through June 14, 2018, Wellfleet, Massachusetts. $R^2$, coefficient of determination.

A storm surge on January 4, 2018, during a large coastal storm resulted in a maximum storm tide of 9.76 ft above NAVD 88 in Wellfleet Harbor, which resulted in a storm surge of about 2.64 ft above the predicted high tide. This maximum was just higher than the storm of record of 9.70 ft above NAVD 88 that occurred during the blizzard of early February 1978 (National Park Service and others, 2016). The effect of the surge on groundwater levels was complicated by precipitation during the event. The precipitation may not have contributed to the rise in groundwater levels because the air temperatures leading up to the storm event were below freezing, likely leading to frozen ground conditions and limited infiltration.

To understand the factors that affect groundwater-level fluctuations (excluding daily tides) in the study area, regression models were developed for each well. The dependent variable was the daily mean tidally filtered groundwater level (*meanFiltGWalt*) at the wells of interest. The independent variables selected included the following: daily mean tidally filtered Herring River water levels upstream (*meanHerringAlt*) and downstream (*meanHarborAlt*) of the tide-control structure; total precipitation during the preceding 7 days (*precip7day*); the growing degree days 50 °F (*GDD50*); and the quartile of monthly groundwater levels at USGS well MA–WNW 17 in Wellfleet (*longtermGW*) relative to the long-term water level record at the well.

As noted previously, there was a lag time between water-level fluctuations in Wellfleet Harbor and water-level fluctuations in wells in the study area. The lag time was determined for each well by use of a sensitivity analysis that tested different lag times. The best model for each well was selected by maximizing the $R^2$ and minimizing the Akaike information criterion (Akaike, 1988) while varying the lag times from zero to 3 days, in half-day increments.

The independent variables used in the regressions were selected for their potential effects on groundwater levels. The variations in the stage in Wellfleet Harbor were consistent with fluctuations observed in the groundwater levels (fig. 11). The wells in the study area are all near tidal waterbodies that, as surface-water boundaries, strongly influence groundwater levels. The precipitation relates to the potential for recent groundwater recharge. The *GDD*50 accounts for evapotranspiration that reduces recharge from precipitation and increases water loss by evapotranspiration from wetland areas hydraulically connected to the groundwater system. The status of water levels in a long-term well (*longtermGW*) indicates whether regional groundwater levels on this part of Cape Cod are above, at, or below normal (values 1–4, representing the four quartiles in the long-term monthly data) relative to the long-term record at the well. The status at the long-term well is a potentially important consideration in the evaluation of future groundwater levels in the study area during and after the restoration phase.

The coefficients of determination ($R^2$) indicate that these regression models describe about 63 to 81 percent of the variability in the water levels in each well (appendix 2, table 2.1). The variables shown in table 2.1 are all significant at or less than $p$=0.05.

The *meanHarborAlt* variable explained more variability in the tidally filtered daily water levels mean (*FiltGWalt*) than the *meanHerringAlt* variable at most of the wells tested. In two locations, the models using the *meanHerringAlt* data explained more variability in a total of three wells, indicated by an $R^2$ value higher than that of the model that used *meanHarborAlt* as the independent variable (sites MA–WNW 155–0017, MA–WNW 155–0035, and MA–WNW 161, fig. 2, table 2.1). Models for sites identified as having tidal influence from the Herring River (fig. 10) are included in table 2.1. Models using the *meanHerringAlt* data typically had higher variance inflation factors and larger residual standard error than models using the filtered *meanHarborAlt* data. This indicates a greater multicollinearity in the models using the Herring River data. The Herring River data are affected by freshwater discharge that causes temporal change in Herring River height, which is not evident in the Wellfleet Harbor data.

The absolute values of the standardized model coefficients for these models were largest for the variable *meanHarborAlt* (daily mean tidally filtered Wellfleet Harbor altitude) at many of the wells; however, this was not the case for wells along the Mill Creek corridor. The variables with the largest influence on the daily tidally filtered water levels along the Mill Creek corridor were (1) *longtermGW* (quartile of long-term groundwater levels) at well WNW 161, site 4 wells (WNW 157–0012, 0033, 0070), and well WNW 134 and (2) *GDD*50 (growing degree days [50 °F]) at site 2 wells (WNW 155–0017 and 0035) and site 3 well WNW 156–0010 (shallow well). The standardized coefficients are shown in appendix 2, table 2.2.

## Factors Affecting Flooding in Mill Creek

Two areas on the CYCC near Mill Creek routinely flood, limiting use and causing temporary closures of the golf course. Water-stage data collected at upstream and downstream locations on Mill Creek, analysis of photographs taken during several flooding events, and survey information and altitude data from lidar (light detection and ranging) indicate that the flooding threshold elevations for Mill Creek at these two areas on the CYCC can be approximately determined. Near the upstream monitoring site (Mill Creek 1, fig. 2), the altitude of a low part of the golf cart path is about 1.5 ft above NAVD 88, from analysis of the lidar data. Mill Creek stages at or above 1.5 ft are associated with conditions when there is standing water in this area (fig. 12*A*). An analysis of the data for Mill Creek at the upstream site determined that the daily maximum stage was at or higher than 1.5 ft on 146 of 377 days (39 percent) monitored from June 2017 to June 2018.

In the area that frequently floods at the CYCC near the downstream monitoring site for Mill Creek (Mill Creek 2, fig. 2), it was determined that the altitude of the golf cart path was about 1.4 ft above NAVD 88. This was confirmed by a laser-level survey during May 2018. The downstream monitoring site on Mill Creek, however, is at a slightly lower altitude than the area that floods on the golf course. An analysis of Mill Creek stage data and photographs of flooding taken at different times during the study indicate that the area floods when the stage at the downstream Mill Creek monitoring site exceeds about 1.3 ft above NAVD 88 (figs. 4 and 12*B*). The daily maximum stage equaled or exceeded 1.3 ft on 118 of 377 days (31 percent), according to monitoring data from June 1, 2017, through June 14, 2018 (fig. 12*B*).

Likely factors affecting water levels in Mill Creek include local groundwater levels, recent precipitation, and evapotranspiration. Recent precipitation not only recharges the local groundwater system but also provides overland runoff, which contributes directly to flooding and contributes inflow of water from the drainage basin to Mill Creek upstream from the CYCC. High groundwater levels contribute discharge to Mill Creek through multiple pathways, including discharge to Mill Creek upstream from the study area, direct seepage of groundwater into low-lying drainage areas (former salt marsh areas) adjacent to Mill Creek, and direct discharge of groundwater to Mill Creek from the subsurface. High groundwater levels contribute to overland runoff during precipitation events by causing ponding in areas where the water table is at the land surface, thereby exacerbating the flooding. Evapotranspiration removes water from surface runoff, groundwater recharge,

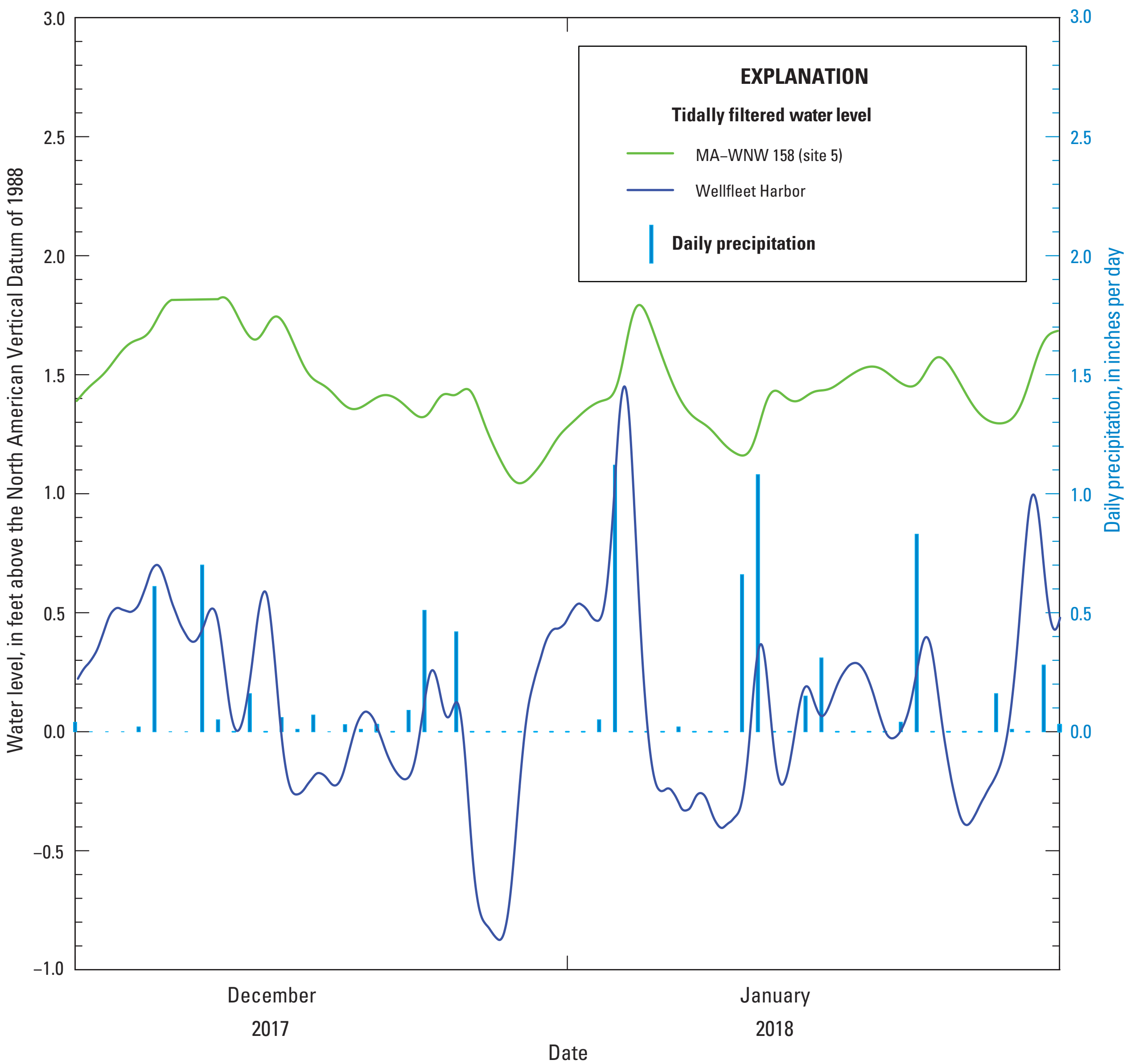


**Figure 11.** Tidally filtered water levels at the Herring River downstream from the tide-control structure (Wellfleet Harbor), tidally filtered water levels at well MA–WNW 158, and daily precipitation from December 2017 to January 2018, Wellfleet, Massachusetts.

and groundwater discharge near the wetland areas around Mill Creek, potentially reducing the severity of flooding during the growing season. Another factor that affects the water levels in Mill Creek is the resistance to flow in the channel of Mill Creek, which causes backwater that exacerbates flooding, and likely causes additional increases in groundwater levels near the creek. The resistance to flow is likely to vary seasonally as the growth of wetland plants such as the nonnative reed *Phragmites australis* increases during the growing season. The water in Mill Creek from storms drains away slowly because of the small gradient in the watercourse. The mean difference in the water-surface altitude between the upstream and downstream sites on Mill Creek was 0.24 ft (table 2), indicating a gradient of about 0.00013, based on the approximate distance between the sites along the creek (1,814 ft).

To describe the variability in Mill Creek stage, regression models to account for some of the factors discussed above were created for the two sites on Mill Creek. The daily maximum values for Mill Creek stage at either site were used as the dependent variable in the regressions. Daily mean groundwater-level data (*meanGWalt*) from nearby wells were used as the primary independent variable. The daily mean values of groundwater-level data were used in this model, rather than the tidally filtered daily mean used in the regressions to evaluate factors related to groundwater levels, as described in the section “Groundwater-Level Fluctuations

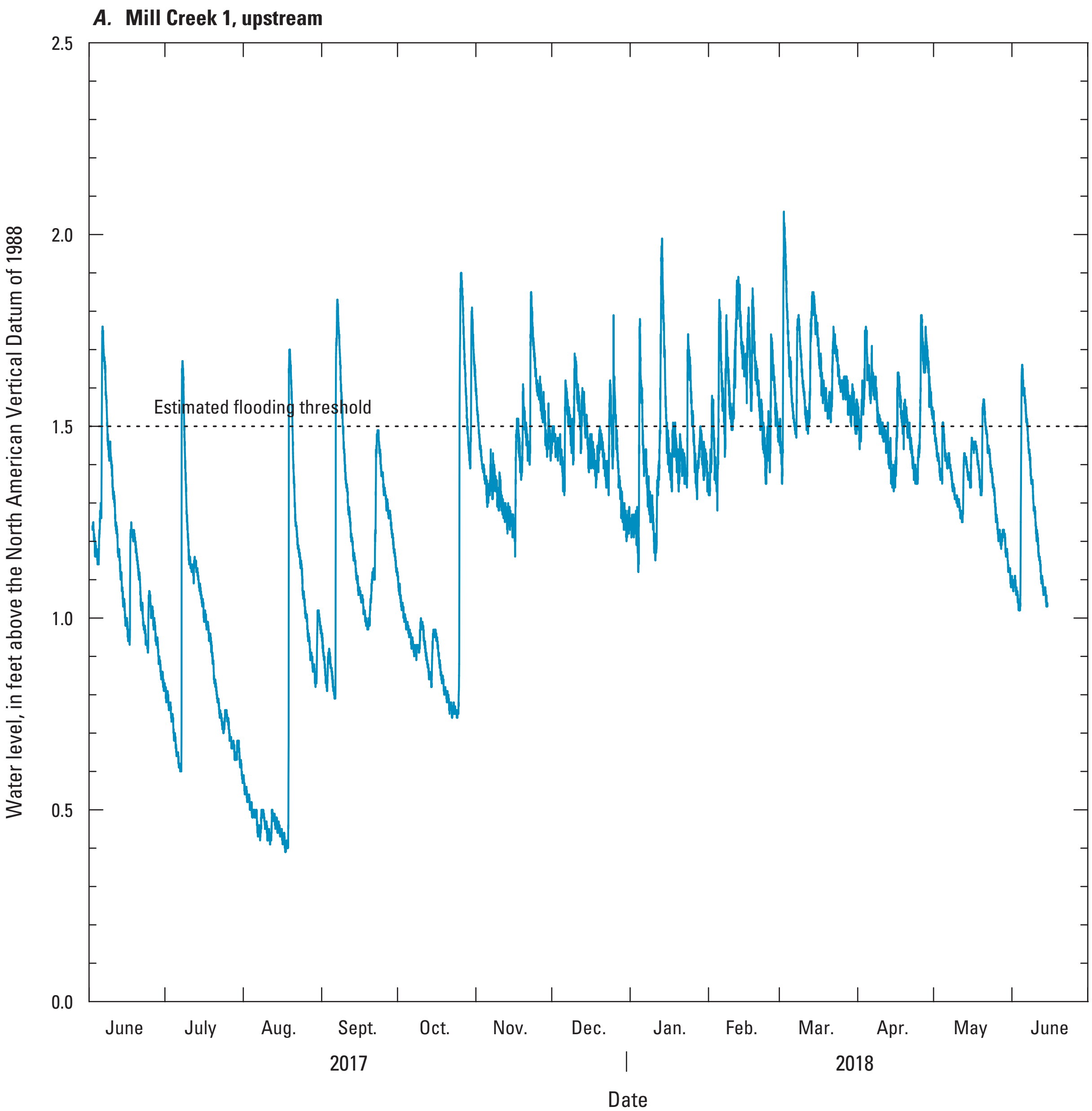


**Figure 12.** Water levels in Mill Creek at *A*, site 1, upstream at Chequessett Yacht and Country Club, and *B*, site 2, downstream, from June 1, 2017, to June 14, 2018, Wellfleet, Massachusetts.

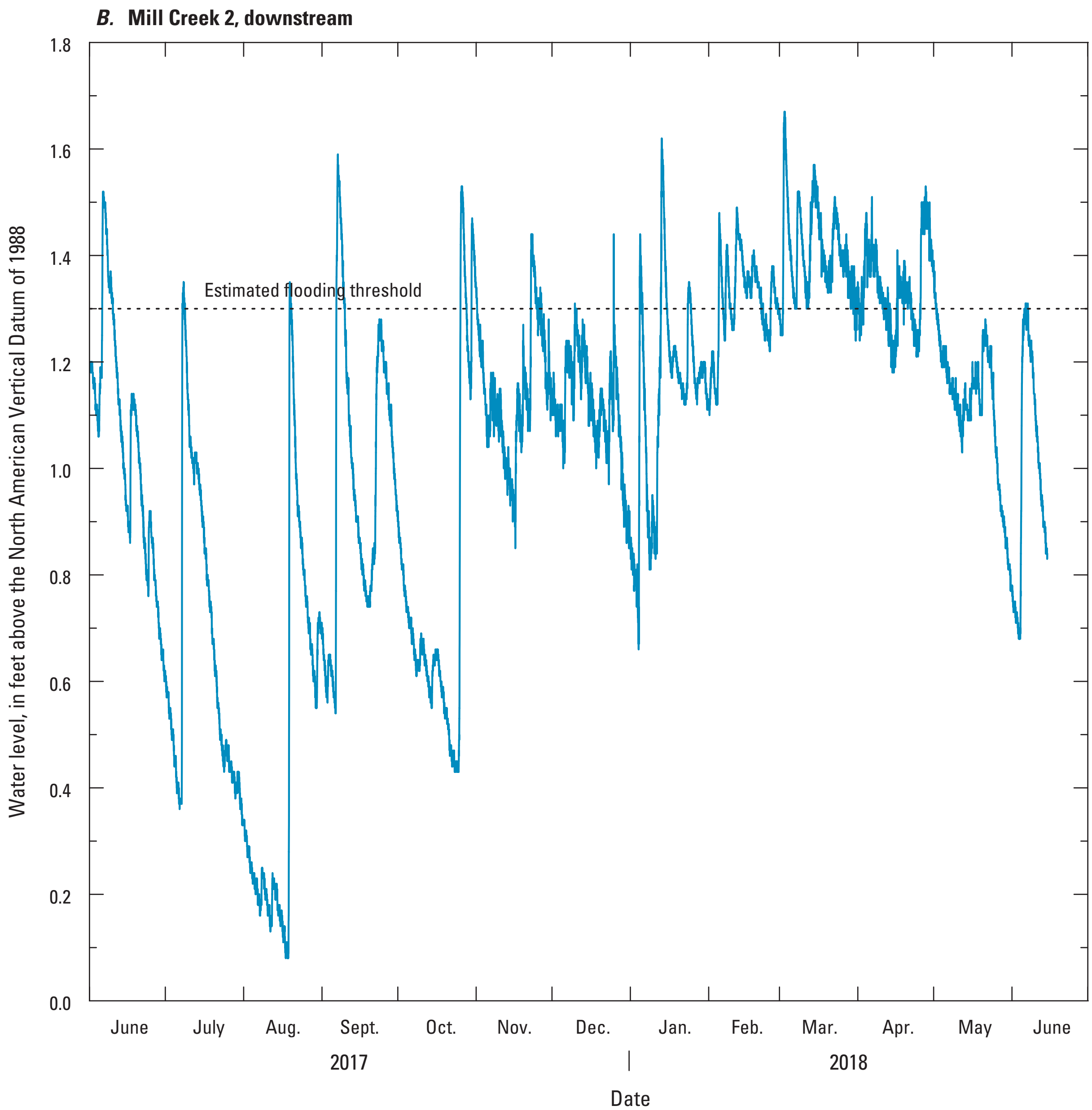


**Figure 12.** Water levels in Mill Creek at *A*, site 1, upstream at Chequessett Yacht and Country Club, and *B*, site 2, downstream, from June 1, 2017, to June 14, 2018, Wellfleet, Massachusetts.—Continued

Over Periods Longer Than Daily Tidal Cycles." The other variables included the total precipitation during the preceding 7 days (*precip*7*day*), the growing degree days (50 °F) (*GDD*50), and a binary variable based on whether Mill Creek is considered above (1) or below (0) the flooding thresholds described above (*flooded*). This variable was used to account for the change in relation between groundwater levels and Mill Creek stage when the channel overflows and water spreads over the flood plain.

The selected models explained about 76 percent of the variability in daily maximum water levels at the upstream site and about 61–89 percent of the variability in daily maximum water levels at the downstream site, based on the coefficients of determination for each model (appendix 2, table 2.3). The *meanGWalt* variable for wells near each site on Mill Creek explained about 31 and 26–75 percent, respectively, of the variability in daily maximum water levels at the upstream and downstream sites. The other variables accounted for additional variability in daily maximum water levels at each site on Mill Creek. This was confirmed with an analysis of the standardized coefficients in these regression models, which indicated the relative importance of each variable in the regression models (appendix 2, table 2.4).

For the upstream site on Mill Creek, the order of the absolute magnitude of the standardized regression coefficients was *GDD50*>*precip*7*day*>*flooded*>*meanGWalt* (table 2.4). For the downstream site, the absolute magnitude of the standardized coefficients was largest for the *meanGWalt* variable for wells MA–WNW 155–0017 and MA–WNW 161, indicating that these wells are important in predicting the likelihood of flooding (table 2.4). These two regression models had the highest $R^2$ values of 0.81 and 0.93, respectively (table 2.3).

The general relations between the stage of Mill Creek and nearby groundwater levels can be summarized as follows: at the upstream site on Mill Creek, the water level rises to or above 1.5 ft above NAVD 88 when the groundwater level in the nearby well (MA–WNW 157–0012, site 4) reached about 1.89 ft (25th percentile, fig. 13*A*). This occurred primarily when the 7-day precipitation was at least 0.92 inch (25th percentile, fig. 13*B*) and when the *GDD*50 value was low or zero.

At the downstream site, the water level rises to or above 1.3 ft above NAVD 88 when the groundwater levels in nearby wells (MA–WNW 155–0017, MA–WNW 156–0010, and MA–159–0012, MA–WNW 161) generally reached 2.33, 1.78, 1.60, and 1.38 ft above NAVD 88, respectively (25th percentile, figs. 14*A*–*D*). This occurred primarily when the 7-day precipitation was at least 1.04 inches (fig. 14*E*).

In addition to the thresholds for nearby groundwater levels and 7-day precipitation, the *GDD*50 variable helped explain some of the variability, as most of the flooding during the study period was during the nongrowing season. Flooding events during the growing season and during times when groundwater levels were low were typically short-duration events caused by recent heavy precipitation. Flooding events during the nongrowing season tended to last longer, as groundwater levels remained above the thresholds described previously (figs. 12*A* and *B*).

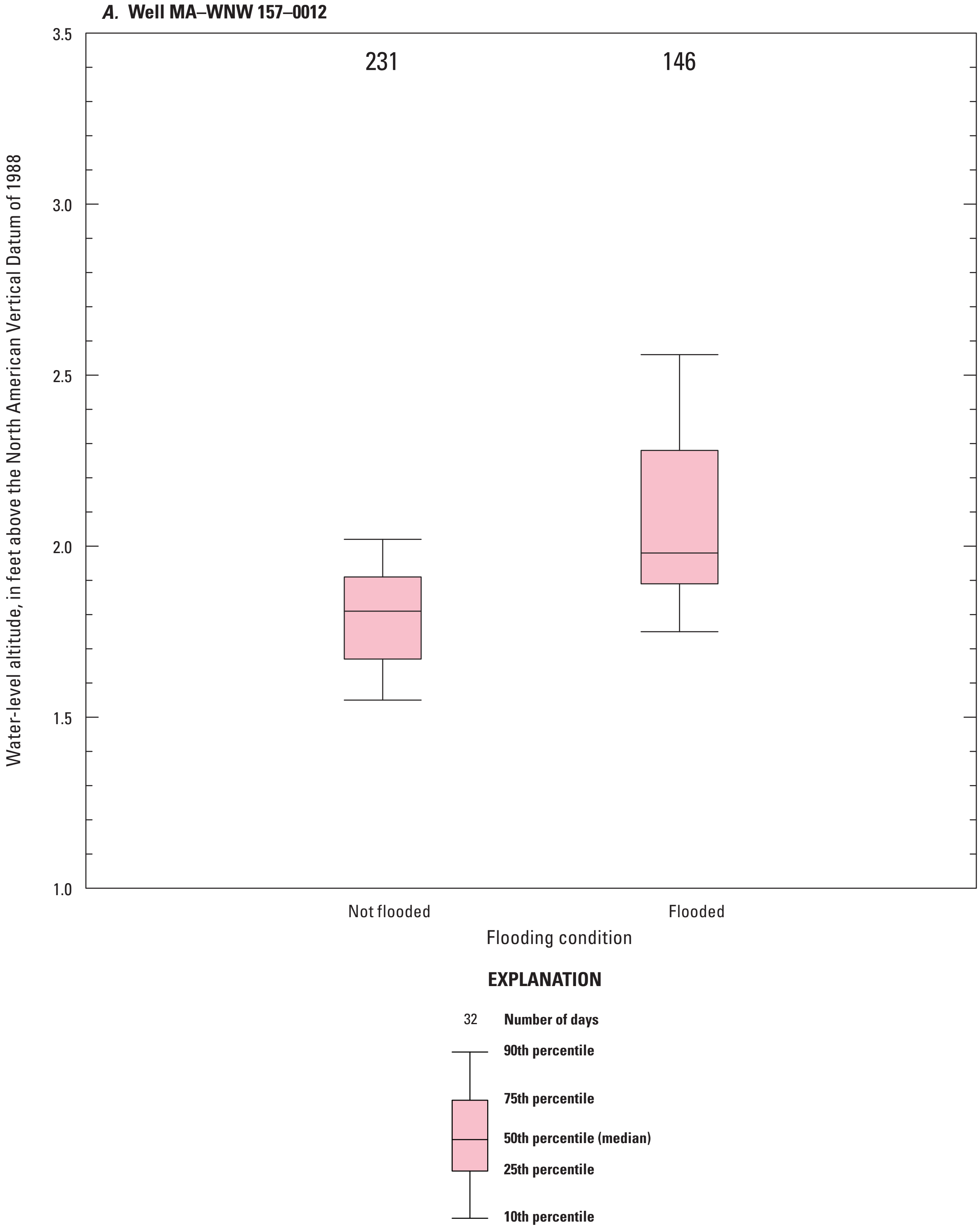


**Figure 13.** The distribution of *A*, groundwater levels at well MA–WNW 157–0012 and *B*, 7-day precipitation under nonflooded and flooded conditions at the upstream site on Mill Creek, June 1, 2017, through June 14, 2018, Wellfleet, Massachusetts.

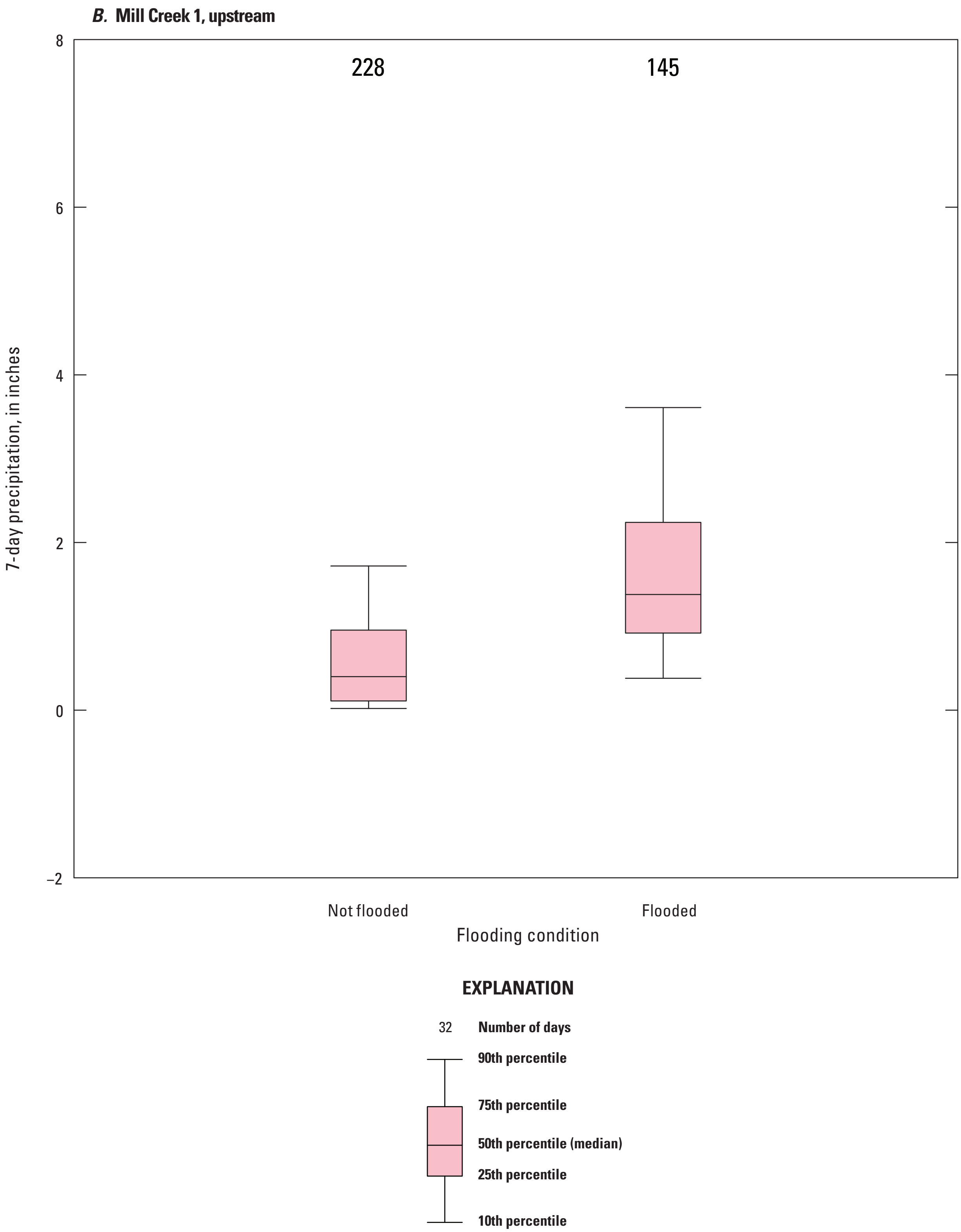


**Figure 13.** The distribution of *A*, groundwater levels at well MA–WNW 157–0012 and *B*, 7-day precipitation under nonflooded and flooded conditions at the upstream site on Mill Creek, June 1, 2017, through June 14, 2018, Wellfleet, Massachusetts.—Continued

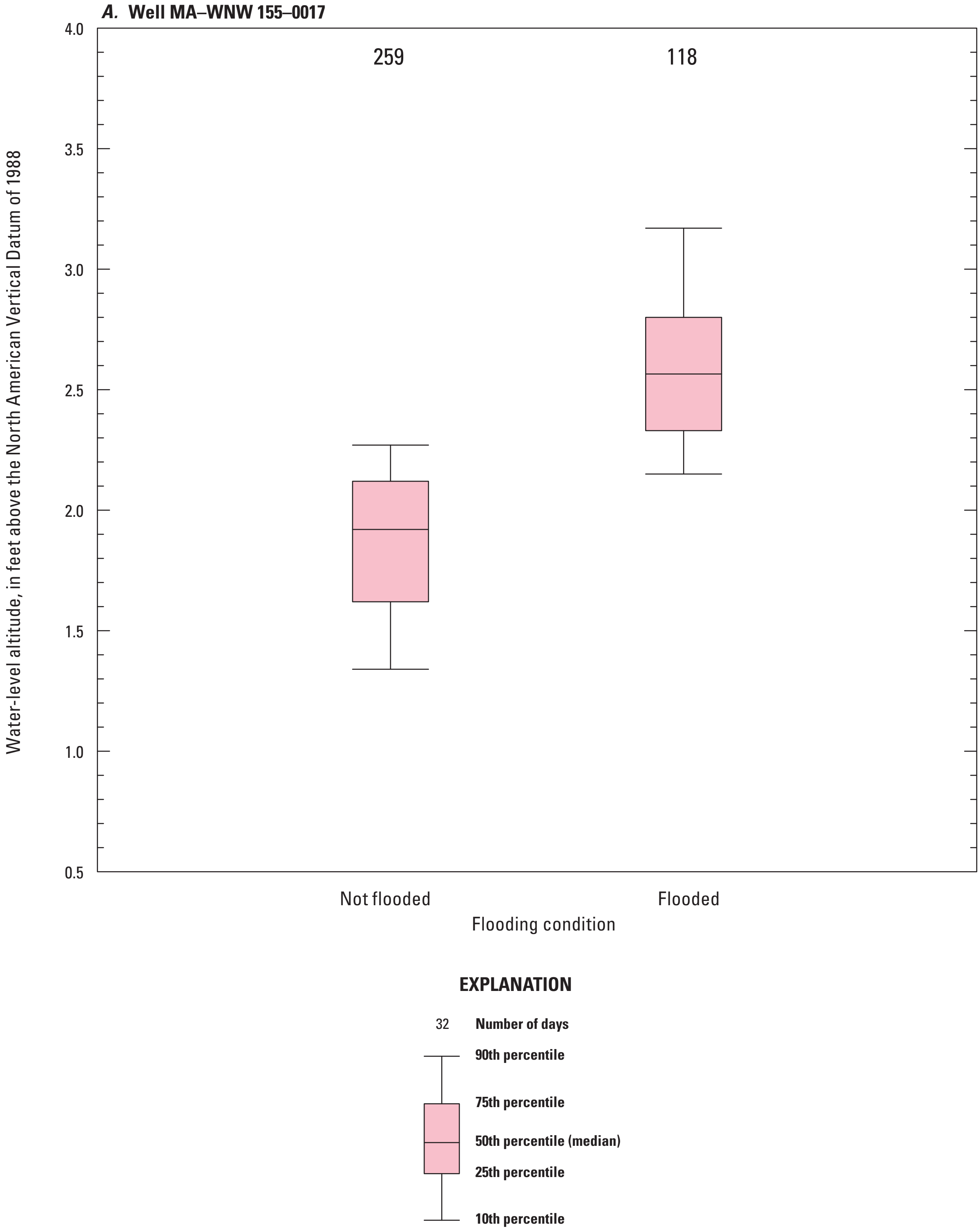


**Figure 14.** The distribution of groundwater levels at *A*, well MA–WNW 155–0017, *B*, well MA–WNW 156–0010, *C*, well MA–WNW 159–0012, and *D*, well MA–WNW 161; and *E*, distribution of 7-day precipitation under nonflooded and flooded conditions at the downstream site on Mill Creek, June 1, 2017, through June 14, 2018, Wellfleet, Massachusetts.

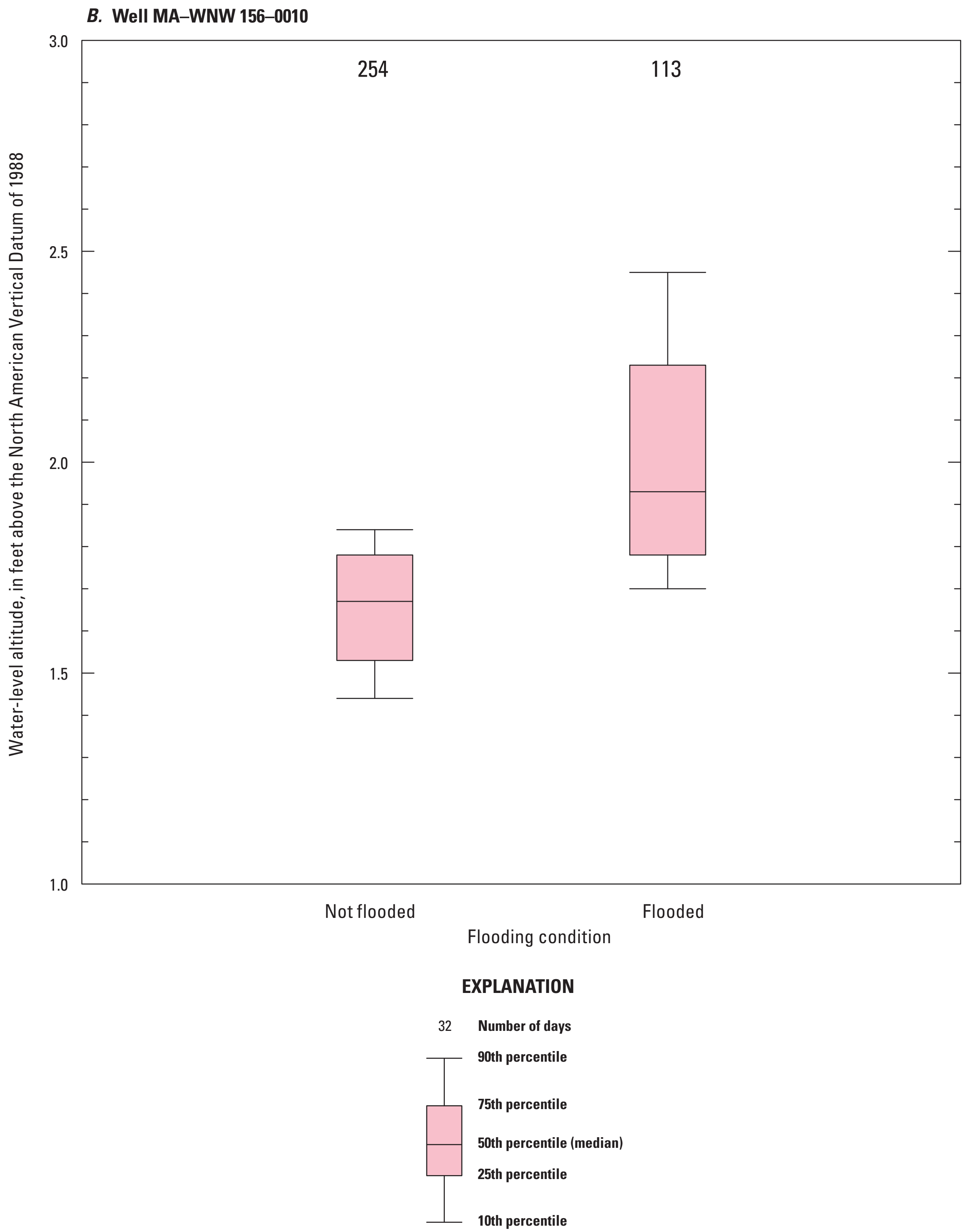


**Figure 14.** The distribution of groundwater levels at *A*, well MA–WNW 155–0017, *B*, well MA–WNW 156–0010, *C*, well MA–WNW 159–0012, and *D*, well MA–WNW 161; and *E*, distribution of 7-day precipitation under nonflooded and flooded conditions at the downstream site on Mill Creek, June 1, 2017, through June 14, 2018, Wellfleet, Massachusetts.—Continued

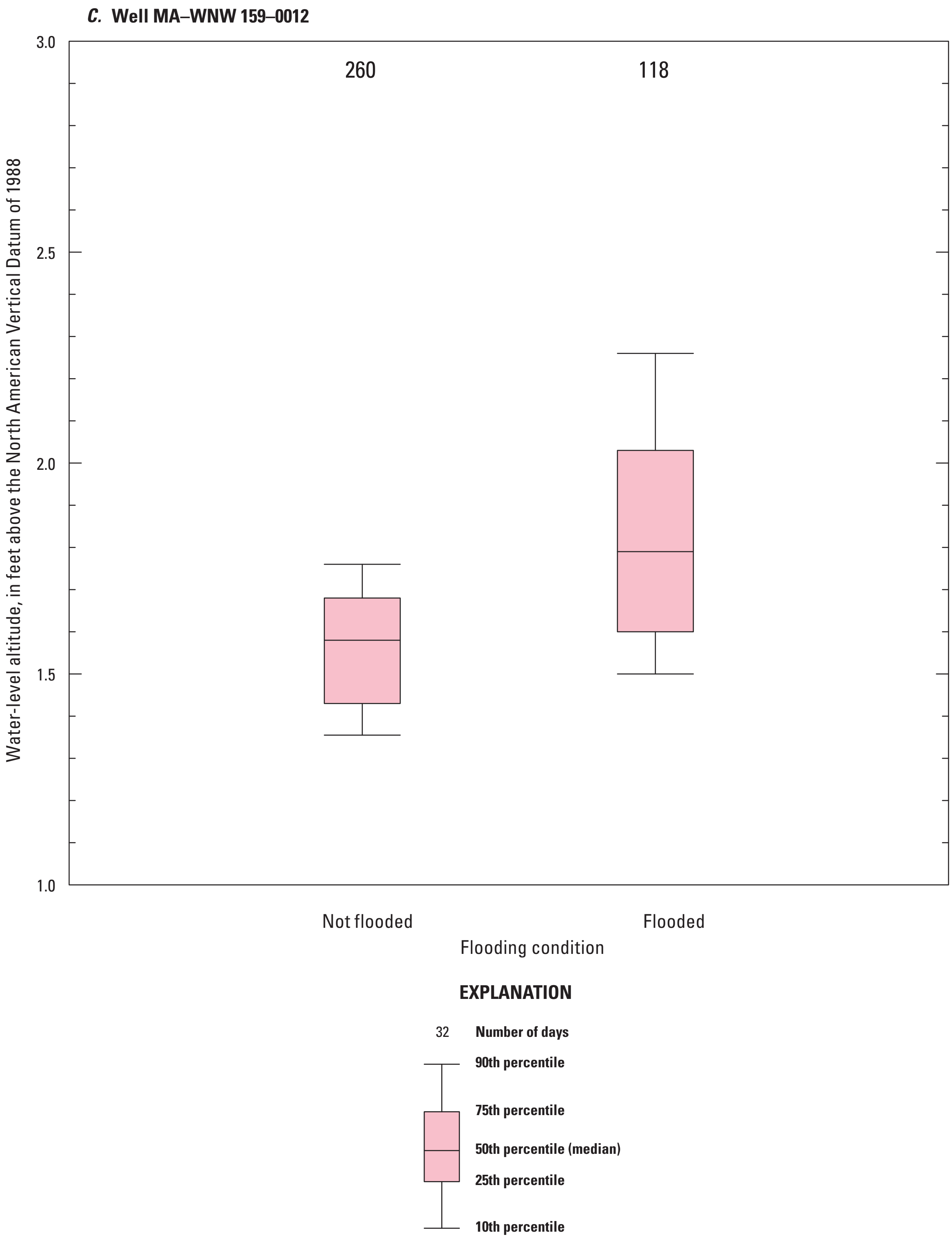


**Figure 14.** The distribution of groundwater levels at *A*, well MA–WNW 155–0017, *B*, well MA–WNW 156–0010, *C*, well MA–WNW 159–0012, and *D*, well MA–WNW 161; and *E*, distribution of 7-day precipitation under nonflooded and flooded conditions at the downstream site on Mill Creek, June 1, 2017, through June 14, 2018, Wellfleet, Massachusetts.—Continued

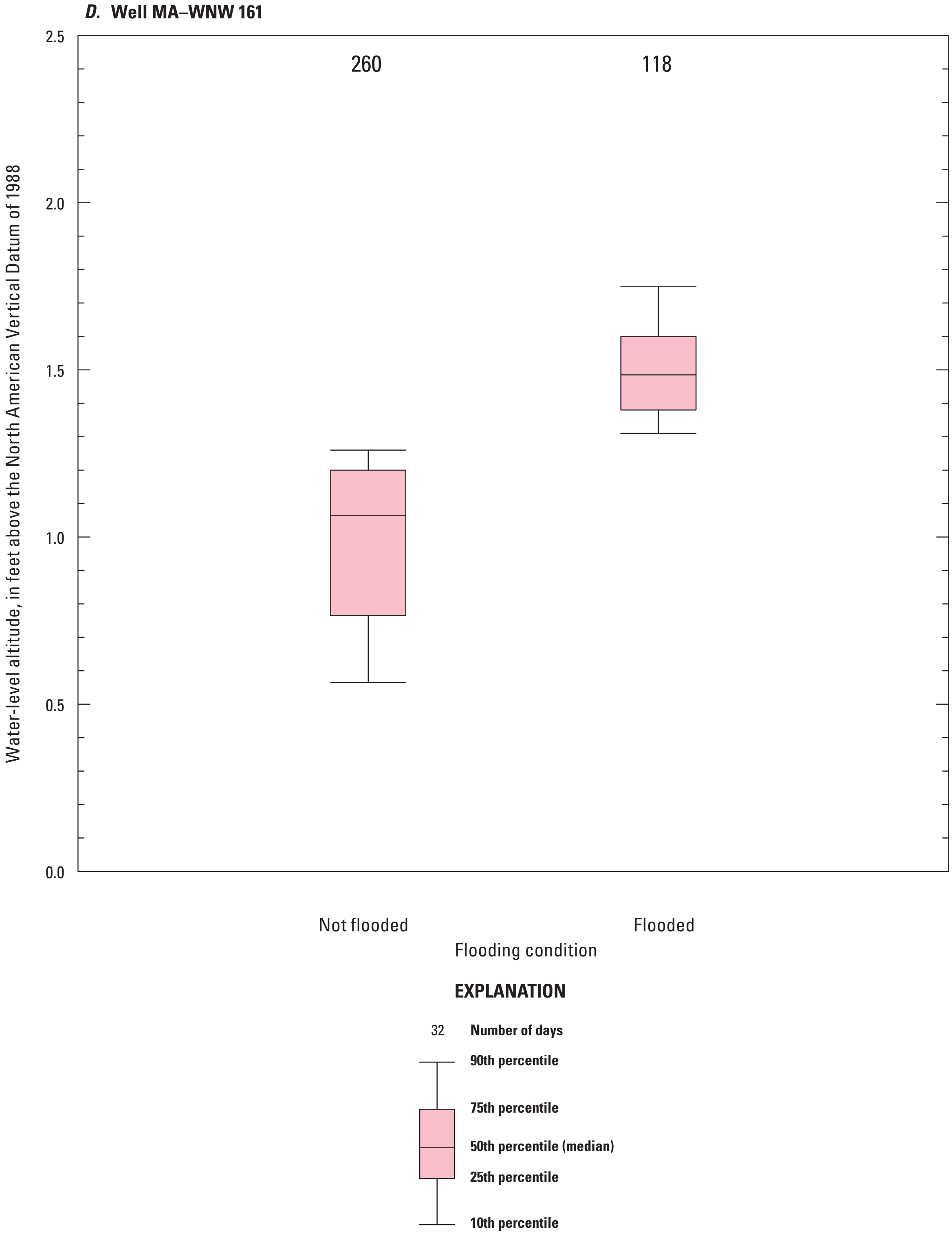


**Figure 14.** The distribution of groundwater levels at *A*, well MA–WNW 155–0017, *B*, well MA–WNW 156–0010, *C*, well MA–WNW 159–0012, and *D*, well MA–WNW 161; and *E*, distribution of 7-day precipitation under nonflooded and flooded conditions at the downstream site on Mill Creek, June 1, 2017, through June 14, 2018, Wellfleet, Massachusetts.—Continued

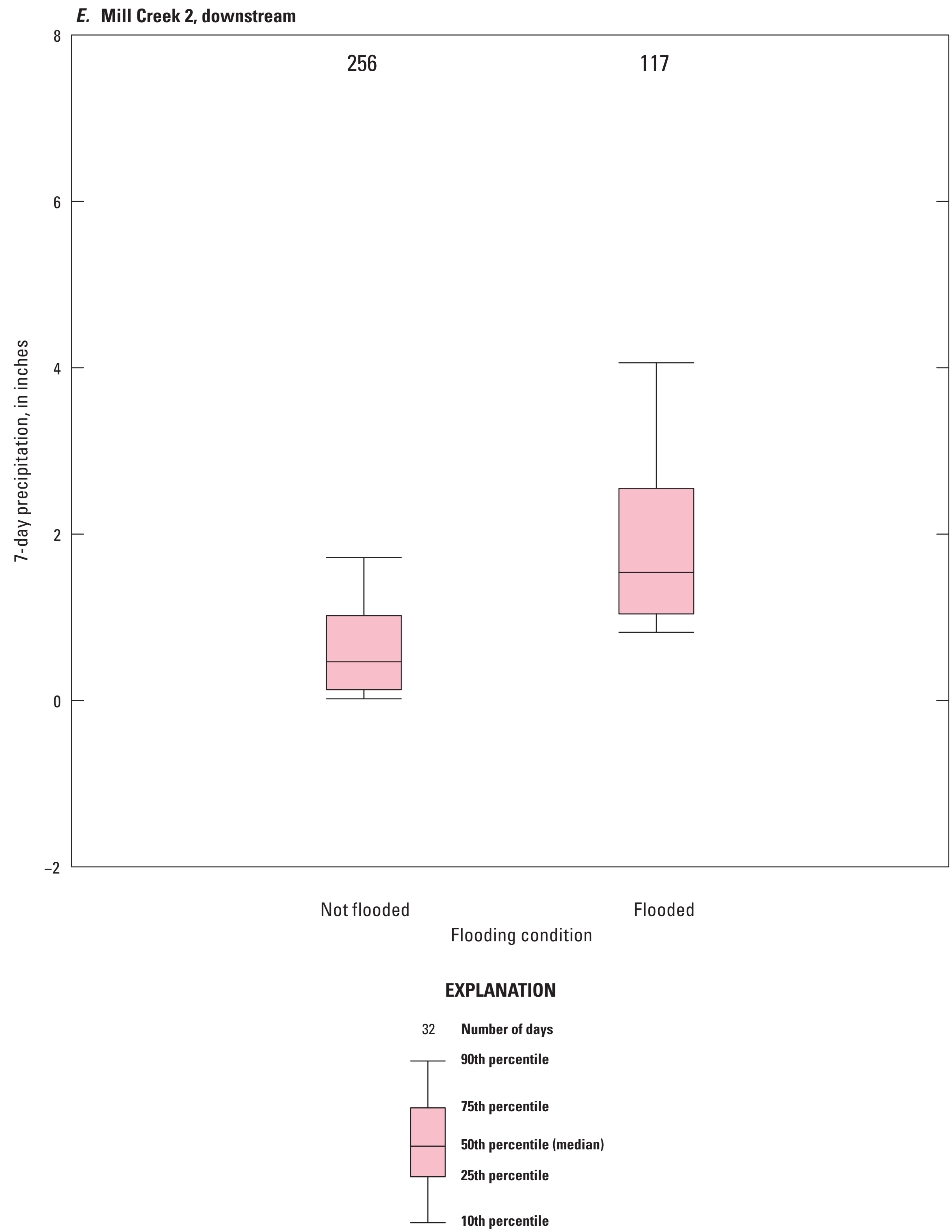


**Figure 14.** The distribution of groundwater levels at *A*, well MA–WNW 155–0017, *B*, well MA–WNW 156–0010, *C*, well MA–WNW 159–0012, and *D*, well MA–WNW 161; and *E*, distribution of 7-day precipitation under nonflooded and flooded conditions at the downstream site on Mill Creek, June 1, 2017, through June 14, 2018, Wellfleet, Massachusetts.—Continued

## Summary and Conclusions

The Herring River estuary is in the towns of Wellfleet and Truro, Massachusetts, on Cape Cod Bay. The natural tidal flow of the Herring River has been limited since the construction of a dike with tide gates (tide-control structure) near the mouth of the river at Chequessett Neck in 1909. The National Park Service has a goal to restore tidal flow to a large part of the 1,100 acres of habitat that have been degraded by the presence of the tide-control structure, with a minimal impact on private properties and cultural resources. Restoration will be done by replacing the existing tide-control structure with a new structure that will allow for incremental adjustment of the tide range.

There is concern about increased flooding, under the proposed restoration plan, resulting from high groundwater levels on the golf course at the Chequessett Yacht and Country Club (CYCC), which was built on some low-lying areas, including former salt marshes. A new tide-control structure also would be constructed on the Mill Creek tributary to block upstream movement of the tide, when the tide range is increased in the Herring River, to protect private properties.

To monitor the water levels near the Mill Creek area prior to restoration activities, the U.S. Geological Survey, in cooperation with the Friends of Herring River, established a monitoring network that included new and existing wells. New wells were drilled at eight locations, including four locations with wells installed at multiple depths.

Surface-water-level monitoring sites were established at upstream and downstream locations on Mill Creek, and tidal fluctuations were measured at existing sites on the Herring River upstream and downstream from the existing tide-control structure. Groundwater levels and water levels in Mill Creek were monitored from June 2017 to June 2018. Water levels in the Herring River were monitored for the same time period upstream from the tide-control structure and from September 2017 to June 2018 at the downstream side of the tide-control structure (Wellfleet Harbor).

From new and existing information on site geology, it was determined that salt marsh deposits at the CYCC range from zero to 18 feet (ft) thick. The deposits directly underlying the marsh sediments are typically finer than the sediments in the adjacent upland areas and are likely estuarine sediments. In the adjacent upland areas at the CYCC, away from the former salt marsh deposits, the glacial deposits are primarily medium to very coarse sand. The depth to the transition zone from freshwater to saltwater ranged from 15 to 95 ft, depending on location and altitude of each site.

The water levels from short-term tidal fluctuations at individual wells and the Herring River were analyzed by filtering the tidal signal from the groundwater levels and regressed on five common tidal harmonics, and the amplitude and phase of each of the tidal components were determined. The largest amplitude (0.12 ft) in the M2 (principal lunar semidiurnal constituent) was observed at site 1 (MA–WNW 154), adjacent to the Herring River. The next largest amplitude (0.06 ft) was observed at site 5 (MA–WNW 158), which is the well closest to Wellfleet Harbor. Short-term tidal fluctuations (greater than 0.01 ft) were generally limited to an area within 1,500 ft of Wellfleet Harbor.

Under the proposed initial restoration scenario (little or no change in mean tide), the amplitude of the tidal range in the Herring River would increase to 2.5 ft, and the tidal influence would move closer to the CYCC by about 700 ft. The tidal fluctuations in Mill Creek would extend to the downstream side of a proposed tide-control structure on Mill Creek. Under these conditions, it is possible that the daily tidal fluctuations in groundwater levels on parts of the CYCC nearest to the proposed tide-control structure could increase; however, they should be limited to less than 0.06 ft, the maximum tidal fluctuation observed in well MA–WNW 158, which was nearest to Wellfleet Harbor, under the influence of the full tidal range of Wellfleet Harbor.

Regression models were developed to describe the variability in groundwater levels at individual wells and at the upstream and downstream monitoring sites on Mill Creek. For the groundwater levels, a tidal filter was used to remove the effects of the daily tidal fluctuations. The daily mean tidally filtered groundwater level was the dependent variable. The significant independent variables included daily mean filtered Herring River (downstream or upstream) stage lagged in time by zero to 2 days, precipitation in the preceding 7 days, growing degree days (50 degrees Fahrenheit), and the quartile of local groundwater storage for a long-term monitoring site (well MA–WNW 17). An analysis of the standardized coefficients for these models indicated that for wells away from the Mill Creek corridor, the variable with the largest absolute value was the tidally filtered water level in Wellfleet Harbor. For wells along the Mill Creek corridor, the variables with the largest absolute values were the growing degree days (50 degrees Fahrenheit) and the quartile of the long-term groundwater levels.

For the monitoring sites upstream and downstream on Mill Creek, approximate flooding thresholds were established. At the upstream site on Mill Creek, the flooding threshold was met or exceeded on about 39 percent of the days monitored during the study period from June 1, 2017, through June 14, 2018. At the downstream site on Mill Creek, the flooding threshold was met or exceeded on about 31 percent of the days during the study period.

Regression models were developed to explain the variability of daily maximum water levels at both sites on Mill Creek. The independent variables included daily mean groundwater levels in nearby observation wells, precipitation in the preceding 7 days, growing degree days (50 degrees Fahrenheit), and a binary variable indicating whether the Mill Creek stage at each site was above the estimated flood stage. The models explained about 76 percent of the variability in daily mean water levels at the upstream site and about 61–89 percent of the variability in daily mean water levels at the downstream site. Based on an examination of the standardized coefficients for these models, the daily mean groundwater levels were the variable with the largest absolute coefficients for two of the closest wells at the downstream site, whereas, at the upstream site, the variable for the daily mean groundwater levels had the smallest absolute coefficient.

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# Appendix 1. Graphs of Water Levels in Wells Monitored for the Study of the Mill Creek Study Area, June 2017–June 2018

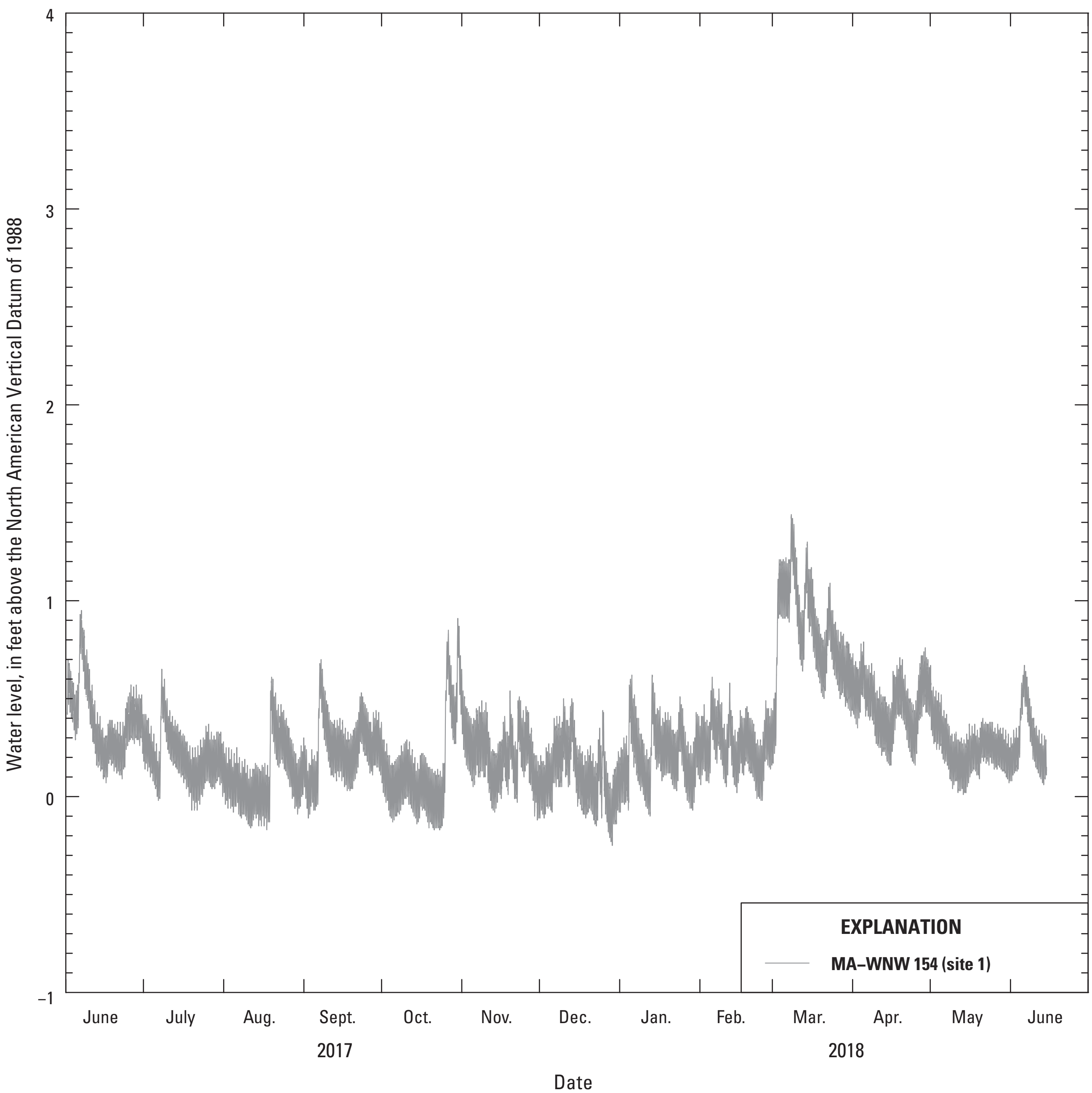


**Figure 1.1.** Water levels at well MA–WNW 154 (site 1) from June 2017 to June 2018, Mill Creek study area, Wellfleet, Massachusetts.

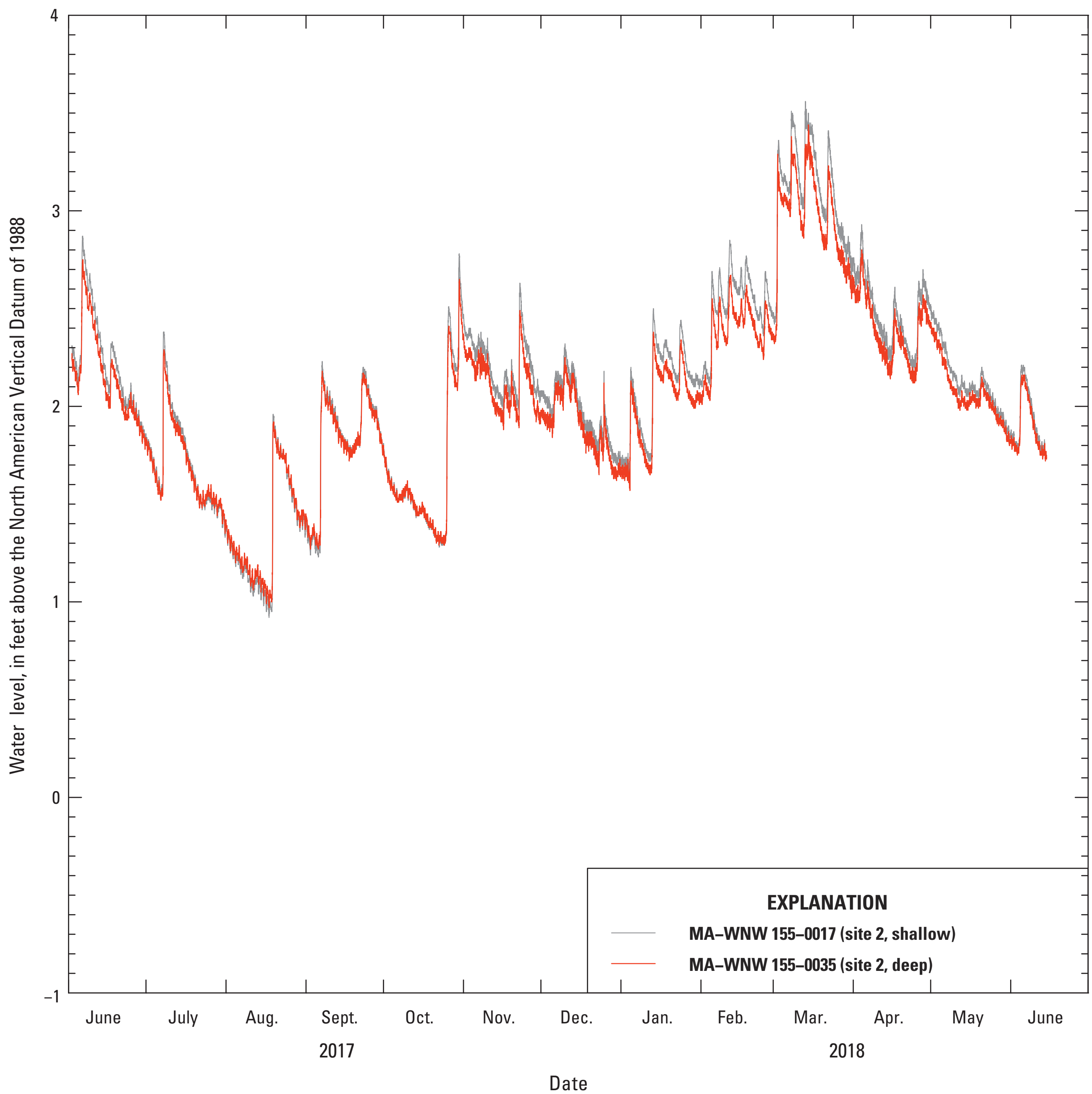


**Figure 1.2.** Water levels at well MA–WNW 155–0017 and MA–WNW 155–0035 (site 2) from June 2017 to June 2018, Mill Creek study area, Wellfleet, Massachusetts.

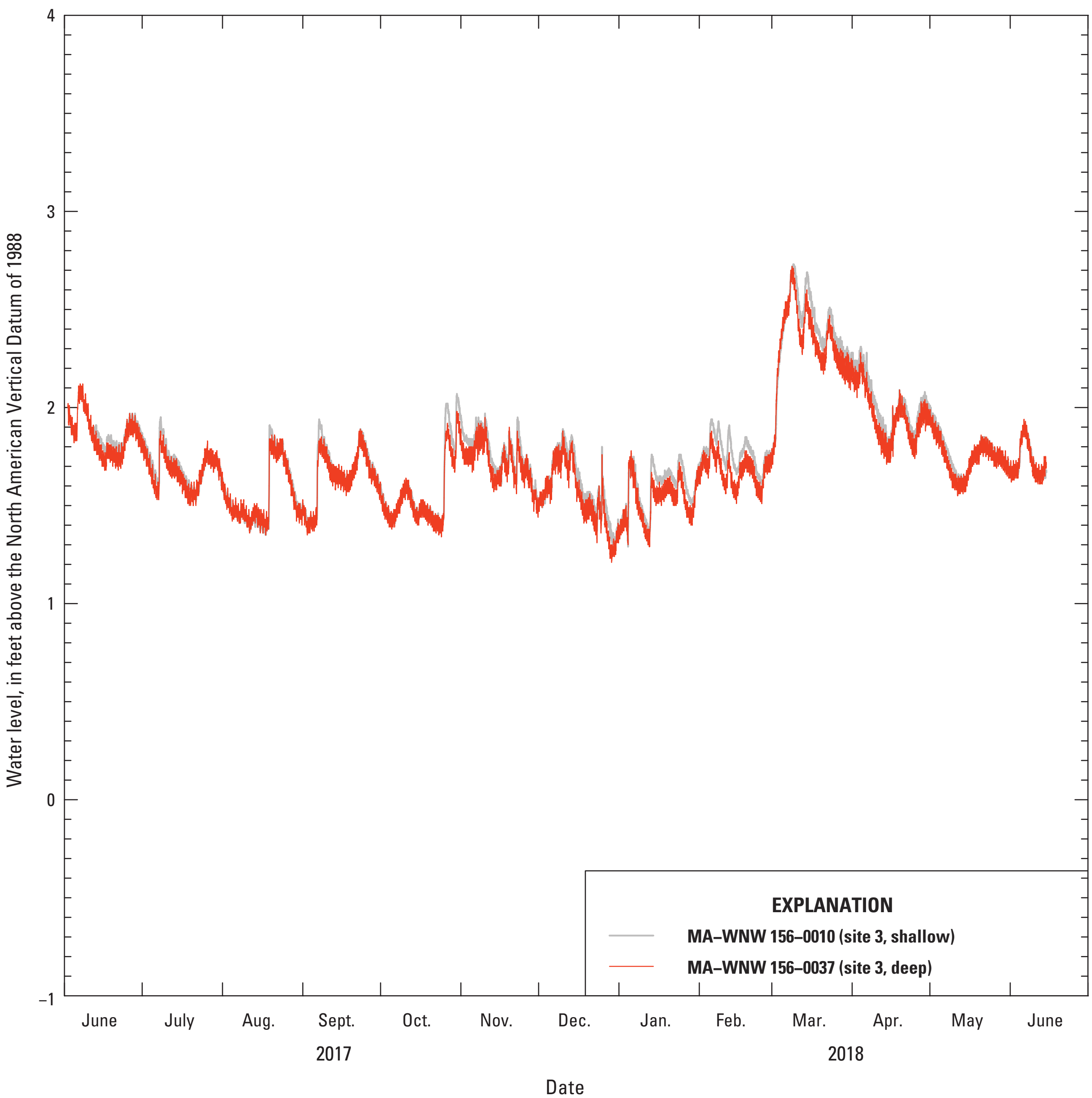


**Figure 1.3.** Water levels at well MA–WNW 156–0010 and MA–WNW 156–0037 (site 3) from June 2017 to June 2018, Mill Creek study area, Wellfleet, Massachusetts.

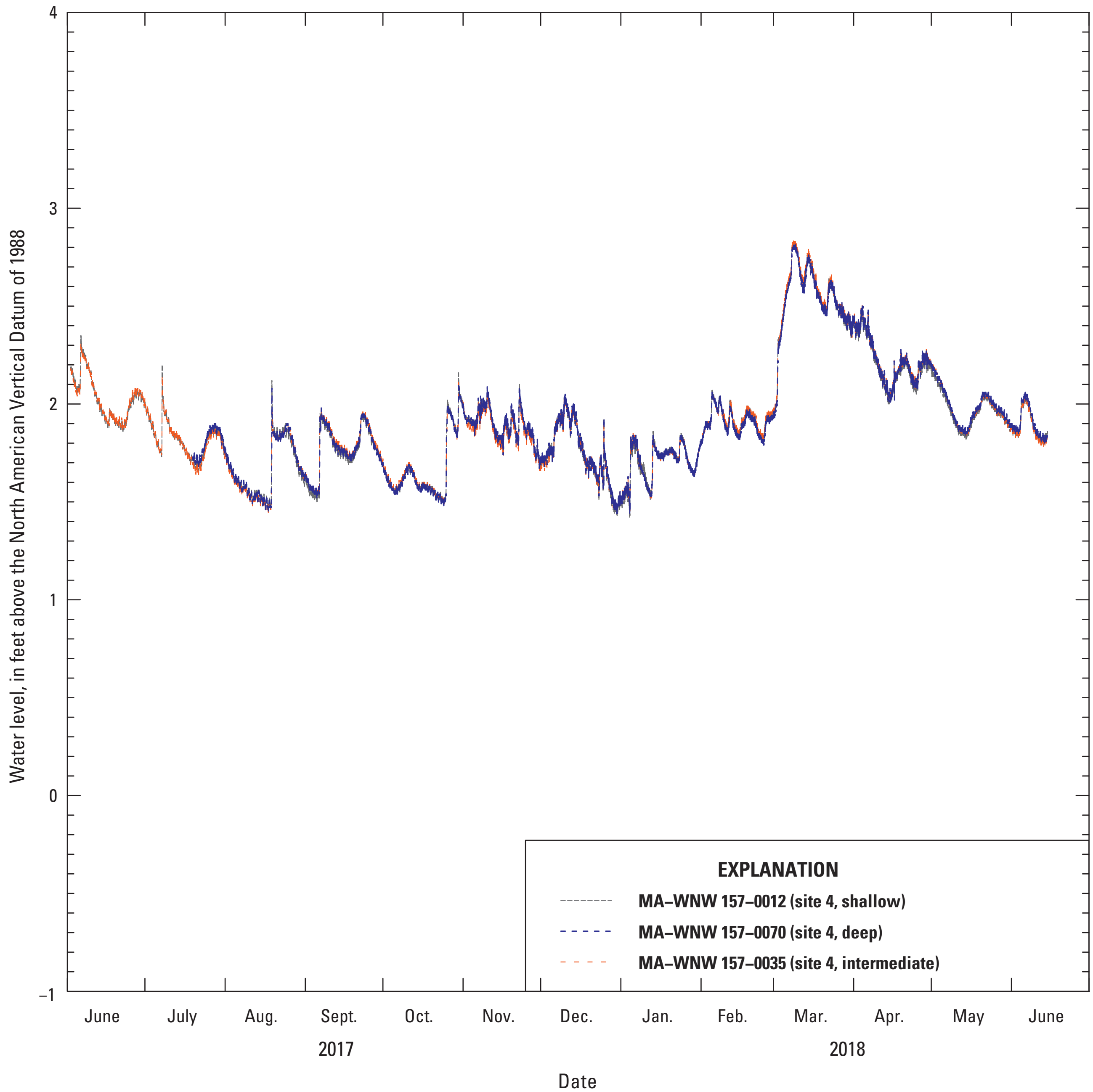


**Figure 1.4.** Water levels at well MA–WNW 157–0012, MA–WNW 157–0070, and MA-WNW 157–0035 (site 4) from June 2017 to June 2018, Mill Creek study area, Wellfleet, Massachusetts.

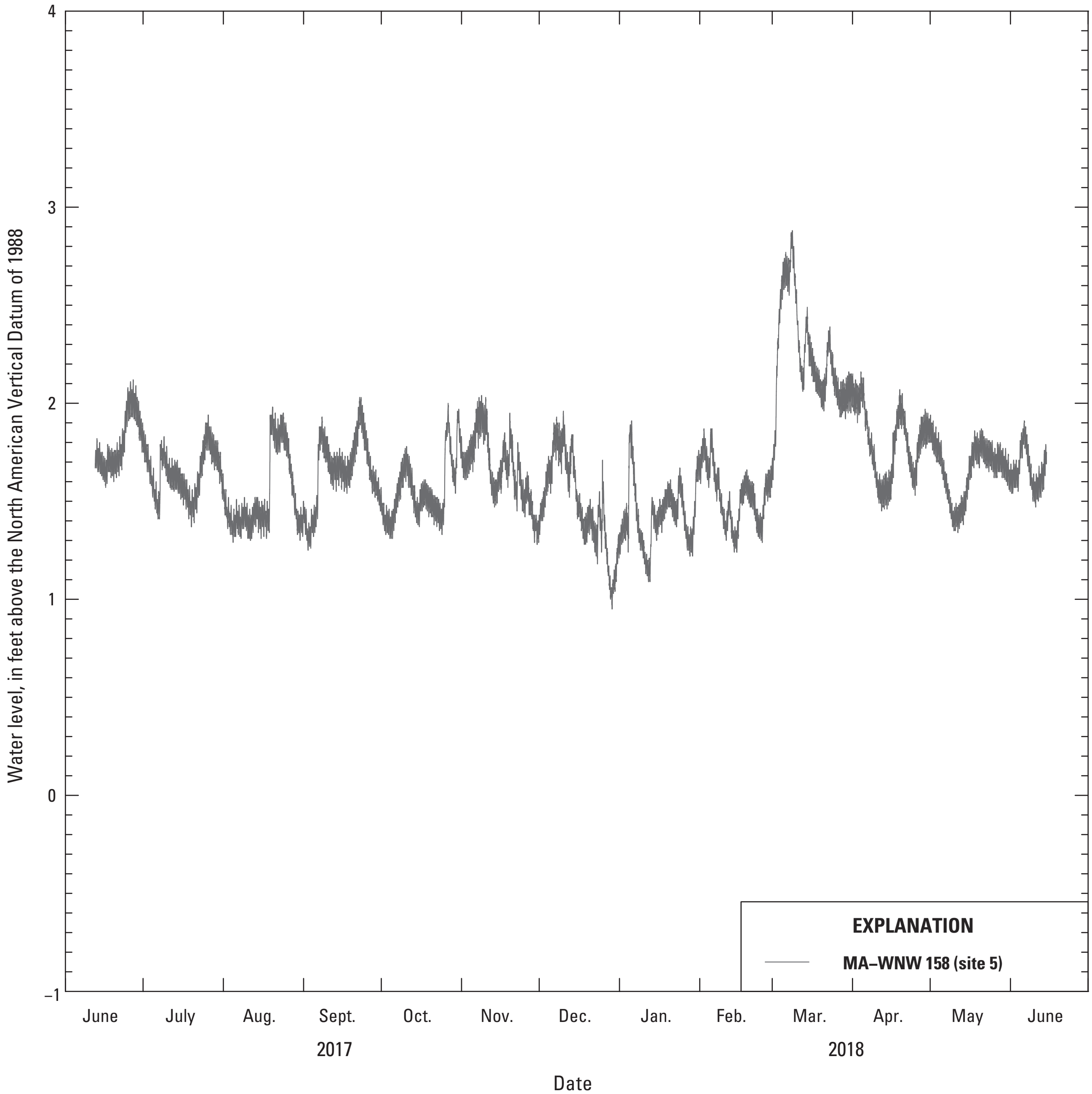


**Figure 1.5.** Water levels at well MA–WNW 158 (site 5) from June 2017 to June 2018, Mill Creek study area, Wellfleet, Massachusetts.

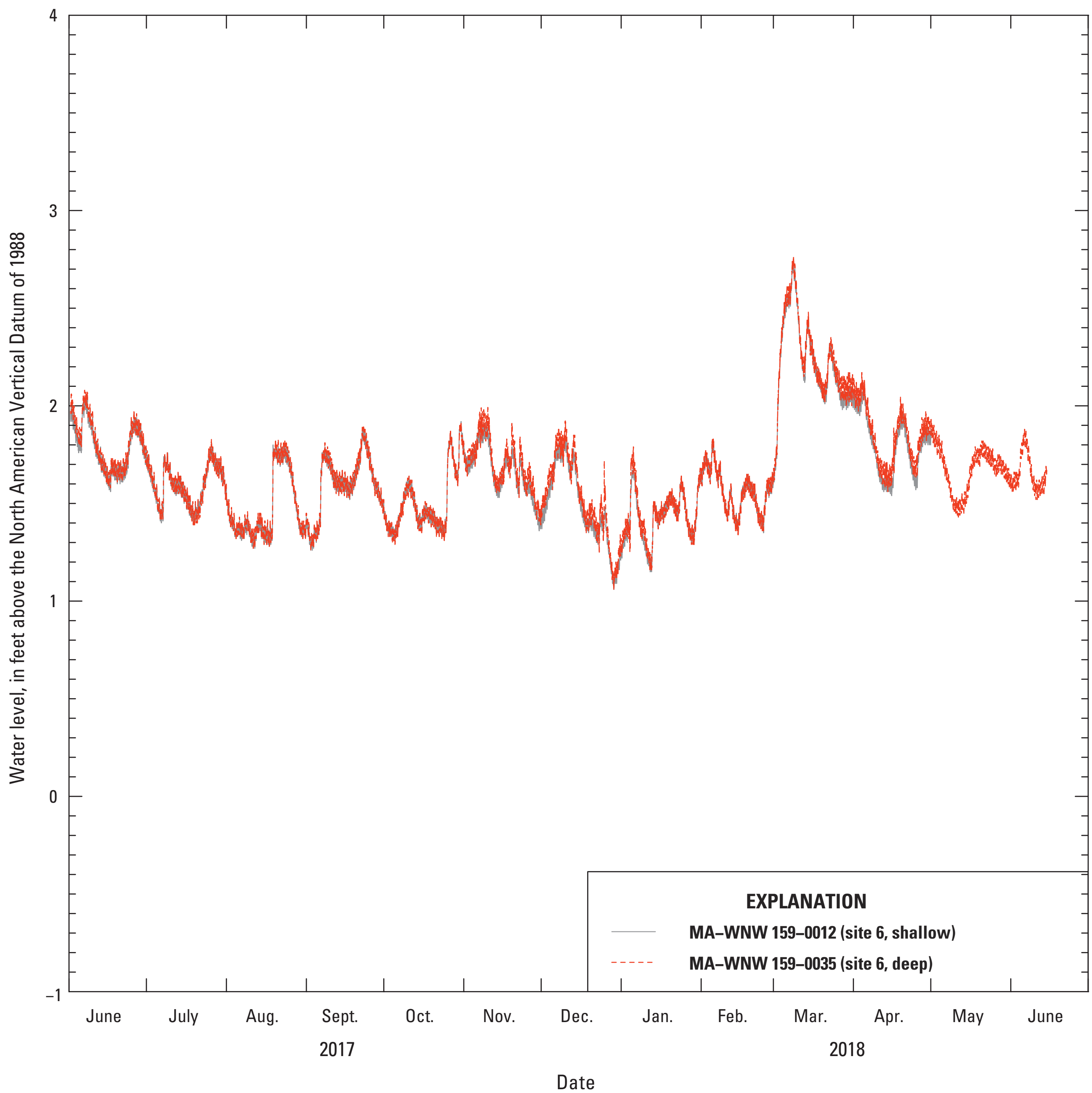


**Figure 1.6.** Water levels at well MA–WNW 159–0012 and MA–WNW 159–0035 (site 6) from June 2017 to June 2018, Mill Creek study area, Wellfleet, Massachusetts.

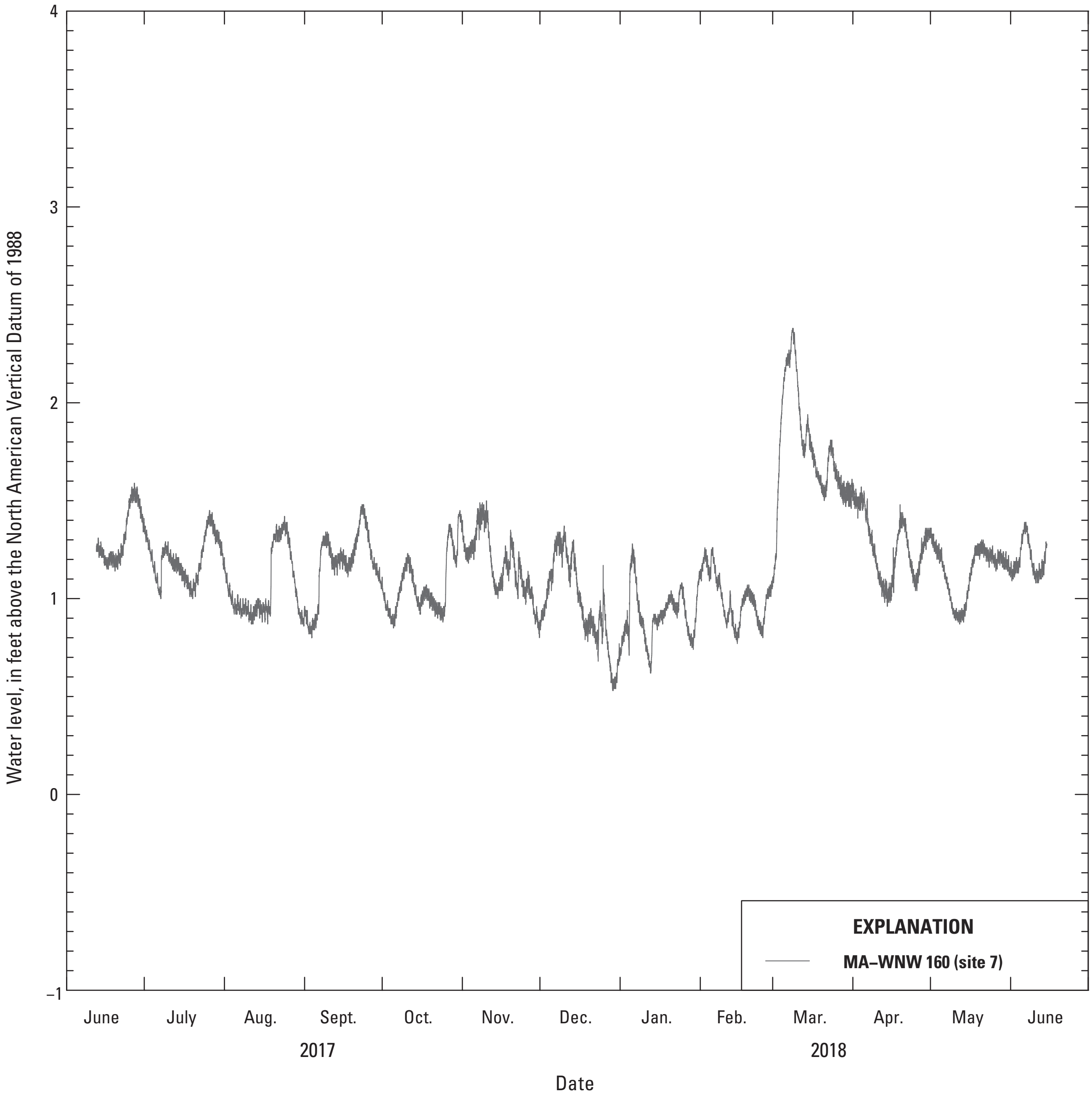


**Figure 1.7.** Water levels at well MA–WNW 160 (site 7) from June 2017 to June 2018, Mill Creek study area, Wellfleet, Massachusetts.

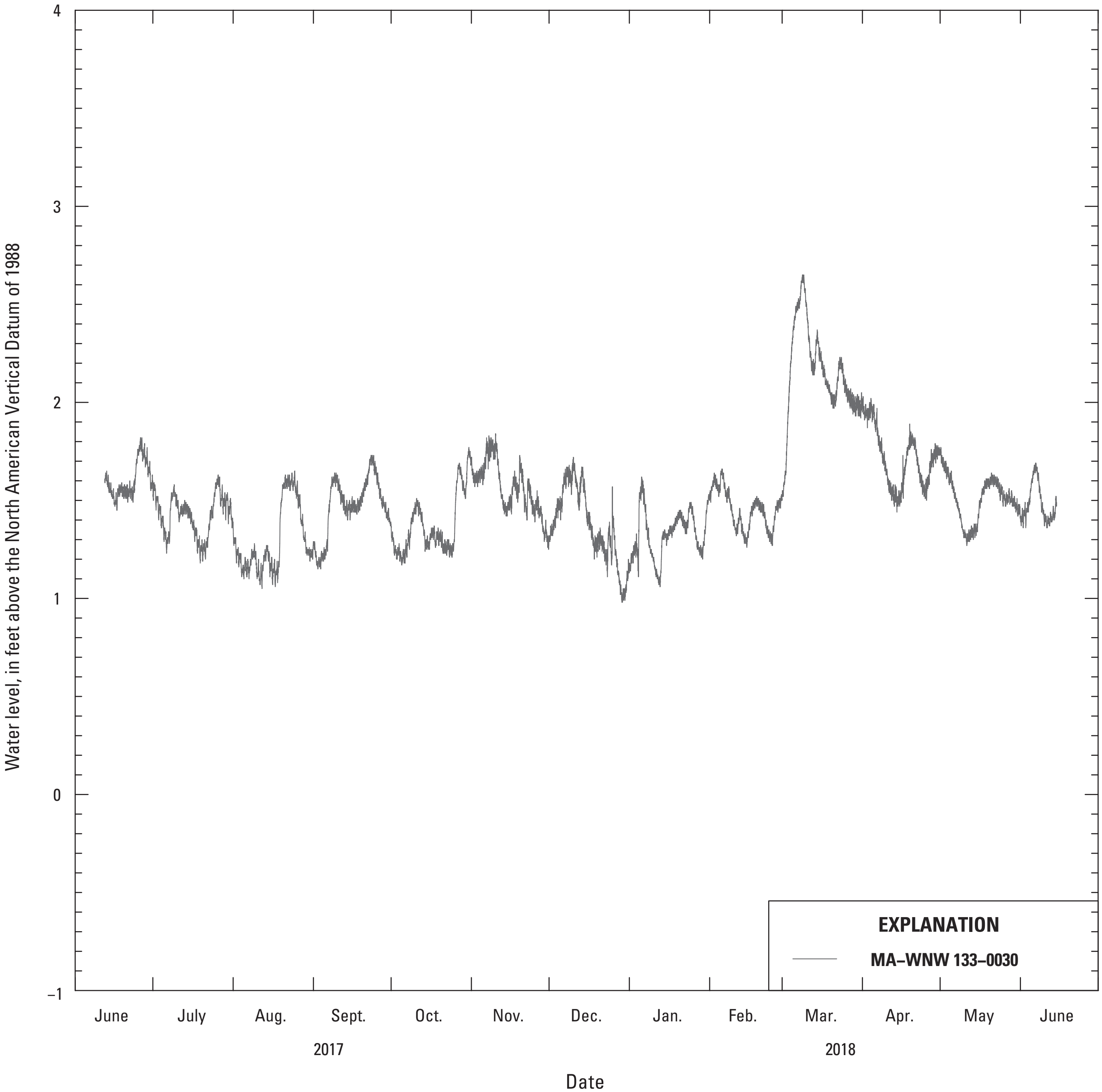


**Figure 1.8.** Water levels at well MA–WNW 133–0030 from June 2017 to June 2018, Mill Creek study area, Wellfleet, Massachusetts.

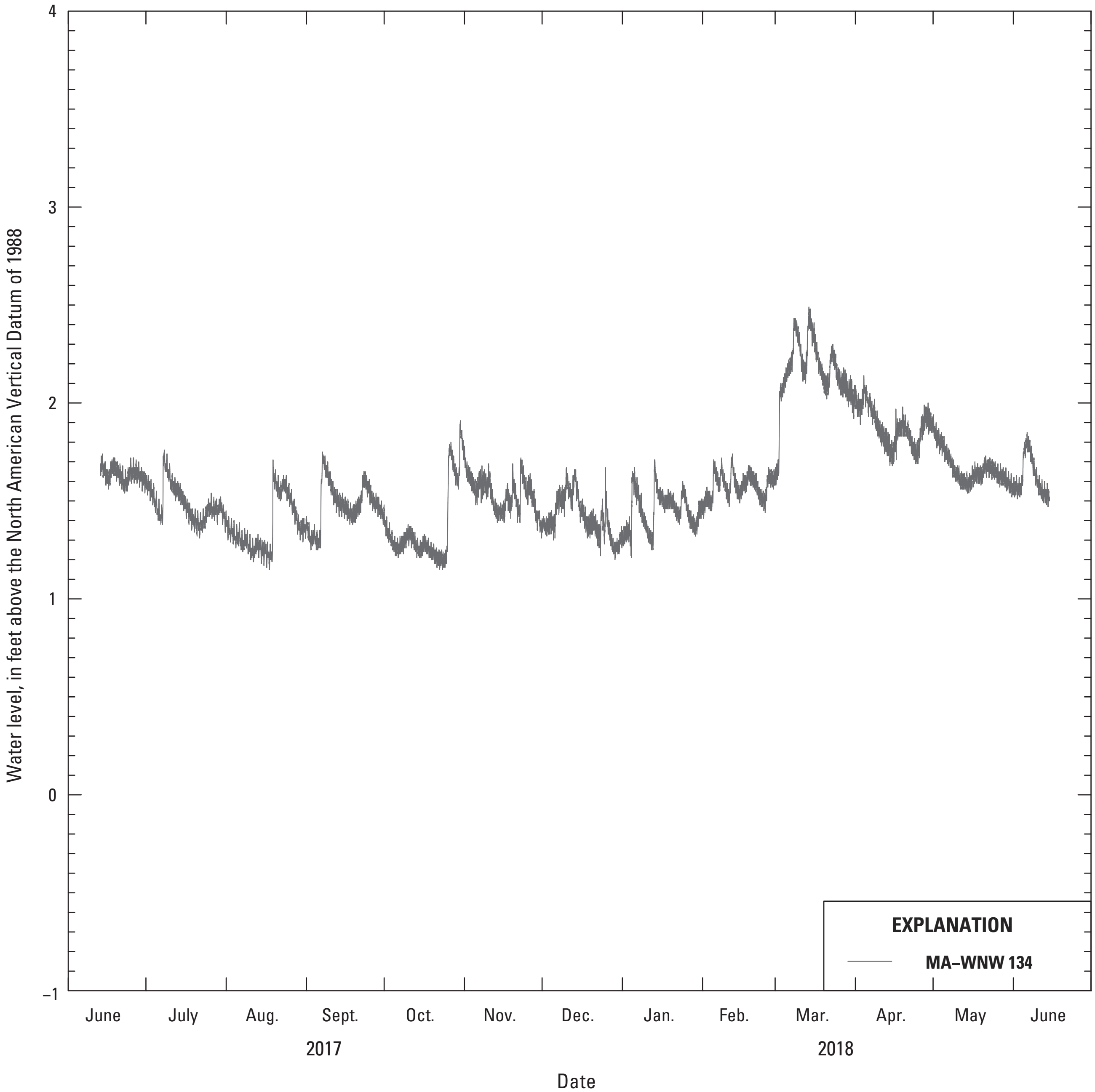


**Figure 1.9.** Water levels at well MA–WNW 134 from June 2017 to June 2018, Mill Creek study area, Wellfleet, Massachusetts.

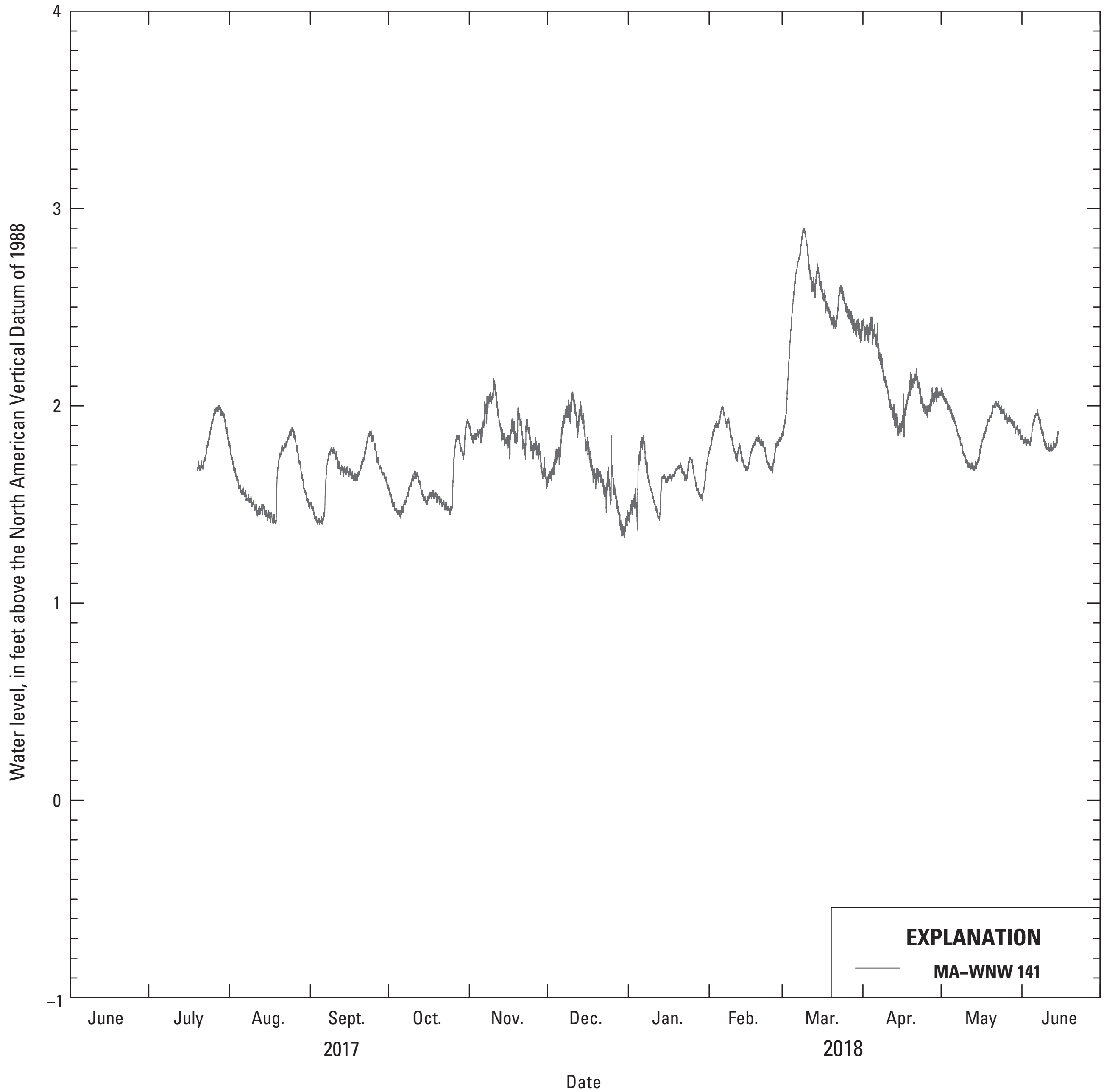


**Figure 1.10.** Water levels at well MA–WNW 141 from June 2017 to June 2018, Mill Creek study area, Wellfleet, Massachusetts.

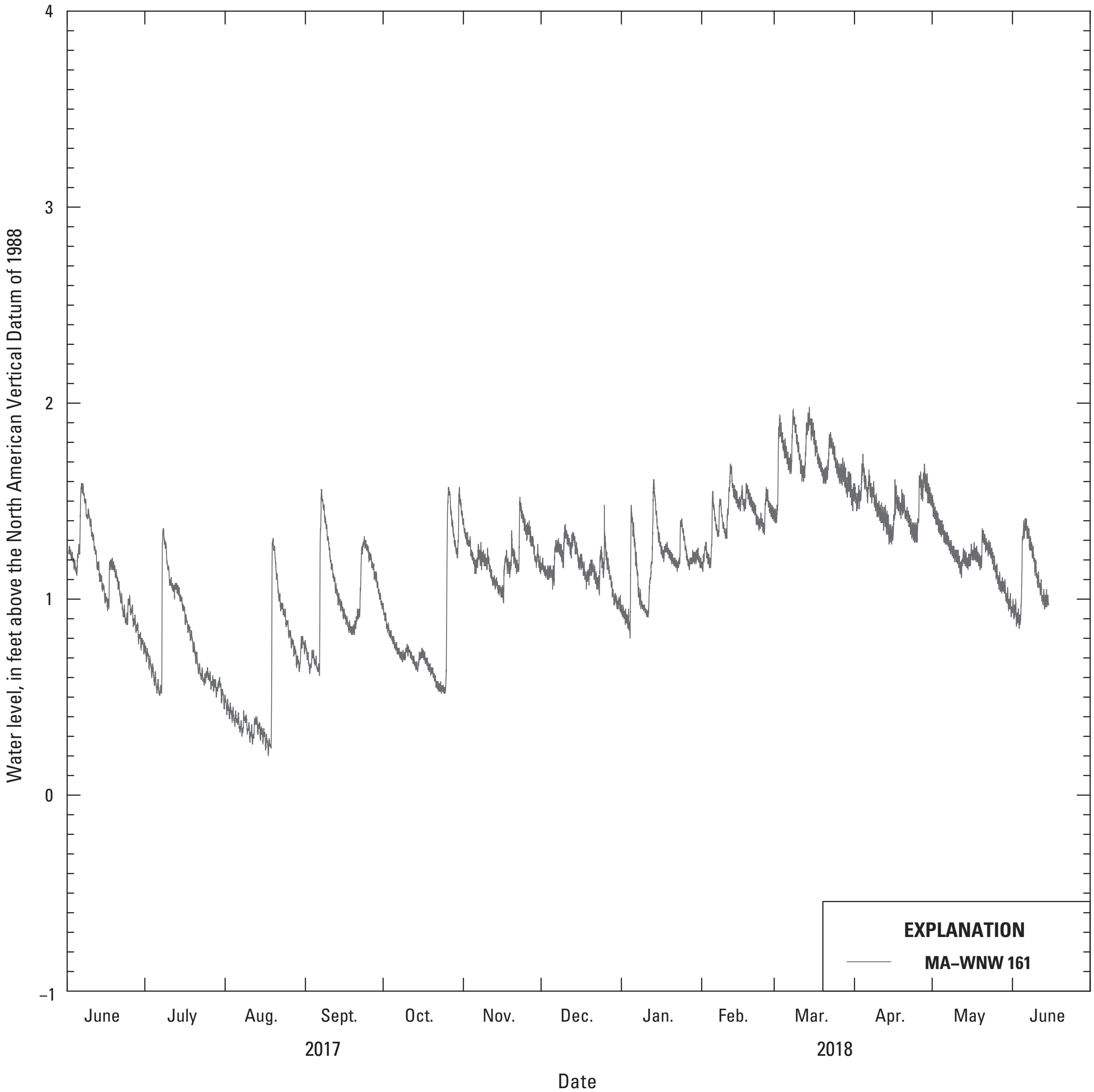


**Figure 1.11.** Water levels at well MA–WNW 161 from June 2017 to June 2018, Mill Creek study area, Wellfleet, Massachusetts.

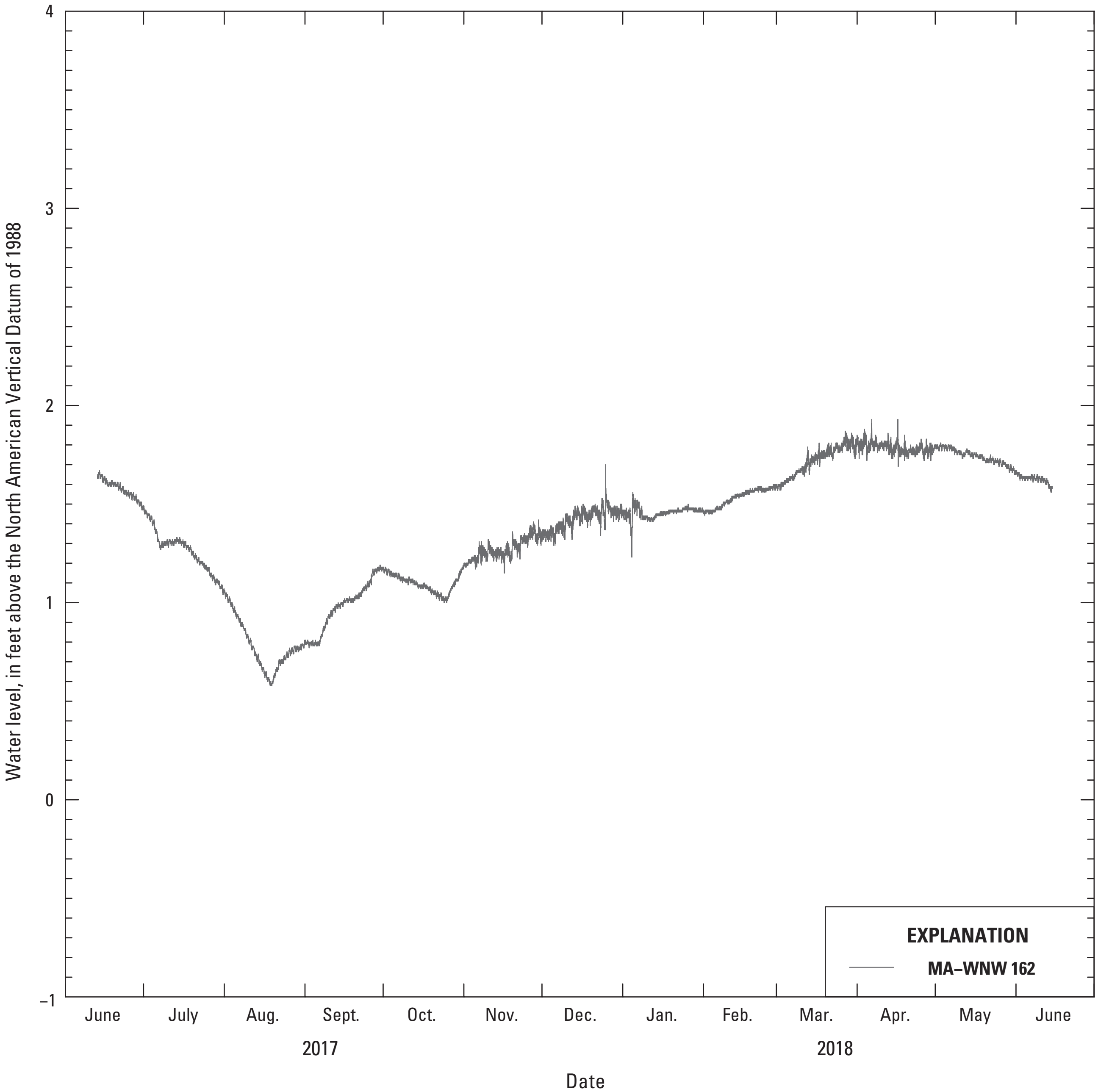


**Figure 1.12.** Water levels at well MA–WNW 162 from June 2017 to June 2018, Mill Creek study area, Wellfleet, Massachusetts.

# Appendix 2. Regression Coefficients and Metrics for Linear Regression Models Describing the Variability in Groundwater Levels and Surface-Water Levels Near the Herring River, Wellfleet, Massachusetts, From June 2017 To June 2018

**Table 2.1.** Coefficients and other regression metrics for linear regression models used to describe the variability in daily mean tidally filtered groundwater levels in monitoring wells near the Herring River, Wellfleet, Massachusetts, from June 2017 to June 2018.

[Dependent variable name: *meanFiltGWalt*, daily mean groundwater altitude for each well, daily tidal effects filtered from dataset. Independent variables: *meanHarborAlt*, daily mean water altitude at Herring River downstream from tide-control structure, daily tidal effects filtered from dataset; *meanHerringAlt*, daily mean water altitude at Herring River upstream from tide-control structure, daily tidal effects filtered from dataset; *precip7day*, sum of precipitation in the preceding 7 days; *GDD*50, growing degree days (base temperature 50 degrees Fahrenheit); *LongtermGW*, quartile of monthly groundwater levels at U.S. Geological Survey MA–WNW 17 (1, ≤25th percentile; 2, ≤50th percentile, 3, ≤75th percentile; 4, >75th percentile). SE, standard error; $R^2$, coefficient of determination; --, not applicable]

| Well (*meanFiltGWalt*) | *meanHarborAlt* | SE | *meanHerringAlt* | SE | *precip7day* | SE | *GDD*50 | SE | *Long term GW* | SE | Constant | SE | Observation (day) | Selected lag time for groundwater data, in days | $R^2$ | Adjusted $R^2$ | Residual SE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MA–WNW 154 | 0.304 | 0.021 | -- | -- | 0.093 | 0.007 | −0.011 | 0.001 | 0.113 | 0.009 | −0.148 | 0.027 | 242 | 1 | 0.786 | 0.783 | 0.119 |
| MA–WNW 154 | -- | -- | 0.640 | 0.051 | 0.042 | 0.008 | −0.003 | 0.001 | 0.085 | 0.010 | 0.516 | 0.063 | 268 | 1 | 0.748 | 0.744 | 0.127 |
| MA–WNW 155–0017 | 0.226 | 0.044 | -- | -- | 0.172 | 0.016 | −0.037 | 0.003 | 0.214 | 0.019 | 1.504 | 0.057 | 246 | 1 | 0.681 | 0.675 | 0.257 |
| MA–WNW 155–0017 | -- | -- | 0.577 | 0.117 | 0.121 | 0.018 | −0.022 | 0.002 | 0.193 | 0.024 | 2.035 | 0.143 | 295 | 1 | 0.681 | 0.677 | 0.299 |
| MA–WNW 155–0035 | 0.245 | 0.039 | -- | -- | 0.154 | 0.014 | −0.033 | 0.003 | 0.200 | 0.017 | 1.468 | 0.050 | 250 | 1 | 0.690 | 0.685 | 0.231 |
| MA–WNW 155–0035 | -- | -- | 0.587 | 0.106 | 0.104 | 0.016 | −0.020 | 0.002 | 0.176 | 0.021 | 2.032 | 0.130 | 286 | 1 | 0.696 | 0.691 | 0.269 |
| MA–WNW 156–0010 | 0.300 | 0.027 | -- | -- | 0.074 | 0.010 | −0.015 | 0.002 | 0.146 | 0.011 | 1.274 | 0.035 | 245 | 2 | 0.703 | 0.698 | 0.157 |
| MA–WNW 156–0037 | 0.335 | 0.025 | -- | -- | 0.060 | 0.009 | −0.012 | 0.002 | 0.141 | 0.010 | 1.235 | 0.032 | 245 | 2 | 0.741 | 0.736 | 0.142 |
| MA–WNW 157–0012 | 0.261 | 0.026 | -- | -- | 0.067 | 0.009 | −0.016 | 0.002 | 0.182 | 0.011 | 1.339 | 0.033 | 249 | 2 | 0.740 | 0.736 | 0.150 |
| MA–WNW 157–0033 | 0.264 | 0.025 | -- | -- | 0.066 | 0.009 | −0.016 | 0.002 | 0.190 | 0.011 | 1.320 | 0.032 | 249 | 2 | 0.753 | 0.749 | 0.149 |
| MA–WNW 157–0070 | 0.265 | 0.025 | -- | -- | 0.062 | 0.009 | −0.016 | 0.002 | 0.187 | 0.011 | 1.334 | 0.033 | 245 | 2 | 0.755 | 0.751 | 0.147 |
| MA–WNW 158 | 0.517 | 0.024 | -- | -- | 0.047 | 0.009 | −0.005 | 0.002 | 0.079 | 0.010 | 1.273 | 0.031 | 242 | 1.5 | 0.775 | 0.771 | 0.140 |
| MA–WNW 159–0012 | 0.432 | 0.025 | -- | -- | 0.055 | 0.009 | −0.010 | 0.002 | 0.093 | 0.010 | 1.250 | 0.032 | 249 | 2 | 0.729 | 0.724 | 0.145 |
| MA–WNW 159–0035 | 0.438 | 0.024 | -- | -- | 0.054 | 0.010 | −0.010 | 0.002 | 0.104 | 0.010 | 1.248 | 0.031 | 245 | 2 | 0.752 | 0.748 | 0.141 |
| MA–WNW 160 | 0.507 | 0.026 | -- | -- | 0.057 | 0.009 | −0.005 | 0.002 | 0.081 | 0.011 | 0.751 | 0.033 | 249 | 2 | 0.741 | 0.736 | 0.152 |
| MA–WNW 161 | 0.106 | 0.024 | -- | -- | 0.108 | 0.009 | −0.026 | 0.002 | 0.148 | 0.010 | 0.786 | 0.031 | 246 | 1 | 0.748 | 0.743 | 0.142 |
| MA–WNW 161 | -- | -- | 0.235 | 0.072 | 0.108 | 0.011 | −0.019 | 0.001 | 0.149 | 0.015 | 0.945 | 0.089 | 287 | 1 | 0.766 | 0.763 | 0.184 |
| MA–WNW 133–0030 | 0.435 | 0.026 | -- | -- | 0.059 | 0.009 | −0.012 | 0.002 | 0.103 | 0.011 | 1.180 | 0.033 | 249 | 2 | 0.724 | 0.720 | 0.153 |
| MA–WNW 134 | 0.188 | 0.020 | -- | -- | 0.078 | 0.007 | −0.013 | 0.001 | 0.190 | 0.009 | 1.000 | 0.026 | 247 | 1 | 0.809 | 0.805 | 0.118 |
| MA–WNW 134 | -- | -- | 0.414 | 0.053 | 0.044 | 0.008 | −0.003 | 0.001 | 0.161 | 0.011 | 1.454 | 0.066 | 280 | 1 | 0.755 | 0.751 | 0.133 |
| MA–WNW 141 | 0.387 | 0.028 | -- | -- | 0.048 | 0.010 | −0.016 | 0.002 | 0.157 | 0.012 | 1.334 | 0.035 | 245 | 2.5 | 0.731 | 0.727 | 0.162 |

**Table 2.2.** Standardized coefficients for independent variables used to describe the variability in daily mean tidally filtered groundwater levels in monitoring wells near the Herring River, Wellfleet, Massachusetts, from June 2017 to June 2018.

[Dependent variable name: *meanFiltGWalt*, daily mean groundwater altitude for each well, daily tidal effects filtered from dataset. Independent variables: *meanHarborAlt*, daily mean water altitude at Herring River downstream from tide-control structure, daily tidal effects filtered from dataset; *meanHerringAlt*, daily mean water altitude at Herring River upstream from tide-control structure, daily tidal effects filtered from dataset; *precip7day*, sum of precipitation in the preceding 7 days; *GDD*50, growing degree days (base temperature 50 degrees Fahrenheit); *LongtermGW*, quartile of monthly groundwater levels at U.S. Geological Survey MA–WNW 17 (1, ≤25th percentile; 2, ≤50th percentile, 3, ≤75th percentile; 4, >75th percentile); --, not applicable]

| Well (*meanFiltGWalt*) | *meanHarborAlt* | *meanHerringAlt* | *precip7day* | *GDD*50 | *LongtermGW* | Constant |
|---|---|---|---|---|---|---|
| MA–WNW 154 | 0.4735 | -- | 0.3908 | −0.2230 | 0.4192 | 0 |
| MA–WNW 154 | -- | 0.5305 | 0.2019 | −0.1131 | 0.3142 | 0 |
| MA–WNW 155–0017 | 0.2064 | -- | 0.4056 | −0.4429 | 0.4504 | 0 |
| MA–WNW 155–0017 | -- | 0.2230 | 0.2831 | −0.3858 | 0.3373 | 0 |
| MA–WNW 155–0035 | 0.2381 | -- | 0.3958 | −0.4274 | 0.4601 | 0 |
| MA–WNW 155–0035 | -- | 0.2501 | 0.2638 | −0.3755 | 0.3367 | 0 |
| MA–WNW 156–0010 | 0.4239 | -- | 0.2801 | −0.2751 | 0.4837 | 0 |
| MA–WNW 156–0037 | 0.4876 | -- | 0.2338 | −0.2379 | 0.4827 | 0 |
| MA–WNW 157–0012 | 0.3584 | -- | 0.2455 | −0.2961 | 0.5910 | 0 |
| MA–WNW 157–0033 | 0.3566 | -- | 0.2389 | −0.2923 | 0.6064 | 0 |
| MA–WNW 157–0070 | 0.3643 | -- | 0.2279 | −0.2920 | 0.6037 | 0 |
| MA–WNW 158 | 0.7137 | -- | 0.1736 | −0.0964 | 0.2558 | 0 |
| MA–WNW 159–0012 | 0.6287 | -- | 0.2129 | −0.1823 | 0.3195 | 0 |
| MA–WNW 159–0035 | 0.6267 | -- | 0.1834 | −0.1888 | 0.3488 | 0 |
| MA–WNW 160 | 0.6876 | -- | 0.2085 | −0.0813 | 0.2594 | 0 |
| MA–WNW 161 | 0.1532 | -- | 0.4116 | −0.4947 | 0.4975 | 0 |
| MA–WNW 161 | -- | 0.1272 | 0.3516 | −0.4733 | 0.3608 | 0 |
| MA–WNW 133–0030 | 0.6029 | -- | 0.2193 | −0.2179 | 0.3385 | 0 |
| MA–WNW 134 | 0.3066 | -- | 0.2949 | −0.2721 | 0.6571 | 0 |
| MA–WNW 134 | -- | 0.3181 | 0.1959 | −0.1168 | 0.5561 | 0 |
| MA–WNW 141 | 0.5037 | -- | 0.1693 | −0.2689 | 0.4798 | 0 |

**Table 2.3.** Coefficients and other regression metrics for linear regression models used to describe the variability in daily maximum altitude of water levels at two sites on Mill Creek, Wellfleet, Massachusetts, from June 2017 to June 2018.

[Shading indicates significance *p* at less than 0.01. Dependent variable: maximum daily stage (altitude) of Mill Creek, in feet above the North American Vertical Datum of 1988 (NAVD 88). Independent variables: *meanGWalt*, daily mean groundwater altitude, in feet above NAVD 88; *precip7day*, sum of precipitation in the preceding 7 days; *GDD*50, growing degree days (base temperature 50 degrees Fahrenheit); *flooded*, Mill Creek flooded (1) or not flooded (0). SE, standard error; $R^2$, coefficient of determination]

| Site | Well (data used in *meanGWalt*) | *meanGWalt* | SE | *precip7day* | SE | *GDD*50 | SE | *flooded* | SE | Constant | SE | Observation (day) | $R^2$ | Adjusted $R^2$ | Residual SE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mill Creek 1 (upstream) | (Site 4) MA–WNW 157–0012 | 0.228 | 0.040 | 0.093 | 0.009 | −0.018 | 0.001 | 0.187 | 0.026 | 0.878 | 0.074 | 373 | 0.761 | 0.759 | 0.173 |
| Mill Creek 2 (downstream) | (Site 2) MA–WNW 155–0017 | 0.429 | 0.024 | 0.068 | 0.008 | −0.009 | 0.001 | 0.013 | 0.024 | 0.180 | 0.050 | 373 | 0.814 | 0.812 | 0.148 |
| Mill Creek 2 (downstream) | (Site 3) MA–WNW 156–0010 | 0.389 | 0.048 | 0.088 | 0.010 | −0.017 | 0.001 | 0.102 | 0.031 | 0.405 | 0.082 | 367 | 0.708 | 0.705 | 0.186 |
| Mill Creek 2 (downstream) | (Site 6) MA–WNW 159–0012 | 0.291 | 0.047 | 0.089 | 0.010 | −0.018 | 0.001 | 0.151 | 0.030 | 0.602 | 0.075 | 373 | 0.685 | 0.682 | 0.193 |
| Mill Creek 2 (downstream) | MA–WNW 161 | 0.871 | 0.023 | 0.040 | 0.005 | −0.002 | 0.001 | −0.034 | 0.015 | 0.077 | 0.027 | 373 | 0.927 | 0.927 | 0.093 |

**Table 2.4.** Standardized coefficients for independent variables used to describe the variability in daily maximum altitude of water levels at two sites on Mill Creek, Wellfleet, Massachusetts, from June 2017 to June 2018.

[Shading indicates significance *p* less than 0.01. Dependent variable: maximum daily stage (altitude) of Mill Creek, in feet above the North American Vertical Datum of 1988 (NAVD 88). Independent variables: *meanGWalt*, daily mean groundwater altitude, in feet above NAVD 88; *precip7day*, sum of precipitation in the preceding 7 days; *GDD*50, growing degree days (base temperature 50 degrees Fahrenheit); *flooded*, Mill Creek flooded (1) or not flooded (0)]

| Site | Well (data used in *meanGWalt*) | *meanGWalt* | *precip7day* | *GDD*50 | *flooded* | Constant |
|---|---|---|---|---|---|---|
| Mill Creek 1 (upstream) | (Site 4) MA–WNW 157–0012 | 0.174 | 0.308 | −0.481 | 0.259 | 0 |
| Mill Creek 2 (downstream) | (Site 2) MA–WNW 155–0017 | 0.622 | 0.234 | −0.248 | 0.018 | 0 |
| Mill Creek 2 (downstream) | (Site 3) MA–WNW 156–0010 | 0.296 | 0.291 | −0.470 | 0.137 | 0 |
| Mill Creek 2 (downstream) | (Site 6) MA–WNW 159–0012 | 0.213 | 0.305 | −0.480 | 0.205 | 0 |
| Mill Creek 2 (downstream) | MA-WNW 161 | 0.895 | 0.135 | −0.059 | −0.047 | 0 |

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