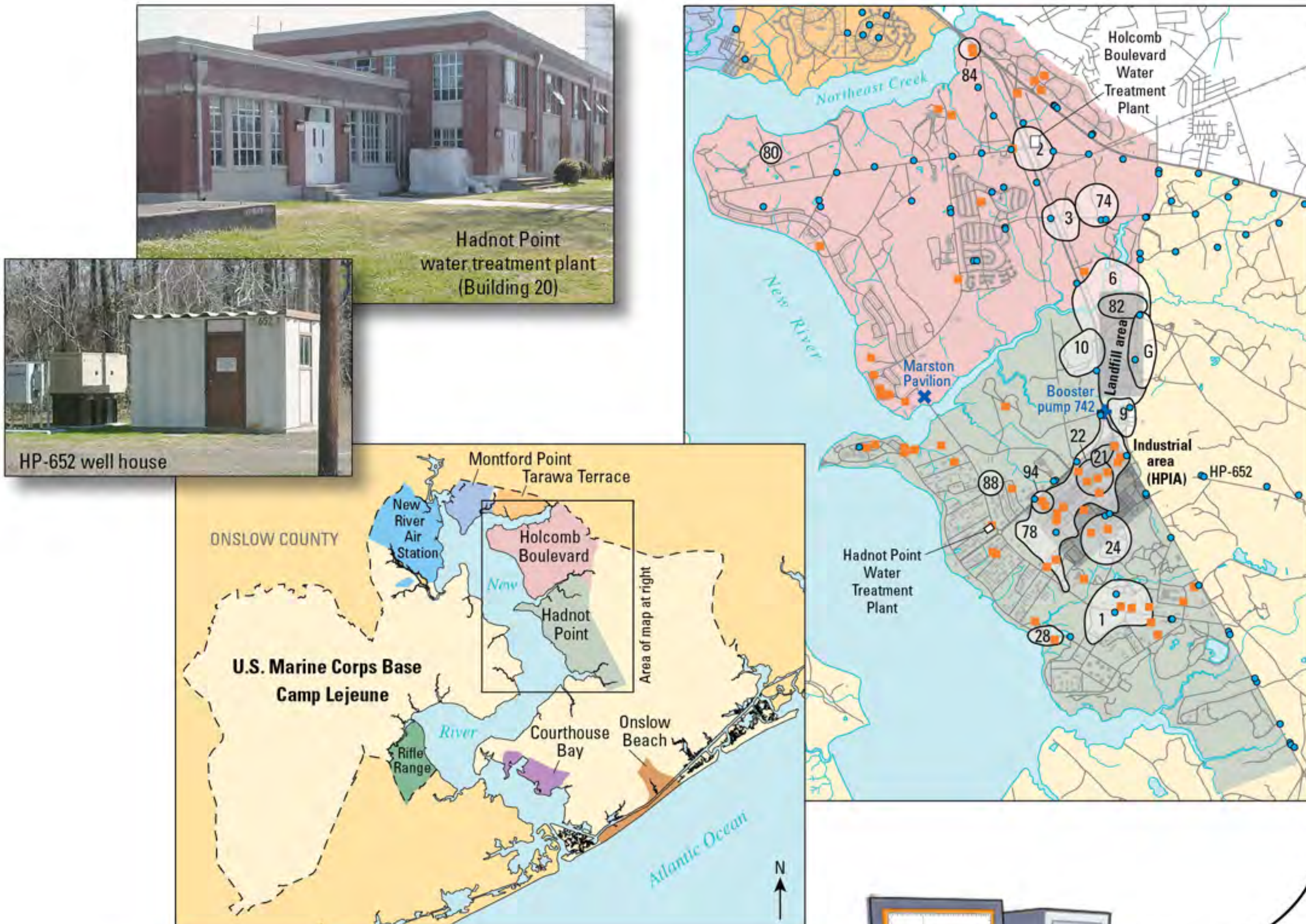
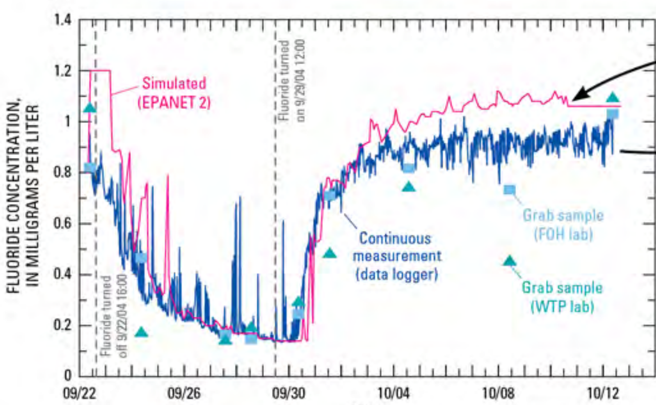
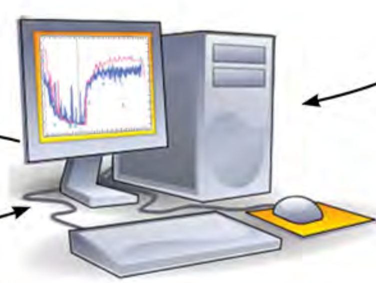
Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina

Chapter A–Supplement 2
Development and Application of a Methodology to Characterize Present-Day and Historical Water-Supply Well Operations







AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY

Atlanta, Georgia – March 2013

Front cover: Historical reconstruction process using data, information sources, and water-modeling techniques to estimate historical contaminant concentrations.

Maps: U.S. Marine Corps Base Camp Lejeune, North Carolina; Holcomb Boulevard and Hadnot Point areas showing extent of sampling at Installation Restoration Program sites (white numbered areas), above-ground and underground storage tank sites (orange squares), and water-supply wells (blue circles).

Photograph (upper): Hadnot Point water treatment plant (Building 20).

Photograph (lower): Well house building for water-supply well HP-652.

Graph: Measured fluoride data and simulation results for Paradise Point elevated storage tank (S-2323) for tracer test of the Holcomb Boulevard water-distribution system, September 22–October 12, 2004; simulation results obtained using EPANET 2 water-distribution system model assuming last-in first-out plug flow (LIFO) storage tank mixing model. [WTP lab, water treatment plant water-quality laboratory; FOH lab, Federal Occupational Health Laboratory]

Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina

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By Ilker T. Telci, Jason B. Sautner, René J. Suárez-Soto, Barbara A. Anderson, Morris L. Maslia, and Mustafa M. Aral

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Suggested citation

Telci IT, Sautner JB, Suárez-Soto RJ, Anderson BA, Maslia ML, and Aral MM. Development and Application of a Methodology to Characterize Present-Day and Historical Water-Supply Well Operations—Supplement 2. In: Maslia ML, Suárez-Soto RJ, Sautner JB, Anderson BA, Jones LE, Faye RE, Aral MM, Guan J, Jang W, Telci IT, Grayman WM, Bove FJ, Ruckart PZ, and Moore SM. Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—Chapter A: Summary and Findings. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2013.

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Contents

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Tables

List of Notations Used in This Supplement

[–]	Dimensionless (no units)
$AvOpDays(w,i)$	Number of operational days for each well w in calendar month i [–]
$C_w(d)$	Capacity of well w on day d [L^3T^{-1}]
$C_w^m(m)$	Monthly average capacity of well w in month m [L^3T^{-1}]
d	Day index [–]
d_b	Beginning day for the daily flow sum revision period [–]
d_e	Ending day for the daily flow sum revision period [–]
d_i^m	Initial day of month m [–]
d_f^m	Final day of month m [–]
M	Set of all months during training period
m	Month index [–]
m_p	The month when some of the wells are estimated to operate in excess of the total number of days of in month m_p [–]
N	Number of wells [–]
$N_{add}^d(w)$	Number of additional days for each well in set Φ [–]
$N_{ex}^d(w)$	Number of excess days in month m_p for well w [–]
N_m^d	Number of days in month m_p [–]
N_d^m	Number of days in month m
N_{wld}	Number of wells in set Φ [–]
$OpDay(w,m)$	Operational days for well w in month m [T]
$\overline{OpDay}(w,m)$	Adjusted operational days for well w in month m [T]
$OpHr(w,d)$	Operational hours for well w on day d [T]
$PrOpDays(w,m)$	Monthly predicted operating days for well w during month m [T]
$\overline{PrOpDay}(w,m)$	Adjusted monthly predicted operational days for well w during month m [T]
$q_w(d)$	Flow produced at well w during day d [L^3]

$q_w^m(m)$	Monthly flow produced by well w during month m [L^3]
$Q_{ex}^m(w)$	Monthly excess flow for well w during month m [L^3]
Q_T^m	Total monthly flow produced by all wells during month m [L^3]
$Q_T^d(d)$	Total daily flow produced by all wells during day d [L^3]
Q_{Tex}^m	Total monthly excess flow during month m [L^3]
$Q_{WTP}^d(d)$	WTP daily raw-water volume recording during day d [L^3]
$Q_{WTP}^m(m)$	WTP monthly raw-water volume data for month m [L^3]
$S_w(d)$	Operational status of well w on day d [–]
w	Well index [–]
$\delta_d(m,i)$	Delta function indicating whether adjusted number of operational days for well w during month m is zero due to "–1" labeled original data [–]
$\delta_m(m,i)$	Delta function indicating whether month m is the ith month of the year.
$\Delta Q^d(d)$	Difference between the calculated total daily flow produced by all wells and the measured WTP raw-water volume on day d [L^3]
$\Delta Q^m(m)$	Difference between the calculated total daily flow produced by all wells and the measured WTP raw water volume during month m [L^3]
$\Delta Q_{ex}^m(w)$	Amount of excess flow to be added to the flow produced by wells in set Φ [L^3]
η	Well efficiency [–]
Φ	The set of wells that are operating less than the total number of days in month m_p [–]
Ω	The set of wells that have adjusted operating days exceeding the total number of days in a month [–]

See the Glossary section in Chapter A of this report for definitions of terms and abbreviations used throughout this supplement.

Use of trade names and commercial sources is for identification only and does not imply endorsement by the Agency for Toxic Substances and Disease Registry or the U.S. Department of Health and Human Services.

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Chapter A–Supplement 2
Development and Application of a Methodology to Characterize Present-Day and Historical Water-Supply Well Operations

By Ilker T. Telci,[1] Jason B. Sautner,[2] René J. Suárez-Soto,[2] Barbara A. Anderson,[2] Morris L. Maslia,[2] and Mustafa M. Aral[3]

Introduction

In this supplement of Chapter A (Supplement 2), a methodology is developed to estimate the historical volume of groundwater pumped from water-supply wells on a monthly basis. The available data on the operational pattern of the water-supply wells consist of the capacities of the wells, the operational state of the wells on a daily basis, and the volume of water delivered to the Hadnot Point water treatment plant (HPWTP) and Holcomb Boulevard water treatment plant (HBWTP) on daily and monthly bases. The overall operating periods of both water treatment plants are divided into two parts: a "training period," representing present-day conditions (January 1998–June 2008) for analyses presented herein and a "prediction period," representing historical reconstruction conditions (January 1942–December 1997).[4] The training period is defined as the time during which daily water-supply well operational data are available. The prediction period is defined as the time when water-supply well operational data are limited or unavailable. This original methodology was developed specifically for this study and uses the daily operational data in the training period to determine the monthly operational behavior of water-supply wells that satisfy the total water volume delivered to the WTPs. Once the average monthly operating days in the training period are estimated for each calendar month, they are used in the prediction process, which is based on the same principle of satisfying the total monthly flow delivered to the WTPs. This methodology is an efficient and effective way of integrating available data for present-day conditions (1998–2008) with the prediction process for the historical years (1942–1997). Results demonstrate that historical estimates of water-supply well operations using the methodology described herein are reasonable, and therefore, results can be readily applied to groundwater-flow and contaminant fate and transport simulations, which are described in subsequent supplements of the Hadnot Point–Holcomb Boulevard (HPHB) study area Chapter A report (Maslia et al. 2013).

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[2] Agency for Toxic Substances and Disease Registry, Atlanta, Georgia.

[3] Georgia Institute of Technology, School of Civil and Environmental Engineering, Multimedia Environmental Simulations Laboratory, Atlanta, Georgia.

[4] The terms "training period" and "prediction period" also are terms used in the artificial intelligence discipline. It is not the intent of the authors to imply that any types of artificial intelligence concepts were applied or used for the current study. As defined in the Glossary section of this Chapter A report, the terms "training period" and "prediction period" refer strictly to present-day conditions and historical reconstruction conditions, respectively, for the purposes of reconstructing historical monthly water-supply well operations.

Background

A study and reconstruction of historical contamination events in finished water[5] at U.S. Marine Corps Base (USMCB) Camp Lejeune, North Carolina, is being conducted by the Agency for Toxic Substances and Disease Registry (ATSDR). USMCB Camp Lejeune has been used as a military training facility since 1942 and is located in Onslow County in the central part of the North Carolina Coastal Plain. The Base is located south of the City of Jacksonville and about 70 miles northeast of the City of Wilmington (Figure S2.1).

The historical reconstruction of contaminant fate and transport in groundwater of the Tarawa Terrace base housing area of USMCB Camp Lejeune and historical finished-water concentrations supplied by the Tarawa Terrace WTP have been extensively studied by ATSDR. Those studies, analyses, and results are described in previous reports (Maslia et al. 2007; Wang and Aral 2008; Maslia et al. 2009). Current studies (2010 and thereafter) focus on historical reconstruction of contaminant concentrations in groundwater and finished water in the Holcomb Boulevard and Hadnot Point water-distribution systems (also referred to as the HPHB study area). This reconstruction process requires gathering information about the groundwater system, characterizing contaminant sources, and simulating contaminant fate and transport in the groundwater system and the water distribution systems serving the HPHB study area. The WTPs serving these areas of the base obtained groundwater from 96 water-supply wells (hereafter referred to as wells or supply wells) distributed in these areas and on the east side of USMCB Camp Lejeune (Figure S2.1). Therefore, information on the historical operational schedules of these wells is a prerequisite for the simulation of groundwater flow, contaminant fate and transport, and the distribution of finished water in the HPHB study area.

The purpose of this part of the historical reconstruction analysis (and the details described in this supplement of the Chapter A report) is to reconstruct the pumping (operational) schedules of wells supplying groundwater to the HPWTP and HBWTP. The estimated monthly flows produced by the wells will be used as input data to the groundwater-flow and contaminant fate and transport models described in subsequent supplements of the HPHB Chapter A report (Suárez-Soto et al. 2013; Jones et al. 2013).

Detailed daily data pertaining to the pumping schedule of the wells are available subsequent to January 1998 (Scott R. Williams, U.S. Marine Corps Base Camp Lejeune, written communication, December 2008). Prior to 1998, data pertaining to well operations are limited or unavailable. Similarly, daily WTP raw-water volumes are available after December 1994. Between 1980 and 1994, monthly raw-water volumes are available; yearly volumes are available for some years prior to 1980. A trendline was used to estimate raw-water flows for years prior to 1980 when no data exist. Monthly raw-water flow percentages were then calculated using known monthly data for the period 1980–2004. These values were used to estimate monthly raw-water flows prior to 1980. This methodology is based on two assumptions: (1) similar characteristics of the operational patterns of the wells and WTPs for the periods of time before and after January 1998, and (2) equality between total water volume delivered to the WTP from the operating wells and the WTP raw-water volume data at all times.

Data Availability

Data Sources[6]

Four types of data sources pertinent to water-supply well operational records and WTP raw-water records are used in this supplement. These are (1) daily operational records, January 1998–June 2008 (Scott R. Williams, U.S. Marine Corps Base Camp Lejeune, written communication, December 2008), (2) Camp Lejeune Historic Drinking Water Consolidated Document Repository records (CLHDW CDR 2011), (3) Camp Lejeune Water Documents (CLW 2007), and (4) U.S. Geological Survey (USGS) well inventory documents (USGS, well inventory, written communication, March 2004). Using these data sources, operational chronologies for 96 wells supplying groundwater (raw water) to the HPWTP and HBWTP were developed (Figure S2.2). Details on the descriptions and characterizations of data pertinent to well capacities, histories, and operations are found in Sautner et al. (2013).

[5] For this study, finished water is defined as groundwater (or raw water) that has undergone treatment at a WTP and is delivered to a person's home or other facility.

[6] Certain documents have been provided to ATSDR by the Department of the Navy (Headquarters Marine Corps, Eastern Area Counsel Office, and Marine Corps Base Camp Lejeune) under terms of "For Official Use Only" (FOUO) documents. Some of these documents are not releasable by ATSDR under the terms of FOUO.

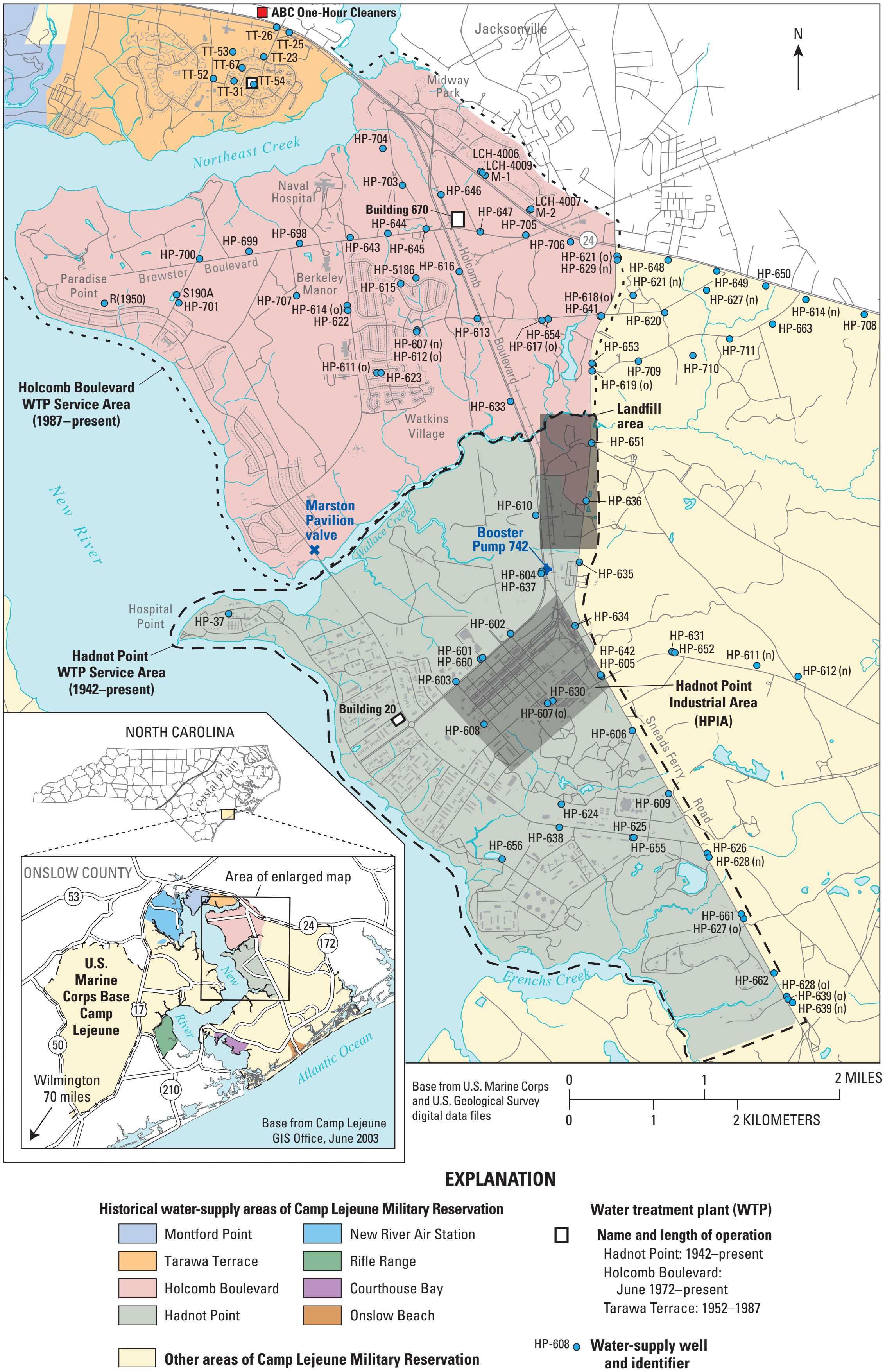

Figure S2.1. The Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

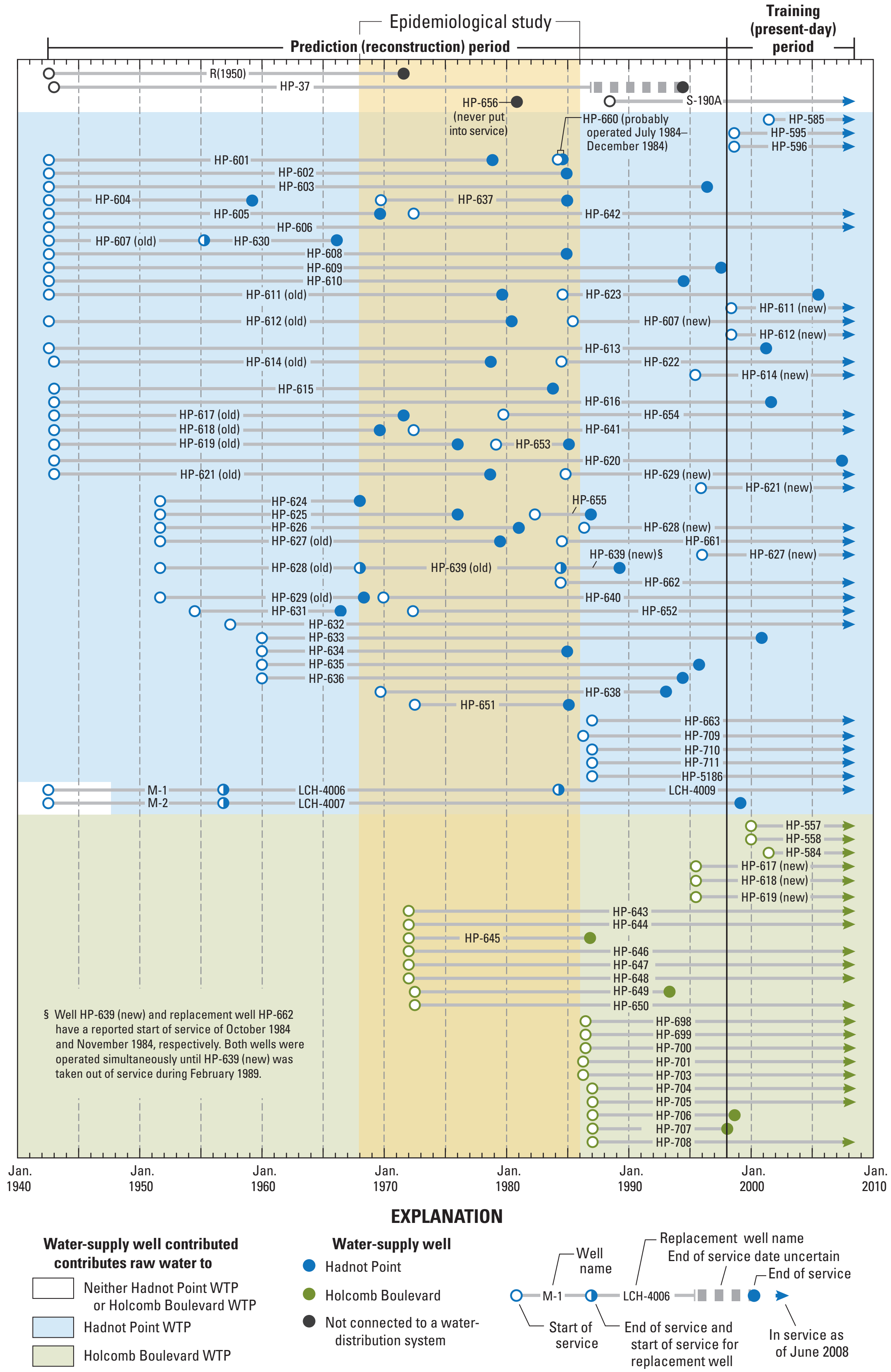

Figure S2.2. Operational chronology of Hadnot Point and Holcomb Boulevard water-supply wells, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1942–2008.

Figure S2.2 shows the operational chronology of wells that supplied raw water to the HBWTP and HPWTP. The numbers of wells that have been supplying groundwater to the HBWTP (since 1972) and the HPWTP (since 1942) are 24 and 72, respectively. These wells have daily well operational records for the period January 1998–June 2008 (Scott R. Williams, U.S. Marine Corps Base Camp Lejeune, written communication, December 2008). Prior to January 1998, daily well operational records are unknown except for some intermittent periods (CLW 2007; CLHDW CDR 2011). Therefore, the available data are divided into two periods, delineated by the vertical line in Figure S2.2. The period of January 1998–June 2008, during which the daily operational records of the wells in the Holcomb Boulevard and Hadnot Point service areas are known, is identified in this supplement as the "training period." The time prior to January 1998 is called the "prediction period" in this supplement. For Holcomb Boulevard, the prediction period begins during January 1972; for Hadnot Point the prediction period begins during July 1942.

A daily well operational record consists of a date, the operational status, and capacity (maximum volume of flow that can be delivered by the pump in the well, in gallons per minute) of the well on that specific date. For a given date, a well may be in several different operational states. These states and an explanation of their corresponding values in the daily operational records are listed in Table S2.1.

In addition to daily operational records, WTP raw-water flow-rate data (in million gallons [Mgal]) also are available (USGS, well inventory, written communication, March 2004; CLW 2007; CLHDW CDR 2011). Daily WTP flow rates are known for January 1995–June 2009 for the HPWTP and HBWTP. Prior to January 1995, monthly flow-rate data (in Mgal) are available or have been determined based on the methodology previously described. A WTP flow rate represents the sum of the flows produced by all wells supplying water to the HPWTP or HBWTP.

Table S2.1. Status, explanation, and interpretation of water-supply wells in daily operation records, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base, Camp Lejeune, North Carolina.

[Data sources: Camp Lejeune Public Works Department, Utility Section; CLHDW CDR (2011); CLW (2007), U.S. Geological Survey, well inventory, written communication, March 2004]

Status	Explanation	Interpreted as
?	Status not known	Prediction
0	Well not operating and water treatment system being operated under everyday normal conditions	0
1	Well operating and water treatment system being operated under everyday normal conditions	1
2	Well operating, however, water treatment system not being operated under everyday normal conditions	1
–1	Out of service; well "down" or "pulled" from system temporarily	0
–2	Well not operating and water treatment system not being operated under everyday normal conditions	0
NA	Not available; status not known	[1]0 or 1
0-1	Well operating part of day and not operating part of day	0

[1] Depends on –1 operational status prior to and after "NA" period.

Data Interpretation

As stated in the Data Sources section, a well can be in several different operational states depending on the operational conditions of the well and the WTP (Table S2.1). An empty data slot (shown as a "?" in the status column of Table S2.1) indicates that the operational status of the well is unknown and the operating dates occur during the prediction period (Figure S2.2). In addition to the aforementioned prediction status, a well can be in seven different operational states. These seven operational states are represented by a binary code that is assigned a value of 0 when the well is not operating and a value of 1 when the well is operating. The "NA" (not available) operational status data that intermittently occur in the training period for 1–6 months (simultaneously for all wells in a WTP) are interpreted in this analysis as either half operation or no operation, depending on the operational status of the well prior to and after the "NA" period. If the well is in a "–1" operational status (out of service) prior to and after the "NA" period, all "NA"s are interpreted as a "0" operational status (not operating). Otherwise, it is assumed that the well had operated for half of the "NA" period. As a result of the aforementioned operational assumptions, all wells are assigned operational status values of either "0" (not operating) or "1" (operating) for all days in the training period. The available data are now ready to be used for training of the wells. The operational status of the wells was determined by ATSDR water-modeling staff after a review of available data. Given these data, the methodology developed below is based on the assumption that historical operations of the water-supply wells can be approximated by the demand and supply criteria for present-day (January 1998–June 2008) operations. Thus, the overall model derived for this analysis and described in this supplement is unique for present-day operational patterns (January 1998–June 2008) recorded for Hadnot Point and Holcomb Boulevard water-supply wells.

Present-Day Period (1998–2008)—Training Process (TP)

The training process (TP) is composed of several calculations and checking steps (Figure S2.3). The results of these steps were reported in separate sheets of a Microsoft Excel® workbook. The TP is summarized below, and computational details that are pertinent to each step (TP1–TP11) are provided in subsequent report sections.

The training process starts by calculation of the daily sums of flows (TP1) produced by all available wells using the interpretation of operational status data (Table S2.1) and assuming a 24-hour operating schedule. According to the rule explained in report sections that follow, daily flow sums are revised for days when less than three wells are operating (TP2). The number of daily operating hours (TP3) is calculated by an adjustment process that forces the daily flow sums to be equal to the daily WTP raw-water volume data. The number of operating days in a month (TP4) can be calculated from the total number of operating hours in that month. This information can then be used in conjunction with monthly average capacities (TP5) to calculate monthly total flows produced by all available wells. These total flows are then compared with the monthly WTP raw-water volume data as a check on monthly flows (TP6). Next, the number of operating days in a month is adjusted (TP7) such that the total monthly flows produced by all available wells are equal to the monthly WTP raw-water volume data. If the adjusted number of operating days in a specific month exceeds the total number of days in that month, the excess flow due to the excess number of days is distributed to other available wells to obtain the revised adjusted number of operating days in a month (TP8). The monthly adjusted trained flow for each well (TP9) is then calculated using the corresponding revised adjusted number of operating days and the monthly average capacities. A final monthly adjusted flow check (TP10) is computed to demonstrate that total monthly adjusted flows produced by all available wells are equal to the monthly WTP raw-water volume data. To end the training process, monthly average operating days (TP11) of the wells for each calendar month are calculated and used in the prediction process (PP).

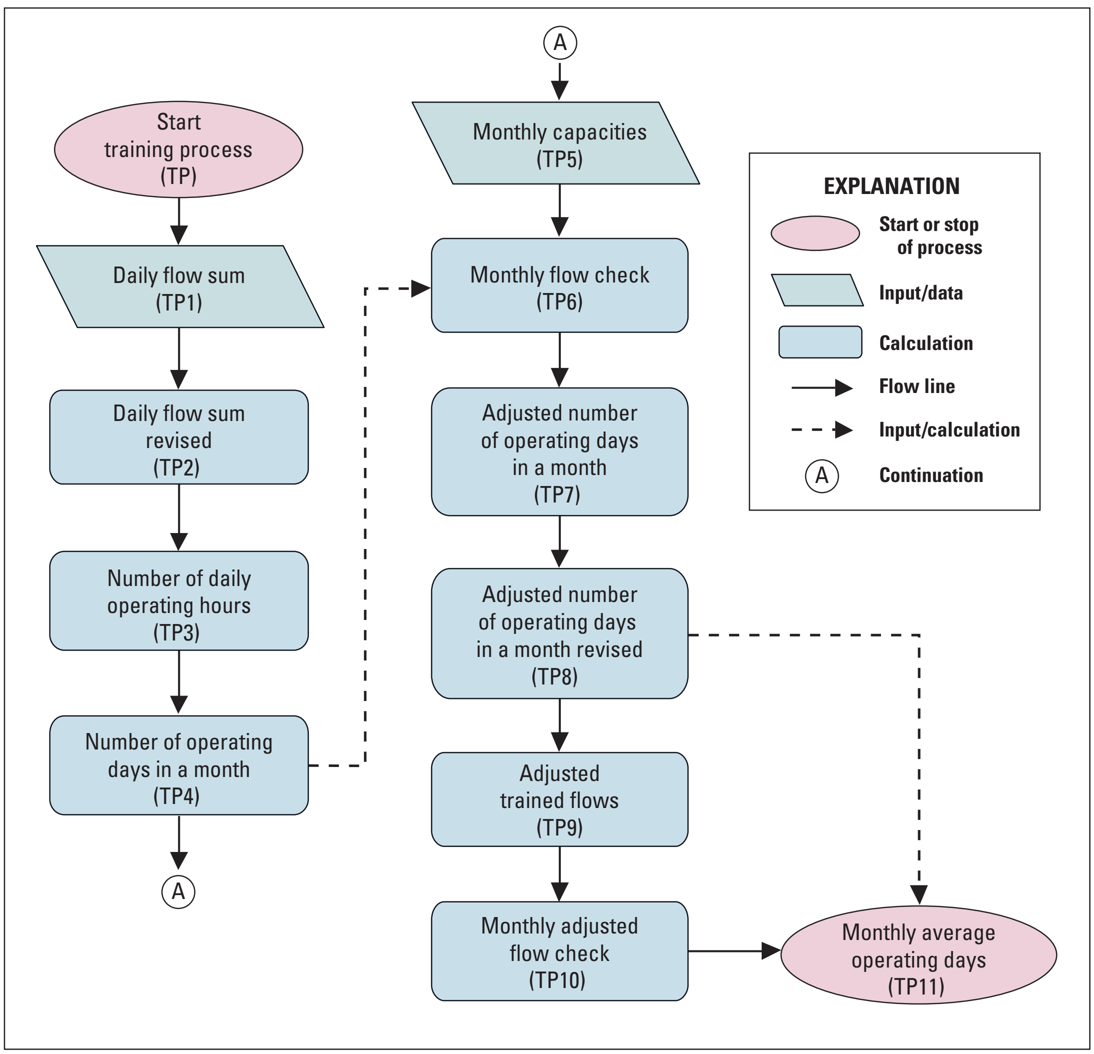

Figure S2.3. Flowchart of the training process, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. (Note: For computational details, refer to individual report sections as shown in flowchart boxes.)

Daily Flow Sum (TP1)

Initially, all available wells are assumed to operate 24 hours per day. The flow rates produced by each well are calculated by using Equation S2.1:[7]

$$q_w(d) = \eta C_w(d) S_w(d), \tag{S2.1}$$

where

$q_w(d)$	is the flow produced by well *w* during day *d*,
η	is the well efficiency,
$C_w(d)$	is the capacity of well *w* on day *d*, and
$S_w(d)$	is the interpreted status of the well *w* on day *d* defined as a step function according to Equation S2.2.

$$S_w(d) = \begin{cases} 0 \text{ if well } w \text{ is not working on day } d. \\ 1 \text{ if well } w \text{ is working on day } d. \end{cases} \tag{S2.2}$$

The total flow produced by all wells is calculated by using Equation S2.3 and is compared with WTP daily raw-water volume data (Equation S2.4):

$$Q_T^d(d) = \sum_{w=1}^{N} q_w(d) \quad \text{and} \tag{S2.3}$$

$$\Delta Q^d(d) = Q_T^d(d) - Q_{WTP}^d(d), \tag{S2.4}$$

where

$Q_T^d(d)$	is the total daily flow produced by all wells during day *d*,
N	is the number of wells,
$Q_{WTP}^d(d)$	is the WTP daily raw-water volume data for day *d*, and
$\Delta Q^d(d)$	is the difference between the calculated total daily flow produced by all wells [$Q_T^d(d)$] and the measured WTP raw-water volume [$Q_{WTP}^d(d)$].

[7] Refer to the List of Notations in the front part of Supplement 2 for a complete list of mathematical notations.

Daily Flow Sum Revised (TP2)

After the Daily Flow Sum (TP1) step is completed, the $Q_T^d(d)$ value can be too small for some days in the TP, especially when there are less than three wells reported as operating. Because this issue will cause very long daily operating hours (on the order of 100 hours) in the Number of Daily Operating Hours (TP3) step, the available data are modified for days on which the original operational state of the wells is not reported as NA (Table S2.1). The revision process starts with determining the periods containing less than three operating wells. Once such a period is determined, the previous normal (three or more wells) operating day is labeled as day d_b, and the normal operating day after this period is labeled as d_e. The operating schedule for current day *d*, which is in the period when less than three wells are operating ($d_b < d < d_e$), is replaced by the schedule of d_b or d_e, whichever has a closer WTP raw-water volume measurement when compared with that of the current day (Equation S2.5).

$$q_w(d) = \begin{cases} q_w(d_b) & if\ \left|Q_{WTP}^d(d) - Q_{WTP}^d(d_b)\right| < \left|Q_{WTP}^d(d) - Q_{WTP}^d(d_e)\right| \\ q_w(d_e) & otherwise \end{cases} \tag{S2.5}$$

After this process, some of the $Q_T^d(d)$ are still small enough that the number of daily operating hours exceeds 24. However, the number of hours in excess of 24 is not large enough to cause a significant excess in the number of operating days so that they exceed the number of calendar days in a month (i.e., 28, 29, 30, or 31 days). In this study, the choice of using less than three operating wells in a day is made in order to achieve reasonable results with minimum modification of the available data.

Number of Daily Operating Hours (TP3)

The number of operating hours of a well *w* on day *d* is calculated by modifying the initial assumption of a 24-hour operational schedule by an adjustment factor such that the resulting total daily flow produced by all operating wells is equal to the WTP raw-water volume data on that day (Equation S2.6). According to this equation, the wells will operate less than 24 hours on days when $\Delta Q^d(d)$ is positive and more than 24 hours on days when $\Delta Q^d(d)$ is negative. However, as discussed in the Daily Flow Sum Revised (TP2) section, these excess hours do not cause substantially large excessive monthly operating days that exceed the number of calendar days in a specific month.

$$OpHr(w,d) = 24\frac{Q_{WTP}^d(d)}{Q_T^d(d)}S_w(d) \tag{S2.6}$$

Number of Operating Days in a Month (TP4)

Number of operating days for each well in a month (TP4) is calculated as the summation of estimated daily operating hours during that month (Equation S2.7).

$$OpDay(w,m) = \frac{1}{24}\sum_{d=d_i^m}^{d_f^m} OpHr(w,d), \tag{S2.7}$$

where d_i^m and d_f^m are the first and last days of month *m* respectively.

Monthly Capacities (TP5)

The monthly capacities (TP5) of a well are calculated by taking the average of the daily capacity values of a well during each month. Only days when a well is operating are included in the averaging process (Equation S2.8).

$$C_w^m\left(m\right)=\frac{1}{\sum_{d=d_i^m}^{d_f^m} S_w\left(d\right)}\sum_{d=d_i^m}^{d_f^m} C_w\left(d\right)S_w\left(d\right)\ , \tag{S2.8}$$

where $C_w^m\left(m\right)$ is the monthly average capacity of well *w* in month *m*.

If a well is not operating for an entire month (28, 29, 30, or 31 days), the monthly average capacity for that specific well in that month is not calculated. This is because the average monthly capacity for that specific well is not needed in subsequent calculations.

Monthly Flow Check (TP6)

Once the monthly average capacities (TP5) and number of operating days in a month (TP4) are calculated (Equations S2.8 and S2.7, respectively), the total monthly flow produced by all operating wells can be calculated (Equation S2.9) and compared with the monthly raw-water volume data from the WTP (Equation S2.10).

$$Q_T^m\left(m\right)=\sum_{w=1}^{N} C_w^m\left(m\right)\eta OpDay\left(w,m\right) \text{ and} \tag{S2.9}$$

$$\Delta Q^m\left(m\right)=Q_T^m\left(m\right)-Q_{WTP}^m\left(m\right), \tag{S2.10}$$

where

$Q_T^m\left(m\right)$ is the total monthly flow produced by all wells during month *m*,

$Q_{WTP}^m(m)$ is the WTP monthly raw-water volume data for month *m*, and

$\Delta Q^m\left(m\right)$ is the difference between the calculated total monthly flow produced by all wells and the measured WTP raw-water volume.

Adjusted Number of Operating Days in a Month (TP7)

In this step, the number of operating days in a month is adjusted such that the total monthly flow (Equation S2.9) produced in all wells is equal to the WTP monthly flow-rate record as shown in Equation S2.11. According to Equation S2.11, the number of operating days of the wells for a specific month will decrease for positive $\Delta Q^m\left(m\right)$ and will increase for negative $\Delta Q^m\left(m\right)$. The increase in the number of operating days may cause the total number of operating days for a specific month to exceed the number of days in a calendar month—this issue is resolved in the next step of the training period procedure (TP8).

$$\overline{OpDay}\left(w,m\right)=OpDay\left(w,m\right)\frac{Q_{WTP}^m\left(m\right)}{Q_T^m\left(m\right)} \tag{S2.11}$$

Adjusted Number of Operating Days in a Month Revised (TP8)

When the adjusted numbers of operating days in a month (calculated in the previous step, TP7) are checked, these values exceed the total number of days in a calendar month for some months and wells. To resolve this issue, the excess flow due to these excess days is equally distributed among remaining wells that operate less than the total number of days in a specific calendar month. As a result, for wells whose operating days exceed the number of days in a calendar month, the adjusted operating days are decreased to the number of days in a specific calendar month; for the remaining operating wells, the number of operating days in the same calendar month is increased. Because the aforementioned increase may cause some of the remaining wells to operate in excess of the total number of days in a specific calendar month, the TP8 step is performed in an iterative loop until all available wells operate for no more than the total number of days in a specific calendar month (28, 29, 30, or 31 days). To further explain step TP8 process in detail, let us assume that some wells are estimated to operate in excess of the total number of days for months m_p. Then, the solution method is summarized in the following 8-step procedure:

1. Determine the wells that have Adjusted Operating Days (Equation S2.11) that exceed the number of days in a month. Let $\boldsymbol{\Omega}$ be the set of such wells.

2. Let N_m^d be the number of days in m_p and determine excess days, $N_{ex}^d(w)$, for each of the wells (Equation S2.12).

$$N_{ex}^d(w) = \overline{OpDay}(w, m_p) - N_m^d, \quad \forall w \in \Omega \tag{S2.12}$$

3. Calculate monthly excess flow $Q_{ex}^m(w)$ for each well (Equation S2.13).

$$Q_{ex}^m(w) = N_{ex}^d(w)\eta C_w^m(m_p), \quad \forall w \in \Omega \tag{S2.13}$$

4. Calculate total monthly excess flow Q_{Tex}^m for each well (Equation S2.14).

$$Q_{Tex}^m = \sum_{\forall w \in \Omega} Q_{ex}^m(w) \tag{S2.14}$$

5. Distribute total monthly excess flow to all available wells that are operating less than the total number of days in month m_p. Let $\boldsymbol{\Phi}$ be the set of such wells and N_{wld} be the number of wells in this set.

$$\Delta Q_{ex}^m(w) = \frac{Q_{Tex}^m}{N_{wld}}, \quad \forall w \in \boldsymbol{\Phi}, \tag{S2.15}$$

   where $\Delta Q_{ex}^m(w)$ is the amount of excess flow to be added to the flow produced by the wells in set Φ.

6. For each well in set Φ, calculate the number of additional operating days required to produce the excess flow, $\Delta Q_{ex}^m(w)$ (Equation S2.16).

$$N_{add}^d(w) = \frac{\Delta Q_{ex}^m(w)}{\eta C_w^m(m_p)}, \quad \forall w \in \boldsymbol{\Phi} \tag{S2.16}$$

7. Calculate revised adjusted number of operating days in month m_p (Equation S2.17).

$$\overline{OpDay}(w, m_p) = \begin{cases} \overline{OpDay}(w, m_p) + N_{add}^d(w) & \text{if } w \in \Phi \\ N_m^d & \text{if } w \in \Omega \end{cases} \tag{S2.17}$$

8. Determine if the adjusted number of operating days for any well exceeds the total number of days for a specific month (28, 29, 30, or 31 days). If the answer is yes, then go to Step 1 and repeat the aforementioned process. If all wells in month m_p operate for less than or equal to the total number of days in month m_p, the revision process for month m_p is complete.

Adjusted Trained Flows (TP9)

In this step, monthly flow rates produced by each well are calculated by using the adjusted number of operating days in a month (TP7) revised in the previous step (TP8), well efficiency (η), and the monthly capacity [$C_w^m(m)$] values (Equation S2.18).

$$q_w^m(m) = \eta C_w^m(m)\overline{OpDay}(w,m) \quad \text{(S2.18)}$$

Monthly Adjusted Flow Check (TP10)

The total monthly flow produced by all wells is calculated by using Equation S2.19 and is compared with the WTP monthly raw-water volume data (Equation S2.20).

$$Q_T^m(m) = \sum_{w=1}^{N} q_w^m(m) \text{ and} \quad \text{(S2.19)}$$

$$\Delta Q^m(m) = Q_T^m(m) - Q_{WTP}^m(m) \text{ ,} \quad \text{(S2.20)}$$

where

$Q_T^m(m)$ is the total monthly flow produced by all wells during month *m*,

N is the number of wells,

$Q_{WTP}^m(m)$ is the WTP monthly raw-water volume data for month *m*, and

$\Delta Q^m(m)$ is the difference between the calculated total monthly flow produced by all wells and the measured WTP raw-water volume.

As a final check on the training process, it is noted that all calculated $\Delta Q^m(m)$ values are zero for all months in the training period.

Monthly Average Operating Days (TP11)

The average number of operating days for each well in a calendar month is calculated by taking the average over the years during training period of the revised adjusted number of operating days (TP8) for that specific month. In the averaging process, if a well has zero operating days in a month (having a "–1" status, Table S2.1), then the month is excluded from the average calculation. To calculate the average, let *M* be the set of all months during the training period. Equations S2.21 and S2.22 define two delta functions as follows:

$$\delta_m(m,i) = \begin{cases} 0 \text{ if } m \text{ is not } i^{th} \text{ month of the year.} \\ 1 \text{ if } m \text{ is } i^{th} \text{ month of the year.} \end{cases} \quad \text{(S2.21)}$$

$$\delta_d(m,i) = \begin{cases} 0 & \text{if } \overline{OpDay}(w,m) = 0 \text{ due to "–1" labeled original data.} \\ 1 & \text{otherwise.} \end{cases} \quad \text{(S2.22)}$$

The number of operating days for each well *w* in calendar month *i* can be calculated using Equation S2.23.

$$AvOpDays(w,i) = \frac{\sum_{\forall m \in M} \delta_m(m,i)\delta_d(m,i)\overline{OpDay}(w,m)}{\sum_{\forall m \in M} \delta_m(m,i)\delta_d(m,i)} \quad \text{(S2.23)}$$

The average values calculated using Equation S2.23 will be used as the operating days of wells for a specific calendar month if historical operational data during the prediction period are not available.

Historical Reconstruction Period (1942–2007)—Prediction Process (PP)

Similar to the training process, the prediction process (PP) is structured as a series of calculations and checking steps (Figure S2.4). The results of these steps were placed in separate sheets of a Microsoft Excel® workbook. Because some wells did not physically exist during the training period, surrogate wells were selected to represent these untrained wells.

The prediction process starts with gathering information on monthly average operating days (obtained from the TP11 step) and surrogate wells. Then, monthly predicted operating days (PP2, Figure S2.4) are assigned to each well for the prediction period. During the assignment process, if data for an entire month are available, these data are used to calculate the monthly predicted operating days. For each well, monthly average capacities (PP3) also are calculated during the prediction process. Monthly predicted flows (PP4) are then estimated, and monthly total flow is compared with the WTP monthly raw-water volume data in the monthly total flow check (PP5). Next, monthly predicted operating days are adjusted (PP6)

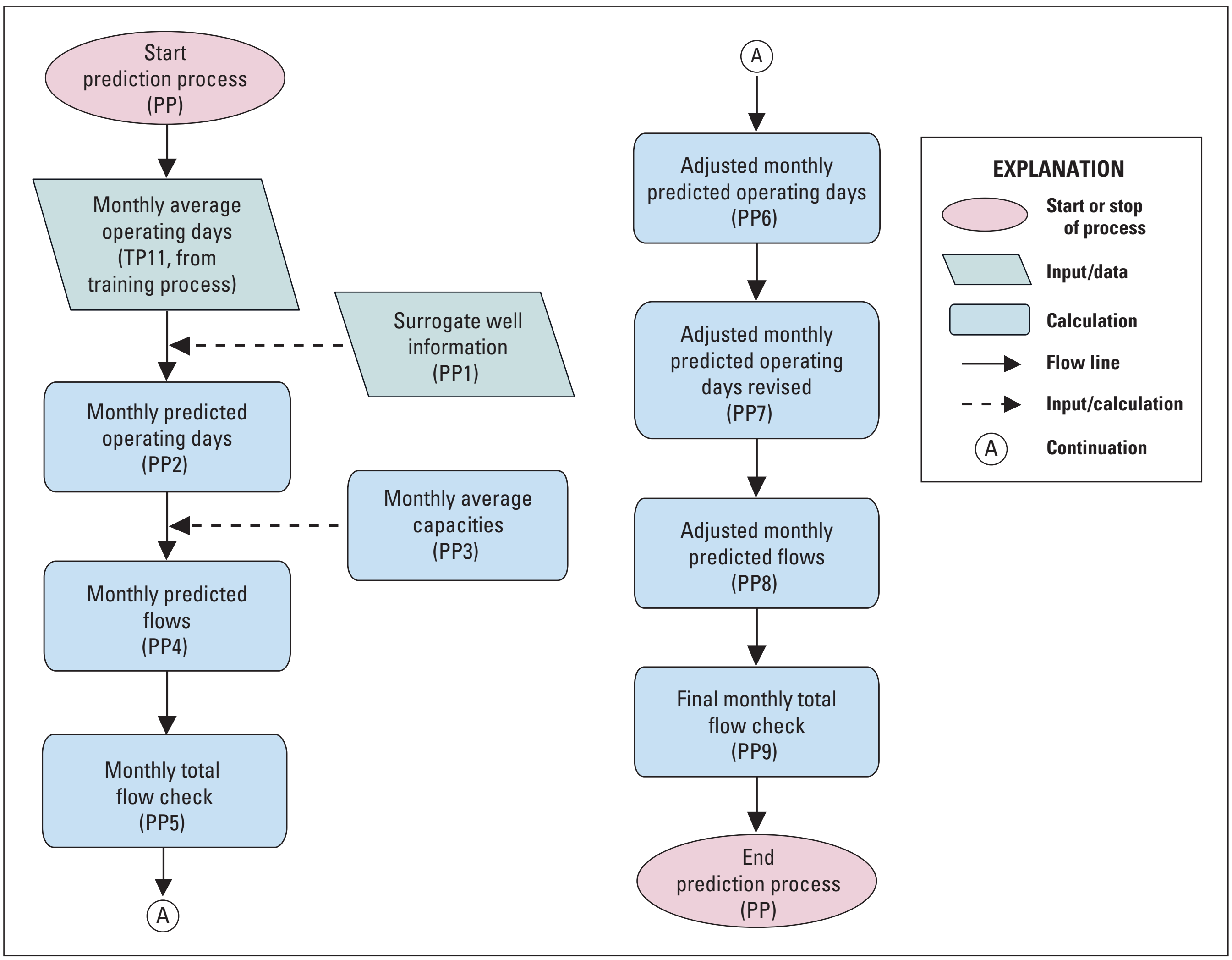

Figure S2.4. Flowchart of the prediction process, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. (Note: For computational details, refer to individual report sections as shown in flowchart boxes.)

such that total monthly flow produced by all wells is equal to the monthly raw-water volume recording at the WTP. As a result of step PP6, it is observed that the adjusted operating days during some months exceed the total number of days for a specific month (28, 29, 30, or 31). To resolve this issue, excess flows due to the excess number of days are distributed to other operating wells to obtain the revised adjusted monthly operating days (PP7). Subsequent to this revision process, the adjusted monthly predicted flow (PP8) for each well is calculated using the corresponding revised adjusted operating days (PP7) and monthly average capacities (PP3). To conclude the prediction process, a monthly total flow check (PP9) is conducted to demonstrate that total flows produced by all operating wells are equal to the monthly WTP raw-water volume data. Details for each of the prediction process steps are presented in the next sections of this report.

Surrogate Well Information (PP1)

Some of the water-supply wells operating during the historical prediction (reconstruction) period were not in service during the training period (e.g., wells HP-602 and HP-651, Figure S2.2). These wells, for which data were not available during the training period (January 1998–June 2008), were represented by "surrogate" or replacement wells during the prediction period for this analysis. Some of the untrained wells were replaced by wells that did have training data (Figure S2.2). These wells were assumed to operate using the same operational patterns (scheduling) as their replacements having the same monthly average operating days. Other untrained wells that did not have replacement wells during the training period were assigned surrogate wells based on several factors: (1) geohydrologic and hydrogeologic characteristics of the surrounding aquifers and water-bearing zones, (2) well characteristics such as capacity and demand data, and (3) proximity of the surrogate well to the well it replaced (e.g., wells HP-634 and HP-606, Figure S2.1). Table S2.2 lists the surrogate and untrained wells contributing raw water to the HBWTP and HPWTP. As listed in Table S2.2, 4 surrogate wells were selected to represent the untrained wells for the Holcomb Boulevard service area, and 39 surrogate wells were selected to represent untrained wells for the Hadnot Point service area. Once the surrogate wells were selected using the aforementioned selection factors, all wells were then assigned monthly average operating-day information (TP11 and PP1, Figure S2.4) that could be used during the prediction process.

Table S2.2. Identification of surrogate water-supply wells used to represent untrained wells, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[Refer to Figure S2.1 for water-supply well locations and Figure S2.2 for operational chronologies]

Water-supply wells	
Untrained	**Surrogate**
Holcomb Boulevard water treatment plant service area	
HP-645	HP-644
HP-649	HP-648
HP-706	HP-705
HP-707	HP-704
Hadnot Point water treatment plant service area	
HP-601	HP-606
HP-602	HP-642
HP-603	HP-606
HP-604	HP-642
HP-605	HP-642
HP-607 (old)	HP-642
HP-608	HP-606
HP-609	HP-628 (new)
HP-610	HP-633
HP-611 (old)	HP-623
HP-612 (old)	HP-607 (new)
HP-614 (old)	HP-622
HP-615	HP-616
HP-617 (old)	HP-654
HP-618 (old)	HP-641
HP-619 (old)	HP-620
HP-621 (old)	HP-629 (new)
HP-624	HP-628 (new)
HP-625	HP-662
HP-626	HP-628 (new)
HP-627 (old)	HP-661
HP-628 (old)	HP-662
HP-629 (old)	HP-640
HP-630	HP-642
HP-631	HP-652
HP-634	HP-606
HP-635	HP-642
HP-636	HP-642
HP-637	HP-642
HP-638	HP-628 (new)
HP-639 (new)	HP-662
HP-639 (old)	HP-662
HP-651	HP-633
HP-653	HP-633
HP-655	HP-662
HP-660	HP-606
LCH-4006	LCH-4009
M-1	LCH-4009
M-2	LCH-4007

Monthly Predicted Operating Days (PP2)

For each well, the number of operating days in a month was predicted to be equal to the average number of operating days calculated for that calendar month in the training process (TP11). If operational data were available for a complete month during the prediction period, then the available data were used, rather than relying on prediction results. Monthly predicted operating days of a well are defined by the following function in Equation S2.24:

$$Pr\,OpDays\left(w,m\right)=\begin{cases}\sum_{d=d_i^m}^{d_f^m} S_w\left(d\right) \text{ if data are available for well } w \text{ during month } m. \\ AvOpDays\left(w,i\right) \text{ such that } m \text{ is } i^{th} \text{ month of the year, otherwise.}\end{cases} \quad \text{(S2.24)}$$

The first and last days of month *m* are d_i^m and d_f^m, respectively.

Monthly Average Capacities (PP3)

To calculate monthly predicted flows, information pertinent to monthly average capacities of the wells is required. This information is obtained for each well by calculating the average of the daily capacity for each month. In this calculation, which is different from the monthly capacities calculated during the training process (TP5), all of the days are included in the averaging process because the daily operational status of the wells (when the wells were operating or not operating) is unknown. Thus, the average monthly well capacity for each well in the prediction process is calculated according to (Equation S2.25):

$$C_w^m\left(m\right)=\frac{1}{N_d^m}\sum_{d=d_i^m}^{d_f^m} C_w\left(d\right), \quad \text{(S2.25)}$$

where N_d^m is the number of days in month *m*.

Monthly Predicted Flows (PP4)

Monthly flows produced by each well during the prediction process are calculated by using the monthly predicted operating days during a month (PP2), the well efficiency (η), and the monthly average capacity (PP3) values as described by Equation S2.26:

$$q_w^m(m)=\eta C_w^m(m) PrOpDays(w,m). \quad \text{(S2.26)}$$

Monthly Total Flow Check (PP5)

Once the monthly predicted flows ($q_w^m\left(m\right)$, calculated during step PP4 in Figure S2.4) are known, the total monthly flow produced by all available wells can be calculated (Equation S2.27) and compared with monthly raw-water volume data from the WTP (Equation S2.28). These calculations are similar to those used during the training process (Equations S2.19 and S2.20) in step TP10.

$$Q_T^m\left(m\right)=\sum_{w=1}^{N} q_w^m\left(m\right) \text{ and} \quad \text{(S2.27)}$$

$$\Delta Q^m\left(m\right)=Q_T^m\left(m\right)-Q_{WTP}^m\left(m\right), \quad \text{(S2.28)}$$

where

$Q_T^m(m)$ is the total monthly flow produced by all wells during month *m*,

N is the number of wells,

$Q_{WTP}^m(m)$ is the WTP monthly raw-water volume data for month *m*, and

$\Delta Q^m(m)$ is the difference between the calculated total monthly flow produced by all wells and the measured WTP raw-water volume.

Adjusted Monthly Predicted Operating Days (PP6)

Similar to adjustments during the training process (TP7, Figure S2.3), the number of operating days in a month is adjusted such that the total monthly flow produced by all operating wells is equal to the WTP monthly flow-rate data (Equation S2.29).

$$\overline{PrOpDay}(w,m) = PrOpDay(w,m)\,\frac{Q_{WTP}^m(m)}{Q_T^m(m)} \tag{S2.29}$$

As described in the adjustment step of the training process (TP7), the number of operating days of the wells during a month will decrease for positive $\Delta Q^m(m)$ values and will increase for negative $\Delta Q^m(m)$ values. The increase may cause the number of predicted days to be greater than the total number of days for a specific calendar month (28, 29, 30, or 31), and this issue is resolved in the next step of the predictive process (PP7).

Adjusted Monthly Predicted Operating Days Revised (PP7)

When the adjusted monthly predicted operating days ($\overline{PrOpDay}(w,m)$) calculated in the previous predictive process step (PP6) are examined, it is observed that some wells are predicted to operate in excess of the number of days in a calendar month (28, 29, 30, or 31). This issue is resolved much like the explanation in the "Adjusted Number of Operating Days in a Month Revised" section of the training process (TP8). As such, Equations S2.12 to S2.17 are also applied to the adjustment process during the prediction process (step PP7). Note, however, that Equations S2.12 to S2.17 are applied to months during the prediction process; therefore, the function $\overline{Pr\,OpDay}(w,m)$ will be used instead of the function $\overline{OpDay}(w,m)$.

Adjusted Monthly Predicted Flows (PP8)

In this step, monthly predicted flows produced by each well (Equation S2.30) are calculated by using the parameters of adjusted monthly predicted operating days revised, which is discussed in the previous prediction process step (PP7), well efficiency (η), and the monthly capacity values $C_w^m(m)$.

$$q_w^m(m) = \eta C_w^m(m)\,\overline{Pr\,OpDay}(w,m) \tag{S2.30}$$

Final Monthly Total Flow Check (PP9)

The predicted total monthly flow produced by all wells, $Q_T^m(m)$ is estimated by inserting the revised adjusted monthly predicted flow values $q_w^m(m)$, which are calculated in Equation S2.30, into Equation S2.27. These monthly total flows are then compared with WTP monthly raw-water volume data using Equation S2.28. As a final check of the prediction process (Figure S2.4), it is observed that $\Delta Q^m(m)$ values obtained by applying Equation S2.28 are zero for all calendar months during the prediction period.

Results and Discussion

In this study, the aforementioned methodologies for the TP and PP were applied to the HBWTP and HPWTP and the wells that supplied them with raw water. Because the supply wells associated with each WTP were analyzed separately (Figure S2.2), results for each WTP service area are presented and discussed separately in the following sections. In report sections that follow, results for three groups of analyses are presented and discussed: (1) comparisons are provided for the total raw-water volume delivered to the WTPs and the maximum volume that can be produced by their associated wells; (2) the number of operating days for individual wells are analyzed; and (3) volumes of water produced by individual wells that will be needed for input data to groundwater flow and contaminant fate and transport models are presented. Illustrations showing volumes of water produced by individual wells and delivered to the WTPs are discussed in Supplement 2 sections that follow for complete periods of record for each WTP.[8] Results for each water-supply well—derived using the original methodologies previously described—are part of the data input file required for groundwater-flow modeling (Suárez-Soto et al. 2013).[9] The TP calculated values are for the period January 1998–June 2008, and the PP calculated values are for the historical period prior to January 1998, which for some wells begins as early as July 1942 (Figure S2.2).

Holcomb Boulevard Water-Supply Wells

Figure S2.5 shows a graph representing total monthly raw-water volume delivered to the HBWTP (Figure S2.1) and maximum monthly total water volume that can be produced by all operating wells. Monthly WTP raw-water volume (indicated by the bottom line in Figure S2.5) also represents the total estimated monthly flow produced by all operating wells as a result of the conditions imposed that guarantee equality between WTP flow-measurement data and total estimated flow produced by all operating wells. The maximum water volume that can be produced by all operating wells—assuming that they operate for an entire month at full capacity—is represented in Figure S2.5 by the top line. This top line also represents the limit for WTP raw-water measurement data because the WTP data do not exceed values indicated by this line. The small fluctuations in the top line of Figure S2.5 are a consequence of the varying numbers of total days for calendar months (28, 29, 30, or 31 days), whereas larger changes in value for the top line are indicative of significant water-distribution system modifications. The following example is noteworthy. The top line in Figure S2.5 indicates a sudden and significant increase in the maximum produced water volume by all operating wells from 75 to 175 Mgal during 1987. This 100-Mgal increase in the volume of water produced by the wells is explained by analyzing the data shown in Figure S2.2. For the Holcomb Boulevard service area prior to 1987, there were eight operating water-supply wells (HP-643, HP-644, HP-645, HP-646, HP-647, HP-648, HP-649, and HP-650). After 1987, the number of operating wells more than doubles to 17, thereby accounting for the sudden and significant increase of 100 Mgal (133 percent increase) in water volume production.

Monthly operating schedules for each well providing raw water to the HBWTP (Figure S2.2), estimated as operating days for each calendar month, are shown in Figures S2.6–S2.29.[10] In these figures, the top line shows the number of days in a calendar month (28, 29, 30, or 31) for the time period June 1972–June 2008, as indicated on the horizontal axis. Similar to Figure S2.5, the top line is a reasonable limit for the estimated number of operating days for each of the Holcomb Boulevard wells. The small fluctuations in the top line represent the varying number of days for each calendar month (28, 29, 30, or 31). The bottom lines in the graphs (blue and/or green lines) indicate the estimated monthly operating days of a well during the training period (January 1998–June 2008) and during the prediction period (prior to January 1998).[11] The blue and green lines in the lower portions of Figures S2.6–S2.29 are defined for times when a well is in service, as shown in Figure S2.2. If a well is operating solely during the training period (January 1998–June 2008), then the graph for that specific well only has a blue line in the bottom part of the figure (e.g., well HP-557, Figure S2.6). Likewise, if a well is operating solely during the prediction period (prior to January 1998), then the graph for that specific well only has a green line in the bottom part of the figure (e.g., well HP-645, Figure S2.14); this indicates that one of the surrogate wells listed in Table S2.2 is assigned to that specific well (e.g., HP-644) for the prediction of operating days in a month. For some wells, the estimated number of monthly operating days is equal to the number of days for a specific calendar month (e.g., for HP-557, shown in Figure S2.6, this occurs for the months of July, August, and September 2006). The data and results for these specific months demonstrate that initially the well (e.g., HP-557) was estimated to have an adjusted number of operating days that exceeded the number of calendar days in the aforementioned months. This issue was resolved in the

[8] Period of record: HPWTP, July 1942–June 2008; HBWTP, June 1972–June 2008.

[9] Reconstructed monthly raw-water volumes (expressed in terms of a daily rate) for each of the 24 Holcomb Boulevard and 72 Hadnot Point water-supply wells are provided on the compact disc, read-only memory (CD-ROM) media located in the back pocket of the Chapter A report.

[10] Figures S2.6–S2.29 are located in the back of this Supplement 2 section.

[11] For wells that were operating solely during the training period (e.g., HP-557), there is only one line shown in the bottom graph (e.g., blue line in Figure S2.6). For wells that were operating solely during the prediction period (e.g., HP-645), there is only one line shown in the bottom graph (e.g., green line in Figure S2.14).

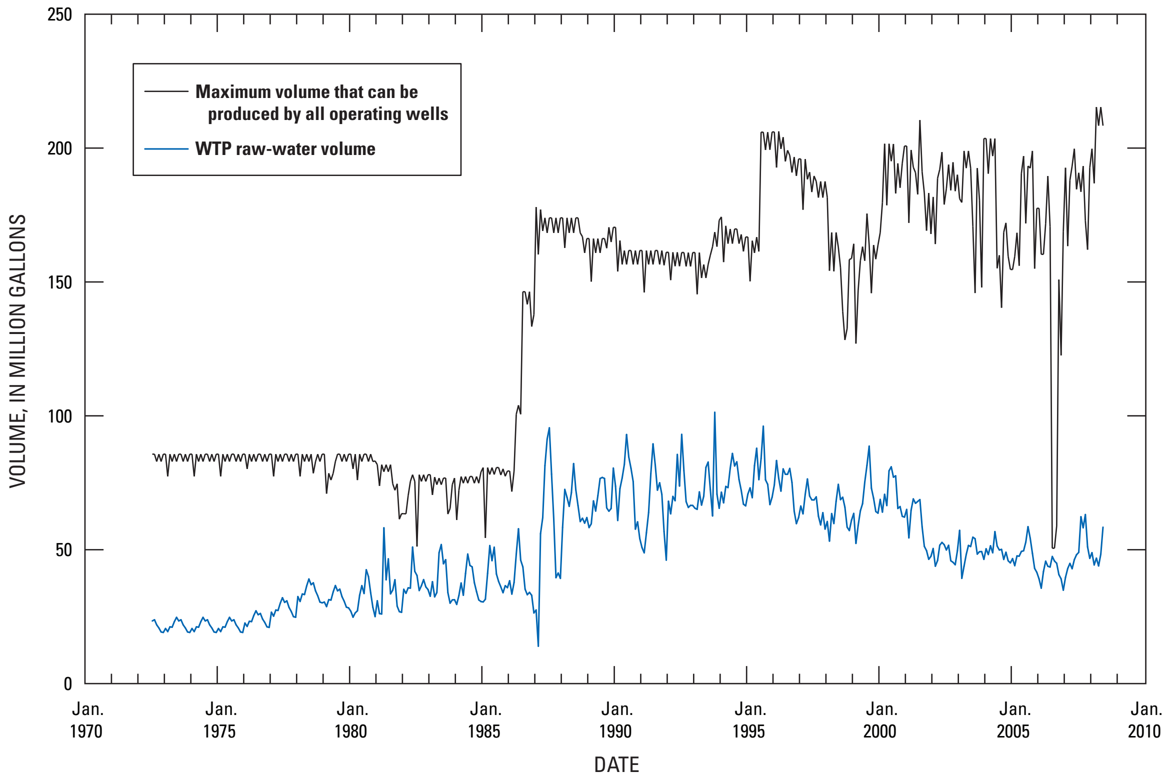

Figure S2.5. Monthly water treatment plant (WTP) raw-water volume data and maximum water volume that can be produced by all operating wells in the Holcomb Boulevard service area, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, June 1972–July 2008.

"Adjusted Number of Operating Days in a Month Revised" step of the training process (TP8, Figure S2.3).

Figures S2.30–S2.53[12] show estimated monthly water volumes produced by individual wells supplying raw water to the HBWTP. In these illustrations, the top line indicates the reasonable limit for the estimated monthly water volume produced by individual wells. The small fluctuations in the top line of Figures S2.30–S2.53 are a consequence of the varying number of days for each calendar month (28, 29, 30, or 31), thereby resulting in varying maximum volumes produced using a constant well capacity. Large changes in the top line are indicative of well capacity changing during a specific month.

The bottom lines in Figures S2.30–S2.53 indicate the estimated monthly flow produced by a well during the training period (blue line, January 1998–June 2008) and during the prediction period (green line, prior to January 1998). Thus, the water-volume values can never exceed the values represented by the top line. The lines on the graphs of Figures S2.30–S2.53 are defined solely for the time when a specific well is operational (Figure S2.2). Where the top and bottom lines coincide (e.g., for well HP-557 during the months of July, August, and September 2006, Figure S2.30), this demonstrates that the well was initially estimated to have an adjusted number of operating days that exceeded the number of calendar days in the aforementioned months. This issue was resolved in the "Adjusted Number of Operating Days in a Month Revised" step of the training process (TP8, Figure S2.3).

The estimated monthly flow production for specific wells (bottom lines, Figures S2.30–S2.53) is the final output of this analysis. This information will be needed for input data to groundwater-flow and contaminant fate and transport models, which are discussed in other supplements of the Chapter A report of the HPHB report series (Maslia et al. 2013).

[12] Figures S2.30–S2.53 are located in the back of this Supplement 2 section.

Hadnot Point Water-Supply Wells

Figure S2.54 shows graphs representing total monthly raw-water volume delivered to the HPWTP (Figure S2.1) and maximum monthly total water volume that can be produced by all operating wells. Monthly WTP raw-water volume (indicated by the bottom line in Figure S2.54) also represents the total estimated monthly flow produced by all operating wells as a result of the conditions imposed that guarantee equality between WTP flow-measurement data and total estimated flow produced by all operating wells. The maximum water volume that can be produced by all operating wells—assuming that they operate for an entire month at full capacity—is represented in Figure S2.54 by the top line. This top line also represents the limit for WTP raw-water measurement data because the WTP data do not exceed values indicated by this line. The small fluctuations in the top line of Figure S2.54 are a consequence of the varying numbers of total days for calendar months (28, 29, 30, or 31 days), whereas larger changes in value for the top line are indicative of significant water-distribution system modifications. The following example is noteworthy. The top line in Figure S2.54 indicates a sudden and significant increase in the maximum produced water volume by all operating wells from 155 to 213 Mgal during January 1943. This 58-Mgal increase in the volume of water produced by the wells is explained by analyzing the data shown in Figure S2.2. For the Hadnot Point service area prior to January 1943, there were 15 operating water-supply wells (Figure S2.2). After January 1943, the number of operating wells increased to 21, thereby accounting for the sudden and significant increase of 58 Mgal (37 percent increase) in water-volume production.

Monthly operating schedules for each well providing raw water to the HPWTP (Figure S2.2), estimated as operating days for each calendar month, are shown in Figures S2.55–S2.126.[13] In these figures, the top line shows the number of days in a calendar month (28, 29, 30, or 31) for the time period June 1972–June 2008, as indicated on the horizontal axis. Similar to Figure S2.54, the top line is a reasonable limit for the estimated number of operating days for each of the Hadnot Point wells. The small fluctuations in the top line represent the varying number of days for each calendar month (28, 29, 30, or 31). The bottom lines in the graphs (blue and/or green lines) indicate the estimated monthly operating days of a well during the training period (January 1998–June 2008) and during the prediction period (prior to January 1998). The blue and green lines in the lower portions of Figures S2.55–S2.126 are defined for times when a well is in service, as shown in Figure S2.2. If a well is operating solely during the training period (January 1998–June 2008), then the graph for that specific well only has a blue line in the bottom part of the figure (e.g., well HP-585, Figure S2.55). Likewise, if a well is operating solely during the prediction period (prior to January 1998), then the graph for that specific well only has a green line in the bottom part of the figure (e.g., well HP-601, Figure S2.58); this indicates that one of the surrogate wells listed in Table S2.2 is assigned to that specific well (e.g., HP-606) for the prediction of operating days in a month. For some wells, the estimated number of monthly operating days is equal to the number of days for a specific calendar month (e.g., for HP-602, shown in Figure S2.59, this occurs for the months of November 1941, November 1951, November 1952, and January 1953). The data and results for these specific months demonstrate that the well (e.g., HP-602) was initially estimated to have an adjusted number of operating days that exceeded the number of calendar days in the aforementioned months. This issue was resolved in the "Adjusted Number of Operating Days in a Month Revised" step of the training process (TP8, Figure S2.3).

Figures S2.127–S2.198 show estimated monthly water volumes produced by individual wells supplying raw water to the HPWTP.[14] In these illustrations, the top line indicates the reasonable limit for the estimated monthly water volume produced by individual wells. The small fluctuations in the top line of Figures S2.127–S2.198 are a consequence of the varying number of days for each calendar month (28, 29, 30, or 31), thereby resulting in varying maximum volumes produced using a constant well capacity. Large changes in the top line are indicative of well capacity changing during a specific month.

The bottom lines in Figures S2.127–S2.198 (i.e., blue and green lines, depending on the specific well) indicate the estimated monthly flow produced by a well during the training period (blue line, January 1998–June 2008) and during the prediction period (green line, prior to January 1998). Thus, the water-volume values can never exceed the values represented by the top line. The lines on the graphs of Figures S2.127–S2.198 are defined solely for the time when a specific well is operational (Figure S2.2). When the top and bottom lines coincide (e.g., for well HP-602 during the months of November 1941, November 1951, November 1952, and January 1953, Figure S2.59), this demonstrates that the well was initially estimated to have an adjusted number of operating days that exceeded the number of calendar days in the aforementioned months. This issue was resolved in the "Adjusted Number of Operating Days in a Month Revised" step of the training process (TP8, Figure S2.3).

The estimated monthly flow production for specific wells (bottom lines, Figures S2.127–S2.198) is the final output of this analysis. This information will be needed for input data to groundwater-flow and contaminant fate and transport models, which are discussed in other supplements of the Chapter A report of the HPHB report series (Maslia et al. 2013).

[13] Figures S2.55–S2.126 are located in the back of this Supplement 2 section.

[14] Figures S2.127–S2.198 are located in the back of this Supplement 2 section.

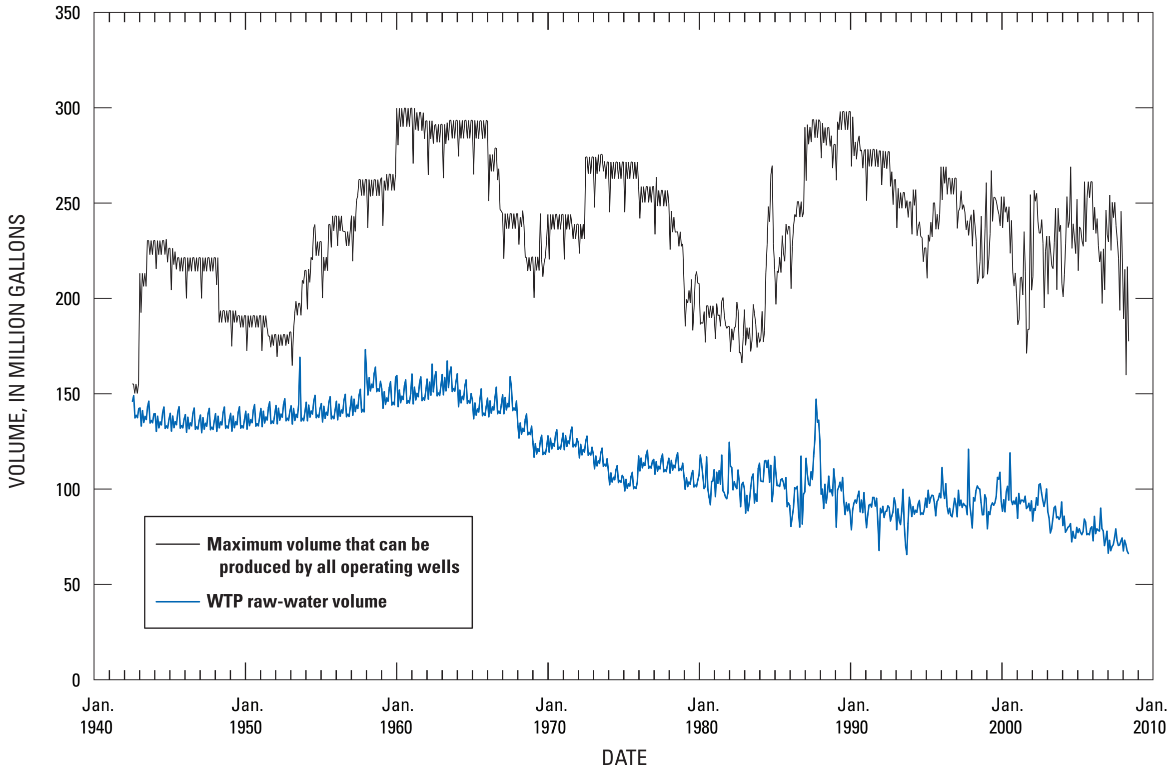

Figure S2.54. Monthly water treatment plant (WTP) raw-water volume data and maximum water volume that can be produced by all operating wells in the Hadnot Point service area, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, July 1942–July 2008.

Sensitivity, Uncertainty, and Variability

As with any study relying on field data and modeling analyses, sensitivity, uncertainty, and variability are inherent characteristics that need to be addressed. Sensitivity can be defined in a general sense as assessing the effect of varying model input parameters and determining their effect on model output parameters. By definition, uncertainty pertains to a lack of knowledge with respect to a model or parameter (e.g., well capacity); variability refers to differences or diversity in a model or parameter (e.g., differences in operational schedules for a specific water-supply well). In this study of water-supply well operations, uncertainties about specific on-off cycling times and data related to water-supply well characteristics, such as changes in capacity over time, are acknowledged. Thus, the issue is how and when to include an analysis for uncertainty and variability and how sensitive model output parameters (e.g., finished-water concentrations) are to variations in water-supply well operations. Based on historical reconstruction analyses conducted for the Tarawa Terrace study area, water-supply well pumping is but one of a number of data and modeling parameters that need to be assessed for sensitivity, uncertainty, and variability (Maslia et al. 2009). Because the data generated for this supplement (i.e., well operations) will be used as input data for groundwater-flow, contaminant fate and transport, and water-distribution system modeling, conducting an uncertainty or sensitivity analysis for a single parameter in isolation or in absence of a multitude of other parameters would not yield meaningful or useful results in terms of the goals for the overall study (historical reconstruction of monthly finished-water concentrations). Additionally, as discussed in Maslia et al (2009), certain parameter values assessed during an uncertainty analysis may result in physically implausible solutions at the next step. Because of these factors, it has been decided that a more useful and insightful approach for conducting uncertainty and sensitivity analyses with respect to historical water-supply well operations is to allow this parameter (water-supply well operation) to vary in concert with additional modeling parameters during subsequent groundwater-flow and contaminant fate and transport modeling phases of the historical reconstruction analysis. During these phases, sensitivity and uncertainty analyses are conducted as part of the historical reconstruction process (Maslia et al. 2013). Thus, the most important concept to consider is the effect of sensitivity and uncertainty of numerous parameters on the historical drinking-water concentrations and not the analysis of senstivity and uncertainty of solely one parameter (e.g., water-supply well operations). For summaries of sensitivity and uncertainty analyses, readers should refer to the appropriate sections in the Chapter A report (Maslia et al. 2013).

Conclusions

In this analysis of present-day (1998–2008) and historical (1942–1997) water-supply well operations, an original methodology is developed and applied to estimate the historical monthly operating patterns of wells supplying groundwater (raw water) to the HBWTP and HPWTP. This information is required by ATSDR for its water-modeling analyses of groundwater flow and contaminant fate and transport. The model simulations are being used by ATSDR to reconstruct contaminant concentrations in finished water as part of the agency's health studies at Camp Lejeune. The methodology described in this supplement of Chapter A is based on using available data with maximum efficiency and effectiveness to estimate the monthly operational patterns of the wells. The period spanning January 1998–June 2008, when detailed daily data are available, is referred to as the present-day period or "training period." The period of time prior to January 1998, during which little or no data pertaining to the operating schedules of the wells are available, is referred to as the historical reconstruction period or "prediction period." The methodology estimates the historical monthly operational pattern of wells based on the assumption that the operational patterns that characterize the prediction period are based on the same operational patterns observed during the training period. Wells that were not operational during the training period (or for which data were not available) were assigned "surrogate wells" based on (1) geohydrologic and hydrogeologic characteristics of the surrounding aquifers and water-bearing zones, (2) well characteristics such as capacity and demand data, and (3) proximity of the surrogate well to the well it replaced. Because the majority of the wells operating during the training period were trainable, the surrogate well assumption did not introduce a limiting restriction to the methodology described herein. The training process was based on the principle of satisfying the total volume of water delivered to the WTP during the training period. In the prediction period, the monthly operational pattern was assumed to be similar to that of the training period for identical calendar months. The same principle used in the training process—satisfying the total volume of water supplied to the WTP—was used to predict historical well operational patterns during the prediction period. The results indicate that the outcomes of the estimation methodology are within acceptable limits when estimated monthly operating days and the number of calendar days in a month are considered. Similarly, estimated flows produced by the wells do not exceed the maximum flow that can be produced by those same wells. In some cases, the produced flows are estimated to be equal to the maximum producible flow. However, these limiting estimates do not introduce substantial restrictions on the reliability of the methodology because these cases occur in a small number of months for a small number of wells. Using the methodology described herein, available data are used effectively to estimate historical operational schedules of water-supply wells serving the HBWTP and HPWTP. Results of the analyses presented herein were used in groundwater-flow and contaminant fate and transport simulations to reconstruct historical contaminant concentrations in finished water that was supplied by the HPWTP to USMCB Camp Lejeune family housing areas and other facilities.

References[15]

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[15] Certain documents have been provided to ATSDR by the Department of the Navy (Headquarters Marine Corps, Eastern Area Counsel Office, and Marine Corps Base Camp Lejeune) under terms of "For Official Use Only" (FOUO) documents. Some of these documents are not releasable by ATSDR under the terms of FOUO.

Figures S2.6–S2.29. Estimated Monthly Operating Days for Holcomb Boulevard Wells

For operational chronology of all water-supply wells see Figure S2.2 in text.

Graphs showing estimated monthly operating days for—

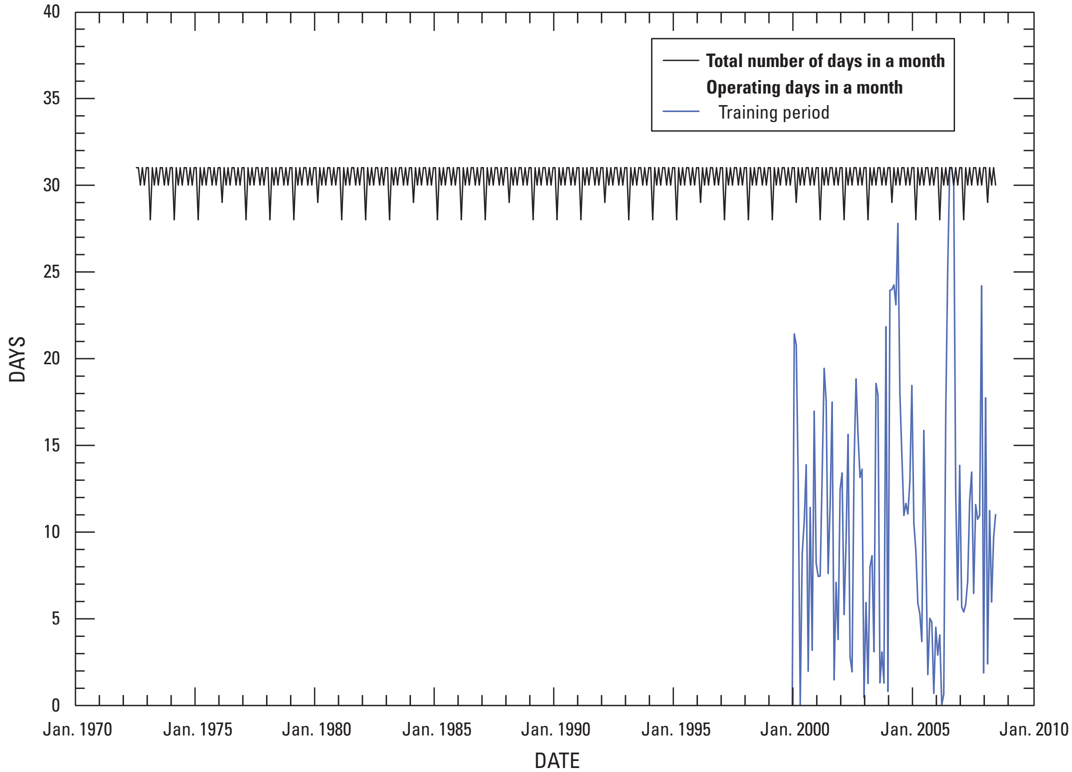

Figure S2.6. Estimated monthly operating days for well HP-557.

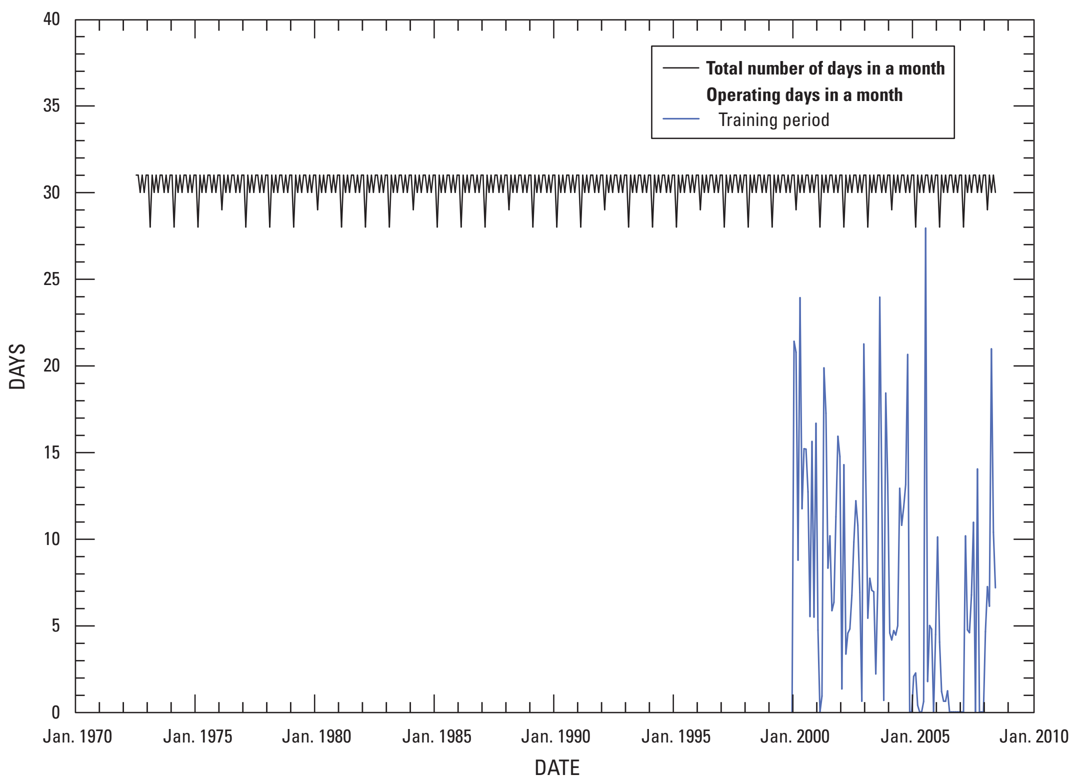

Figure S2.7. Estimated monthly operating days for well HP-558.

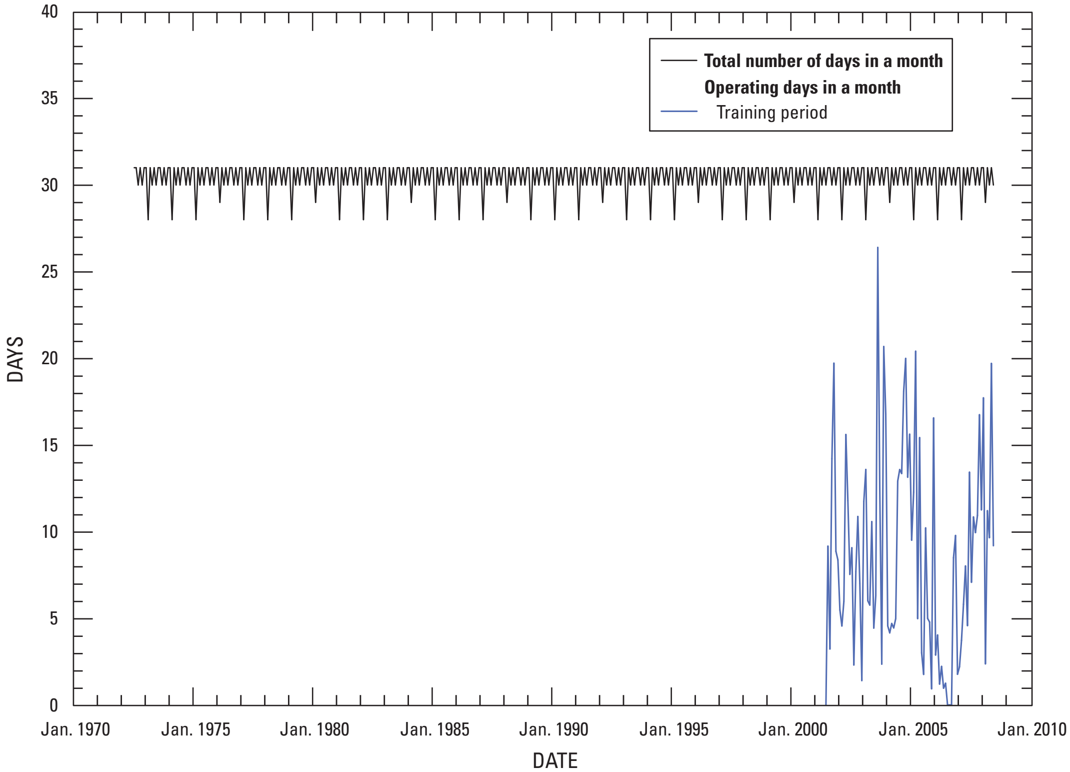

Figure S2.8. Estimated monthly operating days for well HP-584.

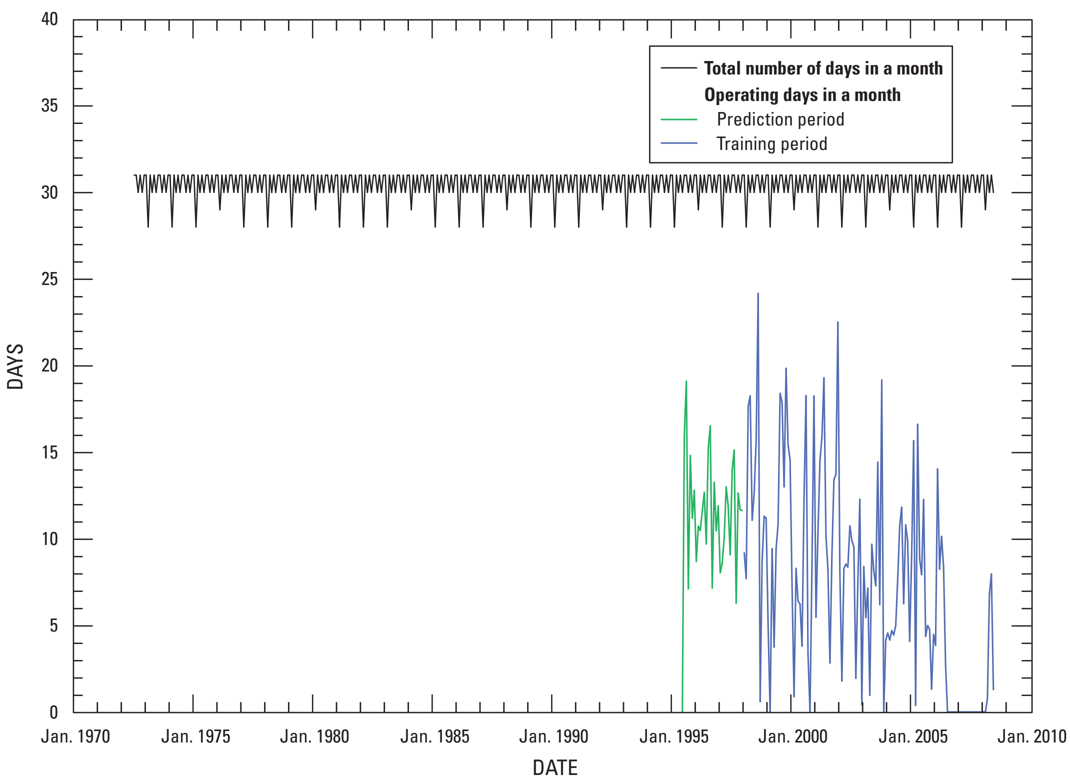

Figure S2.9. Estimated monthly operating days for well HP-617 (new).

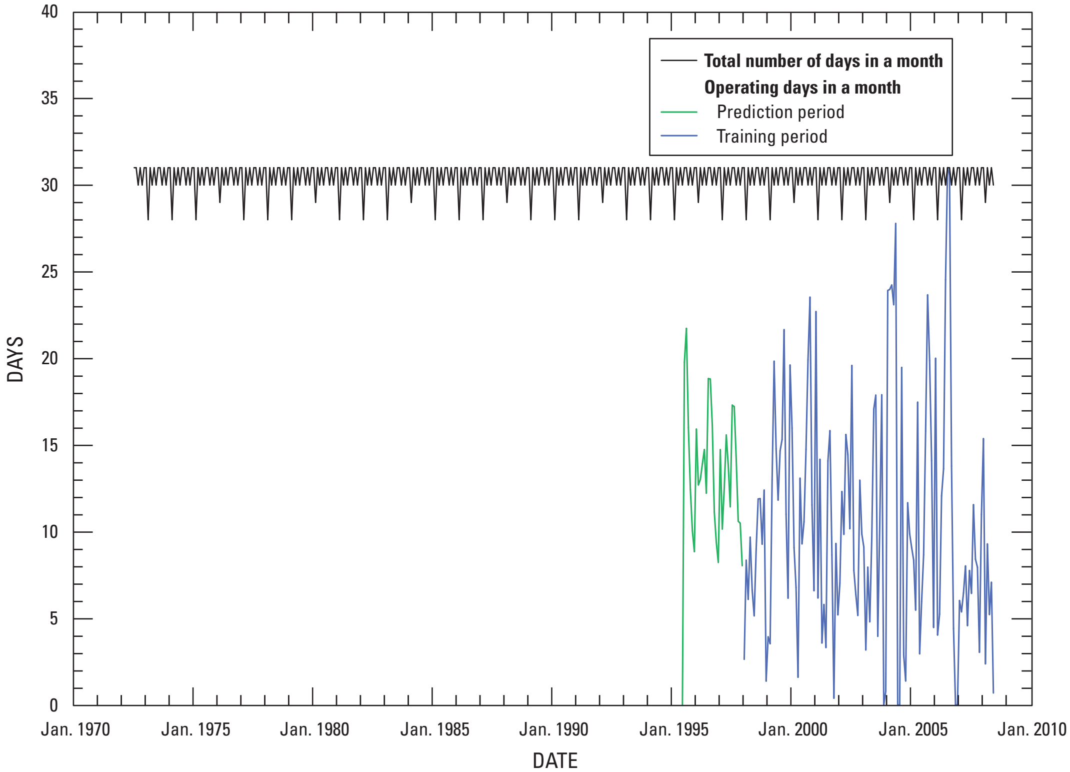

Figure S2.10. Estimated monthly operating days for well HP-618 (new).

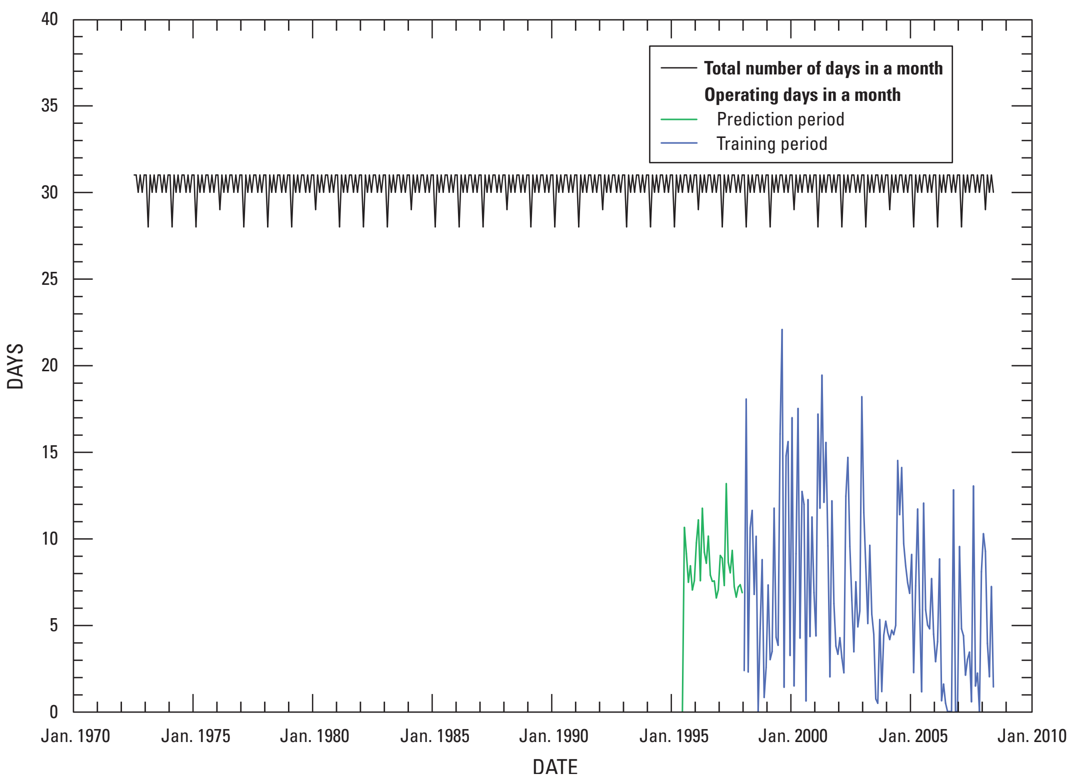

Figure S2.11. Estimated monthly operating days for well HP-619 (new).

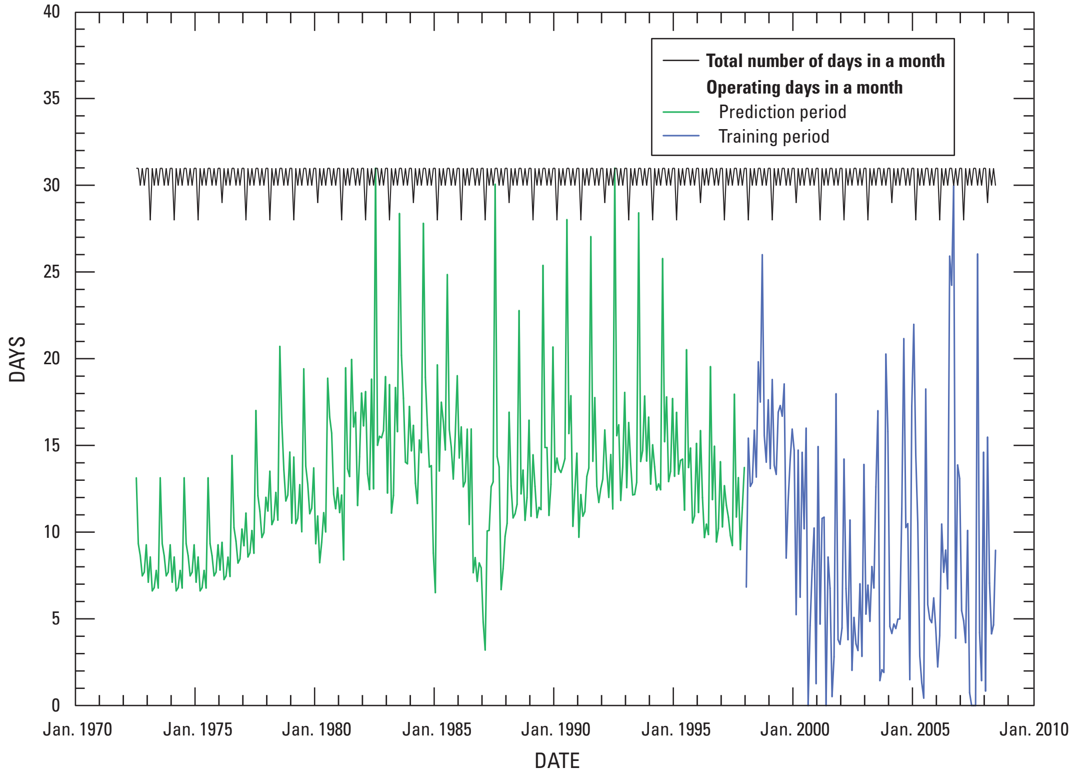

Figure S2.12. Estimated monthly operating days for well HP-643.

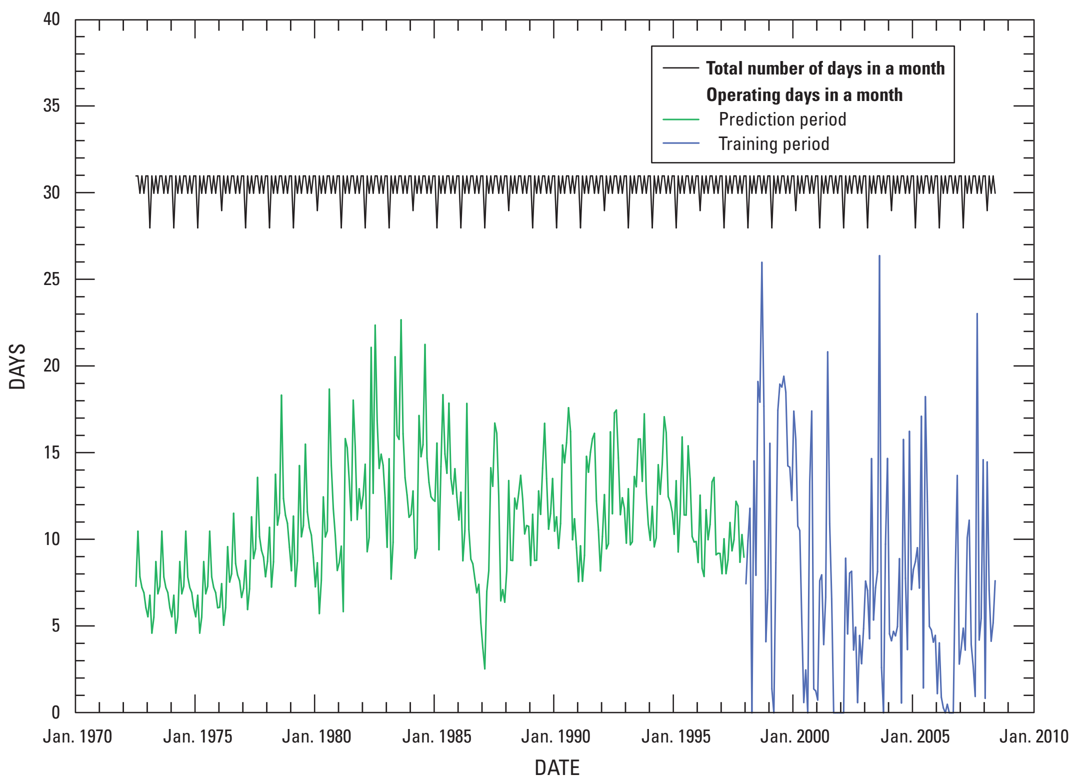

Figure S2.13. Estimated monthly operating days for well HP-644.

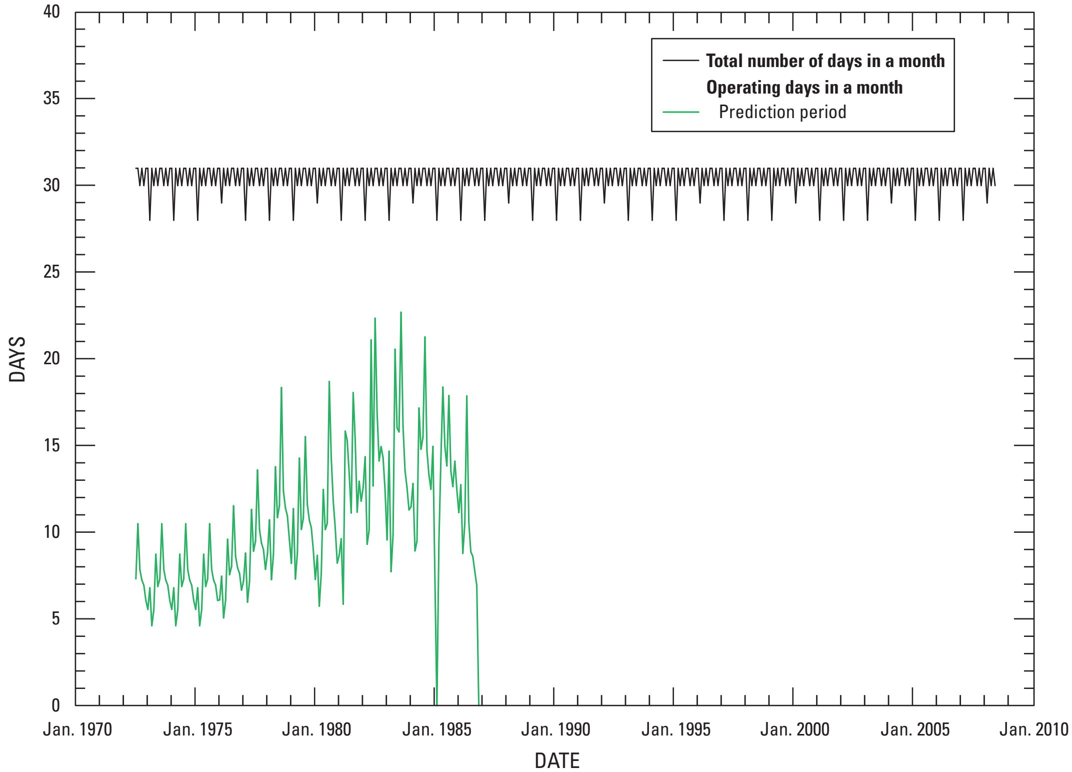

Figure S2.14. Estimated monthly operating days for well HP-645.

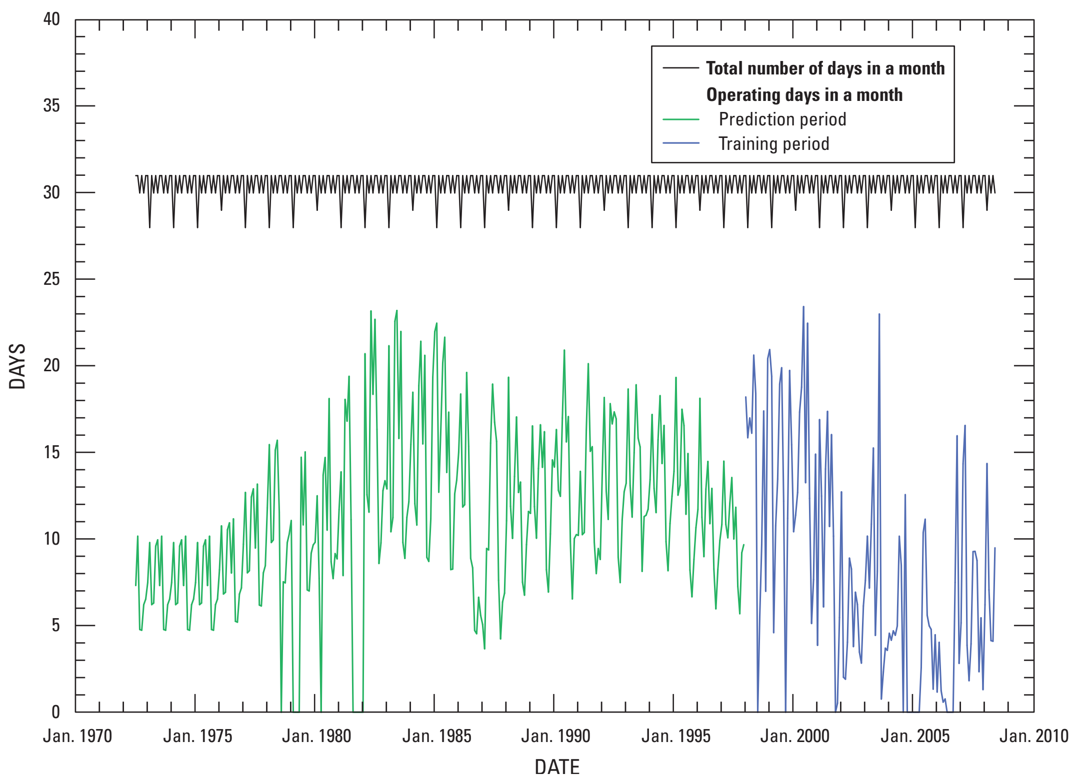

Figure S2.15. Estimated monthly operating days for well HP-646.

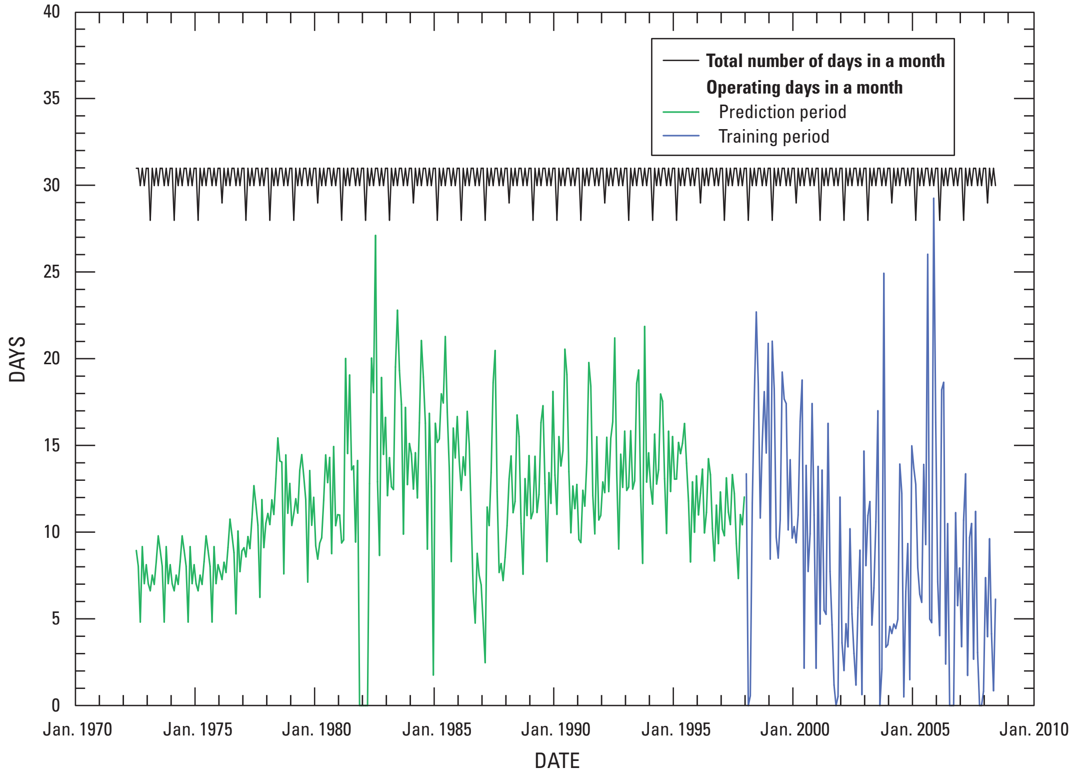

Figure S2.16. Estimated monthly operating days for well HP-647.

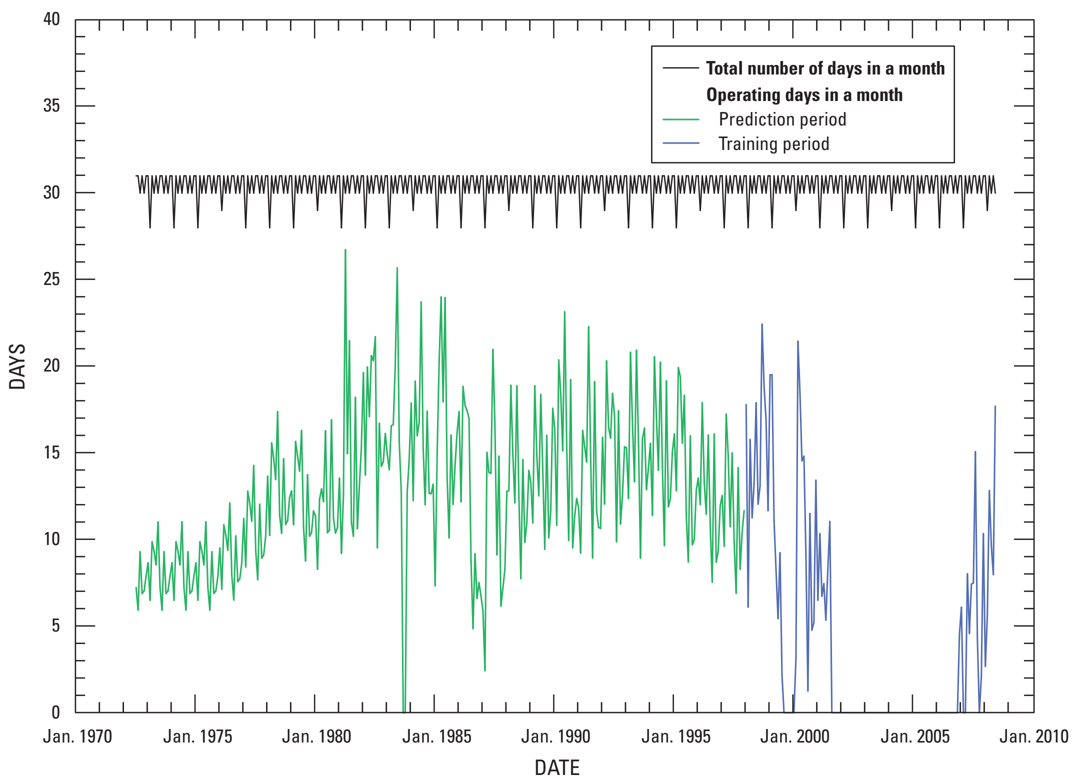

Figure S2.17. Estimated monthly operating days for well HP-648.

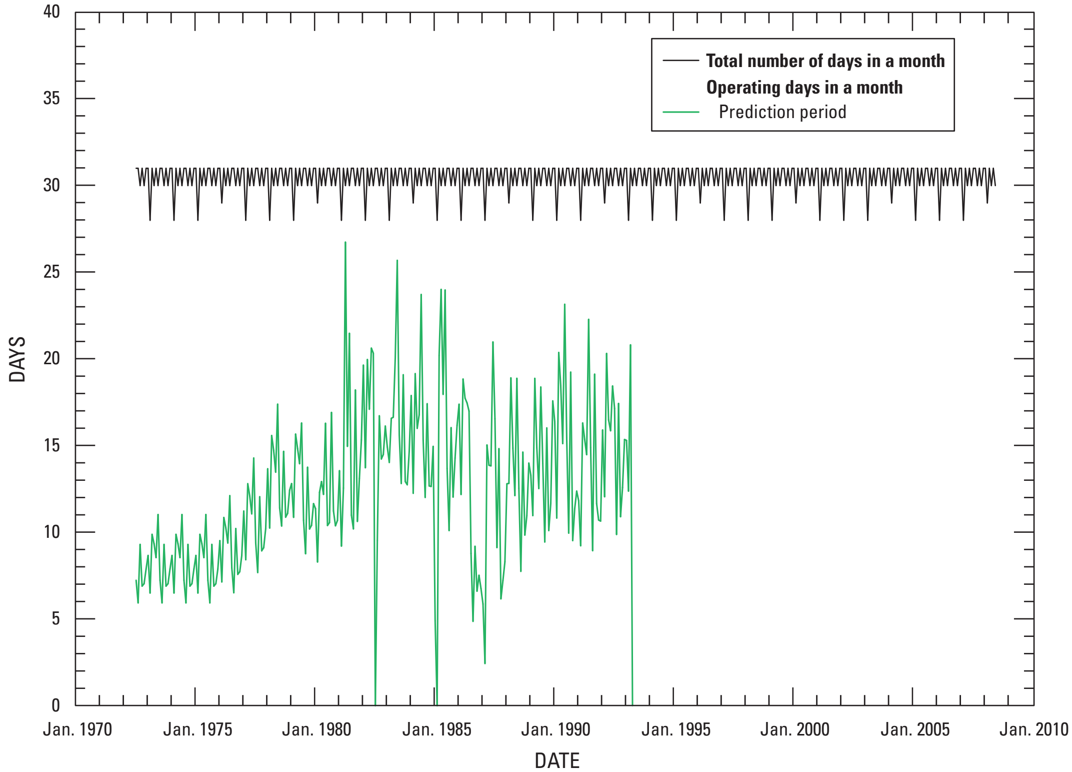

Figure S2.18. Estimated monthly operating days for well HP-649.

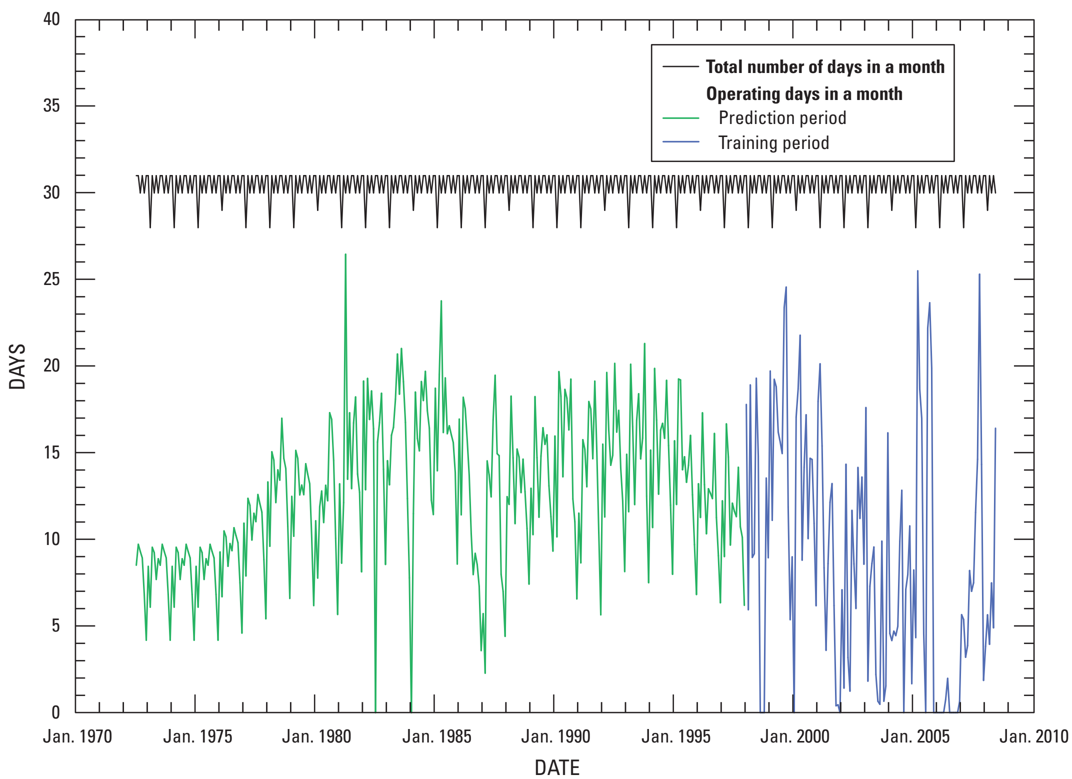

Figure S2.19. Estimated monthly operating days for well HP-650.

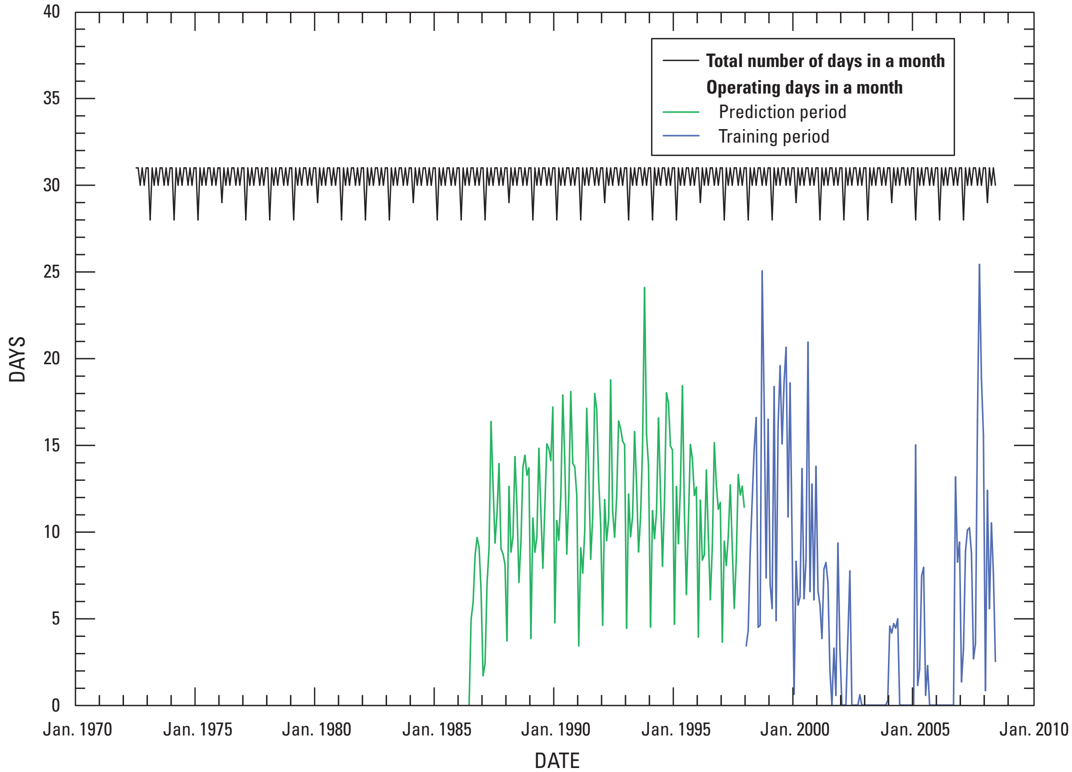

Figure S2.20. Estimated monthly operating days for well HP-698.

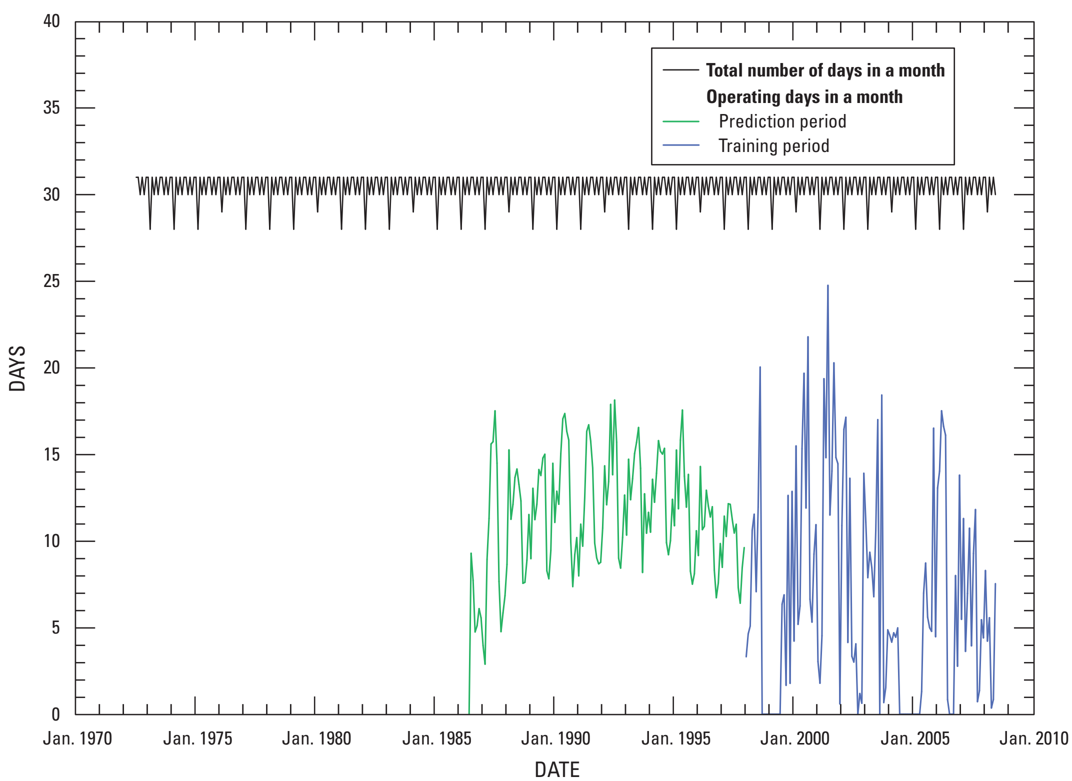

Figure S2.21. Estimated monthly operating days for well HP-699.

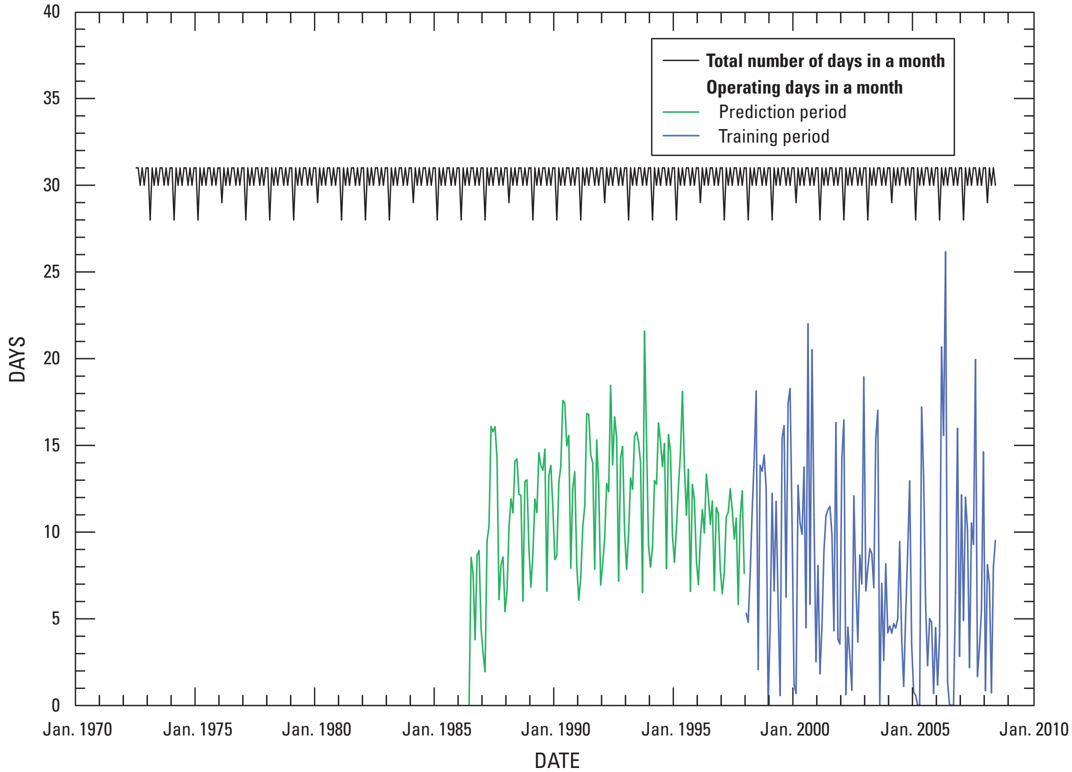

Figure S2.22. Estimated monthly operating days for well HP-700.

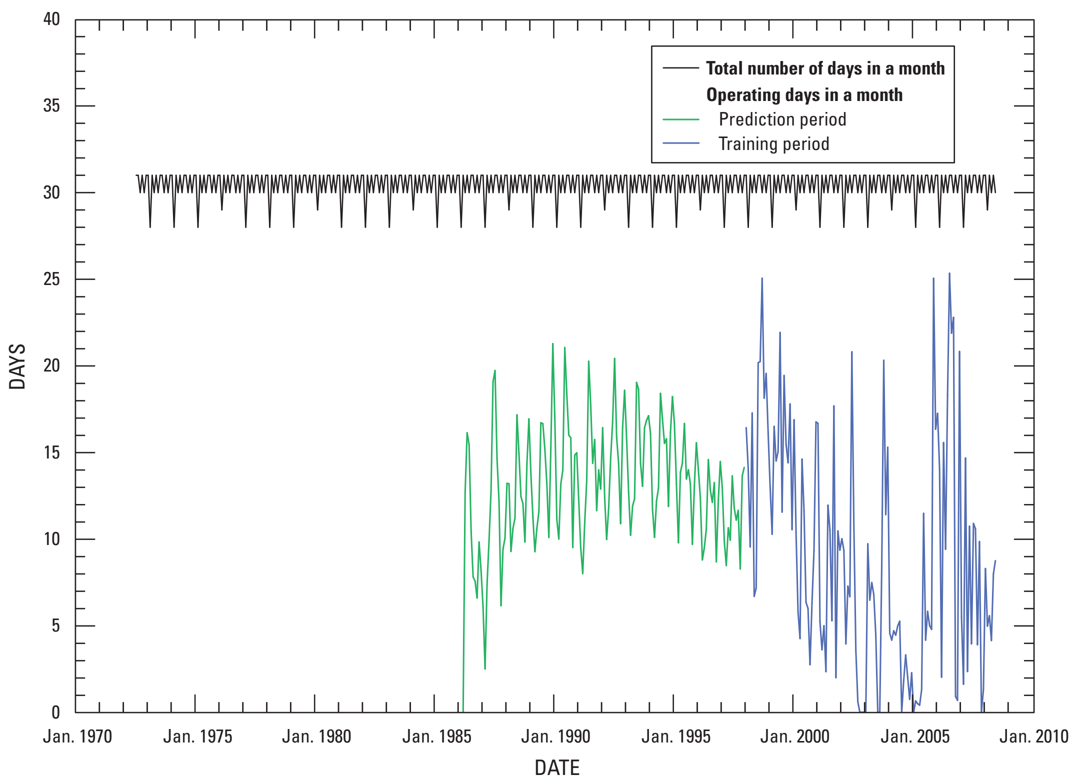

Figure S2.23. Estimated monthly operating days for well HP-701.

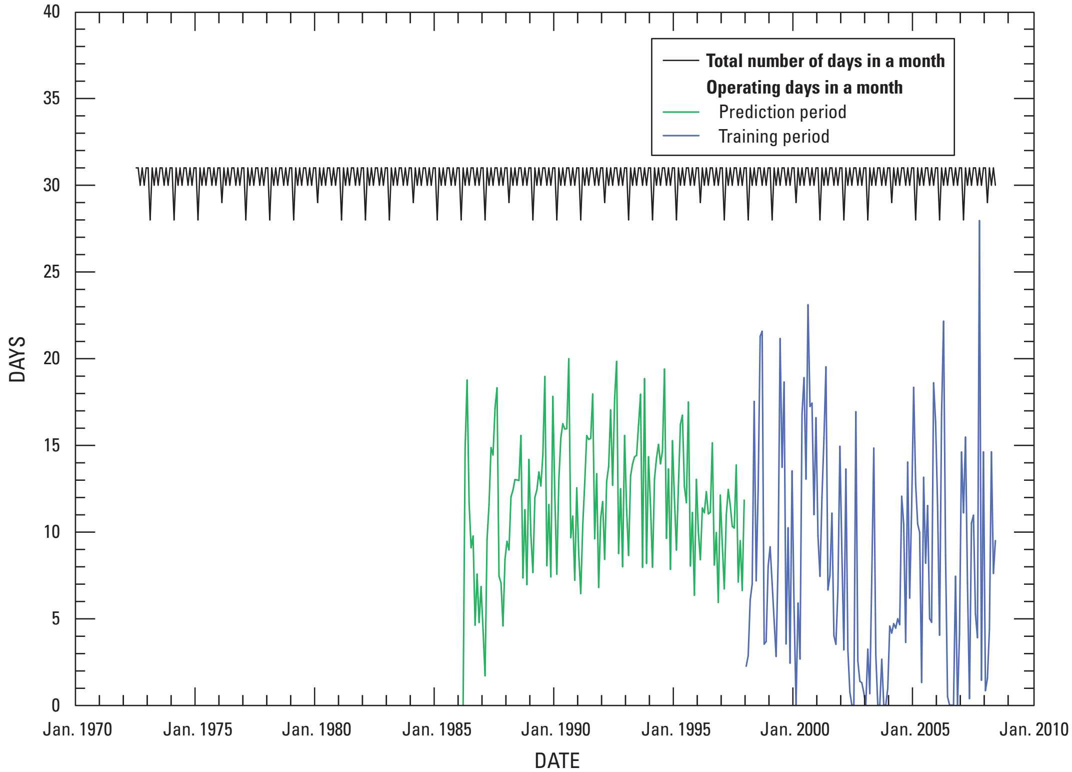

Figure S2.24. Estimated monthly operating days for well HP-703.

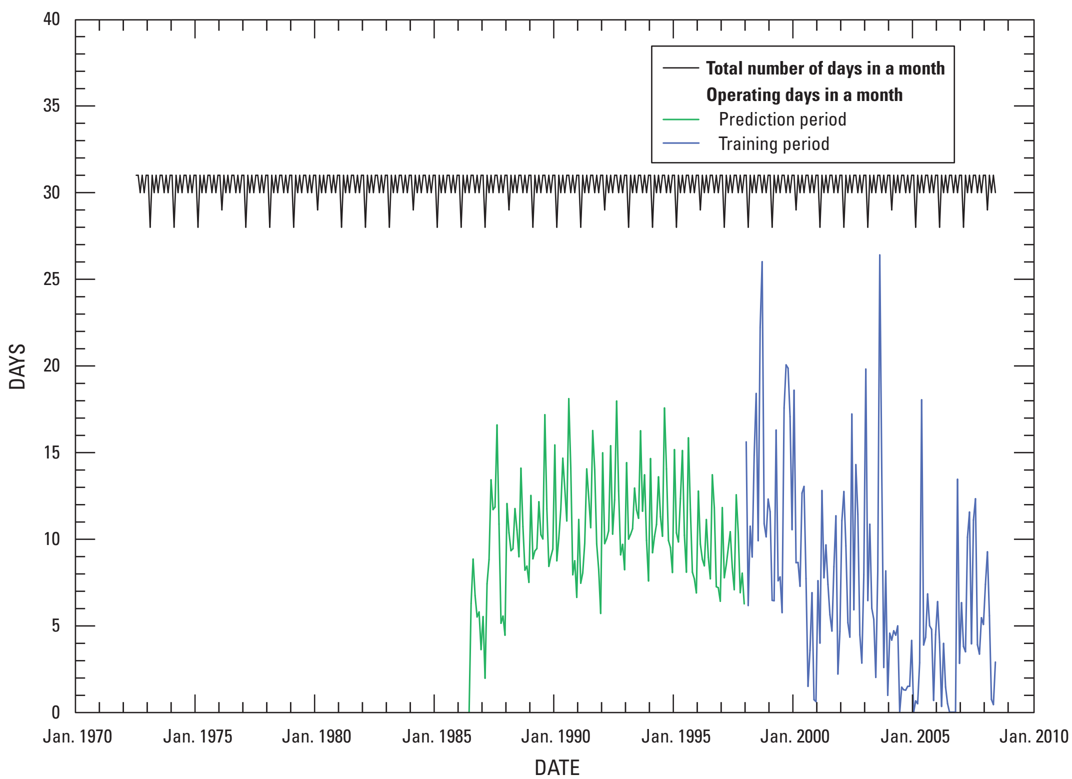

Figure S2.25. Estimated monthly operating days for well HP-704.

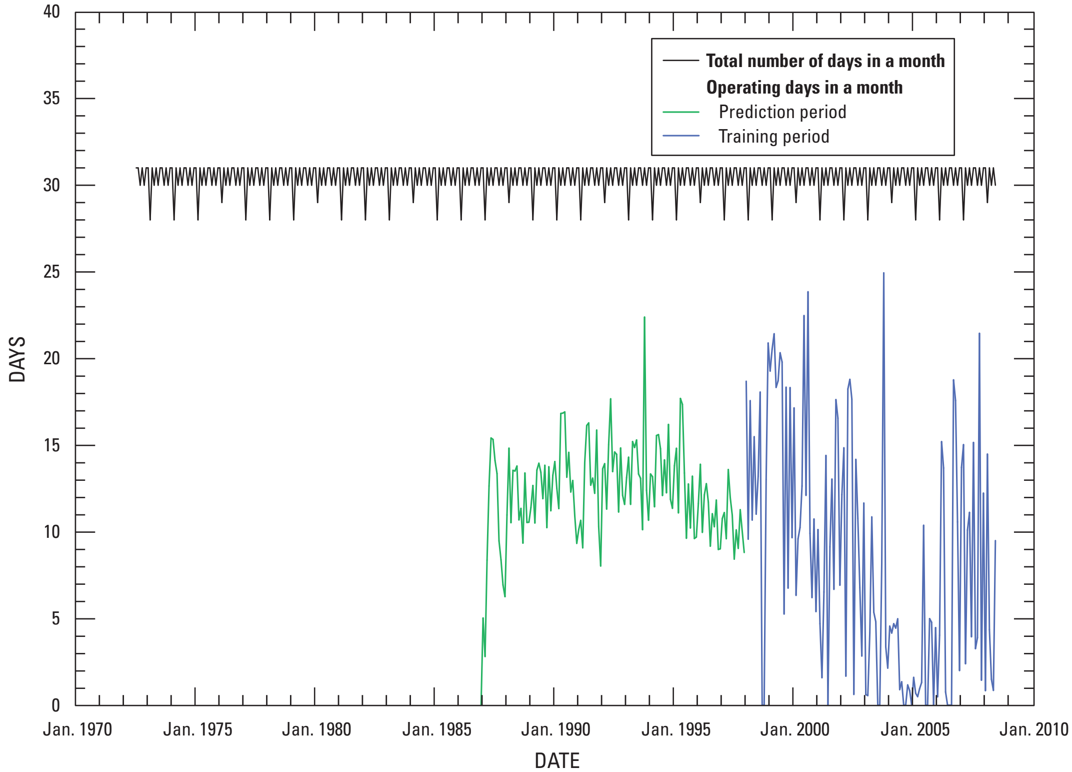

Figure S2.26. Estimated monthly operating days for well HP-705.

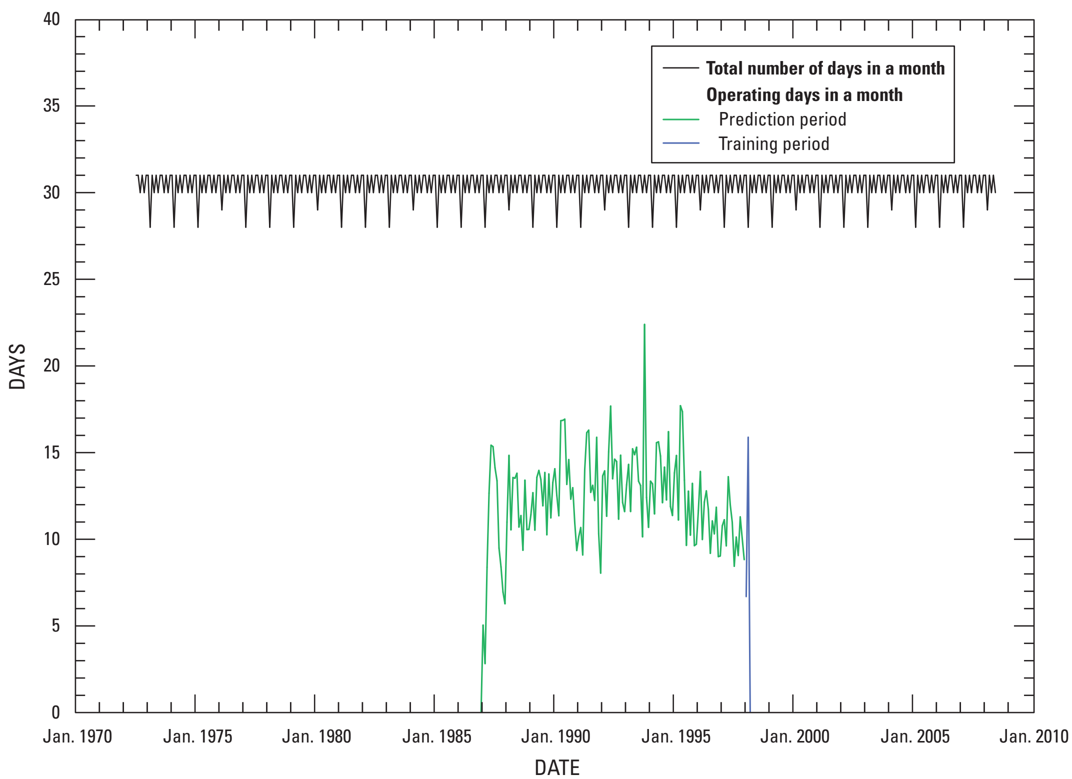

Figure S2.27. Estimated monthly operating days for well HP-706.

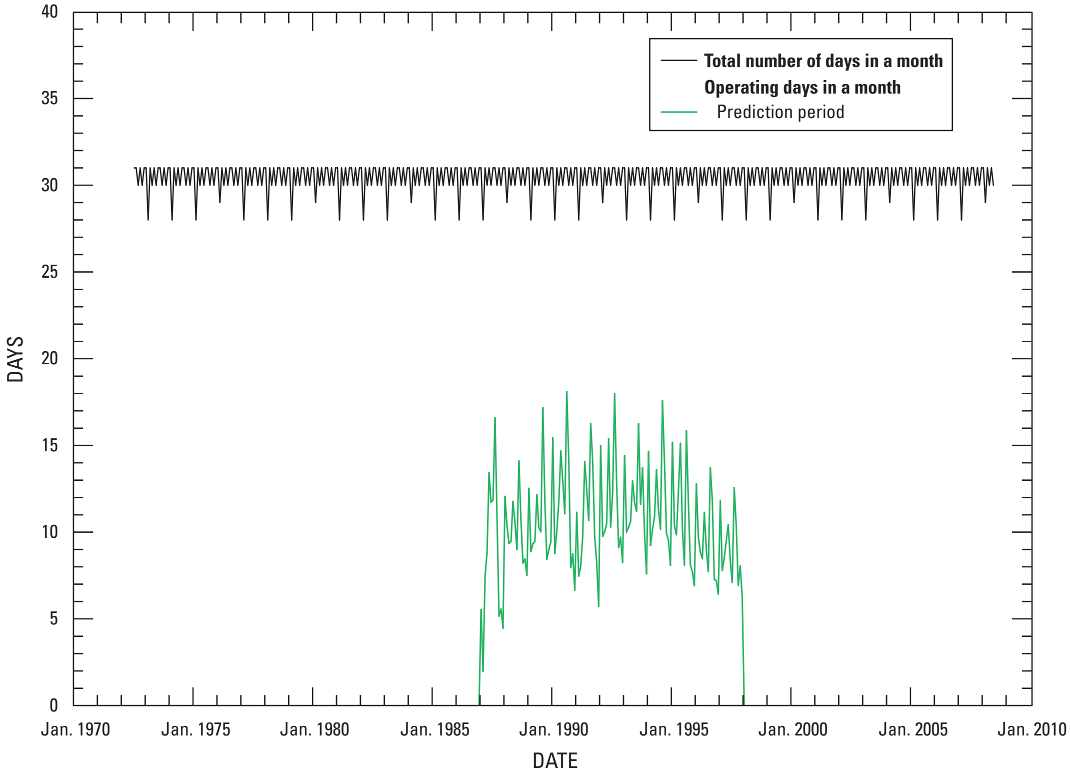

Figure S2.28. Estimated monthly operating days for well HP-707.

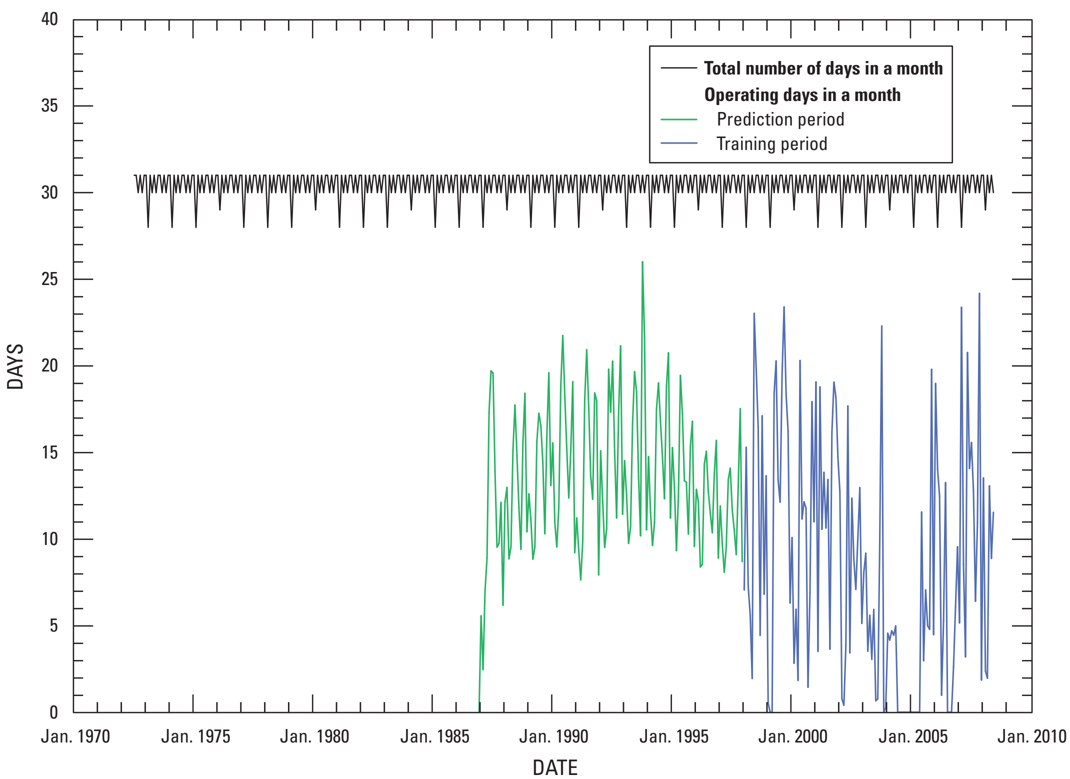

Figure S2.29. Estimated monthly operating days for well HP-708.

Figures S2.30 – S2.53. Estimated Monthly Water Volume Produced at Holcomb Boulevard Wells

For operational chronology of all water-supply wells see Figure S2.2 in text.

Graphs showing estimated monthly water volume produced at—

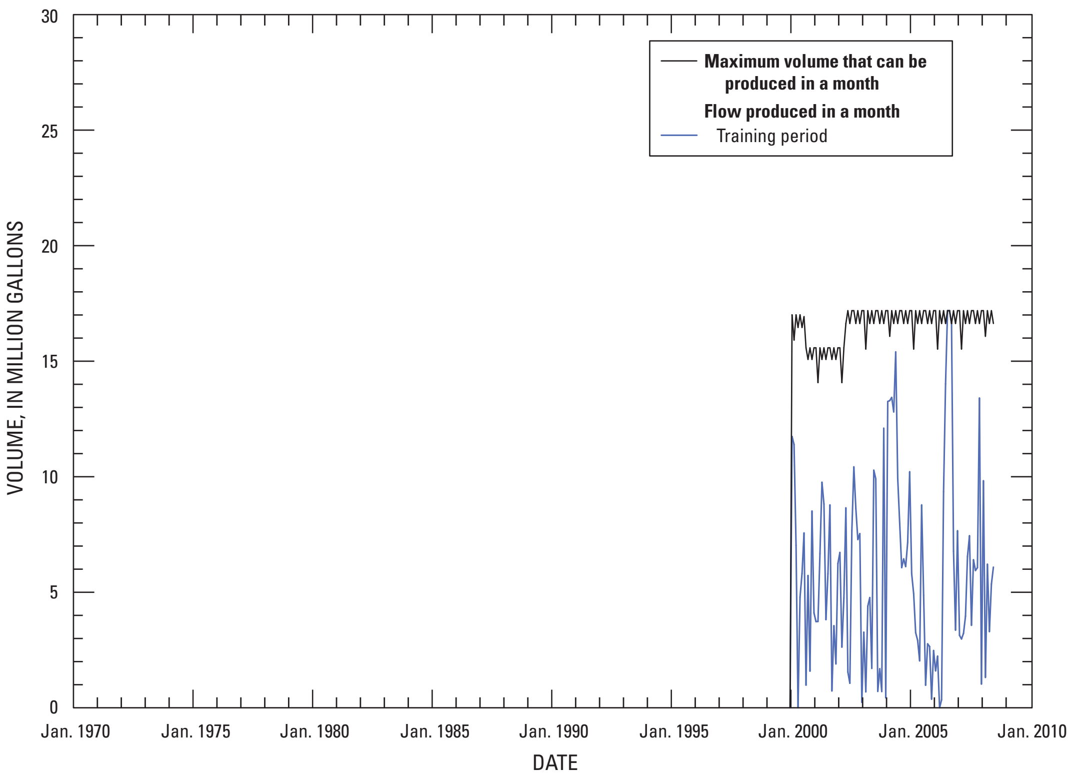

Figure S2.30. Estimated monthly water volume produced at well HP-557.

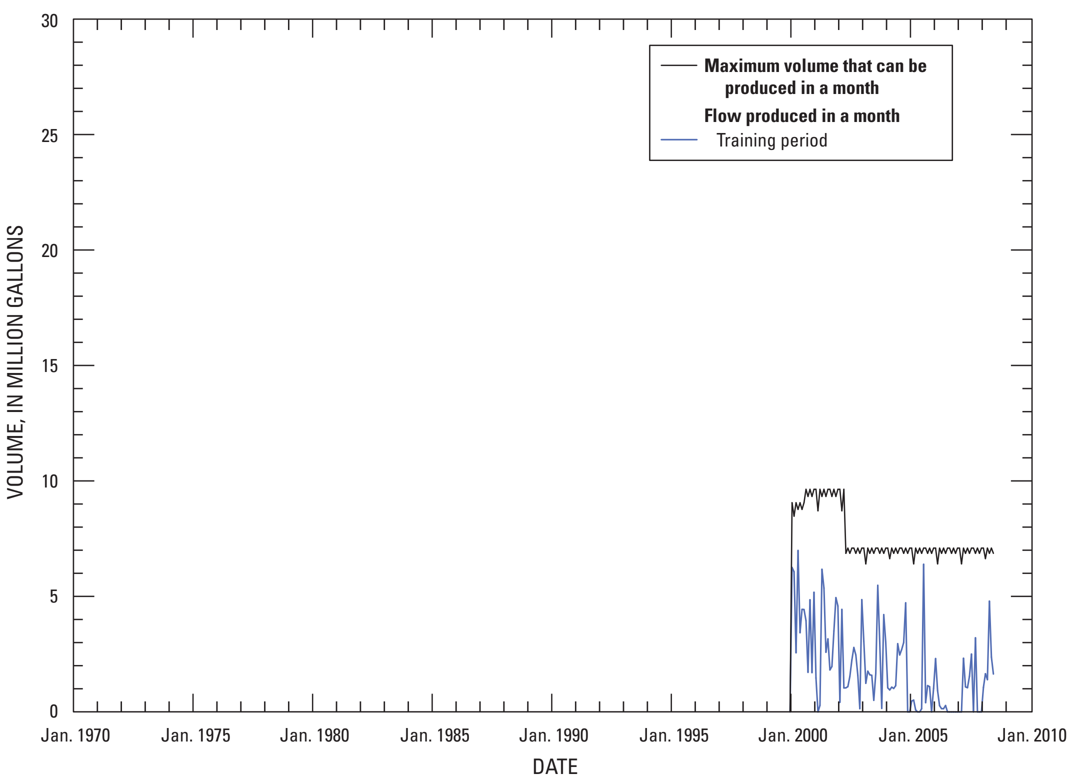

Figure S2.31. Estimated monthly water volume produced at well HP-558.

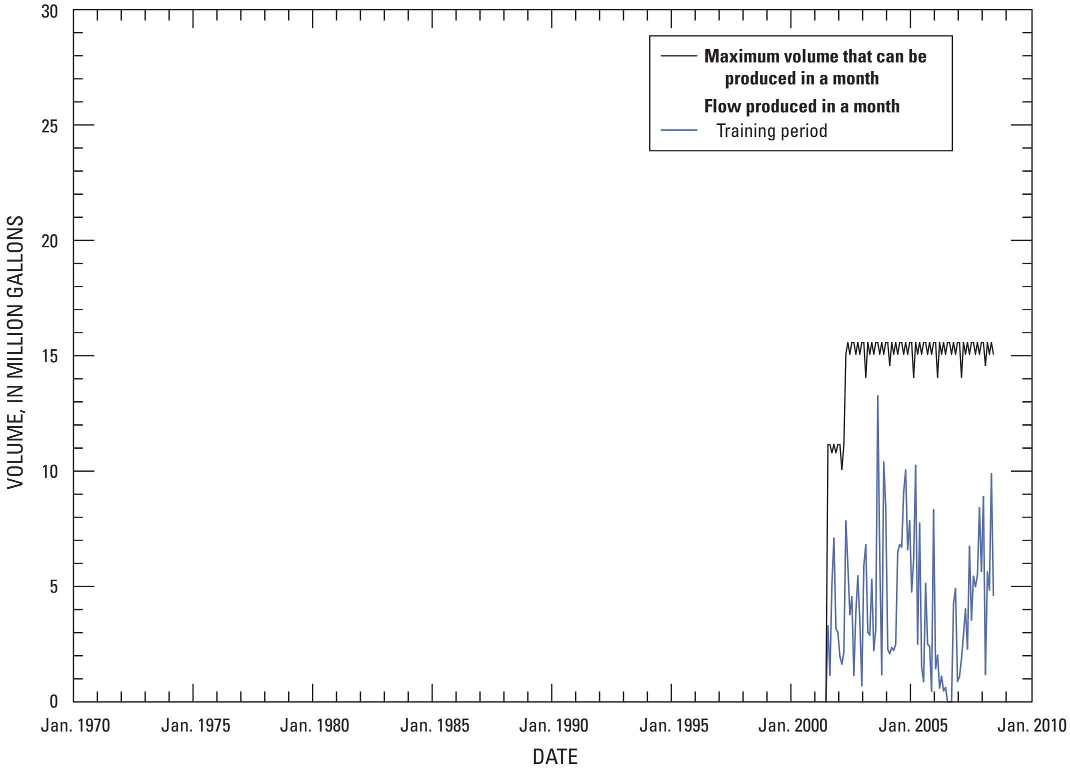

Figure S2.32. Estimated monthly water volume produced at well HP-584.

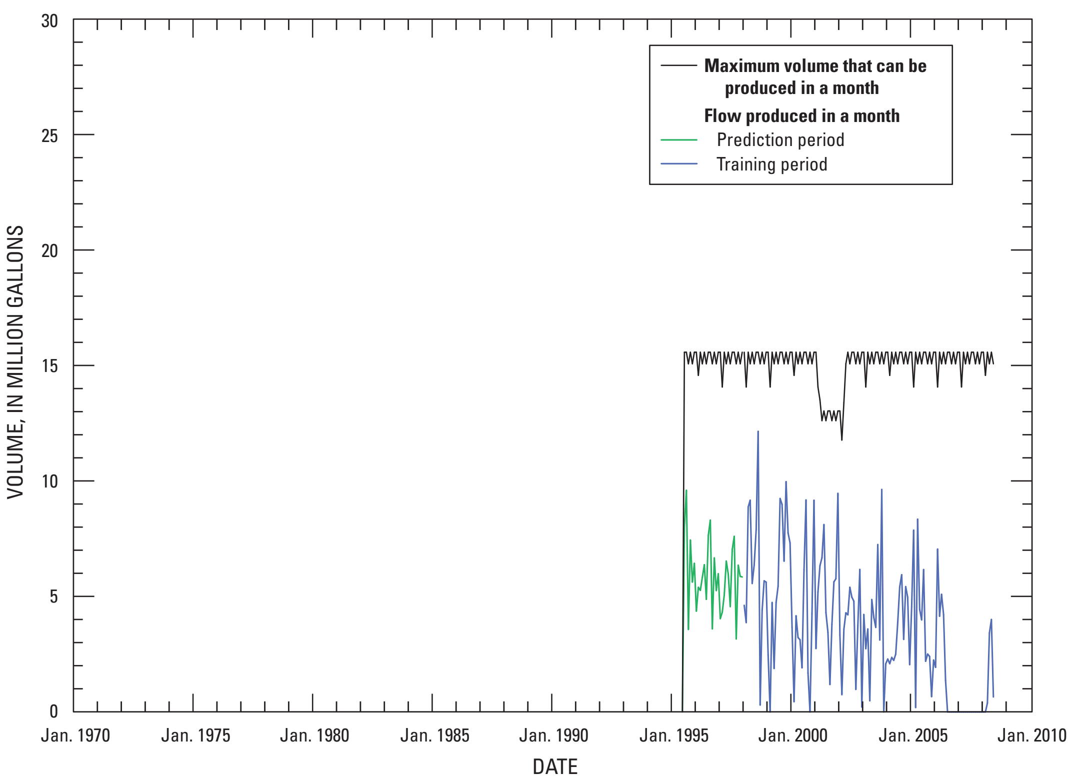

Figure S2.33. Estimated monthly water volume produced at well HP-617 (new).

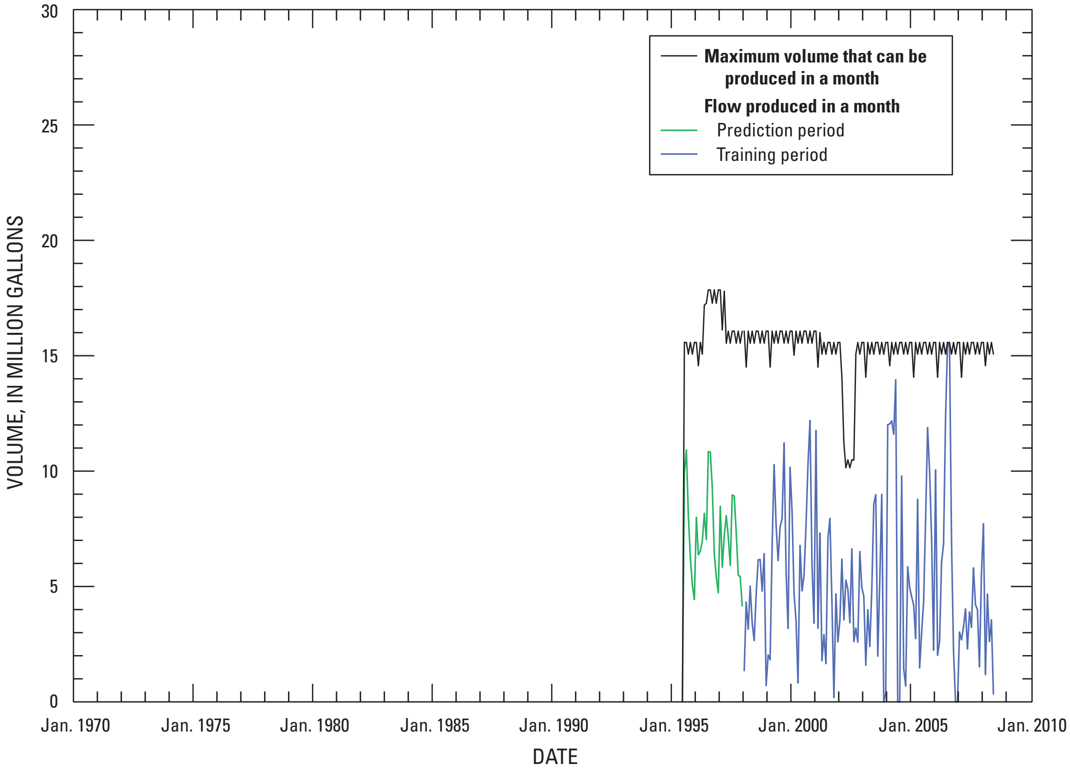

Figure S2.34. Estimated monthly water volume produced at well HP-618 (new).

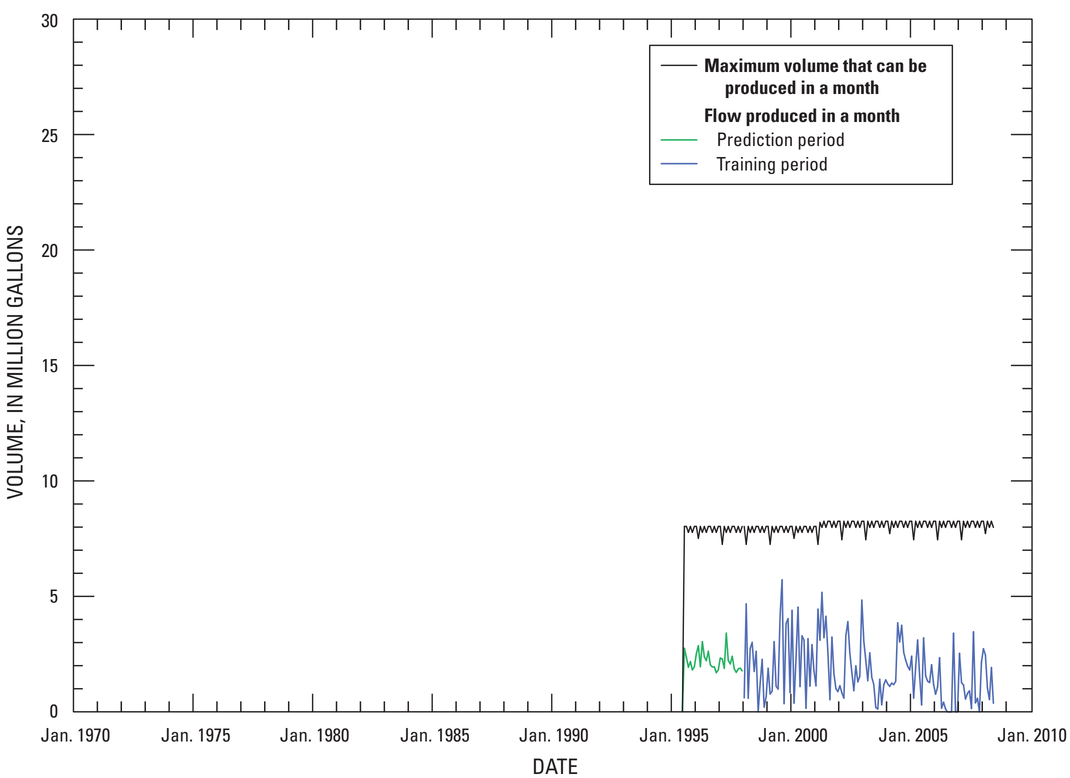

Figure S2.35. Estimated monthly water volume produced at well HP-619 (new).

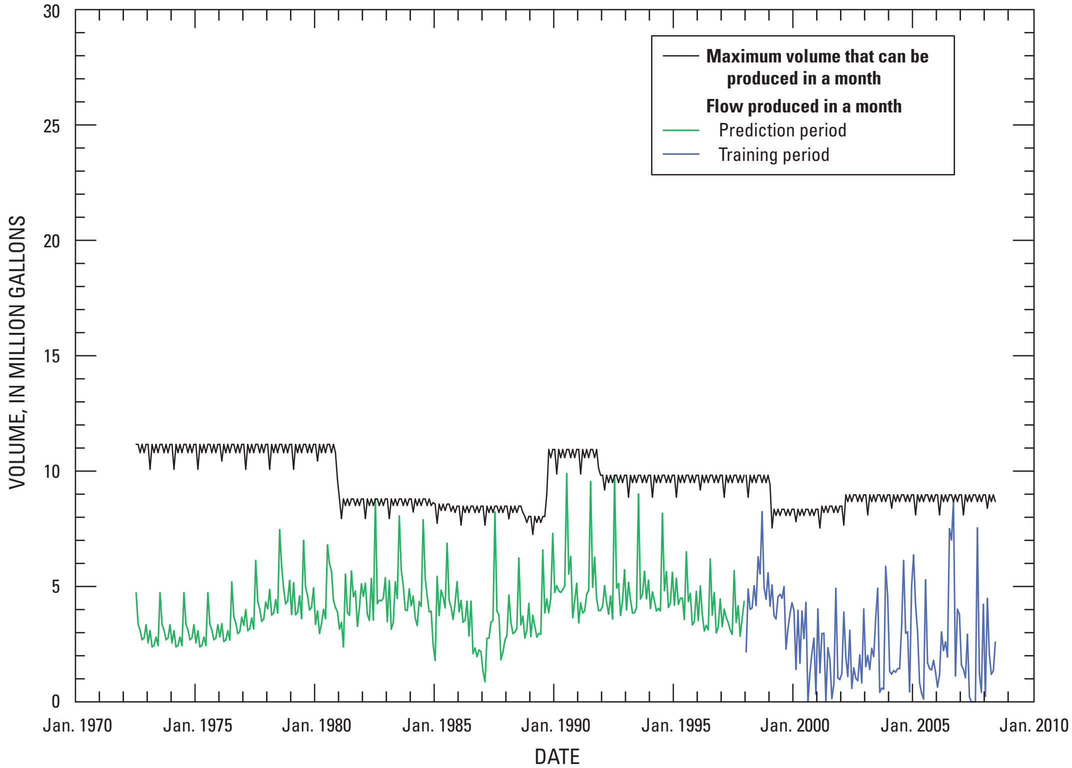

Figure S2.36. Estimated monthly water volume produced at well HP-643.

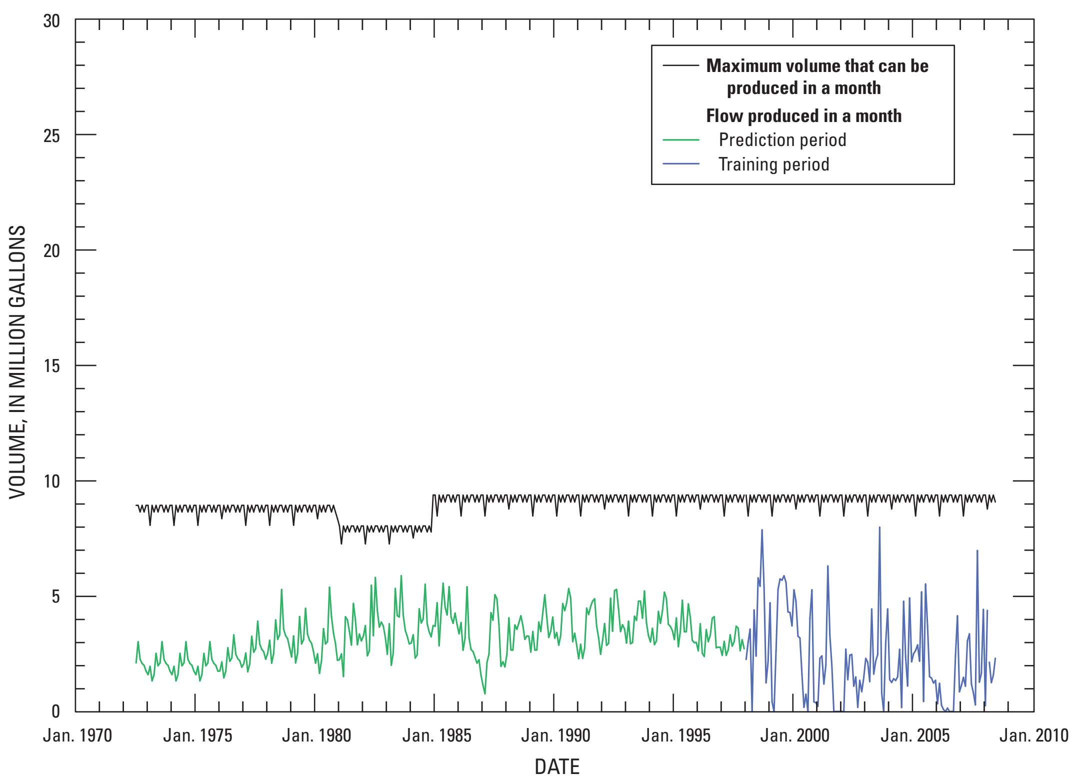

Figure S2.37. Estimated monthly water volume produced at well HP-644.

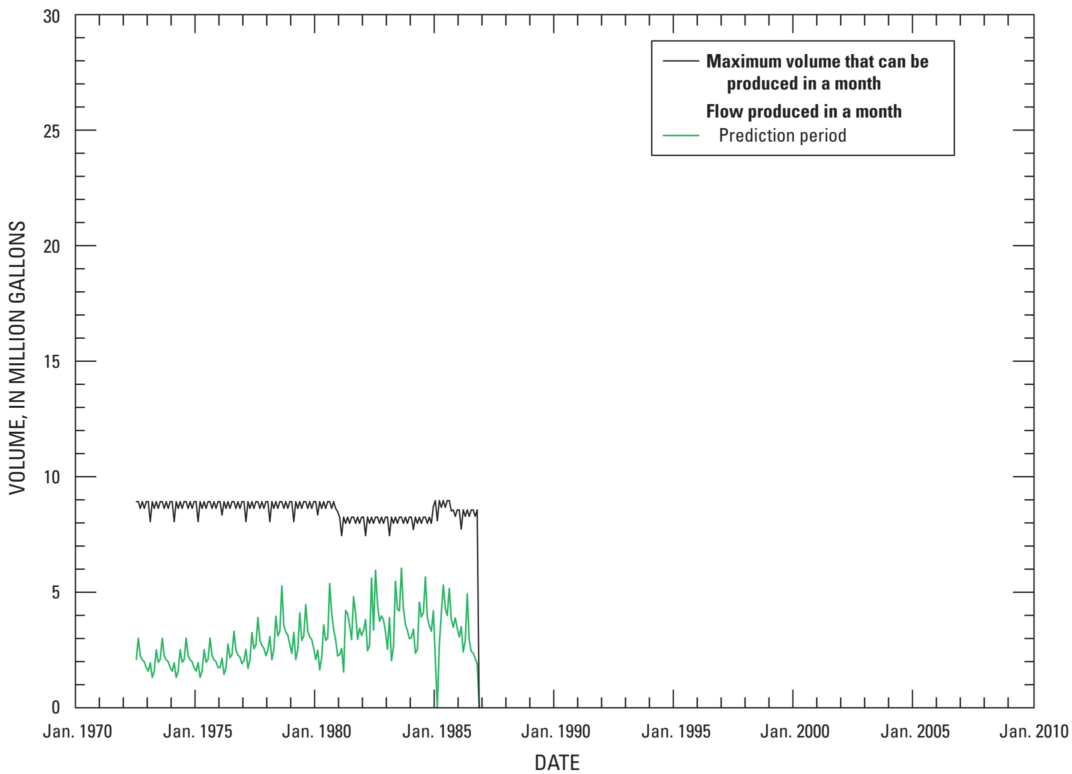

Figure S2.38. Estimated monthly water volume produced at well HP-645.

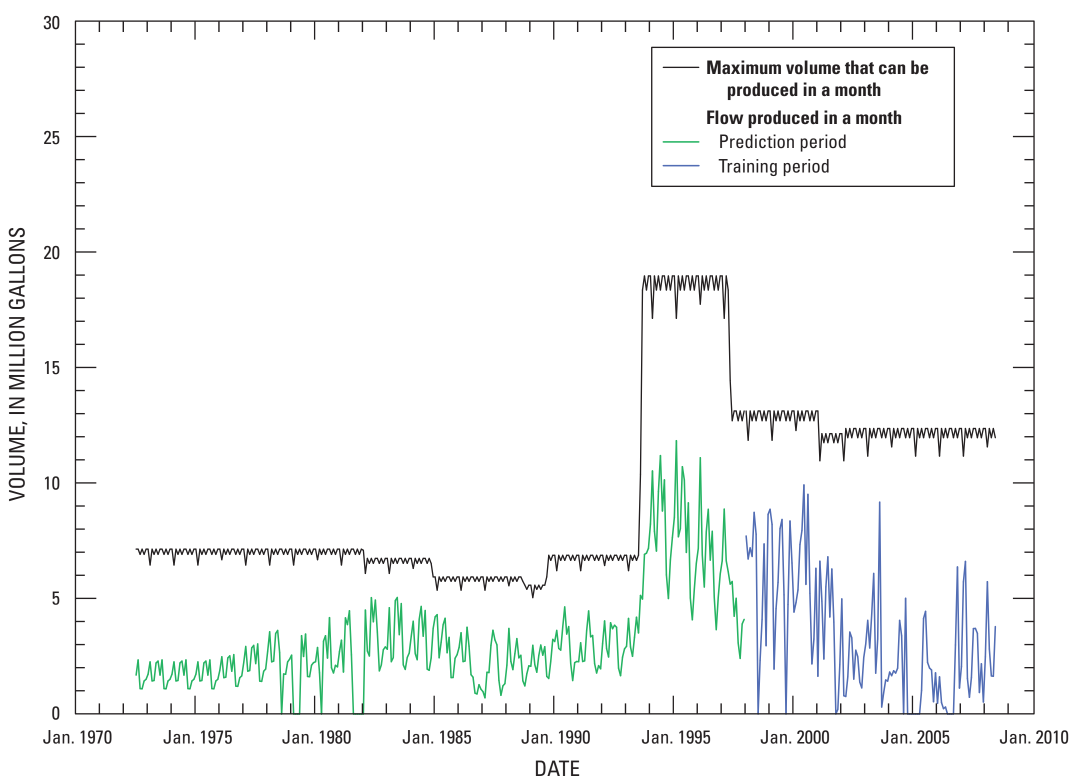

Figure S2.39. Estimated monthly water volume produced at well HP-646.

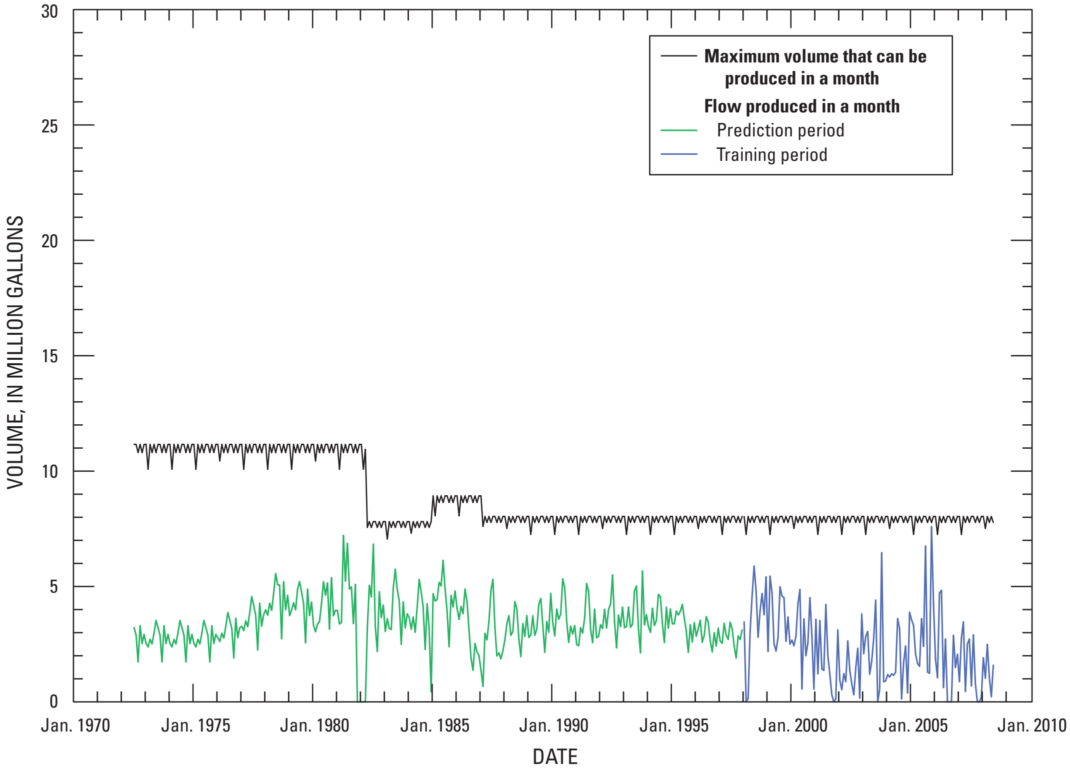

Figure S2.40. Estimated monthly water volume produced at well HP-647.

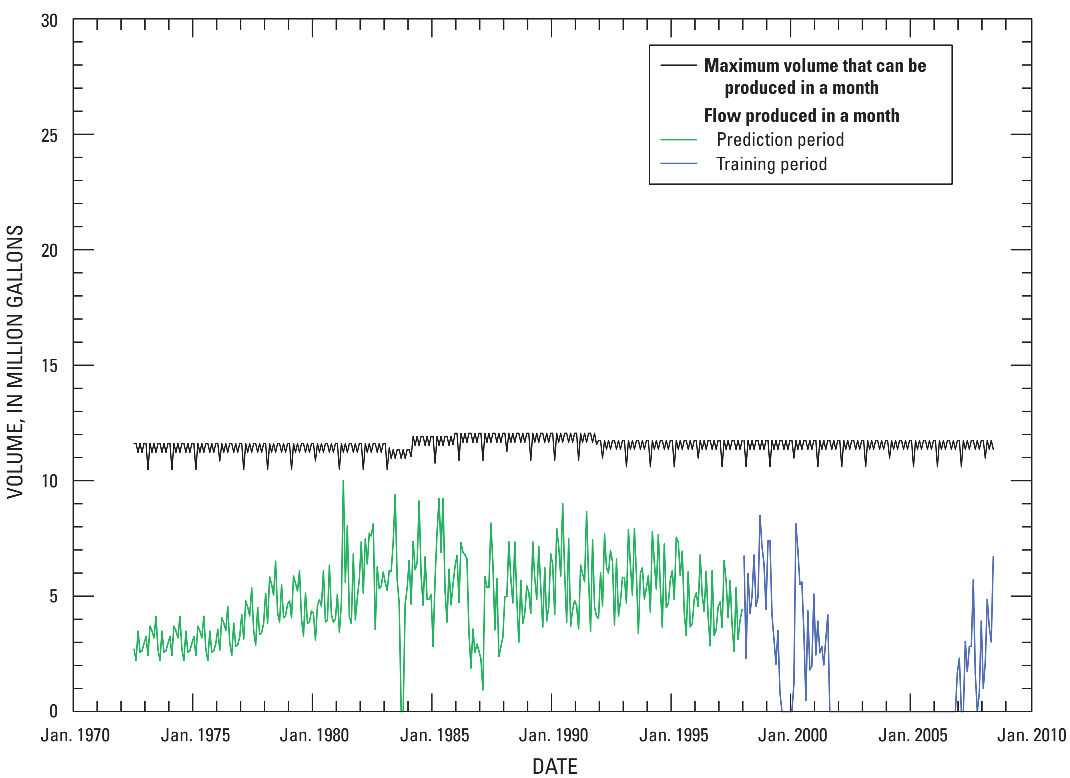

Figure S2.41. Estimated monthly water volume produced at well HP-648.

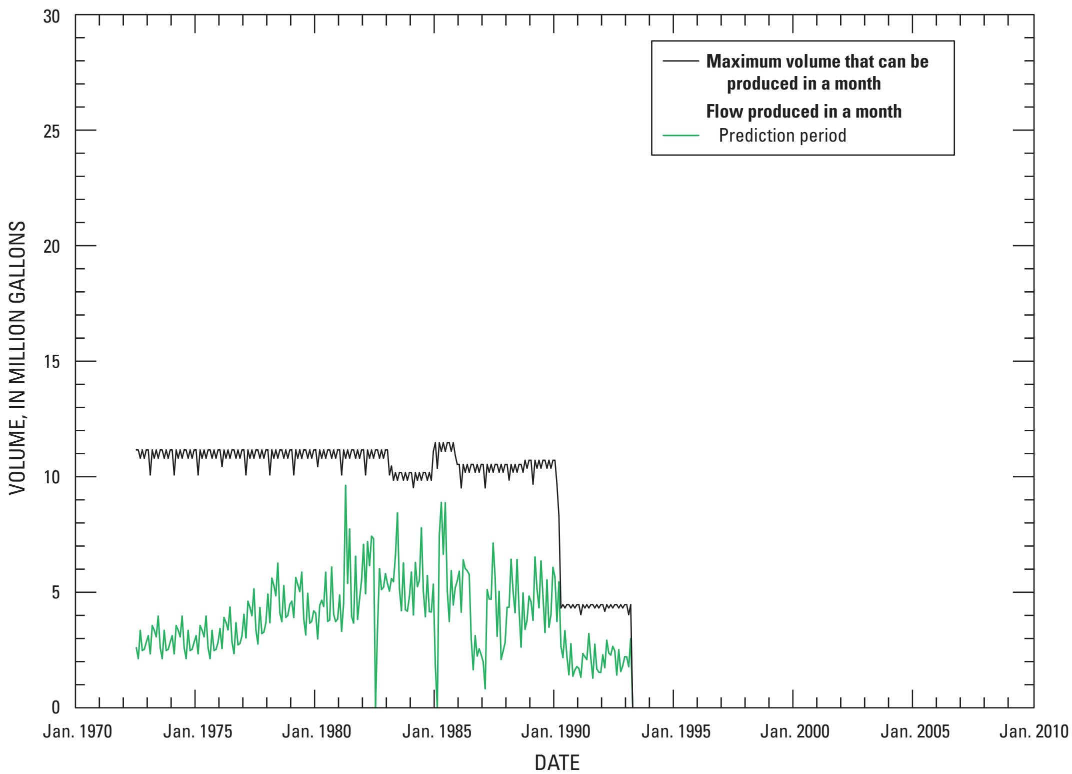

Figure S2.42. Estimated monthly water volume produced at well HP-649.

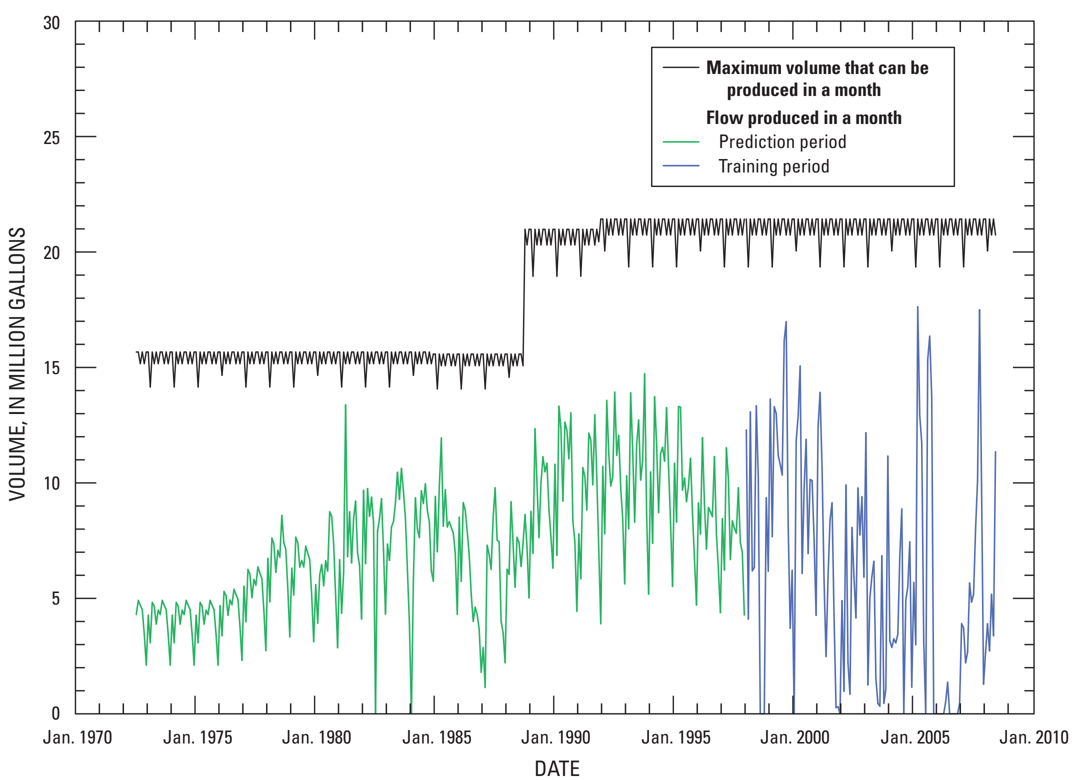

Figure S2.43. Estimated monthly water volume produced at well HP-650.

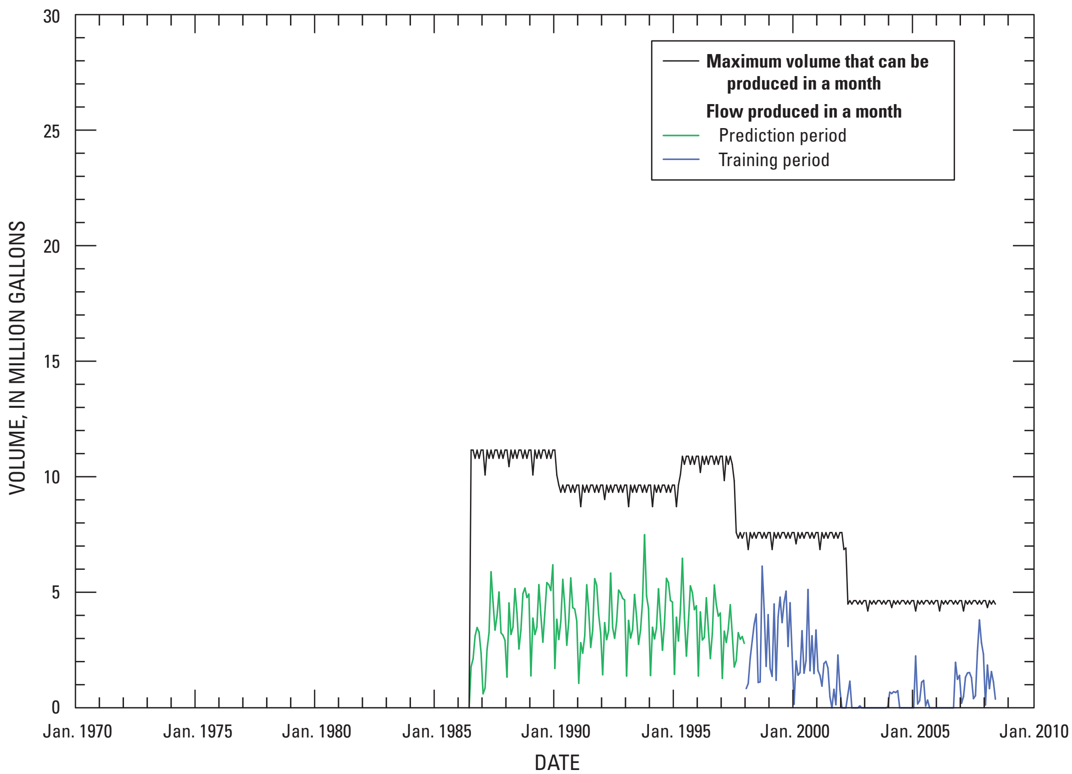

Figure S2.44. Estimated monthly water volume produced at well HP-698.

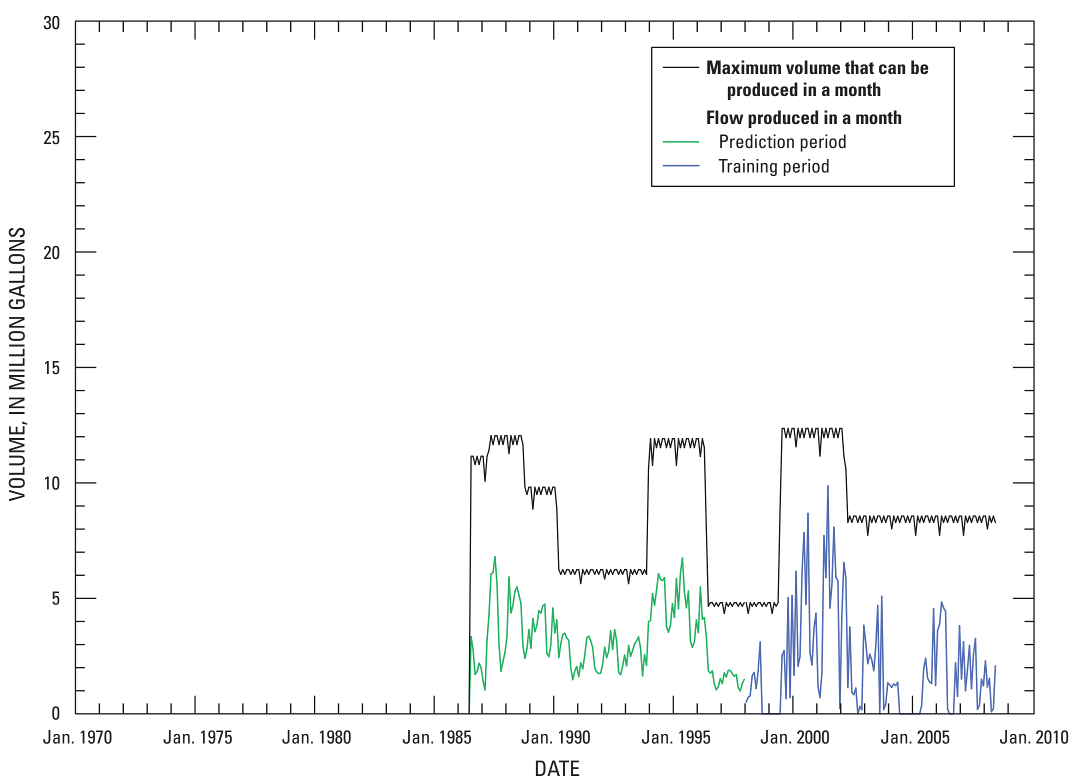

Figure S2.45. Estimated monthly water volume produced at well HP-699.

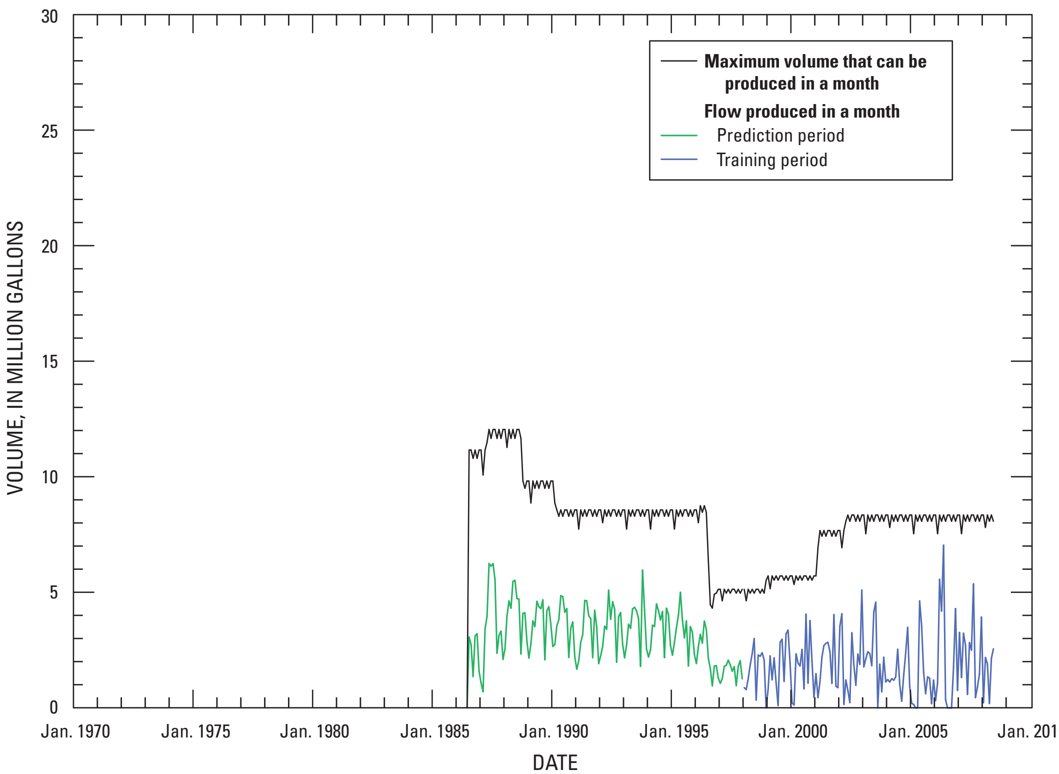

Figure S2.46. Estimated monthly water volume produced at well HP-700.

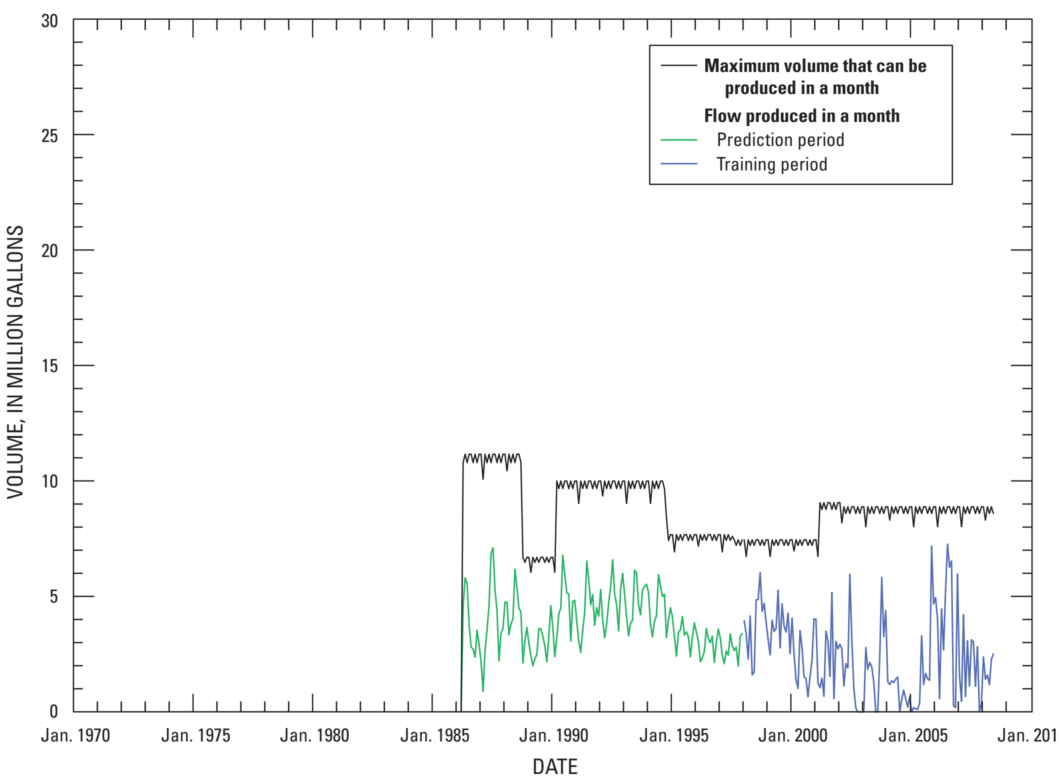

Figure S2.47. Estimated monthly water volume produced at well HP-701.

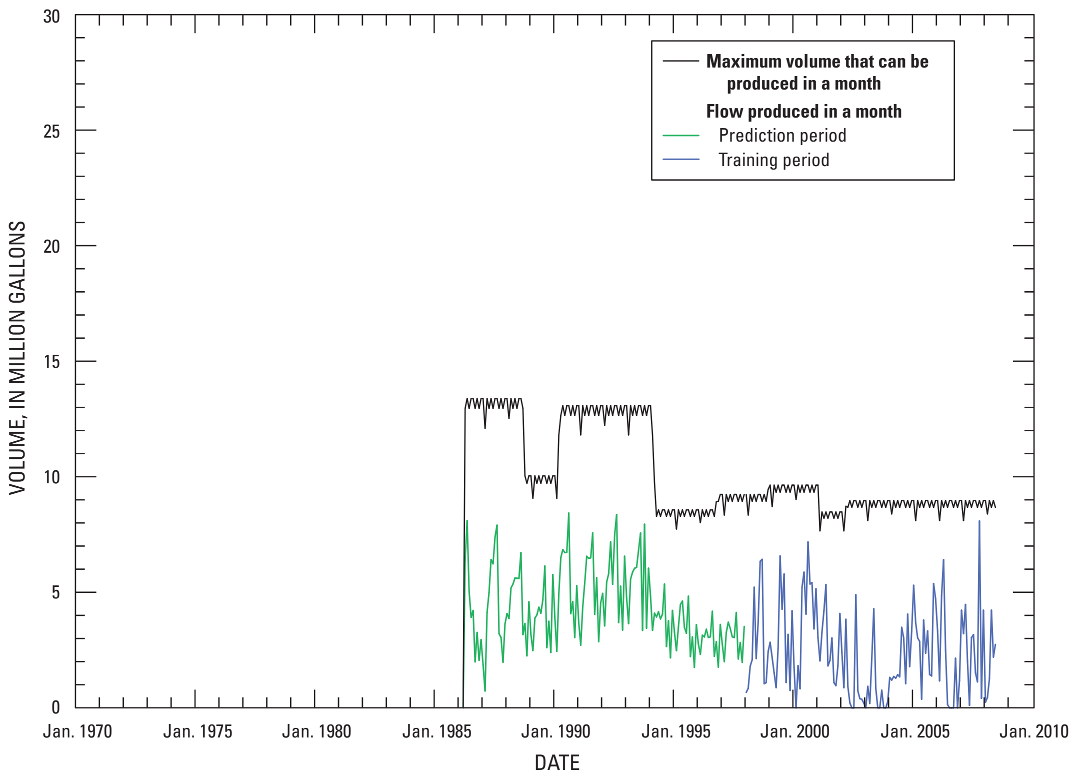

Figure S2.48. Estimated monthly water volume produced at well HP-703.

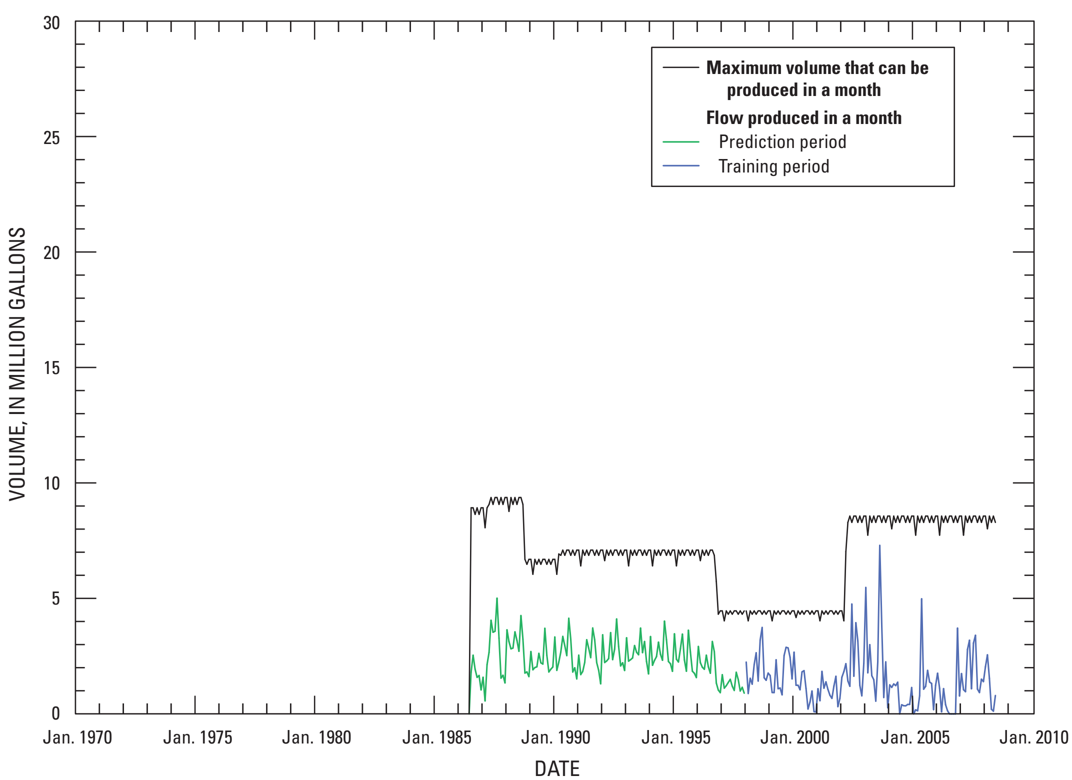

Figure S2.49. Estimated monthly water volume produced at well HP-704.

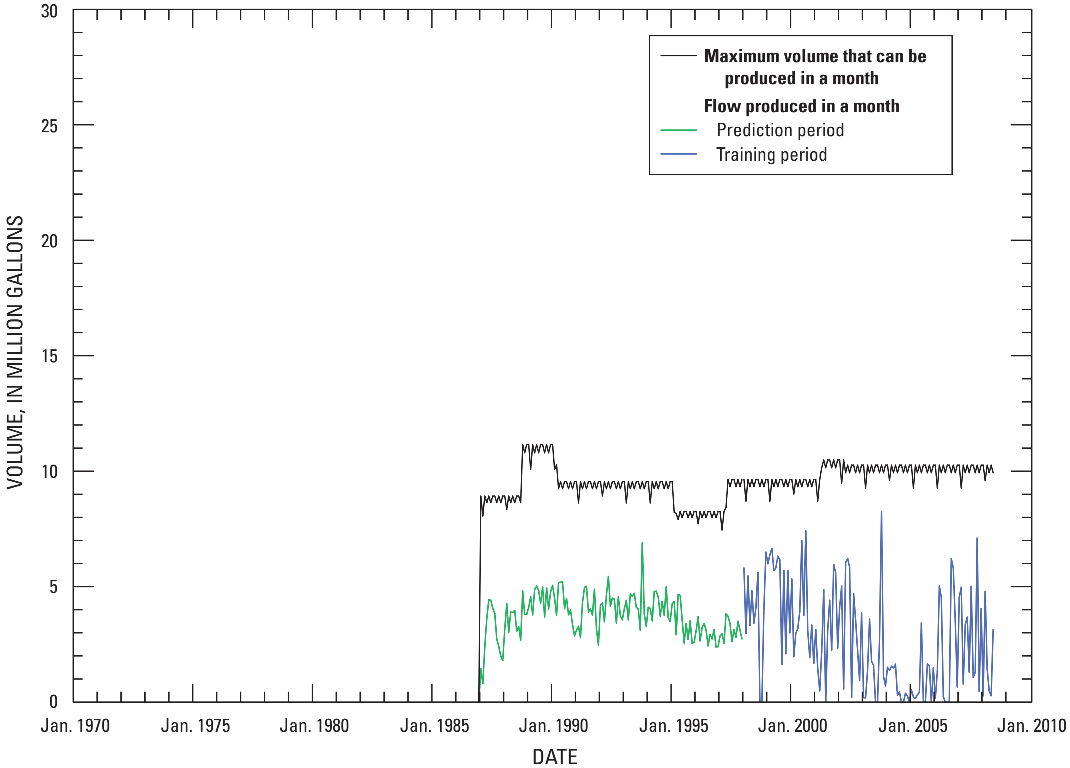

Figure S2.50. Estimated monthly water volume produced at well HP-705.

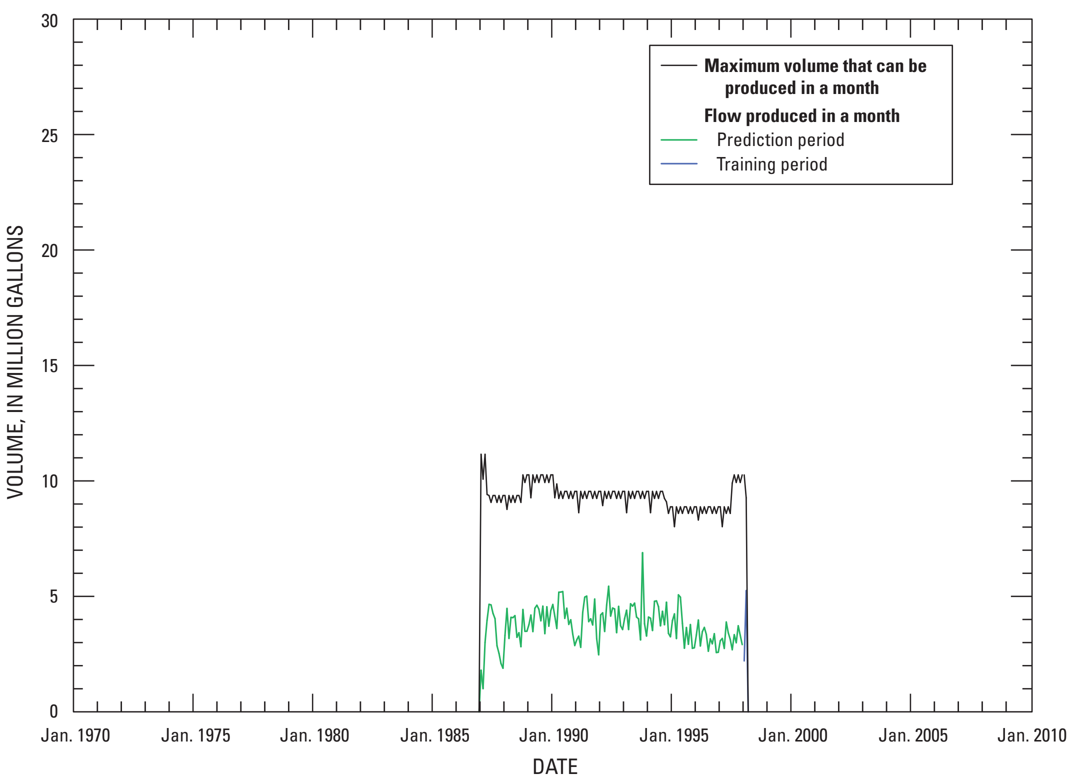

Figure S2.51. Estimated monthly water volume produced at well HP-706.

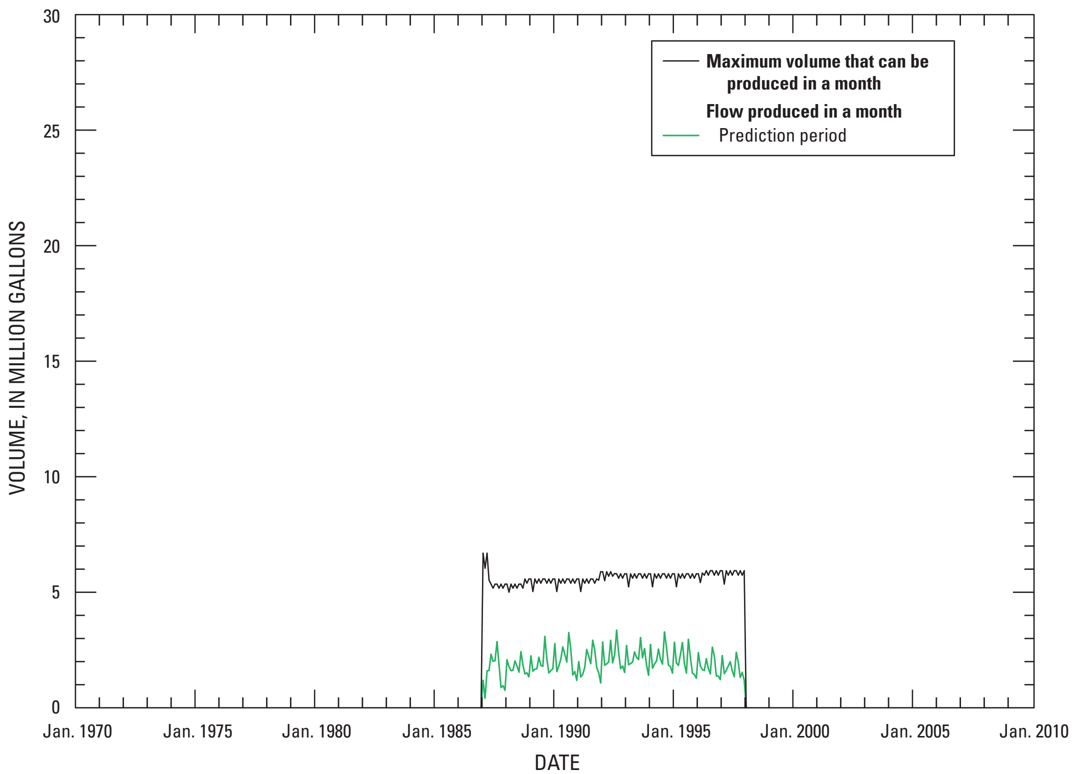

Figure S2.52. Estimated monthly water volume produced at well HP-707.

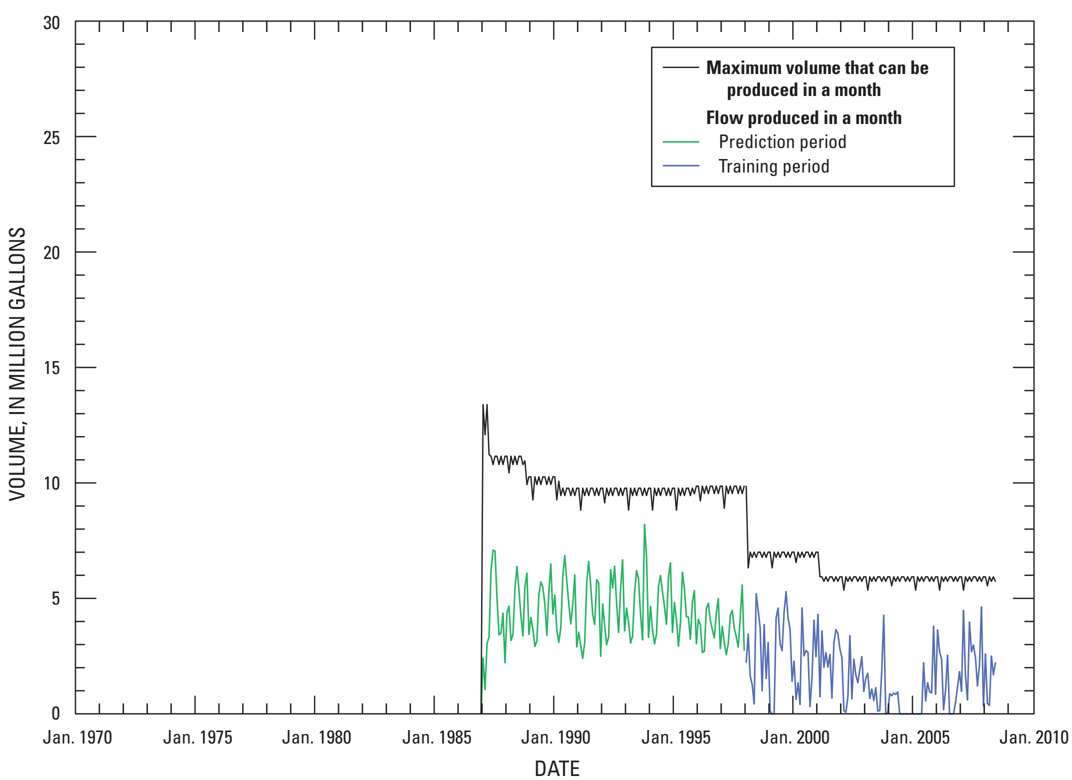

Figure S2.53. Estimated monthly water volume produced at well HP-708.

Figures S2.55–S2.126. Estimated Monthly Operating Days for Hadnot Point Wells

For operational chronology of all water-supply wells see Figure S2.2 in text.

Graphs showing estimated monthly operating days for—

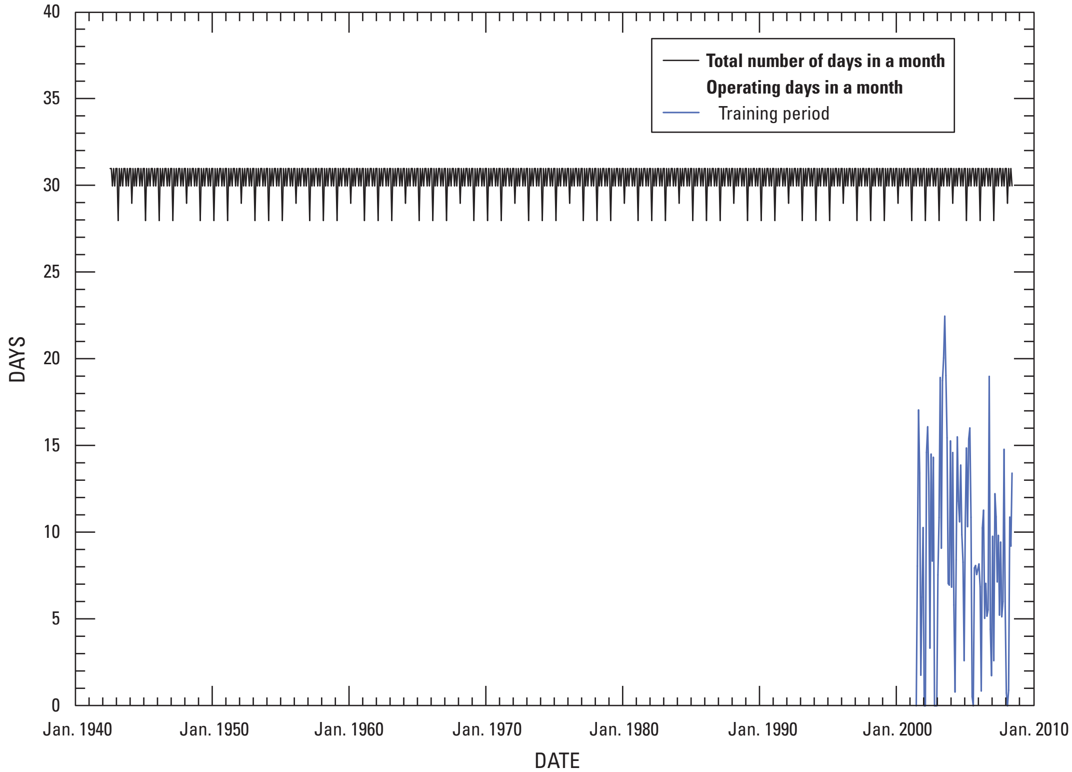

Figure S2.55. Estimated monthly operating days for well HP-585.

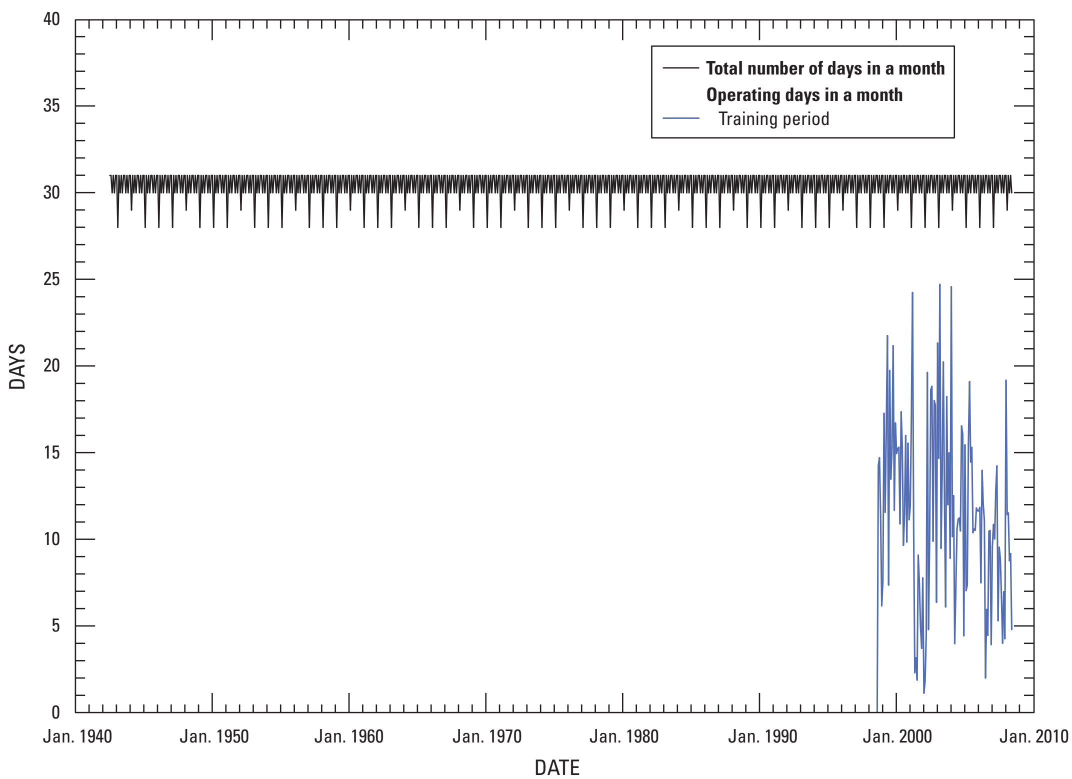

Figure S2.56. Estimated monthly operating days for well HP-595.

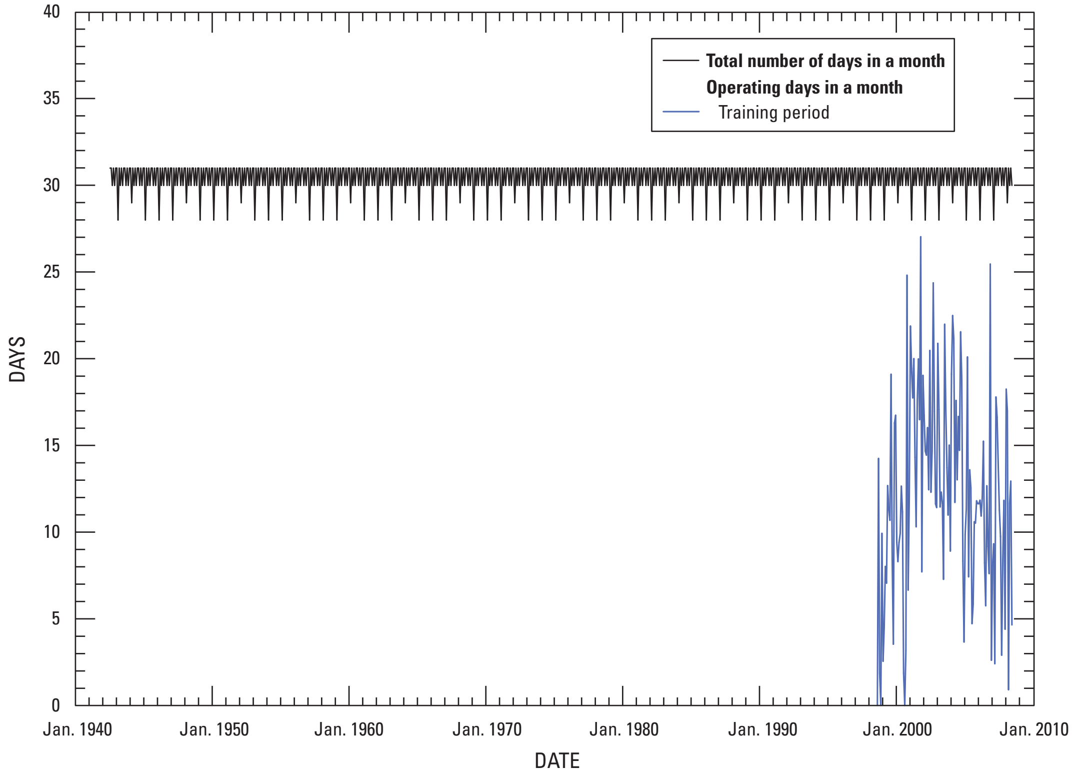

Figure S2.57. Estimated monthly operating days for well HP-596.

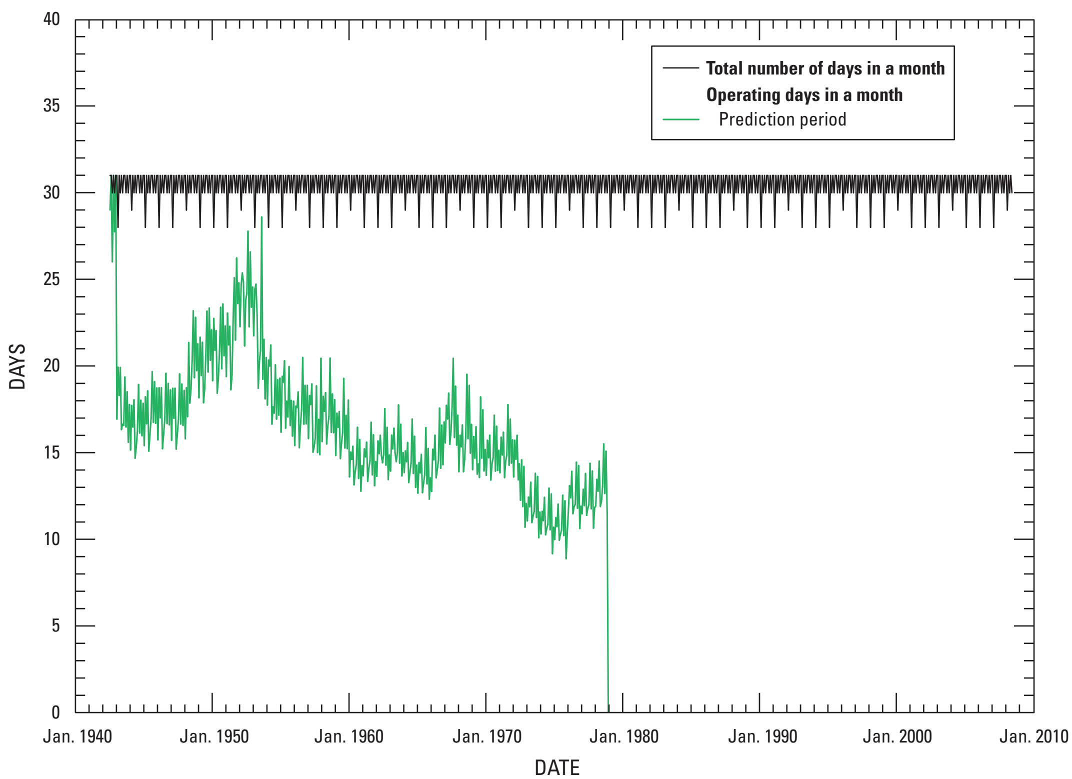

Figure S2.58. Estimated monthly operating days for well HP-601.

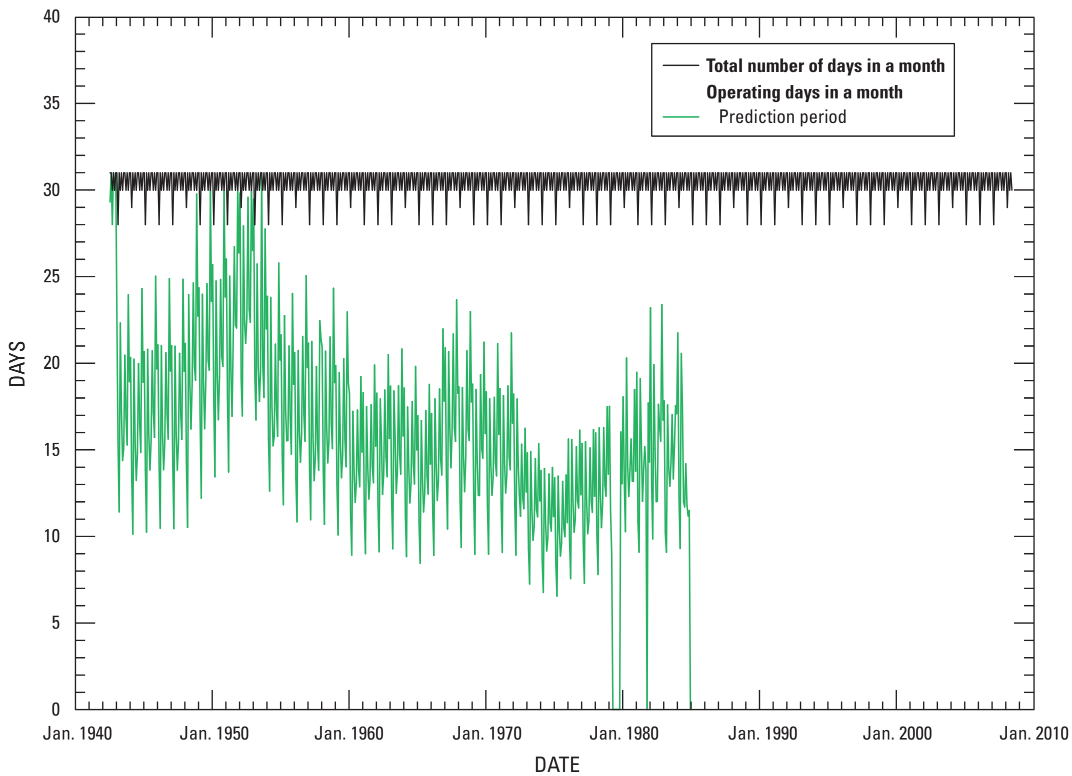

Figure S2.59. Estimated monthly operating days for well HP-602.

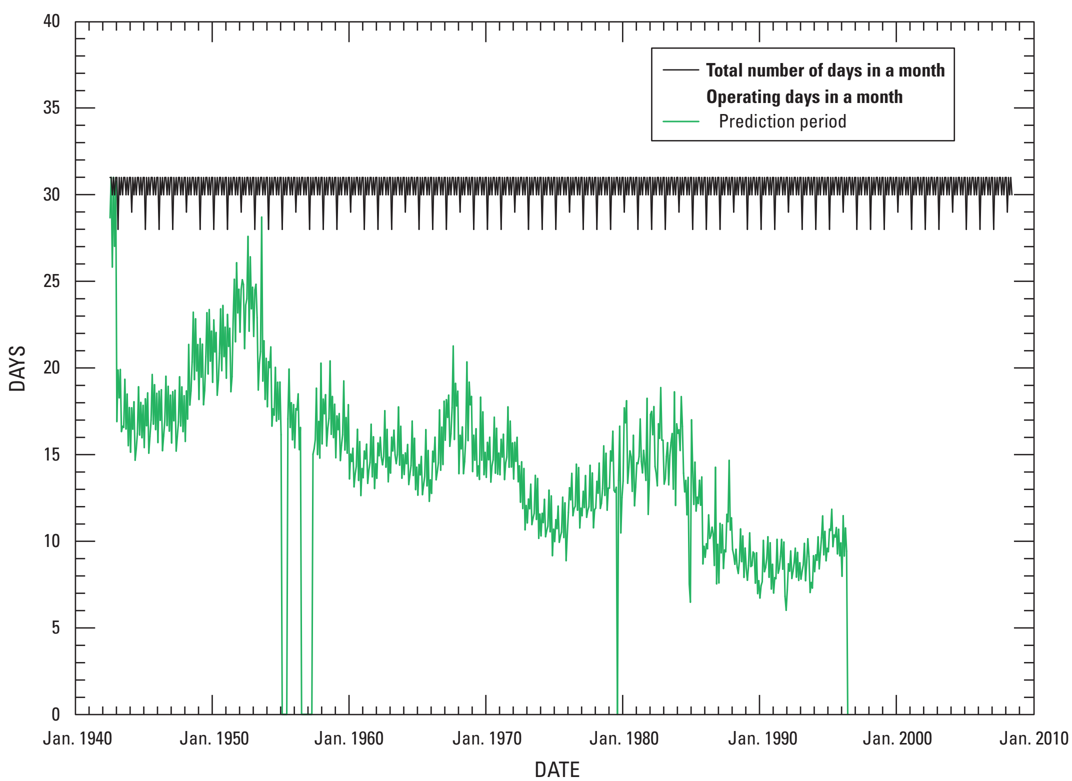

Figure S2.60. Estimated monthly operating days for well HP-603.

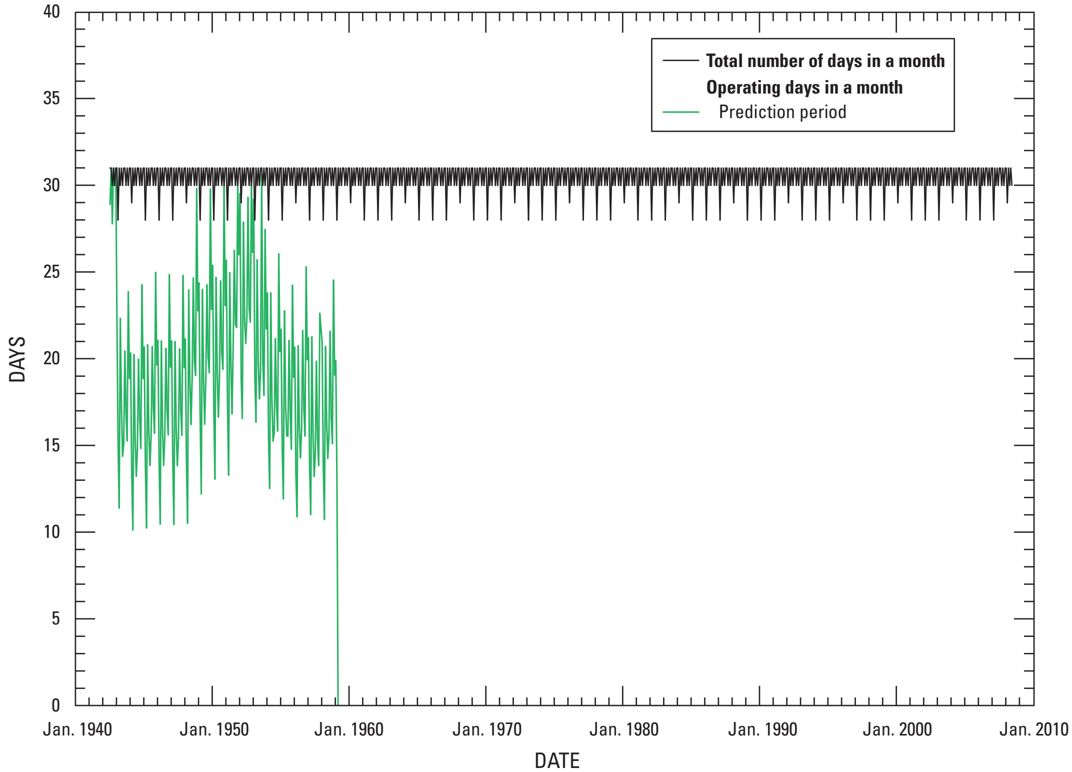

Figure S2.61. Estimated monthly operating days for well HP-604.

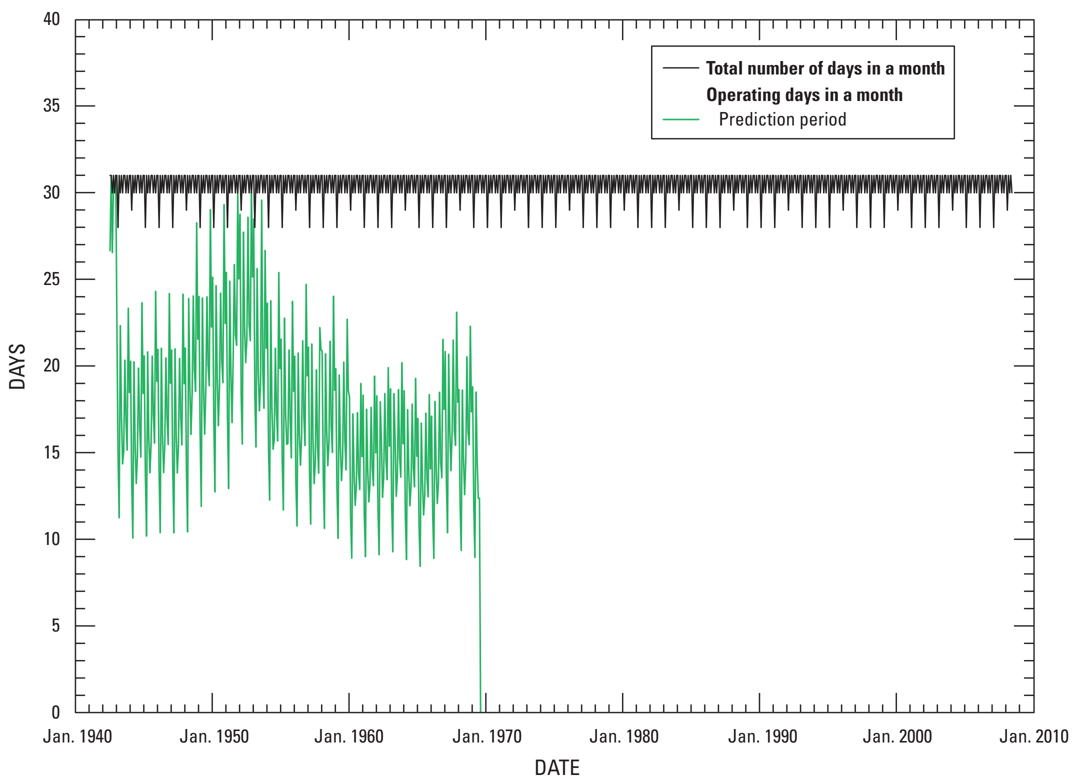

Figure S2.62. Estimated monthly operating days for well HP-605.

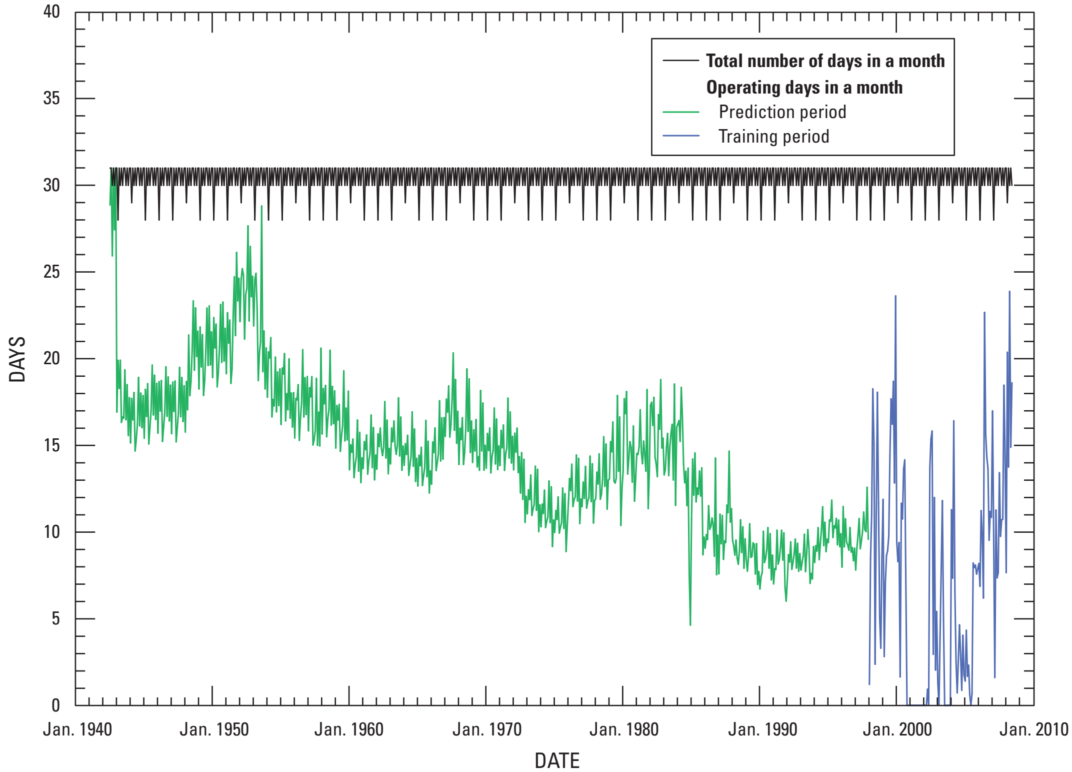

Figure S2.63. Estimated monthly operating days for well HP-606.

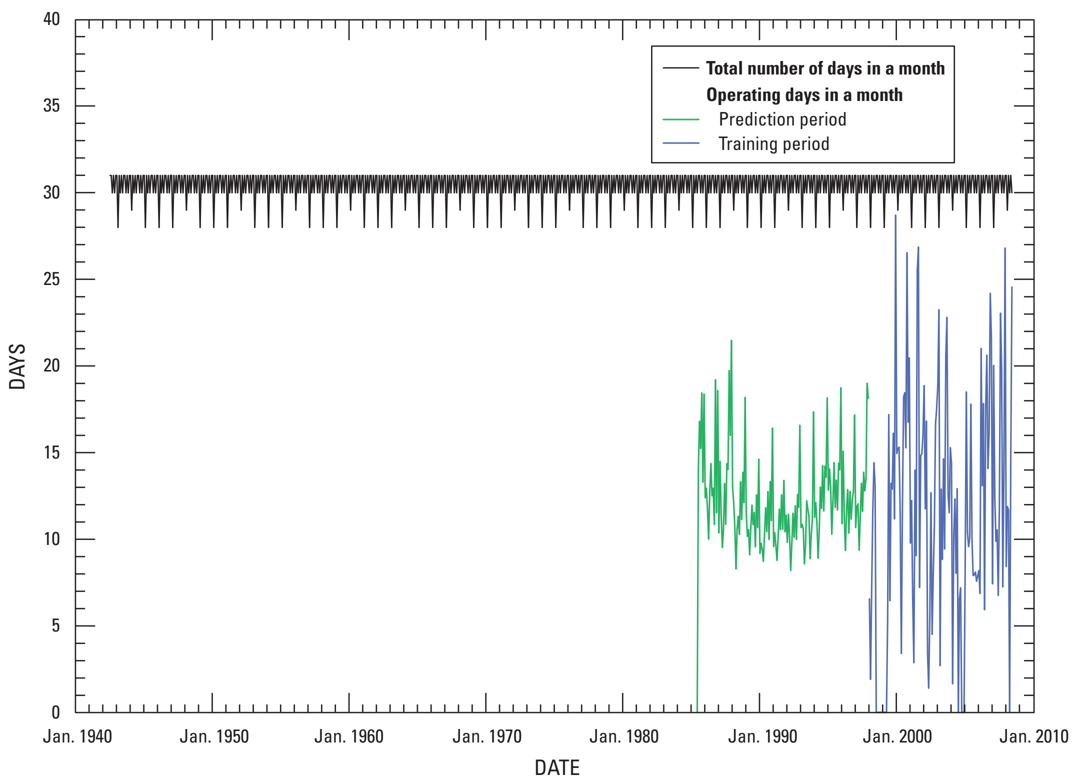

Figure S2.64. Estimated monthly operating days for well HP-607 (new).

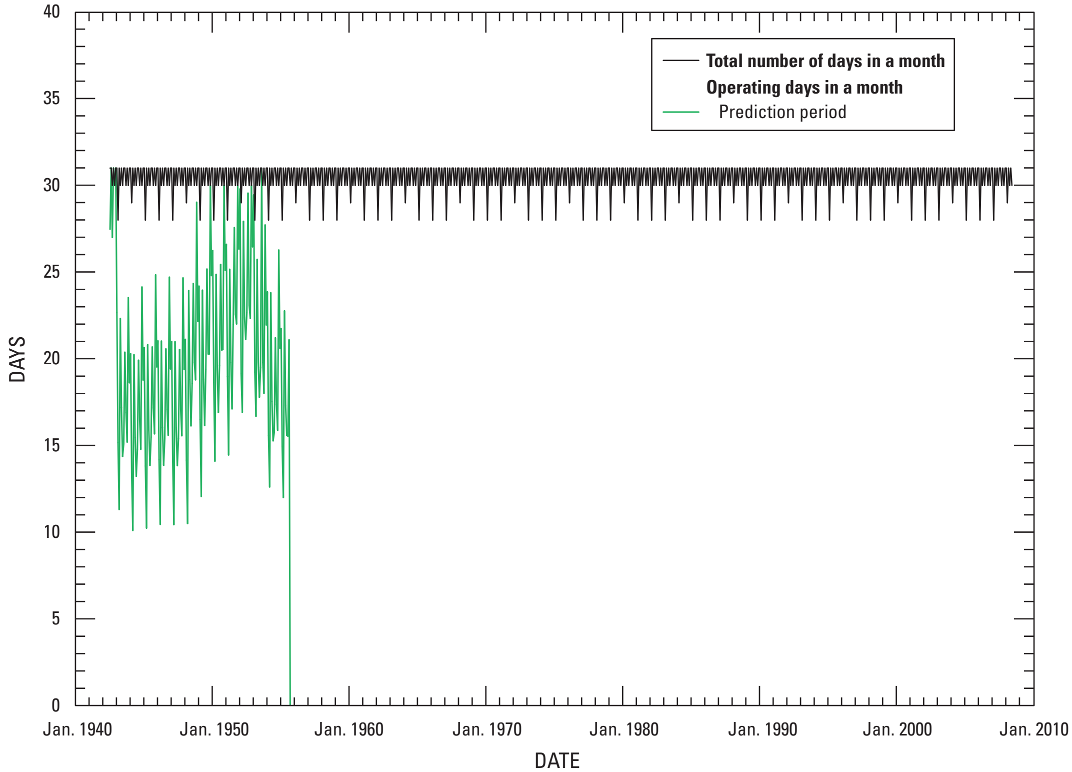

Figure S2.65. Estimated monthly operating days for well HP-607 (old).

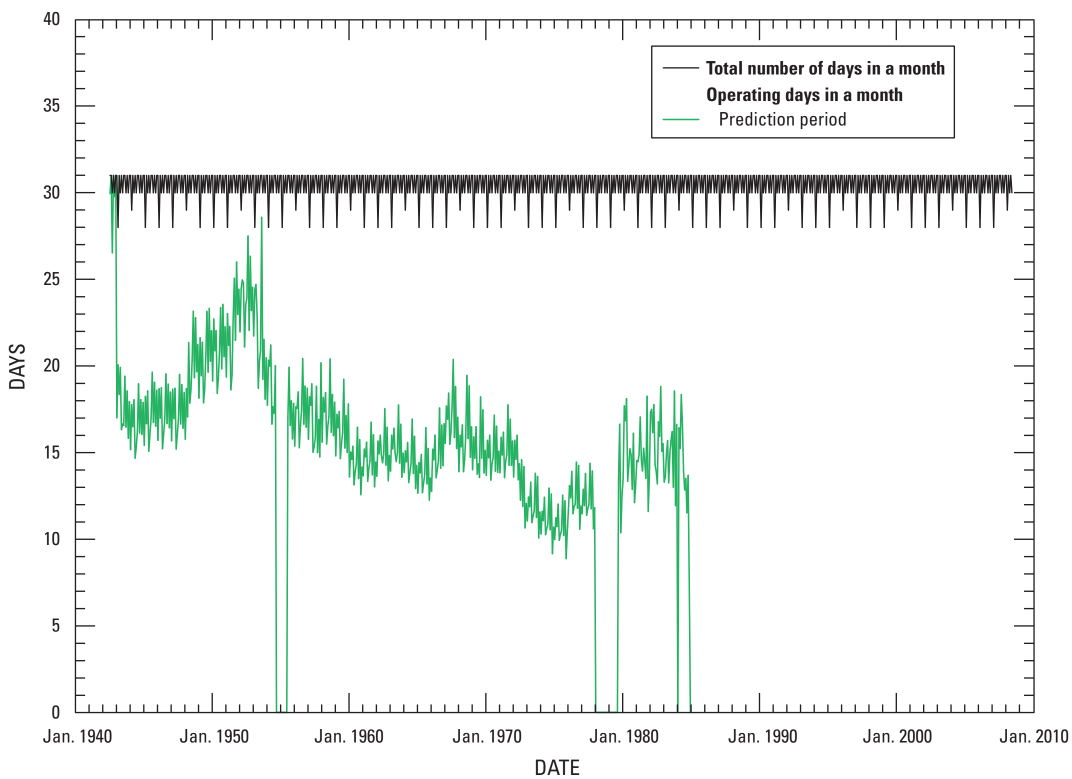

Figure S2.66. Estimated monthly operating days for well HP-608.

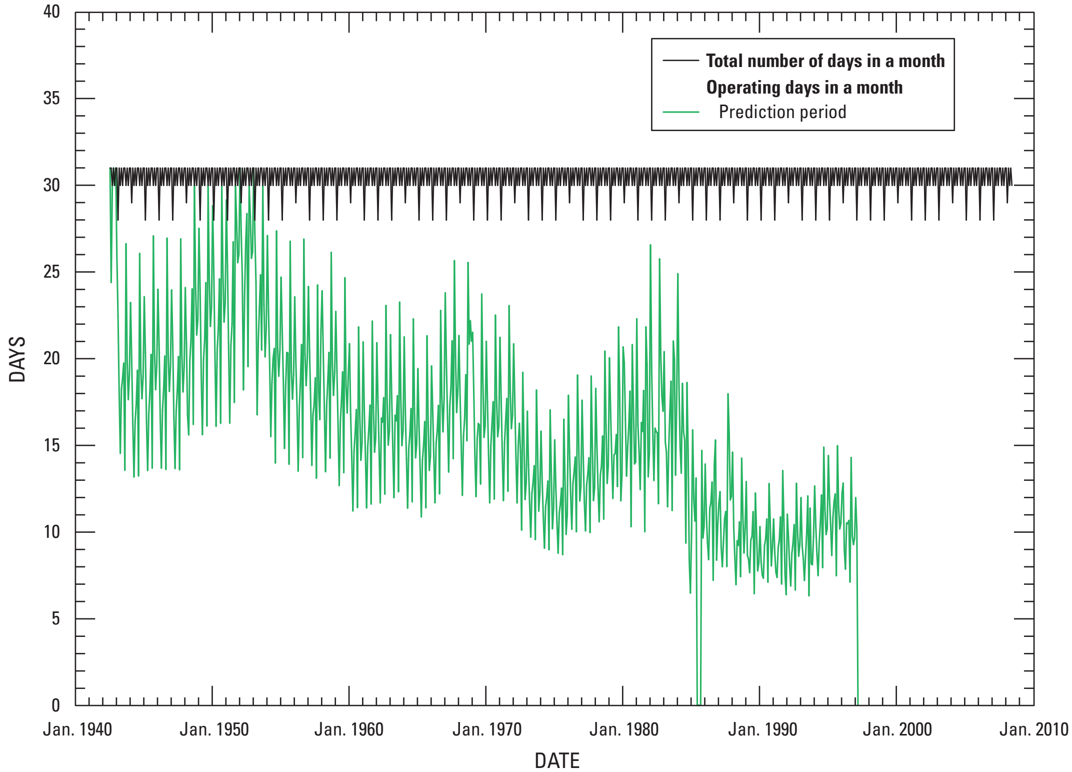

Figure S2.67. Estimated monthly operating days for well HP-609.

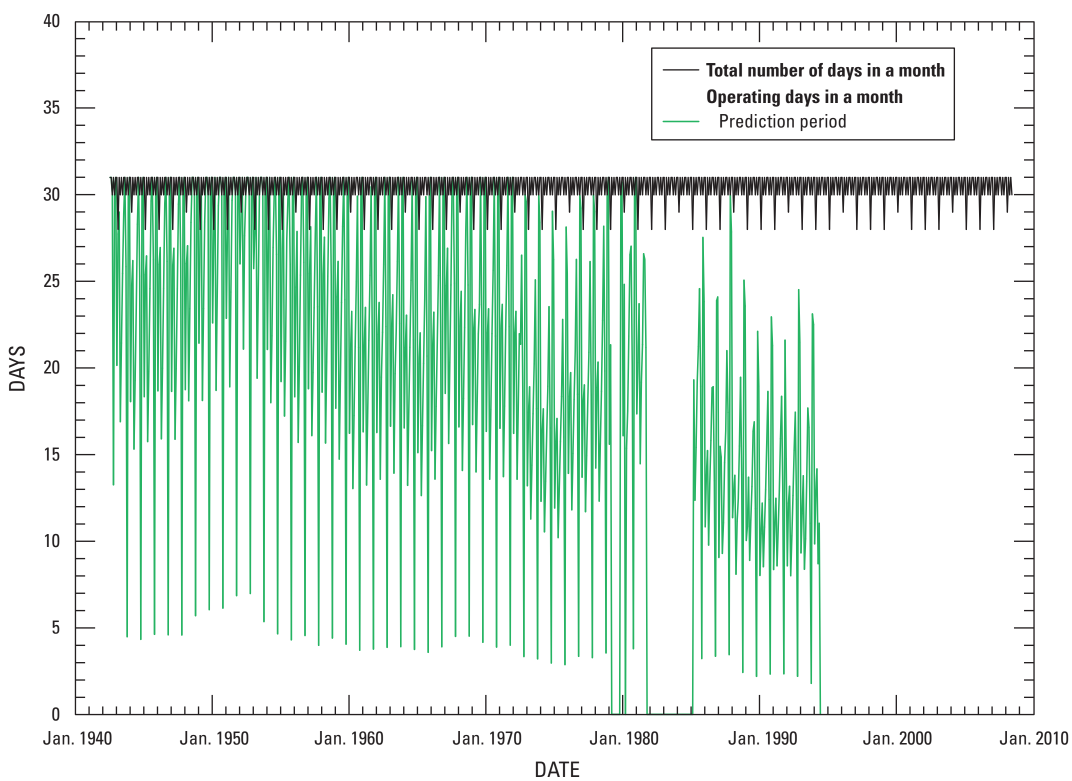

Figure S2.68. Estimated monthly operating days for well HP-610.

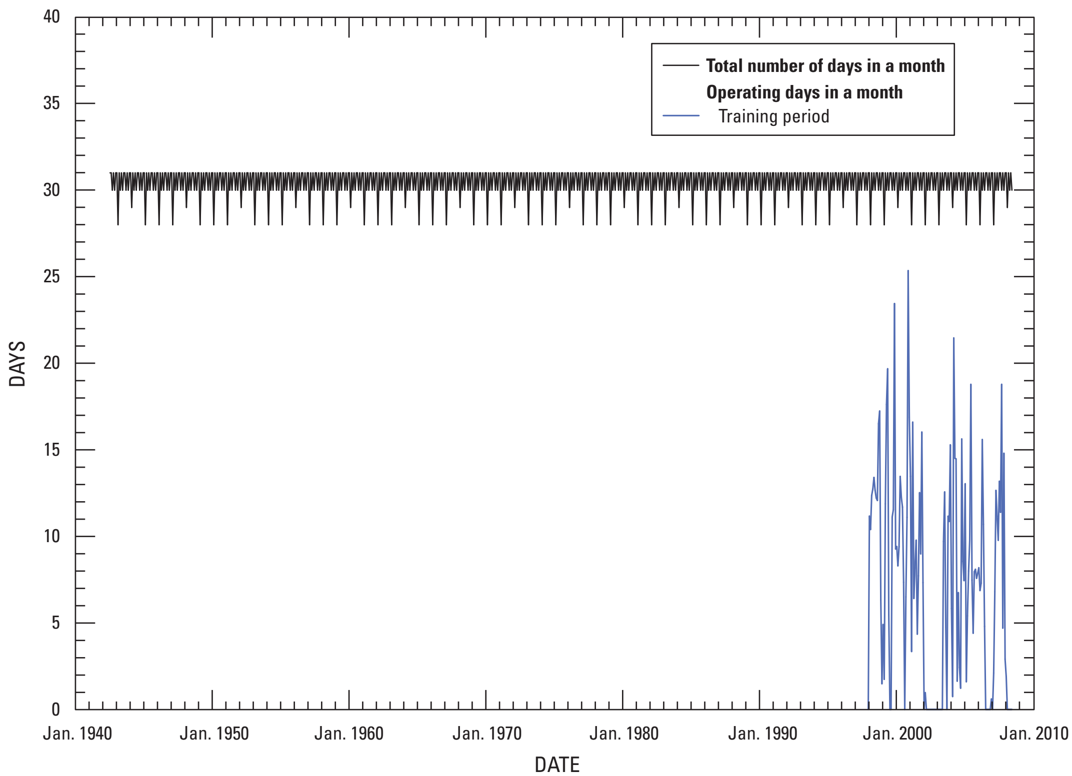

Figure S2.69. Estimated monthly operating days for well HP-611 (new).

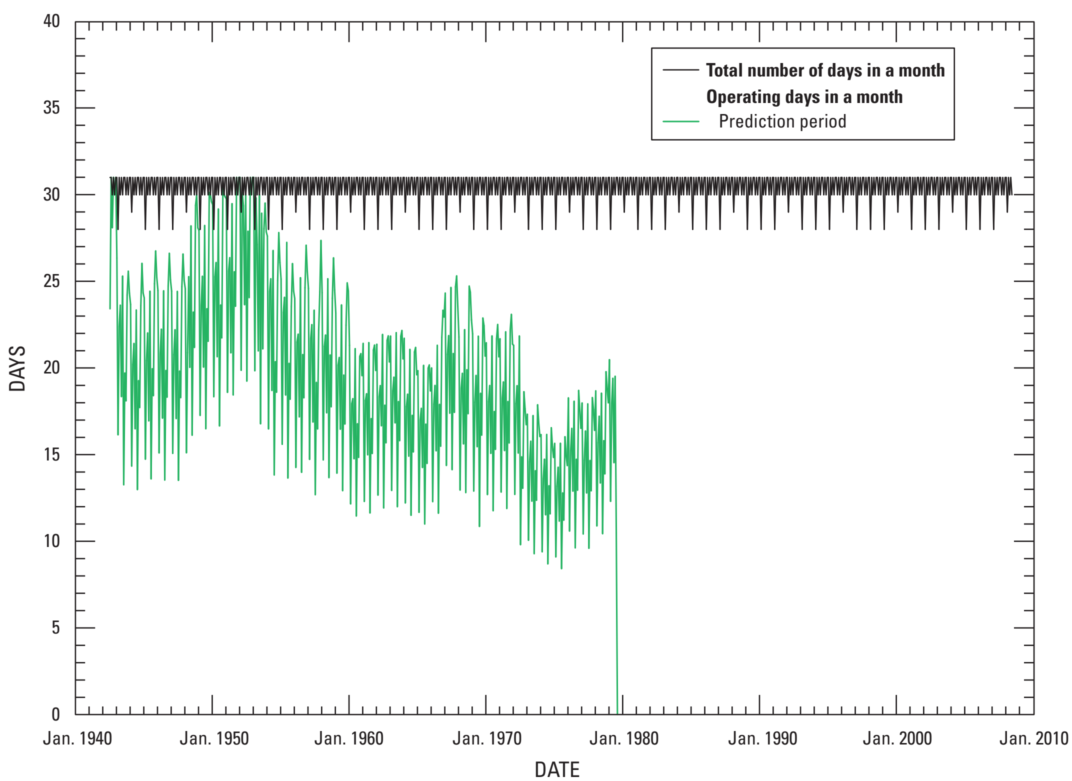

Figure S2.70. Estimated monthly operating days for well HP-611 (old).

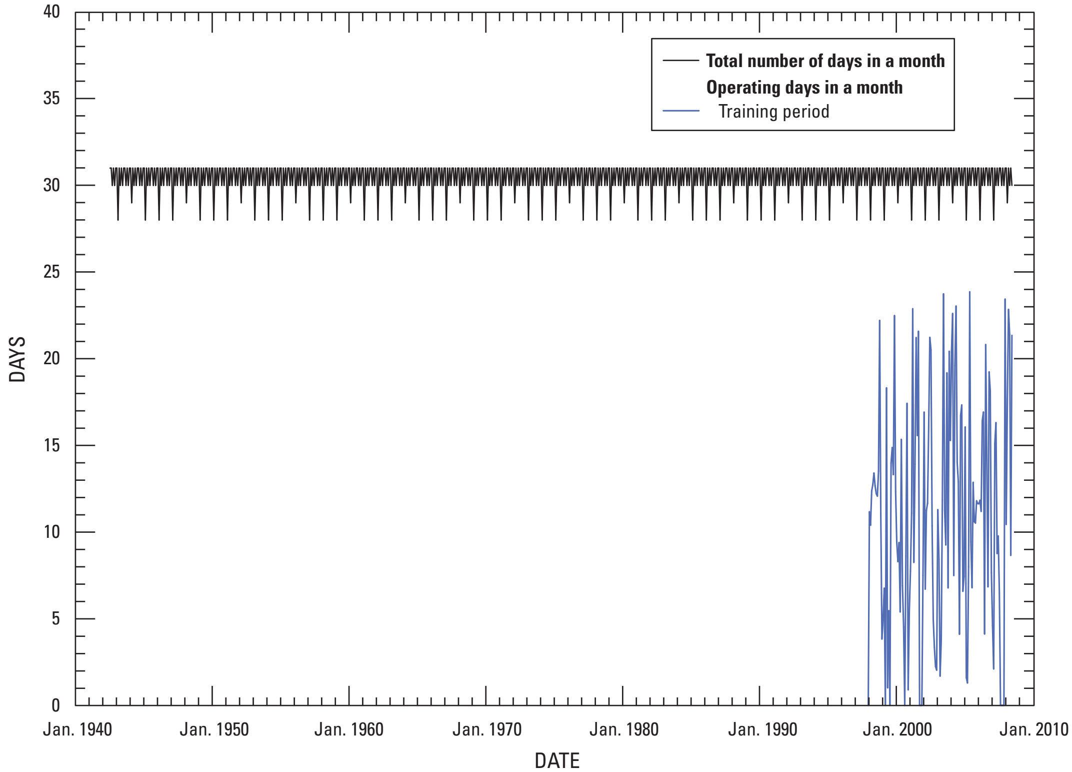

Figure S2.71. Estimated monthly operating days for well HP-612 (new).

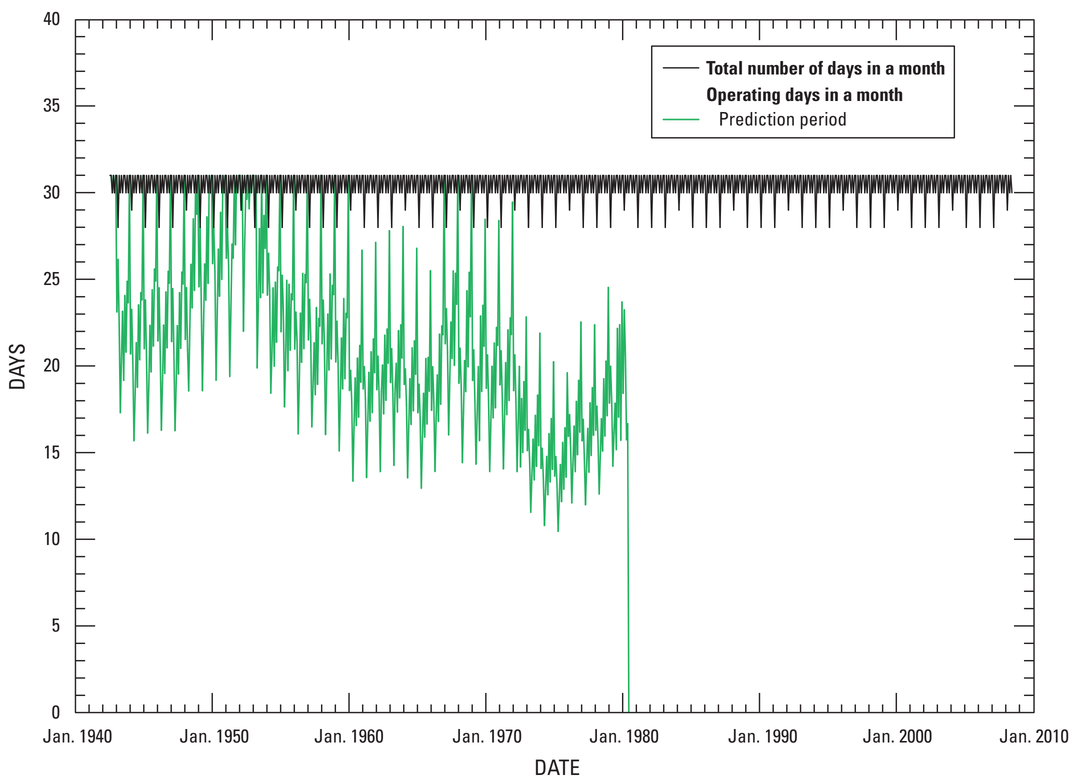

Figure S2.72. Estimated monthly operating days for well HP-612 (old).

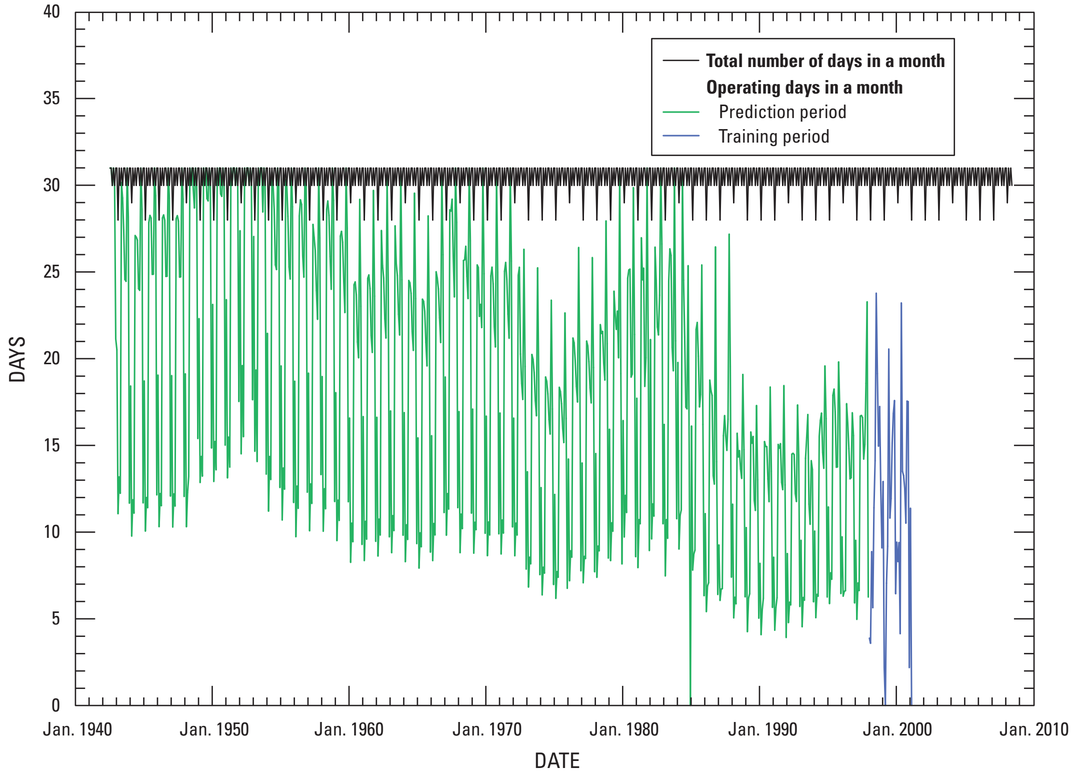

Figure S2.73. Estimated monthly operating days for well HP-613.

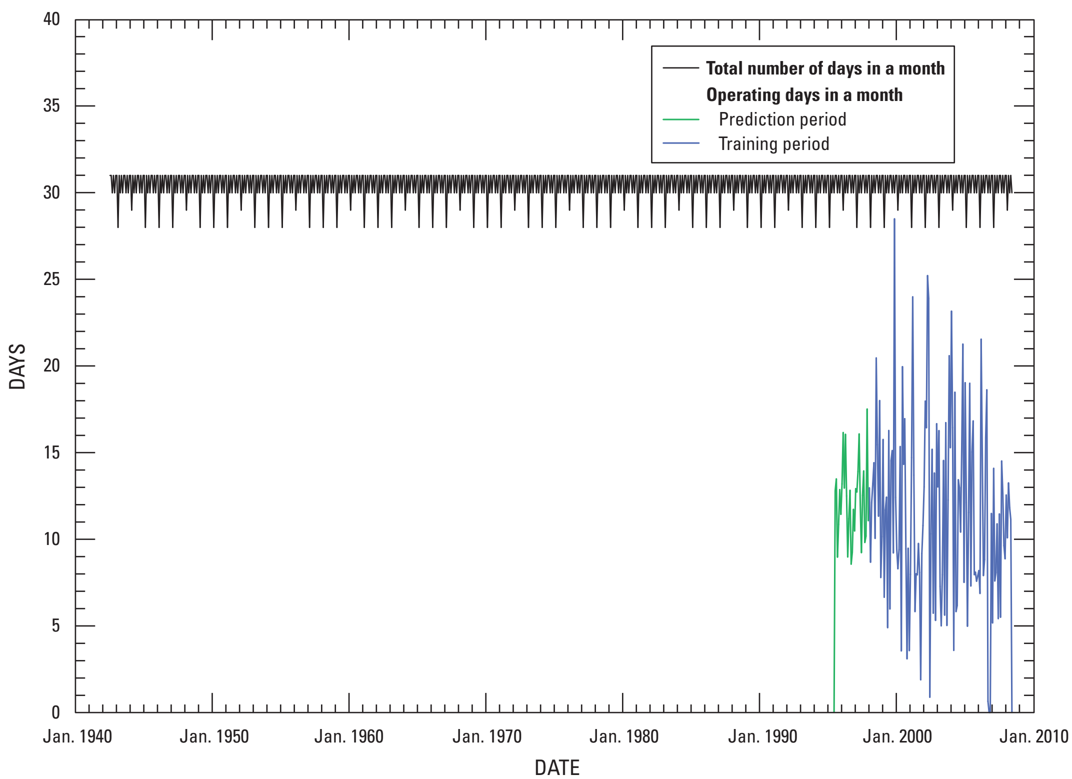

Figure S2.74. Estimated monthly operating days for well HP-614 (new).

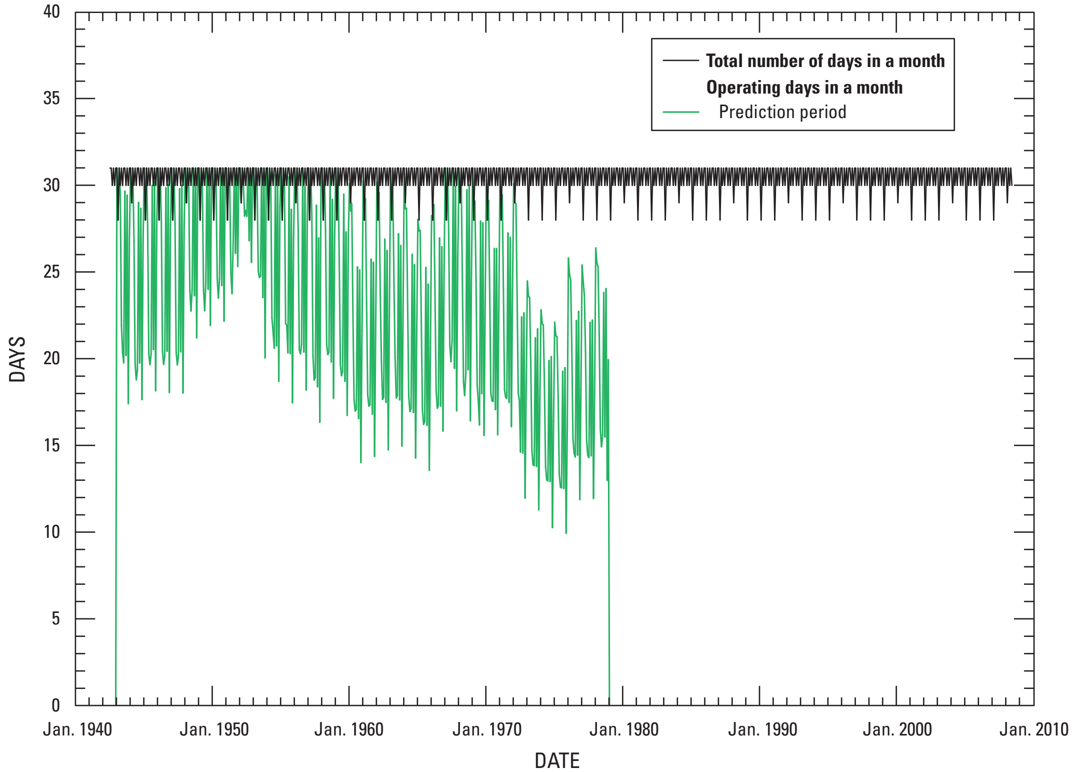

Figure S2.75. Estimated monthly operating days for well HP-614 (old).

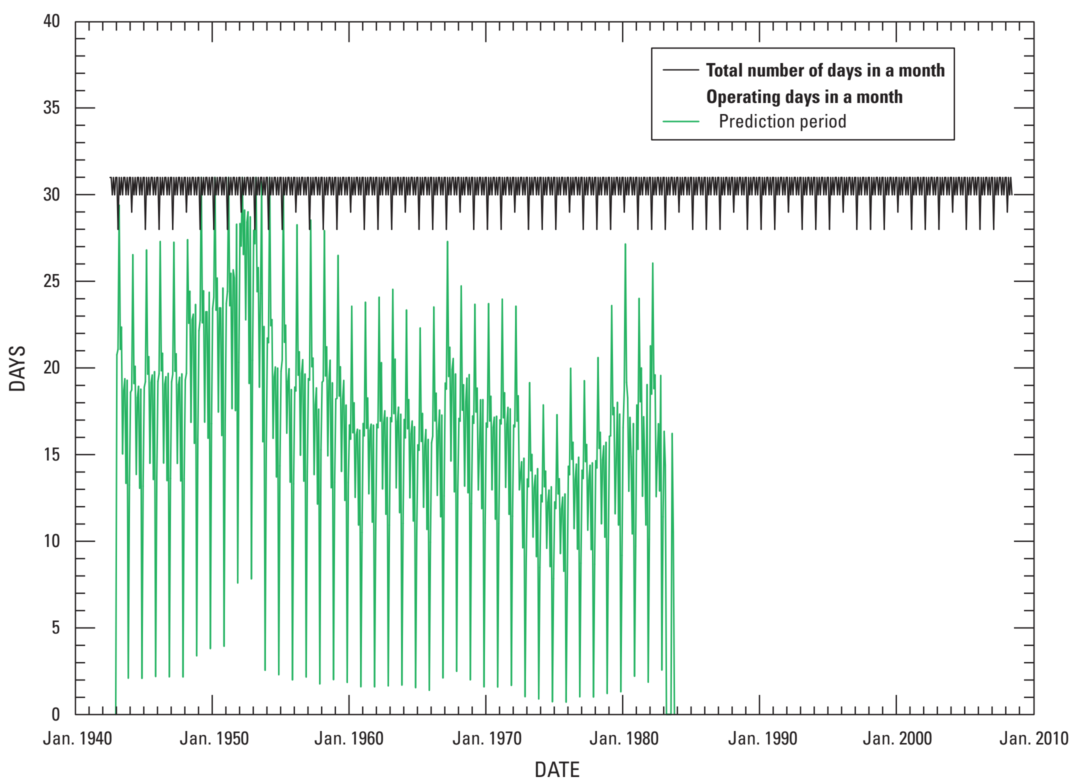

Figure S2.76. Estimated monthly operating days for well HP-615.

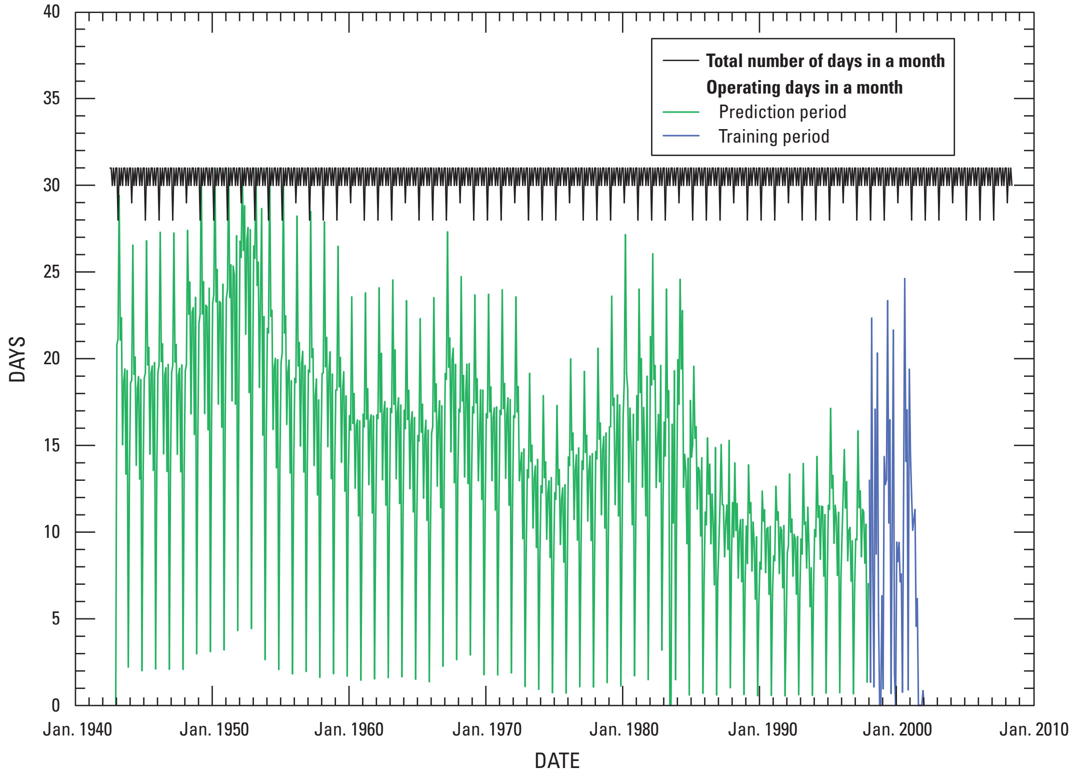

Figure S2.77. Estimated monthly operating days for well HP-616.

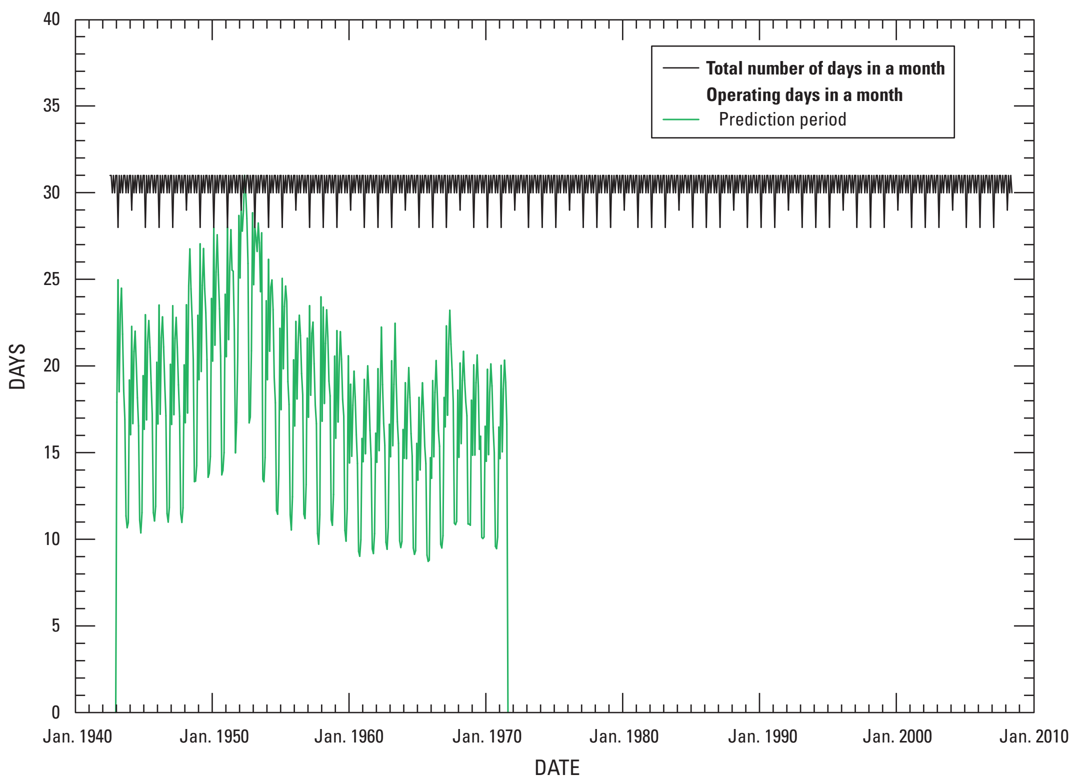

Figure S2.78. Estimated monthly operating days for well HP-617 (old).

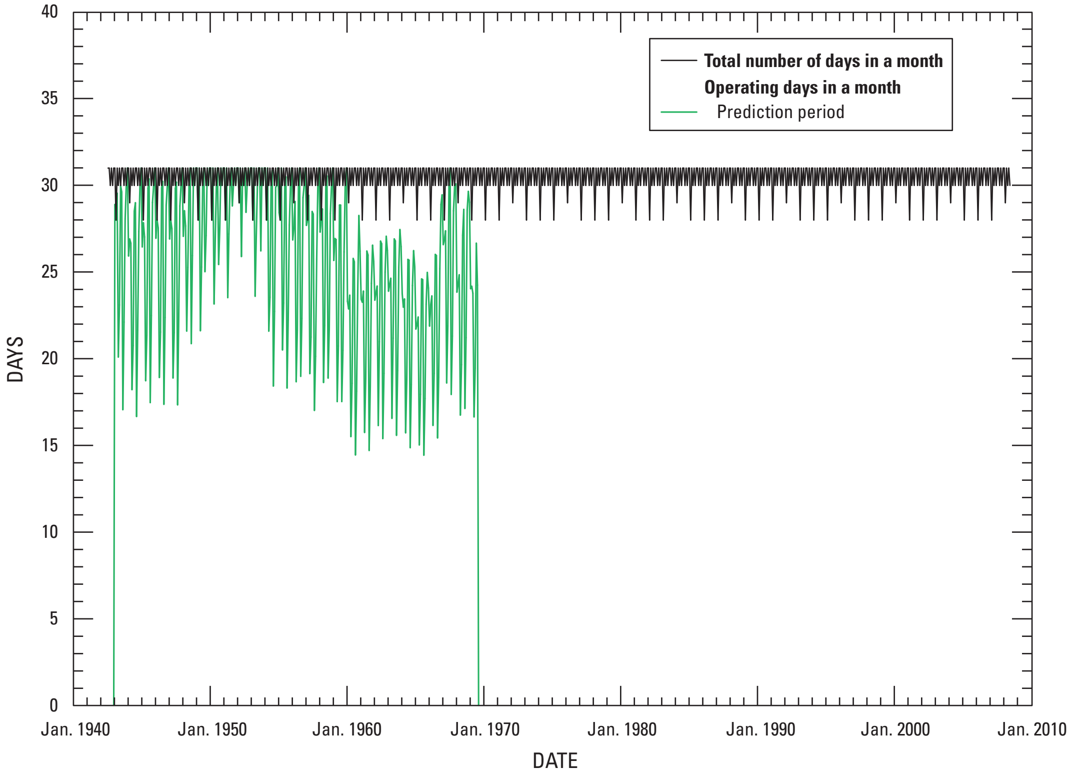

Figure S2.79. Estimated monthly operating days for well HP-618 (old).

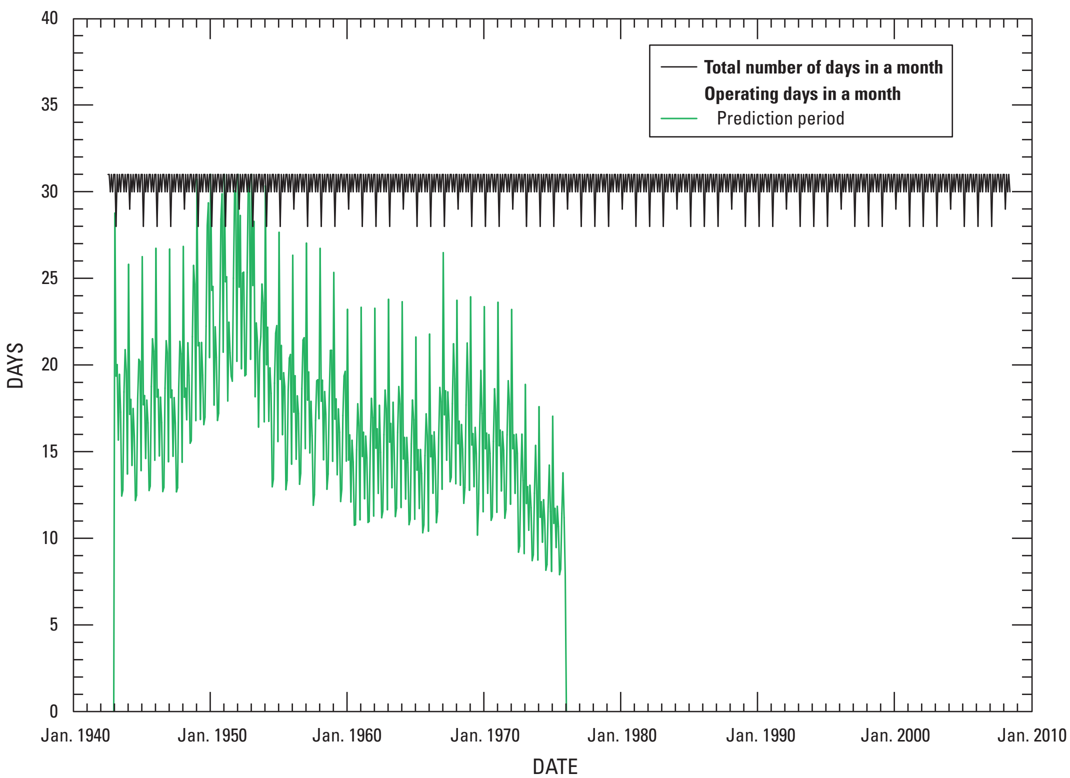

Figure S2.80. Estimated monthly operating days for well HP-619 (old).

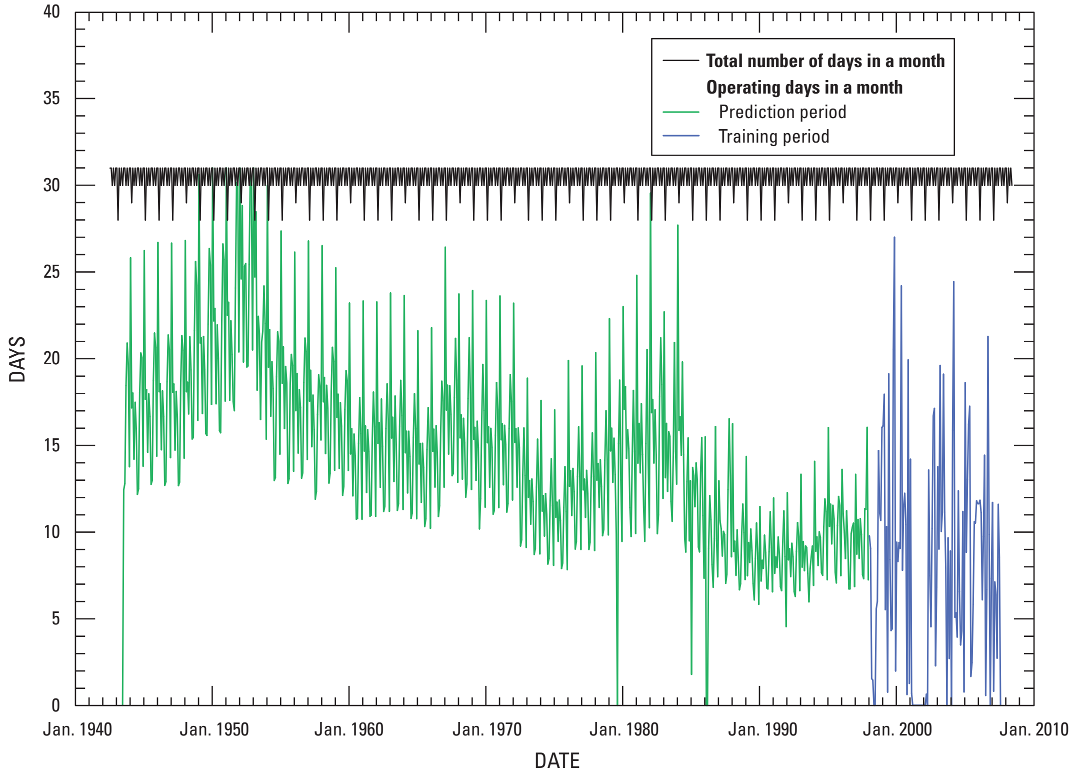

Figure S2.81. Estimated monthly operating days for well HP-620.

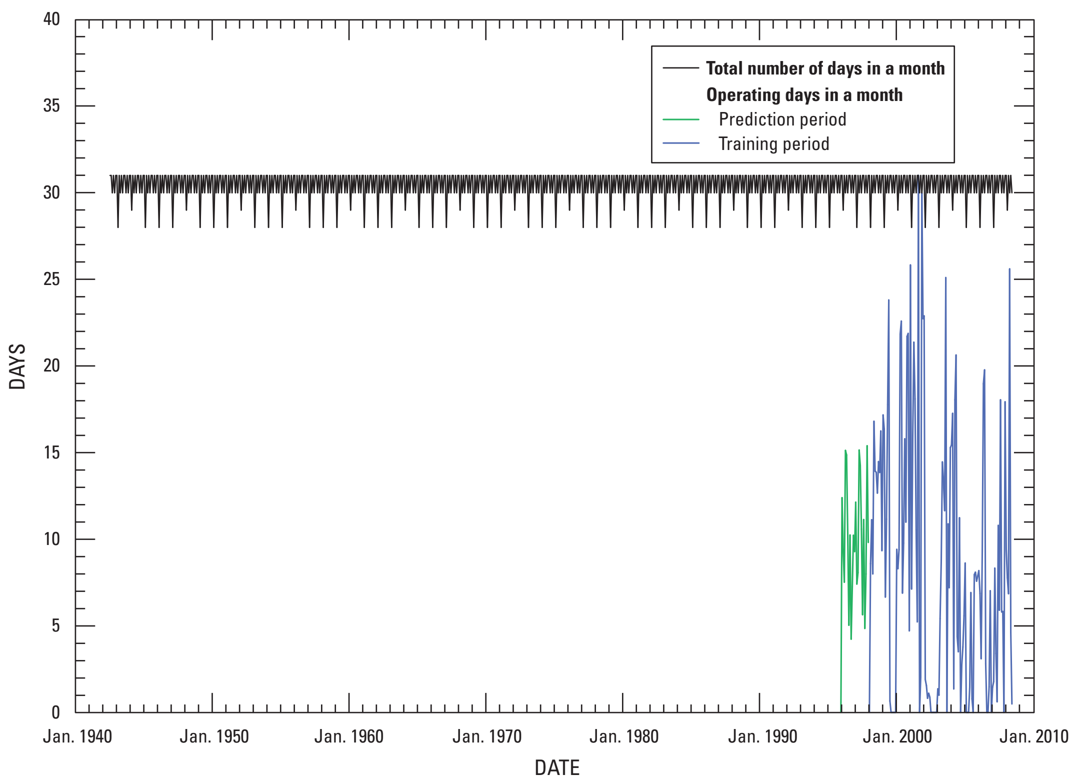

Figure S2.82. Estimated monthly operating days for well HP-621 (new).

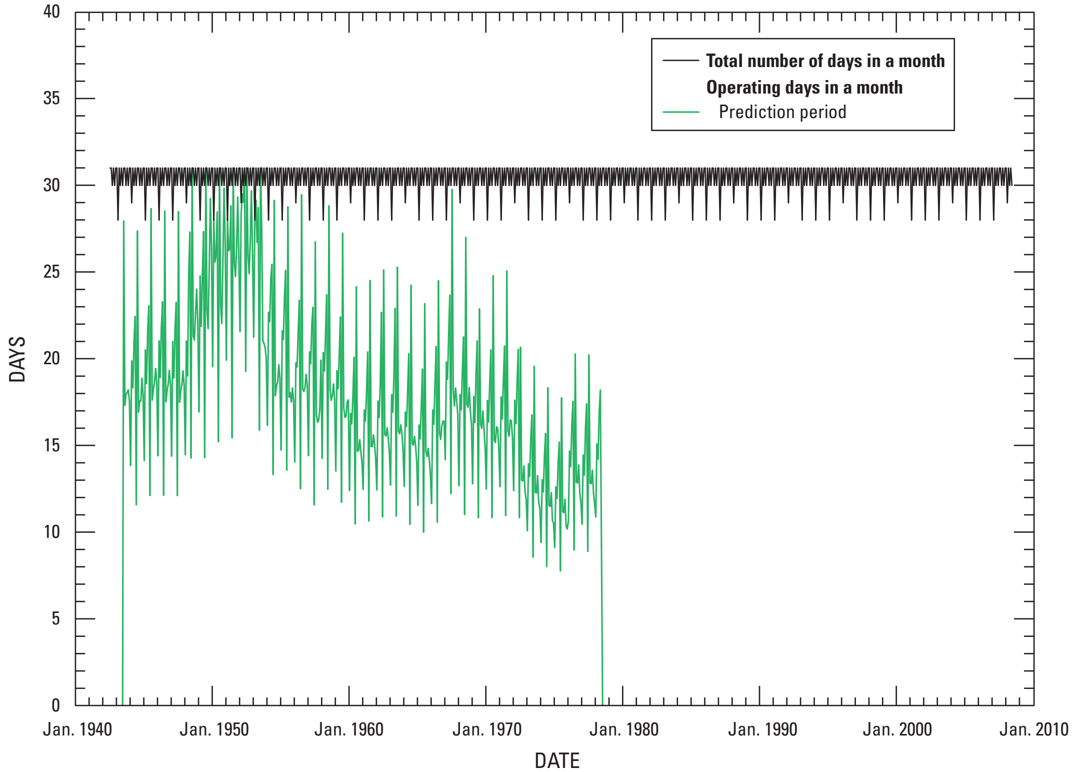

Figure S2.83. Estimated monthly operating days for well HP-621 (old).

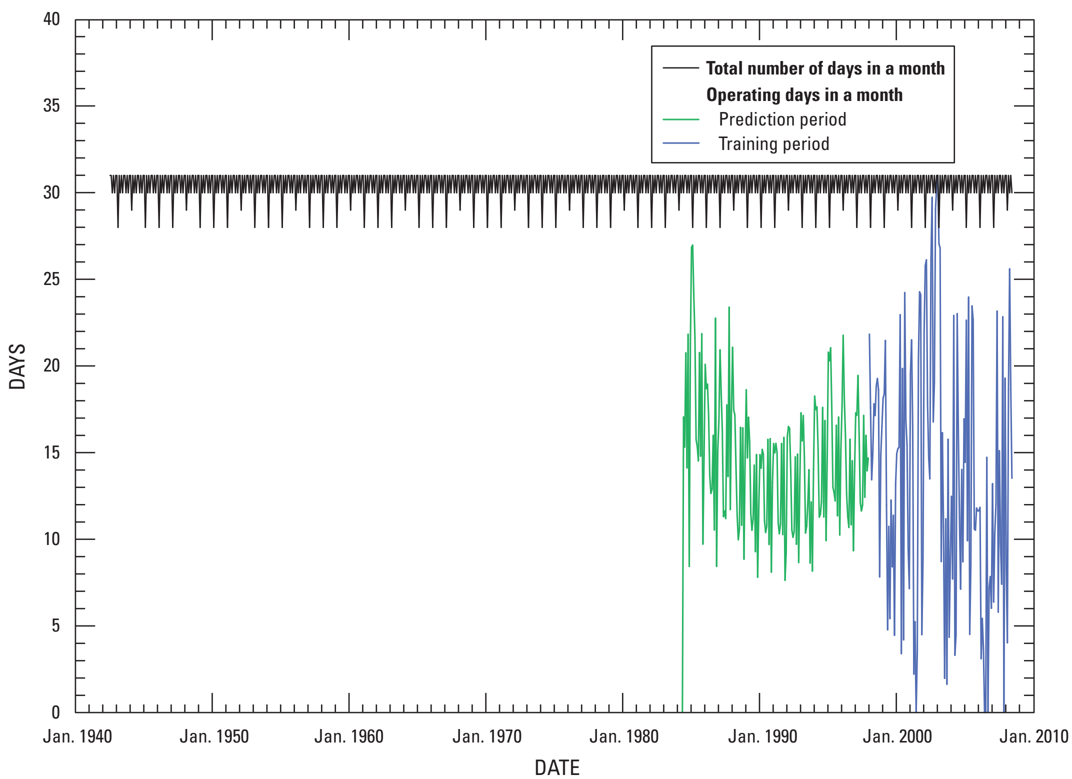

Figure S2.84. Estimated monthly operating days for well HP-622.

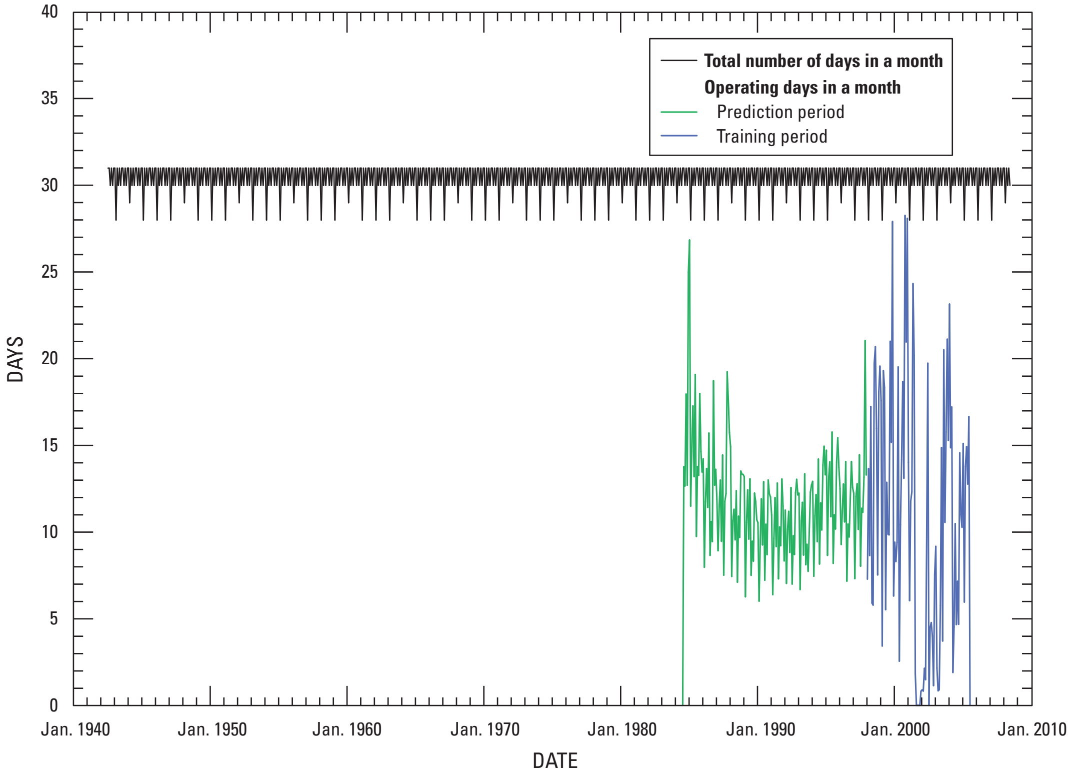

Figure S2.85. Estimated monthly operating days for well HP-623.

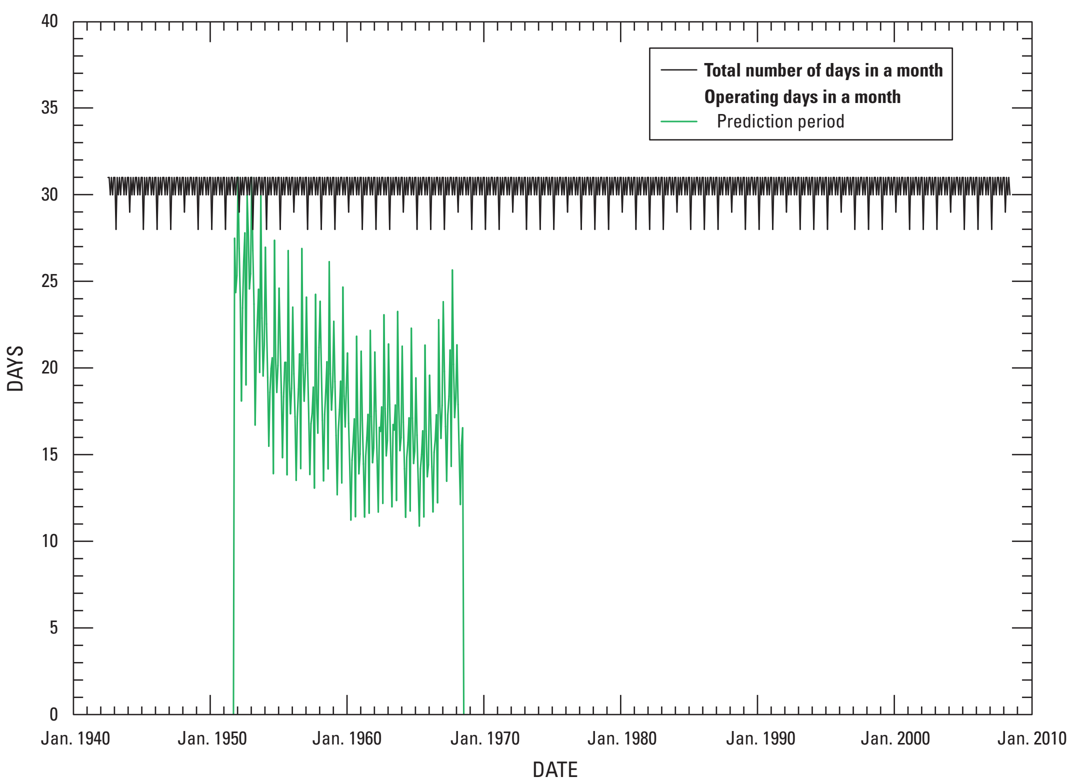

Figure S2.86. Estimated monthly operating days for well HP-624.

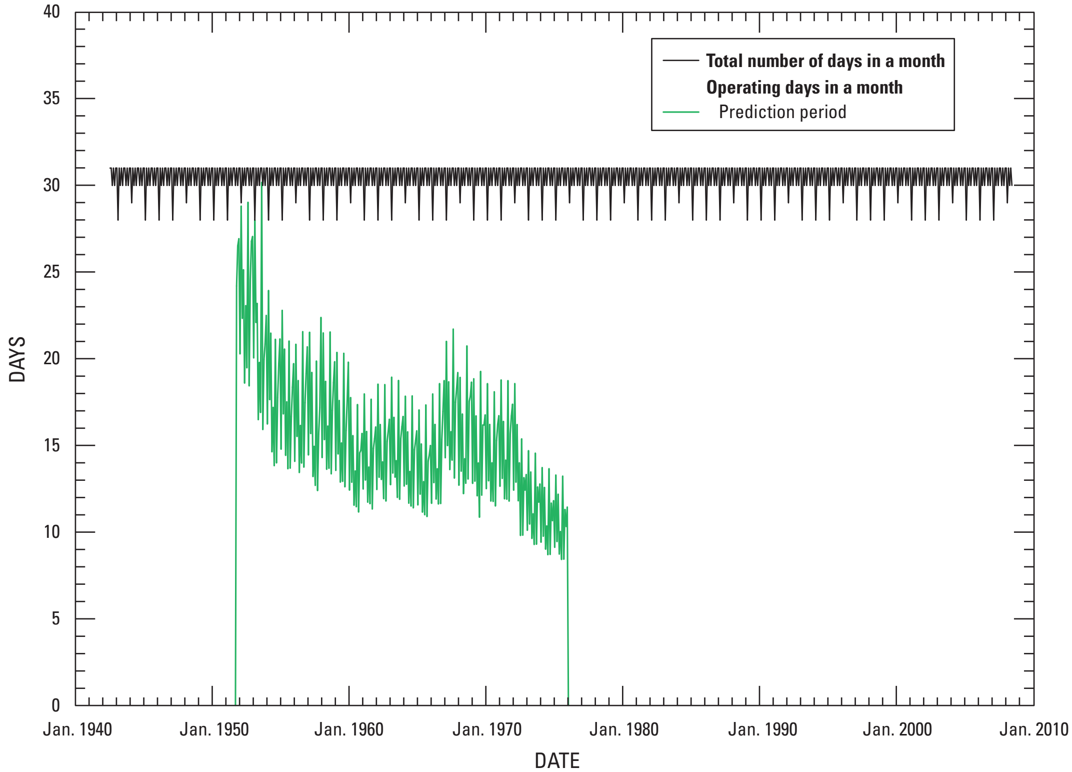

Figure S2.87. Estimated monthly operating days for well HP-625.

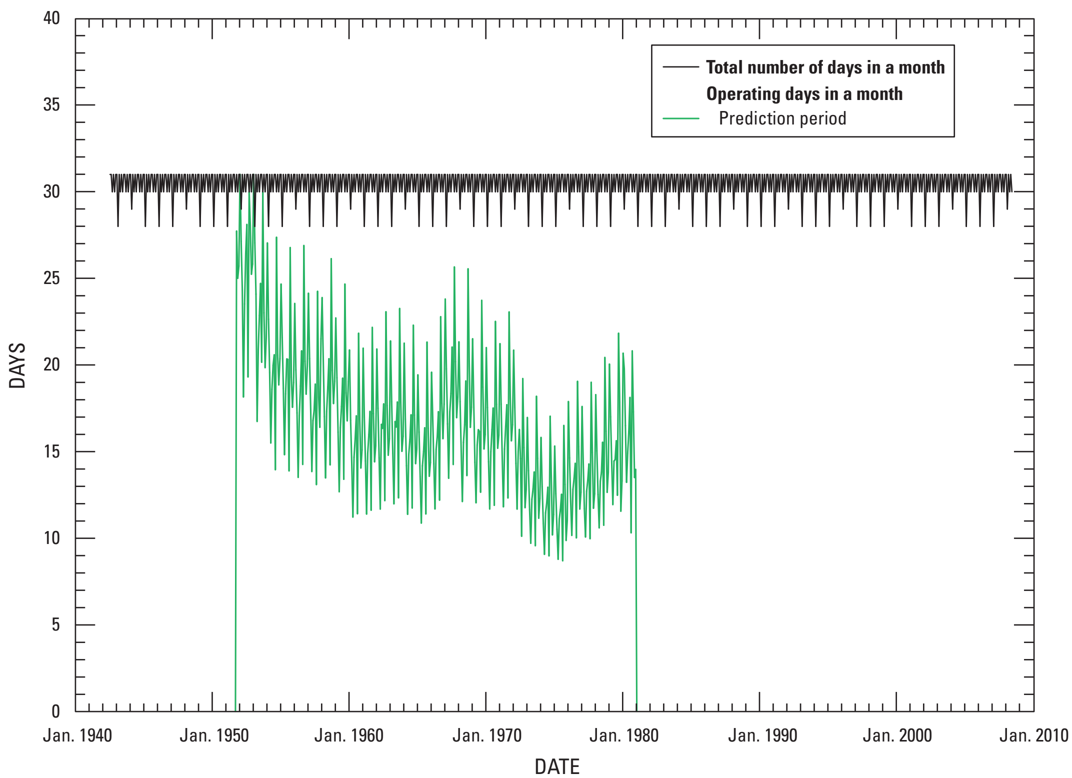

Figure S2.88. Estimated monthly operating days for well HP-626.

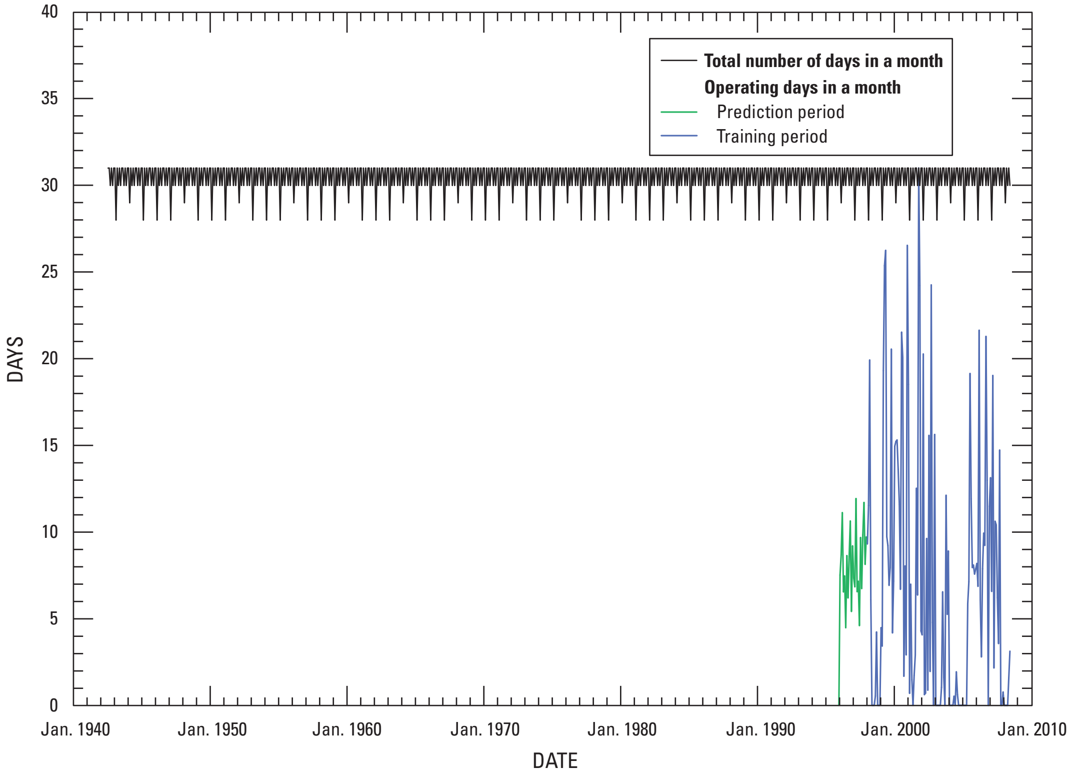

Figure S2.89. Estimated monthly operating days for well HP-627 (new).

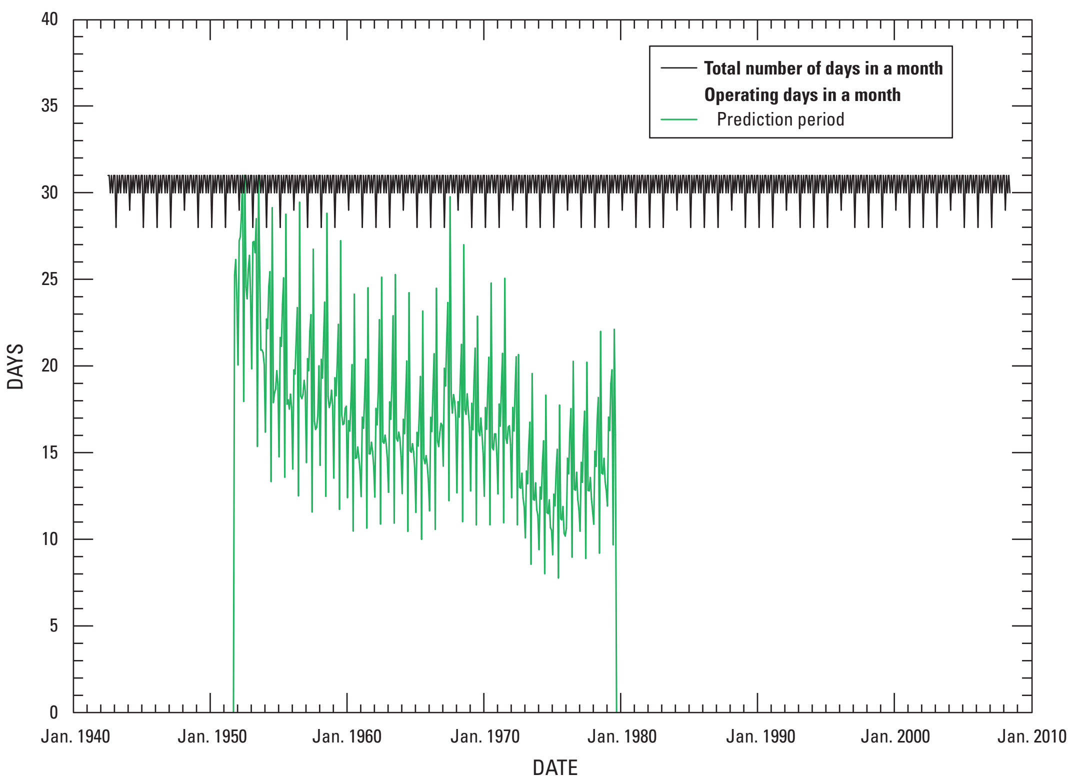

Figure S2.90. Estimated monthly operating days for well HP-627 (old).

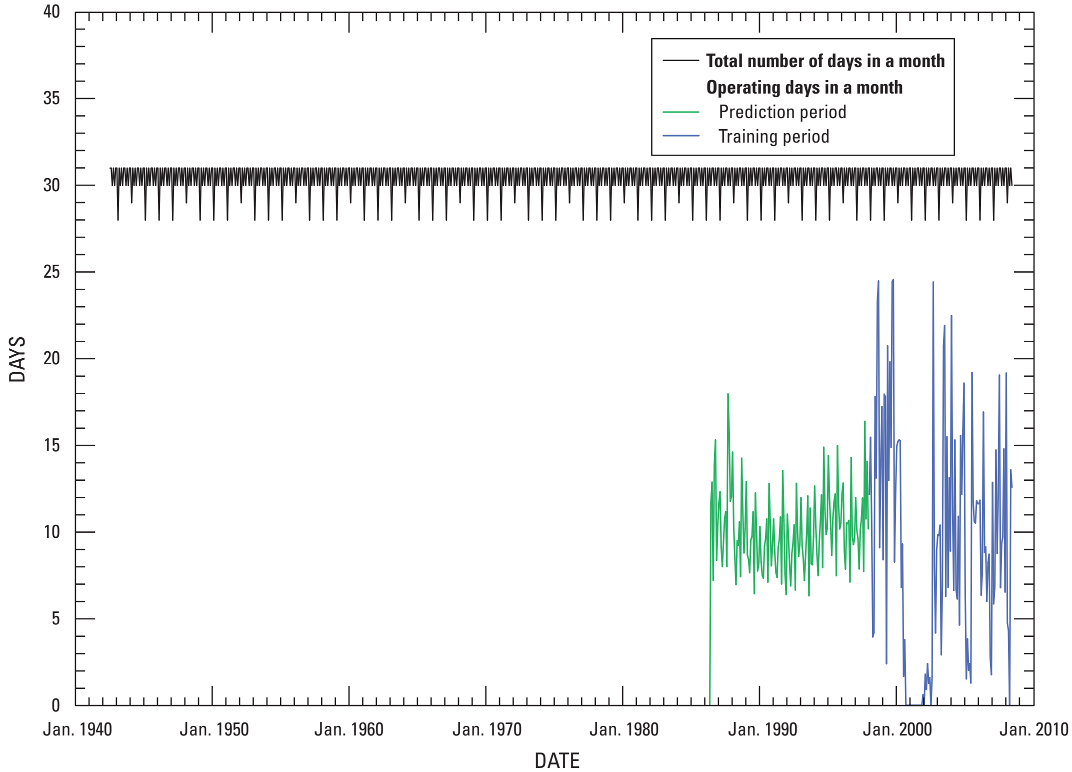

Figure S2.91. Estimated monthly operating days for well HP-628 (new).

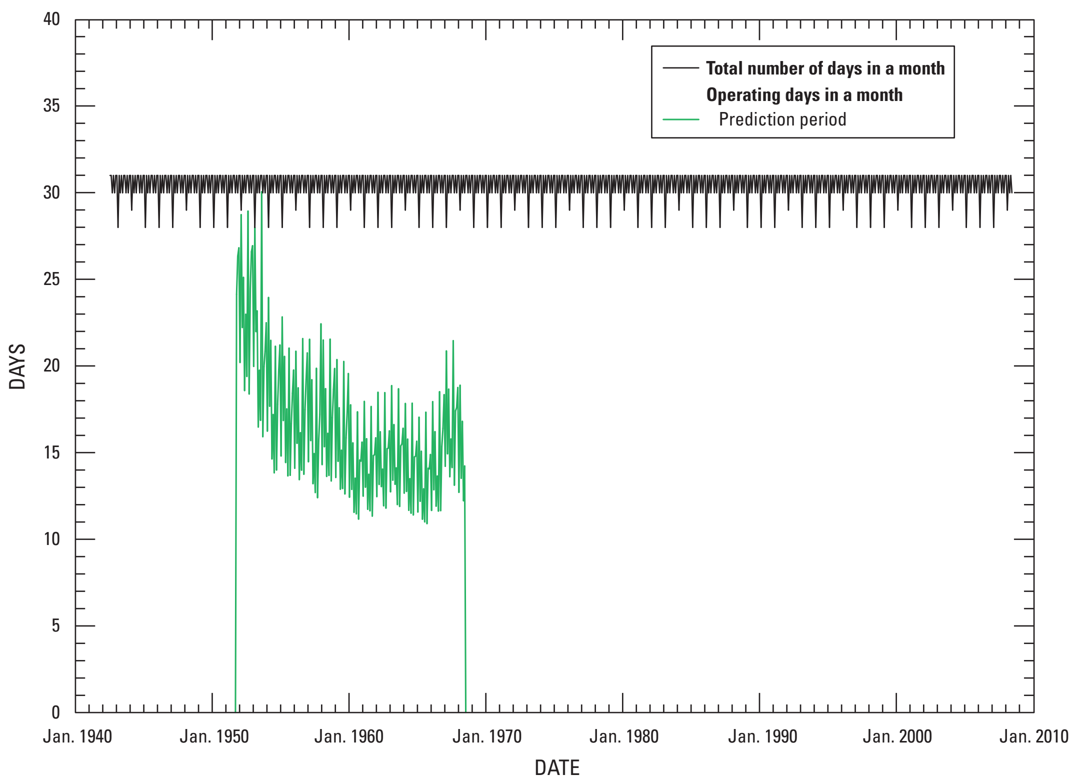

Figure S2.92. Estimated monthly operating days for well HP-628 (old).

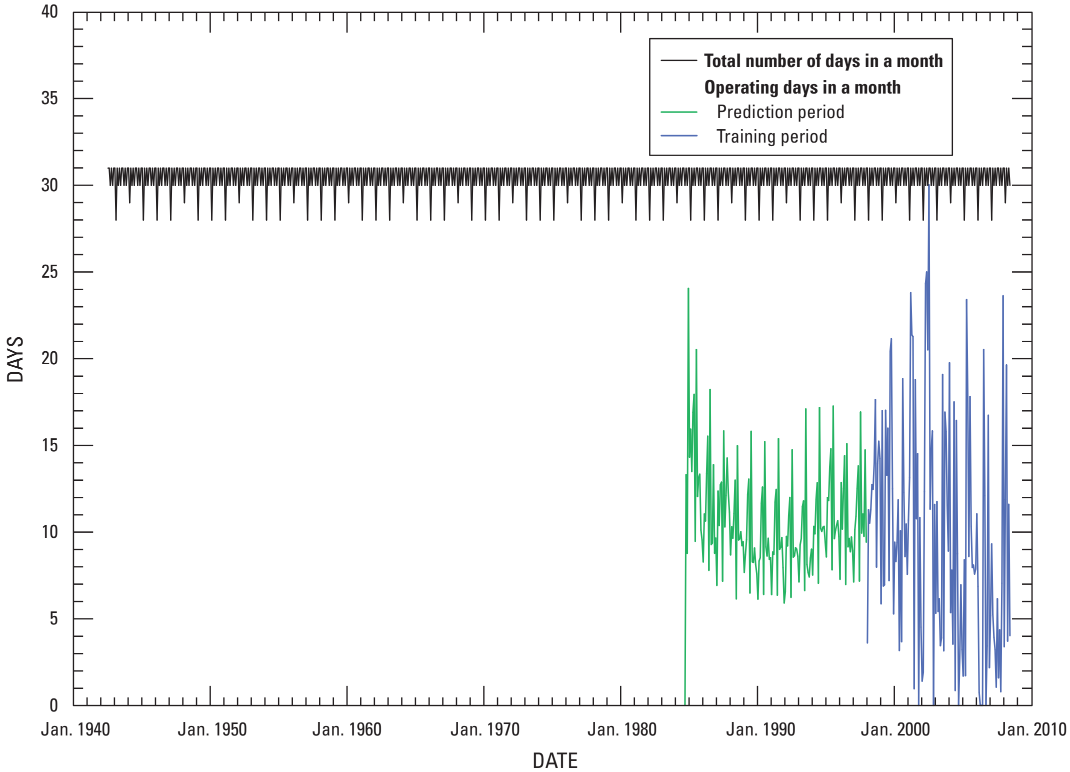

Figure S2.93. Estimated monthly operating days for well HP-629 (new).

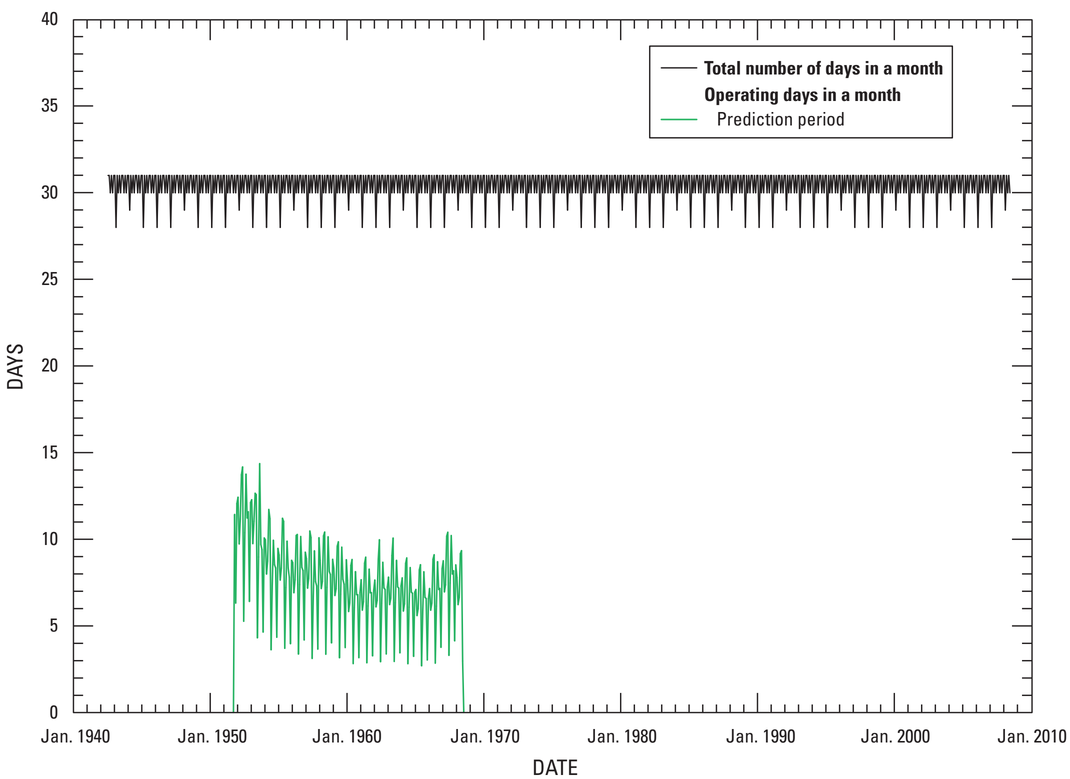

Figure S2.94. Estimated monthly operating days for well HP-629 (old).

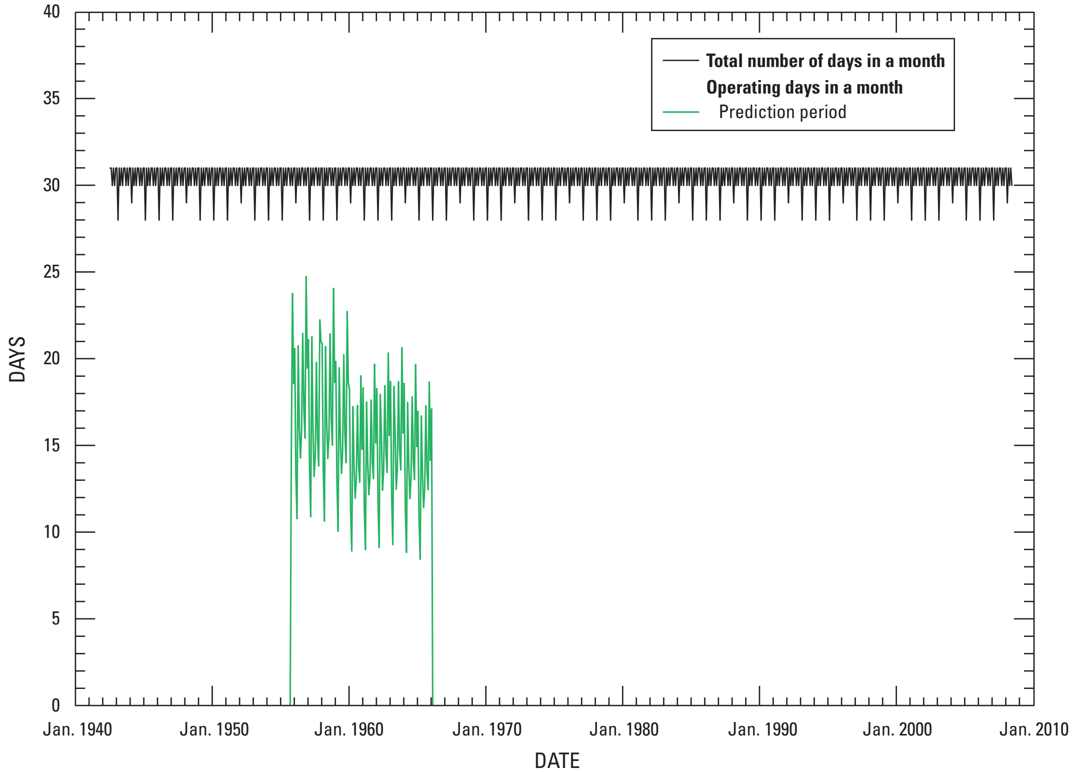

Figure S2.95. Estimated monthly operating days for well HP-630.

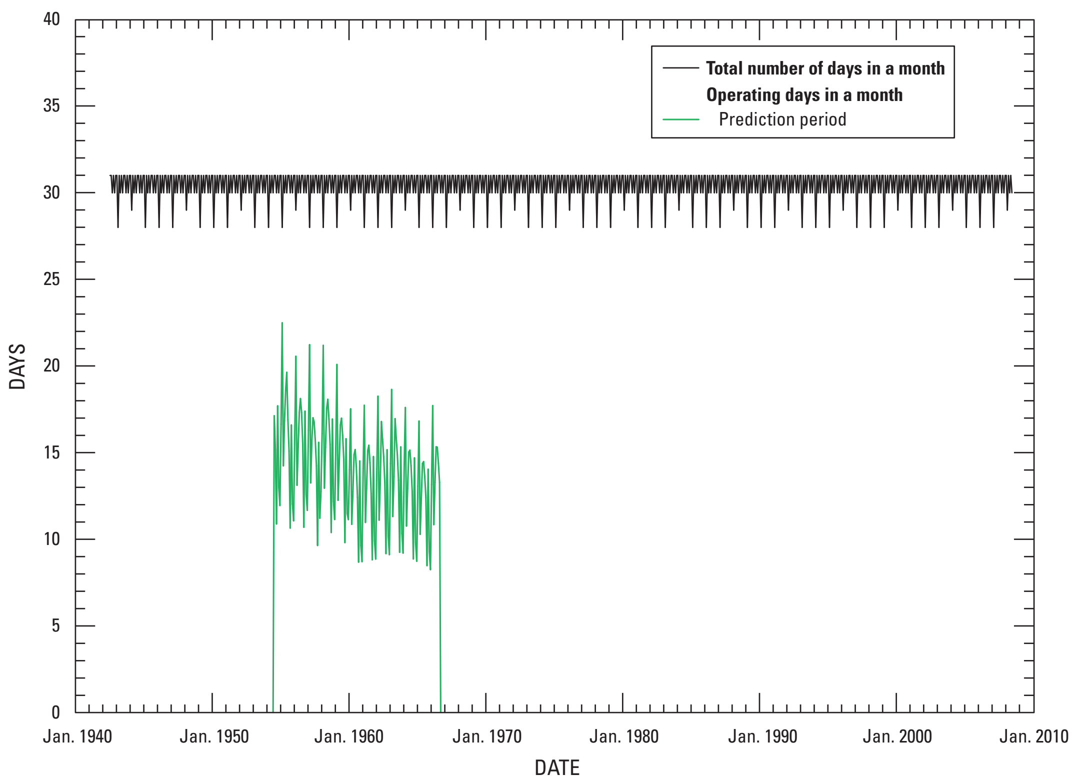

Figure S2.96. Estimated monthly operating days for well HP-631.

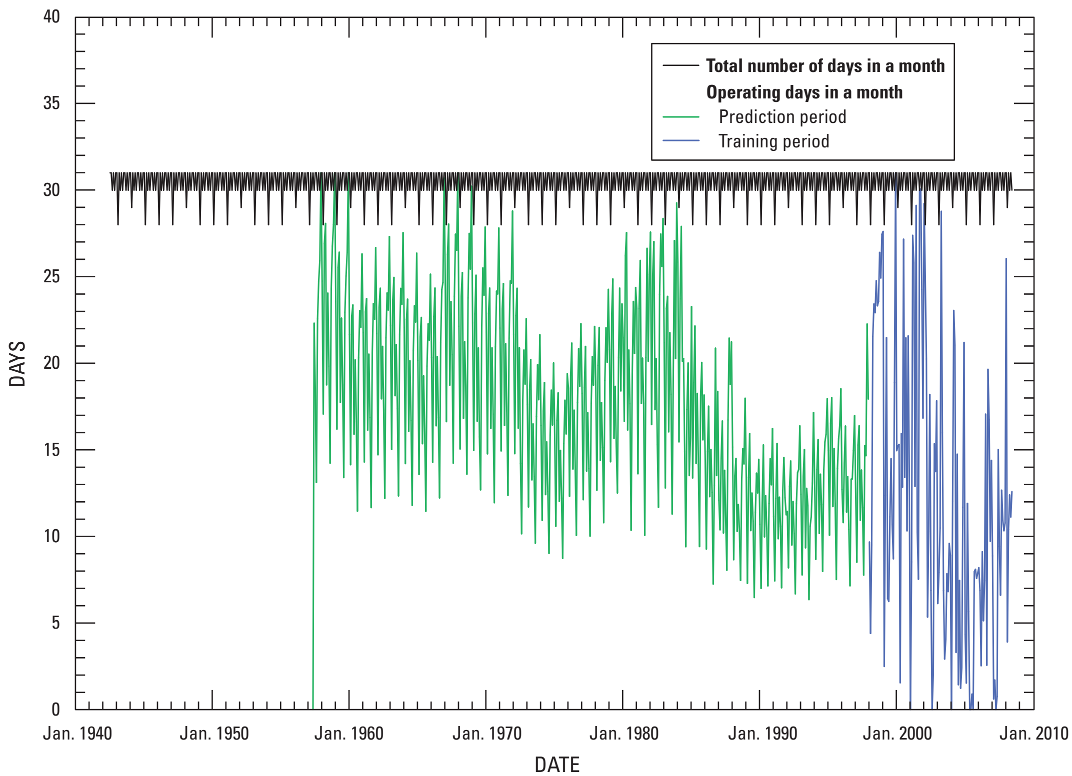

Figure S2.97. Estimated monthly operating days for well HP-632.

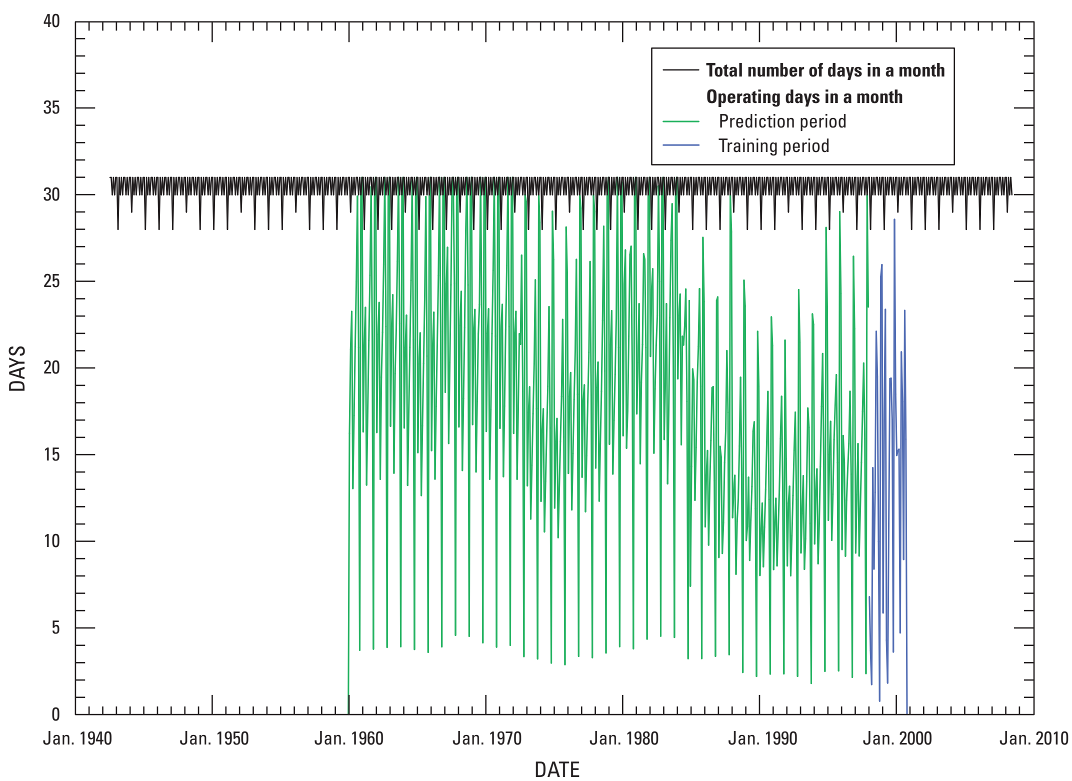

Figure S2.98. Estimated monthly operating days for well HP-633.

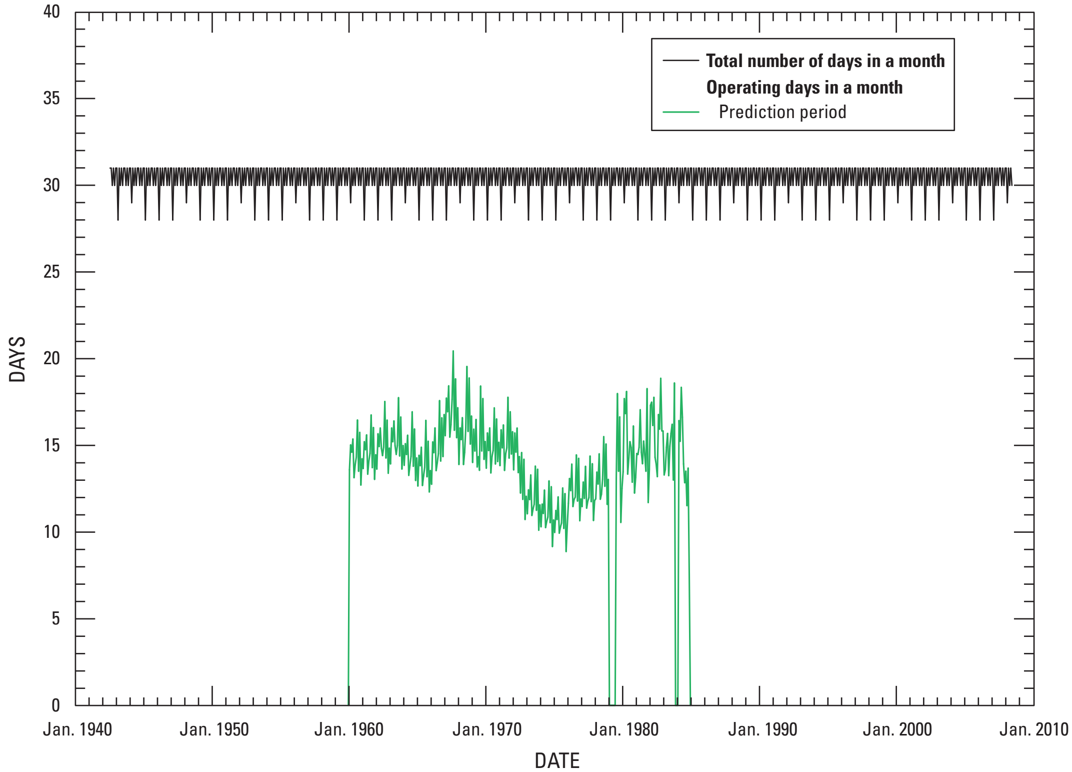

Figure S2.99. Estimated monthly operating days for well HP-634.

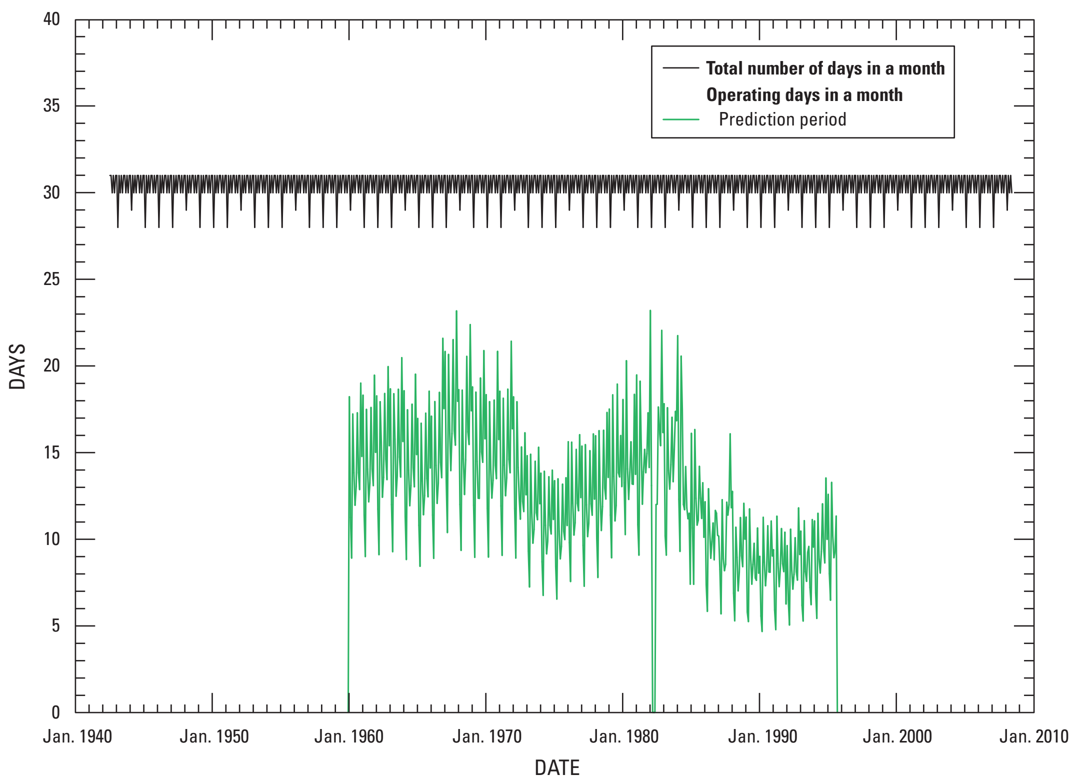

Figure S2.100. Estimated monthly operating days for well HP-635.

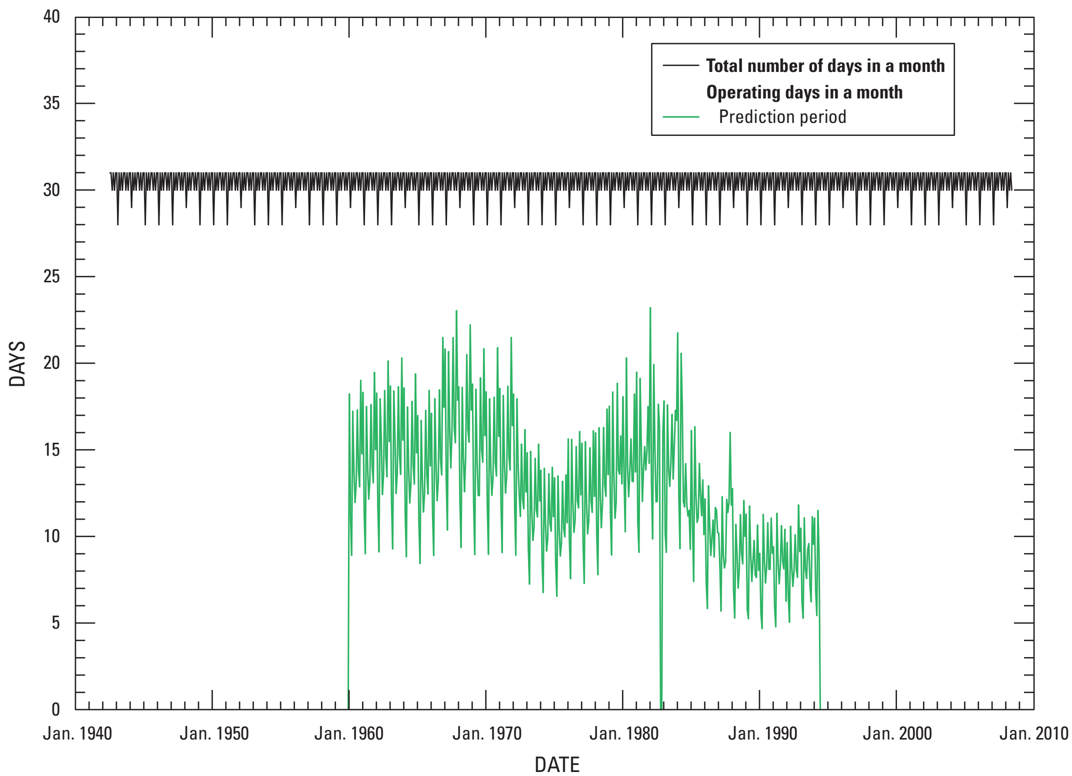

Figure S2.101. Estimated monthly operating days for well HP-636.

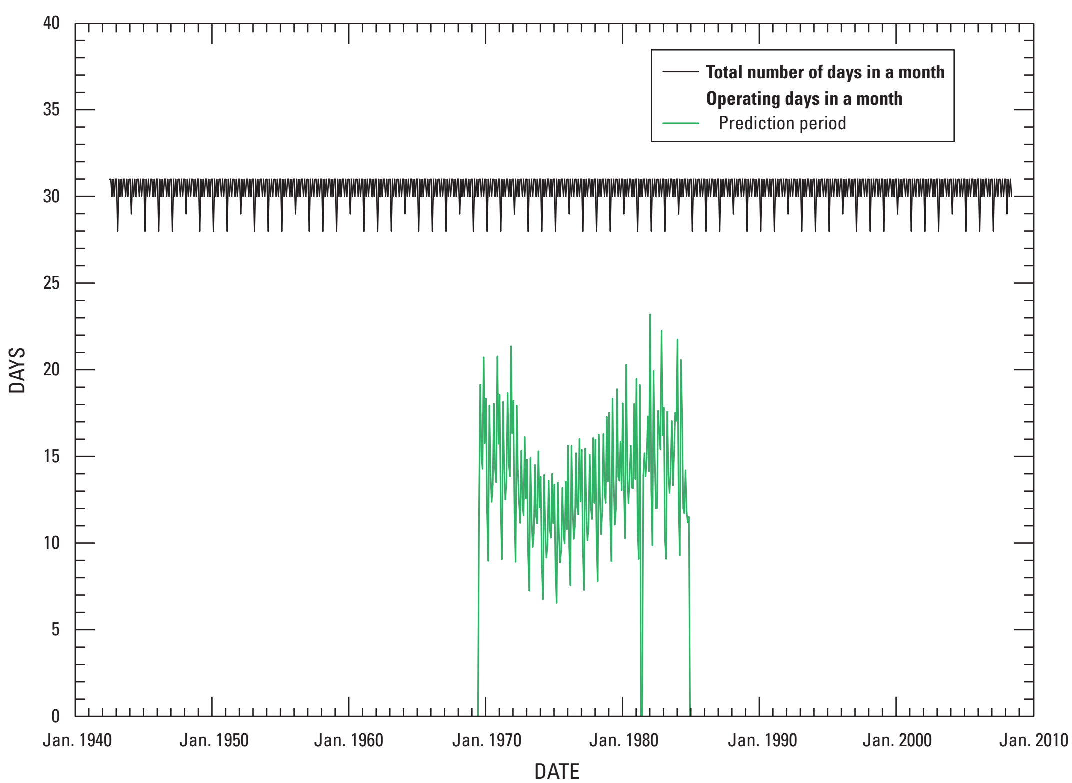

Figure S2.102. Estimated monthly operating days for well HP-637.

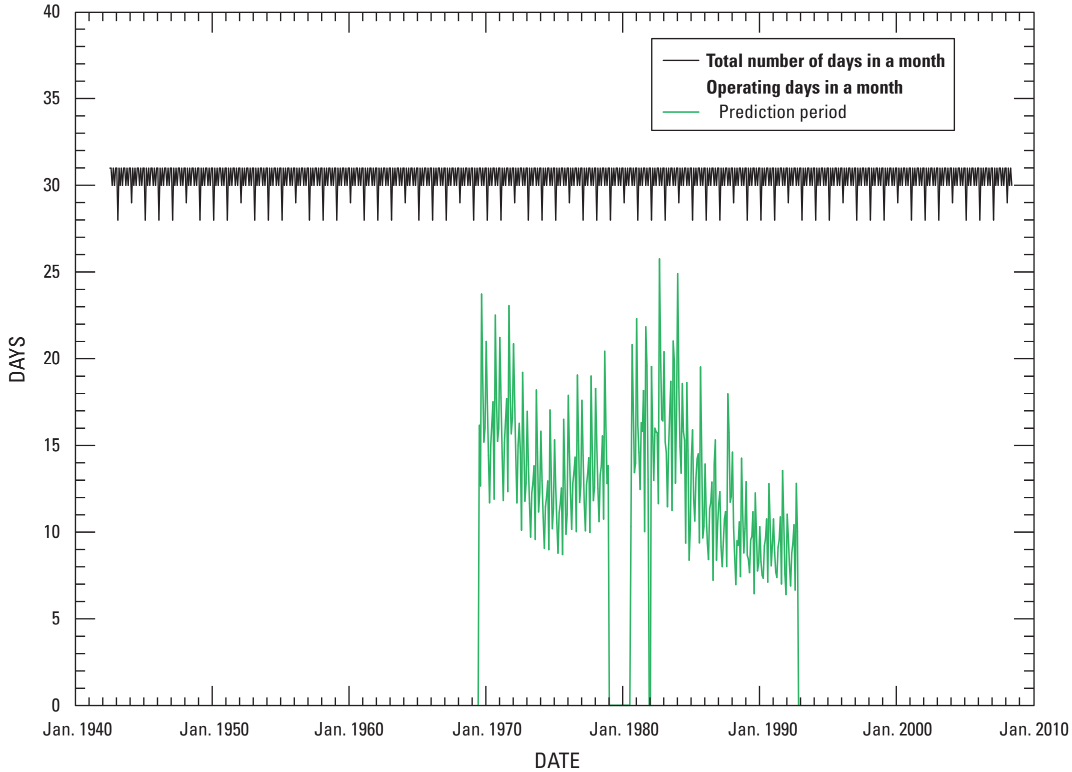

Figure S2.103. Estimated monthly operating days for well HP-638.

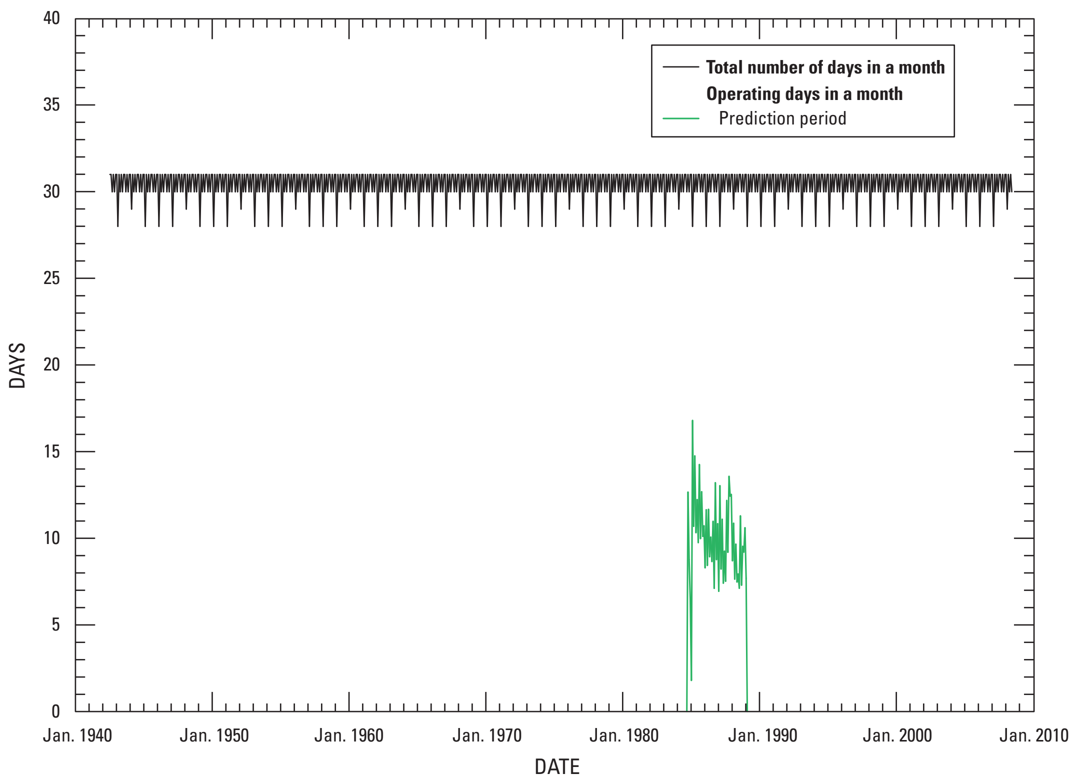

Figure S2.104. Estimated monthly operating days for well HP-639 (new).

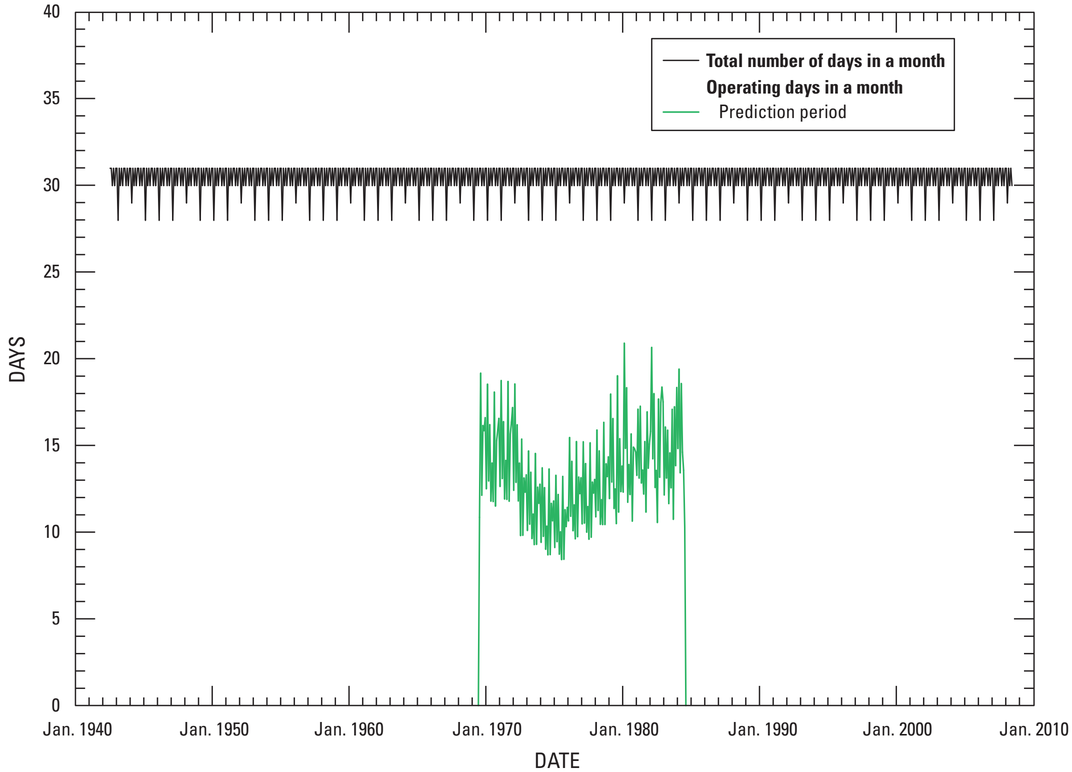

Figure S2.105. Estimated monthly operating days for well HP-639 (old).

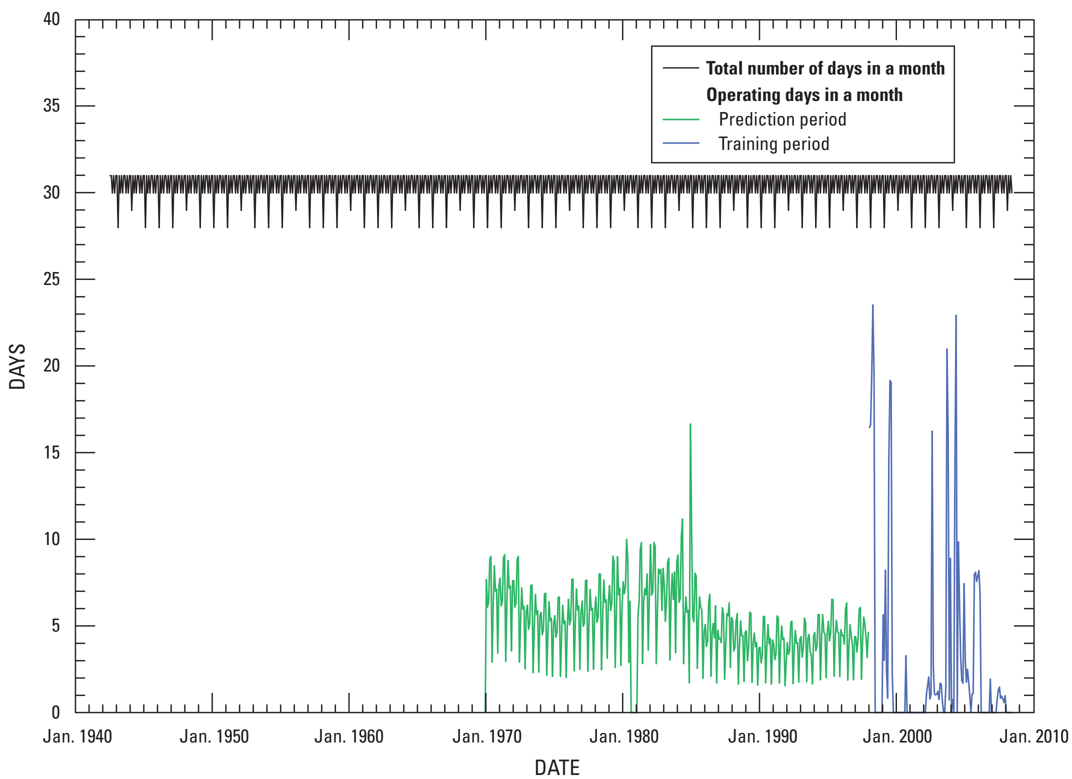

Figure S2.106. Estimated monthly operating days for well HP-640.

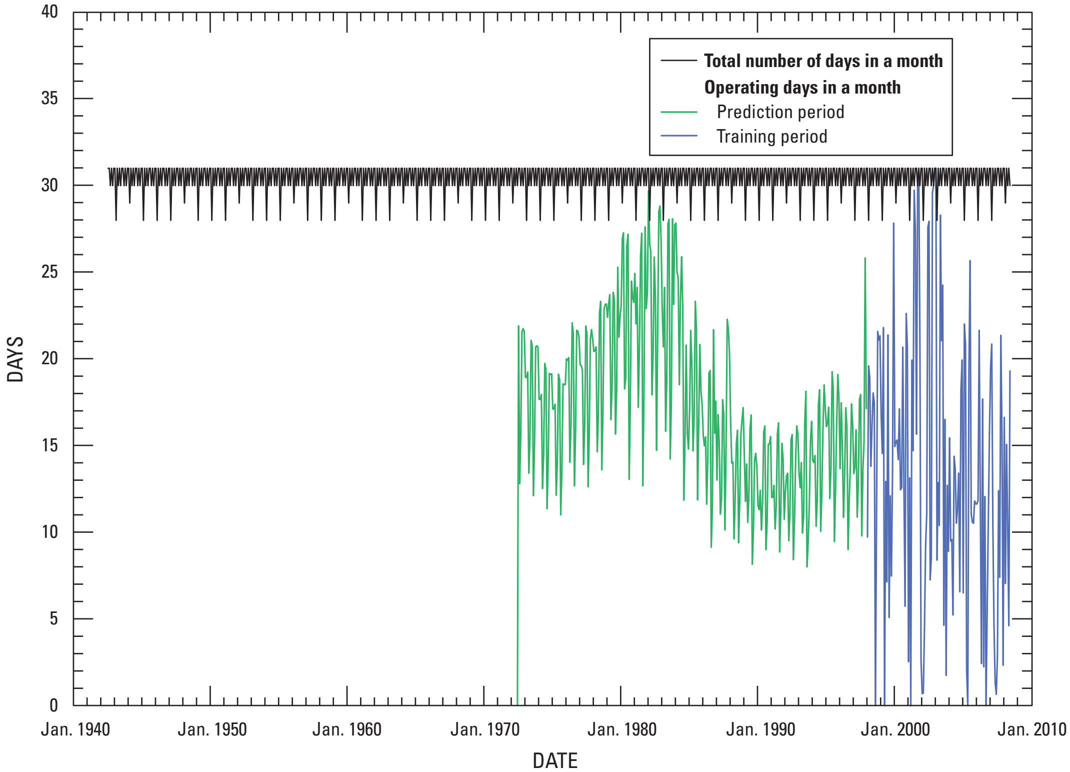

Figure S2.107. Estimated monthly operating days for well HP-641.

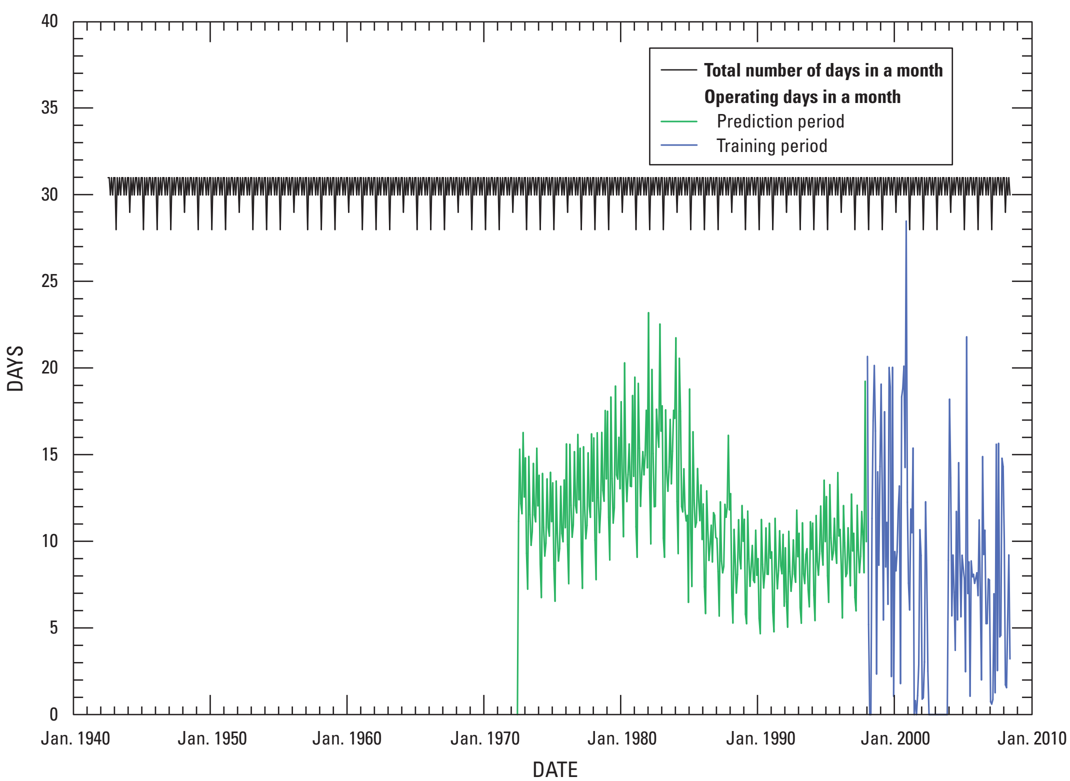

Figure S2.108. Estimated monthly operating days for well HP-642.

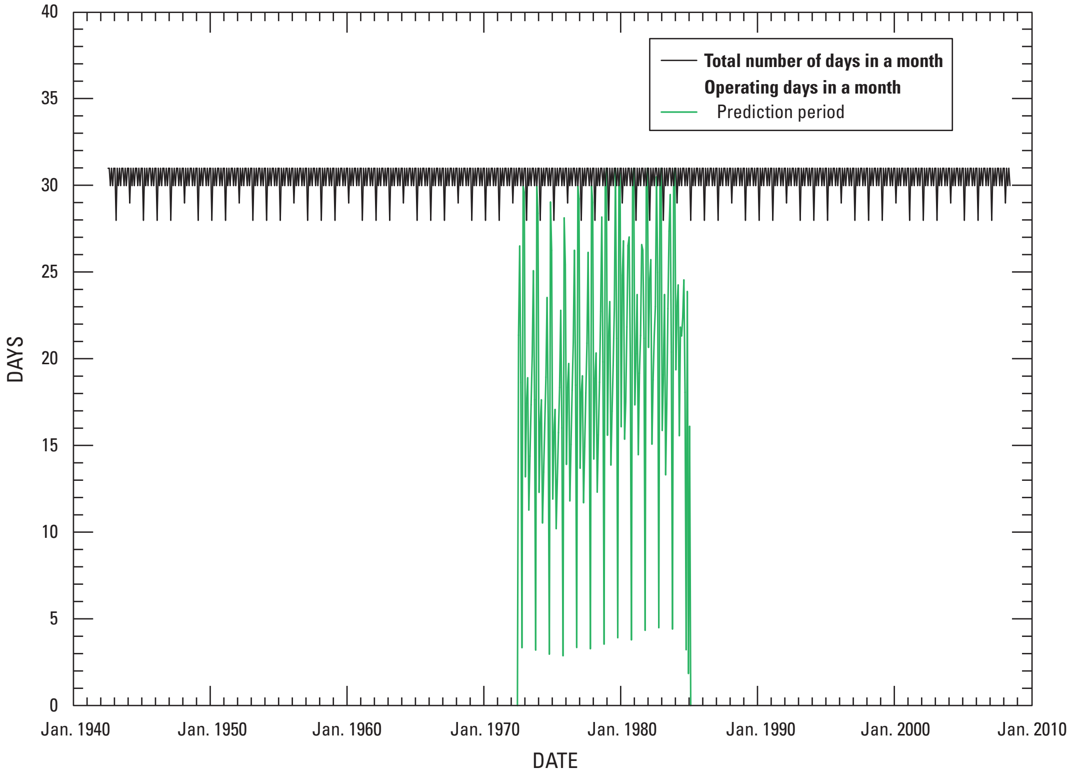

Figure S2.109. Estimated monthly operating days for well HP-651.

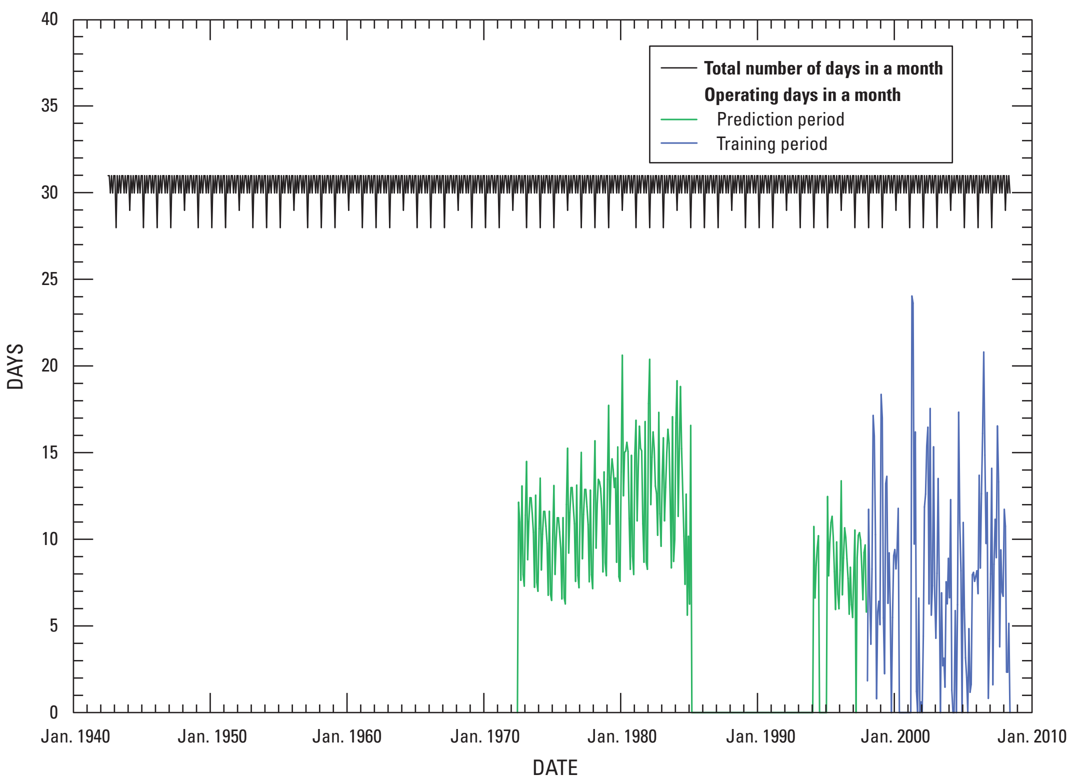

Figure S2.110. Estimated monthly operating days for well HP-652.

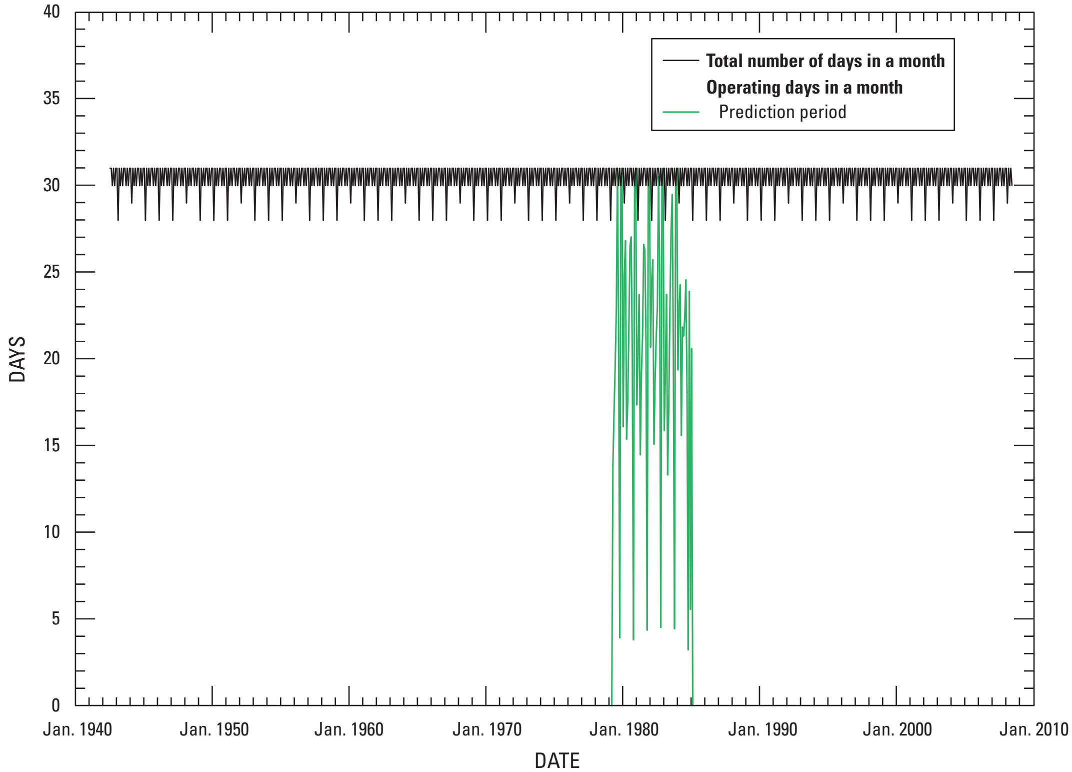

Figure S2.111. Estimated monthly operating days for well HP-653.

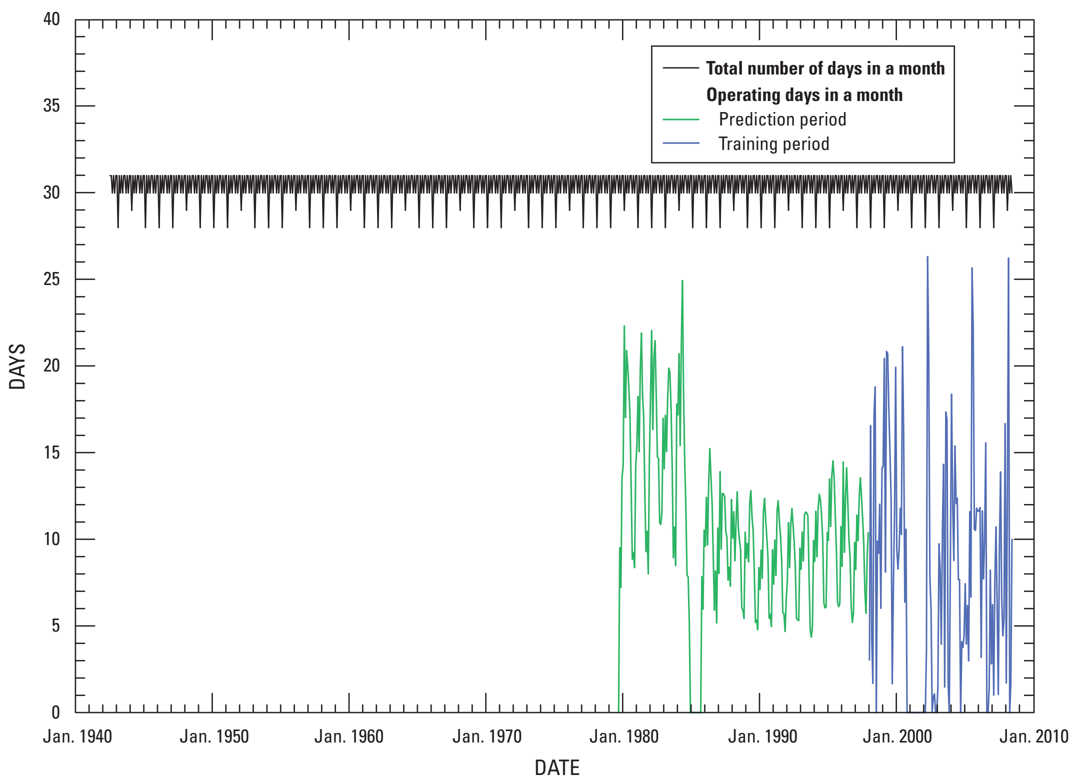

Figure S2.112. Estimated monthly operating days for well HP-654.

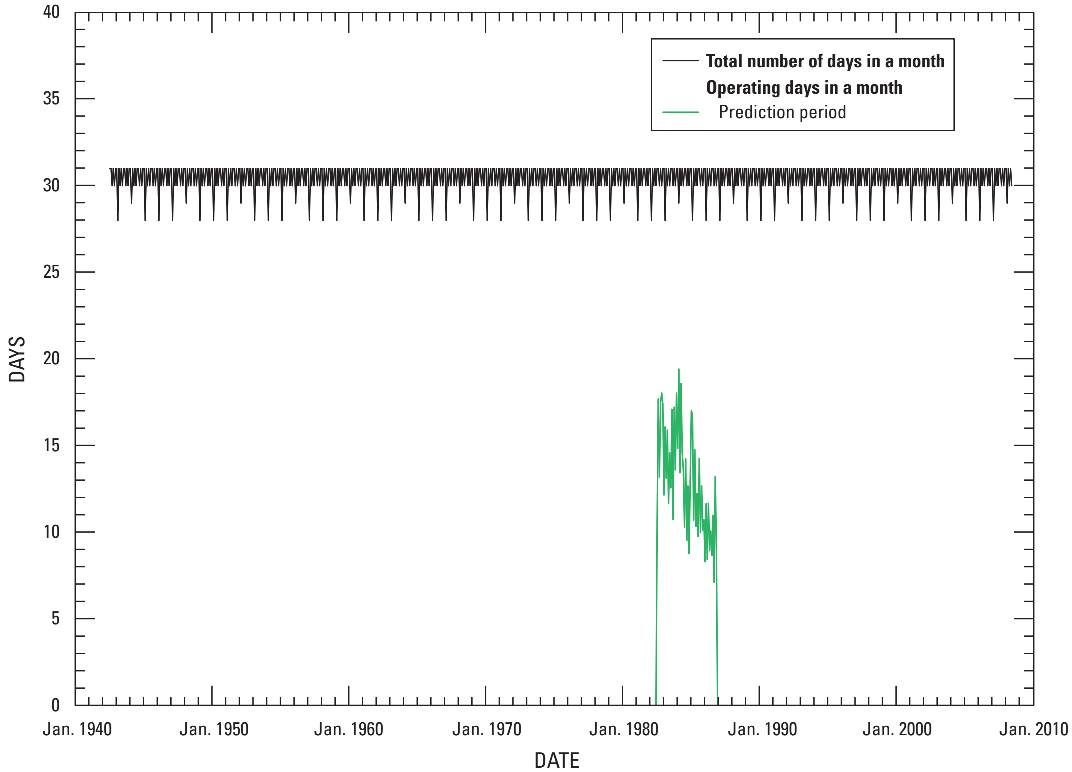

Figure S2.113. Estimated monthly operating days for well HP-655.

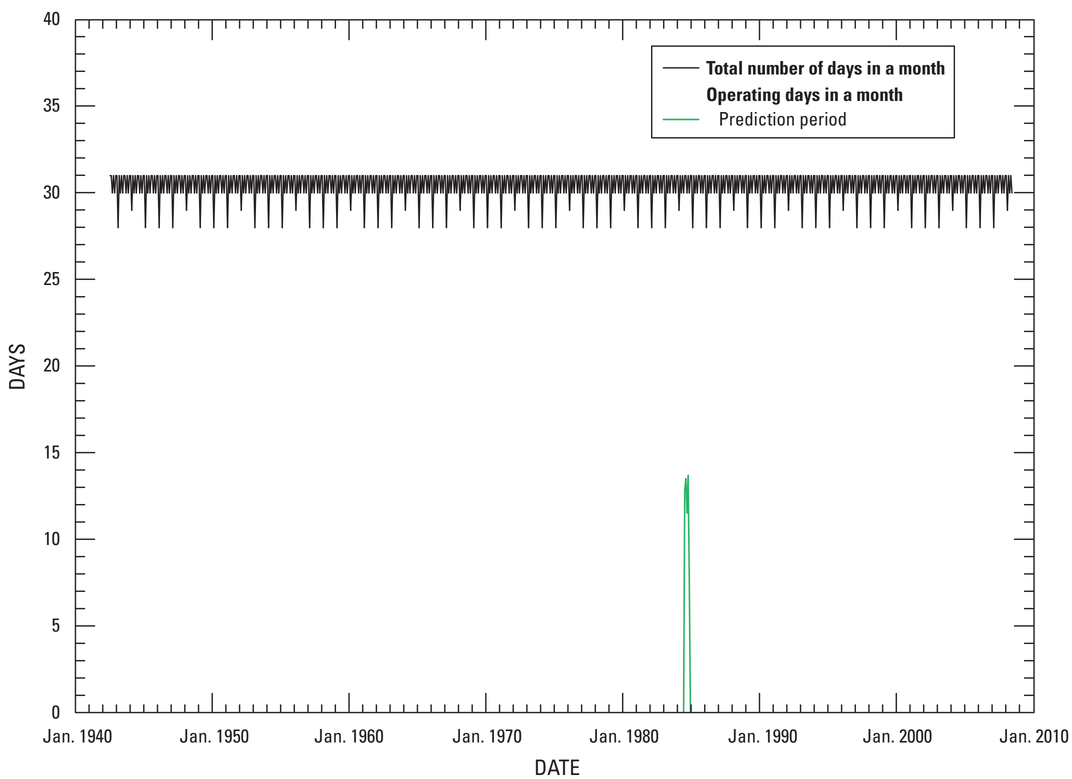

Figure S2.114. Estimated monthly operating days for well HP-660.

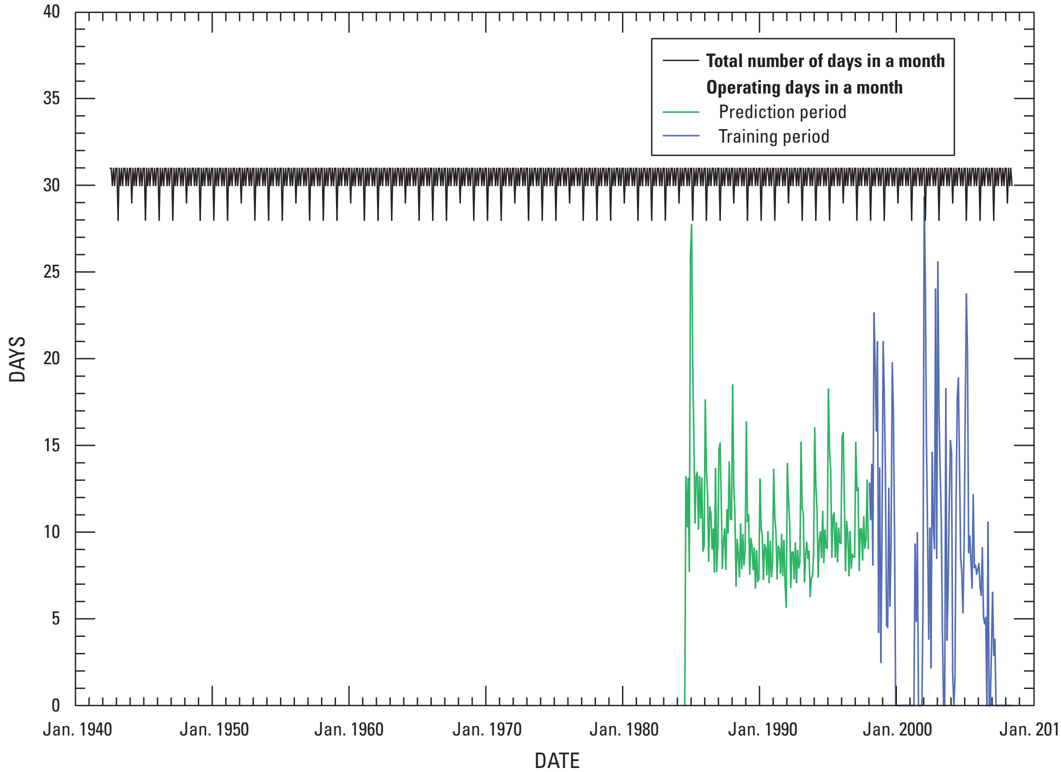

Figure S2.115. Estimated monthly operating days for well HP-661.

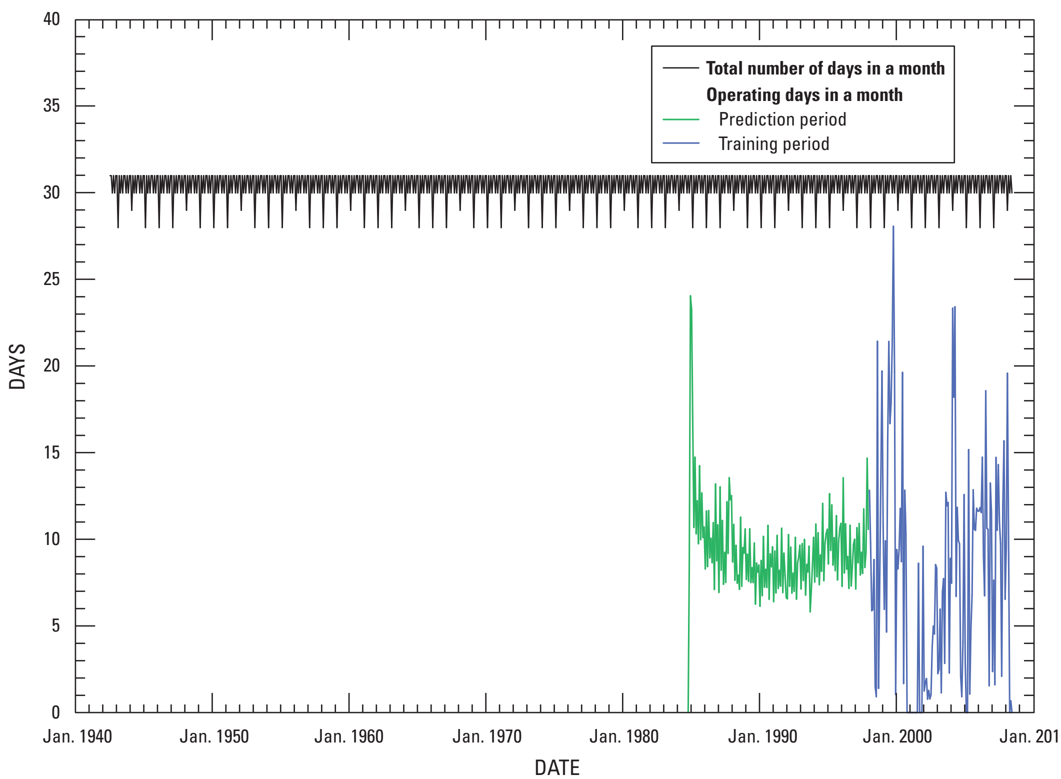

Figure S2.116. Estimated monthly operating days for well HP-662.

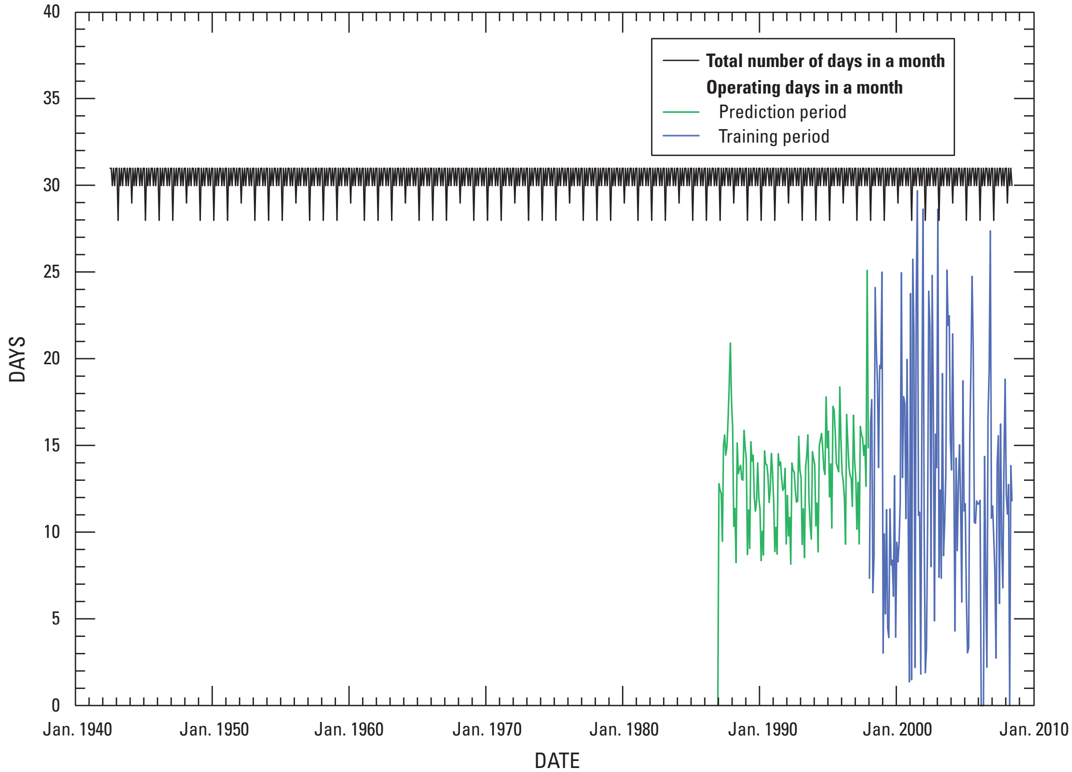

Figure S2.117. Estimated monthly operating days for well HP-663.

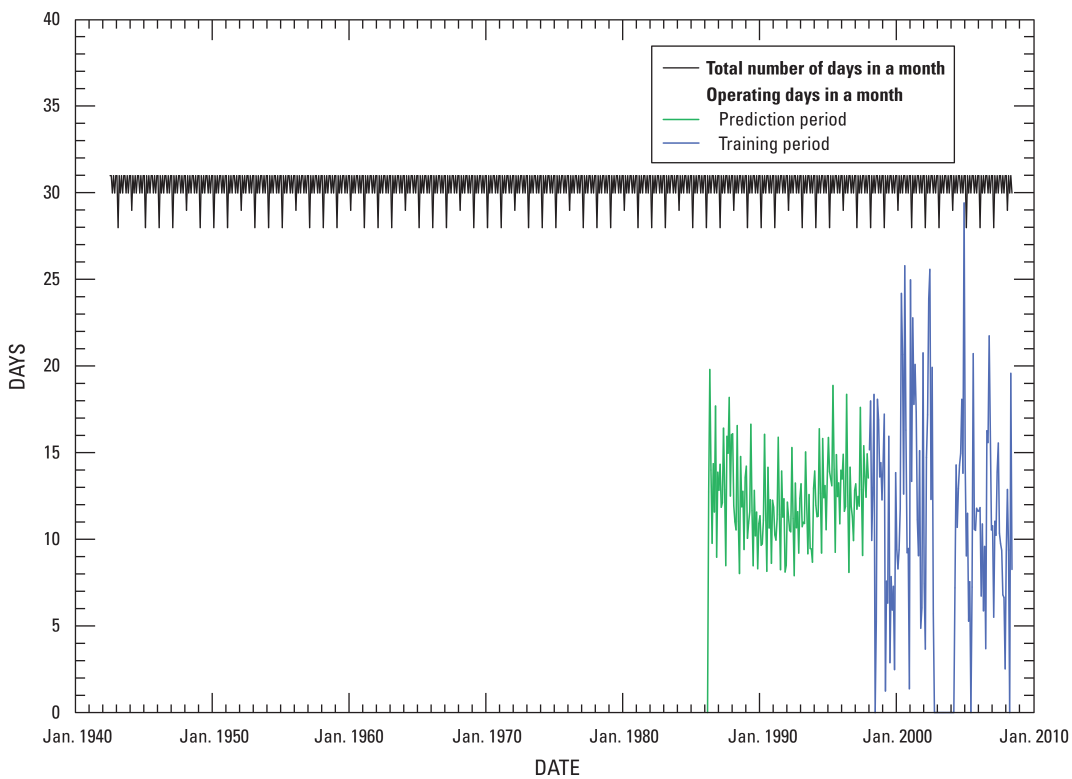

Figure S2.118. Estimated monthly operating days for well HP-709.

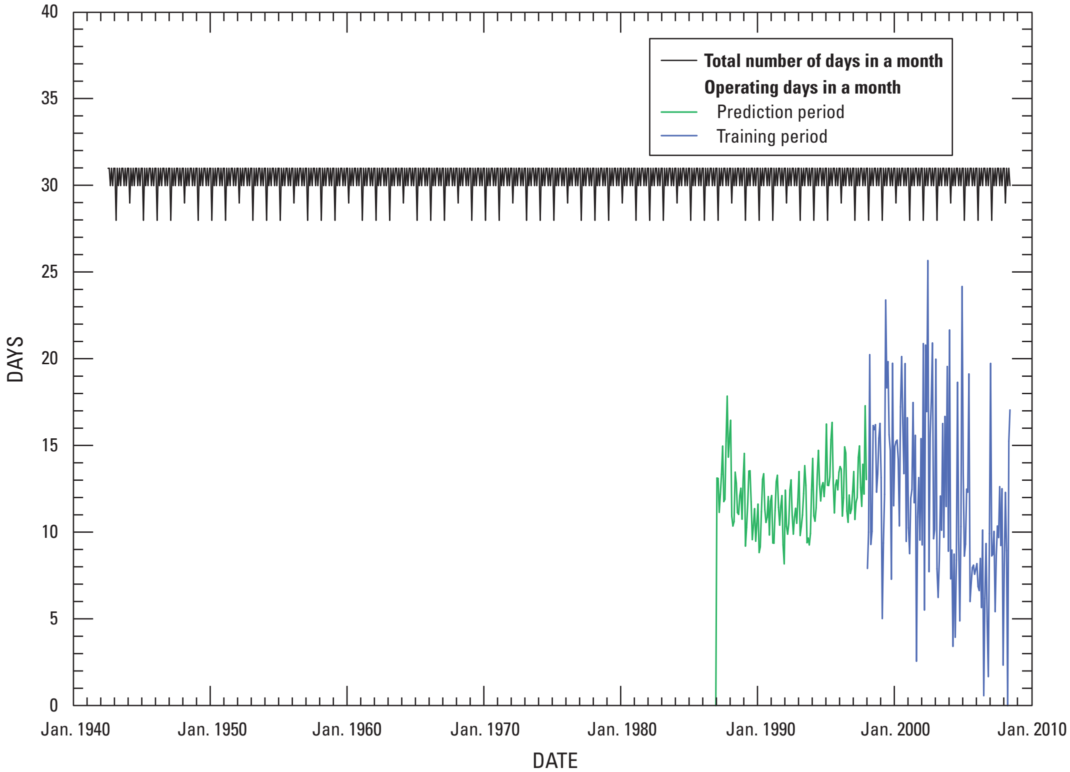

Figure S2.119. Estimated monthly operating days for well HP-710.

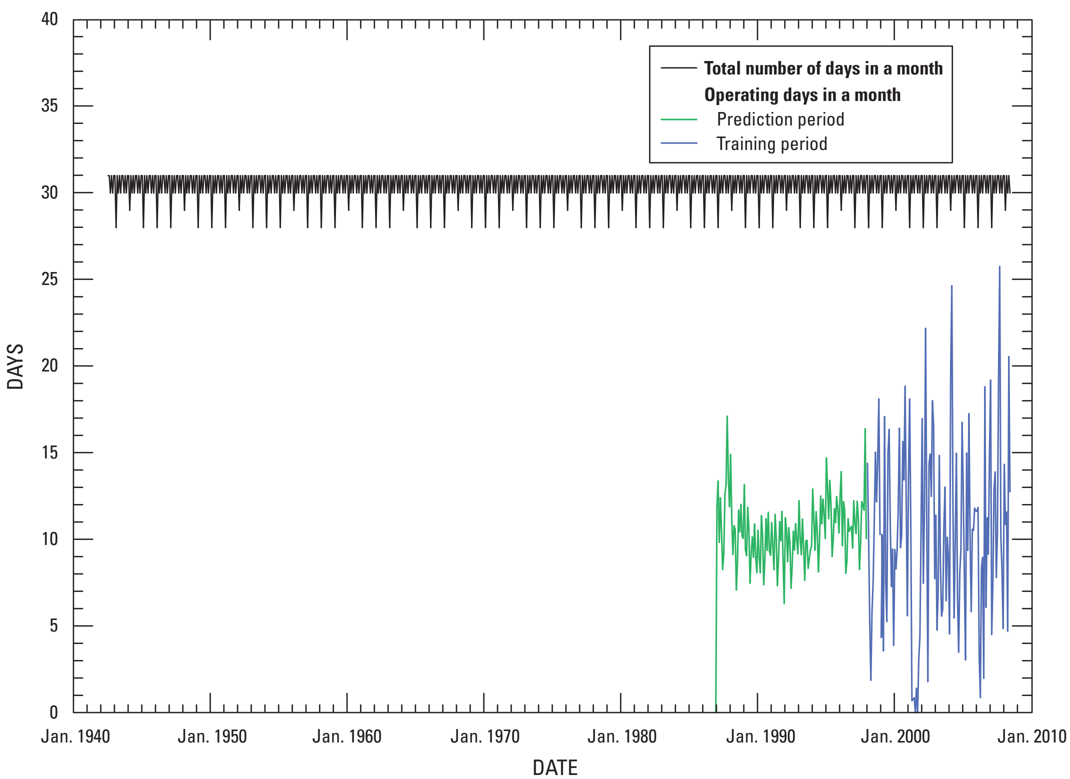

Figure S2.120. Estimated monthly operating days for well HP-711.

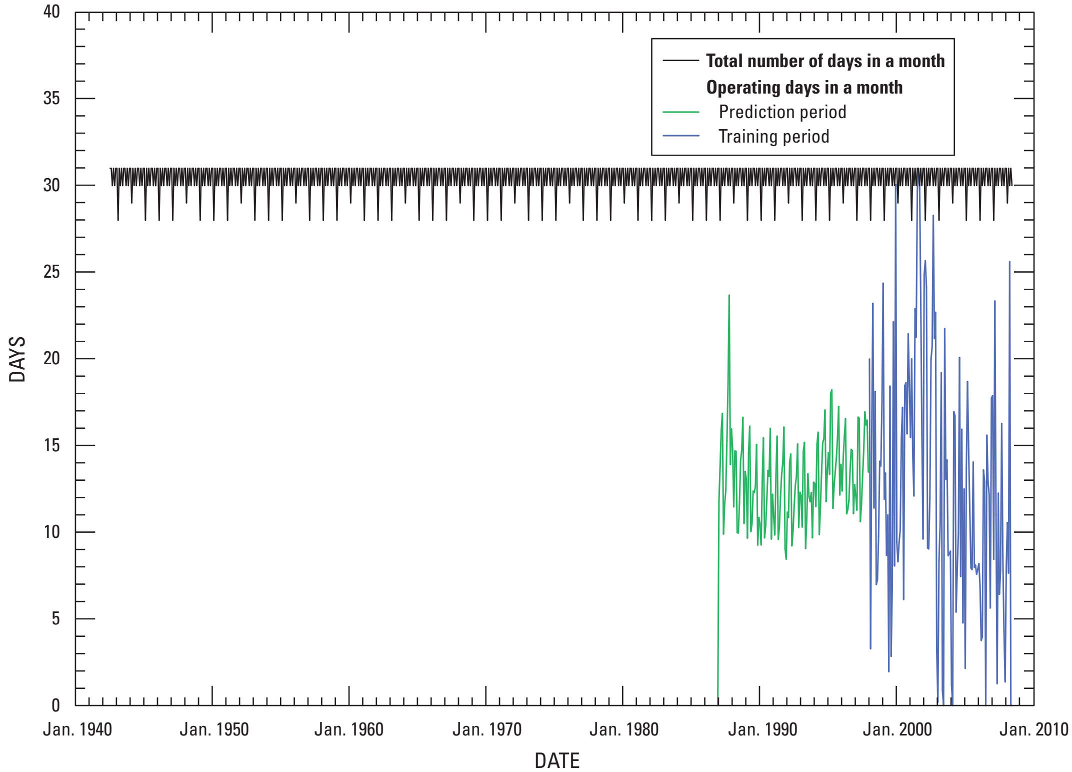

Figure S2.121. Estimated monthly operating days for well HP-5186.

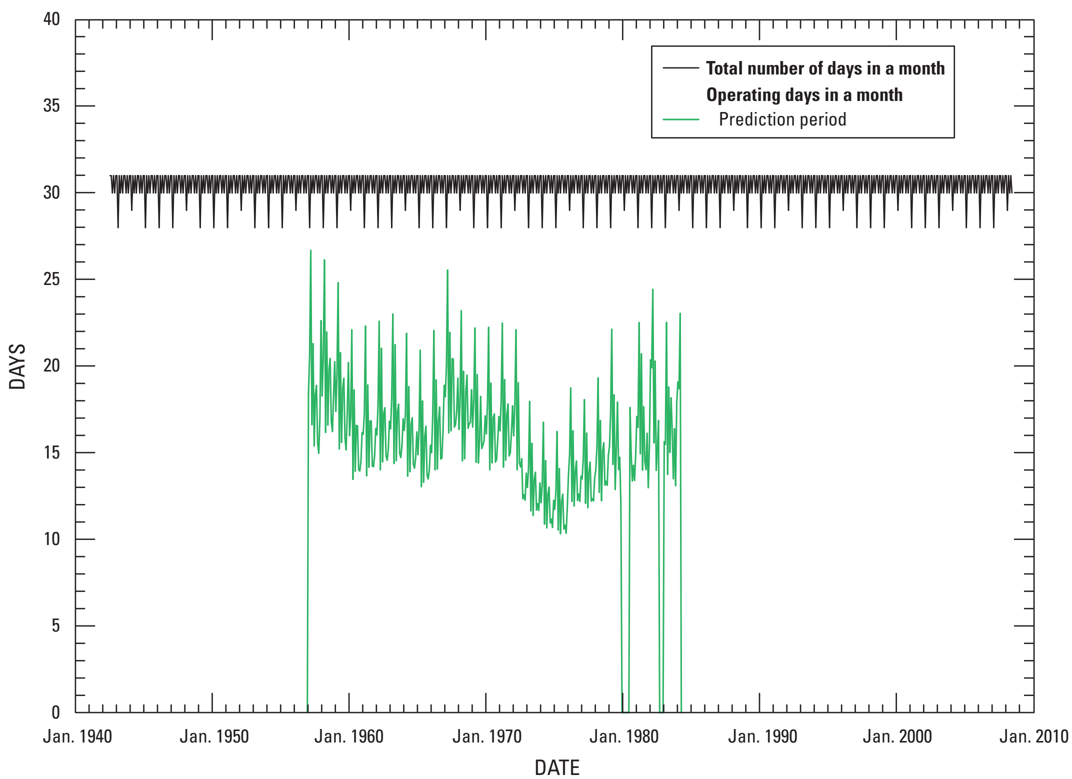

Figure S2.122. Estimated monthly operating days for well LCH-4006.

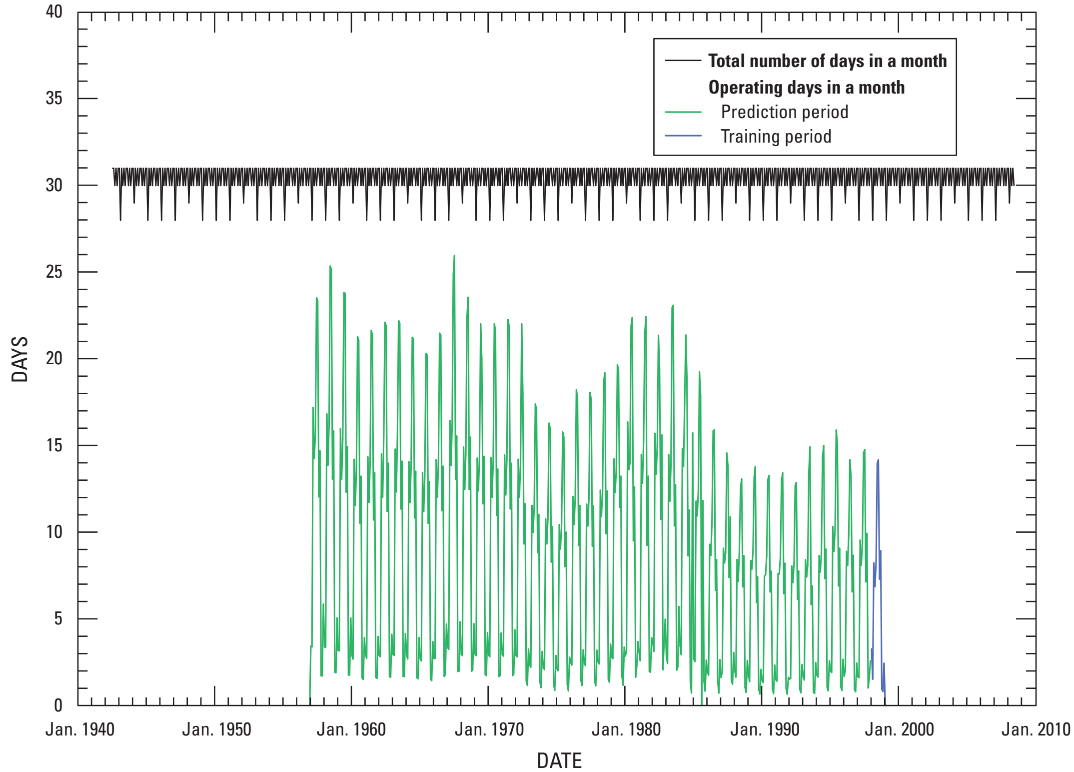

Figure S2.123. Estimated monthly operating days for well LCH-4007.

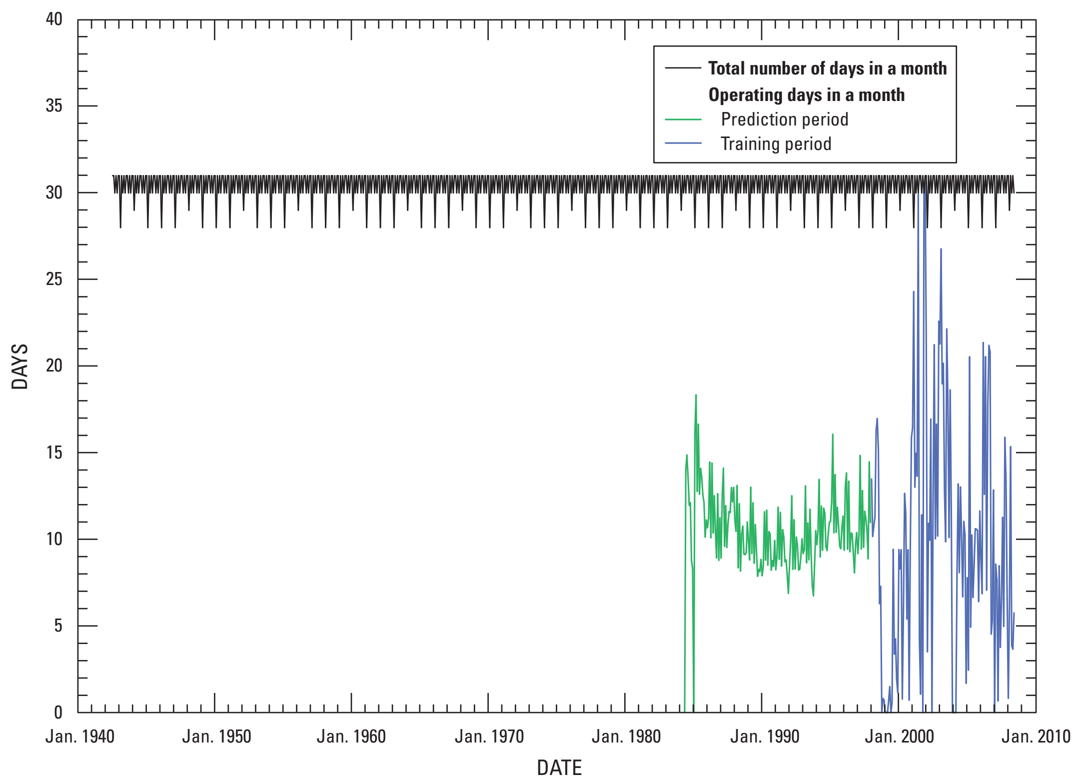

Figure S2.124. Estimated monthly operating days for well LCH-4009.

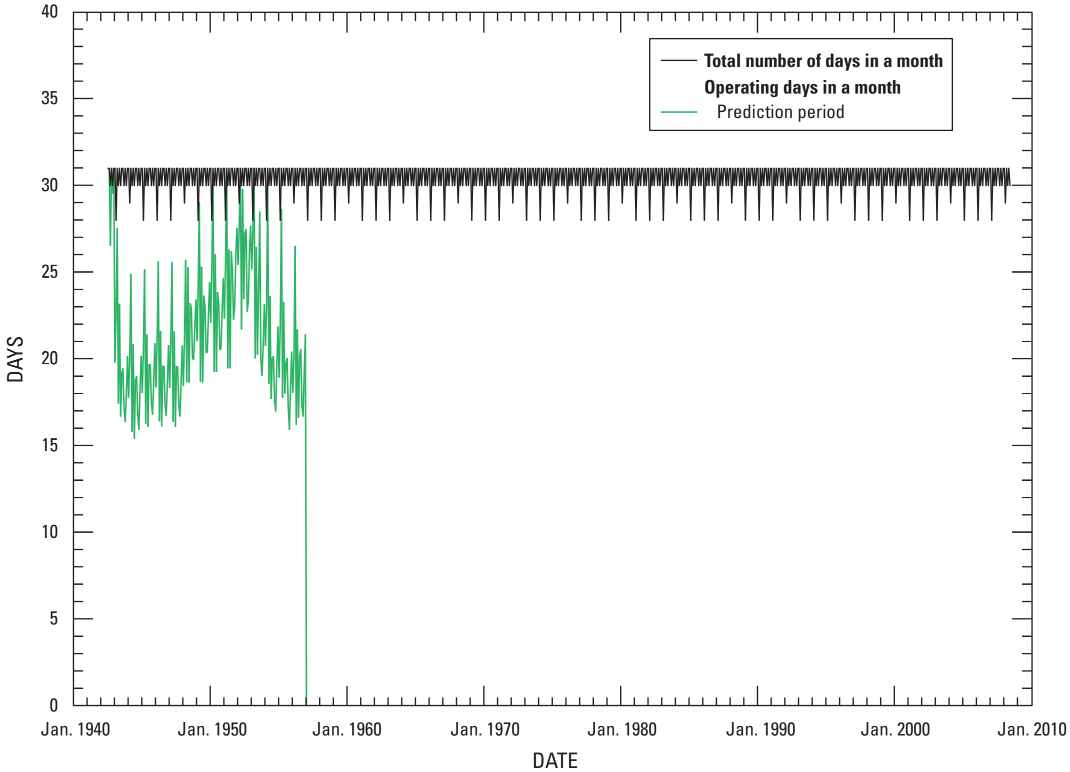

Figure S2.125. Estimated monthly operating days for well M-1.

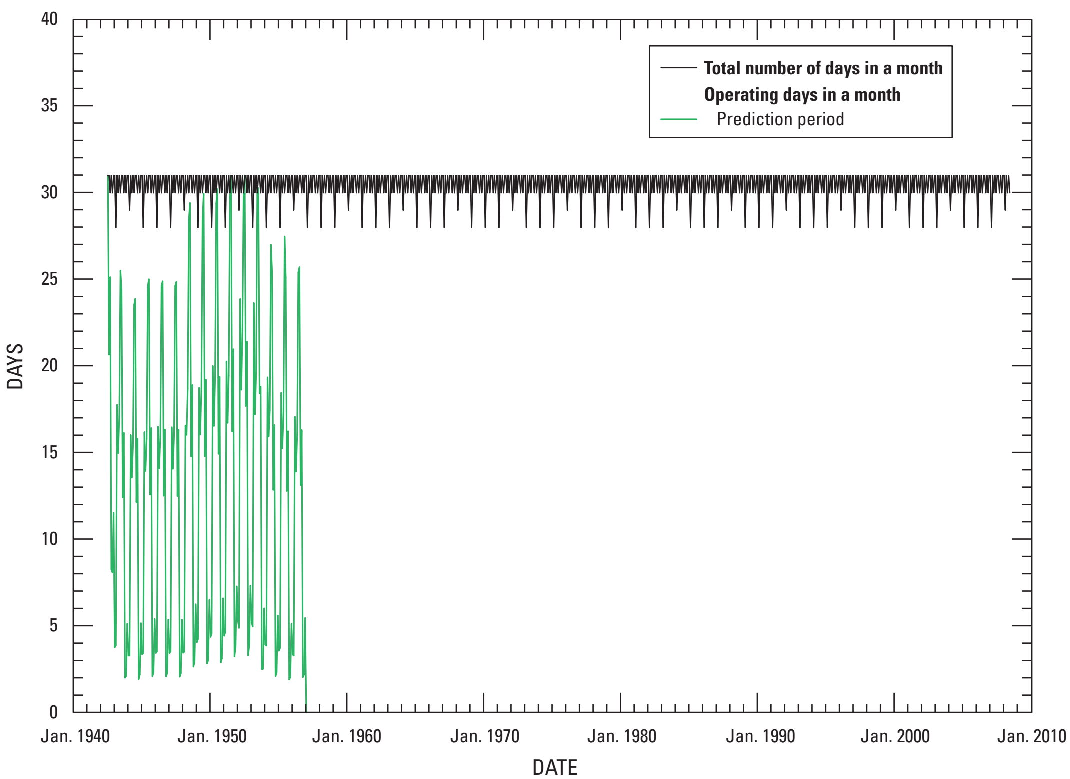

Figure S2.126. Estimated monthly operating days for well M-2.

Figures S2.127–S2.198. Estimated Monthly Water Volume Produced at Hadnot Point Wells

For operational chronology of all water-supply wells see Figure S2.2 in text.

Graphs showing estimated water volume produced at—

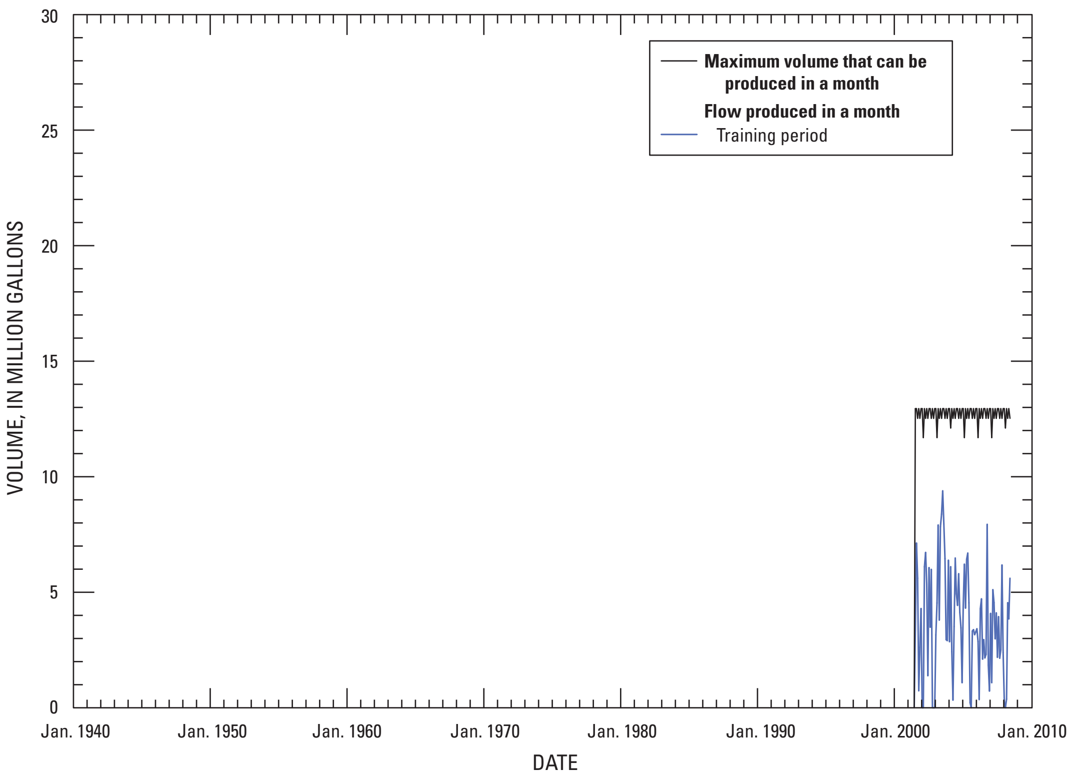

Figure S2.127. Estimated monthly water volume produced at well HP-585.

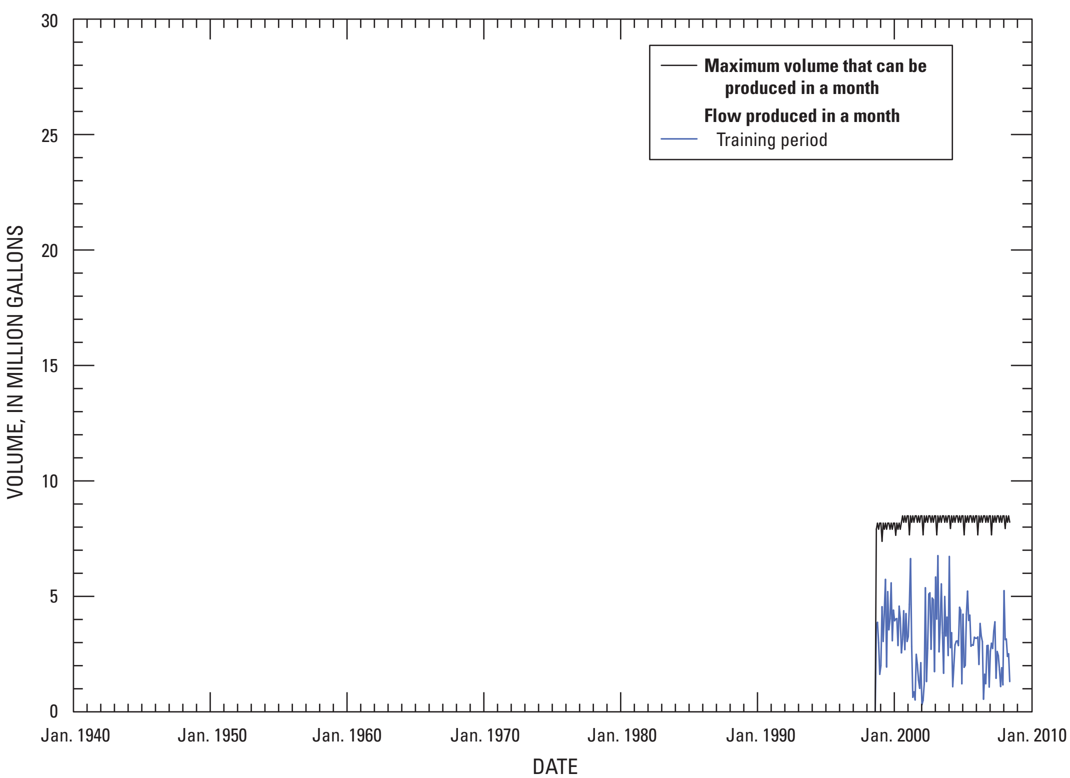

Figure S2.128. Estimated monthly water volume produced at well HP-595.

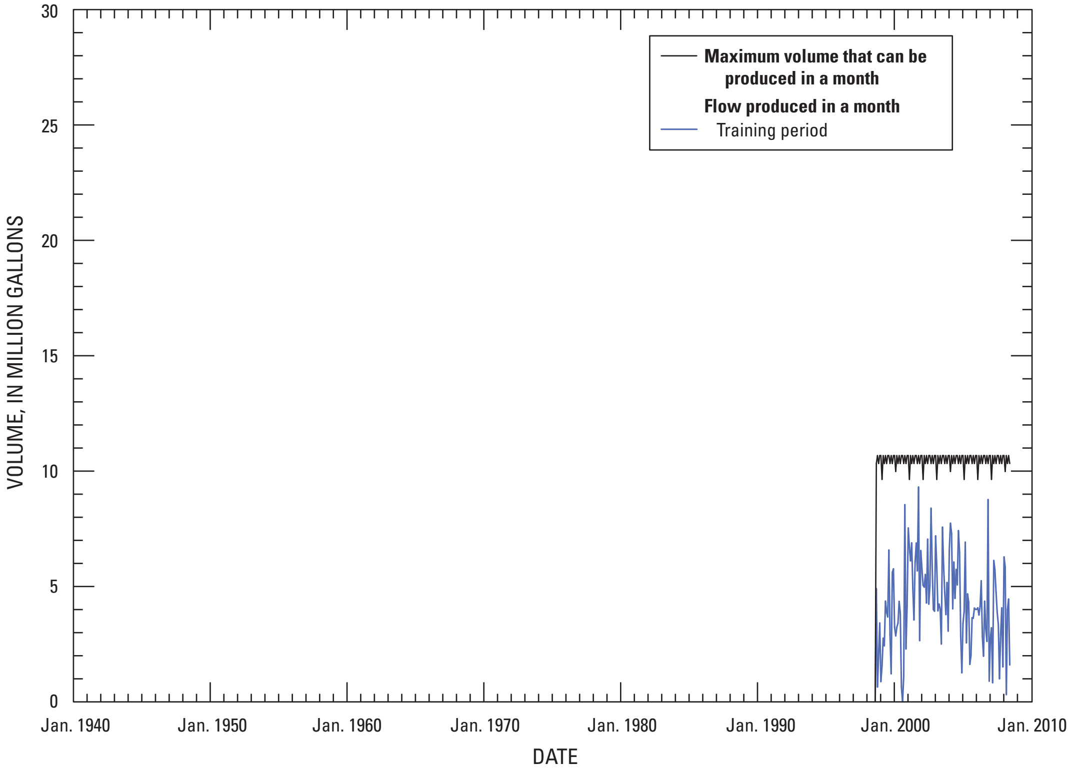

Figure S2.129. Estimated monthly water volume produced at well HP-596.

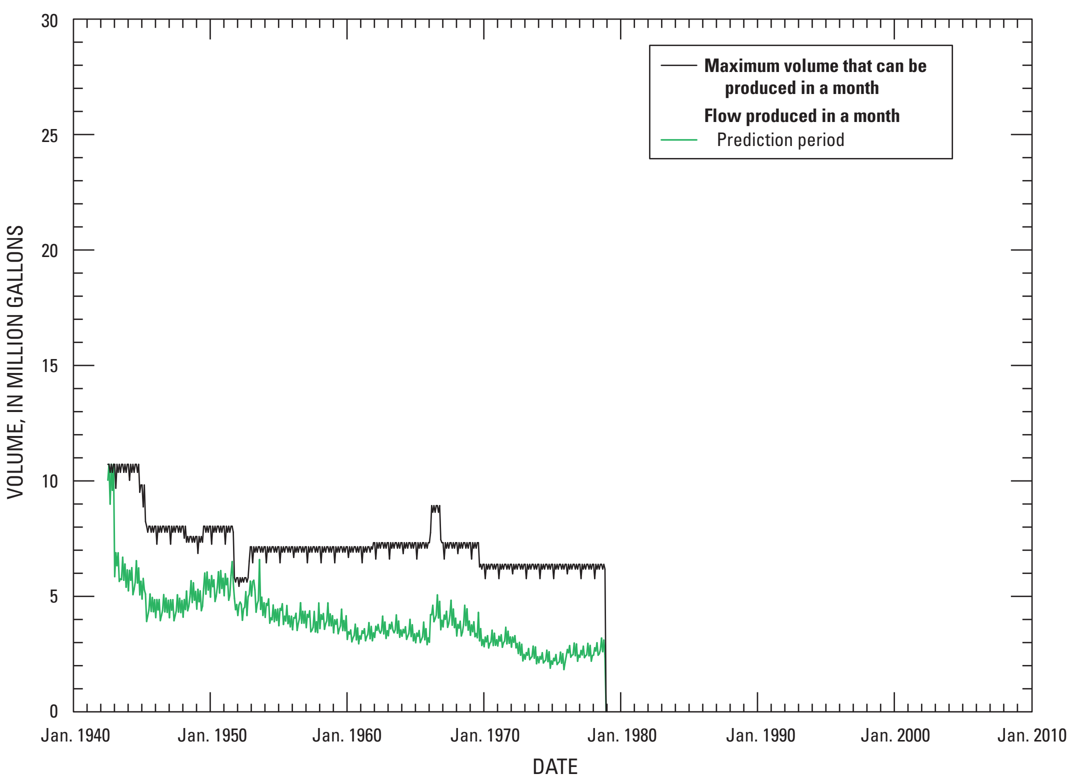

Figure S2.130. Estimated monthly water volume produced at well HP-601.

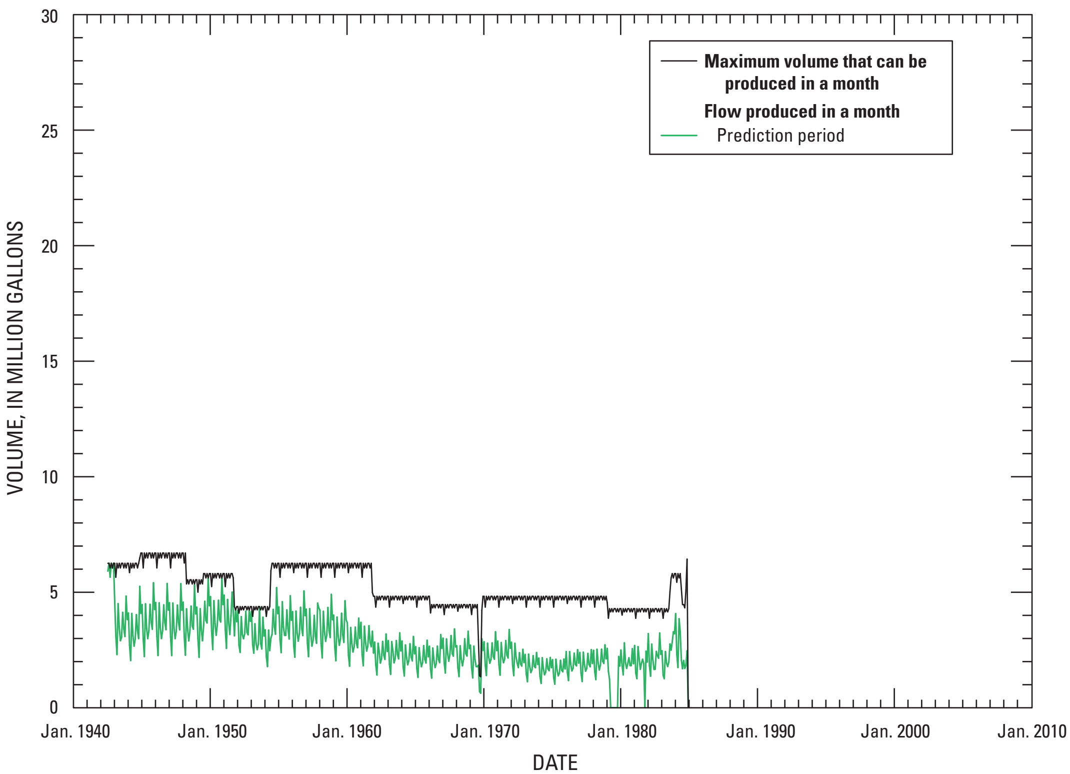

Figure S2.131. Estimated monthly water volume produced at well HP-602.

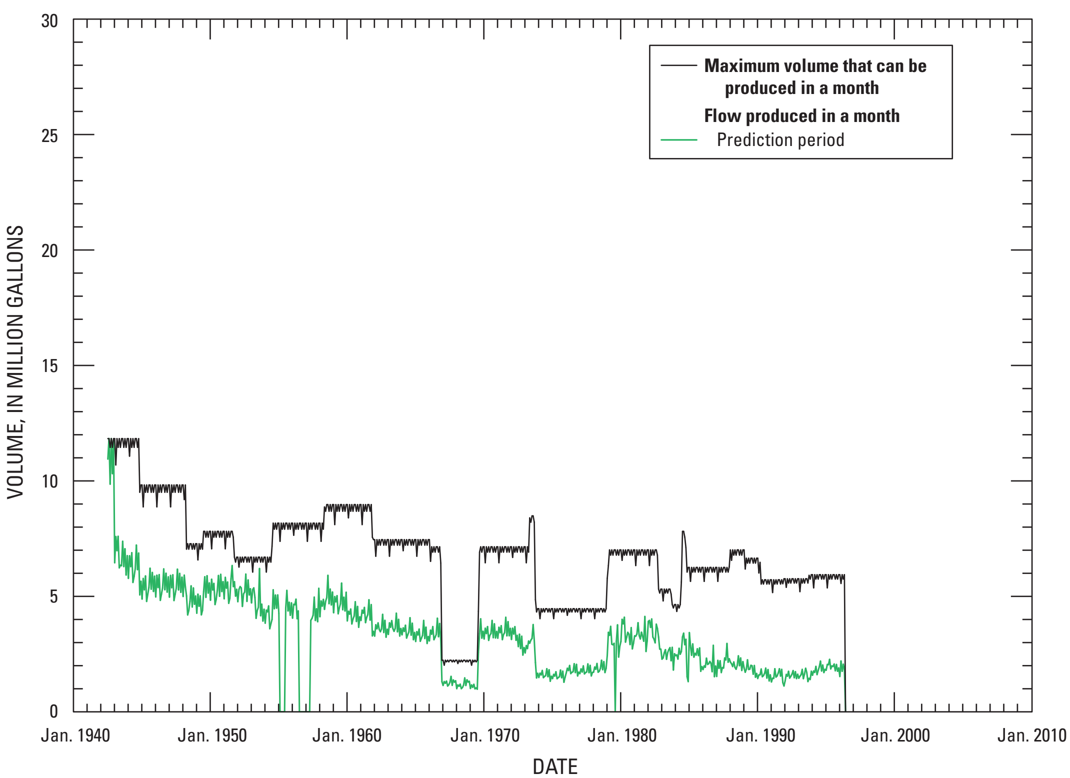

Figure S2.132. Estimated monthly water volume produced at well HP-603.

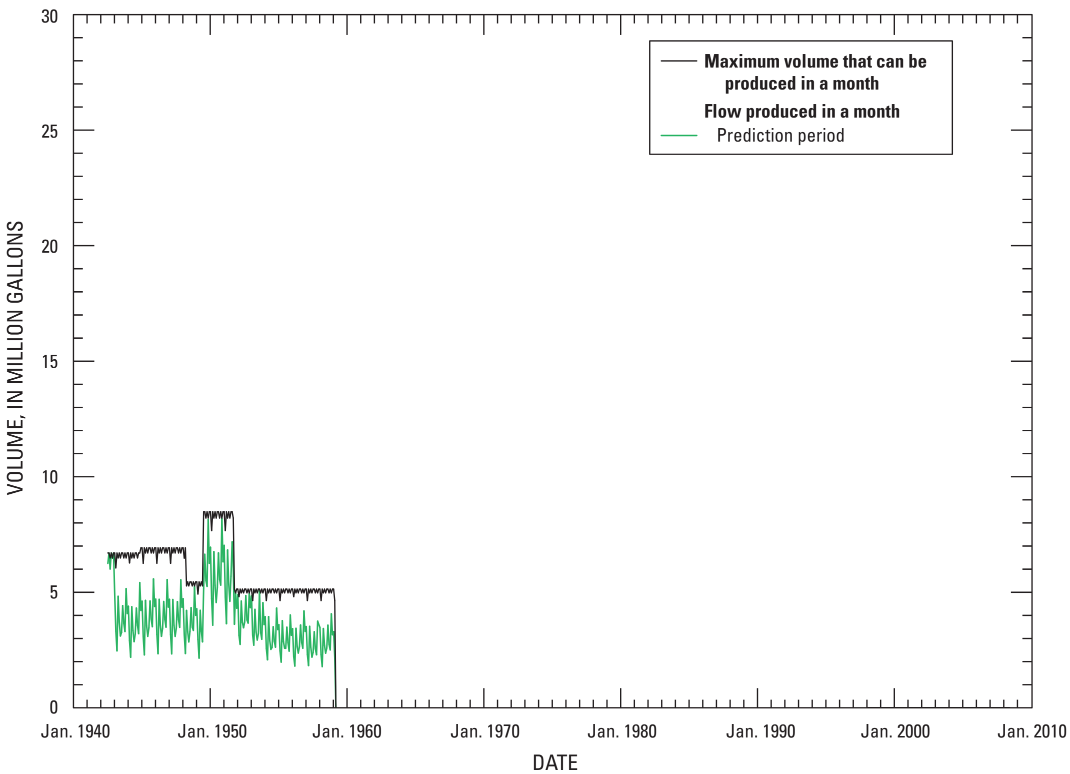

Figure S2.133. Estimated monthly water volume produced at well HP-604.

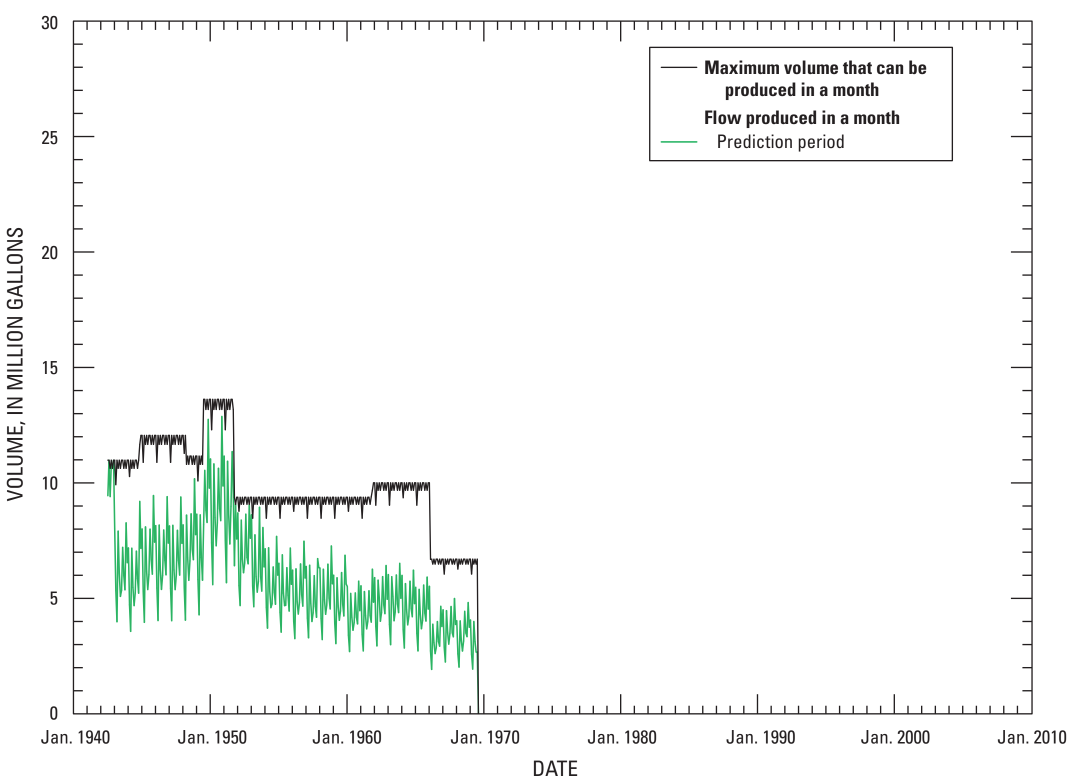

Figure S2.134. Estimated monthly water volume produced at well HP-605.

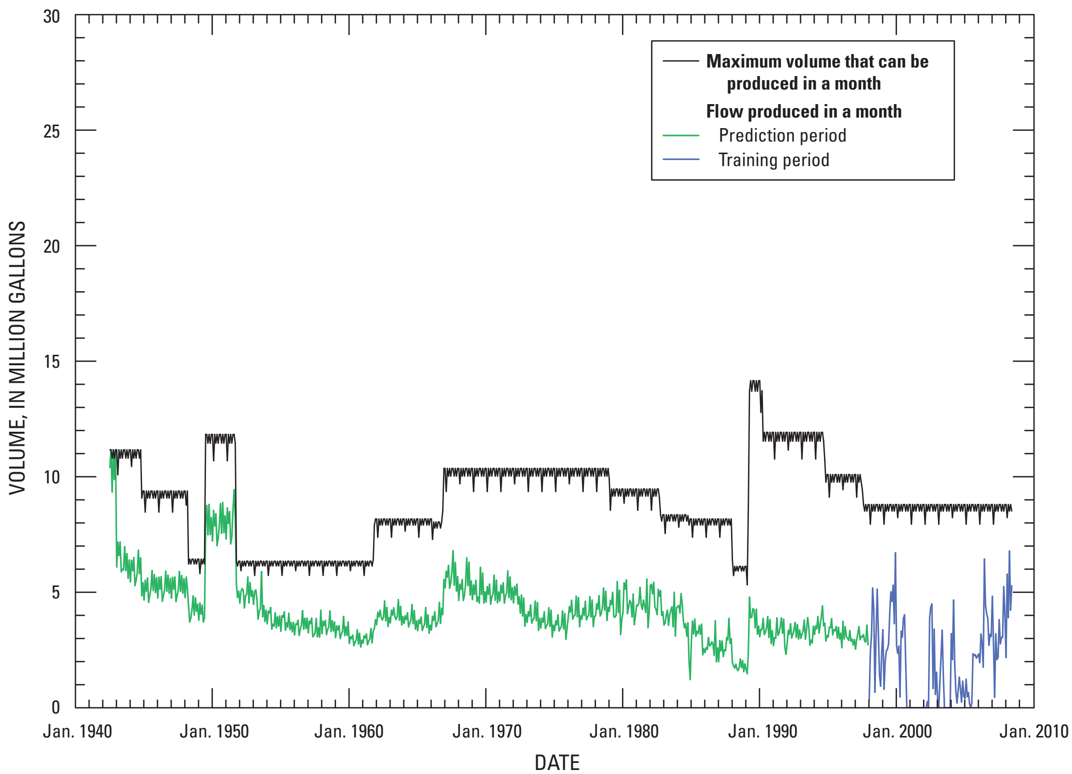

Figure S2.135. Estimated monthly water volume produced at well HP-606.

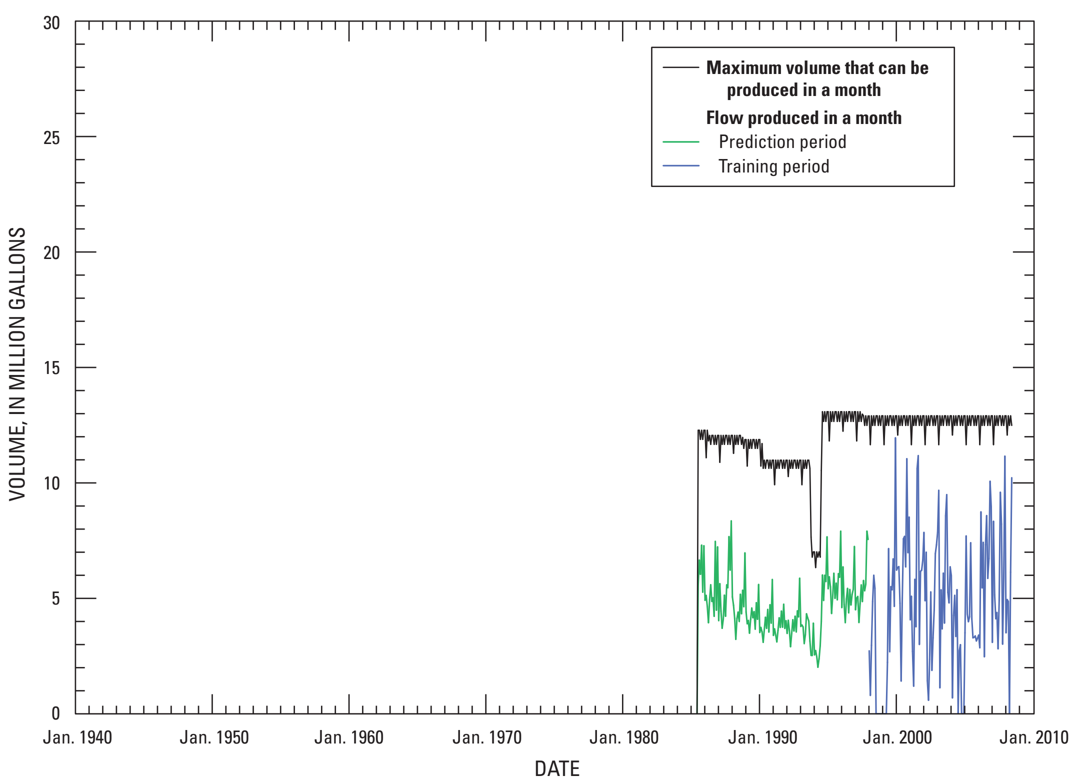

Figure S2.136. Estimated monthly water volume produced at well HP-607 (new).

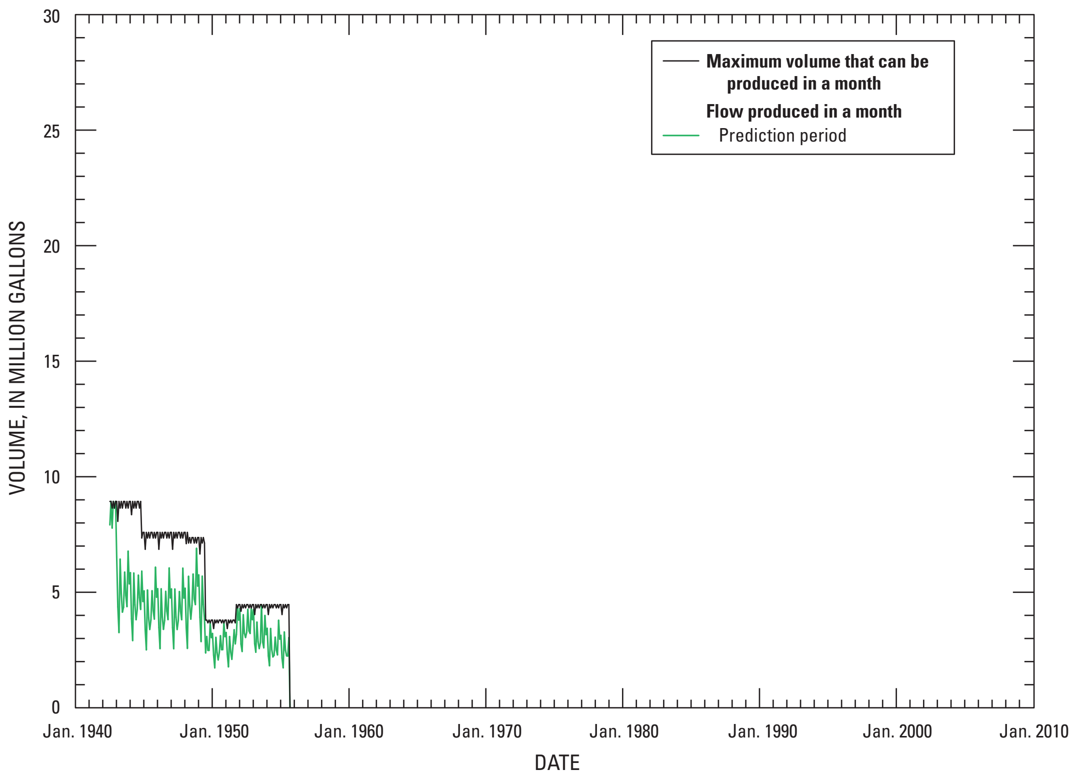

Figure S2.137. Estimated monthly water volume produced at well HP-607 (old).

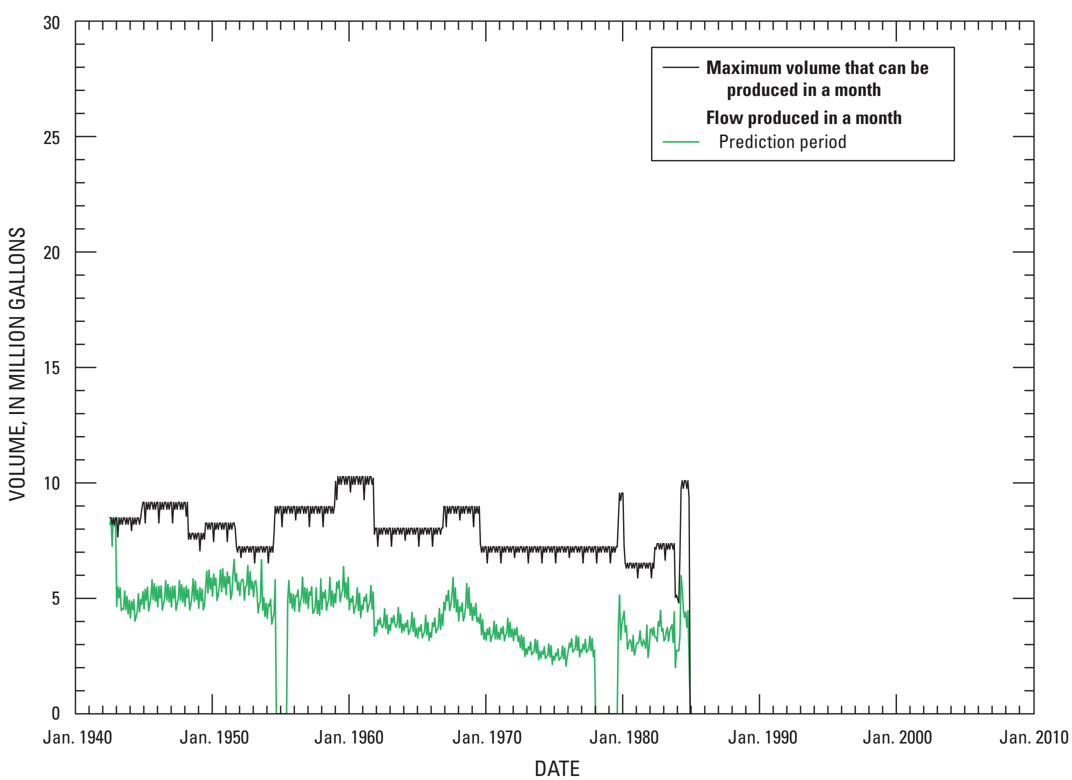

Figure S2.138. Estimated monthly water volume produced at well HP-608.

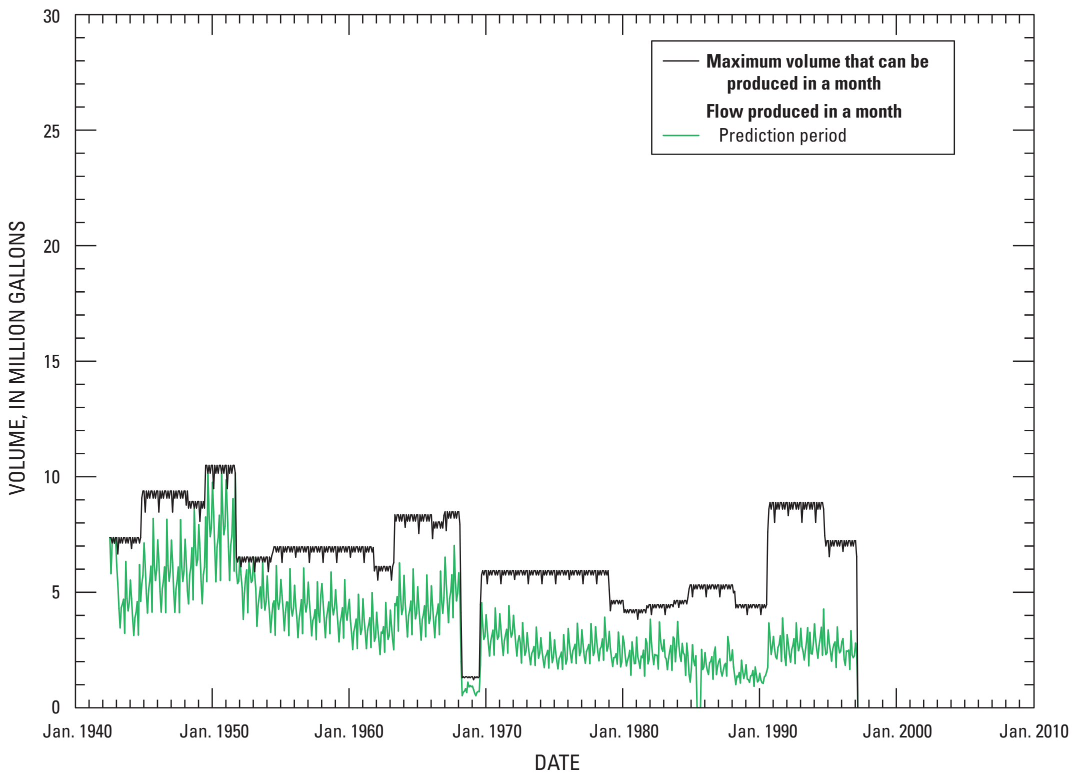

Figure S2.139. Estimated monthly water volume produced at well HP-609.

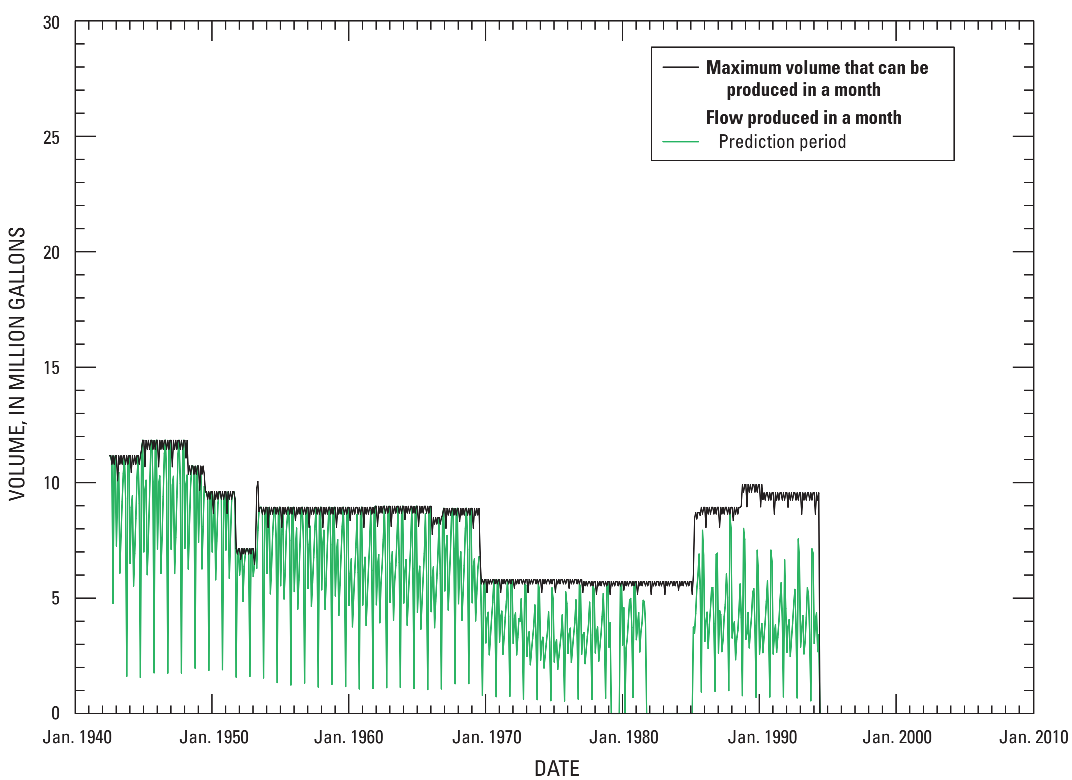

Figure S2.140. Estimated monthly water volume produced at well HP-610.

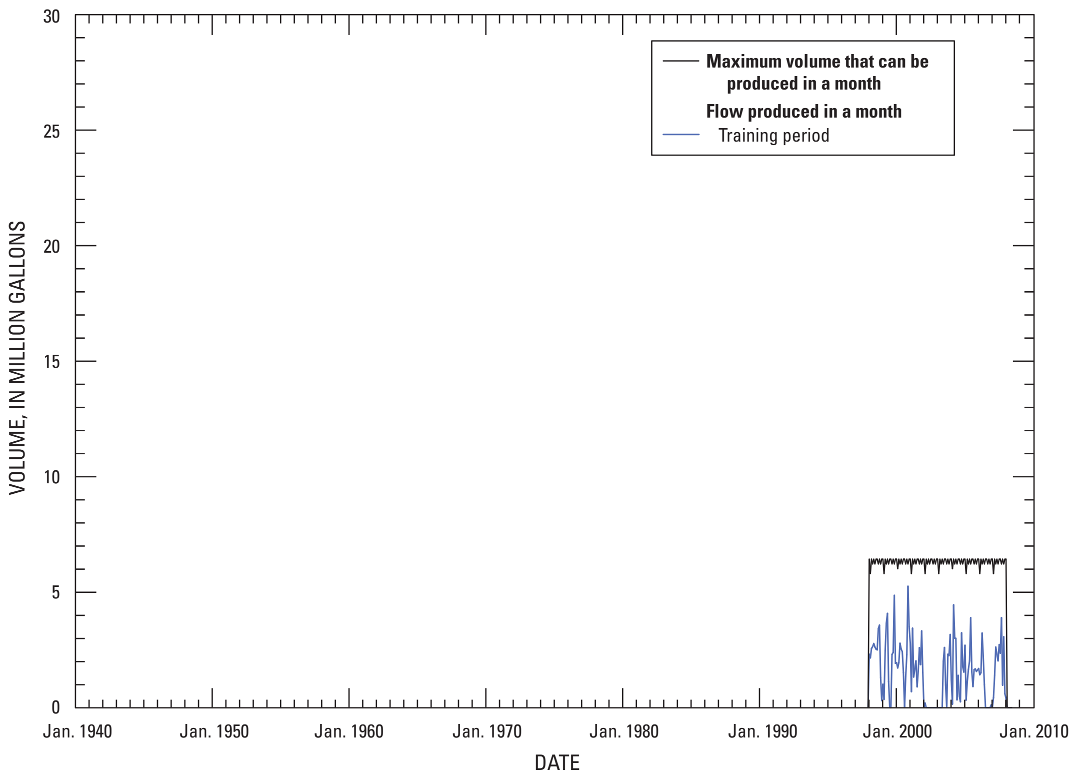

Figure S2.141. Estimated monthly water volume produced at well HP-611 (new).

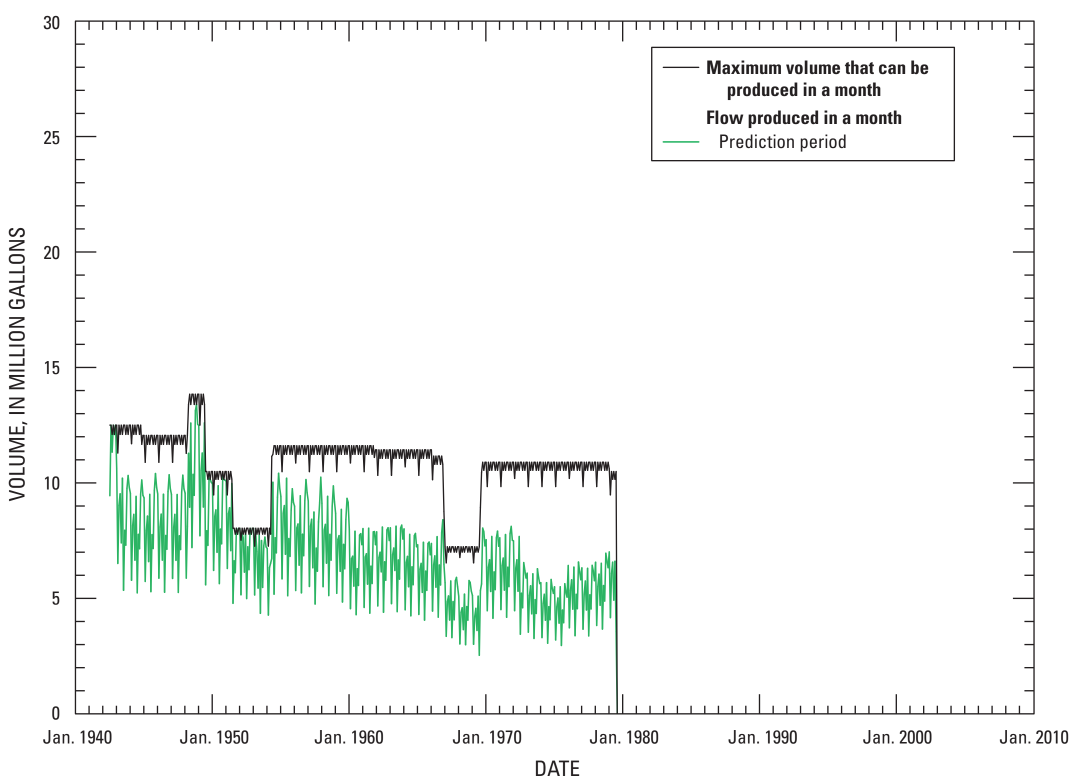

Figure S2.142. Estimated monthly water volume produced at well HP-611 (old).

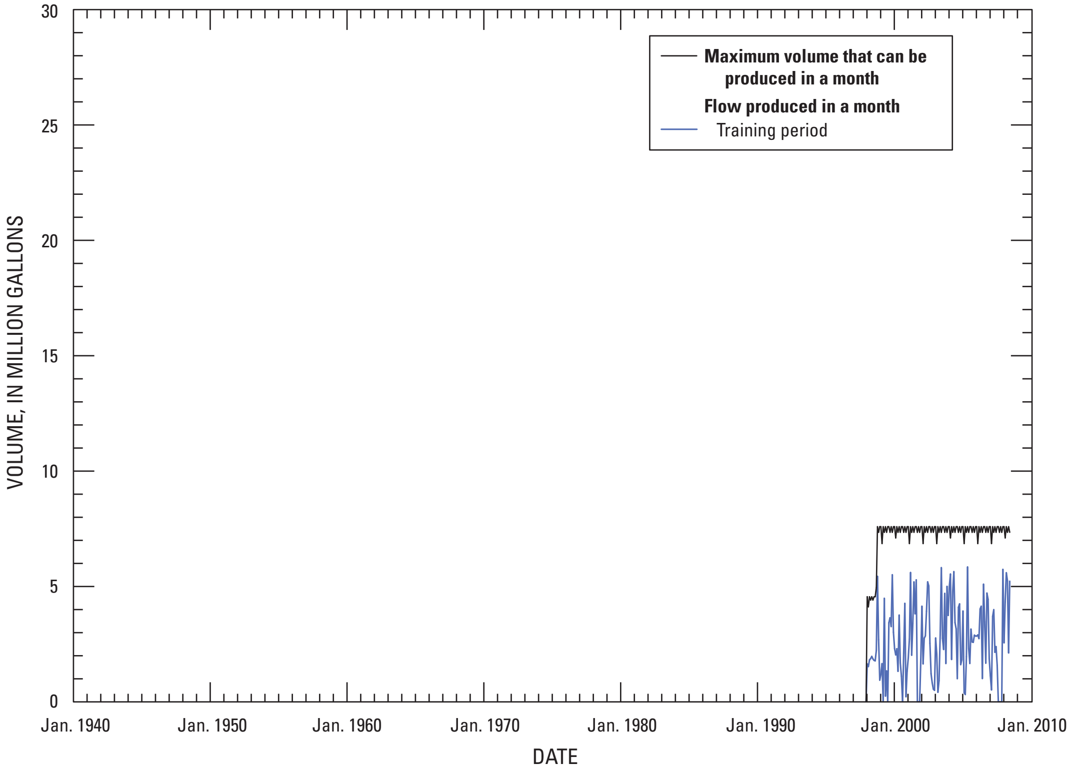

Figure S2.143. Estimated monthly water volume produced at well HP-612 (new).

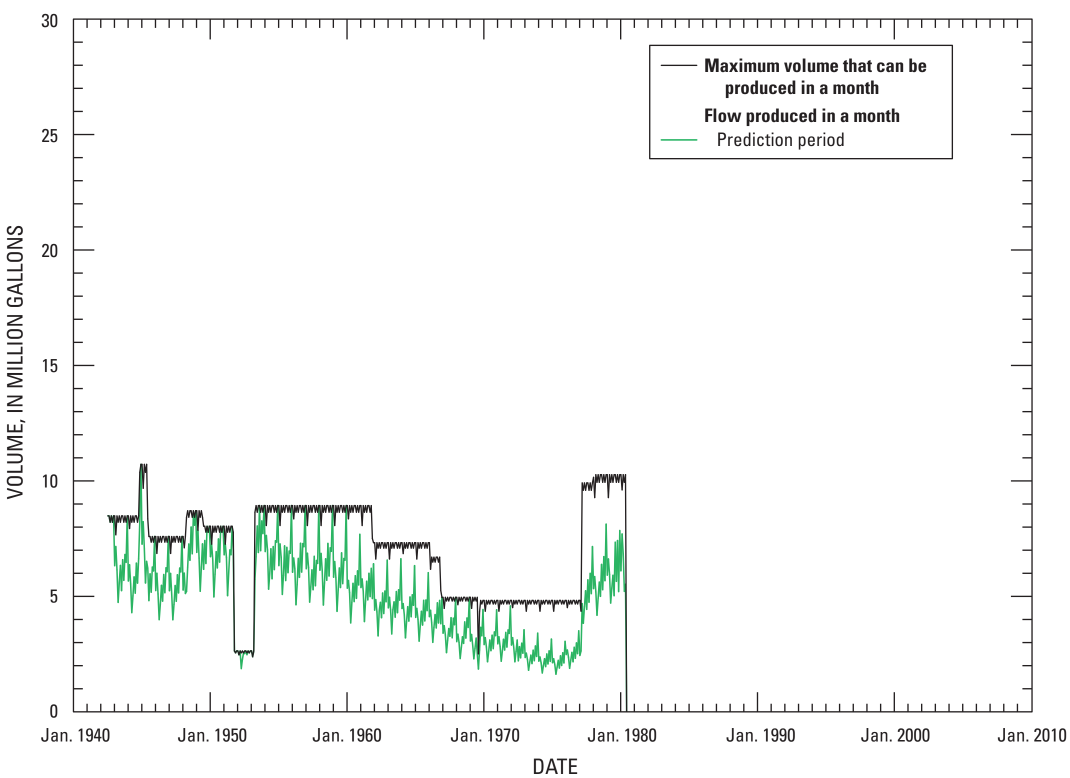

Figure S2.144. Estimated monthly water volume produced at well HP-612 (old).

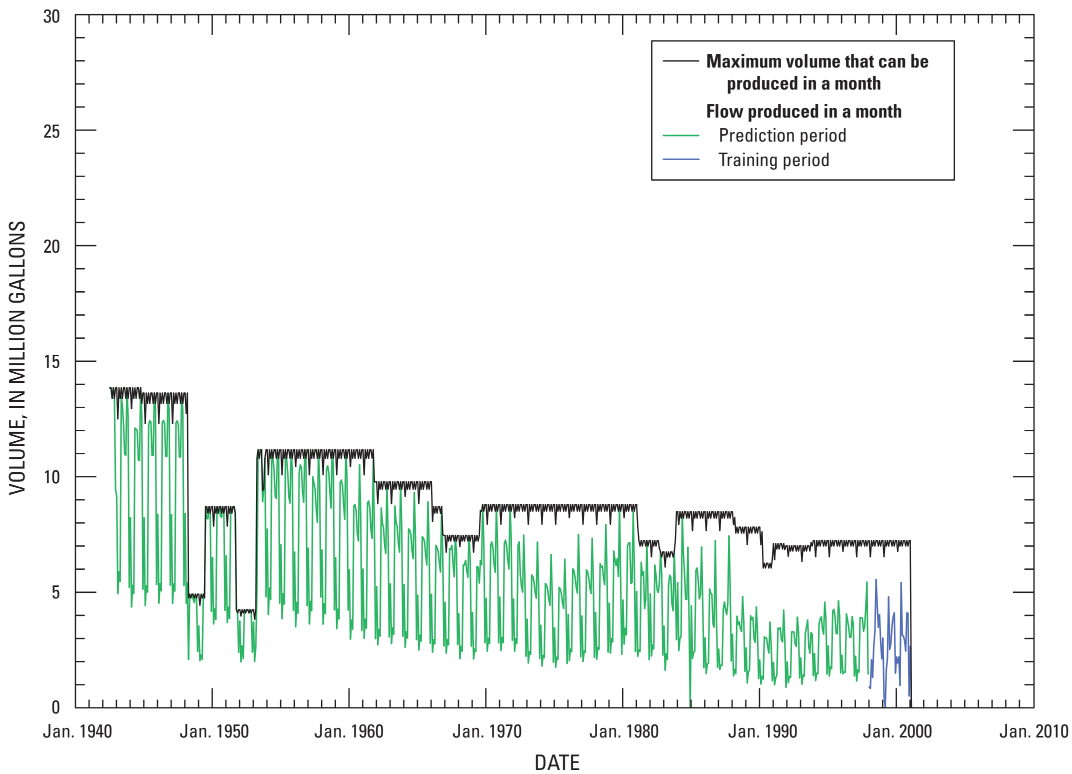

Figure S2.145. Estimated monthly water volume produced at well HP-613.

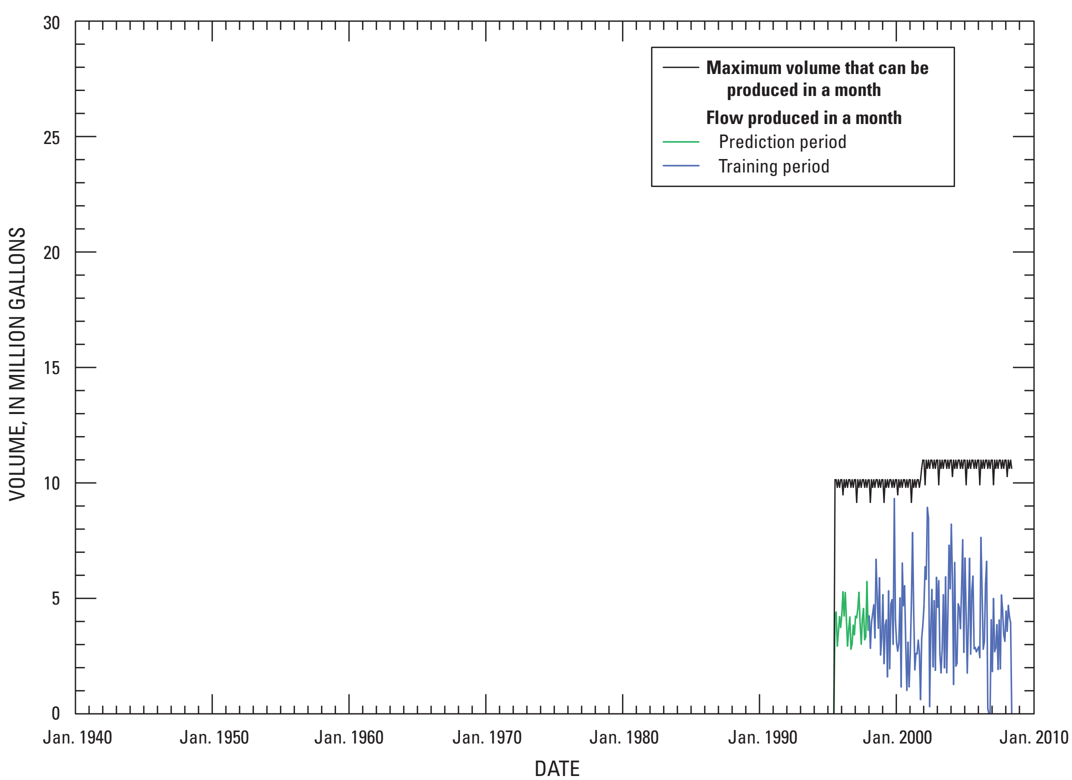

Figure S2.146. Estimated monthly water volume produced at well HP-614 (new).

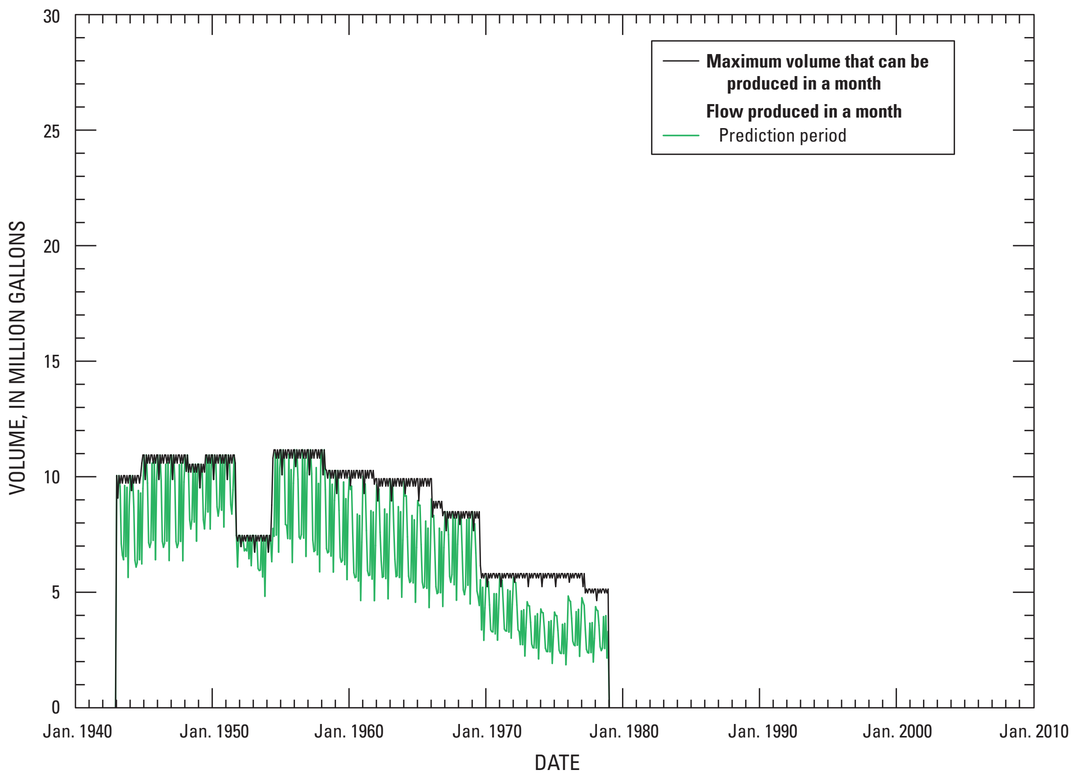

Figure S2.147. Estimated monthly water volume produced at well HP-614 (old).

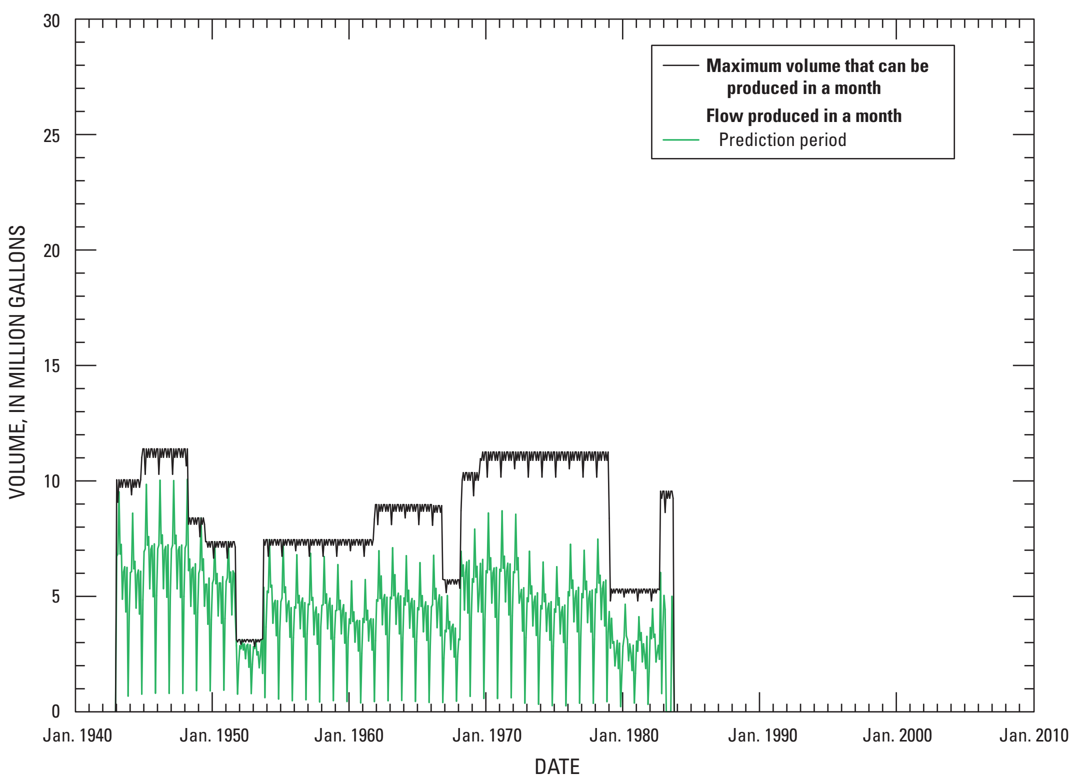

Figure S2.148. Estimated monthly water volume produced at well HP-615.

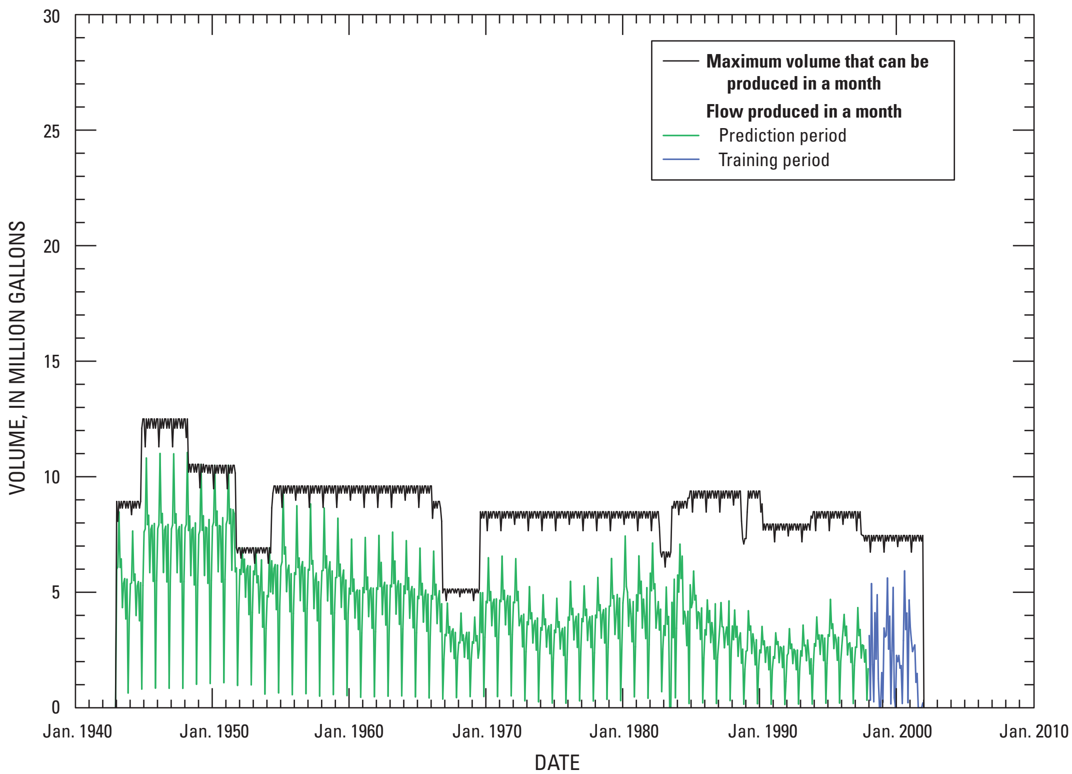

Figure S2.149. Estimated monthly water volume produced at well HP-616.

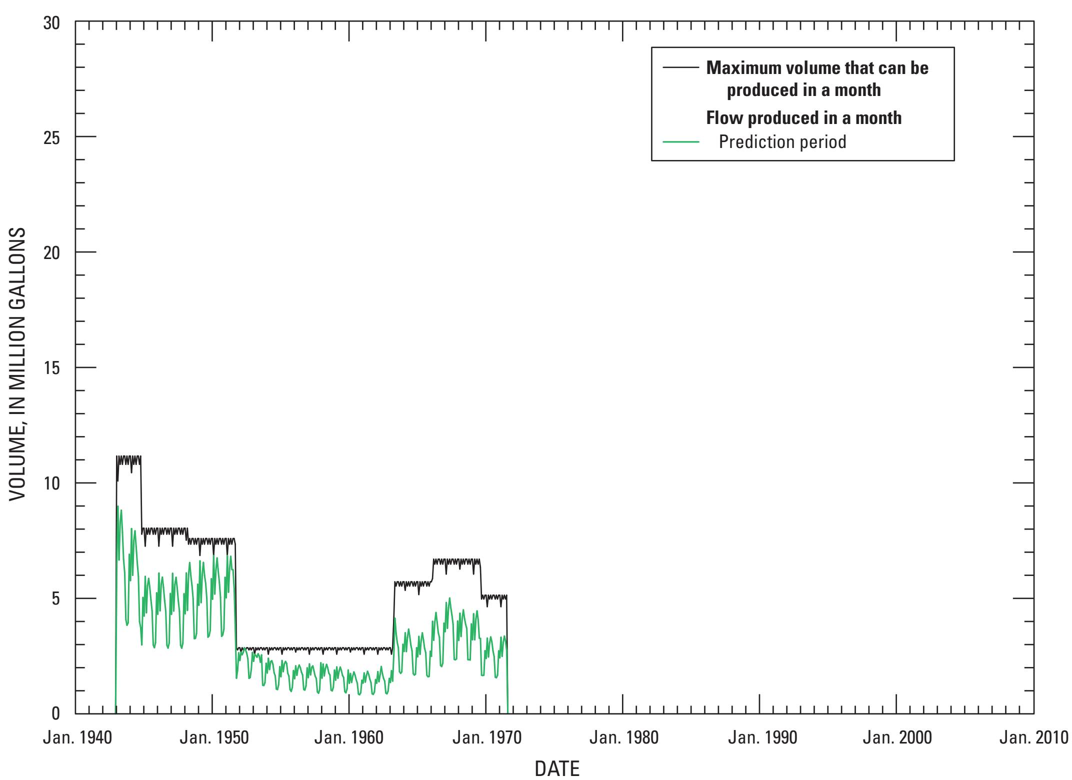

Figure S2.150. Estimated monthly water volume produced at well HP-617 (old).

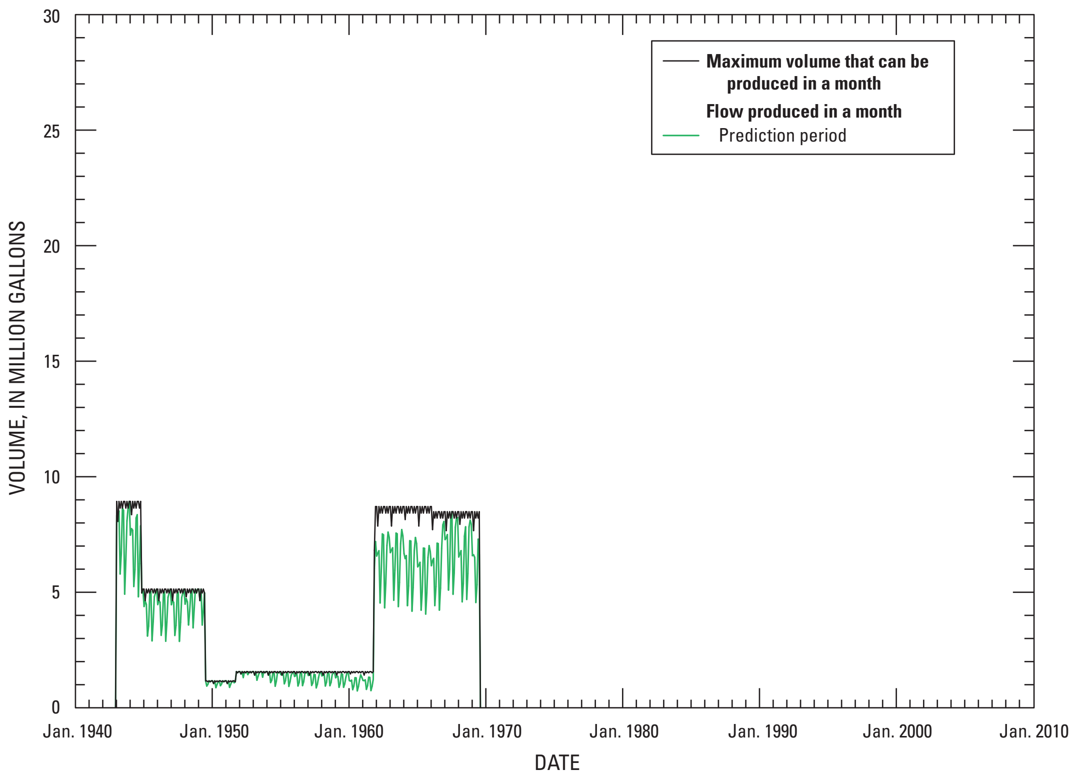

Figure S2.151. Estimated monthly water volume produced at well HP-618 (old).

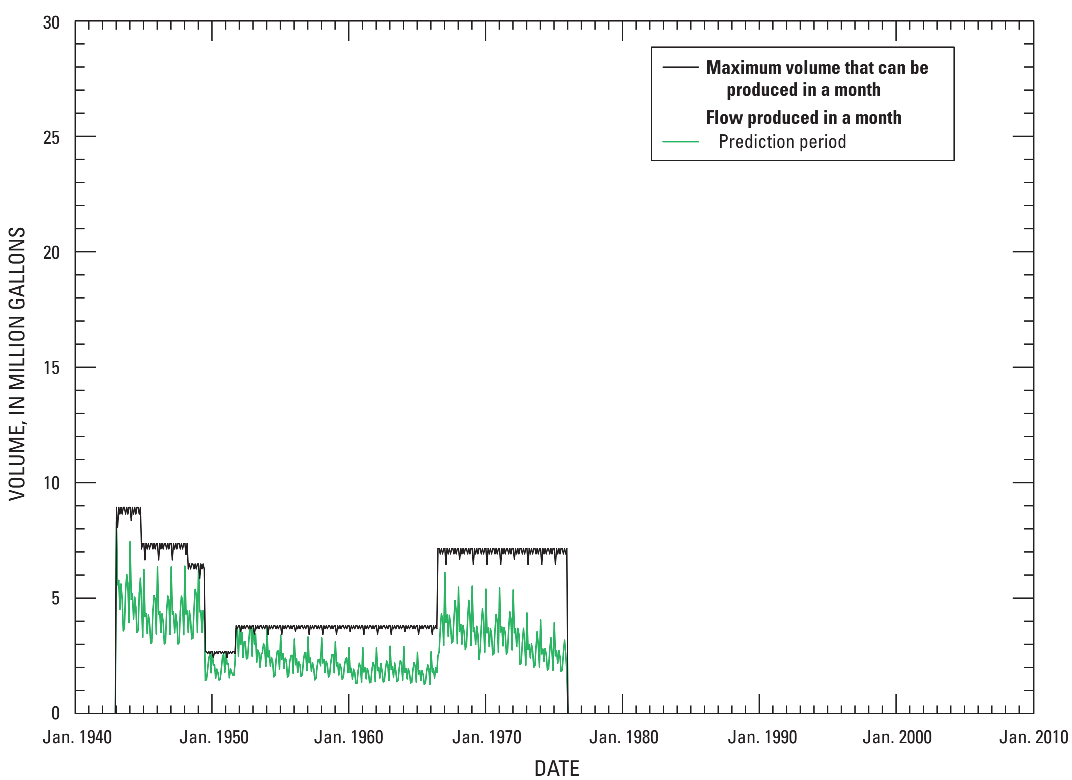

Figure S2.152. Estimated monthly water volume produced at well HP-619 (old).

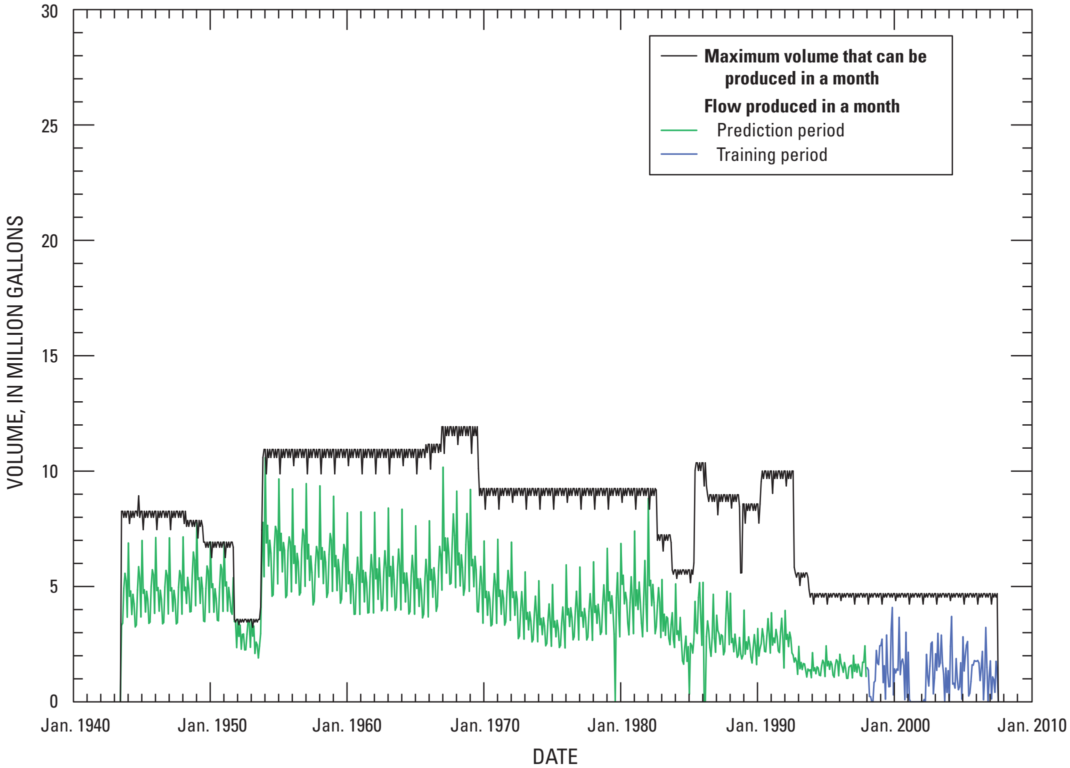

Figure S2.153. Estimated monthly water volume produced at well HP-620.

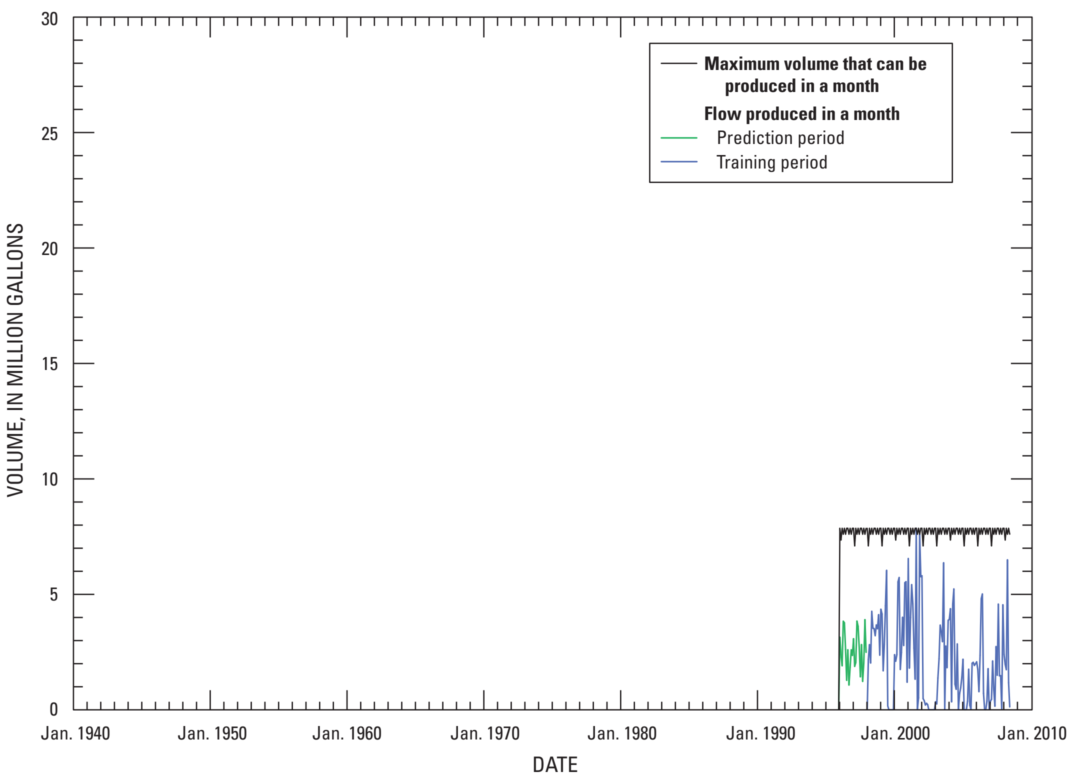

Figure S2.154. Estimated monthly water volume produced at well HP-621 (new).

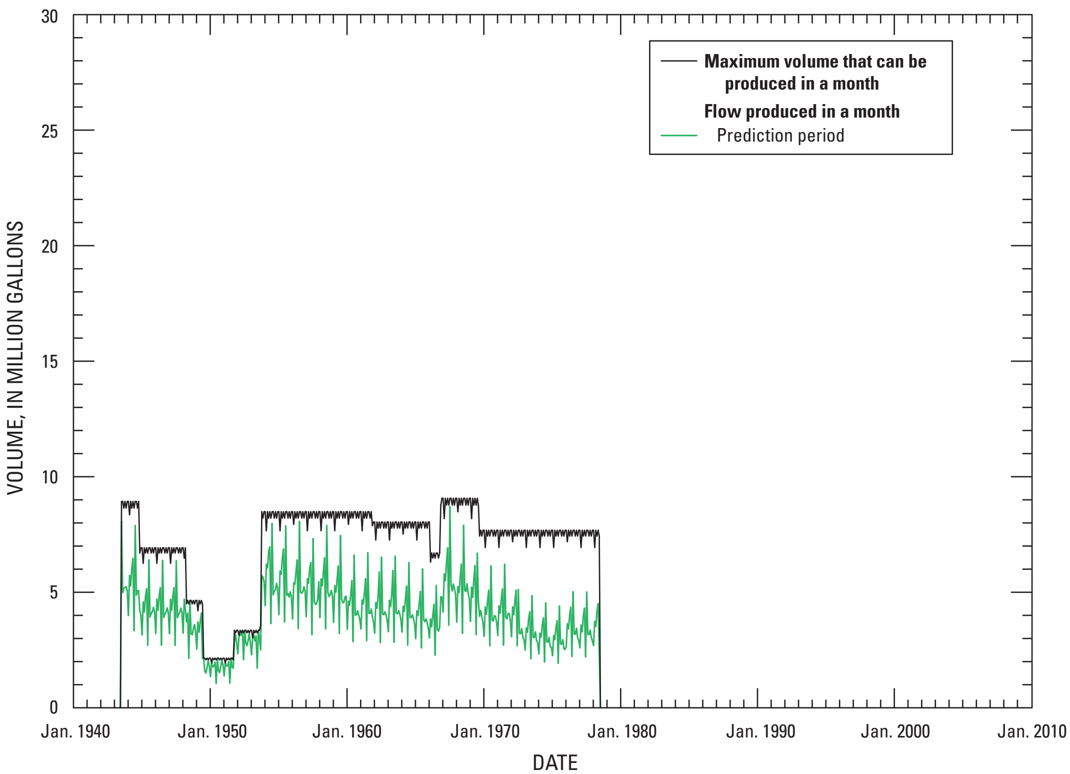

Figure S2.155. Estimated monthly water volume produced at well HP-621 (old).

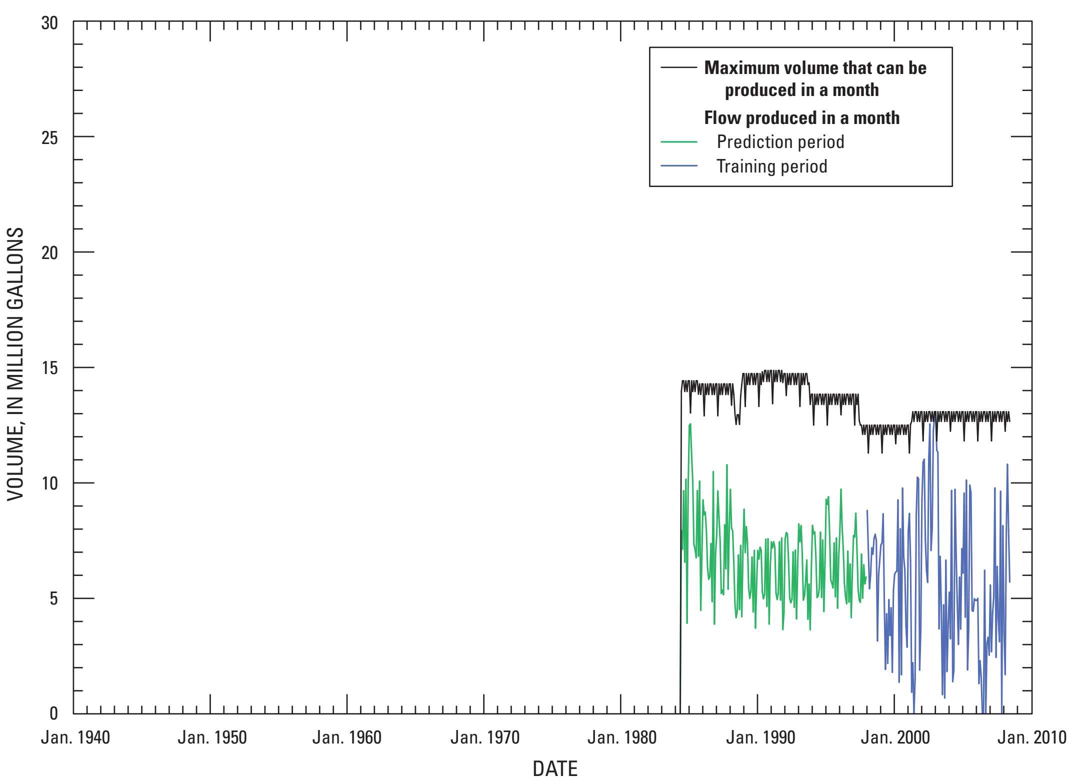

Figure S2.156. Estimated monthly water volume produced at well HP-622.

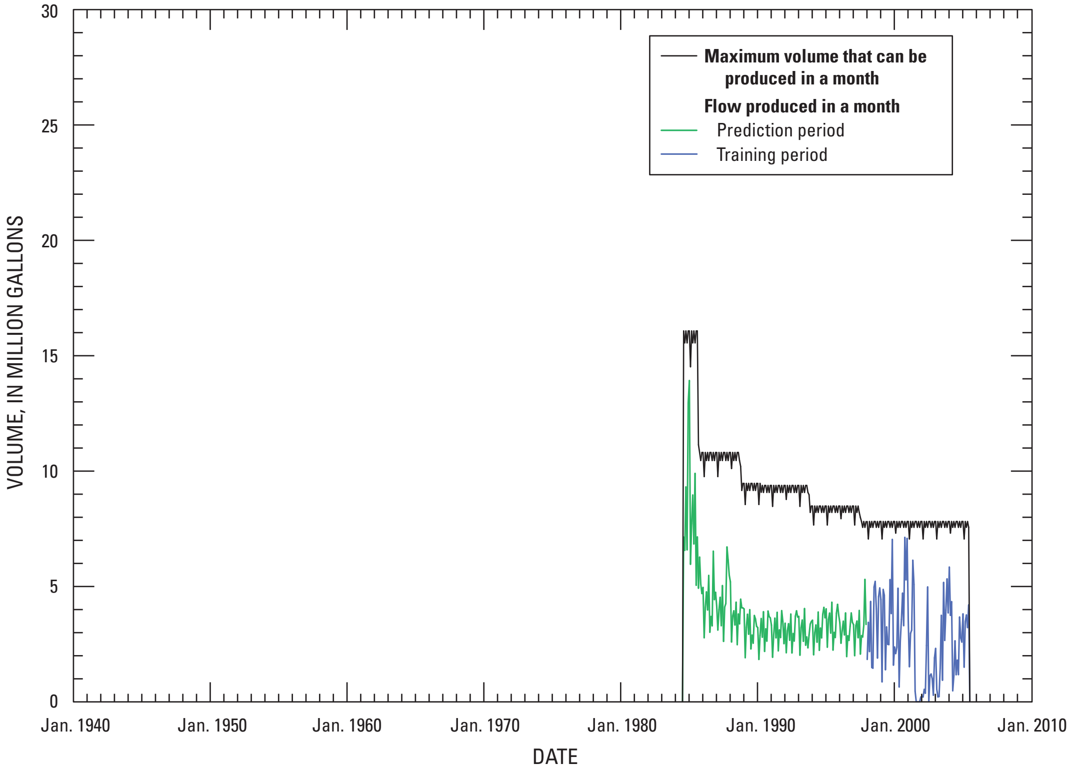

Figure S2.157. Estimated monthly water volume produced at well HP-623.

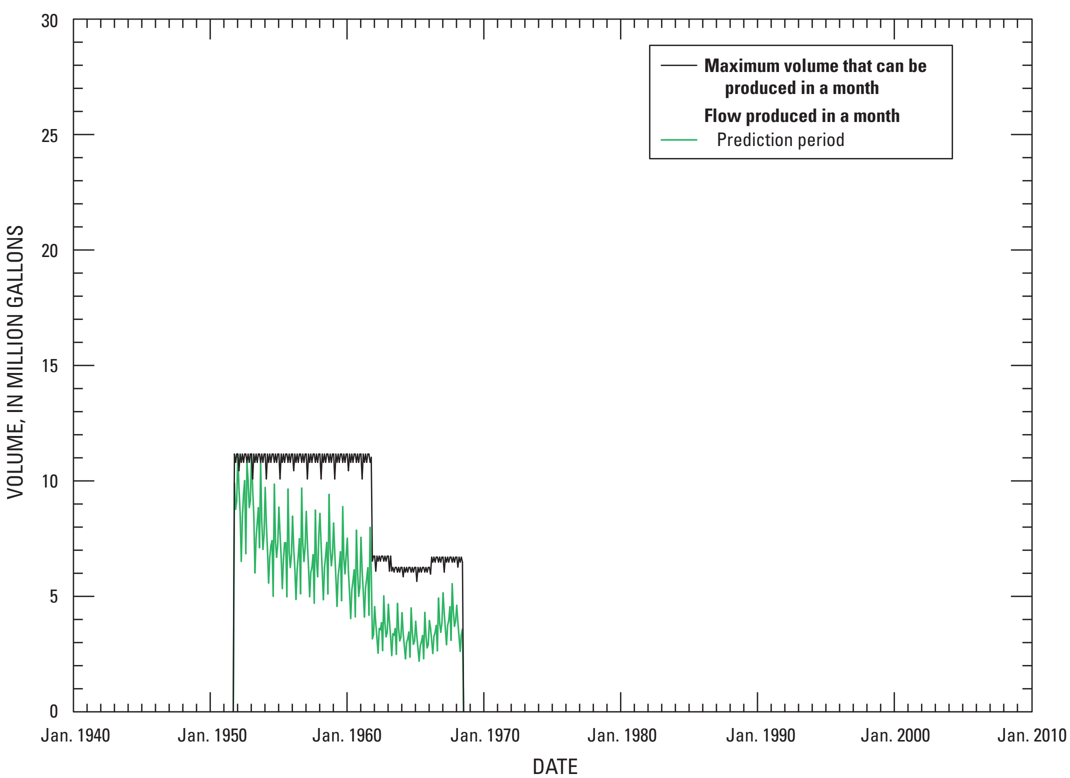

Figure S2.158. Estimated monthly water volume produced at well HP-624.

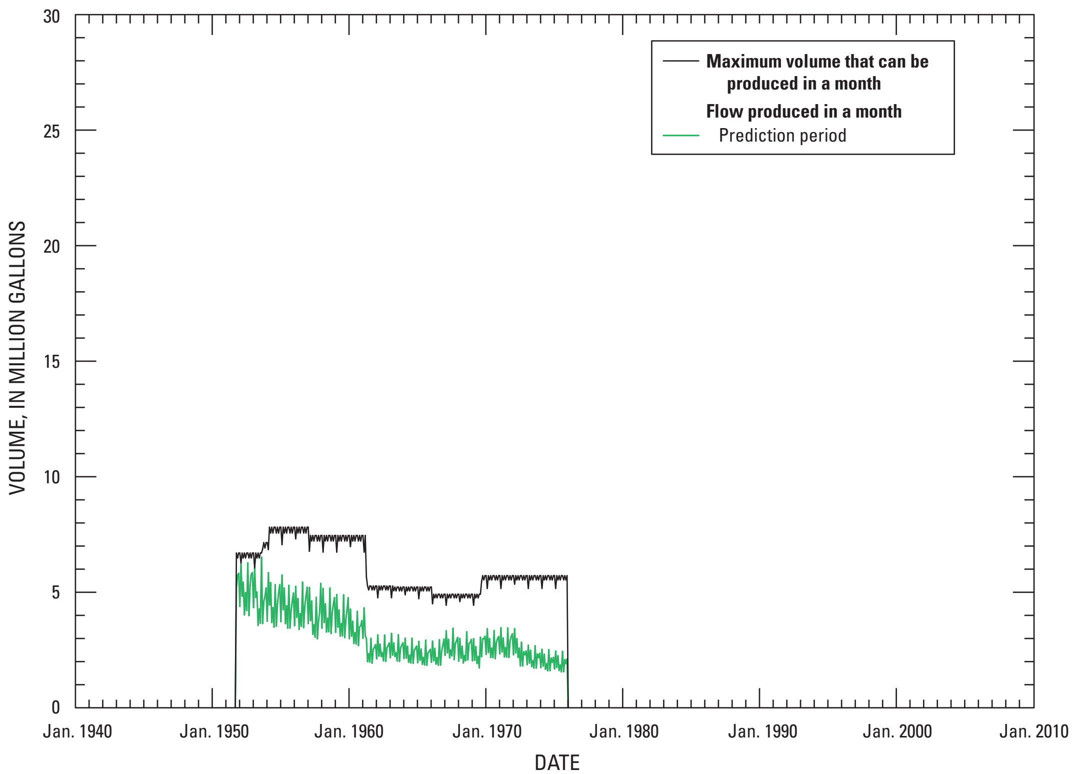

Figure S2.159. Estimated monthly water volume produced at well HP-625.

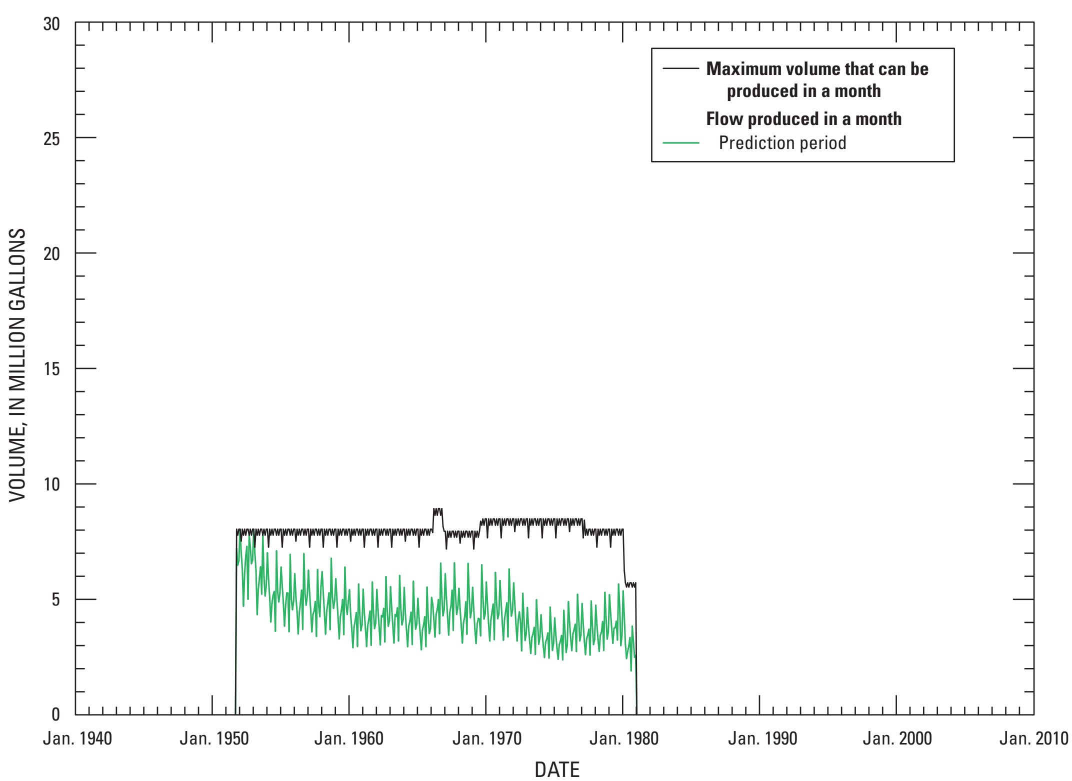

Figure S2.160. Estimated monthly water volume produced at well HP-626.

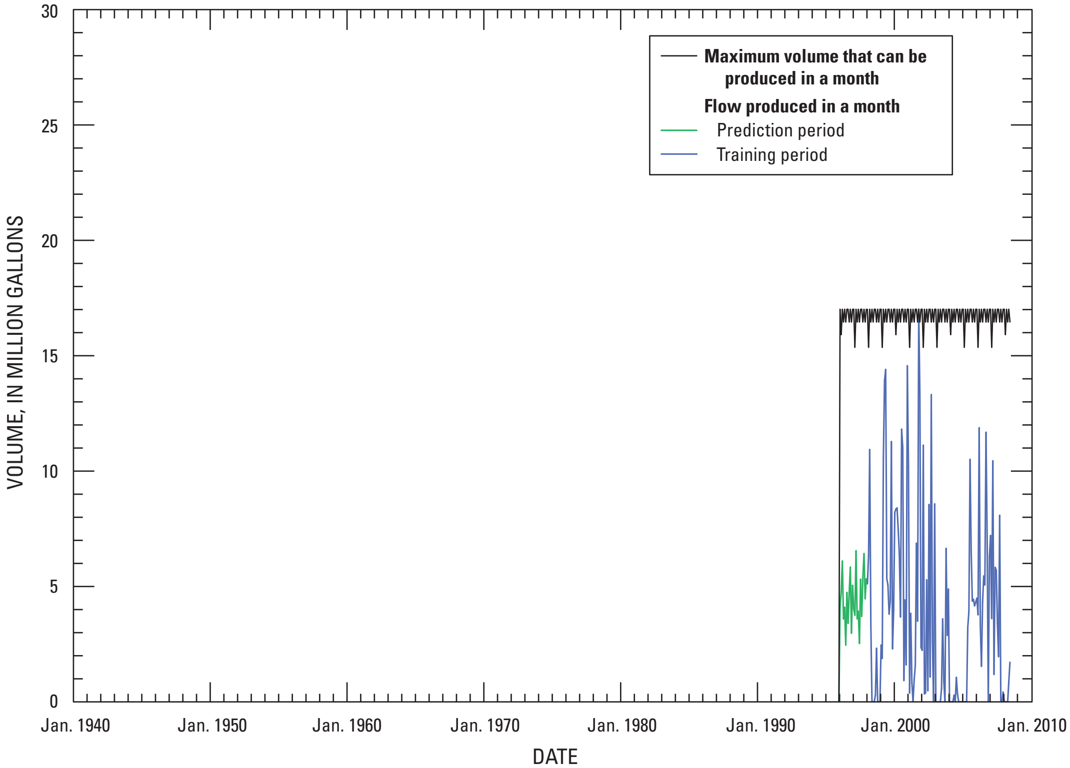

Figure S2.161. Estimated monthly water volume produced at well HP-627 (new).

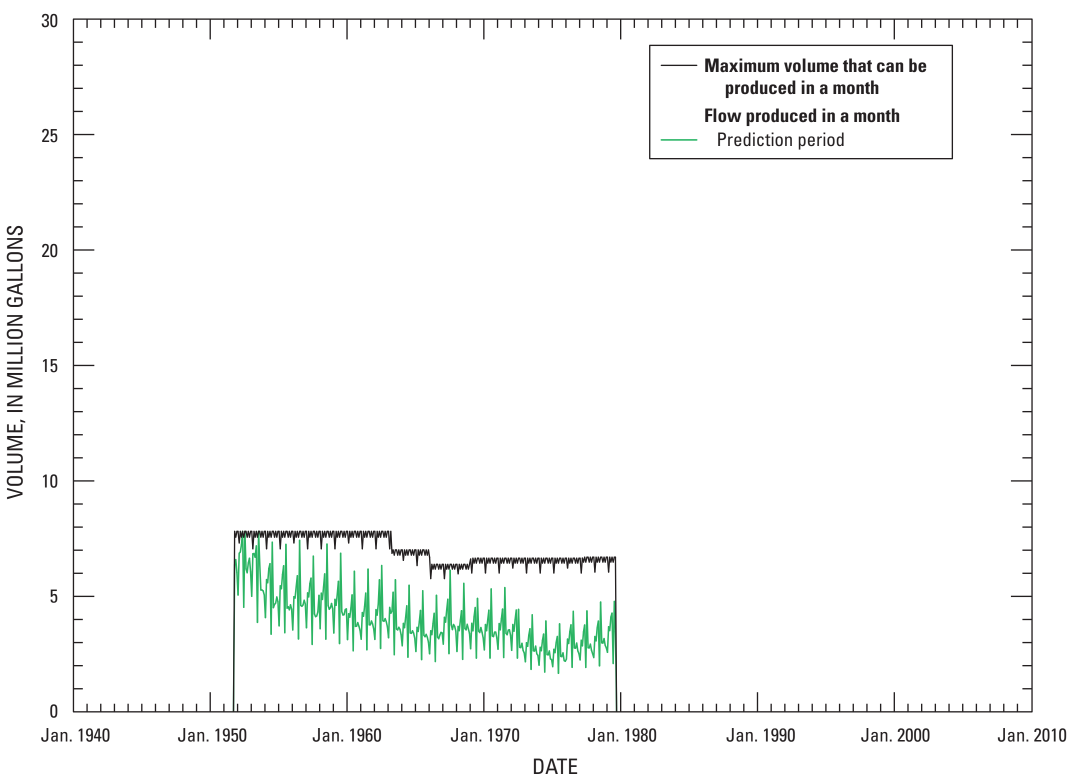

Figure S2.162. Estimated monthly water volume produced at well HP-627 (old).

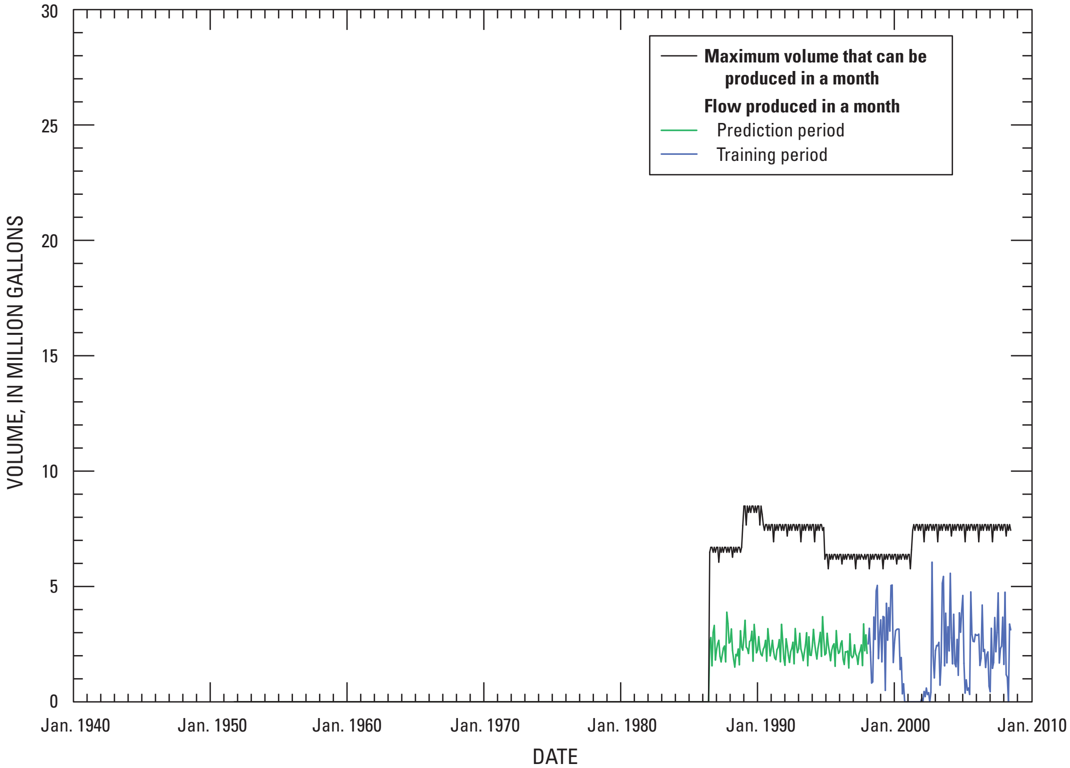

Figure S2.163. Estimated monthly water volume produced at well HP-628 (new).

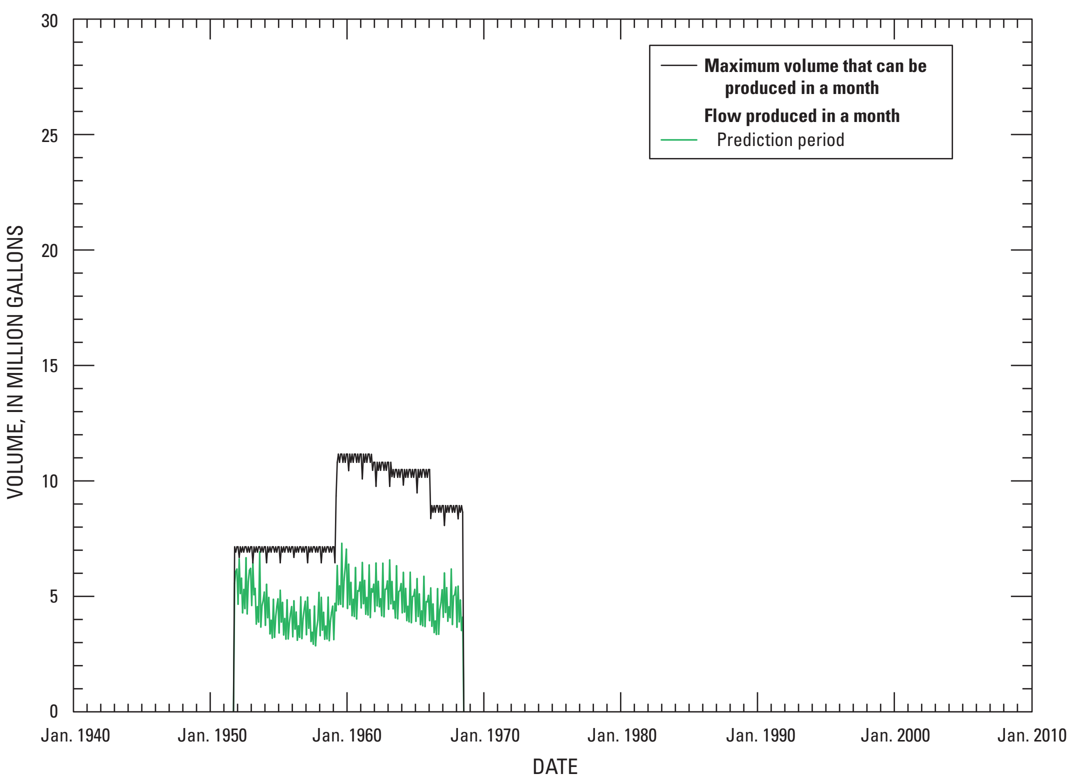

Figure S2.164. Estimated monthly water volume produced at well HP-628 (old).

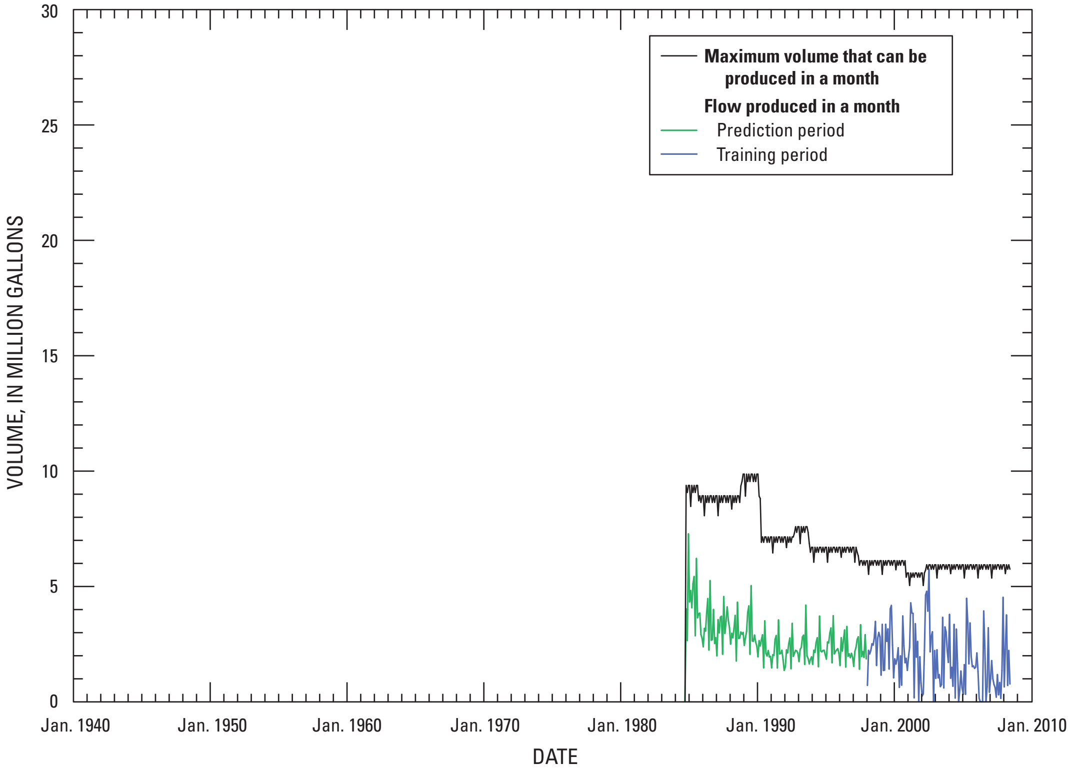

Figure S2.165. Estimated monthly water volume produced at well HP-629 (new).

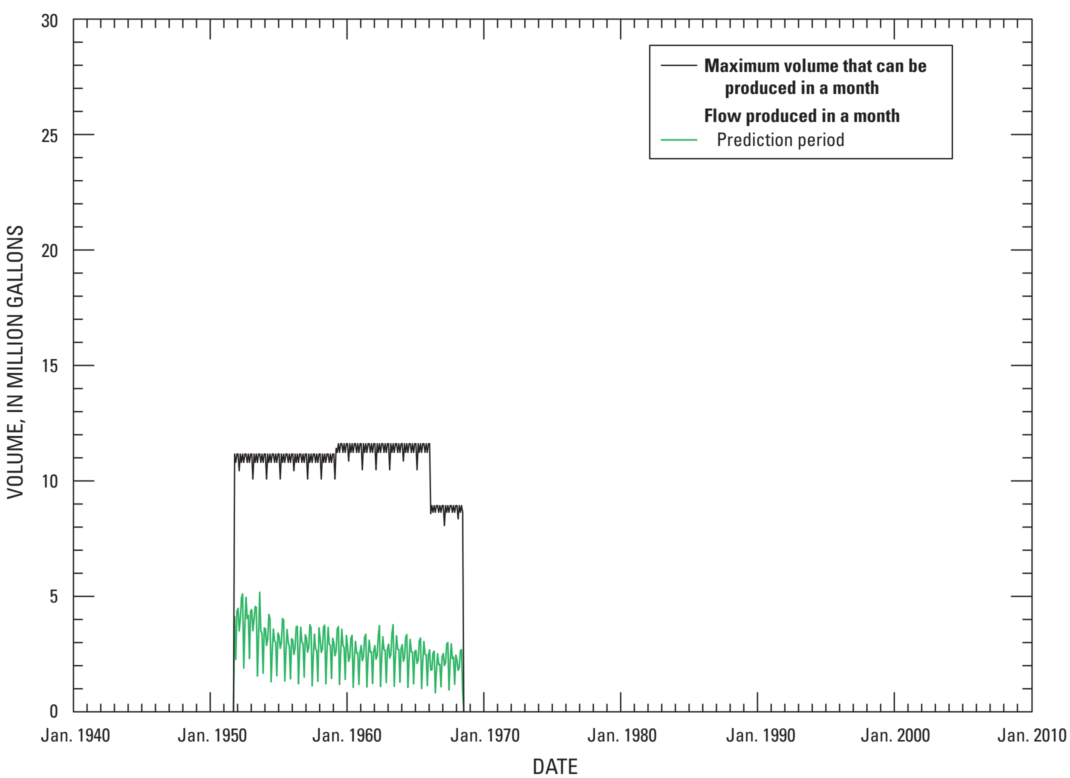

Figure S2.166. Estimated monthly water volume produced at well HP-629 (old).

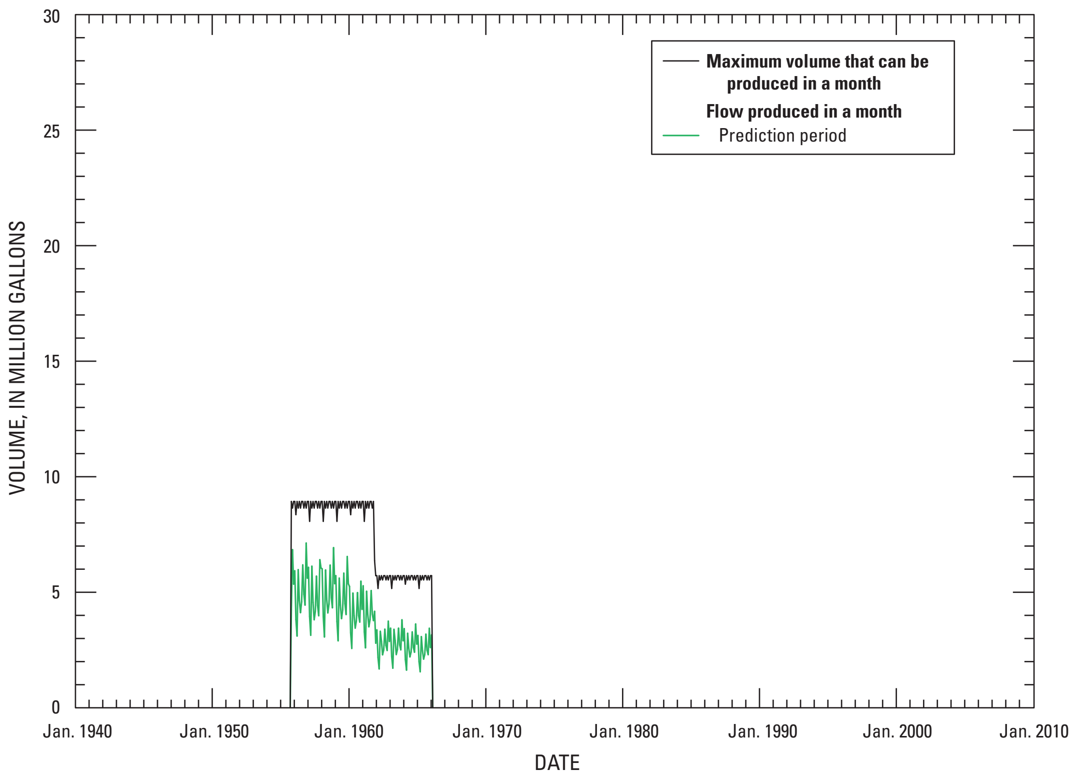

Figure S2.167. Estimated monthly water volume produced at well HP-630.

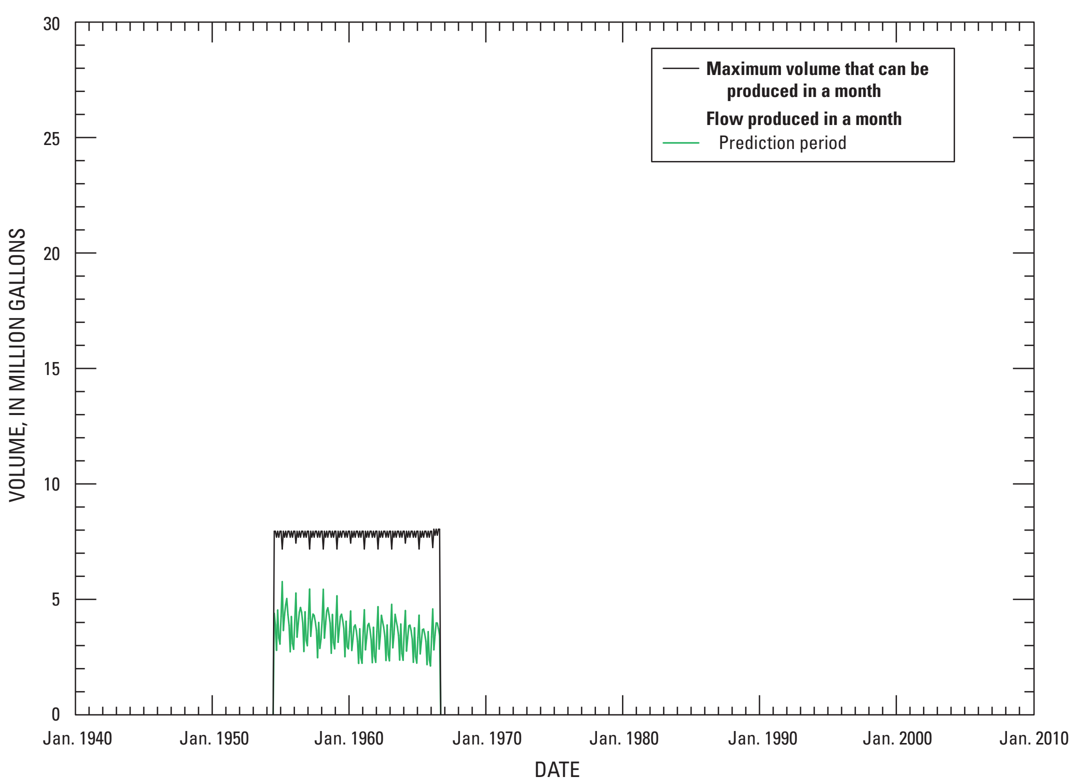

Figure S2.168. Estimated monthly water volume produced at well HP-631.

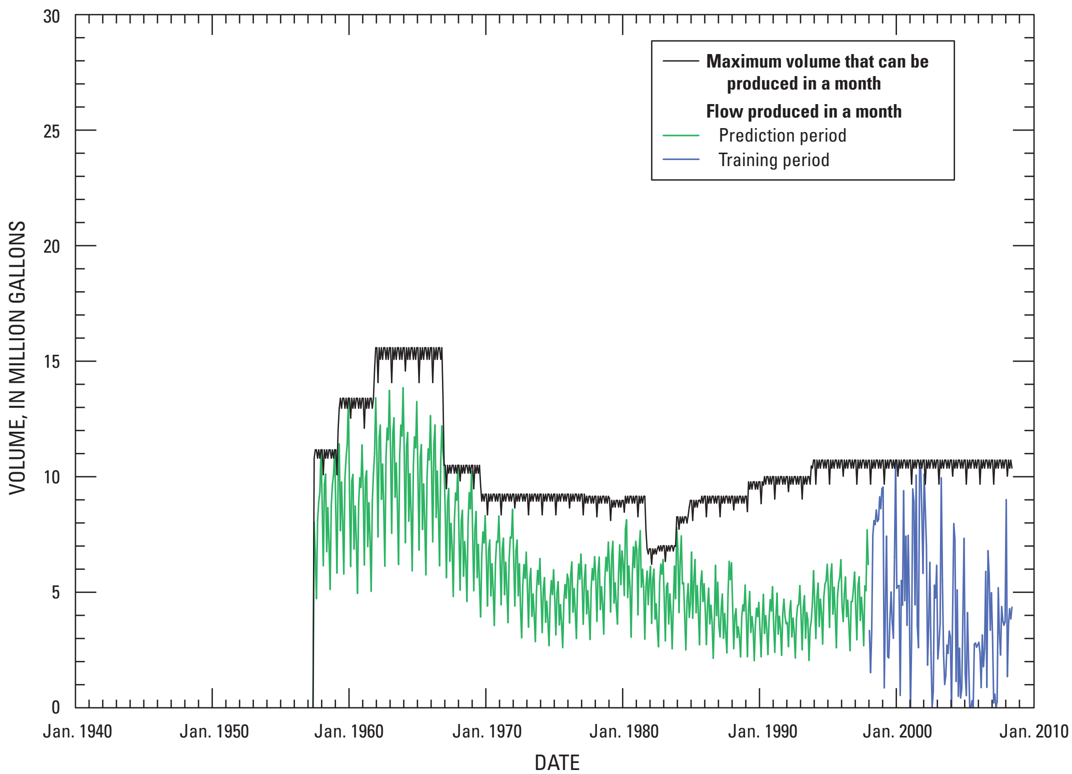

Figure S2.169. Estimated monthly water volume produced at well HP-632.

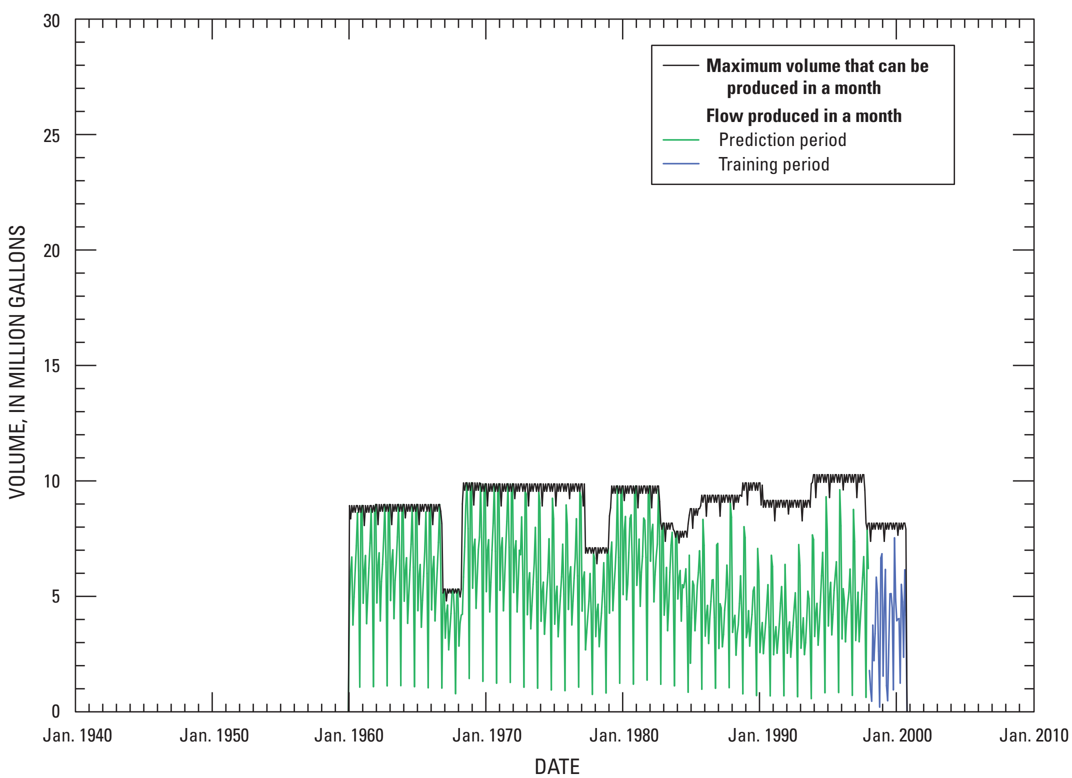

Figure S2.170. Estimated monthly water volume produced at well HP-633.

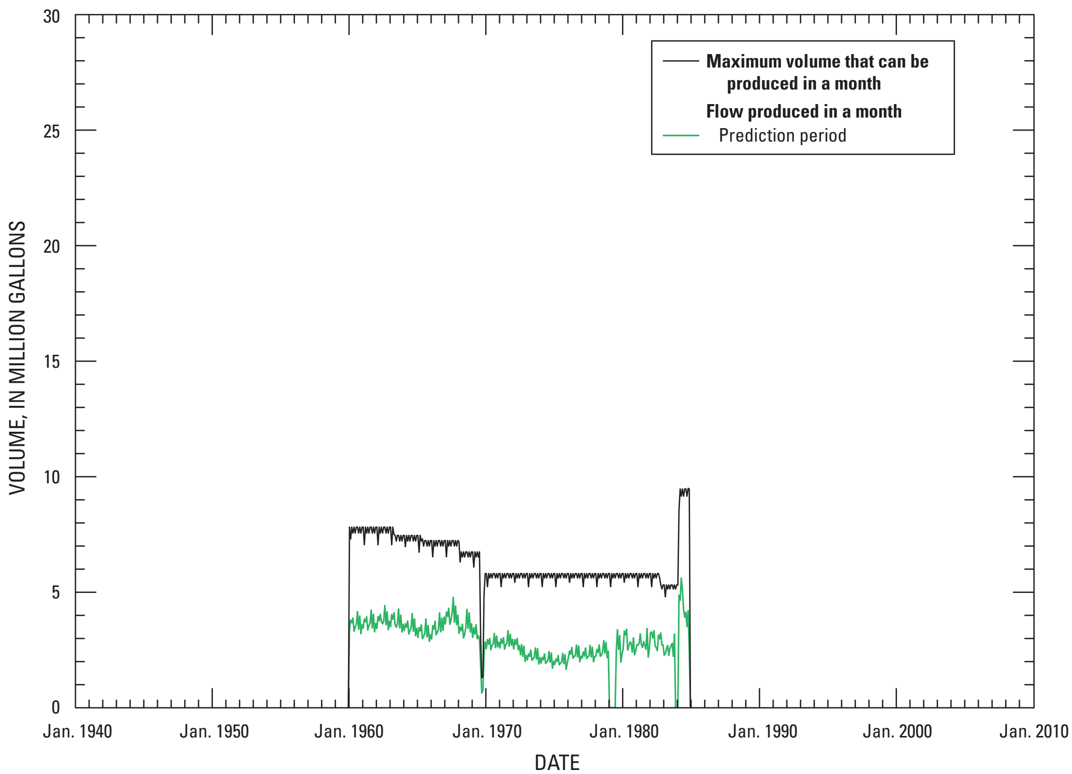

Figure S2.171. Estimated monthly water volume produced at well HP-634.

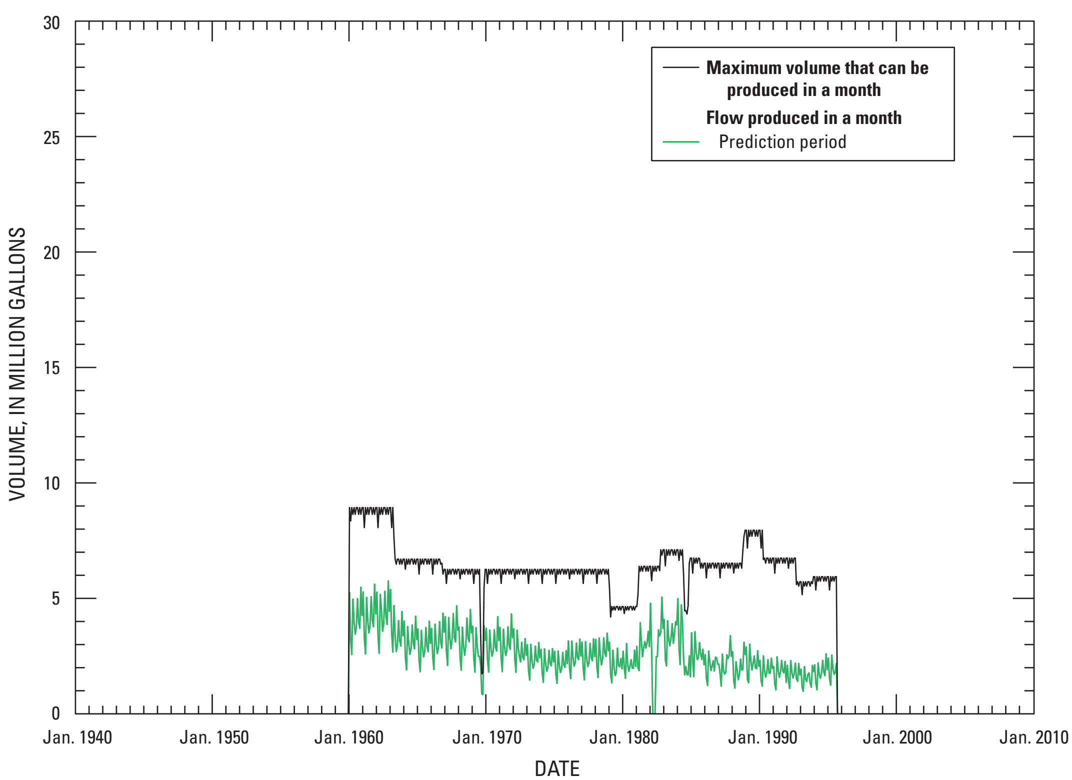

Figure S2.172. Estimated monthly water volume produced at well HP-635.

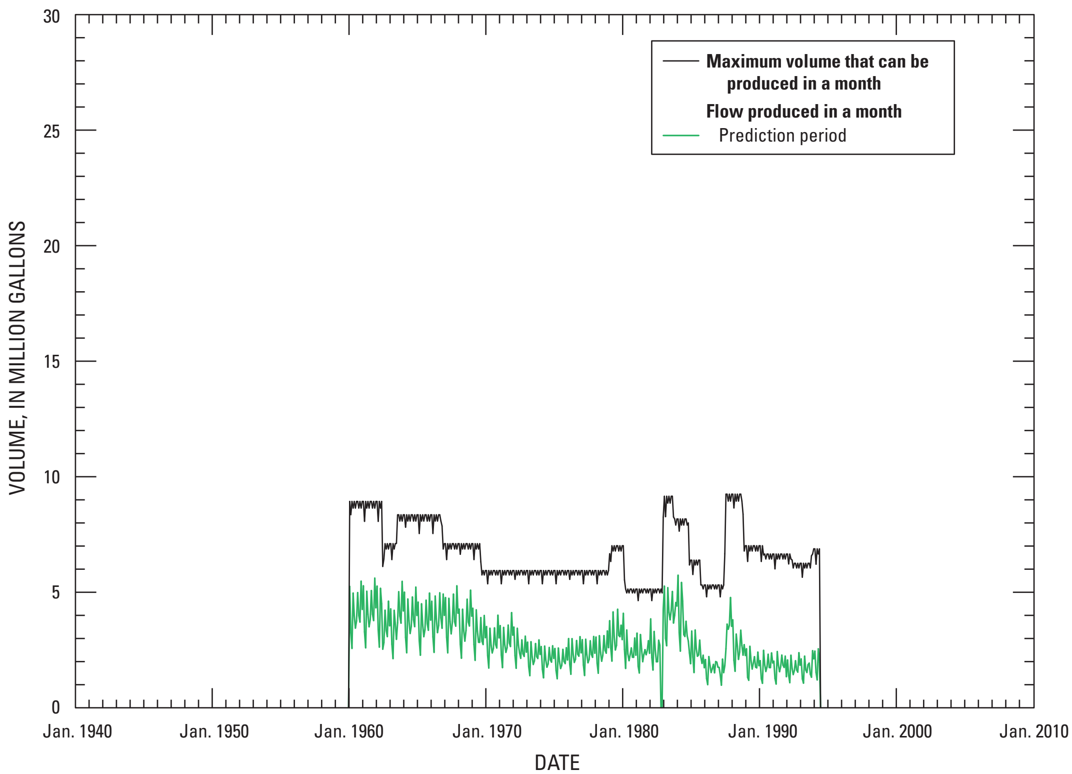

Figure S2.173. Estimated monthly water volume produced at well HP-636.

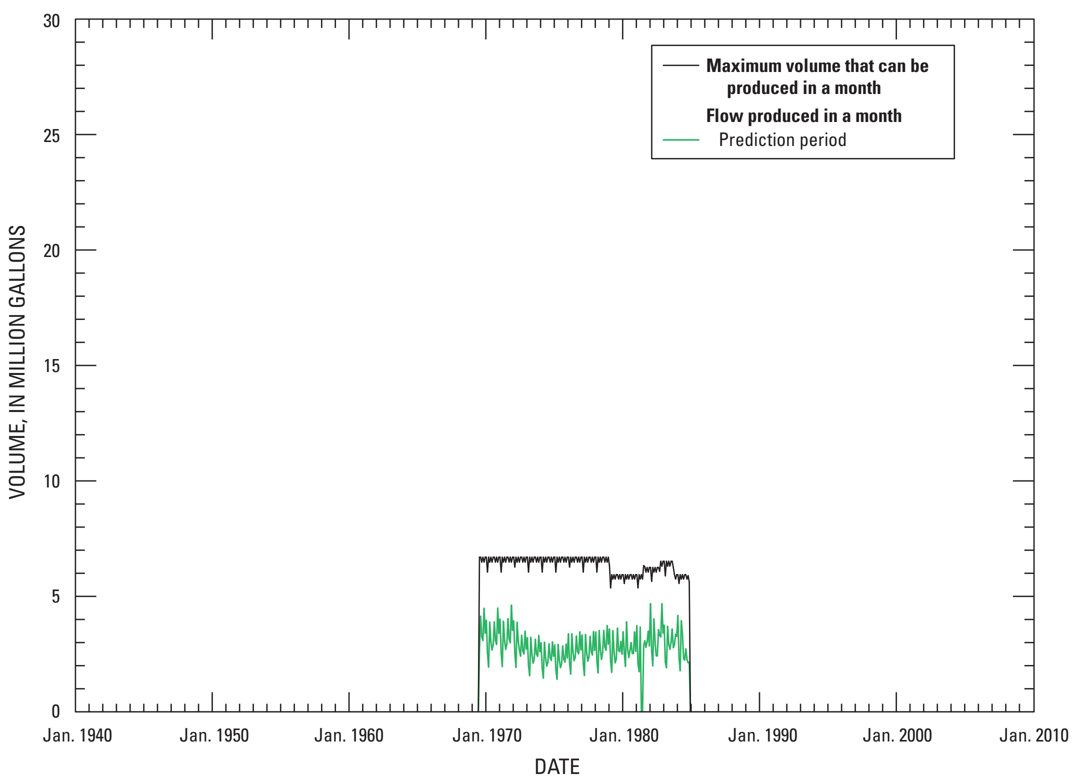

Figure S2.174. Estimated monthly water volume produced at well HP-637.

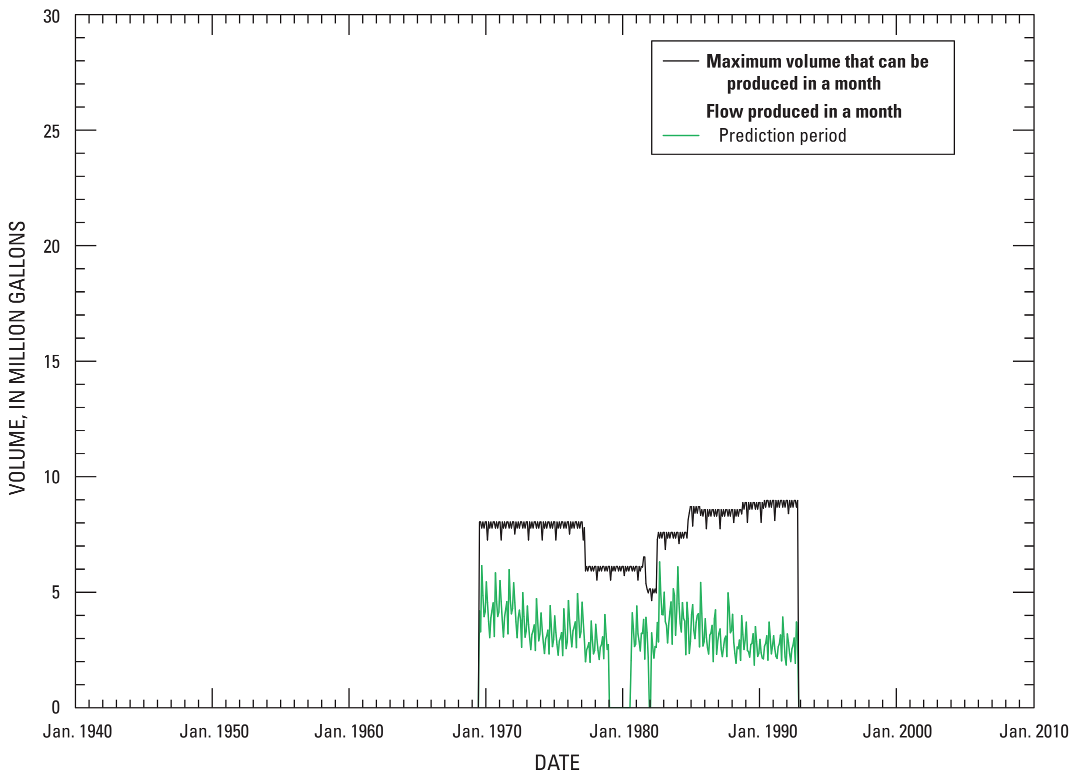

Figure S2.175. Estimated monthly water volume produced at well HP-638.

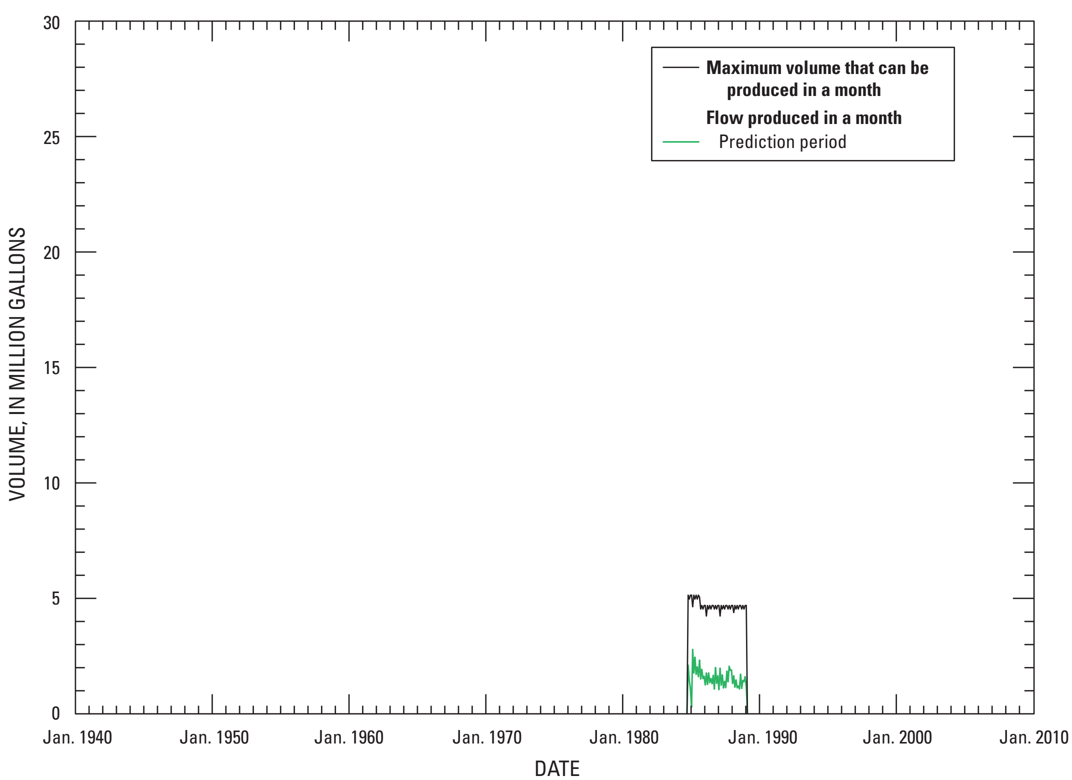

Figure S2.176. Estimated monthly water volume produced at well HP-639 (new).

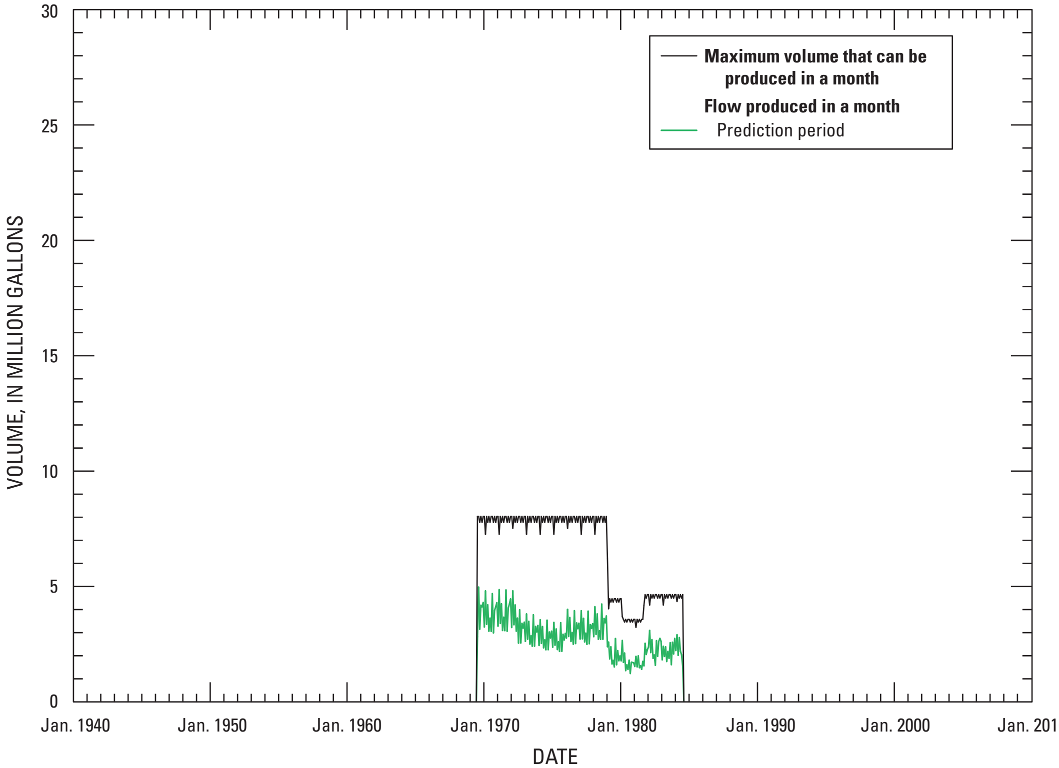

Figure S2.177. Estimated monthly water volume produced at well HP-639 (old).

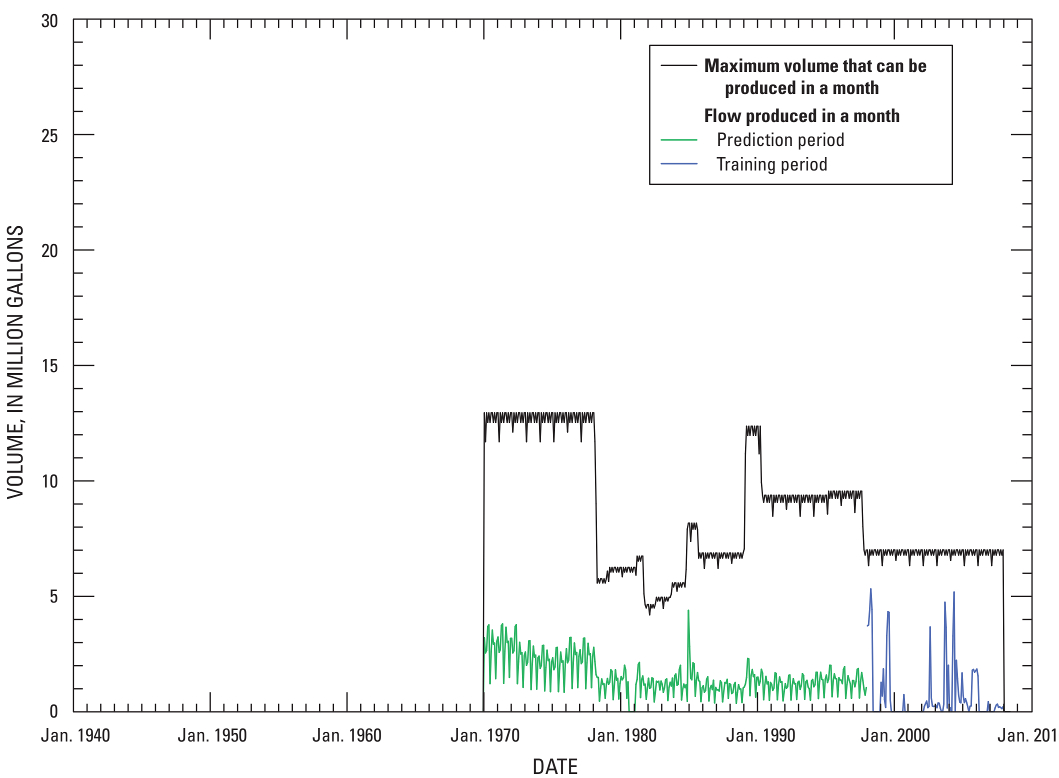

Figure S2.178. Estimated monthly water volume produced at well HP-640.

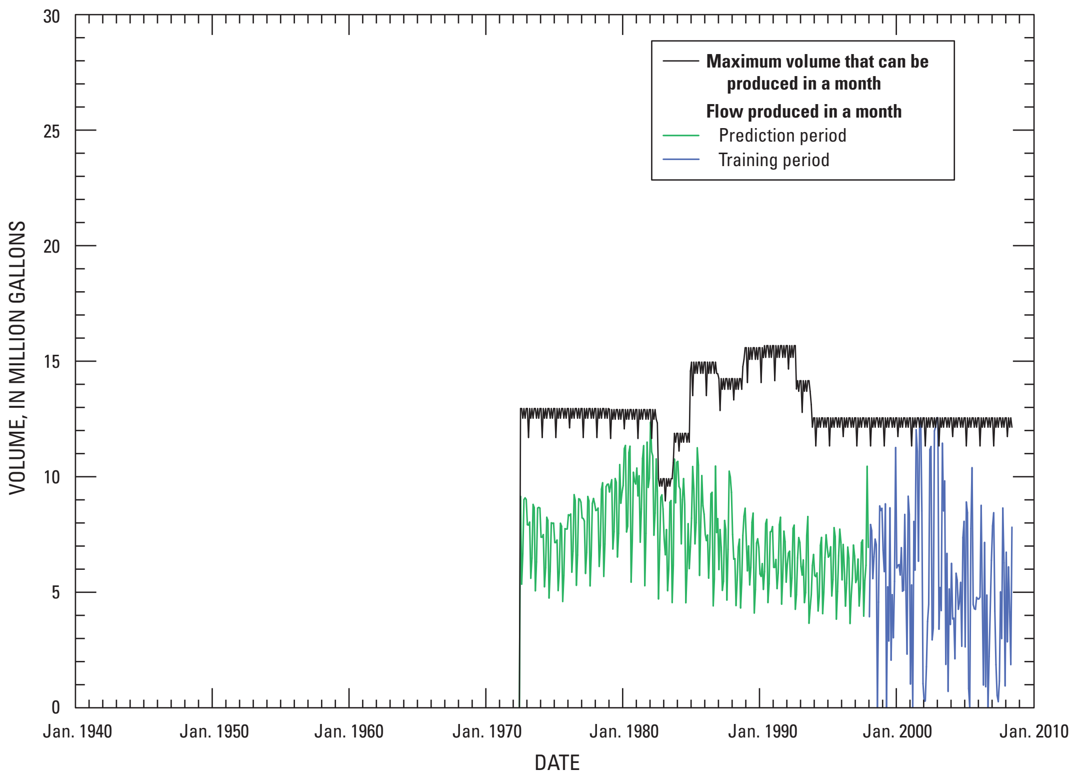

Figure S2.179. Estimated monthly water volume produced at well HP-641.

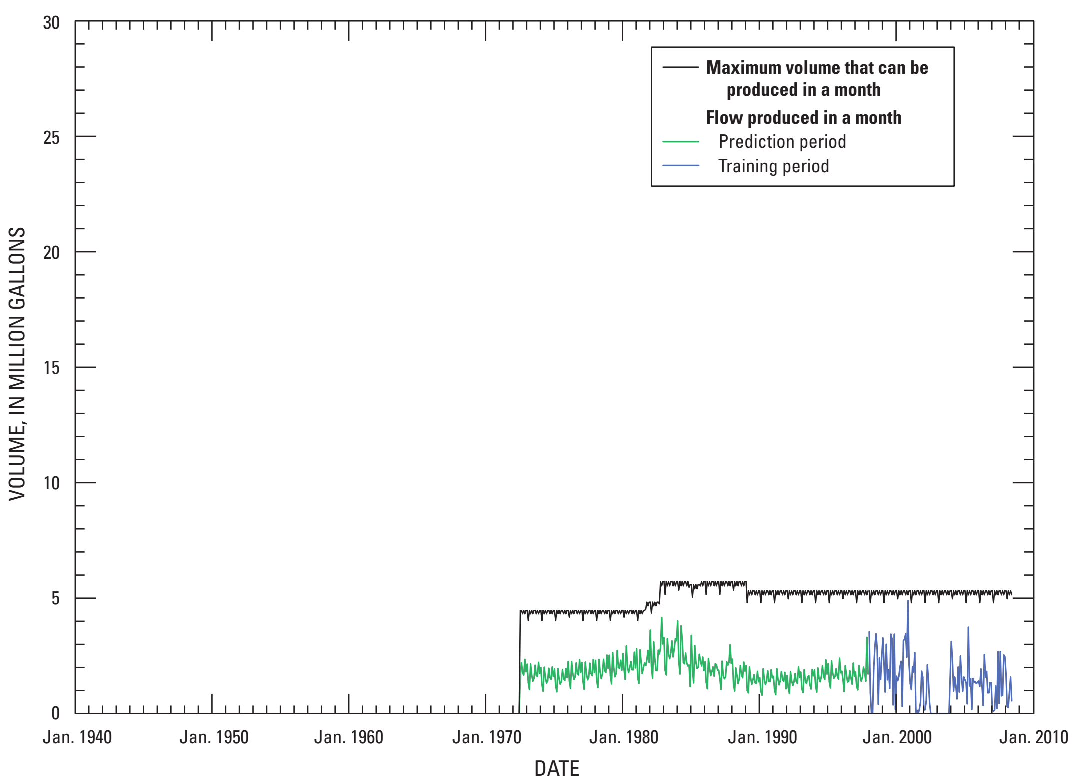

Figure S2.180. Estimated monthly water volume produced at well HP-642.

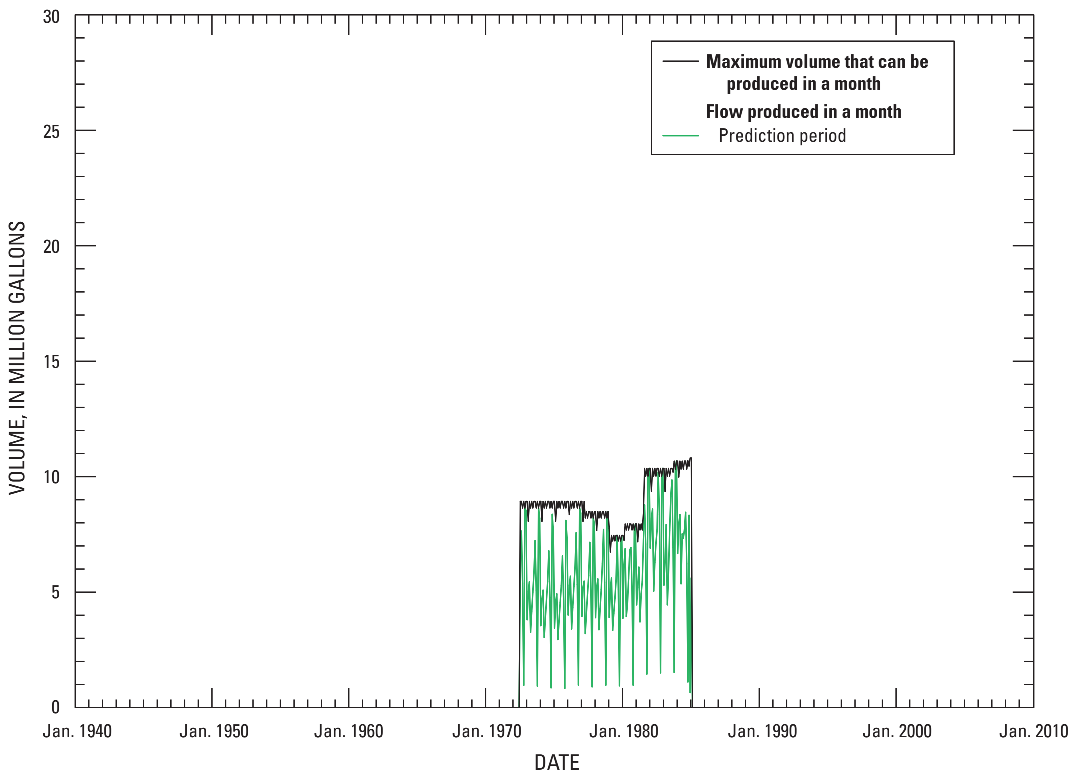

Figure S2.181. Estimated monthly water volume produced at well HP-651.

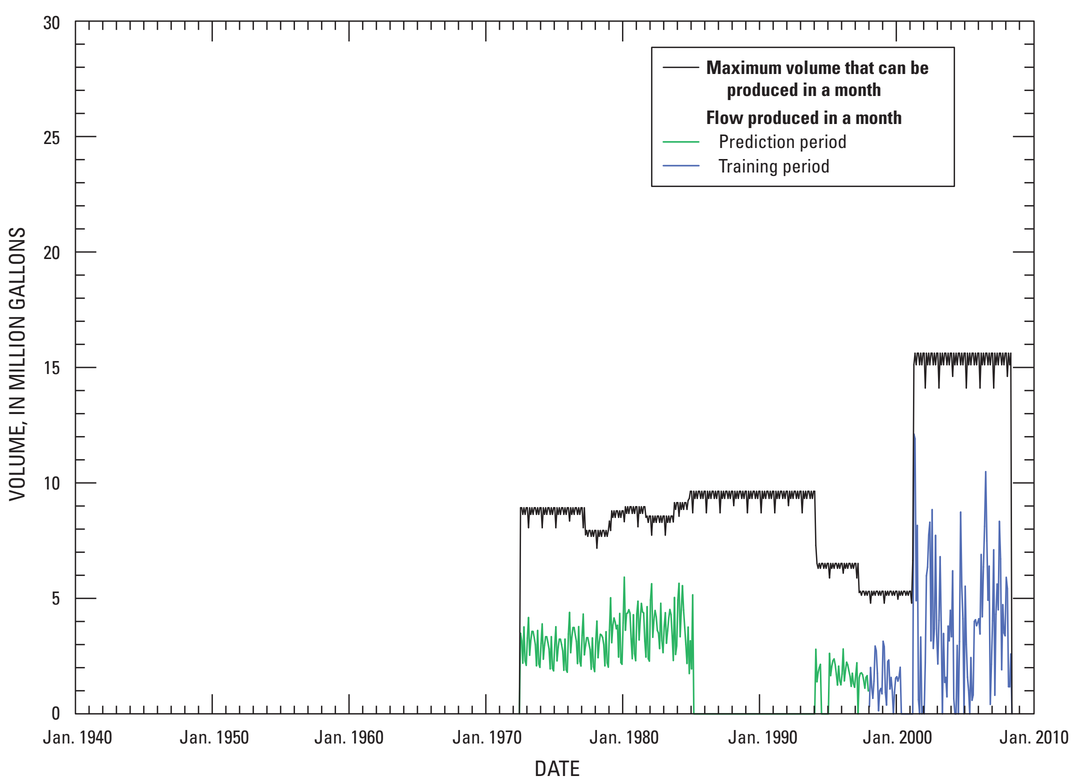

Figure S2.182. Estimated monthly water volume produced at well HP-652.

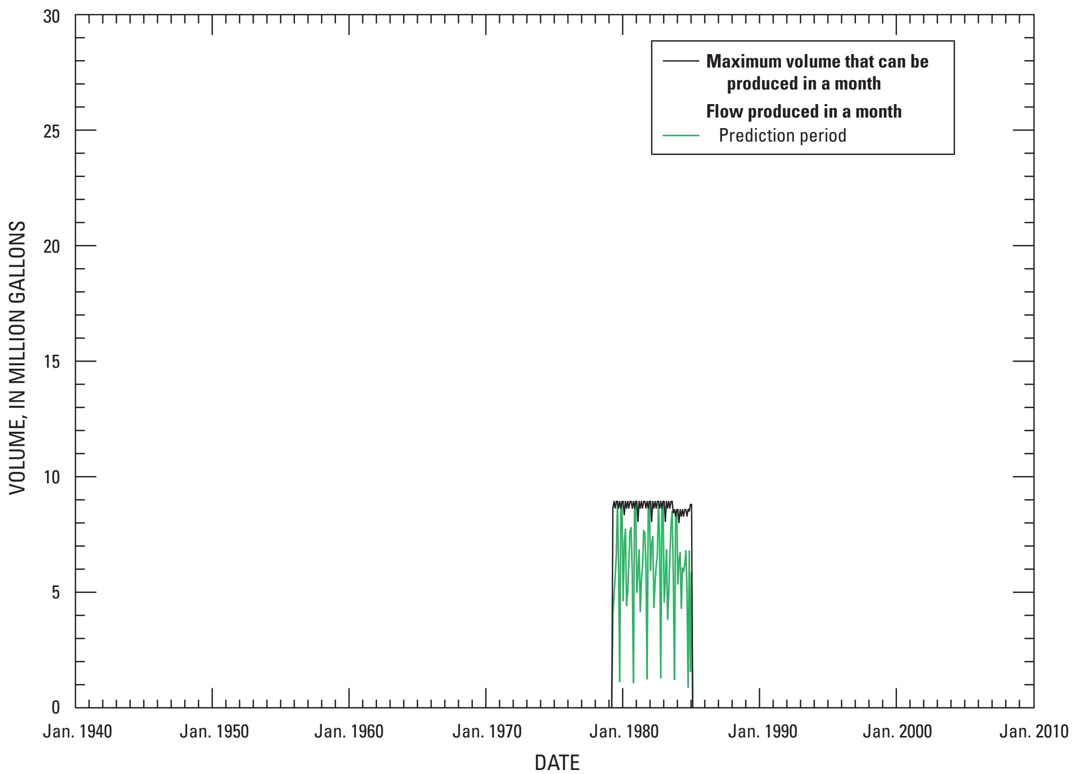

Figure S2.183. Estimated monthly water volume produced at well HP-653.

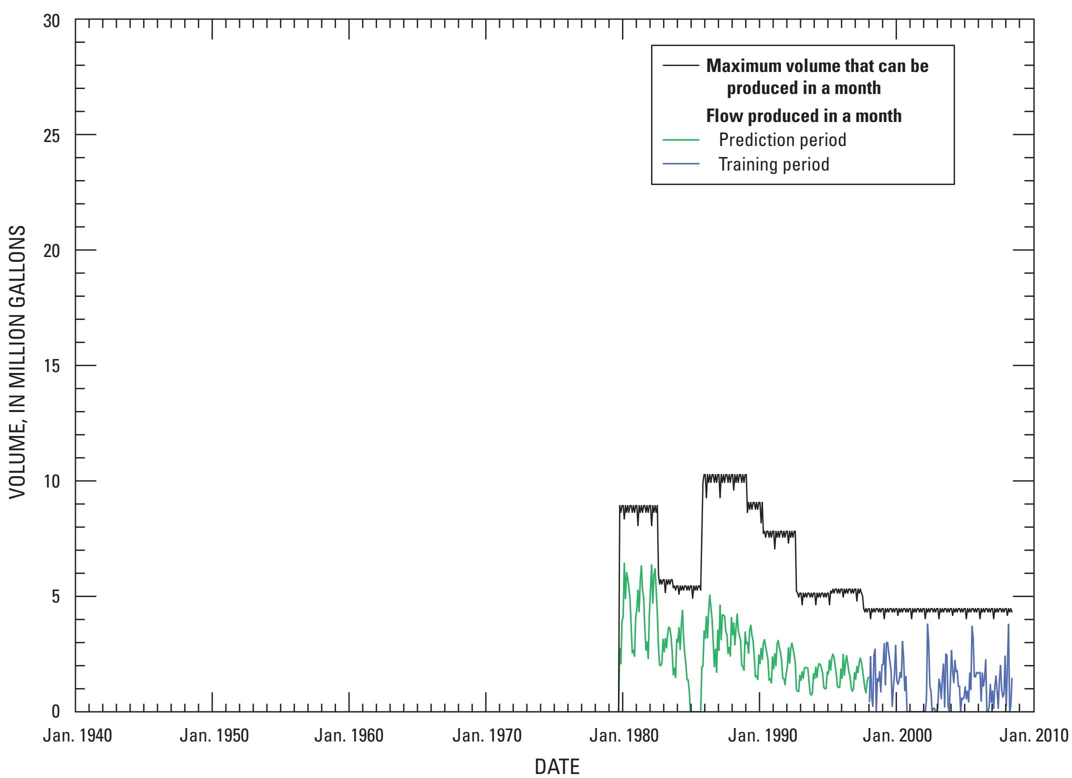

Figure S2.184. Estimated monthly water volume produced at well HP-654.

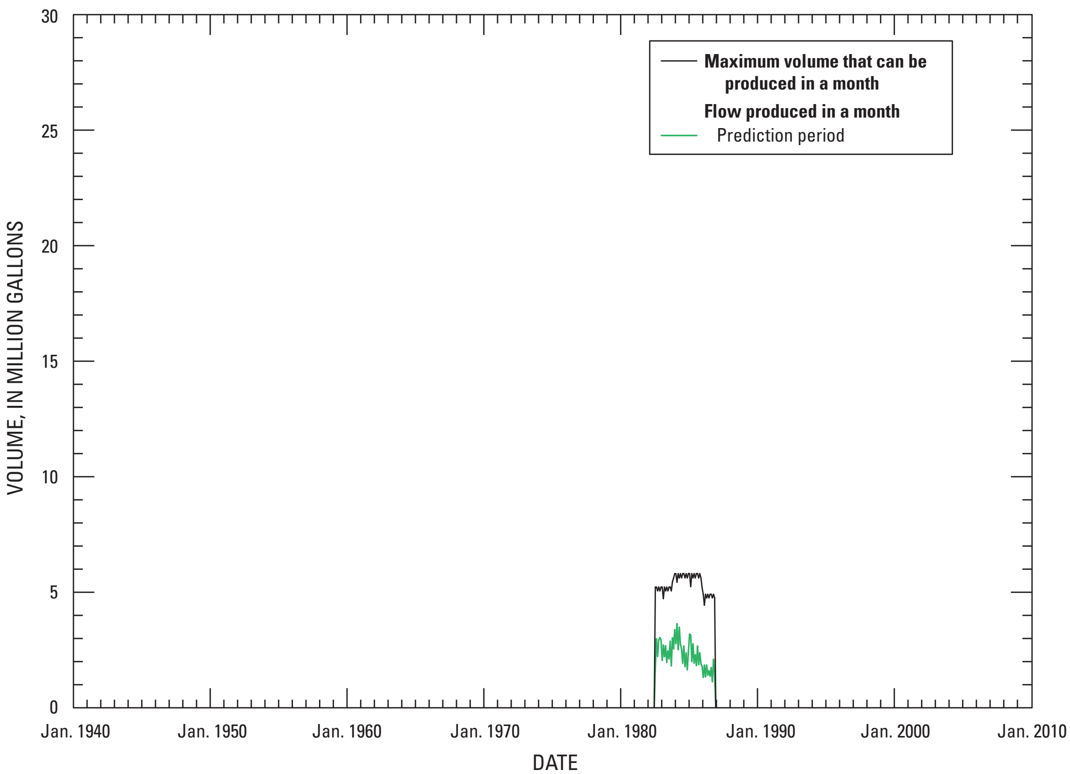

Figure S2.185. Estimated monthly water volume produced at well HP-655.

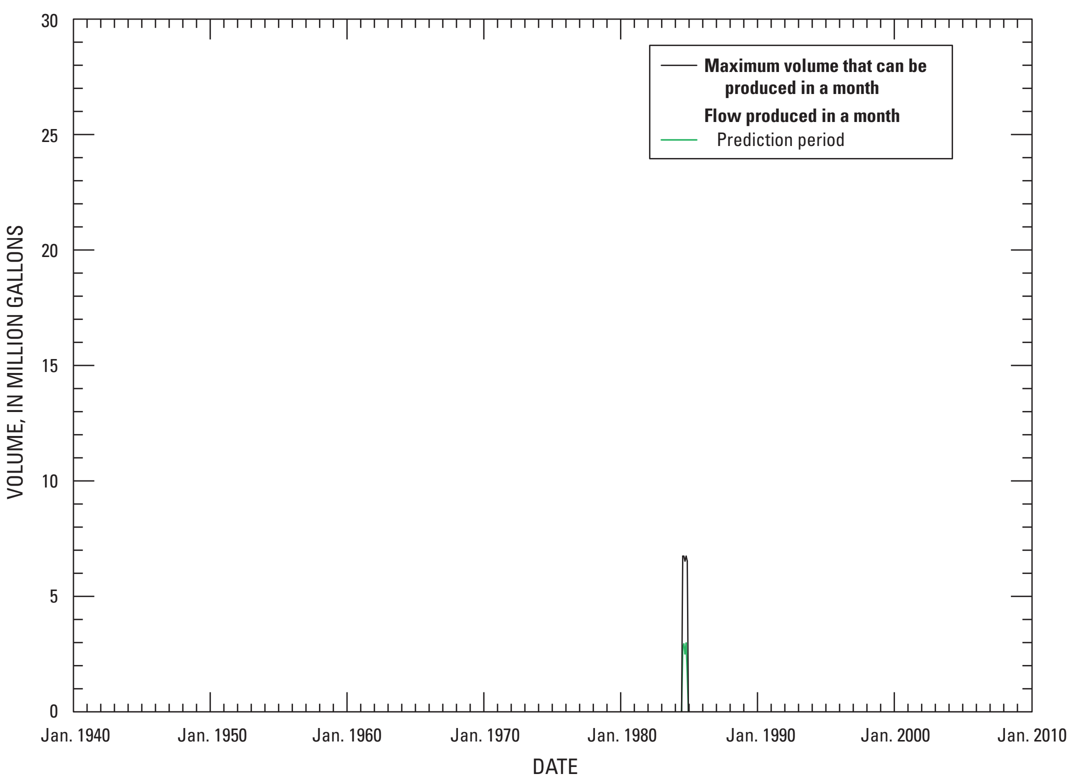

Figure S2.186. Estimated monthly water volume produced at well HP-660.

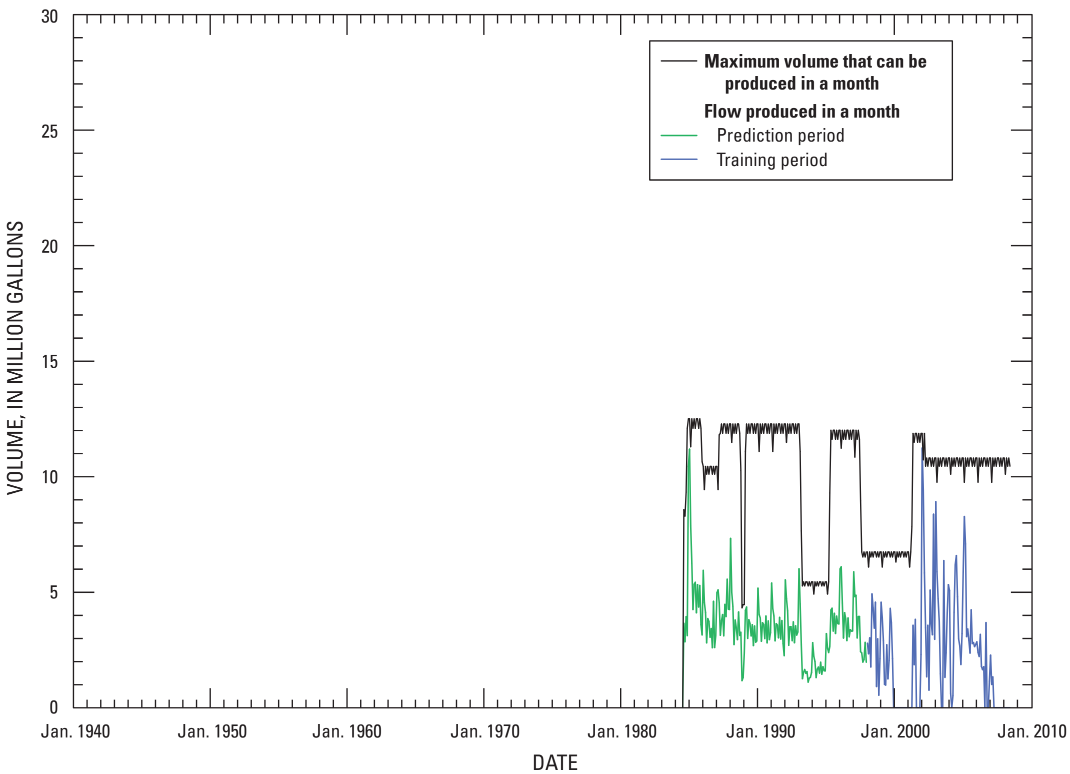

Figure S2.187. Estimated monthly water volume produced at well HP-661.

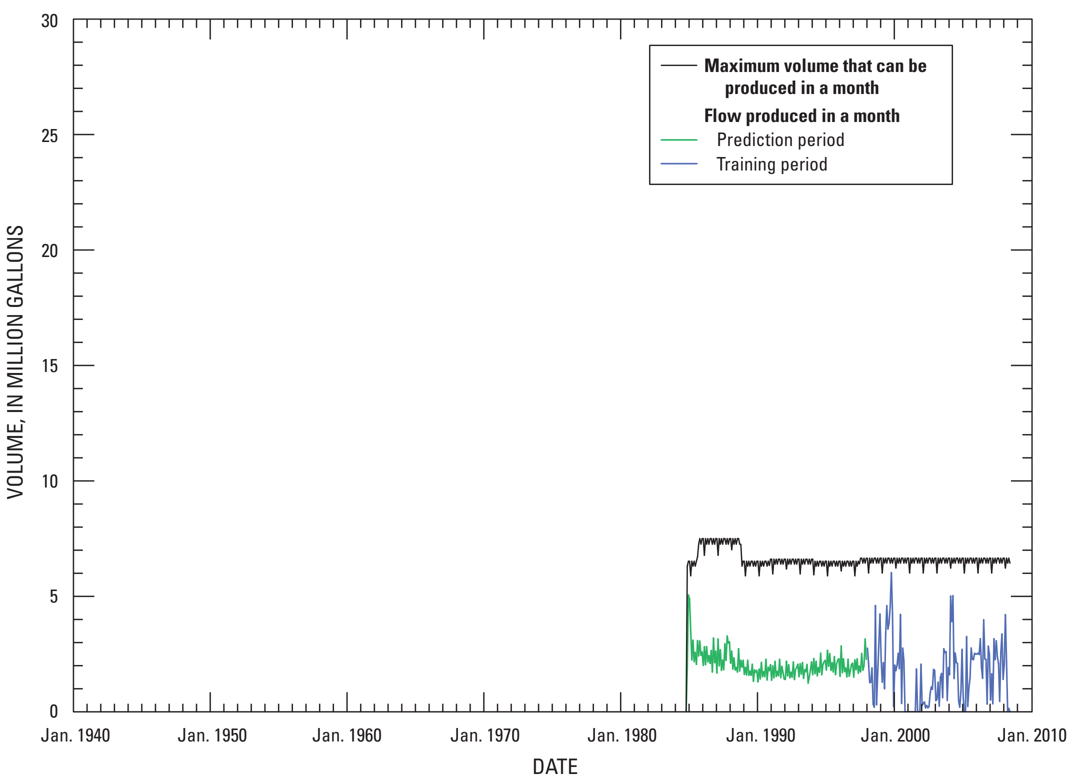

Figure S2.188. Estimated monthly water volume produced at well HP-662.

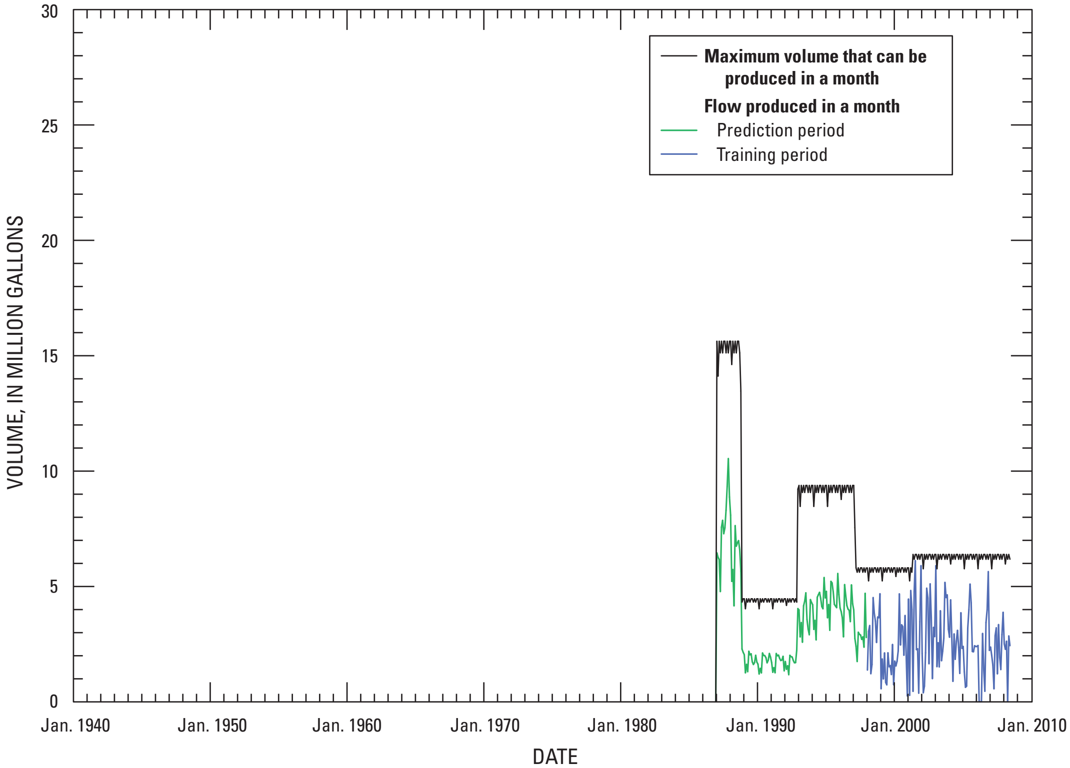

Figure S2.189. Estimated monthly water volume produced at well HP-663.

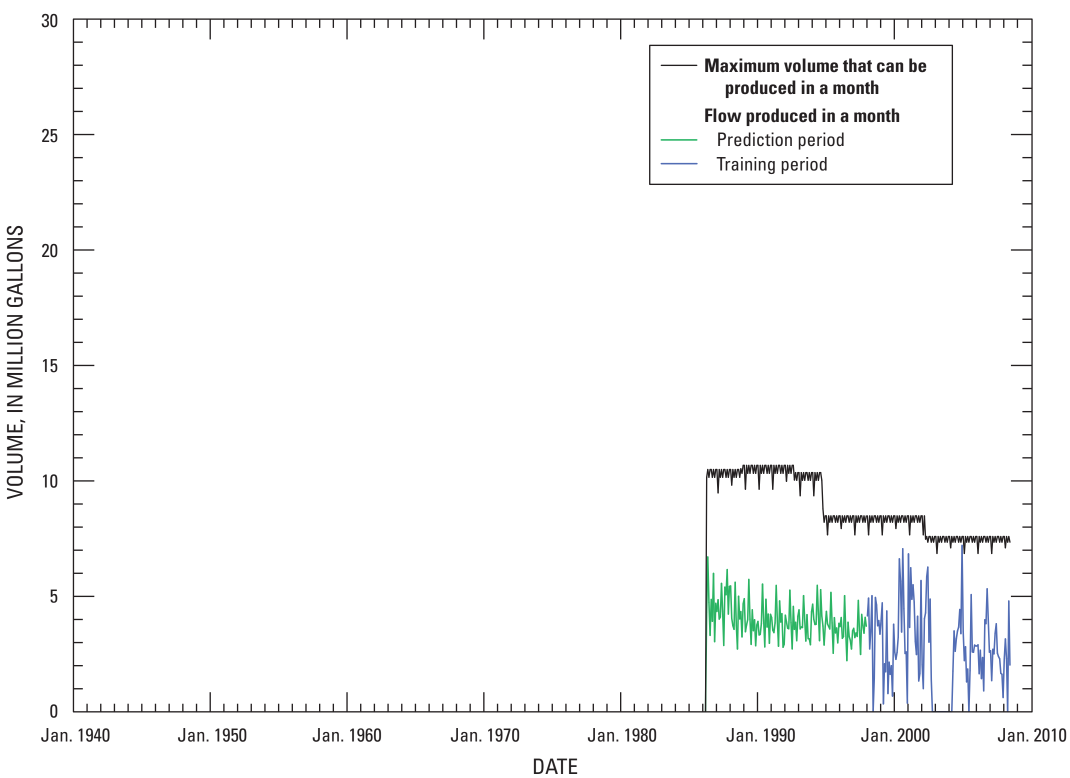

Figure S2.190. Estimated monthly water volume produced at well HP-709.

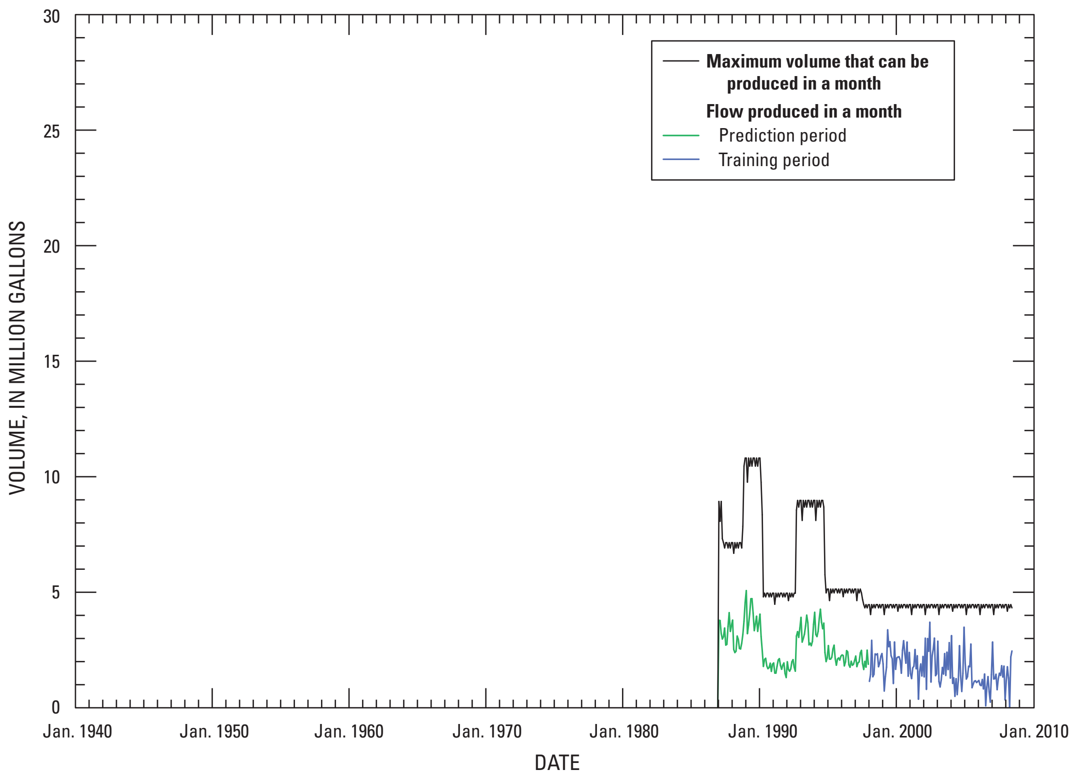

Figure S2.191. Estimated monthly water volume produced at well HP-710.

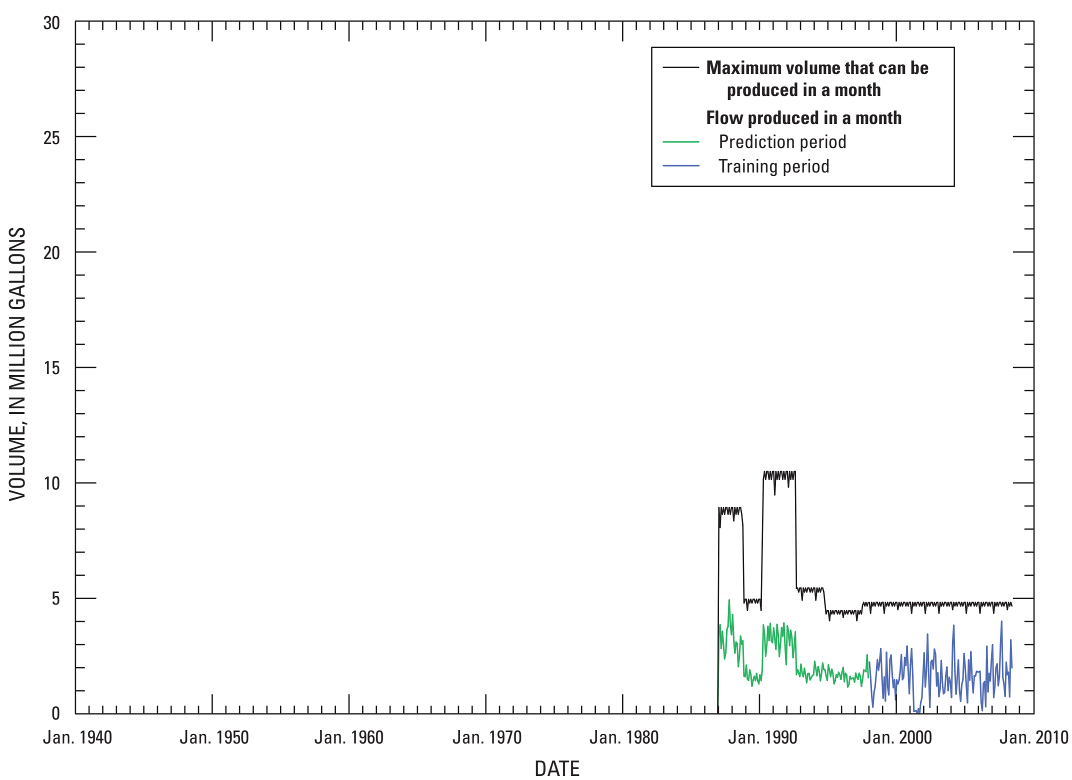

Figure S2.192. Estimated monthly water volume produced at well HP-711.

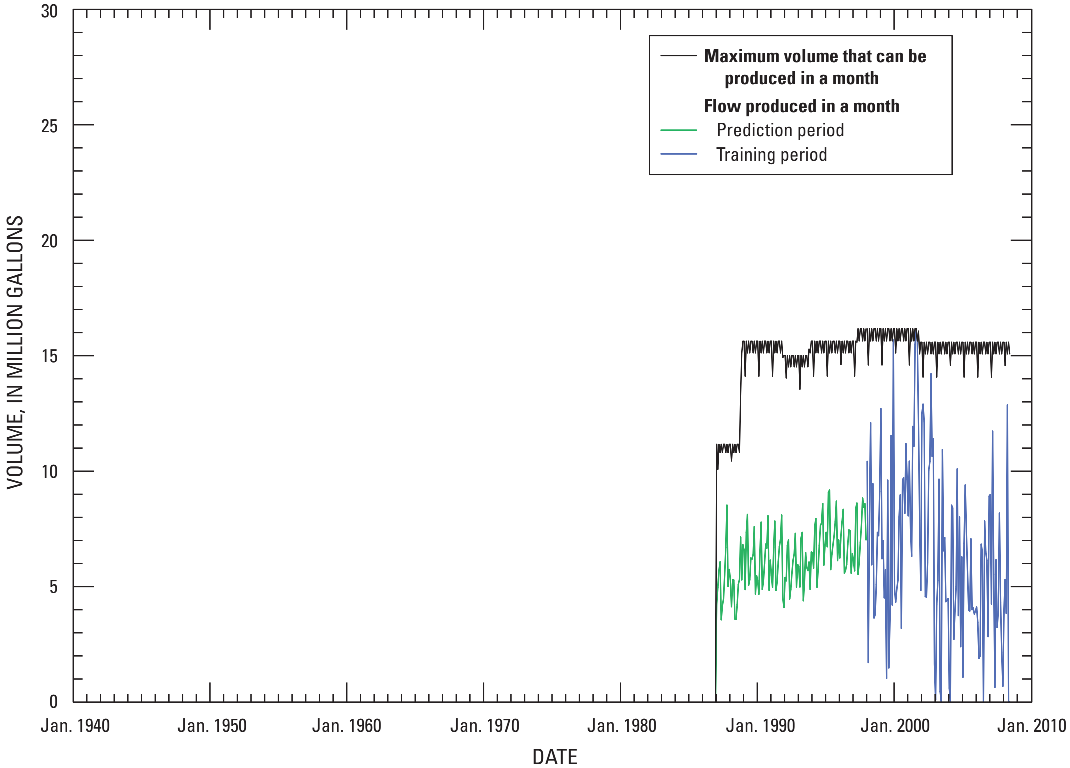

Figure S2.193. Estimated monthly water volume produced at well HP-5186.

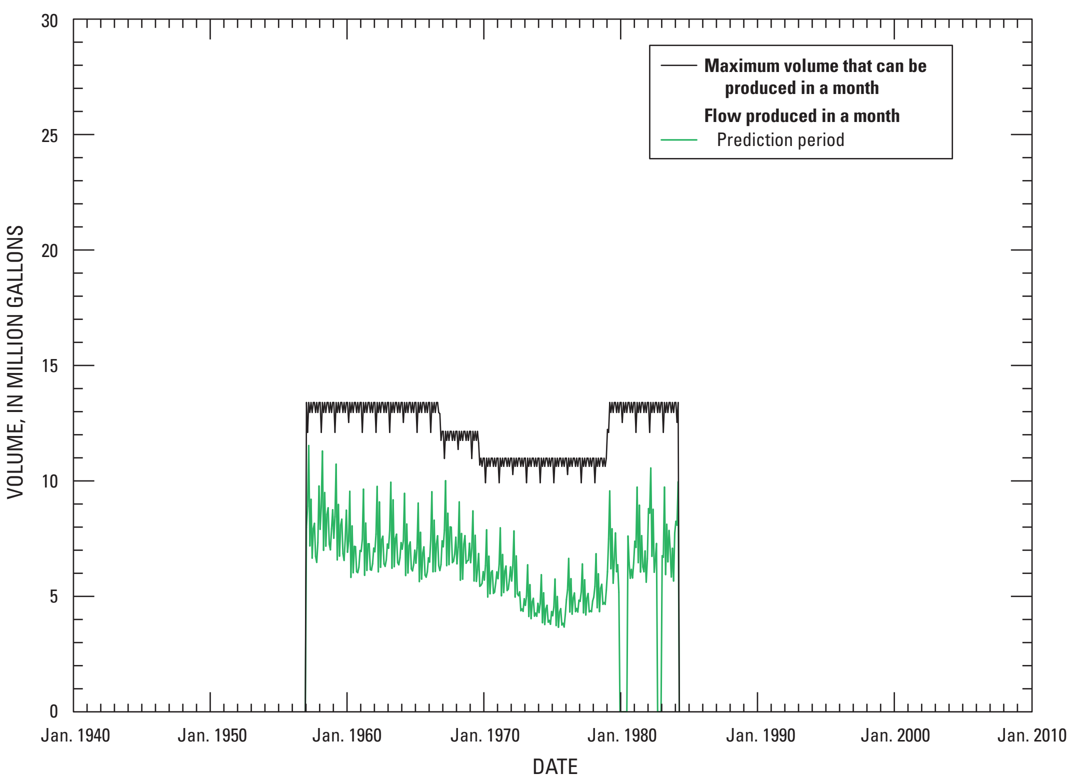

Figure S2.194. Estimated monthly water volume produced at well LCH-4006.

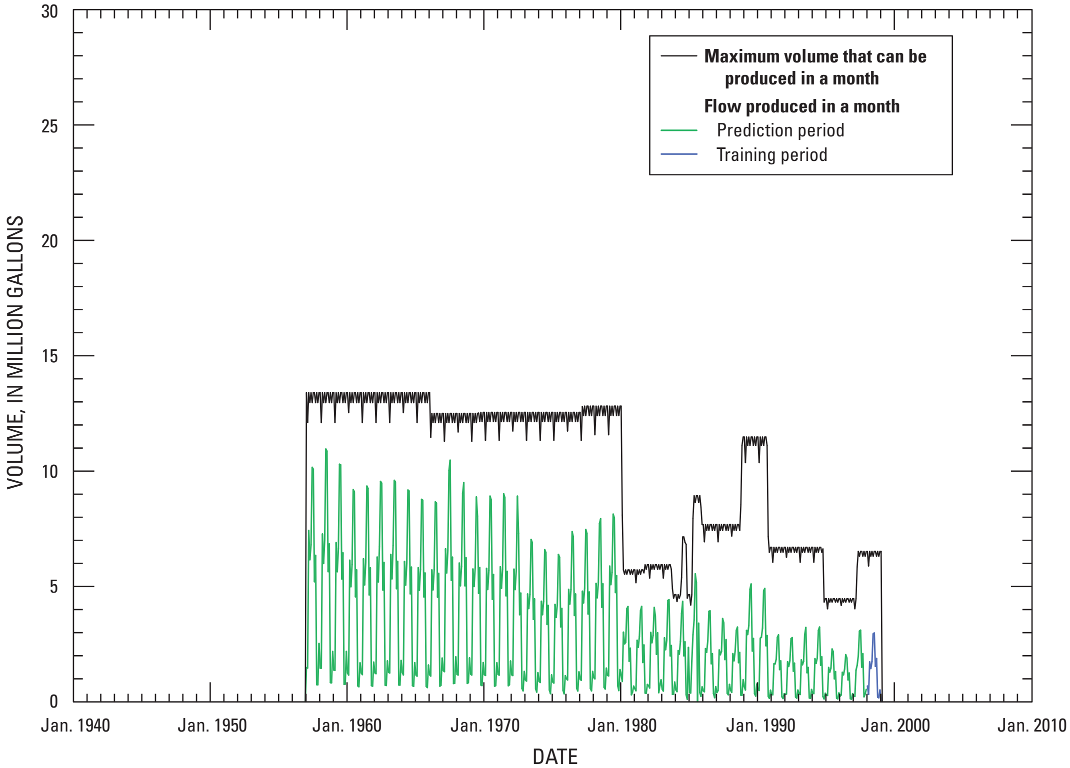

Figure S2.195. Estimated monthly water volume produced at well LCH-4007.

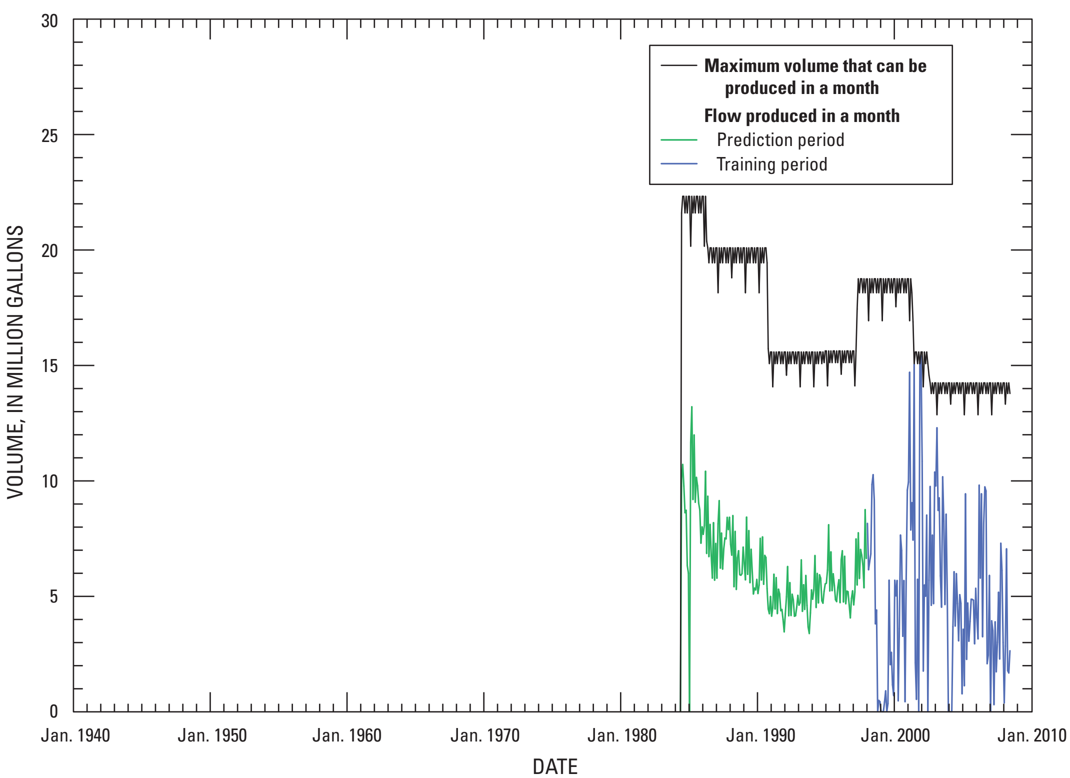

Figure S2.196. Estimated monthly water volume produced at well LCH-4009.

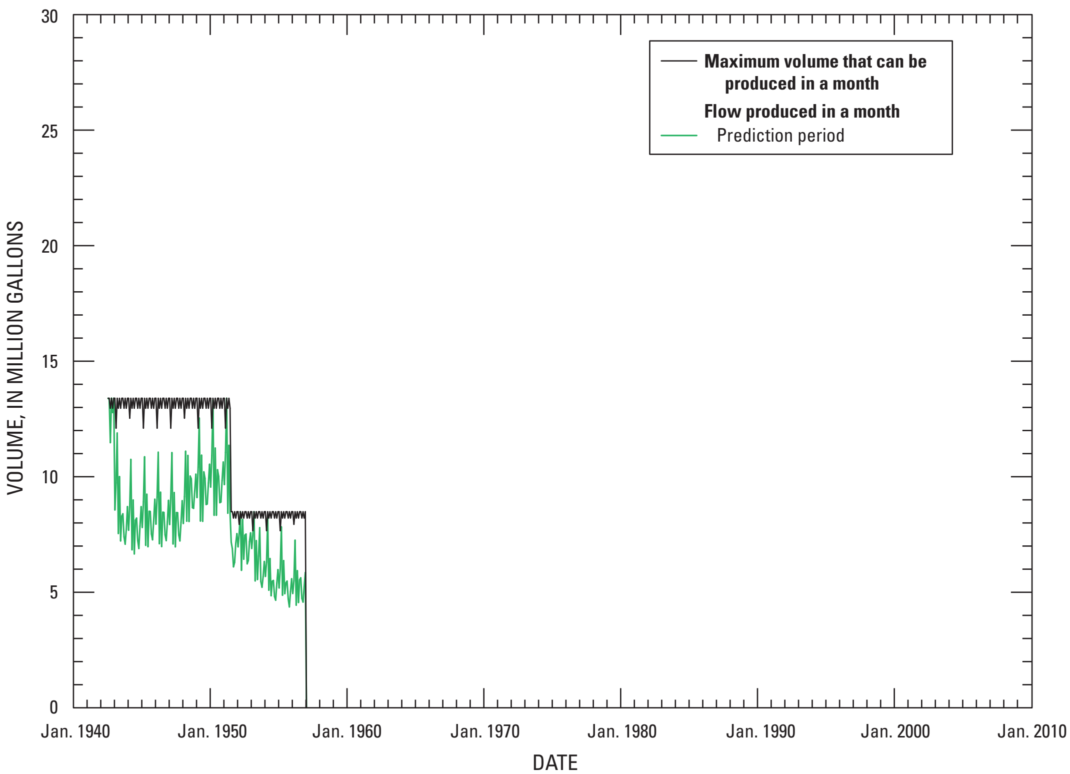

Figure S2.197. Estimated monthly water volume produced at well M-1.

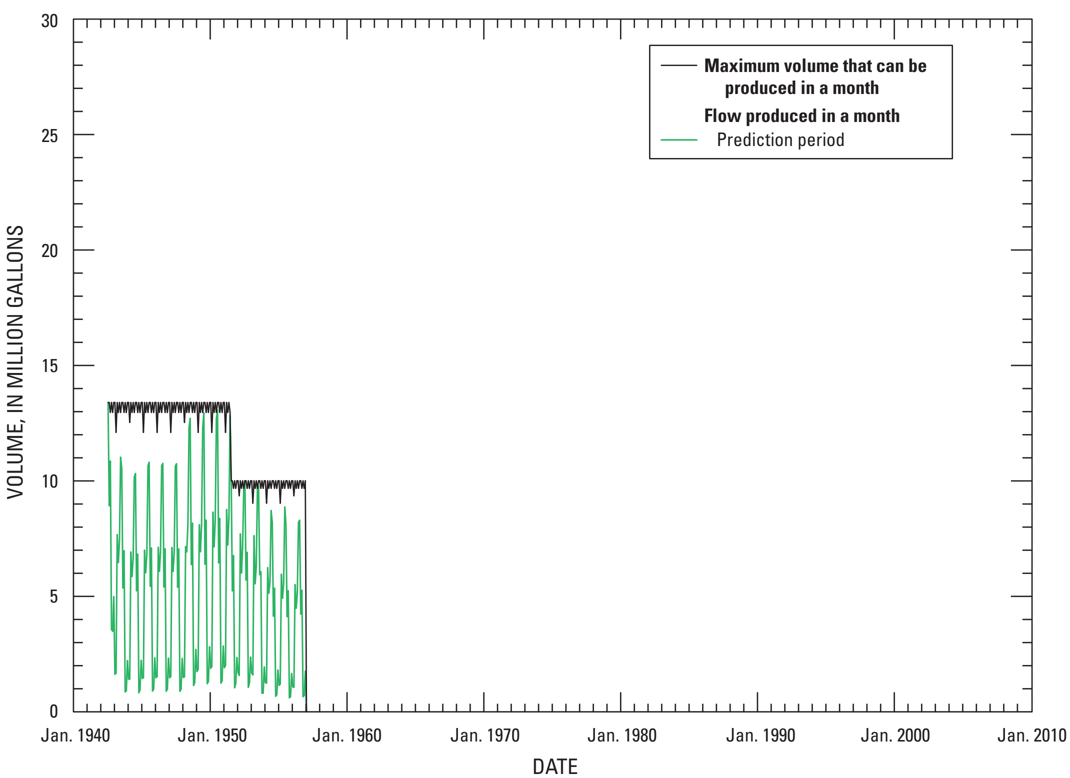

Figure S2.198. Estimated monthly water volume produced at well M-2.

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Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—Chapter A–Supplement 2: Development and Application of a Methodology to Characterize Present-Day and Historical Water-Supply Well Operations