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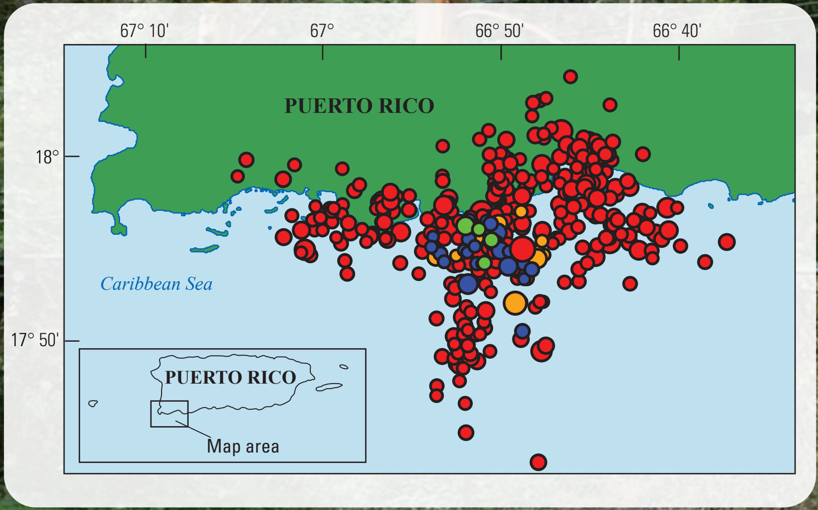
Potential Duration of the Aftershocks of the 2020 Southwestern Puerto Rico Earthquake



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Cover figure. Map of the 2020 southwestern Puerto Rico earthquake sequence. Each earthquake from December 29, 2019, through the end of January 22, 2020 (UTC), is plotted as a circle on the map. Foreshocks to the magnitude 5.0 earthquake on December 29, 2019, are plotted in green. The magnitude 5.0 earthquake on December 29, 2019, and its aftershocks are plotted in blue. The magnitude 5.8 earthquake on January 6, 2020, and its aftershocks are plotted in orange. Finally, the magnitude 6.4 earthquake on January 7, 2020, and its aftershocks are plotted in red. Circle sizes are proportional to each earthquake's magnitude.

Cover image. Juan Carlos Aragon of USGS and Jaffet Martínez with the Puerto Rico Strong Motion Program are retrieving data and programming the strong motion seismic instrumentation at Maricao Fire Station. U.S. Geological Survey photograph.

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By Nicholas J. van der Elst, Jeanne L. Hardebeck, and Andrew J. Michael

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)

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

°F = (1.8 × °C) + 32.

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

°C = (°F – 32) / 1.8.

Datum

Vertical coordinate information is referenced to Puerto Rico Vertical Datum of 2002 (PRVD 02).

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

Abbreviations

ETAS	epidemic-type aftershock sequence
Km	kilometer
USGS	U.S. Geological Survey

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Abstract

Aftershocks (earthquakes clustered spatially and chronologically near the occurrence of a causative earthquake) are ongoing in southwestern Puerto Rico after a series of earthquakes, which include a magnitude 6.4 earthquake that occurred near Barrio Indios, Guayanilla, on January 7, 2020, and affected the surrounding area. This report estimates the expected duration of these aftershocks by incorporating observations of aftershocks as of January 17, 2020, into a well-established statistical model of how earthquake sequences behave. Aftershocks will persist for years to decades, although with decreasing frequency, and earthquakes will likely be felt on a daily basis for up to several months. These estimates have significant uncertainty owing to different scenarios of how the earthquake sequence may evolve over time and could also change if a new large aftershock occurs. This report also estimates the amount of time remaining until the annual probability of magnitude 5, 6, and 7 or greater aftershocks—which could cause additional damage—decreases to 50, 25, 10, 5, and 1 percent. As of this writing, the chance of having a magnitude 6 or greater earthquake within a given year, going forward, will not fall below 25 percent for another 3 months to 3 years. The chance of having a magnitude 5 or greater earthquake will not fall below 25 percent for a decade or more. The aftershocks discussed in this report would be located in the same general area as the aftershocks that have already occurred. Our results do not imply a change in the risk of earthquakes in other parts of Puerto Rico.

Introduction

Puerto Rico is located where the Caribbean and the North American tectonic plates meet, with the island being compressed between the two plates. Earthquakes are common in Puerto Rico because of its geographic location. Earthquakes behave differently from other natural hazards, such as floods, hurricanes, or wildfires, in that earthquake sequences can last for weeks, years, or decades, rather than occurring as just one event or season. This report estimates how long there will be aftershocks following a sequence of earthquakes that began off the southwestern coast of Puerto Rico in December 2019.

Aftershocks are earthquakes that are triggered by previous earthquakes, and they cluster in time and in space around their causative earthquakes, often called mainshocks. The first magnitude 5 or larger earthquake, in a sequence that includes 10 earthquakes that large or larger, occurred on December 28, 2019, local time zone (table 1; fig. 1). The largest of these has been a magnitude 6.4 earthquake on January 7, 2020. The duration of the aftershock sequence is estimated using observations of the earthquake sequence through January 17, 2020. Changes in the behavior of the aftershock sequence, including the occurrence of a new large aftershock, could require new estimates.

Whereas most aftershocks are smaller than the earthquake that caused them, this is not always the case, and aftershocks still have the potential to be damaging or deadly. For example, the damaging 2011 magnitude 6.2 Christchurch, New Zealand, earthquake was an aftershock of the less damaging 2010 magnitude 7.1 Darfield, New Zealand, earthquake (Kaiser and others, 2012). A small fraction of earthquakes are followed by a larger earthquake, in which case the first earthquake is referred to as a foreshock. For example, the 2011 magnitude 9.1 off-Tohoku, Japan, earthquake and tsunami were preceded by a magnitude 7.3 foreshock two days before (Hirose and others, 2011), and the 2019 magnitude 7.1 Ridgecrest, California, earthquake was preceded by a magnitude 6.4 earthquake 33 hours earlier (Ross and others, 2019).

2020 Southwestern Puerto Rico Earthquake Aftershock Sequence

Aftershocks are generally located within a radius of 1 to 2 times the rupture length of the mainshock. That radius can be estimated using empirical relations that estimate rupture length based on the earthquake's magnitude. For this calculation, we use the equations from Wells and Coppersmith (1994). In the 2020 southwestern Puerto Rico earthquake aftershock sequence, we include aftershocks within 33 kilometers (km) of a point near the magnitude 6.4 mainshock epicenter (appendix 1). Future aftershocks are expected to occur within or close to this same area. These earthquakes are the first large earthquakes to be recorded by modern seismographic instruments in this region of Puerto Rico.

Table 1. Magnitude 5 and larger earthquakes between December 29, 2019[1], and January 17, 2020, recorded in the Advanced National Seismic System U.S. Geological Survey comprehensive catalog.

Date (UTC)	Time (UTC)	Magnitude	Latitude	Longitude	Depth[2], in kilometers
Dec. 29, 2019	01:06:00	5.0	17.885° N	66.864° W	6.0
Jan. 6, 2020	10:32:18	5.8	17.867° N	66.819° W	6.0
Jan. 7, 2020	08:24:26	6.4	17.916° N	66.813° W	10.0
Jan. 7, 2020	08:34:02	5.6	17.922° N	66.731° W	10.0
Jan. 7, 2020	08:50:45	5.0	17.953° N	66.677° W	10.0
Jan. 7, 2020	11:18:43	5.6	18.022° N	66.776° W	9.0
Jan. 10, 2020	22:26:25	5.2	17.935° N	66.883° W	9.0
Jan. 11, 2020	12:54:45	5.9	17.949° N	66.851° W	5.0
Jan. 11, 2020	12:56:22	5.2	17.824° N	66.795° W	10.0
Jan. 15, 2020	15:36:23	5.2	17.916° N	67.017° W	5.0

[1] Times and dates in this table are reported in the UTC time zone. Local time during these earthquakes is Atlantic Standard Time which is 4 hours behind UTC.

[2] Depths are poorly constrained for these earthquakes, which are occurring mostly offshore, far from seismic sensors.

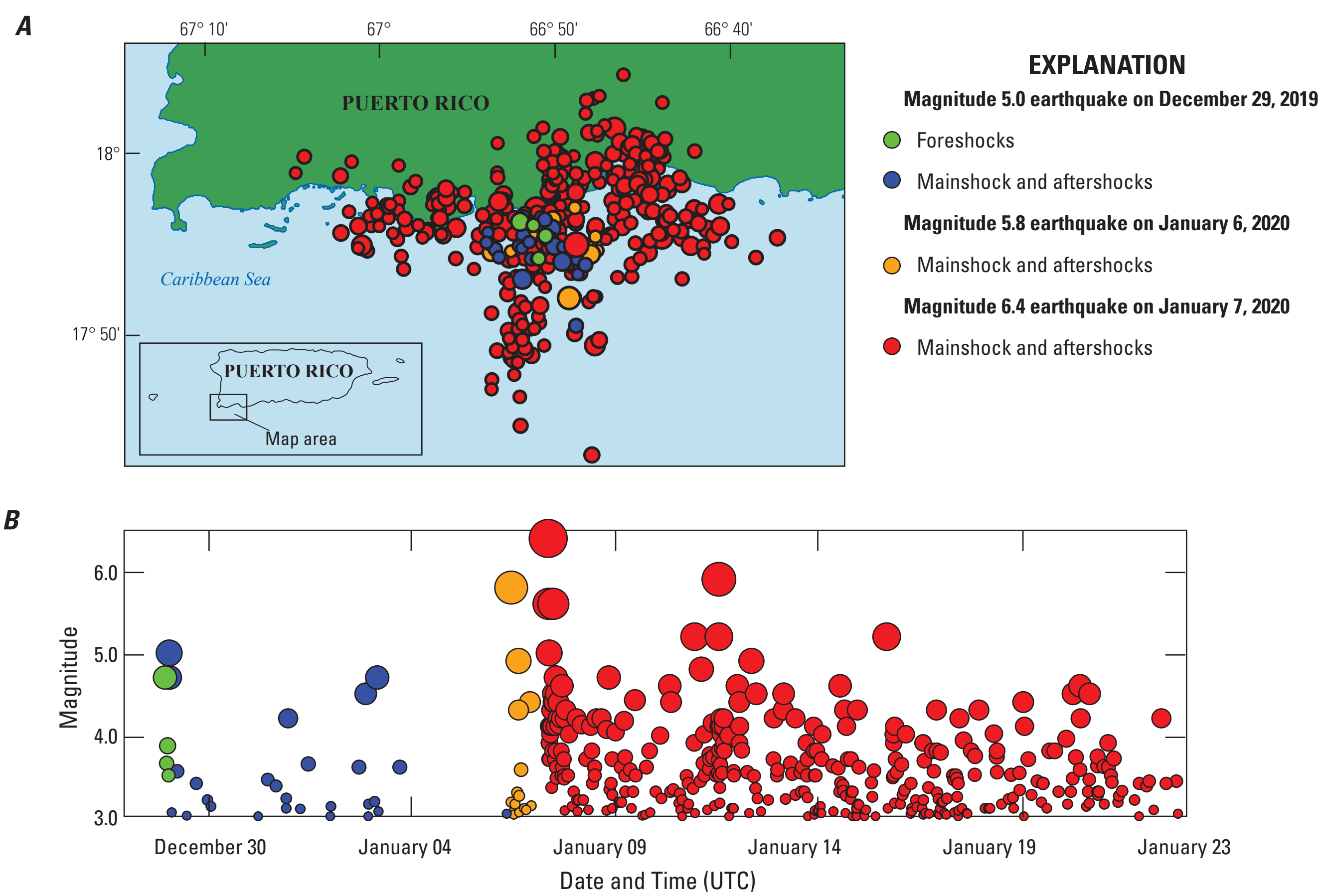

Figure 1. (*A*) Map and (*B*) magnitude-time plot of the 2020 southwestern Puerto Rico earthquake sequence. Each earthquake from December 29, 2019, through the end of January 22, 2020 (UTC), is plotted as a circle showing the location on the map and the time it occurred and its magnitude on the magnitude-time plot. Only earthquakes through January 17 were used to estimate this report's results. Circle sizes are proportional to each earthquake's magnitude.

In the time between the first magnitude 5 earthquake on December 28, 2019 to 10 days following the January 7, 2020 mainshock, there have been over 260 magnitude 3 or greater earthquakes. Most of these are aftershocks of the January 7, 2020, earthquake. The rate of aftershocks is expected to decrease as time passes. Observations of aftershock sequences around the globe find that most sequences decrease approximately in proportion to 1/time (Omori, 1894). Hence, the rate of aftershocks on the tenth day after the mainshock is generally about 1/10 (10 percent) of what it was on the first day and the rate on the 100th day is about 1/100 (1 percent) of what it was on the first day after the mainshock. Whereas the rate of aftershock occurrence on any given day decreases with time, aftershocks can still pose a significant risk to each phase of the disaster recovery process. This is because the phases of disaster recovery increase in length as society moves from emergency response, to restoration of services, to reconstruction of damaged buildings, to betterment projects, and onto a return to long-term normal activity (Michael, 2012). Even after the rates have decreased, individual aftershocks retain the same potential to be as large and damaging as those that occur early in the sequence.

Modeling the Aftershock Sequence

The time decay and duration of the aftershock sequence can be estimated using a mathematical approach called the epidemic-type aftershock sequence model (ETAS) (Ogata 1988). This model considers not only the effect of the mainshock setting off aftershocks, but also the effect of large aftershocks (for example, the magnitude 5 aftershocks listed in table 1), which can cause aftershocks of their own. In this report, we model the behavior of the sequence up to 10 years out from the magnitude 6.4 mainshock. The rate of aftershocks may remain elevated beyond this time, but we will require a longer period of observation in order to calculate the aftershock model for times longer than a decade. The model parameters as of January 17, 2020, are presented in appendix 1. To capture uncertainty in the forecast, two sets of ETAS model parameters are presented, which together give an upper and lower limit for our aftershock sequence duration estimates. As more time passes and more data are collected, it may become possible to refine these limits.

As of January 17, 2020, earthquakes are being felt in southwestern Puerto Rico on a daily basis. Using the aftershock sequence model, we can determine how long one can expect to feel earthquakes on a daily, weekly, or monthly basis. We report in table 2 on expected durations of magnitude 3 and larger earthquakes, which are commonly felt by people near the earthquake epicenter (within several tens of kilometers), as well as magnitude 4 and larger earthquakes, which tend to be more widely felt and can deliver strong surface shaking. Table 2 summarizes the periods over which people can expect to regularly experience these small to moderate earthquakes. Aftershocks will continue past the time that they are felt on a monthly basis, but with less frequency.

Table 2. Expected duration for earthquakes occurring on a regular basis[1] after January 17, 2020[2].

Frequency of earthquakes	Magnitude 3 or greater	Magnitude 4 or greater
Daily	2–6 months	5–13 days
Weekly	1.5–10 years	4–16 months
Monthly	10 or more years	1.5–10 years

[1] We define regular basis as having more than a 50 percent probability of an earthquake occurring during the next day, week, or month.

[2] Ranges are based on the two sets of parameters for the aftershock decay (appendix 1).

Next, we calculate the times until the annual probabilities of aftershocks with magnitudes 5, 6, and 7 or greater decrease to 50, 25, 10, 5, and 1 percent. These magnitudes were chosen because a magnitude 5 aftershock could cause light-moderate damage, depending on its location, whereas a magnitude 6 aftershock could cause considerable damage. A magnitude 7 earthquake in this region would be likely to cause severe shaking and significant damage. The results are shown in table 3. We calculate that it will be a minimum of 3 years (and possibly more than 10 years) before the annual probability of a magnitude 5 or greater aftershock drops below 50 percent. It will take only 1–2 weeks for the annual probability of a magnitude 6 or greater aftershock to decrease below 50 percent, but it will take 2–10 or more years for the annual probability to drop below 10 percent. The time ranges represent the lower and upper limit scenarios for how the aftershock sequence decreases over time.

Table 3. Timeframe after January 17, 2020, when the annual probability of an aftershock decreases to a given level[1]

Probability of 1 or more earthquakes in the next year, in percent	Magnitude 5 or greater	Magnitude 6 or greater	Magnitude 7 or greater
50	3–10 or more years	1–2 weeks	already below 50 percent
25	9–10 or more years	3–36 months	already below 25 percent
10	more than 10 years	2–10 or more years	1–7 days
5	more than 10 years	5–10 or more years	1–10 months
1	more than 10 years	more than 10 years	2–10 or more years

[1] Ranges for timeframes are based on the two sets of parameters for the aftershock decay (appendix 1).

If a large aftershock (similar in size to the magnitude 6.4 mainshock) occurs during the forecast time period, it would increase the rate of aftershocks and reset the clock on the aftershock duration calculations. The tables provided in this document would then need to be revised. As of this writing, we estimate that an earthquake larger than magnitude 6.4 has a 24–30 percent chance of occurring in the year following Jan 17, 2020, and an earthquake larger than magnitude 7 has a 6–10 percent chance of occurring in that same time period.

Conclusions

Earthquake sequences can last for weeks, years, or decades. Our models suggest that aftershocks of the magnitude 6.4 southwestern Puerto Rico earthquake will decrease in frequency as time goes on but will persist for a long time. This sequence is very productive and the probabilities of magnitude 5 or greater aftershocks remain sufficiently high to warrant concern and will for some time into the future. The timeframe when these probabilities reduce to lower levels could be used to guide public policy decisions or other actions in concert with additional considerations. The aftershocks discussed in this report would be located in the same general area as the aftershocks that have already occurred. Our results do not imply a change in the risk of earthquakes in other parts of Puerto Rico. The results in this report are based on the current behavior (as of January 17, 2020) of this aftershock sequence and may need to be modified if that behavior changes, including if a larger earthquake occurs.

References

de Arcangelis, L., Godano, C., and Lippiello, E, 2018, The Overlap of Aftershock Coda Waves and Short-Term Postseismic Forecasting: Journal of Geophysical Research, Solid Earth, v. 123, no. 7, p. 5661–5674.

Hirose, F., Miyaoka, K., Hayashimoto, N., Yamazaki, T., and Nakamura, M., 2011, Outline of the 2011 off the Pacific coast of Tohoku Earthquake (M_w 9.0)—Seismicity; foreshocks, mainshock, aftershocks, and induced activity: Earth, Planets, and Space, v. 63, no. 1, p. 513–518, https://doi.org/10.5047/eps.2011.05.019.

Kaiser, A., Holden, C., Beavan, J., Beetham, D., Benites, R., Celentano, A., Collett, D., Cousins, J., Cubrinovski, M., Dellow, G., Denys, P., Fielding, E., Fry, B., Gerstenberger, M., Langridge, R., Massey, C., Motagh, M., Pondard, N., McVerry, G., Ristau, J., Stirling, M., Thomas, J., Uma, S.R., and Zhao, J., 2012, The M_w 6.2 Christchurch earthquake of February 2011—Preliminary report: New Zealand Journal of Geology and Geophysics, v. 55, no. 1, p. 67–90, https://doi.org/10.1080/00288306.2011.641182.

Michael, A.J., 2012, Do aftershock probabilities decay with time?: Seismological Research Letters, v. 83, no. 4, p. 630–632, https://doi.org/10.1785/0220120061.

Ogata, Y. 1988 Statistical models for earthquake occurrences and residual analysis for point processes: Journal of the American Statistical Association, v. 83, no. 401, p. 9–27.

Omi, T., Ogata, Y., Hirata, Y., and Aihara, K., 2015, Intermediate-term forecasting of aftershocks from an early aftershock sequence—Bayesian and ensemble forecasting approaches: Journal of Geophysical Research, Solid Earth, v. 120, no. 4, p. 2561–2578.

Omori, F., 1894, On the aftershocks of earthquakes: Journal of the College of Science, Imperial University of Tokyo, v. 7, p. 111–200.

Ross, Z.E., Idini, B., Jia, Z., Stephenson, O.L., Zhong, M., Wang, X., Zhan, Z., Simons, M. Fielding, E.J., Yun, S., Hauksson, E., Moore, A.W., Liu, Z., and Jung, J., 2019, Hierarchical interlocked orthogonal faulting in the 2019 Ridgecrest earthquake sequence, Science, v. 366, no. 6463, p. 346–351, https://doi.org/10.1126/science.aaz0109.

Wells, D.L., and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, p. 974–1002.

Appendix 1

This appendix presents the technical parameters for the two scenarios used to estimate aftershock probabilities. These values are presented so that the calculations in this report can be reproduced. The forecast is made using the epidemic-type aftershock sequence model (Ogata 1988). For details on parameter definitions and methodology see Omi and others (2015). We substitute the parameter $a = \log_{10}K_0$ for aftershock productivity in equation 3 of Omi and others (2015). We also introduce some modifications to the method of Omi and others (2015). First, the mainshock of this sequence is more productive in creating aftershocks than average, and we use an additional parameter a_0 to model the primary contribution of the magnitude 6.4 mainshock. Second, as is common and expected after large earthquakes, the earthquake catalog is incomplete at early times following the magnitude 6.4 due to overlapping seismograms from almost simultaneous events. We model this using a magnitude-dependent time constant $c(\mathrm{M}) \propto 10^{\gamma \mathrm{M}}$ in Omori's law, following de Arcangelis and others (2018). Finally, in order to model realistic aftershock sequences, the parameters of the epidemic-type aftershock sequence model must be restricted to values that give a decreasing rate, on average. Combinations of parameters that would produce accelerating sequences over a duration less than 10 years are excluded from the modeling. Using the model, we generate 10,000 simulated aftershock sequences that describe what could happen in the next 10 years. We then extract the percentage of simulated sequences that include earthquakes matching the criteria in tables 1 and 2 to estimate probabilities and durations.

We fit the first 10 days of observations after the magnitude 6.4 mainshock to obtain a most likely set of parameters (table 1.1). To generate upper and lower limit scenarios (scenario 1 and 2 in table 1.1, respectively), we then fix the aftershock rate decay parameter p to +/- one standard deviation away from the most likely value of $p = 0.95$, and reestimate the remaining parameters.

Table 1.1. Model parameters and one standard deviation uncertainties used for estimates in this report.

Parameters common to scenarios 1 and 2	
Mainshock magnitude	6.4
Centroid of aftershock sequence	17.9402° N, 66.8289° W
Radius of aftershock sequence	33.5 kilometers (1.5 times the Wells and Coppersmith (1994) radius + 10 kilometers)
Gutenberg-Richter slope (assumed)	$b = 1.0$
Background Rate (assumed)	$\mu = 0$
Duration of observations used to train model	10 days
Duration used for limiting accelerating sequences	10 years
Minimum magnitude	4.0
Maximum magnitude	7.05
Number of simulations	10,000
Best fitting parameters (maximum likelihood solution)	
Primary aftershock productivity	$a_0 = -1.57 \pm 0.09$
Secondary aftershock productivity	$a_1 = -2.10 \pm 0.13$
Aftershock decay	$p = 0.95 \pm 0.07$, $\log_{10}c = -2.35 \pm 0.38$
Scenario 1 parameters (high decay rate)	
Primary aftershock productivity	$a_0 = -1.57 \pm 0.10$
Secondary aftershock productivity	$a_1 = -2.07 \pm 0.20$
Aftershock decay	$p = 1.02$, $\log_{10}c = -2.06 \pm 0.22$
Scenario 2 parameters (low decay rate)	
Primary aftershock productivity	$a_0 = -1.53 \pm 0.10$
Secondary aftershock productivity	$a_1 = -2.17 \pm 0.20$
Aftershock decay	$p = 0.88$, $\log_{10}c = -2.55 \pm 0.35$

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