Response to Comment on "How will induced seismicity in Oklahoma respond to decreased saltwater injection rates?"

Cornelius Langenbruch* and Mark D. Zoback

Goebel et al. question our forecasted response of induced seismicity to reduction of saltwater injection rates in north-central Oklahoma and raise the concern that "the probability of future damaging earthquakes may be underestimated." We compare our prediction to earthquake data recorded in the 8 months after publication. Observed seismicity rates and magnitudes agree with the forecast of our model. Our use of a probabilistic model accounts for uncertainties and observed $M \geq 4.5$ to date confirm the conservative nature of our prediction. The "realistic parameter range" suggested by Goebel et al. is based on a misunderstanding of our statistical model and disagrees with the long-term decay of seismicity in the region.

In their Comment, Goebel et al. (1) question the basic framework of our model (2) and the parameters we used and assert that the model (2) "is not able to predict several moderate earthquakes that have already occurred, and thus, the probability of future damaging earthquakes may also be underestimated." We show below that Goebel et al. misunderstand important aspects of our model. The "more realistic" parameter range they suggest is not based on seismicity triggered by produced water injection and disagrees with long-term seismicity decay occurring in the region since injection rates began to significantly decrease in 2015.

In Fig. 1, we present earthquake rates ($M \geq 3$) observed in the area subjected to mandated saltwater injection rate reduction in north-central Oklahoma. The earthquake catalog contains 8 months of data (October 2016 to May 2017) recorded after our study (2, 3) was accepted for publication. Earthquake data available to date confirm our model of seismicity increase proportional to injection rates above a critical level, and the seismicity decay we forecast using the modified seismogenic index model and a modification of Omori's law (4) after injection rates started to decrease. As predicted by our model (2), the number of widely felt $M \geq 3$ earthquakes had significantly decreased by the end of 2016 and has continued to decrease in 2017. Seismicity rates ($M \geq 3$) observed during the first 5 months of 2017 are about 75% lower than earthquake rates observed in 2015.

The observed decay rate is in agreement with our prediction according to a modification of Omori's law with a physics-based choice of p value ($p = 2$). In a previous study, Langenbruch and Shapiro (4) demonstrated that p values expected from pore pressure diffusion as the triggering mechanism of induced seismicity after injection results in p values of ≥ 2. We note that our model is not designed to forecast short-term spikes of seismicity caused by aftershocks of moderate-sized earthquakes (see Fig. 1). Our model relates long-term trends of produced water injection to long-term changes of seismicity. We decided to use a physics-based p value that ignores the spikes of seismicity related to aftershocks following the $M \geq 4.7$ earthquakes in the Cherokee, Fairview, and Pawnee areas, which mask the long-term decay of seismicity related to reduced injection rates.

In their comment, Goebel et al. criticize the fact that "Langenbruch and Zoback even suggest that $p = 2$ is a conservative estimate, whereas the vast majority of studies find tectonic p values close to 1 (5)." In this

regard, Goebel et al. do not recognize that we chose a p value of 2 to be a conservative decay rate associated with earthquakes related to pore pressure diffusion (4). Note that our choice of $p = 2$ as being "conservative" is related to the fact that had we chosen a p value of >2, the predicted earthquake decay rate would have been even more rapid.

Mistakenly, Goebel et al. determine a "realistic parameter choice" of p values. First, they fit seismicity dominated by spikes of aftershocks and not long-term changes related to reduction of injection rates and suggest $p = 1.4$. Second, they suggest $p = 1.2$ from a catalog declustered with a technique that, because it is developed for tectonic seismicity (6), removes inherent clustering changes of induced seismicity caused by changes of injection rates. As shown in Fig. 1, seismicity rates resulting from the parameter range recommended by Goebel et al. seriously disagrees with the long-term decay of seismicity in the region subjected to injection rate reduction.

Goebel et al. further challenge the applicability of the Gutenberg-Richter law (7) and doubt that "the occurrence of large-magnitude events can be determined by extrapolating the rate of small-magnitude events." A recently published study (8), coauthored by the corresponding author of the comment, analyzes the statistics of numerous induced earthquake catalogs (including Oklahoma) and concludes that "Probabilistic hazard assessment is appropriate for induced seismicity. In particular, the rate of triggered small earthquakes can be used to forecast the rate of large earthquakes, just like for tectonic environments." We point out the fact that our model assumption of forecasting the occurrence probability of larger-magnitude earthquakes from the model expectation of $M \geq 3$ earthquakes is in agreement with conclusions coauthored by T. H. W. Goebel.

Figure 1 demonstrates that the extrapolation of our model expectation from $M \geq 3$ to $M \geq 3.5$ agrees with observations. Because Goebel et al. specially challenge "the applicability of the model for the most societally significant events" of larger magnitudes, we compare observed magnitude distributions to expectations of our model. Figure 2A demonstrates that the magnitude distribution expected from our model is a good description of magnitudes observed to date (2009 to May 2017). Note that our choice of b values was based on a maximum likelihood fit to the cumulative magnitude distribution observed in the area of interest until December 2015 and is confirmed by observations. Not only are seismicity rates of $M \geq 3$ and $M \geq 3.5$ consistent with our model (Fig. 1), but our model's expectation of four $M \geq 5$ earthquakes also agrees with what has actually happened (see Fig. 2A).

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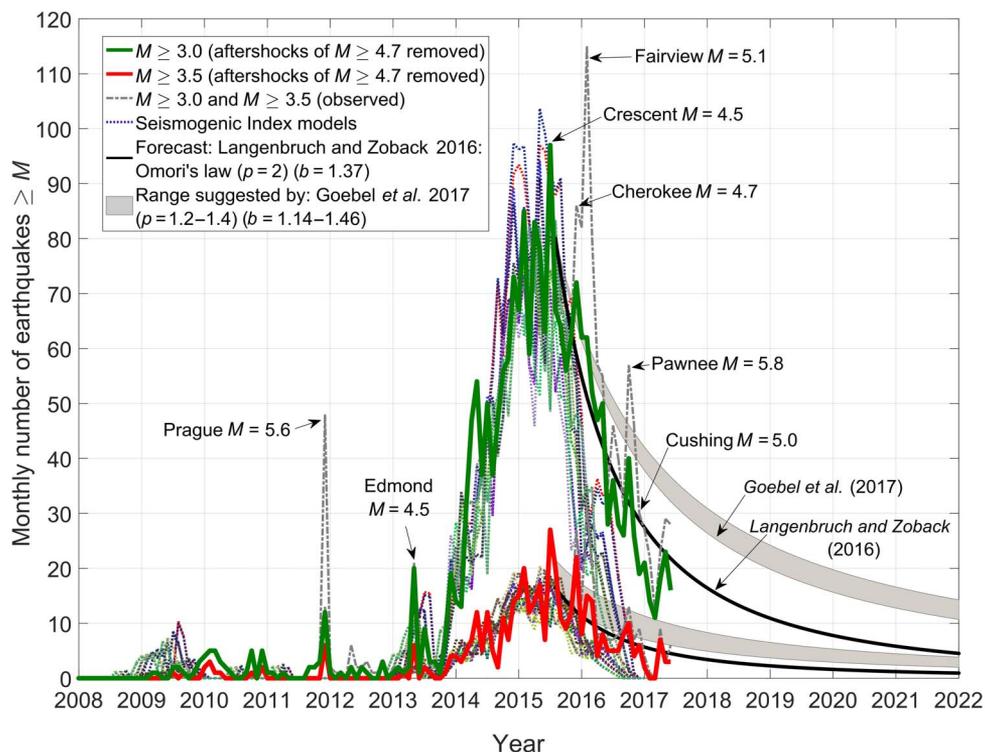*Corresponding author. Email: langenbr@stanford.edu

Fig. 1. Observation and prediction of induced seismicity in north-central Oklahoma. The monthly number of observed earthquakes ($M \geq 3$, green; $M \geq 3.5$, red) (aftershocks of $M \geq 4.7$ events have been removed), complete earthquake catalogs (gray dashed lines), seismogenic index (SI) models calibrated to different times between June 2014 and December 2015 (dotted lines), predicted decay rates according to Omori's law ($p = 2$) (black solid lines), and seismicity rates resulting from the suggested parameter range by Goebel et al. (gray areas). The figure is an updated version of Fig. 4 presented in Langenbruch and Zoback (2) and includes seismicity in the region subjected to injection rate reduction mandated in early 2016. The eight month of earthquake data (October 2016 to May 2017) has been recorded after our forecast was accepted for publication.
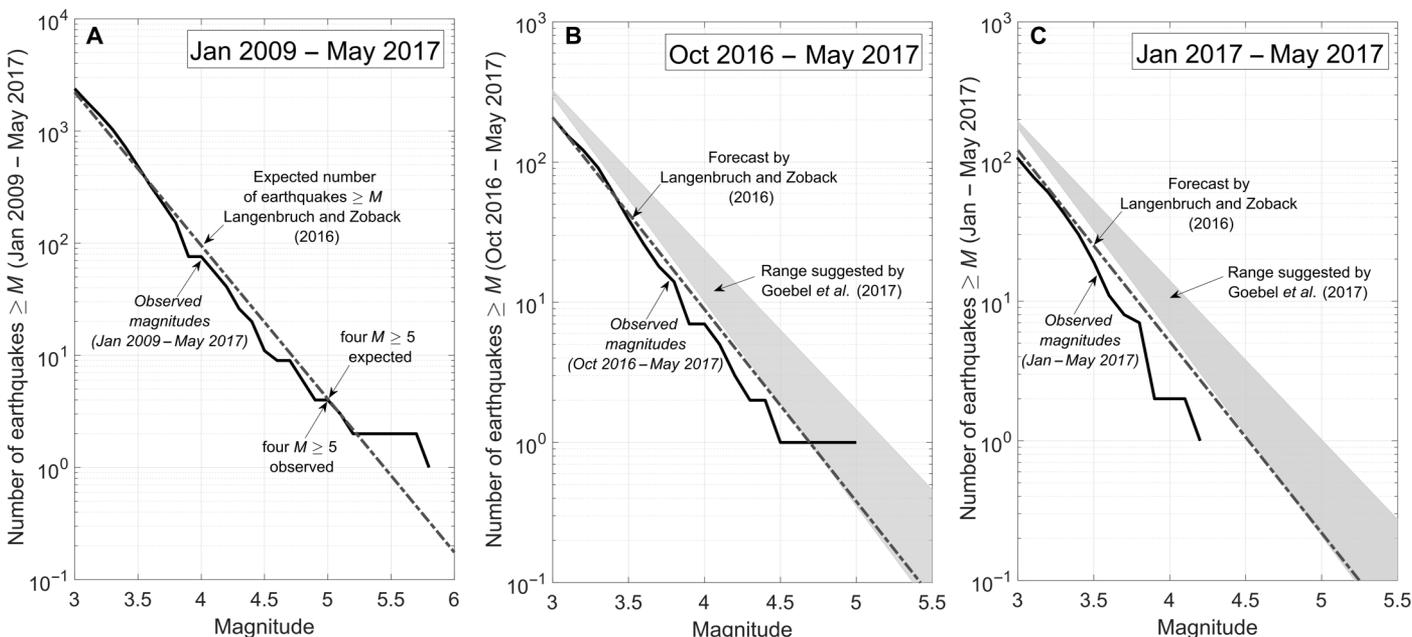

Fig. 2. Comparison of observed, expected, and forecasted magnitude distributions. (**A**) The complete earthquake catalog ($M \geq 3$) from January 2009 to May 2017 (solid line) and the magnitude distribution expected from our model in the same time window. (**B**) The magnitude distribution of earthquakes (solid line) recorded from October 2016 to May 2017 after our forecast (dashed line) was accepted for publication. (**C**) Observed and forecasted magnitude distributions for 2017 (January to May). Magnitude distribution resulting from the "realistic parameter choice" suggested by Goebel et al. [gray shaded areas in (B) and (C)] disagree with observations.

Figure 2 (B and C) shows magnitude distributions recorded after our forecast was accepted for publication. Magnitude distributions expected from our model are confirmed by observations (Fig. 2, B and C). The fact that the number of observed magnitudes in 2017 falls below our forecast reconfirms that our physics-based choice of $p = 2$ is conservative. As observed for seismicity rates of $M \geq 3$ and $M \geq 3.5$ (Fig. 1), magnitude distributions resulting from the parameter choice suggested by Goebel *et al.* significantly disagree with observations (Fig. 2, B and C).

Goebel *et al.* point at the occurrence times of the four $M \geq 5$ earthquakes and suggest that the structure of our model requires reexamination because it is "not able to predict several moderate earthquakes that have already occurred." In Fig. 3, we demonstrate that the criticism seems to result from a misunderstanding of how to assess the performance of a probabilistic model. Our model forecasts four $M \geq 5$ earthquakes in the complete catalog from 2009 to May 2017 (see also Fig. 2A) and describes their occurrence in time well within the 95% confidence interval of a Poisson process. It requires no further discussion to understand that the assertion by Goebel *et al.* that our model "is not able to predict several moderate earthquakes that have already occurred" is incorrect. As shown in Fig. 3A, the occurrence of one $M \geq 5$ earthquake in 2011 and three $M \geq 5$ earthquakes in 2016 is not a statistically valid basis to challenge our model. Moreover, Goebel *et al.*'s expressed concern that our model is underestimating the occurrence of larger-magnitude earthquakes has no basis. The opposite is the case; our model is conservative because it tends to overpredict the number of moderate-sized $M \geq 4.5$ earthquakes (see Fig. 3A).

Figure 3A further demonstrates that our use of a probabilistic model accounts for the uncertainties of our forecast. It considers the occurrence of induced earthquakes as a Poisson process (9, 10) with a rate parameter (the expected number of earthquakes) determined by the modified seismogenic index model and a modification of Omori's law. Our model expects occurrence of five $M \geq 5$ earthquakes between 2009 and 2022. However, on the basis of the 95% confidence interval,

our model does account for the possibility of 1 to 11 $M \geq 5$ earthquakes. Moreover, as shown in Fig. 3B, our model expects 1.21 additional $M \geq 5$ earthquakes from 2017 to 2022 but accounts for the possibility of zero (30%), one (36%), two (22%), or three (9%) $M \geq 5$ earthquakes within the 95% confidence interval of a Poisson process.

Note that the occurrence of the $M = 5.8$ Pawnee earthquake falls well within the prediction because our model expectation of 0.33 $M \geq 5.8$ earthquakes result in a probability of 28% to observe one or more $M \geq 5.8$ earthquakes between 2009 and May 2017. The observation of Goebel *et al.* that the seismic moment, which is dominated by large magnitudes, is not proportional to the injected fluid volume is correct, but it is not relevant to our model.

We acknowledge the comment by Goebel *et al.* that "Assessments of seismic response to injection rate reduction in Oklahoma are model-dependent and remain uncertain in 2017 and beyond." First, the probabilistic nature of our model accounts for uncertainties, especially for a small number of expectations ($M \geq 5$). Second, we stated in our original article that "The main purpose of this paper was to clarify whether the mandated injection reductions are expected to cause seismicity to decrease in the future. We did not intend to present a final and reliable seismic hazard model for Oklahoma." Third, we went to great lengths in our paper to discuss the limitations of our model and suggested that updating our model would be warranted as soon as observed and forecasted seismicity rates start to differ in a statistically significant manner. However, observation of earthquakes to date confirm that (i) as predicted by our model, the number of widely felt $M \geq 3$ earthquakes in north-central Oklahoma had significantly decreased by the end of 2016 and has kept decreasing in 2017. Seismicity rates ($M \geq 3$) observed during the first 5 months of 2017 are about 75% lower than earthquake rates in 2015. (ii) Forecasted and observed magnitude distributions are in agreement. (iii) The observed magnitude distribution in 2017 and observed $M \geq 4.5$ to date confirm the conservative nature of our forecast. (iv) The observed occurrence of four $M \geq 5$ earthquakes agrees with our model expectation. (v) Our use of a probabilistic
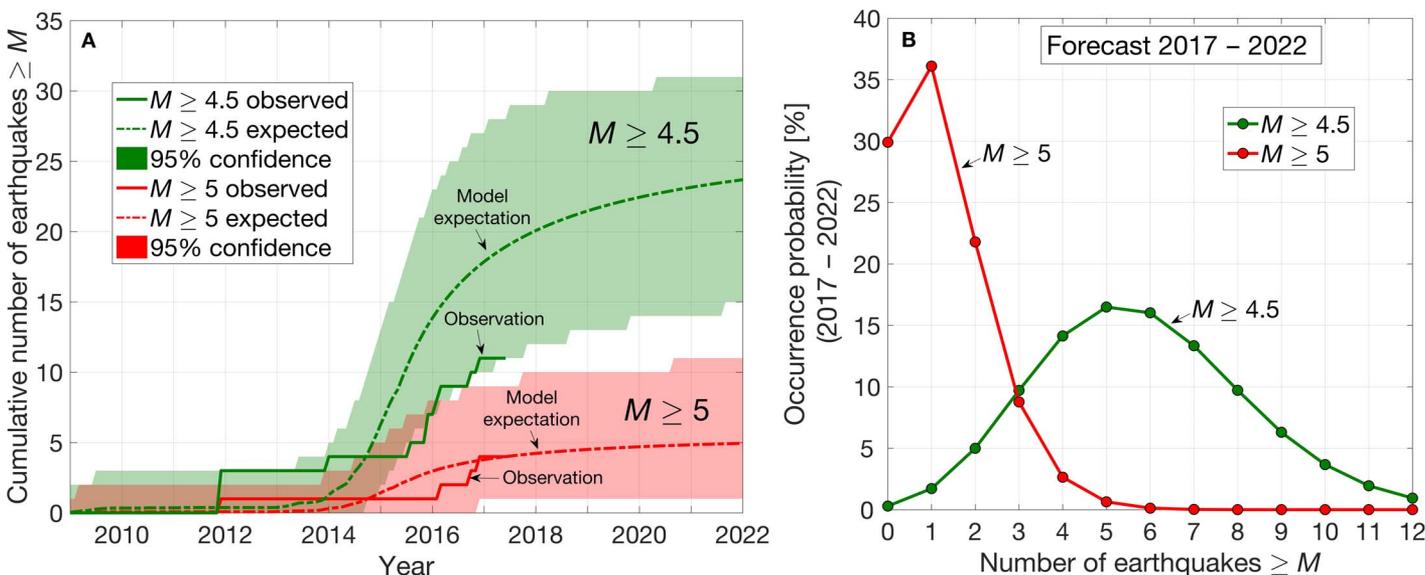

Fig. 3. Expected, observed, and forecasted $M \geq 4.5$ and $M \geq 5$ earthquakes. (A) Observed $M \geq 5$ earthquakes (solid lines) occur within the 95% confidence interval (shaded areas) around the model expectation (dashed lines). The 95% confidence interval is computed according to a Poisson process. Occurrence of four $M \geq 5$ earthquakes through May 2017 was expected. (B) Forecasted occurrence probabilities of $M \geq 5$ and $M \geq 4.5$ from 2017 to 2022. Our model expects 1.21 $M \geq 5$ earthquakes but accounts for the possibility of zero (30%), one (36%), two (22%), or three (9%) $M \geq 5$ earthquakes within the 95% confidence interval.

model accounts for the uncertainties of our forecast. (vi) The parameter range suggested by Goebel *et al.* is based on a misunderstanding of our statistical model and is in disagreement with the seismicity that is occurring.

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