Thank you for reviewing our manuscript entitled "Risk-based analysis of monitoring time intervals for landslide prevention" for *Natural Hazards and Earth System Sciences*. We are grateful to the referee for the constructive comments provided. The suggestions have been very useful for improving our manuscript. Our replies to the general comments, specific comments, and technical comments are given point by point.

[General Comments]

[Comment G-1]: Although a high number of landslides were triggered and may thus provide a good spatial estimate of landslide probability, determining a landslide frequency from a single event is, at least in my view, highly speculative. Thus, some questions remain unanswered (e.g., does prolonged, intense rainfall trigger landslide, or is it only extreme events?) and I think the temporal frequency for the different hazard classes may be over- or underestimated.

Thank you for your comment. We agree that this is an important point, and the results are somewhat speculative at this time. Thus, we want to make it clear that this aspect of our study is limited to an extreme weather event. Unfortunately, the data available for the study were limited to the landslide inventory after Typhoon Ewiniar. Inventory data regarding the landslides triggered by prolonged, intense rainfall events after that extreme weather event were not available. However, we attempt to show through this case study that the landside monitoring time interval can be decided upon quantitatively based on a risk analysis. The main purpose of this study was to analyse monitoring time intervals quantitatively based on a risk study and to propose a plan for periodic landslide monitoring by considering risk reduction effects. We believe that the other regions with accumulated frequency data will be able to estimate landslide probability more accurately using the method presented in this study. We acknowledge that further research should examine the rainfall threshold based on continuous landslide inventories of multiple weather events. This detailed response also applies to questions S-2b, S-3, and S-4.

[Comment G-2]: In your analysis, one year is given as the minimum. Depending on the failure mechanism, some slopes may require a monitoring frequency well below one year. … Given that the title of the paper is "Risk based analysis of monitoring time interval to prevent landslide". Hence, it would be more appropriate to include significantly higher monitoring frequencies (hourly/daily/weekly/yearly).

Thank you for your helpful advice. We agree that some slopes may require a monitoring frequency of less than one year. Through appropriate decision-making, more frequent monitoring (monthly or weekly) can be planned using the method presented in the manuscript. We have added calculations for monthly and weekly monitoring frequencies, and have inserted a corresponding additional table in the Appendix. Please see Lines 20-21 on Page 14 and Table 3 on Page 19. For significantly higher monitoring frequencies, such as hourly and daily intervals, monitoring equipment capable of continuous logging and transmitting would be required. The possible need for more frequent monitoring has been addressed in the discussion. Please see Lines 12-15 on Page 18.

In addition, the methodology presented in the manuscript is focused on monitoring methods with low temporal resolution. Therefore, we have changed the title of the manuscript to "Risk-based analysis of monitoring time intervals for landslide prevention: A case study of low temporal resolution methods". Please see the revised title of the manuscript. If you have any further comments on this issue, it would be appreciated.

[Page 14, Lines 20-21] Results for setting the monitoring interval for grade 1 to higher frequencies of monthly and weekly are shown in the Appendix.

[Page 18, Lines 12-15] In addition to regular pore water pressure monitoring and deformation monitoring, efforts should be made to increase monitoring activities in the rainy season. Installing monitoring equipment capable of continuous logging and transmitting will also be required to protect core vulnerable areas against landslides.

[Page 19, Table 3]

Table 3. Monitoring time interval sets producing the same average probability of landslide occurrence on a yearly, monthly and weekly basis.

Landslide hazard grade	Yearly monitoring time interval for grade 1 (days)			
	365	1314	4672	14126
1	1.06E-04	3.82E-04	1.36E-03	4.11E-03
2	2.96E-05	1.07E-04	3.79E-04	1.15E-03
3	8.29E-06	2.99E-05	1.06E-04	3.21E-04
4	2.74E-06	9.87E-06	3.51E-05	1.06E-04
Landslide Hazard grade	Monthly monitoring time interval for grade 1 (days)			
	30	107	384	1161
1	8.72E-06	3.12E-05	1.12E-04	3.38E-04
2	2.44E-06	8.72E-06	3.12E-05	9.43E-05
3	6.82E-07	2.44E-06	8.72E-06	2.64E-05
4	2.25E-07	8.07E-07	2.88E-06	8.72E-06
Landslide hazard grade	Weekly monitoring time interval for grade 1 (days)			
	7	25	90	271
1	2.03E-06	7.29E-06	2.60E-05	7.88E-05
2	5.68E-07	2.03E-06	7.27E-06	2.20E-05
3	1.59E-07	5.69E-07	2.03E-06	6.15E-06
4	5.26E-08	1.88E-07	6.73E-07	2.03E-06

[Comment G-3]: However, the strict and comparably long description of the methodology is unnecessary. I would suggest reducing the description of the standard approaches, and extending the description of the novel risk analysis.

Thank you for your suggestion. We have shortened the presentation of the methodology to minimize the description of the standard approaches. If you have further specific comments, please let us know. Regarding the suggestion to extend the description of the novel risk analysis, we try to highlight that this study presents a method to estimate the landslide monitoring time interval quantitatively based on a risk analysis adopting the concept of reliability. For the analysis, a pixel unit of GIS-based spatial information was considered as a component to identify the frequency of landside occurrence, and the equation for the probability of occurrence was derived from the definition of reliability. With this method, it becomes possible to calculate the monitoring time interval needed to reduce the risk of landslide occurrence below the desired level. Please see Lines 12-14 on Page 7 and Lines 16-18 on Page 9.

[Page 7, Lines 12-14] When a pixel unit of GIS-based spatial information was considered as a component to find the frequency of landside occurrence, the equation for the probability of occurrence can be derived from the definition of reliability.

[Page 9, Lines 16-18] In order to quantitatively estimate the monitoring interval, we adopted the concept of time-average probability of failure. With this method, it becomes possible to calculate the monitoring interval needed to reduce the risk of landslide occurrence below the desired level.

[Comment G-4]: The paper would also benefit from a revision of grammar and sentence structure by a native English speaker. There are many very long sentences. I suggest splitting those sentences in two or three separate sentences.

We have revised the entire manuscript carefully and tried to avoid grammar errors and long sentences. In addition, a native English speaker and professional editor has checked the English. We believe that the language is now acceptable for the review process.

[Specific comments]

[Comment S-1] Page 3, Line 14: You mention that topography is the main factor for landslides in the area. Although this may be the case, the geology will almost certainly play a major role as well. Hence, please add some description of the local geology (bedrock and soil cover).

Thank you for your helpful advice. We agree that geologic characteristics play a major role in causing landslides, as well as topographic features. A description of the local geology has been added to the manuscript. Please see Lines 8-11 on Page 3.

[Page 3, Lines 8-11] The bedrock of the Pyeongchang area is composed of Precambrian metamorphic sedimentary and granitic rocks, and Palaeozoic sedimentary rocks and Jurassic granite are distributed throughout the region (Kim et al., 1997). The soil cover in the study area is mainly sandy loam and clay loam, and sandy loam predominates in the mountainous areas where landslides have occurred (K.N.S.D.I.P., 2017). These topographic and geologic features make the study site prone to landslides.

References used in this response:

Kim, J. H., Cheong, C. S., Son, Y. C. and Koh, H. J.: Geology and Sr, Nd and Pb isotopic compositions of Precambrian granitoids in the Pyeongchang area, Korea, Journal of the Geological Society of Korea, 33, 27-35, 1997. (in Korean)

Korea National Spatial Data Infrastructure Portal: Soil cover map of Gangwon province, http://market.nsdi.go.kr/goods/detail.do?gno=13114, last access: 2 January 2017.

[Comment S-2a] Page 5, Line 14: I think developing a landslide susceptibility map on just one weather event is not ideal. …

The landslide hazard map used for the study is a national-scope dataset produced by the Korea Forest Service (Governmental sector) in 2012, based on multiple weather events. In particular, the landslide hazard map was made based on a logistic regression analysis of around 2000 landslide inventory data points. A description of the landslide hazard map has been added to the manuscript. Please see Lines 5-7 on Page 4. The data based on one weather event are the landslide inventory after Typhoon Ewiniar, which was provided separately by the local government of Gangwon Province. This issue regarding the limitation of using data from a single weather event is discussed in the answer for the question S-2b below.

[Page 4, Lines 5-7] …, we used the landslide hazard map prepared in national scope by the Korea Forest Service in 2012 (Korea Forest Service, 2012). The landslide hazard map was made based on a logistic regression analysis of around 2000 landslides caused by multiple weather events (Korea Forest Service, 2013).

References used in this response:
Korea Forestry Service: Integrated management plan for landslide hazard, 2013. (in Korean)

[Comment S-2b] Was there no previous data available? If not, please add a discussion on the limitation of using the landslide data of one extreme weather event only and its impact on the reliability of your estimated temporal and spatial landslide probability.

Thank you for your comment. This is a critical limitation and should be improved in future research. Unfortunately, the data that we could use for the study were limited to the landslide inventory after Typhoon Ewiniar. The typhoon caused massive landslide damage in the study area, and detailed investigations were conducted by the municipality right after the weather event. However, no continuous inventory data since then are available. The national-level inventory data based on multiple weather events used for the landslide hazard map are not provided to individual researchers because of potential implications for property values. We believe that it is necessary to construct an open information system for a continuous landslide inventory on the national level in the future.
In addition, we agree with your opinion that this limitation impacts the reliability of the estimated landslide probability. We have added a discussion on the limitation of using landslide data from only a single extreme weather event. Please, see Lines 26-27 on Page 17. The other sentences related to this limitation have also been revised accordingly. Please, see Lines 24-25 on Page 2, Lines 7-8 on Page 5, Line 26-27 on Page7, Lines 6-7 on Page 9, Lines 5-7 on Page 17, and Lines 27-28 on Page 18.

[Page 17, Line 26-27] Due to the lack of landslide inventory data accumulated continuously in the study area, the estimation of landslide frequency was limited to an extreme weather event in our study.

[Page 2, Line 24-25] ..., the frequency of landslide occurrence limited to an extreme weather event was estimated by establishing a rainfall threshold.

[Page 5, Line 7-8] …, the frequency of landslide occurrence limited to extreme weather event was estimated with this cross-sectional data …

[Page 7, Line 26-27] In this study, we attempted to identify the relative temporal frequency of landslides limited to an extreme weather event …

[Page 9, Line 6-7] …, the rainfall threshold was used to estimate the frequency of landslide occurrence limited to the extreme weather event for this case study.

[Page 17, Line 5-7] After reliable frequency data for landslide occurrence have been established with continuous inventories and the extent of the scope of the area is fixed, meaningful calculation results for risk reduction can be obtained.

[Page 18, Line 27-28] The frequency data limited to an extreme weather event were used to calculate the probability of landslide occurrence.

[Comment S-3] Page 8, Lines 11-12: Can Typhoon Ewiniar be classified as a common example of regional weather patterns that are likely to be reoccurring, or was this a truly exceptional event? In that case, how reliable are your estimates of landslide probability?

It is true that the rainfall from Typhoon Ewiniar cannot be classified as a common example of regional weather patterns. However, extreme weather events are increasing due to climate change in South Korea, and this exceptional event may reoccur, causing landslides. Therefore, we want to make it clear that this study is limited to an extreme weather event. Please see the discussion added to Lines 21-23 on Page 16. In addition, please refer to the answer and the revised sentences for question S-2b above.

[Page 16, Line 21-23] In this study, we performed the risk analysis by limiting to the extreme weather event because of lack of continuous landslide inventory data. This limitation should be improved in future research to reflect a common example of regional weather patterns.

[Comment S-4] Page 12, Lines 18-21: I think it is highly speculative to define a rainfall threshold based on a landslide inventory of just one event. Next to extreme events, are landslides triggered by prolonged, intense rainfall events, which may be more characteristic for years 2010-2014?

We agree that this result is speculative at this time, and we have edited the text to state that the result is limited to an extreme weather event. Please see Lines 19-20 on Page 11. Unfortunately, inventory data regarding the landslides triggered by prolonged, intense rainfall events for the years 2010-2014 were not available for the reason described in response to question S2-b. However, other regions that maintain more accurate frequency data can obtain reliable landslide probability estimations by applying the methods shown in this manuscript. The focus in our work is to suggest a quantitative method for determining the monitoring time interval to prevent landslides based on risk analysis. We acknowledge that further research should examine the rainfall threshold based on continuous landslide inventories of multiple weather events.

[Page 11, Line 19-20] Thus, the probabilistic period of landslide occurrence limited to extreme weather events was estimated as 3.7 years.

[Comment S-5] Page 18, Lines 5-8: Is this necessarily true? The unit is given as landslide event × pixel-1 × year-1; if the pixel size increases the probability will decrease, but with increasing size more events may be counted. Please revise this statement.

We did not intend to suggest that the probability will decrease if the pixel size increases by giving the unit of landslide event × $pixel^{-1}$ × $year^{-1}$. As the referee explained in the comment, with increasing size, more events may be counted, and the frequency will be increased. Following the equation describing the probability of landslide occurrence (Eq. 3 and Eq. 10), an increasing probability can be demonstrated as the pixel size increases from 100 m^2 to 1 km^2 as below, based on the results shown in the revised Table 1. We have revised the text to clarify. Please see Lines 10-12 on Page 17.

When a pixel size is 100 m^2	When a pixel size is 1 km^2
Landslide occurrence frequency for grade 1 (event / pixel / year) = 111 / (142761 – 111) / 3.7 = 111 / 142650 / 3.7 = 0.00021 Probability of landslide occurrence $(1 - e^{-\lambda t})$ $= 1 - e^{-0.00021 \times 3.7}$ = 0.00078	Landslide occurrence frequency for grade 1 (event / km^2 / year) = 111 / 14.265 / 3.7 = 2.1 Probability of landslide occurrence $(1 - e^{-\lambda t})$ $= 1 - e^{-2.1 \times 3.7}$ = 0.99958

[Page 17, Lines 10-12] If the size of the unit area increases from the pixel unit to the area unit of km2, or to the entire county, the occurrence frequency will be increased. This means that the probability of disaster occurrence for a larger unit area will increase as the frequency of occurrence increases,…

In addition, we apologize for the editing error in Table 1 and Table 2. We have corrected the column of landslide occurrence frequency in Table 1 and the column of a monitoring time interval for 38.7 years in Table 2. The sentences related to this editing error have been reviewed and revised accordingly. Please see Lines 5-7 on Page 13, Table 1 on Page 14 and Table 2 on Page 15. We have confirmed that the other calculation results shown in the manuscript are correct. The spreadsheet used for the calculations is attached as a supplemental file for your review.

[Page 13, Lines 5-7] The area of landslide hazard grade 1 had the highest value of landslide occurrence frequency, 2.12E-04 (landslide event × pixel-1 × year-1), and the frequency sequentially decreased from grade 2 to grade 4.

[Page 14, Table1]

Table 1. The calculated landslide occurrence frequency

Landslide hazard grade	No. of landslides (N)	Total area * (A)	Occurrence ratio (N/A)	Landslide occurrence frequency ** (λ)
1	111	142761	7.78E-04	2.12E-04
2	938	4316864	2.17E-04	5.93E-05
3	446	7334461	6.08E-05	1.66E-05
4	5	248687	2.01E-05	5.48E-06

* The unit of total area A is one pixel (10 m × 10 m)
** The unit of landslide occurrence rate (λ) is landslide event × pixel $^{-1}$ × year $^{-1}$

[Page 15, Table2]

Table 2. Monitoring time intervals yielding the same average probability of landslide occurrence

Landslide hazard grade	Monitoring time interval (years)			
	1	3.6	12.8	38.7
1	1.06E-04	3.82E-04	1.36E-03	4.11E-03
2	2.96E-05	1.07E-04	3.79E-04	1.15E-03
3	8.29E-06	2.99E-05	1.06E-04	3.21E-04
4	2.74E-06	9.87E-06	3.51E-05	1.06E-04

[Technical comments]

[Comment T-1] Page 1, Lines 14-15: "manually read inclinometer and piezometer" – continuously logging and transmitting inclinometer and piezometer are available, but you are talking about manually logged installations.

The referee is right to point out that the conventional inclinometers or piezometers described in the manuscript involve manually read installations without the ability to continuously log and transmit data. We have modified "inclinometer or piezometer" to "manually read inclinometers or piezometers" in Lines 14-16 on Page 1. Please, also see Lines 5-6 on Page 2, Lines 25-27 on Page 10, Lines 4-5 on Page 16, and Lines 18-19 on Page 18.

[Page 1, Lines 14-16] Monitoring methods based on low temporal resolution instruments, such as manually read inclinometers or piezometers, can be effective and cost-efficient solutions.

[Page 2, Line 5-6] Manually read monitoring methods with a low temporal resolution, such as conventional inclinometers to detect subsurface deformation and piezometers to monitor pore water pressure, can be effective solutions (Uhlemann et al., 2016).

[Page 10, Line 25-27] … manually read inclinometers that detect subsurface deformation and piezometers that monitor ground water have low temporal resolution, and they can be effective solution for monitoring areas at risk of landslides (Uhlemann et al., 2016).

[Page 16, Line 4-5] This finding is valid for landslide monitoring methods with a low temporal resolution, such as manually read inclinometer or piezometer.

[Page 18, Lines 18-19] an optimized set of landslide monitoring time intervals for low temporal resolution methods, such as manually read inclinometer or piezometer.

[Comment T-2a] Page 2, Line 2: "relatively expensive" is potentially a misleading expression, perhaps "comprehensive monitoring methods" may be a better choice.

We agree with your suggestion. The expression of "relatively expensive" has been changed to "comprehensive monitoring methods". Please see Lines 1-2 on Page 2.

[Page 2, Line 1-2] However, almost all countries find it challenging to allocate sufficient financial and human resources for major engineering works or comprehensive monitoring methods to mitigate disasters,…

[Comment T-2b] Page 2, Line 5: I don't think that singular is the right choice here. Although, a single inclino- and piezometer is the bare minimum, in real applications, you would have more than that.

We agree with your opinion. The use of a singular form for inclinometer and piezometer was changed to a plural form when these devices are described as an effective solution. Please see Lines 14-16 on Page 1, Lines 5-6 on Page 2, and Lines 25-27 on Page 10.

[Page 1, Lines 14-16] Monitoring methods based on low temporal resolution instruments, such as manually read inclinometers or piezometers, can be effective and cost-efficient solutions.

[Page 2, Line 5-6] Manually read monitoring methods with a low temporal resolution, such as conventional inclinometers to detect subsurface deformation and piezometers to monitor pore water pressure, can be effective solutions (Uhlemann et al., 2016).

[Page 10, Line 25-27] … manually read inclinometers that detect subsurface deformation and piezometers that monitor ground water have low temporal resolution, and they can be effective solution for monitoring areas at risk of landslides (Uhlemann et al., 2016).

[Comment T-2c] Page 2, Line 6: Also, could you please clarify the last two parts of the sentence.

The last two parts of this sentence have been revised to clarify the meaning. We intended to state that manually read inclinometers and piezometers can be cost-efficient for controlling the risk from multiple areas susceptible to landslides over a broad region. Please see Lines 6-7 on Page 2.

[Page 2, Line 6-7] These methods can also be cost-efficient for controlling risks incurred by multiple areas that are susceptible to landslides over a broad region.

[Comment T-3] Page 2, Line 10: "a few articles have addressed the time intervals for monitoring" – missing references.

Thank you for your helpful comment. We acknowledge that the sentence used to present the originality of the study. The text has been modified to include the references that we reviewed. Please see Lines 9-11 on Page 2.

[Page 2, Line 9-11] Uhlemann et al. (2016) briefly described the temporal resolution of landslide monitoring methods. In this study, we present a quantitative analysis of the monitoring time interval based on a risk analysis.

[Comment T-4] Page 2, Lines 23-29: This is a reoccurring issue in the paper – please avoid those very long sentences, these are confusing and very difficult to follow.

The reoccurring part of the introduction was deleted, and the long sentences have been modified. Please see Line 24-26 on Page 2.

[Page 2, Lines 24-26] Due to the lack of the accumulated landslide inventory data over the study region, the frequency of landslide occurrence limited to an extreme weather event was estimated by establishing a rainfall threshold. The criteria for rainfall threshold setting were determined by referring to the local research results.

[Comment T-5] Page 7, Line 6: Missing full stop after "items N"?

We have adjusted the text to be clearer. Please see Line 24-25 on Page 6.

[Page 6, Line 24-25] From the equation for the unreliability rate *f(t)*, we obtain the hazard rate *h(t)* shown below with a more conservative meaning in terms of reliability. The hazard rate *h(t)* is normalized with its surviving items *Ns(t)* instead of the total number of items *N*.

[Comment T-6] Figure 3: Do the red points correspond to dates with landslide occurrence?

We apologize for the insufficiently clear caption of Figure 3. The figure caption has been corrected, and the rainfall threshold has been marked to the figure itself. Please see Figure 3 on Page 12.

[Page 12, Figure 3]

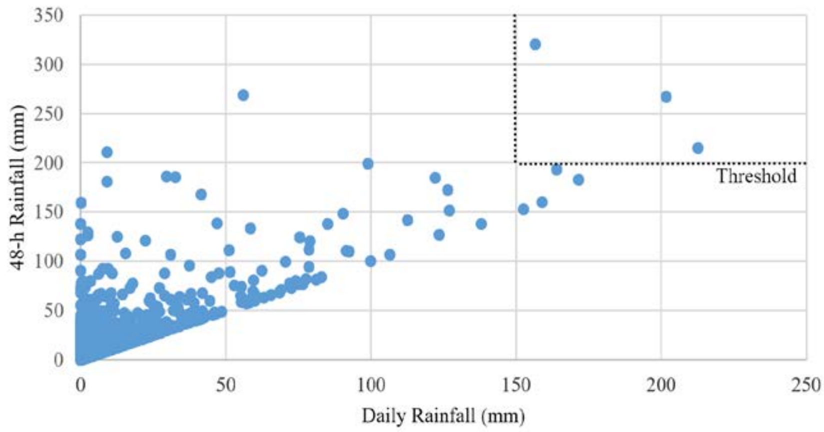

Figure 3. Scatter diagram of daily rainfall and 48-hour cumulative rainfall showing that 3 events exceeded the rainfall threshold in Pyeongchang County in 11 years (2006-2015).

[Comment T-7] Figure 4: I think it would be better to show landslide occurrence on the map of the hazard grades.

The comment was very helpful. We have replaced Figure 4 to show landslide occurrence on the map of the hazard grades, and a zoom-in map has been added to improve its readability. Please see Figure 4 on Page 13.

[Page 13, Figure 4]

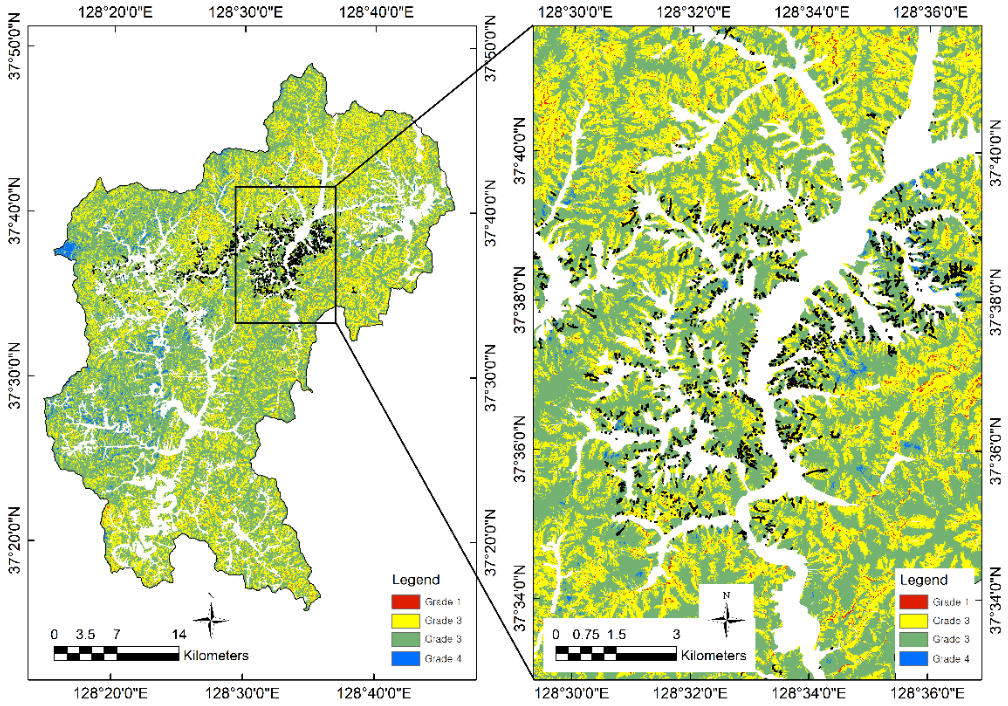

Figure 4. Landslide hazard grade and locations of landslide occurrence in the study area

[Comment T-8] Figure 5: axis label should read ". . . Landslide Occurrence"

The Y-axis label of Figure 5 has been corrected to “Landslide Occurrence”. Please see Figure 5 on Page 15.

[Page 15, Figure 5]

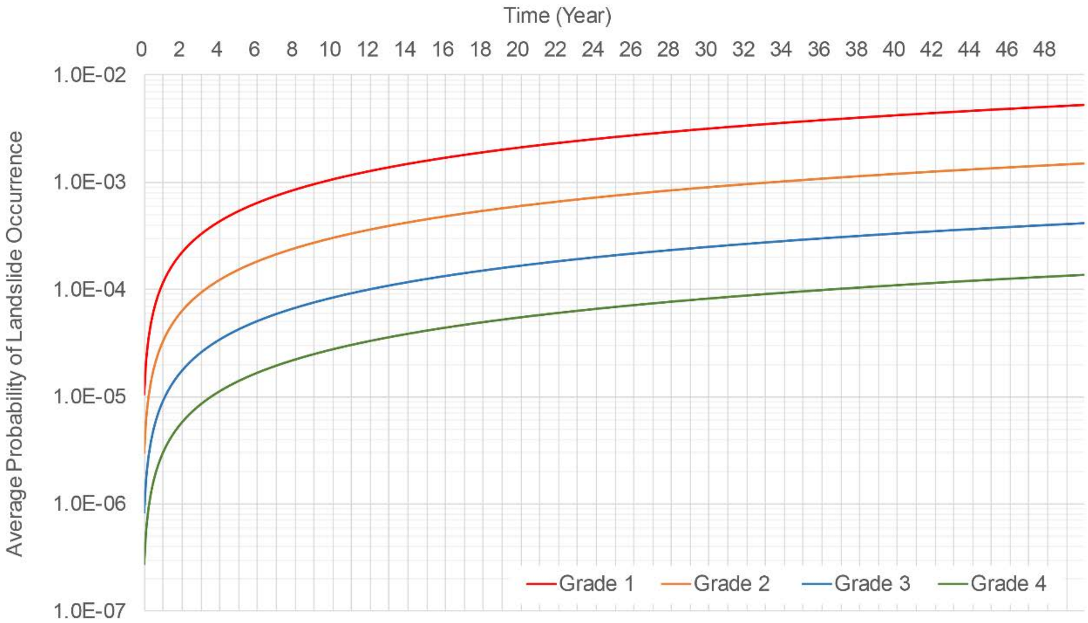

Figure 5. Change in average probability of landslide occurrence