Hydrol. Earth Syst. Sci. Discuss.,
https://doi.org/10.5194/hess-2018-360-AC2, 2018

Hydrology and Earth System Sciences Discussions
Open Access

Interactive comment on "Hydrogeological responses to the 2016 Gyeongju earthquakes, Korea" *by* Jaeyeon Kim et al.

Jaeyeon Kim et al.

kklee@snu.ac.kr

Received and published: 7 November 2018

Dear Editor and Referee, Taking into account the useful comments we received from two referees, we provided a new version of the manuscript with adequate corrections. We already uploaded our responses to Referee #1's comments and details how we revised out manuscript. We enclose below our responses to Referee #2's comments, which surely improve the initial manuscript. We are confident that provided changes are sufficient for reconsidering our manuscript. Best Regards, For the Authors

Comments provided by Anonymous Referee #2

1) general comments The manuscript submitted for publication by Kim et al., in HESS seeks to evaluate the impact of seismic events on groundwater dynamics and geo-

Printer-friendly version

Discussion paper

chemistry, in the case of the September 12, 2016 Gyeongju earthquakes in Korea. This scientific issue is of importance and in the scope of the scientific themes published in HESS. The work is based on an annual monitoring of groundwater level, temperature and electro-conductivity of several wells in the geographical area impacted by the seism. Such a monitoring should allow the authors to study the variations of the above parameters before, during and after the earthquakes, which should be at the heart of a discussion on the potential hydrological modifications linked to the seismic events, which is actually not the case. The authors rather based their discussion on geochemical data, including Sr isotope ratios and Rn data, of water samples collected in January 2017, after the seism and on a statistical analysis ("Self-Organizing Map (SOM) ") of the hydrogeochemical characteristics of the groundwaters. Except if I have misunderstood the manuscript, I do not really understand such a choice, and I have many difficulties to really understand the arguments developed by the authors to sustain/defend the interpretations given in the discussion. The discussion under its present form is based on many general considerations on the origin of Sr isotope ratios and Rn concentrations in groundwaters, which are not new, and whose interest for the present study is not convincing. I'm surprised that the discussion is no more hierarchical / structured around the following questions: -What information can be deduced from the annual monitoring of the hydrogeochemical parameters analyzed before, during and after the earthquake, in terms of hydrogeological modifications of water reservoirs related to the earthquake. - How the geochemical data collected after the seismic event, in particular the Sr and Rn data (but perhaps not only, because the other chemical information is not really discussed in the article) can be used to constrain the different scenarios based on the annual monitoring or to choose among them. Also, I do not really understand the relevance of the SOM analysis, as made and used in this paper. I'm wondering if making the SOM analysis at the start of the article does not lead the authors to forget to do a relatively extensive presentation and discussion of the data, especially the geochemical data, relevant for their purpose. The latter is to build a sound conceptual model to explain possible mechanisms for the hy-

Printer-friendly version

Discussion paper

drological and geochemical responses of groundwaters to the earthquake. The SOM analysis indicates the presence of strongly related parameters. Why not rely on this information to examine in more detail the key geochemical parameters, and to discuss their variability in binary or other diagrams, in order to evaluate their meanings in terms of water reservoirs, of water pathways,.., involved in the formation of groundwaters, and that could have been modified in response to the earthquake..? Actually, very little is done with the geochemical data: just a rapid presentation of the data in the 87Sr/86Sr vs. 1/Sr and Ca vs Sr diagrams. Why? Is it because they do not help much? Why not looking at Piper diagrams for example or other binary mixing diagrams, that can give information about the different sources potentially involved in the geochemical constitution of groundwaters (in terms of rock water interaction or in terms of water mixing) To summarize, the construction of the paper under its present form is for me very confused. At this stage the interpretations remain very hypothetical and poorly justified by the data, even if the database is of good quality and the question of how to constrain the hydrological modifications related to earthquakes is interesting. Therefore, I do not recommend publication of this manuscript under its present form: I encourage the authors to restructure and rewrite their paper in order to better justify and defend their interpretations, before resubmitting it at HESS or in another journal.

RESPONSE: We thank the referee for taking his/her time to review our paper. We have attempted to satisfy all suggestions, so it made us to produce a stronger paper, adequate to be published on HESS. Please see the responses to the referee' comments below and subsequent changes in the revised manuscript (marked in red color). Thanks in advance for reconsidering the revised manuscript positively. If we understood correctly, Referee # 2 gave questions about the two most important issues in our paper. The two major issues are: 1) extensive interpretation with pre-, co-, and post-seismic monitoring data; and 2) most fundamental and important analyses based on hydrogeochemical data through traditional but most fundamental ways of analysis such as Piper diagram, binary mixing, and comparison of major components. We completely agree with the suggestions of the Referee #2 regarding what should have been done at first with our monitoring data. The comments of the Referee #2 have pointed out precisely the problems that the authors have been troubled with. We have pre-, co-, and post-seismic time-series monitoring data on water level, temperature, and electric conductivity thanks to the operation of the national groundwater monitoring stations in Korea. However, they did not have the geochemical data of major groundwater constituents because few earthquakes usually occur in Korea. There have been quite many efforts by hydrogeologists to find or interpret any hydrogeologic changes by the earthquakes focused on the time-series monitoring data. However, regardless existence of the earthquake, water level and electrical conductivity showed ups and downs at scattered locations according to other factors such as seasonal effect. In addition to that, major chemical constituents only showed some noticeable difference between alluvial and bedrock aquifers in the Piper diagram, but not indicative of changes due to seismic events. This is why we tried to do more statistical clustering first and interpretation focused on the isotopes data for finding a mechanism, which explains the hydrogeologic responses to the earthquakes for each of the clusters derived. The comments of the Referee #2 might be based on the argument that a grouping or clustering that could be accomplished by a statistical analysis should also be possible by using major ions and few representative geochemical parameters. For example, such method like binary mixing models using major chemical constituents should be applied to wells showing mixing of deep geothermal waters. We agree with this point. What was done here in our study is to apply a statistical method first by using extended list (or most measured items) of hydrogeochemical data available for extracting similarity patterns, i.e., clustering. And then, each cluster is reasonably explained with hydrogeology. We hope it is well understood that the authors have chosen an approach for better grouping of the wells showing correlation with similar hydrogeological conditions. Regarding the time-series of water level, temperature, and electric conductivity data, temporal changes in sequence of pre- co- and post- seismic events usually do not have consistency in trends. There are many monitoring wells showing similar changes regardless of the seismic events. This is limitations of that data. Moreover, it was

Printer-friendly version

Discussion paper

difficult to derive a reasonable hydrologic interpretation with only the major ionic constituents because we do not have information on end member concentrations of the major constituents. The isotopic data (radon and strontium) employed in this study, on the other hands, made us possible to tell the groundwater in specific wells was affected by the earthquake. Based on the comments by the Referee #2, we also tried to reorganize our manuscript focused on the followed four points. The details of revision are as follows: First, we have divided the discussion section into three sub-chapters for more clear and logical interpretation and for better hierarchical/structured discussion as follows: 5.1 Groundwater level, temperature, and EC changes 5.2 Isotopic data (radon and strontium) 5.3 Conceptual model with the grouping results In addition, the results section has been also rearranged as follows: 4.1 Groundwater level, temperature, and EC changes 4.2 Hydrogeochemical characteristics including isotopes (radon and strontium) 4.3 Self-Organizing Map (SOM) Second, we have totally revised the discussion section to reflect the referee's main/minor comments. The hydrochemical data analysis has been included in section 4.2 (L258-264) and the Piper diagram has been added in section 5.3 to avoid one sided interpretation using the Sr and Rn data (Fig. S1). Before submission of our original paper, we had tried to draw and analyze the Piper diagram. However, the reason why we did not use the diagram in the original paper was that the diagram only considered major ions (Na, K, Ca, Mg, Cl, SO4, and HCO3) and it was difficult to find an explanatory basis without including other hydrochemical parameters (NO3, Sr, 87Sr/86Sr, temperature, pH, DO, EC, TDS, and salinity). The Piper diagram showed the distinct trend when the plot was drawn by dividing the groundwater wells into two groups; the alluvial aquifer wells and the bedrock aquifer wells. While the diagram indicated the ionic composition characteristics depended on the groups of water sample wells, it was not appropriate to estimate changes or differences due to the effects of the earthquakes. This diagram can also be used to explain the water-rock interactions in general, but a total system should be considered for interpreting the changes due to the earthquakes. In this regards, for more convincing interpretation about an overall characterization of the groundwater system related to the earthquakes, we tried the SOM methods by using 16 hydrogeochemical parameters (Na, K, Ca, Mg, Cl, NO3, SO4, HCO3, Sr, 87Sr/86Sr, temperature, pH, DO, EC, TDS, and salinity). However, as the referee pointed out, we agree that the Piper diagram is also important for understanding water chemistry and quality, so we have added the diagram as Supplementary Figure 1. If it is recommended to be included in the main paper, we would add the Piper diagram as one of the main figures, not as a supplementary figure. The interpretation of 87Sr/86Sr vs. 1/Sr and Ca vs Sr diagrams has been also used in the discussion section (indicated see Fig.8). Third, the SOM analysis showed the correlation and clustering results graphically. The SOM method has an advantage in visualization of the multi-dimensional data, which is helpful to identify the dependencies between the variables (e.g. hydrogeochemical and isotopic data) and to classify the wells. This statistical method is not newly developed in this study, however, our study showed very interesting results that the grouping was in accordance with the lithostratigraphic units. This is not common case because many other results (in other sites or other time periods) did not show the correlation each other. Especially, this method also provided the detailed local relationship between the variables by the component planes, which was helpful to understand groundwater systems visually (L305-309). The local interpretation is important for the studies related to the earthquakes. In addition, as mentioned above, this method used the extended various hydrochemical parameters (Na, K, Ca, Mg, Cl, NO3, SO4, HCO3, Sr, 87Sr/86Sr, temperature, pH, DO, EC, TDS, and salinity). Based on the efficient explanatory ability of the SOM method for the groundwater study related to the earthquakes, we can suggest the application of SOM to researches in other sites for making statistically explanatory basis and then provide geological and hydrogeological interpretations of the observed phenomena. However, as the referee mentioned, we agree that the statistical results should be explained in close relations with the hydrogeochemical data and variables. Thus, we have entirely revised the discussion section. Please see the revised manuscript. Fourth, the groundwater level, temperature, and EC monitoring data before, during and after the earthquake and the geochemical data collected after the seismic event were used in this paper. Because few earthquakes usually occur in Korea, especially in the study site, the data before the earthquake was insufficient. For this, we tried to add after-earthquake data by sampling most of national groundwater monitoring wells near the epicenters. We used additional data to deduce the relations between the origin of Sr isotope ratios and Rn concentrations in rocks and groundwater and the effects of the earthquakes. We think the proposed possible mechanisms of hydrogeological system changes due to the earthquakes in the study site are very important to extending scie3ntific understanding on the characteristically very local, heterogeneous, and irregular of the groundwater system to earthquakes.

2) Specific comments L.253 and L. 358-359: If the SOM analysis simply leads to conclude that the classification obtained is close to the classification based on lithostratigraphic unit data, we can question the interest of such an analysis. It is well established today that at the first order the chemical composition of groundwater is controlled by the interactions of the waters with the aquifer rocks! As already suggested above, would not it be more relevant to use some key geochemical parameters to evaluate if the geochemical differences between the different groups or the geochemical dispersion within a single water group can or cannot be related to hydrological characteristics of the aquifers (connectivity between reservoirs for example,). Such information could eventually be used as arguments to prove or defend some hypotheses made in the discussion section. RESPONSE: Thank you for comments. As the response to main comments above, to avoid one sided interpretation using the radon and strontium isotopic data, we have entirely revised the results and discussion section. Please see the revised manuscript. We have also added more interpretation of geochemical data including the correlations results of the SOM (Fig. 9) and 87Sr/86Sr vs. 1/Sr and Ca vs Sr diagram (Fig.6 and Fig. 7). In addition, as mentioned above responses, the SOM was conducted using geochemical dataset (Na, K, Ca, Mg, Cl, NO3, SO4, HCO3, Sr, 87Sr/86Sr, temperature, pH, DO, EC, TDS, and salinity), not including geological data. Some results did not show the high correlation between the SOM grouping results and the lithostratigraphic unit data in other researches and there are few cases using

SOM for the hydrological systems related to the earthquakes. Moreover, this method is useful for understanding groundwater systems visually by 2D diagram. Thus, we suggested that this is also helpful for analyzing hydrochemical characteristics, not as the only method.

L. 345-356: The conclusion, that the large variation of Sr isotopic ratios in the groundwater can be explained by the nature of the aquifer lithology, is again not a very new conclusion. RESPONSE: We agree with your comments. For the background information, the general values and ranges were written in that part. As mentioned above responses, the data was insufficient in the study site because few earthquakes occur in Korea. It is the process for further study.

L. 361-362 I do not understand why this grouping is different as the one given L 253 RESPONSE: In L322, the grouping was conducted as follows: Group 1 (KW 1, KW 2, KW 9-1, and KW 10-1), Group 2 (KW 3, KW 5-1, KW 5-2, KW 6-2, KW 11-3, and KW 12-1), Group 3 (KW 4-1 and KW 4-2), and Group 4 (KW 8-1, KW 11-1, and KW 11-2). The SOM does not include all input wells. The U-matrix shows the selected wells which showed high correlation each other. Thus, the results may not include some input wells. Our study results also did not include KW 6-1, KW 7-1, KW 7-2, KW 8-2, KW 9-2, KW 10-2, and KW 12-2 in the U-matrix. However, the classification results had high similarity with the classification based on lithostratigraphic unit data. In L175, the study area was divided into four sections; (i) Hayang-group shale and sandstone (KW 1, KW 2, KW 9-2, KW 10-2), (ii) Bulguksa-group biotite granite (KW 3, KW 5-2, KW 12-2), (iii) tuff and tuffaceous sedimentary rocks of Yeonil-group and Janggi group (KW 4-2, KW 6-2, KW 7-2), and (iv) Cretaceous volcanic rocks mainly composed of andesite (KW 8-2, KW 11-2). This lithostratigraphic unit data can be used for arranging the bedrock aquifer wells based on bedrock characteristics, so this classification does not include the alluvial aquifer wells. For convincing interpretation of this study, we conducted the new grouping to reflect the two grouping results (L175 and L253). In conclusion, the final grouping has been conducted combining L175 (lithostratigraphic unit) and L322 (SOM results). This has been performed by binding the alluvial and bedrock aquifer wells: Group A (KW 1, KW 2, KW 9, and KW 10); Group B (KW 3, KW 5, and KW 12); Group C (KW 4, KW 6, and KW 7); and Group D (KW 8 and KW 11) (as written in L361). However, as the referee pointed out, this explanation was not sufficient in the manuscript, so we have written additional explanation (L380-400).

L. 372: All what explained here is maybe right but without sound arguments it is difficult to be convinced/ Why invoking exchanges processes. . .based on which observation? If there is no sound observation, it is a possible scenario, but likely, one among others.... RESPONSE: As suggested in general comment, we entirely revised the results and discussion section including additional hydrogeochemistry interpretation. Among them, Group A scenario was described focused on the Ca vs Sr diagrams and the SOM component maps. This group had high values and high positive correlations between Sr and Ca, which indicate the similar behavior in both rock and groundwater. This chemical parameter showed the one possible scenario, which is the strong water-rock interaction. This was illustrated in L419-421 and L462-464.

L. 400: when is invoked a seawater intrusion. . . RESPONSE: By considering the comments of the referee, the results and discussion section were revised entirely. Especially, the Group C mechanism, which suggested the possibility of sea water intrusion in the wells, was revised including the Piper diagram analysis (L437-442).

L. 391- 392 : I fully agree with the authors that with only geochemical and isotopic data on water samples collected after the earthquakes, it is difficult here to be very conclusive ("it is difficult to confidently determine an effect of upwelling because data were only collected after the earthquake, not prior"). This is true here but more or less all along the discussion. It is why, above, I have suggested the authors to discuss first the annual monitoring data, the only one collected before, during and after the earthquake, and then only the other geochemical data, including Sr isotope ratios and Ra concentration data. RESPONSE: Thank for considerable comments. As the response to main comments above, we have rearranged the contents of the paper; 4.

Results 4.1 Groundwater level, temperature, and EC changes 4.2 Hydrogeochemical characteristic including isotopes (radon and strontium) 4.3 Self-Organizing Map (SOM) 5. Discussion 5.1 Groundwater level, temperature, and EC changes 5.2 Isotopic data (radon and strontium) 5.3 The conceptual model with the grouping results We also have redrawn the Fig. 1 in detail. Please see the revised manuscript.

Please also note the supplement to this comment:
https://www.hydrol-earth-syst-sci-discuss.net/hess-2018-360/hess-2018-360-AC2-supplement.pdf

---

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-360, 2018.

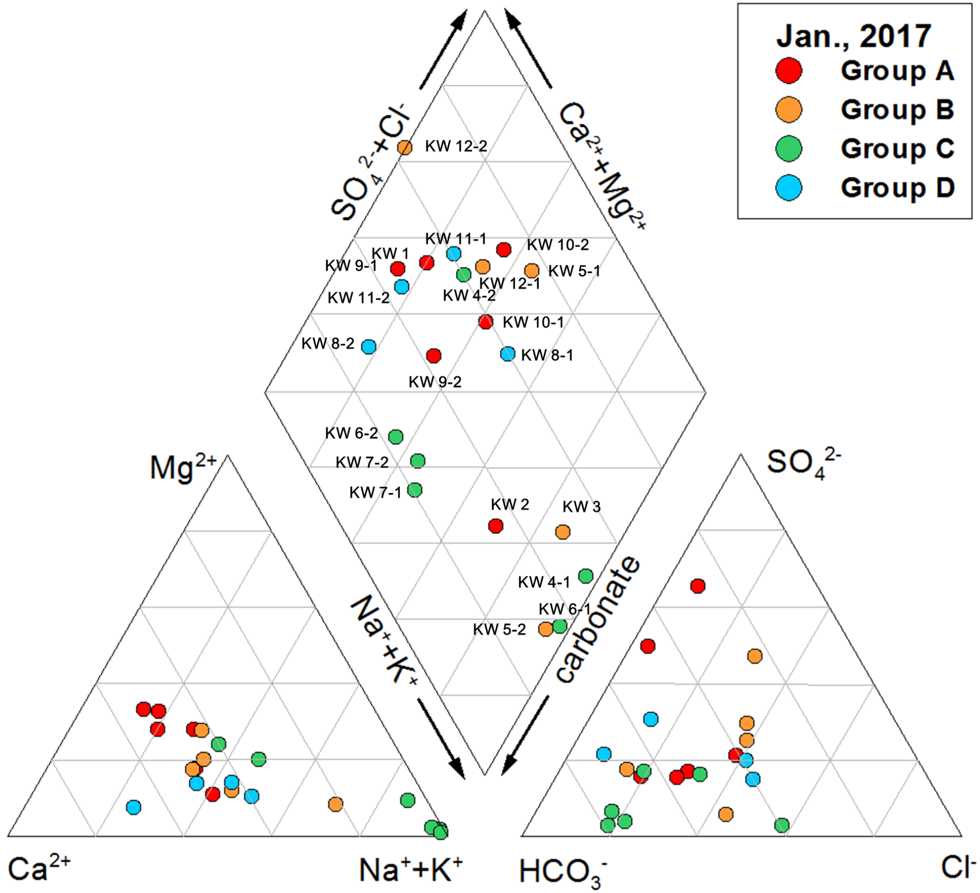
Jan., 2017
Group A
Group B
Group C
Group D
$SO_4^{2-}+Cl^-$
$Ca^{2+}+Mg^{2+}$
Na^++K^+
carbonate
Mg^{2+}
Ca^{2+}
Na^++K^+
SO_4^{2-}
HCO_3^-
Cl^-
KW 12-2
KW 11-1
KW 10-2
KW 1
KW 9-1
KW 5-1
KW 12-1
KW 11-2
KW 4-2
KW 10-1
KW 8-2
KW 8-1
KW 9-2
KW 6-2
KW 7-2
KW 7-1
KW 2
KW 3
KW 4-1
KW 6-1
KW 5-2

Fig. 1. Fig. S1.