Dear Editor and Referee,

Taking into account the useful comments we received until now, we provided a new version of the manuscript with adequate corrections. We enclose below our responses to all Referee's comments, which surely improve the initial manuscript. For the moment we do not include the new version of the manuscript but we are ready to submit when required. Otherwise, the totally revised manuscript will be uploaded after reflecting other reviewer's comments. We are confident that provided changes are sufficient for reconsidering our manuscript, and we wait for additional comments by the same or other reviewers.

Best Regards,

For the Authors

Comments provided by Anonymous Referee #1

1) general comments

The manuscript is a technical report which provides an interesting analysis of hydrological data and discusses the evolution of hydrological quantities before, during and after some earthquakes in South Korea.

The work is largely based on well-established methods and the scientific novelty is not very remarkable. The main goal is stated in the introduction at lines 105 to 107 and then later at lines 357 & 358. However, the neural network method applied in this paper (SOM - Self-Organizing Map) is not new and it is not apparent its advantage with respect to other clustering methods. See also the specific comment # 4.

The manuscript is generally well organized and written, but it requires linguistic improvements, some of which are listed in the technical comments below. From the scientific point of view, at some points, the manuscript is not sufficiently precise and rigorous, as described, e.g., in the specific comments # 1, 2 & 3 and in the technical comments # 9 & 10 below.

I am sorry, but I think that the innovative character of the work is not sufficient to publish the paper on HESS, whereas the manuscript is more adequate for a strictly hydrogeological journal.

RESPONSE:

We thank the reviewer 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 reviewers' comments below and subsequent changes in the revised manuscript (marked in red color). Thanks in advance for reconsidering the revised manuscript positively.

The novelty of this paper is to combine the hydrologic, hydrogeochemical, and lithostratigraphic characteristics by applying the neural network method 'SOM'. 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. Especially, it provides the detailed local relationship between the variables by the component planes. The local interpretation is important for the studies related to the earthquakes. The clustering analysis of the SOM is not special compared to other statistical methods, however, this paper shows the interesting results that the grouping was in accordance with the lithostratigraphic unit. This is powerful results to understand the hydrologic response to the earthquakes considering the geologic characteristics, which can be applied to other sites. Moreover, there are few cases using SOM for the groundwater study related to the earthquakes, so we 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.

The manuscript was checked by a professional editing service. After revision work of other reviewers, we will check final manuscript one more time by other editing service.

2) Specific comments

1. Lines 37 to 41. The list of references shows that it is debatable to state that "few" studies

are devoted to this research topic. A simple and fast search on google scholar shows a lot of papers related to the effects of earthquakes on hydrological processes and quantities. Perhaps, the Authors want to stress that most papers are devoted to earthquake precursors or to the study of co-seismic phenomena.

RESPONSE:

We agree that the statement might cause misunderstanding. According to your comments, we have rewritten those sentences.

[L35-38] Typically, most studies have focused on earthquake forecasting, i.e. changes prior to earthquakes, or co-seismic behavior. There have been a limited number of studies that discuss the responses of groundwater systems, especially, emphasize the hydrogeologic changes after earthquakes.

2. Throughout the paper, it would be necessary to consider in a more accurate and rigorous way the considered time scales. The following remarks provide some instances.

• Lines 43 & 44. If the changes are related to seismic waves, they should disappear after the earthquake. Effects at different time-scales should be separated more clearly. The sentence “Seismic waves... geochemistry” should be better connected with the preceding one “Seismicity... groundwater systems”.

• Line 187. The time scales should be considered in a more accurate and rigorous way. In fact, the sampling period of hydrological data is high with respect to the duration of the earthquake wave train.

RESPONSE:

We have moved “Seismic waves... geochemistry” sentence to follow “Seismicity... groundwater systems” sentence (L41-45).

In line 187, we explained the information with erroneous descriptions, so we corrected that sentence. [L185-187] The hourly data, which were monitored every hour on the hour, were used to observe the responses before, during, and after the earthquake. [L188-189] These daily data correspond to the cumulative quantities during the day.

3. Line 93. Surface area is an extensive property: does radon concentration (which is an intensive property) depend on it? Should "surface area" be substituted with the intensive property "specific surface"?

RESPONSE:

We agree with your comment. "Surface area" was replaced by "specific surface" (L88-89).

4. In section 5 it is shown that several different processes might explain the behavior of collected data. However, most (if not all) of such processes have been hypothesized in previously published papers: many of the papers cited in this section were published in the second half of the XX century. Such a discussion has a great value for local land management and natural risks mitigation, but a more limited interest for the international scientific community. Moreover, the declared goal of the paper is to show the relevance of the use of SOM, but the discussion of the relevance of this method – as compared with other possible approaches – is almost absent.

RESPONSE:

We have added some references recently published as:

[L337-338] (Fleeger et al., 1999; Kitagawa et al., 2006; Rojstaczer and Wolf, 1992; Rojstaczer et al., 1995; Wang et al., 2004)

[L349] (Claesson et al., 2007; Hartmann and Levy, 2005)

[L387] (Sparks, 2003)

[L427] (Bullen et al., 1997; Franklyn et al., 1991; Négrel, 2006)

[L442-443] (King and Cocco, 2001; Nur and Booker, 1972; Peng and Zhao, 2009; Scholz, 2002; Scholz et al., 1973)

Moreover, we have split the discussion part into three chapters for more clearly and logically interpretation as;

5.1 Groundwater level, temperature, and EC changes

5.2 Isotopic data (radon and strontium)

5.3 The conceptual model with the SOM method

The additional explanations including ‘see Fig. 3’ mark were written in discussion part for showing the relevance of the use of SOM with the conceptual model.

[L372-375] The dependencies between the variables, hydrochemical parameters including strontium isotopes, could be interpreted with the component plane results from the SOM (see Fig. 3). These correlations were also used for analyzing the possible mechanisms at each group.

[L379] low $^{87}Sr/^{86}Sr$ ratio and low pH (see Fig. 3 and Fig. 10)

[L385-389] The capacity of the cation-bearing soil (cation-exchange capacity; CEC) depends on the pH of the surrounding water, and the CEC of a soil generally show decreases with pH decreases (Sparks, 2003). The acidic water of KW10-2 (pH = 2.27) would lead to lower CEC and lead to leaching of Ca^{2+} and Sr^{2+} from the soil to surrounding groundwater.

[L411-412] Moreover, KW 4-1, KW 4-2, and KW 6-2 had high values of EC, Cl, TDS, and salinity values (see Fig.3)

[L414-415] The strontium concentration and Ca values are also low in these wells (see Fig. 3 and Fig. 10).

[L426-427] The former occurs more rapidly, providing Ca^{2+} and Sr^{2+} with a low $^{87}Sr/^{86}Sr$ ratio (see Fig. 3) (Bullen et al., 1997; Franklyn et al., 1991; Négrel, 2006).

5. Carefully revise the number of significant digits used for several quantities. For instance, with reference to Table 3, is it physically significant to express concentrations with three or four significant digits, radon activity with up to five significant digits and Sr isotopic ratio with six significant digits?

RESPONSE:

We have corrected the significant digits totally.

In general, the ion concentrations used two-four significant digits and $^{87}Sr/^{86}Sr$ used six-eight significant digits. The significant digits of ion concentration in wrong place were united in accordance with the digits. Please check this work in Table 3. Moreover, the significant digits in the text were also adjusted to the indicated digits as shown in Table 3.

The radon concentration used two or three significant digits in pCi/L, three or four significant digits in Bq/L, and three-six significant digits in Bq/m^3. The radon concentration in groundwater was mostly expressed by the unit of in Bq/L or Bq/m^3. The measurement device, RTM1688-2 of SARAD, expressed the radon concentration in water as the unit 'Bq/m^3'. After measurement, the radon concentrations were calibrated by the decay equation considering the sampling time and measurement time, so we used these values without changing significant digits.

[L299-302] The $^{87}Sr/^{86}Sr$ values ranged from 0.705688 to 0.712368 (see Table 3). In the alluvial aquifer wells, the $^{87}Sr/^{86}Sr$ values ranged from 0.706191 to 0.708353, and these values were from 0.705688 to 0.712368 in the bedrock aquifer wells.

[L305-306] The $^{87}Sr/^{86}Sr$ values of the Bulguksa group (KW 3, KW 5-2, and KW 12-2) ranged from 0.706575 to 0.708022.

[L356-358] Generally, Cretaceous granites comprising the Gyeongsang basin had a strontium concentration from 62 ppm to 428 ppm and an $^{87}Sr/^{86}Sr$ ratio from 0.704610 to 0.711400 (Cheong and Jo, 2017).

[L358-360] Basaltic rocks near the Yeonil group and Janggi group had strontium concentration from 439 ppm to 518 ppm and an $^{87}Sr/^{86}Sr$ ratio from 0.703850 to 0.704630 (Shimazu et al., 1990).

[L360-362] In the Chaeyaksan basaltic volcanics of the Yucheon group, strontium concentration ranged from 731 ppm to 1667 ppm and the $^{87}Sr/^{86}Sr$ ratio from 0.705870 to 0.706440 (Yun, 1998).

3) Technical comments

1. Line 9. Specify M_L.

RESPONSE:

We have corrected it as:

[L9-11] The September 12, 2016 Gyeongju earthquakes (M_L = 5.1 of foreshock and M_L =5.8 of mainshock) had significant effects on groundwater systems along the Yangsan Fault System composed of NNE-trending, right-lateral strike-slip faults in Korea.

2. Lines 15 & 16. Rephrase “with bedrock characteristics”.

RESPONSE:

We have changed that from “with bedrock characteristics” to “with lithostratigraphic classification” (L16).

3. Lines 16 to 19. Erase “To analyze... from the earthquakes” and rephrase the remaining part of the sentence “annual monitoring data... during January 2017”.

RESPONSE:

We have rewritten this sentence as:

[L16-18] For this, annual monitoring data (groundwater level, temperature, and electrical conductivity) and collected data (hydrochemical parameters, radon-222, and strontium isotopes) were used.

4. Line 35. Substitute “underground” with “groundwater”.

RESPONSE:

It was done. We have replaced “underground” word to “groundwater” (L34).

5. Line 55. Rephrase “By using hydraulic properties”.

RESPONSE:

We have rewritten that sentence as:

[L55-56] Some studies also have proposed some conceptual models for describing the aquifer responses to earthquakes by analyzing hydraulic properties.

6. Line 61. Rephrase “was recorded as the largest”.

RESPONSE:

We have rephrased the sentence as:

[L61-62] The mainshock of the Gyeongju events was recorded as the largest earthquake in Korea since instrumental seismic monitoring started in Korea in 1978.

7. Line 64 to 69. The sentences “The occurrence... near the YSF (Lee and Jin, 1991;Lee and Na, 1983)” could be erased, since they do not give any scientific information relevant for the paper’s objectives.

RESPONSE:

Thank you for your comment to make the paragraph contextually much better. We have erased the sentence completely.

8. Line 69. Substitute “interpreted” with “shown”.

RESPONSE:

We have corrected the vocabulary; from “interpreted” to “shown” (L65).

9. Lines 72 to 75. The sentence “The occurrence... following the Gyeongju earthquakes” is

quite self-evident and could be better rephrased.

RESPONSE:

We have rewritten the sentence as:

[L67-70] Gyeongju area is spatially close to the YSF, thus the Gyeongju events might allow more detailed studies about characteristics of the YSF and its branch faults, including groundwater responses after earthquakes.

10. Lines 81 & 82. Please explain how temperatures can be derived from measurements of groundwater level.

RESPONSE:

We have rewritten the sentence as:

[L76-77] Temperature changes are commonly analyzed using heat transport modeling (EkemenKeskin, 2010; Wang et al., 2012).

11. Lines 97 & 98. Add references.

RESPONSE:

We have added references (L93-94).

1.Adinolfi Falcone, R., Carucci, V., Falgiani, A., Manetta, M., Parisse, B., Petitta, M., Rusi, S., Spizzico, M., and Tallini, M.: Changes on groundwater flow and hydrochemistry of the Gran Sasso carbonate aquifer after 2009 L'Aquila earthquake, Italian Journal of Geosciences, 131, 459-474, 2012.

2. Igarashi, G., and Wakita, H.: Groundwater radon anomalies associated with earthquakes, Tectonophysics, 180, 237-254, 1990.

3. Igarashi, G., Tohjima, Y., and Wakita, H.: Time-variable response characteristics of groundwater radon to earthquakes, Geophysical research letters, 20, 1807-1810, 1993.

12. Line 99. Specify “these”: strontium only or radon and strontium?

RESPONSE:

We have specified from “these” to “Strontium isotopes” (L95).

13. Line 101. Rephrase “according to the rock type in the bedrock of aquifers”

RESPONSE:

We hope that the sentence below may be more clearly than the previous one.

[L97-98] The $^{87}Sr/^{86}Sr$ ratios of the bedrock aquifers were different according to rock types of bedrock.

14. Line 129. Substitute “is approximately 21–35 km” with “varies between 21 km and 35 km”.

RESPONSE:

We have changed the phrase “is approximately 21–35 km” to “varies between 21 km and 35 km” (L125).

15. Lines 235 to 237. Rephrase, possibly as “The raw data were normalized in order to work with transformed quantities with zero mean and unit standard deviation”.

RESPONSE:

Thank you for your suggestion. We have revised it according to your suggestion (L240-241).

16. Line 238. Substitute “have” with “show”.

RESPONSE:

We have replaced from “have” to “show” (L241).

17. Line 287. Correct the exponent in Bq · m^{-3}.

RESPONSE:

We have corrected that.

18. Line 333 & 334. Rephrase the sentence “Groundwater level oscillation... of the aquifer”.

RESPONSE:

We have rephrased the sentence as:

[L339-341] Groundwater level oscillation also depends on the interactions between inflow/outflow of the well and of the aquifer (Cooper et al., 1965).

19. Line 355. Rephrase “were expected compared to those”.

RESPONSE:

We have rewritten the whole sentence to make the meaning clear, in addition to rephrasing the previous “were expected compared to those”.

[L362-364] Thus, samples of the Bulguksa granite would be more radiogenic than those of the Yucheon group rocks, because of the composite minerals of the Bulguksa granite (plagioclase, feldspar, and biotite) which have high $^{87}Sr/^{86}Sr$ ratios.

20. Line 359. Rephrase “which was useful”.

RESPONSE:

We have rephrased to “which was used” and deleted “, based on bedrock characteristics” (L368).

21. Line 363. Rephrase "as one well binding the alluvial and bedrock aquifer wells".

RESPONSE:

We have deleted the "as one well" which is unnecessary description (L372).

22. Line 382. Substitute "885–7851 ppb" with "from 885 ppb to 7851 ppb".

RESPONSE:

We agree and made changes (L393-394).

23. Line 476. What about hydrogeochemical data?

RESPONSE:

We have added the sentence "The hydrogeochemical dataset was shown in Table 3." (L489).

24. Line 765. Use capital letters for "C.-Y.".

RESPONSE:

We have corrected that.

25. Table 3. Rephrase the text of the footnote. Moreover, information is given for KW *-1 and KW *-2: what about KW 11-3? I am afraid that further details are missing: are the screened intervals located at different depths, or are these clusters of wells with different depths?

RESPONSE:

We have written additional information about that.

[Table 3] [†]KW ##-1 refers the alluvial aquifer well, KW ##-2 or no hyphen well refers the bedrock aquifer well, and KW 11-3 indicates the surface water sample near the KW 11 wells.

The further details of the wells were also added in the text.

[L152-156] The wells generally were installed by two types at each point. The one well (as labeled KW ##) indicates that the sampling point is consisted of only one type well, bedrock aquifer well. The alluvial aquifer wells were labeled KW##-1 and the bedrock aquifer wells were labeled KW## or KW##-2. The KW 11-3 refers the surface water sample near the KW 11 well.

26. Figure 1. Sorry, but I do not understand this Figure. A more accurate and thorough description in the figure caption is necessary.

RESPONSE:

We have redrawn the figure 1 and added further information in the caption.

[L819-823] Study flow that processes observation data and obtains conceptual models. The used data (groundwater level, temperature, EC, radon-222, and strontium isotopes) and the adopted method (SOM statistical method) were described with related main results. At the end of flow map, the conceptual models using the grouping results were described by the table.

27. Figure 2. The colour scale of map (a) is a representation of ground surface level, isn't it? Maps (a) and (b) have the same extension, haven't they? Add this information in the figure caption and the colour scale bar in map (a).

RESPONSE:

We are sorry for our carelessness. Colorbar for the elevation (Elev. in meter) is now added to the right side of the bottom of Fig. 2. The information about the colorbar and the map scale is also added to the figure caption of Fig.2.

[L825-827] A color scale bar for the elevation map (Elev. in meter) was shown in the right bottom of the figure.

[L834-835] The two maps (Figs. 2(a) and 2(b)) use the same map scale, which is located in the right side of Fig. 2(b).

28. Figures 3 & 4. These representations are not easily interpreted. More details in the text and in the figure captions could be useful.

RESPONSE:

We have added more interpretation of the component plane as:

[L234-238] This method also provides the detailed local relationship between the variables by the component planes, which is helpful to understand groundwater systems visually. The contribution map of the variables is shown in the component map (Fig. 3). Each component plane represents the average component value at each node in a certain color; the white indicates the high values and the deep brown indicates the low values.

[L249-250] Deep brown shades on the U-matrix indicate a large distance between neighborhood nodes whereas white shades correspond to a short distance between nodes.

[L837-838]The white indicates the high values of nodes and the deep brown is the low values of nodes.

[L840] The word of a hexagon denotes the sample number.