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# Geophysical Reactions to Remote 2022 Tonga Eruption and to Türkiye Earthquakes in Georgia (Caucasus): Hydrogeology, Geomagnetics and Seismicity

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## Abstract

The paper is devoted to analysis of hydrogeological, geomagnetic and seismic response to the two great remote geophysical events, 2022 Tonga volcano eruption and 2020-2023 Türkiye earthquakes in Georgia (Caucasus). The geophysical observation system in Georgia, namely, water level stations in the network of deep wells, atmospheric pressure and the geomagnetic sensors of the Dusheti Geophysical Observatory (DGO) as well as seismic data in Garni Observatory (Armenia) respond to the Tonga event by anomalies in the time series. These data show that there are two types of respond: infrasound disturbances in atmospheric pressure and seismic waves in the Earth generated by the eruption. After Tonga eruption January 15 at 04:21 UTC three groups of N-shaped waveforms were registered in the water level corresponding to the global propagation characteristics of the N-shaped waveform of infrasound signals on the barograms generated by eruption at the distance ~15,700 km: they were identified as the Lamb wave, a surface wave package running in the atmosphere with a velocity around ~314 m/s. The paper also presents the WL reactions to three strong EQs that occur in Türkiye 2020-2023, namely Elazığ, Van and Türkiye-Syria EQs. WL in Georgian well network reacts to these events by anomalies of different intensity, which points to the high sensitivity of hydrosphere to remote (several hundred km) strong EQs. The intensity and character of WL reactions depend strongly on the local hydrogeological properties of rocks, surrounding the well.

## Keywords

2022 Tonga Eruption, Türkiye Earthquakes, Hydrogeological, Geomagnetic and Seismic Reactions in Georgia

## 1. Introduction

**Hydrogeological, geomagnetic and seismic response to strong geodynamic events**

It is well known that strong earthquakes can cause large hydrologic response on great distances [1] [2] [3] [4] due to dynamic stress changes in the solid Earth crust. The less was known on possible global effects connected with giant volcano eruption. The event like Tonga eruption was not recorded for a century and it brought a lot of new information on its remote global effects [5] [6]. The geophysical observation system in Georgia, namely, water level stations in the network of deep wells, atmospheric pressure and the geomagnetic sensors of the Dusheti Geophysical Observatory (DGO) as well as seismic data in Garni Observatory (Armenia) respond to the Tonga event by anomalies in the time series. After Tonga eruption January 15 at 04:21 UTC three groups of N-shaped waveforms were registered in the water level corresponding to the global propagation characteristics of the N-shaped waveform of infrasound signals on the barograms generated by eruption at the distance ~15,700 km: they were identified as the Lamb wave, a surface wave package running in the atmosphere with a velocity around ~314 m/s.

We also present the WL reactions to three strong EQs that occur in Türkiye 2020-2023, namely Elazığ, Van and Türkiye-Syria EQs in order to study the possible effect of generated seismic waves on the dynamics of underground water as well as dependence of WL response to the local hydrogeological conditions. WL in Georgian well network reacts to these events by anomalies of different intensity, which points to the high sensitivity of hydrosphere to remote (several hundred km) strong EQs [3].

## 2. Material and Methods

***WL stations' network*: *materials*.** WL monitoring network in Georgia includes several deep wells, drilled in confined sub-artesian aquifer (**Figure 1**), here we use the data of the stations with the most systematic records. The water data are presented either in the pressure units KPa (**Figure 2(a)**, **Figure 2(b)**) or in WL units, cm (**Figure 2(c)**, **Figures 4-8**); 10 cm of WL change are equivalent to pressure change of 1 KPa. [7] [8] [9].

***WL stations' network*: *methods*.** The sampling rate at all these wells is 1/min. Measurements are done by sensors MPX5010 with resolution 1% of the scale (company Freescale Semiconductors; https://www.freescale.com/) and recorded by data logger XR5 SE-M (company Pace Scientific). The data are transmitted remotely by the modem Siemens MC-35i Terminal (company Siemens) using program LogXR.

***Geomagnetic data*: *materials*:** We use the data of Dusheti Geophysical Observatory (DGO) with coordinates Lat.42.088˚N; Long. 44.701˚E, which records geomagnetic field from 1834.

***Geomagnetic data methods*:** Magnetic variations are recorded by the fluxgate magnetometer FGE-95 (Japan), registering x, y, z components at a count rate 1/sec; the data in **Figure 3** are presented in nanotesla (nT). The data are representative for a whole territory of Georgia. It is equipped with modern precise Fluxgate

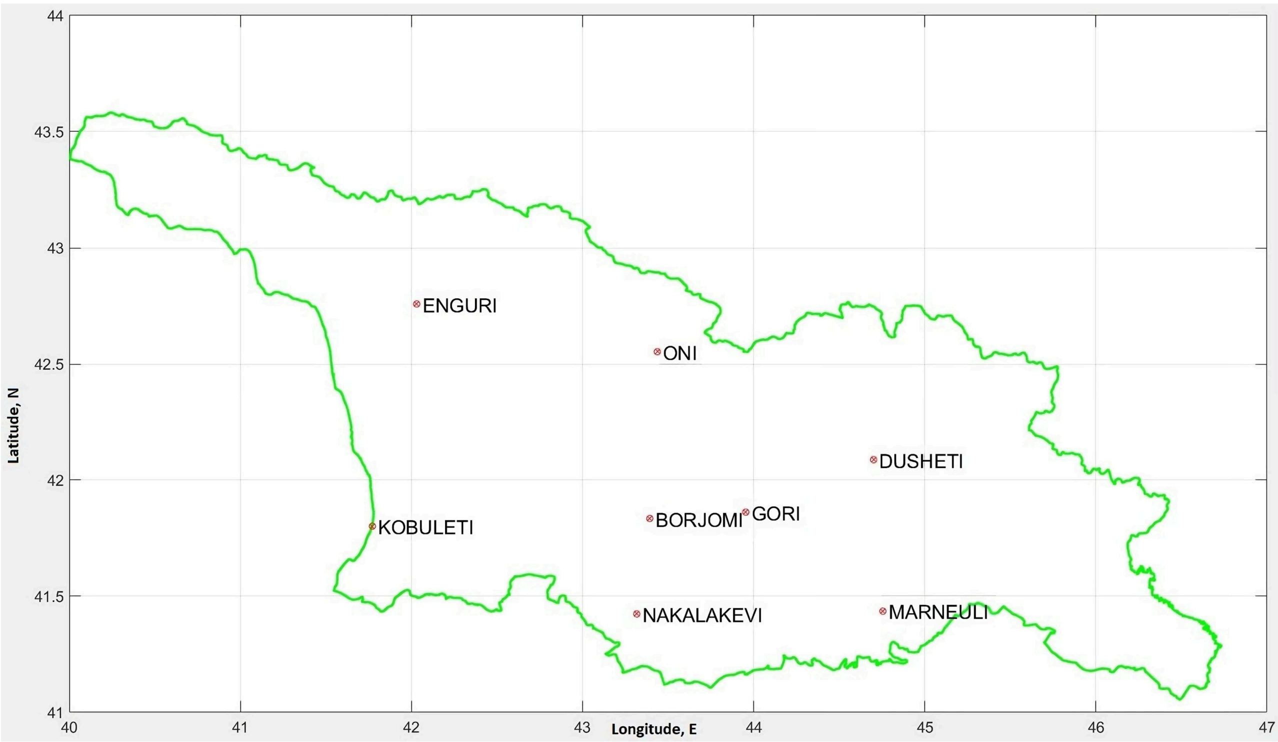
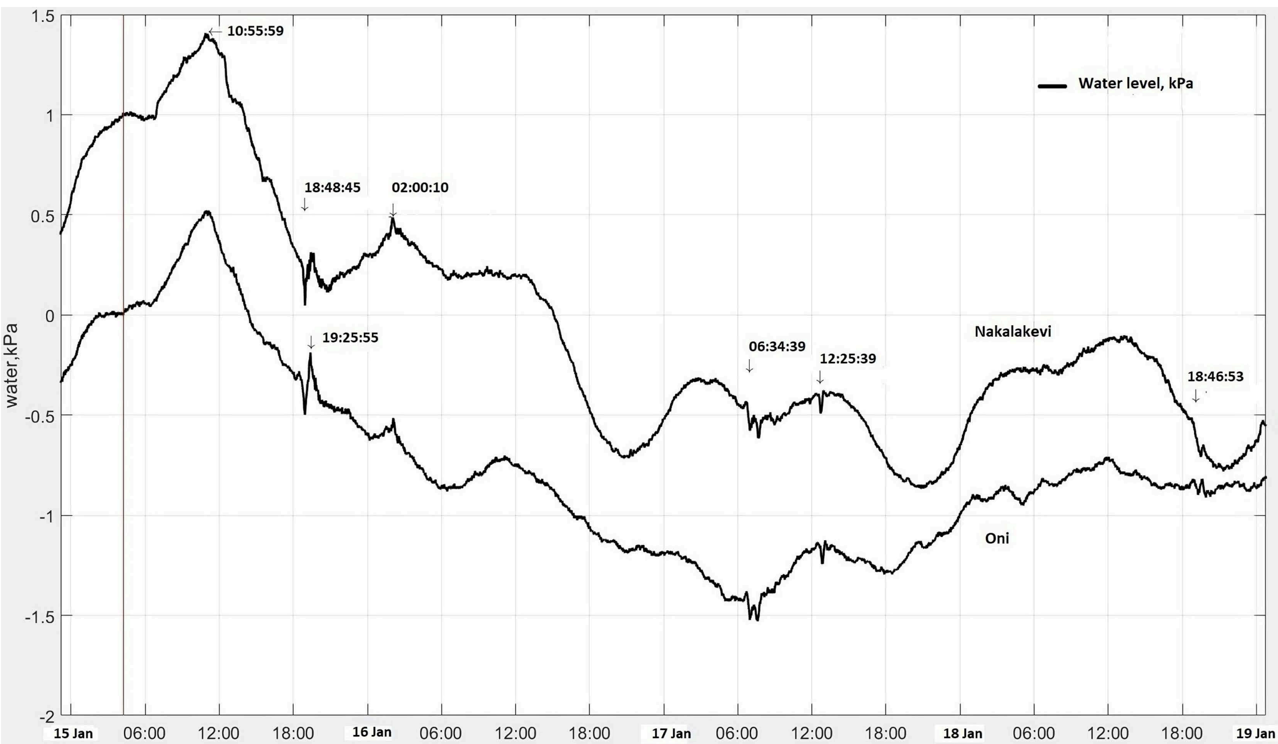
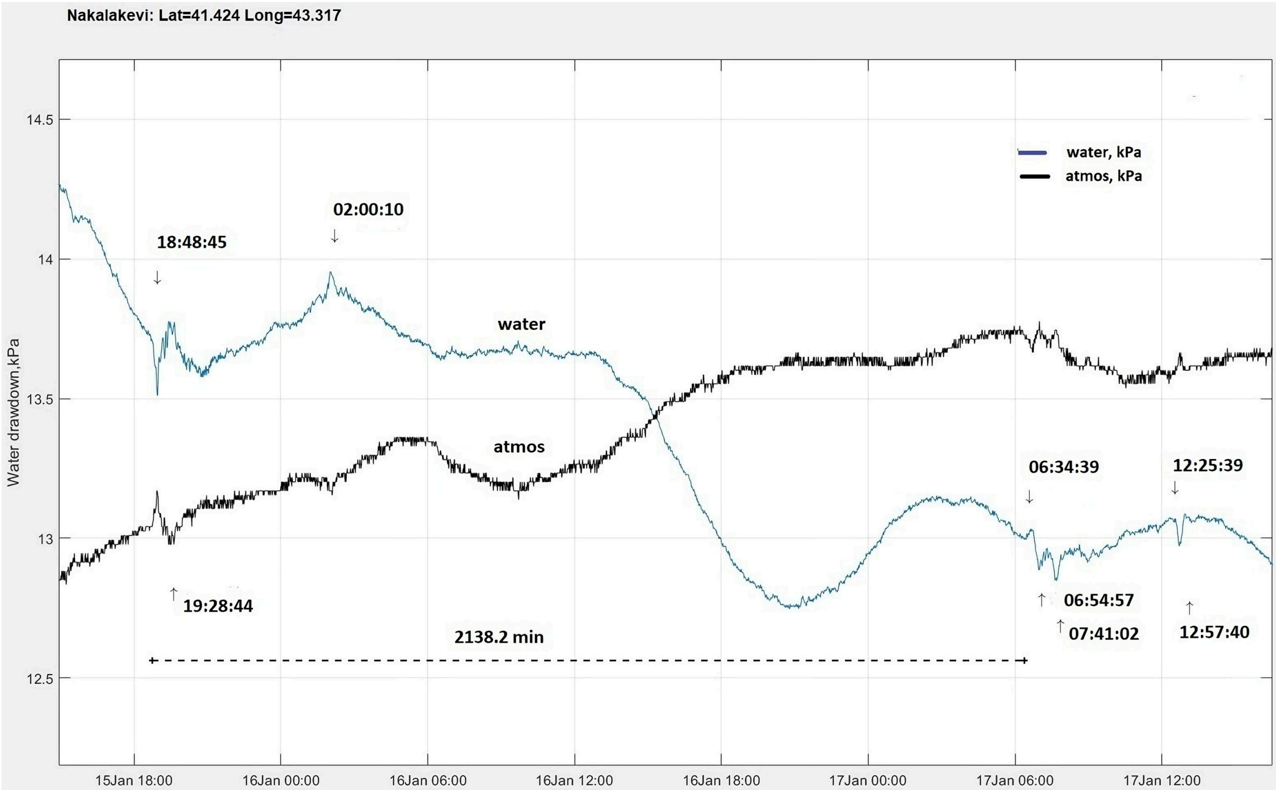


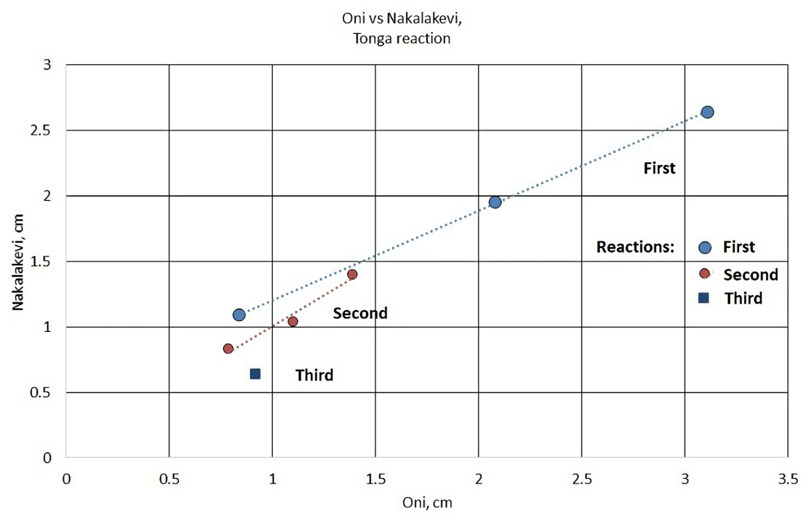

**Figure 1.** The map of Georgia with positions of water level stations and Dusheti Magnetic Observatory.




(a)




(b)




(c)

**Figure 2.** (a), (b), (c). Water Level reactions to the Tonga eruption event in Georgia. The numbers in **Figure 2** and (b) show the moments of spikes: (a) WL at Nakalakevi with time marks of wave arrivals; (b) WL (blue) and atmospheric pressure (black) at Nakalakevi with time marks of wave arrivals; (c) comparison of the WL reactions to the three different groups of waves of Tonga event at Oni and Nakalakevi stations.

Magnetometer Model LGI and it accomplishes non-stop registration of X, Y, Z elements variations [10]. The absolute values of components for January 2022 are X-23822.4 nT; Y-2768.3 nT; Z-43543.3 nT.

The time scale for all graphs is presented in UTC.

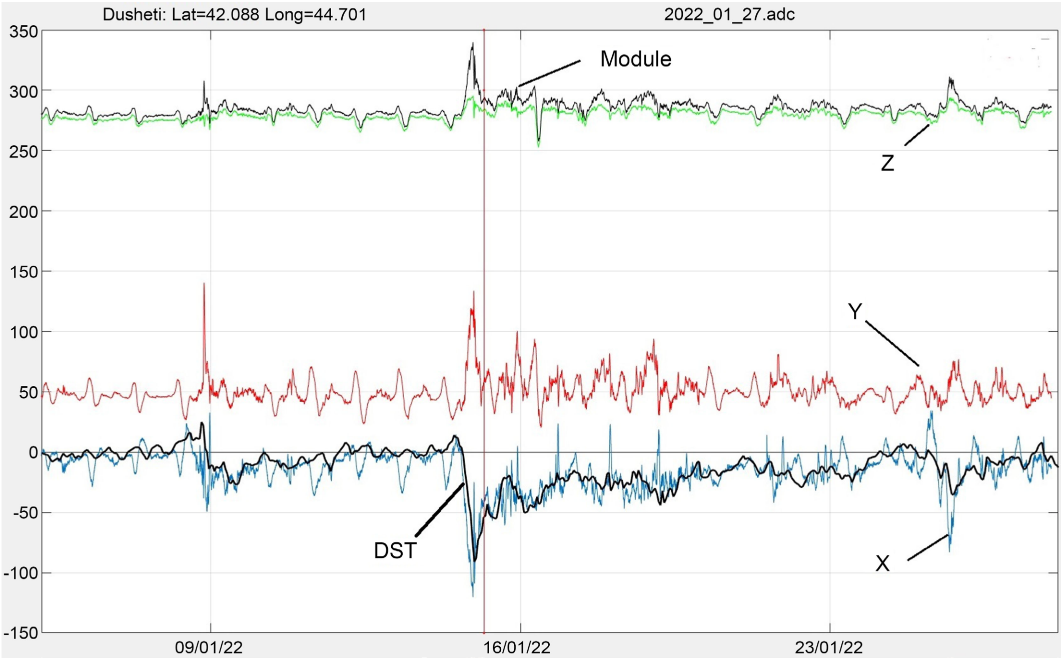



**Figure 3.** Geomagnetic field variations (in nanoTesla - nT) at Dusheti Geophysical Observatory, Georgia, from 14 to 18 January 2022: the figure shows results for X, Y, Z components as well as for the module and DST values. The red line marks the moment of Tonga eruption.

# 3. Results and Discussion

## 3.1. Water Level, Geomagnetic and Seismic Reactions to the Tonga Event in Georgia

### 3.1.1. WL at the Stations in the Georgian Network of Deep Wells during Tonga Event

There are many publications devoted to atmospheric and oceanic reactions to the giant Tonga eruption with two main episodes: the first one, on January 13, 2022 at 15:20 UTC and the major eruption on January 15 at 04:02 UTC with a maximum intensity at 04:08 UTC. The eruption, which was the most violent event in the last 138 years, generates a lot of near-field and global-scale anomalies in the Earth environment [5] [6]. The remote terrestrial effects connected with the event are of great interest. The main global impacts of these events are: the infrasonic pressure waves and the long-period seismic signals generated by the $M$5.8 event with an origin time of 04:14:45 January 15, 2022 (UTC).

The expected geophysical reactions to Tonga event, which could be registered at geophysical stations in Georgia and Caucasus are: 1) the fast responses, due to arrivels of seismic waves exited by explosion/$M$ 5.8 earthquake; 2) the long-period signals due to different atmospheric disturbances [5] [6]. The geophysical observation system in Georgia (Caucasus), namely, water level stations in the network of deep wells, atmospheric pressure and the geomagnetic sensors of the Dusheti Geophysical Observatory (DGO) with coordinates Lat. 42.088˚N; Long. 44.701˚E (**Figure 1**) responds to the Tonga event by anomalies in the time series. Besides, we analyzed the seismic record at the Garni seismic observatory (Armenia) in order to find the respond to the seismic waves generated by the

Tonga event.

After Tonga eruption January 15 at 04:21 UTC three groups of waves were registered in the water level in deep wells Nakalakevi and Oni (**Figure 1**); the water pressure change is of the order of 0.36 kPa in Oni to 0.28 in Nakalakevi to the first impact. The arrivals of the first group of waves were registered at both stations 867 min (14.45 hours) after eruption. As the distance from wells to Tonga is approximately 15,800 km, the velocity of the first wave is 302 m/s. The second group of waves arrives to wells 50.13 h after eruption and the third after 87.02 h. The time interval between the first and second wave package arrivals is 35.6 h, which corresponds to the distance 38,673 km covered at the velocity 302 m/s. This distance is less than the length of equator by 1335 km. The time interval between arrivals of the second and third WL wave packages is 36.9 h, which corresponds to covering the distance 40,123 km by the same velocity, this distance is by 115 km larger than the equator length. The above two first wave groups as a rule, contain two spikes (a doublet), which are retarded by approximately the same intervals: by 6.81 h in the first doublet and 6.13 h for the second one. The observed WL anomalies' time marks (**Figure 2(a)**, **Figure 2(b)**) correspond to the global propagation characteristics of the N-shaped waveform of infrasound signals on the barograms generated by eruption at the distance ~15,700 km: they were identified as the Lamb wave, a surface wave package running in the atmosphere with a velocity around ~314 m/s. There are three groups of waves; the first two groups form doublets, as a result, we have five clear wave arrivals, we call them N1, N2, N3, N4, N5. Note that the record of the ionospeheric disturbance N1 is connected with Lamb wave propagation, covering the shortest distance from Tonga to Georgia, 15,700 km (115.2˚) with a velocity 18.12 km/min in 14 h. The N2 arriwal is connected with the rebound Lamb wave, travelling from Tonga to Georgia from the opposite side of the globe: it arrive after eruption in 1279 min covering the distance 23176 km (115.2˚ + 180˚). The N3 and N4 waves follow the same pattern as N1 and N2 (actually, as a result of the second turn of the N1 and N2 waves). The third WL signal recorded 87 h after eruption and 36.9 h has not the form of doublet. Generally, the pattern of WL anomalies follow that of the travelling ionospheric disturbances (TEDs), which, according to [5], circled around the globe three times with the interval 1.5 days (36 h). Analysis of **Figure 2(b)** shows that the graph of time series of WL anomalies is closely anti-correlated with that of atmospheric pressure changes.

In **Figure 2(c)** we present WL reactions to the offsets of different groups of waves of Tonga event at Oni and Nakalakevi stations [9]. The amplitudes of WL signals in Nakalakevi ($y$) to those in Oni ($x$) are close to each other (WL response in Oni is slightly stronger than that in Nakalakevi. The WL response follows the equations: $y = 0.68x + 0.52$ for the first and $y = 0.95x + 0.06$ for the second group of onsets. The reaction of the second group of waves to Tonga event is weaker, which can be explained by a smaller amplitude of the atmospheric pressure change due to the mentioned group, see **Figure 2(b)**. There is not practically significant difference in response amplitudes between mentioned two wells for the third group of waves.

#### 3.1.2. Geomagnetic Field, Registered at the Dusheti Geophysical Observatory (DGO) during Tonga Event

Clear disturbances of geomagnetic field, possibly connected with Tonga eruption, were registered in Georgia by the Dusheti Geophysical Observatory (DGO) at 15 Jan. 2022 (**Figure 3**). Time is given in UTC.

The geomagnetic field at DGO is sensitive to remote earthquakes [10] [11]. There are two magnetic anomalies mainly in X and Y components, approximately around 09.01.22 (relatively weak) and 14.01.2022 (strong). Exactly, the starting time of the 14 January strong anomaly is 18 h 14 m UTC with the strong spike on 14 January at 22 h and it lasts 3 - 4 days. The data on the top 50 geomagnetic storms of 2022 in the table of official Kp-values from the GFZ in Potsdam, Germany [12] were no storms at 8 January, but there was a storm of Kp = 6 on 14 January at 21 h. Still, the characteristic anomalous behavior of X and Y components in our records (**Figure 3**) lasts much longer than perturbations connected with the typical geomagnetic storms, namely in our records the anomalous behavior lasts several weeks from 14 January to February, which seems anomalous. So we cannot exclude that both anomalies recorded at DGO (at 09.01.22 and the strong anomaly starting at 14.01.2022 and lasting many weeks) reflect a prolonged deformation process (say, slow earthquake) in the depth, preceding and during the Tonga event. The decisive proof will be the discovery of similar anomalies in the Tonga event recordings by other magnetic observations.

#### 3.1.3. Seismic Response to Tonga Event in Caucasus

The USGS reported a surface-wave package following $M$ 5.8 event during eruption process, with an origin time of 04:14:45 January 15, 2022 (UTC), located at 20.546˚ S, 175.390˚ E (USGS, 2022). Seismograms of the event filtered from $10^{-3}$ to $10^{-1}$ highlight surface Lamb waves of a speed of 3.9 km/s, and ground-coupled airwaves induced by the infrasound waves, propagating at ~300 m/s [6]. The presumption of Lamb wave global propagation at 300 - 350 m/s is consistent with our main observational results on the WL anomaly (**Figure 2(b)**). These waves provide the main carriers for eruption energy leaking into the upper atmosphere because of atmospheric resonance to forcing provided by these waves at ~300 m/s phase speed, equivalent to the speed of sound in the troposphere [5].

## 4. WL Reactions to the Strong Türkiye Earthquakes (2021-2023) in Georgia

Türkiye is prone to devastating EQs, which occur regularly along regional fault zones. On February 6, 2023, the earthquake of the moment magnitude Mw7.8 occurred in the southern Türkiye near the northern border of Syria at UTC 01:17:35 35 near to the junction of Eurasian, Arabian, African, and Anatolian plates [13]. The EQs occurred on southwest end of the East Anatolia fault zone, EAFZ [14] [15], where no EQs of $M > 6$ - 6.9 were registered from 1900 to 2020. The earthquake was followed by many aftershocks, the strongest of them of the Mw7.6 occur 9 h later in Kahramanmaraş Province. The last strong aftershock of 2023 event of M6.3 occurs 20 February at 17:04. Besides this major event, last years south-eastern Türkiye experienced two strong EQs: Elazığ EQ of $M$6.8 (24 January 2020) and Van EQ of $M$7.2 (23 October 2011).

### 4.1. Water Level Reactions to Türkiye-Syria Event in the Network of Deep Wells in Georgia

The water level reactions in Georgia to the 2023 Türkiye-Syria earthquake sequence are presented in **Figure 4**. The response to these events was different in the hydrogeoseismological network of Georgia, which is typical for WL data [1] [2] [8] [16].

The WL response to the main 2023 M7.8 event in Georgia is very different, the Gori well response was very strong: the WL first drops for 17 cm and then rises for almost 110 cm in a pulse-like manner. The Gori response to the strongest foreshock of M7.6 is also clear as well as the reaction to 20 February M6.3 aftershock (**Figure 5(a)**). Note, that the first WL response in Gori is sustained (Liu, C.-Y. *et al.* 2023), *i.e.* the WL change irreversibly after this event, but the strongest aftershock of M7.6 did not cause the sustained WL change. In Oni the WL records of the M7.8 and M7.6 event remind the "hydroseismogram" pattern (**Figure 5(b)**); again, as in Gori, the WL at the main shock first drops by 29 cm

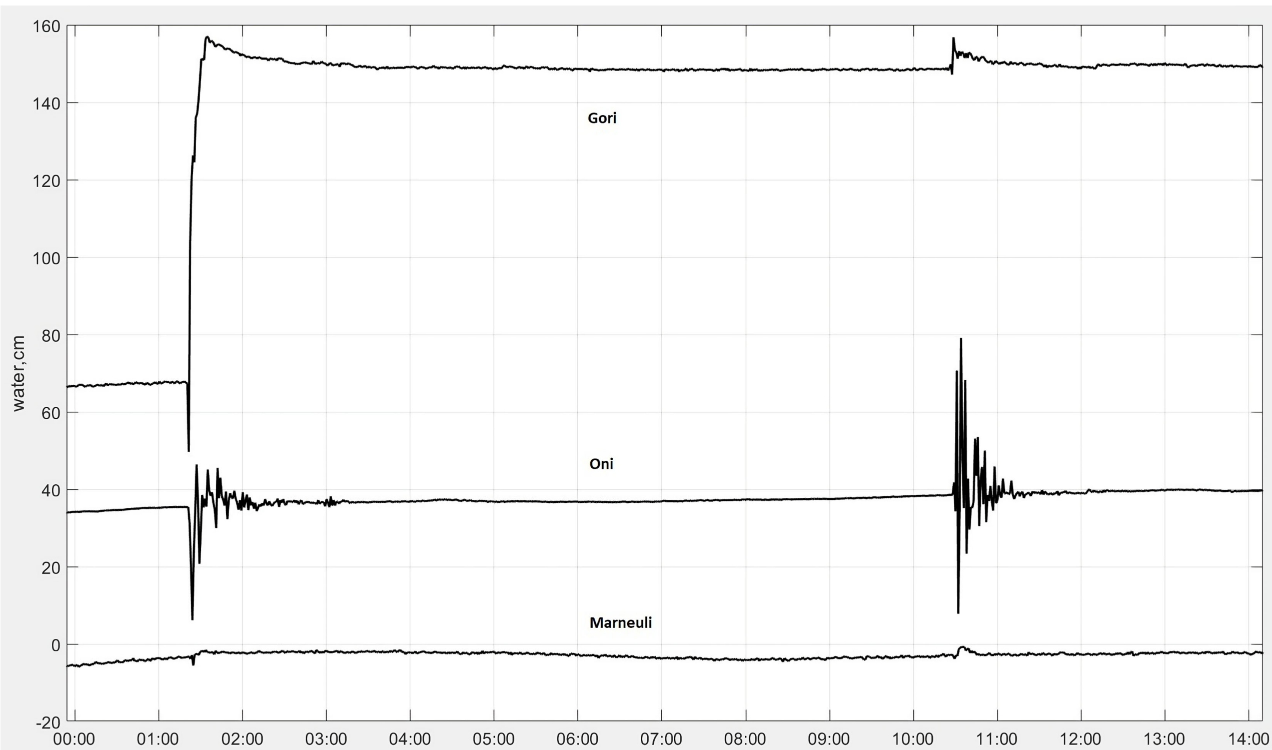
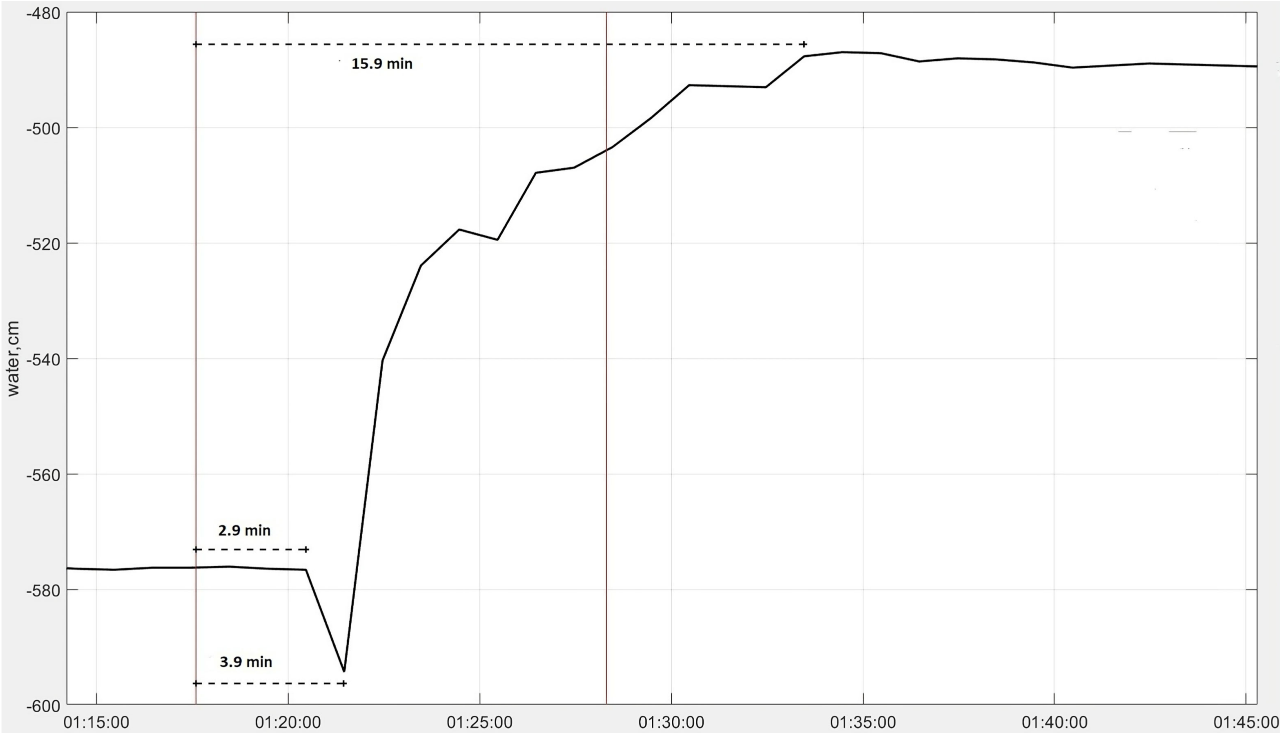
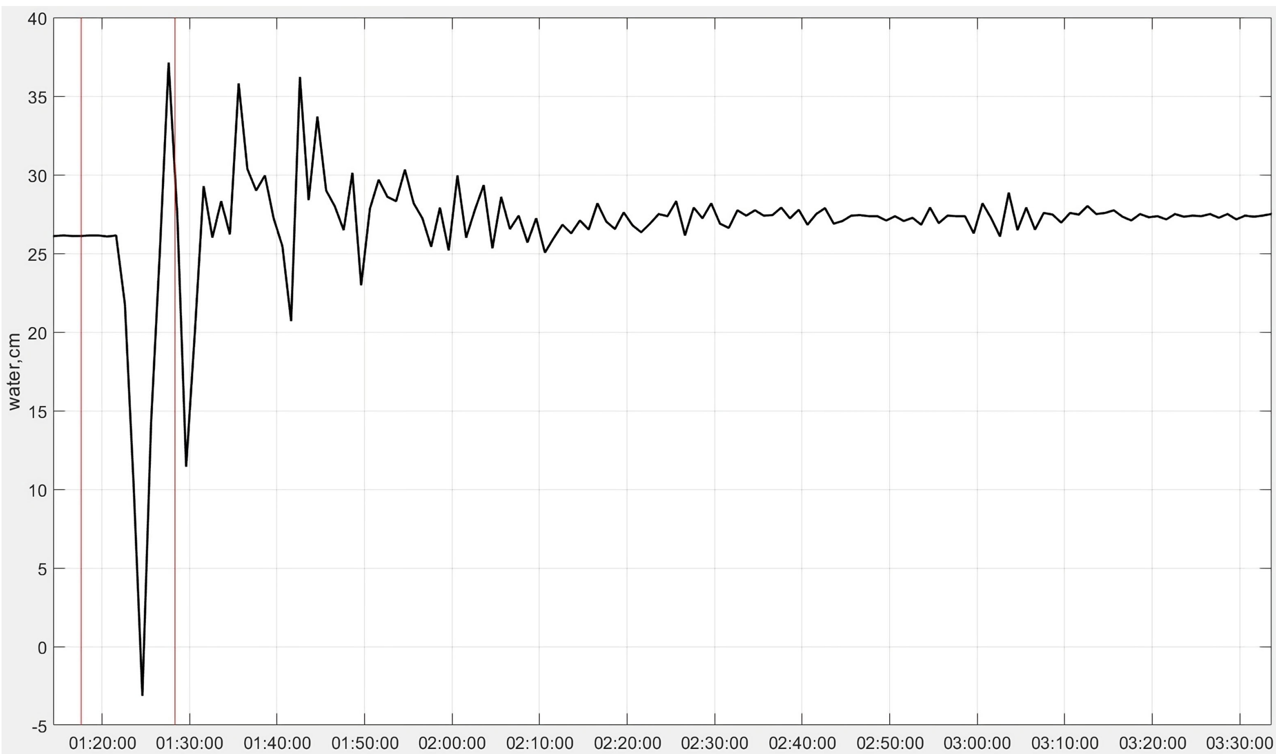



**Figure 4.** The records of water level reactions in Georgia to the Türkiye-Syria 2023 earthquake sequence at Gori, Oni and Marneuli: the two spikes correspond to arrivals of the mainshock and first aftershock.




(a)




(b)

**Figure 5.** (a), (b). The Türkiye EQ 2023 mainshock arrivals to Georgian WL stations: (a) Gori; (b) Oni. The red lines show the EQs moments of the mainshock and the first aftershock; the numbers in (a) show the retardation of the events' arrival relative to the time in the epicenter.

and then rise by 40 cm; at the M7.6 event the amplitude of the WL response in Oni was even larger, 70.5 cm. The reaction in Marneuli was the smallest (**Figure 4**), at both main shock and M7.6 aftershock the WL change only by 3 cm. These differences in reaction can be caused by peculiarities in the hydrogeological response to the EQ wave impact. As a rule, significant sustained WL changes are observed after local EQs and oscillatory variations, after strong remote events. At the same time, there are some exclusions: sustained WL change was recorded in Taiwan, after M8.1 Wenchuan EQ 12 May 2008 in China, at the distance 1900 km from the epicenter (Liu, C.-Y. *et al.* 2023). In addition, observations show that in the convergent plate boundaries (and the TransCaucasia is such a system) the groundwater level typically rises after strong EQs due to compression of the crust in the thrust fault systems. It seems that the extremal sustained response to the main shock in Gori, which is located at the distance 3500 km from the epicenter of the 2023 Türkiye event, also is not typical for the remote WL station reaction. The effect can be explained by the clearing of the (critical) pores system in Gori area by strong vibrations caused by the mainshock [3] [17]. Note, that the reaction to the next strong event, 20 February M6.3 aftershock, is a typical hydroseismogram, similar to the Marneuli record. The reversed sequence of WL reactions to the main shock and the aftershock in Oni can be explained by reversed sequence of hydraulic responses of pore space to the seismic events compared to that of Gori; namely in this case the main event did not change the pore space transmission or even blocked it and the following aftershock cleared the critical pores allowing stronger reaction to a weaker event.

According to the hydroseismograms the strong response to the Türkiye 2023 EQ that occur at 01:17:35 UTC is clearly seen at the Gori borehole at 01:20:30 UTC and in Oni well at 01:20:00 UTC. The seismic record of this event in the Garni station fixes the arrival of the surface/Rayleigh waves from Türkiye EQ at 01:20:30 UTC or 3 min after the mainshock. Thus the start of the first WL response to the Türkiye main shock coinside with the arrival of the surface/Rayleigh waves to WL stations in Georgia at 01:20:00 ± 5.

The impact of the M7.6 earthquake of February 6, 2023 in the Turkish-Syrian border region on the Borjomi mineral water deposit has changed very significantly the water level in some wells and increased the output; at the same time the chemical composition of the water has not changed or changed insignificantly. Exactly, WL measured 19 February, 13 days after the event in the system of 11 wells in the Borjomi area rises from approximately 1 m in the shallow (200 - 300 m) wells to impressive values of 5 - 25 m in the deep (1000 - 1800 m) wells [18]. Note, that the WL tests in the wells were carried out some days after the event, so the immediate WL changes after EQ should me even larger. The very high sensitivity of some deep Borjomi wells to the Türkiye EQ can be explained by the high stress-sensitivity of the network of cracks, at the critical concentration of percolating cracks (percolation threshold), when the cracks form so called infinite cluster able to transport large volume of pore water [19]. This change in the water transport ability (permeability) can be temporal (like in Oni and Marneuli) or permanent (like in Gori) depending on the pore space reaction to the strain wave [20].

### 4.2. Water Level Reactions to Türkiye 2020 and 2021 Strong Events in the Network of Deep Wells in Georgia

The WL stations in Georgia clearly respond also to the Elazığ earthquake of *M* 6.8, which occur in Türkiye on the same East Anatolia fault 24 January 2020 [15].

The WL stations in Georgia also clearly respond to the Van EQ, which occur 2021 23 October 2011 of *M* 7.2 (**Figure 8**), but no WL reaction was registered on the following EQ of Mw 5.6 which struck Van in November 9, 2011.

According to [3] the WL response to EQ depend on the distance to event *r* and EQ magnitude *M* and can be expressed in terms of the seismic energy density *e* (J/m$^3$), which depends on the magnitude of the EQ and the distance to the EQ source *r*:

$$\log r = 0.48 - 0.33 \log e(r) - 1.4$$

In **Table 1** are presented results of calculations the seismic energy density *e* for mentioned above three EQs in Tukey. It shows that the values of *e* are small, though the event is clearly recorded by the WL stations (**Figures 4-8**). Note, that the only sustained response was recorded in Gori: $e = 10^{-4}$ (**Figure 4**, **Figure 5(b)**) is in agreement with the remark of [3], that the sustained WL change in boreholes can be observed at the threshold value of $e = 10^{-4}$. Such sustained effect was not observed in other wells, though the seismic energy density there was of the same order, which confirms the idea that the seismic wave impact of the mentioned energy density may still break up the weak clogs even in the remote but critically sensitive wells, where a small water pressure increase can destroy the barrier for the water flow.

**Table 1.** The seismic energy density *e* at WL stations (in Georgia) for different Türkiye EQs.

| Event | WL stations | Distance, km | Log *r* | *e*, J/m$^3$ |
|---|---|---|---|---|
| Karamanmaraz, *M* 7.8 | Oni | 3750 | 3.575 | $2 \times 10^{-4}$ |
| | Gori | 3770 | 3.576 | $2 \times 10^{-4}$ |
| | Marneuli | 3780 | 3.577 | $2 \times 10^{-4}$ |
| Elagiz, *M* 6.8 | Akhalkalaki | 2700 | 3.430 | $2 \times 10^{-5}$ |
| | Oni | 1970 | 3.290 | $5 \times 10^{-5}$ |
| Van, *M* 7.2 | Marneuli | 1300 | 3.110 | $6.7 \times 10^{-4}$ |
| | Kobuleti | 1400 | 3.150 | $5 \times 10^{-4}$ |
| | Borjomi | 1340 | 3.130 | $6 \times 10^{-4}$ |

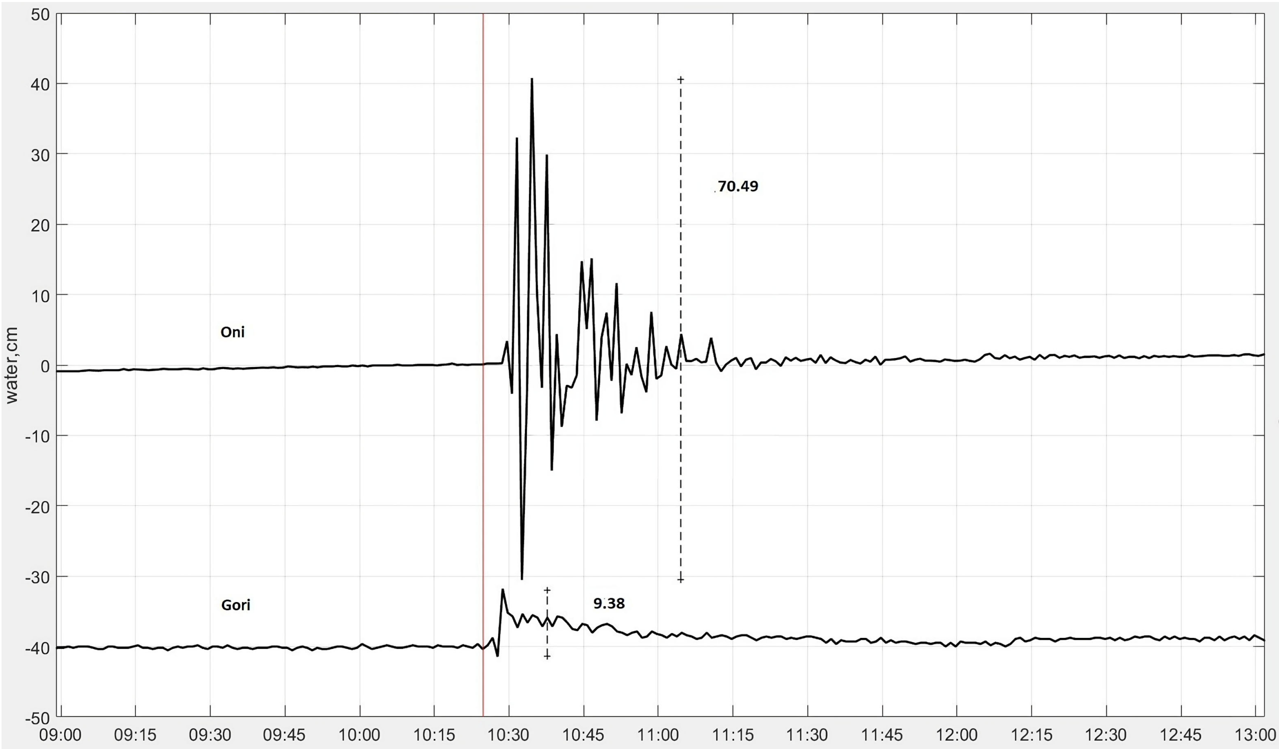



**Figure 6.** WL reaction to 2023 Türkiye EQ $M$ 7.6 aftershock in Oni and Gori. The red lines show the moment of the mainshock and the dashed lines with numbers, the value of the WL maximal difference.

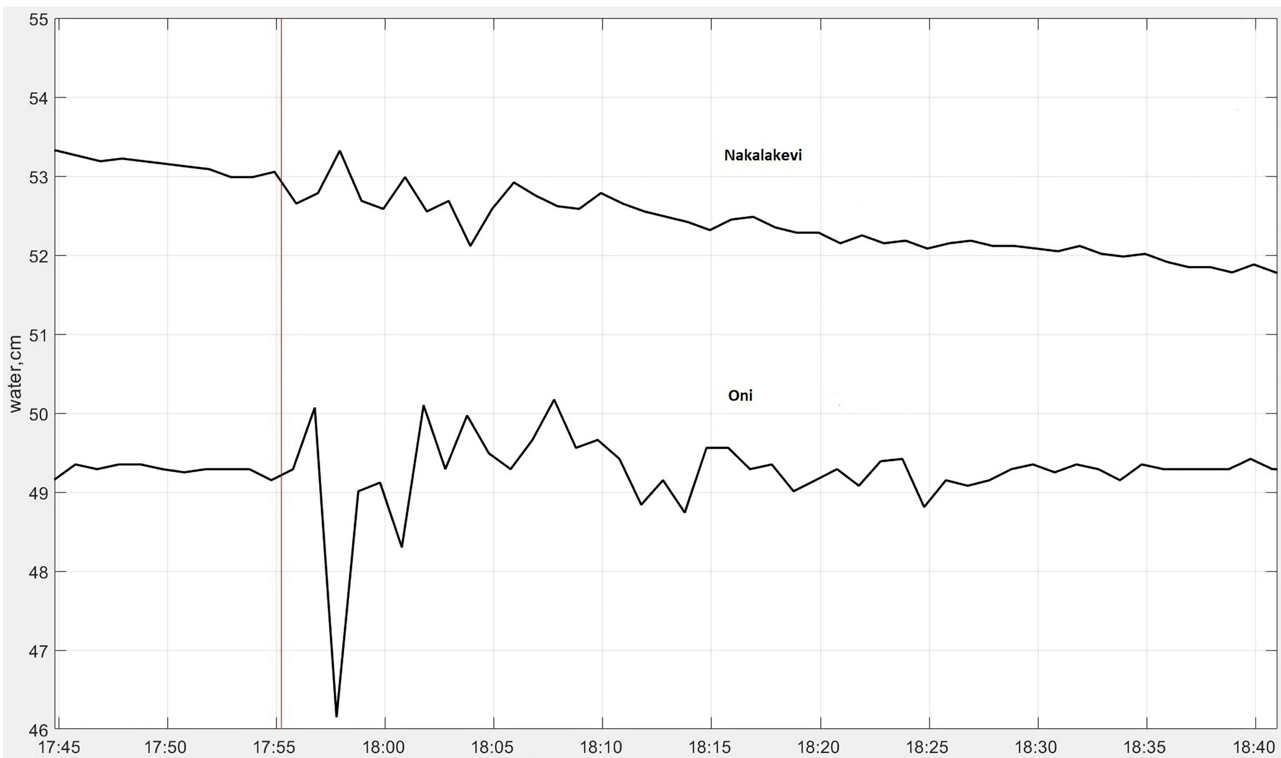



**Figure 7.** WL reaction to the Türkiye Elazığ earthquake of $M$ 6.8, 24 January 2020. Nakalakevi (top) and Oni (low). The red lines show the moment of the mainshock.

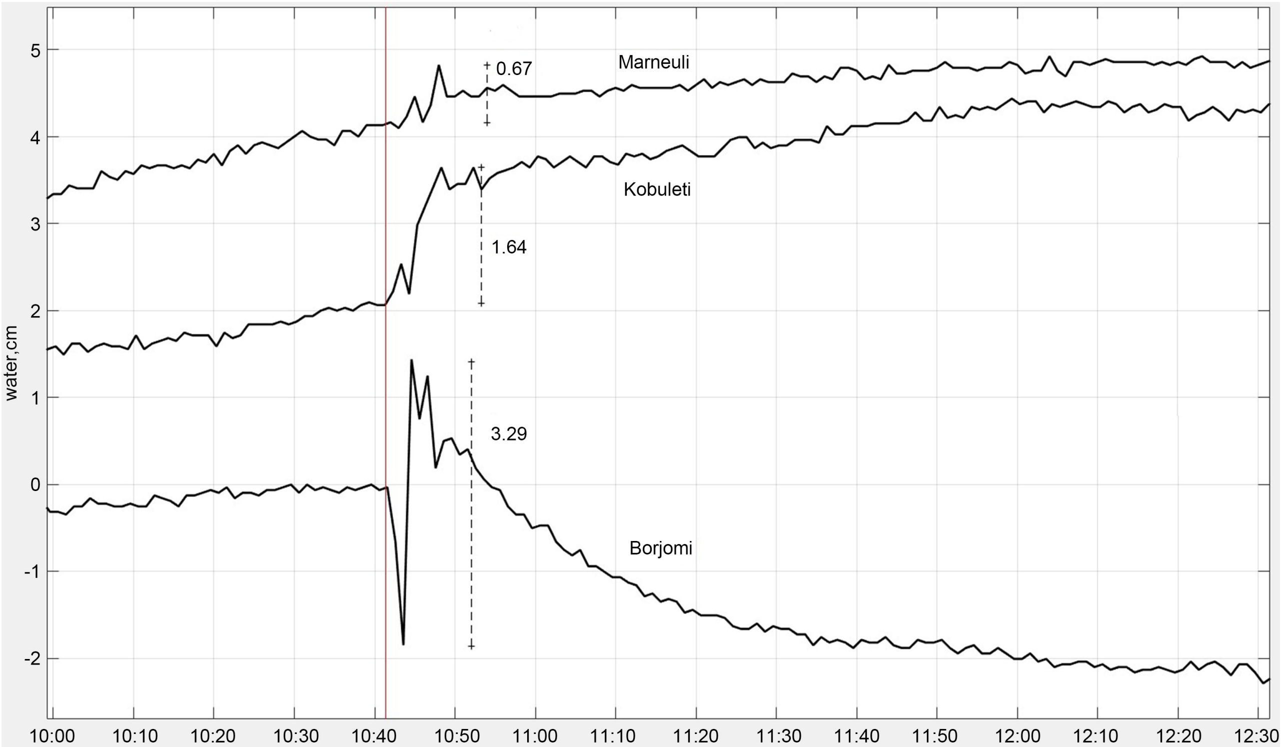



**Figure 8.** WL reaction to the Van (Türkiye) earthquake of *M* 7.2, which occur 23 October 2011. The red line show the moment of the mainshock and the dashed lines with numbers, the value of the WL maximal difference for a given moment.

## 5. Conclusion

The analysis of hydrogeological, geomagnetic and seismic time series during strong global impact (Tonga volcano eruption) and regional strong seismic events (Türkiye earthquakes), registered in Caucasus allow to understand better the mechanisms of registered anomalies in the geophysical fields as well as role of local geological conditions affecting the response amplitude of mentioned fields to remote EQs.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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