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Exploring the Feasibility of Quake-Catcher Network based Earthquake Warning System in North Eastern Tanzania Using the Simulated records of Magnitude 5.9 Lake Natron Earthquake of 2007

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Abstract— Following the acceptance of MEMS accelerometer as the low-cost alternative seismic sensors capable of catching moderate – large earthquakes in urban areas, and the successful deployment of Quake-Catcher Network (QCN) for earthquake early warning purposes in various regions, the study explores the establishment of the QCN based earthquake early warning system in North Eastern Tanzania (NETZ) with the hope of providing some warning times in urban areas. To accomplish the task, we simulate the 2007 magnitude 5.9 Lake Natron earthquakes using the MEMS sensor network proposal for South Western Tanzania (SWTZ) and estimate the possible warning times at selected target sites in NETZ region. The result suggests the addition of few more sensors in NETZ for maximization of warning times at the target sites. With the new MEMS sensor network positioning across NETZ, the study show that the Arusha and Moshi urban areas can be issued with 9 seconds and 23 seconds of warning times, respectively, before the onset of destructive waves from the considered event.

Keywords— Earthquake early warning, Earthquake Hazard, Warning times, P-waves, S-waves

I. INTRODUCTION

The earthquake early warning systems based on the Quake-Catcher Network platforms are currently being deployed in several regions [1]–[3]. The Quake-Catcher Networks (QCN) uses the low-cost MEMS accelerometer sensors either attached to the computer via USB or internally built into the laptops to catch moderate to large earthquakes in urban areas [1],[6]. The methodology is currently used in California, Mexico, Chile, New Zealand, Taiwan and France, to mention few [1]–[3]. Technically, MEMS sensors deployed under QCN in urban areas, monitors the earthquakes and communicates the sensed data to a central QCN server hosted at Stanford University either through an Internet connected computer or via any available wireless connection using the Berkeley Open Infrastructure for Network Computing (BOINC). Thus, on earthquake occurrence, the sensor computer system detects the abrupt changes in the acceleration recordings and transmits trigger data packet (sensor location, ground motion at trigger) to the QCN server [3]-[5]. Trigger data from sensors that are correlated in space and time are then associated by the server into event.

Studies analyzing QCN recorded data from several regions, has shown that the reliability of the recorded data is good, the speed and accuracy of earthquake magnitude and event location estimation is also promising for earthquake early warning system purposes [1],[2]. Under normal network operations, QCN detects and characterizes earthquakes within 9.1 s of the earthquake rupture and determines the magnitude within 1 magnitude unit of that reported in the GNS catalog for 90% of the detections [1],[4],[6]. Specifically for the denser MEMS sensor network deployed in California, the mean trigger data latencies have been found to be about 3.4 s and over 90% of all triggers are registered within 6 s [1],[4],[6]. For world wide data, the mean trigger data latencies are about 4.2 s and over 90% of all triggers are registered within 7 s [1]-[6]. Thus, feasibility of earthquake early warning systems based on QCN platform, has been proven to be a cost effective for mitigation of earthquake hazards in urban areas.

All the QCN system approaches rely on the rapid identifications of the two seismic waves generated during the earthquakes. The P-waves or primary waves commonly observed first with small amplitude that are less destructive, and the S-waves or secondary waves generally observed second with larger amplitude that induces the damage to buildings in an earthquakes. Like any other earthquake early warning system, QCN philosophy strive to optimally install seismic sensor networks to enable rapid detection of the first P-waves and prediction of the severities of upcoming S-waves at specified target sites before onset of destructive waves. Specifically, QCN server uses the P-wave observed vibration data in the first four seconds at the recording sites to quantify the earthquake effects in terms of P- and S-wave across the region. The time interval between the arrivals of P- and S-waves at the site, which varies according to the distance of the nearest recording station, is used as earthquake warning times. In ideal case, sensor stations should be at any grid point and very close to all seismic sources to promptly capture the P-waves and generate alert to population at risk with maximum warning times. Utilizing the QCN approach, MEMS sensor network optimized for Lake Tanganyika and Lake Nyasa seismic sources, has been proposed for providing earthquake warning to Southern Tanzania area [10]. In this paper, we explore the feasibility of QCN based earthquake early warning system across NETZ in terms of warning time possible from the utilization of MEMS sensor network proposed for SWTZ through simulation of magnitude 5.9 Lake Natron earthquake of 2007. The severity of ground shaking parameters from this earthquake is also simulated and compared to the available reports.

II. STUDY AREA AND TARGET SITES

The North Eastern Tanzania (NETZ) including the urban area of Arusha and Kilimanjaro, and is located along the eastern branch of the East African Rift System (EARS) in Tanzania. The NETZ is affected by earthquakes with magnitude between 5 and 6 on Richter scale as results of EARS splitting movements [8],[9]. Example, from July to August 2007 this area was struck by series of seismic swamps with the largest earthquake being the magnitude 5.9 Lake Natron earthquakes on 17 July 2007 [11], [12]. According to the collected data, areas shaken by the quake included Longido town, Namanga town, Monduli town, Arusha city and Moshi city [12]. Specifically in Arusha, it was reported that the Arusha International Conference Centre were evacuated during the earthquake. On the process many people ended up in the staircases while the building was still jerking, but no damages or injuries were reported. The Arusha urban area is a major step point for tourists who come to experience the wonders of the tectonic made features in Tanzania, as well as the home for many international activities. Considering the economic importance of the area and the consequences of large earthquakes in this region without adequate warning time, the feasibility study of optimal earthquake early warning system that can provide adequate time for safe evacuation of people is explored. Therefore, the selected target sites are among the areas shaken by the quake, Longido, Namanga, Monduli, Arusha and Moshi.

III. METHODOLOGY

The methodology adopted for the study was first evaluating the severity of the earthquake by simulating its induced ground motion to estimate peak ground acceleration (proxy for damage) across the affected region. To accomplish that, PGA attenuation equation proposed for SWTZ was adopted [10]. For evaluating the warning time capability from the magnitude 5.9 Lake Natron earthquake of 2007, first the MEMS sensor network were used to record the simulated seismic waves (P- and S-waves) propagating from the source to the selected target sites for calculation of warning times. After evaluating the achievable warning times, the positions for the additional new sensors specifically in NETZ were identified and added to the MEMS network. Then, the simulation process was repeated with new MEMS network (Fig 1) that included the additional stations across NETZ strategically positioned for the event.

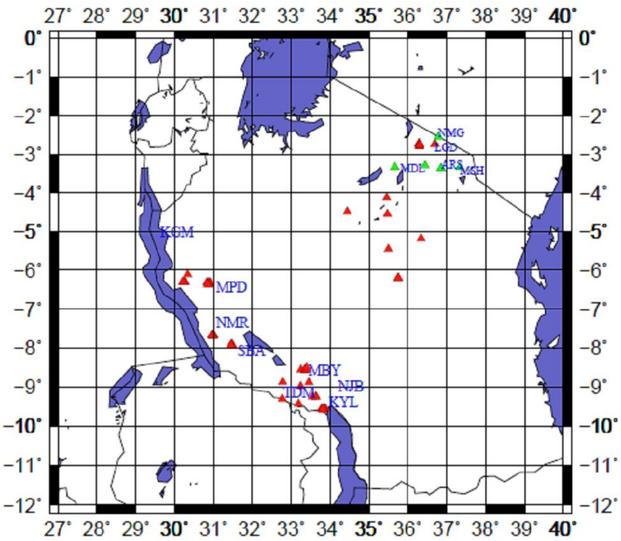


Fig. 1: Proposed MEMS sensor station for QCN warning system. While red triangles are old sensor stations for first simulation, green triangles are newly added sensor stations for the second simulation.

A. Computation of Simulated PGA values

To assess the severity of induced ground shaking due to magnitude 5.9 Lake Natron earthquake of 2007 at each point across the NETZ region, the computation of PGA values adopted Equation (1) proposed for SWTZ [10].

$$PGA = 1.42 \exp(1.43M) R-1.2 (0.719 \log(\tau)) \qquad (1)$$

Where PGA is peak ground acceleration at a specified point, M is earthquake magnitude estimated from the measurements of large P-wave signal within the first four seconds, R is the epicentral distance and τ is the P-wave observation time plus the arrival time difference between P- and S-waves at that point.

B. Computation of Warning Times at Target sites

Warning time (Tw) is defined in this study as the time difference between the reporting of event by QCN system (T_r) and the arrival of S-waves (T_S) at the target site. To report the event, QCN serve requires the recorded first four seconds of P-wave from at least five stations to quantify the earthquake characteristics. Therefore, time taken for P-waves (P-wave arrival time) to reach the first sensor station (Tp), time to wait for the earthquake to reach all five station (tw), time for each station to transmit the trigger packet to QCN server (Tt), and time for actual trigger data association and declaration into event (tp) are parameters considered in event processing time Tr. Using the simulated arrival time of P-wave at the first station (Tp), and S-wave arrival time at a specific target site (TS), the warning time at the target site is estimated as shown in Equation (2).

$$T_W = T_S - T_r \qquad (2)$$

In which TW is the warning time, TS is the time for the S-waves to reach target site, and Tr is the event reporting time by the QCN systems given by Equation (3).

$$T_r = T_p + t_w + T_t + t_p \qquad (3)$$

In principle, the time Tp for the earthquake to reach the first sensor station, the time tw for the five stations to be triggered by the event are variable. Tp depends on the location of sensing station in relation to the event location, such that when sensors are deployed close to the event source the Tp value will be small. The time tw depends on the separation distances between the sensing stations in the network, such that the value will be less for an array as compared to regional network sensors. From several implementations of QCN sensor networks across the global time for QCN to declare the global events have been found to be about 10 seconds [1], [3],[4]. In most case this includes the time for each station to transmit the trigger packet to QCN server (Tt) varied from 5 sec to 7s s, and time for actual trigger data association and declaration into event (tp) which is less than a second for seismic arrays.

IV. RESULTS AND ANALYSIS

For each simulation process, recorded sensor station trigger data packet includes the sensor location (SLat, SLon), P-wave arrival time (Tp), and Peak P-wave amplitude within the first four seconds to prove that the amplitude threshold level was exceeded at the station at the time of trigger. The simulated data for target sites includes the target location (TLat, TLon), P- and S-wave arrival times (Ts and Tp), and the expected PGA at the target sites (PGA). Using the simulated earthquake information at the sensor stations and target sites, earthquake warning times at each target site and the severity level of ground shaking (PGA) were computed.

A. Simulated PGA values for 2007 magnitude 5.9 Lake Natron earthquakes

Simulated values of peak ground acceleration used as damage proxies in this result for the propagation of 2007 magnitude 5.9 Lake Natron earthquakes across the region resulted in the data presented in Fig. 2. This is a PGA attenuation curve from the utilized ground motion attenuation equation.

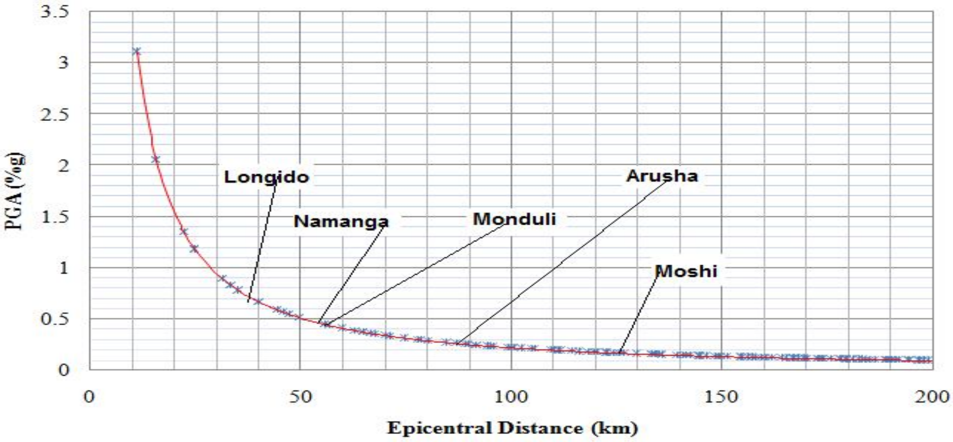


Fig. 2: PGA Attenuation curve for magnitude 5.9 Longido earthquakes of 2007

For simplicity, in this study PGA values above 0.5g are considered to cause severe ground shaking , PGA values between 0.5 g and 0.2g are considered to cause strong ground shaking , PGA values below 0.2g but above 0.001 are classified to cause weak ground shaking, and PGA values below 0.001 g are considered unfelt.

From Fig. 2, simulated PGA values were severe up to a distance of about 90 km, strongly felt between a distance of 90 km to 150 km, and weakly felt above a distance of 150 km. Specifically, in Longido, Namanga, Monduli, Arusha, and Moshi, simulated earthquake ground shaking were about 0.67g, 0.49g, 0.47g, 0.25g, and 0.15g, respectively. Thus, Longido is simulated with severe ground shaking with possible damages, Namanga, Monduli and Arusha are simulated with strong ground shaking, while Moshi is simulated with weak ground shaking.

Also, the simulated PGA values for the event were mapped into PGA shaking maps shown in Fig 3. In generating the PGA shaking maps, PGA values above 0.5g were coloured red to orange, values between 0.5g and 0.2g were green coloured, and values below 0.2g but above 0.001g were coloured blue.

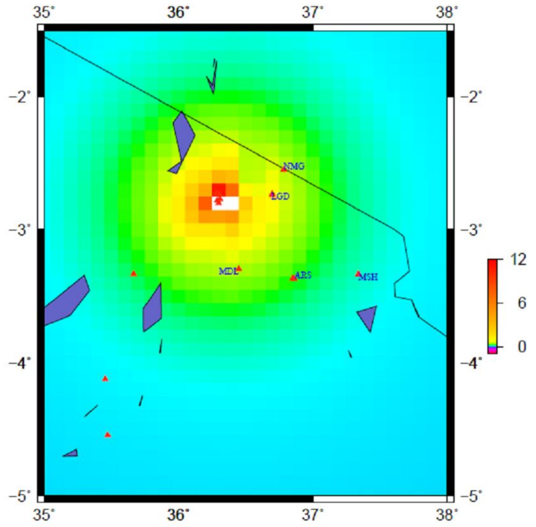
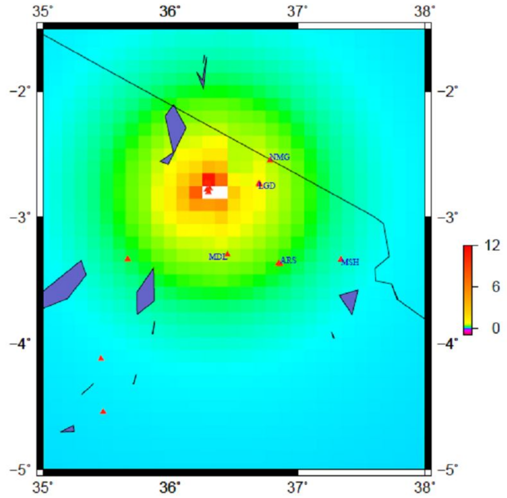


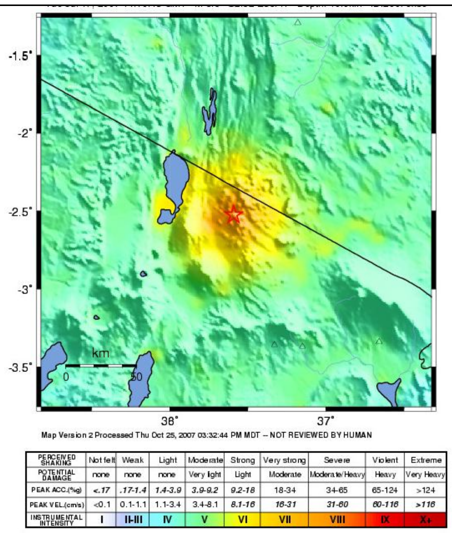
Fig 3: Simulated PGA Shaking maps for 2007 magnitude 5.9 Lake Natron earthquakes

According to Fig 3, Longido town was coloured red-orange for severe shaken area with possible damages, Namanga, Monduli, and Arusha were coloured green for strongly shaken, while Moshi was coloured blue for weakly shaken area.

Comparison was performed between the simulated PGA shaking maps and eyewitness based USGS ShakeMaps published for the event as shown in Fig 4.



Simulated PGA map



USGS ShakeMaps [12]

Figure 4: Comparisons of event ShakeMaps

From Fig 4, simulated PGA shaking maps for the 2007 magnitude 5.9 Lake Natron earthquakes, show similar areas within strong ground shaking as compared to the USGS ShakeMaps. Example, Namanga and Arusha are mapped under strong ground shaking region for both maps, and Moshi city is mapped under weak ground shaking region with both maps. Thus, the simulated PGA shaking maps portrayed well the locations for earthquake possible damaged zones for its applicability in seismic hazard mitigation measures.

B. Simulated Warning times for 2007 magnitude 5.9 Lake Natron earthquakes

According to Equation (2) and (3), computation of warning times at a specific point, requires S-wave arrival data at that point, as well as the QCN event processing time. Adopting the presented methodology, the various parameters in Equation (2) and Equation (3) were evaluated for the two arrangements of sensors (with and without additional sensors) considered in simulation. Assuming that the QCN server can issue earthquake report within 10 seconds (T_p+T_t), the resulting warning times are presented in Fig 5 for the two cases of MEMS sensor network (with and without additional sensors).

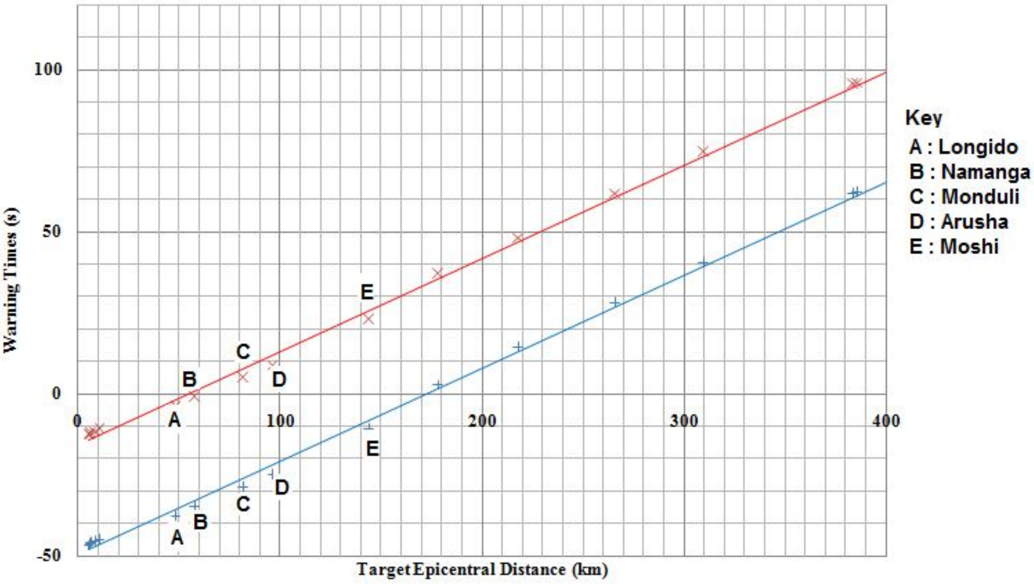


Fig. 5: Target warning time graph. Blue (bottom) line represents warning times without new stations and Red (upper) line represents warning times with added new stations.

From Fig 5, without new stations in NETZ, the warning times in Longido, Namanga, Monduli, Arusha, and Moshi are -38, -35, -29, -25 and -11, respectively. When new stations are included, the new warning times are -4, -1, 5, 9, and 23 seconds, for Longido, Namanga, Monduli, Arusha and Moshi, respectively. That is, Namanga, Arusha and Moshi receive some valuable warning times for evacuation if the new stations are included. An attempt to reduce the five minimum number of station triggers required in event characterization by QCN to three was also made. For requirement of only triggers from three stations, Fig 6 presents the warning times.

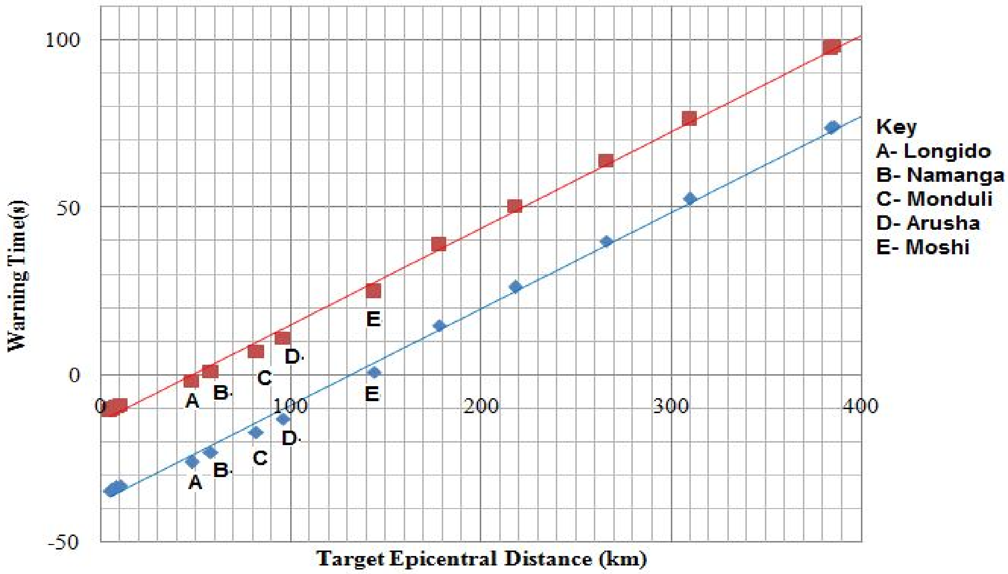


Figure 6: Warning time with three trigger threshold. Blue (bottom) line represents warning times without new stations and Red (upper) line represents warning times with added new stations.

From Fig 6, without new stations in NETZ, the warning times in Longido, Namanga, Monduli, Arusha, and Moshi are -26, -23, -17, -13 and 1, respectively. When new stations are included, the new warning times are -2, 1, 7, 11, and 25 seconds, for Longido, Namanga, Monduli, Arusha and Moshi, respectively. With the use of only three triggers, the change in warning times at each target site is about 24 seconds.

For further analysis of the new sensor network warning time performances, warning time for five, three and one station triggers are compared in Fig 7.

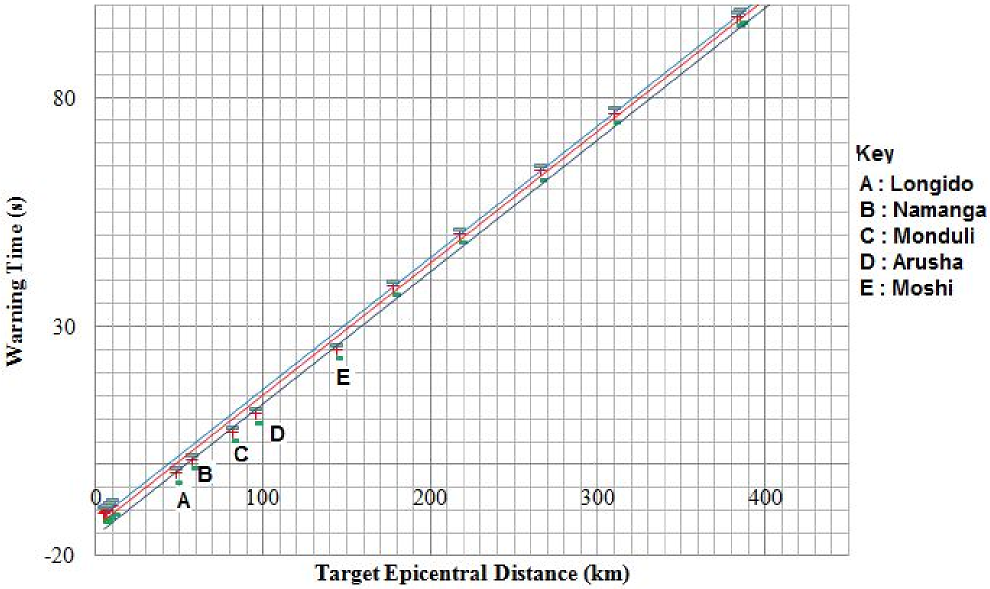


Fig 7: Warning times with new stations at varying station trigger thresholds. Green (bottom) line represents warning times with five trigger thresholds, Red (middle) line represents warning times with three station trigger threshold, and Blue (upper) line represents warning times with one station trigger threshold.

From Fig 7, the target warning times are very close for the proposed MEMS sensor station. Example, the variation in target warning times when station trigger threshold is varied from five to three is 2 seconds at each point and when the trigger threshold is varies from three to one it is 1 second. For each case, Arusha and Moshi cities are given at least 11 seconds, just enough for evacuation of buildings.

V. CONCLUSIONS

In this paper, we proposed the establishment of QCN based earthquake early warning system in North eastern Tanzania. By simulating the PGA spatial variability across the region from magnitude 5.9 Lake Natron earthquakes of 2007, we have shown that Longido town experienced severe shaking with possible damages, and Arusha, Namanga, Monduli experienced strong shaking, while Moshi experienced weak shaking. By simulating the seismic waves propagation time from the earthquake, we have shown that at least 9 seconds can be available for warning populations in the urban cities of Arusha and Moshi if QCN based earthquake early warning system is implemented.

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