Unique Quantitative Analysis of Tsunami Waves using Statistical Software: A Case Study of The Major Recorded Hawaii Incidents

Mostafa Essam Eissa[1,*] **and Engy Refaat Rashed**[2]

[1]Microbiology and Immunology Department (Independent Researcher & Candidate), Faculty of Pharmacy, Cairo University, Cairo, Egypt
[2]Drug Radiation Research Department, National Centre for Radiation Research and Technology, Atomic Energy Authority, PO Box 29, Nasr City, Cairo, P.O.11787, Cairo, Egypt.

***Corresponding author: E-mail: mostafaessameissa@yahoo.com**

***Web of Science Researcher ID: AAK-6095-2020**
***ORCID ID: orcid.org/0000-0003-3562-5935**

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Facing the rage of nature appears to be unavoidable with its catastrophic impact on human life. However, every event is an opportunity to learn and set control measures to avoid or at least minimize the damage as much as possible. One of the most devastating natural phenomena is Tsunami. Pacific region is one of the most impacted areas in the world that is affected by this type of incident. A comprehensive record of southeastern islands in Hawaii was gathered as a comma-separated values file for measuring heights of Tsunami waves at coastal locations. The database was modified and stratified for trending and descriptive analysis using a unique approach through the statistical process control (SPC) platform. Quantitative analysis of the database showed Tsunami in 1946 was the strongest one with destructive waves striking most locations. Control charts for separate and averaged Tsunami incidences showed the average wave heights, upper tidal thresholds and excursions in the wave level in the recorded locations. Some preceding points before the apparently highest waves showed warning signals of tidal drift from the mean coastal Tsunami wave level. Fast, simple and inexpensive SPC methodologies can be used as a quantitative tool in crisis risk evaluation, decision-making and resources management.

Introduction

Natural disasters are massive unstoppable destructive power of Mother Nature by which human civilization devastation occurs where destruction affects human life, properties and economy. One of the most catastrophic phenomena that affect coastal regions is Tsunami waves. Tsunami has influenced humanity since ancient civilizations such as Minoan culture, which has been swept by a huge wave of about 60 meters high due to volcanic eruption on one of the Cyclades islands in the Aegean Sea named Santorini [**1**].

While the damaging massive waves have been always known in large open seas and oceans, many records have shown also their common occurrence in closed water bodies, such as the Mediterranean Sea. In July 1958, the best-recorded and most recent tsunamigenic earthquake in the Aegean waters between Greece and Turkey occurred near the southwest shore of Amorgos Island, killing 53 persons, injuring 100 individuals and destroying many homes. The waves were particularly high on Amorgos' southern coast and on Astypalaea's northern shore. Tsunami Alarm System (2020) data showed that the tidal waves at these two places reached approximately 82 and 66 feet, respectively [**2**]. Also, in August 1999, a huge damaging seismic tremor struck northwest Turkey and created a nearby tidal wave inside the encased Sea of Marmara. It happened along the Northern Anatolian Fault zone. Its focal point was in the Gulf of Izmit. Official evaluations demonstrated that around 17000 individuals lost their lives and thousands more were harmed according to the records of Tsunami Alarm System (2020) [**3**].

In the Pacific Ocean where the bulk of those waves are generated, the history, although brief, shows tremendous destruction. In Japan which has one in every of the foremost populated coastal regions within the world and an extended history of earthquake activity; Tsunamis have destroyed entire coastal communities. There is also a history of Tsunamis destruction in Alaska, within the archipelago, and in South America [**4**].

These huge surface waves carry much momentum and a considerable amount of kinetic energy that may lift heavy objects out of its ways such as several tons of boulders and vehicles. In the current focus analysis, the unique perspective means to study these gigantic waves was by the application of quantitative statistical techniques for appropriate pattern analysis that might aid in the decision-making actions in the future - in addition to the advanced early warning system - through learning from past experiences using comprehensive previous data which could be analyzed by the application of simple and time-saving statistical process control (SPC) methodologies and tools. One of the best model examples that might be interesting is the study of the Hawaiian Islands' major recorded of Tsunamis using height level at different coastal locations as a marker for disaster monitoring.

Experimental

The descriptive-analytical study requires extensive and comprehensive data to investigate the pattern and trends of the natural disaster in a specific area. The worked case, which would be subjected to the research herein, is the Hawaiian Islands. The current approach would investigate Tsunami accidents through a unique approach to the statistical tools that were commonly used in the industrial and later in the non-industrial fields [**5-7**].

Study Area of Coastal Regions for Tsunami Accidents: Hawaiian southeastern (windward) archipelago (island group or chain) is shown in **Fig. 1** which is demonstrating the geographical locations of the heights of the waves' sensory monitoring locations with normal and cluster views [**8,9**]. It is one of the most affected regions by high waves and long-term monitoring data were comprehensively recorded with enough data to be interpreted using SPC techniques.

Source of Database of Tsunami Wave Heights and Coordinates: Data were obtained as a Comma-Separated Value (CSV) file based on the dataset of Hawaii Statewide GIS Program (2017) [**10**]. Dataset was then processed using Microsoft Excel functions for arrangement, segregation and stratification. The final modified record was subjected to further treatment using a statistical program platform. Records of five major Hawaiian Tsunami were detailed as 472-recorded points for 1946, 1952, 1957, 1960 and 1964 waves**.** However, it should be noted that some islands' location points were absent from the report for the last four Tsunamis.

Application of SPC Software on Output Excel Data: The resultant output data could be analyzed using the SPC program such as Minitab® v17.1.0. The investigational analysis would be covered by the following methodologies [**11**]:

Contour Plot [**12**]**:** Contour Plot is used in the examination of a model and needs to plot the connection between coordinates and areas of wave heights (in feet). Thus, spotting regions of high waves and patterns would be easily visualized. These types of plot shows a two-dimensional view in which focuses that have similar tidal elevations esteem are associated with produce isopleths lines shape.

Histogram [**13**]**:** A method to display a fortune of inputs from locations coordinates to show the abundance of monitoring points for each island in terms of longitude and altitude, which demonstrates the spreading and the pattern of distribution of the sensory places for wave height monitoring areas. Gap areas also would be easily reported and interpreted.

Box-And-Whisker Diagram (Boxplot or Box plot) [**14**]**:** Useful in comparison of different sets of Tsunami Tidal data and visualization of wave patterns around the island's shores with aberrant and abnormally high waves - from the normal trend of the Tsunami waves attack for each accident - are shown toward the upper side of the box indicating exceptionally high waves.

Laney-Adjusted Control Charts [**15**]**:** Control chart for local monitoring (m: abbreviation in the y-axis of the process-behavior charts) of wave heights (in feet) were used to analyze the Tsunami patterns that had stricken the shores for Hawaii Islands, in addition to the overall collective wave height trending of all five events. The use of Laney modification to correct data dispersion has been addressed previously in other studies that had applied it in the analysis of outbreak disasters [**16,17**].

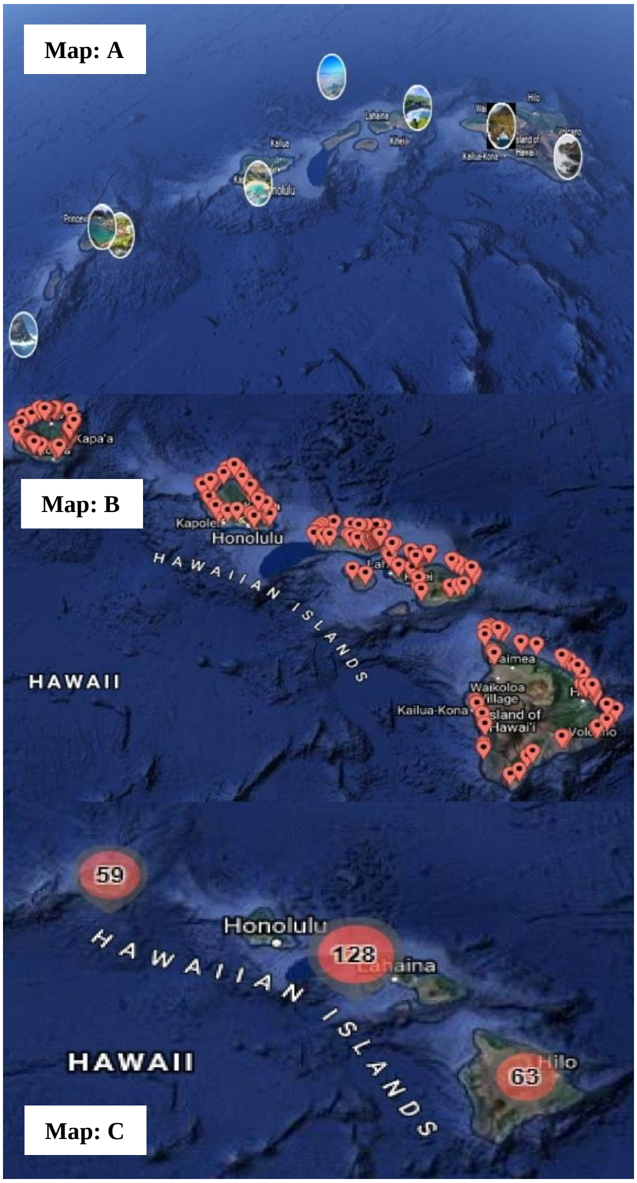

Fig. 1. (A) Maps of Hawaiian Islands: West-side view of the islands with main features of the area, (B) data view of the tidal sensory monitoring and (C) the general cluster view.

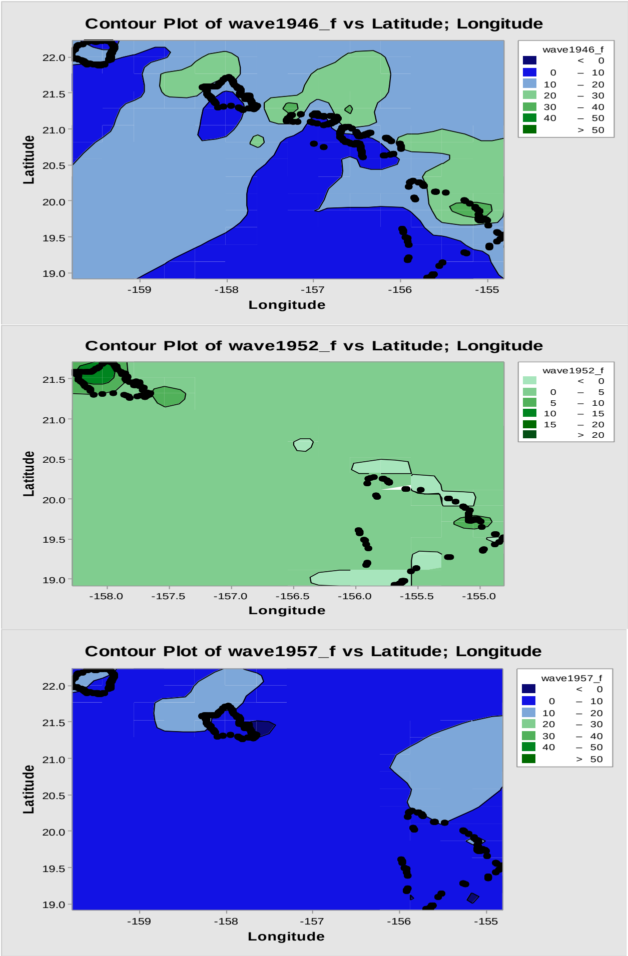

Fig. 2. Contour plots showing Tsunami wave pattern in Hawaiian region in years 1946, 1952 and 1957.

Results and discussion

SPC was used in the analysis of Hawaiian Tsunami for the southeastern (windward) islands wave strikes using available sensory data of the coastal regions that measured the heights (in feet) in the dedicated locations in **Fig. 1**. Major pacific attacks were scanned using contour plots and demonstrated in **Fig. 2** and **Fig. 3** illustrating far-field occurrence Tsunami 1946 (Aleutian-born Tsunami), 1952 (Kamchatka Tsunami), 1957 (Aleutian-born Tsunami), 1960 (Chilean Tsunami), 1964 (Alaskan Tsunami) and the average points of all monitoring locations. The Tsunami of 1975 was not reported in the current dataset and excluded from this study because it was of a local innate type that aroused from a regional earthquake [**18**]. The patterns of waves striking the islands in the graphs were directive for the location from which Tsunami attacks had arrived. However, the southeastern side was generally the most impacted area with the giant waves in The Big Island (Hawai'i). Several reports have previously recorded the great damages in this region due to damaging floods of water mass such as in Hilo [**19-21**]. However, some Tsunami waves were relatively lower in heights causing less damaging effects due to remote earthquakes with less significant impact such as those of 1952 and 1964 [**23**] and could be demonstrated in Contour plots. The middle four-island group namely Maui (The Valley Isle), Moloka'i (The Friendly Isle), Lāna'i (The Pineapple Isle) and Kaho'olawe (The Island of Kanaloa), in addition to the next island to the north viz. O'ahu (The Gathering Place) was also at hazard risk due to Alaskan Tsunamis. From Contour graphs, northwest beaches of the latest islands were usually at greatest risk from the high waves of Tsunami accidents, notably O'ahu. Nevertheless, Kaua'i Island was relatively at higher impact risk from Kamchatka Tsunami.

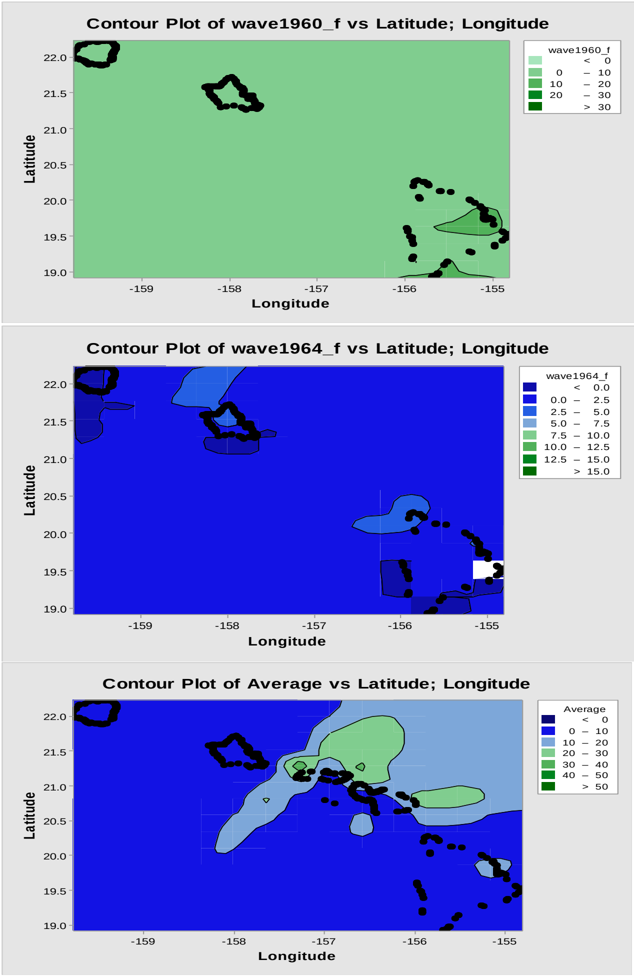

Fig. 3. Contour plots showing Tsunami wave pattern in Hawaiian region in years 1960 and 1964, in addition to the overall averages of all points.

Descriptive abundance analysis of the wave monitoring stations on the islands expressed as latitudinal and longitudinal directions histograms could be seen in **Fig. 4**. Each histogram coexists and overlaps with other distributions indicating different islander pattern of distribution for the monitoring beacons. Gaps in monitoring regions were indicated for both latitude and longitude, in addition to the clustering that is pertaining to each island. It should be noted that the four-middle islands group showed a mixed distribution pattern where they are very close to each other leading to the coordinates overlap. Moreover, the sensory distribution of each island is dependent on the coastal shape and length in addition to its relative position to the other islands. Despite the presence of the extensive wave height sensory mentoring stations, some of the points were not recording during the occurrence of some of Tsunami accidents in some places [**24**]. Complementarily, measurements of the monitored Tsunamis as Box-and-Whisker in **Fig. 5**. Wave dispersion pattern and behavior could be shown from numerical data for each catastrophe with outlier waves with abnormally high tides in comparison with the others are shown with "asterisks". Since Tsunami of 1946 was the most violent - with the whole region was impacted by the water flood as a secondary consequence of Aleutian earthquake - waves distribution was homogenous (with no outliers) but at greater magnitude, if compared with the other Tsunamis [**25**]. Tsunamis of the later years showed lower amplitude waves with few exceptionally high peaks in some locations. This graph showed another evidence for Tsunamis of 1952 and 1964 as limited incidents with low wave magnitude [**23**].

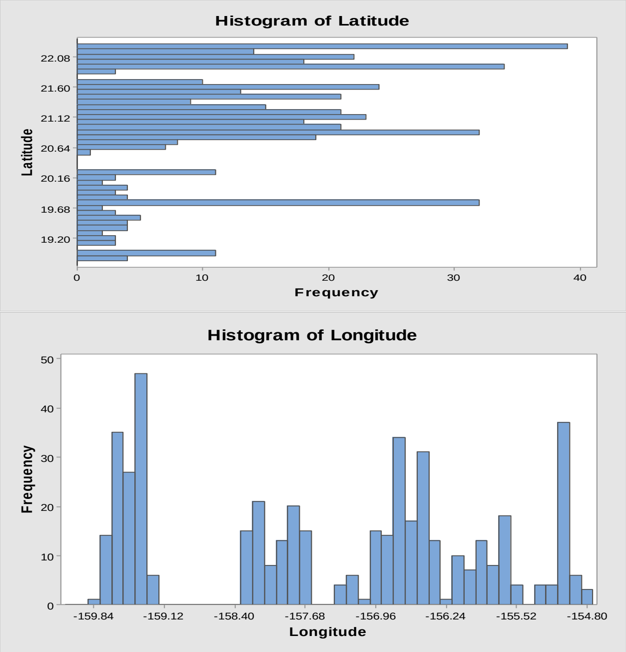

Fig. 4. Coordinates histograms showing the abundance of waves monitoring locations in Hawaiian Islands.

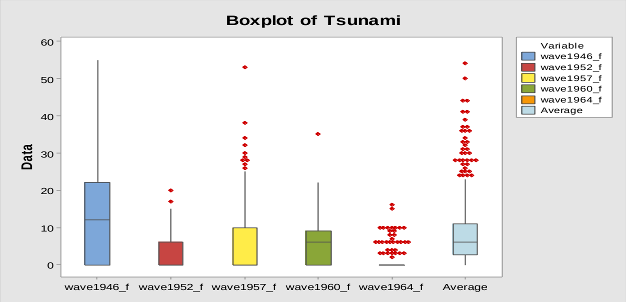

Fig. 5. Box-and-Whisker graph demonstrating tidal heights distribution pattern in Hawaiian area in each major Tsunami Catastrophe (Asterisks are indication of exceptionally outlier waves with aberrant heights).

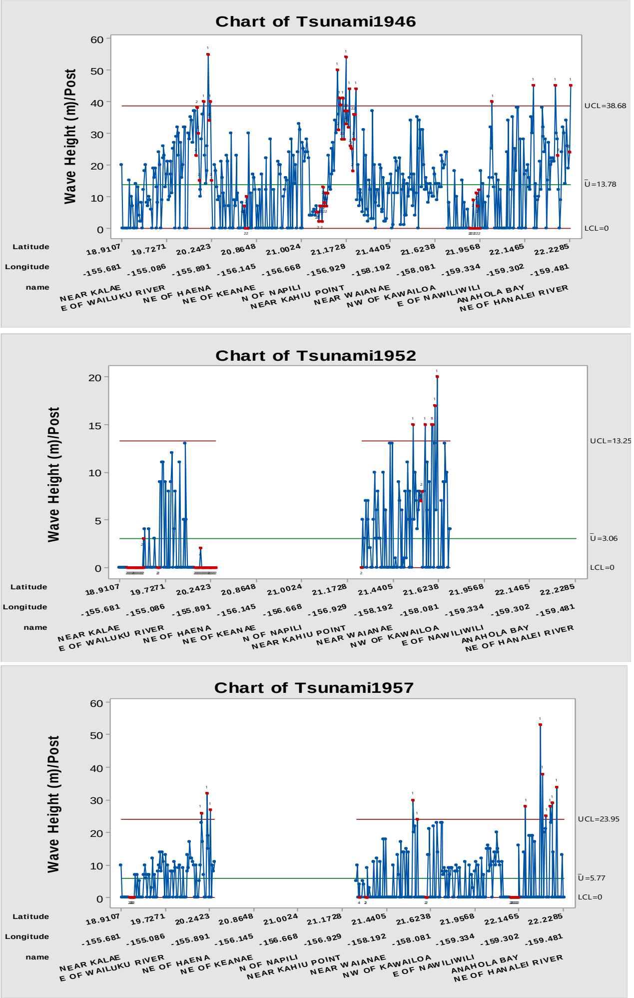

Fig. 6. Trending charts showing the wave heights of Tsunami for 1946, 1952 and 1957 disasters striking Hawaii.

The previous analysis could be useful in inter- and intra-events investigation and comparison. However, quantitative monitoring of the inspection characteristic was approached through the application of the control chart using a coordinate series order that was selected as ascending latitude with subcategory ascending longitude order. Importantly, σZ-value is an indicator for the threshold correction factor accounted for over-dispersion or under-dispersion of data that could deviate the record from the hypothetical assumed distribution of the process-behavior chart that might result in false alarms. **Fig. 6** and **Fig. 7** depict the wave coastal strikes for each Tsunami accident and the final overall trend of the five-recorded events. Since some Tsunamis did not have full records for all points, the presented charts were interrupted and appeared as discontinuation of the graph lines. Upper Control Limits (UCLs) and Lower Control Limits (LCLs) are indicators for the wave dynamicity windows were all lower thresholds are normally devolving to zero but the maximum sills are dependent on the general behavior of the waves hitting the islands. Very few waves were showing abnormal high values "denoted by 1 red dot" above the UCL line striking some locations in every

Tsunami. Alarming points in certain locations within the threshold limits are indicators for the shift, abnormal drift or fluctuation in the mean of the wave heights in a single Tsunami accident "marked by type-2 red alarm". Some of these warning signals predispose excursion waves as in Tsunami of 1946 or 1952 and partially for 1960 and 1964 but none for 1957. This observation might require further investigational study through trending charts from the other coordinates directions.

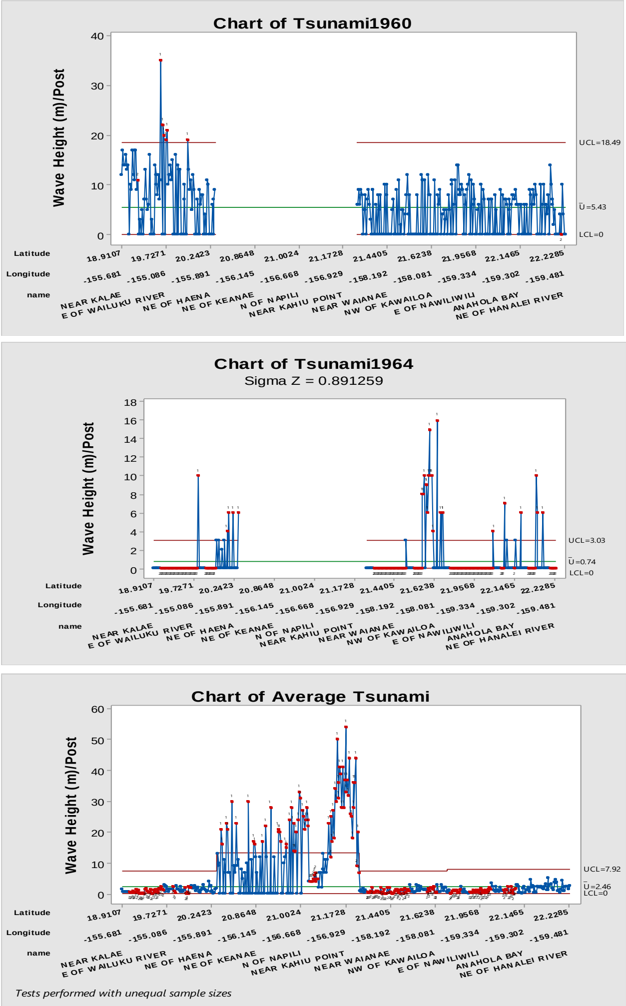

Fig. 7. Trending charts showing the wave heights of Tsunami for 1960, 1964 and the means for all five Tsunamis disasters striking Hawaii.

On the other hand, Control Limit (CL) is a measure for the average value of the wave height that also reflects the severity of each tidal attack, which agrees with the previous illustration of the box plot diagram. A quantitative measure of the tidal magnitude and hence the possible impact could be deduced from both the mean and threshold for each Tsunami for relative comparison for the severity by the product of multiplication of both. A similar approach has been adopted previously in outbreak datasets studies [**25**]. The multiplication would amplify small differences for the ease of quantitative ranking. For instance, the calculation average with wave spreading per single Tsunami incident would yield values of 533.010, 40.545, 138.192, 100.401 and 2.242 ft^2 for 1946. 1952, 1957, 1960 and 1964 events, respectively. The descending order of Tsunamis strength - based on the waves height - is Y1946 > Y1957 > Y1960 > Y1952 > Y1964. This ranking is almost in-line with what was discussed before by Pararas-Carayannis [**23**]. The final process-behavior chart in **Fig. 7** is the point average for all Tsunamis together with the mean value at about 6 feet. Taking into consideration that not all locations hold the same number of records, yield UCL in a non-linear shape as the subgroups for each area are not equal and varied with the weight of output data. The major alarming signals of high waves "red 1" are usually preceded directly or indirectly - separated by few points - by other warning alarms "no. 2" in early latitudinal locations. This area requires further investigation for addressing the value of this finding for such behavior. The study demonstrated the applicability of SPC in the decision-making and disaster monitoring, assessment and management which could be found in the same line with previous works [**26, 27**]. More advances in this field might be required to discover the full potential of this methodology in the quantitative study of natural disasters.

Conclusion

The Hawaiian Islands have been impacted by several Tsunami accidents, 60% of them headed from the Alaskan region. Thus, shores of the northeast arc of the islands group are at greater risk of the catastrophic attack than the opposite southwest side, notably Island of Hawai‘i. This would be useful in the decision-making and resources management during preventive measure establishment for the future natural disasters. The current case study provided a detailed analysis of a natural catastrophic phenomenon using industrial statistical techniques through a multidimensional perspective. SPC methodologies are useful tools in interpretation of the long record of high-waves incidents in a timely, cost-effective, simple and effective manner using commercial software packages. The current descriptive investigation would be useful for a quantitative description of not only Tsunamis in other parts of the world but also other natural catastrophic events if up-to-date databases would be available. Moreover, objective comparison between different disasters would provide unbiased metric for the assessment of the catastrophic event. It would be more convenient and accurate that future studies might include the velocity factor for each wave monitoring location to access the risk based on the kinetic energy or momentum as a measure for the aggressiveness of the tidal attack. Nevertheless, the presented statistical tools delivered unique insight into the coastal risk points. Each Tsunami event had special wave mean and threshold height numeric values. Moreover, the mean tidal chart demonstrated an interesting pattern that would require further investigation and close on-spot analysis that may derive further important outcomes from the application of the process-behavior charts.

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Conflicts of interest

There are no conflicts to declare.

Keywords

Control chart, contour plot, Hawaii, tsunami, wave height.

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Authors biography

Mostafa Essam Ahmed Mostafa Eissa is a former inspector at CAPA and a former research specialist in a national pharmaceutical company in Cairo, Egypt. In addition, he acquired a master degree in pharmaceutical sciences. He worked as microbiology, compliance and raw material section head. He published over 100 cultural and scientific articles and one book. He is currently working in several projects involving the application of the statistical process control in a non-industrial field.

Dr. Engy Refaat Rashed is an Associate Professor of Biochemistry in National Centre for Radiation Research and Technology since February 2001. She is expert in radiation biology and neurochemistry. The scientist has published nine innovative papers in well reputable international radiation biology journals. The current work includes researches in radio-protective agents.

Graphical abstract