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VALIDATION OF JOKO TINGKIR SOFTWARE USING TSUNAMI IMPORTANCE

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ABSTRACT

Joko Tingkir program, an application for tsunami early warning, has been utilised using real-time data processing at the Research and Development Centre, Indonesian Agency for Geophysics, Climatology and Meteorology since 2013. The program can also be used to analyse earthquake events before 2013. The aim of this study is thus to validate Joko Tingkir program for an improved performance of the Indonesian tsunami early warning system using the data recorded by at least 6 seismic stations managed by BMKG-Net where data collecting for each event is limited to only 3 minutes after origin time. The data were used to determine new tsunami parameters: the duration of rupture (T_{dur}), the 50 second exceed duration (T_{50Ex}), and the dominant period (T_d). Hierarchical Product Platform Realisation Method (HPPRM), which had three different phases: defining phase, modeling phase and solving phase, was used to validate the program. This study exercises records before 2014 and during 2014-2015 available at the intranet 172.19.0.13/litbang/www. For earthquakes that occurred before 2008, we make use of IRIS DMC seismic stations at http://ww.iris.edu since BMKG-Net has not yet operated. All of the data in the present study were events having magnitudes of greater than 6.5. After a conversion of quantitative data into qualitative data, the results are compared to those of tsunami importance provided by NOAA database. It was found that there is no significant differences between the results derived from the current study and the NOAA database, leading to a conclusion that the software developed is valid.

Keywords: *Joko Tingkir software, tsunami early warning, HPPRM, tsunami importance*

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1. INTRODUCTION

After a catastrophic disaster of the Indian Ocean tsunami in December 26, 2004, several countries nearby the Ocean have all committed to the development of a tsunami early warning system. In the light of this, Indonesia has developed the Indonesian Tsunami Early Warning System (Ina-TEWS) since 2008, which automatically processes the hypocentre (epicentre and depth) and magnitude of an earthquake once it occurs. If an earthquake occurs in the oceans at a depth of < 100 km and has a magnitude of > 7, the Ina-TEWS releases a tsunami early warning, suggesting that the earthquake may then generate tsunami. However, such suggestion needs to be evaluated in some cases owing to the need for rapid information of high accuracy (Madlazim, 2011). For example, false assessment of tsunami hazard alert by the Ina-TEWS was issued for 30 events during 2007-2010, where only 8 cases were correctly announced (personal communication with BMKG authority). This indicates that the study regarding improvement of Ina-TEWS performance remains challenging and important for some reasons.

The need for a rapid, correct analysis for a particular earthquake event therefore calls for validation of a method applied in use. Pedersen *et al*. (2000) asserted that validation of a research method is a vital process for developing confidence in its usefulness with respect to a specific purpose. They associate usefulness, effectiveness and efficiency of a method with whether the method provides correctly designed solutions with acceptable performance. It follows that the solutions are desired solutions with more accurate, faster, less cost and time. Hence, the validating process aims to evaluate the effectiveness and efficiency of the method based on separate qualitative and quantitative data sets or a combined set of both.

In line with the above ideas, product validation is an important step for developing theoretical and practical aspects (Daniel *et al*., 2006). They further stated that, for example, engineers who design specific products or processes usually exercise some design methods. The methods are expected to have positive impacts of all aspects of success, including performance quality, time and cost upon users. Thus, it is reasonable to seek validation procedures for design methods similar to the ones successfully applied in medical treatment, as carried out by Daniel *et al*. (2006). In other fields, such as geophysics, the associated procedures must be well-documented, objective and evidence-based.

The Faculty of Mathematics and Natural Sciences in the State University of Surabaya (Unesa) has collaborated with the Research and Development Centre (Puslitbang) of Indonesian Agency for Geophysics, Climatology and Meteorology (BMKG) to conduct research on an enhanced reliable method for better prediction of tsunami alert in areas potential to tsunami threats since 2012. The collaboration research has been performed by implementing Joko Tingkir software and combining Graphical User Interface (GUI) from Puslitbang BMKG. The enhanced method was applied for evaluating tsunami early warning using the data collected from distributed stations accessed by BMKG-Net during the first three-minute time after origin time of the likely tsunamigenic earthquake event. As reported by Masturyono *et al*. (2013), this method was well-validated using earthquake data in 2013 with magnitudes ranging from 5.0 to 7.2 and found that the software was in good agreement with the majority (96.5%) of cases considered.

To go further, the present study has made use of field records from various places in Indonesia before 2014 and during 2014-2015 with a magnitude of > 6.5 for better accuracy, relatively

compared to previous work of Masturyono *et al*. (2013). In the process, we have adopted here a simple formula used by Lomax and Michelini (2011) to define an approximate measure of the so-called tsunami importance (I_t) for earthquake events under consideration based on a maximum water height h and 0-4 descriptive indices i of tsunami effects, such as deaths, injuries, damages, and houses destroyed given by the NOAA historical tsunami database at http://www.ngdc.noaa.gov/hazard/tsu_db.shtml, where I_t is defined as $I_t = i_{height} + i_{death} + i_{injury} + i_{damage} + i_{houses\ destroyed}$ with i_{height} = 4, 3, 2, 1, 0 corresponding to values for h = 10, 3, 0.5 m, h > 0, h = 0, respectively.

According to Lomax and Michelini (2009) and Madlazim (2013), an earthquake is said to be potential to trigger a tsunami if $I_t \geq 2$. We set $I_t = 0$ for events not listed in the database and note that I_t is approximate and unstable since it depends strongly on the instrumentation, coastal bathymetry and population density in the region, where the tsunamigenic earthquake takes place. A value of $I_t \geq 2$ directly corresponds to the Japan Meteorological Agency (JMA) threshold issued for tsunami warnings while the most devastating tsunamis typically refer to $I_t \geq 10$ (Lomax and Michelini, 2009).

The purpose of the current study is to evaluate and hence validate Joko Tingkir software as an 'additional tool' to the existing system for an improved tsunami early warning using tsunami importance. The software monitors and records real-time data, off-line *P*-wave rupture duration (T_{dur}), dominant period (T_d), and rupture duration longer than 50 s (T_{50Ex}) for large earthquakes in Indonesia with magnitudes > 6.5, observed as the vertical component of waveforms by seismometer. The validating proces is thus aimed to test whether the software developed is valid for use.

2. METHODS

As previously outlined, the methods used in this research are separated into two parts. The first method, the so-called Hierarchical Product Platform Realisation Method (HPPRM), suggested by Pedersen *et al*. (2000), having three independent different phases, that is, defining phase, modeling phase and solving phase. This method directly corresponds to validating processes of the Joko Tingkir software in use. Summarised processes in each phase are as follows. In the first phase, data were collected and processed; then in the second phase, the processed data were compared to a reference value provided by NOAA tsunami database; in the final step, well-suited problems were solved using correct decision making.

Here we provide a more detailed process in each phase. The first phase served as 'numerical taxonomy' where inputs were associated with the data collected within framework of standarised procedures by means of data gathering and/or data clustering. This step refers to an objective selection whereas data interpreting is more based on subjective judgements. The second phase, also known as 'technology diffusion', was named after considering alternative techniques according to their benefits to the existing technology. The use of discounting factor to leave factors irrelevant to the problem in this phase is objective while decisions regarding learning rates and leverage potentials are based on subjective judgements. The third phase is more about to compromise a 'decision support problem', which was used to enable model designers to achieve

their goals effectively and efficiently with respect to better operational performance, lesser operational time and operational cost. In this final phase, compromised solutions regarding the problem in question are considered objective whereas decisions based on scenarios are regarded as subjective ones.

Thus, the HPPRM is a method of validation containing logic and systematic procedures that are merely based on determination of whether the associated procedure in each step of validation processes is objective. In its performance, the validation method here is not meant to replace the existing tsunami early warning system, *i.e.*, the Ina-TEWS with a new warning system. Instead, the alternative system developed by implementing Joko Tingkir software can better influence on the Ina-TEWS, leading to an improved performance of the new tsunami early warning system.

The second method in this research directly corresponds to ways of determining enhanced tsunami prediction using Joko Tingkir software. Madlazim and Hariyono (2014) developed Joko Tingkir application to examine parameters relevant to or being indicators of an oceanic earthquake generating a tsunami. The parameters are the rupture duration (T_{dur}) and the dominant period (T_d), associated with the 'length' and 'width' of rupture zone, respectively, the exceed duration (T_{50Ex}), and the corresponding products of the three, that is, $T_{dur} \times T_d$ and $T_{50Ex} \times T_d$. Note that T_{50Ex} is referred to here as a better estimate of the 'length' of rupture zone than T_{dur}. Lomax and Michelini (2011) stated that $T_{dur} \times T_d$ and $T_{50Ex} \times T_d$ can be associated with the 'cross-sectional areas' of the rupture zone, which is proportional to the strength of the earthquake source.

The followings are flowchart of the software for calculations of new tsunami parameters: (1) readings of vertical component of *P*-wave velocity (as it gives a smaller noise relatively compared to other velocity components); (2) *P*-wave onset picking; (3) 5-20 Hz bandpass filtering; (4) determination of T_{dur}, T_d, T_{50Ex}, $T_{dur} \times T_d$ and $T_{50Ex} \times T_d$; (5) tsunami criteria testing. Design implementation of the software in relation to Ina-TEWS is shown in Figure 1.

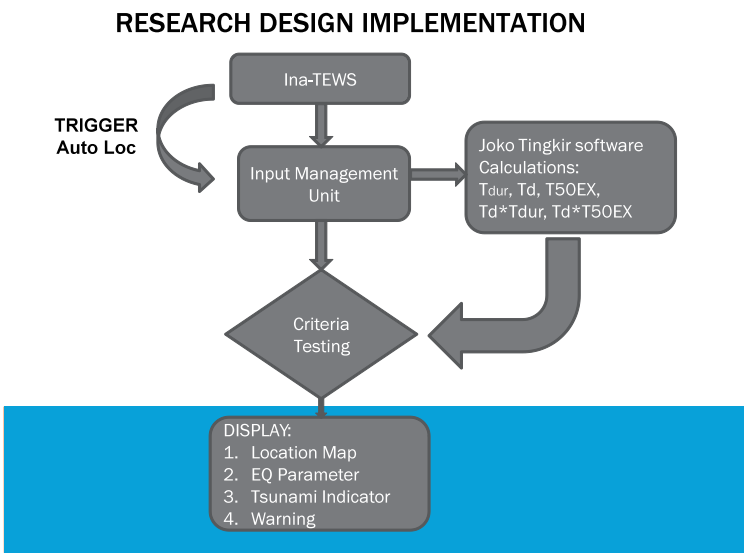

Figure 1. Design implementation of Joko Tingkir software (taken from Masturyono *et al*., 2013).

3. DATA

The data in this study were obtained from records comprising 32 events before 2014 and in 2014-2015 around the country and were provided by the intranet 172.19.0.13/litbang/www for real-time data processing. These events were monitored by grouped seismic stations that are managed by BMKG-Net covering large areas of the Indonesian archipelago, as shown in Figure 2. In addition, we also accessed IRIS DMC seismic stations at http://ww.iris.edu to further analyse 10 events before 2008 for off-line data processing, owing to the lack of real-time data at times when BMKG-Net has not yet existed in the country. All the events taken as the data have magnitudes of greater than 6.5 as these events are likely to generate tsunamis.

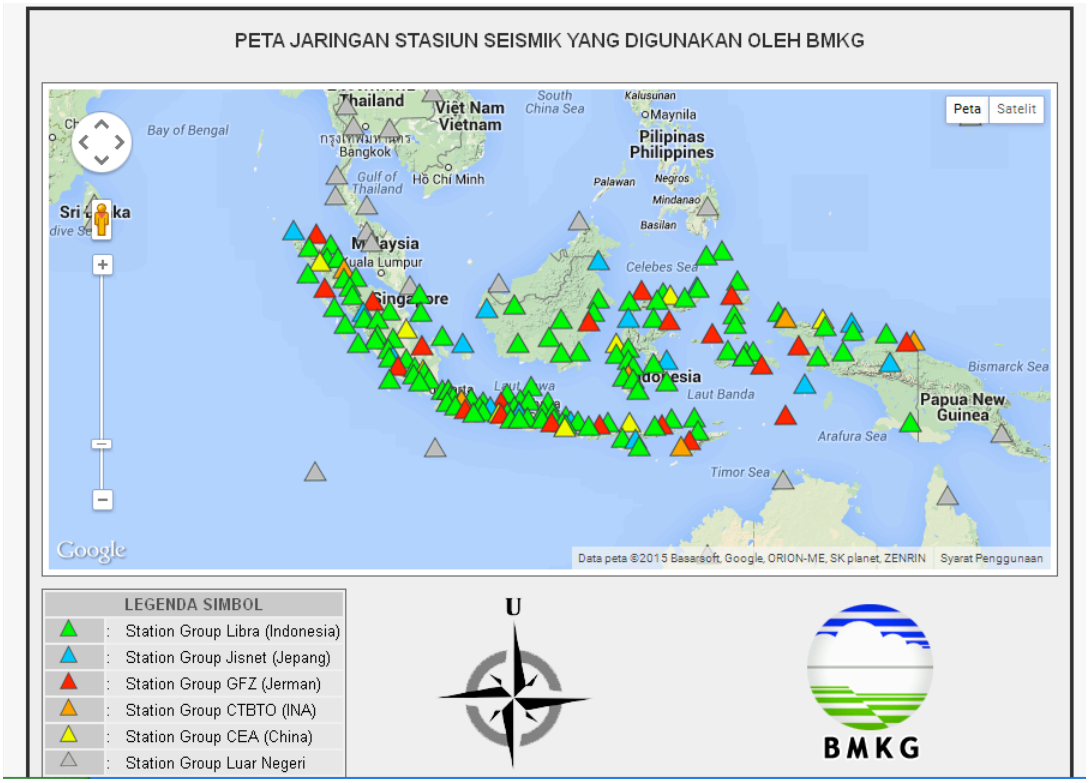

Figure 2. Seismic stations across large areas in Indonesia run by several countries and managed by BMKG-Net (taken from https://inatews.bmkg.go.id/new/meta_eq.php with permission from the Puslitbang BMKG authority for use of this study).

Along with the existing system, the data provided by the new tsunami warning system consist of geographical location where the event occurs, date and corresponding origin time, epicenter, depth of the earthquake source, map of the epicenter, magnitude of the earthquake, and relatively new tsunami parameters known as five discriminants: rupture duration T_{dur}, dominant period T_d, exceed duration T_{50Ex}, $T_{dur} \times T_d$ and $T_{50Ex} \times T_d$. After rapid assessment, these give directly a set of both observed and threshold values of the new tsunami parameters, from which status is given and therefore a corresponding decision for tsunami hazard alert is or is not officially declared. We here provide one case study for an example seen in Figure 3, describing how the tsunami application works.

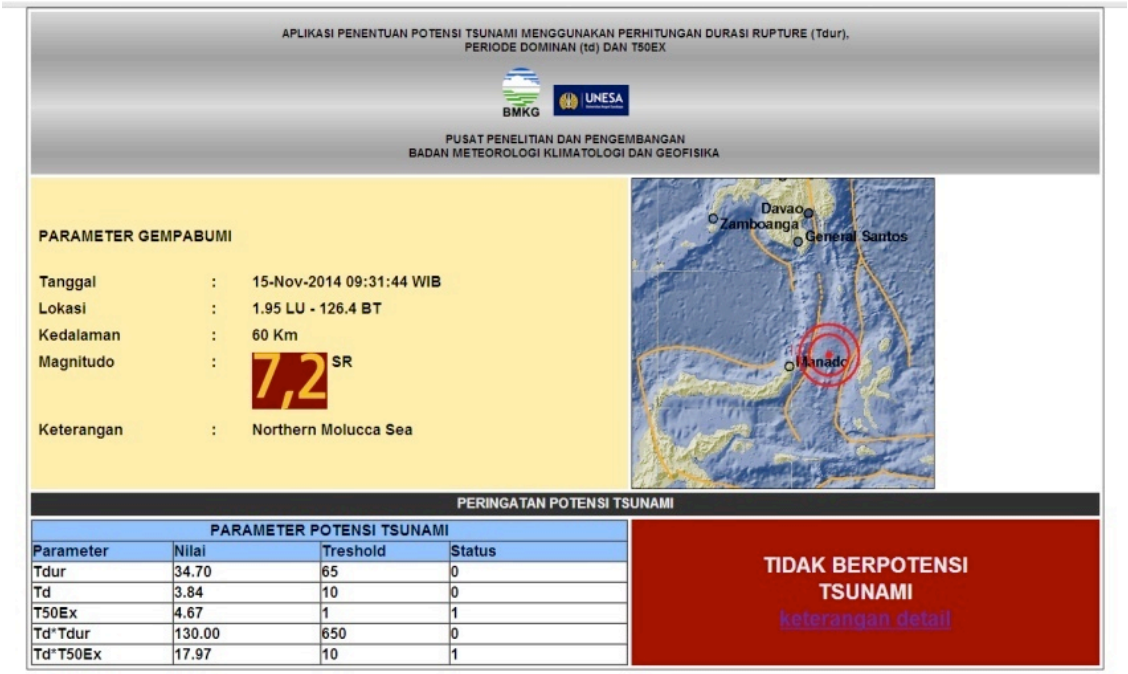

Figure 3. Performance of Joko Tingkir application as a new tsunami early warning system (Puslitbang BMKG, 2015). For a particular event, three of five discriminants having values less than corresponding thresholds, indicating that the earthquake was not a tsunamigenic event (taken from the intranet 172.19.0.13/litbang/www with permission from the Puslitbang BMKG authority for use of this study).

4. RESULTS AND DISCUSSION

Following Madlazim (2011; 2013), rapid determination of tsunami assessment using five discriminant parameters was performed using Joko Tingkir software. A set of tsunami criteria were thus as follows: $T_{dur} \geq 65$ s, $T_d \geq 10$ s, $T_{50Ex} \geq 1$ s, $T_{dur} \times T_d \geq 650$ s^2 and $T_{50Ex} \times T_d \geq 10$ s^2. When at least three parameters of the five discriminants were equal to or greater than relevant critical values or thresholds for tsunami to occur, the application would provide important complementary information for early assessment of earthquake tsunami potential. This is very important for hazard mitigation to minimise disaster risks due to the lack of reliable, rapid and accurate analyses.

As the dominant period T_d can be quickly obtained for less than a minute after the first arrival of consecutive *P*-waves, it was still possible to examine T_{dur} rapidly for an earthquake. Following the procedures of Lomax and Michelini (2009), we determined T_{dur} for an event, which was likely to exceed 50-55 s derived from a high frequency analysis of vertical component of the velocity provided by broadband seismograms. On the 5-20 Hz bandpass filtered for a set of regional seismograms, we calculated the ratio of the root-mean-square amplitudes for 50 - 60 s after the *P*-wave arrival to the root-mean-square amplitudes for the first 25 s after the *P*-wave arrival to obtain a station duration exceed level for 50-55 s. Based on these facts and previous work (Madlazim, 2011; 2013) with large earthquake data sets, we estimated that field observations from 6-15 seismic stations were needed to obtain reliable, stable valus for T_{dur}, T_{50Ex} and T_d.

Table 1 below describes the numerical results of real-time data processing for 32 events before 2014 and in 2014-2015 (available from BMKG-Net database) and the results of off-line data assessing for 10 events before 2008 (using IRIS DMC seismic stations) considered. As earlier mentioned, the data collecting was limited by the Joko Tingkir during the first three-minutes, after which an additional time of at least one minute was required for data analysing. Thus, the availability of the five period-duration tsunami discriminants (shown in the second column in Table 1) is at 4 minutes after origin time (OT). This method of rapid data assessment is approximately a minute quicker than that of using earthquake magnitudes. According to Madlazim (2011; 2013), from the five tsunami discriminants listed here: T_{dur}, T_d, T_{50Ex}, $T_{50Ex} \times T_d$ and $T_{dur} \times T_d$, three of these discriminants along with $T_{50Ex} \times T_d$ taken as the tsunami parameter discussed in Lomax and Michelini (2011) to better accurate prediction of tsunami alert than $T_{dur} \times T_d$ as the parameter used by Lomax and Michelini (2009) were observed to correctly identify 92%, 92% and 77% of the likely tsunamigenic earthquakes with $I_t \geq 2$, respectively, as tsunamis.

Table 1. Validation of the new tsunami early warning system for real-time and off-line data processing using tsunami importance (I_t).

Discriminant	Available after OT (minutes)	Critical value	Correctly identified[a]			Missed $I_t \geq 2$	False $I_t < 2$
			$I_t \geq 2$	Per cent[b]	$I_t < 2$		
magnitude	5+	M ≥ 7	9	69	19	0	14
three of five period-duration discriminants (Madlazim, 2011, 2013)	4	$T_{dur} \geq 65$ s $T_d \geq 10$ s $T_{50Ex} \geq 1$ s $T_{50Ex}\ T_d \geq 10$ s^2 $T_{dur}\ T_d \geq 650$ s^2	12	92	28	0	2
$T_{50Ex}\ T_d$ (LM-11)	4	10	12	92	28	0	2
$T_{dur}\ T_d$ (LM-09)	4	650	10	77	26	3	3

Note: [a] 13 of 42 events classified tsunamigenic; [b] the percentage of correctly identified events with $I_t \geq 2$. LM-09 refers to Lomax and Michelini (2009); LM-11 refers to Lomax and Michelini (2011).

Table 1 also describes missed cases and false warnings for all the data used in this study, consecutively given in the last two columns. Missed cases were those in the assessment that cannot be processed due to many noises disturbed. False warnings could be adequately large earthquakes with magnitudes of greater than 6.5 and were issued as tsunamis but they in fact did not exist or events having relatively small magnitudes and thus were not declared as danger but generating tsunamis.

Using three of the five tsunami parameters, no missed cases with $I_t \geq 2$ were reported by Madlazim (2011; 2013), as well as using the product of $T_{50Ex} \times T_d$ for the same cases found by Lomax and Michelini (2011), including an oceanic strike-slip earthquake with $I_t = 6$ and $M_w = 7.5$ of the Sulawesi May 4, 2000 event (shown in the first row in Table 1). In contrast, three cases

were observed by Lomax and Michelini (2009) but with only a 77% reliability of identification (shown in the last row in Table 1).

A total of 21 (14+2+2+3) cases in the last column were announced as false warnings or tsunamigenic events, where most of these cases have $I_t = 1$ and hence producing only small tsunamis. The large uncertainty in a 14 false-warning case using earthquake magnitudes as a discriminant indicates that this method is unreliable to predict whether a tsunami is generated. This is also supported by the percentage (less than 70%) of all events correctly issued for tsunamis using the magnitude method. For all the data, a total of 13 earthquakes (containing 13 of 32 cases before 2014 and in 2014-2015 and a zero record of 10 events before 2008) were then classified as tsunamigenic events as they go with $I_t \geq 2$. The detailed results of numerical calculation of the parameters are given below.

As demonstrated in Table 1, calculations of tsunamigenic-potential earthquakes based on the new five discriminants do not require accurate knowledge of either earthquake location or magnitude for most of all events. The overall performance of the discriminants is marginally better than that of the magnitude parameter having 69% of cases correctly identified, where field data with magnitudes of equal to or greater than 7 for the magnitude discriminant were used by the Ina-TEWS (but with no Joko Tingkir software inserted into the existing system).

The results also capture another feature of the nature of calculations using the new tsunami parameters. The period-duration discriminants gave mixed results to identify tsunami potential of oceanic, inter-plate thrust and strike-slip events. Some of these events may be falsely identified as tsunamigenic (when they are high magnitudes or long rupture durations) since tsunami excitation for vertical, strike-slip faults is very low, relatively compared to other faulting types (*e.g.*, Kajiura, 1981). In contrast, other oceanic, inter-plate thrust and strike-slip events may be missed as tsunamigenic (*i.e.*, when they have moderate magnitudes or rupture durations) because tsunami excitation in these cases can be augmented by the horizontal displacement of ocean floor topography (Tanioka and Satake 1996), an effect somewhat independent of the source size, measured as length, width, and displacement (*LWD*) and thus is not well-quantified by any of all the discriminants. The results for all cases presented in this study demonstrate that with a large certainty in the numerical calculations (more than ninety per cents of reliability in calculation) three of the new five discriminants together with a $T_{50Ex} \times T_d$ parameter can identify tsunami generation at seas better than both $T_{dur} \times T_d$ and T_{dur} parameters. A plausible reason of this fact is that determination of T_{dur} is not adequately accurate for local events (Lomax and Michelini, 2009).

5. CONCLUSIONS

Joko Tingkir software as a new tool for a rapid analysis of tsunami hazard assessment has been implemented using real-time and off-line data flow within the Ina-TEWS Network for validation purposes. The validating process shows that 92 % of total 42 events comprising 32 events (before 2014 and during 2014-2015) and 10 events (before 2008) with magnitudes greater than 6.5 tested are consistent with a set of tsunamigenic criteria derived for HPPRM validation method. The criteria are $T_{dur} \geq 65$ s, $T_d \geq 10$ s, $T_{50Ex} \geq 1$ s, $T_{dur} \times T_d \geq 650$ s^2 and $T_{50Ex} \times T_d \geq 10$ s^2 for oceanic earthquakes generating tsunamis. Relatively compared to tsunami importance I_t, no

significant differences are found between the current results derived from the software and those obtained from the NOAA database. These findings bring into a simple conclusion that the Joko Tingkir is firmly valid for use.

The total time required for all assessment processes begining from data collection up to data processess takes about 4 minutes, directly measured from the origin time of a particular earthquake. This is made possible by the Trigger – an effective instructional syntax used in the program – that analyses system automatic location to work on determining the depth and epicentre, or equally like, the hypocentre, of the eartquake source and at the same time calculating all the new five tsunami discriminants. Therefore, the method of validation and the method of rapid, accurate assessment of tsunami hazard proposed in the present study are valid and worth to put into effect in the fields.

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