Nowcasting Earthquakes in Sulawesi Island, Indonesia

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ABSTRACT

Large devastating events such as earthquakes often display frequency-magnitude statistics that exhibit power-law distribution. In this study, we implement a new method of nowcasting (Rundle et al. 2016) to evaluate the current state of earthquake hazards in the seismic prone Sulawesi province, Indonesia. The nowcasting technique considers statistical behavior of small event counts, known as natural times, to infer the seismic progression of large earthquake cycles in a defined region. To develop natural time statistics in the Sulawesi Island, we employ four probability models, namely exponential, exponentiated exponential, gamma, and Weibull distribution. Statistical inference of natural times reveals that (i) exponential distribution has the best representation to the observed data; (ii) estimated nowcast scores (%) corresponding to M≥6.5 events for 21 cities are Bau-bau (41), Bitung (70), Bone (44), Buton (39), Donggala (63), Gorontalo (49), Kendari (27), Kolaka (30), Luwuk (56), Makassar (52), Mamuju (58), Manado (70), Morowali (37), Palopo (34), Palu (62), Pare-pare (82), Polewali (61), Poso (42), Taliabu (55), Toli-toli (58), and Watampone (55); and (iii) the results are broadly consistent to the changes of magnitude threshold and area of local regions. Therefore, the present nowcasting analysis, similar to the traditional earthquake hazard assessment techniques, offers a simple yet versatile metric to the scientists, engineers and policymakers to examine the current state of earthquake hazards in the thickly populated Sulawesi Island.

Keywords: Natural times, nowcast scores, Sulawesi Island, probability models.

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1.0 INTRODUCTION

Sulawesi is one of the four Greater Sunda Islands in Indonesia which has a prolonged seismic activity. Earthquake sources in these regions come from tectonic processes on land and sea, fault systems in the middle, and subduction zone in the north (Cardwell et al., 1980; Mc Caffrey & Sutardjo 1982, Mc Caffrey, 1982; Silver et al., 1983; Walpersdorf et al., 1998; Stevens et al., 1999; Gomez et al., 2000; Hall, 2009). Many destructive events in the Sulawesi province have occurred in the vicinity of the major cities that often knit together to form a global hub of economic and industrial activity (Cipta et al., 2017). In recent years, the entire island has observed a rapid growth of urban population and infrastructure development as an outflow of worldwide economic empowerment and industrial revolution. However, the fear of large damaging earthquakes looms over the Sulawesi region which is surrounded by a network of active fault lines and has many seismic non-resistant traditional structures (Widiyanto et al., 2019; Omira et al., 2019).

The seismicity in the Sulawesi area is so high that it has experienced 25 major earthquakes \( (M_w \geq 7.0) \) during a span of about 50 years (1969–2020). The latest of them is the 28\(^{th}\) September 2018 \( M_w 7.5 \) “supershear” Sulawesi earthquake occurring in the northern part of the Palu-Koro fault that has not been well studied before (Bao et al., 2019). This earthquake was categorized as one of the deadliest earthquakes in 2018 as it was accompanied by an unusual tsunami generated either by an earthquake-induced movement in extremely fast rupture on a straight tilted fault within the bay or by a rock fall move down to the sea (Ulrich et al., 2019). Liquefaction was observed in the Palu city which sits at the end of the bay surrounded by a river delta (Bradley et al., 2019). Similar to the September 2018 Sulawesi earthquake, other disastrous events may also occur along the less studied geological faults that pass through the major cities (Cipta et al., 2017). Therefore, it is imperative to evaluate the current level of seismic hazards for all populous cities in the Sulawesi province for a nationwide disaster preparation and mitigation. In light of this, the present study develops a statistical, data-driven nowcasting approach (viz. Rundle et al., 2016) to estimate the contemporary state of earthquake progression in several regions of the Sulawesi Island.

The nowcasting method in seismology has evolved from the understanding that in a dynamic, non-linear, power-law behaved earthquake system (similar to typhoons, landslides, market economy crashes), the distribution of events can be broadly aligned in a frequency-magnitude spectrum where the large magnitude events are usually preceded by several smaller events (Rundle et al., 2016, 2018, 2019a, 2019b). This method has found significant applications in economics (e.g., growth nowcast, inflation nowcast, market-stress nowcast), meteorology (e.g., thunderstorm nowcast), and political sciences (e.g., electoral campaign nowcast) where the interest is to assess the uncertain current state in view of the data of immediate past, present, or very near future. The nowcasting technique in seismology utilizes the key idea of natural times (e.g., Varostos et al., 2011), the interevent small earthquake counts braced by successive large
earthquakes in a specified region, rather than the usual calendar or clock times to elucidate the present state of earthquake system through earthquake cycle. It is built upon the assumption that the underlying seismicity statistics in local regions is embedded in a homogeneous larger region from which the seismicity statistics will be developed. This assumption seems reasonable in light of the ergodic dynamics in the statistical physics of seismicity, in which the statistics of smaller regions over longer times are considered to be similar to the statistics of broader regions over large spatial domains and longer periods (Tianpo et al., 2003; Holliday et al., 2016). Under this set up, the nowcasting method describes the seismic progression of a region in terms of earthquake potential score (EPS) measured through the cumulative probability for the current event counts (Rundle et al., 2016, 2018; Pasari, 2019). The method has been successfully applied to several seismogenic cities such as Ankara, Dhaka, Islamabad, Kolkata, Lima, Manila, New Delhi, Taipei, Tokyo, Los Angeles and San Francisco (Rundle et al., 2016; Pasari, 2019; Pasari & Sharma, 2020).

The method of earthquake nowcasting is conceptually different from earthquake forecasting which looks ahead in time. Nowcasting technique, unlike forecasting, is applicable for a dataset involving dependent as well as independent events (Rundle et al., 2016). Nowcasting enables a systematic ranking of cities as to their current exposure to the earthquake hazard, whereas forecasting deals with several probability measures for long-term planning and preparation (Rundle et al., 2016, 2018). The nowcasting method provides a fast and sophisticated alternative means to understand the current state of progress of a regional fault system, which is otherwise traditionally determined from direct or indirect, physical or remote observation of a tectonic stress regime (Scholz, 2019).

2.0 STUDY AREA AND EARTHQUAKE DATA

2.1 Geology and Tectonics

Split by the equator, the study area encompasses a quadrangle bounded by the geographical limits 115°–130° E and 10° S–5° N (Fig. 1). Due to the inherent setting from the ongoing trio-convergence between the north moving Australian plate, south-southeast moving Eurasia plate and the west moving Pacific plate, the Sulawesi island and its contiguous areas exhibit an exceedingly complex seismotectonic pattern (Silver et al. 1983a, b). The tectonic process, mainly the drifted collision of the triple plates, started since the Mesozoic era when it experienced a spreading exposure in the northwestern part of several microcontinent fragments derived from the Australian continent (Audy-Charles et al., 1988). The relentless tectonic process in a number of episodes eventually constitutes a triple junction – a unique, unusual K-shape of the Sulawesi island with four characteristic arms (Monnier et al., 1995, Katili, 1978). The convergence zone of this tri-junction accommodates a composite domain of accretionary complexes, micro-continental fragments, melange terrains, island arcs and ophiolites (Hall, 2012). The stratigraphic development of Sulawesi is
mainly controlled by the successive accretion from the east of oceanic and microcontinental material (Wilson et al., 2000, Bosence & Wilson, 2003). As a consequence, the K-shaped Sulawesi Island is considered to be a response to the post-collision rotation of the curvatures of four arms originally being convex to being concave (Monnier et al., 1995).

**Figure 1.** Topography of the Sulawesi island including the tectonics and major cities

Sitting in the central part of Indonesia archipelago, Sulawesi Island is one of the most enigmatic areas with its geological formation, process and structure (Silver et al. 1983a, b; Monier et al., 1995; Wakita et al., 1996; Villeneuve et al., 2002; Hall, 1996, 1998, 2002, 2009). Under the influence of Australia-Phillipine plate convergence, the Sulawesi domain persistently collides with the Eurasian plate. The tectonic collision is accommodated by subduction at the north Sulawesi trench and by the motions along the Palu–Koro and Matano faults at the southwestern and southern domains (Walpersdrof et al., 1998; Socquet et al., 2006; Bellier et al., 2006). One of them forms the southern margin of the Celebes Sea (Walpersdorf et al., 1998). Associated with the tectonic collisions, there was development of NNW-SSE trending Palu-Koro left-lateral transcurrent fault, along which the part of eastern Sulawesi has moved northwards with regard to western Sulawesi. Opening of pull-apart basins, such as lakes of Poso, Matano and Towuti, Palu depression and other tectonic features are evident as a result of recent transtensional movements during the Quaternary period continuing to the present time. Several disastrous events along the Palu-Koro and nearby major faults reveal that the system is probably active (Hall, 2009).

Tectonically, Sulawesi Island, due to enormous external pressure, deforms continuously. Such pressure comes from the Flores Sea in the southern part and activates Palu-Koro, Walanae and Banggai-Sula fault (Jaya & Nishikawa, 2013). External pressure from Banda Sea in the eastern to central part activates Matano, Batui, Lawanoppo and Kolaka fault, whereas the pressure from Sulawesi Sea in the northen part activates North Sulawesi subduction and Gorontalo fault. Pressure from North Maluku subduction plate from northeast often cause large earthquakes and volcanoes in North Sulawesi area. These ongoing tectonic phenomena in the Sulawesi island produces four major transcurrent faults, namely the Sorong-Matano fault, Palu-Koro fault, Walanae sinistral fault, and the Gorontalo dextral fault (Watkinson et al., 2011, 2017). The pathways of these active faults exhibit high earthquake and tsunami potential in the study region.

Several earthquakes located in the sea floor have tsunami potential. The extent of the tsunami size is often influenced by steep subsurface topography of the seabed and coast (Hamzah et al., 2000). Both southern and northern Sulawesi have witnessed disastrous tsunamis (Baeda, 2011). In southern part, stretched from Majene to Mamuju or from Palu to Toli-toli, tsunamis occur due to earthquakes in the intersection of Paternoster fault and Makassar Strait normal fault or in the intersection of Palu-Koro fault.
and Makassar Strait fault. In the northern part, tsunamis occur in Gorontalo, Luwuk-Banggai and Kendari-Wawoni-Buton areas due to events located in the intersections of Gorontalo fault and North Sulawesi subduction, Gorontalo fault and North Maluku subduction, and Lawanoppo fault and Wawoni thrust (Watkinson et al., 2011, 2017). Areas that have been hit by tsunami since 1967 are Majene-Pinrang in 1967, Palu in 1968 and 2018, Mamuju in 1969, Donggala in 1996, Toli-toli in 2000 and Luwuk-Banggai in 1999 and 2000. Exploring the nowcasting technique, which provides a way to determine the current progress of an earthquake cycle in a fault system thus appears to be interesting to indirectly assess earthquake/tsunami hazards in the Sulawesi Island (Rundle et al., 2016).

2.2 Earthquake data
To develop nowcasting technique, we prepare a uniform earthquake catalog (1963 – 2020) of instrumental data from the compilation of global and regional catalogs, such as the International Seismological Centre (ISC) catalog (http://www.isc.ac.uk/iscbulletin/search/catalogue/), Advanced National Seismic System (ANSS) comprehensive catalog (http://www.ncedc.org/anss/catalog-search.html) and the Meteorological Geophysical Agency of Indonesia (BMKG) catalog. As the BMKG network comprising 162 broadband seismometers is locally maintained, recent events are easily accessible from this catalog (Fig. 2).

Figure 2. Pictorial summary of earthquake data (1969-2020) that are used for the present nowcasting analysis; subplots highlight several characteristics of the catalog.

In the analysis, we consider magnitude 4.5 as the threshold of small earthquake events (also, the magnitude completeness threshold) and 200 km as the threshold of maximum focal depth, since deep-seated oceanic earthquakes often exhibit weaker signal and are generally less damaging (Rundle et al., 2016; Pasari, 2019). During January 01, 1969 to November 21, 2020, a total of 17082 events \((4.5 \leq M \leq 7.9)\) have occurred in the study region providing 87 earthquake cycles of \(M \geq 6.5\) events. The associated earthquake interevent counts (natural times) will be used to develop the natural time statistics. Recall that nowcasting analysis via natural time statistics does not require declustering of dependent events, such as foreshocks and aftershocks (Rundle et al., 2016).

3.0 PROCEDURE AND RESULTS
Nowcasting method comprises three major steps in succession: tabulation of natural times (interevent counts between large events), performing statistical inference, and computation of earthquake potential score (nowcast scores). While tabulation of natural time essentially requires the description of “large” and “small” events in a specified homogenous region, the statistical inference involves probability model
description, parameter estimation and model performance analysis. Knowing the data-derived seismicity statistics of natural times, we use cumulative distribution function (CDF) of the best-fit probability distribution to calculate earthquake potential score (EPS) for a number of selected cities. These EPS scores will serve as “thermometer” readings to the scientists and decision-makers to estimate the progress of a city through its repetitive cycle of major earthquakes.

Let \( A \) be the geographical area of a broad seismically-active region and \( A_1, A_2, A_3, \ldots, A_n \) be the geographical areas of the \( n \) number of selected cities in a way that \( A_1 \subset A, A_2 \subset A, A_3 \subset A, \ldots, A_n \subset A \). Also, let \( M_a \) and \( M_A \) respectively denote the magnitude of the small and large earthquake events in a sense that “large” events have the potential to cause human death or notable destruction to society. The value of \( M_a \) is usually guided by the data-completeness threshold in the frequency-magnitude relationship (Scholz 1990; Rundle et al., 2016), whereas the value of \( M_A \) is decided based on the extent of damages in a city. Once \( M_a \) and \( M_A \) are decided, we define natural time (say, \( X \)) as the interspersed small event counts between two successive large events. It is obvious that natural time (\( X \)) exhibits randomness.

For the present study with 1969–2020 catalog, we consider \( M_a = 4.5 \) and \( M_A = 6.5 \). This yields a random sample of natural times \( \{X_1, X_2, \ldots, X_{87}\} \) to infer underlying seismicity statistics in the Sulawesi region. While the sample range of interevent counts varies from 1 to 1034, other descriptive statistics such as mean, median, standard deviation and skewness turn out to be 192, 145, 189 and 2, respectively. Thus, the observed dataset reveals asymmetry with a skew towards right, having sample mean higher than sample median.

The nowcasting approach or the natural time statistics is independent to the background seismicity rate \( (a) \) as long as the Gutenberg–Richter \( b \)-value (slope in frequency-magnitude relation) is close to a constant. To illustrate, let the cumulative number of small earthquake counts be \( N_a \left(=10^{a-bM_a}\right) \) and cumulative number of large event counts be \( N_A \left(=10^{a-bM_A}\right) \). Then, using the Gutenberg-Richter law, it is found that \( N_a = 10^{(M_A-M_a)N_A} N_A \). The number of small earthquakes, \( N \), that occur between two large earthquakes can then be obtained by setting \( N_A = 1 \) (Luginbuhl et al., 2018b). Thus, \( N = 10^{(M_M-M_a)} \). As a consequence, \( N \) is independent to the background seismicity rate \( (a) \) and it scales exponentially with the difference of magnitudes \( M_A \) and \( M_a \) (Rundle et al., 2016). Furthermore, with the assumption that \( b \)-value remains constant in time and space, the natural time (\( N \)) scales exponentially to the actual magnitude (say, \( M \geq M_A \)) of large earthquakes, as the “small” magnitude threshold is always kept fixed (say, \( M_a = 4.5 \)).
For example, in the present study with $b = 1.23$ and $M_a = 4.5$, we get $N(M) = 10^{1.23(M-4.5)}$, where $M \geq M_a$.

Moreover, as the actual magnitude of large earthquake varies from even to event, the natural time count varies for each earthquake cycle. As a consequence, it is reasonable to consider exponential distribution and its primary variants gamma, Weibull, and exponentiated exponential in developing the data-derived cumulative distribution function (CDF) and associated earthquake potential score (EPS) computation.

These time-dependent, time-independent, and exponentiated class of probability distributions (see Table 1) have noteworthy applications in statistical seismology (e.g., Pasari & Dikshit, 2014, 2015; Pasari, 2019). For estimating model parameters, we use the method of maximum likelihood that involves maximizing a likelihood function for a given data. After parameter estimation, the performance of the studied distributions is analyzed on the basis of two popular goodness-of-fit measures: Akaike information criterion (AIC) value and Kolmogorov-Smirnov (K-S) distance. While AIC is founded on information theory and is designed to prioritize a number of distributions based on the relative amount of discrepancy (lost information) from the true distribution, the K-S test is a non-parametric procedure that prioritizes candidate distributions based on the vertical distances between the empirical distribution function (EDF) and the CDF of the assumed distribution (Johnson et al., 1995). Parameter estimation and model selection results are presented in Table 1. Measures of K-S and AIC statistics suggest that exponential distribution has the best fit to the observed natural times in the Sulawesi region.

**Table 1**: Probability distribution and the results of statistical inference for the present dataset

| 3.1  | Earthquake Potential Score: Illustration for Cities |
|------|-----------------------------------------------------|
| Once the natural time statistics of the larger region $(A)$ is derived, we define earthquake potential score (EPS) for a circular city region $(A_i, i=1,2,L,n)$ as $EPS \equiv P\{X \leq n(t)\};$ $n(t)$ is the number of small earthquake counts at (calendar) time $t$ since the last large event within the city circle. Notice that EPS is a monotonically non-decreasing function which returns to 0 immediately after the completion of an earthquake cycle. | |

For the present analysis, we compute nowcast values or EPS scores for 21 cities in the Sulawesi region. These cities are Palu, Makassar, Manado, Kendari, Bitung, Gorontalo, Palopo, Bau-bau, Luwuk, Toli-toli, Pare-pare, Poso, Bone, Kolaka, Buton, Watampone, Polewali, Donggala, Taliabu, Mamuju, and Morowali. Centered at the city center, a circle of radius 300 km defines the city region $(A_i, i=1,2,L,21)$ (Figure 3). Assuming that the natural time statistics of $A$ and $A_i$ are indifferent, the EPS scores are nothing
Table 2: Nowcast values for $M_{\alpha} \geq 6.5$ earthquakes in 21 cities of the Sulawesi area with $M_{\alpha} = 4.5$ and $R = 300$ km

Table 2 highlights that EPS for Pare-pare is about 82 percent; Manado and Bitung have an EPS of about 70 percent; Palu, Makassar, Luwuk, Toli-toli, Watampone, Polewali, Donggala, Taliabu, and Mamuju have an EPS between 50 to 65 percent, and other cities have lesser EPS. This means, for example, that Palu is about 62% through its cycle for 6.5 magnitude or greater earthquakes, while Pare-pare is about 82% of the way through its cycle.

### 3.2 Sensitivity Testing

Although nowcasting technique inevitably provides a surrogate tool to examine the development of a region through large earthquake cycles, numerical EPS values are influenced by the selection of magnitude thresholds ($M_{\alpha}, M_{\beta}$) and geographical areas ($A, A'$). Therefore to perform a sensitivity testing, we vary small earthquake magnitude $M_{\alpha}$ from 4.0 to 5.0 and circular city radius ($R$) from 250 km to 350 km. The associated results are pictorially depicted in Fig. 3. It is observed that the results are generally consistent across all parameter values, although there are a few variations due to the inclusion of recent large events in the extended circular city region (Pasari & Sharma, 2020).

### 4.0 DISCUSSION

We have implemented a new method of nowcasting to characterize the contemporary state of earthquake hazard at different cities of Sulawesi region through the concepts of natural time and earthquake cycle. In this method, the key idea is to derive the seismicity statistics of a large defined area and then apply the same to the regional areas. The process requires constructing cumulative distribution function (CDF) for natural times obtained from a sequence of earthquake cycles in the defined geographic region. In effect, natural times, counts between major events, act as a measure of stress-strain accumulation between large earthquakes in a specific region. There are at least three advantages of this approach. First, the method inherently accounts for the possible contribution from dependent events as natural time count is unaffected when aftershocks dominate, when background seismicity dominates, and when both contribute. Second,
statistics of natural times remains unaltered with the changes of background seismicity rate as long as \( b \)-value remains constant. Third, the nowcast score – a proxy measure of the current exposure to earthquake hazard, provides a systematic ranking of cities in a rapid, efficient and reproducible way. However, we re-emphasize that nowcast score evaluated at current time is not necessarily an implication of future seismic activity of a region, although better characterization of future state of a fault system, given the current state, should be possible (Rundle et al., 2016; Rundle & Donnellan, 2020).

As noted earlier, the method of earthquake nowcasting requires an assumption that the \( b \)-value is homogenous in space and time (e.g., Rundle et al. 2016; 2018). To verify this basic assumption, we estimated \( b \)-values for several combinations of space and time, as summarized in Table 3 (Pasari & Sharma, 2020). The frequency-magnitude statistics of five different time periods of earthquake catalog illustrate that the \( b \)-value estimates are generally homogeneous in the time domain. Similarly, the frequency-magnitude statistics of five different spatial sub-regions along with 21 circular city regions demonstrate that the \( b \)-value estimates are largely homogenous in space.

| Table 3: The \( b \)-value estimates for a variety of space-time regions in the study region

| Space-Time Region | Estimated \( b \)-Value |
|-------------------|-----------------------|
| Region A          | 1.2                   |
| Region B          | 1.3                   |
| Region C          | 1.4                   |

In addition to computational advances through ubiquitous web-based computation using global catalog (e.g., Rundle et al., 2018), improvements of the nowcasting idea in seismology have taken place in two predominant directions – to strengthen the foundation of nowcasting in light of the ergodicity dynamics of statistical physics coupled with information theory (e.g., Holliday et al. 2016; Rundle et al. 2016, 2018, 2019a) and to explore applicability of nowcasting for anticipating the occurrence of induced seismicity (e.g., Luginbuhl et al. 2018a, 2018b), global seismicity (e.g., Luginbuhl et al. 2018c; Rundle et al. 2019a, b) and global tsunami risk (e.g., Rundle et al. 2019). In order to support the presumptions in nowcasting analysis, Rundle et al. (2003, 2012, 2018) have used several concepts like percolation, ergodic property and phase transitions of statistical mechanics of complex dynamical threshold systems (Tiampo et al., 2003). They found that the fluctuations in the statistical distribution of seismicity averaged over many cycles take a form of Fisher-Stauffer droplet model, as mentioned below:

\[
\begin{align*}
\Pi(s) &= n_0 \frac{s_0}{s} \exp \left\{ -\left( \frac{s}{s_0} \right)^\sigma \right\}, \\
\end{align*}
\]

where \( s \) is the droplet or cluster size in earthquakes, \( n_0 \) is a constant, \( s_0 \) is a scale factor, and \( \tau \) and \( \sigma \) are scaling exponents (Rundle et al. 2018). Using the information of elastic energy released during earthquake (seismic moments), they also estimated droplet size for events having seismic moment larger than \( W \) and threshold moment \( W_0 \) as below:
\[ n(W) = \frac{n_0}{W^{z-1}} \exp \left\{ -\left( \frac{W}{W_0} \right)^{\alpha} \right\} \approx \frac{n_0}{W^{z-1}} 10^{-\left(\frac{W}{W_0}\right)^{\alpha}} \]  

(2)

Efforts are also made to convert natural time to calendar (clock) time using Poisson rate and thereby to carry out earthquake forecasting through a Weibull projection (e.g., Holliday et al. 2016). A careful development and formulation leads to calculating conditional probability of occurrence of a large event in a time interval \( \Delta t \) in the future given the natural time count \( n(t) \) and time-averaged rate \( \omega \) of natural times \( (N) \) (Holliday et al. 2016).

\[ P(\Delta t/t) = 1 - \exp \left\{ \left[ \frac{n(t)}{N} \right]^{\beta} - \left[ \frac{n(t) + \omega \Delta t}{N} \right]^\beta \right\} \]  

(3)

The concept of Shannon information entropy, together with a definition of magnitude probability, has recently been introduced to nowcast seismic information for a sequence of great earthquakes and megatsunamis (Rundle et al. 2019a, 2019b). The mathematical expression for the average or expectation of Shannon self-information is:

\[ I \equiv \langle I_m \rangle = -\sum_m p_i \log_2(p_i). \]  

(4)

where \( p_i \) is the probability that system is in the \( i^{th} \) state centered on magnitude \( m_i \). For a set of magnitude “bins”, each of width \( \Delta m \), e.g., \( m_i, m_i + \Delta m, \cdots \), the average information entropy \( I_{avg} \) for each polygonal zone may be evaluated as

\[ I_{avg} = -\sum_{m_i} I_m = -\sum_{m_i} p(m) \log_2(p(m)), \]  

(5)

where \( m \) is the magnitude of the \( i^{th} \) bin and \( p(m) \) is the probability that the magnitude \( m \) of an earthquake lies within a small interval \( \Delta m \) centered around \( m \) (Rundle et al. 2019a). It was concluded that incorporating magnitude information into natural time counts did not produce any significantly different EPS values for the source zones. Nonetheless, the proposed method provided insights to the interevent time analysis, deviation of large events from the frequency-magnitude Power law and related characteristics of earthquake sequences (Rundle et al. 2019a). Recently, Rundle & Donnellan (2020), though some machine learning algorithms of the seismicity clustering patterns of aftershock sequences and seismic swarms in Southern California, have further extended the application of nowcasting method for regional fault characterization in terms of cycles of recharge (stress accumulation) and discharge (stress release) similar to the concept of the elastic rebound theory in earthquake mechanics.

To summarize, nowcasting method is deemed to be a potential surrogate tool for earthquake hazard estimation of any seismic region at current time. It utilizes simple empirical scaling laws that apply to the collective behavior of earthquakes in a network of geological faults. In this study, we concentrated on the
seismic prone Sulawesi region and computed earthquake potential score for 21 cities. Scientists, engineers and policy-makers may use these values as a surrogate way of estimating how much tectonic stress has built up in a city since the last major event.

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**Data and Resources**

Earthquake data were downloaded from public and regional catalogs: Advanced National Seismic System comprehensive catalog (http://www.ncedc.org/anss/catalog-search.html), Meteorological Geophysical Agency of Indonesia catalog (http://repogempa.bmkg.go.id/repo_new/), and International Seismological Centre catalog (http://www.isc.ac.uk/iscbulletin/search/catalogue/). All websites were last accessed in November, 2020.

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Figure 1. Topography of the Sulawesi island including the tectonics and major cities.
Figure 2. Pictorial summary of earthquake data (1969-2020) that are used for the present nowcasting analysis; subplots highlight several characteristics of the catalog, including epicentral distributions on map, cross section views of hypocentral depth, magnitude of completeness, and occurrence time of large earthquakes in the study region.
Figure 3: Sensitivity testing of nowcast scores for different cities in Sulawesi region. The first subplot demonstrates the circular city region for the Palu city corresponding to a radius of 250 km, 300 km, and 350 km. Current number of small event counts since the last major earthquake in each circular city region are shown in the lower panel.
### Table 1. Probability distributions and results of statistical inference of natural times

| Distribution                  | Density function \((t > 0)\) | Statistical Inference | MLE         | AIC          | K-S         |
|-------------------------------|-------------------------------|-----------------------|--------------|--------------|-------------|
| Exponential (best-fit)        | \(\frac{1}{\alpha} e^{-\frac{t}{\alpha}}\) | \(\hat{\alpha} = 191.9540\) | 1090.7625 | 0.0567       |
| Gamma                        | \(\frac{1}{\Gamma(\beta)} \frac{t^{\beta-1} e^{-\frac{t}{\alpha}}}{\alpha^\beta}\) | \(\hat{\alpha} = 231.1659\) | 1093.8716 | 0.0888       |
| Weibull                      | \(\frac{\beta}{\alpha^\beta} t^{\beta-1} e^{-\frac{t}{\alpha}}\) | \(\hat{\alpha} = 191.0590\) | 1092.7447 | 0.0596       |
| Exponentiated Exponential    | \(\alpha^\beta (1-e^{-\alpha t}) e^{-\alpha t}\) | \(\hat{\alpha} = 197.3369\) | 1092.6662 | 0.0617       |

MLE: Maximum likelihood estimation; AIC: Akaike information criterion; K-S: Kolmogorov-Smirnov

### Table 2. Nowcast values for \(M_a \geq 6.5\) earthquakes in the Sulawesi area with \(M_a = 4.5\) and \(R = 300\ km\)

| City               | City center   | Lat (°N) | Long (°E) | Date of last large event | Magnitude of last large event | Current small event count | Cycles | EPS (%) |
|--------------------|---------------|----------|-----------|--------------------------|-----------------------------|---------------------------|--------|---------|
| Palu               |               | -0.8679  | 119.9047  | 9/28/2018                | 7.5                         | 186                       | 08     | 62      |
| Makassar           |               | -5.1477  | 119.4327  | 2/23/1969                | 6.9                         | 140                       | 01     | 52      |
| Manado             |               | 1.4748   | 124.8421  | 11/14/2019               | 7.1                         | 232                       | 21     | 70      |
| Kendari            |               | -3.9985  | 122.5130  | 4/12/2019                | 7.0                         | 60                        | 03     | 27      |
| Bitung             |               | 1.4404   | 125.1217  | 11/14/2019               | 7.1                         | 229                       | 22     | 70      |
| Gorontalo          |               | 0.6999   | 122.4467  | 4/12/2019                | 7.0                         | 128                       | 09     | 49      |
| Palopo             |               | -3.0016  | 12.1.1985  | 4/12/2019               | 7.0                         | 80                        | 03     | 34      |
| Bau-Bau            |               | -5.5071  | 122.5969  | 2/19/2005                | 6.5                         | 100                       | 02     | 41      |
| Luwuk              |               | -0.9388  | 122.7928  | 4/12/2019                | 7.0                         | 157                       | 08     | 56      |
| Toli-toli          |               | 0.8768   | 120.7580  | 9/28/2018                | 7.5                         | 165                       | 11     | 58      |
| Pare-pare          |               | -4.0096  | 119.6291  | 2/3/1969                 | 6.9                         | 329                       | 01     | 82      |
| Poso               |               | -1.3950  | 120.7538  | 4/12/2019                | 7.0                         | 106                       | 09     | 42      |
| Bone               |               | -4.7443  | 120.0665  | 2/19/2005                | 6.5                         | 113                       | 02     | 44      |
| Kolaka             |               | -3.9947  | 121.5827  | 4/12/2019                | 7.0                         | 69                        | 03     | 30      |
| Buton              |               | -5.3096  | 122.9888  | 2/19/2005                | 6.5                         | 96                        | 02     | 39      |
| Watampone          |               | -4.5388  | 120.3250  | 2/19/2005                | 6.5                         | 155                       | 02     | 55      |
| Polewali           |               | -3.4155  | 119.3367  | 5/29/2017                | 6.6                         | 180                       | 02     | 61      |
| Donggala           |               | -0.4233  | 119.8352  | 9/28/2018                | 7.5                         | 189                       | 07     | 63      |
| Talatau            |               | -1.8268  | 124.7741  | 4/12/2019                | 7.0                         | 152                       | 08     | 55      |
| Mamuju             |               | -2.4920  | 119.3250  | 9/28/2018                | 7.5                         | 165                       | 03     | 58      |
| Morowali           |               | -2.6987  | 121.9018  | 4/12/2019                | 7.0                         | 88                        | 04     | 37      |
Table 3: Homogeneity of the study region shown through estimated $b$-values for a variety of time and space combinations

| Catalog span | Total number of events ($M \geq 4.5$) | Estimated $b$-value | Coefficient of Determination ($R^2$) in G-R frequency-magnitude linear regression model (using the principle of least-squares estimation) |
|--------------|--------------------------------------|---------------------|---------------------------------------------------------------------------------|
| Several $b$-value estimates in time |                                      |                     |                                                                                |
| 1969 – 2020  | 17082                                | 1.2263              | 0.9949                                                                         |
| 1979 – 2020  | 15564                                | 1.1968              | 0.9950                                                                         |
| 1989 – 2020  | 13100                                | 1.1602              | 0.9946                                                                         |
| 1969 – 1999  | 7786                                 | 1.2220              | 0.9963                                                                         |
| 1979 – 2009  | 10563                                | 1.1629              | 0.9951                                                                         |

| Spatial region | Total number of events ($M \geq 4.5$) | Estimated $b$-value | Coefficient of Determination ($R^2$) in G-R frequency-magnitude linear regression model |
|----------------|--------------------------------------|---------------------|---------------------------------------------------------------------------------|
| 115° – 123° E, 2° – 10° S | 1969                                | 1.2201              | 0.9893                                                                         |
| 122° – 130° E, 2° – 10° S | 5077                                | 1.1571              | 0.9969                                                                         |
| 122° – 130° E, 3° S – 5° N | 9698                                | 1.2178              | 0.9975                                                                         |
| 115° – 123° E, 3° S – 5° N | 1700                                | 1.0189              | 0.9906                                                                         |
| 118° – 128° E, 7° S – 3° N | 7694                                | 1.1367              | 0.9961                                                                         |

| Several $b$-value estimates in space |                                      |                     |                                                                                |
| Palu        | 1182                                 | 0.9870              | 0.9869                                                                         |
| Makassar    | 144                                  | 1.0868              | 0.9415                                                                         |
| Manado      | 5281                                 | 1.2922              | 0.9936                                                                         |
| Kendari     | 322                                  | 0.8924              | 0.9701                                                                         |
| Bitung      | 5540                                 | 1.2778              | 0.9927                                                                         |
| Gorontalo   | 2266                                 | 1.0470              | 0.9826                                                                         |
| Palopo      | 626                                  | 1.1387              | 0.9933                                                                         |
| Bau-Bau     | 216                                  | 0.8744              | 0.9383                                                                         |
| Luwuk       | 2419                                 | 1.0910              | 0.9780                                                                         |
| Toli-toli   | 1578                                 | 1.0114              | 0.9900                                                                         |
| Pare-pare   | 333                                  | 1.2598              | 0.9564                                                                         |
| Poso        | 1503                                 | 1.0257              | 0.9887                                                                         |
| Bone        | 225                                  | 1.1066              | 0.9814                                                                         |
| Kolaka      | 426                                  | 0.9636              | 0.9704                                                                         |
| Buton       | 200                                  | 0.8611              | 0.9399                                                                         |
| Watampone   | 292                                  | 1.1631              | 0.9844                                                                         |
| Polewali    | 461                                  | 1.1916              | 0.9946                                                                         |
| Donggala    | 1197                                 | 0.9948              | 0.9821                                                                         |
| Taliabu     | 2056                                 | 1.0615              | 0.9777                                                                         |
| Mamuju      | 580                                  | 1.0509              | 0.9897                                                                         |
| Morowali    | 973                                  | 0.9880              | 0.9665                                                                         |

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