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Integrating Geodetic Constraints into Earthquake Source Characterization for Probabilistic Seismic Hazard Analysis: A Dual Statistical–Physical Framework

Yuliastuti Yuliastuti[1,2], Irwan Meilano[3], Nanang T. Puspito[4], Suchi Rahmadani[3]

[1] Doctoral Program of Earth Sciences, Faculty of Earth Sciences and Technology, Institut Teknologi Bandung, Jl. Ganesha 10, Bandung, 40132, Jawa Barat, Indonesia
[2]Research and Innovation Agency (BRIN), Building No 80, B.J. Habibie Science and Technology Area, South Tangerang 15314, Indonesia
[3]Faculty of Earth Sciences and Technology, Institut Teknologi Bandung, Jl. Ganesha 10, Bandung, 40132, Jawa Barat, Indonesia
[4]Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jl. Ganesha 10, Bandung, 40132, Jawa Barat, Indonesia

Correspondence to: Yuliastuti Yuliastuti (yuli032@brin.go.id)

Abstract. Reliable earthquake source characterization is essential for probabilistic seismic hazard analysis (PSHA), yet remains particularly challenging in low-seismicity regions where sparse earthquake catalogs introduce substantial epistemic uncertainty. Although geodetic observations provide independent constraints on contemporary crustal deformation, existing hybrid earthquake source models have generally been selected solely on the basis of statistical forecasting performance without explicitly considering their physical consistency with regional deformation. This study presents a statistical–physical hybrid framework that integrates independently validated catalog-based and GNSS-derived geodetic earthquake source models for PSHA. The proposed framework combines retrospective earthquake forecast evaluation using the Collaboratory for the Study of Earthquake Predictability (CSEP) with independent physical screening based on the regional geodetic moment budget. A total of 126 candidate hybrid models were evaluated for Kalimantan, Indonesia, representing alternative catalog models, geodetic scenarios, and hybrid formulations. Although several candidates improved retrospective forecasting skill, only three satisfied both the statistical and physical selection criteria, with the preferred adaptive-smoothing hybrid model achieving the highest average retrospective pass rate (67.5%). Physical screening rejected six of the seven evaluated geodetic scenarios because their implied seismic moment release exceeded the available geodetic moment budget. Incorporating the selected hybrid models into PSHA increased median peak ground acceleration by approximately 2–29% for the 475-year return period and 2–23% for the 2475-year return period. In contrast, equal-weight and performance-based logic-tree ensembles produced nearly identical hazard estimates, differing by less than 1.5%. These results demonstrate that integrating statistical forecasting skill with independent geodetic constraints provides a physically consistent framework for earthquake source characterization and a transferable methodology for improving earthquake hazard assessment in low-seismicity regions.

Keywords: Hybrid earthquake source model; dual-constraint model selection; geodetic moment budget; CSEP; probabilistic seismic hazard analysis; low-seismicity region.

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1 Introduction

Reliable earthquake source characterization is fundamental to probabilistic seismic hazard analysis (PSHA) because earthquake source models define the expected spatial and temporal occurrence of future earthquakes and therefore directly influence seismic hazard estimates, engineering design, and disaster risk mitigation (Cornell, 1968; McGuire, 2004; Porter et al., 2017). Although robust source characterization can often be achieved in tectonically active regions with abundant instrumental records, well-documented historical seismicity, and mapped active faults, substantial epistemic uncertainty remains in many low-seismicity regions where earthquake catalogs are sparse and fault information is incomplete (Bommer and Scherbaum, 2008; Frankel, 1995). Under these conditions, developing earthquake source models that are both statistically reliable and physically consistent remains one of the principal challenges in earthquake hazard assessment.

Low-seismicity regions present a particularly demanding environment because no single observational dataset sufficiently constrains long-term earthquake occurrence. Kalimantan, located within the Sunda Plate, exemplifies this challenge (Hall, 1995, 2012). Although instrumental seismicity is relatively limited, recent geological investigations have identified several active crustal faults (Koesoemadinata, 2020; Pusat Studi Gempa Nasional, 2025), while continuous Global Navigation Satellite System (GNSS) observations indicate measurable crustal deformation across the region (Yuliastuti et al., 2026b). Consequently, earthquake catalogs, active-fault information, and geodetic observations each provide only a partial description of the regional seismotectonic system. These characteristics make Kalimantan a representative test case for evaluating earthquake source modelling frameworks applicable to low-seismicity regions where multiple independent datasets must be integrated to improve seismic hazard assessment.

Earthquake source models are commonly developed using either historical seismicity or geodetic observations of crustal deformation (Field et al., 2017; Frankel, 1995). Catalog-based approaches, particularly smoothed seismicity models (Frankel, 1995; Helmstetter et al., 2007; Werner et al., 2010, 2011), estimate future earthquake occurrence directly from the spatial distribution of past earthquakes and have been extensively evaluated through retrospective and prospective forecasting experiments within the Collaboratory for the Study of Earthquake Predictability (CSEP) (Schorlemmer et al., 2010; Werner et al., 2010; Zechar et al., 2013). Their principal advantage lies in their direct probabilistic formulation and objective statistical validation. However, their predictive capability depends strongly on catalog completeness and observation period, limitations that become increasingly important in regions with sparse seismicity.

In contrast, geodetic approaches infer long-term seismic potential from contemporary crustal deformation measured by GNSS observations (Ward, 1998). Because crustal strain reflects ongoing tectonic loading rather than historical earthquake occurrence, geodetic models provide an independent physical constraint that complements earthquake catalogs, particularly in regions with limited seismic records. Nevertheless, converting geodetic strain into earthquake occurrence rates requires assumptions regarding crustal rheology, seismogenic thickness, seismic coupling, and earthquake scaling relationships, introducing additional epistemic uncertainty into the resulting source models (Bird et al., 2010; Bird and Liu, 2007; Ward, 1998).

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Recent studies have independently advanced both approaches for Kalimantan. A statistically optimized catalog-based earthquake source model was developed using Bayesian parameter optimization and retrospective CSEP evaluation (Yuliastuti et al., 2026a), while a complementary GNSS-derived earthquake source model was established through strain-rate inversion and geodetic moment-rate analysis (Yuliastuti et al., 2026b). Although both models demonstrated robust individual performance, they characterize different aspects of the earthquake generation process. The catalog-based model provides statistically validated estimates of earthquake occurrence, whereas the geodetic model constrains the spatial distribution of ongoing crustal deformation. Together, these studies suggest that the two approaches are complementary rather than competing and therefore provide a natural basis for integrated earthquake source characterization.

This complementarity has motivated increasing interest in hybrid earthquake models that combine earthquake catalogs with geodetic or geological information. Previous studies have consistently demonstrated that integrating multiple independent datasets generally improves spatial forecasting performance relative to models based on a single data source (Rhoades et al., 2017; Strader et al., 2018). Existing hybrid models primarily employ either additive formulations (Rhoades and Gerstenberger, 2009; Rhoades and Stirling, 2012) or multiplicative formulations (Bayona et al., 2022; Rhoades et al., 2014, 2017; Shebalin et al., 2014). In particular, multiplicative formulations preserve the spatial structure of the baseline seismicity model while allowing complementary geophysical information to modify earthquake occurrence rates. Both retrospective and prospective evaluations have demonstrated that such approaches can improve earthquake forecasting when the integrated datasets provide complementary information. Consequently, hybrid modelling has emerged as a promising strategy for improving earthquake source characterization for seismic hazard applications.

Despite these advances, an important gap remains between hybrid earthquake forecasting and earthquake source characterization for PSHA (Bayona et al., 2022; Rhoades et al., 2017). Existing hybrid studies have primarily selected models according to statistical forecasting performance using likelihood optimization, information gain, or prospective forecast evaluation (Bayona et al., 2022; Rhoades et al., 2017; Strader et al., 2018). Although these criteria are appropriate for earthquake forecasting, they do not necessarily ensure that the resulting earthquake source models remain physically compatible with long-term tectonic deformation. Consequently, hybrid models that perform well statistically may still imply unrealistic long-term seismic moment release, potentially propagating physically inconsistent source characteristics into subsequent seismic hazard calculations. To our knowledge, explicit evaluation against an independent regional geodetic moment budget has not been incorporated as a formal criterion for hybrid model selection (Bayona et al., 2022; Rhoades et al., 2017).

Motivated by this gap, this study investigates whether statistically optimized hybrid earthquake source models can simultaneously satisfy the independent physical constraints required for long-term seismic hazard assessment. We develop a statistical–physical hybrid framework that integrates independently validated catalog-based and GNSS-derived geodetic earthquake source models through a dual-constraint model selection strategy combining retrospective CSEP evaluation with physical consistency screening based on the regional geodetic moment budget. The framework is demonstrated using Kalimantan as a representative low-seismicity region and subsequently propagated into probabilistic seismic hazard analysis

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to evaluate its influence on regional hazard estimates and epistemic uncertainty. Beyond the specific case study, the proposed framework provides a transferable methodology for improving earthquake source characterization and PSHA in low-seismicity regions where historical seismicity alone cannot adequately constrain long-term seismic potential.

2 Method

2.1 Overview of the proposed statistical-physical framework

This study proposes a statistical–physical framework for improving earthquake source characterization in probabilistic seismic hazard analysis (PSHA) through the integration of independently developed catalog-based and GNSS-derived geodetic earthquake source models. Rather than replacing the baseline catalog model, geodetic information is incorporated as an additional spatial constraint to improve earthquake source characterization while preserving both statistical consistency with historical seismicity and physical consistency with long-term tectonic deformation. The framework therefore combines statistical calibration, objective forecast evaluation, and independent physical screening to identify hybrid source models suitable for subsequent seismic hazard calculations (Fig. 1).

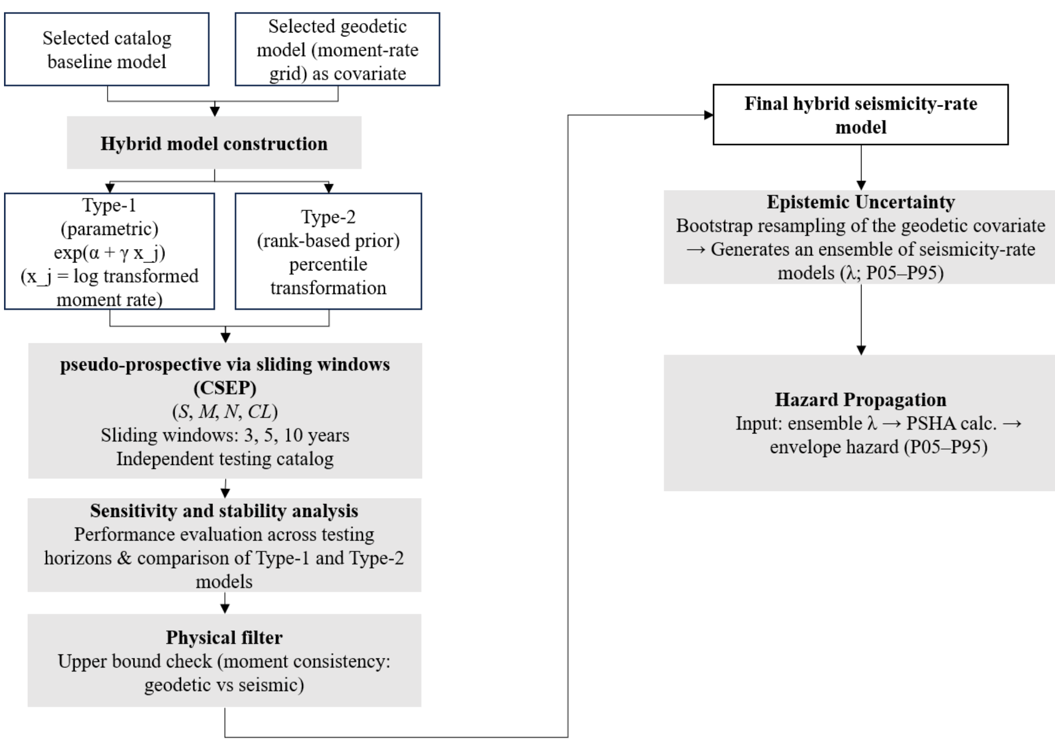

Figure 1: Workflow of the proposed dual statistical–physical framework for hybrid earthquake source model selection and probabilistic seismic hazard analysis (PSHA).

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The overall workflow consists of five sequential stages. First, independently developed and validated catalog-based and GNSS-derived earthquake source models from our previous studies (Yuliastuti et al., 2026a, b) were adopted as the baseline components of the hybrid framework. Second, geodetic information was incorporated into the baseline seismicity model through alternative hybrid formulations representing both parametric and non-parametric integration strategies. Third, all candidate hybrid models were evaluated using retrospective CSEP experiments to quantify their statistical forecasting performance over multiple testing horizons. Fourth, statistically acceptable models were subjected to an independent physical consistency test based on the regional geodetic moment budget. Finally, the selected hybrid models were propagated through bootstrap-based uncertainty analysis and classical PSHA to quantify their influence on regional seismic hazard estimates and associated epistemic uncertainty.

2.2 Baseline earthquake source models

The proposed hybrid framework was constructed from two independently developed earthquake source models that represent complementary descriptions of crustal seismicity. A catalog-based model provides the statistically calibrated spatial distribution of historical earthquake occurrence, whereas a geodetic model characterizes the contemporary deformation field inferred from continuous GNSS observations. Both components were developed and validated independently in previous studies (Yuliastuti et al., 2026a, b) and are integrated here within a unified statistical–physical framework.

The catalog-based component was adopted from Yuliastuti et al. (2026a), in which spatial smoothing models were developed from a completeness-corrected earthquake catalog using Bayesian parameter optimization and retrospective CSEP evaluation. Three representative baseline models were selected for the present study. BF provides the statistically optimal fixed-bandwidth solution identified through Bayesian optimization, SF4 represents a conventional fixed-kernel formulation, whereas SA9 represents an adaptive smoothing approach in which the kernel bandwidth varies according to the local seismicity density. These three models were selected because they represent the statistically preferred catalog-based formulations identified in the previous study after Bayesian optimization, retrospective CSEP evaluation, and posterior uncertainty analysis. Collectively, these models span the principal classes of catalog-based smoothing methods considered in this study and provide the basis for evaluating the robustness of hybridization across different baseline representations of seismicity.

To ensure that the hybrid framework was constructed from robust baseline models, a parameter robustness analysis was performed for each selected catalog model prior to hybridization. The sensitivity analysis evaluated the influence of the Gutenberg–Richter b-value together with the minimum and maximum magnitudes (M_{min} and M_{max}) on model stability using the same retrospective CSEP framework employed in the original model development. Candidate values of b=0.8, 1.0, and 1.2, M_{min} =4.5–4.9, and M_{max} =6.3–6.7 were examined using identical sliding-window evaluations over 1-, 3-, 5-, and 10-year forecasting horizons. Model selection was based on the consistency of CSEP pass rates across multiple testing periods rather than performance within a single evaluation window. The preferred parameter combination was subsequently adopted as the baseline configuration for hybrid model construction.

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The geodetic component was adopted from the geodetic seismicity model developed by Yuliastuti et al. (2026b), in which continuous GNSS observations were converted into strain-rate fields and subsequently transformed into geodetic moment-rate distributions through a physically based strain-to-moment framework. The original model was evaluated using retrospective CSEP testing together with sensitivity analyses of physical parameters controlling the strain-to-seismicity conversion, including seismogenic thickness, seismic coupling, and minimum magnitude. In the present study, the final geodetic configuration selected for hybrid integration corresponds to the preferred model identified after these evaluations and employs the 46-station GNSS network, which provides improved spatial coverage and lower relative uncertainty than the screened 25-station configuration while preserving comparable statistical performance. Consequently, the geodetic model is incorporated exclusively as a spatial covariate representing long-term crustal deformation, whereas earthquake occurrence rates remain governed by the catalog-based baseline models.

2.3 Hybrid model construction

The hybrid earthquake source model was developed to integrate statistically calibrated catalog-based seismicity with independent geodetic constraints while preserving the probabilistic structure of the baseline earthquake source model (Rhoades et al., 2014, 2017). Rather than replacing the catalog-derived seismicity rates, geodetic information was introduced as a spatial modifier that redistributes earthquake occurrence according to contemporary crustal deformation. This strategy enables complementary geodetic information to refine the spatial pattern of long-term seismicity without redefining the underlying seismicity model.

2.3.1 Parametric hybrid model (Type-1)

The parametric hybrid model follows the multiplicative formulation proposed by Rhoades et al. (2014), in which the baseline earthquake occurrence rate is modified by an exponential function of a geodetic covariate, as shown in Eq. (1).

$$\lambda_H(j,k) = \lambda_0(j,k)\, e^{(\alpha+\gamma x_j)} \tag{1}$$

Where $\lambda_0(j,k)$ is the baseline earthquake occurrence rate for grid cell j, x_j represents the normalized geodetic moment-rate covariate for grid cell j, while α and γ are calibration parameters estimated from the training earthquake catalog using Poisson maximum likelihood estimation.

The geodetic covariate was derived from the preferred GNSS-based moment-rate model. Moment-rate values were first transformed using a logarithmic function, $x = log(1+M)$, to reduce the influence of highly skewed moment-rate distributions. The transformed values were subsequently standardized using the median and interquartile range (IQR) (Huber, 1981), followed by symmetric clipping to predefined limits in order to reduce the influence of localized deformation anomalies during parameter estimation. This robust transformation preserves the relative spatial variability of the geodetic field while improving numerical stability during likelihood optimization.

Following parameter estimation, the resulting exponential multiplier was normalized to a median value of one before being applied to the baseline earthquake rates. A second normalization was then performed independently within each magnitude–depth bin to preserve the total earthquake occurrence rate of the baseline model. Consequently, the hybrid formulation modifies only the spatial distribution of seismicity while maintaining the original regional seismicity rate across all magnitude bins.

2.3.2 Non-parametric hybrid model (Type-2)

To evaluate the sensitivity of hybridization to the choice of integration strategy, an alternative non-parametric hybrid formulation was also investigated. Instead of estimating calibration parameters, the geodetic moment-rate field was converted into a spatial prior based on percentile ranks. Each grid cell was assigned a normalized spatial rank derived from the interpolated geodetic moment rate, and the corresponding alarm value was defined as in Eq. (2).

$$A_j = \left(\frac{r_j}{N}\right)^P \quad (2)$$

where r_j is the rank of grid cell j, N is the total number of grid cells, and P controls the strength of the spatial weighting. The hybrid earthquake occurrence rate was then obtained by multiplying the baseline rate by the corresponding alarm value.

Unlike the parametric formulation, the rank-based approach does not require statistical parameter estimation and therefore provides a purely data-driven benchmark for evaluating the contribution of geodetic information. After applying the spatial weights, global mass-preserving normalization was performed to ensure that the total regional earthquake occurrence rate remained identical to that of the baseline model.

Both hybrid formulations were constructed for each of the three baseline catalog models (BF, SF4, and SA9) using all candidate geodetic moment-rate configurations, generating the complete set of hybrid source models subsequently evaluated through the statistical and physical validation procedures described in the following sections.

2.4 Statistical evaluation using CSEP

To isolate the effect of hybridization from the evaluation procedure itself, the retrospective testing framework established in the preceding catalog-based and geodetic studies was adopted without modification. Hybrid models were evaluated using the Collaboratory for the Study of Earthquake Predictability (CSEP) through pseudo-prospective sliding-window experiments with independent testing catalogs (Savran et al., 2022; Schorlemmer et al., 2010; Werner et al., 2010; Zechar et al., 2013). The same spatial discretization, training and testing periods, forecasting horizons (3, 5, and 10 years), and statistical evaluation metrics were retained to ensure direct comparability with the baseline models. Forecast performance was assessed using the standard Number (N), Spatial (S), Magnitude (M), and Conditional Likelihood (CL) consistency tests, allowing improvements associated with geodetic integration to be evaluated independently of changes in the validation protocol. Statistical evaluation served as the first stage of model selection and was subsequently complemented by an independent physical consistency assessment based on regional geodetic moment budgets.

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2.5 Dual-constraint model selection

Statistical performance alone does not guarantee that an earthquake source model is physically compatible with long-term tectonic deformation. Therefore, hybrid model selection was based on two independent criteria: statistical consistency evaluated using the CSEP framework and physical consistency evaluated against the regional geodetic moment budget.

For each statistically acceptable hybrid model, the implied annual seismic moment release was calculated from the final hybrid seismicity-rate model assuming a truncated Gutenberg–Richter magnitude–frequency distribution with the selected values of Mmin, Mmax, and b (Eq. 3). The resulting moment release was then compared with the independent geodetic moment budget derived from the GNSS-based strain model. A tolerance of 10% was adopted to account for uncertainties in the physical parameters used in the strain-to-moment conversion.

$$\dot{M}_H = \sum_m \lambda(m)\, M_o(m) \tag{3}$$

Where $\dot{M}_H$ is the annual seismic moment release implied by the hybrid earthquake source model, $\lambda(m)$ is the annual earthquake occurrence rate for magnitude bin m, and $M_o(m)$ is the expected seismic moment corresponding to magnitude mmm, calculated using the magnitude–moment relation of Hanks and Kanamori (1979).

Hybrid models whose implied moment release exceeded this threshold were classified as over-injected and excluded from further analysis. Because the hybrid formulation preserves the total earthquake occurrence rate through mass-preserving normalization, this screening evaluates only the physical plausibility of the spatial redistribution introduced by the geodetic covariates. Consequently, only models satisfying both the statistical and physical criteria were retained for the subsequent uncertainty and hazard analyses.

2.6 Epistemic uncertainty propagation

Following statistical and physical model selection, epistemic uncertainty was quantified by propagating bootstrap realizations of the GNSS-derived moment-rate field through the selected hybrid models while keeping the baseline catalog rates and calibrated model parameters fixed. Consequently, the resulting ensemble represents uncertainty associated solely with the spatial variability of the geodetic constraint.

For the parametric (Type-1) formulation, each bootstrap realization was propagated through the calibrated multiplicative model and subsequently subjected to the same mass-preserving normalization used during hybrid model construction. For the non-parametric (Type-2) formulation, bootstrap moment-rate fields were first converted into percentile-rank alarm functions before applying an identical normalization procedure. In both cases, normalization ensured that uncertainty affected only the spatial distribution of earthquake occurrence while preserving the total regional seismicity rate. The ensemble was summarized using the mean, standard deviation, and the 5th, 50th, and 95th percentile seismicity-rate models, which were subsequently propagated into the PSHA calculations.

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2.7 Hazard propagation

The influence of the hybrid earthquake source models on seismic hazard was evaluated using classical probabilistic seismic hazard analysis (PSHA) implemented in the OpenQuake Engine (v3.21) (Pagani et al., 2014; Silva et al., 2014). Epistemic uncertainty was represented at two complementary levels. First, uncertainty associated with the geodetic constraint was propagated through bootstrap realizations of each selected hybrid model, producing percentile source models (P05, P50, and P95). Second, inter-model uncertainty was represented through a source-model logic tree comprising the three selected hybrid source models derived from the Bayesian-optimized fixed-kernel (BF), fixed-kernel (SF4), and adaptive-kernel (SA9) catalog models (Fig. 2).

Two alternative weighting schemes were considered for the source-model logic tree. The first assigned equal weights to the three hybrid models, whereas the second employed performance-based weights derived from the retrospective CSEP evaluation. For the latter, each model was assigned a score based on the average pass rate of the combined CSEP metrics (passALL) over the 3- and 5-year testing horizons as shown in Eq. (4).

$$\text{score}_i = \frac{1}{2} p_{i,3yr} + \frac{1}{2} p_{i,5yr} \quad (4)$$

where $p_{i,3yr}$ and $p_{i,5yr}$ denote the corresponding pass rates. Logic-tree weights were subsequently obtained by normalizing the model scores as shown in Eq. (5).

$$w_i = \frac{\text{score}_i}{\sum_j \text{score}_j} \quad (5)$$

Hybrid seismicity-rate models were converted into grid-based point-source models with a spatial resolution of 0.1° × 0.1°. Each source was represented by a truncated Gutenberg–Richter magnitude–frequency distribution using the preferred values of M_{min}, M_{max}, and b identified from the preceding sensitivity analyses. All other source and calculation parameters, including tectonic region type, hypocentral depth distribution, focal mechanism distribution, temporal occurrence model, reference site conditions, and OpenQuake configuration (Table 1), were kept identical for all baseline and hybrid models, ensuring that differences in hazard estimates originated exclusively from earthquake source characterization.

Table 1 Common PSHA calculation parameters used for all baseline and hybrid source models.

Parameter	Value / Configuration
Hazard engine	OpenQuake Engine v3.21
Calculation mode	Classical PSHA
Source representation	Grid-based point sources (0.1° × 0.1°)
Tectonic region type	Active shallow crust
Logic-tree sampling	10 samples
Investigation time	1 year
Intensity measure type (IMT)	PGA

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Intensity measure levels	Logspace (0.005–3.0 g, 15 levels)
Truncation level	5 σ
Maximum source distance	300 km
Rupture mesh spacing	5 km
Point-source distance	200 km
Magnitude bin width	0.1 Mw
Area source discretization	10 km
Reference site condition	Vs30 = 800 m/s, Z1.0 = 30 m, Z2.5 = 0.57 km
Output statistics	Mean, P05, P50, P95
Annual probabilities of exceedance	0.002105 (475-year RP), 0.000404 (2475-year RP)

3 Results

3.1 Candidate hybrid models

The hybrid framework generated 126 candidate earthquake source models spanning two alternative integration strategies. Rather than selecting the best-performing model solely on statistical performance, candidate models were progressively screened using retrospective CSEP evaluation followed by an independent physical consistency test. This sequential selection substantially reduced the candidate model space before the final hazard analysis. The parametric Type-1 experiment comprised 42 configurations, combining two covariate-truncation levels with each baseline–geodetic pair. The non-parametric Type-2 experiment comprised 84 configurations obtained using four rank-alarm exponents. Table 2 summarizes the experimental design.

Table 2 Candidate hybrid earthquake source models evaluated in this study. The parameter space was defined by combining three catalog baseline models (BF, SF4, and SA9), two hybrid formulations (Type-1 and Type-2), seven geodetic scenarios (A–G), and the corresponding parameter ranges for each hybrid formulation.

Catalog baseline	Hybrid type	Geodetic scenarios	Parameter space	Candidate models
BF	Type-1 (parametric)	A–G	clip = ±3σ, ±5σ	14
BF	Type-2 (rank-based)	A–G	P = 0–3	28
SF4	Type-1 (parametric)	A–G	clip = ±3σ, ±5σ	14
SF4	Type-2 (rank-based)	A–G	P = 0–3	28
SA9	Type-1 (parametric)	A–G	clip = ±3σ, ±5σ	14
SA9	Type-2 (rank-based)	A–G	P = 0–3	28

3.2 Retrospective statistical performance of candidate hybrid models

The 126 candidate hybrid models were first evaluated solely on the basis of retrospective forecasting performance using the CSEP framework. At this stage, no physical constraints were imposed, allowing the statistical contribution of the geodetic covariates to be assessed independently from the subsequent physical consistency screening. Statistical performance varied substantially among hybrid configurations, indicating that the choice of geodetic scenario and integration strategy strongly influenced forecast skill.

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Among the evaluated formulations, the Type-1 hybrid produced the most consistent improvement across the three baseline models (Fig.2). For BF and SA9, pass rates increased from 67% to 78% and from 67% to 89%, respectively, at the 3-year horizon, while SF4 showed its largest improvement at the same horizon, increasing from 67% to 89%. At the 5-year horizon, improvements became smaller, with BF and SA9 converging toward similar performance between the baseline and hybrid models, whereas SF4 exhibited a slight decrease relative to its baseline. At the 10-year horizon, the Type-1 models converged to the same pass rate as the corresponding baseline models.

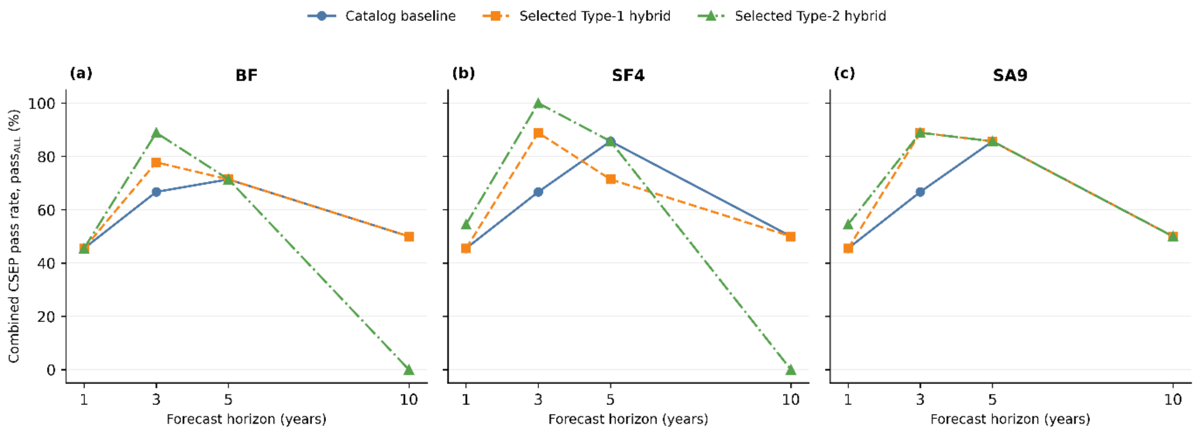

Figure 2: Retrospective statistical performance of the catalog-based baseline models and their statistically preferred hybrid counterparts evaluated using the CSEP framework across four forecasting horizons (1, 3, 5, and 10 years). For each baseline model (BF, SF4, and SA9), the figure compares the combined pass rate (passALL) of the original catalog-based model with the selected Type-1 (parametric) and Type-2 (non-parametric) hybrid formulations. The selected hybrid models correspond to the statistically best-performing configurations retained for subsequent physical consistency screening.

The Type-2 formulation exhibited a different temporal behavior (Fig. 2). At short forecasting horizons (1–3 years), Type-2 generally produced the highest statistical performance among all evaluated models, reaching pass rates of 89–100% at the 3-year horizon. However, its performance deteriorated substantially for longer forecasting windows. For both BF and SF4, the combined pass rate decreased to zero at the 10-year horizon, whereas SA9 maintained performance comparable to the baseline throughout the entire evaluation period.

These results demonstrate that several hybrid formulations substantially improve retrospective forecasting performance, particularly over short and intermediate forecasting horizons. However, statistical performance alone does not guarantee that the resulting hybrid models remain physically consistent with long-term tectonic deformation. Therefore, only the statistically preferred configurations were subsequently subjected to the independent physical consistency screening described in the following section.

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3.3 Physical consistency screening

After statistical evaluation, the selected hybrid models were further examined using the independent physical consistency criterion introduced in Section 2.5. Unlike the CSEP evaluation, which assesses retrospective forecasting skill, this screening evaluates whether the implied long-term seismic moment release remains compatible with the regional geodetic moment budget. Consequently, only hybrid models satisfying both statistical and physical criteria were retained for subsequent uncertainty propagation and hazard analysis.

Table 3 Physical consistency screening of candidate geodetic scenarios.

Geodetic scenario	Geodetic moment budget ($\times 10^{17}$ Nm/ yr)	Implied hybrid moment rate ($\times 10^{17}$ Nm/ yr)	Hybrid/Budget	Decision
A	0.74	3.18–3.23	4.30–4.40	Rejected
B	1.18	3.18–3.23	2.70–2.80	Rejected
C	1.62	3.18–3.23	~2.00	Rejected
D	0.59	3.18–3.23	5.40–5.50	Rejected
E	1.18	3.18–3.23	2.70–2.80	Rejected
F	**3.58**	**3.18–3.23**	**0.89–0.90**	**Selected**
G	2.87	3.18–3.23	1.11–1.13	Rejected

Note: Hybrid models were considered physically admissible when the implied seismic moment rate did not exceed 110% of the corresponding geodetic moment budget.

Table 3 shows that the majority of the evaluated geodetic scenarios generated implied seismic moment rates substantially exceeding the available geodetic moment budget. Scenarios A–E and G consistently produced hybrid models with hybrid-to-budget ratios ranging from approximately 2.0 to 5.5 and were therefore classified as over-injecting the long-term tectonic deformation. These scenarios were excluded from further analysis despite several of them exhibiting satisfactory statistical performance in the preceding CSEP evaluation.

The implied seismic moment rate remained nearly constant across all hybrid configurations because mass-preserving normalization conserves the total earthquake occurrence rate. Consequently, differences in physical admissibility were governed primarily by variations in the geodetic moment budget associated with each geodetic scenario.

Only Scenario F satisfied the physical consistency criterion for all three catalog-based baseline models. The corresponding implied seismic moment release ranged from 3.18 to 3.23 $\times 10^{17}$ Nm/yr, remaining below the allowable upper limit defined by the regional geodetic moment budget within the adopted 10% tolerance. Consequently, Scenario F was selected as the sole geodetic constraint for the subsequent uncertainty analysis and hazard calculations.

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3.4 Final Hybrid Model Selection

Combining the statistical evaluation with the physical consistency screening substantially reduced the number of admissible hybrid configurations. Among the 126 candidate models, only three satisfied both criteria and were therefore retained for subsequent uncertainty propagation and hazard analysis (Table 4).

Table 4 Final hybrid models selected after statistical evaluation and physical consistency screening.

Baseline	Selected hybrid	Geodetic scenario	Integration parameter	1 yr	3 yr	5 yr	10 yr	Mean pass rate (%)
BF	Type-2	F	P = 1	45.5	88.9	71.4	0	51.5
SF4	Type-2	F	P = 0	45.5	66.7	71.4	50	58.4
SA9	Type-1	F	clip = 3	45.5	88.9	85.7	50	67.5

All selected models employed the same geodetic scenario (Scenario F), confirming the outcome of the physical consistency screening. However, the preferred hybrid formulation differed among the three catalog-based baselines. BF and SF4 were optimally combined using the non-parametric Type-2 formulation, whereas SA9 retained the parametric Type-1 formulation with a clipped geodetic covariate (clip = 3).

Among the final models, the SA9-based Type-1 hybrid achieved the highest average CSEP pass rate (67.5%), followed by the SF4-based Type-2 (58.4%) and the BF-based Type-2 (51.5%). These three configurations constitute the final hybrid earthquake source models considered in the subsequent uncertainty and hazard analyses.

3.5 Epistemic uncertainty of the preferred hybrid model

Because uncertainty propagation through the parametric Type-1 formulation explicitly preserves the calibrated statistical relationship between seismicity and geodetic deformation, uncertainty analysis was performed for the preferred SA9-based hybrid model selected in the previous section. This model exhibited the highest overall retrospective performance while simultaneously satisfying the physical consistency criterion.

Figure 3 presents the spatial distributions of the P05, P50, and P95 annual earthquake occurrence rates together with the corresponding relative epistemic uncertainty, expressed as (P95−P05)/P50. The three percentile maps exhibit very similar spatial patterns, with differences primarily reflected in the estimated occurrence-rate values rather than in the locations of elevated seismicity.

The relative uncertainty map indicates that epistemic uncertainty is spatially heterogeneous across the study region. Higher relative uncertainty is observed in several localized areas, whereas lower uncertainty characterizes much of the remaining region. Overall, the uncertainty estimates provide spatially explicit bounds for the preferred hybrid model that are subsequently propagated into the probabilistic seismic hazard analysis presented in the following section.

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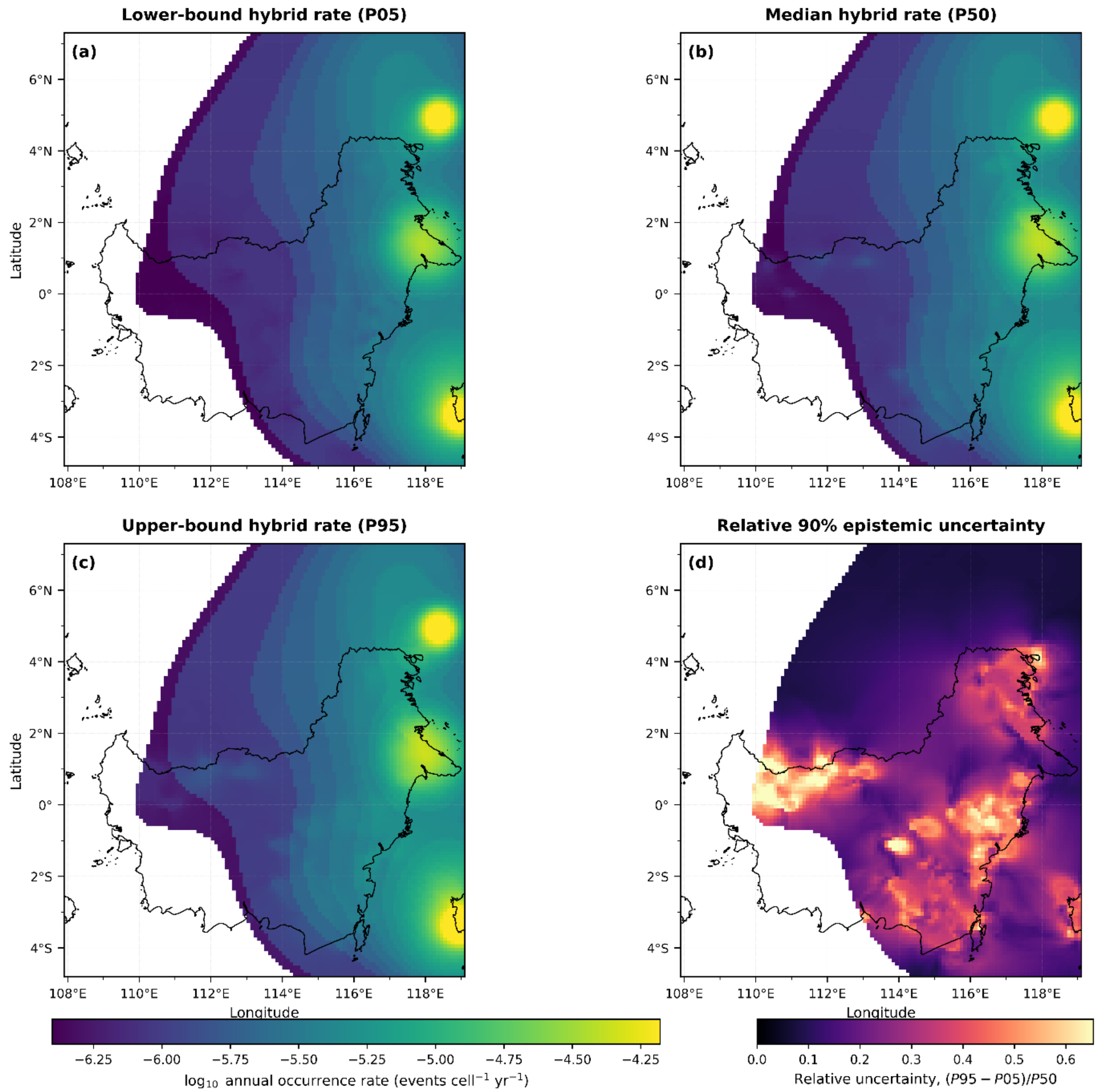

365 **Figure 3: Spatial distribution of epistemic uncertainty for the preferred SA9-based hybrid earthquake source model. Panels show the (a) lower (P05), (b) median (P50), and (c) upper (P95) annual earthquake occurrence rates derived from bootstrap realizations of the hybrid model. Panel (d) presents the relative epistemic uncertainty, quantified as the normalized width of the 90% credible interval, (P95−P05)/P50. The occurrence-rate maps are displayed using a common logarithmic color scale to facilitate comparison among the three percentile realizations.**

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3.6 Propagation of hybrid source models into seismic hazard

The selected source models were propagated through classical PSHA to evaluate their influence on PGA at return periods of 475 and 2475 years. Results were compared for the three catalog-based baselines, their corresponding hybrid models, and the equal-weight and CSEP-performance-weighted source-model ensembles. Regional hazard distributions were subsequently evaluated using the performance-weighted ensemble.

Across the five provincial capitals, the individual hybrid models generally produced higher median PGA values than their corresponding catalog baselines (Fig. 4). For the 475-year return period, the relative increases ranged from approximately 2% to 29%. The largest changes occurred at Tanjung Selor for the BF- and SF4-based hybrids, where median PGA increased by approximately 29%, while the SA9-based hybrid produced its largest increase at Banjarmasin, at approximately 25%. Smaller changes were observed for the BF- and SF4-based hybrids at Banjarmasin.

For the 2475-year return period, increases in median PGA ranged from approximately 2% to 23%. The largest changes were again obtained at Tanjung Selor for the BF- and SF4-based hybrids, whereas the SA9-based hybrid showed increases of approximately 21% at Banjarmasin and 20% at Tanjung Selor. Despite differences in amplitude among the source-model families, the relative ordering of hazard among the five cities remained stable, with Tanjung Selor and Samarinda exhibiting the highest PGA values and Pontianak the lowest.

The equal-weight and CSEP-performance-weighted ensembles produced nearly identical PGA estimates across all five evaluation sites and for both return periods. Relative differences between the two weighting schemes ranged from −0.29% to 1.40% for the 475-year return period and from −0.22% to 0.90% for the 2475-year return period (Fig. 4). In all cases, the ensemble estimates remained within the range defined by the three individual hybrid models and preserved the same ranking of hazard among the five cities.

Figure 5 shows the regional PGA distribution obtained from the CSEP-performance-weighted ensemble. For both return periods, hazard increased from western and central Kalimantan toward the eastern and northeastern parts of the island. The highest PGA values were concentrated in northeastern Kalimantan, while the lowest values occurred in the western region. The 2475-year map retained the same broad spatial pattern as the 475-year map but exhibited higher PGA values throughout the study area.

4 Discussion

4.1 Statistical versus physical consistency in hybrid earthquake source modelling

Reliable earthquake source characterization for PSHA requires models that are capable of reproducing observed earthquake occurrence while remaining physically compatible with long-term tectonic deformation. The results demonstrate that these two requirements are not necessarily equivalent. Although several hybrid models achieved satisfactory retrospective

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forecasting performance within the CSEP framework (Fig. 2), the subsequent physical consistency screening showed that only three of the 126 candidate hybrid models satisfied both statistical and physical selection criteria (Tables 3 and 4).

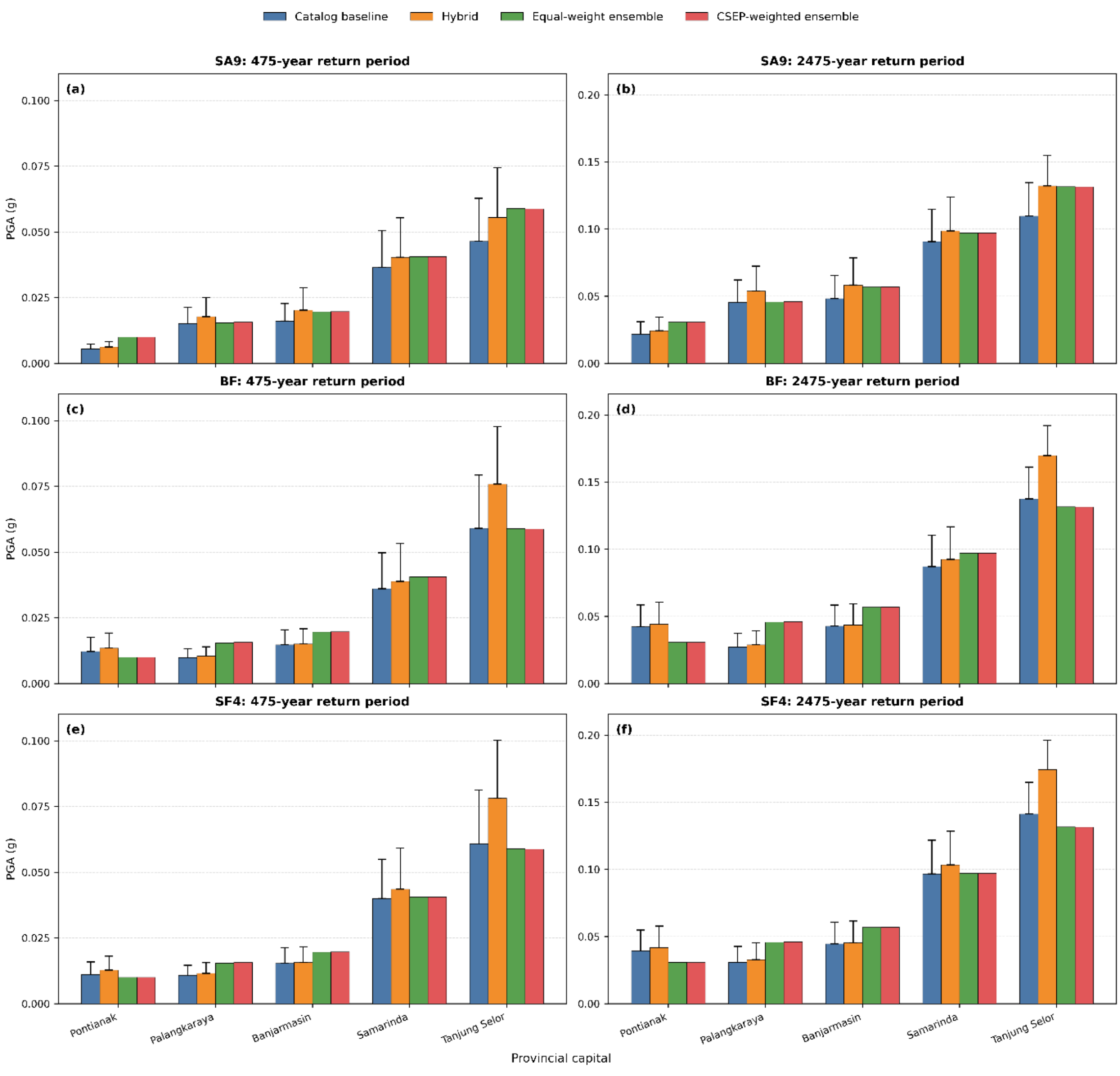

Figure 4: Comparison of PGA estimates from the catalog-based baseline, the corresponding hybrid source model, the equal-weight ensemble, and the CSEP-performance-weighted ensemble at five provincial capitals in Kalimantan. Rows correspond to the SA9, BF, and SF4 model families, while columns show return periods of 475 and 2475 years. Bars represent median PGA values. Upper error bars for the baseline and individual hybrid models indicate the interval from P50 to P95 obtained from the propagated epistemic source-model realizations.

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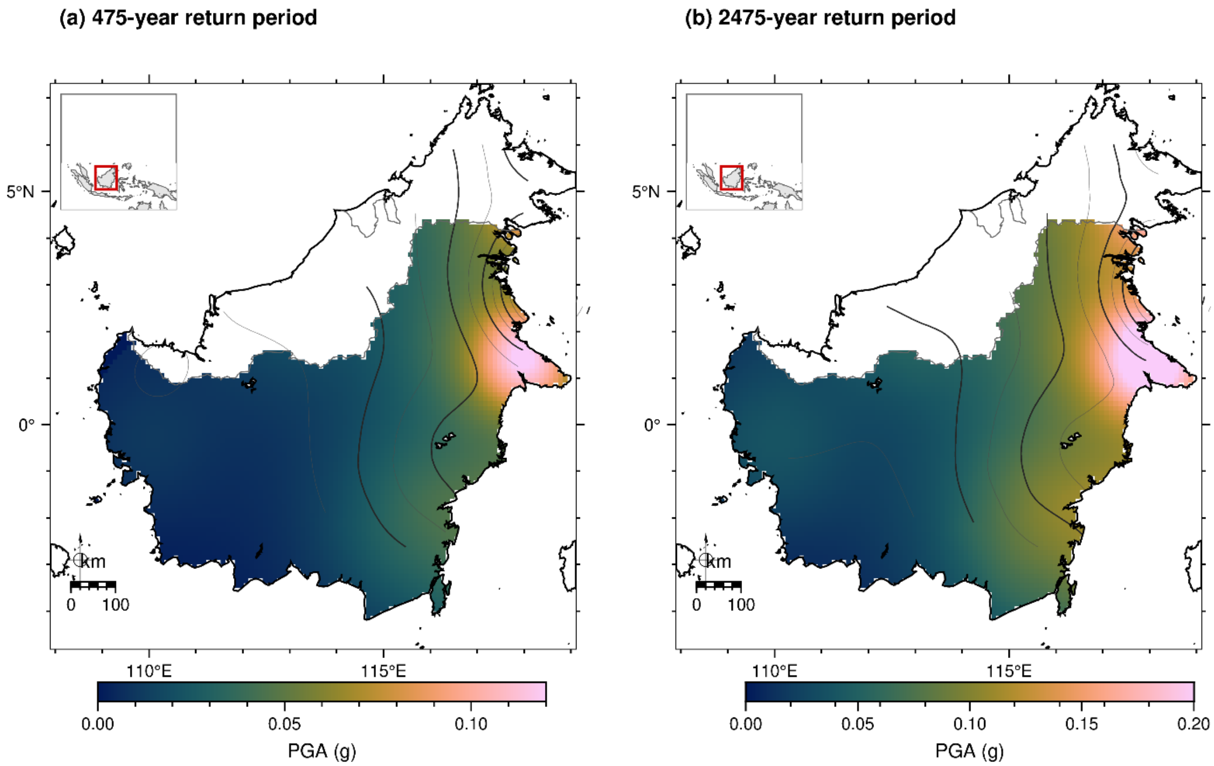

Figure 5 Regional distributions of peak ground acceleration obtained from the CSEP-performance-weighted hybrid source-model ensemble for return periods of (a) 475 years and (b) 2475 years. PGA values are expressed in units of g on a $0.1^\circ \times 0.1^\circ$ grid. The two panels use the same sequential color palette but separate color scales to preserve spatial variations within each return period.

A key finding of this study is that good retrospective forecasting performance does not necessarily imply physically realistic long-term earthquake productivity. As shown in Table 3, six of the seven evaluated geodetic scenarios generated implied seismic moment rates approximately 2.0–5.5 times larger than their corresponding regional geodetic moment budgets and were therefore rejected despite several exhibiting favorable CSEP performance. Only Scenario F satisfied the adopted physical consistency criterion, with a hybrid-to-budget ratio of 0.89–0.90, indicating compatibility between the implied long-term seismic moment release and the independently estimated tectonic deformation budget.

Previous studies have demonstrated that multiplicative hybrid models combining earthquake catalogs with geological or geodetic information can improve earthquake forecasting performance relative to single-data-source models (Rhoades et al., 2014, 2017; Strader et al., 2018). However, hybrid model selection has generally relied on statistical criteria such as likelihood improvement, information gain, or prospective forecasting performance. In contrast, the present framework introduces regional geodetic moment balance as an additional, independent screening criterion. Because geodetic deformation provides an observational constraint on long-term tectonic loading, comparison between geodetic and implied seismic moment release offers a physically meaningful test of whether statistically successful models remain compatible with regional deformation rates (Ward, 1998, 2007).

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Taken together, these findings indicate that statistical forecasting skill and physical consistency should be regarded as complementary rather than alternative criteria for earthquake source model selection. While retrospective CSEP evaluation identifies models that best reproduce observed seismicity, geodetic moment-budget screening ensures that the implied long-term seismicity remains physically compatible with regional tectonic deformation. The proposed dual-constraint framework therefore provides a more robust basis for PSHA source characterization and offers a transferable methodology for other low-seismicity regions where sparse earthquake catalogs coexist with measurable crustal deformation.

4.2 Role of Geodetic Constraints in Improving Hybrid Earthquake Source Models

The incorporation of geodetic information consistently improved the predictive capability of the catalog-based earthquake source models while preserving their probabilistic structure. As shown in Fig. 2, several hybrid models achieved substantially higher retrospective CSEP pass rates than their corresponding catalog-based baselines, particularly over the 3-year forecasting horizon, where improvements reached approximately 20 percent points for both the SA9 and SF4 model families. These results indicate that geodetic observations provide complementary spatial information that is not fully represented by historical earthquake catalogs alone.

This complementarity is physically expected because earthquake catalogs and geodetic observations describe different stages of the earthquake cycle. Earthquake catalogs record accumulated stress release through past seismic events, whereas GNSS-derived strain fields quantify the ongoing accumulation of tectonic deformation. Consequently, geodetic observations can provide independent information on the spatial distribution of future earthquake occurrence, particularly where historical seismicity is sparse (Bird and Kreemer, 2015; Nishimura, 2022; Rhoades et al., 2017; Shen et al., 2007). Bird and Kreemer (2015) further emphasized that geodetic strain reflects long-term tectonic loading, making it physically complementary to catalog-based earthquake occurrence.

The contribution of geodetic constraints is particularly relevant for Kalimantan, where moderate-to-large earthquakes are relatively infrequent and recurrence intervals are long. Under these conditions, catalog-based smoothing models inevitably suffer from larger epistemic uncertainty because future earthquake occurrence must be inferred from a limited number of historical events. By introducing independently observed crustal deformation, the hybrid framework supplements the incomplete spatial information contained in the earthquake catalog without replacing its empirical constraints on earthquake occurrence. This interpretation is supported by the hazard results (Fig. 5), where the selected hybrid models consistently produced higher median PGA values than the corresponding catalog-based models, with increases ranging from approximately 2–29% for the 475-year return period and 2–23% for the 2475-year return period.

The present findings are consistent with previous studies demonstrating that hybrid earthquake forecasting models generally outperform individual catalog-based or geodetic models when the underlying datasets provide complementary information. Rhoades et al. (2017) showed that incorporating strain-rate covariates into multiplicative forecasting models significantly increased forecasting skill relative to catalog-only models. Similarly, Bird et al. (2015) demonstrated that the GEAR1 hybrid model consistently outperformed either its seismicity- or geodetic-based parent models at the global scale. Bayona et al. (2022)

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further reported that although the performance of hybrid models may vary under prospective evaluation because of temporal variability in optimized parameters, hybrid approaches remain one of the most effective strategies for integrating independent geophysical datasets into earthquake forecasting. Likewise, Nishimura (2022) concluded that GNSS-derived models are most informative when combined with seismicity-based models rather than used independently. The present study extends these findings by demonstrating that similar benefits can also be achieved in a low-seismicity continental region where earthquake catalogs alone provide relatively weak spatial constraints.

Nevertheless, the results should not be interpreted as indicating that geodetic observations can replace earthquake catalogs. GNSS-derived deformation fields may include aseismic deformation and remain sensitive to assumptions regarding crustal rheology, coupling coefficients, and the conversion from strain rate to seismic moment rate (Bird and Kreemer, 2015; Nishimura, 2022). Conversely, earthquake catalogs remain indispensable because they directly constrain long-term earthquake frequency and magnitude distributions. The principal contribution of the proposed framework therefore lies in integrating these two independent sources of information into a physically consistent earthquake source model rather than substituting one for the other.

4.3 Performance-Based Logic-Tree Weighting in PSHA

Logic trees provide the standard framework for representing epistemic uncertainty in PSHA by combining alternative earthquake source models through weighted branches (Bommer and Scherbaum, 2008; Field et al., 2017). In this study, however, the hazard estimates obtained using equal-weight and CSEP-performance-weighted ensembles were nearly indistinguishable (Fig. 4). Across the five evaluation sites, the difference in median PGA ranged from −0.29% to 1.40% for the 475-year return period and from −0.22% to 0.90% for the 2475-year return period, while the regional hazard patterns remained virtually identical (Fig. 5). These results indicate that the selected hybrid models contributed consistently to the final hazard estimates regardless of the adopted weighting strategy.

The limited influence of branch weighting is expected because the three selected hybrid models exhibited similarly high retrospective forecasting performance (Table 4), resulting in normalized branch weights that remained close to equal weighting. Consequently, the principal improvement in hazard estimation originated from the prior selection of statistically and physically admissible earthquake source models rather than from the weighting scheme itself. This observation suggests that equal weighting may provide a reasonable approximation when competing models exhibit comparable predictive skill, whereas performance-based weighting is likely to become more influential when candidate models display substantially different forecasting performance (Bommer and Scherbaum, 2008; Field et al., 2017; Werner et al., 2010).

4.4 Limitations and Future Work

This study has several limitations that should be considered when interpreting the proposed framework. The methodology was evaluated using Kalimantan as a natural laboratory for a low-seismicity region, and its applicability to tectonically more active environments remains to be demonstrated. In addition, the hybrid formulation incorporated only GNSS-derived geodetic

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moment-rate information as the physical constraint, whereas other datasets such as active-fault geometry, geological slip rates, or additional geophysical observations may provide complementary information. Future work should therefore evaluate the framework across contrasting tectonic settings, including regions such as Java and Sumatra, extend the hybrid formulation to integrate multiple physical constraints, and assess its temporal robustness through prospective CSEP experiments. Such developments would further strengthen the proposed statistical–physical framework and broaden its applicability for earthquake source characterization in probabilistic seismic hazard analysis.

5 Conclusion

This study developed a statistical–physical framework for integrating independently validated catalog-based and GNSS-derived geodetic earthquake source models for probabilistic seismic hazard analysis (PSHA). Unlike previous hybrid approaches that primarily relied on statistical forecasting performance, the proposed framework combined retrospective CSEP evaluation with an independent physical screening based on the regional geodetic moment budget. Of the 126 candidate hybrid models evaluated, only three satisfied both statistical and physical selection criteria, demonstrating that satisfactory forecasting performance alone is insufficient to ensure physically plausible earthquake source models. Among the selected models, the hybrid derived from the adaptive smoothing baseline achieved the highest average retrospective CSEP pass rate (67.5%), while physical screening rejected six of the seven evaluated geodetic scenarios because their implied seismic moment release exceeded the available geodetic moment budget.

Propagation of the selected hybrid models into PSHA showed that incorporating geodetic constraints systematically increased median peak ground acceleration by approximately 2–29% for the 475-year return period and 2–23% for the 2475-year return period through spatial redistribution of earthquake occurrence while preserving the regional seismicity rate. In contrast, equal-weight and CSEP-performance-weighted logic-tree ensembles produced nearly identical hazard estimates, differing by less than 1.5%, indicating that careful selection of statistically and physically admissible source models had a greater influence on hazard estimates than the branch-weighting strategy itself. Overall, the proposed framework provides a physically consistent and statistically validated methodology for earthquake source characterization and offers a transferable approach for improving PSHA in low-seismicity regions where earthquake catalogs alone provide limited constraints on long-term seismic potential.

Code and data availability

All analyses were performed using open-source scientific software, including Python, OpenQuake Engine, PyCSEP, GMT, and PyGMT. The scripts developed for hybrid model construction, statistical evaluation, uncertainty analysis, and hazard calculations are available from the corresponding author upon reasonable request. The relocated earthquake catalog used in this study was provided by the Indonesian National Center for Earthquake Studies (PuSGeN) and is not publicly available.

The processed datasets, hybrid seismicity-rate models, hazard outputs, and analysis scripts used in this study are available from the corresponding author upon reasonable request.

Supplement link

Not applicable.

Author contributions

Yuliastuti: Conceptualization, methodology, software, formal analysis, investigation, visualization, writing—original draft, and project administration. Irwan Meilano: Supervision, methodology, validation, writing—review and editing, particularly on the geodetic methodology and interpretation of geodetic constraints. Nanang T. Puspito: Supervision, validation, writing—review and editing, particularly on seismic hazard methodology and interpretation of the results. Suchi Rahmadani: Validation, visualization, writing—review and editing. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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