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Disaster impact forecasting framework for multi hazard disaster risk assessment

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Disaster Risk Management:
Evidence based disaster risk reduction policy making

- The decision problem for Disaster Risk Reduction
  - Find the optimal solution to mitigate the disaster risk.
- Evidence based decision making:
  - The severity of disaster impact should be measured
  - The disaster risk is being measured based on the impact of the disaster.

Disaster Risk Management: Evidence based disaster risk reduction policy making

Definition:

- Disaster impact metrics $M_1, \ldots, M_k$ are random variable that quantify the impact of a disastrous event.
- The decision makers need to have an estimation of disaster impact metrics $\boldsymbol{M} = (M_1, \ldots, M_k)'$ under different scenarios.

Disaster Risk Management:
Evidence based disaster risk reduction policy making

- Classic decision analysis approach:

$$\min_{\boldsymbol{\mathcal{D}}} L(\widehat{\boldsymbol{m}}), \qquad \widehat{m}_i = E(M_i \mid \boldsymbol{\mathcal{S}})$$

- $L(\cdot)$: The loss function
- $\widehat{m}_i$: ith dimension of estimated disaster impact
- $\boldsymbol{\mathcal{D}}$: The state space for decision vector (the decision space)
- $\boldsymbol{\mathcal{S}}$: Sigma-filed containing all the information used for estimating the impacts.

Disaster Risk Management:
Evidence based disaster risk reduction policy making

- $\boldsymbol{\mathcal{S}}$ is generated by three random vectors:
- Multi-Hazards severity: $\boldsymbol{H} = \left(H_1, \ldots, H_{m_1}\right)'$
- Other Systematic Risk drivers (uncontrollable at the moment): $\boldsymbol{R} = \left(R_1, \ldots, R_{m_2}\right)'$
- Intervention variables (decision variables): $\boldsymbol{X} = \left(X_1, \ldots, X_{m_3}\right)'$
- Suppose $\boldsymbol{\mathcal{H}}$, $\boldsymbol{\mathcal{R}}$, and $\boldsymbol{\mathcal{X}}$ are sigma-fields generated by $\boldsymbol{H}$, $\boldsymbol{R}$, and $\boldsymbol{X}$ respectively:
- $\boldsymbol{\mathcal{S}} = \boldsymbol{\mathcal{H}} \otimes \boldsymbol{\mathcal{R}} \otimes \boldsymbol{\mathcal{X}}$

Disaster Risk Management:
Evidence based disaster risk reduction policy making

- Classic decision analysis approach:

$$\min_{\mathcal{D}} L(\widehat{\boldsymbol{m}}) = L\big(E(\boldsymbol{M}|\boldsymbol{h},\boldsymbol{r},\boldsymbol{x})\big),$$

- For a linear loss function:

$$\min_{\mathcal{D}} L(\widehat{\boldsymbol{m}}) = \boldsymbol{w} \cdot E(\boldsymbol{M}|\boldsymbol{h},\boldsymbol{r},\boldsymbol{x})$$

- Challenges:
  - Finding the estimated impact
  - Accounting for uncertainty
  - Accounting for time (considering the dynamic system)

Accounting for uncertainty: Disaster impact probability distribution

- One approach is to have an estimation of the conditional distribution, rather than the average point estimation

$$F_{\boldsymbol{M}}(\boldsymbol{m}\,|\boldsymbol{\mathcal{S}}) = \; P\;(M_1 < m_1, \dots, M_k < m_k |\; \boldsymbol{\mathcal{S}})$$

$F_{\boldsymbol{M}}(\boldsymbol{m}|\boldsymbol{\mathcal{S}})$: Disaster Impact Probability (DIP) distribution.

- Using $F_{\boldsymbol{M}}(\boldsymbol{m} \mid \boldsymbol{\mathcal{S}})$ we can have an interval estimation for the loss function
- DIP distribution can be used for analyzing systemic risks as well.

Other Disaster Risk Measures

Definition: Disaster impact Value at Risk ($\boldsymbol{DiVaR}$)

- Suppose the random Vectors $\boldsymbol{M}$, $\boldsymbol{H}$, $\boldsymbol{R}$, and $\boldsymbol{X}$ are defined as mentioned before.
- Disaster impact Value at Risk at the risk level α ($\boldsymbol{DiVaR}^{\alpha}$) is a multivariate Value at Risk measure, showing the worst-case scenario at the given risk level α, under conditions defined by $\boldsymbol{H}$, $\boldsymbol{R}$, and $\boldsymbol{X}$:

$$P\left(M_1 < DiVaR_1^{\alpha}, \dots, M_k < DiVaR_k^{\alpha} | \boldsymbol{\mathcal{S}}\right) = F_{\boldsymbol{M}}\left(DiVaR_1^{\alpha}, \dots, DiVaR_k^{\alpha} | \boldsymbol{\mathcal{S}}\right) = 1 - \alpha$$

Accounting for time:

- The random vectors $\boldsymbol{M}$, $\boldsymbol{H}$, $\boldsymbol{R}$, and $\boldsymbol{X}$ are not time invariant
  - Climate change can have impact on severity of hazards.
  - Socioeconomic, environmental and other factors are changing over time as well.
  - The intervention variables also are changing over time.
- $\boldsymbol{M}_t$ is impact measure vector at time t
- $\boldsymbol{H}_t$ is hazard severity measure vector at time t
- $\boldsymbol{R}_t$ is other Systematic Risk drivers' vector at time t
- $\boldsymbol{X}_t$ is Intervention's vector at time t

Accounting for time: Time-variant DPI distribution

- The Time-Variant DIP distribution can be defined as:

$$F_{\boldsymbol{M}_t}(\boldsymbol{m}|\boldsymbol{\mathcal{S}}_t) = P\left(M_{t,1} < m_1, \dots, M_{t,k} < m_k | \boldsymbol{\mathcal{S}}_t\right)$$

- IF the impact at time of the disaster only depends on the current situation of random vectors $\boldsymbol{H}_t$, $\boldsymbol{R}_t$, and $\boldsymbol{X}_t$,
- Then **DPI forecasting distribution** at time t:

$$F_{\boldsymbol{M}_t}(\boldsymbol{m}|\boldsymbol{\mathcal{S}}_{t-1}) = \int_{Suport(\boldsymbol{h},\boldsymbol{r},\boldsymbol{x})} F_{\boldsymbol{M}_t}(\boldsymbol{m}|\boldsymbol{h},\boldsymbol{r},\boldsymbol{x})\, dF_{\boldsymbol{H}_t,\boldsymbol{R}_t,\boldsymbol{X}_t}(\boldsymbol{h},\boldsymbol{r},\boldsymbol{x}|\boldsymbol{\mathcal{S}}_{t-1})$$

Accounting for time:
Risk measure forecasting

- Accordingly, the other risk measures can be estimated:

$$P\left(M_1 < DiVaR_1^{\alpha}, \dots, M_k < DiVaR_k^{\alpha} \middle| \boldsymbol{\mathcal{S}}_{t-1}\right) = 1 - \alpha$$

- New Practical Challenge: estimating forecasting DIP distribution

$$F_{\boldsymbol{M}_t}(\boldsymbol{m}|\boldsymbol{\mathcal{S}}_{t-1}) = \int_{Suport(\boldsymbol{h},\boldsymbol{r},\boldsymbol{x})} F_{\boldsymbol{M}_t}(\boldsymbol{m}|\boldsymbol{h},\boldsymbol{r},\boldsymbol{x})\, dF_{\boldsymbol{H}_t,\boldsymbol{R}_t,\boldsymbol{X}_t}(\boldsymbol{h},\boldsymbol{r},\boldsymbol{x}|\boldsymbol{\mathcal{S}}_{t-1})$$

A Multi-Hazard Example:
Earthquake and Tsunami risk forecasting in India

- Disaster impact metrics:
  - Casualties
  - Infrastructure damage (million USD)
- Hazard severity metrics
  - Earthquake Magnitude
  - Tsunami height (m)
- Risk factors and decision variables
  - Maximum and Minimum Population Density (district level)
  - Wealth inequality (Gini Coefficient; district level)
  - Gross National Income per capita (district level)
  - Human Development Index (district level)
  - Subnational Vulnerability Index (SGVI; district level)
  - Flood Risk Index (district level)

- Dataset:
- Earthquakes and Tsunamis from 2000 to 2025
- Contains 20 regions (to districts)
- Time series are also from 2000 to 2025

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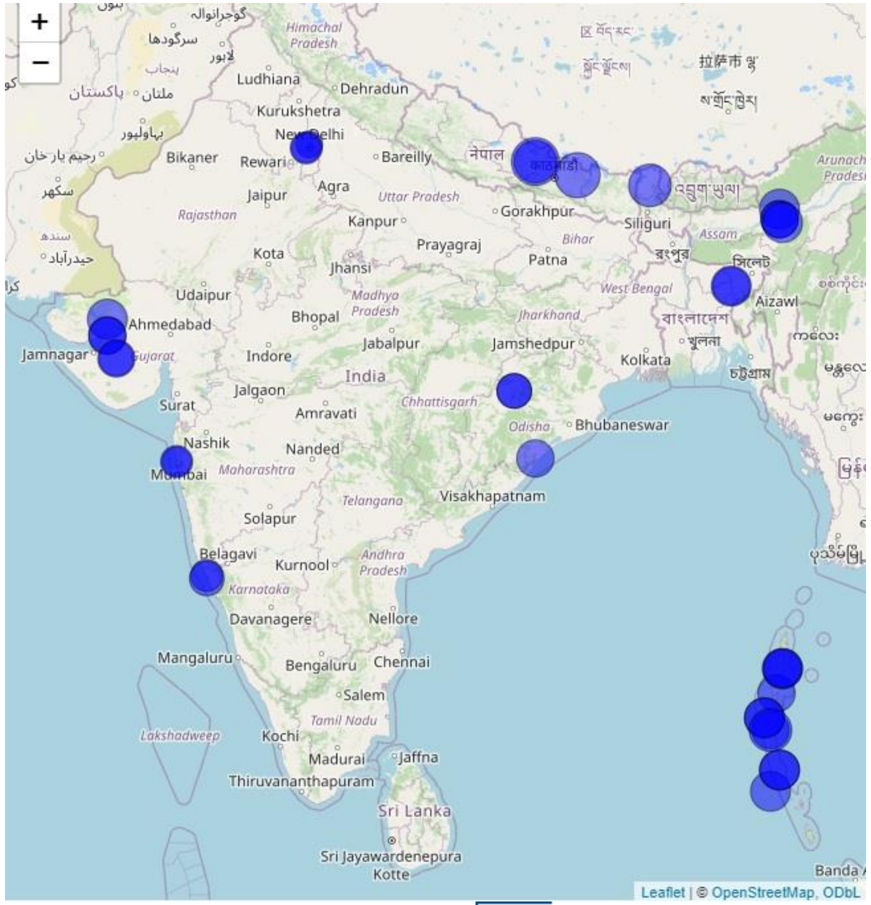
Earthquake Magnitude



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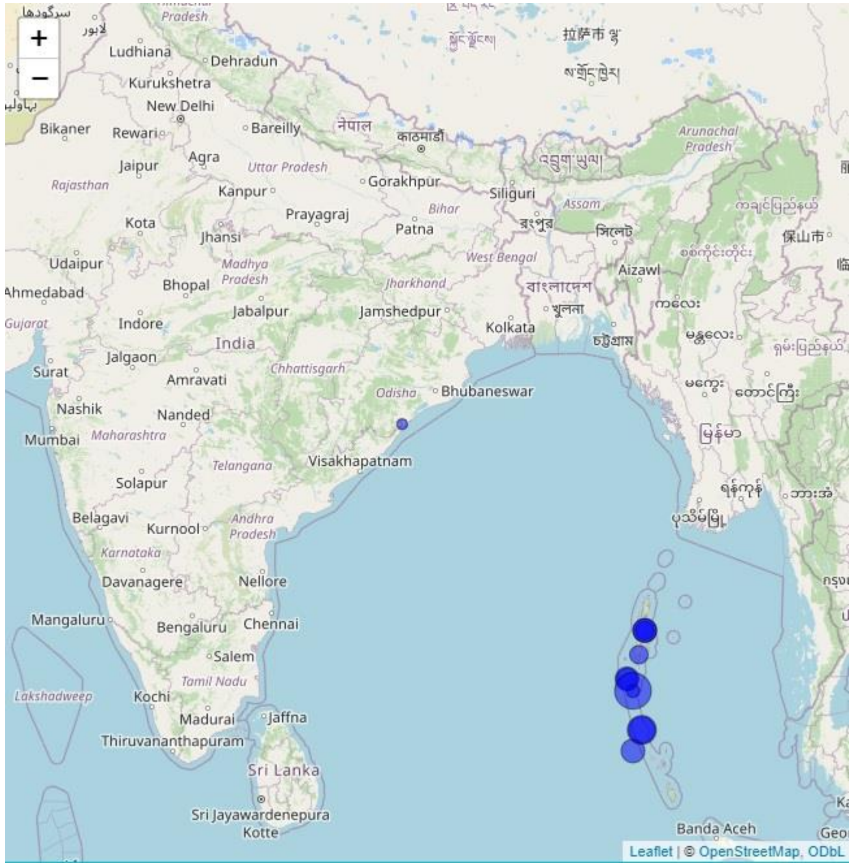
Tsunami height (m)



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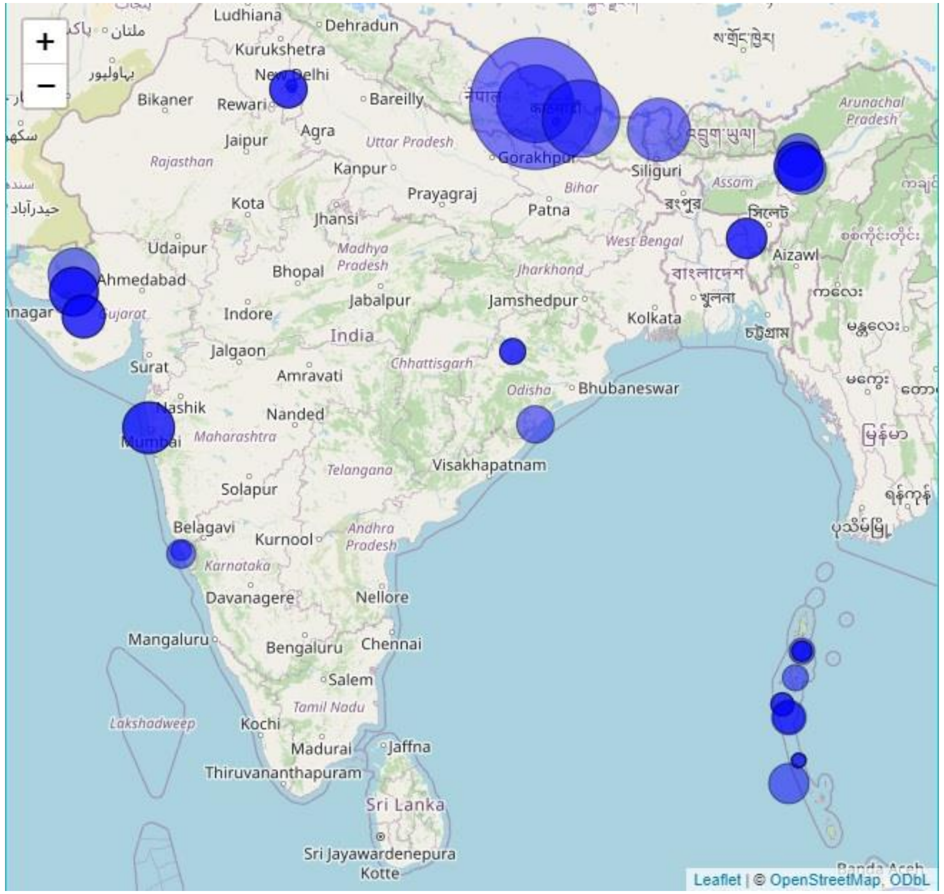
Casualties (Log)



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A Multi-Hazard Example:
Earthquake and Tsunami risk forecasting in India

- Disaster impact metrics:
  - Casualties (Log)
  - Infrastructure damage (million USD;Log)
- Hazard severity metrics
  - Earthquake Magnitude
  - Tsunami height (m)
- Risk factors and decision variables
  - Maximum and Minimum Population Density (district level)
  - Wealth inequality (Gini Coefficient; district level)
  - Gross National Income per capita (district level)
  - Human Development Index (district level)
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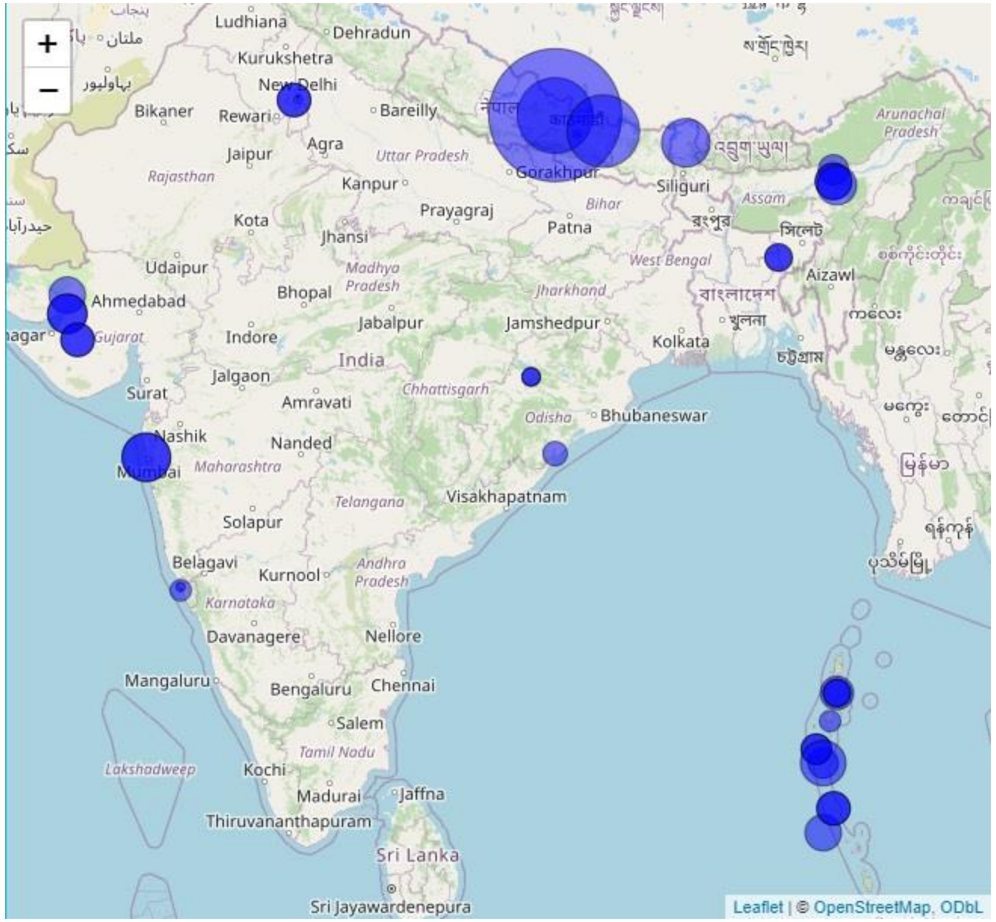
Infrastructure damage (Log)



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A Multi-Hazard Example: Earthquake and Tsunami risk forecasting in India

- Expected loss function forecasting

Casualties (log)

Coefficient	Estimate	StdError	t.value	P.Value
(Intercept)	-2.00462	0.762024	-2.63065	0.013502
HDI	-1.63288	0.683523	-2.38892	0.023625
Flood Risk Index * Tsunami Generated: $FRI*Tsunami$	-1.07342	0.195957	-5.47783	6.73E-06
Max. Population Density: PD_{max}	1.60E-05	2.83E-06	5.639259	4.30E-06
Magnitude: Mag	0.646867	0.081571	7.930146	9.56E-09
Building vulnerability (High & Very High): BVH	0.34236	0.114703	2.984758	0.005712

Infrastructural Damage (log)

Coefficient	Estimate	StdError	t.value	P.value
(Intercept)	-3.37143	0.627612	-5.37184	9.03E-06
HDI	-0.5386	0.562958	-0.95674	0.346608
Flood Risk Index * Tsunami Generated: $FRI*Tsunami$	-0.64485	0.161393	-3.99554	0.000405
Max. Population Density: PD_{max}	1.92E-05	2.33E-06	8.218684	4.62E-09
Magnitude: Mag	0.690487	0.067183	10.27778	3.53E-11
Building vulnerability (High & Very High): BVH	0.415559	0.094471	4.398827	0.000134

A Multi-Hazard Example:
Earthquake and Tsunami risk forecasting in India

- DiVaR ($\alpha = 0.1$)

Casualties (log)

Coefficient	β	Lower Bd.	Upper Bd.
(Intercept)	-2.50737	-2.50737	-0.9376
HDI	-1.13671	-2.55026	-0.74083
Flood Risk Index * Tsunami Generated: $FRI*Tsunami$	-0.77245	-0.82771	-0.45736
Max. Population Density: PD_{max}	2.18E-05	1.40E-06	1.797E+308
Magnitude: Mag	0.711235	0.604371	0.739076
Building vulnerability (High & Very High): BVH	0.27368	-1.797E+308	0.528711

Infrastructural Damage (log)

Coefficient	β	Lower Bd.	Upper Bd.
(Intercept)	-3.37367	-3.37461	-1.9943
HDI	-0.39462	-1.68982	-0.21934
Flood Risk Index * Tsunami Generated: $FRI*Tsunami$	-0.68063	-0.71278	-0.35131
Max. Population Density: PD_{max}	2.63E-05	8.95E-07	1.797E+308
Magnitude: Mag	0.714562	0.631419	0.726271
Building vulnerability (High & Very High): BVH	0.315278	-1.797E+308	0.553073

A Multi-Hazard Example:
Earthquake and Tsunami risk forecasting in India

- DiVaR ($\alpha = 0.1$)

$$
\begin{cases}
\widehat{DiVaR}^{\alpha}_{\text{Casualties (log)}|s_t} = \\
\hat{\beta}^{\alpha}_{0,1} + \hat{\beta}^{\alpha}_{1,1} HDI_t + \hat{\beta}^{\alpha}_{2,1} FRI * Tsunami + \\
\hat{\beta}^{\alpha}_{3,1} PD^{max}_t + \hat{\beta}^{\alpha}_{4,1} Mag + \hat{\beta}^{\alpha}_{5,1} BVH \\
\\
\widehat{DiVaR}^{\alpha}_{\text{Infrastructural Damage (log)}|s_t} = \\
\hat{\beta}^{\alpha}_{0,2} + \hat{\beta}^{\alpha}_{1,2} HDI_t + \hat{\beta}^{\alpha}_{2,2} FRI * Tsunami + \\
\hat{\beta}^{\alpha}_{3,2} PD^{max}_t + \hat{\beta}^{\alpha}_{4,2} Mag + \hat{\beta}^{\alpha}_{5,2} BVH
\end{cases}
$$

A Multi-Hazard Example:
Earthquake and Tsunami risk forecasting in India

- Scenario based risk forecasting:

Scenario:

  - Region: Gopalpur (Orissa), time: 2030; 2035
  - Hazards: $\mathrm{M} = 6.6$ earthquake with triggering tsunami
  - Disaster risk measures: Current situation

Historical event:

2002: $\mathrm{M} = 6.6$ earthquake with triggered tsunami

A Multi-Hazard Example:
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- Scenario based risk forecasting:

	Casualties	Infrastructure damage(million usd)	$\widehat{DiVaR}^{\alpha}_{\text{Cas.}\mid s_t}$	$\widehat{DiVaR}^{\alpha}_{\text{Inf. Damage}\mid s_t}$
Historical event (2002)	15	5.6	-	-
Scenario based forecast (2030)	3.301051 (expected value)	2.791313 (expected value)	9.637927	4.889014
Scenario based forecast (2035)	3.079464 (expected value)	2.735143 (expected value)	9.201114	4.827700

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Practical Challenges

- Detecting risk factors
- Including local characteristics
- Including policy-makers' interested disaster impact metrics
- Accounting tail dependencies
- Accessing Necessary data

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Effective policy crafting hinges on informative models.

The impact of a model depends on its practical usability.

Q&A

Building Models for Policy Making

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