

Volume-06|Issue-08|August|Year-2026 ISSN: 3049-2343

International Journal of Academic and Industrial Research Innovations(IJAIRI)

**Research Book Title :Deep-Learning Geophysics for Earthquake Forecasting,
Subsurface Characterization and Geological Carbon Storage**

¹Murali Krishna Pasupuleti

¹Research Director

¹National Education Services,

¹New Delhi,India

¹mkrishnap2050@gmail.com

Abstract:

Deep-learning geophysics connects heterogeneous observations to uncertain processes in the crust and subsurface. This monograph develops a research framework for earthquake forecasting, subsurface characterization and geological carbon storage using only relevant or transferable methods in the supplied source corpus. Ten themes link scale-aware inference, prospective seismic forecasting, inverse uncertainty, storage containment, spatial causality, physical constraints, graph structure, provenance, adaptive monitoring and public accountability. Five chapters progress from earth-system foundations through statistical explanation and deep learning to scalable data operations and applications. The framework distinguishes event detection from future-earthquake probabilities, a plausible subsurface image from a unique geological truth, and measured carbon outcomes from modelled storage expectations. Proposed research outputs include catalog audits, uncertainty budgets, causal ledgers, graph-construction records, physics-constrained surrogates, prospective forecast archives and storage monitoring plans. Validation uses chronological and spatial holdouts, numerical forward comparisons, proper scoring rules and sensitivity to alternative geology. Carbon accounting links subsurface, site and atmospheric observations without treating any one stream as conclusive. The supplied bibliography supports several methods directly, but earthquake forecasting is developed as a research design rather than presented as a result from those works. Applications are framed as staged tests with independent review, response thresholds and locally governed data access. The result is a bounded evidence standard for geophysical prediction and climate-related subsurface decisions.

Keywords

deep-learning geophysics, earthquake forecasting, seismicity, subsurface characterization, geological carbon storage, inverse problems, seismic waveforms, physics-informed learning, neural operators, graph neural networks, fault connectivity, probabilistic forecasts, spatiotemporal inference, remote sensing, monitoring verification, geospatial data, uncertainty quantification, digital twins, reservoir monitoring, model governance, climate integrity

Copyright:

© 2026 by Murali Krishna Pasupuleti.

Table of Contents

Abstract and Keywords

Chapter 1 Earth-system foundations and geophysical research design

Chapter 2 Statistical explanation, spatial inference and causal design

Chapter 3 Deep learning, physics constraints and validation

Chapter 4 Scalable geophysical data and reproducible operations

Chapter 5 Hazard, resource and climate applications

1.1 Physical systems and observational scales

1.2 Seismic observations and earthquake forecasting targets

1.3 Subsurface characterization as an inverse problem

1.4 Geological carbon storage and containment

1.5 Hazard ethics and defensible inference

2.1 Spatiotemporal baselines and clustering

2.2 Uncertainty propagation across sensors and models

2.3 Spatial causal inference for anthropogenic impacts

2.4 Carbon accounting and storage verification

2.5 Sensitivity to geological priors and sparse coverage

3.1 Waveform encoders and event representation

3.2 Graph learning for faults and sensor networks

3.3 Physics-informed inversion and neural operators

3.4 Prospective earthquake forecast evaluation

3.5 Carbon-plume prediction and interpretability

4.1 Multisource spatial data engineering

4.2 Streaming seismic and reservoir monitoring

4.3 Simulation ensembles and digital twins

4.4 Model releases, drift and independent challenge

4.5 Integrity, access and auditability

5.1 Regional earthquake hazard services

5.2 Fault mapping and subsurface decisions

5.3 Carbon storage site screening

5.4 Long-term monitoring and corrective action

5.5 Research agenda and public accountability

Glossary

References

Analytical Index

List of Figures

Figure 1.1 Earth-observation and inference pathway

Figure 2.1 Spatial explanation and uncertainty chain

Figure 3.1 Physics-constrained prediction design

Figure 4.1 Reproducible geophysical monitoring lifecycle

Figure 5.1 Hazard and storage governance loop

List of Tables

Table 1.1 Domain scales and measurement limits

Table 2.1 Statistical identification and uncertainty

Table 3.1 Deep-learning validation gates

Table 4.1 Geospatial data and operations controls

Table 5.1 Application evidence and action thresholds

Chapter 1 Earth-system foundations and geophysical research design

The first chapter defines three geophysical questions whose observations and consequences differ. Scale, physical assumptions and uncertainty organize a defensible research design. The chapter's proposals are research protocols, not findings (Pasupuleti 2026d; Pasupuleti 2026i; Pasupuleti 2023e).

For earth-system foundations and geophysical research design, record the unit, time horizon, source and interpretation for every claim. Where evidence cannot distinguish plausible mechanisms, report that uncertainty as a substantive result. The figure and evaluation table set out the tests needed for this chapter.

Figure 1.1 Earth-observation and inference pathway

Physical domain → Measured signal → Bounded inference

Schematic research pathway; arrows denote analytical dependencies rather than observed causal effects.

Table 1.1 Domain scales and measurement limits

Analytical object	Key test	Research record
Scale	What process and horizon?	Domain matrix
Seismicity	Which events are detected?	Catalog audit
Subsurface	Which properties are identifiable?	Inverse map
Storage	What containment evidence?	Site model

1.1 Physical systems and observational scales

Earthquake sequences, subsurface structure and injected carbon dioxide involve different processes and time scales. A common learning framework must preserve those differences. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2026d; Pasupuleti 2026i; Pasupuleti 2023e). Its claims should be transferred only within the assumptions of the earth-system setting.

Define spatial support, temporal resolution, governing processes and measurement error separately for each application. This design should distinguish an observed

geophysical signal from an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2026d; Pasupuleti 2026i; Pasupuleti 2023e).

The expected research output is a three-domain scale and evidence matrix. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

A seismic waveform and a satellite pixel have different sampling support; averaging them into one feature can conceal a mismatch of scale. For physical systems and observational scales, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

For physical systems and observational scales, compare alternative sensor footprints and spatial scales. A change in detection capacity can appear as a change in the underlying earth process. Report the quantitative range with units and thresholds.

The physical reading of a three-domain scale and evidence matrix identifies what was resolved and what remains hidden. Core observations, field logs or waveform diagnostics can corroborate a process, while extrapolation beyond them remains conditional.

The next study using a three-domain scale and evidence matrix should target the least observed structure capable of overturning its conclusion. Specify a feasible new measurement and its expected resolving power.

A scale table should separate wave propagation at station level from tectonic loading over years and plume migration over decades. Analysts can then mark which variables are observed and which are inferred. Such a table prevents a shared neural architecture from implying a shared physical forecast target.

1.2 Seismic observations and earthquake forecasting targets

Seismic catalogs and waveforms describe events after detection; earthquake forecasts concern future probabilities over a specified region and horizon. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2026c; Pasupuleti 2023d; Pasupuleti 2022a). Its claims should be transferred only within the assumptions of the earth-system setting.

Separate event detection, location, magnitude estimation and probabilistic forecasting; predefine the forecast target and baseline. This design should distinguish an observed geophysical signal from an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2026c; Pasupuleti 2023d; Pasupuleti 2022a).

The expected research output is a catalog-quality audit and prospective forecasting protocol. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

A newly installed station can increase recorded small events without changing underlying seismicity. Catalog completeness must be revisited. For seismic observations and earthquake forecasting targets, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

For seismic observations and earthquake forecasting targets, compare alternative sensor footprints and spatial scales. A change in detection capacity can appear as a change in the underlying earth process. Report the quantitative range with units and thresholds.

The physical reading of a catalog-quality audit and prospective forecasting protocol identifies what was resolved and what remains hidden. Core observations, field logs or waveform diagnostics can corroborate a process, while extrapolation beyond them remains conditional.

The next study using a catalog-quality audit and prospective forecasting protocol should target the least observed structure capable of overturning its conclusion. Specify a feasible new measurement and its expected resolving power.

Earthquake catalogs should retain station metadata and detection methods with every revision. A blind benchmark can hold out a later interval, count missed smaller events and evaluate probabilities in predefined spatial cells. It must not promote accurate event classification into a claim of predicting occurrence.

1.3 Subsurface characterization as an inverse problem

Surface and borehole measurements constrain underground properties indirectly, with many earth models fitting the same observations. The literature in the supplied corpus

supplies conceptual or methodological support for this question (Pasupuleti 2023e; Pasupuleti 2026i; Pasupuleti 2022b). Its claims should be transferred only within the assumptions of the earth-system setting.

Combine geologic prior information, spatial data and forward-model residuals; record nonuniqueness and resolution limits. This design should distinguish an observed geophysical signal from an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2023e; Pasupuleti 2026i; Pasupuleti 2022b).

The expected research output is an inverse-problem specification with uncertainty maps. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

Two velocity models may explain the same travel times yet place a fault at different depths. Retain both when making decisions. For subsurface characterization as an inverse problem, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

For subsurface characterization as an inverse problem, compare alternative sensor footprints and spatial scales. A change in detection capacity can appear as a change in the underlying earth process. Report the quantitative range with units and thresholds.

The physical reading of an inverse-problem specification with uncertainty maps identifies what was resolved and what remains hidden. Core observations, field logs or waveform diagnostics can corroborate a process, while extrapolation beyond them remains conditional.

The next study using an inverse-problem specification with uncertainty maps should target the least observed structure capable of overturning its conclusion. Specify a feasible new measurement and its expected resolving power.

A synthetic forward experiment with two plausible earth structures can establish where seismic travel times distinguish them and where they do not. The inversion output should report these ambiguity zones. A decision about drilling or storage should carry both realizations when they imply different fault locations.

1.4 Geological carbon storage and containment

Subsurface carbon storage requires evidence on reservoir capacity, seal integrity, fluid migration and monitoring detectability. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2026k; Pasupuleti 2026e; Pasupuleti 2026g). Its claims should be transferred only within the assumptions of the earth-system setting.

Specify reservoir, pressure, fault and plume variables with distinct observation sources and monitoring times. This design should distinguish an observed geophysical signal from an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2026k; Pasupuleti 2026e; Pasupuleti 2026g).

The expected research output is a storage-site conceptual model and evidence register. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

A high capacity estimate can coexist with a poorly understood seal. Keep capacity and containment as separate decision gates. For geological carbon storage and containment, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

For geological carbon storage and containment, compare alternative sensor footprints and spatial scales. A change in detection capacity can appear as a change in the underlying earth process. Report the quantitative range with units and thresholds.

The physical reading of a storage-site conceptual model and evidence register identifies what was resolved and what remains hidden. Core observations, field logs or waveform diagnostics can corroborate a process, while extrapolation beyond them remains conditional.

The next study using a storage-site conceptual model and evidence register should target the least observed structure capable of overturning its conclusion. Specify a feasible new measurement and its expected resolving power.

Storage studies can pair a capacity estimate with a separate seal and monitoring analysis. Pressure history, injection volume and repeated geophysics constrain different parts of the system. One useful research question is whether the available array would detect an unexpected pathway before it reaches a sensitive boundary.

1.5 Hazard ethics and defensible inference

An uncertain forecast or storage warning can affect public decisions. Communication must separate model capability from operational authorization. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2026c; Pasupuleti 2026b; Pasupuleti 2024b). Its claims should be transferred only within the assumptions of the earth-system setting.

Pre-register thresholds, oversight roles, reporting uncertainty and response paths before a pilot. This design should distinguish an observed geophysical signal from an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2026c; Pasupuleti 2026b; Pasupuleti 2024b). The expected research output is a hazard communication and governance protocol. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

Public communication should not turn a changing probability into a precise event prediction. Specify the horizon and response. For hazard ethics and defensible inference, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

For hazard ethics and defensible inference, compare alternative sensor footprints and spatial scales. A change in detection capacity can appear as a change in the underlying earth process. Report the quantitative range with units and thresholds.

The physical reading of a hazard communication and governance protocol identifies what was resolved and what remains hidden. Core observations, field logs or waveform diagnostics can corroborate a process, while extrapolation beyond them remains conditional.

The next study using a hazard communication and governance protocol should target the least observed structure capable of overturning its conclusion. Specify a feasible new measurement and its expected resolving power.

A communication rehearsal can give emergency managers forecasts with different levels of calibration and ask how decisions change. The goal is to test whether probability, uncertainty and time horizon are understood. Public-facing language should be reviewed independently of the model's mathematical score.

Chapter 2 Statistical explanation, spatial inference and causal design

The second chapter studies spatial dependence, competing explanations and the propagation of uncertainty. Statistical inference supports interpretation only when detection and priors are explicit. The chapter's proposals are research protocols, not findings (Pasupuleti 2023d; Pasupuleti 2026f; Pasupuleti 2021).

For statistical explanation, spatial inference and causal design, record the unit, time horizon, source and interpretation for every claim. Where evidence cannot distinguish plausible mechanisms, report that uncertainty as a substantive result. The figure and evaluation table set out the tests needed for this chapter.

Figure 2.1 Spatial explanation and uncertainty chain

Spatial observation → Alternative causes → Uncertainty audit

Schematic research pathway; arrows denote analytical dependencies rather than observed causal effects.

Table 2.1 Statistical identification and uncertainty

Analytical object	Key test	Research record
Dependence	How do events cluster?	Baseline fit
Sensors	What uncertainty propagates?	Error budget
Causality	Could operations explain change?	Identification ledger
Carbon	Which observations reconcile?	MRV map

I. Scale-aware earth-system inference

Physical processes and sensor supports must remain explicit. For scale-aware earth-system inference, identify the measured quantity, spatial support, observation time and relevant physical process (Pasupuleti 2026d; Pasupuleti 2026i; Pasupuleti 2023e). A credible interpretation compares the proposed mechanism with at least one alternative compatible with the observations. The supplied studies motivate these

transferable methods (Pasupuleti 2026d; Pasupuleti 2026i; Pasupuleti 2023e). Limits of location, detection and model form must remain visible.

The research artifact for scale-aware earth-system inference records assumptions, independent validation and a decision boundary. Reviewers should know whether a claim arises from direct measurement, forward simulation or a learned approximation.

II. Prospective seismic forecasting

A probability forecast requires a fixed horizon and future test. For prospective seismic forecasting, identify the measured quantity, spatial support, observation time and relevant physical process (Pasupuleti 2026c; Pasupuleti 2023d; Pasupuleti 2022a).

A credible interpretation compares the proposed mechanism with at least one alternative compatible with the observations. The supplied studies motivate these transferable methods (Pasupuleti 2026c; Pasupuleti 2023d; Pasupuleti 2022a). Limits of location, detection and model form must remain visible.

The research artifact for prospective seismic forecasting records assumptions, independent validation and a decision boundary. Reviewers should know whether a claim arises from direct measurement, forward simulation or a learned approximation.

III. Subsurface inverse uncertainty

Multiple earth models can fit the same incomplete data. For subsurface inverse uncertainty, identify the measured quantity, spatial support, observation time and relevant physical process (Pasupuleti 2023e; Pasupuleti 2026i; Pasupuleti 2022b).

A credible interpretation compares the proposed mechanism with at least one alternative compatible with the observations. The supplied studies motivate these transferable methods (Pasupuleti 2023e; Pasupuleti 2026i; Pasupuleti 2022b). Limits of location, detection and model form must remain visible.

The research artifact for subsurface inverse uncertainty records assumptions, independent validation and a decision boundary. Reviewers should know whether a claim arises from direct measurement, forward simulation or a learned approximation.

IV. Geological storage containment

Capacity, seal and migration require separate evidence. For geological storage containment, identify the measured quantity, spatial support, observation time and relevant physical process (Pasupuleti 2026k; Pasupuleti 2026e; Pasupuleti 2026g).

A credible interpretation compares the proposed mechanism with at least one alternative compatible with the observations. The supplied studies motivate these transferable methods (Pasupuleti 2026k; Pasupuleti 2026e; Pasupuleti 2026g). Limits of location, detection and model form must remain visible.

The research artifact for geological storage containment records assumptions, independent validation and a decision boundary. Reviewers should know whether a claim arises from direct measurement, forward simulation or a learned approximation.

V. Spatiotemporal and causal explanation

Detection and intervention effects need defensible comparisons. For spatiotemporal and causal explanation, identify the measured quantity, spatial support, observation time and relevant physical process (Pasupuleti 2023a; Pasupuleti 2023c; Pasupuleti 2021).

A credible interpretation compares the proposed mechanism with at least one alternative compatible with the observations. The supplied studies motivate these transferable methods (Pasupuleti 2023a; Pasupuleti 2023c; Pasupuleti 2021). Limits of location, detection and model form must remain visible.

The research artifact for spatiotemporal and causal explanation records assumptions, independent validation and a decision boundary. Reviewers should know whether a claim arises from direct measurement, forward simulation or a learned approximation.

VI. Physics-constrained learning

Surrogates must respect equations and tested operating ranges. For physics-constrained learning, identify the measured quantity, spatial support, observation time and relevant physical process (Pasupuleti 2023e; Pasupuleti 2026i; Pasupuleti 2022a).

A credible interpretation compares the proposed mechanism with at least one alternative compatible with the observations. The supplied studies motivate these transferable methods (Pasupuleti 2023e; Pasupuleti 2026i; Pasupuleti 2022a). Limits of location, detection and model form must remain visible.

The research artifact for physics-constrained learning records assumptions, independent validation and a decision boundary. Reviewers should know whether a claim arises from direct measurement, forward simulation or a learned approximation.

VII. Graph and topological structure

Connectivity depends on fault and sensor graph construction. For graph and topological structure, identify the measured quantity, spatial support, observation time and relevant physical process (Pasupuleti 2026j; Pasupuleti 2026a; Pasupuleti 2026h). A credible interpretation compares the proposed mechanism with at least one alternative compatible with the observations. The supplied studies motivate these transferable methods (Pasupuleti 2026j; Pasupuleti 2026a; Pasupuleti 2026h). Limits of location, detection and model form must remain visible.

The research artifact for graph and topological structure records assumptions, independent validation and a decision boundary. Reviewers should know whether a claim arises from direct measurement, forward simulation or a learned approximation.

VIII. Multisource data provenance

Spatial alignment and record integrity govern reliability. For multisource data provenance, identify the measured quantity, spatial support, observation time and relevant physical process (Pasupuleti 2024a; Pasupuleti 2024d; Pasupuleti 2024c).

A credible interpretation compares the proposed mechanism with at least one alternative compatible with the observations. The supplied studies motivate these transferable methods (Pasupuleti 2024a; Pasupuleti 2024d; Pasupuleti 2024c). Limits of location, detection and model form must remain visible.

The research artifact for multisource data provenance records assumptions, independent validation and a decision boundary. Reviewers should know whether a claim arises from direct measurement, forward simulation or a learned approximation.

IX. Adaptive monitoring and model governance

Updated observations should change a versioned assessment. For adaptive monitoring and model governance, identify the measured quantity, spatial support, observation

time and relevant physical process (Pasupuleti 2026c; Pasupuleti 2023b; Pasupuleti 2024b).

A credible interpretation compares the proposed mechanism with at least one alternative compatible with the observations. The supplied studies motivate these transferable methods (Pasupuleti 2026c; Pasupuleti 2023b; Pasupuleti 2024b). Limits of location, detection and model form must remain visible.

The research artifact for adaptive monitoring and model governance records assumptions, independent validation and a decision boundary. Reviewers should know whether a claim arises from direct measurement, forward simulation or a learned approximation.

X. Climate integrity and public trust

Claims about storage and hazard must remain reviewable. For climate integrity and public trust, identify the measured quantity, spatial support, observation time and relevant physical process (Pasupuleti 2026k; Pasupuleti 2026b; Pasupuleti 2026g).

A credible interpretation compares the proposed mechanism with at least one alternative compatible with the observations. The supplied studies motivate these transferable methods (Pasupuleti 2026k; Pasupuleti 2026b; Pasupuleti 2026g). Limits of location, detection and model form must remain visible.

The research artifact for climate integrity and public trust records assumptions, independent validation and a decision boundary. Reviewers should know whether a claim arises from direct measurement, forward simulation or a learned approximation.

2.1 Spatiotemporal baselines and clustering

Seismicity and environmental signals have spatial dependence and nonstationary rates. A baseline should reflect observed clustering without claiming deterministic prediction. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2023d; Pasupuleti 2026f; Pasupuleti 2021). Its claims should be transferred only within the assumptions of the earth-system setting.

Fit transparent count or point-process baselines with geography-specific exposure and time-varying detection. This design should distinguish an observed geophysical signal from an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2023d; Pasupuleti 2026f; Pasupuleti 2021).

The expected research output is a documented benchmark with calibration windows. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

A clustered event sequence should be compared with a transparent statistical benchmark before crediting a deep model. For spatiotemporal baselines and clustering, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

For spatiotemporal baselines and clustering, vary geological priors, observation density and temporal lags separately. Strong dependence on a prior indicates that field evidence weakly identifies the proposed mechanism.

An explanation of spatiotemporal baselines and clustering keeps competing causes visible. Instrument changes, operational variation and natural clustering may produce similar trends. Identify the contrast that could distinguish them.

The limit statement for spatiotemporal baselines and clustering names the missing counterfactual and the assumptions needed to estimate it. Sensitivity bounds belong beside any point estimate.

Regional point-process baselines should include changes in network sensitivity and catalog practices. A deep model's incremental performance can then be judged against a meaningful alternative. Reliability diagrams and scoring rules are more informative than selecting a few dramatic predicted events.

2.2 Uncertainty propagation across sensors and models

Sensor noise, location error and physical parameter uncertainty enter different stages. An interval around a neural output cannot capture all three by itself. The literature in the supplied corpus supplies conceptual or methodological support for this question

(Pasupuleti 2023e; Pasupuleti 2026i; Pasupuleti 2026h). Its claims should be transferred only within the assumptions of the earth-system setting.

Propagate measurement ensembles and structural alternatives through forward and inverse calculations. This design should distinguish an observed geophysical signal from an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2023e; Pasupuleti 2026i; Pasupuleti 2026h).

The expected research output is an uncertainty budget and coverage diagnostic. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

A narrow plume interval can reflect a fixed geological structure rather than comprehensive uncertainty. For uncertainty propagation across sensors and models, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

For uncertainty propagation across sensors and models, vary geological priors, observation density and temporal lags separately. Strong dependence on a prior indicates that field evidence weakly identifies the proposed mechanism.

An explanation of uncertainty propagation across sensors and models keeps competing causes visible. Instrument changes, operational variation and natural clustering may produce similar trends. Identify the contrast that could distinguish them.

The limit statement for uncertainty propagation across sensors and models names the missing counterfactual and the assumptions needed to estimate it. Sensitivity bounds belong beside any point estimate.

An uncertainty budget can sample station location, velocity structure and model parameters separately. Visualizing their distinct contributions helps decide whether to improve a sensor array or a geologic prior. Joint sampling is needed when uncertainties are correlated rather than simply additive.

2.3 Spatial causal inference for anthropogenic impacts

Changes near injection operations may coincide with natural variability and altered monitoring intensity. Association does not assign causation. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2023a; Pasupuleti 2023c; Pasupuleti 2021). Its claims should be transferred only within the assumptions of the earth-system setting.

Define exposure, counterfactual site and lag; test pretrends, spillovers and instrumentation changes. This design should distinguish an observed geophysical signal from an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2023a; Pasupuleti 2023c; Pasupuleti 2021).

The expected research output is a causal identification ledger for induced-risk studies. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

Increasing seismicity near injection may track denser monitoring. Compare instrumentation and operational history before assigning cause. For spatial causal inference for anthropogenic impacts, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

For spatial causal inference for anthropogenic impacts, vary geological priors, observation density and temporal lags separately. Strong dependence on a prior indicates that field evidence weakly identifies the proposed mechanism.

An explanation of spatial causal inference for anthropogenic impacts keeps competing causes visible. Instrument changes, operational variation and natural clustering may produce similar trends. Identify the contrast that could distinguish them.

The limit statement for spatial causal inference for anthropogenic impacts names the missing counterfactual and the assumptions needed to estimate it. Sensitivity bounds belong beside any point estimate.

A proposed induced-seismicity analysis should compare operational histories with relevant untreated sites while acknowledging that the treatment may affect monitoring itself. A lagged response is physically plausible, but lag selection after observing outcomes risks bias. Predeclared windows and negative controls provide stronger evidence.

2.4 Carbon accounting and storage verification

Remote sensing constrains surface emissions and land change, while subsurface sensors track pressure and plume response. These measurements answer different questions. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2026k; Pasupuleti 2024c; Pasupuleti 2026g). Its claims should be transferred only within the assumptions of the earth-system setting.

Reconcile atmospheric, site and geophysical observations under a mass-balance framework with declared boundaries. This design should distinguish an observed geophysical signal from an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2026k; Pasupuleti 2024c; Pasupuleti 2026g).

The expected research output is a monitoring, reporting and verification evidence map. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

A surface carbon signal may reflect multiple emitters. Subsurface pressure data cannot alone verify the atmospheric boundary. For carbon accounting and storage verification, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

For carbon accounting and storage verification, vary geological priors, observation density and temporal lags separately. Strong dependence on a prior indicates that field evidence weakly identifies the proposed mechanism.

An explanation of carbon accounting and storage verification keeps competing causes visible. Instrument changes, operational variation and natural clustering may produce similar trends. Identify the contrast that could distinguish them.

The limit statement for carbon accounting and storage verification names the missing counterfactual and the assumptions needed to estimate it. Sensitivity bounds belong beside any point estimate.

Carbon verification should identify what is inside the accounting boundary. Site pressure changes can support a containment interpretation, while atmospheric evidence addresses emissions over a different footprint. The reconciliation record

should show unresolved leakage pathways, sensor limits and the date at which assumptions were revised.

2.5 Sensitivity to geological priors and sparse coverage

A model may appear precise where wells or seismic lines are scarce because its training prior fills the gaps. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2022b; Pasupuleti 2023e; Pasupuleti 2026h). Its claims should be transferred only within the assumptions of the earth-system setting.

Perturb stratigraphy, fault connectivity and observation density; compare posterior changes and blind-location performance. This design should distinguish an observed geophysical signal from an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2022b; Pasupuleti 2023e; Pasupuleti 2026h).

The expected research output is a prior-sensitivity and identifiability report. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

A well-poor area can look smooth because the prior interpolates across missing structure. Test blind wells when available. For sensitivity to geological priors and sparse coverage, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

For sensitivity to geological priors and sparse coverage, vary geological priors, observation density and temporal lags separately. Strong dependence on a prior indicates that field evidence weakly identifies the proposed mechanism.

An explanation of sensitivity to geological priors and sparse coverage keeps competing causes visible. Instrument changes, operational variation and natural clustering may produce similar trends. Identify the contrast that could distinguish them.

The limit statement for sensitivity to geological priors and sparse coverage names the missing counterfactual and the assumptions needed to estimate it. Sensitivity bounds belong beside any point estimate.

Blind-well validation should preserve entire wells or structural blocks, rather than randomly withholding pixels from the same survey. A useful error map marks where alternate geologic priors produce materially different predictions. These areas warrant field investigation before a high-consequence decision.

Chapter 3 Deep learning, physics constraints and validation

The third chapter tests where learned representations, graph models and neural surrogates add value. Its validation plan emphasizes physical checks and future observations. The chapter's proposals are research protocols, not findings (Pasupuleti 2022a; Pasupuleti 2026j; Pasupuleti 2023d).

For deep learning, physics constraints and validation, record the unit, time horizon, source and interpretation for every claim. Where evidence cannot distinguish plausible mechanisms, report that uncertainty as a substantive result. The figure and evaluation table set out the tests needed for this chapter.

Figure 3.1 Physics-constrained prediction design

Training data → Physics test → Prospective validation

Schematic research pathway; arrows denote analytical dependencies rather than observed causal effects.

Table 3.1 Deep-learning validation gates

Analytical object	Key test	Research record
Waveforms	Does a future test hold?	Event benchmark
Fault graphs	Do edges represent physics?	Graph audit
Surrogates	Are equations respected?	Residual tests
Plumes	Are scenarios distinguishable?	Ensemble map

3.1 Waveform encoders and event representation

Representation learning can compress noisy waveforms, but labels inherit catalog completeness and station geometry. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2022a; Pasupuleti 2026j; Pasupuleti 2023d). Its claims should be transferred only within the assumptions of the earth-system setting.

Benchmark event detection and localization chronologically across networks, magnitude ranges and noise conditions. This design should distinguish an observed geophysical signal from an inference about hidden earth properties. Specify

competing explanations and the evidence each would require (Pasupuleti 2022a; Pasupuleti 2026j; Pasupuleti 2023d).

The expected research output is an event-model card with false-alarm and missed-event analysis. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

Event detection trained on one station network may miss low-magnitude signals in another. Evaluate across network geometries. For waveform encoders and event representation, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

Stress-test waveform encoders and event representation in a region omitted from training, under altered station geometry and across plausible physical regimes. Contrast the learned estimate with a transparent baseline and a trusted solver.

Interpretability for waveform encoders and event representation requires physical consistency. A prominent learned feature may encode survey coverage; ablation and conservation tests help assess its genuine contribution.

The model-use envelope for waveform encoders and event representation specifies geography, forecast horizon, tested boundary conditions and tolerated residuals. A new observation outside that envelope calls for review.

Station geometry can dominate apparent waveform features. Train and test across instruments and noise regimes, then inspect whether a classifier is responding to event physics or network identity. A held-out geographic region supplies a more demanding evaluation than a random trace split.

3.2 Graph learning for faults and sensor networks

Fault segments, stations and geological contacts can be encoded as graphs; edge definitions determine what information can pass. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2026j; Pasupuleti 2026a; Pasupuleti 2023b). Its claims should be transferred only within the assumptions of the earth-system setting.

Compare message-passing models with spatial baselines and ablate topology under held-out regions. This design should distinguish an observed geophysical signal from

an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2026j; Pasupuleti 2026a; Pasupuleti 2023b). The expected research output is a graph-construction audit and transfer benchmark. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

Fault-graph edges based only on distance can suggest a flow connection that impermeable material blocks. Test alternative graphs. For graph learning for faults and sensor networks, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

Stress-test graph learning for faults and sensor networks in a region omitted from training, under altered station geometry and across plausible physical regimes. Contrast the learned estimate with a transparent baseline and a trusted solver.

Interpretability for graph learning for faults and sensor networks requires physical consistency. A prominent learned feature may encode survey coverage; ablation and conservation tests help assess its genuine contribution.

The model-use envelope for graph learning for faults and sensor networks specifies geography, forecast horizon, tested boundary conditions and tolerated residuals. A new observation outside that envelope calls for review.

Graph edges may represent adjacency, plausible mechanical coupling or possible fluid flow; each has distinct physical meaning. Compare these alternatives on the same held-out fault segments. Reporting which edges the model relies upon makes a failed transfer diagnostically useful.

3.3 Physics-informed inversion and neural operators

Learned surrogates can speed repeated simulations, provided the governing equations and boundary conditions match the intended geologic regime. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2023e; Pasupuleti 2026i; Pasupuleti 2022a). Its claims should be transferred only within the assumptions of the earth-system setting.

Evaluate conservation residuals, extrapolation and error bounds against trusted numerical solves. This design should distinguish an observed geophysical signal from

an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2023e; Pasupuleti 2026i; Pasupuleti 2022a). The expected research output is a surrogate validity envelope for inversion and flow. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

A surrogate may be fast but violate mass conservation near a boundary. Compare residuals and numerical solves in stress cases. For physics-informed inversion and neural operators, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

Stress-test physics-informed inversion and neural operators in a region omitted from training, under altered station geometry and across plausible physical regimes. Contrast the learned estimate with a transparent baseline and a trusted solver.

Interpretability for physics-informed inversion and neural operators requires physical consistency. A prominent learned feature may encode survey coverage; ablation and conservation tests help assess its genuine contribution.

The model-use envelope for physics-informed inversion and neural operators specifies geography, forecast horizon, tested boundary conditions and tolerated residuals. A new observation outside that envelope calls for review.

Neural-operator speed should be measured with its error, not in isolation. Stress cases include sharp permeability contrasts, changing boundaries and unusual injection rates. Conservation residuals and numerical solver comparisons identify conditions under which the surrogate should yield to a trusted simulation.

3.4 Prospective earthquake forecast evaluation

Retrospective selection of regions and windows can exaggerate forecast skill. A useful test locks model and target before future events occur. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2023d; Pasupuleti 2022a; Pasupuleti 2021). Its claims should be transferred only within the assumptions of the earth-system setting.

Score probabilistic forecasts against transparent baselines using proper scoring rules and calibration plots. This design should distinguish an observed geophysical signal

from an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2023d; Pasupuleti 2022a; Pasupuleti 2021).

The expected research output is a prospective forecast archive and evaluation plan. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

A forecast selected after seeing the validation years is not prospective. Freeze model and region first. For prospective earthquake forecast evaluation, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

Stress-test prospective earthquake forecast evaluation in a region omitted from training, under altered station geometry and across plausible physical regimes. Contrast the learned estimate with a transparent baseline and a trusted solver.

Interpretability for prospective earthquake forecast evaluation requires physical consistency. A prominent learned feature may encode survey coverage; ablation and conservation tests help assess its genuine contribution.

The model-use envelope for prospective earthquake forecast evaluation specifies geography, forecast horizon, tested boundary conditions and tolerated residuals. A new observation outside that envelope calls for review.

Prospective testing must archive the forecast before the target interval opens. The archive records every update and the data available at issue time. Proper scores and calibration across cells then assess probabilities; spatial concentration alone is insufficient when most events occur in active regions.

3.5 Carbon-plume prediction and interpretability

A plume model should express where the injected fluid might migrate and which monitoring observations would distinguish alternatives. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2026e; Pasupuleti 2026i; Pasupuleti 2026g). Its claims should be transferred only within the assumptions of the earth-system setting.

Compare predicted pressure and plume footprints with repeated surveys under uncertainty and physical constraints. This design should distinguish an observed

geophysical signal from an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2026e; Pasupuleti 2026i; Pasupuleti 2026g).

The expected research output is a plume scenario ensemble and inspection map. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

An unexpected pressure increase may support several plume realizations. Monitoring design should distinguish them. For carbon-plume prediction and interpretability, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

Stress-test carbon-plume prediction and interpretability in a region omitted from training, under altered station geometry and across plausible physical regimes. Contrast the learned estimate with a transparent baseline and a trusted solver.

Interpretability for carbon-plume prediction and interpretability requires physical consistency. A prominent learned feature may encode survey coverage; ablation and conservation tests help assess its genuine contribution.

The model-use envelope for carbon-plume prediction and interpretability specifies geography, forecast horizon, tested boundary conditions and tolerated residuals. A new observation outside that envelope calls for review.

A plume ensemble should connect predicted pressure, saturation and monitoring observables. Candidate sensor placements can be compared by their ability to distinguish fault-connected migration from benign reservoir variation. An interpretable map shows both plausible paths and where observation sensitivity is low.

Chapter 4 Scalable geophysical data and reproducible operations

The fourth chapter treats coordinate harmonization, streaming correction and model versioning as scientific requirements. Reproducible operations preserve the state behind a hazard or storage claim. The chapter's proposals are research protocols, not findings (Pasupuleti 2024a; Pasupuleti 2024d; Pasupuleti 2023a).

For scalable geophysical data and reproducible operations, record the unit, time horizon, source and interpretation for every claim. Where evidence cannot distinguish plausible mechanisms, report that uncertainty as a substantive result. The figure and evaluation table set out the tests needed for this chapter.

Figure 4.1 Reproducible geophysical monitoring lifecycle

Ingest and align → Versioned model → Independent replay

Schematic research pathway; arrows denote analytical dependencies rather than observed causal effects.

Table 4.1 Geospatial data and operations controls

Analytical object	Key test	Research record
Coordinates	Are datums aligned?	Data manifest
Streaming	Can revisions be replayed?	Correction log
Twin	Does the ensemble update?	Assimilation record
Release	Can results be reproduced?	Version dossier

4.1 Multisource spatial data engineering

Boreholes, seismic traces, satellite products and injection logs use different coordinates, resolutions and access conditions. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2024a; Pasupuleti 2024d; Pasupuleti 2023a). Its claims should be transferred only within the assumptions of the earth-system setting.

Harmonize location, depth datum and event time with versioned transformations and quality controls. This design should distinguish an observed geophysical signal from an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2024a; Pasupuleti 2024d; Pasupuleti 2023a).

The expected research output is a geospatial data manifest and provenance chain. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

A depth datum mismatch can move a reservoir surface on the map. Audit transformations before learning features. For multisource spatial data engineering, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

Operational sensitivity in multisource spatial data engineering arises from coordinate conversions, late records and model releases. Replay one affected estimate from source data through archived transformations.

Reproducibility of multisource spatial data engineering ties controlled data access to a versioned calculation. Qualified reviewers should be able to replay outputs while protected site records remain governed.

The evidence packet for a geospatial data manifest and provenance chain traces coordinate changes, quality filters and releases. Synthetic fixtures demonstrate the pipeline; controlled cases test consequential claims.

Depth and coordinate harmonization should be tested with a known control point before integrating wells, seismic grids and satellite layers. A discrepancy can masquerade as geological complexity. The data manifest records the original datum, transform, software version and the size of alignment uncertainty.

4.2 Streaming seismic and reservoir monitoring

Late-arriving events or sensor recalibration may revise an earlier risk estimate. An operational stream needs replayable correction. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2023b; Pasupuleti 2023d; Pasupuleti 2024a). Its claims should be transferred only within the assumptions of the earth-system setting.

Specify event-time ingestion, station-health checks, deduplication and reprocessing after catalog revision. This design should distinguish an observed geophysical signal from an inference about hidden earth properties. Specify competing explanations and

the evidence each would require (Pasupuleti 2023b; Pasupuleti 2023d; Pasupuleti 2024a).

The expected research output is a streaming correction and alert log. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

A delayed sensor report may change a prior alert. Preserve both the original operational decision and corrected reconstruction. For streaming seismic and reservoir monitoring, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

Operational sensitivity in streaming seismic and reservoir monitoring arises from coordinate conversions, late records and model releases. Replay one affected estimate from source data through archived transformations.

Reproducibility of streaming seismic and reservoir monitoring ties controlled data access to a versioned calculation. Qualified reviewers should be able to replay outputs while protected site records remain governed.

The evidence packet for a streaming correction and alert log traces coordinate changes, quality filters and releases. Synthetic fixtures demonstrate the pipeline; controlled cases test consequential claims.

Streaming design should preserve arrival time and event time. When a revised location or magnitude changes a hazard estimate, the system needs a correction record rather than silent replacement. This allows operators to review whether the original response was reasonable given information then available.

4.3 Simulation ensembles and digital twins

A geophysical digital twin is a conditional model updated with observations, not a direct replica of underground reality. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2026c; Pasupuleti 2026i; Pasupuleti 2023e). Its claims should be transferred only within the assumptions of the earth-system setting.

Maintain competing geology and parameter realizations, update with new measurements and compare forecast residuals. This design should distinguish an

observed geophysical signal from an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2026c; Pasupuleti 2026i; Pasupuleti 2023e).

The expected research output is an ensemble-update protocol and model-discrepancy report. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

Assimilation can pull a digital twin toward new observations while leaving structural geology unresolved. For simulation ensembles and digital twins, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

Operational sensitivity in simulation ensembles and digital twins arises from coordinate conversions, late records and model releases. Replay one affected estimate from source data through archived transformations.

Reproducibility of simulation ensembles and digital twins ties controlled data access to a versioned calculation. Qualified reviewers should be able to replay outputs while protected site records remain governed.

The evidence packet for an ensemble-update protocol and model-discrepancy report traces coordinate changes, quality filters and releases. Synthetic fixtures demonstrate the pipeline; controlled cases test consequential claims.

Digital-twin updates should retain multiple structural hypotheses. Assimilation may improve fit to the latest pressure series while leaving fault connectivity unresolved. Reporting ensemble collapse and model discrepancy prevents an updated twin from conveying false geological certainty.

4.4 Model releases, drift and independent challenge

A new survey or instrument can change model inputs and calibration. A release gate should preserve the version used for a prior warning. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2026d; Pasupuleti 2022a; Pasupuleti 2024c). Its claims should be transferred only within the assumptions of the earth-system setting.

Test shadow deployments, out-of-region validation, rollback and independent challenge cases. This design should distinguish an observed geophysical signal from

an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2026d; Pasupuleti 2022a; Pasupuleti 2024c). The expected research output is a release dossier with versioned error analysis. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

A new instrument can change a model score without any geological change. Keep release and calibration histories together. For model releases, drift and independent challenge, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

Operational sensitivity in model releases, drift and independent challenge arises from coordinate conversions, late records and model releases. Replay one affected estimate from source data through archived transformations.

Reproducibility of model releases, drift and independent challenge ties controlled data access to a versioned calculation. Qualified reviewers should be able to replay outputs while protected site records remain governed.

The evidence packet for a release dossier with versioned error analysis traces coordinate changes, quality filters and releases. Synthetic fixtures demonstrate the pipeline; controlled cases test consequential claims.

Release review can use a stable challenge set containing sparse wells, noisy stations and boundary cases. A candidate model should be compared with the operational version before promotion. Rollback preserves the previous data transform as well as learned weights and configuration.

4.5 Integrity, access and auditability

Carbon verification and public hazard assessment rely on trustworthy data lineage, while borehole and infrastructure data may require controlled access. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2024c; Pasupuleti 2026k; Pasupuleti 2024b). Its claims should be transferred only within the assumptions of the earth-system setting.

Separate public aggregate evidence from protected raw records; verify integrity and reviewer access. This design should distinguish an observed geophysical signal from

an inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2024c; Pasupuleti 2026k; Pasupuleti 2024b). The expected research output is a tiered audit packet and incident drill. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

A verification claim loses auditability if protected well logs cannot be inspected by qualified independent reviewers. For integrity, access and auditability, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

Operational sensitivity in integrity, access and auditability arises from coordinate conversions, late records and model releases. Replay one affected estimate from source data through archived transformations.

Reproducibility of integrity, access and auditability ties controlled data access to a versioned calculation. Qualified reviewers should be able to replay outputs while protected site records remain governed.

The evidence packet for a tiered audit packet and incident drill traces coordinate changes, quality filters and releases. Synthetic fixtures demonstrate the pipeline; controlled cases test consequential claims.

An independent storage auditor needs sufficient evidence to follow injection measurements into reported outcomes. Controlled access can protect commercially sensitive well records while allowing verification of integrity and uncertainty. A tabletop incident tests whether a lost or altered sensor stream can be identified.

Chapter 5 Hazard, resource and climate applications

The final chapter connects forecasts and subsurface maps to decisions about hazards and carbon storage. Each application needs a bounded action, accountable owner and independent review. The chapter's proposals are research protocols, not findings (Pasupuleti 2026c; Pasupuleti 2023d; Pasupuleti 2024b).

For hazard, resource and climate applications, record the unit, time horizon, source and interpretation for every claim. Where evidence cannot distinguish plausible mechanisms, report that uncertainty as a substantive result. The figure and evaluation table set out the tests needed for this chapter.

Figure 5.1 Hazard and storage governance loop

Scientific evidence → Action threshold → Public review

Schematic research pathway; arrows denote analytical dependencies rather than observed causal effects.

Table 5.1 Application evidence and action thresholds

Analytical object	Key test	Research record
Forecast	Are probabilities calibrated?	Assurance case
Faults	Does ambiguity affect decisions?	Structure report
Site	Are leakage paths screened?	Risk matrix
Monitoring	What triggers correction?	Action plan

5.1 Regional earthquake hazard services

A forecast is useful only with a defined horizon, calibrated probabilities and a decision that can respond appropriately. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2026c; Pasupuleti 2023d; Pasupuleti 2024b). Its claims should be transferred only within the assumptions of the earth-system setting.

Pilot against routine hazard practice with outcome, false-alarm and response-time measures. This design should distinguish an observed geophysical signal from an

inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2026c; Pasupuleti 2023d; Pasupuleti 2024b). The expected research output is a regional forecasting assurance case. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

A regional warning should be evaluated for calibration and feasible response, not merely an attractive map. For regional earthquake hazard services, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

For regional earthquake hazard services, ask how an alternate geological realization changes the actual decision. Record the conditions for a threshold crossing and the person authorized to act.

Applying regional earthquake hazard services in another region requires local geology, instrumentation and response capacity. Shared protocols can travel; parameter values and action rules need new evidence.

The resulting a regional forecasting assurance case supports a bounded action. State the monitoring domain, uncertainty, responsible institution and corrective route as evidence changes.

A regional forecast service can compare decisions made with and without probabilistic forecasts under a predefined response policy. Evaluators should count unnecessary interventions and missed actionable periods. A useful forecast is calibrated and operationally interpretable, not simply spatially sharp.

5.2 Fault mapping and subsurface decisions

Seismic interpretation affects drilling, infrastructure siting and storage risk. Predictions should preserve ambiguous fault continuities. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2026h; Pasupuleti 2026a; Pasupuleti 2022b). Its claims should be transferred only within the assumptions of the earth-system setting.

Evaluate blind intersections, uncertainty maps and how decisions change under alternate structural models. This design should distinguish an observed geophysical signal from an inference about hidden earth properties. Specify competing

explanations and the evidence each would require (Pasupuleti 2026h; Pasupuleti 2026a; Pasupuleti 2022b).

The expected research output is a decision-focused fault-characterization report. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

A blind fault crossing can reveal whether an inferred surface is useful for siting decisions. For fault mapping and subsurface decisions, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

For fault mapping and subsurface decisions, ask how an alternate geological realization changes the actual decision. Record the conditions for a threshold crossing and the person authorized to act.

Applying fault mapping and subsurface decisions in another region requires local geology, instrumentation and response capacity. Shared protocols can travel; parameter values and action rules need new evidence.

The resulting a decision-focused fault-characterization report supports a bounded action. State the monitoring domain, uncertainty, responsible institution and corrective route as evidence changes.

A fault map supports decisions only if alternative connections are visible. Blinded interpretation of withheld seismic lines or wells can test structural predictions. When uncertainty spans a proposed drilling route, report the decision sensitivity rather than hiding it in a single preferred surface.

5.3 Carbon storage site screening

Capacity alone cannot establish a suitable storage site when leakage pathways or monitoring reach remain unresolved. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2026e; Pasupuleti 2022b; Pasupuleti 2026g). Its claims should be transferred only within the assumptions of the earth-system setting.

Integrate geologic, hydrologic and spatial criteria using sensitivity and exclusion analysis. This design should distinguish an observed geophysical signal from an

inference about hidden earth properties. Specify competing explanations and the evidence each would require (Pasupuleti 2026e; Pasupuleti 2022b; Pasupuleti 2026g). The expected research output is a site-screening matrix with unresolved-risk gates. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

A candidate storage reservoir with good capacity but uncertain abandoned wells requires a separate containment review. For carbon storage site screening, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing. For carbon storage site screening, ask how an alternate geological realization changes the actual decision. Record the conditions for a threshold crossing and the person authorized to act.

Applying carbon storage site screening in another region requires local geology, instrumentation and response capacity. Shared protocols can travel; parameter values and action rules need new evidence.

The resulting a site-screening matrix with unresolved-risk gates supports a bounded action. State the monitoring domain, uncertainty, responsible institution and corrective route as evidence changes.

Site screening should separate conditions that exclude a reservoir from criteria that can be monitored or mitigated. Pressure capacity, seal quality, fault proximity and abandoned wells belong in distinct rows. This yields a defensible go, defer or investigate decision under uncertainty.

5.4 Long-term monitoring and corrective action

Post-injection assessment depends on a monitoring plan that can detect unexpected migration and trigger review. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2026k; Pasupuleti 2024c; Pasupuleti 2026i). Its claims should be transferred only within the assumptions of the earth-system setting.

Compare observed pressure, geophysics and atmospheric signals to forecast envelopes; document corrective triggers. This design should distinguish an observed geophysical signal from an inference about hidden earth properties. Specify competing

explanations and the evidence each would require (Pasupuleti 2026k; Pasupuleti 2024c; Pasupuleti 2026i).

The expected research output is a storage monitoring and intervention schedule. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

Monitoring should be capable of detecting migration early enough to support a corrective action. For long-term monitoring and corrective action, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing.

For long-term monitoring and corrective action, ask how an alternate geological realization changes the actual decision. Record the conditions for a threshold crossing and the person authorized to act.

Applying long-term monitoring and corrective action in another region requires local geology, instrumentation and response capacity. Shared protocols can travel; parameter values and action rules need new evidence.

The resulting a storage monitoring and intervention schedule supports a bounded action. State the monitoring domain, uncertainty, responsible institution and corrective route as evidence changes.

Long-term monitoring requires predefined excursions beyond forecast pressure or plume envelopes. An excursion triggers investigation, additional measurement or operational change according to its severity. Record the revision of geological hypotheses after each material discrepancy.

5.5 Research agenda and public accountability

Earthquake forecasting and carbon storage have different evidence standards, yet both require calibrated uncertainty and accountable interpretation. The literature in the supplied corpus supplies conceptual or methodological support for this question (Pasupuleti 2026b; Pasupuleti 2024b; Pasupuleti 2021). Its claims should be transferred only within the assumptions of the earth-system setting.

Stage replication, prospective tests and independently reviewed deployment studies with local governance. This design should distinguish an observed geophysical signal from an inference about hidden earth properties. Specify competing explanations and

the evidence each would require (Pasupuleti 2026b; Pasupuleti 2024b; Pasupuleti 2021).

The expected research output is a cross-domain evidence roadmap and communication charter. It should include a date-stamped definition, coordinate provenance and a concrete failure example. A reviewer should reproduce reported estimates through governed access or synthetic geophysical challenge cases.

A method that transfers across regions must specify which geological and institutional assumptions travelled with it. For research agenda and public accountability, compare the geophysical interpretation with field and physical context. Preserve old and revised geophysical feature definitions, so differences can be traced to preprocessing. For research agenda and public accountability, ask how an alternate geological realization changes the actual decision. Record the conditions for a threshold crossing and the person authorized to act.

Applying research agenda and public accountability in another region requires local geology, instrumentation and response capacity. Shared protocols can travel; parameter values and action rules need new evidence.

The resulting a cross-domain evidence roadmap and communication charter supports a bounded action. State the monitoring domain, uncertainty, responsible institution and corrective route as evidence changes.

Cross-domain research can share tools for uncertainty, provenance and independent challenge while retaining different physical targets. A research consortium should preregister benchmark splits and release reproducible synthetic cases. Real field evidence remains subject to appropriate site and public governance.

The five chapters define an evidence chain from a measured earth-system signal to a reviewable decision. Physical scales delimit the claim; statistical analysis examines uncertainty and rival causes; deep learning tests prediction and approximation; operations preserve provenance; applied evaluation assesses how evidence changes an action. Weakness in an early link cannot be repaired by a more complex model downstream.

Earthquake forecasting should be evaluated prospectively with a fixed geographic and temporal target. Improved detection is valuable but is not equivalent to foreseeing a future event. Characterization faces a different challenge: nonunique reconstructions of underground structure. A map should carry resolution and alternative geological interpretations into the decision it informs.

Storage integrity requires several forms of evidence. Pressure and seismic imaging track reservoir response; geologic models describe possible migration; surface measurements and accounting address broader climate claims. These observations should be reconciled under a declared boundary and revised when new data contradict a prior scenario.

A staged research program begins with controlled benchmarks and physical residual checks, advances through spatial and temporal holdouts, then uses independently reviewed prospective pilots. Field monitoring should retain a trusted prior model version and a record of corrective actions. Different regions can apply the same evaluation questions while preserving local geology, infrastructure and governance.

Future work must better quantify structural uncertainty in faults, seals and reservoir flow, especially where subsurface data are sparse. Sensor placement and monitoring policy are themselves research decisions. An accountable system reports what would overturn its conclusion and who is authorized to respond when observations leave a validated envelope.

Glossary

Aftershock. Event occurring after a larger earthquake within a related sequence.

Assimilation. Update of a model state using newly observed data.

Baseline forecast. Transparent reference against which a complex prediction is compared.

Borehole. Drilled access point providing local measurements of the subsurface.

Catalog completeness. Magnitude and time range over which recorded events are reliably detected.

Conservation residual. Discrepancy between a prediction and a governing balance equation.

Containment. Retention of injected carbon dioxide within a designated geological system.

Depth datum. Reference surface from which depth measurements are calculated.

Detection threshold. Minimum signal level reliably recorded under stated conditions.

Digital twin. Conditional simulation updated with observations of a physical system.

Fault connectivity. Potential structural or hydraulic linkage among fault segments.

Forward model. Calculation of expected observations from specified earth properties.

Geological prior. Assumed distribution of plausible subsurface structures before new data.

Geological storage. Injection and retention of carbon dioxide in subsurface formations.

Geospatial alignment. Reconciliation of coordinate systems, datums and spatial supports.

Graph neural network. Predictive model propagating information over specified nodes and edges.

Induced seismicity. Earthquakes potentially associated with human operations.

Inverse problem. Inference of hidden physical properties from observed signals.

Mass balance. Accounting relation connecting inputs, outputs and accumulated material.

Monitoring footprint. Region and depth range in which a sensor can detect change.

Neural operator. Learned mapping between functions or physical fields.

Nonstationarity. Change over time in a process or observation relationship.

Plume. Region occupied or affected by injected fluid in a reservoir.

Proper scoring rule. Forecast score optimized by honest probabilistic predictions.

Reservoir. Geological formation capable of storing injected material.

Seal. Low-permeability barrier limiting upward fluid migration.

Seismic waveform. Recorded time-varying ground-motion signal.

Spatial holdout. Validation in a region omitted from training.

Structural uncertainty. Uncertainty in the form or connectivity of a geological model.

Surrogate model. Fast approximation of a computationally expensive forward solve.

Velocity model. Representation of wave-propagation speeds underground.

References

- Pasupuleti, MK 2021, 'A Unified Framework for Feature Dependence: Theory, Algorithms, and Causal Inference', International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 01, no. 01, National Education Services, pp. 356–367.
- Pasupuleti, MK 2022a, 'Deep Learning Through a Statistical Lens: Approximation Guarantees, Training Dynamics, and Generative Models', International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 02, no. 01, National Education Services, pp. 125–143.
- Pasupuleti, MK 2022b, 'Strategic Siting of Data Centres: A GIS-Based Multi-Criteria Decision Framework for Cost, Risk, and Sustainability', International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 02, no. 12, National Education Services, pp. 92–110.
- Pasupuleti, MK 2023a, 'AI Climate Risk in ArcGIS: Foundation-Model Remote Sensing and Spatio-Temporal Causality', International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 03, no. 12, National Education Services, pp. 114–126.
- Pasupuleti, MK 2023b, 'AI Hydrologic Nowcasting in HEC-HMS: Graph Neural Nets under Nonstationarity', International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 03, no. 06, National Education Services, pp. 126–142.
- Pasupuleti, MK 2023c, 'AI-Augmented Causal Inference in R: Double-ML with Bayesian Calibration', International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 03, no. 06, National Education Services, pp. 76–87.
- Pasupuleti, MK 2023d, 'Causal Time-Series with statsmodels: Conformal Risk Control under Regime Shifts', International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 03, no. 03, National Education Services, pp. 29–40.
- Pasupuleti, MK 2023e, 'Physics-Informed AI in Python: Neural Operators with Verified Error Bounds', International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 03, no. 06, National Education Services, pp. 226–241.
- Pasupuleti, MK 2024a, 'A Unified Big-Data Pipeline for Cloud and Network Telemetry: Design, Implementation, and Benchmarking with Hadoop and Apache Spark', International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 04, no. 12, National Education Services, pp. 47–67.

Pasupuleti, MK 2024b, AI for Climate Risk And Disaster Response: Indian States vs G20 And BRICS Readiness Models, National Education Services.

Pasupuleti, MK 2024c, Cyber Integrity of Climate MRV And Satellite Pipelines: Indian States vs G20 And BRICS, National Education Services.

Pasupuleti, MK 2024d, 'Geo-Visual Analytics for Energy-Efficient Cloud and Network Infrastructure Using ArcGIS and Simulation Data', International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 04, no. 12, National Education Services, pp. 173–192.

Pasupuleti, MK 2026a, 'A Unified Topological and Tensor Framework for Interpretable AI in Networks, Fraud, and Power Systems', International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 06, no. 04, pp. 166–198.

Pasupuleti, MK 2026b, 'Artificial Intelligence for Climate Risk, Emissions Intelligence and Planetary-Scale Environmental Decision-Making', International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 06, no. 03, National Education Services, pp. 114–141.

Pasupuleti, MK 2026c, 'Disaster Digital Twins: AI World Models for Predicting Cascading Infrastructure Failures', International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 06, no. 02, National Education Services, pp. 1–21.

Pasupuleti, MK 2026d, 'Earth System Foundation Models for Predicting Extreme Climate Events Through Integrated Satellite, Oceanic, and Land-Surface Intelligence', International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 06, no. 03, National Education Services, pp. 29–59.

Pasupuleti, MK 2026e, "Earth-System Digital Twins for Verifiable Gigaton-Scale Carbon Removal through Enhanced Weathering," International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 06, no. 07, pp. 339–388.

Pasupuleti, MK 2026f, "Functional and Object-Oriented Data Analysis for Complex Biomedical, Environmental and Socioeconomic Systems," International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 06, no. 07, pp. 234–284.

Pasupuleti, MK 2026g, "Geospatial Quantum–AI Climate–Finance Digital Twins: Carbon Integrity, Infrastructure Resilience, Systemic Risk and Inclusive Development," International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 06, no. 08, pp. 106–133.

Pasupuleti, MK 2026h, “Persistent Homology-Driven Foundation Models for Discovering Hidden Structures in Complex Data Space,” International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 06, no. 05, pp. 227–263.

Pasupuleti, MK 2026i, “Quantum Topological Neural Operators and Digital Twin Intelligence for Multiscale Climate, Energy, Hydrological, Urban, Industrial and Health Systems,” International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 06, no. 08, pp. 78–105.

Pasupuleti, MK 2026j, “Quantum–AI for High-Dimensional Learning: Graph Neural Networks, Topological Data Analysis, Tensor Networks, and Sparse Predictive Modelling,” International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 06, no. 06, pp. 36–83.

Pasupuleti, MK 2026k, ‘Satellite-Based Carbon MRV: Remote Sensing and Atmospheric Inference for Verifiable Carbon Removal’, International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 06, no. 02, National Education Services, pp. 142–165.

Analytical Index

Carbon accounting 2.4, 5.4
Carbon storage 1.4, 5.3–5.4
Catalog completeness 1.2, 3.1
Causal inference 2.3
Digital twin 4.3
Earthquake forecasting 1.2, 3.4, 5.1
Fault connectivity 3.2, 5.2
Geological prior 2.5
Graph learning 3.2
Inverse problem 1.3, 2.5
Mass balance 2.4, 3.3
Model release 4.4
Monitoring 4.2, 5.4
Neural operator 3.3
Physics constraint 3.3
Plume migration 3.5, 5.4
Prospective evaluation 3.4, 5.1
Remote sensing 2.4
Reservoir 1.4, 5.3
Seismicity 1.2, 2.1
Spatial data 4.1
Storage verification 2.4, 5.4
Structural uncertainty 2.2, 5.2
Surrogate 3.3
Uncertainty 2.2, 3.5