From data availability to evidence sufficiency. PIH MS as an auditable framework for diagnosing hydrogeological knowledge gaps in Mato Grosso do Sul, Brazil

Carlos Busón Buesa[1]* · Sandra Garcia Gabas[1]

[1] Universidade Federal de Mato Grosso do Sul (UFMS), Graduate Program in Environmental Technologies (PPGTA), Faculty of Engineering, Architecture, Urbanism and Geography (FAENG), Campo Grande, Mato Grosso do Sul, Brazil

Carlos Busón Buesa · carlos.buson@ufms.br · ORCID 0000-0002-1446-2252

Sandra Garcia Gabas · sandra.gabas@ufms.br · ORCID 0000-0002-1027-0288

* Corresponding author · Carlos Busón Buesa · carlos.buson@ufms.br

Preprint manuscript prepared for EarthArXiv

From data availability to evidence sufficiency. PIH MS as an auditable framework for diagnosing hydrogeological knowledge gaps in Mato Grosso do Sul, Brazil

Carlos Busón Buesa[1]* · Sandra Garcia Gabas[1]

[1] Universidade Federal de Mato Grosso do Sul (UFMS), Graduate Program in Environmental Technologies (PPGTA), Faculty of Engineering, Architecture, Urbanism and Geography (FAENG), Campo Grande, Mato Grosso do Sul, Brazil

Carlos Busón Buesa · carlos.buson@ufms.br · ORCID 0000-0002-1446-2252

Sandra Garcia Gabas · sandra.gabas@ufms.br · ORCID 0000-0002-1027-0288

* Corresponding author · Carlos Busón Buesa · carlos.buson@ufms.br

Preprint manuscript prepared for EarthArXiv

Abstract

Groundwater registries can be extensive yet fail to demonstrate the evidence chain required to answer a hydrogeological question. We present PIH MS, an experimental framework that audits a bounded corpus of acquired records and makes knowledge gaps visible without predicting groundwater occurrence. The framework organises 12 evidence layers, nine knowledge dimensions, 39 declared requirement instances, five questions, and six families of scientific units. The corpus contains 3,877 provisional well identifiers. The audit recovered 1,591 stable hydraulic-test identities, 1,970 stable chemical-sample identities, 3,213 exact well-to-test-date links for hydraulic parameters, and 2,557 consistent chemical result-to-sample links. These relationships did not form a complete evidence chain. Captured-interval identity, verified units, complete analytical quality assurance, stable same-variable series, and a declared monitoring-network design remained unavailable. No complete case was demonstrated for Q01 to Q04 or Q05a, and Q05b could not be evaluated. This result diagnoses corpus fitness under explicit evidence contracts. It neither indicates methodological failure nor implies an absence of hydrogeological knowledge in the state. Controlled synthetic inputs reached UNKNOWN and every implemented stage from P1 to P4, confirming that P4 is attainable. Experimental context gates influenced intermediate stages and mapped patterns but have not yet undergone external validation. Full-chain blockers were assessed separately. Twelve question-requirement combinations, corresponding to eight unique fields, acted as universal blockers. Enumeration of 1,472 subsets yielded minimum failure distances of one, three, three, two, and four requirements for Q01 to Q05, respectively. Five grid scales and four origins were compared at 14,284 fixed support points. Overall agreement among origins ranged from 64.24% to 66.81%, whereas agreement at locations classified under at least one origin ranged from 29.82% to 34.86%. The primary grids comprised 45,145 cell-question pairs, of which 32,405 were UNKNOWN, 2,801 P1, 5,448 P2, 4,491 P3, and none P4. P5 was not implemented. A single execution regenerated 21 priority outputs as byte-identical files. The proposed contribution is an auditable architecture that specifies evidence before mapping, preserves unknown states, exposes concurrent blockers, evaluates logical and spatial sensitivity, and retains a reverse path to source records.

Keywords

groundwater data quality, groundwater knowledge gaps, hydrogeological evidence, question-driven assessment, non-compensatory rules, entity linkage, multiscale sensitivity, data provenance, Mato Grosso do Sul, Brazil

Plain language summary

A region can contain many registered wells and millions of stored table rows while still lacking a complete evidence package for a specific hydrogeological question. PIH MS first states the question and the evidence needed to answer it. It then checks which parts are present, whether they belong to the correct test, sample, interval, series, or network, where the chain breaks, and whether the mapped result changes with grid size or grid position. The project found substantial positive information, including test and sample links, but no complete entity-linked case under the declared rules. A controlled test supplied progressively complete evidence and reached every implemented stage, including P4 when the full local minimum was present. The observed zero therefore describes the acquired corpus rather than a class that the code cannot produce. PIH MS does not predict where groundwater exists. It makes a bounded and traceable knowledge gap visible so that researchers can see what must be located, linked, verified, or acquired.

1 Introduction

Groundwater knowledge is assembled from heterogeneous observations, well records, construction logs, pumping tests, water levels, chemical analyses, geological interpretations, and monitoring series. These components are not interchangeable. A registered well does not necessarily include a documented screened interval. A pumping-test entry does not necessarily contain the metadata required to interpret a hydraulic parameter under established test-analysis procedures (Kruseman et al., 1994). A dated water-level value does not constitute a time series, whose scientific value depends on sustained and purpose-oriented measurement (Taylor and Alley, 2001). A chemical value without sampling and analytical context does not demonstrate comparability (International Organization for Standardization, 2009 and U.S. Geological Survey, 2018). The availability of records therefore differs from the availability of evidence that is sufficient for a particular question.

This distinction has become increasingly important as groundwater information systems grow in size and accessibility. International initiatives emphasize the need to separate wells, constructions, observations, samples, and tests, and to preserve the metadata that allow groundwater data to be exchanged and interpreted (Brodaric, 2021). The FAIR principles similarly treat data, metadata, vocabularies, and workflows as connected research objects rather than isolated files (Wilkinson et al., 2016). Long-term groundwater monitoring depends on explicit objectives, appropriate well characteristics, consistent measurement procedures, and sustained temporal records (Subcommittee on Ground Water, 2013). At the global scale, groundwater modelling and monitoring research continues to identify dispersed information, inconsistent metadata, and uneven observation coverage as barriers to reliable synthesis (Condon et al., 2021).

Brazil illustrates both the value and the difficulty of large public groundwater databases. SIAGAS and RIMAS provide a substantial national information base (Serviço Geológico do Brasil, 2023). GWDBrazil consolidated and quality-controlled hundreds of thousands of Brazilian well records while documenting missingness and harmonisation difficulties in lithological, construction, pumping, chemical, and monitoring information (Uchôa et al., 2025). That work substantially improves national data availability. It does not eliminate the need to ask whether the evidence required for a specific hydrogeological question is jointly demonstrated for the same scientific entity.

Most regional mapping workflows begin with variables that are combined to estimate groundwater potential, vulnerability, suitability, or monitoring value. Reviews show wide variation in predictor choice, weighting, model technique, and validation, while recent criticism also questions what a groundwater-potential class actually establishes (Díaz-Alcaide and Martínez-Santos, 2019, Thanh et al., 2022, and Bradbury, 2025). PIH MS addresses a different problem. It does not estimate the distribution of groundwater and does not infer unobserved values. Instead, it asks what information would be required to support a stated hydrogeological question, what part of that information is demonstrably present in an acquired corpus, what requirement interrupts the chain, and whether the resulting documentary classification persists across alternative spatial supports.

The central research question is the following.

> *How can a heterogeneous public well corpus be transformed into a traceable, question-driven, and spatially sensitive diagnosis of documentary sufficiency without converting missing information into absence of groundwater?*

A simple Q02 example illustrates this distinction. A registered well may have a pumping-test date, discharge, static water level, and dynamic water level. These fields constitute useful stored information, but they do not yet demonstrate an aquifer-specific hydraulic interpretation. PIH MS asks whether the result belongs to an identifiable test, whether the unit and interpretation method are verified, whether the captured interval and hydrostratigraphic unit are linked to that construction, and whether the minimum chain is complete. If the chain stops at any required link, the output records the documentary stage and the unmet requirement. It does not reinterpret the record as evidence that groundwater or hydraulic information is absent. Figure 3 follows this example through the complete diagnostic structure.

The study has seven objectives.

1. To define an explicit architecture linking source records, audited attributes, evidence, knowledge dimensions, requirements specified as indispensable, hydrogeological questions, local sufficiency, and documentary research priority
2. To apply that architecture to a bounded public corpus for Mato Grosso do Sul using non-compensatory rules that preserve UNKNOWN
3. To quantify the sensitivity of the documentary classification to five grid scales and four grid origins using fixed comparison points
4. To preserve an auditable reverse route from every mapped result to the unmet requirement, provisional identifier, derived field, and source code
5. To test whether the diagnosis is controlled by one requirement or by concurrent failures and to identify whether every requirement is evaluated at the proper scientific unit
6. To determine whether stored well-level associations can be recovered as entity-linked tests, samples, results, series, and network designs
7. To position the integration relative to selected antecedents, document the rights associated with each source family, and assess the computational repeatability of the priority module

The contribution does not lie in the isolated use of wells, hexagons, data auditing, or conjunctive rules. It lies in the operational integration of eight properties. The scientific question organises the assessment. Required evidence is specified before classification. Each requirement is assigned to a scientific unit and a required link. Non-compensatory logic prevents abundant unrelated information from substituting for a component declared necessary but absent. UNKNOWN remains distinct from demonstrated absence. The diagnosis retains an auditable reverse path. Logical sensitivity is tested through individual and joint requirement perturbations. Spatial sensitivity is examined across selected grid scales and origins.

Version 0.4.2 tests a proposition that remained implicit in the earlier architecture. The preserved V2.6 implementation shows that Boolean components were associated with the same provisional well identifier. V0.4.2 reconstructs only links demonstrable from stable identifiers or from one unambiguous exact match between well and date. It then separates stored presence, entity linkage, and complete question sufficiency. This distinction prevents a date in one row and a value in another from being treated as a single scientific observation merely because both rows share a well identifier.

The zero-complete-case result is not used as evidence that the method failed or that the state lacks hydrogeological knowledge. A diagnostic designed to detect breaks in an evidence chain is functioning when it identifies a reproducible break and records its cause. The method would fail scientifically if it converted missing linkage into demonstrated absence, if its classes were unreachable by construction, or if the zero result disappeared under an unreported change of rule. Entity auditing, synthetic reachability tests, complete requirement-subset enumeration, context-gate ablation, spatial perturbations, and isolated reproduction were included to distinguish those possibilities.

The proposed contribution is not a new missing-data index or another groundwater map. PIH MS turns a knowledge gap into a falsifiable diagnostic object. For a stated question, it specifies the scientific entities and links required, tests their non-compensatory conjunction, records each unmet component, subjects the diagnosis to logical and spatial perturbations, and preserves a reverse path between the map and the source record. The resulting map shows where and why the acquired corpus ceases to support the question, without converting missing documentation into an absence of groundwater. Figure 3 presents a complete operational example for Q02.

This article presents an experimental implementation and its application to Mato Grosso do Sul. It does not claim that all public sources were acquired, that no complete hydrogeological study exists in the state, that the method has been externally validated, or that international precedence has been established. The documented comparison of antecedents describes how the proposed architecture differs within the examined set.

The eight features were defined by the authors and do not constitute an independent test of originality or precedence.

2 Scientific background and related work

2.1 From data availability to fitness for a question

Data quality cannot be evaluated independently of intended use. A location may be adequate for displaying a registered well and inadequate for analysing hydraulic connection. A positive total depth may document drilling depth and still fail to locate the screened interval. A chemical observation may confirm that a parameter was reported and still be unsuitable for temporal or spatial comparison. PIH MS adopts this question-dependent view and expresses it through observable requirements rather than a single quality score. This position is consistent with work showing that provenance, metadata, and fitness for use become decisive when heterogeneous water data are opened for reuse (Larsen et al., 2016). The approach also follows the FAIR emphasis on explicit metadata and reusable workflows while adding a hydrogeological fitness-for-question test (Wilkinson et al., 2016).

GroundWaterML 2 provides a domain-specific model that distinguishes groundwater features, wells, constructions, and observations (Brodaric, 2021). This separation supports traceability and interoperability, but it does not by itself determine whether a local set of records is sufficient for a specific hydrogeological question. PIH MS operates at that later interpretive boundary. Its analytical-unit model distinguishes identifiers, constructions, intervals, observations, tests, samples, results, series, and networks.

2.2 Groundwater databases and monitoring systems

National and international groundwater systems demonstrate the importance of stable identifiers, construction metadata, geological context, water-level observations, water-quality information, and temporal continuity. The US National Ground-Water Monitoring Network distinguishes network objectives and minimum data elements (Subcommittee on Ground Water, 2013). The Brazilian SIAGAS and RIMAS systems provide broad public access to well and monitoring information (Serviço Geológico do Brasil, 2023). GWDBrazil adds harmonisation, quality flags, and state-level summaries of missing data (Uchôa et al., 2025). Decision-driven water-data research likewise begins with a use case and identifies the data needed for that use, including gaps in availability, accessibility, interoperability, and resolution (Cantor et al., 2021). These resources are essential antecedents and inputs. PIH MS does not replace them. It uses an acquired subset to test question-specific documentary sufficiency and the spatial persistence of diagnosed gaps.

2.3 Difference from groundwater potential mapping

Groundwater potential mapping combines environmental or hydrogeological predictors to delineate areas interpreted as more or less favourable for groundwater occurrence or development. Reviews have raised questions about variable selection, weighting, validation, and the meaning of potential (Díaz-Alcaide and Martínez-Santos, 2019, Thanh et al., 2022, and Bradbury, 2025). PIH MS produces no groundwater potential surface. It uses no AHP, no weighted overlay, no kriging to fill missing values, and no machine-learning prediction. A later documentary stage does not mean high or low groundwater potential. It means that the acquired evidence chain progressed farther under the rule for a particular question.

2.4 Non-compensatory evaluation

Compensatory models allow strength in one criterion to offset weakness in another. Such trade-offs are inappropriate when a requirement is logically indispensable to a scientific interpretation. A well with many documented attributes cannot establish aquifer-specific hydraulic properties if the captured interval or hydraulic unit is not demonstrated. PIH MS therefore uses conjunctive rules for requirements specified as indispensable. The approach is deliberately conservative and must be tested for dominance by universally missing fields.

2.5 Spatial scale and zoning sensitivity

Aggregating point records into cells introduces scale and zoning effects. The modifiable areal unit problem shows that results can change when the size, shape, or origin of spatial units changes (Openshaw, 1984 and Fotheringham and Wong, 1991). PIH MS treats this dependence as an empirical result rather than hiding it behind one selected grid. Five nominal cell areas and four selected origins are compared at fixed support points. Agreement describes the repeatability of the documentary class across these configurations. It does not demonstrate scientific correctness, independence, or territorial representativeness.

2.6 Proposed contribution and position relative to antecedents

The literature encompasses groundwater-database harmonisation, quality flagging, entity standards, monitoring-network design, decision-driven data-system design, information-based site prioritisation, data-gap surveys, groundwater-potential mapping, spatial sensitivity studies, and use-specific data-quality frameworks. Larsen et al. (2016) show why water-data quality must be interpreted in relation to intended use and communicated with provenance. Cantor et al. (2021) place decision needs before water-data system design. GroundWaterML 2 distinguishes wells, constructions, observations, and related entities (Brodaric, 2021). Josset et al. (2019) examine water-data availability and gaps across US jurisdictions. GWDBrazil and the US groundwater-well database demonstrate both the value and the persistent heterogeneity of national integration efforts (Uchôa et al., 2025 and Lin et al., 2024). Monitoring-network methods assess information content, redundancy, and site selection rather than the sufficiency of a declared evidence chain (Keum et al., 2017 and Jia et al., 2022).

PIH MS does not claim to originate any of these components. Its proposed contribution is their operational integration within a question-to-gap architecture. Eight features describe that integration. The workflow begins with an explicit hydrogeological question. Required evidence is specified separately for each question. Declared requirements are joined through a non-compensatory conjunction. Unknown states remain explicit. Requirements are assigned to the identity of constructions, intervals, events, tests, samples, results, series, or networks. Individual and joint requirement removals are tested. Sensitivity to grid scale and origin is assessed at fixed locations. The output retains a reverse path to the supporting source record.

To position the proposed architecture, a scoped review conducted on 7 September 2026 documented ten search families, screened 18 closely related sources and systems, and compared the candidates against these eight features. No candidate exhibited all eight within the examined set. Because the features were defined by the authors from the architecture itself, the matrix is a descriptive comparison rather than an independent validation of originality. Subscription databases, non-indexed reports, local systems, unpublished workflows, and works in languages outside the search may contain closer equivalents. The manuscript describes a distinct integration within the documented set and does not claim to be the first worldwide, the only such system in Brazil, unique, or unprecedented.

3 Case-study context and corpus boundary

3.1 Geographic and hydrographic setting

Mato Grosso do Sul lies in west-central Brazil and borders Bolivia and Paraguay. The state covers 357,142.01 square kilometres and contains 79 municipalities (Instituto

Brasileiro de Geografia e Estatística, 2026). Its territory spans the Paraná and Paraguay hydrographic regions. The state water-management geography used by PIH MS contains 15 planning and management units. This combination of a large state area, two major hydrographic regions, international borders, and geographically dispersed municipalities makes the scale and location of evidence operationally important.

Figure 1 locates the study area and summarises the territorial context used in the analysis. The 15 management units are contextual reporting areas rather than the analytical units used to calculate documentary stages. PIH MS uses hexagonal cells and fixed comparison points for those calculations, allowing the effects of cell size and grid displacement to be measured explicitly. The figure shows Mato Grosso do Sul within South America and Brazil together with the 3,877 spatially usable provisional well identifiers. The contextual panel reports the state area, municipalities, two hydrographic regions, 15 water-planning and management units, and the granular, fractured, and karst hydrolithological domain families described by the state-scale reference. State geometry derives from the preserved official boundary, whereas the regional locator uses Natural Earth public-domain geometry. The figure does not map a captured aquifer or a complete evidence package.

3.2 Hydrogeological heterogeneity

The 2024 Hydrogeological Map of Mato Grosso do Sul provides a principal state-scale hydrogeological reference used in this study at a scale of 1:1,000,000 (Abreu et al., 2024). The preserved cartographic layer distinguishes three broad hydrolithological domain families. They are granular, fractured, and karst. These families express different modes of groundwater storage and circulation and make a single undifferentiated interpretation of well records scientifically unsafe. A recorded depth, yield, water level, hydraulic parameter, or chemical result can support a hydrogeological interpretation only when the relevant construction, captured interval, unit, test, sample, or series is demonstrably linked.

The state-scale map is a regional framework rather than proof of the aquifer captured by an individual well. PIH MS therefore treats mapped geological and hydrogeological context as supporting information and does not substitute polygon membership for a documented captured interval. The mapped domains also do not convert the analytical hexagons into hydrogeological units.

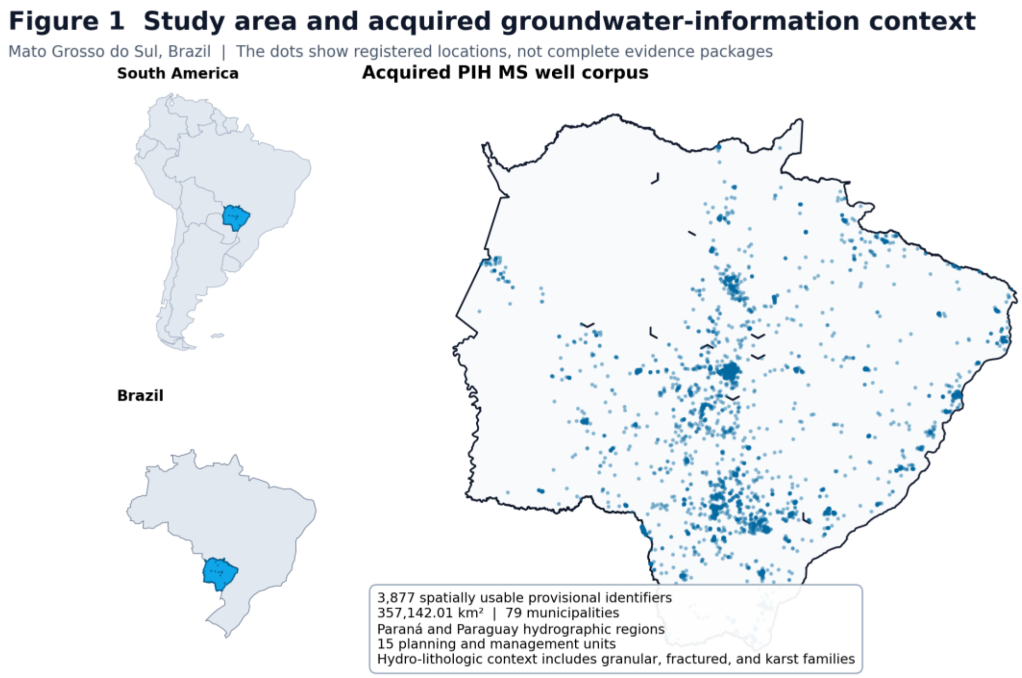

Figure 1. Study area and hydrogeological context of Mato Grosso do Sul

3.3 Institutional and information landscape

The state is not devoid of groundwater information. It participates in a wider Brazilian information ecosystem that includes SIAGAS, the RIMAS integrated monitoring network, SGB geological and hydrogeological cartography, state licensing and reporting, basin plans, laboratory analyses, and institutional studies. The information was created for different purposes, at different times, with different identifiers and levels of granularity. PIH MS examines whether an acquired subset of that ecosystem can be connected into evidence packages designed to answer five stated questions.

The institutional record also shows change through time. The 2010 state water-resources plan described the groundwater information and monitoring situation at that time (Mato Grosso do Sul, 2010). In 2021, Imasul reported the first edition of a permanent state groundwater-quality effort based on self-monitoring data collected in 2018 and 2019. That edition comprised 144 samples from 69 authorised wells, 22 analytical parameters, and nine of the 15 state planning units (Instituto de Meio Ambiente de Mato Grosso do Sul, 2021). These figures describe that programme and period. They are not counts of the PIH MS corpus.

At national scale, RIMAS reported 465 active monitoring wells in 2025, 15 telemetry stations, simultaneous groundwater-level and precipitation recording at 44 wells, and five new wells in the Guarani Aquifer System (Moura, 2025). These are national network figures, not Mato Grosso do Sul totals. They demonstrate that structured monitoring exists in Brazil while also showing why a state corpus assembled from registry, monitoring, cartographic, and administrative sources cannot be treated as one homogeneous table.

The PIH MS scientific cutoff was 29 August 2026. Inclusion was restricted to sources identified, acquired, preserved, and documented by that date. The main inputs included SIAGAS-derived well records, RIMAS-related information, the 2024 Hydrogeological Map of Mato Grosso do Sul, the state geological map, the official state boundary, and contextual state water-resource documents. Each source retained its role, scale, version, date, fields, and stated limitations.

3.4 Corpus boundary and units of count

The resulting corpus contained 3,877 spatially usable provisional well identifiers. The word provisional is essential. The workflow preserved candidate duplicates and did not treat geographic proximity or similar attributes as sufficient proof that two records refer to the same physical well. Consequently, the 3,877 identifiers must not be interpreted as 3,877 demonstrated independent physical wells.

The V2.7.1 package contains 254 CSV files and 3,839,462 physical rows distributed across sources, audits, matrices, derived spatial products, and results. These rows are storage records generated at different stages of the workflow. They are not independent groundwater observations. The article therefore reports the unit associated with every count.

4 Methods

4.1 Scientific architecture

PIH MS was organized into 13 workflow stages.

1. Corpus delimitation
2. Record resolution
3. Scientific entity audit
4. Attribute audit
5. Evidence matrix
6. Separate knowledge dimensions

7. Question model
8. Entity-linked and well-level sufficiency
9. Local cell-level sufficiency
10. Multiscale spatial structure
11. Documentary research priority
12. Cartographic agreement
13. Reproducibility and reverse traceability

Each stage has an input, an explicit rule, an output, a primary file, an allowed interpretation, and a prohibited interpretation. The website and PWA are communication layers. They do not reclculate the scientific architecture.

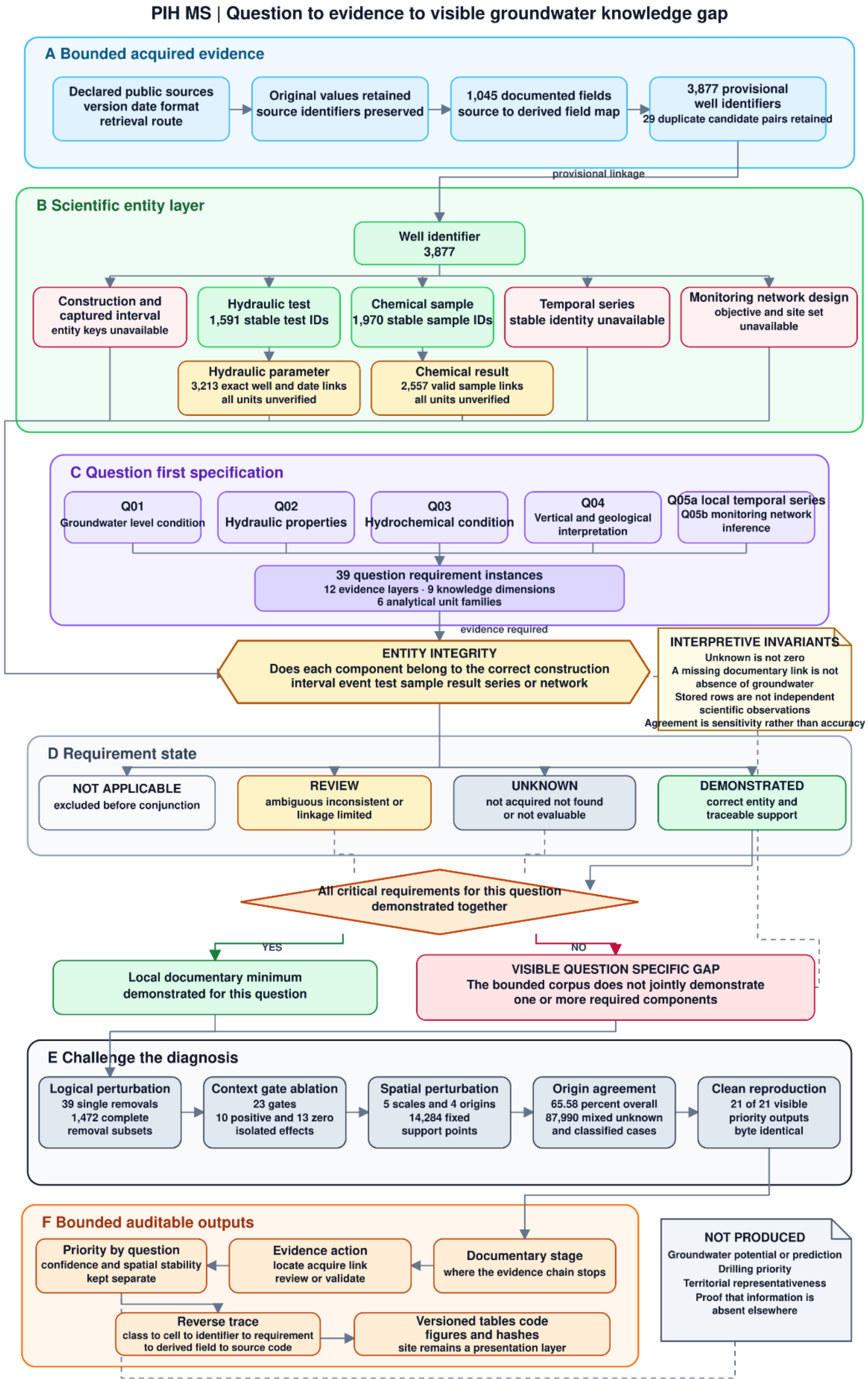

Figure 2. PIH MS architecture

Figure 2. PIH MS architecture. The bounded-evidence, scientific-entity, and question-specification branches converge before the non-compensatory conjunction. A failed link produces a visible question-specific diagnosis within the acquired corpus. Logical perturbation, context-gate ablation, scale and origin comparison, and clean reproduction challenge the diagnosis before the auditable output is accepted. The figure does not represent absence of groundwater or information outside the corpus.

4.2 Source preservation and attribute audit

Original values were preserved separately from validated and derived fields. The audit evaluated the existence, format, domain, unit, internal coherence, and provenance of acquired attributes. Missing values were not inferred. Alerts were retained rather than silently corrected. The package documents 1,045 fields across source, audit, derived, and output structures.

An absence of an audit alert does not certify complete data quality. It means only that the implemented check did not identify the corresponding condition. This distinction is maintained in the data dictionary and in the interpretation of all derived evidence.

4.3 Provisional record resolution

Current and historical records were associated through preserved identifiers and explicit candidate-linkage procedures. Candidate duplication was recorded for review. No automatic merging was accepted as proof of physical identity or hydrogeological independence. The approach follows the distinction between probabilistic or rule-based record linkage and confirmed entity resolution (Fellegi and Sunter, 1969 and Christen, 2012).

4.4 Scientific entity audit

The entity audit treated the provisional well identifier as one parent identifier and searched for demonstrable child entities. The required model distinguishes construction, captured interval, water-level event, hydraulic test, hydraulic result, chemical sample, chemical result, temporal series, and monitoring-network design. A conjunction was accepted only when every component could be related to the same identifiable scientific entity.

Hydraulic parameter rows did not carry a stored test identifier. A parameter was therefore linked to a test only when exactly one test shared the same provisional well identifier and exact test date. Ambiguous matches and unmatched rows remained unavailable. This conservative rule recovered structure without treating proximity in a table as identity.

Chemical results contained sample identifiers. A chemical link was accepted only when the result referred to an existing sample and both rows carried the same provisional well identifier. Dates, units, and quality-assurance information were then evaluated within that sample-to-result chain.

For Q01 to Q04 and Q05a, the audit searched for at least one real case satisfying all declared requirements without removing a requirement and without replacing a missing entity by a well-level proxy. A zero count was interpreted as no complete entity-linked chain demonstrated in the acquired corpus. It was not interpreted as absence of the underlying hydrogeological phenomenon. Q05b required a declared monitoring-network design and site-set entity. Because neither was available in the acquired corpus, Q05b was classified as not evaluable rather than assigned a zero.

4.5 Evidence layers

Twelve evidence layers were derived from auditable conditions.

Code	Documentary evidence or flag	Provisional identifiers
E01	Spatially usable provisional well identifier	3,877
E02	Reported positive total depth	3,414
E03	Aquifer name reported in the register	3,097
E04	Static water level reported	3,213
E05	Dynamic water level reported	3,180
E06	Non-negative specific capacity reported	3,051
E07	Pumping test registered	1,106
E08	Test with minimum registration metadata	1,096
E09	Transmissivity reported	51
E10	Partial hydrochemical evidence	2,053
E11	Dated hydrogeological evidence	1,637
E12	Hydrostratigraphic review required	1,823

The evidence counts overlap and must not be added. E01 to E11 primarily describe documented presence under their individual rules. E12 is a review flag and must not be interpreted as positive hydrostratigraphic evidence. Reported presence does not establish sufficiency, methodological validity, unit comparability, or independence.

4.6 Knowledge dimensions

The evidence and audit states were organized into nine separate dimensions covering spatial, hydrostratigraphic, vertical, hydraulic, hydrochemical, temporal, independence, documentary quality, and cross-cutting uncertainty conditions. The dimensions were not summed and received no weights. The 39 question requirements draw from eight substantive dimensions. Uncertainty remains cross-cutting.

4.7 Questions and declared requirements

Five questions organized the sufficiency assessment.

Code	Hydrogeological question	Requirements (n)	Direct-evidence identifiers	Complete-minimum identifiers
Q01	Water level and depth	7	3,213	0
Q02	Hydraulic properties	9	3,081	0
Q03	Hydrochemistry	9	2,053	0
Q04	Aquifer geometry and stratigraphy	6	3,415	0
Q05 legacy well-level projection	Temporal monitoring	8	1,637	0

The questions do not compensate for one another. The number and content of requirements are versioned methodological decisions. The evidence contract was constructed by decomposing each question into components that, under the implemented specification, must be associated with the corresponding scientific entity and link for the requested interpretation to be demonstrable. It was not derived from field frequency or availability in the corpus. Similar requirements may therefore belong to different units and are not interchangeable among wells, constructions, intervals, tests, samples, results, series, or networks. Assigning each requirement to its unit, entity, and link makes the contract explicit and open to review. Its scientific indispensability and the intermediate context gates remain subject to external review and sensitivity testing.

The V2.4 requirement registry classifies all 39 conditions as critical at record level. The V0.4.2 audit shows that this classification is not scientifically adequate. The underlying requirements belong to six unit families.

Unit code	Scientific unit	Requirement instances
U1	Provisional well identifier and location	5
U2	Construction, profile, captured interval, and captured-unit relation	13
U3	Measurement event, hydraulic test, sample, or analytical result	13
U4	Temporal series at one site for one normalized variable	2
U5	Monitoring-network design and site set	1
UQ	Question-scoped audit of the records used in the evidence chain	5

Every requirement is listed with its implemented unit, proposed scientific entity, required entity key, link rule, present linkage state, and audit decision in PIH_MS_REQUIREMENT_ANALYTICAL_UNITS_V02.csv. The filename records the audit stage at which the registry was created. The assignment is a methodological proposal for review and does not silently change the preserved V2.6 output.

The main conflict occurs in Q05. independence_demonstrated is a property of a monitoring design or network, not a property that one well record can demonstrate alone. The dimension matrix already labels independence as cell-critical while the requirement registry evaluates Q05_R07 per record. The source constructor also sets the field to false for all identifiers. The audit therefore separates Q05a, local temporal-series sufficiency, from Q05b, network-level inference capacity. Q05a excludes network independence but still requires an entity-linked repeated series. Q05b cannot be evaluated from the present well-level boolean matrix.

4.8 Non-compensatory sufficiency

For provisional well identifier (w), question (q), and the set of declared requirements (R_q), the complete documentary minimum preserved in V2.6 was defined as

$$M_{wq} = \bigwedge_{r \in R_q} I_{wr}$$

where (I_{wr}=1) only when requirement (r) is demonstrated under the implemented rule. A requirement marked UNKNOWN cannot satisfy the conjunction and is not compensated by other documented fields. This logical treatment does not mean that UNKNOWN is a measured zero or physical absence. Partial counts are retained for diagnosis but do not create a complete minimum.

The subscript (wr) accurately describes the implemented matrix but not necessarily the scientific entity. Hydraulic units and chemical parameters are aggregated using an any-record-per-well rule. Other components are projected from different well-level tables. A positive conjunction can therefore demonstrate association with the same provisional identifier without proving that every component belongs to the same event, test, sample, result, or series. V0.4.2 requires an entity-integrity condition for future implementation.

$$I_{weqr}^{linked} = 1$$

only when requirement (r) is demonstrated for identifier (w), scientific entity (e), and question (q) through the declared entity key. Complete future sufficiency must be calculated on linked entities before it is projected back to a well or cell. The current corpus cannot support this full recalculation because several necessary entity identifiers and relationships were not acquired.

For a cell (c) containing the set of acquired identifiers (W_c), the number of complete local records was

$$N_{cq}^{min} = \sum_{w \in W_c} M_{wq}$$

A value above zero would demonstrate at least one locally associated identifier satisfying the implemented conjunction. It would not establish representativeness of the complete cell or hydrogeological unit.

4.9 Requirement sensitivity and concurrent-blocker analysis

The sensitivity audit evaluates how strongly the zero-minimum result depends on each requirement. For every question and requirement (r), the leave-one-requirement-out result is

$$M_{wq}^{(-r)} = \bigwedge_{s \in R_q, s \neq r} I_{ws}$$

The analysis reports the number and percentage of identifiers blocked by the requirement, the number completing the conjunction after removal, the gain from removal, the number for which the removed requirement was the sole blocker, and the number of other concurrent blockers. The gain and sole-blocker count must be identical. This equality is used as an internal control.

A universal blocker is a requirement not demonstrated for any of the 3,877 identifiers. Universality and decisiveness are different. A universal blocker can produce zero gain when other universal or near-universal blockers fail in the same records. The analysis therefore adds joint removal of the universal blockers within each question.

The complete power set of requirement removals was also enumerated. The five question registries contain 7, 9, 9, 6, and 8 requirements. Their power sets contain 128, 512, 512, 64, and 256 subsets, respectively. All 1,472 subsets were evaluated. For each number of removed requirements, the analysis records the maximum number of identifiers satisfying the retained conjunction and the subset producing that maximum. These counterfactual results measure logical sensitivity. They do not justify deleting a requirement.

Two spatial variants were defined. minimum_only modifies only the complete conjunction and retains the original direct-evidence and context definitions. stage_consistent also removes the requirement from the context gate when it is one of the declared gate components. The variants answer different questions and are reported separately.

The requirement-removal recalculation covers the five preserved O00 primary grids. It reproduces all 45,145 baseline cell-question classes and every O00 priority code at the 14,284 fixed support points without mismatches. The separate origin audit does not apply each requirement-removal scenario to every shifted polygon. It directly recomputes agreement and transitions from the four origin-specific codes preserved at each fixed support location.

4.10 Direct evidence, context gates, and complete minimum

Each question was evaluated through a staged documentary sequence.

1. Direct evidence
2. Experimental context gate
3. Complete documentary minimum
4. Territorial representativeness as a future and unimplemented level

The context gate separates isolated direct evidence from evidence accompanied by selected interpretive context. It does not replace the complete minimum. V0.4.2 reports the removal of each of the 23 context-requirement instances one at a time and measures the number of additional provisional identifiers retained. A zero isolated effect was not treated as evidence that a gate is unnecessary because another concurrent gate may mask it. The five question-specific context gates remain experimental and require external hydrogeological review.

4.11 Multiscale and multi-origin spatial design

Five distinct hexagonal grids were generated with nominal cell areas of 100, 150, 250, 500, and 1,000 square kilometres. Their primary O00 versions contained 3,763, 2,525, 1,537, 791, and 413 cells, respectively, for a total of 9,029 cells. No scale was selected as the final or true representation.

The V2.7.1 public viewer also retains an earlier family of candidate grids with nominal cell areas of 250, 500, and 1,000 square kilometres, comprising 1,554, 793, and 412 cells, respectively. They correspond to data/malha_250km2_candidata.geojson, data/malha_500km2_candidata.geojson, and data/malha_1000km2_candidata.geojson. These are not the analytical O00 grids used in this article, which are stored as data/scale_study/scale_primary_250km2.geojson, data/scale_study/scale_primary_500km2.geojson, and data/scale_study/scale_primary_1000km2.geojson. The two grid families are distinct products and must not be compared as if they represented the same geometry.

Four origins were examined at each scale. They were O00, OX25, OY25, and OXY25. A fixed support of 14,284 points allowed the same locations to be compared across grid configurations. These support points are comparison instruments, not field observations. The full design contained 357,100 support-scale-question combinations.

The four origins comprise the primary grid and positive 25% shifts along one or both grid axes. They provide a selected test of zoning sensitivity and do not exhaust the possible origins. The origin comparison retained the same fixed support location and scale before comparing the four stored priority codes. Reported measures included exact agreement across all four origins, any change between origins, transitions between UNKNOWN and a classified stage, changes spanning at least two codes, and all pairwise origin comparisons. The 25% displacement requires further scientific justification. The broader PIH MS package also reports descriptive nearest-neighbour distances, sample quantiles, Jaccard presence similarity, and Spearman rank association under their established definitions (Clark and Evans, 1954, Hyndman and Fan, 1996, Jaccard, 1901 and Spearman, 1904). These diagnostics are not treated as independent observations, inferential sample sizes, or external validation.

4.12 Documentary stage classes

The V2.6 implementation uses four inputs for each cell and question. They are the number of acquired identifiers, the number with direct evidence, the number satisfying the context gate, and the number satisfying the complete minimum.

Implemented condition	Output
No acquired identifier in the cell	UNKNOWN
At least one identifier and no direct evidence	P1, direct-evidence stage not reached
Direct evidence and no context gate	P2, context-gate stage not reached
Context gate and no complete minimum	P3, complete-minimum stage not reached
At least one complete local minimum	P4, local complete-minimum stage reached

The order describes the documented stage at which the implemented evidence chain stops. The original interface labels critical, high, moderate, and low may imply urgency that has not been validated. This article therefore treats P1 to P4 as experimental documentary stages. The classes are not a weighted score, territorial urgency index, groundwater-potential class, cost-effectiveness ranking, or drilling recommendation.

Priority is calculated only when a cell contains at least one acquired identifier. A cell without acquired support remains UNKNOWN. It is not assigned P1 and does not enter an ordinal comparison with supported cells. Consequently, PIH MS V2.6 does not prioritise the entire state. Planning data acquisition in unsupported areas requires a separate future module.

P5 was documented conceptually as a complete minimum with demonstrated territorial representativeness. The V2.6 function has no representativeness input and cannot return code 5. P5 is therefore a reserved future class, not an empty operational result.

4.13 Cartographic agreement

The field previously labelled confidence summarizes exact agreement of the priority class across scales and origins. It is stored separately from priority, but it is derived from the stability of that same classification. The scientifically accurate term used in this article is cartographic agreement class. C1 to C5 are not probabilities, confidence intervals, accuracy estimates, or external validation. Raw agreement percentages must accompany categorical summaries.

4.14 Reverse auditability and reproducibility

The forward chain connects source, preserved record, audited attribute, evidence, dimension, requirement, question, documentary state, and spatial behaviour. The reverse structure permits an audit route from a cell class to its blocking state, unmet requirement, provisional identifier, derived field, and source code. A complete row-to-byte reconstruction cannot exist for a component that was not acquired. This article therefore uses reverse auditability rather than claiming exhaustive source reconstruction.

CSV is the primary open tabular reference, and GeoJSON stores the spatial results. Scripts implement the derivations. Markdown methodology files and field dictionaries document the rules and limitations. Excel is a complementary format for human review. The interactive website is a consultation layer. The manuscript and scientific package are the authoritative references for definitions, limitations, units of count, and computational results.

V0.4.2 uses the isolated question-specific priority-builder test on a copy of the preserved release, with Python 3.12.13 and pinned direct versions of GeoPandas, NumPy, Pandas, Pyogrio, PyProj, and Shapely. Every visible result in the research-priority directory was compared by SHA-256 with its preserved counterpart. The scientific package also contains a file-level SHA-256 manifest, allowing every table, figure, script, and manuscript object to be checked against the deposited bytes. This test evaluates the computational repeatability of the module. It does not establish a source-repository commit, the complete identity of the transitive environment, or legal permission to redistribute all inputs.

The reproduction demonstrated in this study covers calculations performed from the derived matrices included in the scientific package. It does not demonstrate that a third party can reconstruct the entire corpus from the original bytes of every external source. Source-corpus reconstruction, documentary traceability, and computational repeatability are distinct levels of verifiability and are reported separately.

4.15 Scoped review of antecedents

Ten documented search families covered groundwater-data completeness, water-data fitness for use, decision-driven information systems, knowledge-gap mapping, data deficiency, non-compensatory decision support, SIAGAS quality control, groundwater entity standards, monitoring-network design, and groundwater-potential mapping.

Searches were conducted on 7 September 2026 using scientific and institutional sources accessible online and were checked against the 55-source PIH MS bibliography. The exact English-language search strings, screening actions, retained candidates, and query-specific limitations are preserved in PIH_MS_ORIGINALITY_SEARCH_LOG_V03.csv. Title and abstract screening was used when full text was unavailable. Accessible full texts and standards documentation were used when identified. A total of 18 closely related sources and systems were then compared against the eight integration features described in Section 2.6 using PIH_MS_ORIGINALITY_FEATURE_MATRIX_V04.csv. V0.4.2 corrects the column alignment of the TDWG row in the inherited matrix without changing its recorded feature values.

The eight comparison features were defined by the authors from the proposed architecture and were not validated by an independent third party. The matrix records the presence or absence of these features within the examined set and does not convert that comparison into proof of substantive originality.

This protocol is traceable but does not constitute a systematic review of a fixed bibliographic database. The search interface did not provide stable total result counts, screening was performed by a single reviewer on one date, and subscription databases and non-indexed sources were not exhaustively examined. The result is therefore a scoped feature comparison rather than an independent validation of originality or evidence of absolute precedence.

4.16 Source rights and clean scholarly object

Software created for PIH MS is declared under AGPL-3.0-or-later. Original scientific text, documentation, and figures are declared under CC BY-NC-SA 4.0 unless a file states otherwise. External data, maps, services, and publications retain their own terms. Public access was not treated as redistribution permission. The EarthArXiv package was therefore designed to contain the manuscript, original figures, analysis scripts, derived audit summaries, machine-readable validation, and source retrieval instructions. Raw external source bytes with unresolved rights were excluded.

5 Results

5.1 Scale of the analytical system

The workflow generated 19,385 well-question pairs and 151,203 well-requirement pairs from the 3,877 provisional identifiers. The five O00 grids contained 9,029 cells and generated 45,145 cell-question pairs. The fixed spatial support generated 71,420 support-question pairs, 357,100 support-scale-question pairs, and 557,076 support-requirement pairs. These analytical pairs are repeated evaluations of defined units and must not be described as independent hydrogeological observations.

5.2 Evidence availability

Basic registration fields were common but not universal. Positive total depth was available for 3,414 identifiers, a registered aquifer name for 3,097, static water level for 3,213, and dynamic level for 3,180. Hydraulic evidence became much narrower when the question moved from reported well performance to interpretable test information. Pumping tests were registered for 1,106 identifiers, 1,096 passed the minimum registration-metadata rule, and only 51 reported transmissivity. Partial hydrochemical evidence occurred in 2,053 identifiers. Dated hydrogeological evidence occurred in 1,637. These counts demonstrate different forms of documentary presence and not complete question-level sufficiency.

5.3 Entity identity and recovered links

The entity inventory showed that the acquired corpus has both recoverable relational structure and decisive missing identities.

Scientific entity	Demonstrated structure	Decisive limit
Provisional well identifier	3,877 unique identifiers	29 duplicate-candidate pairs require review
Well construction	No stable relational construction entity	Depth and construction fields remain well-level projections
Captured interval	316 coherent raw top and base pairs	No pair can be demonstrated as a screened or open captured interval
Hydraulic test	1,591 unique test identifiers	Interpretation method is present for only two tests
Hydraulic parameter	7,493 unique parameter identifiers	Test identifier is not stored and every unit is unverified
Chemical sample	1,970 unique sample identifiers	Sampling and laboratory metadata remain incomplete

Scientific entity	Demonstrated structure	Decisive limit
Chemical result	2,557 unique result identifiers	Every unit is unverified and complete analytical quality assurance is unavailable
Water-level event	No stable event identifier	A value and a date cannot be proven to describe the same event
Temporal series	No stable series identifier	Repeated observations of one normalized variable cannot be established
Monitoring-network design	No network and design-version entity	Objective, site set, dependence model, and sampling design are unavailable

The hydraulic audit recovered 3,213 parameter rows from 1,581 provisional identifiers that linked to exactly one test through the same identifier and exact test date. These links included 1,581 specific-capacity values, 1,581 stabilized-yield values, and 51 transmissivity values. Only four parameter rows from two identifiers contained a method. Those four reported specific capacity or stabilized yield rather than transmissivity. No row combined exact test linkage, a parameter, a verified unit, and a documented interpretation method.

The chemical audit recovered all 2,557 result-to-sample relations with consistent well identifiers. Among them, 960 result rows belonged to samples with both collection and analysis dates. No result chain combined its sample and result identities, both dates, a verified unit, and complete analytical quality assurance. The positive links show that the corpus is not uniformly unstructured. The missing components show why stored presence is not equivalent to an interpretable evidence package.

The positive-case search found no complete entity-linked case for Q01, Q02, Q03, Q04, or Q05a. Q01 lacked construction, captured-interval, captured-unit, and water-level event identities. Q02 lacked captured interval, verified hydraulic unit, and a complete test-to-result chain. Q03 lacked captured interval, verified chemical unit, and a complete analytical chain. Q04 lacked construction, lithological-profile, captured-interval, and captured-unit identities. Q05a lacked stable site, normalized variable, and series identity. Q05b was not evaluable because the corpus contained no declared monitoring network and design version. These are corpus-bounded linkage findings.

5.4 Question-level sufficiency

Direct evidence existed for every question in part of the corpus. It ranged from 1,637 identifiers for temporal monitoring to 3,415 for aquifer geometry and stratigraphy. The experimental context gates retained between 228 and 1,632 identifiers. No provisional identifier met the implemented complete minimum for any question.

Question	Direct evidence	Context gate	Complete minimum
Q01	3,213	1,583	0
Q02	3,081	555	0
Q03	2,053	228	0
Q04	3,415	1,632	0
Q05 legacy well-level projection	1,637	812	0

The defensible result is that the required boolean components were not jointly demonstrated for the same provisional well identifier under the implemented rules. V2.6 does not yet establish co-occurrence within one measurement event, hydraulic test, sample, result, temporal series, or network design. The result does not show that no hydrogeological knowledge exists in Mato Grosso do Sul.

5.5 Context-gate ablation

Direct evidence was common for some questions, but the experimental context gates excluded substantial portions of the direct-evidence subset.

Question	Direct evidence	Context gate	Excluded between direct and context	Context requirements
Q01	3,213	1,583	1,630	5
Q02	3,081	555	2,526	4
Q03	2,053	228	1,825	6
Q04	3,415	1,632	1,783	4
Q05 legacy well-level projection	1,637	812	825	4

Removal of one context requirement produced ten positive isolated effects and thirteen zero isolated effects. Hydrostratigraphic consistency accounted for gains of 1,627 identifiers in Q01, 541 in Q02, 284 in Q03, 1,779 in Q04, and 825 in Q05. Removing minimum hydraulic-test metadata added 972 Q02 identifiers. Removing the hydrochemical-date gate added 641 Q03 identifiers. Removing the chemical-parameter gate added three Q03 identifiers. Removing the question-scoped invalid-record veto added one identifier in Q01 and one in Q04.

The maximum value of 1,632 identifiers, observed for Q04, represents attainment of the context stage under the implemented conditions, not complete entity-linked cases. Likewise, gains produced by ablation enlarge the subset that reaches the context stage but do not demonstrate a complete chain. The universal blockers reported in Section 5.6 remain a separate assessment.

These results show that the context gates are active specification choices. A large gain identifies an influential gate and not a scientifically incorrect gate. A zero isolated gain does not prove redundancy because another concurrent gate may still fail in every newly eligible identifier. P2 and P3 therefore remain descriptive stages in an experimental chain and not validated urgency classes.

5.6 Universal blockers

Twelve question-requirement combinations were not demonstrated for any of the 3,877 identifiers. They corresponded to eight unique fields.

Field	Questions affected
Documented screened interval	Q01, Q02, Q03, Q04, Q05
Verified hydraulic unit	Q02
Verified chemical unit	Q03
Complete analytical quality control	Q03
Explicit documented lithological profile	Q04
Demonstrated same-variable time series	Q05
Identified repeated temporal variable	Q05
Demonstrated hydrogeological independence	Q05

The screened-interval field affected every question. Three fields were set directly to false in the V2.4 question-sufficiency constructor. They were complete chemical quality control, identified temporal variable, and demonstrated independence. The same-variable series was preserved as not acquired. Every hydraulic and chemical result in the source-audit tables carried the code SOURCE_UNIT_NOT_VERIFIED, which explains the two unit blockers. Explicit lithological profiles were not demonstrated in the acquired boolean matrix.

The zero-complete-minimum result is therefore correct under the implemented rules, but it is partly controlled by structural properties of the acquired data model and constructor. A zero is not sufficient evidence that the remaining requirements discriminate among records. Sensitivity must be assessed directly.

5.7 Leave-one-requirement-out results

A total of 39 individual removals were evaluated. Only one produced any complete identifier. Removing Q01_R05, the captured-interval requirement, yielded eight identifiers. Every individual removal in Q02 to Q05 left the complete count at zero.

Question	Requirements tested	Largest gain from one removal	Requirement producing that gain
Q01	7	8	Q01_R05
Q02	9	0	None
Q03	9	0	None
Q04	6	0	None
Q05	8	0	None

The zero gains in Q02 to Q05 do not make the requirements irrelevant. They show that concurrent blockers mask their individual effects. This distinction is visible in the 12 universal question-requirement blocks. Q01_R05 has no other universal blocker in Q01 and therefore becomes empirically decisive when removed. Each universal blocker in Q02 to Q05 leaves between one and three other universal blockers in the retained conjunction.

The internal identity between leave-one-out gain and sole-blocker count held for all 39 requirements. No removal reduced the number of complete identifiers.

5.8 Joint blockers and complete subset enumeration

Joint removal of every universal blocker within each question produced different outcomes.

Question	Universal blockers removed	Complete identifiers after joint removal
Q01	1	8
Q02	2	0
Q03	3	228
Q04	2	1,632
Q05	4	812

Q02 remained at zero even after both universal blockers were omitted. The two identifiers with a documented interpretation method and the 51 identifiers with reported transmissivity were disjoint sets at identifier level. Their intersection contained no identifier. This is direct evidence of fragmentation in the well-level projection, although it does not establish whether a missing link could be recovered from unacquired test files.

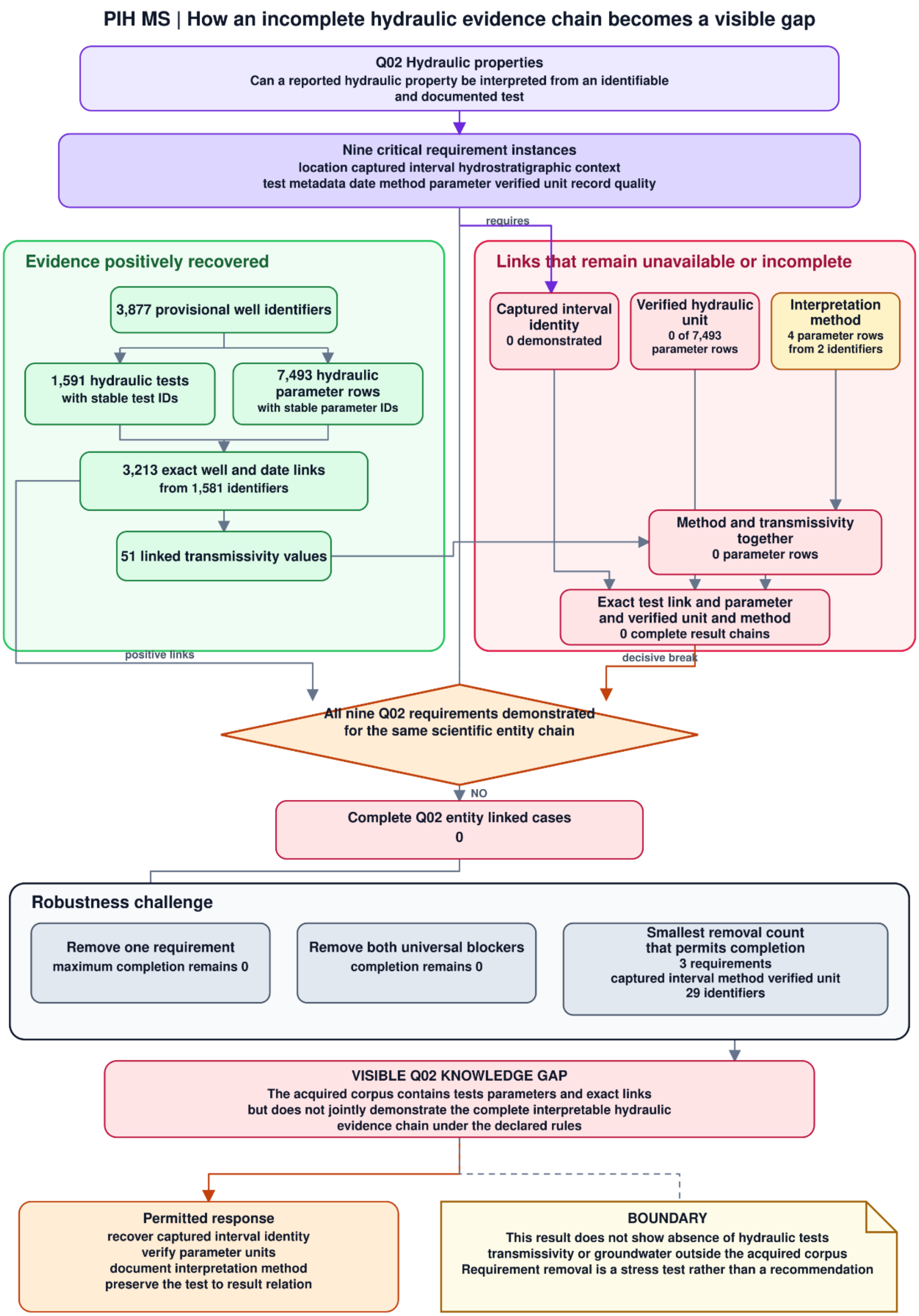

Figure 3. Q02 documentary-gap diagnosis

Figure 3. The Q02 entity-linked diagnosis and its sensitivity tests. The positive-evidence branch records information recovered from the corpus. The missing-link branch identifies the exact relations that remain unavailable or incomplete. The sensitivity branch challenges the result through single and joint requirement removal. Counts refer to provisional identifiers or scientific entities as stated. Requirement removal is a counterfactual robustness test and not a recommendation to weaken the evidence chain.

Enumeration of all 1,472 possible requirement-removal subsets quantified the shortest observed distance to the implemented conjunction.

Question	Minimum failed requirements	Identifiers at that minimum	Maximum completed after removal	Removal set
Q01	1	8	8	Q01_R05
Q02	3	31	29	Q02_R02, Q02_R06, Q02_R08
Q03	3	228	228	Q03_R02, Q03_R07, Q03_R08
Q04	2	1,632	1,632	Q04_R03, Q04_R04
Q05	4	812	812	Q05_R02, Q05_R04, Q05_R06, Q05_R07

For Q02, 31 identifiers had three failures, but the failure pattern was not identical across identifiers. The single three-requirement removal set producing the maximum yielded 29 identifiers. A second three-requirement pattern, Q02_R02, Q02_R07, and Q02_R08, yielded two identifiers. This difference shows why reporting only the minimum number of failures would hide structurally different evidence packages.

The subset frontier is a stress test. It does not identify dispensable requirements. A requirement may be scientifically necessary even when its removal generates many completions. Conversely, a universal blocker may be logically masked and still be necessary.

5.9 Documentary stages and spatial support

The primary O00 grids produced 45,145 cell-question classifications.

Class	Cell-question pairs	Share of 45,145
UNKNOWN	32,405	71.78%
P1, no direct evidence	2,801	6.20%
P2, no context gate	5,448	12.07%

Class	Cell-question pairs	Share of 45,145
P3, no complete minimum	4,491	9.95%
P4, local complete minimum	0	0.00%

The shares were calculated directly from the verified class totals. UNKNOWN predominated because many cell-question combinations contained no acquired identifier. P1 to P3 identify the stage at which the documentary chain stopped in supported cells. They do not establish critical, high, or moderate territorial urgency. No observed pair reached P4 because no identifier satisfied a complete minimum. P4 is functionally reachable. P5 was not implemented in the V2.6 function.

Because unsupported cells remain UNKNOWN, the combined class distribution must not be read as a state-wide ranking of research urgency. It also repeats the same spatial domain across five scales and five questions, so 45,145 is not a count of independent territories. The number and effective area of cells containing at least one acquired identifier increased strongly with scale.

Nominal scale	Cells with identifiers	Share of cells	Share of effective state area covered by those cells
100 km²	774	20.57%	21.29%
150 km²	657	26.02%	26.94%
250 km²	523	34.03%	35.40%
500 km²	354	44.75%	47.53%
1,000 km²	240	58.11%	62.13%

These percentages describe acquired spatial support under each grid. They do not show the proportion of the state whose groundwater is scientifically known.

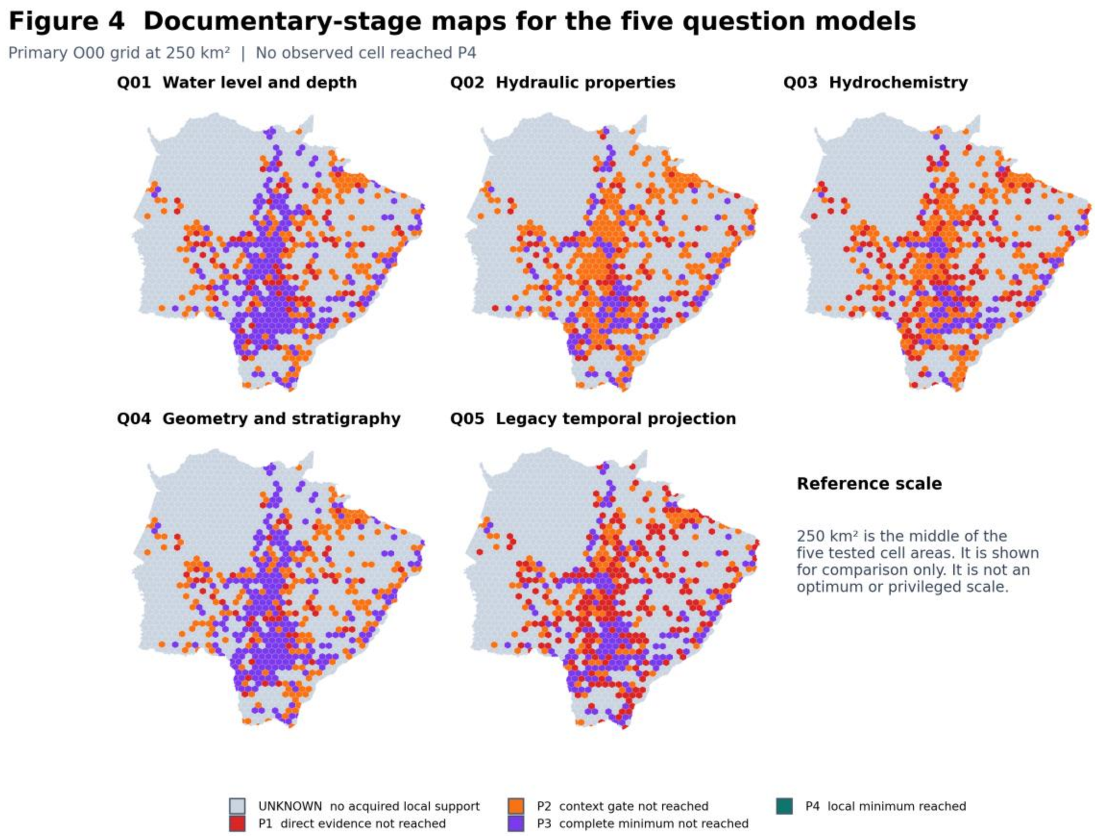

Figure 4. Documentary-stage maps for five question models

Figure 4. Question-specific documentary stages in the primary O00 grid at 250 square kilometres. This cell area is shown because it is the middle of the five tested scales and permits a common visual comparison. It is not an optimum or privileged scale. Grey cells are UNKNOWN because no acquired local identifier supports classification. P1 to P3 show the stage at which the implemented documentary chain stopped. P4 was functionally reachable but not observed.

5.10 Spatial scale sensitivity and cartographic agreement

Exact cross-scale agreement of the V2.6 documentary stage at the 14,284 fixed support points was 41.59% for Q01, 40.40% for Q02, 38.98% for Q03, 41.56% for Q04, and 39.27% for Q05. These global percentages include 4,814 support points that remained UNKNOWN at all five scales for every question. When the denominator is restricted to locations classified at least once, exact agreement falls to between 7.96% and 11.90%, depending on the question. Among locations classified at all five scales, exact agreement ranges from 36.46% to 54.50%. Global and conditioned measures answer different questions and are therefore reported together.

Question	Exact documentary-stage agreement across the five O00 scales
Q01	41.59%
Q02	40.40%
Q03	38.98%
Q04	41.56%
Q05	39.27%

The global denominator contains 4,814 locations per question that were UNKNOWN at all five scales, equivalent to 33.70% of the fixed support. The conditioned results were as follows.

Question	Global exact agreement	Exact when classified at least once	Exact when classified at all five scales
Q01	41.59%	11.90%	54.50%
Q02	40.40%	10.11%	46.28%
Q03	38.98%	7.96%	36.46%
Q04	41.56%	11.86%	54.30%
Q05 legacy well-level projection	39.27%	8.39%	38.44%

The result indicates that more than half of the fixed support locations changed priority stage across at least part of the scale comparison. A single grid cannot therefore be presented as a scale-independent territorial result.

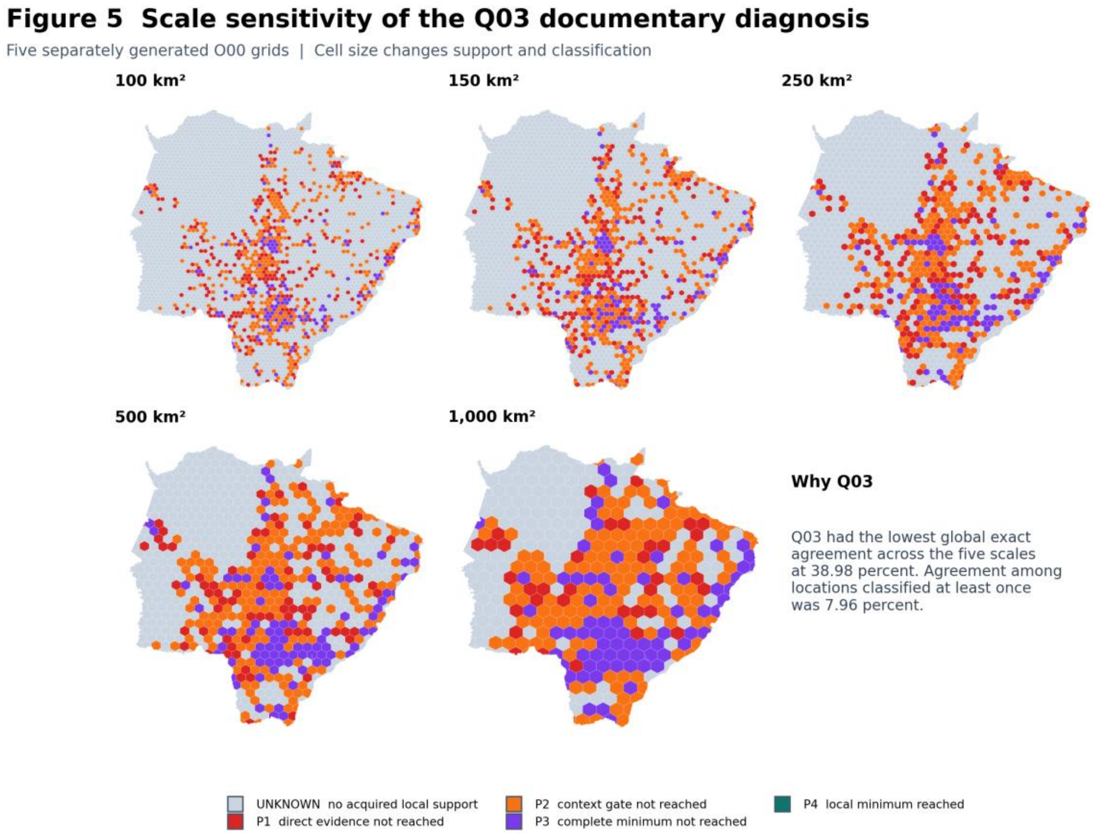

Figure 5. Q03 documentary-stage sensitivity across five scales

Figure 5. Q03 documentary-stage maps for the five independently generated O00 scales. Q03 was selected because it had the lowest global exact agreement across scales, at 38.98%, and the lowest agreement among locations classified at least once, at 7.96%. The panels illustrate changes in support and classification, not progression towards a preferred scale.

The preserved cartographic agreement output contained 32,430 UNKNOWN, 2,229 C1, 3,783 C2, 5,512 C3, 873 C4, and 318 C5 cell-question pairs. These counts sum to 45,145. Of the 32,430 agreement records coded UNKNOWN, 32,405 corresponded to an UNKNOWN priority and 25 had priority P1 to P3 but no fixed support point inside the cell. The latter comprised 15 cell-question pairs at 100 km² and 10 at 150 km². Future outputs should separate UNKNOWN_PRIORITY from NO_SUPPORT_POINT_FOR_AGREEMENT.

The C1 to C5 rules also compress raw percentages. In particular, an intermediate class can combine very different partial-agreement values. Raw scale and origin agreement percentages are therefore the primary scientific quantities. Categorical classes are auxiliary communication devices.

In the minimum_only sensitivity, joint removal of universal blockers changed 40 O00 cell-question classifications in Q01, none in Q02, 496 in Q03, 1,292 in Q04, and 817 in Q05 across the five primary scales. Every change was P3 to P4. No transition moved towards an earlier documentary stage. The numbers by scale were as follows.

Question	100 km²	150 km²	250 km²	500 km²	1,000 km²
Q01	8	8	8	8	8
Q02	0	0	0	0	0
Q03	122	112	102	87	73
Q04	371	325	262	191	143
Q05	213	199	166	133	106

Exact cross-scale agreement for Q01 decreased from 41.59% to 41.05% after removal of Q01_R05, a reduction of 78 support points with exact agreement. Agreement was unchanged in the remaining joint universal-removal scenarios, although some cells shifted from P3 to P4. This occurred because the changes were reproduced consistently across the compared O00 scales at the affected support locations. Logical sensitivity and cross-scale agreement therefore measure different properties.

The stage_consistent tests showed that the experimental context gates are themselves influential. Removing hydrostratigraphic consistency from the gate increased retained identifiers from 1,583 to 3,210 in Q01, from 555 to 1,096 in Q02, from 228 to 512 in Q03, from 1,632 to 3,411 in Q04, and from 812 to 1,637 in Q05. Removing test metadata increased the Q02 gate from 555 to 1,527. Removing the hydrochemical date increased the Q03 gate from 228 to 869. These are specification-sensitivity results and show why the gates require independent hydrogeological review.

5.11 Grid-origin sensitivity

Across the five scales and 14,284 fixed support points, the same documentary-stage code occurred at all four origins in 64.24% to 66.81% of support-point-by-scale combinations, depending on the question. The global denominator includes 35,027 of the 71,420 combinations that remained UNKNOWN at all origins for each question. When the comparison is restricted to locations classified under at least one origin, exact agreement ranges from 29.82% to 34.86%. Among locations classified under all four origins, it ranges from 57.74% to 67.51%. The lower conditioned values show that unsupported locations make the global measure appear more stable than the classified spatial pattern.

Question	Support point × scale combinations	Same code at all four origins	Exact agreement	Changed under any origin	Mixed UNKNOWN and classified
Q01	71,420	47,643	66.71%	23,777	17,598
Q02	71,420	46,697	65.38%	24,723	17,598
Q03	71,420	46,266	64.78%	25,154	17,598
Q04	71,420	47,715	66.81%	23,705	17,598
Q05	71,420	45,880	64.24%	25,540	17,598

The global denominator contains 35,027 combinations per question that were UNKNOWN under all four origins, equivalent to 49.04%. The conditioned results were as follows.

Question	Global exact agreement	Exact when classified in at least one origin	Exact when classified in all four origins
Q01	66.71%	34.67%	67.12%
Q02	65.38%	32.07%	62.09%
Q03	64.78%	30.88%	59.80%
Q04	66.81%	34.86%	67.51%
Q05 legacy well-level projection	64.24%	29.82%	57.74%

Across all questions, 234,201 of 357,100 combinations retained exactly the same code under all four origins, corresponding to 65.58% agreement. The remaining 122,899 combinations changed under at least one origin. A total of 87,990 combinations included both UNKNOWN and a classified stage across origins. The identical mixed count of 17,598 for each question arises because the presence of an acquired well in a shifted cell is shared by all five question assessments at a fixed support location.

Unconditioned overall agreement among origins decreased as nominal cell area increased for every question. At 100 square kilometres, exact four-origin agreement ranged from 76.11% to 76.85%. At 1,000 square kilometres, it ranged from 52.01% to 58.62%. Conditioned agreement among locations classified under at least one origin followed the opposite direction, increasing from 24.50% to 26.82% at 100 square kilometres to 34.02% to 43.10% at 1,000 square kilometres. The lowest global exact agreement occurred for Q05 at 1,000 square kilometres, at 52.01%, whereas the highest occurred for Q04 at 100 square kilometres, at 76.85%. The greatest pairwise contrast occurred between O00 and OXY25 for Q05 at 1,000 square kilometres. Only 9,280 of 14,284 support points retained the same code, whereas 2,367 transitioned between UNKNOWN and a classified stage and 2,444 changed by at least two codes.

No origin is physically privileged. The result demonstrates a substantive zoning effect within the selected quarter-spacing perturbation family. It does not estimate positional accuracy, classification reliability, or hydrogeological truth. It also does not establish that these four origins span every plausible displacement.

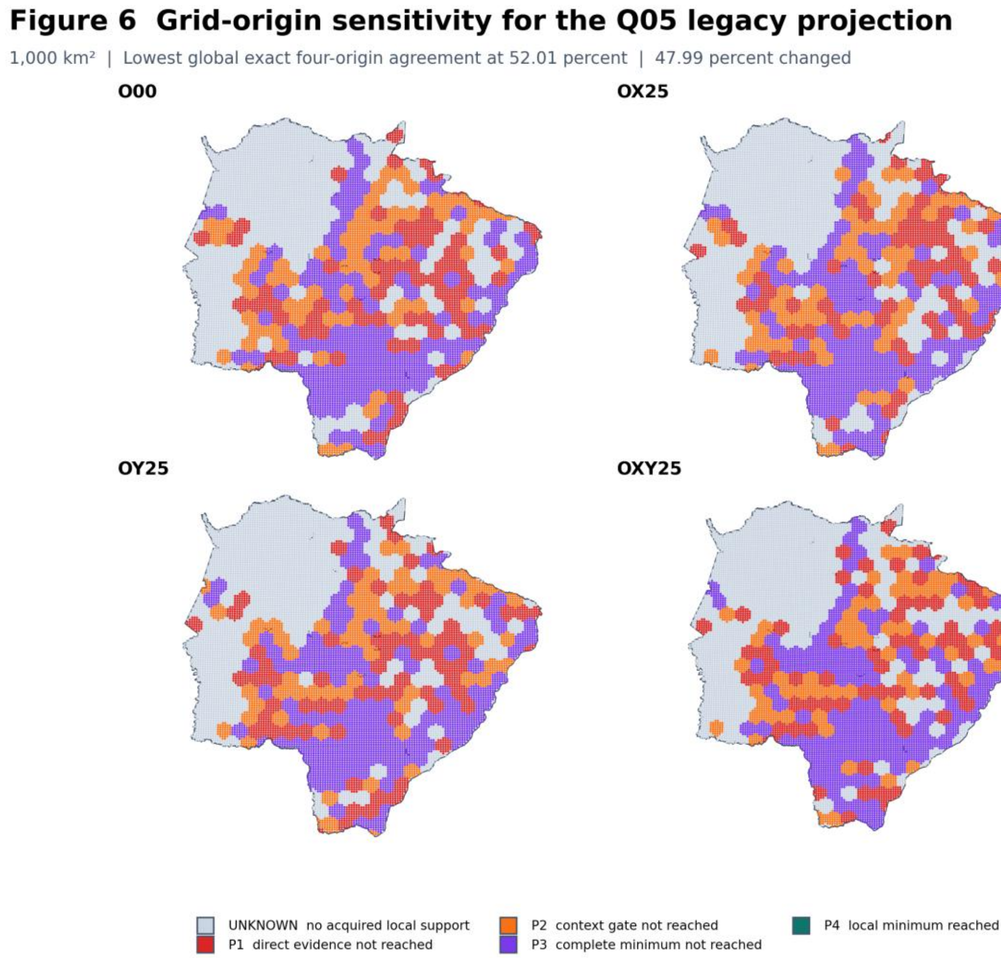

Figure 6. Q05 grid-origin sensitivity at 1,000 square kilometres

Figure 6. Legacy well-level projection of Q05 documentary stages under the four grid origins at the 1,000-square-kilometre scale. This combination was selected because it produced the lowest global exact agreement among the four origins, at 52.01%. In total, 47.99% of fixed locations changed under at least one origin. The map does not imply that Q05b monitoring-network inference was evaluated.

5.12 Q05 separation and class reachability

Removing Q05_R07 from the well-level conjunction creates the proposed Q05a local-series rule, but the complete count remains zero because no same-variable series and no stable temporal-variable identity were demonstrated in the acquired matrix. Q05a can therefore be evaluated only as a well-level projection with unresolved entity linkage. Q05b network-inference capacity is not evaluable from the present matrix because network independence requires a declared objective, site set, dependence model, and sampling design.

Controlled synthetic inputs tested the full decision function independently of the observed corpus. The six cases supplied progressively different combinations of local support, direct evidence, context, complete minimum, and an attempted representativeness flag.

Controlled input	Expected output	Observed output	Interpretation
No acquired identifier in the cell	UNKNOWN	UNKNOWN	Unsupported cells remain outside the ordinal stages
Identifier present and no direct evidence	P1	P1	The chain stops before direct evidence
Direct evidence and no context gate	P2	P2	The direct component is present but context is incomplete
Context gate and no complete minimum	P3	P3	The chain reaches context but not the full local contract
At least one complete local minimum	P4	P4	The implemented function reaches a complete local minimum
Complete local minimum plus attempted P5 condition	P4	P4	Representativeness is not an implemented input

All six tests passed. The machine-readable cases are preserved in PIH_MS_PRIORITY_REACHABILITY_TESTS_V02.csv. P4 is therefore operationally reachable whenever at least one complete local minimum is supplied. Its absence from the observed results is caused by the zero complete-minimum count and not by an unreachable branch. P5 is different. The function has no representativeness input and returns only codes 0 to 4. P5 is not operationally reachable.

5.13 Clean reproduction

The isolated execution of the V2.6 question-specific priority constructor completed successfully. It regenerated the expected 9,029 cells, 45,145 cell-question pairs, 3,877 provisional identifiers, 39 requirement instances, and 1,045 documented output fields. It also reproduced the exact documentary-stage distribution of 32,405 UNKNOWN, 2,801 P1, 5,448 P2, and 4,491 P3. No observed pair reached the functionally available P4 stage. P5 was not implemented.

All 21 visible files in the reproduced research-priority directory were byte-identical to the preserved outputs. The reproduced cartographic agreement distribution was also exact with 32,430 UNKNOWN, 2,229 C1, 3,783 C2, 5,512 C3, 873 C4, and 318 C5. The constructor checksum is preserved in the supplementary manifest rather than used as a scientific result in the narrative.

This result supports deterministic computational repeatability of the priority module under the tested environment. The acquired project directory is not a Git worktree, and one preserved source manifest still carries the obsolete value 0.5.0. A frozen article archive checksum and a permanent archive identifier remain necessary for final deposit.

5.14 Findings from the antecedent comparison and source-rights audit

Several sources begin with a decision use, model groundwater entities, audit missing data, map data gaps, test spatial support, or design monitoring networks. Within the documented search, none of the 18 examined antecedents and systems exhibited all eight author-defined features. This finding positions the integrated architecture within a scoped comparison. It does not independently validate originality or support a claim of international precedence.

The rights audit confirmed that PIH MS software and original content carry explicit licences. It did not find sufficiently clear downstream redistribution evidence for every raw external source file in the acquired project. The scholarly package therefore excludes the raw SIAGAS snapshot, uncertain source vectors, cached basemap tiles, and publication full texts. This exclusion does not alter the reported derived calculations, but it constrains full independent reconstruction from the original source bytes. It makes the legal and scientific boundaries of the deposit explicit.

5.15 Reverse diagnostic value

The principal result is not only the number of cells in each class. For every supported cell and question, the structure permits the user to identify whether the chain stopped at direct evidence, the context gate, or the complete minimum, and then locate the blocking requirement, provisional identifier, derived field, and source code. The entity audit adds the missing distinction between stored presence and a demonstrated test, sample, result, series, or network link. This reverse diagnostic pathway is the mechanism by which PIH MS makes the gap visible. A complete row-to-byte route remains unavailable for components not acquired in the source corpus.

6 Discussion

6.1 Abundant records and incomplete evidence packages

The Mato Grosso do Sul case shows a strong difference between registry abundance and question-level sufficiency. Thousands of identifiers contained depth, aquifer names, water levels, pumping information, chemistry, or dates. The 3,839,462 physical CSV rows in V2.7.1 contained raw records, audits, repeated matrices, scale and origin evaluations, support assignments, and outputs. They did not represent 3,839,462 independent observations.

The entity audit provides a more precise result than either data abundance or data absence. The corpus contains 1,591 identifiable hydraulic tests, 1,970 identifiable chemical samples, 3,213 exact hydraulic well and date links, and 2,557 verified result-to-sample links. These positive elements did not connect with the captured interval, verified unit, method, complete analytical chain, temporal-series identity, or monitoring design required by the respective question. Under the implemented rules, no complete entity-linked evidence chain was demonstrated.

The defensible conclusion is limited to the acquired corpus and the explicit PIH MS rules. It is not that Mato Grosso do Sul lacks groundwater knowledge. Local reports, private investigations, academic studies, administrative documents, or records not acquired before the cutoff may contain additional evidence. The demonstrated finding is that the acquired corpus did not jointly demonstrate the complete set of proposed components for any evaluated question.

This distinction explains why a gap had to be made visible. A database can show thousands of points while hiding the break between the location, construction, captured interval, observation, method, unit, quality control, and temporal identity needed for interpretation. PIH MS does not infer the break from a blank map. It declares the evidence chain first, searches for each link using reproducible rules, preserves the reason when a link is not demonstrated, and tests whether the diagnosis survives logical and spatial perturbation.

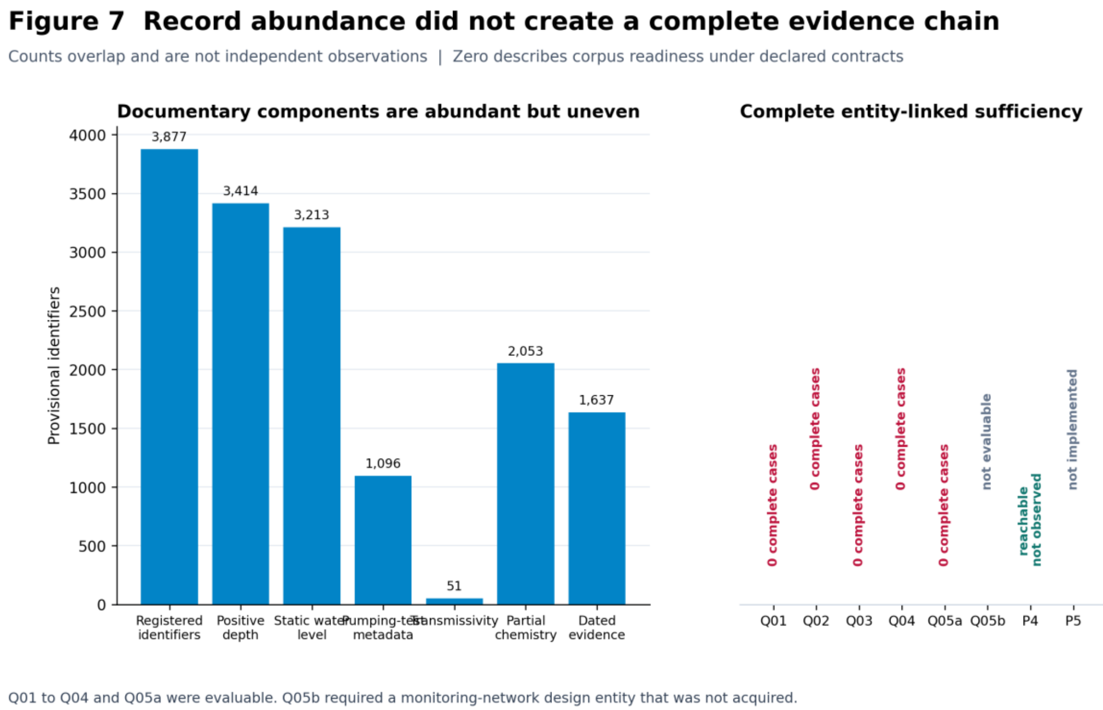

Figure 7. Record abundance and complete evidence sufficiency

Figure 7. Abundant documentary components did not form a complete entity-linked evidence package. Counts are overlapping indicators and must not be added. The zero values for Q01 to Q04 and Q05a are corpus-readiness findings under the declared contracts. Q05b was not evaluable. P4 was available in the implemented function but not observed. P5 was not implemented.

6.2 Captured intervals as a cross-cutting break in the evidence chain

The absence of demonstrated captured intervals affected all five questions. The source contained 316 coherent raw top and base pairs, but the acquired metadata did not establish that these were screens or open intervals connected to the observed water. Total well depth and mapped surface geology cannot identify the depth interval contributing water to a well. Without that vertical connection, registered water levels, hydraulic parameters, chemistry, stratigraphic descriptions, and temporal events may be difficult to attribute to a specific aquifer interval. PIH MS makes this break visible instead of allowing other abundant fields to offset it.

This result must be interpreted carefully. The workflow demonstrates that captured-interval identity was not documented in the acquired and processed structures under the current rule. It does not prove that interval information never existed, that it cannot be found in individual reports, or that every registered value is scientifically unusable.

Future acquisition should preserve construction and interval identifiers, interval type, top and base reference, captured-unit link, source document, and review state.

6.3 Value of non-compensation

Non-compensation makes scientific assumptions visible. The absence of a requirement proposed as indispensable remains visible even when many related fields are present. This prevents the framework from producing a reassuring composite score that could conceal a break in the documentary chain. The same rigidity also creates a risk because one universally blocked requirement may determine every result.

The results show why individual removal is not enough. In Q02 to Q05, every leave-one-out gain was zero because other blockers remained. Joint removal and complete subset enumeration revealed the hidden structure. Q04 was two missing links away from the implemented conjunction for 1,632 identifiers, while Q05 was at least four away for 812 identifiers. Q02 showed a more complex pattern because method and transmissivity were disjoint in the well-level projection. The entity audit strengthened that finding because the only four method-bearing parameter rows concerned specific capacity or stabilized yield rather than transmissivity.

Logical distance is not a ranking of importance and does not identify a dispensable requirement. It describes how far an observed evidence profile lies from the declared contract and whether simultaneous blockers conceal each other.

6.4 Value of multiscale testing

The scale-and-origin experiment prevents a single selected grid from becoming an unexamined source of authority. Global exact agreement of the V2.6 documentary stages across the five O00 scales ranged from 38.98% to 41.59%, depending on the question. When the analysis was restricted to locations classified at least once, agreement fell to 7.96% to 11.90%. With scale held constant, global exact agreement across the four origins ranged from 64.24% to 66.81%, depending on the question, and from 29.82% to 34.86% among locations classified under at least one origin. For each question, almost one quarter of support-point-by-scale combinations transitioned between UNKNOWN and a classified stage when origins were compared.

Global unconditioned agreement among origins decreased as nominal cell area increased for every question, while agreement conditioned on locations classified in at least one origin increased. Larger cells included more records, but their boundaries also moved over larger spatial extents when the origin shifted. The opposing directions confirm that the denominator and the prevalence of shared UNKNOWN locations must be stated. More aggregation did not remove zoning sensitivity. This sensitivity is information about how support geometry changes the apparent distribution of acquired evidence. The fixed support permits comparable locations to be followed across configurations, although its deterministic spacing and the four selected origins do not exhaust spatial sensitivity.

The logical perturbation results add a second insight. A requirement change can alter many cell classes while leaving exact cross-scale agreement unchanged when the same transition repeats at the compared support locations. Agreement therefore cannot be treated as strength of evidence or correctness. It measures only whether the same stage repeats under the selected spatial configurations.

The low conditioned agreement precludes use of any one grid as a definitive operational priority surface at present. In their current form, the maps have three bounded functions. They identify gaps that persist across configurations, locate areas sensitive to scale or origin, and show where additional evidence acquisition should precede a territorial decision. Operational use must consider the five scales and four origins jointly rather than select a single grid as the final answer.

6.5 Relationship to databases, models, and monitoring design

PIH MS complements harmonised databases such as GWDBrazil and the US groundwater-well database (Uchôa et al., 2025 and Lin et al., 2024). Database harmonisation improves access, consistency, and reuse. PIH MS adds question-level requirement logic, entity integrity, and spatial diagnosis for a bounded corpus. It also operates upstream of predictive groundwater modelling. A model may require hydraulic, vertical, chemical, or temporal inputs. Before modelling begins, PIH MS can identify whether those inputs are present, linked, and documented. It does not determine model structure or predict aquifer behaviour.

The current framework also differs from monitoring-network optimization. It identifies documentary needs but does not optimize station locations, cost, entropy, model-error reduction, or sampling schedules (Keum et al., 2017). Any future transition from documentary stage to field-investment optimization would require objectives, constraints, representativeness criteria, costs, permissions, and validation that are not part of V2.6.

6.6 Why the analytical unit changes the result

The analytical-unit audit is not a terminological refinement. It changes what a positive conjunction would mean. A method, parameter, date, and unit can all be present somewhere under one provisional identifier and still fail to form one interpretable hydraulic test. A chemical date and a reported parameter can belong to different samples. Multiple dated events can concern different variables and therefore not form a series. Network independence cannot be inherited by one record.

The recovered links show that the data model is not uniformly unstructured. Every chemical result linked to an existing sample with a consistent well identifier, and many hydraulic parameters linked unambiguously through exact well and date equality. The model needs stable construction, interval, water-level event, result, series, and network relations, together with verified units and preserved method and quality-assurance records.

The current matrix remains useful as a conservative screening system because no positive complete minimum was produced. It must not certify a complete evidence package until entity-linked conjunction occurs before projection to the well and cell.

6.7 Integrated contribution and limits of the comparison

The strongest contribution concerns the architecture and the way it makes a bounded gap observable. PIH MS operationalises a knowledge gap as the failure of a declared, question-specific evidence chain within an acquired corpus. The framework connects question-driven requirement definition, specification of scientific entities, non-compensatory assessment, explicit unknown states, individual and joint logical perturbations, context-gate ablation, scale and origin tests, documentary-stage mapping, and reverse auditability.

Each component has antecedents. The proposed contribution lies in their operational integration for groundwater-evidence auditing. The scoped review identified related systems concerned with fitness for use, database harmonisation, entity modelling, data-gap surveys, monitoring-network design, and spatial sensitivity. No candidate exhibited all eight author-defined features within the examined set. This finding positions the proposed architecture but does not validate a claim of precedence or uniqueness. The demonstrated value lies in the explicit way a gap is defined, identified, challenged, mapped, bounded, and traced.

This formulation is stronger and safer than calling PIH MS data mining. The method does not discover a latent predictive pattern or infer groundwater occurrence. It applies declared rules to observable evidence and reports where the evidence contract fails. Future machine-learning work would constitute a different study and would require independent targets and validation.

6.8 Interpretive boundaries

PIH MS does not produce groundwater potential, water availability, environmental risk, drilling priority, territorial urgency, or administrative authorization. Cell boundaries are analytical supports and not hydrogeological units. A cartographic agreement class does not prove validity. A locally complete entity would not by itself prove territorial representativeness. A provisional identifier does not prove an independent physical well. P1 to P4 are implemented documentary stages and not validated urgency categories.

The current UNKNOWN class also groups causes that may demand different actions, including no acquired local support, information not located, inaccessible information, missing extraction fields, illegible values, unverified units, contradictions, unverified independence, unverified representativeness, and non-applicability. Future outputs should preserve these causes separately rather than relying on one colour or one aggregate count.

The corpus boundary is equally important. Public files and public consultation systems may not contain private reports, municipal archives, academic theses, consultant records, laboratory systems, or later source updates. No statement in this article should be generalized from no complete chain acquired to no complete chain existing in the state.

7 Limitations

7.1 Scientific limitations reported rather than concealed

The current corpus does not permit a fully entity-linked recalculation because construction, captured-interval, water-level-event, time-series, and monitoring-network identities were not acquired. PIH MS therefore reports the preserved V2.6 well-level projection separately from the V0.4.2 entity audit. No complete evidence package is certified on co-occurrence alone.

The 29 duplicate-candidate pairs require stratified human adjudication. The 3,877 count remains provisional. This limit affects record identity and not the central observation that complete linked evidence chains were not demonstrated.

No positive complete entity-linked case was available within the acquired corpus for Q01 to Q04 or Q05a. P4 has functional reachability but lacks real linked validation. Q05b was not evaluable because monitoring-network design was not acquired. P5 was not implemented because territorial representativeness was not defined.

The context gates are influential experimental specifications. Their ablation results are reported, but their hydrogeological necessity has not been externally validated. P2 and P3 must therefore retain stage wording.

The four origins form one selected quarter-spacing perturbation family. They do not exhaust all zoning configurations. The fixed support is a deterministic comparison instrument and not a probability sample.

The antecedent review was scoped and was not systematic across all subscription databases. Its search log and feature matrix make this limitation auditable. The features were defined by the authors and were not validated by an independent assessor. The manuscript describes a distinct integration within the examined set and does not claim international precedence.

7.2 Items completed for the scholarly package

Entity identities and their partial linkage were audited. The search for positive cases was completed and its zero result is reported. All context requirements underwent ablation. The four stored origins were compared. The priority module completed isolated byte-level reproduction. The scoped antecedent search and feature comparison were documented. Source rights were classified, and external bytes with unresolved status were excluded from the planned supplement.

These controls support a transparent presentation of the experimental method and its limitations, but they do not validate PIH MS as a decision system.

7.3 Work reserved for later scientific versions

Future versions should implement stable construction, interval, event, result, series, and network identities throughout the data model. They should validate at least one positive P4 case using independent, linked documentation. Monitoring objectives and representativeness must be defined before Q05b or P5 is implemented. Future work should test additional grid origins and support designs, conduct a stratified manual audit of entity resolution, and broaden the antecedent review with a second independent assessor.

These tasks define the validation and development agenda for subsequent scientific versions.

8 Conclusions

PIH MS provides an experimental method for asking a question that conventional groundwater maps often leave implicit. Does the bounded corpus of acquired records jointly demonstrate the evidence chain required by the requested interpretation?

In Mato Grosso do Sul, 3,877 provisional well identifiers provided substantial but fragmented documentary evidence. The corpus preserved 1,591 stable hydraulic-test identities, 1,970 stable chemical-sample identities, 3,213 exact hydraulic parameter links, and 2,557 valid chemical result-to-sample links. These are real positive assets. They did not form a complete entity-linked chain because captured-interval identity, verified units, methods, complete analytical quality assurance, or temporal-series identity remained unavailable. No complete real case was demonstrated for Q01 to Q04 or Q05a. Q05b was not evaluable because a declared monitoring design and site-set entity were absent from the acquired corpus.

The logical stress tests show that the result cannot be interpreted through one number alone. Twelve question-requirement combinations involving eight unique fields were universal blockers. Q01 produced eight complete identifiers after captured interval was removed. Q02 to Q05 contained mutually masking blockers. Complete enumeration of 1,472 requirement subsets found observed minimum failure distances of one, three, three, two, and four requirements for Q01 to Q05. These counterfactual results make logical fragility visible without treating scientific requirements as disposable.

The context-gate audit found ten positive and thirteen zero isolated effects among 23 requirement instances. This confirms that P2 and P3 depend on experimental specification choices. The stages remain useful because they locate where the implemented chain stops, but they are not validated urgency categories.

The spatial experiment showed that the diagnosis is sensitive to both scale and zoning. Global exact agreement of documentary stages across the five primary scales ranged from 38.98% to 41.59%. When the analysis was restricted to locations classified at least once, the range was 7.96% to 11.90%. With scale held constant, global exact agreement across the four origins ranged from 64.24% to 66.81%, depending on the question, whereas the corresponding conditioned range was 29.82% to 34.86%. Across all questions, 87,990 support-point-by-scale combinations transitioned between UNKNOWN and a classified stage under at least one origin. These are repeated question assessments on shared spatial support, not independent events. The framework therefore reports documentary stage separately from spatial agreement and retains both global and conditioned percentages.

The isolated builder regenerated the 21 visible priority outputs as byte-identical files. The documented comparison examined 18 antecedents and systems using eight author-defined features. No candidate exhibited all eight within the examined set. This finding positions the proposed integration but does not constitute independent validation of originality or evidence of international precedence.

The proposed contribution is an integrated, auditable architecture that defines a groundwater knowledge gap before mapping it. The chain begins with a question, specifies the required evidence and scientific entity, tests non-compensatory sufficiency, preserves the causes of unknown states, identifies concurrent blockers, examines sensitivity to logical rules, grid scale, and grid origin, and maintains a reverse audit path. This makes the absence of joint demonstration visible, attributable, and contestable before investment in fieldwork or predictive modelling.

PIH MS should therefore be understood as a transparent experimental infrastructure for evidence auditing and question-specific knowledge-gap diagnosis. It does not prove that information or groundwater is absent outside the acquired corpus. Its scientific value lies in showing exactly what was found, what can be linked, what remains unavailable, how that conclusion changes under challenge, and which new evidence would be required to answer the question.

Data availability

The public PIH MS interface and repository are available at the following addresses.

Project website https://cbuson.github.io/pih-ms/

Source repository https://github.com/cbuson/pih-ms

Existing Zenodo record doi 10.5281/zenodo.22180863

Use of computational and language assistance

Computational tools were used to execute scripted analyses, compare file hashes, render Graphviz figures, inspect source structures, and assist language revision. Every numerical statement must remain connected to the included code or an identified preserved source output. The authors retain responsibility for the scientific rules, interpretation, references, and final wording.

References

Abreu, M. C., Paula, T. L. F. de, Rempel, K., and Senhorinho, E. M. 2024. Mapa hidrogeológico do estado de Mato Grosso do Sul. Serviço Geológico do Brasil. Scale 1:1,000,000.

Bradbury, K. R. 2025. Groundwater potential mapping. A misused and dubious concept. Groundwater, 63, 664 to 665. doi 10.1111/gwat.70013

Brodaric, B., editor. 2021. OGC WaterML 2 Part 4. GroundWaterML 2, version 2.2.1. Open Geospatial Consortium document 19-013 and 16-032r3.

Cantor, A., Kiparsky, M., Hubbard, S. S., Kennedy, R., Cano Pecharroman, L., Guivetchi, K., Darling, G., McCready, C., and Bales, R. 2021. Making a water data system responsive to information needs of decision makers. Frontiers in Climate, 3, 761444. doi 10.3389/fclim.2021.761444

Christen, P. 2012. Data Matching. Concepts and Techniques for Record Linkage, Entity Resolution, and Duplicate Detection. Springer. doi 10.1007/978-3-642-31164-2

Clark, P. J., and Evans, F. C. 1954. Distance to nearest neighbor as a measure of spatial relationships in populations. Ecology, 35, 445 to 453. doi 10.2307/1931034

Condon, L. E., Kollet, S., Bierkens, M. F. P., Fogg, G. E., Maxwell, R. M., Hill, M. C., and colleagues. 2021. Global groundwater modeling and monitoring. Opportunities and challenges. Water Resources Research, 57, e2020WR029500. doi 10.1029/2020WR029500

Díaz-Alcaide, S., and Martínez-Santos, P. 2019. Review. Advances in groundwater potential mapping. Hydrogeology Journal, 27, 2307 to 2324. doi 10.1007/s10040-019-02001-3

Fellegi, I. P., and Sunter, A. B. 1969. A theory for record linkage. Journal of the American Statistical Association, 64, 1183 to 1210. doi 10.1080/01621459.1969.10501049

Fotheringham, A. S., and Wong, D. W. S. 1991. The modifiable areal unit problem in multivariate statistical analysis. Environment and Planning A, 23, 1025 to 1044. doi 10.1068/a231025

Hyndman, R. J., and Fan, Y. 1996. Sample quantiles in statistical packages. The American Statistician, 50, 361 to 365. doi 10.1080/00031305.1996.10473566

Instituto Brasileiro de Geografia e Estatística. 2026. Mato Grosso do Sul. Cidades e Estados. Area and municipal divisions consulted 7 September 2026. https://www.ibge.gov.br/cidades-e-estados/ms.html

Instituto de Meio Ambiente de Mato Grosso do Sul. 2021. Monitoramento realizado pelo Imasul aponta boa qualidade das águas subterrâneas de MS. Published 26 July 2021. https://www.imasul.ms.gov.br/monitoramento-realizado-pelo-imasul-aponta-boa-qualidade-das-aguas-subterraneas-de-ms/

International Organization for Standardization. 2009. ISO 5667-11. Water quality sampling. Guidance on sampling of groundwaters.

Jaccard, P. 1901. Étude comparative de la distribution florale dans une portion des Alpes et du Jura. Bulletin de la Société Vaudoise des Sciences Naturelles, 37, 547 to 579. doi 10.5169/seals-266450

Jia, R., Wu, J., Zhang, Y., and Luo, Z. 2022. Site prioritization and performance assessment of groundwater monitoring network by using information-based methodology. Environmental Research, 212, 113181. doi 10.1016/j.envres.2022.113181

Josset, L., Allaire, M., Hayek, C., Rising, J., Thomas, C., and Lall, U. 2019. The U.S. Water Data Gap. A survey of state-level water data platforms to inform the development of a national water portal. Earth's Future, 7, 433 to 449. doi 10.1029/2018EF001063

Keum, J., Kornelsen, K. C., Leach, J. M., and Coulibaly, P. 2017. Entropy applications to water monitoring network design. A review. Entropy, 19, 613. doi 10.3390/e19110613

Kruseman, G. P., de Ridder, N. A., and Verweij, J. M. 1994. Analysis and Evaluation of Pumping Test Data. Second edition. International Institute for Land Reclamation and Improvement.

Larsen, S., Hamilton, S., Lucido, J., Garner, B., and Young, D. 2016. Supporting diverse data providers in the Open Water Data Initiative. Communicating water data quality and fitness of use. Journal of the American Water Resources Association, 52, 859 to 872. doi 10.1111/1752-1688.12406

Lin, C. Y., Miller, A., Waqar, M., and Marston, L. T. 2024. A database of groundwater wells in the United States. Scientific Data, 11, 335. doi 10.1038/s41597-024-03186-3

Mato Grosso do Sul. 2010. Plano Estadual de Recursos Hídricos de Mato Grosso do Sul. Secretaria de Estado de Meio Ambiente, do Planejamento, da Ciência e Tecnologia and Instituto de Meio Ambiente de Mato Grosso do Sul. Editora UEMS, Campo Grande. ISBN 978-85-99880-24-1.

Moura, I. B. M. de. 2025. Relatório Síntese da Rede Integrada de Monitoramento das Águas Subterrâneas, RIMAS 2025. Serviço Geológico do Brasil, Rio de Janeiro, 56 pages. https://rigeo.sgb.gov.br/handle/doc/25832

Natural Earth. 2026. Admin 0 countries, 1 to 110 million cultural vector data. Public-domain dataset consulted 7 September 2026. https://www.naturalearthdata.com/

Openshaw, S. 1984. The Modifiable Areal Unit Problem. Concepts and Techniques in Modern Geography 38. Geo Books.

Serviço Geológico do Brasil. 2023. Sistema de informações de águas subterrâneas, SIAGAS. Manual de usuário. Serviço Geológico do Brasil.

Spearman, C. 1904. The proof and measurement of association between two things. The American Journal of Psychology, 15, 72 to 101. doi 10.2307/1412159

Subcommittee on Ground Water, Advisory Committee on Water Information. 2013. A National Framework for Ground-Water Monitoring in the United States. Revised July 2013.

Taylor, C. J., and Alley, W. M. 2001. Ground-water-level monitoring and the importance of long-term water-level data. U.S. Geological Survey Circular 1217. doi 10.3133/cir1217

Thanh, N. N., Thunyawatcharakul, P., Ngu, N. H., and Chotpantarat, S. 2022. Global review of groundwater potential models in the last decade. Parameters, model techniques, and validation. Journal of Hydrology, 614, 128501. doi 10.1016/j.jhydrol.2022.128501

Uchôa, J. G. S. M., Oliveira, P. T. S., Ballarin, A. S., Gastmans, D., Anache, J. A. A., Scanlon, B. R., Camacho, C. R., Freddo Filho, V. J., and Wendland, E. C. 2025. A groundwater well database for Brasil, GWDBrasil. Scientific Data, 12, 1582. doi 10.1038/s41597-025-05843-7

U.S. Geological Survey. 2018. General introduction for the National Field Manual for the Collection of Water-Quality Data, version 1.1. Techniques and Methods 9-A0. doi 10.3133/tm9A0

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., and colleagues. 2016. The FAIR Guiding Principles for scientific data management and stewardship. Scientific Data, 3, 160018. doi 10.1038/sdata.2016.18