

DATA BEFORE CONCRETE: MEASUREMENT CAPACITY AS AN INFRASTRUCTURE PRECONDITION

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ABSTRACT

Infrastructure decisions are made about systems that have not been measured. A pipe network is renewed without a failure database, a source developed without knowing what share of production reaches a customer, an abstraction limit set without a model of the aquifer. This study argues that measurement capacity is a precondition of infrastructure investment rather than an accompaniment to it, and that the customary reform sequence inverts the dependency. The method is a structured conceptual review of research published between 2017 and 2024 across water loss and asset management, groundwater and subsidence modelling, and access measurement. Model accuracy is bounded by data drawn from operator records, so a renewal programme without a failure database cannot be prioritised whatever technique is applied. Measurement pays measurable returns: hyperparameter tuning on network data improved one failure model's mean absolute error by 20.51 per cent, and a classifier using full features achieved 88.5 per cent accuracy with an area under the curve of 0.91, while a model using asset type alone performed poorly. The instruments are now inexpensive. Governance rather than technique is the binding constraint. Measurement's absence is invisible: a system that is not measured generates no evidence of its own decline.

ABSTRAK

Keputusan infrastruktur diambil atas sistem yang belum diukur. Jaringan pipa direhabilitasi tanpa basis data kegagalan, sumber air dikembangkan tanpa mengetahui berapa bagian produksi yang sampai ke pelanggan, batas pengambilan air tanah ditetapkan tanpa model akuifer, dan penurunan muka tanah diatur tanpa mengetahui di mana tanahnya bergerak. Kajian ini berargumen bahwa kemampuan mengukur merupakan syarat yang mendahului investasi infrastruktur, bukan pelengkap, dan bahwa urutan reformasi yang lazim membalik ketergantungan tersebut. Metodenya adalah telaah konseptual terstruktur atas riset terbitan 2017 hingga 2024 pada bidang kehilangan air dan pengelolaan aset, pemodelan air tanah dan penurunan muka tanah, analisis pertumbuhan kota dan tutupan lahan, serta pengukuran akses. Lima temuan mengikutinya. Ketepatan model dibatasi oleh data yang diambil langsung dari catatan operator, sehingga program rehabilitasi tanpa basis data kegagalan tidak dapat diprioritaskan dengan teknik apa pun. Pengukuran memberi hasil yang terukur: penyetelan parameter pada data jaringan memperbaiki galat mutlak rata-rata satu model kegagalan sebesar 20,51 persen, dan satu pengklasifikasi dengan rangkaian peubah lengkap mencapai ketepatan 88,5 persen dengan luas di bawah kurva 0,91 sementara model yang hanya memakai jenis sarana berkinerja buruk. Instrumennya kini murah, dengan interferometri satelit dan pembelajaran mesin memberi cakupan nasional dan global dari data yang tidak

	perlu dikumpulkan sendiri oleh pemerintah daerah. Tata kelola, bukan teknik, yang menjadi kendala pengikatnya, sebab ranah kebijakan yang terpecah dan pembingkaihan yang memperlakukan perubahan fisik sebagai hal alamiah menghalangi hasil pengukuran mencapai keputusan. Adapun ketiadaan pengukuran itu sistematis tidak tampak, karena sistem yang tidak diukur tidak menghasilkan bukti tentang kemerosotannya sendiri. Kata kunci: pengelolaan aset; kemampuan pengukuran; perencanaan infrastruktur; penginderaan jauh; tata kelola data
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1. INTRODUCTION

An infrastructure decision requires four things: knowing what the system currently does, knowing what limits it, choosing an intervention proportionate to that limit, and observing whether the intervention worked. Only the third of these is an engineering question. The other three are measurement questions, and in the systems examined here they are answered last or not at all.

The dependency runs in one direction and is regularly inverted in practice. Forero-Ortiz et al. (2023), reviewing pipe failure prediction models and their explanatory variables, conclude that model accuracy is bounded by data and that a substantial, reliable dataset drawn directly from utility databases is a prerequisite for understanding variable interactions and for meaningfully assessing model performance. The statement is about modelling; its policy content is that a renewal programme in a utility without such a database cannot be prioritised, whatever technique is applied to whatever data exist.

The same dependency appears wherever the literature examines it. Shushu et al. (2021) could establish that about eighty-seven per cent of losses in a metered district were real rather than commercial only because the district was metered; without that step the composition of loss is unknown and the choice between enforcement and pressure management is a guess. Ambel et al. (2023), training classifiers on water quality testing data, achieved 88.5 per cent accuracy with an area under the curve of 0.91 using full features, and found that a model using source type alone performed poorly — which means the administrative variable most widely available is the one least able to predict the outcome.

What has changed recently is cost. Davydzienka et al. (2024), training a deep learning model on more than 46,000 subsidence observations and twenty-three environmental parameters, produce a global map estimating over 6.3 million square kilometres of significantly subsiding land including 231,000 square kilometres of urban and dense settlement and a population near two billion. Harintaka et al. (2024) derive multi-track displacement time

series for a metropolitan region across six years from satellite radar. Neither required a local authority to install anything.

Four questions organise the analysis. First, what does the evidence establish about the dependency of decisions on measurement? Second, what does measurement demonstrably buy? Third, what does it now cost? Fourth, if technique is no longer the constraint, what is?

2. LITERATURE REVIEW

Asset management: the dependency stated directly

Forero-Ortiz et al. (2023) review pipe failure prediction models and explanatory variables across fifteen years and conclude that a substantial, reliable dataset drawn directly from utility databases is a prerequisite for meaningful failure-rate modelling. Taiwo et al. (2024) demonstrate what becomes possible once the data exist, training five ensemble algorithms on data from four distribution networks, improving one model's mean absolute error by 20.51 per cent through tuning, and identifying pipe age, diameter and length as the dominant contributors to wall thickness loss through interpretable attribution.

Ganjidoost et al. (2021) supply the financial counterpart, validating a three-layer asset management framework against three utilities and identifying an optimal combination of an annual fee increase of about eight per cent with a rehabilitation rate of about 1.3 per cent per year and a cash reserve of one to four per cent depending on network condition. The parameters are specific because the condition data existed; in a utility without them the same framework yields no numbers.

Laucelli et al. (2023) describe the fuller apparatus, applying a digital water services strategy combining spatial data upgrading, advanced hydraulic modelling, complex-network topological analysis and machine learning to two operating networks. Elkhartbotly et al. (2022) build neural network models alongside regression to predict non-revenue water ratios from district metered area data, with the neural approach outperforming regression. Both begin with the district metering step, and neither could have begun without it.

What measurement establishes about water systems

Shushu et al. (2021) provide the most complete diagnostic in the corpus. In a metered district, non-revenue water of fifty per cent decomposed into about eighty-seven per cent real loss, with fifty-two per cent of nodal junctions above recommended pressure and

inadequate velocities in about eighty-three per cent of pipes because the mains were oversized. The composition, the pressure profile and the design defect are three separate findings, and all three required metering.

Macharia et al. (2021), assessing five service providers against nine indicators, report non-revenue water of twenty-six to sixty-three per cent, up to three times the regulated benchmark, and calculate a leakage-reduction potential of up to seventy per cent with energy savings up to twelve megawatt hours annually. Bandari and Sadhukhan (2021), regressing per capita supply on service-level benchmark indicators across thirty large cities, find coverage of connections, extent of metering, extent of non-revenue water and continuity of supply all having considerable effects — with metering appearing as a determinant of delivered quantity, not merely of billing.

Ngoben and Breitenbach (2021) apply data envelopment analysis to nine bulk water entities with losses modelled as an undesirable output and find average technical efficiency of forty-nine per cent with only three efficient. The technique requires loss data; where it is absent, the entity's inefficiency is indistinguishable from its circumstances. Ghorpade et al. (2021), screening 1,080 publications to ninety-one, organise the drivers of intermittent supply into five groups of which four are governance categories including failed district metering and inadequate asset management.

Ferrante et al. (2024) test intermittent supply experimentally across feeding conditions, outflows and air-valve configurations. Abhijith et al. (2023) introduce an open-source modelling extension and find that the clock time of supply determines whether households can meet demand. Ramani et al. (2023) optimise network design for resilience and a uniformity coefficient measuring supply equity. All three produce decision-relevant findings from models, and all three models require network data that many systems do not hold.

Access measurement: when the recorded variable does not predict the outcome

Ambel et al. (2023) train classifiers on water testing data and achieve 88.5 per cent accuracy with an area under the curve of 0.91, then apply the model to survey waves lacking testing. Demographic, socioeconomic and geospatial variables perform comparably to the full feature set, while a model using water source type alone performs poorly. The finding is a direct challenge to source-type-based monitoring and an equally direct demonstration that imputation can substitute for measurement at scale once a training sample exists.

Cronk et al. (2024), across 37,105 household surveys and 6,395 samples in fourteen countries, find ten per cent of households switching primary source between seasons, twenty-three per cent using a secondary source of which thirty-seven per cent were unimproved, sixty-nine per cent of samples containing indicator bacteria, and only seven per cent of households with safely managed water free of contamination at point of use. Daly et al. (2021), screening 5,318 studies and including seventy-four, find multiple source use from four to one hundred per cent of study populations.

Rajapakse et al. (2023) report progress against the relevant global targets and the multiples by which current rates must rise. Gurung et al. (2023), using national microdata, identify the household characteristics predicting access. Together with Ambel et al. (2023) these establish that the measurement instrument determines the reported result, and that the instrument in widest use is the one with the weakest predictive relationship to the outcome it stands for.

Groundwater and subsidence: modelling before regulating

Rusli et al. (2024) couple a distributed hydrological model with a groundwater model under climate and abstraction scenarios and find climate change alone producing no notable change in recharge while confined heads decline by up to 7.14 metres by 2030, 15.25 by 2050 and 29.51 by 2100 at current abstraction, roughly doubling if abstraction grows with population. Projected status is dominated by anthropogenic activity rather than climatic forcing — a conclusion available only from a model.

Phan et al. (2023) supply the regulatory counterpart. Coupling groundwater flow, saltwater transport and subsidence models for one province, they test the existing abstraction restrictions and find that all scenarios formally satisfy the regulation while producing storage depletion, seawater intrusion, subsidence and capture of inflow from neighbouring provinces, with intrusion potentially reaching four to five kilometres inland and cumulative subsidence 1.5 metres by 2100 under business as usual. Only a scenario halving abstraction with a 1.5-fold recharge increase achieved sustainability. A rule that every scenario satisfies is a rule calibrated without a model.

Harintaka et al. (2024) derive multi-track displacement time series for a metropolitan region from satellite radar across six years, attributing subsidence to urbanisation and intensive groundwater extraction and locating the largest movement in specific districts. Davydenka et al. (2024) extend the approach globally, training on more than 46,000 observations and

twenty-three parameters and estimating over 6.3 million square kilometres subsiding including 231,000 square kilometres of urban settlement and a population near two billion, with a positive correlation between abstraction intensity and subsidence rate.

Siriwardane-de Zoysa et al. (2021) supply the governance finding that determines whether any of this reaches a decision. Combining interferometry with policy mapping across three cities, they find socio-temporal variability in subsidence rates that frustrates uniform regulatory action, and a governance landscape spanning urban water supply, groundwater extraction, land-use zoning, building codes, tenure security and land reclamation that is fragmented and incongruous — with all three cities framing subsidence as reversible, quasi-natural or an individualised problem.

Land cover and urban growth: the same dependency on the land side

Addae and Oppelt (2019) conduct land-use and land-cover change analysis with urban growth modelling for a metropolitan area, and Mahmoudzadeh et al. (2022) do the same for a second, both establishing baseline change rates that no administrative record contained. Mithun et al. (2022) build a comparative framework for spatially explicit urban growth modelling; Sahana et al. (2023) apply related methods to a further setting. Arifin et al. (2023) forecast coastal land-use dynamics.

Diaconu et al. (2023) demonstrate remote monitoring of river sand and gravel extraction; Gruel and Latrubesse (2021) build a monitoring system for sand mining in a large river and apply it; Nascimento et al. (2020) trace land cover changes in open-cast mining areas. Park (2024) quantifies the extent and compounded impacts of extraction in a delta system, and Hackney et al. (2021) find extraction far outpacing natural supply in a large alluvial system. Koehnken et al. (2020) synthesise the ecological consequences.

Every one of these studies produces a quantity that a regulator would need and that no permitting record contains, and every one derives it from imagery or models rather than from a reporting obligation on the regulated party. That is the practical significance of the cost change: the measurement no longer depends on the cooperation of the entity being measured.

RESEARCH GAP

Three gaps follow. The first is that measurement capacity is not costed as a component of infrastructure programmes. Studies report what models achieve once data exist and what

fails when they do not; none estimates what establishing the data would cost relative to the asset investment it would inform.

The second is that the dependency is not treated as a sequencing question. The asset management literature states that data must precede modelling, and the utility efficiency literature states that loss data must precede performance assessment, but no study asks what an infrastructure programme should do first in a system where neither exists.

The third is that the governance obstacle identified by Siriwardane-de Zoysa et al. (2021) — fragmented policy domains and framings that naturalise physical change — has not been connected to the measurement literature. Better data reaching a fragmented decision structure changes nothing, and no study assesses which fragmentation actually blocks which measurement from reaching which decision.

3. METHOD

The study is a structured conceptual review organised around a sequencing proposition. It generates no new observations and produces no measurements; it reads published findings against the question of what must exist before an infrastructure decision can be made well.

A corpus was assembled of peer-reviewed research published between 2017 and 2024 across four domains: water loss, network modelling and asset management; groundwater, subsidence and coastal land modelling; urban growth, land-cover change and extraction monitoring; and access measurement. Each item was verified against the publisher record, the digital object identifier resolver, or an indexing record. Conference proceedings were excluded, as were journals whose indexing standing could not be established.

Two analytical procedures were applied. Each study producing a decision-relevant quantity was classified by what measurement it required and by whether that measurement is held by the deciding authority in typical practice. And each was classified by the source of its data: operator records, primary survey, or remotely sensed and modelled sources requiring no local collection. The second classification is what establishes whether the constraint is cost or governance.

Three limitations apply. The corpus is confined to published studies, which over-represents settings where measurement was possible. The judgement that a measurement is not typically held by deciding authorities is inferred from the studies' own framing rather than

from a survey of authorities. And the study argues for a sequence without costing it, which is the exercise the first research gap identifies as missing.

4. RESULTS AND DISCUSSION

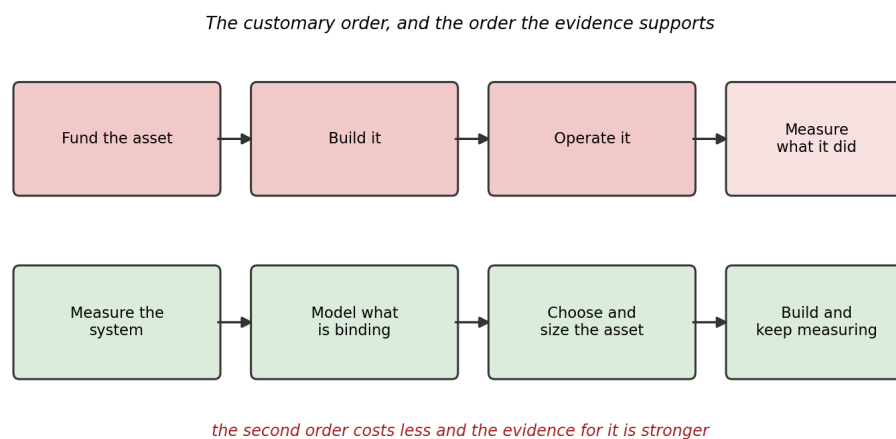


Figure 1. The customary sequence and the sequence the evidence supports

Finding one: the dependency is stated in the literature and inverted in practice

Forero-Ortiz et al. (2023) state the dependency without qualification: model accuracy is bounded by data drawn directly from utility databases. Ngoben and Breitenbach (2021) require loss data to compute efficiency with losses as an undesirable output. Elkhartbotly et al. (2022) and Laucelli et al. (2023) both begin from district metered area data. Ganjidoost et al. (2021) produce specific renewal and tariff parameters because condition data existed for the three utilities studied.

Against that, the customary reform sequence funds an asset, builds it, operates it and measures afterwards, if at all. The inversion is not irrational — an asset is visible, a database is not, and financing institutions are constituted to lend against physical collateral. But it means the decision about what to build is taken at the point of least information, and the information arrives after the decision it would have informed.

Shushu et al. (2021) show what the inversion costs concretely. Their district was found to have oversized mains producing inadequate velocities in about eighty-three per cent of pipes, generating both leakage and a stagnation-driven quality problem. That is a specification error made years earlier by someone who did not have demand data at the

resolution the decision required, and its correction now costs more than the original design would have.

Finding two: measurement pays returns that are themselves measured

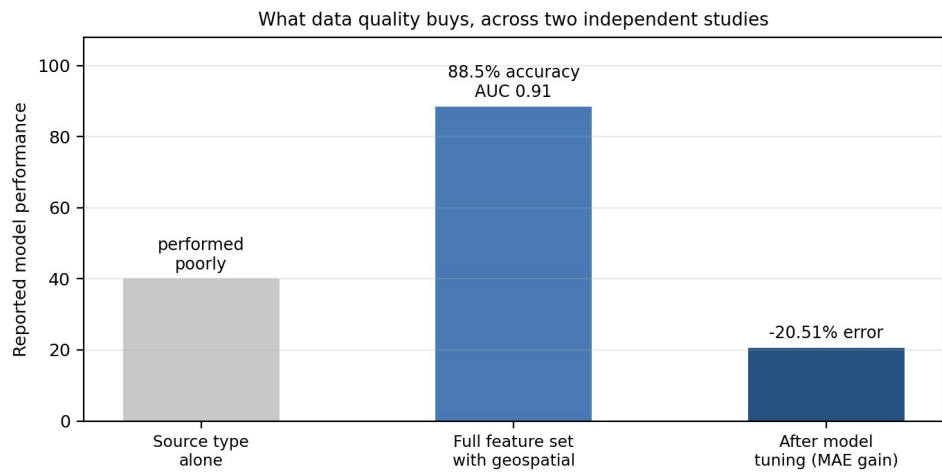


Figure 2. What data quality buys, across two independent studies

Two studies quantify the return on data quality directly. Taiwo et al. (2024) improved a failure model's mean absolute error by 20.51 per cent through hyperparameter tuning on network data from four distribution systems, with interpretable attribution identifying pipe age, diameter and length as dominant. Ambel et al. (2023) achieved 88.5 per cent classification accuracy with an area under the curve of 0.91 using the full feature set, while a model using source type alone performed poorly.

The second result is the more consequential for policy, because source type is the variable that administrative systems record and that international monitoring uses. A model built on the variable a decision-maker already holds performs poorly; a model built on variables that are collectable performs well. The gap between the two is the value of the missing measurement, and it is expressed here in units any evaluator can read.

Bandari and Sadhukhan (2021) supply the aggregate version: metering extent, non-revenue water extent, connection coverage and supply continuity all substantially affect per capita supply across thirty cities. Metering is on that list as a determinant of the quantity delivered, not merely of the quantity billed — which means that in this literature measurement is not only an input to decisions but an input to performance.

Table 1. Decision-relevant quantities, the measurement each requires, and its source

Quantity a decision	Measurement required	Data source	Held by the deciding
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requires			authority?
Composition of water loss	District metering and water balance	Operator records	Frequently not
Renewal priority across a network	Failure history by pipe attribute	Operator records	Frequently not
Whether an entity is inefficient	Loss modelled as undesirable output	Operator records	Frequently not
Safe abstraction limit	Coupled flow and subsidence model	Modelled from monitoring wells	Rarely
Where the ground is moving	Satellite interferometry time series	Remote, no local collection	Available
Whether supply is safe at point of use	Quality testing plus imputation model	Survey plus modelling	Rarely
Extent of extraction from a river	Remote monitoring of channel change	Remote, no local collection	Available

Note. Compiled by the author from the reviewed corpus. The final column reports the typical position implied by the studies' own framing rather than a survey of authorities.

Finding three: the instruments are no longer the expensive part

Three studies in the corpus produce national or global quantities from data that no local authority must collect. Davydzienka et al. (2024) map global subsidence from more than 46,000 observations and twenty-three environmental parameters, estimating over 6.3 million square kilometres subsiding including 231,000 square kilometres of urban settlement and a population near two billion, with abstraction intensity positively correlated with subsidence rate. Harintaka et al. (2024) derive six years of multi-track displacement time series for a metropolitan region, locating the largest movement in named districts and improving accuracy by up to fifty-three per cent at some sites through a two-dimensional approach.

Diaconu et al. (2023), Gruel and Latrubesse (2021) and Nascimento et al. (2020) monitor extraction and mining-related land cover change remotely. Addae and Oppelt (2019), Mahmoudzadeh et al. (2022), Mithun et al. (2022) and Sahana et al. (2023) model urban growth from imagery. Arifin et al. (2023) forecast coastal land-use dynamics. Ambel et al. (2023) impute water quality from survey and geospatial variables where testing was not performed.

The pattern across these is that the measurement no longer depends on the cooperation of the regulated party or on the installation of local instrumentation. That is a substantial change from the position the asset management literature assumes, and it narrows the

domain in which cost is a defensible reason for not measuring. It does not eliminate that domain: pipe failure history, water balance and pressure profiles remain operator-generated and cannot be sensed remotely, which is why district metering retains its position as the first step in any water programme.

Finding four: governance rather than technique is the binding constraint

Siriwardane-de Zoysa et al. (2021) supply the finding that determines whether measurement changes anything. Across three cities they find socio-temporal variability in subsidence rates frustrating uniform regulatory action, and a governance landscape spanning six policy domains — urban water supply, groundwater extraction, land-use zoning, building codes, tenure security and land reclamation — that is fragmented and incongruous, with all three cities framing subsidence as reversible, quasi-natural or an individualised problem.

Phan et al. (2023) demonstrate the same obstacle in regulatory form. All modelled abstraction scenarios formally satisfy the existing regulation while producing depletion, intrusion and subsidence, with only a halving of abstraction combined with a 1.5-fold recharge increase achieving sustainability. The regulation is not violated; it is miscalibrated, and it was miscalibrated because it was written without the model that would have shown what it permitted.

Ghorpade et al. (2021) reach the same conclusion for intermittent supply, with four of five driver groups falling into governance categories — design and analysis failures, operation and maintenance failures, revenue failures and institutional capacity. Rusli et al. (2024) find projected groundwater status dominated by anthropogenic activity rather than climatic forcing, which locates the decision squarely in the administrative arena rather than the environmental one.

The implication for sequencing is a qualification rather than a reversal. Establishing measurement first is necessary and not sufficient: a measurement that reaches a fragmented decision structure, or one whose framing treats the measured change as natural, produces knowledge without producing action. The governance step therefore belongs in the sequence alongside the measurement step rather than after it.

Finding five: unmeasured deterioration is invisible by construction

The final finding is structural and explains why the inversion persists. A system that is not measured produces no evidence of its own deterioration, so the case for investing in it is

made without data while the case for a new asset is made with an engineering estimate. The comparison at the appraisal table is therefore systematically biased toward construction.

Cronk et al. (2024) illustrate the same asymmetry at population scale: only seven per cent of households were found to have safely managed water free of contamination at point of use, against far higher figures in official reporting, because the official instrument records source type and the study measured what reached the household. Daly et al. (2021) find multiple source use ranging up to one hundred per cent of study populations. Rajapakse et al. (2023) report the multiples by which current rates of progress must rise to meet targets — multiples computed against a baseline the two preceding studies show to be overstated.

A programme assessed against an overstated baseline appears closer to its target than it is, which further reduces the apparent urgency of measuring. Gurung et al. (2023) identify the household characteristics predicting access, which is the information that would target remedial investment and is absent from source-type reporting entirely.

A proposed sequence

Four steps follow, ordered by dependency rather than by cost. First, establish the operator-side measurement that cannot be obtained remotely: district metering, water balance, pressure profiles and a failure register. Forero-Ortiz et al. (2023) establish that nothing downstream is possible without it, and Shushu et al. (2021) show what it reveals in a single district.

Second, acquire the remotely sensed and modelled layers, which now require no local collection: subsidence displacement, land-cover change, extraction monitoring and, where monitoring wells exist, a coupled groundwater model. Davydenko et al. (2024), Harintaka et al. (2024) and Phan et al. (2023) demonstrate that each is available, and Phan et al. (2023) demonstrate what happens to a regulation written without one.

Third, resolve the governance fragmentation that determines whether a measurement reaches a decision. Siriwardane-de Zoysa et al. (2021) identify six policy domains that must act together and find them incongruous; naming which authority acts on which measurement is a procedural task that costs nothing and is not currently performed.

Fourth, size and build the asset. This is where the customary sequence begins and where the evidence places it last — not because construction is unimportant but because its return is

determined by decisions taken in the three preceding steps, and those decisions cannot be taken well without them.

Limitations

Four limits bound the argument. The corpus over-represents settings where measurement was feasible, since a study of an unmeasured system is difficult to publish. The judgement that particular measurements are not typically held by deciding authorities is inferred rather than surveyed. The proposed sequence is not costed, so its affordability relative to asset investment is asserted rather than demonstrated. And the argument concerns what good decisions require, not whether any particular investment was mistaken.

5. CONCLUSION

Infrastructure decisions require knowing what a system does, what limits it, and whether an intervention worked. Three of the four things a decision needs are measurements, and the literature is unambiguous that they come first: model accuracy is bounded by data drawn from operator records, loss composition requires metering, efficiency assessment requires loss data, and an abstraction limit written without a coupled model turns out to permit every scenario including the unsustainable ones.

Measurement now pays returns that are themselves quantified — a 20.51 per cent error reduction from tuning on network data, an 88.5 per cent classification accuracy against a source-type model that performed poorly — and its cost has fallen sharply, with global subsidence mapping, land-cover change and extraction monitoring all derivable without local instrumentation.

What has not changed is governance. Six fragmented policy domains, a framing that treats physical change as natural, and a regulation that every scenario satisfies together ensure that better data reaching a decision structure of this kind produces knowledge and not action. Establishing the measurement is necessary; naming who must act on it is the step that makes it worth establishing.

The deepest reason the sequence keeps inverting is that an unmeasured system generates no evidence of its own decline, so at every appraisal the case for a new asset arrives with numbers and the case for maintaining an existing one arrives without them. Data before concrete is not an argument against building. It is an argument for knowing what to build.

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Author contributions (CRediT)

Muhammad Alhamdani Amin: conceptualisation; methodology; formal analysis; writing - original draft; writing - review and editing.

Conflict of interest

The authors declare that they have no competing interests.

Data availability

All data supporting the findings of this study are available within the article and from the publicly accessible sources cited therein.

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Declaration on the use of artificial intelligence

No generative artificial intelligence tool was used in the preparation of this manuscript.

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