

HUMAN CAUSE OR NATURAL VARIATION: ATTRIBUTION AS A PRECONDITION FOR ENVIRONMENTAL REGULATION

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ABSTRACT

An environmental rule can only address the part of a change that human action produced. Establishing that share is an attribution problem, and where it is unresolved a regulation is written against an unknown target. This study examines attribution as the causal step preceding environmental regulation. The method is a structured conceptual review of research published between 2017 and 2024 on groundwater and subsidence modelling, extraction monitoring, land-cover change and water service delivery, classified by whether the study separates anthropogenic from natural drivers. Attribution is achievable and has been achieved: one coupled model finds climate change alone producing no notable change in recharge while confined heads decline by up to 29.51 metres by 2100 under current abstraction, concluding that projected status is dominated by anthropogenic activity; a global model trained on more than 46,000 observations finds abstraction intensity positively correlated with subsidence rate. Where attribution is absent the regulation is miscalibrated: one study found every modelled abstraction scenario formally satisfying the existing rule while producing depletion, saline intrusion and subsidence. Governance framings that treat physical change as quasi-natural pre-empt attribution rather than following from it. The study proposes that an attribution statement accompany any environmental rule setting a quantitative limit.

ABSTRAK

Aturan lingkungan hanya dapat menangani bagian perubahan yang ditimbulkan tindakan manusia. Menetapkan bagian itu merupakan persoalan atribusi, dan bila belum terselesaikan, peraturannya disusun terhadap sasaran yang tidak diketahui. Kajian ini menelaah atribusi sebagai langkah kausal yang mendahului pengaturan lingkungan dan menanyakan apa yang ditetapkan bukti mengenainya. Metodenya adalah telaah konseptual terstruktur atas riset terbitan 2017 hingga 2024 mengenai pemodelan air tanah dan penurunan muka tanah, pemantauan penambangan, perubahan tutupan lahan, dan penyediaan layanan air, digolongkan menurut apakah studinya memisahkan pendorong antropogenik dari pendorong alamiah. Empat temuan mengikutinya. Atribusi dapat dilakukan dan telah dilakukan: satu model terpadu menemukan perubahan iklim semata tidak menimbulkan perubahan berarti pada pengimbuhan sementara muka piezometrik tertekan turun hingga 29,51 meter pada 2100 dengan laju pengambilan sekarang, dan menyimpulkan keadaan proyeksinya didominasi aktivitas antropogenik alih-alih paksaan iklim; satu model global yang dilatih pada lebih dari 46.000 pengamatan menemukan intensitas pengambilan berkorelasi positif dengan laju penurunan tanah. Kedua, bila atribusinya tidak ada, peraturannya salah kalibrasi, dengan satu studi menemukan seluruh

	skenario pengambilan yang dimodelkan secara formal memenuhi aturan yang berlaku sambil menimbulkan penyusutan cadangan, intrusi air asin, dan penurunan tanah. Ketiga, pembingkai tata kelola yang memperlakukan perubahan fisik sebagai hal kuasi-alamiah mendahului atribusi alih-alih mengikutinya. Keempat, instrumennya kini tersedia tanpa pemasangan alat setempat. Kajian ini mengusulkan pernyataan atribusi menyertai setiap aturan lingkungan yang menetapkan batas kuantitatif. Kata kunci: atribusi kausal; pengaturan lingkungan; pengambilan air tanah; penurunan muka tanah; pendorong antropogenik
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1. INTRODUCTION

Ground subsides. An aquifer falls. A river changes shape. Forest cover declines. In each case two explanations are available — the system was going to do this anyway, or somebody did it — and the regulatory consequence depends entirely on which is correct, because a rule can only address the second.

This is an attribution problem, and it is causal in the strict sense. Establishing that abstraction caused a head decline requires knowing what the head would have done under the same climate without the abstraction, which is a counterfactual and not an observation. The methods for constructing it exist and are used in the physical sciences; the question this study asks is what happens to regulation when they are not.

The answer is documented. Phan et al. (2023), coupling groundwater flow, saltwater transport and subsidence models for one province and testing the abstraction restrictions in force, find that every modelled scenario formally satisfies 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 alongside a 1.5-fold recharge increase achieved sustainability.

A rule that every scenario satisfies is a rule that was calibrated without knowing what it needed to restrain. That is the practical form of an unresolved attribution: not a rule that is wrong on its face but a rule that permits the outcome it was written to prevent.

Three questions organise the analysis. First, has attribution been achieved, and by what means? Second, what happens to regulation when it has not? Third, what would an attribution requirement look like?

2. LITERATURE REVIEW

Attribution achieved: separating human action from natural variation

Rusli et al. (2024) supply the clearest case. Coupling a distributed hydrological model with a groundwater model, they run climate projections under two emissions pathways against three abstraction scenarios and evaluate at three horizons. Climate change alone produces no notable change in recharge. Confined piezometric heads decline by maxima of 7.14 metres by 2030, 15.25 by 2050 and 29.51 by 2100 at current abstraction, roughly doubling if abstraction grows with population. The conclusion — that projected groundwater status is dominated by anthropogenic activity rather than climatic forcing — is an attribution statement, and it is available only because the two drivers were varied separately.

Davydzenka et al. (2024) achieve attribution at global scale by a different route. A deep learning model trained on more than 46,000 subsidence observations and twenty-three environmental parameters produces 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, and finds a positive correlation between groundwater abstraction intensity and subsidence rate. The correlation is not itself identification, but it is established across a sample large enough to hold many natural drivers constant.

Harintaka et al. (2024) supply the spatial attribution. Multi-track satellite radar displacement time series across six years locate the largest subsidence in specific districts and attribute it to rapid urbanisation and intensive groundwater extraction, with a two-dimensional approach improving accuracy by up to fifty-three per cent at some sites. Locating the movement is what permits a rule addressed to particular places rather than to a metropolitan average.

Hackney et al. (2021) attribute river change by comparing extraction rates with natural sediment supply and finding extraction far outpacing supply in a large alluvial system. That comparison is the attribution: a river losing sediment faster than it receives it is losing it to something, and the quantity removed is measured. Park (2024) quantifies extent and compounded impacts in a delta system; Koehnken et al. (2020) synthesise the ecological consequences of riverine extraction.

Attribution absent: regulation written against an unknown target

Phan et al. (2023) is the central case, and its structure deserves emphasis. The regulation exists, specifies abstraction restrictions, and is satisfied by every scenario the authors model — including scenarios producing four to five kilometres of saline intrusion and 1.5 metres of cumulative subsidence. The rule was not evaded; it was met, and the outcome occurred anyway.

Siriwardane-de Zoysa et al. (2021) explain how a governance system arrives at such a rule. Combining satellite interferometry with policy mapping across three cities, they find socio-temporal variability in subsidence rates frustrating 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. All three cities frame subsidence as reversible, quasi-natural, or an individualised problem.

The framing finding is the important one for this study, because it pre-empts attribution rather than following from it. A phenomenon described as quasi-natural has already been assigned to the natural column before any model was run, and no rule addressed to human action follows from that assignment. The framing is not a conclusion drawn from evidence; it is a substitute for the evidence.

Ghorpade et al. (2021), screening 1,080 publications to ninety-one, organise the drivers of intermittent water supply into five groups of which four are governance categories — design and analysis failures, operation and maintenance failures, revenue failures and institutional capacity. That distribution is itself an attribution result: a phenomenon widely experienced as a scarcity problem is principally produced by decisions.

Attribution in service systems: what causes the health effect

Gallandat et al. (2024) supply the strongest causal design in the corpus applied to a service system. A pragmatic trial of piped supply improvements yields incidence rate ratios for confirmed cholera of 0.84 for service quality, 0.76 for quantity and 0.75 for continuity, with the authors estimating that an additional five litres per user per day, or 1.2 more hours per day of production, would reduce confirmed cholera by twenty-four and twenty-five per cent respectively.

The three ratios are an attribution across attributes of the same intervention. A programme could not have learned from an aggregate estimate that continuity carries most of the effect,

and continuity is the attribute a utility can act on directly. Wu et al. (2023), using an instrumented ordered probit across 641 villages in eight provinces, find intermittent supply raising the probability of merely fair self-rated health by 18.2 per cent and reducing the probability of excellent health by 58.8 per cent, mediated through household storage behaviour and sanitary water habits — an attribution to a mechanism rather than to an exposure.

Ambel et al. (2023) attribute measurement error rather than physical change, training classifiers on water testing data to reach 88.5 per cent accuracy with an area under the curve of 0.91, and finding that a model using water source type alone performs poorly. Cronk et al. (2024), across 37,105 household surveys in fourteen countries, find only seven per cent of households with safely managed water free of contamination at point of use. Daly et al. (2021) find multiple source use ranging from four to one hundred per cent of study populations. Together these establish that what a monitoring system attributes to a source may not be where the household's water came from.

Land and extraction: attributing change to an actor

Lo et al. (2024) attribute deforestation to an extractive expansion across a national dataset, identifying the concentration of loss where a single industry dominates the revenue base. Nascimento et al. (2020) trace land cover changes in open-cast mining areas. Gruel and Latrubesse (2021) build a monitoring system for sand extraction in a large river and apply it. Diaconu et al. (2023) demonstrate remote monitoring of river sand and gravel extraction.

Each of these attributes a physical change to a specific activity by observing the activity rather than inferring it from the change. That distinction matters for regulation, because a rule requires a regulated party and an attribution that names only a category — urbanisation, development, climate — identifies nobody.

Andreucci et al. (2023) supply the political economy in which the attribution operates, arguing that the fiscal dependence of subnational governments on extraction is itself a driver of expansion rather than merely a consequence. Akhmaddhian et al. (2023) assess post-mining rehabilitation effectiveness and find implementation weak where enforcement capacity is thin. Untari et al. (2022) trace how conservation restrictions redirect livelihoods across activities rather than removing pressure. Haq et al. (2023) analyse the redesign of extraction policy; Torres et al. (2017), Bendixen et al. (2019) and Lamb et al. (2019) establish the global scale of the problem and the livelihoods omitted from its accounting.

Addae and Oppelt (2019), Mahmoudzadeh et al. (2022), Mithun et al. (2022) and Sahana et al. (2023) model urban growth and land-cover change, establishing baseline change rates against which a particular actor's contribution can be assessed. Arifin et al. (2023) forecast coastal land-use dynamics. Arifanti et al. (2023) examine mangrove ecosystem management and find outcomes depending on institutional arrangements rather than formal designation.

What attribution is worth to a fiscal instrument

Attribution has a second use beyond justifying a prohibition: it is the precondition for pricing. Nasir (2022) examines an ecological fiscal transfer protecting forested areas and identifies the design problem — a jurisdiction bearing the opportunity cost of retention receives no fiscal recognition unless an instrument supplies one. Busch et al. (2021) survey such transfers across jurisdictions and document the conditions under which they change behaviour.

Best et al. (2020), examining carbon pricing efficacy across countries, establish that price instruments change emissions trajectories, which is the premise for treating retention as a monetisable activity. Colenbrander et al. (2018) address the difficulty of routing climate finance to the subnational level at which land-use decisions are made. Bartzas and Komnitsas (2024) demonstrate that the environmental cost of an extractive value chain can be computed when someone is required to compute it.

A payment for retention requires knowing what would have happened without it, which is the same counterfactual an attribution supplies. Maroun et al. (2019) and Banda (2023) show that fiscal regime parameters determine whether extraction occurs at all, which means the attribution and the price are connected: an activity correctly attributed can be priced, and a priced activity changes.

RESEARCH GAP

Two gaps follow. The first is that no reviewed study assesses whether an existing environmental regulation was calibrated against an attribution. Phan et al. (2023) demonstrate the test — model the scenarios the rule permits and ask whether any produces the outcome the rule targets — and apply it once.

The second is that the framing effect identified by Siriwardane-de Zoysa et al. (2021) has not been connected to regulatory outcomes. Whether jurisdictions that describe subsidence as

quasi-natural regulate differently from those that attribute it to abstraction is an empirical question with observable variation across the cities and provinces already studied.

3. METHOD

The study is conceptual and methodological. It advances no measurement; it classifies existing studies by whether and how they separate anthropogenic from natural drivers, and asks what the classification implies for regulation.

A corpus was assembled of peer-reviewed research published between 2017 and 2024 on groundwater, subsidence, extraction monitoring, land-cover change and water service delivery. 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.

Each study was classified on two dimensions specified in advance: whether it separates anthropogenic from natural drivers, and by what means — coupled scenario modelling, large-sample statistical association, direct observation of the activity, or experimental variation. Studies not attempting separation were classified as descriptive.

Two limitations apply. The corpus is not a systematic sample of the physical science literature and is selected for regulatory relevance. And the classification records what each study did rather than assessing whether its attribution is sound, which requires engagement with each model's assumptions.

4. RESULTS AND DISCUSSION

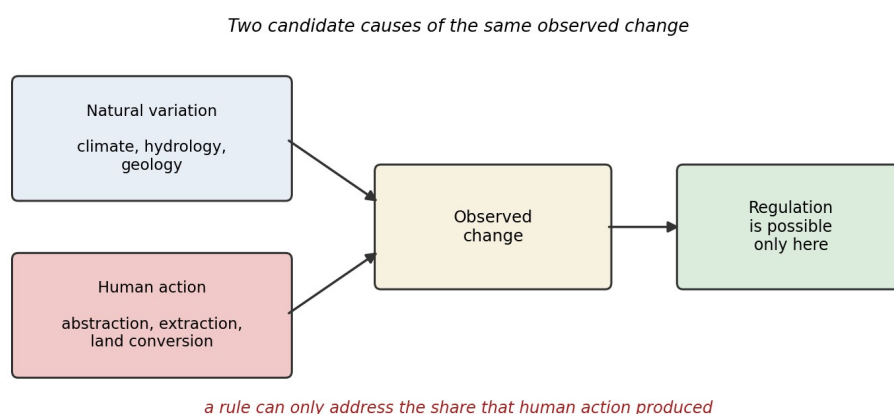


Figure 1. Attribution as the step preceding regulation

Finding one: attribution is achievable and has been achieved

Four methods appear in the corpus. Coupled scenario modelling varies drivers separately, as Rusli et al. (2024) do in finding climate alone producing no notable recharge change while abstraction produces head declines up to 29.51 metres. Large-sample statistical association holds natural drivers constant across many settings, as Davydenka et al. (2024) do across more than 46,000 observations. Direct observation of the activity measures the human contribution rather than inferring it, as Gruel and Latrubesse (2021), Diaconu et al. (2023) and Hackney et al. (2021) do for extraction. Experimental variation randomises the intervention, as Gallandat et al. (2024) do in a pragmatic trial.

None of these requires a laboratory, and three of the four require no local instrumentation at all. The constraint on attribution is therefore not technical availability.

Table 1. Attribution methods applied to environmental questions

Method	How the counterfactual is obtained	Example finding
Coupled scenario modelling	Drivers varied separately in the same model	Climate alone produces no notable recharge change (Rusli et al., 2024)
Large-sample association	Natural drivers held constant across many settings	Abstraction intensity correlates with subsidence rate (Davydenka et al., 2024)
Direct observation of activity	The human contribution is measured, not inferred	Extraction far outpaces natural sediment supply (Hackney et al., 2021)
Spatial time series	Movement located and matched to activity	Largest subsidence in specific districts (Harintaka et al., 2024)
Experimental variation	Intervention randomised across units	Continuity carries the health effect, IRR 0.75 (Gallandat et al., 2024)
Regulatory scenario test	Every permitted scenario modelled against the target	All scenarios satisfy the rule and produce the harm (Phan et al., 2023)

Note. Compiled by the author from the reviewed corpus.

Finding two: without attribution the rule is miscalibrated rather than absent

The failure mode Phan et al. (2023) document is worth distinguishing from the one usually assumed. The province in question has an abstraction regulation. It is not being flouted. Every scenario the authors model formally satisfies it, and those scenarios produce storage depletion, four to five kilometres of saline intrusion and 1.5 metres of cumulative subsidence by 2100.

Only one modelled path achieved sustainability: halving abstraction combined with a 1.5-fold recharge increase. That path lies far outside what the rule requires, which means the gap between the regulation and the sustainable path was never estimated when the regulation was written. A rule calibrated without an attribution cannot know how much restraint the problem requires, so it specifies an amount that sounds substantial and permits an outcome nobody intended.

Ghorpade et al. (2021) show the same structure in a different system, finding four of five driver groups for intermittent supply to be governance rather than hydraulic categories. A supply problem attributed to scarcity attracts source development; a supply problem attributed to design, maintenance, revenue and institutional capacity attracts a different programme entirely, and the two attributions lead to opposite investment decisions.

Finding three: framing pre-empts attribution

Siriwardane-de Zoysa et al. (2021) find three cities framing subsidence as reversible, quasi-natural or individualised, across a governance landscape of six fragmented policy domains. Each framing performs the attribution before any evidence is considered, and each assigns the phenomenon away from the human column.

This matters because attribution is expensive to reverse once it has been settled informally. A phenomenon classified as natural generates monitoring designed to describe rather than to apportion, which produces data unsuited to reattribution later. Rusli et al. (2024) find the opposite conclusion — anthropogenic dominance — only because the study was designed to test the two drivers against each other.

Andreucci et al. (2023) identify the interest served by a naturalising framing, arguing that subnational fiscal dependence on extraction drives expansion rather than following it. Where a jurisdiction's revenue depends on the activity that would be attributed, the incentive runs toward the framing that attributes elsewhere. Akhmaddhian et al. (2023) find post-extraction rehabilitation weak where enforcement capacity is thin — the same jurisdictions.

Finding four: the instruments no longer require local collection

Davydzenka et al. (2024) produce a global subsidence map from remotely sensed and environmental data. Harintaka et al. (2024) derive six years of displacement time series for a metropolitan region from satellite radar. Gruel and Latrubesse (2021) and Diaconu et al.

(2023) monitor extraction remotely. Addae and Oppelt (2019), Mahmoudzadeh et al. (2022), Mithun et al. (2022) and Sahana et al. (2023) model land-cover change from imagery. Nascimento et al. (2020) trace mining-related change the same way. Ambel et al. (2023) impute water quality where testing was not performed.

The significance is that attribution no longer depends on the cooperation of the party whose contribution is being attributed. A regulator that could not previously establish who caused a change, because the data belonged to the operator, can now establish it independently. That removes the most common practical justification for leaving attribution unresolved.

What remains is the coupled modelling that requires local monitoring wells and hydrogeological data, which Rusli et al. (2024) and Phan et al. (2023) both use. That is the expensive component, and it is the one that produces the strongest attribution — which suggests a sequence in which remotely sensed attribution establishes where the problem is and coupled modelling establishes how much restraint it requires.

What an attribution requirement would specify

Four elements follow. First, any environmental rule setting a quantitative limit should be accompanied by a statement of what share of the observed change is attributed to the activity being limited, and on what basis. Where the share is unknown, the statement should say so, which is more informative than silence.

Second, the rule should be tested against the scenarios it permits, following Phan et al. (2023). Modelling the permitted envelope and asking whether any scenario within it produces the harm the rule targets is a single exercise that would have exposed the miscalibration in that case before it was enacted.

Third, the framing should be examined explicitly. Siriwardane-de Zoysa et al. (2021) establish that descriptions of a phenomenon as natural or individualised are doing attributive work; requiring the attribution to be stated separately from the description prevents it being performed by adjective.

Fourth, where attribution supports it, the activity should be priced rather than only limited. Nasir (2022) and Busch et al. (2021) document ecological fiscal transfers in operation; Best et al. (2020) establish that price instruments change trajectories; Bartzas and Komnitsas (2024) show the environmental cost of a value chain is computable. An attributed harm is a priceable harm, and pricing reaches decisions that prohibition does not.

Limitations

Three limits bound the argument. The corpus is selected for regulatory relevance rather than systematically sampled from the physical science literature. The classification records method rather than assessing whether each attribution is sound. And the study proposes an attribution requirement without estimating what it would cost to satisfy, which varies enormously between a remotely sensed assessment and a coupled hydrogeological model.

5. CONCLUSION

An environmental rule can only restrain what people do. Establishing how much of an observed change people did is a causal question with a counterfactual at its centre, and it is answerable: one coupled model finds climate alone producing no notable change in recharge while abstraction drives heads down by up to 29.51 metres, and concludes that projected status is dominated by human activity rather than climatic forcing.

Where the question is not answered, the rule is not absent but miscalibrated. In one province every modelled abstraction scenario formally satisfies the regulation while producing depletion, four to five kilometres of saline intrusion and 1.5 metres of subsidence — and only halving abstraction alongside a recharge increase achieves sustainability. The rule permits the outcome it exists to prevent, because nobody estimated how much restraint the problem required.

Attribution is also performed informally, and that is the more dangerous route. Three cities describing subsidence as reversible, quasi-natural or individualised have assigned the phenomenon away from human action before any model was run, and the jurisdictions with the strongest incentive to do so are the ones whose revenue depends on the activity in question.

The technical obstacle has largely gone. Global subsidence mapping, satellite displacement series, remote extraction monitoring and land-cover modelling all now proceed without the cooperation of the party being attributed. What remains is the requirement: that a rule setting a limit should state what share of the harm it is limiting, and should be tested against the scenarios it allows.

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Author contributions (CRediT)

Achmad Zein Maulana: 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

Claude (Anthropic) was used for language editing and for translation of the manuscript into English. The authors reviewed and verified all content, and take full responsibility for the final text. No generative tool was used for data analysis, for the interpretation of results, or for the generation of scholarly content. AI is not listed as an author.

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