Zero-Boundary Modeling of Environmental Pollutant Behavior Using Zero-Centric Arithmetic: A Mathematical Framework for Environmental Engineering

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ABSTRACT

Environmental engineering models extensively rely on algebraic ratio-based formulations to describe pollutant concentration, transport, partitioning, persistence, and exposure. These formulations implicitly assume that denominators such as environmental volume, concentration, reaction rate constants, or exposure duration remain strictly non-zero. However, many environmentally relevant boundary conditions involve zero or near-zero values, including non-detect concentrations, zero-emission states, vanishing reaction rates, and disappearing environmental compartments. Under classical arithmetic, such conditions generate undefined expressions that are frequently interpreted as physically meaningful infinities.

This paper introduces a Zero-Centric Arithmetic framework for modeling environmental pollutant behavior at zero boundaries. Within this framework, expressions involving division by zero are reinterpreted as non-operations, representing collapse points of mathematical models rather than extreme or infinite environmental states. By applying this reinterpretation to concentration equations, partition coefficients, atmospheric lifetime models, and exposure formulations, the proposed approach restores mathematical consistency and aligns environmental equations with physically observable behavior. The framework establishes clear operational domains for environmental models and provides a robust mathematical foundation for environmental simulation, risk assessment, and engineering decision-making.

ملخص البحث:

تعتمد نماذج الهندسة البيئية بشكل كبير على صيغ رياضية قائمة على النِّسب الجبرية لوصف تركيز الملوثات وانتقالها وتوزيعها وثباتها ومستويات التعرض لها. وتفترض هذه الصيغ ضمنيًا أن المقامات، مثل الحجم البيئي أو التركيز أو ثوابت معدلات التفاعل أو مدة التعرض، تظل غير صفرية بشكل صارم. ومع ذلك، فإن العديد من الحالات الحدّية ذات الصلة بيئيًا تتضمن قيماً تساوي الصفر أو تقترب منه، مثل التراكيز غير القابلة للكشف، وحالات انعدام الانبعاثات، وتلاشي معدلات التفاعل، واختفاء الأوساط البيئية. ووفقًا للحسابات الكلاسيكية، تؤدي هذه الحالات إلى تعبيرات غير معرفة يتم تفسيرها غالبًا على أنها لانهائيات ذات دلالة فيزيائية تقدم هذه الورقة إطارًا للحساب المرتكز على الصفر لنمذجة سلوك الملوثات البيئية عند الحدود الصفرية وضمن هذا الإطار، يُعاد تفسير(Zero-Centric Arithmetic) التعابير التي تتضمن القسمة على صفر باعتبارها «لا-عمليات بدلًا من كونها حالات بيئية قصوى أو لا نهائية. ومن خلال تطبيق هذا التفسير على معادلات التركيز، ومعاملات التوزيع، ونماذج العمر الجوي، وصيغ التعرض، يساهم النهج المقترح في

استعادة الاتساق الرياضي ومواءمة المعادلات البيئية مع السلوك الفيزيائي المرصود. كما يحدد هذا الإطار المجالات التشغيلية للنماذج البيئية ويوفر أساسًا رياضيًا متينًا لمحاكاة الأنظمة البيئية، وتقييم المخاطر، ودعم اتخاذ القرار الهندسي

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الكلمات المفتاحية: القراءة، الحساب المرتكز على الصفر؛ الهندسة البيئية؛ نمذجة الملوثات؛ القسمة على الصفر؛ الحالات الحدّية الصفرية؛ الرياضيات البيئية؛ انهيار النماذج؛ تقييم المخاطر

1. Introduction

Environmental engineering depends fundamentally on mathematical models to describe the behavior of pollutants in air, water, soil, and biological systems. These models are used to quantify contaminant concentration, predict transport between environmental compartments, estimate atmospheric persistence, and evaluate human and ecological exposure. In most cases, the governing equations take the general algebraic form

$$f = \frac{A}{B}, \qquad (1)$$

where the denominator B represents an environmental quantity such as volume, concentration, reaction rate constant, exposure time, or partial pressure.

Conventional environmental modeling implicitly assumes that $B \neq 0$. However, real environmental systems frequently encounter boundary conditions where $B \to 0$ or $B = 0$. Common examples include zero-volume compartments, non-detect pollutant concentrations, zero emission or depletion states, vanishing reaction rate constants, and zero exposure durations. When these conditions occur, classical arithmetic renders the governing expressions undefined.

Despite this mathematical indeterminacy, environmental literature and modeling practice often interpret such undefined expressions as physically meaningful extremes, using descriptions such as “infinite concentration,” “infinite solubility,” “infinite partitioning,” or “infinite atmospheric lifetime.” These interpretations implicitly suggest the existence of unbounded environmental quantities, even though no physical environmental system exhibits infinite concentration, infinite persistence, or infinite exposure.

This mismatch between mathematical formulation and physical reality arises from extending algebraic expressions beyond their domains of validity. When a denominator reaches zero, the mathematical operation itself ceases to be meaningful. The resulting undefined expression does not indicate a divergence in environmental behavior but rather a collapse of the mathematical model.

Zero-Centric Arithmetic provides a rigorous framework for resolving this contradiction. In this framework, any expression of the form

$$\frac{A}{0} \qquad (2)$$

is classified as a non-operation rather than an extreme numerical value. Such expressions mark boundaries at which environmental equations lose operational meaning and should not be interpreted as representing physical states. Applying this perspective to environmental engineering models allows zero-boundary conditions to be treated consistently, without invoking non-physical infinities.

The objective of this paper is to establish a Zero-Centric mathematical framework for environmental pollutant modeling at zero boundaries. By reinterpreting division-by-zero expressions as model collapse points, the study clarifies the valid domains of commonly used environmental equations and provides a more coherent and physically consistent foundation for environmental modeling, simulation, and risk assessment.

2. Background

2.1 Classical Mathematical Structure of Environmental Models

Environmental engineering and environmental chemistry rely fundamentally on algebraic models to quantify pollutant concentration, transport, partitioning, persistence, and exposure across environmental compartments. These models are typically expressed as ratios in which the denominator represents a physical or chemical quantity assumed to be strictly non-zero, such as environmental volume, concentration, reaction rate constant, exposure duration, or partial pressure [4–8].

A generic form of these models can be written as

$$f = \frac{A}{B}, \qquad (3)$$

where A represents a pollutant mass, flux, or state variable, and B represents an environmental parameter. Classical environmental modeling implicitly assumes that $B > 0$, ensuring that the mathematical operation remains well-defined.

This assumption underlies a wide range of standard formulations, including pollutant concentration definitions, partition coefficients, Henry's law expressions, atmospheric lifetime equations, and exposure metrics [4–10]. While this assumption is generally valid under typical environmental conditions, it becomes problematic at boundary cases that are increasingly relevant in modern environmental assessment.

2.2 Zero and Near-Zero Conditions in Environmental Systems

Real environmental systems frequently encounter zero or near-zero conditions that violate the non-zero denominator assumption. Examples include non-detect concentrations in environmental monitoring, zero-emission or depletion states, vanishing reaction rate constants for inert compounds, and boundary conditions involving disappearing environmental compartments [4–6].

For instance, pollutant concentration is defined as

$$C = \frac{m}{V}, \qquad (4)$$

where m is pollutant mass and V is the environmental volume. While small values of V may correspond to high concentrations, the case $V = 0$ produces

$$C = \frac{m}{0}, \qquad (5)$$

which is mathematically undefined. Nevertheless, environmental interpretations sometimes describe such situations as representing "extreme" or "infinite" concentrations, despite the absence of any physical system with zero environmental volume [4,5].

Similar contradictions arise in air–water partitioning. Henry's law is commonly written as

$$H = \frac{P}{C}, \qquad (6)$$

where P is the partial pressure of a compound in air and C is its aqueous concentration. When $P = 0$, Equation (6) becomes undefined, yet this condition is sometimes loosely interpreted as implying unbounded solubility, even though Henry's law is explicitly defined only for positive pressures [9].

2.3 Division by Zero in Environmental Kinetics and Exposure Models

Atmospheric persistence is typically described using a first-order lifetime expression

$$\tau = \frac{1}{k}, \qquad (7)$$

where k is the reaction rate constant. For very small values of k, compounds are described as long-lived. However, when $k = 0$, Equation (7) yields

$$\tau = \frac{1}{0}, \qquad (8)$$

which is undefined. Despite this, the literature occasionally refers to such species as having "infinite lifetime," even though infinite persistence is not physically realizable in atmospheric systems [6].

Human exposure and risk models exhibit similar behavior. Exposure dose is often expressed as

$$D = \frac{I\,t}{M}, \qquad (9)$$

where I is intake rate, t is exposure time, and M is body mass. While $t = 0$ correctly yields zero dose, normalized exposure or risk metrics frequently introduce ratios in which zero exposure duration or zero intake produces undefined expressions. Regulatory guidelines explicitly caution against evaluating such models under zero-exposure conditions, recognizing the mathematical breakdown involved [7,10].

2.4 Beyond Division: Zero in Multiplication, Addition, and Subtraction

The mathematical difficulties observed in environmental models are not limited to division by zero. Zero-valued quantities also appear implicitly in multiplication, addition, and subtraction operations within environmental balance equations.

For example, mass balance equations often include additive terms of the form

$$M_{\text{total}} = M_{\text{in}} + M_{\text{out}} + M_{\text{react}}, \qquad (10)$$

where zero terms are commonly treated as neutral contributors. However, when zero represents the absence of a physical pathway rather than a numerical quantity, the operation itself becomes non-representative of environmental reality. Similar issues arise in multiplicative transport or reaction terms when coefficients or state variables vanish entirely.

Traditional environmental modeling does not explicitly distinguish between zero as a numerical value and zero as an indicator of non-existence of a physical process. As a result, algebraic operations may be formally applied even when the underlying physical meaning has collapsed.

2.5 Zero-Centric Arithmetic as a Foundational Framework

Zero-Centric Arithmetic provides a unified mathematical framework for addressing these inconsistencies by redefining the role of zero across all fundamental arithmetic operations [1–3]. Within this framework, expressions involving division by zero are classified as non-operations rather than extreme numerical outcomes. More broadly, zero is interpreted as signaling the absence of an operational domain, not as a value that can always participate in algebraic manipulation.

Formally, for any non-zero quantity A,

$$\frac{A}{0} \qquad (11)$$

is not interpreted as a limit or infinity, but as a boundary at which the governing model ceases to be valid [1]. This interpretation extends consistently to multiplication, addition, and subtraction when zero represents the absence of a physical process rather than a measurable magnitude [2,3].

Applying this framework to environmental engineering clarifies that undefined expressions in concentration, partitioning, lifetime, and exposure models represent mathematical collapse points rather than physically meaningful extremes. Zero-Centric Arithmetic thus provides a rigorous theoretical foundation for identifying the operational limits of environmental models and avoiding misinterpretation of zero-boundary conditions.

2.6 Positioning of the Present Study

Building on the Zero-Centric Arithmetic framework [1–3] and the classical environmental modeling literature [4–10], the present study applies zero-centric reasoning to environmental pollutant modeling at zero boundaries. Rather than modifying individual equations ad hoc, the study adopts a unified arithmetic reinterpretation that spans division, multiplication, addition, and subtraction involving zero.

This approach establishes a consistent mathematical basis for environmental modeling under boundary conditions, aligns algebraic formulations with physically observable systems, and resolves long-standing contradictions associated with undefined expressions in environmental engineering.

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3. Mathematical Framework of Zero-Centric Arithmetic in Environmental Pollutant Modeling

3.1 Definition of the Non-Operation Concept

In classical arithmetic, the four fundamental operations (addition, subtraction, multiplication, and division) are defined over the real numbers under specific conditions. These conditions are violated when zero appears in contexts where it represents physical absence rather than numerical magnitude. **Zero-Centric Arithmetic** formalizes this distinction through the concept of a **non-operation**.

A non-operation is defined as follows:

If a mathematical operation depends on a quantity that represents a physical operational condition, and that condition is equal to zero, then the operation itself is classified as a **non-operation** and does not yield a numerical result.

In particular, for any real quantity $A \neq 0$:

$$\frac{A}{0} \notin \mathbb{R}, \qquad (12)$$

and this expression is not interpreted as infinity, divergence, or a limiting value, but as an operational collapse of the mathematical model.

3.2 Division by Zero as a Model Collapse Point in Environmental Systems

Division is widely used in environmental engineering models to relate physical quantities to volume, time, or rate parameters. The general form

$$f = \frac{A}{B}, \qquad (13)$$

implicitly assumes that $B > 0$. However, environmental boundary conditions frequently produce cases where $B = 0$, including:

- zero environmental volume,
- non-detect concentrations,
- zero reaction rate constants,
- zero partial pressures.

Under these conditions, the model reduces to

$$f = \frac{A}{0}, \qquad (14)$$

which does not represent an extreme environmental state. Instead, it indicates that the mathematical relationship has lost its physical domain of validity. Within the Zero-Centric framework, Equation (14) is classified as a **non-operation**, signaling the collapse of the environmental model rather than the emergence of an infinite quantity.

3.3 Multiplication by Zero and the Absence of Physical Pathways

Multiplication is commonly used in environmental models to represent mass transfer, reaction rates, and fluxes, such as

$$F = k \cdot C, \qquad (15)$$

where k is a transfer or reaction coefficient and C is concentration.

In classical arithmetic, if $k = 0$, then

$$F = 0. \qquad (16)$$

Zero-Centric Arithmetic distinguishes between two fundamentally different cases:

1. $k = 0$ as a measurable numerical value,
2. $k = 0$ as an indicator of **absence of a physical pathway**.

In the second case, Equation (16) does not represent a zero-valued flux, but rather the non-existence of the process itself. Consequently, the multiplication operation loses physical meaning and is reclassified as a **non-operation**.

3.4 Addition and Subtraction with Zero in Mass Balance Equations

Addition and subtraction are central to environmental mass balance formulations, such as

$$M(t+\Delta t) = M(t) + M_{\text{in}} - M_{\text{out}} - M_{\text{loss}}, \qquad (17)$$

where zero-valued terms are typically treated as neutral elements.

Zero-Centric Arithmetic distinguishes between:

- zero as a numerical quantity, and
- zero as an indicator of absence of a physical source or sink.

If $M_{\text{in}} = 0$because no physical inflow exists, then its inclusion in the equation represents a formal algebraic step without a corresponding physical operation. In such cases, the addition or subtraction is considered **operationally null**, indicating that no physical process is occurring rather than that a numerical zero has been added or removed.

3.5 Unified Zero-Centric Interpretation of the Four Operations

Zero-Centric Arithmetic provides a unified interpretation of zero across the four fundamental operations:

- **Division by zero**: operational collapse ⟶ non-operation
- **Multiplication by physically absent zero**: absence of process ⟶ non-operation
- **Addition with physically absent zero**: no state change ⟶ formal operation only
- **Subtraction with physically absent zero**: no removal process ⟶ formal operation only

In this framework, zero is interpreted as an indicator of **absence of an operational domain**, not as a universally admissible numerical operand.

3.6 Application to Environmental Pollutant Modeling

When applied to environmental pollutant models, the Zero-Centric framework leads to several key consequences:

1. Undefined expressions identify model breakdown, not extreme environmental behavior.
2. Infinite numerical outputs signal mathematical misuse rather than physical reality.
3. Zero-boundary conditions must be treated as domain limits, not computable values.

This approach enables the construction of environmental models that remain consistent with physical observability and prevents the propagation of non-physical infinities in analytical and numerical simulations.

3.7 Section Summary

This section has established the mathematical foundation of Zero-Centric Arithmetic as a unified framework for redefining the four fundamental operations in the presence of zero. By classifying division, multiplication, addition, and subtraction involving physically absent zero as non-operational cases, the framework provides a rigorous basis for resolving recurring contradictions in environmental pollutant modeling.

This formulation prepares the ground for the next section, which will demonstrate **environmental engineering case studies** illustrating the practical differences between classical and Zero-Centric interpretations.

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4. Environmental Engineering Case Studies

4.1 Pollutant Concentration at Zero Environmental Volume

In environmental engineering, pollutant concentration is defined as

$$C = \frac{m}{V}, \qquad (18)$$

where $m$is the pollutant mass and $V$is the volume of the environmental compartment. For very small values of V, Equation (18) predicts large concentration values. However, when the boundary condition $V = 0$is reached, the expression becomes

$$C = \frac{m}{0}, \qquad (19)$$

which is mathematically undefined.

Classical interpretations often describe this condition as an "infinite concentration." Under the Zero-Centric framework, Equation (19) is identified as a **non-operation**, indicating that the concept of concentration is undefined in the absence of an environmental medium. The result does not describe an extreme pollution event but rather the collapse of the concentration model itself.

4.2 Henry's Law at Zero Partial Pressure

Air–water partitioning is commonly described using Henry's law:

$$H = \frac{P}{C}, \qquad (20)$$

where $P$is the partial pressure in air and $C$is the aqueous concentration. At zero partial pressure ($P = 0$), Equation (20) reduces to

$$H = \frac{0}{C}. \qquad (21)$$

While Equation (21) evaluates to zero numerically, the inverse formulation used in solubility interpretations,

$$C = \frac{P}{H}, \qquad (22)$$

becomes undefined when both $P = 0$ and H is treated as constant. Zero-Centric Arithmetic classifies such boundary evaluations as non-operational, clarifying that Henry's law is not valid at zero-pressure conditions rather than implying infinite or anomalous solubility.

4.3 Soil–Water Partitioning at Non-Detect Concentrations

Soil–water partitioning is often modeled using

$$K_d = \frac{C_s}{C_w}, \qquad (23)$$

where C_s is the concentration in soil and C_w is the aqueous concentration. For hydrophobic compounds, C_w may fall below detection limits. Substituting $C_w = 0$ yields

$$K_d = \frac{C_s}{0}. \qquad (24)$$

Traditional interpretations may describe this as "extreme" or "infinite" sorption. In contrast, the Zero-Centric framework recognizes Equation (24) as a non-operation, indicating that partitioning cannot be defined when one phase contains no measurable contaminant.

4.4 Atmospheric Lifetime at Zero Reaction Rate

Atmospheric lifetime is defined by

$$\tau = \frac{1}{k}, \qquad (25)$$

where k is the reaction rate constant. For very small k, pollutants are described as long-lived. However, when $k = 0$,

$$\tau = \frac{1}{0}, \qquad (26)$$

which is undefined.

Rather than interpreting Equation (26) as infinite lifetime, Zero-Centric Arithmetic identifies this condition as the absence of a valid kinetic pathway. The lifetime model collapses because the physical process it describes no longer exists.

4.5 Human Exposure Models at Zero Duration or Intake

Human exposure dose is often expressed as

$$D = \frac{I \cdot t}{M}, \qquad (27)$$

where I is intake rate, t is exposure duration, and M is body mass. While $t = 0$ yields $D = 0$, normalized exposure or risk indices often involve ratios that become undefined at zero exposure.

Under the Zero-Centric framework, such expressions are treated as non-operations, emphasizing that risk cannot be computed when exposure does not physically occur.

4.6 Engineering Implications

Across these case studies, Zero-Centric Arithmetic consistently reclassifies undefined expressions as indicators of model collapse rather than extreme environmental behavior. This distinction:

1. Prevents misinterpretation of boundary conditions,
2. Improves numerical stability in simulations,
3. Clarifies the operational limits of environmental equations,
4. Aligns mathematical results with physical observability.

4.7 Section Summary

The case studies demonstrate that zero-boundary conditions arise naturally in environmental engineering practice. Applying Zero-Centric Arithmetic ensures that such conditions are handled as non-operational limits, restoring consistency between mathematical models and real environmental systems.

5. Discussion

5.1 Reinterpreting Zero-Boundary Results in Environmental Models

The case studies presented in Section 4 reveal a consistent structural issue across environmental engineering models: whenever a zero-boundary condition is reached, the corresponding mathematical formulation loses operational validity. Classical interpretations often attempt to preserve the equation by assigning physical meaning to undefined expressions, typically in the form of infinite concentration, infinite lifetime, or infinite partitioning.

Zero-Centric Arithmetic demonstrates that such interpretations are mathematically unjustified and physically misleading. An expression of the form

$$\frac{A}{0} \qquad (28)$$

does not represent an extreme environmental state but instead signals that the governing equation has exceeded its domain of applicability. Recognizing this distinction shifts the interpretation of zero-boundary results from physical divergence to model collapse.

5.2 Implications for Numerical Simulation and Model Stability

In computational environmental modeling, division-by-zero conditions often lead to numerical instability, overflow, or the propagation of non-physical infinite values. These artifacts can significantly distort simulation outcomes, particularly in long-term fate and transport models or risk assessment tools.

By classifying zero-boundary expressions as non-operations, the Zero-Centric framework provides a principled mechanism for handling such cases. Rather than forcing numerical evaluation, the model can explicitly terminate or flag the computation at the collapse point. This approach enhances numerical robustness and prevents misleading outputs from being interpreted as valid environmental predictions.

5.3 Domain Awareness and Model Validity

A central contribution of the Zero-Centric approach is the explicit enforcement of domain awareness in environmental equations. Traditional models often rely on implicit assumptions regarding the positivity of volumes, concentrations, and rates. When these assumptions fail, the equations continue to be applied without formal acknowledgment of invalidity.

Zero-Centric Arithmetic makes these assumptions explicit by treating zero as a boundary marker rather than a permissible operand. This perspective clarifies that environmental equations are valid only within specific operational domains, and that extending them beyond those domains produces non-physical results.

5.4 Unified Treatment of the Four Operations

Unlike approaches that focus solely on division by zero, the Zero-Centric framework extends consistently to multiplication, addition, and subtraction involving physically absent zero. This unified treatment is particularly important in environmental engineering, where mass balance equations, transport terms, and kinetic expressions often combine multiple operations within a single model.

By distinguishing between numerical zero and physical absence, Zero-Centric Arithmetic avoids the conflation of mathematical formality with physical reality. This distinction improves conceptual clarity and ensures that mathematical operations reflect actual environmental processes.

5.5 Regulatory and Engineering Relevance

Environmental regulations and engineering decision-making frequently rely on model outputs for compliance assessment, risk evaluation, and remediation design. Misinterpreting undefined expressions as extreme values may lead to overly conservative or physically unrealistic conclusions.

The Zero-Centric framework supports more defensible regulatory interpretation by clearly identifying when a model result reflects mathematical breakdown rather than environmental hazard. This distinction can improve transparency in environmental reporting and reduce misinterpretation of boundary-condition scenarios.

5.6 Limitations and Scope of the Present Framework

While Zero-Centric Arithmetic resolves fundamental inconsistencies at zero boundaries, it does not replace classical environmental models within their valid domains. Instead, it complements existing formulations by defining their operational limits.

The framework is not intended to eliminate uncertainty or measurement limitations, nor to redefine physical laws. Its role is strictly mathematical and interpretive: to prevent invalid operations from being misrepresented as physical phenomena.

5.7 Discussion Summary

The discussion demonstrates that zero-boundary contradictions in environmental engineering arise from extending algebraic models beyond their domains of validity. Zero-Centric Arithmetic provides a coherent and unified reinterpretation of these cases, reclassifying undefined expressions as non-operations rather than extreme environmental states.

This shift has significant implications for model interpretation, numerical stability, regulatory application, and theoretical clarity. By aligning mathematical operations with physical observability, the Zero-Centric framework strengthens the logical foundation of environmental engineering models.

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6. Conclusion and Future Work

6.1 Conclusion

This study has demonstrated that zero-boundary conditions in environmental engineering models do not represent extreme or unbounded physical phenomena, but rather indicate points at which mathematical formulations lose their operational validity. Classical interpretations that describe such conditions as infinite concentration, infinite solubility, infinite partitioning, or infinite atmospheric lifetime arise from extending algebraic expressions beyond their domains of applicability.

By introducing and applying the Zero-Centric Arithmetic framework, the paper reclassifies expressions involving zero—across division, multiplication, addition, and subtraction—as non-operations when zero represents physical absence rather than numerical magnitude. This reinterpretation resolves long-standing conceptual contradictions in environmental pollutant modeling and restores consistency between mathematical expressions and physically observable environmental systems.

The case studies presented illustrate that undefined expressions are not environmental extremes, but model collapse points that must be explicitly recognized. Treating these points correctly improves numerical stability, prevents the propagation of non-physical infinities, and clarifies the valid operational domains of environmental equations. As a result, the Zero-Centric framework strengthens the theoretical foundations of environmental engineering models and enhances their interpretability in both scientific and regulatory contexts.

6.2 Future Work

Future research may extend the Zero-Centric framework in several important directions. One area of development involves integrating zero-centric logic into numerical solvers and environmental simulation software, allowing models to explicitly detect and manage non-operational states rather than forcing numerical evaluation. Such integration could significantly improve the robustness of long-term fate and transport simulations.

Another promising direction lies in the application of Zero-Centric Arithmetic to coupled multi-media models, including fugacity-based systems, watershed-scale transport models, and atmospheric–soil–water interaction frameworks. These models frequently encounter near-zero or zero-valued parameters, making them natural candidates for zero-centric domain enforcement.

Further work may also explore the implications of zero-centric reasoning in regulatory risk assessment, particularly in handling non-detect data, zero-exposure scenarios, and boundary-condition reporting. Developing standardized guidelines for identifying and reporting non-operational model states could improve transparency and consistency in environmental decision-making.

Finally, the conceptual scope of Zero-Centric Arithmetic may be extended beyond environmental engineering to other applied fields——such as chemical kinetics, energy systems, and computational modeling——where zero-boundary conditions produce similar mathematical and interpretive challenges. These extensions would further establish zero-centric reasoning as a general mathematical framework for managing operational boundaries in real-world systems.

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