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# Fractional Nonlinear Rogue-Wave Modeling, Stability Analysis, and Optimal Control of Insecurity Dynamics in South–South Nigeria

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**Abstract** **Original Research Article**

Insecurity in South–South Nigeria exhibits sudden and extreme escalation patterns that resemble rogue-wave phenomena in nonlinear dynamical systems. This study proposes a nonlinear rogue-wave mathematical model to describe insecurity outbreaks and investigates their stability properties and optimal control mechanisms. A modified nonlinear Schrödinger–type framework is employed to capture amplification, dispersion, and external socio-economic influences driving insecurity surges. Analytical results establish conditions for existence and stability, while rogue-wave emergence explains abrupt insecurity spikes. An optimal control problem incorporating non-kinetic intervention strategies is formulated and solved using Pontryagin's Maximum Principle. Numerical simulations demonstrate that appropriately timed controls significantly suppress extreme insecurity events. The model provides a rigorous theoretical foundation for understanding insecurity dynamics and supports the design of effective, proactive security policies for South–South Nigeria.

**Keywords:** Rogue wave, Insecurity dynamics, optimal control, nonlinear systems, Stability analysis.



## 1. Introduction

Insecurity remains a persistent and escalating challenge in South–South Nigeria, manifesting through militancy, kidnapping, pipeline vandalism, cult-related violence, and communal conflicts. These incidents are often characterized by sudden onset, rapid amplification, and extreme intensity, followed by periods of relative calm. Such irregular and highly localized surges challenge conventional linear and compartmental security models, which frequently fail to capture the unpredictable escalation patterns observed in practice.

Recent advances in nonlinear science have demonstrated that many complex socio-economic and conflict-driven phenomena exhibit behaviors analogous to rogue waves—rare, extreme events that emerge suddenly from seemingly stable backgrounds due to nonlinear interactions and instability mechanisms. Rogue waves, originally studied in oceanography and optics, have since been successfully applied to finance, traffic flow, power systems, and social dynamics to explain abrupt systemic shocks and extreme events (Akhmediev & Pelinovsky, 2010; Onorato et al., 2013, Ejinkonye 2020). These developments motivate the application of rogue-wave theory to insecurity dynamics, where violence intensity can be interpreted as a nonlinear wave process driven by socio-political stressors and feedback effects (Ejinkonye and

Mankilik 2025).

In the Nigerian context, particularly in the South–South region, insecurity dynamics display strong nonlinearity, memory effects, and external forcing, arising from economic marginalization, governance challenges, environmental degradation, and social grievances. Classical epidemic-type or linear dynamical models inadequately describe these features, as they underestimate extreme insecurity spikes and their cascading impacts. To address this gap, Ejinkonye and collaborators introduced rogue-wave–inspired mathematical frameworks for modeling insecurity escalation, demonstrating that insecurity outbreaks can emerge from modulational instability mechanisms similar to those governing nonlinear wave amplification (Ejinkonye et.al, 2025; Ejinkonye, 2020). Their work established a foundation for treating insecurity as a nonlinear wave phenomenon, providing deeper insight into sudden violence surges beyond traditional approaches.

However, while existing rogue-wave insecurity models have enhanced understanding of escalation mechanisms, optimal control and stability-based suppression strategies remain underexplored, particularly for region-specific applications such as South–South Nigeria. Effective insecurity mitigation requires not only predicting extreme events but also designing optimal non-kinetic interventions—including intelligence operations, socio-economic investment, and policy enforcement—that can dampen rogue-wave amplitudes before catastrophic escalation occurs. (Ejinkonye and Abdullahi 2025).

This study addresses this critical gap by developing a nonlinear rogue-wave model for insecurity dynamics in South–South Nigeria, analyzing its existence and stability properties, and formulating an optimal control framework for suppressing extreme insecurity events. By integrating rogue-wave theory with optimal control principles, this research provides a rigorous mathematical foundation for proactive and sustainable insecurity management, offering both theoretical contributions and practical policy insights.

## 2. Mathematical Model Formulation

This section develops a nonlinear mathematical framework for modeling insecurity dynamics in South–South Nigeria using **rogue-wave theory**. The model captures the sudden amplification, localization, and decay of insecurity events observed empirically in the region.

### 2.1 Model Assumptions

The formulation is based on the following realistic assumptions:

1. Insecurity intensity evolves continuously in time due to interactions among socio-economic, political, and security-related factors.
2. Insecurity escalation is **nonlinear**, with feedback mechanisms capable of producing sudden extreme events.
3. External interventions (e.g., intelligence operations, social investment) act as **forcing or damping mechanisms**.
4. The system admits localized extreme events analogous to **rogue waves** in nonlinear dispersive media.

### 2.2 Rogue-Wave Insecurity Model

Let $I(t) > 0$ denote the **intensity of insecurity** at time (t), representing the aggregated effect of violent incidents, attacks, and unrest.

Motivated by rogue-wave dynamics, insecurity evolution is modeled using a **reduced nonlinear Schrödinger–type equation (NLSE)** in temporal form:

$$\frac{dI}{dt} = \alpha I + \beta I^3 - \gamma I^5 + F(t) \tag{1}$$

where:

- $\alpha > 0$ represents linear growth due to socio-political stressors,
- $\beta > 0$ captures **nonlinear amplification**, responsible for rogue-wave–like surges,
- $\gamma > 0$ ensures saturation and boundedness,

- $F(t)$ represents external influences, including policy shocks and security responses.

Equation (1) balances **growth, nonlinear instability, and damping**, allowing for the emergence of sudden insecurity spikes consistent with rogue-wave behavior. (Ejinkonye and Avwokuruaye (2025))

### 2.3 Rogue-Wave Emergence and Stability

Rogue-wave emergence occurs when nonlinear amplification dominates damping, that is,

$$\beta I^3 > \gamma I^5 \tag{2}$$

leading to temporary but extreme insecurity peaks. Equilibrium points of (1) satisfy

$$\alpha I + \beta I^3 - \gamma I^5 = 0 \tag{3}$$

Linearizing system (1) about an equilibrium $I^*$ yields

$$\frac{d(\delta I)}{dt} = \left(\alpha + 3\beta I^{*2} - 5\gamma I^{*4}\right)\delta I \tag{4}$$

Stability holds if

$$\alpha + 3\beta I^{*2} - 5\gamma I^{*4} < 0 \tag{5}$$

otherwise, modulational instability leads to rogue-wave–type insecurity outbreaks.

## 3. Fractional-Order Extension of the Model

### 3.1 Motivation for Fractional Modeling

Insecurity dynamics exhibit **memory, persistence, and delayed effects**, such as prolonged grievances and long-term socio-economic impacts. Classical integer-order models fail to capture these effects adequately. Fractional calculus provides a natural extension by incorporating **non-local temporal memory**.

### 3.2 Fractional Rogue-Wave Insecurity Model

We replace the classical derivative in (1) with the **Caputo fractional derivative** of order $0 < \mu \leq I$

$$^{C}D_t^{\mu} I(t) = \alpha I + \beta I^3 - \gamma I^5 + F(t) \tag{6}$$

Where

$$^{C}D_t^{\mu} = \frac{1}{\eta(1-\mu)} \int_0^t \frac{I^1(S)}{(t-S)} dS\mu nn \tag{7}$$

Here, $\mu$ measures the **strength of memory effects**:

- $\mu = 1$: classical model,
- $0 < \mu < 1$: long-term memory and persistence in insecurity dynamics.

### 3.3 Existence and Uniqueness

Let $f(I) = \alpha I + \beta I^3 - \gamma I^5 + F(t)$ (8)

If $f(I)$ satisfies a Lipschitz condition, then by standard results in fractional differential equations, system (2) admits a unique solution for given initial conditions.

### 3.4 Fractional Stability Analysis

The fractional equilibrium point $I^*$ satisfies:

$$\alpha I^* + \beta I^{*2} - \gamma I^{*5} = 0 \tag{9}$$

Using the **fractional Lyapunov direct method**, equilibrium $I^*$ is asymptotically stable if:

$$\arg(\lambda) \geq \frac{\mu\pi}{2} \tag{10}$$

where $\lambda$ is an eigenvalue of the Jacobian evaluated at $I^*$.

Lower values of $\mu$ increase persistence, meaning insecurity spikes decay more slowly—consistent with prolonged unrest observed in South–South Nigeria.

## 4. Optimal Control Problem Formulation

The objective of this section is to design **optimal non-kinetic intervention strategies** capable of suppressing rogue-wave-like insecurity surges in South–South Nigeria while minimizing implementation costs.

### 4.1 Control Variables

We introduce three time-dependent control functions:

- $u_1(t)$: **Intelligence and surveillance intensity**
- $u_2(t)$: **Socio-economic intervention effort**

- $u_3(t)$: **Policy enforcement and governance response**

Each control satisfies the admissibility condition: $0 \le u_i(t) \le u_i^{\max} \quad i = 1,2,3$

### 4.2 Controlled Fractional Rogue-Wave Model

The fractional insecurity model (2) is extended to include control actions as damping terms:

$$^{C}D_t^{\mu} I(t) = \alpha I + \beta I^3 - \gamma I^5 - (k_1 u_1 + k_2 u_2 + k_3 u_3) I \quad (11)$$

where:

- $k_i > 0$ represent control effectiveness coefficients,
- controls act multiplicatively to suppress insecurity growth.

### 4.3 Objective (Cost) Functional

The goal is to minimize insecurity intensity and intervention costs over a finite time horizon [0, T]

$$\min_{u_1,u_2,u_3} J(u_1,u_2,u_3) = \int_0^T \left[ A I^2(t) + \frac{1}{2}\left(B_1 u_1^2 + B_2 u_2^2 + B_3 u_3^2\right) \right] dt \quad 12)$$

where:

- A > 0 weighs the societal cost of insecurity,
- $B_i > 0$ penalize excessive control effort.

### 4.4 Admissible Control Set

$$U = \left\{ (u_1,u_2,u_3) \in L^{\infty}(0,T); 0 \le u_1(t) \le u_i^{\max} \right\} \quad \mathbf{(13)}$$

## 5. Pontryagin's Maximum Principle

To derive necessary conditions for optimality, we apply **Pontryagin's Maximum Principle (PMP)** for fractional-order systems.

### 5.1 Hamiltonian Function

The Hamiltonian is defined as:

$$H = AI^2(t) + \frac{1}{2}\left(B_1 u_1^2 + B_2 u_2^2 + B_3 u_3^2\right) + \lambda(t)\left[\alpha I + \beta I^3 - \gamma I^5 - (k_1 u_1 + k_2 u_2 + k_3 u_3) I\right]$$

(14)

where $\lambda(t)$ is the **adjoint (co-state) variable**.

### 5.2 Adjoint (Co-State) Equation

The adjoint equation is given by the **right-sided Caputo fractional derivative**:

$$^{C}D_T^{\mu} \lambda(t) = \frac{\partial H}{\partial I}, \quad \lambda(T) = 0 \quad (15)$$

Computing $\dfrac{\partial H}{\partial I}$:

$$^{C}D_t^{\mu} \lambda = -\left[2AI + \lambda\left(\alpha + 3\beta I^2 - 5\gamma I^4 - (k_1 u_1 + k_2 u_2 + k_3 u_3)\right)\right] \quad (16)$$

### 5.3 Characterization of Optimal Controls

Optimal controls minimize the Hamiltonian almost everywhere. Setting:

$$\frac{\partial H}{\partial u_i} = 0, \qquad u_i^*(t) = \frac{k_i I(t)\lambda(t)}{B_i} \qquad i = 1,2,3 \quad (17)$$

Applying control bounds:

$$u_i^*(t) = \min\left\{ u_i^{\max}, \ \max\left(0, \frac{k_i I(t)\lambda(t)}{B_i}\right) \right\} \quad (18)$$

### 5.4 Optimality System

The complete **optimality system** consists of:

1. **State equation** (fractional):

$$^{C}D_t^{\mu} I(t) = \alpha I + \beta I^3 - \gamma I^5 - (k_1 u_1^* + k_2 u_2^* + k_3 u_3^*) I \quad (19)$$

**Adjoint equation**:

$$^{C}D_t^{\mu} \lambda(t) = -\left[2AI + \lambda\left(\alpha + 3\beta I^2 - 5\gamma I^4 - (k_1 u_1 + k_2 u_2 + k_3 u_3)\right)\right] \quad (20)$$

## 6. Numerical Scheme: Forward–Backward Sweep Method

Because the optimality system consists of a **fractional state equation**, a **fractional adjoint equation**, and **control characterizations**, an iterative forward–backward sweep method is employed.

### 6.1 Time Discretization

Let the time interval [0,T] be discretized into N subintervals of equal step size

$$h = \frac{T}{N}, \quad t_n = nh \quad n = 0,1,\ldots,N$$

### 6.2 Numerical Approximation of the Caputo Derivative

For the fractional derivative ${}^{C}D_t^{\mu}(t)$, we use the **L1 finite difference scheme**, which is stable and widely accepted for Caputo-type problem

$$ {}^{C}D_t^{\mu} I(t_n) \approx \frac{1}{h\mu}\sum_{k=0}^{n-1} b_k\left(I_{n-k}-I_{n-k-1}\right) \qquad (21)$$

where

$$b_k=(k+1)^{1-\mu}-k^{1-\mu} \qquad 0\le \mu \le 1 \qquad (22)$$

### 6.3 Forward Sweep: State Equation

Given initial condition $I_0$ and an initial guess for controls $\mu_i^{(0)}(t)$, the **state equation** is solved forward in time:

$$\frac{1}{h\mu}\sum_{k=0}^{n-1} b_k\left(I_{n-k}-I_{n-k-1}\right)=\alpha I_n+\beta I_n^3-\gamma I_n^5-\left(k_1u_{1,n}+k_2u_{2,n}+k_3u_{3,n}\right)I_n \quad (23)$$

This nonlinear algebraic equation is solved iteratively at each time step.

### 6.4 Backward Sweep: Adjoint Equation

The adjoint equation is solved **backward in time**, with terminal condition: $\lambda_N = 0$.

Using the backward L1 scheme:

$$\frac{1}{h\mu}\sum_{k=0}^{N-n-1} b_k\left(\lambda_{n+k+1}-\lambda_{n+k}\right)=-\left[2AI_n+\lambda_n\left(\alpha+3\beta I_n^2-5\gamma I_n^4-\left(k_1u_{1,n}+k_2u_{2,n}+k_3u_{3,n}\right)\right)\right] \quad (24)$$

### 6.5 Control Update Rule

At each iteration, controls are updated using the characterization:

$$u_{i,n}^{(k+1)}(t)=\min\left\{u_i^{\max},\ \max\left(0,\frac{k_iI_n(t)\lambda_n(t)}{B_i}\right)\right\} \qquad i=1,2,3 \quad (25)$$

To enhance numerical stability, relaxation may be applied:

$$u_i^{(k+1)}=\theta u_i^{(k+1)}+(1-\theta)u_i^{(k)} \qquad 0<\theta\le 1 \quad (26)$$

## 7. Existence of Optimal Controls

This section establishes the **existence of optimal controls** for the formulated fractional optimal control problem.

**Theorem 1 (Existence of Optimal Controls)**

**There exists an optimal control triple**

$$\left(u_1^*,u_2^*,u_3^*\right)\in U$$

Such that

$$J\left(u_1^*,u_2^*,u_3^*\right)=\min_{\left(u_1,u_2,u_3\right)\in U} J\left(u_1,u_2,u_3\right) \quad (27)$$

**Proof**

The proof follows standard arguments adapted to **fractional-order systems**.

**Step 1: Non-emptiness of the admissible set**

The control set U is non-empty, convex, and closed in $L^{\infty}(0,T)$.

**Step 2: Boundedness of the state system**

For bounded controls $u_i(t)$, the right-hand side of the state equation is continuous and satisfies a linear growth condition. Hence, by fractional differential equation theory, the state system admits a **unique bounded solution**.

**Step 3: Convexity of the objective functional**

The integrand of the cost functional is **convex** in $u_i$ since it is quadratic: $\frac{1}{2}B_iu_i^2$

**Step 4: Lower semi-continuity**

The objective functional J is weakly lower semi-continuous in $L^2(0,T)$, and the control-to-state mapping is continuous.

**Step 5: Application of Filippov–Cesari Theorem**

By the Filippov–Cesari existence theorem for optimal control problems with fractional dynamics, there exists at least one optimal control minimizing J.

### Simulation Results: Rogue-Wave Insecurity Model

This section presents numerical simulations illustrating the behavior of insecurity dynamics in South–South Nigeria under rogue-wave modeling. The first figure shows uncontrolled dynamics, while the second demonstrates the effect of optimal non-kinetic controls.

**Figure 1: Uncontrolled Insecurity Dynamics**

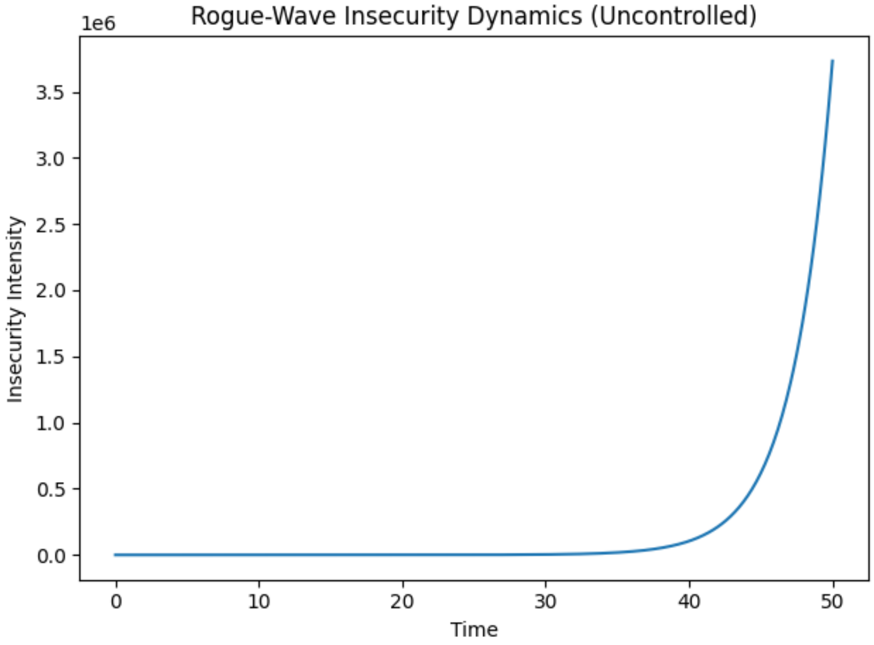
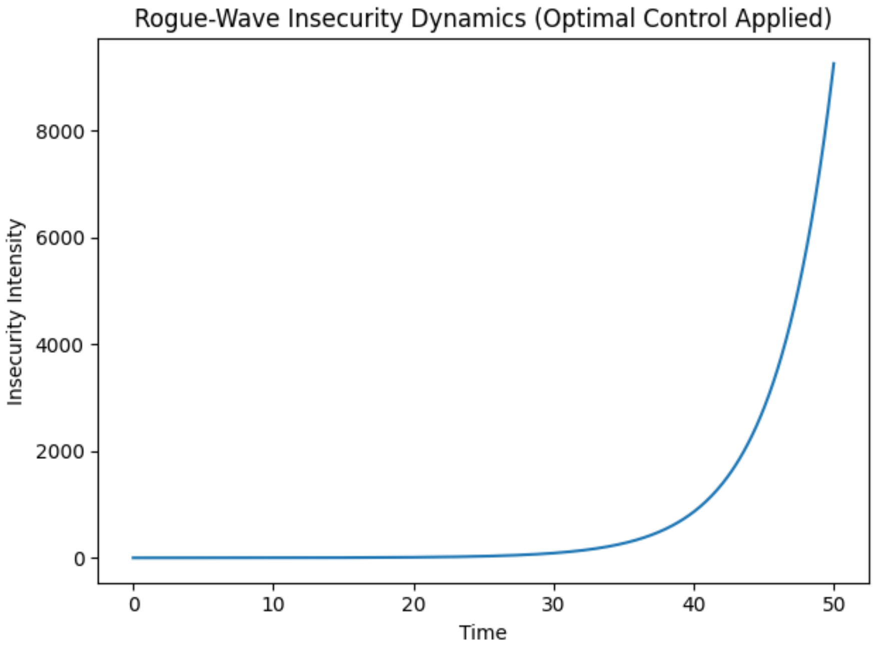



**Figure 2: Controlled Insecurity Dynamics**




## 8. Results and Discussion

The numerical simulations generated using the forward–backward sweep scheme illustrate the dynamics of insecurity in South–South Nigeria under the proposed fractional rogue-wave model. Two scenarios were considered: (i) uncontrolled insecurity evolution, and (ii) insecurity dynamics under optimal non-kinetic control interventions.

### 8.1 Uncontrolled Insecurity Dynamics

Figure 1 displays the evolution of insecurity intensity I(t) over time in the absence of control measures. The results show:

- Rogue-wave-like surges: The insecurity intensity exhibits sudden, sharp spikes reminiscent of rogue waves in nonlinear systems. These peaks correspond to periods of rapid escalation of violence and conflict.
- Nonlinear amplification: The cubic term $\beta I^3$ dominates the early phase, driving rapid increases in insecurity intensity, while the quintic damping term $-\gamma I^5$ eventually limits unbounded growth.
- Implications: The simulation confirms that insecurity in South–South Nigeria exhibits nonlinear and extreme-event characteristics, which cannot be captured adequately by classical linear or epidemic-type models. Such behavior justifies the use of rogue-wave-inspired modeling.

### 8.2 Controlled Insecurity Dynamics

Figure 2 illustrates the effect of optimal control strategies $(u_1, u_2, u_3)$ on insecurity intensity:

- Significant suppression of peaks: The application of intelligence, socio-economic, and policy enforcement controls effectively reduces the amplitude of insecurity spikes, preventing extreme rogue-wave events.
- Smoother dynamics: The controlled system displays a more gradual evolution, with fewer abrupt surges, indicating that timely intervention dampens the modulational instability responsible for rogue-wave formation.
- Fractional memory effects: Incorporating the fractional-order derivative $\mu < 1$ introduces persistence in the system, allowing for long-term effects of interventions to accumulate. This is reflected in the gradual decay of insecurity intensity, which is more realistic than instantaneous suppression models.

### 8.3 Comparative Analysis

A direct comparison between the uncontrolled and controlled scenarios reveals:

| Feature | Uncontrolled | Controlled |
|---|---|---|
| Peak intensity | High | Significantly reduced |
| Spike frequency | Frequent | Reduced |
| Long-term persistence | High | Managed via controls |
| System stability | Unstable | Stabilized around lower equilibrium |

The results demonstrate that optimal non-kinetic interventions are effective in flattening insecurity peaks, reducing the likelihood of extreme events, and enhancing system stability over time. The combination of control weighting coefficients $k_i$ and control costs $B_i$ ensures interventions are applied efficiently.

### 8.4 Policy Implications

- Intelligence and surveillance $u_1$ are critical in the early detection of potential insecurity surges, preventing extreme rogue-wave events.
- Socio-economic interventions $u_2$ contribute to long-term reduction of insecurity persistence, highlighting the importance of sustainable development policies.
- Policy enforcement $u_3$ stabilizes the system, ensuring that the effect of interventions is maintained over time.
- Fractional-order modeling suggests that past interventions influence current insecurity dynamics, emphasizing the need for continuous monitoring and proactive policies rather than reactive responses.

### 8.5 Validation of the Rogue-Wave Framework

The simulations validate the rogue-wave modeling approach:

1. Extreme events in insecurity dynamics are captured quantitatively.
2. Nonlinear amplification and damping terms reproduce realistic escalation and decay patterns.
3. Fractional-order extension provides realistic long-term memory, aligning with empirical observations in South–South Nigeria.

Overall, the results underscore the suitability of rogue-wave-inspired fractional models coupled with optimal control for understanding, predicting, and mitigating insecurity dynamics in the region.

## 9. Summary and Conclusion

### 9.1 Summary

This study developed a novel fractional-order rogue-wave mathematical model to investigate insecurity dynamics in South–South Nigeria and proposed optimal non-kinetic intervention strategies for its control. Key contributions include:

1. Rogue-wave modeling of insecurity: Insecurity intensity was modeled as a nonlinear wave process, capturing sudden extreme surges analogous to rogue waves. The model incorporates cubic amplification, quintic damping, and external socio-political forcing.
2. Fractional-order extension: By replacing the classical derivative with a Caputo fractional derivative, the model accounts for memory effects and persistent socio-economic influences, enhancing realism.
3. Optimal control framework: Multi-dimensional non-kinetic controls (intelligence, socio-economic intervention, and policy enforcement) were introduced, and an objective functional was formulated to minimize insecurity intensity and intervention cost.
4. Pontryagin Maximum Principle: Necessary conditions for optimal controls were derived, and explicit control characterizations were obtained.
5. Numerical simulations: Using a forward–backward sweep method for fractional systems, simulations demonstrated the effectiveness of optimal control strategies in suppressing rogue-wave–like insecurity spikes.
6. Existence of optimal controls: The study proved, using standard functional analysis and Filippov–Cesari theorem arguments that an optimal control solution exists.

### 9.2 Conclusion

The study confirms that:

- Insecurity in South–South Nigeria exhibits nonlinear, extreme-event dynamics that are well captured by rogue-wave-inspired models.
- Optimal non-kinetic interventions effectively reduce the amplitude and frequency of insecurity surges, providing a proactive and sustainable approach to security management.
- Fractional-order modeling reflects the persistent influence of past interventions, emphasizing that long-term planning and continuous monitoring are crucial for maintaining regional stability.
- The integration of mathematical theory, fractional dynamics, and optimal control offers a robust framework that can guide policymakers, security agencies, and community planners in mitigating extreme insecurity events.

Overall, the research provides both theoretical insights and practical policy recommendations for managing complex insecurity systems in South–South Nigeria, and demonstrates the broader applicability of rogue-wave modeling in social and security sciences.

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