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From Deterministic to Stochastic Modelling of Security Threats in Nigeria: A Review and Research Agenda

Timinibife N. Charles[1,*], Dickson E. A. Omorogbe[2], Aniayam B. Okrinya[3]

[1]Department of Mathematics, Faculty of Science, Niger Delta University, Wilberforce Island, Bayelsa State, Nigeria

[2]Department of Mathematics, Faculty of Physical Sciences, University of Benin, Benin City, Edo State, Nigeria

[3]Department of Mathematics, Faculty of Science, Niger Delta University, Wilberforce Island, Bayelsa State, Nigeria

***Corresponding Author:** charlesnoah615@gmail.com

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Abstract

Terrorism, banditry and kidnapping, here called the triple security threat, have become a central obstacle to stability and sustainable development in Nigeria. This paper reviews the concept, causes and existing mathematical models of these threats. We find that the modelling literature is small and almost entirely deterministic, built on systems of ordinary differential equations whose solutions are fixed once parameters and initial conditions are fixed. Security incidents, by contrast, are discrete, rare, clustered and driven by unpredictable human decisions, so a deterministic model can be misleading: it cannot express the chance that a criminal network dies out by itself or flares up despite control. We survey six classical stochastic processes (Markov chain, Wiener process, random walk, Poisson process, Bernoulli process and queueing models) and assess their fitness for security-threat modelling. Using the kidnapping model of Okrinya and Charles [24] as a worked case, we show how its deterministic threshold maps onto a continuous-time Markov chain and a stochastic differential equation, and how a branching-process approximation yields a probability of kidnapping extinction even when the basic reproduction

number exceeds one. We close with four research gaps and a research agenda: an easy-to-use stochastic model, its implementation with pseudo-random and survey data in an intuitionistic fuzzy framework, and an efficient computational procedure.

Keywords: security threat;kidnapping;banditry;terrorism;stochastic modelling;Markov chain;Wiener process;Nigeria

1. Introduction

Insecurity is now one of the most critical obstacles to sustainable development and social stability in Nigeria [21]. In this paper, a *security threat* (ST) means the triple crimes of terrorism, banditry and kidnapping. The three are distinct in motive but overlap in practice: the same armed groups often raid villages, abduct for ransom and use violence for ideological ends.

> **Terrorism** is the deliberate use of violence, intimidation or threats, often against civilians or state institutions, to create fear in pursuit of political, religious or ideological goals [26].
>
> **Banditry** is organised criminal activity such as armed robbery, village raids, cattle rustling and violent attacks, usually by armed groups in rural or semi-urban areas.
>
> **Kidnapping** is the forceful abduction and unlawful detention of persons, usually for ransom, political bargaining or intimidation [1].

Recent incidents show the scale of the problem: the abduction of a High Court judge in Bayelsa State [19], the Palm Sunday attack on Zikke village in Plateau State in which more than 120 people were reported killed [16], the 91 Chibok schoolgirls still missing or in captivity ten years after their abduction [28], and the abduction of 22 people in fresh bandit attacks on Kaduna communities [2].

1.1. Causes of security threats in Nigeria

The literature attributes the triple threat to a common set of drivers: unemployment; poverty; political differences; the "quick-money" syndrome; poor governance and corruption; a weak security system; ethnic and religious conflict; and religious fanaticism. In compartmental models these drivers enter mainly through the recruitment rate into the criminal class, which is why most models conclude that socio-economic measures must accompany enforcement.

1.2. Statement of the problem

Security threats in Nigeria have widened in scope and become ubiquitous despite sustained efforts by government and other stakeholders. Mathematical work on the problem is scanty, and the few available models are deterministic. Yet the phenomenon itself is stochastic: attacks are discrete events, offender numbers are small and fluctuate, and decisions to join, leave or relapse are individual and uncertain. A deterministic model returns a single trajectory and a sharp threshold; it cannot say how likely an outcome is, how widely outcomes vary, or whether a small criminal group may die out by chance. Using a deterministic model for a stochastic phenomenon can therefore be misleading.

1.3. Aim and contribution

The aim of this paper is to lay the groundwork for a robust stochastic model of terrorism, banditry and kidnapping in Nigeria. Its contributions are to:

1. review the deterministic models of security threats and the evidence they provide;
2. assess six classical stochastic processes for their suitability to security-threat dynamics;
3. show, on an existing kidnapping model, how a deterministic formulation extends to a continuous-time Markov chain and a stochastic differential equation, and what new information this yields; and
4. identify research gaps and set out an agenda for an easy-to-use stochastic model implemented with pseudo-random and real survey data.

The rest of the paper is organised as follows. Section 2 reviews deterministic models. Section 3 surveys stochastic processes. Section 4 develops the stochastic extension. Section 5 sets out research gaps and frontiers, and Section 6 concludes.

2. Deterministic models of security threats: a review

Every mathematical model of security threats we found treats the problem deterministically, and most share a compartmental structure borrowed from epidemiology. Offenders play the role of infectives, the general population the role of susceptible, and recruitment into crime the role of transmission.

2.1. The first kidnapping model

Mathematical modelling of kidnapping was introduced by Okrinya [23]. The population N is split into susceptible humans K_s, active kidnappers K_{pa} and kidnapped victims K_{pc}:

$$\frac{dK_s}{dt} = \lambda N + \omega K_{pc} - \gamma K_{pa}\frac{K_s}{N} - \mu K_s - \beta K_{pa}\frac{K_s}{N}. \tag{1}$$

$$\frac{dK_{pa}}{dt} = \gamma K_{pa}\frac{K_s}{N} - \mu K_{pa} - a_1 K_{pa} K_{pc}. \tag{2}$$

$$\frac{dK_{pc}}{dt} = \beta K_{pa}\frac{K_s}{N} - \mu K_{pc} - a_2 K_{pa} K_{pc} - \omega K_{pc}. \tag{3}$$

Here λ is the recruitment rate into the population, γ the rate at which susceptibles are recruited into kidnapping, β the abduction rate, ω the release rate of victims, μ the natural death rate, and a_1 and a_2 are interaction coefficients between kidnappers and victims. The model yields a threshold quantity C_{PN}: kidnapping can be eradicated when $C_{PN} < 1$ and persists when $C_{PN} > 1$. Simulations show all compartments settling to steady states within a few hundred time units.

Okrinya and Consul [25] added a rehabilitated class and recommended rehabilitation as the main remedy. A weakness of that remedy is relapse: rehabilitated kidnappers may return to kidnapping.

2.2. Kidnapping with apprehended kidnappers

To address relapse, Okrinya and Charles [24] proposed apprehension and subsequent removal of kidnappers. The population is split into the vulnerable V, hostages H, active kidnappers Q and apprehended kidnappers A, with $N = V + H + Q + A$:

$$\frac{dV}{dt} = \lambda N + \rho H - \beta \frac{V}{N} Q - \mu V - \theta N^2. \tag{4}$$

$$\frac{dH}{dt} = \alpha\beta \frac{V}{N} Q - (\mu + \delta + \rho) H. \tag{5}$$

$$\frac{dQ}{dt} = (1-\alpha)\beta \frac{V}{N} Q - (\mu + \gamma + \sigma) Q. \tag{6}$$

$$\frac{dA}{dt} = \sigma Q - \mu A. \tag{7}$$

$$\frac{dN}{dt} = (\lambda - \mu) N - \delta H - \gamma Q - \theta N^2. \tag{8}$$

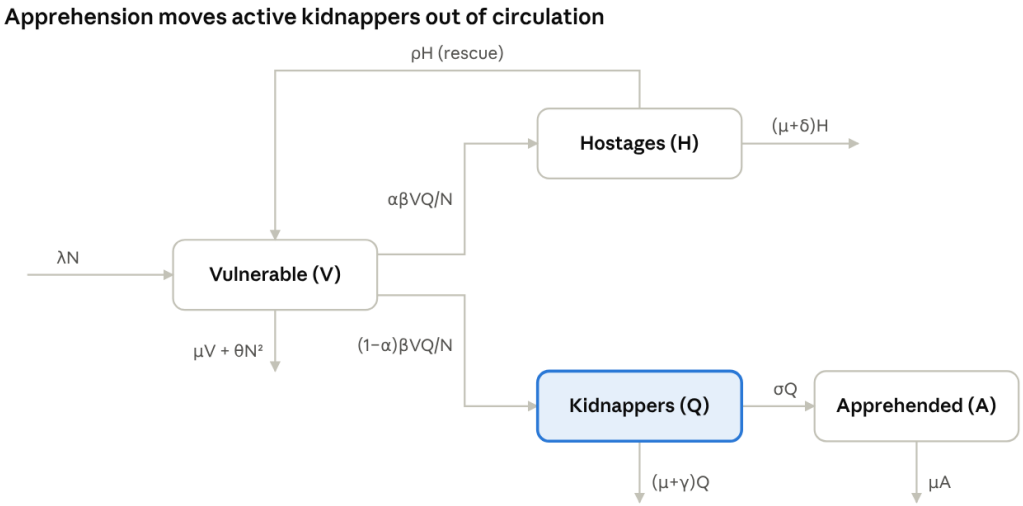


Figure 1: Flow diagram of model (4)–(8). Kidnapping encounters split vulnerable individuals into hostages (fraction α) and new kidnappers (fraction $1-\alpha$); apprehension at rate σ is the control that removes active kidnappers.

Parameter	Description
λ	Recruitment rate into the population
ρ	Rescue rate of hostages
β	Kidnapping contact (recruitment) rate
α	Fraction of kidnapping encounters producing a hostage
μ	Natural death rate
θ	Saturation (crowding) coefficient

Parameter	Description
δ	Death rate of hostages during rescue
γ	Death rate of kidnappers during rescue
σ	Apprehension rate of kidnappers

At the kidnapper-free state $V = N$, so equation (6) gives the basic reproduction number directly:

$$R_0 = \frac{(1-\alpha)\beta}{\mu + \gamma + \sigma}. \tag{9}$$

Kidnapping dies out when $R_0 < 1$ and persists when $R_0 > 1$. Raising the apprehension rate σ lowers R_0 directly. In simulations without control ($R_0 = 12.55$), hostages peaked near 26 before settling near 15, the vulnerable class fell from 100 to about 10, and apprehended kidnappers rose to about 12. With control ($R_0 = 0.7714$), active kidnappers declined from 3 towards zero over 200 time units, hostages fell to near zero, and the vulnerable population grew to about 130. The study concluded that strong law enforcement combined with socio-economic improvement is the most effective strategy.

2.3. Models of banditry and terrorism

Study	Threat	Approach	Main finding
Misal et al. [20]	Terrorism	Compartmental ODE model	Poverty, unemployment and radicalisation drive recruitment; security operations and rehabilitation reduce terrorism; $R_0 < 1$ eliminates it
Baba et al. [5]	Kidnapping	Fractional-order Lotka–Volterra (predator–prey)	Kidnapping depends on victim availability and past activity (memory); interventions stabilise and reduce incidents
Tasiu et al. [30]	Banditry	Compartmental model with repentant bandits	Military operations, rehabilitation and empowerment reduce banditry; recruitment from poverty sustains it
Gambo and Olarewaju [10]	Terrorism	Compartmental ODE model with control	Control measures reduce terrorist populations
Baryamureeba and Tushabe [6]	Crime in fragile states	Agent-based model	Crime spreads through social interaction; policing, governance and development reduce it

2.4. Limitation common to these models

All of these models except the agent-based one are deterministic. Each returns one trajectory for a given set of parameters and a sharp threshold at $R_0 = 1$. None can quantify the probability that a small group of offenders is eliminated by chance, the

spread of outcomes around the mean, or the effect of random shocks such as a sudden ransom payment, a military raid or an economic downturn. These are precisely the features that policy makers need.

3. Classical stochastic processes and their fitness for security threats

A stochastic process is a family of random variables {X(t), t ∈ T} indexed by time. Unlike an ODE solution, each run of a stochastic model produces a different sample path, and the object of study is the distribution of those paths. We review the processes most relevant to security-threat modelling.

3.1. Markov chains

A Markov chain describes a system that moves between states over time, where the probability of the next state depends only on the current state and not on the past [22, 29]. A *state* is a possible condition of the system at a given step, for example the number of active kidnappers in a community. If X_n is the state at step n, the Markov property is

$$P(X_{n+1} = j \mid X_n = i, X_{n-1}, \ldots, X_0) = P(X_{n+1} = j \mid X_n = i). \tag{10}$$

The transition probabilities are collected in the matrix

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix}, \tag{11}$$

$$p_{ij} = P(\text{next state} = j \mid \text{current state} = i), \qquad \sum_{j=1}^{n} p_{ij} = 1.$$

Markov chains are used in queueing and service systems [29], economics and finance, forecasting, computing and artificial intelligence, and crime analysis [22]. Their simplicity, tractability and computational efficiency make them a natural first choice for security threats, where a community or individual can be classified into states such as *vulnerable*, *kidnapped*, *offender* and *apprehended*. In continuous time the chain is specified by transition rates rather than probabilities, which links it directly to compartmental models (Section 4).

3.2. The Wiener process

The Wiener process W(t), or Brownian motion, is a continuous-time process that models completely random, unpredictable change. It is used in physics [9], finance [8], signal processing [27] and control [7]. Its defining properties are:

1. **Initial condition:** $W(0) = 0$.
2. **Independent increments:** for $t_0 < t_1 < \cdots < t_n$, the increments $W(t_1) - W(t_0)$, $\ldots$, $W(t_n) - W(t_{n-1})$ are independent.

3. **Stationary Gaussian increments:** for s, t ≥ 0,

$$W(t+s) - W(s) \sim \mathcal{N}(0, t). \tag{12}$$

4. **Continuous paths:** W(t) is continuous in t but nowhere differentiable, so dynamics are written with the differential $dW(t)$ rather than dW/dt.

A general stochastic differential equation (SDE) driven by W(t) is

$$dX(t) = uX(t)\,dt + \alpha X(t)\,dW(t). \tag{13}$$

where $uX(t)\,dt$ is the deterministic drift and $\alpha X(t)\,dW(t)$ the random fluctuation [18]. Equation (13) is the template for adding environmental noise to any of the deterministic models in Section 2.

3.3. Comparison of classical stochastic processes

Table 1. Summary of classical stochastic processes and their relevance to security-threat modelling.

Process	Typical uses	Advantages	Limitations	Fit for security threats
Markov chain	Queueing, finance, population studies, forecasting, reliability, social science	Simple, intuitive, tractable, computationally efficient	Memoryless; large state spaces; constant transition probabilities; data-hungry	High: states map onto offender and victim classes
Wiener process	Finance, biology, engineering	Tractable; strong theoretical base; universal noise model	Constant volatility; simple structure; hard to estimate from sparse data	High: adds environmental noise to ODE models
Random walk	Finance, physics, ecology, computer science, criminology	Simple, flexible, realistic for uncertainty	Independence assumption; ignores external drivers; poor long-term prediction; fails in non-stationary settings	Medium: suits spatial movement of armed groups
Poisson process	Queueing, networks, reliability, epidemiology, actuarial science	Tractable; good for rare random events; basis for extensions	Independent events; constant rate; variance equals mean; no simultaneous events	High for incident counts, once extended to non-homogeneous or self-exciting forms

Process	Typical uses	Advantages	Limitations	Fit for security threats
Bernoulli process	Statistics, simulation, communications, machine learning, risk	Simple; foundation for other models; easy parameter estimation	Binary outcomes only; independence; constant probability	Low alone; useful for attack/no-attack data
Queueing model	Operations, telecoms, healthcare, transport	Predictive; flexible; supports decisions	Hard for non-Markovian or networked systems; neglects human factors	Medium: suits prosecution and rehabilitation pipelines

Sources: [3, 13, 14, 17, 29].

The Markov chain and the Wiener process are the most promising building blocks. The first captures demographic randomness, the chance events of individual recruitment, abduction and arrest. The second captures environmental randomness, the shocks that move rates up or down for everyone at once. A hybrid of the two is the natural framework for security threats.

4. From deterministic to stochastic: the kidnapping model as a worked case

The deterministic model (4)–(8) can be reformulated stochastically in two complementary ways, and each answers a question the ODE cannot. We use it as a template because its structure is shared by the banditry and terrorism models of Section 2.

4.1. Demographic randomness: a continuous-time Markov chain

Let V(t), H(t), Q(t), A(t) be non-negative integer counts. The state changes by single events whose rates are the terms of (4)–(8). In a short interval Δt, each event occurs with probability rate $\times\, \Delta t + o(\Delta t)$.

Table 2. Events and transition rates of the stochastic kidnapping model.

Event	Change in state	Rate
Recruitment into population	$\mathrm{V} \to \mathrm{V}+1$	$\lambda \mathrm{N}$
Kidnapping producing a hostage	$\mathrm{V} \to \mathrm{V}-1,\ \mathrm{H} \to \mathrm{H}+1$	$\alpha\beta \mathrm{VQ/N}$
Recruitment into kidnapping	$\mathrm{V} \to \mathrm{V}-1,\ \mathrm{Q} \to \mathrm{Q}+1$	$(1-\alpha)\beta \mathrm{VQ/N}$
Rescue of hostage	$\mathrm{H} \to \mathrm{H}-1,\ \mathrm{V} \to \mathrm{V}+1$	$\rho \mathrm{H}$
Hostage death during rescue	$\mathrm{H} \to \mathrm{H}-1$	$\delta \mathrm{H}$
Kidnapper death during rescue	$\mathrm{Q} \to \mathrm{Q}-1$	$\gamma \mathrm{Q}$
Apprehension of kidnapper	$\mathrm{Q} \to \mathrm{Q}-1,\ \mathrm{A} \to \mathrm{A}+1$	$\sigma \mathrm{Q}$
Natural death	$\mathrm{X} \to \mathrm{X}-1,\ \mathrm{X} \in \{\mathrm{V}, \mathrm{H}, \mathrm{Q}, \mathrm{A}\}$	$\mu \mathrm{X}$
Saturation (crowding) loss	$\mathrm{V} \to \mathrm{V}-1$	θN^2

The expected change per unit time of each count reproduces equations (4)–(8), so the

ODE is the mean-field limit of this chain for large populations. Sample paths can be generated exactly with Gillespie's [11] stochastic simulation algorithm.

The chain yields a result the ODE cannot. Near the kidnapper-free state $V \approx N$, each active kidnapper produces a new kidnapper at rate $(1-\alpha)\beta$ and is removed at rate $\mu+\gamma+\sigma$. This is a linear birth–death branching process [3], and the probability that kidnapping dies out starting from Q_0 kidnappers is

$$P_{\text{ext}} \approx \begin{cases} 1, & R_0 \le 1, \\ \left(\dfrac{1}{R_0}\right)^{Q_0}, & R_0 > 1. \end{cases} \tag{14}$$

For the uncontrolled case $R_0 = 12.55$, a single new kidnapper has about an 8% chance of dying out without intervention, while a group of three has about a 0.05% chance. The deterministic model predicts persistence in both cases. The stochastic model shows that early, decisive action against a newly formed group is far more effective than action against an established one, a finding with direct policy value.

4.2. Environmental randomness: a stochastic differential equation

Ransom payments, military operations, elections and economic shocks change the kidnapping rate for the whole population at once. Following Gray et al. [12], we perturb the contact rate as $\beta\ \mathrm{dt} \to \beta\ \mathrm{dt} + \xi\ \mathrm{dB(t)}$, where B(t) is a Wiener process and ξ the noise intensity. Equations (5) and (6) become

$$\begin{aligned} dH = &\left[\alpha\beta\frac{V}{N}Q - (\mu+\delta+\rho)H\right]dt \\ &+ \alpha\xi\frac{V}{N}Q\,dB(t). \end{aligned} \tag{15}$$

$$\begin{aligned} dQ = &\left[(1-\alpha)\beta\frac{V}{N}Q - (\mu+\gamma+\sigma)Q\right]dt \\ &+ (1-\alpha)\xi\frac{V}{N}Q\,dB(t). \end{aligned} \tag{16}$$

with the matching negative term $-\xi(\mathrm{V/N})\mathrm{Q\ dB(t)}$ in dV. Linearising (16) near $V = N$ and applying Itô's formula to ln Q gives the growth rate $(1-\alpha)\beta-(\mu+\gamma+\sigma)-(1-\alpha)^2\xi^2/2$. This suggests a stochastic threshold

$$R_0^S = R_0 - \frac{(1-\alpha)^2\xi^2}{2(\mu+\gamma+\sigma)}. \tag{17}$$

with kidnapping dying out almost surely when $R_0^S < 1$. Since $R_0^S < R_0$, environmental noise can drive kidnapping to extinction even when the deterministic model predicts persistence. A rigorous proof, using a Lyapunov-function argument as in Mao [18] and Gray et al. [12], is part of the research agenda below.

4.3. A hybrid Markov–Wiener framework

The two sources of randomness can be combined. A finite Markov chain r(t) switches the system between security regimes, for example *normal*, *escalation* and *crackdown*, and

in each regime the parameters β, σ and ξ take different values. The resulting regime-switching SDE captures both sudden policy shifts and continuous background noise, and it can be calibrated against incident data. We regard this hybrid as the most promising model class for security threats in Nigeria.

5. Research gaps and frontiers

The review identifies four gaps in the literature:

1. Existing models of security threats in Nigeria are deterministic and cannot capture the phenomenon as a stochastic process.
2. No literature applies a stochastic process to the dynamics of security threats in Nigeria.
3. No model of security threats in Nigeria uses intuitionistic fuzzy variables [4] to handle the vague and partly reliable data typical of crime reporting.
4. No computational framework exists for efficient, simplified computation of such models.

We therefore propose the following research frontiers:

1. Develop an easy-to-use stochastic model, built on the hybrid Markov–Wiener framework of Section 4, that captures the dynamics of terrorism, banditry and kidnapping in Nigeria.
2. Implement the model with pseudo-randomly generated data and with real-life data obtained from a field survey, within an intuitionistic fuzzy framework.
3. Provide an intelligent and efficient computational procedure for simulation, estimation and computation, for example Gillespie simulation for the Markov chain and the Euler–Maruyama scheme [15] for the Stochastic Differential Equation (SDE).

6. Conclusion

The mathematical literature on terrorism, banditry and kidnapping in Nigeria is small and is deterministic. These models have produced useful insights: recruitment driven by poverty and unemployment sustains crime, and a threshold $R_0 = 1$ separates elimination from persistence. But security threats are stochastic, and deterministic models can be misleading in practice.

As a result, this paper proposes a research agenda that adopts a stochastic approach to addressing security threats, because security problems are stochastic rather than deterministic.

We recommend the adoption of easy-to-use stochastic models, in particular a hybrid Markov–Wiener framework, for the analysis of security threats in Nigeria. Future work will develop such a model, calibrate it with pseudo-random and field-survey data in an intuitionistic fuzzy setting, and provide an efficient computational procedure for its implementation.

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