Journal of Hunan University (Natural Sciences)

Vol. 52 No. 11

November 2025

Available online at

https://jonuns.com

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Open Access Article https://doi.org/10.55463/issn.1674-2974.52.11.16

Modeling Dengue Virus Spread Using Differential Equations with Noise Terms to Simulate Transmission Variability

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Article history
Received: November 18, 2025
Revised: December 10, 2025
Accepted: December 17, 2025
Published: December 30, 2025

Abstract: In this paper, we propose a modeling framework to analyze the spread of the dengue virus in human populations by explicitly incorporating noise terms to simulate variability in transmission. A system of differential equations is employed to represent the transmission dynamics of the virus, and the effects of stochastic perturbations on these dynamics are systematically investigated. The effectiveness and robustness of the proposed model are demonstrated through numerical simulations that examine how the inclusion of noise influences the reliability and accuracy of transmission predictions. The results highlight the importance of accounting for variability in transmission rates and provide valuable insights into the behavior of dengue virus spread under realistic conditions. In particular, this study addresses a key limitation of traditional deterministic dengue models by introducing noise terms to represent realistic fluctuations in transmission dynamics. The central research question focuses on how stochastic variability affects infection trajectories and the stability of dengue outbreaks. The novelty of this work lies in the integration of noise-modulated differential equations with the Adomian Decomposition Method, which enables a semi-analytical characterization of uncertainty in disease transmission.

Our findings demonstrate that random perturbations can either amplify or attenuate outbreak intensity, depending on system conditions, thereby offering a more robust framework for epidemiological forecasting. Overall, this study provides an original contribution by bridging deterministic and stochastic modeling approaches to enhance the predictive capability of vector-borne disease simulations.

Keywords: Adomian method, noise terms, Dengue virus, Semi-numerical method, Iterative method.

基于含噪声项的微分方程对登革热病毒传播变异性的建模

摘要：在本文中，我们采用一种建模方法来分析登革热病毒在人群中的传播过程，并在微分方程模型中显式引入噪声项，以模拟传播过程中的随机波动与变异性。通过建立包含噪声项的微分方程系统，我们刻画了病毒的传播动力学，并系统性地分析了随机扰动对传播行为的影响。

本研究的核心问题在于探讨随机波动如何影响感染轨迹以及登革热疫情暴发的稳定性。为此，我们结合数值模拟，对比分析了引入噪声前后模型在传播预测可靠性与稳健性方面的差异。结果表明，考虑传播率的随机变异对于提高模型预测精度具有重要意义，并有助于更真实地反映实际传播情景下登革热病毒的行为特征。

本文的创新之处在于将含噪声调制的微分方程模型与 Adomian 分解方法（ADM）相结合，实现了对传播不确定性的半解析刻画。研究结果显示，随机扰动既可能放大疫情暴发强度，也可能在特定条件下缓解传播过程，从而影响疫情的发展趋势。

总体而言，本研究通过融合确定性与随机建模方法，在登革热等媒介传播疾病的模拟与预测方面提供了一种更为稳健的建模框架，为流行病学预测与公共卫生决策提供了新的理论支持。

关键词：Adomian 分解法，噪声项，登革热病毒，半数值方法，迭代方法

1. Introduction

The dengue transmission model was selected as the object of study due to its mathematical structure and epidemiological relevance. Its dynamics are strongly shaped by environmental uncertainty and biological fluctuations, making it ideal for assessing the effects of noise terms. Incorporating stochastic perturbations allows evaluating how real-world variability influences outbreak magnitude and system stability. These findings support more adaptive public-health strategies and extend ADM to non-deterministic epidemiological systems.

The Adomian Decomposition Method (ADM) is a semi-numerical technique developed for solving ordinary and partial differential equations (ODEs and PDEs). Introduced by Adomian, this method constructs analytical solutions in the form of a polynomial series. ADM offers an alternative approach for obtaining series solutions to differential equations, where the series often approximates the Taylor expansion of the true solution around $x_0=0$. Notably, the series can converge rapidly within a localized region, providing accurate approximations[1].

In the context of modeling the spread of the dengue virus, incorporating noise terms into differential equations can significantly enhance the realism and accuracy of simulations. The inclusion of noise terms addresses the inherent variability and uncertainties in disease transmission. This approach is particularly advantageous in capturing the dynamic nature of epidemic outbreaks, where transmission rates can fluctuate due to various factors. While noise terms are typically introduced in non-homogeneous PDEs, they can also be relevant in homogeneous cases[2].

The ADM facilitates a fast convergence of solutions by leveraging these noise terms, which may appear in different components u_k of the series[3]. By analyzing the iterations, it can be observed that terms in u_0 that are canceled in subsequent iterations contribute to the overall solution. This iterative process helps in accurately representing the spread of the dengue virus, providing valuable insights into the epidemic dynamics and improving predictive models..

2. Method ADM

The Adomian Decomposition Method (ADM) is a semi-analytical technique developed to solve both linear and nonlinear ordinary differential equations (ODEs) and partial differential equations (PDEs). Proposed by George Adomian, this method is notable for its ability to decompose complex problems into a series of simpler problems that can be solved iteratively.

ADM is based on the decomposition of the solution and nonlinear terms into series of polynomials known as Adomian polynomials, which facilitate obtaining approximate solutions in a systematic way. The main advantage of this method is its ability to provide solutions in the form of infinite series, which often converge quickly to the exact solution of the given problem[4,5].

The Adomian Decomposition Method is applied to a nonlinear equation

$$Lu+Ru+Nu-g=0, \quad (1)$$

Where, the linear terms are decomposed into $L+R$ and the nonlinear terms are represented by Nu. Here, L is the operator of the highest-ordered derivatives with respect to t and R is the remainder of the operator. Thus, we get

$$Lu=-Ru-Nu+g. \quad (2)$$

Now, there is an inverse operator L^{-1} of L defined by

$$L^{-1}(\cdot)=\int_0^t\int_0^t(\cdot)\ dt\,dt \quad (3)$$

Now, if L is a second order operator, then L^{-1} is defined by a two-fold indefinite integral

$$L^{-1}Lu=u(x,t)-u(x,0)-t\frac{\partial u(x,0)}{\partial t} \quad (4)$$

Now, operating on both sides of Eq. (1) by using L^{-1} we obtain

$$L^{-1}Lu=L^{-1}g-L^{-1}Ru-L^{-1}Nu \quad (5)$$

Therefore, we have

$$u(x,t)=u(x,0)+t\frac{\partial u(x,0)}{\partial t}+L^{-1}g-L^{-1}Ru-L^{-1}Nu \quad (6)$$

The ADM represents the solution of Eq. (6) as a series

$$u(x,t)=\sum_{n=0}^{\infty}u_n(x,t) \quad (7)$$

Now, the operator Nu (nonlinear) is decomposed as

$$Nu=\sum_{n=0}^{\infty}A_n \quad (8)$$

Therefore, substituting (7) and (8) into (6) we obtain

$$\sum_{n=0}^{\infty}u_n(x,t)=u_0-L^{-1}R\sum_{n=0}^{\infty}u_n(x,t)-L^{-1}\sum_{n=0}^{\infty}A_n$$

(9)

Where

$$u_0=u(x,0)+t\frac{\partial u(x,0)}{\partial t}+L^{-1}g \quad (10)$$

Then, we can get

$$\begin{aligned} u_1&=-L^{-1}Ru_0-L^{-1}A_0\\ u_2&=-L^{-1}Ru_1-L^{-1}A_1\\ &\vdots\\ u_{n+1}&=-L^{-1}Ru_n-L^{-1}A_n \end{aligned} \quad (11)$$

Here, $u_n(x,t)$ will be determined recurrently and A_n are the polynomials (Adomian) of $u_0,\ldots,u_n$ defined by

$$A_n=\frac{1}{n!}\frac{d^n}{d\lambda^n}\left[F\left(\sum_{n=0}^{\infty}\lambda_i u_i\right)\right],\quad n=0,1,2,\ldots \quad (12)$$

In this case, we get

$$\begin{aligned} A_0&=f(u_0)\\ A_1&=u_1f'(u_0)\\ A_2&=u_2f''(u_0)+\frac{1}{2!}u_1^2f''(u_0)\\ &\vdots \end{aligned} \quad (13)$$

Therefore, if we introduce the parameter λ, we can obtain that

$$u(\lambda)=\sum_{n=0}^{\infty}\lambda^n u_n \quad (14)$$

Where we can write

$$N(u(\lambda))=\sum_{n=0}^{\infty}\lambda^n A_n \quad (15)$$

Finally, expanding by Taylor's series at $\lambda=0$ we have

$$N(u(\lambda))=\sum_{n=0}^{\infty}\frac{1}{n!}\left[\frac{d^n}{d\lambda^n}N(u(\lambda))\right]\lambda^n \quad (16)$$

$$N(u(\lambda))=\sum_{n=0}^{\infty}\frac{1}{n!}\left[\frac{d^n}{d\lambda^n}N\left(\sum_{n=0}^{\infty}\lambda^i u_n\right)\right]\lambda^n \quad (17)$$

The Adomian's polynomials A_n can be calculated using the recurrence equation

$$A_n=\sum_{n=0}^{\infty}\frac{1}{n!}\left[\frac{d^n}{d\lambda^n}N\left(\sum_{n=0}^{\infty}\lambda^i u_n\right)\right] \quad (18)$$

at $\lambda=0$.

If we are working with systems of differential equations (or equally of an algebraic type), the non-linear terms N can be of the form

$$N=N(u_1,\ldots,u_k,\ldots) \quad (19)$$

Where

$$u_k=\sum_{n=0}^{\infty} u_{ki}. \quad (20)$$

Similarly, Adomian's polynomials can be obtained by using the recurrence equation

$$A_n=\frac{1}{n!}\left[\frac{d^n}{d\lambda^n}N(\sum_{n=0}^{\infty} u_{1i},\sum_{n=0}^{\infty} u_{2i},\ldots,\sum_{n=0}^{\infty} u_{ki},\ldots)\right] \quad (21)$$

The level of precision for the approximation of u will be much better the more components are calculated, i.e,

$$u=\lim_{n\to\infty} \varphi_n \quad (22)$$

Where

$$\varphi_n=\sum_{k=0}^{n-1} u_k \quad (23)$$

2.1. The Noise Terms

In the application of the **Adomian Decomposition Method (ADM)**, the emergence of noise terms may, in certain cases, require the computation of additional polynomial components. These terms are characterized by pairs of identical expressions with opposite signs, which ideally cancel out in the limit of the series expansion. However, this cancellation is not observed directly between the components u0u_0u0 and u1u_1u1 , making it necessary to evaluate further terms in the solution u(t)u(t)u(t). It should also be noted that the presence of noise terms is not a universal feature of all non-homogeneous equations.

For this reason, it is essential to verify that the non-canceled terms in u0u_0u0 satisfy the governing partial differential equation. A necessary condition for the occurrence of noise terms in non-homogeneous PDEs is that the zeroth-order component u0u_0u0 contains the exact solution u(t)u(t)u(t) together with additional, non-essential terms. To provide a clear demonstration of the method's effectiveness and to validate this condition, a representative partial differential equation has been selected as a case study.

Now, noise terms typically emerge when solving non-linear and non-homogeneous equations using ADM. They are artifacts of the iterative decomposition process and represent terms that should ideally cancel out during the computation[6]. However, these cancellations often do not occur completely, especially when higher-order terms are considered, resulting in residuals known as noise terms. This phenomenon can significantly impact the accuracy of the solution, as the presence of noise terms indicates that the convergence to the true solution might be slower or incomplete without additional corrections[7,8].

The noise terms are specifically those terms that cancel out as the limit of the series is approached, but until this cancellation is fully realized, they persist within the intermediate components of the solution, such as u_0 and u_1. Importantly, these terms do not generally appear directly between u_0 and u_1, necessitating the calculation of further components u_2, u_3,… to fully capture their effect and ensure accurate representation of the solution.

2.1.1. Conditions for the Presence of Noise Terms

Not all non-homogeneous equations exhibit the noise terms phenomenon. For noise terms to manifest, certain conditions must be met within the structure of the ADM series[9-11]:

- **Component Structure:** The zeroth component u_0 must contain not only the exact solution but also other residual terms that interact with subsequent components.
- **Non-Cancellation:** The terms within u_0 that do not cancel during the generation of u_1 play a pivotal role in the persistence of noise terms.
- **Equation Characteristics:** Non-homogeneous PDEs are more likely to exhibit noise terms due to their inherent complexity and the presence of non-linearities and source terms that complicate the decomposition process.
- **Iterative Interactions:** The interaction between components u_0, u_1,… must be such that identical terms with opposite signs emerge and persist until higher-order components effectively cancel them out.

3. Results And Discussion

The following is an application to a biological model using the Adomian Method to describe the transmission dynamics of a viral disease, such as dengue fever, through the Aedes aegypti mosquito[12,14].

The objective is to model the spread of dengue virus in a human population using a system of differential equations that includes a noise term to simulate variations in transmission.

The classical model of dengue transmission involves two populations: humans and mosquitoes. We will use the following system[15,16]:

Equation for infected humans $I_h(t)$:

$$\frac{dI_h(t)}{dt}=\beta_{mh}S_h(t)I_m(t)-\gamma_h I_h(t)+N_h(t) \quad (24)$$

Equation for infected mosquitoes $I_m(t)$:

$$\frac{dI_m(t)}{dt}=\beta_{hm}S_m(t)I_h(t)-\gamma_m I_m(t)+N_m(t) \quad (25)$$

Where,

- $S_h(t)$ and $S_m(t)$ are susceptible humans and mosquitoes, respectively.
- β_{mh} is the rate of mosquito-to-human transmission.
- β_{hm} is the rate of transmission from humans to mosquitoes.
- γ_h and γ_m are human and mosquito recovery rates.
- $N_h(t)$ and $N_m(t)$ are noise terms that represent random fluctuations, such as changes in weather or health intervention.

The objective in this problem is to solve these equations using the Adomian Method (ADM) to see how noise affects the transmission dynamics.

We start with the decomposition of the solutions and the nonlinear terms.

We decompose the solutions I_h (t) and I_m (t) into series, and similarly decompose the nonlinear terms involved in the transmission rates:

$$I_h(t)=\sum_{n=0}^{\infty} I_{h,n}(t) \quad (26)$$

And

$$I_m(t)=\sum_{n=0}^{\infty} I_{m,n}(t) \quad (27)$$

and transmission rates are also expanded using the Adomian $A_{h,n}$ and $A_{m,n}$ polynomials generated from the terms of each iteration.

The polynomials $A_{h,n}$ and $A_{m,n}$ are calculated based on the previous iterations of $I_h(t)$ and $I_m(t)$

For example, for n=0

$$A_{h,0}=\beta_{mh} S_h(0) I_{m,0}(t) \quad (28)$$

Now, for $n = 1$ we have:

$$A_{h,1} = \beta_{mh} S_h(0) I_{m,1}(t) + \text{noise correction} \quad (28)$$

Now we iterate the solution:

- First Iteration for humans ($n = 0$):

$$I_{h,0}(t) = I_h(0) + \int_0^t \left(\beta_{mh} S_h(0) I_{m,0}(s) - \gamma_h I_{h,0}(s) + N_{h,0}(s)\right) ds \quad (29)$$

Here, $N_{h,0}(t)$ can be modeled as a simple stochastic function, for example, $N_{h,0}(s) = 0.01\cos t$.

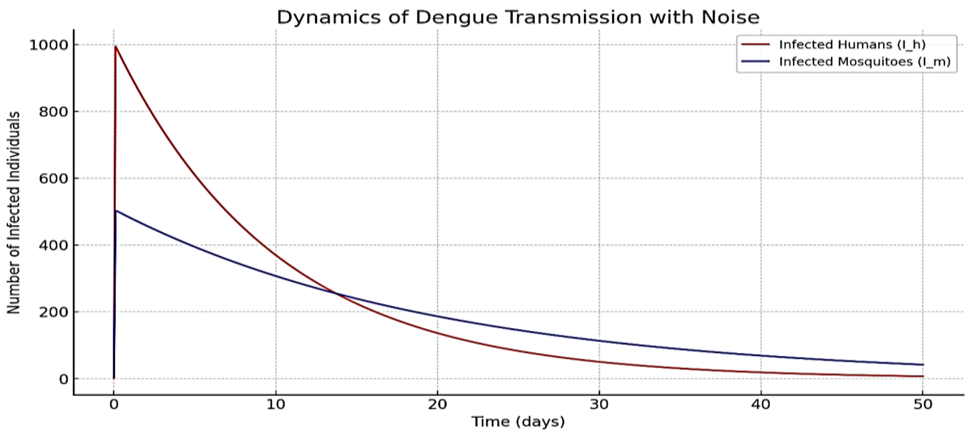

Figure1: The graph shows the dynamics of dengue transmission between humans and infected mosquitoes with the inclusion of a noise term to simulate variations in transmission.

- First Iteration for Mosquitoes ($n = 0$):

$$I_{m,0}(t) = I_m(0) + \int_0^t \left(\beta_{hm} S_m(0) I_{h,0}(s) - \gamma_m I_{m,0}(s) + N_{m,0}(s)\right) ds \quad (30)$$

With $N_{m,0}(t) = 0.02\sin t$ by simulating environmental perturbations.

Finally, if we evaluate the following iterations, we can see that these fit the noise terms and the Adomian polynomials. As $n + 1$ terms are added, we observe how noise impacts the stability and behavior of the solution.

Figure 1 (red line) represents the number of infected humans (I_h (t)) over time. A rapid initial increase is observed followed by a decrease as those infected recover or die. Now, (blue line) represents the number of infected mosquitoes (I_m (t)). Also shows a tendency to decrease over time, but at a slower rate due to the lower recovery rate compared to humans.

It is worth emphasizing that the modified approach exhibits a slower convergence rate compared to the method employed in the present example. This observation leads to the conclusion that implementing methodological modifications does not necessarily guarantee an acceleration in the convergence toward the solution, and in certain cases may, in fact, impede computational efficiency..

4. Conclusion

Based on the results, we recommend extending dengue modeling to incorporate environment-driven noise functions to reflect seasonal effects. Future studies should explore hybrid ADM–stochastic solvers to validate convergence under high variability. Applying this approach to other vector-borne diseases may improve early-warning systems for public-health decision making.

This study contributes to the academic field by demonstrating how the integration of noise terms within the ADM framework provides a more realistic representation of dengue transmission. Unlike deterministic models, our approach captures stochasticity and reveals how random fluctuations affect outbreak behavior. This advances the theoretical understanding of semi-analytical methods for stochastic systems and highlights ADM's potential for modeling infectious diseases under uncertainty.

In this study, we applied the Adomian Decomposition Method (ADM) to model the spread of the dengue virus in human populations using differential equations with noise terms to simulate transmission variability. The incorporation of noise terms plays a crucial role in capturing the inherent randomness of disease transmission, reflecting real-world conditions more accurately. ADM significantly enhances the convergence rate of solutions to partial differential equations (PDEs) and reduces computational complexity when an exact solution exists. Even in cases where a closed-form solution cannot be obtained, ADM provides highly accurate approximate solutions.

Our results demonstrate that this iterative method is highly efficient for deriving closed-form solutions when possible and produces analytical solutions in the form of rapidly convergent series, making the solution procedure both robust and computationally attractive. The approach highlights the power of ADM in simulating complex dynamics of dengue transmission, offering a valuable tool for understanding and predicting the spread of infectious diseases with variable transmission patterns.

5. Acknowledgment

I gratefully acknowledge the support of the Universidad Industrial de Santander through its institutional research funding programs. In particular, I recognize the financial support provided to projects 4216 and 4242, which has been instrumental in enabling their development. This support reflects the university's enduring commitment to the advancement of scientific knowledge and innovation.

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Word count: 3,662 words, excluding references.

Peer-review record:
Fast-track status: Not fast-tracked
First-round reviews received: 3 reports
Revision cycles completed: 3 rounds
Final version submitted: December 17, 2025

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