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Research article

The novel stochastic structure of solitary waves to the stochastic Maccari's system via Wiener process

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Abstract: This article investigates the nonlinear Maccari model with multiplicative noise using the unified technique. Numerous new important solitary wave solutions are presented with free physical parameters. These solutions play a vital role in various domains, including nonlinear optics, plasma physics, and hydrodynamics. The investigation shows that the solution process is quick and clear, where a comparatively higher number of novel solutions are obtained. The performance of the used approach is compared with that of other methods. We create 2D and 3D graphs for certain solutions of the study, utilizing suitably selected values for the physical parameters. We also address the impact of model parameters on the solution characteristics. We observe that our results may help to resolve some physical problems in the actual world by determining the motion of a single wave in a tiny region. Finally, the outcomes show how simple and effective this method is at producing rich, accurate solutions to nonlinear models in mathematical physics as well as complex nonlinear wave structures.

Keywords: Maccari system; unified method; Wiener process; solitary wave solution; nonlinearity structures
Mathematics Subject Classification: 34A34, 35C07, 35Q62

1. Introduction

Nonlinear partial differential equations (NPDEs) are widely employed in the description of several natural processes, including optical fiber communications, blood pulses in macroscopic physics, fluid mechanics, chemical investigations, electro-magnetic wave propagation, plasma physics, biological processes, and so on [1–4]. These equations can more accurately represent changes in space and time; therefore, they are particularly helpful for describing complicated physical events in nature. The key issues with these models are determining their exact solutions, which are employed to describe the complex qualitative and quantitative patterns of nonlinear events in various disciplines of mathematical physics and nonlinear sciences [5–7].

Recently, stochastic partial differential equations (SPDEs) have been receiving too much attention and are thought to be an extension of dynamical systems theory to include noise in models. That is a significant expansion since actual systems are inherently unable to be completely isolated from their surroundings, which means that this external random influence is constant. Solving stochastic equations is more challenging than solving deterministic equations due to the added random components [8–10]. A stochastic process reflects an notice at a certain moment, and the consequence is a random variable. The Wiener (Brownian motion) process is a standard example of a stochastic process that exhibits the properties of a martingale and a Markov process [11]. The Wiener process is essential for describing stochastic processes, as it is the foundation of stochastic calculus. It serves as a crucial foundation for the validation of molecular dynamics models and is significant in stochastic dynamics and stochastic processes. Furthermore, there are a number of unknown reasons for the stochastic disturbances that manifest in the physical context. We trust that recent improvements in stochastic calculus through SPDEs will offer a basis for modeling sophisticated equations in a comprehensive fashion [12, 13]. More than anyone else, mathematicians are still at ease applying the SPDEs and stochastic processes to natural models.

Maccari's system (MS) is a type of integrable NPDEs that was produced from the Kadomtsev-Petviashvili model via a reduction strategy employing Fourier expansion and spatiotemporal rescaling [14]. It designates a well-known class of NPDEs that was widely employed in several fields of superfluid, plasma physics, nonlinear optics, and quantum mechanics to illustrate the dynamics of an isolated wave in a tiny area of space [15–17]. Maccari [18] demonstrated how the MS precisely described the crucial features of rogue waves and how they might be utilized in the study of various nonlinear forms, such as fluid mechanics, standing waves, and nonlinear optical fibers. Furthermore, the idea was put out that the MS model might be utilized for more intricate systems in order to investigate the behaviour of water waves and the generation of energy waves. The nonlinear auroral Langmuir electrostatic waveforms were recognized and analyzed for their electrostatic wave characteristics and collapsing energy [19,20]. Additionally, the previous research was conducted from a deterministic perspective. The coupled MS reads [16,21,22]

$$\begin{aligned} &i\Psi_t + \Psi_{xx} + R\Psi = 0\,, \\ &R_t + R_y + (|\,\Psi\,|^2)_x = 0, \end{aligned} \tag{1.1}$$

$\Psi = \Psi(x, y, t)$, $R = R(x, y, t)$ symbolize complex scalar and real scalar fields, respectively. Zhao [23] introduce several solitary waves for system (1.1). Moreover, many soliton and periodic waves of the above model have recently been found in [16, 21, 22]. In this paper, we consider model (1.1) via the Wiener process as follows:

$$\begin{aligned} &i\Psi_t + \Psi_{xx} + R\Psi - i\sigma\Psi W_t = 0\,, \\ &R_t + R_y + (|\,\Psi\,|^2)_x = 0. \end{aligned} \tag{1.2}$$

The noise W_t is a Wiener times derivative of $W(t)$, and σ denotes noise strength [11]. The authors in [24] extracted new stochastic solutions for model (1.2), such as dark, breather, rational explosive, dispersive and explosive dissipated wave solutions. This model was investigated by using the sub-equation mathematical approach in [25]. Bifurcation theory was used to demonstrate the system's dynamical behavior and its perturbation case [26]. It is suitable to provide a description of the Wiener process $\{W(t)\}_{t\geq 0}$ that meets the specified criteria:

(i) $W(t)$; $t \geq 0$ is a continuous function of t,
(ii) $W(t) - W(s)$ is independent of increments when $s < t$,
(iii) $W(t) - W(s)$ has a normal distribution with mean 0 and variance $t - s$.

Despite several study outcomes on Maccari's system (1.2), many novel solutions have yet to be developed. As part of our continuing work, we use a unified method to produce several new stochastic solitary waves for this model restricted by multiplicative noises in the Itô sense. The unified approach is a highly straightforward and an effective way of finding traveling wave solutions to NPDEs [27]. This method provides several vital sorts of solitary waves through physical characteristics. The presented solutions open up important applications in plasma physics, hydrodynamics, and optical fibers [28,29]. To our knowledge, the unified method for solving the stochastic MS model has never been considered.

The following sections comprise the whole work. Section 2 provides a summary of the unified method. Section 3 presents new stochastic solitary waves for MS in the Itô sense. The physical explanation of the solutions for model (1.2) is given in Section 4. Moreover, we illustrate the translation of solutions physically and depict the effect of the noise term on these solutions. Section 5 contains closing observations and recommendations for the future.

2. Description of the method

This section presents a reduced version of the unified method [27]:

(1) Consider the NPDEs for $\chi(x,t)$:

$$G_1(\chi, \chi_t, \chi_x, \chi_{tt}, \chi_{xx}, ...) = 0, \tag{2.1}$$

that converted into an ODE

$$G_2(\chi, \chi', \chi'', \chi''', ...) = 0, \tag{2.2}$$

utilizing the wave transformation $\chi(\zeta) = \chi(x,t)$, $\zeta = x + kt$, k is the wave speed.

(2) Equation (2.2) is integrated provided each term has a derivative; if we suppose that the integration constant is zero, we get a simplified ODE.

(3) Assuming that the nonlinear partial differential equation solution may be represented by the following ansatz:

$$\chi(\zeta) = a_0 + \sum_{j=1}^{N} [a_j \phi^j + b_j \phi^{-j}], \tag{2.3}$$

where $\phi(\zeta)$ fulfills the Riccati differential equation

$$\phi'(\xi) = \phi^2(\xi) + b, \tag{2.4}$$

Equation (2.4) has the following solutions:

Family I: At $b < 0$, we have

$$\phi(\zeta) = \begin{cases} \frac{\sqrt{-(A^2+B^2)b} - A\sqrt{-b}\,cosh(2\sqrt{-b}\,(\xi+\xi_0))}{A\,sinh(2\sqrt{-b}\,(\xi+\xi_0)))+B}, \\ \frac{-\sqrt{-(A^2+B^2)b} - A\sqrt{-b}\,cosh(2\sqrt{-b}\,(\xi+\xi_0))}{A\,sinh(2\sqrt{-b}\,(\xi+\xi_0)))+B}, \\ \sqrt{-b} + \frac{-2A\sqrt{-b}}{A+cosh(2\sqrt{-b}\,(\xi+\xi_0))-sinh(2\sqrt{-b}\,(\xi+\xi_0))}, \\ -\sqrt{-b} + \frac{-2A\sqrt{-b}}{A+cosh(2\sqrt{-b}\,(\xi+\xi_0))+sinh(2\sqrt{-b}\,(\xi+\xi_0))}. \end{cases} \tag{2.5}$$

Family II: At $b > 0$, we have

$$\phi(\zeta) = \begin{cases} \frac{\sqrt{(A^2+B^2)b} - A\sqrt{b}\,cos(2\sqrt{b}\,(\xi+\xi_0))}{A\,sin(2\sqrt{b}\,(\xi+\xi_0)))+B}, \\ \frac{-\sqrt{(A^2+B^2)b} - A\sqrt{b}\,cos(2\sqrt{b}\,(\xi+\xi_0))}{A\,sin(2\sqrt{b}\,(\xi+\xi_0)))+B}, \\ i\sqrt{b} + \frac{2A\,i\sqrt{b}}{A+cos(2\sqrt{b}\,(\xi+\xi_0))-sin(2\sqrt{b}\,(\xi+\xi_0))}, \\ -i\sqrt{b} + \frac{2A\,i\sqrt{b}}{A+cos(2\sqrt{b}\,(\xi+\xi_0))+sin(2\sqrt{b}\,(\xi+\xi_0))}. \end{cases} \tag{2.6}$$

Family III: At $b = 0$, we have

$$\phi(\zeta) = -\frac{1}{\xi + \xi_0}, \tag{2.7}$$

where A, B, and ξ_0 are real arbitrary constants.

(1) The highest-order and higher nonlinear terms are balanced to yield N.
(2) Inserting Eqs (2.3) and (2.4) into Eq (2.2) and gathering all terms with the same degrees of ϕ together, then putting each coefficient of terms with ϕ^i $(-N \le i \le N)$ to zero provides a set of algebraic systems for parameters a_i, b_i, c, and b.
(3) By substituting these parameters into Eq (2.3) and applying the general solutions of Eq (2.4) in Eqs (2.5)–(2.7), the explicit solutions of Eq (2.1) can be found instantly depending on the value of b.

3. Solutions of MS

Using the transformation:

$$\Psi(x, y, t) = \psi(\zeta)\, e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \quad R(x, y, t) = R(\zeta), \;\; \zeta = x + \beta y - 2kt, \tag{3.1}$$

where k, μ, γ, β are constants, Eq (1.2) becomes

$$\begin{aligned} &\psi''(\zeta) + R(\xi)\psi(\xi) - (\gamma + k^2)\psi(\zeta) = 0, \\ &2e^{2\delta(W(t)-\delta t)}\psi(\zeta)\psi'(\zeta) - (2k - \beta)R'(\zeta) = 0\,. \end{aligned} \tag{3.2}$$

For the second equation of (3.2), taking expectations on both sides results in

$$2e^{-2\delta^2 t}\, E(e^{2\delta W(t)})\psi(\zeta)\psi'(\zeta) - (2k - \beta)R'(\zeta) = 0\,, \tag{3.3}$$

since $E(e^{2\delta W(t)}) = e^{2\delta^2 t}$, Eq (3.3) reduced to

$$2\psi(\zeta)\psi'(\zeta) - (2k-\beta)R'(\zeta) = 0.$$

The integration of the final equation, with the integration constant set to zero, yields

$$R(\zeta) = \left(\frac{1}{2k-\beta}\right)\psi^2(\zeta). \tag{3.4}$$

Substituting Eq (3.4) into the first equation of the system (3.2) yields

$$C_1\psi''(\zeta) + C_2\psi^3(\zeta) + C_3\psi(\zeta) = 0, \tag{3.5}$$

where

$$C_1 = 1,\ C_2 = \frac{1}{2k-\beta},\ C_3 = -(\gamma + k^2). \tag{3.6}$$

Balancing the largest nonlinear term with the highest order derivative results in $N = 1$. This leads to

$$\psi(\zeta) = a_0 + a_1\phi(\zeta) + \frac{b_1}{\phi(\zeta)}, \tag{3.7}$$

where

$$\phi(\zeta) = \begin{cases} \dfrac{\sqrt{-(A^2+B^2)b} - A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}{Asinh(2\sqrt{-b}(\zeta+\zeta_0)) + B}, & b<0,\\ \dfrac{-\sqrt{-(A^2+B^2)b} - A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}{Asinh(2\sqrt{-b}(\zeta+\zeta_0)) + B}, & b<0,\\ \sqrt{-b} + \dfrac{-2A\sqrt{-b}}{A + cosh(2\sqrt{-b}(\zeta+\zeta_0)) - sinh(2\sqrt{-b}(\zeta+\zeta_0))}, & b<0,\\ -\sqrt{-b} + \dfrac{2A\sqrt{-b}}{A + cosh(2\sqrt{-b}(\zeta+\zeta_0)) - sinh(2\sqrt{-b}(\zeta+\zeta_0))}, & b<0,\\ \dfrac{\sqrt{(A^2-B^2)b} - A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}{Asin(2\sqrt{b}(\zeta+\zeta_0)) + B}, & b>0,\\ \dfrac{-\sqrt{(A^2-B^2)b} - A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}{Asin(2\sqrt{b}(\zeta+\zeta_0)) + B}, & b>0. \end{cases}$$

Here, we introduce all valid solitary wave solutions to the stochastic MS model (1.2) for $\zeta = x+\beta y-2kt$, based on the following cases:

First case:

$$a_0 = 0,\ a_1 = \pm\frac{2\sqrt{2}b + \sqrt{2}C_3}{6b\sqrt{-C_2}},\ b_1 = \pm\frac{\sqrt{2}b}{\sqrt{-C_2}}.$$

If $b < 0$, then the traveling wave solutions are

$$\Psi_{1,2}(x,y,t) = \left(\pm\frac{2\sqrt{2}b + \sqrt{2}C_3}{6b\sqrt{-C_2}}\frac{\sqrt{-(A^2+B^2)b} - A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}{Asinh(2\sqrt{-b}(\zeta+\zeta_0)) + B}\right.$$

$$\pm\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}{\sqrt{-(A^2+B^2)b}-A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}\Bigg)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \quad (3.8)$$

$$R_{1,2}(x,y,t)=\frac{1}{2k-\beta}\left(\pm\frac{2\sqrt{2}b+\sqrt{2}C_3}{6b\sqrt{-C_2}}\frac{\sqrt{-(A^2+B^2)b}-A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}\right.$$
$$\left.\pm\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}{\sqrt{-(A^2+B^2)b}-A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}\right)^2, \quad (3.9)$$

$$\Psi_{3,4}(x,y,t)=\left(\pm\frac{2\sqrt{2}b+\sqrt{2}C_3}{6b\sqrt{-C_2}}\frac{-\sqrt{-(A^2+B^2)b}-A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}\right.$$
$$\left.\pm\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}{\sqrt{-(A^2+B^2)b}-A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}\right)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \quad (3.10)$$

$$R_{3,4}(x,y,t)=\frac{1}{2k-\beta}\left(\pm\frac{2\sqrt{2}b+\sqrt{2}C_3}{6b\sqrt{-C_2}}\frac{-\sqrt{-(A^2+B^2)b}-A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}\right.$$
$$\left.\pm\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}{\sqrt{-(A^2+B^2)b}-A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}\right)^2, \quad (3.11)$$

$$\Psi_{5,6}(x,y,t)=\left(\pm\frac{2\sqrt{2}b+\sqrt{2}C_3}{6b\sqrt{-C_2}}\left(\sqrt{-b}+\frac{-2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right.$$
$$\left.\pm\frac{\sqrt{2}b}{\sqrt{-C_2}}\left(\sqrt{-b}+\frac{-2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \quad (3.12)$$

$$R_{5,6}(x,y,t)=\frac{1}{2k-\beta}\left(\pm\frac{2\sqrt{2}b+\sqrt{2}C_3}{6b\sqrt{-C_2}}\left(\sqrt{-b}+\frac{-2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right.$$
$$\left.\pm\frac{\sqrt{2}b}{\sqrt{-C_2}}\left(\sqrt{-b}+\frac{-2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right)^2, \quad (3.13)$$

$$\Psi_{7,8}(\zeta)=\left(\pm\frac{2\sqrt{2}b+\sqrt{2}C_3}{6b\sqrt{-C_2}}\left(-\sqrt{-b}+\frac{2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right.$$
$$\left.\pm\frac{\sqrt{2}b}{\sqrt{-C_2}}\left(-\sqrt{-b}+\frac{2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \quad (3.14)$$

$$R_{7,8}(x,y,t) = \frac{1}{2k-\beta}\left(\pm\frac{2\sqrt{2}b+\sqrt{2}C_3}{6b\sqrt{-C_2}}\left(-\sqrt{-b}+\frac{2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right.$$
$$\left.\pm\frac{\sqrt{2}b}{\sqrt{-C_2}}\left(-\sqrt{-b}+\frac{2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right)^2. \tag{3.15}$$

If $b > 0$, then the traveling wave solutions are

$$\Psi_{9,10}(x,y,t) = \left(\pm\frac{2\sqrt{2}b+\sqrt{2}C_3}{6b\sqrt{-C_2}}\frac{\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}\right.$$
$$\left.\pm\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}{\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}\right)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \tag{3.16}$$

$$R_{9,10}(x,y,t) = \frac{1}{2k-\beta}\left(\pm\frac{2\sqrt{2}b+\sqrt{2}C_3}{6b\sqrt{-C_2}}\frac{\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}\right.$$
$$\left.\pm\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}{\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}\right)^2, \tag{3.17}$$

$$\Psi_{11,12}(x,y,t) = \left(\pm\frac{2\sqrt{2}b+\sqrt{2}C_3}{6b\sqrt{-C_2}}\frac{-\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}\right.$$
$$\left.\pm\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}{-\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}\right)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \tag{3.18}$$

$$R_{11,12}(x,y,t) = \frac{1}{2k-\beta}\left(\pm\frac{2\sqrt{2}b+\sqrt{2}C_3}{6b\sqrt{-C_2}}\frac{-\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}\right.$$
$$\left.\pm\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}{-\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}\right)^2. \tag{3.19}$$

Second case:

$$a_0 = \pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}},\quad a_1 = -\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}},\quad b_1 = \frac{\sqrt{2}b}{\sqrt{-C_2}}.$$

If $b < 0$, then the traveling wave solutions are

$$\Psi_{13,14}(x,y,t) = \left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}} - \frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\frac{\sqrt{-(A^2+B^2)b}-A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}\right.$$
$$\left.+\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}{\sqrt{-(A^2+B^2)b}-A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}\right)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \tag{3.20}$$

$$R_{13,14}(\zeta) = \frac{1}{2k-\beta}\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}} - \frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\frac{\sqrt{-(A^2+B^2)b} - A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}\right.$$
$$\left.+\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}{\sqrt{-(A^2+B^2)b} - A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}\right)^2, \quad (3.21)$$

$$\Psi_{15,16}(x,y,t) = \left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}} - \frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\frac{-\sqrt{-(A^2+B^2)b} - A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}\right.$$
$$\left.+\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}{\sqrt{-(A^2+B^2)b} - A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}\right)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \quad (3.22)$$

$$R_{15,16}(x,y,t) = \frac{1}{2k-\beta}\times$$
$$\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}} - \frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\frac{-\sqrt{-(A^2+B^2)b} - A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}\right.$$
$$\left.+\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}{\sqrt{-(A^2+B^2)b} - A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}\right)^2, \quad (3.23)$$

$$\Psi_{17,18}(x,y,t) = \left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}} - \frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\left(\sqrt{-b}+\frac{-2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0)) - sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right.$$
$$\left.+\frac{\sqrt{2}b}{\sqrt{-C_2}}\left(\sqrt{-b}+\frac{-2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0)) - sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \quad (3.24)$$

$$R_{17,18}(\zeta) = \frac{1}{2k-\beta}\times$$
$$\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}} - \frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\left(\sqrt{-b}+\frac{-2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0)) - sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right.$$
$$\left.+\frac{\sqrt{2}b}{\sqrt{-C_2}}\left(\sqrt{-b}+\frac{-2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0)) - sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right)^2, \quad (3.25)$$

$$\Psi_{19,20}(x,y,t) =$$
$$\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}} - \frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\left(-\sqrt{-b}+\frac{2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0)) - sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right.$$
$$\left.+\frac{\sqrt{2}b}{\sqrt{-C_2}}\left(-\sqrt{-b}+\frac{2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0)) - sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \quad (3.26)$$

$$R_{19,20}(x,y,t)=\frac{1}{2k-\beta}\times$$
$$\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}}-\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\left(-\sqrt{-b}+\frac{2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right.$$
$$\left.+\frac{\sqrt{2}b}{\sqrt{-C_2}}\left(-\sqrt{-b}+\frac{2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right)^2. \tag{3.27}$$

If $b>0$, then the traveling wave solutions are

$$\Psi_{21,22}(\zeta)=\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}}-\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\frac{\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}\right.$$
$$\left.+\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}{\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}\right)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \tag{3.28}$$

$$R_{21,22}(x,y,t)=\frac{1}{2k-\beta}\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}}-\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\frac{\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}\right.$$
$$\left.+\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}{\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}\right)^2, \tag{3.29}$$

$$\Psi_{23,24}(x,y,t)=\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}}-\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\frac{-\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}\right.$$
$$\left.+\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}{-\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}\right)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \tag{3.30}$$

$$R_{23,24}(x,y,t)=\frac{1}{2k-\beta}\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}}-\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\frac{-\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}\right.$$
$$\left.+\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}{-\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}\right)^2. \tag{3.31}$$

Third case:

$$a_0=\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}},\quad a_1=\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}},\quad b_1=-\frac{\sqrt{2}b}{\sqrt{-C_2}}.$$

If $b<0$, then the traveling wave solutions are

$$\Psi_{25,26}(x,y,t)=\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}}+\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\frac{\sqrt{-(A^2+B^2)b}-A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}\right.$$
$$\left.-\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}{\sqrt{-(A^2+B^2)b}-A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}\right)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \tag{3.32}$$

$$R_{25,26}(x,y,t)=\frac{1}{2k-\beta}\times$$
$$\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}}+\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\frac{\sqrt{-(A^2+B^2)b}-A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}\right.$$
$$\left.-\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}{\sqrt{-(A^2+B^2)b}-A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}\right)^2, \tag{3.33}$$

$$\Psi_{27,28}(\zeta)=\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}}+\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\frac{-\sqrt{-(A^2+B^2)b}-A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}\right.$$
$$\left.-\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}{\sqrt{-(A^2+B^2)b}-A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}\right)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \tag{3.34}$$

$$R_{27,28}(\zeta)=\frac{1}{2k-\beta}\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}}+\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\frac{-\sqrt{-(A^2+B^2)b}-A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}\right.$$
$$\left.-\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asinh(2\sqrt{-b}(\zeta+\zeta_0))+B}{\sqrt{-(A^2+B^2)b}-A\sqrt{-b}cosh(2\sqrt{-b}(\zeta+\zeta_0))}\right)^2, \tag{3.35}$$

$$\Psi_{29,30}(x,y,t)=\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}}+\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\left(\sqrt{-b}+\frac{-2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right.$$
$$\left.-\frac{\sqrt{2}b}{\sqrt{-C_2}}\left(\sqrt{-b}+\frac{-2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \tag{3.36}$$

$$R_{29,30}(x,y,t)=\frac{1}{2k-\beta}\times$$
$$\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}}+\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\left(\sqrt{-b}+\frac{-2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right.$$
$$\left.-\frac{\sqrt{2}b}{\sqrt{-C_2}}\left(\sqrt{-b}+\frac{-2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right)^2, \tag{3.37}$$

$$\Psi_{31,32}(x,y,t)=$$
$$\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}}+\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\left(-\sqrt{-b}+\frac{2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right.$$
$$\left.-\frac{\sqrt{2}b}{\sqrt{-C_2}}\left(-\sqrt{-b}+\frac{2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \tag{3.38}$$

$$R_{31,32}(x,y,t)=\frac{1}{2k-\beta}\times$$
$$\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}}+\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\left(-\sqrt{-b}+\frac{2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right.$$
$$\left.-\frac{\sqrt{2}b}{\sqrt{-C_2}}\left(-\sqrt{-b}+\frac{2A\sqrt{-b}}{A+cosh(2\sqrt{-b}(\zeta+\zeta_0))-sinh(2\sqrt{-b}(\zeta+\zeta_0))}\right)\right)^2. \quad (3.39)$$

If $b>0$, then the traveling wave solutions are

$$\Psi_{33,34}(x,y,t)=\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}}+\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\frac{\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}\right.$$
$$\left.-\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}{\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}\right)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \quad (3.40)$$

$$R_{33,34}(x,y,t)=\frac{1}{2k-\beta}\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}}+\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\frac{\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}\right.$$
$$\left.-\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}{\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}\right)^2, \quad (3.41)$$

$$\Psi_{35,36}(x,y,t)=\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}}+\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\frac{-\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}\right.$$
$$\left.-\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}{-\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}\right)e^{i(kx+\mu y+\gamma t)+\delta W(t)-\delta^2 t}, \quad (3.42)$$

$$R_{35,36}(x,y,t)=\frac{1}{2k-\beta}\left(\pm\frac{\sqrt{-4b-C_3}}{\sqrt{5C_2}}+\frac{\sqrt{2}b-\sqrt{2}C_3}{15b\sqrt{-C_2}}\frac{-\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}\right.$$
$$\left.-\frac{\sqrt{2}b}{\sqrt{-C_2}}\frac{Asin(2\sqrt{b}(\zeta+\zeta_0))+B}{-\sqrt{(A^2-B^2)b}-A\sqrt{b}cos(2\sqrt{b}(\zeta+\zeta_0))}\right)^2. \quad (3.43)$$

4. Influences of noise

The majority of conventional studies assessed the proposed management system under deterministic conditions. We used a unified method to identify novel significant stochastic solutions for the stochastic MS model with multiplicative noises in the Itô sense. Most mainstream publications addressed the proposed MS model in deterministic situations. The classical MS model revealed the behavior of Langmuir solitons, which are high-frequency waves used in quantum mechanics, plasma physics, nonlinear optics, superfluid, etc. We examine this model within a stochastic framework, characterized by multiplicative noise in the Itô sense, as opposed to other techniques. A unified strategy was applied to discover innovative random solutions for the stochastic MS model, resulting in various dissipative and dispersive structures. Actually, we presented novel solutions for the first time to the stochastic MS model via multiplicative noise.

We use the symbolic program Matlab to introduce some figures for some selected solutions. We also investigate the influence of multiplicative noise on the presented solitary wave solutions of the stochastic MS model. For certain selected solutions of the suggested model, we offer some 2D and 3D graphs for suitable parametric selections.

The solution (3.8) shows 2D and 3D periodic waves as seen in Figure 1 when there is no noise term, that is, $\sigma = 0$. Figure 2 shows the graphs of 2D and 3D super soliton solution (3.12). Figure 3 depicts the 2D and 3D plots of the periodic wave solutions (3.24). Figure 4 illustrates the 2D and 3D plots of the anti-kink wave solution (3.25).

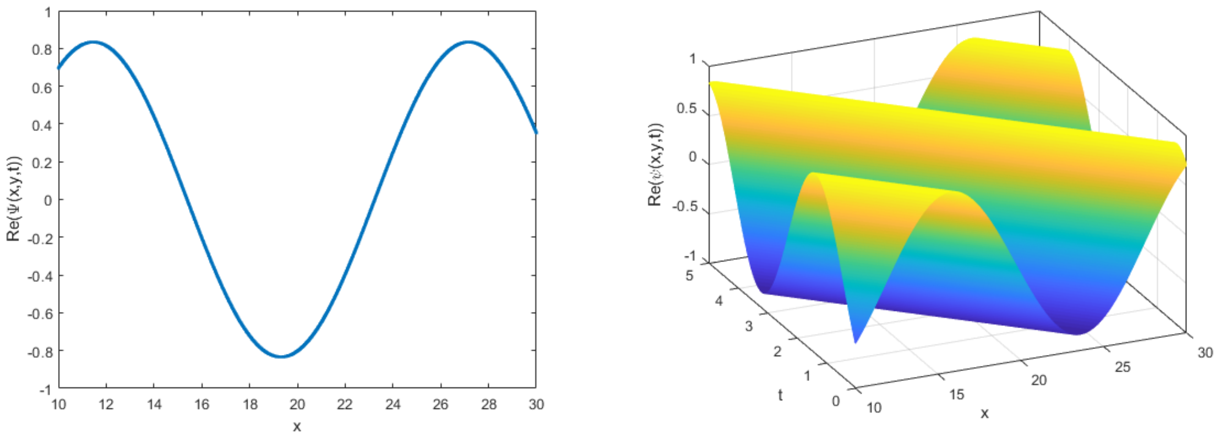

Figure 1. 2D and 3D plots of the periodic wave solution (3.8).

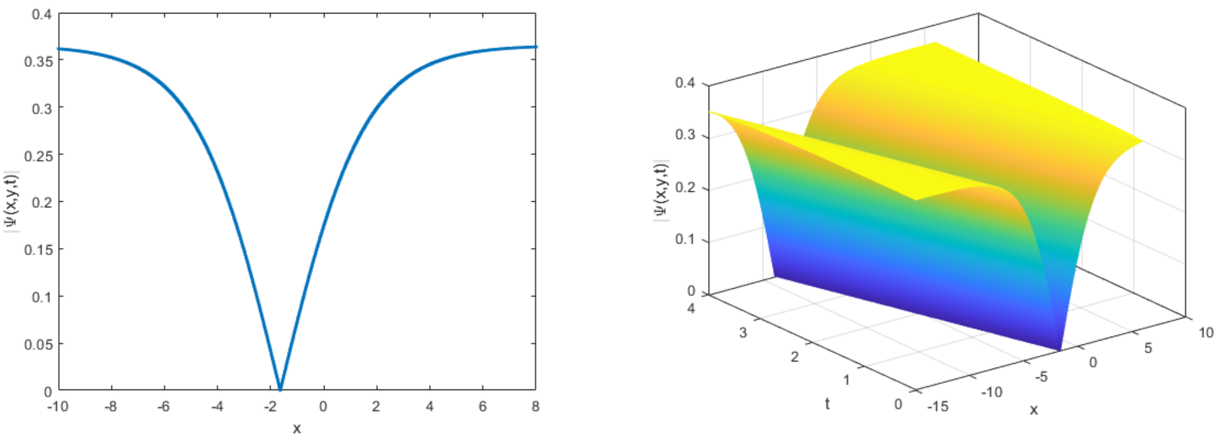

Figure 2. 2D and 3D plots of the super soliton solution (3.12).

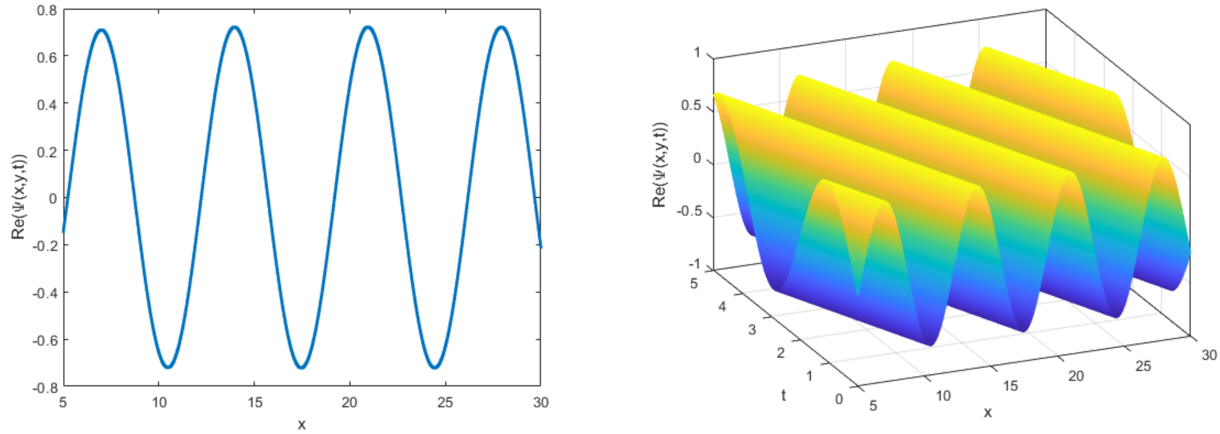

Figure 3. 2D and 3D plots of the periodic wave solution (3.24).

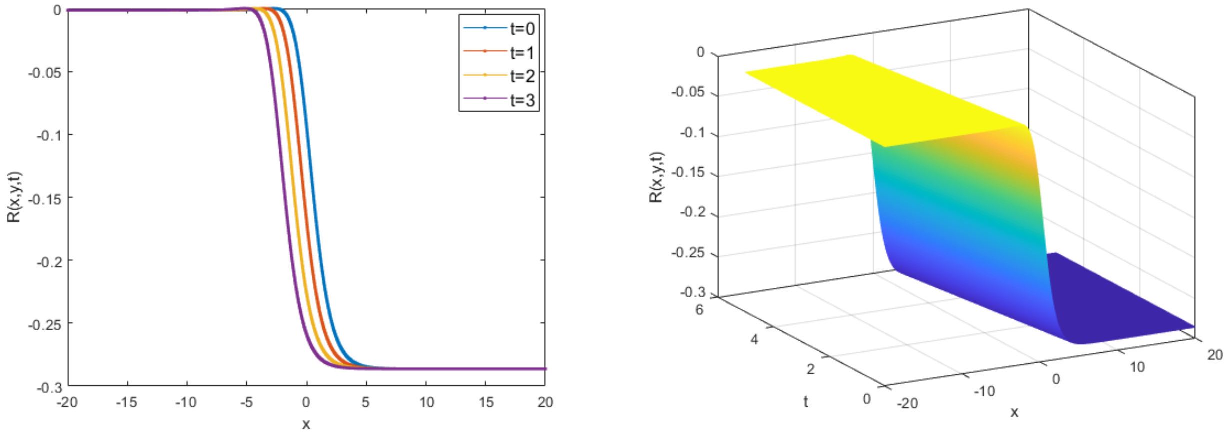

Figure 4. 2D and 3D plots of anti-kink wave solution (3.25).

Figure 5 depicts the 2D and 3D plots of the periodic wave solution (3.26). Figure 6 illustrates the 2D and 3D plots of the kink wave solution (3.27). Figure 7 shows the 2D and 3D plots of the periodic wave solution (3.30). A random structural representation is represented by the solution (3.26), as seen in Figures 8–10. These figures demonstrate the variation of the dissipative solution (3.26) in relation to spatial coordinate x, temporal variable t, and the influence of noise represented by σ. Like σ grew, the rate of distortion increased, and the wave behaved like a dissipative wave, as seen in Figures 8–10, and may be derived shock wave amplitude as depicted in Figure 8.

The effective, straightforward, succinct, and robust method employed for the extraction of solitary wave solutions can be applied to a variety of NPDEs within the realms of mathematical physics and several branches of natural sciences. Finally, the stochastic structure of solutions is able to explain many sophisticated phenomena in these fields and others more.

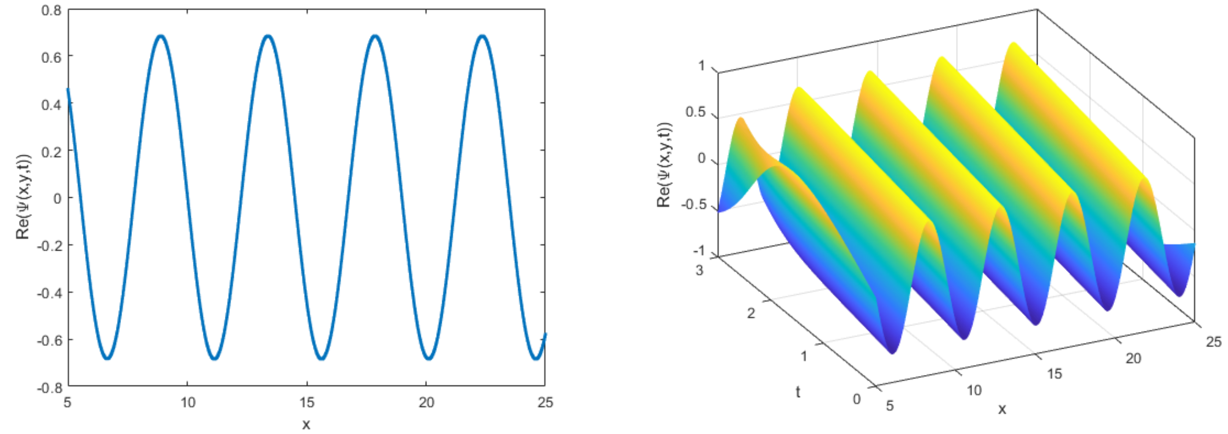

Figure 5. 2D and 3D plots of the periodic wave solution (3.26).

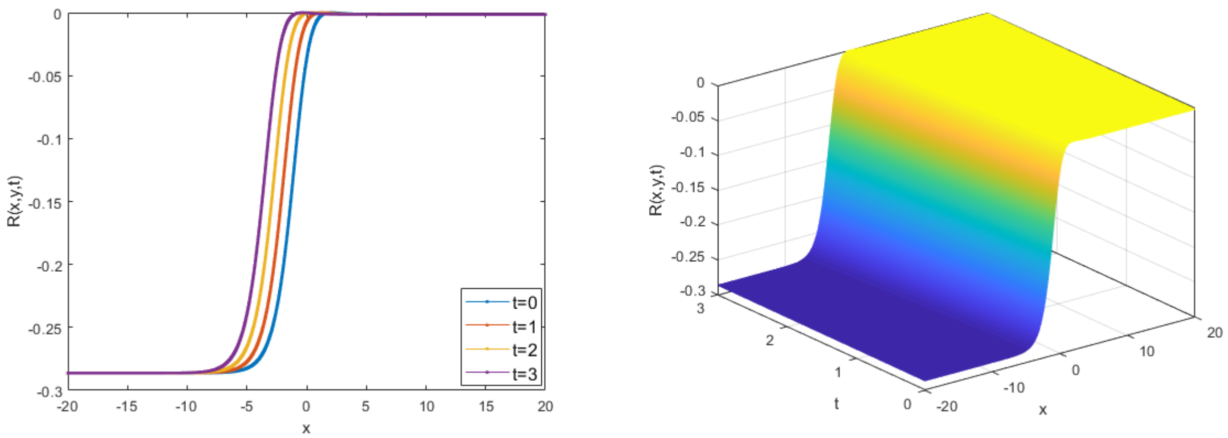

Figure 6. 2D and 3D plots of kink wave solution (3.26).

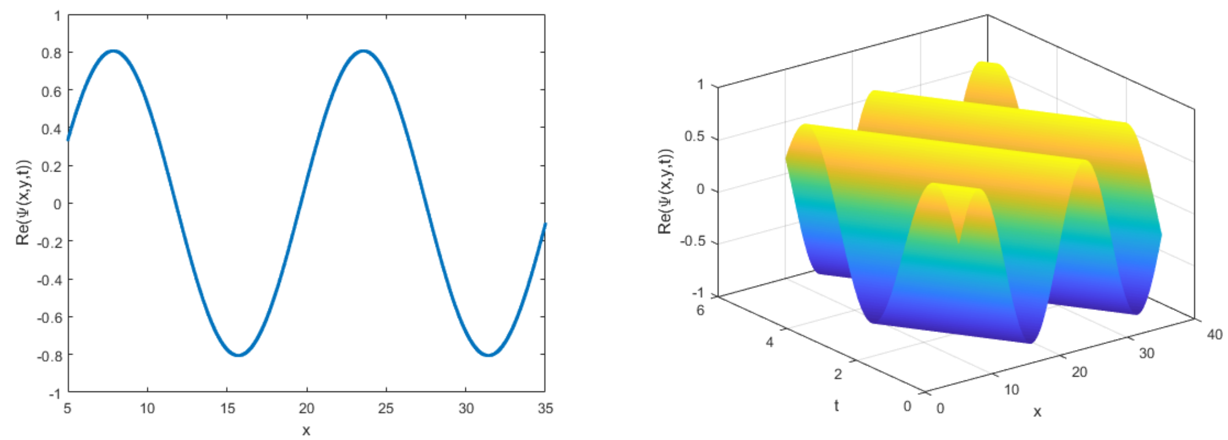

Figure 7. 2D and 3D plots of periodic wave solution (3.30).

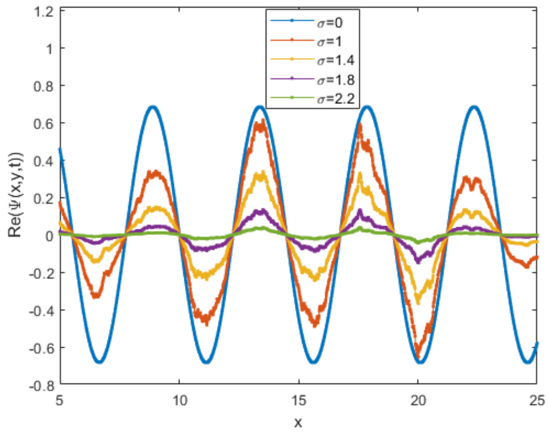

Figure 8. 2D plot of solitary wave (3.26).

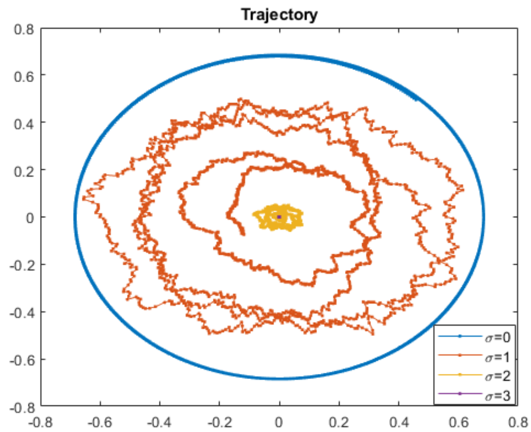

Figure 9. Trajectory of solitary wave (3.26).

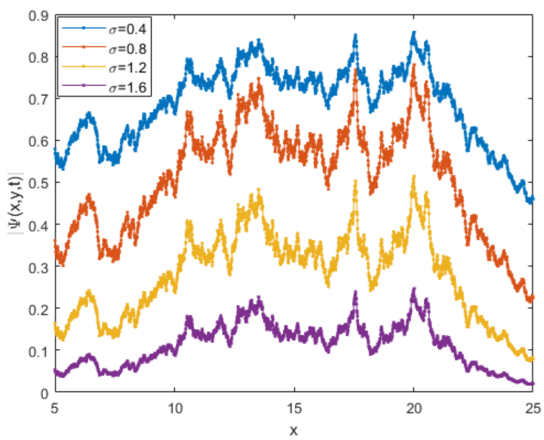

Figure 10. Changes of $|\psi_{19}(x, y, t)|$ with noise strength.

5. Conclusions

In this study, several new stochastic solitary wave solutions to the 2D nonlinear Maccari's system have been successfully derived utilizing the unified approach. These solutions exemplify essential phenomena in the fields of optics, plasma physics, Langmuir solar wind, and hydrodynamics. This work demonstrates a rapid and clear solution procedure, resulting in a higher number of novel solutions than existing methods. Increasing the random parameter was shown to cause both driving shock wave amplitude and frantic solitonic collapse. Several 2D and 3D profiles representing appropriate physical characteristics have been utilized to demonstrate the behavior of solutions. In subsequent research, we will employ alternative analytical methods to obtain more solutions for stochastic traveling waves. Additionally, we will examine the bifurcation and chaotic patterns associated with the Maccari model.

Author contributions

M. B. Almatrafi and Mahmoud A. E. Abdelrahman: Conceptualization, Software, Formal analysis, Writing–original draft. All authors have read and approved the final version of the manuscript for publication.

Use of Generative-AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare that they have no competing interests.

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