Numerical Solution of the Regularized Long Wave Equation using Radial Basis Function Ghost Point Method

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Abstract: - The outcomes of numerical research of the 1-D Regularized Long Wave (RLW) equation using the meshless Radial Basis Function (RBF) collocation Ghost point Method are presented in this research paper. The RLW equation is frequently applied to solitons and to the study of water waves and other fluid mechanics problems. The paper suggests applying the RBF-Collocation method, which uses ghost points to set the boundary conditions, and uses it to analyze the RLW equation for different values of initial & boundary conditions and parameters. The proposed method is accurate and efficient because it matches the solutions found in the available literature for exactly solvable and analytical cases. The results indicate that the RBF-Collocation ghost point method is helpful for solving the RLW equation and can be applied to many real-world problems. The research paper contributes to developing numerical methods for solving partial differential equations without using meshes.

Key-Words: - Collocation method, Ghost points, Meshless Methods, Radial Basis function, Regularized Long Wave equation, Shape parameter.

Received: September 16, 2025. Revised: December 11, 2025. Accepted: January 23, 2026. Published: April 1, 2026.

1 Introduction

The Regularized Long Wave (RLW) equation is identical to the Benjamin-Bona-Mahony (BBM) equation and is frequently examined since it describes long waves with a small but definite amplitude in dispersive media. It follows the traditional way of writing as:

$$u_t + u_x + \varepsilon u u_x - \mu u_{xxt} = 0 \; ; \; x \epsilon \Omega, 0 \le t \le T \quad (1)$$

the wave amplitude is called $u(x,t)$, ε and μ are positive constants that determine the nonlinearity and dispersion, respectively, and $\Omega \subseteq R^d$, where d ≤ 3, stands for the spatial domain. Boundary conditions are also used to explain the equation.

$$u(x,t) = g_1(t); \; x \epsilon \partial\Omega, 0 \le t \le T \quad (2)$$

$$\frac{\partial}{\partial n} u(x,t) = g_2(t); \; x \epsilon \partial\Omega, 0 \le t \le T \quad (3)$$

where n denotes the outward normal to the boundary ∂Ω, and an initial condition

$$u(x,0) = g_3(t); \; x \epsilon \Omega \quad (4)$$

[1] introduced the RLW equation to describe undular bores and waves in shallow waters, and it has been used instead of the classical Korteweg-de Vries (KdV) equation. RLW is successful because it gives accurate results and more stability for long-term simulations of waves. Later, [2] studied the problem of finding and classifying solutions for the RLW equation, and this work made it a central model in the field of nonlinear dispersive waves.

If we look at its physical meaning, the RLW equation describes how nonlinear behaviour and wave dispersion are linked in fluid mechanics, plasma physics, and nonlinear optics. RLW dynamics are notable for having solitary waves that can travel at a constant speed without changing their form, just like waves along shores, channels, and in fluid layers [3]. Because science experiments and reality have shown the existence of solitons, the equation is important for modelling real waves in nature.

Through analytical work, exact and approximate solitary waves have been found using the MEDA [4] as well as (G'/G)-expansion methods [5]. They help to check the success of numerical schemes.

Because the RLW equation is nonlinear and dispersive, its numerical solution has attracted a lot of study due to the main issues involved such as managing nonlinear terms, ensuring stability and properly placing waves. Many research studies have used the traditional finite difference, finite element, and spectral methods [6], [7], [8]. Some useful approaches are quintic and cubic B-spline collocations, Galerkin finite element techniques with extrapolation, and high-order linear structure-preserving schemes [9], [10], [11].

Apart from mesh-based techniques, radial basis function (RBF) collocation and finite-point methods have received attention because they handle complicated geometries and boundary conditions well [12], [13]. With RBF methods, there is no need for a mesh to achieve high accuracy in spatial terms, making them convenient for handling domains or boundaries that vary in shape [14].

There is still much difficulty in dealing with the RLW equation because it involves solving problems with both Dirichlet and Neumann boundary conditions at the same time. Some of the classical approaches require creating detailed meshes and dealing with boundaries, which sometimes makes the outcomes inaccurate or slows down calculations. As a result, ghost point or fictitious point approaches were developed by adding more points around the boundaries to ensure proper enforcement of boundary conditions and keep high-order accuracy [15], [16]. Using ghost point methods with RBF collocation allows RBFs to offer the meshless feature and for ghost methods to be flexible on boundaries, potentially improving the performance of RLW solvers.

Some recent researchers have expanded the RLW equation to cover variable coefficients, more spatial dimensions, and nonlinear coupled wave systems, making it useful for two-dimensional shallow water waves, plasma waves, and nonlinear lattice dynamics [17], [18]. Thanks to progress in high-performance computing and adaptive algorithms, it is now easier to study in detail the ways waves interact, whether the water remains stable, and their evolution over a long period.

Even with these progresses, experts continue their search for improved precision, stability, and efficiency in numerical methods, mainly while solving problems that must be integrated for long times or apply to many dimensions. There is still much interest in finding the best shape parameters for RBFs, building adaptive meshless methods, and integrating ways to compute time with efficient spatial methods [19], [20].

In this field, this paper offers a meshless RBF collocation method along with a ghost point technique to address the one-dimensional RLW equation. Various boundary condition challenges are resolved completely without risk of noise, and the approach shows high accuracy and strong computational performance when compared with classic solitary wave benchmarks. Because of its flexibility and sturdiness, the method can be used for many types of nonlinear dispersive wave problems seen in applied physics and engineering.

2 Radial Basis Function Approximation

Many areas, such as engineering, physics, finance, and data science, use Radial basis function (RBF) approximation as an important approximation method. Because they can handle complex functions in a flexible manner, RBFs are used in many areas. RBFs are functions that are described by their distance from particular points, which are called centers [20]. The most popular RBF is the Gaussian RBF, and it is defined as shown below:

$$\emptyset(x) = e^{-\epsilon^2 r^2}, \quad where\ r = \|x - c\| \tag{5}$$

The RBF at point x is represented by $\emptyset(x)$, c is the center, ϵ is the shape parameter, and $\|x - c\|$ shows the distance between x and c in Euclidean space. A function can be approximated using RBFs by combining a number of RBFs that are centred on different points [20]. It is provided by:

$$f(x) = \sum_{i=1}^{N} \omega_i \varphi(\|x - c_i\|) \tag{6}$$

f(x) stands for the estimated function, ω_i is the weight of the i-th RBF, c_i means the center of the i-th RBF, and N is how many RBFs there are. The weights ω_i are determined by checking how well the approximated function agrees with the actual function at the chosen centers. RBFs have one of the main advantages over using them is their flexibility. Given RBFs are able to model nonlinear and non-smooth functions. This makes them suitable for many real-world applications where the function to be approximated is complex and cannot be modelled by simpler functions. The most used RBFs [20] are given in Table 1.

Table 1 Commonly used RBFs

RBF	$Definition$
Gaussian	$e^{-\varepsilon^2 r^2}$
Inverse Quadric	$\frac{1}{1+\varepsilon^2 r^2}$
Inverse Multiquadric	$\frac{1}{\sqrt{1+\varepsilon^2 r^2}}$
Multiquadric	$\sqrt{1+\varepsilon^2 r^2}$
Spline (Polyharmonic)	$r^k, k = 1,3,5, ----$
	$r^k \log(r), k = 2,4,6, ----$
Spline (Thin plate)	$r^2 \log(r)$

Source: created by the authors

where $r = \|x - x_j\| and\ \varepsilon$ is a Shape Parameter value used to adjust the size of the radial kernel's input.

3 RBF Collocation Method

We introduce the fundamental terms and basic equations required for the RBF approximation to time-dependent partial differential equations. Let the RBF approximation of the function $u(x_j)$ for $j = 1, \dots\dots, N$ be

$$s(x) = \sum_{j=1}^{N} \omega_j \varphi(\|x - x_j\|) \tag{7}$$

where φ is an RBF such as the inverse multiquadric $\varphi(r) = (c^2 r^2 + 1)^{-\frac{1}{2}}$, where c is the shape parameter, which is frequently included in RBFs and whose optimal value selection is still a significant challenge. The coefficients $\omega_j \epsilon R$ are to be determined by the interpolation conditions $s(x_j) = u(x_j), j = 1, \dots\dots, N$.

The matrix form of the equation (7) is

$$A\underline{\omega} = \underline{u} \tag{8}$$

where $A_{ij} = \varphi(\|x - x_j\|), i, j = 1, \dots\dots, N$

$\underline{\omega} = [\omega_1, \dots, \omega_N]^T, \underline{u} = [u(x_1), \dots, u(x_N)]^T$

Using (8), Equation (7) can be written as

$$s(x) = \underline{\varphi}(x)\underline{\omega} = \underline{\varphi}(x)A^{-1}\underline{u} \tag{9}$$

where $\underline{\varphi}(x) = [\varphi(\|x - x_1\|), \dots\dots, \varphi(\|x - x_N\|)]$, for frequently used RBFs like Multiquadric, Inverse Multiquadric, and Gaussians, the matrix A is non-singular [14] .

Let $\underline{\varphi}(x)A^{-1} = \underline{\psi}(x) = [\psi_1(x), \dots\dots, \psi_N(x)]$, using this the equation (9) can be written as

$$s(x) = \underline{\psi}(x)\underline{u} = \sum_{j=1}^{N} \psi_j(x) u(x_j) \tag{10}$$

Applying a linear operator L, we get

$$Ls(x) = L\underline{\psi}(x)\underline{u} = \sum_{j=1}^{N} L\psi_j(x) u(x_j) \tag{11}$$

Now, discretizing the time interval, the approximate solution of $u(x, t)$ is given by

$$s(x, t) = \sum_{j=1}^{N} \psi_j(x) u_j(t) \tag{12}$$

where $u_j(t) \approx u(x_j, t)$ are the unknowns to be determined.

Choice of Shape Parameter: The accuracy and stability of radial basis function collocation methods are known to depend on the choice of the shape parameter c(or ε). In this work, the shape parameter is selected empirically based on numerical experimentation, balancing accuracy and conditioning of the interpolation matrix. Very small values of the shape parameter may lead to ill-conditioning, whereas excessively large values can deteriorate approximation accuracy.

For the present RLW simulations, a moderate fixed value of the shape parameter was chosen to ensure stable time integration and accurate representation of solitary wave profiles. This approach is consistent with common practice in RBF-based solvers for nonlinear dispersive equations, where problem-dependent tuning yields reliable results without introducing excessive computational overhead. Similar strategies have been reported in the literature for RLW and related nonlinear wave equations.

4 Ghost point method for dealing Multiple Boundary conditions

Consider the RLW equation in one dimension and the corresponding multiple boundary conditions.

$$u_t - \mu u_{xxt} = h_u(u)u_x, x\epsilon[-L, L], 0 \le t \le T \quad (13)$$

with the boundary conditions

$$u(\pm L, t) = g_1(\pm L, t), 0 \le t \le T \quad (14)$$

$$u_x(\pm L, t) = g_2(\pm L, t), 0 \le t \le T \quad (15)$$

To handle the multiple boundary conditions, the Ghost point methods have been successfully used in the Finite Differences and Pseudo spectral schemes [15], [16].
Let $-L = x_2 < x_3 \dots < x_{N-1} = L$ be the distinct node points. We introduce two ghost points (additional points) by x_1 & x_N as shown in Figure 1.

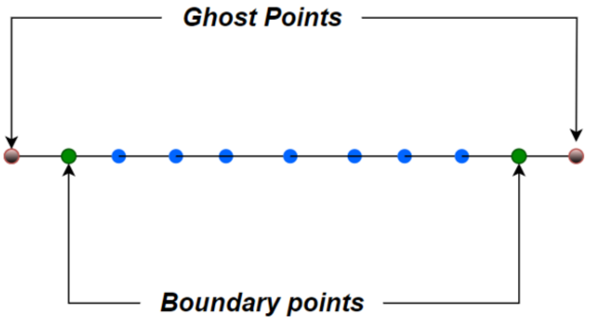

Fig. 1: Node distribution illustrating interior collocation points and symmetrically placed ghost points outside the physical domain boundaries.
Source: created by the authors

The ghost points are placed symmetrically outside the physical domain at distances equal to the interior nodal spacing. This uniform placement ensures consistent enforcement of Neumann boundary conditions while preserving the accuracy of the RBF interpolation near the boundaries.

We have from equation (12)

$$s(x, t) = \sum_{j=1}^{N} \psi_j(x)u_j(t) \quad (16)$$

The Dirichlet conditions can be imposed by taking the values $u(x_2)$ & $u(x_{N-1})$. For Neumann conditions we define $S_g = [u_1(t), u_N(t)]^T$ at the two ghost points, and

$S_d = [u_3(t), \dots \dots, u_{N-2}(t)]^T$ with the values at the interior points of the domain, then we have

$$\underbrace{[\psi_1'(x_2)\psi_N'(x_2)\psi_1'(x_{N-1})\psi_N'(x_{N-1})]}_{B_g} S_g + \underbrace{[\psi_3'(x_2) \dots \psi_{N-2}'(x_2)\psi_3'(x_{N-1}) \dots \psi_{N-2}'(x_{N-1})]}_{B_d} S_d + \underbrace{[\psi_2'(x_2)\psi_{N-1}'(x_2)\psi_2'(x_{N-1})\psi_{N-1}'(x_{N-1})]}_{B_b} G_1(t) = G_2(t) \quad (17)$$

or

$$s(x, t) = \sum_{j=3}^{N-2} \psi_j(x)u_j(t) + G(x, t) \quad (18)$$

where $\psi_j(x)$ & $G(x, t)$ are readily identifiable from the equation (17).
Now, collocating equation (18) with (13) at the node points, we get the system of ordinary differential equations

$$u_i'(t) - \sum_{j=3}^{N-2} \mu \frac{d^2\psi_j}{dx^2}(x_i)u_j'(t) = \sum_{j=3}^{N-2} h_u\big(u_i(t)\big)\frac{d\psi_j}{dx}(x_i)u_j(t) + \mu\, G_{xxt}(x_i, t) + h_u\big(u_i(t)\big)G_x(x_i, t)\,; i = 3, \dots \dots, N-2 \quad (19)$$

The resulting system of ordinary differential equations can be integrated in time using a classical fourth-order Runge–Kutta (RK4) scheme with a sufficiently small-time step to ensure stability and accuracy.

The ghost point technique employed in this work follows well-established formulations previously used in finite difference and pseudo spectral methods. Its stability and consistency for enforcing simultaneous Dirichlet and Neumann conditions have been discussed extensively in the literature. In the present context, the method provides a stable and well-defined semi-discrete system when coupled with RBF collocation, as evidenced by the absence of numerical instabilities in all simulations.

5 Error Estimation

To measure the precision of the developed numerical algorithms, L_2, L_∞ and Root Mean Square (RMS) error norms are obtained using the following formulae:

$$L_2 = \sqrt{h\sum_{i=1}^{N} |u_{exact}(x_i) - u_{num}(x_i)|^2} \quad (20)$$

$$L_\infty = |u_{exact}(x_i) - u_{num}(x_i)| \quad (21)$$

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} |u_{exact}(x_i) - u_{num}(x_i)|^2} \quad (22)$$

6 Numerical Results

Test Problem: Consider the RLW equation of the form

$$u_t + u_x + \varepsilon u u_x - \mu u_{xxt} = 0 \quad (23)$$

where u, t, x denote the amplitude, time, and spatial coordinate respectively & ε, μ are positive constants. The theoretical solitary-wave solution to the RLW equation (23) is given by [6]

$$u(x,t) = 3c\, sech^2[k(x - x_0 - vt)] \quad (24)$$

The initial condition is

$$u(x,0) = 3c\, sech^2[k(x - x_0)] \quad (25)$$

where $v = 1 + \varepsilon c$ is the wave velocity, $3c$ is the amplitude of the solitary wave, x_0 is the peak position of the initially centered wave & $k = \sqrt{\frac{\varepsilon c}{4\mu v}}$. The exact solution (24) gives the boundary conditions.

The simulation of a single solitary wave is done using the suggested method over the domain $-10 \le x \le 10$ and in the time span $0 \le t \le 5$ with the parameters $\mu = 1, \varepsilon = 3, x_0 = 0, c = 0.24,\ N = 50\ (including\ ghost\ points)$. The computational domain was chosen sufficiently large so that the soliton amplitude decays rapidly near the boundaries. Moreover, boundary conditions were imposed using the exact analytical solution, which effectively eliminates artificial wave reflections during the simulation time interval. Comparison of Exact & Numerical solution based on the proposed method is shown in Figure 2. The error norms such as L_2, L_∞ & RMS for different time t are shown in Table 2. It is clear from the plot that the numerical solution is a good estimate of the exact solution for the 1D RLW equation, using only 50 grid points and a domain size of 10. Since the numerical and exact solutions are very close at all the time steps, it proves that the numerical method is reliable for solving the RLW equation and following the soliton.

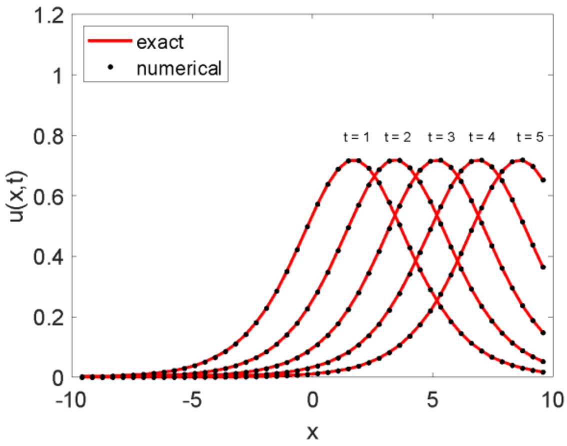

Fig. 2: Comparison of Exact and Approximate Solution with L=10 and N=50
Source: created by the authors

Table 2: Error norms for N=50 and L=10

Time	L_2	L_∞	RMS
T=1	6.20E-06	2.20E-06	8.77E-07
T=2	9.99E-06	4.30E-06	1.41E-06
T=3	1.36E-05	5.66E-06	1.92E-06
T=4	1.57E-05	5.80E-06	2.21E-06
T=5	1.63E-05	5.35E-06	2.31E-06

Source: created by the authors

Now, we solve the equation (21) with exact and initial condition (22), (23) with the following parameters $L = 15\,, N = 80$

Comparison of Exact & Numerical solution based on the proposed method is shown in Figure 3. The error norms such as L_2, L_∞ & RMS for different time t are shown in Table 3.

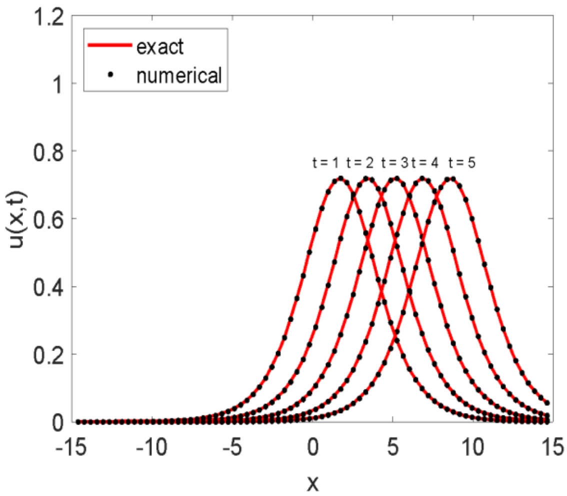

Fig. 3: Comparison of Exact and Approximate Solution with L=15 and N=80
Source: created by the authors

Table 3: Error norms for N=80 and L=15

Time	L_2	L_∞	RMS
T=1	6.50E-06	2.29E-06	7.27E-07
T=2	1.04E-05	4.29E-06	1.17E-06
T=3	1.42E-05	5.80E-06	1.58E-06
T=4	1.58E-05	5.84E-06	1.77E-06
T=5	1.67E-05	5.13E-06	1.87E-06

Source: created by the authors

Although convergence plots are not explicitly shown, the error norms reported in Table 2 and Table 3 demonstrate a clear reduction in error with increasing number of nodes and domain size. This behaviour is consistent with the expected convergence properties of RBF collocation methods, where accuracy improves rapidly with node refinement for smooth solutions such as solitary waves. Similar convergence trends have been widely reported for meshless RBF schemes applied to nonlinear dispersive equations.

The 3-D plot of the exact solution (24) in Figure 4 clearly shows how a solitary wave (soliton) travels in the RLW equation. The soliton keeps its shape as it moves in the positive x-direction, not spreading out, which is a main feature of solitons in nonlinear wave equations.

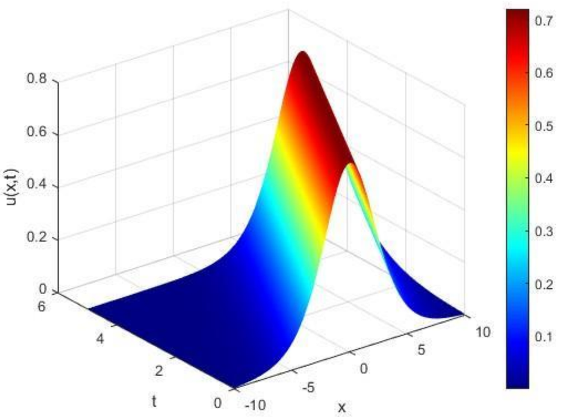

Fig. 4: 3-D profile of exact solution with L=10
Source: created by the authors

7 Conclusion

In the study, the RLW equation was solved numerically using the RBF collocation method with the ghost point technique, and the results were good. The meshless approach of this study is found to be capable of accurately approximating primarily solitary wave solutions and responding to complex boundary conditions in a manner which traditional methods have difficulty with, through a series of numerical experiments. By rigorous error analysis, numerical and exact solutions have a close agreement that testifies the robustness and reliability of the method to capture nonlinear dynamics of the RLW equation.

The flexibility of the RBF ghost point framework makes it a very useful tool for numerically solving nonlinear partial differential equations in a number of applied sciences in that, through insertion of simple constraints, it can retain high accuracy with relatively few discretization points. This technique is easier to manage boundary conditions than conventional mesh-based techniques without loss in solution quality.

In all simulations, the shape parameter was kept constant and selected empirically based on preliminary numerical experimentation. The chosen value provided a balance between approximation accuracy and conditioning of the interpolation matrix. No automated optimization strategy was employed, as the results were found to be robust to small variations in the shape parameter.

Regarding numerical stability, the proposed RBF ghost point formulation exhibited stable soliton propagation over the entire simulated time interval without the emergence of spurious oscillations or numerical damping. The stability is attributed to the smooth global approximation of RBFs combined with the consistent enforcement of boundary conditions through ghost points. These features allow reliable long-time integration of the RLW equation for the tested parameter ranges.

Finally, future research will consider using this technique for RLW problems based on multidimensional RLW and other nonlinear wave equations. Also, better computational efficiency and accuracy could be reached by carefully choosing the shape parameters in the RBF formulation. Extending the approach to handle nonlinear and more real-world situations can be achieved by using adaptive schemes and time integration methods.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.