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Investigating the Impact of J-Head Spur Dike Orientation and Spacing on River Reach Efficiency Using HEC-RAS 2D

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Abstract

The study evaluates the performance of J-head spur dikes in controlling lateral migration and bank erosion along the right bank of the Indus River, downstream of the Ghazi Ghat Bridge in Dera Ghazi Khan district, Punjab, Pakistan. The erosion of the outer bank poses significant threats to infrastructures and local settlements, highlighting the need for spur dikes to regulate flow and implement protection measures. The HEC-RAS 2D model was used for this analysis. The results revealed that spur dikes oriented upstream were generally ineffective due to clogging of an active creek, whereas a downstream orientation at 120° was found more effective in diverting flow towards the main channel than at 135°. To manage high flood events, it was proposed to raise left bund by 2 ft and the spur at RD 138+000 by 1.50 ft. The performance of existing spur dikes was analyzed based on the prevailing spacing of 2 to 5 times the length of the spur at RD 138+000. Additional spur dikes at RD 141+500 and RD 154+000, near Samina Town and Basti Bhai, were introduced to improve flow patterns and protect irrigation infrastructures and local settlements. It was observed that at low flows, the velocity along both creeks was slightly declined from 1.09 to 0.92 ft/sec, while at high flows, the velocity reduced from 1.92 to 1.33 ft/sec between RD 138+000 and RD 148+000, and from 2.69 to 2.34 ft/sec between RD 148+000 and RD 165+000. These findings emphasize the need for customized spur dikes designs, considering orientation, spacing and hydraulic conditions. The findings of this study provide valuable insights and may be used to enhance flood management, infrastructure safety, and sustainable riverbank protection for future interventions.

Keywords: Groynes, Digital Elevation Model (DEM), Irrigation Research Institute (IRI), Manual of Irrigation Practice (MIP), Ghazi Ghat Bridge, HEC-RAS 2D.

1. Introduction

Spurs or groynes are structures constructed from a riverbank into the stream to deflect water and protect the bank from erosion by promoting sediment deposition. Spurs are most cost-effective compared to riprap and other flood protection methods. These structures are used to deflect flow and channelize the stream. Other related structures, such as vanes, jetties, retards, fences are also used for bank protection and land reclamation (Julien, 2002). Spurs are generally built for protection of the banks by controlling velocity and divert flow away towards the center of the channel (Yang et al., 2022).

Outer bank erosion often results in unpredictable lateral migration of rivers, posing significant threats to land and infrastructure. Spurs are widely used as flow-control structures to regulate water movement and protect riverbanks from erosion (Shokrian Hajibehzad et al., 2020). These structures are integral components of river training works, designed to manage the direction, velocity and depth of river flow, thereby reducing hydrodynamic forces acting on the river banks (Patel et al., 2023). In river engineering, spur dikes serve various purposes, including channel regulation, flood prevention, river diversion, banks reclamation, flow depth modification, and the protection of riverbanks and beds (Gu et al., 2020). Spur dikes are widely used as bank protection measures in river training works, where their geometry, orientation and spacing significantly affecting performance (Patel et al., 2023).

Recommended spacing for spur dikes in straight channels varies across studies. Spacing factor for spur dikes generally ranges from 1 to 6 (Patel et al., 2023). The appropriate spacing ranges from 4 to 6 times the effective length of the structure (Kim et al., 2014). Yarahmadi et al. (2020) recommended a spacing of 5.5 times the effective length of the structure. The recommended spacing for a straight channel range from 5 to 6 times the length of the spur, for convex bends 2.5 to 3 times and for concave bends equal to the length of the spur (Zaidi and Azam, 2017).

The effective downstream orientation for spurs was found to be 120° (Giglou et al., 2018; Saleem, 2018). Spur dikes oriented at 120° downstream were observed to result maximum velocity reduction and increased sedimentation areas (Giglou et al., 2018). Hocky-shape spur dikes showed better performance in reducing scour depth compared to straight, mole-head, L-shaped and T-shaped designs (Ezzeldin et al., 2018). According to experts from Irrigation Research Institute, Nandipur, Gujranwala, J-head Spur dikes are commonly employed for effective flow interception, particularly in high-stage flow areas. River training models emphasize optimization by considering both economic and site-specific factors. Flood mitigation is achieved through the application of flood control measures to the site unique requirements. J-head spur dikes are frequently used and highly effective for large river reaches and for high flow conditions, facilitating smooth flow interception and guidance (Ahmad, 2024, (IRI) personal communication).

Ghazi Ghat Bridge, is situated 60 km downstream of Taunsa Barrage with a discharge capacity of 1,000,000 cusecs, connecting Dera Ghazi Khan to Multan. The Indus River in this region is braded, flowing through multiple channels. This section has experienced flooding under medium flow conditions since the construction of the bridge.

The increasing impact of climatic variability has exacerbated flood hazards and riverbank erosion along the Indus River, thereby increasing vulnerability of local communities in the floodplain. Repeated land loss due to erosion has forced many residents to migrate from their native areas (Ahmad et al., 2024). The mighty Indus River exhibits distinct operational modes during the summer and winter seasons, with minimum discharges of 50,000 cusecs in winter, increasing to medium and high flood discharges during summer (Khan and Chohan, 1985). Several villages lie within the floodplain, which are highly vulnerable to flooding. During the 2010 flood, much of the area including Basti Bhai and the left bank region, was inundated. The 2020 flood caused significant damage to the existing J-head spur dike upstream at RD 138+000. The Haiderwala Head Regulator found near canal link-1, lies in close proximity of the damaged spur. Floodwaters also submerged parts of Samina Town, causing erosion in Basti Bhai and directly threatening the irrigation system and adjoining settlements. Subsequently, the 2022 flood exacerbated the erosion, further advancing towards Basti Bhai. In order to safeguard the Head Regulator and Link Canal-1 from erosive action of the river, river training works including spurs and flood protection bund had already been constructed in the subject reach by the Irrigation Department. To protect the head regulator, canal link-1 and the adjoining settlements, the irrigation office D.G. Khan Zone, referred this issue to the Irrigation Research Institute (IRI), Nandipur. The Physical Model was employed at the hydraulic research station to identify suitable remedial measures for repairing the damaged spur at RD 138+000 and to ensuring the safety of the irrigation system, agricultures lands, and local settlements. To safeguard irrigation infrastructure and local settlements, this study investigates the performance of spur dikes at different orientations and spacings along a river reach using HEC-RAS 2D model. HEC-RAS is being applied by many researchers for flood analysis including (Khan et al., 2020). Hydrometeorological trend analysis and flood hazard assessment on the Indus basin has also been carried out by many researchers including (Salah Ud Din et al., 2022; Moazzam and Ali, 2016).

2. Materials and Methods

2.1 Study Area

The study area is located on the right bank of the Indus River, downstream of the Ghazi Ghat Bridge in Dera Ghazi Khan district, Punjab, Pakistan. It focuses on the bank protection works implemented by the Irrigation Department, covering a 33 km stretch from the Ghazi Ghat Bridge to Bait Cheen Wala. The works are designed to safeguard irrigation infrastructure, agricultural land, and local populations from flood damage. The spurs selected for this study are situated along the link-1 canal at RD 138+000, RD 148+000, and RD 165+000. The first spur is positioned 6 km downstream of the Ghazi Ghat Bridge. These structures play an essential role in protecting the local ecosystem and nearby settlements. Consequently, corrective measures are essential to mitigate flood risks effectively. To safeguard irrigation infrastructure and local settlements, this study investigates the performance of spur dikes at different orientations and spacings along a river reach. Using the HECRAS-2D Model, existing spur dikes in the Indus River downstream of Ghazi Ghat Bridge, was analyzed with data and technical guidance from the research station IRI Nandipur. The expected outcome of the study includes suggestions on optimization of orientation and spacing of spur dikes for improved flow patterns within the above-mentioned reach from RD 138+000 to RD 165+000. In this, article the subject reach of the river was analyzed using HEC-RAS 2D model. Table 1 displays latitude and longitude of the existing spurs in the selected reach. Figure 1 shows a Google Earth image of the study area, while Figure 2 provides the layout map of the study area as prepared by IRI Nandipur, Irrigation Department Punjab, Pakistan.

Table 1. Latitude and longitude of existing structures in the subject reach.

Spur at RD 138+000		Spur at RD 148+000		Spur at RD 165+000	
Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
30° 0' 48.24" N	70° 46' 48.72" E	29° 59' 11.76" N	70° 46' 27.12" E	29° 56' 58.92" N	70° 45' 25.2" E

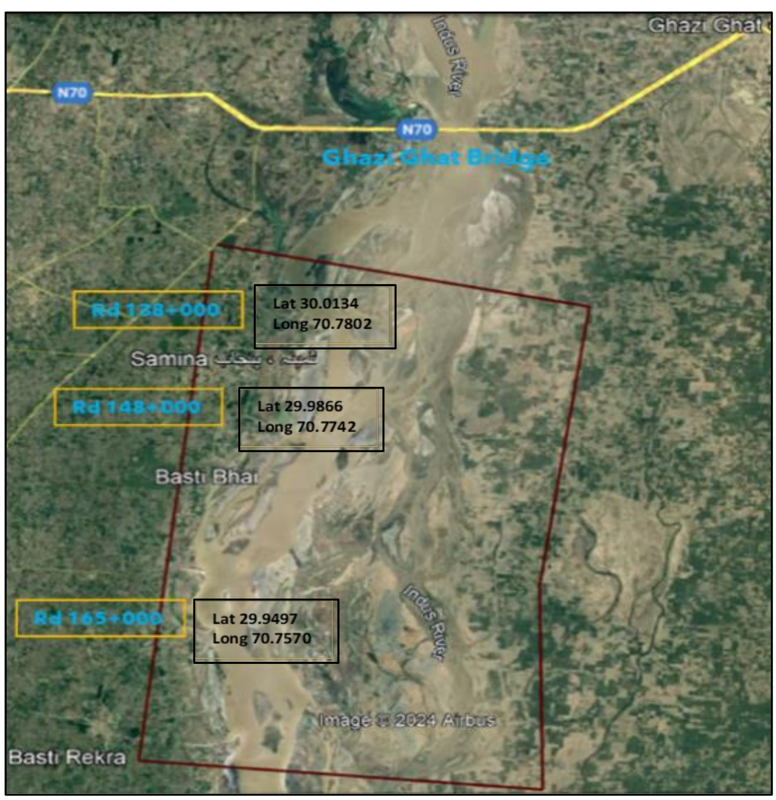

Fig. 1. Google Image of study area

Fig. 2. Layout map of study area

2.2 Data Collection

For this study, data was collected from the IRI Nandipur Gujranwala. The collected data and information included reports, maps, Google images, discharge data, velocity tables, water surface elevations, infrastructure elevations, and technical guidance. In addition, historical river discharge data at the Taunsa Barrage gauge station was retrieved from the IRI and the Annual Report (2021) of Federal Flood Commission, Government of Pakistan. The primary data sources are shown in Table 2.

2.3 HEC-RAS 2D Model

Hydraulic modeling with HEC-RAS 2D involved the creation of a Digital Elevation Model (DEM) as shown in Figure 3, followed by the integration of projection and terrain files, setting up the 2D flow area, and defining upstream and downstream boundary conditions. Flow control structures, such as levees and dikes, were introduced using break lines, and parameters such as mesh size and roughness coefficients were assigned. For unsteady flow, data including upstream hydrograph and downstream normal depth were considered. The simulation results for the unsteady flow were analyzed in RAS Mapper to produce velocity profiles, inundation, water surface elevation, depth and terrain maps.

Table 2. Brief detail of primary data used in this study.

Data Type	Source	Purpose
Technical Guidance, Reports, Design Parameters, Water Surface Levels data from Ghazi Ghat Bridge to Bait Cheen Wala, Location Maps and other required data including conclusions and recommendations of the physical model	Irrigation Research Institution Nandipur, Gujranwala (Irrigation Department Lahore, Pakistan)	Analyzing existing structures along the river for flow patterns at various flow conditions
Historic flood data for the last 38 years (annual peak flow from 1958 to 2023)	Federal Flood Commission Report 2021 and IRI Nandipur	Average flow conditions of study area, flow frequency analysis and return period
Digital Elevation Model (DEM) Data	World Geological Survey 1984 UTM Zone 42 N (Northern Hemisphere) Earth Explorer	Topographical modeling
Projection File	SpatialReference.org	Spatial data alignment in GIS

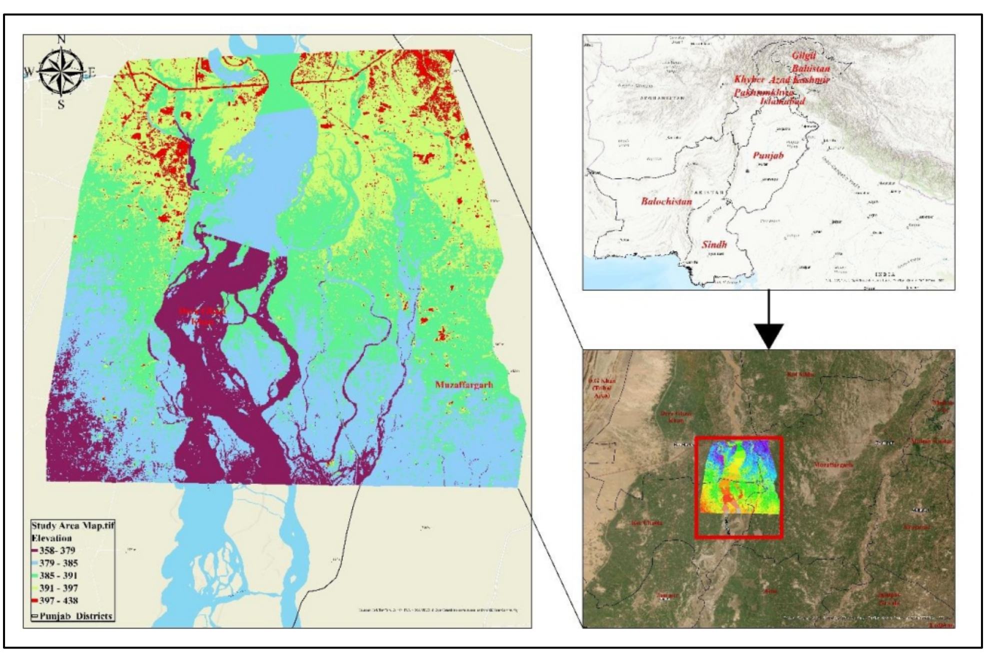

Fig. 3. Digital Elevation Model (DEM) of study area (30 30 ft) Resolution

A projection file, downloaded from Spatialreference.org (WGS84), was used to set the coordinate system for spatial data in HEC-RAS 2D. The first step in modeling was to integrate the projection and terrain files in RAS-Mapper. The terrain file was generated from a DEM obtained from the World Geological Survey using WGS 1984 UTM Zone 42N (Northern Hemisphere). GLO DEM data at a resolution of 30 30 ft represented the terrain of the study area downstream of Ghazi Bridge on the Indus River. A 2D flow area was defined with mesh generation and boundary condition lines to carry out two-dimensional hydraulic computations, simulating flood plains, river banks, and water flow patterns. Flow control structures, including spur dikes and bunds, were introduced using break lines to define boundaries within the 2D flow area. This step was critical for representing flow barriers and controlling water movement in areas of interest, enabling a detailed analysis of flood protection and flow management strategies. After setting up 2D geometry (2D flow area and break lines), mesh sizing, and applying boundary conditions at the upstream and downstream, the model was run for each plan, and an unsteady flow analysis was carried out. The results for various flows and conditions were viewed in RAS Mapper to analyze submergence, flow velocity, water surface elevations, depth, and terrain across the subject reach. The locations of various structures in the study area and the schematic of the study area are shown in Figure 4 and Figure 5.

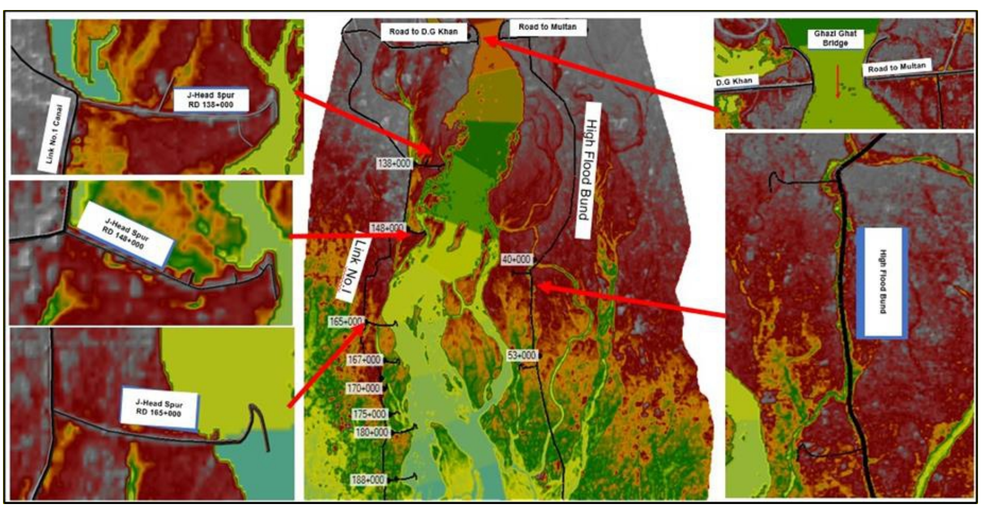

Fig. 4. Locations of structures in the study area

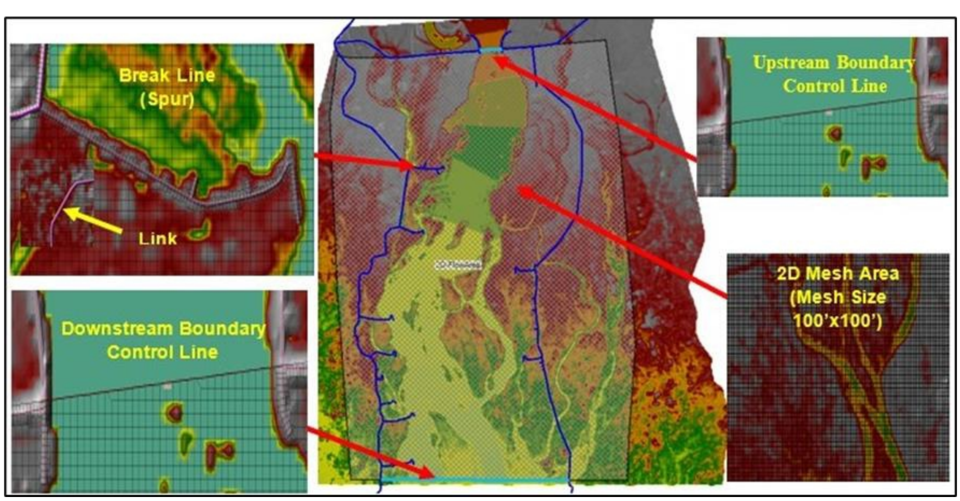

Fig. 5. Schematic of study area

In this study, the HEC-RAS 2D model was analyzed for 300,000, 700,000 and 1,000,000 cusecs. representing low, medium and high flows at natural and left bund raised conditions. This was followed by an investigation of the performance of existing structures at RD 138+000, RD 148+000 and RD 165+000 for different orientations, the prevailing spacing of 2 to 5 times the length of the spur at RD 138+000, and with the introduction of additional structures for different flows and conditions.

3. Results and Discussion

To analyze the model, different scenarios were developed for various flows and conditions. Scenario-I emphasized on analyzing existing structures under prevailing conditions to assess inundation for different flows and natural conditions. Scenario-II focused on the analysis of existing structures at prevailing spacing to determine the velocity profiles along the creeks under left bund raised condition. Scenario-III assessed different orientations of existing structures for their effectiveness under left bund raised conditions. Scenario-IV evaluated the spacing of existing structures and the introduction of proposed additional structures to determine velocity profiles and the impact of flow patterns along the bank under left bund raised conditions.

In Scenario-I, the existing structures at RD 138+000, RD 148+000, and RD 165+000 were evaluated at prevailing conditions for discharges of 700,000 and 1,000,000 cusecs. At discharge of 700,000 cusecs, the left bund was partially overtopped, but the spur dikes remained safe, as shown in Figure 6. However, at a discharge of 1,000,000 cusecs, the left bund along with the spur at RD 138+000, was overtopped, while the spurs at RD 148+000 and RD 165+000 remained unaffected, as shown in Figure 7. To prevent overtopping, raising of the left bund by 2 ft and the spur at RD 138+000 by 1.5 ft was suggested. Meanwhile, the spurs at RD 148+000 and RD 165+000 were deemed safe without modification.

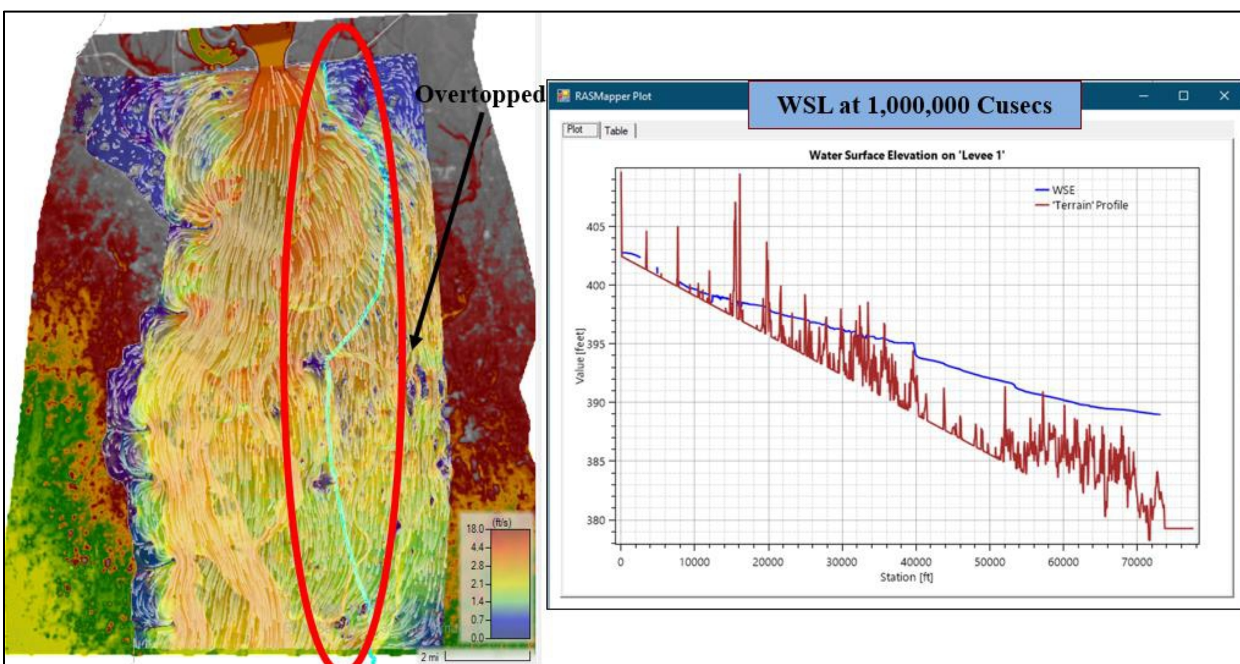

Fig. 6. At existing conditions, left bund was partially overtopped at discharge 700,000 cusecs but the spur dikes remained safe

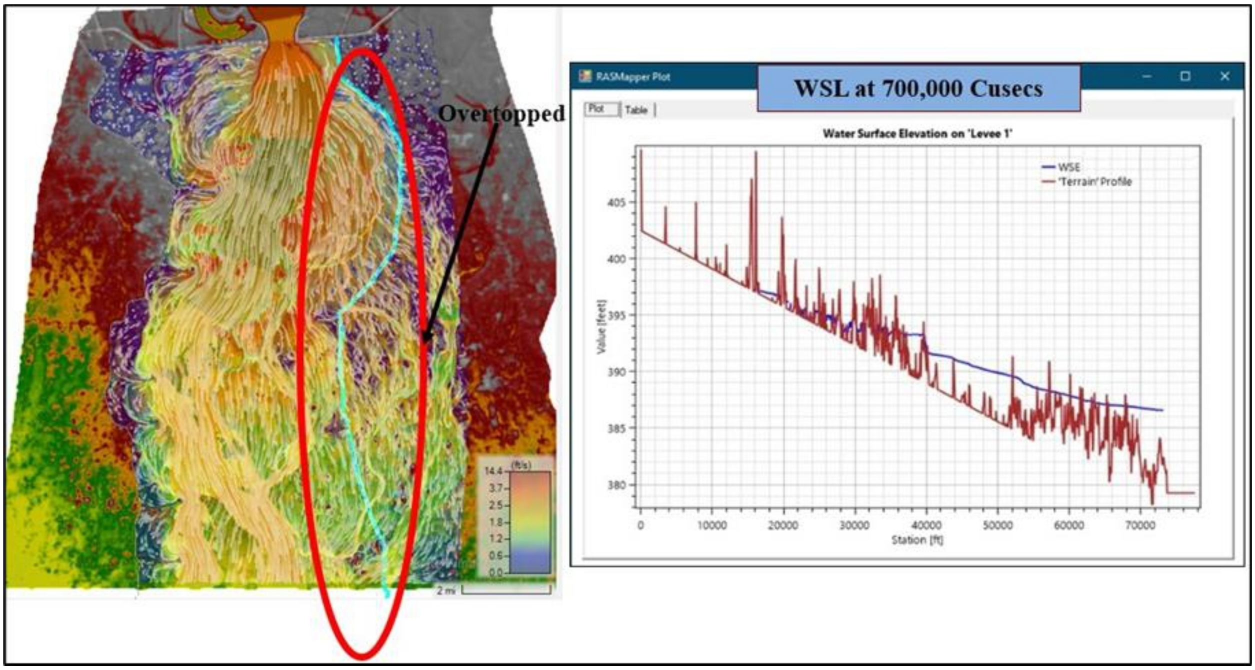

Fig. 7. At existing conditions, left bund along with spur at RD 138 was overtopped at discharge 1,000,000 cusecs, while the spurs at RD 148 & RD 165 remained unaffected.

Results from Scenario-II showed that the spacing between spurs from RD 138+000 to RD 148+000 was 2 times, and from RD 138+000 to RD 165+000, 5 times the length of the spur at RD 138+000, based on which the spurs were analysed for 300,000 and 1,000,000 cusecs under left bund raised conditions. The results indicated stagnant water and slower velocity at lower discharge between RD 138+000 and RD 148+000, which activated a nearby creek as shown in Figure 8, posing a threat to the right bank. At low discharge, village Basti Bhai remained safe but was inundated at high discharge. It was observed that as the flow increased from 300,000 cusecs to 1,000,000 cusecs, the velocity along the creek between RD 138+000 and 148+000, increased from 1.09 ft/sec to 1.92 ft/sec. Similarly, for the second creek, the velocity increased from 1.08 ft/sec to 2.69 ft/sec at 300,000 cusecs and 1,000,000 cusecs, respectively, as shown in Figure 10 and Figure 11. Flow patterns, traced by particles are shown in Figure 8 and Figure 9.

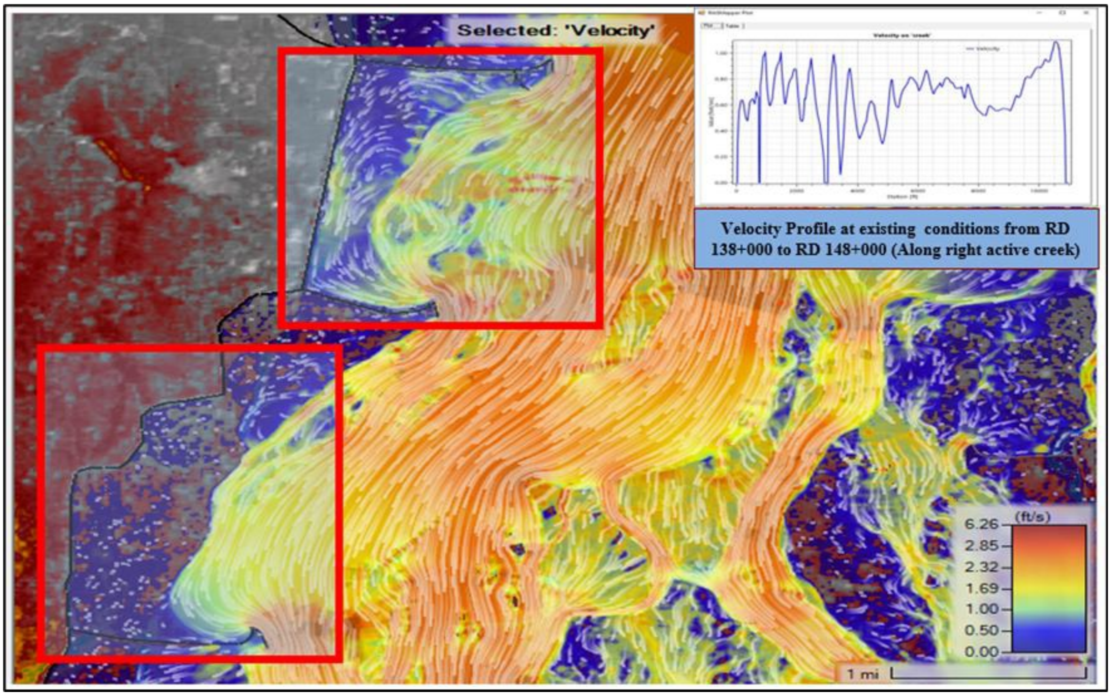

Fig. 8. Flow pattern along the bank between spurs from RD 138 to RD 148 and RD 148 to RD 165 at discharge 300,000 cusecs

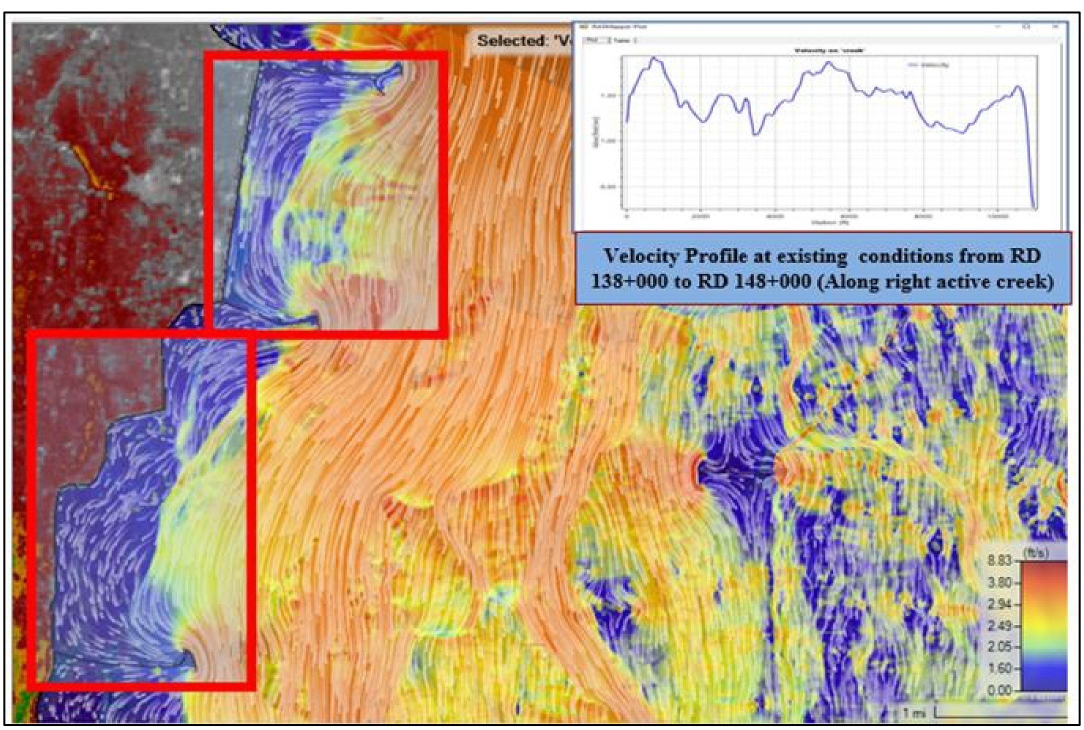

Fig. 9. Flow pattern along the bank between spurs from RD 138 to RD 148 and RD 148 to RD 165 at discharge 1,000,000 cusecs

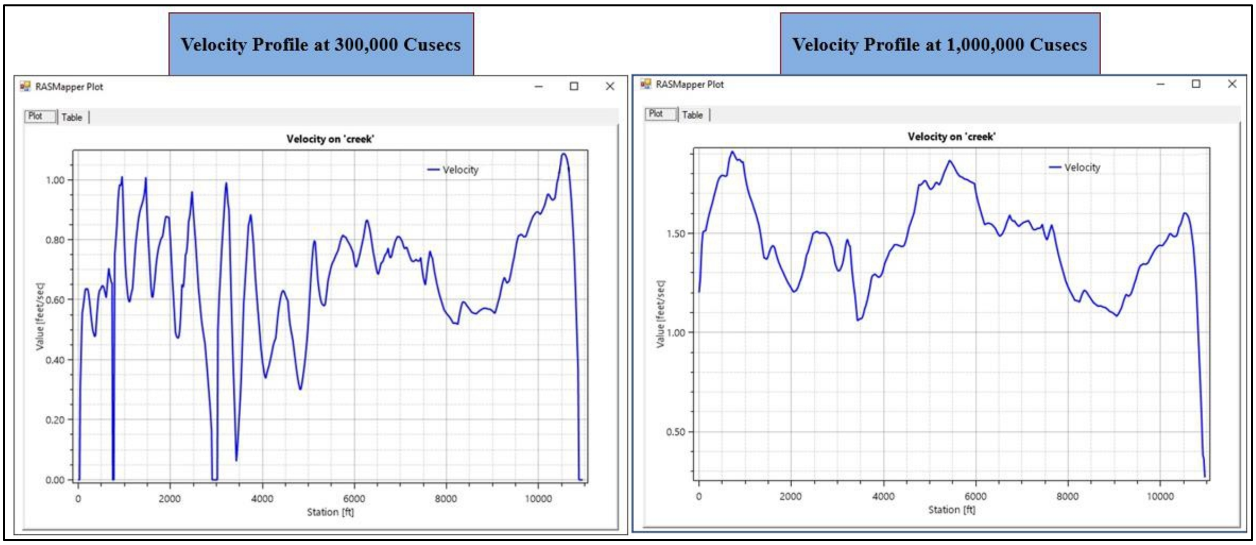

Fig. 10. Velocity Profiles at existing conditions along the creeks between spurs from RD 138 to RD 148 at flows 300,000 & 1,000,000 cusecs

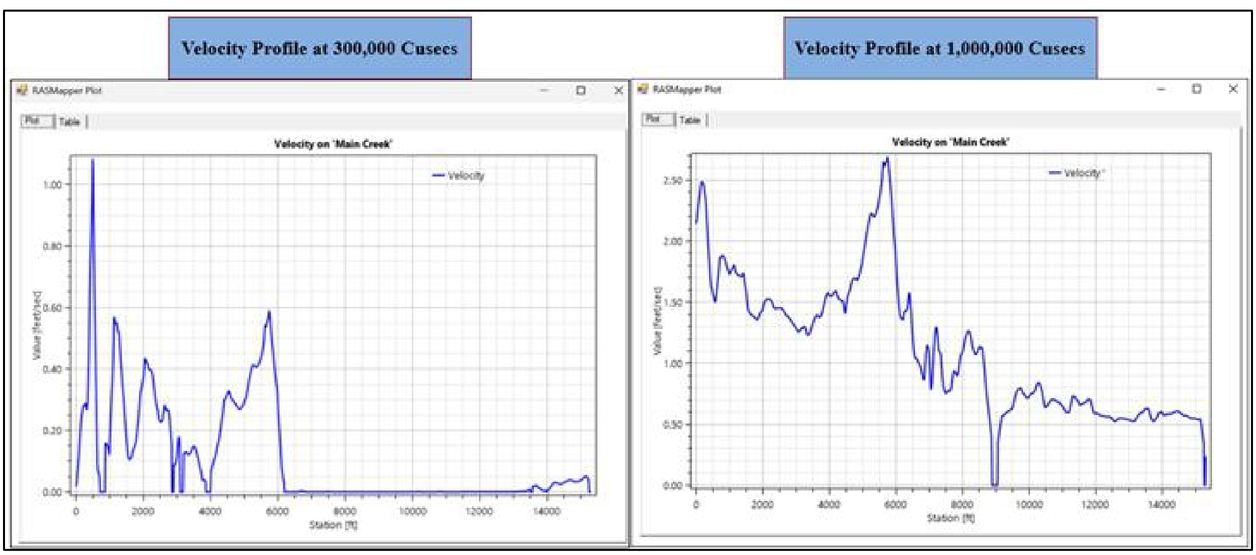

Fig. 11. Velocity Profiles at existing conditions along the creeks between spurs from RD 148 to RD 165 at flows 300,000 & 1,000,000 cusecs

Results from Scenario-III indicated that structures at RD 138+000, RD 148+000, and RD 165+000 were evaluated for angles of 120° and 135°, both for upstream and downstream orientations, at flows of 300,000, 700,000 and 1,000,000 cusecs at left bund raised conditions. The upstream orientation at 120° and discharge 1,000,000 cusecs caused blockage of an active creek and reduced velocity along the bank, leading to deposition. Downstream orientations at both angles were analyzed for all flow levels. The head of the spur was exposed to strong flow currents at the 120° upstream orientation, demanding more armoring. This could result in pondage development and saturation, leading to sloughing and structural damage. Therefore, any upstream orientation was deemed unsuitable due to creek blockage, while the 120° downstream orientation demonstrated more effective in diverting the flow currents towards the main channel. The analysis also indicated that at the 120° downstream orientation, the spur's head was less threatened by flow currents and needed less armoring as compared to upstream orientation. The stud at the connecting bund also played a key role in reducing velocity and enhancing local protection. Similarly, spurs at RD 138+000, RD 148+000, and RD 165+000 were also evaluated at 120° and 135° downstream orientations for the mentioned flows. At 135°, velocity at the head of the structure was substantially reduced as compared to 120°, but flow currents were more likely to divert towards the bank, increasing risk of erosion. Additionally, the 135° orientation was less effective in diverting flow currents towards the main channel. Based on the findings, the 120° downstream orientation was deemed more effective and suggested for future interventions.

In Scenario-IV, additional spurs at RD 141+500 and RD 154+000 were introduced to analyze their impact on flow patterns, velocity and inundation against 300,000 cusecs and 1,000,000 cusecs flows under left bund raised condition. The results indicated that at low discharge, flow remained stagnant along the bank, with a slight decline in velocity and enhanced flow patterns as the active creek shifted away from the right bank of the river with introduction of spur at 141+500 as shown in Figure 8 and Figure 12. The spur at RD 154+000 efficiently reduced erosive action of the river near Basti Bhai, preventing further advancement towards the settlements. At high flow, part of Sameena Town and village Basti Bhai were found inundated, but the newly introduced spurs resulted in improved flow patterns and controlled flow currents. The comparison of velocity profiles, with and without introduction of additional spurs from RD 138+000 to RD 165+000, indicated that at low discharge of 300,000 cusecs, velocity along both the creeks declined from 1.09 to 0.92 ft/sec, leading to more deposition along the bank. At high flow of 1,000,000 cusecs, velocity reduced slightly from 1.92 to 1.33 ft/sec between RD 138+000 and RD 148+000, and from 2.69 to 2.34 ft/sec between RD 148+000 and RD 165+000 as shown in Figure 14 to Figure 17. Decline in velocity along the channel bank with reduced spacing between spurs occurs due to combination of hydrodynamic, flow interaction factors and structural effects. However, factors contributing to decline in velocity along the channel bank may include; deflection of water away from the bank causes changes in flow patterns, redistribution of velocity across the channel, creation of different flow zones, energy dissipation due to turbulence, formation of eddies and changes in surface elevations at upstream and downstream of spurs. Very similar results were obtained by different researchers including Brown (1985), Talaat et al. (2009), Ning et al. (2019), Mojtahedi and Basmenji (2017) and Alauddin et al. (2017). The velocity vector at discharge 300,000 and 1,000,000 cusecs are shown in Figure 12 and Figure 13.

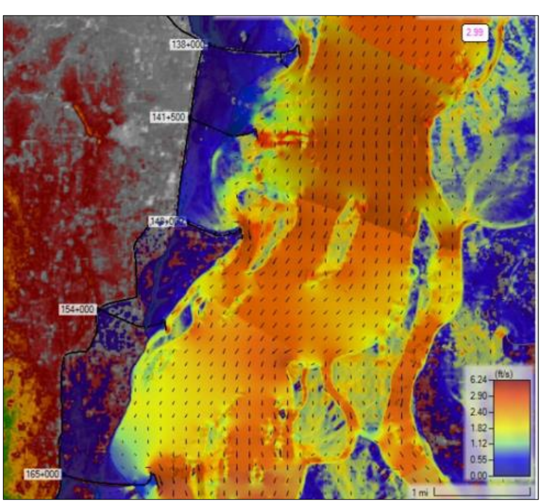

Fig. 12. Velocity Vector at discharge 300,000 cusecs

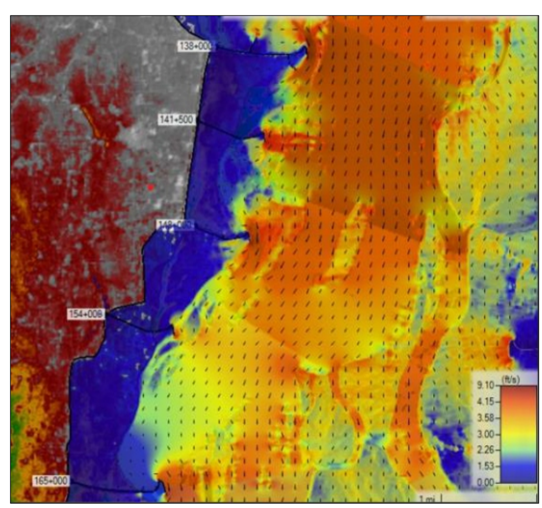

Fig. 13. Velocity vector at discharge 1,000,000 cusecs

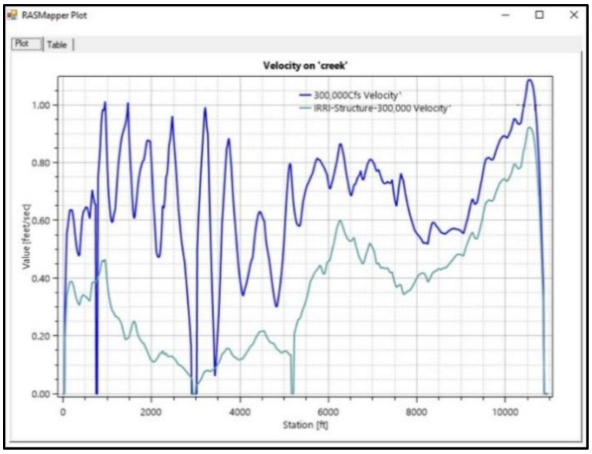

Fig. 14. Comparison of Velocities at 300,000 cusecs along the creek from RD 138 to RD 148

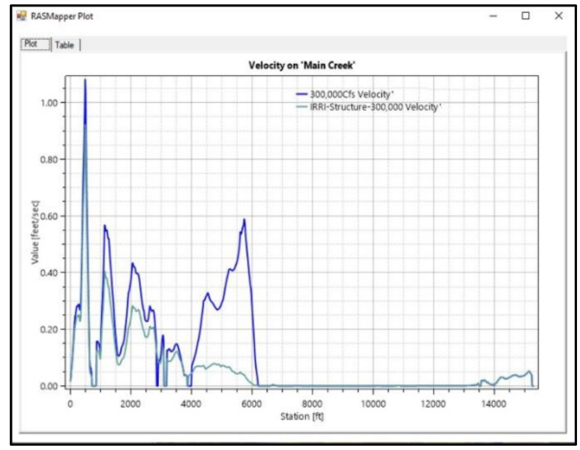

Fig. 15. Comparison of Velocities at 300,000 cusecs along the creek from RD 148 to RD 165

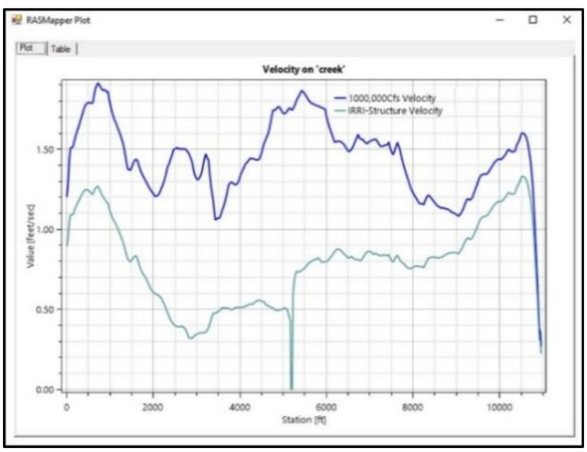

Fig. 16. Comparison of Velocities at 1,000,000 cusecs along the creek from RD 138 to RD 148

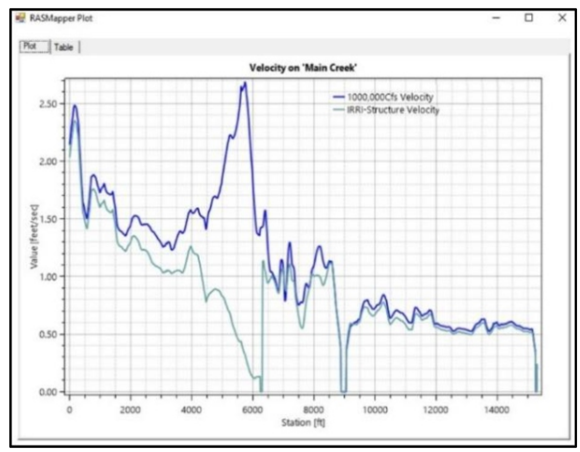

Fig. 17. Comparison of Velocities at 1,000,000 cusecs along the creek from RD 148 to RD 165

4. Conclusions

Downstream of Ghazi Ghat Bridge, flood inundation affected left bank at flows of 700,000 and 1,000,000 cusecs. It was more significant to analyze the structures based on left bank raised conditions, and hence, raising of the left bank was suggested to manage high flows. By changing the orientation of existing spurs to 120° and 135° upstream, it became evident that the upstream orientation at both angles caused issues, such as clogging of river creeks. Based on this, it was concluded that any upstream orientation was not workable and led to problems. Similarly, the 135° downstream orientation was also found ineffective in diverting flow currents towards the main channel. However, 120° downstream orientations were found to be effective, as it successfully diverted flow currents towards the main channel. The existing spurs from RD 138+000 to RD 148+000 and RD 138+000 to RD 165+000 were evaluated at prevailing spacings of approximately 2 to 5 times the length of the spur at RD 138+000, which are among the recommended spacings in the research community. This was followed by the introduction of two additional spurs at RD 141+500 and RD 154+000 to address the issues at subject locations in the reach. After incorporating the additional spurs at RD 141+500 between the structures at RD 138+000 and RD 148+000, at low discharge, the flow remained stagnant along the right bank. With introduction of the spur at RD 141+500, the flow velocity slightly decreased, and the flow pattern improved by successfully shifting the active creek away from right bank toward the main channel. Similarly, the proposed additional spur at RD 154+000, in the vicinity of Basti Bhai also played a key role in reducing the erosive action of the river at low discharges and minimizing further advancement of flow currents towards local settlements during high flow.

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Conflicts of interest:

The authors declare that they have no competing interests related to this study.

Data availability statement:

Data will be made available upon request to the corresponding author.

Author contributions:

M. Khan: Conceptualization and design of the study, data curation, preparation of tables and figures. Khan. M and A. Muhammad: Methodology and analytical framework. All authors contributed to the drafting and revision of the manuscript and approved the final version for publication.

Disclaimer:

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