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REVIEW

Environmental and Hydraulic Considerations in Scour Reduction Around Spur Dikes: A Comprehensive Review

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ABSTRACT

Spur dikes are essential hydraulic structures extensively used in river engineering to control bank erosion, regulate river flow, and enhance navigation. Despite their benefits, spur dikes interact with complex hydrodynamic forces that lead to vortex-induced scouring at their base, which threatens their structural stability and affects the surrounding ecosystem. This paper presents a comprehensive review that combines findings from experimental and numerical studies to explain the mechanisms of scour development around spur dikes, with a particular focus on installations in curved river channels. The review examines how hydraulic, geometric, and material parameters, such as flow velocity, dike location, alignment, shape, and porosity, affect scour depth and extent. Results from previous studies reveal that spur dikes placed near the outer bends of rivers experience more severe scouring due to stronger secondary circular flow and increased sediment entrainment. However, optimizing the spacing, orientation, and geometry of spur dikes can significantly reduce scour, in some cases by up to 80%. The paper also explores the role of dike porosity and material selection in mitigating adverse hydraulic impacts while supporting aquatic habitat diversity. By synthesizing these findings, the review provides practical design recommendations to enhance spur dike performance, minimize scour-related damages, and improve their environmental sustainability. The insights from this study can guide engineers and planners in designing more efficient and eco-friendly spur dike systems for river management and restoration projects.

Keywords: Spur Dikes; Angle of Spur Dikes; Porosity; Shape of Spur Dike; Scour

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1. Introduction

Spur dikes, also known as groynes, are hydraulic structures commonly used in river engineering and coastal management to stabilize riverbanks, regulate flow, and support navigation [1]. Typically constructed perpendicular or at an angle to the flow direction, they extend from the riverbank into the channel to redirect water away from the banks, thereby reducing erosion and controlling sediment deposition [2,3]. Despite their functional benefits, spur dikes introduce complex hydrodynamic interactions such as vortex formation, flow acceleration, and localized scouring at their base, which pose significant design and maintenance challenges [4,5]. Scour, the removal of sediment due to erosive water flow, is a critical issue affecting the structural integrity and long-term performance of spur dikes [6]. This phenomenon results from the three-dimensional flow patterns generated by the interaction between the structure and the channel flow. Various factors influence scour development, including flow velocity, sediment characteristics, spur dike geometry, and channel morphology [3]. If not properly understood and managed, excessive scouring can compromise the effectiveness of the structure, leading to increased erosion, sedimentation, and potential damage to nearby infrastructure [7]. Although vortex-induced scouring is briefly acknowledged, it is essential to understand the complex flow structures that significantly contribute to scour development around spur dikes. When flow interacts with a spur dike, especially in a curved channel, it generates a highly three-dimensional flow field characterized by several vortical structures. At the upstream face of the dike, a horseshoe vortex forms due to flow separation and pressure gradients, intensifying bed shear stress and initiating sediment removal. Downstream of the dike, wake vortices and recirculation zones further disturb the bed, contributing to local scour. Additionally, in bend channels, secondary helical flows caused by channel curvature interact with these vortices, amplifying turbulence and sediment entrainment near the outer banks. These combined hydrodynamic interactions result in deeper and more asymmetrical scour holes, which can undermine the structural integrity of the dike and alter channel morphology. Understanding these mechanisms is critical for developing accurate scour-prediction models and for optimizing spur dike design to ensure hydraulic efficiency and environmental resilience.

Numerous experimental and numerical studies have explored scour around spur dikes, examining parameters such as hydraulic conditions, structural configuration, and environmental impact [8–11]. Research shows that higher flow velocities increase shear stress on the bed, deepening scour holes. Pandey et al. [12] and Tripathi and Pandey [2] emphasized the influence of approach flow conditions, fluid properties, structural geometry (such as angle and size), and channel characteristics like slope, width, and cross-section shape on scour formation. Additionally, the shape and orientation of the dike significantly affect turbulence intensity; tapered designs generally produce less scour than rectangular ones. Design features such as spacing, alignment, and porosity also play vital roles in managing flow deflection and sediment transport, thereby influencing bank stability [13]. Patel et al. [5] discussed the effect of spur dikes on bank erosion control by examining their influence on flow dynamics, turbulence characteristics, and sediment transport. Tripathi and Pandey [14] investigated scour around spur dikes, particularly in curved channels, and enhanced predictions using Gene Expression Programming (GEP). They observed that the developed GEP model accurately predicts maximum scour depth and outperforms existing models under various flow conditions. Pandey et al. [15] developed and evaluated three machine learning models, GBDT, CFNN, and KRR, for predicting scour depth around spur dikes in cohesive sediments, with results showing that the GBDT model provided the most accurate predictions, and that clay content and the cohesion-to-friction angle ratio were the most influential factors for scour at the nose and wake zones, respectively.

Despite a substantial body of research, significant gaps remain in our understanding of scour around spur dikes. Most existing studies focus narrowly on localized scour and immediate hydrodynamic effects, often neglecting the broader influence of design modifications on sediment transport and long-term river morphology.

In particular, the cumulative impact of multiple spur dikes arranged in sequence, especially within curved or meandering channels, has not been sufficiently explored. This is a critical oversight, as spur dikes not only influence local flow structures but also drive large-scale changes in channel evolution. Addressing this gap, the present review offers a novel, integrated synthesis of hydraulic, geometric, and environmental factors affecting scour dynamics. By examining interactions such as porosity combined with spatial alignment in bends and evaluating their ecological implications, this paper provides a multidimensional framework to support more sustainable and efficient spur dike design in natural river systems. Unlike previous reviews that primarily summarize isolated findings, this study critically synthesizes how spur dike parameters, such as geometry, permeability, alignment, and placement, interact under varying hydraulic and morphological conditions to influence scouring behaviour. This work uniquely emphasizes the interdependency of these factors, arguing that optimal scour mitigation cannot be achieved through isolated parameter optimization but must instead be approached holistically. For example, while permeable designs can reduce scour, their performance is contingent upon dike placement relative to bends and channel curvature. This system-based insight fills a significant gap in the literature, which often lacks integration across parameters and real-world variability.

2. Data Collection Method

The primary objective of this review is to systematically evaluate the key hydraulic, geometric, and material factors influencing scour formation around spur dikes, particularly in curved river channels. This includes analyzing how flow velocity, spur dike porosity, alignment, and placement affect local scour patterns and environmental impact. Special emphasis is placed on assessing both experimental and numerical studies to understand the underlying mechanisms and to identify design modifications that can enhance scour mitigation and ecological sustainability. To ensure a comprehensive and focused review, literature was selected based on the following criteria: peer-reviewed journal articles and conference papers published in the last two decades; Studies that specifically address scour around spur dikes in both straight and curved channels; Research incorporating numerical simulations, physical modeling, or field investigations; Publications that present quantitative results related to flow characteristics, scour depth, structural geometry, or environmental considerations.

The data collection process mainly involved the collection of papers from the Scopus-indexed journals. Several steps are used to collect data, starting from conducting a wide review of the knowledge gap and problem statement, and other steps like selecting a suitable database and keywords, ending with writing a paper, as shown in **Figure 1**.

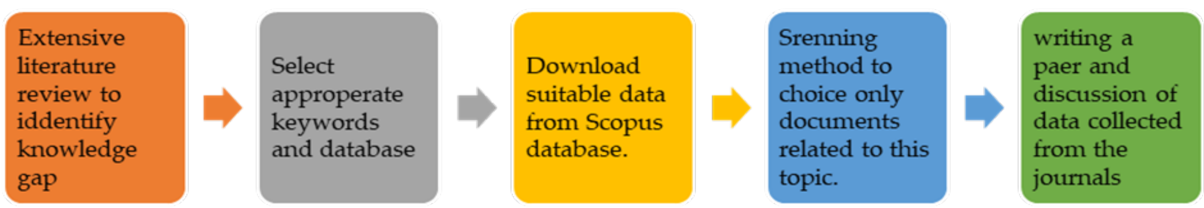

Figure 1. Data collection method.

Source: own elaboration.

As mentioned, the main data collection method was retrieving papers from Scopus-indexed journals. The first step is to select appropriate keywords that present the main topic; in this regard, two keywords were selected, namely "Spur Dikes" AND "Scour". The second step was entering these keywords in the Scopus search machine and limiting the duration from 2000 to 2025. This search was conducted in March 2025 to collect 211 papers, as shown in **Figure 1**. The third step was screening and selecting only papers that had the data required and were related to the aim of the papers, and ignoring other papers. Consequently, only 63 papers were collected to write this review. As shown in **Figure 2a**, the number of documents published fluctuated between 0 and 15 between 2000 and 2022, whereas the number of documents significantly increased after 2023 to reach up to 29 papers by 2024. This increase refers to the importance and interest of the topic among scholars and researchers. On the other hand, research articles accounted for the largest document type with 72%, then conference papers with 21%. While other document types like book chapters and reviews only have 2% for each, as shown in **Figure 2b**. Therefore, there is a critical need for a review paper to present the data obtained from the previous studies to serve as a base of knowledge for researchers and scholars in this area. **Figure 2c** shows that China, Iran, and India published the highest number of documents than other countries, with 70, 54, and 38 papers, respectively. **Figure 3** presents the most important keywords used in the paper collected using VOS viewer software.

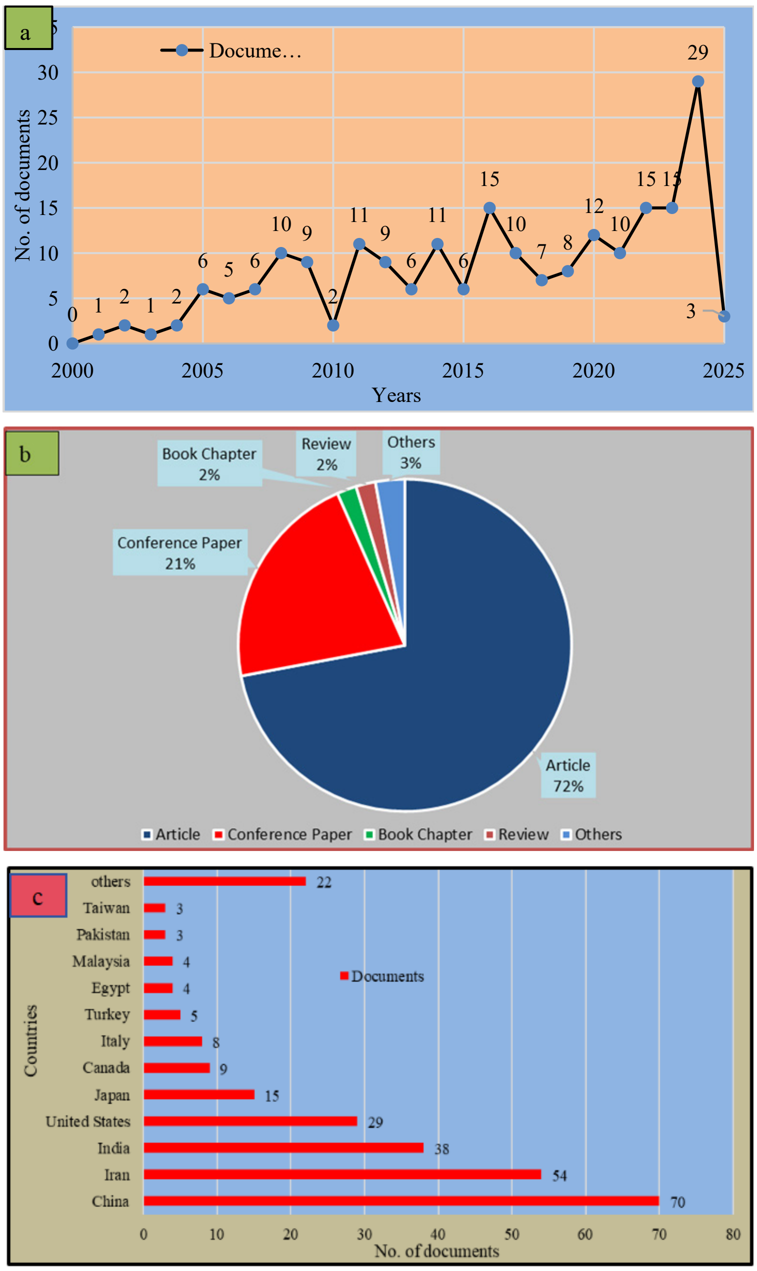

Figure 2. (**a**) Number of documents vs years, (**b**) No. of documents vs type, and (**c**) No. of documents vs countries.

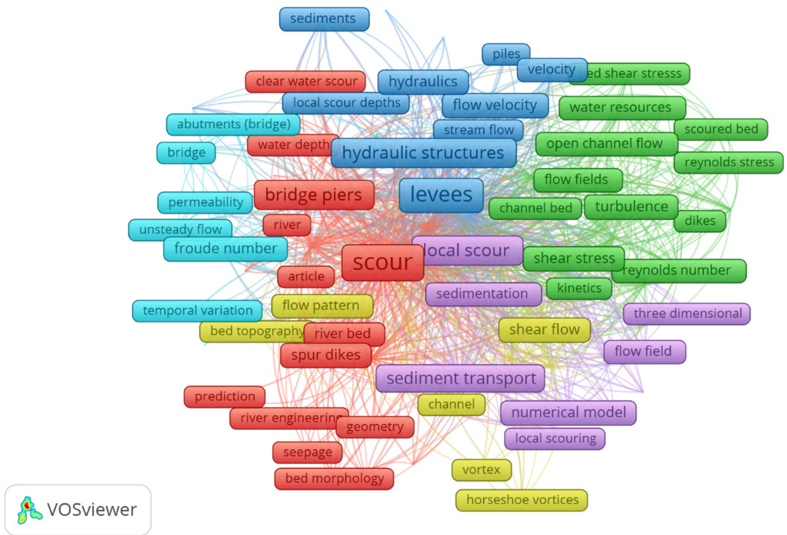

Figure 3. Visualization of keywords for papers collected using VOSviewer software.

For enhanced visualization of the research landscape, VOSviewer software was employed to analyze the keywords from the collected documents. **Figure 3** illustrates a keyword co-occurrence map, where terms are grouped and color-coded based on their frequency and interrelation. Notably, six distinct clusters emerge: the red cluster emphasizes core concepts like scour, spur dike, and river bed, indicating the central focus of most studies on localized erosion mechanisms. The blue cluster highlights hydraulic structure, flow velocity, and stream flow, suggesting a strong linkage to flow behavior and engineering design aspects. Other clusters encompass themes related to sediment transport, channel morphology, and environmental considerations. This figure helps the reader visually grasp the dominant research themes and how different keywords interconnect, offering insight into the multidisciplinary nature and emerging trends within the field.

Both the type and shape of spur dikes substantially influence scouring outcomes. Permeable dikes generally outperform impermeable ones in reducing erosion, but may be less durable under prolonged exposure to high-velocity flows. Similarly, while T- and L-shaped dikes offer flow redistribution advantages, their effectiveness can be compromised without proper angle and length optimization. Most experimental studies differ in setup, making cross-comparison challenging. There is minimal analysis of structural degradation or long-term performance of permeable dikes. Coupled hydrodynamic, morphodynamic simulations are underutilized. More research is needed to assess the ecological impacts of different dike types and shapes, develop multi-parameter optimization models for spur dike design, conduct field-scale experiments to validate lab-scale findings, and investigate the climate-resilience of various dike configurations under extreme flood scenarios.

3. Factors Affecting Scour around Spur Dikes

As introduced in the Introduction section, there are numerous factors affecting scouring around spur dikes. This study investigates the most important factors. The next subsections present these factors and their effect on the scour.

3.1.Angle of Spur Dikes

The angle of the spur dikes is one of the significant factors affecting the performance of spur dikes, as reported by the previous studies [5,16]. For the spur dike in a channel bend, there are additional factors (besides the ones listed above) that affect the erosion depth, such as the location of the spur dike in the channel bend and the angle of bend and central radius. The authors are not aware of much research on the erosion around the spur dike in a channel bend, and the few studies that exist only consider some influencing factors, like the shape of the spur dike and channel, and the condition of the incoming flow. The shape of the channel depends on two important factors, namely how wide it is and how curved it is. These factors also influence how much erosion happens near the spur dike, which is a T-shaped structure placed at a right angle to the channel [17]. The erosion is less severe when the ratio of bend radius to width (Rc/W) is higher, where Rc is the radius of the curve. Another study by Han et al. [18] used a 3D numerical model to study the riverbed scouring around the spur dike and the flow motion with various layout angles, as shown in **Figure 4**. They investigated the effect of spur dike layout angle, sediment parameters, and flow conditions on the maximum scour depth and its coordinates. They concluded that the differences and similarities can be observed in the flow fields when comparing downward-angled and perpendicular angle spur dikes.

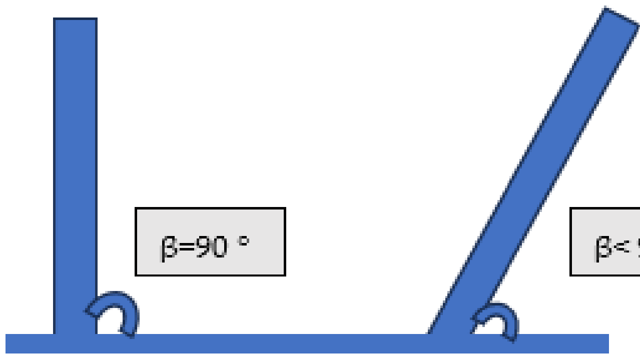

Figure 4. Various angles of spur dikes.

Farshad et al. [19] investigated the evolution of scour depths around spur dikes with varying permeability levels and angles under different hydrographic conditions. As illustrated in **Figure 5**, the experiments were conducted in a rectangular flume measuring 10 m in length, 0.76 m in width, and 0.6 m in depth. The mobile bed consisted of nearly homogeneous sand with a median grain size of 0.8 mm. The study analyzed how spur dike permeability and orientation influenced the temporal progression of scour. The results demonstrated that permeable spur dikes significantly reduced scouring compared to their impermeable counterparts. Moreover, permeability had a more pronounced impact on mitigating scour than the orientation angle. The percentage difference in maximum scour depth between impermeable and permeable spur dikes varied from 44% (at 33% permeability and an orientation angle of 60°) to 88% (at 66% permeability and an orientation angle of 120°). These findings highlight the effectiveness of permeable spur dikes in controlling scour development.

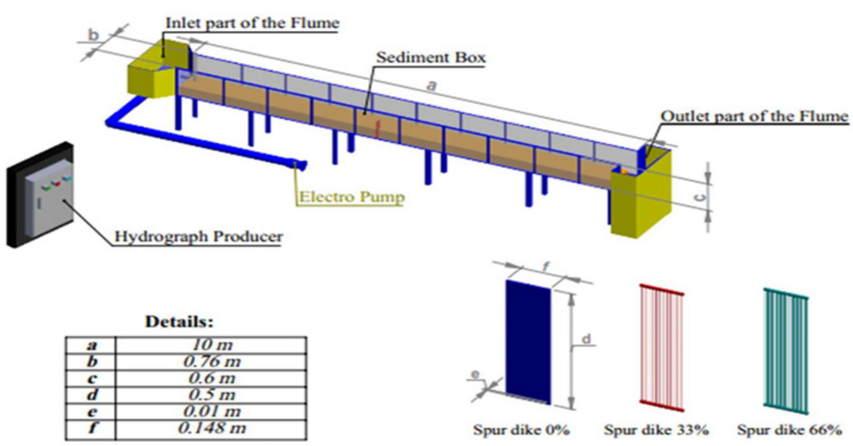

Figure 5. A Diagram shows spur dikes of different permeability [15].

Additionally, the study explored scouring differences under steady and unsteady flow conditions, as well as the influence of hydrograph base time on scour depth. When the hydrograph base time was increased fourfold while maintaining the same peak and base flood discharges, the maximum scour depth increased by approximately 29% for impermeable spur dikes, 42% for spur dikes with 33% permeability, and 25% for spur dikes with 66% permeability. These results emphasize the role of both permeability and hydrograph characteristics in scour development around spur dikes. Sirtasy et al. [20] investigated the reduction of scour around vertical bridge abutments by placing a single spur dike upstream under clear-water scour conditions. The experimental setup used sand as bed material, with a median grain size of 0.80 mm and a geometric standard deviation of 2.27, as shown in **Figure 6**. The study considered three different spur dike configurations, each varying in distance from the abutment, orientation angle, and length. A total of 99 experimental runs were conducted, testing each configuration under nine flow conditions, which included three Froude numbers and three approach flow depths. For each configuration, an empirical equation was developed to relate the relative scour depth to the Froude number. Additionally, four-dimensional equations were derived to describe the relative dimensions of the scour hole at different stages. The results demonstrated that spur dikes effectively reduced scour depth at the abutment. The greatest scour reduction, about 81.5%, was achieved when the spur dike was placed at a distance from the flume wall to the abutment equal to three times the abutment length, with an orientation angle of 90° and a spur dike length perpendicular to the flow direction equal to the abutment length.

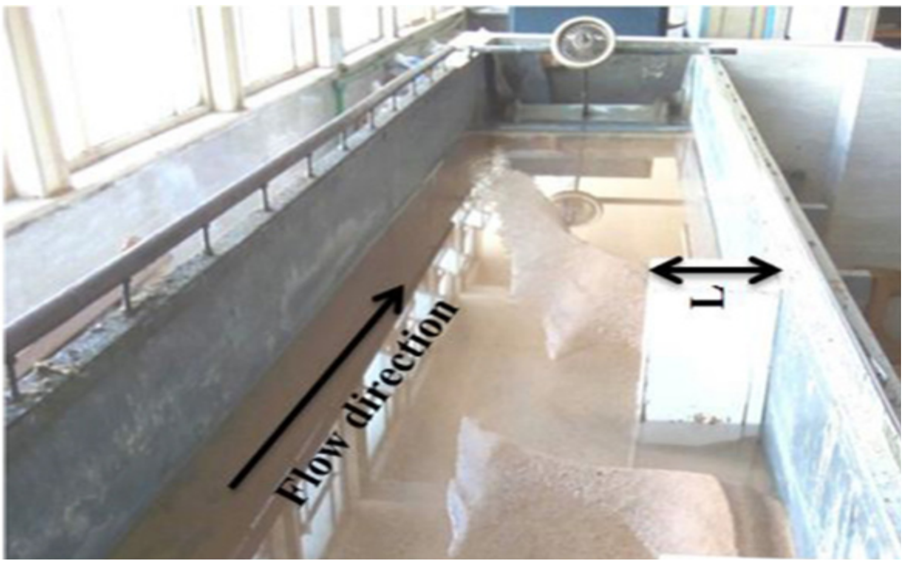

Figure 6. Layout of the vertical wall bridge abutment [16].

Jafari and Sui [21] analyzed the impact of non-submerged spur dike orientation angles on maximum scour depth and scour patterns. Their findings indicated that the dike angle plays a crucial role in scour depth variation, with a 90° dike orientation resulting in greater scour depth than a 60° orientation. Ice cover and its roughness coefficient further influenced channel bed deformation, while flow rate variations affected scour hole dimensions. Advanced numerical and experimental approaches have further expanded the understanding of spur dike effects. Haider et al. [22] employed Computational Fluid Dynamics (CFD) to study turbulence and flow dynamics around permeable spur dikes with varying pore angles and permeabilities. Their results demonstrated that angled pores significantly reduced streamwise velocity and turbulence, enhancing riverbank protection and flood resilience. **Table 1** summarizes the recently studied effect of the angle on scouring depth.

Table 1. Published studies on the effect of angle on scouring depth.

References	Angle Configuration	Key Findings
Haltigin et al. [23]	Varied angles on both sides of an open channel.	Found that increasing the angle of spur dikes from downstream led to higher pressure and velocity near the bed, affecting scour dynamics.
Farshad et al. [19]	Different angles and permeabilities in rectangular channels.	Demonstrated that while angle influences scour depth, permeability had a more significant impact on reducing scour compared to angle alone.
Sirtasy et al. [20]	Multiple angles and distances from bridge abutments.	Showed that a spur dike set at a 90° angle to flow significantly reduced scour depth at abutments but did not eliminate it, instead shifting it to the spur dike.
Jafari and Sui [21]	Several layout angles of non-submerged spur dikes.	Found that the direction angle is important for increasing the depth of the scour; changing the angle from 90° to 60° significantly reduced the upstream scour length.
Haider et al. [22]	Pore angles used in permeable spur dikes are 0°, 15°, 30°, and 60°.	Analyzed how varying pore angles affected flow characteristics, with results showing improved performance at certain angles compared to impermeable designs.

3.2.Porosity of Spur Dikes

The porosity of a spur dike significantly influences its hydraulic performance, structural durability, and environmental impact [23]. Engineers often select materials with specific porosity levels to strike a balance between stability and ecological or hydraulic efficiency. Recent research has focused on evaluating spur dikes with varying porosity ratios and configurations to determine their impact on flow behavior and scour reduction. Shampa et al. [24] conducted a three-dimensional multiphase numerical analysis to assess two different pile arrangements in slit-type spur dikes. Their findings indicated that using permeable spur dikes in a sequence can markedly reduce approach flow velocity within the spur zone. Compared to conventional impermeable dikes, slit-type designs with varying angles and placements effectively minimized bed shear stress, turbulence intensity, and longitudinal velocity near the bank. The study concluded that these permeable structures promote smoother flow transitions and significantly reduce scour intensity. Jian Ning et al. [10] performed a numerical investigation on the influence of spur dike placement on flow patterns and local scour. They found that the first spur dike in a series experiences the deepest scour, and the influence of subsequent dikes diminishes with increased spacing. This highlights the importance of optimal spacing in multi-dike installations to manage scour effectively. Rao et al. [25] explored how inlet flow velocities, spur dike spacing, and porosity affect pollutant removal efficiency in channels. Their results indicated that porosity, flow velocity, and the gap between dikes are critical factors influencing the ecological performance of porous materials used in dike construction.

Qi [26] investigated the effects of collar porosity, width, and length on local scour reduction under clear water conditions using both experimental and numerical methods. The study revealed that collars can reduce local scour by up to 56.9%, with the collar's width having the most significant impact, followed by length and porosity. Numerical simulations showed that flow velocity reductions reached 45% and 25% for permeable and solid collars, respectively. Similarly, shear stress was reduced by 20% and 28.6% compared to conditions without collars. Taken together, these studies underscore the need for a more integrated design approach. Engineers must weigh the benefits of porous structures, such as improved flow dynamics and environmental compatibility, against practical concerns like material strength and maintenance. Future design guidelines should reflect these nuanced trade-offs, particularly in sensitive or high-energy riverine environments where both hydraulic performance and ecological outcomes are paramount. Finally, **Table 2** presents a summary of recent studies highlighting the role of porosity in reducing scour depth around spur dikes.

Table 2. Influence of porosity on scouring depth.

References	Porosity Configuration	Key Findings
Farshad et al. [19]	Varying degrees of permeability (33%, 66%) in spur dikes.	Demonstrated that increased permeability reduces maximum scour depth; the variation in scour depth between impermeable and permeable dikes ranged from 44% to 88%.
Haider et al. [22]	Staggered pore designs with varying angles of permeability.	Investigated how different pore angles (0°, 15°, 30°, 60°) affected flow characteristics, showing that higher porosity improved flow diversion and reduced turbulence.
Jafari and Sui [21]	Non-submerged spur dikes with varying layouts.	Examined how porosity affects scour patterns under different flow conditions, indicating that increased porosity leads to reduced scour depth.

3.3.Velocity of Flow

The velocity of flow around a spur dike in a scouring channel is critical for understanding the hydraulic behavior and the associated scouring process [5]. Groynes are structures extending from the riverbank into the channel to influence flow and sediment transport [27]. The velocity near groynes is affected by various elements, such as the channel geometry, flow conditions, sediment size, and the design of the groyne itself [28]. The radius of curvature significantly influences the velocity distribution [29]. Strongly curved bends have a higher initial velocity near the inner bank before progressively moving toward the outer bank [30]. Below the free surface, the secondary velocities reach their maximum values. As the radius of curvature increases, the secondary velocities decrease. Furthermore, the higher velocity is diverted from the entry and moves into the bend's center. Strongly curved bends' longitudinal velocities provide a good approximation of reality; it is predicted that the higher velocity will move from the bend's inner bank to its outer bank. In practice, though, this happens over a smaller area. It was predicted that the longitudinal velocities in smoothly curved bends would be close to the outer bank and well in the center.

The previous research reported the behavior of spur dikes at different velocities. For instance, Shampa et al. [24] tested two distinct kinds of individual pile position arrangements, and a three-dimensional multiphase flow was carried out experimentally and numerically by approaching the flow from three perspectives. The findings demonstrated that the approach velocity of the flow within the spur dike zone can be significantly decreased by employing a sequence of slit-type spurs. Abad and Garcia [31] discovered that the outer bank is where the highest velocities are located, and the maximum velocity changes from one location to another, depending on several factors like the bed morphology, the dynamics of flow, and others. **Table 3** summarizes the effect of velocity on the scouring depth, as reported by the previous studies.

Table 3. Published studies on the Influence of velocity on scouring depth.

Researchers	Velocity Configuration	Key Findings
Haltigin et al. [23]	Velocity measurements near spur dikes at varying angles.	Found that increasing the angle of spur dikes led to higher pressure and velocity near the bed, significantly affecting scour dynamics. The velocity field was three-dimensional, especially near the dike's nose.
Farshad et al. [19]	Examined how different angles and permeabilities affected flow velocity.	Reported that higher permeability in spur dikes reduced flow velocity at the base, resulting in decreased scour depth compared to impermeable designs.
Sirtasy et al. [20]	Studied velocity reduction at bridge abutments with upstream spur dikes.	Found that strategically placed spur dikes could reduce flow velocity at abutments by up to 81.56%, although some scour was shifted to the spur dike itself.
Jafari and Sui [21]	Evaluated effects of non-submerged spur dikes on flow velocities under ice cover conditions.	Found that varying the angle of spur dikes significantly influenced maximum scour depth and altered flow velocities, particularly under changing hydraulic conditions.

3.4.The Shape of Spur Dikes

The shape of spur dikes significantly influences the scouring process and flow characteristics in channels [32]. Common shapes include straight, angled, round-head, L-shaped, T-shaped, wing-shaped, and inclined dikes, each having unique effects on scour depth and sediment deposition [12]. Straight spur dikes, extending perpendicular to the flow, create concentrated turbulence at their tips, leading to deep scouring pits, while upstream-angled dikes reduce turbulence and encourage sediment deposition near the bank. In contrast, downstream-angled dikes intensify scouring at the tip while facilitating sediment retention downstream. Rounded or parabolic heads facilitate smooth flow transitions, diminishing vortex production and limiting scour depth. T-shaped and L-shaped dikes improve sediment deposition by broadening flow dispersion zones, rendering them efficient for bank stabilization and sediment management. Modern wing-shaped or vortex-based designs are hydrodynamic and environmentally sustainable, reducing turbulence and related scour. Inclined dikes, whether sloping upward or downward, affect flow separation and reduce scour intensity based on their orientation and angle. The selection of dike configuration is essential and must take into account channel sediment transport dynamics, flow velocity, hydraulic efficiency, and the requirement for scour protection [33]. The performance of each shape differs based on site-specific variables, highlighting the necessity of customized designs to reduce scour and maintain channel stability. Zhang and Nakagawa [34] classified the shape of spur dikes into several types according to their structural permeability. However, there are two main types, namely impermeable and permeable, as shown in **Figure 7**. Permeable spur dikes are commonly made up of several rows of reinforced concrete piles, steel, bamboo, or timber. Impermeable spur dikes are made of rocks, gravel, stone, or soil. In general, the shape of spur dikes like T-head and L-head, and hockey-stick-shaped, has a significant effect on the scour around spur dikes [12,35].

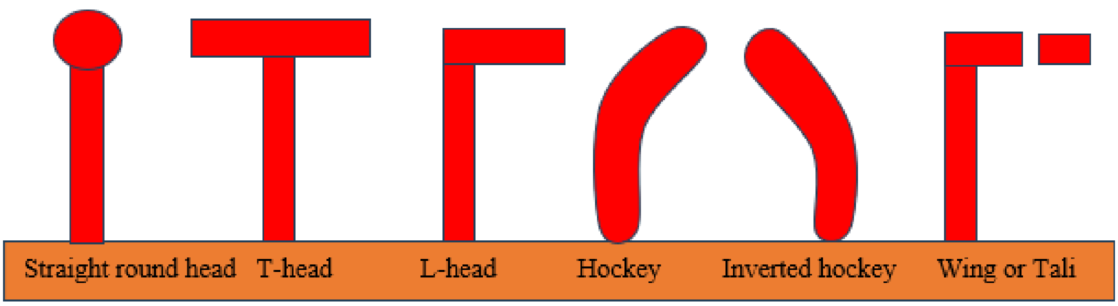

Figure 7. Shape of spur dike.

Previous publications have examined the behavior of spur dikes with various configurations. Chakravarty et al. [16] examined different spur dike configurations, including L-head, T-head, and hockey-shaped designs, emphasizing their impact on channel flow and sediment transport. T-head spurs are notably helpful in mitigating bed scouring by dispersing flow energy. The research emphasizes the necessity of optimizing spur dike shapes tailored to specific sites to accommodate varying hydraulic conditions, offering suggestions for innovative designs to enhance sediment management and channel stability. Patel and Kumar [36] examined the impact of T-shaped spur dikes on flow dynamics and sediment transport across various seepage conditions. Advanced experimental settings demonstrate that T-shaped spurs effectively regulate flow energy and diminish turbulence, thereby minimizing scouring at their tips. The study offered practical insights into the structural benefits of T-shaped spur dikes, rendering them optimal for bank stabilization and erosion protection in fluctuating hydraulic conditions. A further study by Patel and Kumar [37] studied the performance of spur dike configurations under conditions of downward seepage, which frequently intensifies scouring. Through comprehensive studies, it identified ideal shapes that minimize turbulence and scour depth while maintaining effective flow regulation. The research provided practical recommendations for the construction of spur dikes to mitigate seepage-induced instability, thus enhancing performance in challenging channel environments. Recently, Chakravarty et al. [16] conducted a comprehensive review of the effect of the shape of spur dikes on scouring and erosion and summarized the types of spur dikes and their effect on scouring and erosion. They found that a T-head spur dike could more efficiently prevent erosion and change the direction of flow, while an L-head spur dike improves riverbank stability.

Qi et al. [26] presented U-shaped collars as a novel approach to reducing local scour along groynes. The research indicated that these collars successfully modify flow patterns, diminishing turbulence at the dike base and protecting the surrounding bed material. The results indicate that integrating collars into groyne designs can markedly improve their stability and endurance, especially in high-flow areas. Bahrami-Yarahmadi et al. [38] investigated the impact of triangular groynes on scour and flow dynamics under different hydraulic conditions. The findings indicate that triangular dikes can enhance flow separation and diminish vortex intensity, resulting in reduced localized scour relative to conventional designs. The research emphasizes the effectiveness of triangular groynes in managing erosion and regulating flow in channels characterized by significant sediment mobility. Pandey [39] investigated the influence of T-shaped groyne morphology on local scour patterns in reverse meandering channels. The T-shaped configuration of the spur dike markedly affects the flow dynamics surrounding the structure, leading to distinct scour patterns in contrast to alternative dike geometries. The elongated horizontal arm of the T-dike redirects the flow towards the channel's center, resulting in fluctuations in flow velocity and turbulence that induce sediment displacement and heightened scour depth. The intersection of the vertical stem of the T with the bed is particularly prone to increased turbulence, thereby intensifying scour. The research indicated that T-shaped groynes typically cause deeper scour, particularly when situated nearer to the meander's ingress. This design enhances flow acceleration around the dike, resulting in greater local erosion at the dike's base. **Table 4** shows the effect of the shape of the dike on the behavior of the scouring depth.

Table 4. Effect of spur dike shape on the scouring depth.

Researchers	Spur Dike Shape	Key Findings
Chakravarty et al. [16]	L-head, T-head, Hockey-shaped.	T-head spurs are effective in reducing bed scouring by redistributing flow energy. Optimization of geometry is crucial for sediment management.
Patel and Kumar [36]	T-shaped	T-shaped dikes efficiently control flow energy, reduce turbulence, and minimize scouring near tips. Ideal for bank stabilization.
Patel and Kumar [40]	Various (under downward seepage).	Identifies optimal geometries to reduce turbulence and scour depth, ensuring better stability under seepage conditions.
Qi et al. [26]	U-shaped Collars (as a modification).	U-shaped collars effectively alter flow patterns, reducing turbulence and local scour and enhancing dike stability.
Bahrami-Yarahmadi et al. [38]	Triangular	Triangular dikes streamline flow separation, reduce vortex intensity, and minimize localized scour.
Tripathi and Pandey [41]	T-shaped (in the reverse meandering channel).	T-shaped dikes influence flow dynamics uniquely, causing deeper scour at the junction of the vertical stem and base due to increased turbulence.

As shown in **Table 4**, the shape of the spur dikes significantly affects the scouring around the dikes. This method is important because of changes in water velocities in the flow direction. Scour is typically classified into three main kinds: local scour, contraction scour, and general scour.

3.5.Location of Spur Dikes

The location of the spur dikes largely determines the degree of local scour in river channels [9,32]. Spur dikes are structures that are oriented perpendicular to the flow of water [3]. They are usually found along the banks of winding rivers to stabilize the river's course and prevent bank erosion. However, depending on where they are positioned inside the channel, their effectiveness in reducing erosion might vary greatly. Specifically, where the spur dikes are located influences the turbulence and flow patterns around the dike, which impacts the formation of scour holes upstream and downstream of the structure. The position of a spur dike, whether on the inner or outer curve of a meander, near the bend, or further along the straight section, can drastically change the flow velocity, which in turn alters the intensity of sediment transport and the potential for erosion. Understanding how the placement of spur dikes interacts with the natural flow dynamics of a river is key to designing effective riverbank protection strategies and minimizing the adverse effects of scour. Studies like Gupta et al. [42] emphasize the role of flow velocity and sediment transport in scour development, noting that higher velocities near spur dikes increase erosion potential downstream. Similarly, Kuhnle et al. [43] discussed the importance of hydraulic modelling to optimize spur dike placement, ensuring effective erosion control while minimizing undesirable scour effects. Collectively, these findings underscore the importance of considering flow dynamics, dike geometry, and river morphology when designing and positioning spur dikes to achieve sustainable riverbank protection and minimize scour-related risks. **Table 5** summarizes the results from recent studies on the effect of location on scouring depth.

Table 5. The influence of the location of the spur dike on scouring depth.

Researchers	Spur Dike Location	Key Findings
Kuhnle et al. [43]	The spur dike was 22 m downstream.	The volume of local scour was highest in most cases.
Gupta et al. [42]	Flow velocity and sediment transport around spur dikes.	Higher flow velocities near spur dikes increase erosion potential downstream.
Nayyer et al. [44]	Flow characteristics around the triple combinational series.	The most considerable turbulent energy, shear stress, pressure, and flow speed are in the flat bed shaped close to the location of maximum
Ning et al. [10]	Numerical simulation of the effect of location and spacing of spur dikes on scouring depth.	The difference in scouring depths of spur dikes is mainly affected by various locations, because the flow field structure around the spur dikes depends on the spacing between the spur dikes.

Tabassum et al. [33] reported that at a spacing of 3L between spur dikes and a flow velocity of 90% of the critical velocity, around 80% of the maximum scour depth occurs rapidly. Nayyer et al. [44] investigated the effect of the location and shape of spur dikes on the scouring depth and found that the highest pressure, turbulent energy, shear stress, and flow speed in the flatbed formed close to the location of the maximum scour depth. Erosion and scouring are significantly decreased by a reduction in these parameters. The combined use of different geometries of spur dikes contributed to reducing scouring.

4. Discussions and Results

As shown in Section 3, numerous factors are affecting the scouring depth around the spur dike. The factors can be summarized in **Figure 8**.

The analysis of current studies for the scour around spur dikes reveals that both hydraulic and geometric factors play a significant role in determining to scour depth and extent [3]. In terms of geometric aspects, the shape, orientation, and length of spur dikes affect flow patterns, leading to differences in turbulence intensity and sediment transport [2]. Researchers like Jafary [42] and Nandhini et al. [3] showed that a streamlined spur dike with an optimal length-to-channel-width ratio can reduce localized scour, whereas longer structures tend to increase flow disturbances, exacerbating scour depth. Additionally, the angle of spur dike placement relative to the main flow direction significantly affects wake turbulence and vortex formation, with perpendicular structures generally inducing more pronounced scour compared to those set at an oblique angle. The presence of multiple spur dikes in a series also alters sediment deposition and erosion patterns, further complicating scour prediction and control strategies.

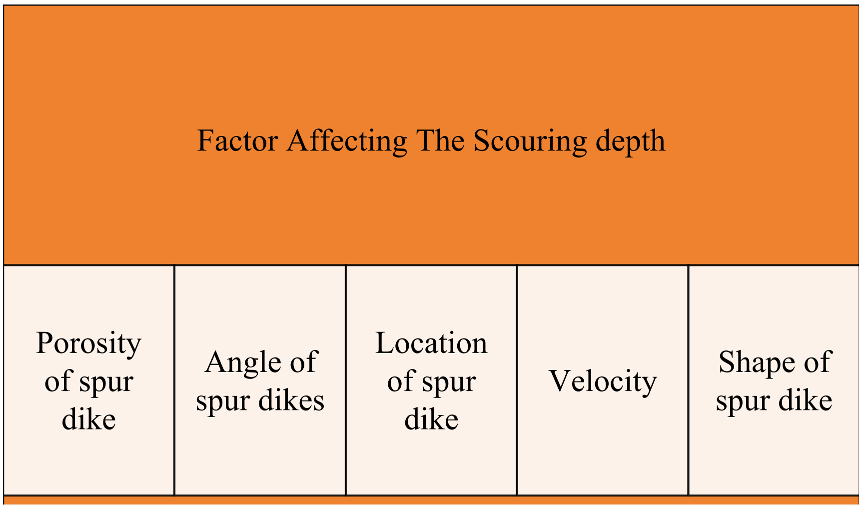

Figure 8. Factors affecting the scouring around Spur dike.

Hydraulic factors, including flow velocity, water depth, and sediment properties, further dictate scour behavior around spur dikes [45]. Higher flow velocities intensify shear stresses near the dike base, promoting deeper scour holes, particularly in cohesionless sediments. For instance, Iqbal and Tanaka [46] used uniform sand to investigate the local scour procedure near a single combined dike (impermeable and permeable). They observed that the maximum scour depth is expected to occur at the upstream edge of the dike, similar to local scour observed around a scaled-down dike in an open channel. **Table 6** presents a comparative analysis of spur dike parameters and their effect on scouring, and **Table 7** shows the main factors affecting scour depth and design recommendations.

Table 6. Comparative analysis of spur dike parameters and their effect on scouring.

Aspect of Study	Researchers	Results
Flow Velocity and Scour	Shao et al. [47] Song et al. [48] Duan et al. [49]	Higher flow velocity increases shear stress and scour depth nonlinearly. Critical velocity leads to maximum scour.
Spur Dike Geometry	Chakravarty et al. [16] Stachew et al. [50] Zhang et al. [51] Farshad et al. [19]	Streamlined/porous designs reduce turbulence and scour compared to rectangular/impermeable dikes. Angle/orientation (e.g., 90° vs. oblique) affects flow deflection and scour patterns.
Permeability	Kang et al. [52] Farshad et al. [19] Hu et al. [53]	Permeable spur dikes reduce flow turbulence, velocity, and scour depth (up to 88% reduction). They also minimize ecological disruption by allowing gradual flow transitions.
Placement and spacing	Kuhnle et al. [54] Vaghefi et al. [55] Sirtasy et al. [20]	Scour depth depends on spur dike position Rc/W, spacing, and alignment. Closer spacing or placement near bends increases localized scour.
Environmental Impact	Hu et al. [53] Ma et al. [56] Hood [57] Deng et al. [58]	Spur dikes can enhance habitat diversity but require balancing engineering goals with ecological sustainability. Excessive scouring disrupts sediment dynamics and aquatic ecosystems.
Scour Mitigation	Sirtasy et al. [20] Farshad et al. [19] Zhang et al. [51] Rafiqii et al. [7]	Permeability and strategic placement (e.g., upstream spur dikes) reduce scour depth by 44–88%. Scour relocation (from abutments to dikes) is a trade-off.
Hydrodynamics	Nandhini et al. [3] Haltigin et al. [23] Lodhi et al. [59] Kuhnle et al. [54]	3D flow vortices form near spur dike noses, causing localized scour. Flow separation and turbulence intensity correlate with scour hole dimensions.

Table 7. Key factors affecting scour depth and design recommendations.

Factor Studied	Researchers	Key Findings	Implications/Recommendations
Spur Dike Geometry entry [2]	Kuhnle et al. [43]	Nonlinear relationship between velocity and scour depth; rapid scour increases at higher velocities.	Design flow conditions should prioritize velocity control.
	Pandy et al. [39]	A linear relationship between flow velocity and scour depth; critical velocity maximizes scour.	Scour mitigation requires velocity reduction near dikes.
	Xu et al. [60]	Streamlined/tapered designs reduce turbulence and scour compared to rectangular dikes.	Optimize dike shape to minimize vortices and local scour.
	Koken and Constantinescu [32]	Orientation (perpendicular vs. angled) affects flow energy distribution and scour patterns.	Angled dikes may improve flow deflection and reduce scour.
Permeability	Farshad et al. [19]	Permeable dikes reduced scour depth by 44–88% compared to impermeable dikes.	Higher permeability (66%) significantly minimizes scour.
	Kang et al. [61]	Permeable dikes lower turbulence and sediment entrainment.	Ideal for ecologically sensitive areas.
Placement and spacing	Kuhnle et al. [43]	Dikes in series/groups alter flow patterns and scour depths compared to isolated dikes.	Strategic spacing improves sediment deposition and flow regulation.
	Vaghefi et al. [55]	Scour depth in bends depends on channel curvature ratio and dike position.	Higher Rc/W ratios reduce scour severity.
	Sirtasy et al. [20]	Upstream spur dikes reduced bridge abutment scour by 81.56% but shifted scour to dike locations.	Trade-offs exist between scour mitigation and localized erosion.
Environmental Impact	Bhuiyan et al. [62]	Unchecked erosion disrupts ecosystems; a spur dike must balance engineering and ecological goals.	Integrate habitat preservation into dike design.
	Hu et al. [53]	Permeable dikes stabilize banks while allowing gradual flow transitions.	Prioritize designs that mimic natural flow conditions.
Channel Morphology	Haltigin et al. [23]	Dike angle affects near-bed pressure and velocity; 3D flow fields dominate near dike noses.	Optimize dike angles to manage flow deflection and bed shear stress.
	Pandy et al. [39]	Meandering channels require tailored dike designs to address helical flow patterns.	Account for channel sinuosity in dike placement and orientation.
Experimental Methods	Farshad et al. [19]	Hydrograph base-time increases scour depth under unsteady flow (29–42% rise with 4x base-time).	Flood duration is crucial in predicting scour for transient flow conditions.
	Sirtasy et al. [20]	Empirical equations linked scour depth to Froude number and dike configuration.	Field validations are needed for generalized scour models.
Scour Mitigation	Zhang et al. [51]	Scour hole volume correlates with alignment angle and flow shallowness.	Uniform scour-volume ratios simplify geometric predictions.

The shape and permeability of spur dikes play a vital role in influencing the flow field and the associated scour patterns around the structure [12]. Different shapes, such as straight, L-shaped, T-shaped, and curved spur dikes, alter flow separation points and vortex development, which in turn affect the location and depth of scour holes [16]. For instance, L-shaped and T-shaped dikes tend to redistribute flow more effectively, promoting sediment deposition in targeted areas while potentially shifting the scour zone toward the junction between the main structure and its transverse arm. This highlights the need for site-specific optimization of spur dike geometry. Permeable spur dikes, constructed with slits or porous materials, significantly reduce flow velocity and turbulence intensity in their vicinity [24]. This reduction leads to lower bed shear stress and, consequently, diminished scour depth. Studies have shown that permeable designs can reduce maximum scour by up to 88% compared to solid, impermeable dikes [19]. This performance is attributed to their ability to dissipate flow energy and enable gradual flow transition, which also supports ecological balance by minimizing habitat disturbance near riverbanks.

Impermeable and rigid structures can disrupt natural flow regimes, fragment aquatic habitats, and alter sediment deposition patterns, potentially degrading spawning grounds and reducing biodiversity. In contrast, environmentally sensitive designs, such as permeable or vegetated spur dikes, can mitigate these impacts. These structures promote gradual flow transitions, support sediment deposition that fosters vegetation growth, and maintain hydraulic connectivity for aquatic organisms. Furthermore, incorporating ecological considerations into spur dike planning, such as aligning structures with natural geomorphology and using materials that support microbial and plant colonization, contributes to long-term river health and sustainability [63]. Thus, optimizing spur dike design is not only an engineering challenge but also a critical aspect of sustainable river management that balances flood protection with ecosystem preservation.

Shao et al. [47] and Song et al. [48] identified a nonlinear relationship between flow velocity and scour depth, Pandey et al. [39] presented a linear correlation, highlighting the variability arising from experimental conditions, such as flume scale, sediment type, and boundary roughness. Rather than treating these as conflicting, they should be interpreted as reflective of the different flow regimes under which the studies were conducted, steady versus unsteady flow conditions, which is consistent with observations by Farshad et al. [19] regarding hydrograph base-time effects. Similarly, the influence of spur dike geometry shows convergence around the benefit of streamlined shapes in reducing turbulence, yet variations in results, such as between Chakravarty et al. [16] and Koken and Constantinescu [32] can be attributed to differing angles of alignment and sediment transport assumptions, which emphasize the importance of contextualizing geometry within channel morphology.

Moreover, to enhance the clarity and focus of each subsection, we have introduced concise introductory statements that orient the reader to the relevance and purpose of each parameter studied. For instance, the subsection on permeability now begins by stating its dual engineering and ecological importance in regulating both scour depth and sediment continuity, setting the stage for interpreting why Farshad et al. [19] and Kang et al. [52] emphasized differing degrees of performance. When evaluating the placement and spacing of spur dikes, we contrast findings by Kuhnle et al. [54] and Vaghefi et al. [55], highlighting that while both support increased scour near bends, the underlying mechanisms, such as secondary flow intensification versus curvature-induced flow convergence, vary in interpretation. This refined structure ensures that the narrative better aligns with best practices as demonstrated in reference articles, offering a synthesized understanding of how specific configurations influence scour and riverine behavior under different hydraulic and morphological conditions.

5. Conclusions

This comprehensive review highlights the key hydraulic and geometric factors that influence scour dynamics around spur dikes in curved channels, providing essential insights for optimizing their design and enhancing environmental sustainability.

- A nonlinear relationship between scour depth and flow velocity was identified. Increased flow velocities intensify sediment entrainment and bed shear stress, emphasizing the need to define and consider critical velocity thresholds during the design phase.
- Geometric modifications, such as angled and tapered spur dikes, significantly reduce scour severity and flow turbulence. Permeable designs prove especially effective, achieving up to an 88% reduction in scour depth by dissipating flow energy and reducing bed shear stress, while also promoting ecological balance through smoother flow transitions.
- Spur dike placement in curved channels plays a critical role in shaping scour patterns. Properly aligned spur dikes located at distances equal to three times

the abutment length can reduce scour by over 80%. In contrast, installations near the outer bank intensify localized erosion due to strong helical currents. While L-shaped and T-shaped dikes encourage sediment deposition, they may also concentrate scour at structural junctions, underscoring the need for site-specific geometry optimization.

- Environmentally compatible designs, including porous materials and collar installations, are vital. Collars, for instance, can reduce local scour by up to 56.9%, helping preserve aquatic habitats while maintaining structural and hydraulic performance.
- The unique contribution of this review lies in its cross-comparative analysis of isolated and combined effects of spur dike characteristics, particularly in complex flow environments such as curved channels. By highlighting how porosity, dike spacing, shape, and alignment interact with hydraulic and sediment transport dynamics, the paper offers a multi-dimensional perspective that can inform future experimental, numerical, and ecological assessments, filling a crucial gap in current river training design literature.

Future research should prioritize investigating the combined effects of multiple spur dikes, particularly in curved channels, using advanced physical modeling and high-resolution numerical simulations. Additionally, integrating ecological considerations such as habitat preservation and material porosity into design frameworks can enhance both hydraulic performance and environmental sustainability.

Author Contributions

I.H.H.: collected the data required and wrote the main manuscript. A.A.J.J.: wrote the main manuscript, collected the data required, formal analysis, and supervised. R.H.I.: methodology, supervision, editing, and review of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

Abbreviations

Parameters	Defined
3D	Three dimensional
CFD	Computational Fluid Dynamics
GEP	Gene Expression Programming
Machine learning models	GBDT
	CFNN
	KRR
Rc/W	bend radius ratio

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