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Multi-Criteria Hydraulic Design of Roadside Ditches

Julián Pulecio-Díaz * and Oscar C. Valderrama-Riveros

Faculty of Engineering, Universidad Cooperativa de Colombia, Edificio I, Ibagué 730006, Colombia; oscar.valderramar@campusucc.edu.co
* Correspondence: julian.puleciod@campusucc.edu.co

Abstract

Roadside ditches play a fundamental role in roadway drainage systems by conveying surface runoff, preserving pavement performance, and mitigating erosion-related deterioration. However, conventional hydraulic design procedures typically require iterative calculations and independent verification of hydraulic capacity, flow velocity, and material-related design criteria, making the design process time-consuming and potentially inconsistent. This study presents a multi-criteria hydraulic design methodology for triangular roadside ditches that integrates hydraulic capacity, minimum self-cleansing velocity, maximum allowable velocity, longitudinal slope, and material-related performance criteria within a unified design framework. The methodology combines the Rational Method, continuity equation, and Manning's equation to generate capacity–velocity–slope relationships for lined and unlined roadside ditches and was implemented in a web-based computational environment. Analytical verification of nine lined cross sections at three representative longitudinal slopes comprised 27 geometry–slope combinations and 54 hydraulic values, showing agreement between analytical calculations and computational outputs apart from numerical rounding. For unlined ditches, seven predefined ditch-floor materials were evaluated through two Manning roughness levels; increasing n from 0.020 to 0.025 reduced both mean flow velocity and discharge capacity by 20% under identical geometry and slope conditions. The results demonstrate that maximum hydraulic capacity alone does not define the most appropriate design, because admissible solutions must simultaneously satisfy conveyance, velocity, slope, and material-resistance requirements. The proposed methodology transforms conventional sequential hydraulic verification into an integrated multi-criteria framework for faster, standardized, and reproducible roadside ditch design.

Keywords: roadway drainage; triangular roadside ditches; hydraulic design; capacity–velocity–slope relationships; velocity-based screening; sediment-related constraints

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1. Introduction

Road drainage systems are essential components of transportation infrastructure because they collect, convey, and safely discharge surface runoff generated during precipitation events. Their proper functioning contributes to pavement preservation, slope stability, erosion control, and roadway safety, whereas inadequate drainage performance may accelerate infrastructure deterioration, increase maintenance costs, and compromise serviceability [1,2]. Recent studies have highlighted the growing vulnerability of transportation networks to extreme rainfall events and climate variability, emphasizing the need for more resilient drainage infrastructure capable of maintaining hydraulic performance under changing environmental conditions [3,4].

1.1. Background and Motivation

Among roadway drainage facilities, roadside ditches are particularly important because they collect and convey surface runoff along road corridors. Their hydraulic performance depends on the interaction between cross-sectional geometry, longitudinal slope, surface roughness, and runoff conditions. Consequently, their design must consider not only adequate conveyance capacity but also permissible flow velocities, erosion resistance, and sediment-related requirements. Established drainage manuals and engineering guidelines provide the fundamental principles and criteria for evaluating these conditions [5–7].

In recent years, climate change has emerged as an additional challenge for roadway drainage systems. Studies have shown that increasing rainfall intensity and the growing frequency of extreme precipitation events may exceed the hydraulic capacities considered during conventional drainage design [3]. Recent investigations have further demonstrated that resilient drainage strategies are essential for maintaining the hydraulic performance of transportation infrastructure under increasingly severe rainfall conditions [8]. Similarly, recent studies have proposed drainage adaptations for hilly roads to mitigate the impacts of climate-induced disasters by improving hydraulic energy dissipation and flow management under extreme rainfall events [9]. Probabilistic assessments of road drainage systems have also demonstrated that future rainfall scenarios may significantly increase the probability of roadway flooding and hydraulic failures, highlighting the need for more resilient and adaptive drainage solutions [4].

In addition, experimental investigations have demonstrated that concentrated runoff discharged from roadway drainage systems can rapidly initiate scour and ravine formation on adjacent slopes when adequate erosion protection measures are not provided. These findings highlight the importance of adequately managing concentrated drainage flows to improve the resilience of transportation infrastructure under increasingly intense rainfall conditions [10].

The consequences of inadequate drainage design and maintenance have been widely documented in transportation infrastructure [11]. Recent hydraulic evaluations of existing roadside drainage systems have demonstrated that insufficient hydraulic capacity and inadequate drainage performance remain recurrent challenges in urban transportation networks, reinforcing the need for systematic drainage assessment and improved hydraulic design methodologies [12]. Investigations conducted in mountainous road corridors have identified sedimentation, scour, culvert blockage, and ditch erosion as major contributors to pavement deterioration, slope instability, and increased maintenance requirements [13]. Similar observations have been reported in agricultural watersheds, where soil erosion and sediment accumulation within roadside ditches have been shown to reduce hydraulic performance, decrease flow conveyance capacity, and compromise the long-term functionality of roadside ditches [14,15]. Recent diagnostic frameworks have further demonstrated that geometric deficiencies, inadequate hydraulic capacity, and insufficient maintenance frequently coexist within roadway drainage infrastructure, emphasizing the need for systematic evaluation and improved hydraulic design methodologies [16]. To address these challenges, recent studies have shown that enhanced roadside drainage systems can significantly improve the hydraulic performance and resilience of transportation infrastructure under challenging environmental conditions [17,18]. Moreover, quantitative analyses of transportation assets have revealed that drainage-related deficiencies are among the primary causes of earthwork failures, demonstrating the strong interaction between hydraulic performance and roadway stability [2].

In addition, recent life-cycle assessments have shown that the selection and design of roadway drainage systems also influence long-term environmental impacts and life-cycle costs, highlighting the importance of technically sound drainage solutions from both engineering and sustainability perspectives [19].

Studies on low-volume roads have additionally confirmed that adequate drainage conditions are essential for preserving structural performance and extending pavement service life [1]. Given the increasing hydraulic demands imposed by climate variability and the critical role of drainage systems in infrastructure performance, the development of efficient, reliable, and practically applicable design methodologies for roadside ditches remains a priority.

1.2. Challenges in Roadside Ditch Hydraulic Design

The hydraulic design of roadside ditches is inherently complex because it requires the simultaneous consideration of multiple interrelated variables. Their performance depends on hydraulic capacity, flow depth, velocity, roughness, channel geometry, and longitudinal slope, all of which influence the overall hydraulic response of the system [20].

Traditional hydraulic analyses are generally based on open-channel flow principles and Manning's equation [5]. Although these approaches provide a robust foundation for hydraulic design, the interaction between channel geometry, flow velocity, and longitudinal slope often results in complex design scenarios requiring iterative calculations [21,22]. Small variations in channel dimensions or slope may significantly alter hydraulic capacity and flow velocities, affecting both drainage efficiency and structural stability.

Another important challenge is the definition of acceptable velocity ranges. Excessively low velocities may promote sediment deposition and progressive reduction in hydraulic capacity, whereas excessively high velocities may generate erosion in unlined channels or abrasion and deterioration in lined channels [23,24].

Traditional approaches such as permissible velocity methods and shear-stress criteria seek to define stable hydraulic conditions, but their implementation often requires iterative procedures and specialized interpretation [25]. Furthermore, uncertainty associated with rainfall intensity, runoff generation, roughness coefficients, and future environmental conditions introduces additional challenges for achieving reliable hydraulic designs [26].

Additional complexity arises from the influence of material properties. In unlined roadside ditches, allowable velocities are governed by soil resistance to erosion, whereas in lined ditches, hydraulic performance is influenced by the characteristics of the lining material and transported sediments [23].

1.3. Limitations of Existing Design Procedures

Despite significant advances in open-channel hydraulics and roadway drainage engineering, existing design procedures remain largely fragmented. Conventional methodologies are predominantly based on hydraulic capacity calculations followed by independent verification of velocity limits, freeboard requirements, erosion criteria, or structural considerations [20].

Recent research has introduced mathematical optimization approaches, uncertainty analyses, hydraulic numerical simulations, integrated hydraulic–hydrologic modeling frameworks, machine-learning and deep-learning techniques, advanced sediment transport models, and decision-support frameworks to improve hydraulic design and roadway drainage management [24,26–33]. Other studies have proposed design curves and computational methodologies to support hydraulic decision-making and improve system performance under multiple operational conditions [34].

Recent developments have also introduced interactive web-based tools for road drainage and flood-risk assessment [35], as well as automated approaches for evaluating urban roadside drainage systems using mobile LiDAR data [36].

Although these computational approaches have expanded the capabilities of hydraulic analysis and decision support, they address different aspects of drainage design and do not necessarily provide an integrated procedure for comparing standardized roadside ditch cross sections under simultaneous hydraulic and material-related constraints. In this context, the contribution of the present study lies in combining analytical open-channel calculations, predefined ditch geometries, hydraulic capacity assessment, and material- and sediment-dependent velocity thresholds within a web-based, constraint-based screening framework. Rather than introducing a new hydraulic optimization algorithm, the proposed methodology facilitates consistent comparisons among alternative roadside ditch configurations and supports preliminary engineering decision-making.

Similarly, advances in lined channel engineering have focused on improving material durability and resistance to environmental degradation [37]. However, these developments generally address specific aspects of channel behavior independently and do not provide an integrated framework specifically oriented to roadside ditch design.

Although existing design procedures address hydraulic capacity, permissible flow velocities, erosion resistance, and other relevant performance requirements, these criteria are often evaluated through separate calculations or sequential verification steps [23,25]. Integrating these assessments into a unified computational screening framework can facilitate consistent comparisons among predefined roadside ditch configurations and reduce repetitive hydraulic calculations.

1.4. Research Objective and Contribution

Therefore, the objective of this study is to develop and verify a multi-criteria hydraulic design methodology for the evaluation of triangular roadside ditch cross sections that integrates hydraulic capacity, minimum and maximum allowable flow velocities, longitudinal slope, soil or lining characteristics, and sediment-related constraints within a unified computational design framework.

The methodology addresses the limitations identified in existing approaches by integrating hydraulic efficiency, self-cleansing requirements, erosion control, and material performance into a single design procedure. The methodology is based on the capacity–velocity–slope relationships developed in this study and is applicable to both lined and unlined roadside ditches.

The main contributions of this study are as follows: (i) the development of a multi-criteria hydraulic design methodology for roadside ditches; (ii) the establishment of capacity–velocity–slope relationships for triangular roadside ditches; (iii) the integration of minimum self-cleansing and maximum allowable velocities into a unified design procedure; (iv) the incorporation of soil characteristics, lining properties, and sediment-related considerations into hydraulic design; (v) the implementation of the methodology in a web-based computational environment; and (vi) the analytical verification of the computational implementation across representative lined roadside ditch configurations and hydraulic conditions.

The remainder of this paper is organized as follows. Section 2 describes the materials and methods, including the development of the multi-criteria hydraulic design methodology, the governing hydraulic principles, the design criteria for lined and unlined roadside ditches, and the computational implementation framework. Section 3 presents and discusses the results obtained from the application and analytical verification of the methodology, including the hydraulic performance of lined and unlined ditch configurations, computa-

tional performance, engineering implications, practical applications, limitations, and future research directions. Finally, Section 4 summarizes the main conclusions of the study.

2. Materials and Methods

This study proposes a multi-criteria hydraulic design methodology for triangular roadside ditches based on the integration of hydrological inputs, hydraulic capacity, flow velocity constraints, longitudinal slope, ditch geometry, lining characteristics, and sediment-related considerations. The methodology integrates the Rational Method with classical open-channel hydraulic principles and velocity-based performance criteria to develop capacity–velocity–slope relationships for both lined concrete and unlined soil roadside ditches. The resulting methodology was subsequently implemented in a web-based computational platform to facilitate practical hydraulic design and engineering decision-making.

Figure 1 provides an overview of the organization of the Materials and Methods section, illustrating the relationship between the methodological framework, hydraulic design criteria, material-related performance constraints, capacity–velocity–slope relationships, and computational implementation. The individual components and their analytical foundations are described in Sections 2.1–2.5, while the application and verification results are presented in Section 3.

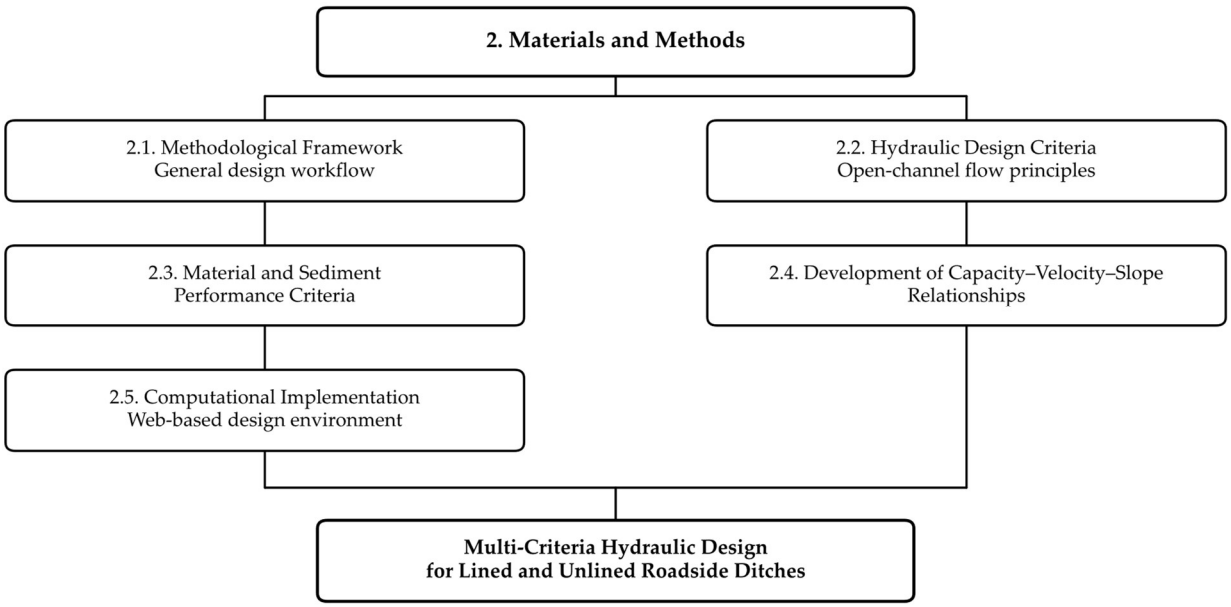


Figure 1. Organization of the Materials and Methods section and relationship between the methodological components used to develop the multi-criteria hydraulic design methodology.

2.1. Methodological Framework

The methodology was developed through a sequential process integrating hydraulic analysis, material performance constraints, and computational implementation. First, the governing hydraulic equations for open-channel flow were established. Second, hydraulic performance criteria associated with flow capacity and velocity limits were defined. Third, the candidate cross sections were systematically evaluated under different combinations of longitudinal slopes and hydraulic conditions to generate the proposed capacity–velocity–slope relationships. Finally, the methodology was implemented in a web-based computational environment. Its application and verification through a representative design example are presented in Section 3.

Figure 2 presents the methodological framework developed in this study. The methodological framework integrates hydrological inputs, open-channel hydraulic analysis, hydraulic response evaluation, and multi-criteria design requirements within a unified procedure for roadside ditch design. The methodology considers hydraulic capacity, minimum self-cleansing velocity, maximum allowable velocity, longitudinal slope, and material-related constraints associated with both lined and unlined ditches. These criteria are subsequently incorporated into the development of the design relationships, which constitute the core contribution of the methodology and provide the analytical basis for the development of the web-based computational implementation presented in Section 2.5.

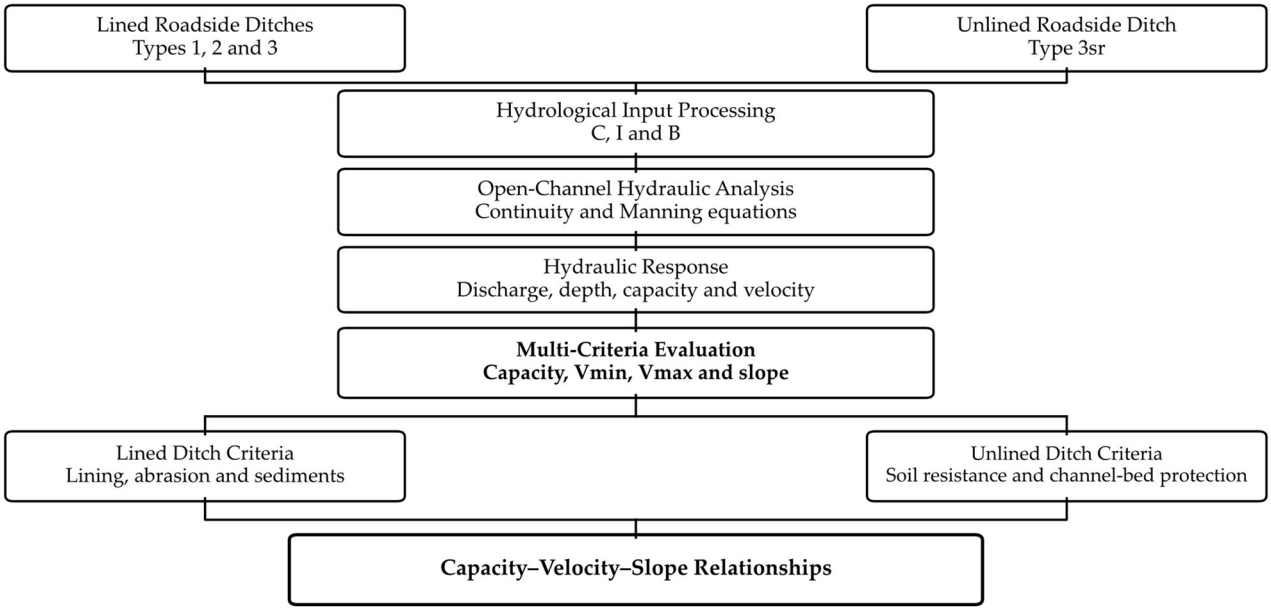


Figure 2. Methodological framework of the proposed multi-criteria hydraulic design methodology for lined and unlined roadside ditches.

In this study, the term multi-criteria refers to the simultaneous consideration of hydraulic conveyance capacity, material-dependent velocity limits, and sediment-related performance constraints within a unified screening framework. The proposed approach is based on constraint-based hydraulic evaluation rather than mathematical multi-objective optimization; therefore, it does not involve objective-function weighting, Pareto-front generation, or automated identification of a globally optimal design. Instead, it identifies admissible hydraulic conditions and supports comparative assessment of predefined roadside ditch configurations.

To provide a clearer understanding of the mathematical basis of the presented methodology, Figure 3 illustrates the conceptual framework linking hydrological inputs, hydraulic analysis, and the development of the capacity–velocity–slope relationships. The framework integrates the Rational Method, continuity equation, and Manning equation to estimate the maximum capacity-based ditch length under specified hydrological and hydraulic conditions. The resulting formulation constitutes the analytical foundation for the generation of the design relationships implemented in the web-based computational environment.

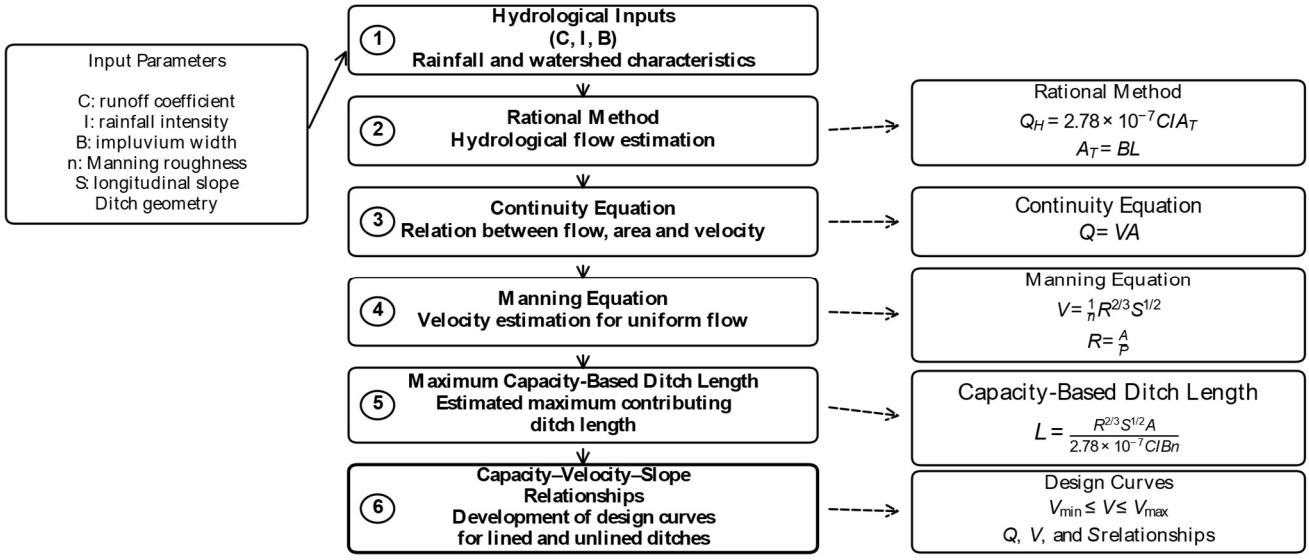


Figure 3. Conceptual mathematical framework used to derive the capacity–velocity–slope relationships from hydrological and hydraulic principles.

2.2. Hydraulic Design Criteria

The hydraulic design procedure is based on uniform open-channel flow principles and the integration of hydrological and hydraulic analyses. Hydrological runoff was estimated using the Rational Method, while hydraulic performance was evaluated through the continuity and Manning equations. The resulting formulation was used to estimate the maximum capacity-based ditch length and to generate the capacity–velocity–slope relationships developed in this study [5].

The hydrological flow rate was estimated using the Rational Method according to Equation (1):

$$Q_H = 2.78 \times 10^{-7} \, C \, I \, A_T, \quad (1)$$

where (Q_H) is the hydrological flow rate (m^3/s), (C) is the runoff coefficient, (I) is the rainfall intensity (mm/h), and (A_T) is the tributary area (m^2).

The conversion factor 2.78×10^{-7} accounts for the units adopted in the Rational Method, converting rainfall intensity expressed in mm/h and contributing area expressed in m^2 into discharge in m^3/s. This factor is obtained by dividing 10^{-3} by 3600, yielding 2.7778×10^{-7}, which is rounded to three significant figures.

The Rational Method is adopted as a simplified design approach for relatively small roadway drainage catchments, where runoff can be represented using a spatially uniform design rainfall intensity and a representative runoff coefficient. The selected rainfall intensity should correspond to the applicable design return period and a storm duration consistent with the catchment time of concentration, in accordance with relevant local drainage design guidelines. The formulation assumes a steady design discharge for hydraulic capacity assessment and does not explicitly simulate rainfall temporal variability, runoff routing, or transient flow conditions. Therefore, its application to larger or hydrologically complex catchments requires additional hydrological assessment.

The tributary area was determined as

$$A_T = B \, L, \quad (2)$$

where (B) is the impluvium width (m) and (L) is the ditch length (m).

Hydraulic flow conditions were evaluated using the continuity equation:

$$Q = V \, A, \quad (3)$$

where (Q) is the flow discharge (m^3/s), (V) is the mean flow velocity (m/s), and (A) is the hydraulic flow area (m^2).

Flow velocity was computed using Manning's equation:

$$V = (1/n)\, R^{2/3}\, S^{1/2}, \tag{4}$$

where (n) is Manning's roughness coefficient, (R) is the hydraulic radius (m), and (S) is the longitudinal slope (m/m).

By combining Equations (1)–(4), the maximum capacity-based ditch length can be estimated as

$$L = (R^{2/3}\, S^{1/2}\, A)/(2.78 \times 10^{-7}\, C\, I\, B\, n), \tag{5}$$

Equation (5) constitutes the analytical basis of the methodology and establishes the relationship between hydrological conditions, hydraulic performance, ditch geometry, and surface characteristics. This formulation was subsequently used to generate the capacity–velocity–slope relationships developed in this study.

Equation (5) provides a capacity-based estimate of the maximum contributing ditch length by equating the accumulated design runoff at the downstream control section to the discharge capacity estimated using Manning's equation. This formulation assumes steady, uniform-flow conditions at the control section and does not represent the spatially varied flow profile resulting from distributed lateral inflow. In actual roadside ditches, discharge generally increases along the channel as runoff is progressively collected, producing longitudinal variations in flow depth and velocity. Consequently, the calculated maximum length should be interpreted as a preliminary hydraulic capacity screening limit rather than a complete hydrodynamic design solution. Furthermore, compliance with the minimum self-cleansing velocity at the downstream control section does not guarantee that this threshold is satisfied along upstream reaches, where lower discharges may promote sediment deposition. Practical applications therefore require consideration of local sediment accumulation, maintenance requirements, downstream transitions, and, where necessary, more detailed spatially varied flow analysis.

The methodology considers standardized cross sections commonly adopted in roadway drainage practice because of their hydraulic efficiency, ease of construction, and reduced right-of-way requirements. Hydraulic calculations included the determination of flow area, wetted perimeter, hydraulic radius, flow depth, and mean flow velocity.

Figure 4 illustrates the generalized asymmetric triangular geometry adopted in this study. The horizontal projections of the left and right wetted sides are denoted by c and d, respectively, while y represents the flow depth. The corresponding lateral side slopes are defined as $z_1 = c/y$ and $z_2 = d/y$, and the total top width is $T = c + d$. The hydraulic flow area (A), wetted perimeter (P), and hydraulic radius (R) are determined from the interior wetted boundary, excluding lining thickness and external construction dimensions. The longitudinal channel slope (S) is subsequently incorporated into Manning's equation.

$$A = (c + d)y/2 \tag{6}$$

$$P = \sqrt{c^2 + y^2} + \sqrt{d^2 + y^2} \tag{7}$$

$$R = A/P, \tag{8}$$

Equations (6)–(8) apply to general triangular sections, including the asymmetric Type 1 and Type 2 configurations and the symmetric Type 3 configuration. For Type 1, $c = 0$ and the left wetted boundary is vertical. For Type 2, c and d are unequal, whereas for Type 3, $c = d = zy$, where z is the horizontal-to-vertical side-slope ratio. All geometric dimensions are referenced to the same water-surface elevation.

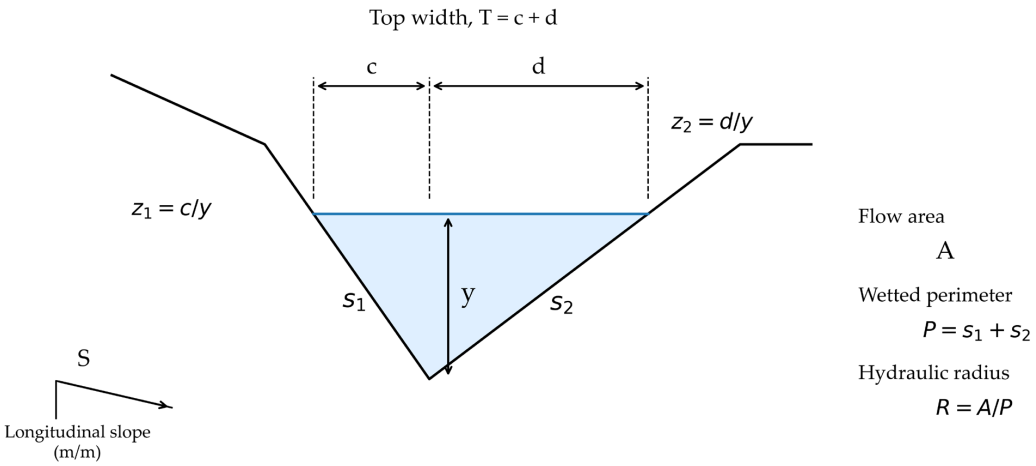


Figure 4. General asymmetric triangular roadside ditch geometry showing the horizontal projections (c and d), flow depth (y), lateral side slopes (z_1 and z_2), wetted side lengths (s_1 and s_2), and hydraulic parameters. The symmetric configuration is obtained when $c = d$.

The standardized roadside ditch geometries considered in this study were adopted from the Colombian National Roads Institute (INVIAS) Manual for the Design of Asphalt Pavements for Low-Volume Roads (2007), specifically Section 6.2.2.1, Figure 6.2, and Table 6.4. The manual defines nine concrete-lined triangular configurations, classified as Types 1, 2, and 3, with three dimensional alternatives (A, B, and C) for each type. The corresponding unlined Type 3 configurations are also documented in Section 6.2.2.2, Figure 6.3, and Table 6.6. These established geometries provide the reference configurations for the present hydraulic assessment, while the proposed methodology extends their evaluation through slope-dependent hydraulic relationships and material-specific velocity constraints [38].

The following hydraulic variables were considered:

- Flow discharge (Q);
- Mean flow velocity (V);
- Hydraulic area (A);
- Wetted perimeter (P);
- Hydraulic radius (R);
- Manning roughness coefficient (n);
- Longitudinal slope (S);
- Flow depth (y).

The design procedure evaluates hydraulic performance over a wide range of longitudinal slopes representative of roadway drainage applications.

2.3. Material and Sediment Performance Criteria

In addition to hydraulic capacity requirements, the methodology incorporates performance criteria associated with flow velocity limits to ensure hydraulic functionality, structural stability, and long-term serviceability of roadside ditches [39]. The hydraulic performance of roadside ditches is also influenced by the characteristics of the selected lining or soil surface, which affect flow resistance, conveyance efficiency, and long-term hydraulic performance. Previous studies have shown that appropriate channel lining improves hydraulic efficiency by reducing flow resistance and hydraulic losses, thereby contributing to more reliable drainage performance [40].

For unlined roadside ditches, the maximum allowable velocity (Vmax) was established according to soil erosion resistance criteria. Excessive flow velocities may initiate particle

detachment, surface erosion, and progressive degradation of ditch geometry, ultimately reducing hydraulic efficiency and increasing maintenance requirements. Therefore, the selected hydraulic condition must satisfy the maximum permissible velocity associated with the soil type and surface protection characteristics.

For lined roadside ditches, the maximum allowable velocity was defined considering the mechanical resistance of the lining material and the abrasive effects of transported sediments. The methodology incorporates the influence of concrete compressive strength and sediment characteristics on the allowable hydraulic conditions, recognizing that high flow velocities combined with sediment transport may accelerate surface wear and reduce lining durability.

The velocity criteria adopted in this study were selected according to ditch material characteristics and transported sediment conditions. The maximum permissible velocities for concrete-lined ditches were derived from the hydraulic design criteria reported by López Cualla [41]. The FHWA Hydraulic Engineering Circular No. 15 [39] provides complementary guidance on the stability of flexible channel linings based on permissible tractive force. For concrete-lined roadside ditches, the adopted maximum velocity limits were differentiated according to concrete compressive strength and sediment characteristics, whereas for unlined roadside ditches, they were differentiated according to soil erosion resistance and sediment characteristics. These values are treated as prescribed hydraulic screening thresholds rather than experimentally calibrated limits specific to the present study. The adopted criteria, including minimum self-cleansing velocities and maximum allowable velocities for different lining materials, soil types, and sediment conditions, are summarized in Table 1.

Table 1. Velocity criteria adopted for lined and unlined roadside ditches, based on López Cualla [41].

Lined Roadside Ditches				
Concrete Compressive Strength (MPa)	***n***	**Vmin (m/s)**	**Vmax (Colloidal Sediments)**	**Vmax (Sand and Gravel Fragments)**
14	0.015	0.60	3.0	2.0
21	0.015	0.60	5.0	3.3
25	0.015	0.60	6.0	4.0
Unlined roadside ditches				
Soil type	*n*	**Vmin (m/s)**	**Vmax (colloidal sediments)**	**Vmax (sand and gravel fragments)**
Fine gravels	0.020	0.60	1.5	1.15
Fine sands	0.020	–	0.75	0.45
Silt (not colloidal)	0.020	0.60	1.05	0.60
Plastic silty clay	0.020	0.60	0.90	0.60
Silt (colloidal)	0.025	0.60	1.50	0.90
Cementitious plastic clay	0.025	0.60	1.05	0.70
Hard clay	0.025	0.60	1.50	0.90

Note: The dash (–) indicates that no minimum self-cleansing velocity is specified for fine sands in the adopted criteria. Accordingly, only the corresponding maximum permissible velocity is applied during hydraulic screening. The absence of a minimum velocity threshold should not be interpreted as evidence of adequate sediment transport or self-cleansing performance. The maximum permissible velocities for concrete-lined ditches are adopted from reference values reported for concrete drainage conduits and are used here as preliminary hydraulic screening thresholds. Their applicability to open triangular ditches should be assessed against project-specific conditions and relevant design standards.

For concrete-lined ditches, the adopted maximum permissible velocities are based on the values reported by López Cualla [41] for concrete drainage conduits, differentiated according to concrete compressive strength and sediment characteristics. The original concrete strength values of 140, 210, and 250 kg/cm^2 were converted to approximately 13.7, 20.6, and 24.5 MPa, respectively, and represented by the rounded nominal values of 14,

21, and 25 MPa in Table 1. These criteria are applied as preliminary hydraulic screening thresholds for roadside ditches rather than experimentally validated erosion or abrasion limits for the specific triangular geometries investigated. Consequently, their applicability should be verified against project-specific hydraulic conditions, sediment characteristics, and relevant local design standards before final implementation.

As shown in Table 1, the admissible velocity range varies according to the resistance of the lining material or soil type and the characteristics of the transported sediments. These limits were incorporated into the hydraulic screening process used to generate the capacity–velocity–slope relationships developed in this study.

In addition to erosion and abrasion limitations, minimum self-cleansing velocities (Vmin) were considered to minimize sediment deposition and preserve hydraulic conveyance capacity. Flow velocities below this threshold may promote sediment accumulation, reduce the effective flow area, and increase maintenance interventions.

Figure 5 illustrates the velocity-based performance criteria incorporated into the methodology. Flow velocities lower than the minimum self-cleansing velocity may promote sediment deposition and progressive reduction in hydraulic capacity, whereas velocities exceeding the maximum allowable velocity may induce soil erosion in unlined ditches or abrasion-related deterioration in lined ditches. Consequently, the acceptable hydraulic design region is bounded by the interval defined by the minimum and maximum admissible velocities.

$$\mathrm{Vmin} \leq \mathrm{V} \leq \mathrm{Vmax}, \tag{9}$$

where V is the mean flow velocity, Vmin is the minimum self-cleansing velocity required to prevent sediment deposition, and Vmax is the maximum allowable velocity determined according to the selected ditch configuration, soil erosion resistance, lining properties, and sediment-related constraints.

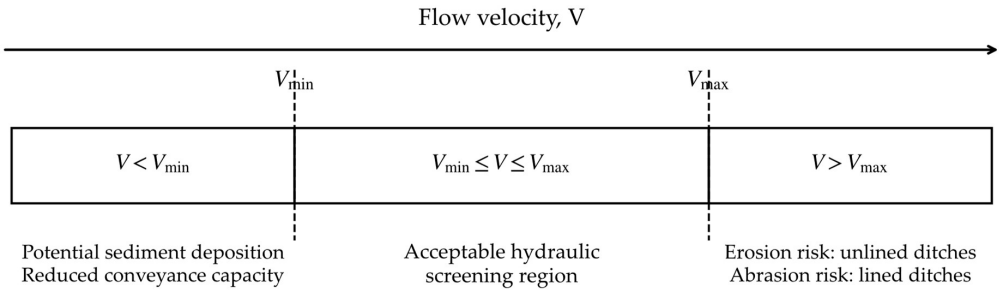


Figure 5. Schematic representation of velocity-based hydraulic screening criteria for lined and unlined roadside ditches. The admissible region is bounded by the prescribed minimum self-cleansing velocity and maximum permissible velocity when both thresholds are specified. Where no minimum velocity is prescribed, screening is performed using the applicable maximum velocity threshold only.

For fine sands, Table 1 does not prescribe a minimum self-cleansing velocity. Consequently, only the corresponding maximum permissible velocity is considered in the hydraulic screening procedure. This treatment is reflected in the SDDRoads 2.0 graphical interface, which displays the maximum permissible velocities of 0.75 m/s and 0.45 m/s without introducing an additional minimum velocity threshold. However, the absence of a prescribed minimum velocity should not be interpreted as evidence of adequate sediment transport or self-cleansing performance.

The applicable velocity constraints constitute fundamental criteria of the proposed methodology and were subsequently incorporated into the development of the relationships presented in Section 2.4. When both velocity thresholds are defined, admissibility is evaluated using Equation (9); otherwise, only the available material-specific velocity limits are applied.

2.4. Development of Capacity–Velocity–Slope Relationships

The core contribution of the methodology consists of the development of capacity–velocity–slope relationships for triangular roadside ditches. These relationships were generated through the systematic hydraulic evaluation of triangular roadside ditch cross sections under different hydraulic, geometric, and material conditions. The candidate cross sections were systematically evaluated under different combinations of longitudinal slope, hydrological input parameters, Manning roughness coefficients, soil types, concrete lining strengths, and sediment characteristics. For each evaluated combination, hydraulic capacity and mean flow velocity were computed using the Rational Method, the continuity equation, and Manning's equation presented in Section 2.2.

The calculated hydraulic solutions were classified according to the velocity-based performance criteria described in Section 2.3. Conditions satisfying the applicable minimum and maximum velocity thresholds were identified as admissible, whereas conditions outside these thresholds were retained for visualization and explicitly distinguished as non-admissible. This representation allows designers to examine the complete hydraulic response of each cross section while identifying the slope intervals that satisfy the adopted velocity constraints. The corresponding maximum ditch lengths represent capacity-based screening estimates and should not be interpreted as verification of self-cleansing conditions throughout the entire channel.

The filtered hydraulic solutions were subsequently organized into capacity–velocity–slope relationships for the evaluated cross sections incorporated into the computational platform. These relationships define the admissible hydraulic design domain for both lined and unlined ditch configurations and constitute the basis of the design curves implemented in the web-based computational tool.

Figure 6 illustrates the procedure used to generate the capacity–velocity–slope relationships developed in this study from hydraulic calculations and velocity-based performance constraints.

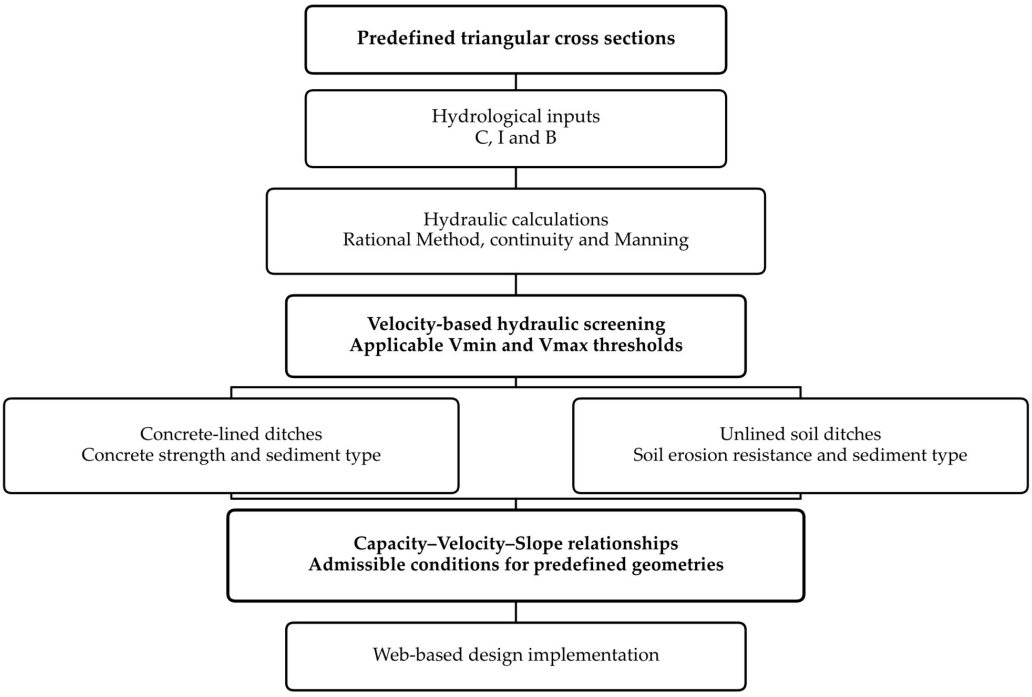


Figure 6. Procedure used to generate the capacity–velocity–slope relationships for lined and unlined triangular roadside ditches.

The resulting design relationships allow designers to rapidly identify feasible ditch configurations without performing the multiple trial-and-error iterations traditionally required in roadside ditch design.

2.5. Computational Implementation

The proposed methodology was implemented in SDDRoads 2.0 (Side Drain Design for Roads), a publicly accessible web-based computational tool available at https://www.ibaing.com/SDDRoadsENew/ (accessed on 3 November 2026). The platform supports the hydraulic evaluation and selection of predefined triangular roadside ditch configurations under different hydrological, geometric, and material conditions. It automatically calculates hydraulic capacity, mean flow velocity, and capacity-based maximum ditch length, while graphically identifying longitudinal slope intervals that satisfy the applicable velocity-based performance criteria.

Users first select one of the predefined triangular roadside ditch configurations before defining the required input parameters. Once the input data are provided, the computational engine automatically evaluates the three standardized cross sections associated with the selected ditch configuration. For each cross section, hydraulic capacity, flow velocity, and the corresponding slope–velocity and slope–discharge relationships are computed. The resulting curves are then compared against the adopted velocity-based performance criteria, enabling the identification of feasible hydraulic design alternatives.

The calculated hydraulic solutions are classified according to the applicable velocity-based performance criteria presented in Section 2.3. Conditions satisfying the prescribed velocity limits are identified as admissible, whereas conditions outside these limits remain available for graphical visualization and are explicitly distinguished as non-admissible. The resulting relationships support the identification and comparison of hydraulically admissible cross-sectional alternatives without suppressing the overall hydraulic response. The corresponding maximum ditch lengths represent capacity-based screening estimates rather than complete hydraulic safety verification.

Figure 7 illustrates the operational workflow of the web-based implementation. The computational workflow begins with the selection of a predefined triangular roadside ditch configuration, followed by the specification of the required hydrological input parameters through the graphical user interface. The computational engine then evaluates the hydraulic response of the selected cross sections and applies the material-dependent velocity criteria. The resulting slope–maximum ditch length (S–L) relationships are graphically displayed, distinguishing admissible and non-admissible velocity conditions through solid and dashed line segments, respectively. These maximum lengths represent capacity-based estimates rather than complete hydraulic safety verification.

The web-based implementation provides several practical advantages, including multiplatform accessibility, no software installation requirements, compatibility with desktop computers, tablets, and smartphones, rapid design evaluation, and immediate graphical visualization of results. These characteristics facilitate the practical application of the developed methodology in roadway drainage design while preserving the analytical consistency of the underlying hydraulic model.

The platform incorporates dedicated computational modules for lined concrete triangular roadside ditches and unlined soil triangular roadside ditches, enabling the proposed methodology to be consistently applied under different hydraulic, material, and environmental conditions through a unified computational framework.

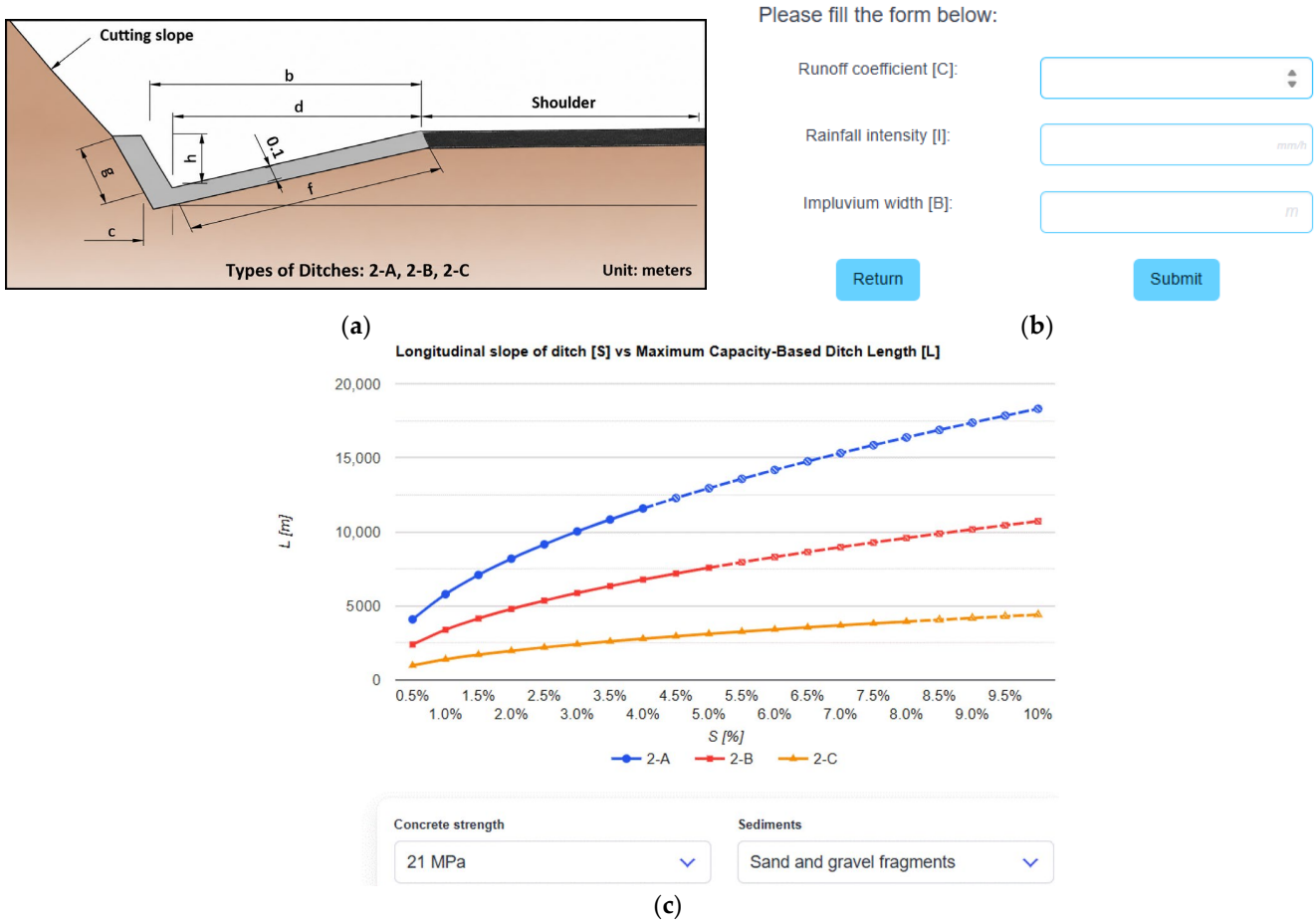


Figure 7. Computational workflow of SDDRoads 2.0: (**a**) selection of predefined triangular roadside ditch configurations; (**b**) specification of hydrological input parameters through the web interface; and (**c**) visualization of slope–maximum ditch length (S–L) relationships for the three cross-sectional alternatives associated with the selected configuration. The maximum ditch length represents a capacity-based estimate at the downstream control section. Solid line segments indicate conditions satisfying the applicable velocity-based performance criteria, whereas dashed segments identify conditions outside the admissible velocity range. The lowercase letters in panel (**a**) denote the geometric dimensions of the roadside ditch cross section, as displayed in the SDDRoads 2.0 interface.

SDDRoads 2.0 extends the original SDDRoads application reported by Pulecio-Díaz et al. (2020) [21]. The original application estimated the theoretical and constructible ditch lengths for three predefined cross-sectional alternatives using a specified longitudinal slope and hydrological input parameters. In contrast, SDDRoads 2.0 expands this length-based calculation by incorporating the systematic evaluation and graphical representation of mean flow velocity, hydraulic discharge, and capacity-based maximum ditch length across a range of longitudinal slopes. The updated platform also integrates material-dependent velocity limits and sediment-related criteria, enabling the graphical identification of admissible and non-admissible hydraulic conditions. These developments facilitate comparative hydraulic screening of alternative ditch configurations while preserving the assumptions of steady, uniform-flow analysis.

3. Results and Discussion

This section presents the application and evaluation of the proposed multi-criteria hydraulic design methodology through a representative verification example, followed by an assessment of its hydraulic and computational performance. First, a Type 1 roadside

ditch configuration is used to illustrate the complete computational workflow and the automatic generation of predefined hydraulic design alternatives. Subsequently, the hydraulic performance of the evaluated cross sections is examined through the slope–velocity, slope–discharge, and slope–capacity-based ditch length relationships, highlighting the influence of cross-sectional geometry and velocity-based design criteria. The computational implementation is then discussed in terms of its ability to automate hydraulic calculations and support engineering decision-making. Finally, the practical implications, limitations, and potential directions for future development are presented.

3.1. Representative Verification Example

To demonstrate the practical application of the methodology, a representative verification example was conducted using the predefined Type 1 roadside ditch configuration incorporated into the proposed web-based computational platform. The example follows the complete hydraulic design workflow described in Section 2 and illustrates the automatic evaluation of the candidate cross sections associated with the selected ditch configuration.

The user-defined input parameters adopted for the representative verification example are summarized in Table 2. Based on these inputs, the computational platform automatically generated the three standardized cross sections corresponding to the selected Type 1 configuration (Figure 8), together with the associated slope–velocity (Figure 9), slope–discharge (Figure 10), and slope–capacity-based ditch length (Figure 11) relationships used to evaluate the hydraulic performance of each alternative.

Table 2. User-defined input parameters adopted for the representative verification example.

Category	Parameter	Symbol	Value	Unit
Configuration	Roadside ditch configuration	-	Type 1	-
Hydrology	Runoff coefficient	C	0.30	-
Hydrology	Rainfall intensity	I	50	mm/h
Hydrology	Impluvium width	B	10	m

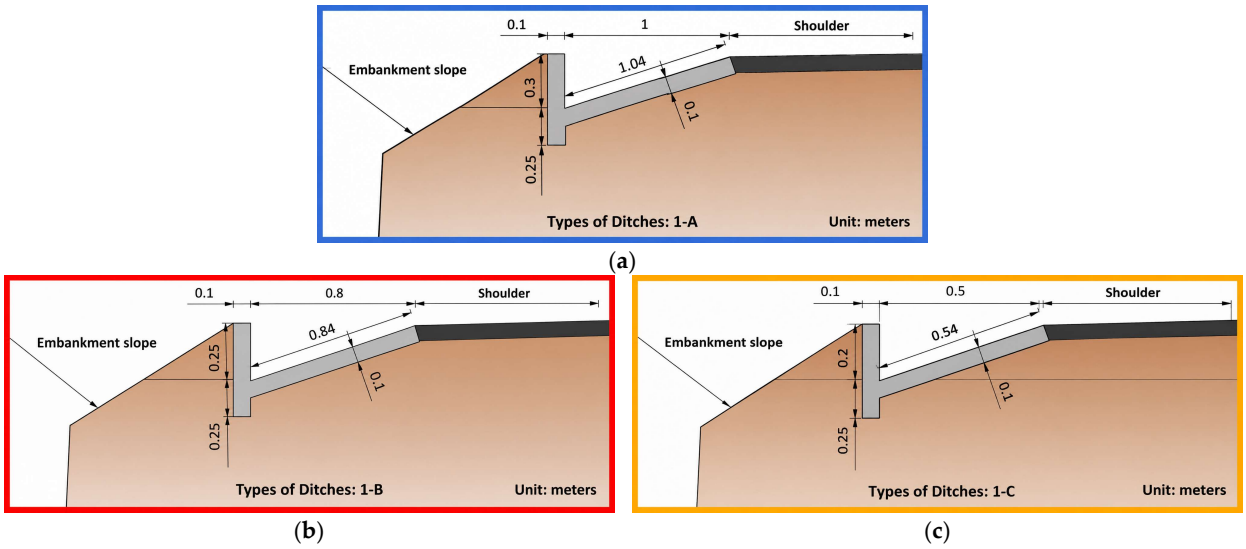


Figure 8. Standardized cross-sectional geometries automatically generated by SDDRoads 2.0 for the selected Type 1 nonsymmetrical concrete roadside ditch configuration: (**a**) 1-A, (**b**) 1-B, and (**c**) 1-C. Dimensions are given in meters.

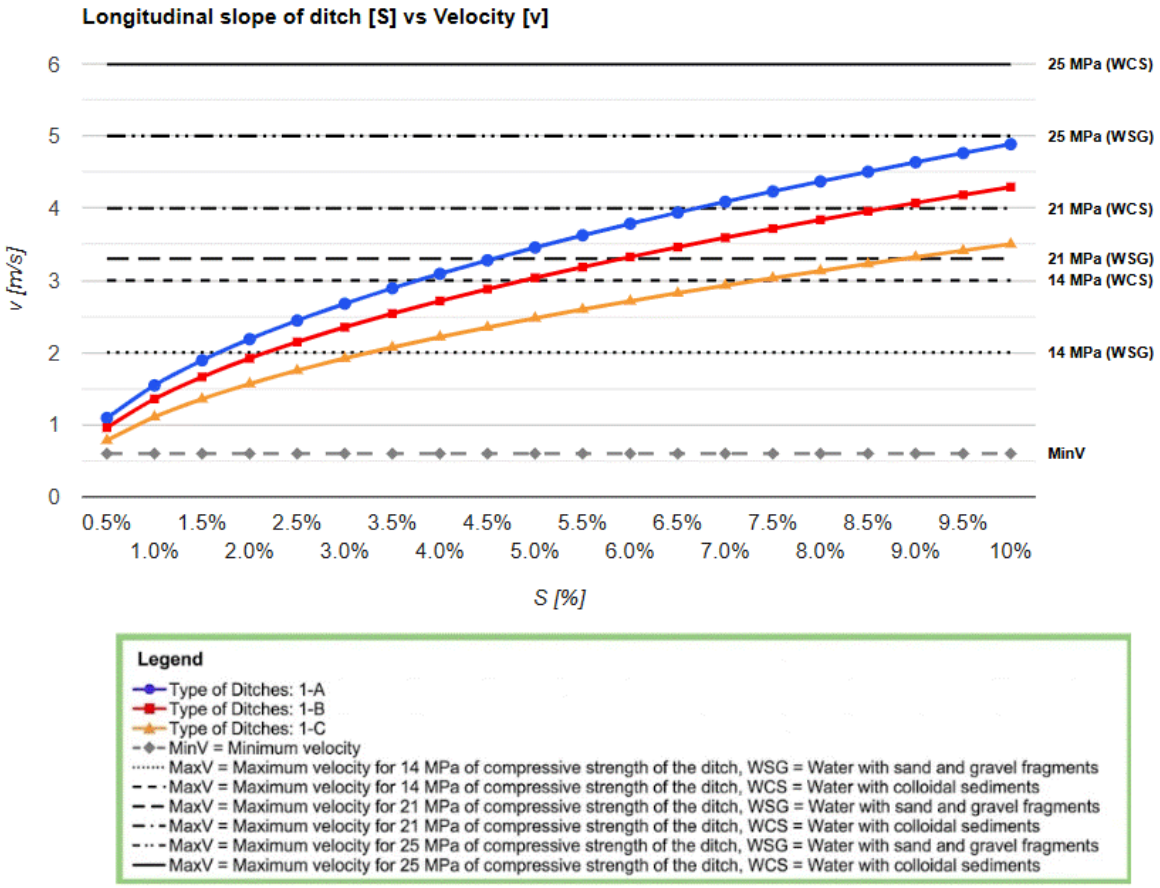


Figure 9. Slope–velocity relationships automatically generated for the three Type 1 cross sections together with the minimum self-cleansing velocity and the maximum allowable velocity limits adopted by the proposed methodology.

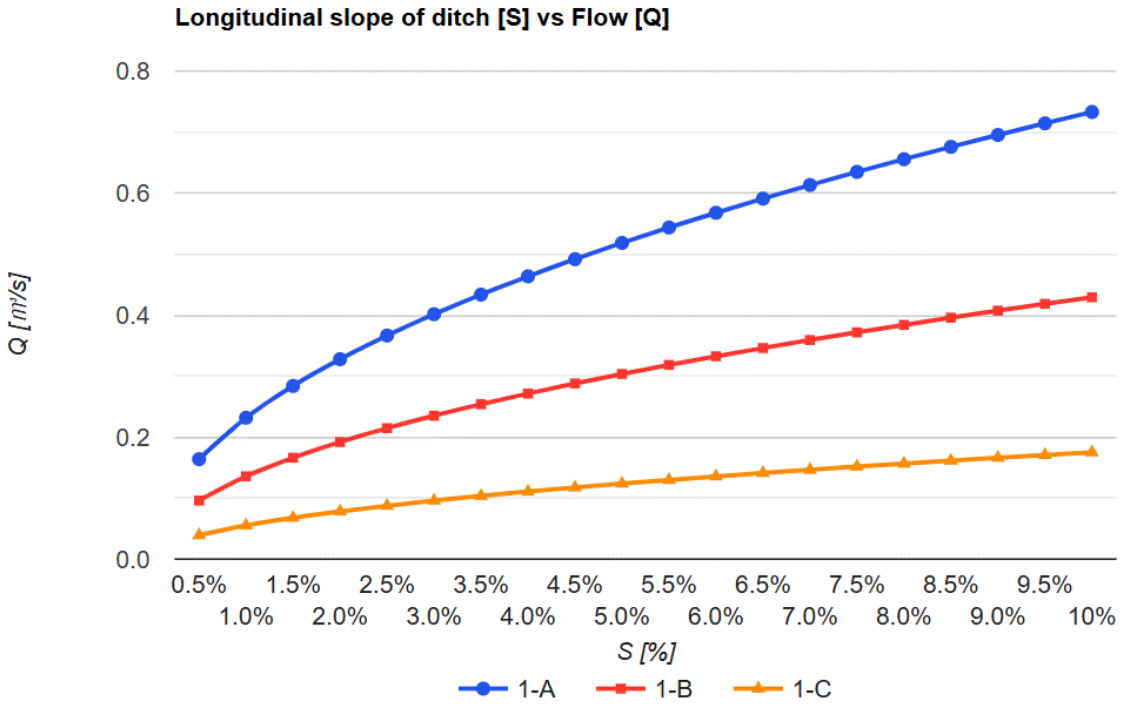


Figure 10. Slope–discharge relationships automatically generated for the three Type 1 cross sections evaluated in the representative verification example.

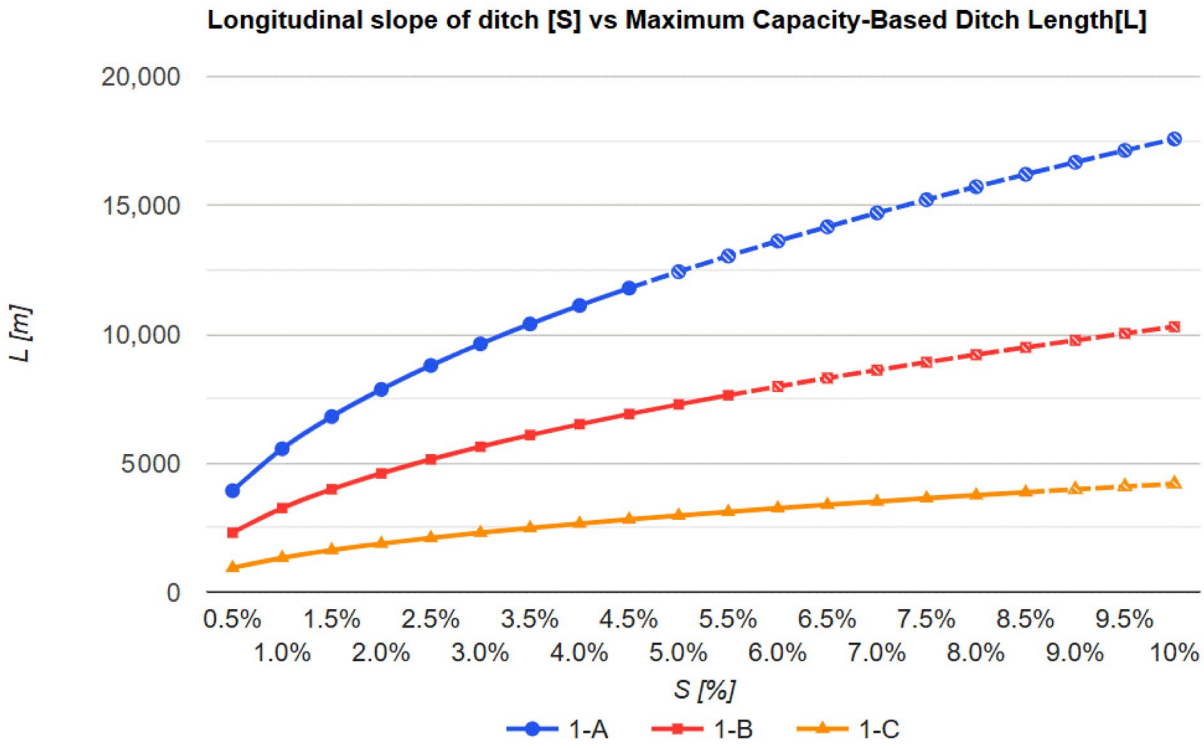


Figure 11. Slope–capacity-based ditch length estimates for the three Type 1 roadside ditch configurations (1-A, 1-B, and 1-C), considering a concrete compressive strength of 21 MPa and water containing sand and gravel fragments. The estimated lengths are based on downstream hydraulic capacity and do not represent a spatially distributed lateral-inflow analysis. Solid line segments indicate conditions satisfying the applicable velocity-based performance criteria, whereas dashed segments identify conditions outside the admissible velocity range.

The blue, red, and orange borders identify configurations 1-A, 1-B, and 1-C, respectively, and correspond to the colors used for their hydraulic response curves in Figures 9 and 11.

The cross-sectional configurations illustrated in Figures 7a and 8 represent different roadside drainage arrangements available in SDDRoads 2.0. Figure 7a depicts Type 2 ditch configurations (2-A, 2-B, and 2-C) adjacent to a cutting slope, whereas Figure 8 illustrates Type 1 ditch configurations (1-A, 1-B, and 1-C) adjacent to an embankment slope. These illustrations demonstrate the applicability of the proposed hydraulic screening methodology to different roadway cross-sectional arrangements. However, the selection and implementation of a particular ditch configuration must consider site-specific topography, runoff collection requirements, roadway geometry, and applicable drainage design standards. The inclusion of these configurations does not imply that roadside ditches are required in all cutting or embankment conditions.

The hydraulic behavior illustrated in Figures 9–11 forms the basis for the performance analysis presented in the following section, where the influence of the predefined cross sections on flow velocity, hydraulic capacity, capacity-based ditch length estimates, and compliance with the adopted velocity-based design criteria is discussed.

The numerical results obtained from SDDRoads 2.0 were assessed through independent analytical calculations based on the continuity and Manning equations, using the geometric and hydraulic parameters specified for the evaluated configurations. This procedure verifies the numerical consistency and reproducibility of the implemented calculations under the adopted steady, uniform-flow assumptions. However, it does not constitute experimental or field validation of roadside ditch performance. Such validation would require measured

flow depths, velocities, discharges, and, where applicable, sediment transport and erosion observations under representative operating conditions.

3.2. Hydraulic Performance and Analytical Verification of Lined Ditch Configurations

The representative verification example presented in Section 3.1 illustrates the hydraulic response of the three standardized cross sections associated with the Type 1 roadside ditch configuration. To provide a more comprehensive assessment of the lined ditch module, the analysis was extended to all Type 1, Type 2, and Type 3 configurations incorporated into the computational platform. The evaluation therefore comprised nine standardized lined cross sections and included both interpretation of the generated slope–velocity and slope–discharge relationships and analytical consistency verification of the computational results.

3.2.1. Hydraulic Performance of the Type 1 Cross Sections

The slope–velocity relationships generated for the Type 1 configuration indicate that mean flow velocity increases continuously with longitudinal slope for all three cross sections, consistent with the square-root dependence on slope established by Manning's equation. The three alternatives exhibit different velocity responses because their hydraulic area, wetted perimeter, and hydraulic radius differ according to the corresponding cross-sectional geometry.

Cross section 1-A consistently produced the highest mean flow velocities throughout the evaluated slope range, followed by 1-B and 1-C. The same ordering was observed in the slope–discharge relationships, with 1-A providing the greatest hydraulic capacity, 1-B an intermediate response, and 1-C the lowest conveyance capacity. These differences demonstrate the direct influence of cross-sectional geometry and hydraulic radius on the hydraulic response of the standardized alternatives.

The generated slope–velocity curves also allow the hydraulic response of each cross section to be evaluated against the adopted minimum self-cleansing velocity and maximum allowable velocity limits. At relatively low longitudinal slopes, flow velocities approach the minimum self-cleansing threshold, indicating an increased potential for sediment deposition. Conversely, increasing longitudinal slope progressively raises flow velocity toward the maximum allowable limits associated with the concrete compressive strength and transported sediment characteristics. Consequently, the admissible hydraulic domain depends on the interaction among cross-sectional geometry, longitudinal slope, and the adopted material-related velocity criteria.

The slope–discharge relationships similarly demonstrate that hydraulic capacity increases continuously with longitudinal slope. Larger hydraulic areas and hydraulic radii result in greater conveyance capacity, whereas smaller alternatives provide lower discharge capacity. Joint interpretation of the slope–velocity and slope–discharge relationships therefore enables the designer to evaluate hydraulic capacity together with self-cleansing and material-protection requirements rather than considering these criteria independently.

3.2.2. Analytical Consistency Verification of Type 1, Type 2, and Type 3 Configurations

To extend the verification beyond the representative Type 1 example, all lined roadside ditch configurations incorporated into the computational platform were evaluated. The verification included Type 1, Type 2, and Type 3, each comprising three standardized cross sections (A, B, and C). A common computational reference condition was adopted for the three configurations, with a runoff coefficient of 0.30, rainfall intensity of 50 mm/h, and impluvium width of 10 m. These hydrological inputs were held constant to ensure consistent

execution of the computational workflow while isolating the influence of cross-sectional geometry on the generated hydraulic relationships.

For each of the nine lined cross sections, the hydraulic area, wetted perimeter, and hydraulic radius were determined directly from the corresponding geometry. Mean flow velocity was subsequently calculated using Manning's equation with a roughness coefficient of ($n = 0.015$), while discharge was determined using the continuity equation. Three representative longitudinal slopes of 1%, 5%, and 10% were selected to represent low, intermediate, and high conditions within the range evaluated by the computational platform. The verification therefore comprised 27 geometry–slope combinations and 54 hydraulic values, considering both mean flow velocity and discharge.

Table 3 summarizes the geometric and hydraulic parameters used in the analytical consistency verification.

Table 3. Geometric and hydraulic parameters of the nine lined triangular roadside ditch cross sections used for analytical consistency verification.

Configuration	Section	Flow Depth, y (m)	Hydraulic Area, A (m^2)	Wetted Perimeter, P (m)	Hydraulic Radius, R (m)	c (m)	d (m)	z_1	z_2
Type 1	1-A	0.30	0.150	1.344	0.1116	0.00	1.00	0.000	3.333
Type 1	1-B	0.25	0.100	1.088	0.0919	0.00	0.80	0.000	3.200
Type 1	1-C	0.20	0.050	0.739	0.0677	0.00	0.50	0.000	2.500
Type 2	2-A	0.30	0.150	1.265	0.1186	0.10	0.90	0.333	3.000
Type 2	2-B	0.25	0.100	1.024	0.0976	0.08	0.72	0.320	2.880
Type 2	2-C	0.20	0.050	0.6861	0.07287	0.07	0.43	0.350	2.150
Type 3	3-A	0.30	0.150	1.166	0.1286	0.50	0.50	1.667	1.667
Type 3	3-B	0.25	0.100	0.943	0.1060	0.40	0.40	1.600	1.600
Type 3	3-C	0.20	0.050	0.640	0.0781	0.25	0.25	1.250	1.250

Note: c and d represent the horizontal projections of the left and right wetted sides, respectively; y denotes the flow depth; and $z_1 = c/y$ and $z_2 = d/y$ represent the corresponding horizontal-to-vertical side-slope ratios. Hydraulic area (A), wetted perimeter (P), and hydraulic radius (R) were calculated using Equations (6)–(8). All dimensions are referenced to the same water-surface elevation.

An important geometric characteristic is that the hydraulic areas of the equivalent A, B, and C alternatives remain constant across the three lined ditch configurations, whereas their wetted perimeters vary substantially. For each size category, the Type 3 configuration exhibits the smallest wetted perimeter and consequently the largest hydraulic radius, followed by Type 2 and Type 1. According to Manning's equation, this increase in hydraulic radius enhances mean flow velocity and conveyance capacity under equivalent slope and roughness conditions.

The analytical hydraulic responses obtained at the selected longitudinal slopes are presented in Table 4.

Table 4. Analytical consistency verification of mean flow velocity and discharge for the Type 1, Type 2, and Type 3 lined roadside ditch configurations.

Section	V at 1% (m/s)	Q at 1% (m^3/s)	V at 5% (m/s)	Q at 5% (m^3/s)	V at 10% (m/s)	Q at 10% (m^3/s)
1-A	1.545	0.232	3.456	0.518	4.887	0.733
1-B	1.358	0.136	3.036	0.304	4.293	0.429
1-C	1.107	0.055	2.476	0.124	3.502	0.175
2-A	1.609	0.241	3.598	0.540	5.089	0.763
2-B	1.413	0.141	3.160	0.316	4.469	0.447
2-C	1.163	0.058	2.601	0.130	3.678	0.184
3-A	1.699	0.255	3.799	0.570	5.372	0.806
3-B	1.493	0.149	3.339	0.334	4.722	0.472
3-C	1.218	0.061	2.723	0.136	3.852	0.193

The analytical values reproduced the numerical results generated by the computational platform for all evaluated geometry–slope combinations. Because the computational engine directly implements the governing continuity and Manning equations, agreement between the analytical calculations and the computational outputs was exact apart from numerical rounding. The purpose of this comparison was therefore to verify the correct numerical implementation of the governing hydraulic equations across the complete set of lined ditch configurations rather than to compare independent hydraulic models.

The results also demonstrate the influence of ditch geometry on hydraulic performance. For corresponding A, B, and C alternatives, the Type 3 configuration consistently produced the highest velocity and discharge values, followed by Type 2 and Type 1. This behavior results from the progressive reduction in wetted perimeter and corresponding increase in hydraulic radius while maintaining the same hydraulic area within each size category.

For example, at a longitudinal slope of 10%, the Type 1-A, Type 2-A, and Type 3-A configurations produced velocities of 4.887, 5.089, and 5.372 m/s, respectively, with corresponding discharge capacities of 0.733, 0.763, and 0.806 m^3/s. Under equivalent hydraulic area, roughness, and slope conditions, Type 3-A therefore provided approximately 9.9% greater mean flow velocity and discharge capacity than Type 1-A. This result quantitatively demonstrates the influence of wetted perimeter and hydraulic radius on the performance of standardized roadside ditch configurations.

Overall, the analytical consistency verification covered nine lined cross sections evaluated at three representative longitudinal slopes, resulting in 27 geometry–slope combinations and 54 verified hydraulic values. The exact agreement, apart from numerical rounding, between the analytical calculations and computational outputs confirms the correct implementation of the hydraulic calculation engine for all Type 1, Type 2, and Type 3 configurations incorporated into the platform. Together with the generated velocity-based performance limits, these results establish the numerical consistency of the lined roadside ditch module before extending the evaluation to the unlined ditch configurations.

3.3. Flow Regime Assessment

The flow regime was additionally assessed using the Froude number (Fr), defined as $Fr = V/(gD)^{1/2}$, where V is the mean flow velocity, g is gravitational acceleration (9.81 m/s^2), and D = A/T is the hydraulic depth. For the triangular cross sections considered in this study, the water-surface width is $T = c + d$, and the hydraulic depth is $D = y/2$. The assessment was performed for the 27 geometry–slope combinations reported in Table 4.

The calculated Froude numbers ranged from approximately 1.118 to 4.428, indicating supercritical flow ($Fr > 1$) in all evaluated scenarios under the assumed uniform-flow conditions. The Froude number increased with longitudinal slope because of the corresponding increase in mean flow velocity. These results characterize the flow regime of the evaluated lined sections but do not constitute a separate validation of rapidly varied flow conditions.

Supercritical flow does not invalidate the Manning-based calculations under their stated assumptions; however, hydraulic capacity and permissible mean velocity alone are insufficient to establish complete hydraulic safety. Practical applications, particularly on steep slopes, may require site-specific assessment of flow transitions, available freeboard, hydraulic jumps, erosion protection, and energy dissipation. The corresponding hydraulic depth, Froude number calculations, and flow regime classifications for all 27 evaluated geometry–slope combinations are provided in Supplementary File S1.

3.4. Influence of Permissible Velocity Criteria on Unlined Ditch Design

Following the analytical verification of the lined ditch configurations, the assessment was extended to the Type 3sr module to examine the influence of surface roughness and

permissible velocity criteria on unlined roadside ditch design. The hydraulic formulation remains the same as that previously described and verified; therefore, the purpose of this analysis was not to repeat the analytical verification of the governing equations, but rather to evaluate how soil-dependent roughness and velocity criteria affect the hydraulic response and feasible operating range of the symmetric triangular configurations 3-A, 3-B, and 3-C.

To maintain consistency with the previous analyses and isolate the influence of the ditch-floor condition, the reference hydrological inputs were maintained at a runoff coefficient of C = 0.30, rainfall intensity of I = 50 mm/h, and contributing width of B = 10 m. The longitudinal slope was evaluated over the range implemented in the computational platform, while the geometries corresponding to configurations 3-A, 3-B, and 3-C were maintained.

The seven predefined ditch-floor materials incorporated into SDDRoads 2.0 are hydraulically represented through two Manning roughness levels. Fine gravels, fine sands, non-colloidal silt, and plastic silty clay are assigned $n = 0.020$, whereas colloidal silt, cementitious plastic clay, and hard clay are assigned $n = 0.025$. Consequently, the seven predefined material alternatives generate two families of hydraulic response curves. Within each roughness family, the applicable permissible velocity criteria are subsequently incorporated into the slope–velocity relationships to evaluate the compatibility of the calculated hydraulic conditions with the selected ditch-floor material. Table 5 summarizes the computational cases evaluated for the Type 3sr module, including the seven predefined ditch-floor conditions, their corresponding Manning roughness coefficients, and the three standardized cross sections considered in the analysis.

Table 5. Computational verification cases evaluated for the Type 3sr unlined roadside ditch module.

Case	Ditch-Floor Condition	Manning *n*	Velocity Criterion	C	I (mm/h)	B (m)	Sections
U01	Fine gravels	0.020	Predefined	0.30	50	10	3-A, 3-B, 3-C
U02	Fine sands	0.020	Predefined	0.30	50	10	3-A, 3-B, 3-C
U03	Silt (not colloidal)	0.020	Predefined	0.30	50	10	3-A, 3-B, 3-C
U04	Plastic silty clay	0.020	Predefined	0.30	50	10	3-A, 3-B, 3-C
U05	Silt (colloidal)	0.025	Predefined	0.30	50	10	3-A, 3-B, 3-C
U06	Cementitious plastic clay	0.025	Predefined	0.30	50	10	3-A, 3-B, 3-C
U07	Hard clay	0.025	Predefined	0.30	50	10	3-A, 3-B, 3-C

The generated results show that mean flow velocity and discharge increase continuously with longitudinal slope for the three cross sections. Within each roughness group, configuration 3-A produces the highest velocity and discharge, followed by 3-B and 3-C. Increasing Manning's roughness coefficient from 0.020 to 0.025 shifts both the slope–velocity and slope–discharge relationships toward lower values while preserving the relative hydraulic hierarchy among the three geometries.

For identical cross-sectional geometry and longitudinal slope, the influence of roughness can be quantified directly from Manning's equation. Since mean flow velocity is inversely proportional to the Manning roughness coefficient,

$$\frac{\mathrm{Vn} = 0.025}{\mathrm{Vn} = 0.020} = \frac{0.020}{0.025} = 0.80, \tag{10}$$

Because discharge is obtained from Q = VA and the hydraulic area remains unchanged for a given geometry,

$$\frac{\mathrm{Qn} = 0.025}{\mathrm{Qn} = 0.020} = 0.80, \tag{11}$$

Accordingly, increasing Manning's roughness coefficient from 0.020 to 0.025 reduces both mean flow velocity and discharge capacity by 20% for the same cross-sectional geometry and longitudinal slope. This response is consistent with the hydraulic relationships

implemented in the computational framework and demonstrates the direct influence of ditch-floor roughness on the hydraulic performance of the unlined configurations.

However, hydraulic roughness alone does not determine the suitability of an unlined ditch. The calculated flow velocity must also be evaluated against the permissible velocity criteria associated with the selected ditch-floor material and sediment condition. Superimposing these criteria on the slope–velocity relationships allows the longitudinal-slope range compatible with each material condition to be identified. Consequently, increasing longitudinal slope improves conveyance capacity but may simultaneously cause the calculated velocity to exceed the applicable erosion-control criterion.

This interaction produces an important design trade-off. Configuration 3-A provides the greatest conveyance capacity but also develops the highest flow velocity and may therefore reach the permissible velocity threshold at a lower longitudinal slope. Conversely, configuration 3-C develops lower velocities and may remain within the permissible range over a wider slope interval, although with lower discharge capacity. The Type 3sr module therefore enables hydraulic capacity and erosion-related velocity constraints to be evaluated jointly rather than independently.

Overall, the Type 3sr assessment demonstrates that the hydraulic performance of unlined roadside ditches is governed by the interaction among cross-sectional geometry, longitudinal slope, surface roughness, hydraulic capacity, and permissible velocity criteria. The evaluation of the seven predefined ditch-floor conditions extends the computational assessment beyond a single representative example and demonstrates the applicability of the Type 3sr module across the range of material conditions considered in the proposed methodology.

3.5. Computational Performance

The computational implementation was developed to automate the hydraulic design procedure described in Section 2. Rather than requiring independent hydraulic calculations for each design alternative, the platform integrates the Rational Method, open-channel hydraulic analysis, velocity-based performance evaluation, and graphical representation of the resulting capacity–velocity–slope relationships within a unified computational workflow.

Recent developments in hydraulic and roadway drainage engineering have increasingly incorporated web-based computational platforms, planning support systems, GIS-based hydraulic–hydrologic modeling frameworks, and automated digital technologies to support flood risk analysis, hydraulic evaluation, and infrastructure management. Examples include the RiskDRAIN platform for climate-resilient road drainage design, planning support systems integrating hydraulic modeling, GIS, and multicriteria analysis for sustainable water infrastructure, hybrid SWAT–SWMM modeling frameworks for urban drainage planning, and mobile LiDAR-based approaches for automated drainage assessment [35,36,42,43]. Recent review studies have further identified computational efficiency, cloud-based implementations, and digital decision-support technologies as key directions for the future development of hydraulic modeling tools, reinforcing the importance of practical computational frameworks for engineering applications [44]. Although these tools address different hydraulic applications, they collectively demonstrate the growing transition toward integrated digital decision-support systems. In contrast, the methodology developed in this study focuses specifically on the automated hydraulic design of lined and unlined triangular roadside ditches through the integration of hydraulic capacity, velocity-based performance criteria, longitudinal slope, and material-related considerations within a unified computational framework.

One of the principal computational advantages of the methodology is the automatic evaluation of the three standardized cross sections associated with the selected roadside

ditch configuration. Conventional hydraulic design generally requires successive calculations for each candidate cross section followed by independent verification of hydraulic capacity and admissible flow velocities. In contrast, the proposed implementation performs these analyses automatically and presents the corresponding hydraulic responses within a single computational procedure.

The computational workflow also integrates the minimum self-cleansing velocity and maximum allowable velocity criteria associated with the selected material condition. Consequently, hydraulic conditions that do not satisfy the applicable velocity limits are identified as non-admissible but remain available in the graphical representation. This distinction allows designers to examine the complete hydraulic response while clearly identifying the slope intervals that satisfy the adopted performance criteria.

As summarized in Table 6, the proposed methodology considerably simplifies the hydraulic design procedure by integrating multiple analytical steps into a single computational environment. Instead of performing repetitive calculations and successive hydraulic verifications, designers receive a complete evaluation of the predefined cross sections together with the corresponding design relationships and admissible hydraulic domain.

Table 6. Comparison between conventional hydraulic design and the proposed computational methodology.

Design Task	Conventional Procedure	Proposed Methodology
Hydraulic calculations	Manual	Automatic
Evaluation of multiple standardized cross sections	Sequential	Integrated
Verification of minimum self-cleansing velocity	Independent	Integrated
Verification of maximum allowable velocity	Independent	Integrated
Generation of slope–velocity relationships	Manual	Automatic
Generation of slope–discharge relationships	Manual	Automatic
Identification of feasible design alternatives	Iterative	Automatic

Although the proposed methodology was implemented through a web-based computational platform, its principal contribution lies in the integration of multiple hydraulic and performance criteria into a unified computational framework capable of supporting consistent engineering decision-making for both lined and unlined roadside ditch design.

Unlike previous computational tools that primarily focus on flood risk assessment, infrastructure inspection, or isolated hydraulic analyses, the proposed methodology integrates hydraulic capacity, velocity constraints, longitudinal slope, and material-related criteria into a single decision-support framework specifically oriented toward roadside ditch design.

3.6. Engineering Implications and Practical Applications

The results obtained for the lined and unlined roadside ditch configurations demonstrate that hydraulic design cannot be based exclusively on conveyance capacity. Although increasing the longitudinal slope generally increases both flow velocity and discharge capacity, the resulting hydraulic condition must also remain compatible with the performance limits associated with the selected ditch material or surface condition. Therefore, the most hydraulically efficient configuration is not necessarily the most appropriate engineering solution.

For lined ditches, the comparison among Types 1, 2, and 3 showed a consistent geometric hierarchy in hydraulic performance. Within each family of standardized cross sections, the larger configuration provided the highest velocity and discharge capacity for a given longitudinal slope, whereas the smaller configuration produced the lowest values. Because these relationships are obtained directly from the governing hydraulic equations,

they provide a deterministic basis for comparing alternative cross sections and identifying the configuration capable of conveying the design runoff under the specified geometric and hydraulic conditions.

However, increasing hydraulic capacity may simultaneously increase flow velocity and therefore the potential for deterioration of the ditch surface. For concrete-lined configurations, this condition requires verification against the allowable velocity associated with concrete compressive strength and the characteristics of the transported water. Consequently, the selection of a lined ditch represents a balance between sufficient conveyance capacity and acceptable hydraulic exposure of the lining.

For unlined Type 3sr configurations, the engineering implications are particularly relevant because the admissible hydraulic domain depends directly on the characteristics of the ditch-floor material. The results showed that the hydraulic response varies with the Manning roughness coefficient assigned to the selected material, while the permissible velocity provides an additional criterion for controlling erosion susceptibility. Fine gravels, fine sands, non-colloidal silt, and plastic silty clay were represented using $n = 0.020$, whereas colloidal silt, cementitious plastic clay, and hard clay were represented using $n = 0.025$. Thus, the same ditch geometry and longitudinal slope can produce different hydraulic responses depending on the selected floor condition.

This distinction has direct implications for practical roadside drainage design. A longitudinal slope that is hydraulically feasible for one ditch-floor material may exceed the permissible velocity for another, even when both alternatives provide sufficient discharge capacity. Accordingly, the design procedure should not be interpreted as the identification of a single maximum-capacity solution, but rather as the determination of an admissible hydraulic domain in which runoff conveyance, flow velocity, longitudinal slope, and material resistance are simultaneously considered.

From a practical perspective, the proposed methodology allows engineers to compare alternative ditch configurations before selecting a final design. For a specified runoff coefficient, rainfall intensity, contributing width, and longitudinal slope, the designer can evaluate whether the resulting discharge capacity is sufficient while simultaneously examining whether the corresponding flow velocity is compatible with the selected lining or ditch-floor condition. This integrated interpretation is particularly useful in road corridors where topography imposes substantial variations in longitudinal slope and where the use of a single ditch configuration along the entire alignment may not be hydraulically or materially appropriate.

Consequently, the methodology provides a rational basis for transitioning between ditch configurations or surface conditions along a roadway. Sections characterized by moderate hydraulic demand may be accommodated by smaller or unlined configurations, provided that the permissible velocity criteria are satisfied, whereas sections subjected to greater runoff or steeper longitudinal slopes may require larger cross sections or lined alternatives. The proposed framework therefore supports not only hydraulic dimensioning but also the systematic selection of roadside drainage solutions according to local hydraulic and material conditions.

3.7. Limitations and Future Work

Despite the integrated hydraulic and material-based framework proposed in this study, several limitations define the current scope of the methodology. First, the hydraulic analysis assumes steady and uniform open-channel flow and applies the Manning equation to predefined roadside ditch geometries. Consequently, transient effects, rapidly varied flow, backwater conditions, hydraulic jumps, and interactions with downstream drainage structures are not explicitly represented. These assumptions are appropriate for the analyti-

cal design framework adopted in this study but should be considered when applying the methodology to road sections characterized by complex hydraulic conditions.

An additional limitation concerns the representation of runoff progressively entering roadside ditches along their longitudinal alignment. Although the proposed methodology estimates the maximum contributing ditch length by comparing accumulated runoff with the hydraulic capacity at the downstream control section, it does not explicitly simulate spatially varied flow resulting from distributed lateral inflow. Consequently, flow depths and velocities may differ along the ditch, particularly in upstream reaches where discharge is lower. Compliance with the minimum self-cleansing velocity at the downstream section should therefore not be interpreted as evidence of sediment-free conditions throughout the channel. Future developments should incorporate spatially varied flow analysis, sediment deposition assessment, and appropriate maintenance considerations to improve the applicability of the methodology under complex drainage conditions.

Another limitation concerns the hydrological component, which is based on the Rational Method, in which runoff is represented through the runoff coefficient, rainfall intensity, and contributing drainage area. This formulation provides a practical approach for roadside drainage design but does not explicitly account for temporal rainfall distribution, infiltration dynamics, antecedent moisture conditions, or spatial variability within the contributing catchment. Future developments could incorporate event-based rainfall–runoff modeling or interfaces with more detailed hydrological models when applications require a higher level of temporal resolution.

For unlined Type 3sr ditches, soil or ditch-floor conditions are represented through predefined Manning roughness coefficients and corresponding permissible velocity criteria. Although this approach enables material-dependent hydraulic evaluation, natural soils may exhibit substantial variability associated with gradation, density, moisture content, vegetation, surface irregularities, and progressive erosion. Therefore, the predefined material categories should be interpreted as engineering design conditions rather than complete representations of field-scale soil behavior. Experimental and field studies are required to evaluate the long-term performance of these materials under repeated runoff events and to refine the corresponding hydraulic resistance and erosion criteria.

Similarly, the allowable velocity criteria adopted for lined ditches provide a practical means of relating hydraulic exposure to concrete compressive strength and transported sediment conditions. However, deterioration of concrete drainage infrastructure can also depend on abrasion, surface defects, construction quality, environmental exposure, and cumulative hydraulic loading. Future research should therefore investigate the relationship between repeated hydraulic loading, sediment characteristics, concrete properties, and long-term lining deterioration to support performance-based durability criteria.

The current implementation evaluates standardized ditch geometries and identifies hydraulically admissible alternatives according to the incorporated capacity and velocity criteria. It does not perform a formal optimization considering construction cost, maintenance requirements, environmental impacts, or life-cycle performance. Future versions could incorporate multi-objective optimization procedures to simultaneously evaluate hydraulic efficiency, erosion resistance, construction requirements, maintenance demand, and economic or environmental criteria.

Further development should also consider spatial integration with roadway and terrain information. Coupling the methodology with geographic information systems, digital elevation models, or road-alignment databases could allow longitudinal slope and contributing drainage areas to be obtained directly from spatial data and could support the automatic identification of transitions between ditch configurations along a road corridor.

Such integration would extend the methodology from individual cross-section evaluation toward network-scale roadside drainage planning.

Finally, field validation represents an important next stage of the research. The analytical verification conducted in this study confirms the consistency of the computational implementation with the governing hydraulic equations; however, field monitoring would allow the predicted hydraulic response to be compared with observed flow velocities, discharge conditions, sediment transport, and erosion or lining performance under actual rainfall events. Combining analytical verification with field-scale observations would strengthen the applicability of the methodology and support future calibration of material-specific design criteria.

4. Conclusions

This study developed and evaluated a multi-criteria hydraulic design methodology for lined and unlined triangular roadside ditches by integrating hydraulic capacity, velocity-based performance criteria, longitudinal slope, and material-related considerations within a unified computational framework. The principal findings, engineering implications, scientific contributions, and future research directions derived from this work are summarized as follows:

- A multi-criteria hydraulic design methodology was developed for lined and unlined triangular roadside ditches by simultaneously integrating hydraulic capacity, minimum self-cleansing velocity, maximum allowable velocity, longitudinal slope, and material-related performance criteria within a unified design framework. The methodology combines established hydraulic principles with predefined triangular roadside ditch cross sections to provide a systematic, consistent, and reproducible hydraulic design procedure.
- Independent analytical verification of the lined ditch module covered nine standardized cross sections evaluated at three representative longitudinal slopes, resulting in 27 geometry–slope combinations and 54 verified hydraulic values. The computational outputs agreed with independent calculations based on the continuity and Manning equations, apart from numerical rounding differences, demonstrating the numerical consistency of the implemented hydraulic calculations for Type 1, Type 2, and Type 3 configurations under the adopted uniform-flow assumptions. This agreement should not be interpreted as experimental or field validation of roadside ditch performance. Furthermore, the simultaneous evaluation of predefined cross sections and velocity-based performance criteria supports the identification of hydraulically admissible alternatives without requiring repetitive manual calculations.
- For unlined Type 3sr ditches, the hydraulic response was directly influenced by the Manning roughness coefficient associated with the ditch-floor condition. Increasing the roughness coefficient from 0.020 to 0.025 reduced both mean flow velocity and discharge capacity by 20% under identical geometry and longitudinal slope conditions. More generally, the results demonstrate that roadside ditch selection should not be based exclusively on maximum conveyance capacity. The cross section providing the highest hydraulic capacity may not constitute the most appropriate engineering solution when the resulting flow velocity exceeds the permissible limits associated with the lining or ditch-floor material. The proposed methodology therefore defines an admissible hydraulic design domain in which runoff conveyance, flow velocity, longitudinal slope, and material-related performance criteria are evaluated simultaneously.
- From an engineering perspective, this study provides a practical decision-support framework for roadway drainage design by reducing repetitive hydraulic calculations, improving the consistency of hydraulic evaluations, and facilitating the simultaneous

comparison of alternative predefined cross sections. These characteristics make the methodology particularly suitable for engineering consulting, highway agencies, and academic environments where standardized hydraulic design procedures are required.

- The principal contribution of this study is not the development of new hydraulic equations or alternative ditch geometries, but the integration of hydrological inputs, hydraulic calculations, velocity-based performance criteria, and predefined cross sections within a unified computational methodology. This integrated framework improves the consistency, reproducibility, and accessibility of roadside ditch hydraulic design while preserving compatibility with established hydraulic design principles. Consequently, the developed framework extends conventional roadside ditch hydraulic design from a sequence of independent calculations toward an integrated, constraint-based multi-criteria screening procedure, without constituting a formal multi-objective optimization method.
- Future research should extend the methodology to additional ditch geometries, alternative lining materials, sediment transport models, and climate-resilient hydraulic design scenarios. The integration of geographic information systems, digital terrain models, and probabilistic hydrological analyses may further broaden its application to a wider range of roadway drainage projects while preserving the integrated design philosophy established in this study.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/designs10060129/s1. Supplementary File S1. Independent hydraulic verification of nine roadside ditch cross sections (Excel file), including geometric parameters; independent analytical verification of flow velocities and discharges; hydraulic depths; Froude number calculations; and flow regime classifications for the 27 evaluated geometry–slope combinations.

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Data Availability Statement: The numerical results and hydraulic verification calculations supporting this study are provided in the manuscript and Supplementary File S1. The SDDRoads 2.0 web-based application is publicly accessible at https://www.ibaing.com/SDDRoadsENew/ (accessed on 3 November 2026). The application enables users to reproduce the hydraulic screening calculations using the input parameters and geometric configurations described in the study. The underlying source code is not publicly available.

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