Earth: Environmental Sustainability
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Review

Understanding, Measuring, Mitigating and Modeling Rill Erosion: A Short Review

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How To Cite: Zema, D.A. Understanding, Measuring, Mitigating and Modeling Rill Erosion: A Short Review. *Earth: Environmental Sustainability* **2025**, *1*(1), 59–70. https://doi.org/10.53941/eesus.2025.100005

Received: 30 June 2025
Revised: 25 August 2025
Accepted: 26 August 2025
Published: 27 August 2025

Abstract: Rill erosion is a critical form of soil degradation**,** characterized by the concentrated flow of water that scours soil and transports sediments downhill, significantly impacting agricultural productivity and water quality. This review synthesizes current literature to elucidate the dynamics of rill erosion, emphasizing the multifaceted factors that influence its formation, including rainfall, soil properties, topography, vegetation cover, and land use. After discussing various erosion forms, the paper outlines the physics of rill erosion and presents methodologies for measuring and monitoring this process, highlighting both traditional and innovative techniques. Furthermore, it examines soil conservation practices aimed at mitigating rill erosion and their effectiveness. Modeling approaches, distinguishing between empirical and process-based models, are also explored, and gaps in current predictive capabilities are identified. In conclusion, the review advocates for integrated research that combines ecological, hydrological, and socio-economic perspectives. This research should develop sustainable land management strategies and enhance predictive accuracy regarding rill erosion under changing climate conditions. This comprehensive understanding is vital for combating soil degradation and preserving ecosystem services.

Keywords: rill morphology; erosion dynamics; climate change; land use change; erosion models; soil conservation techniques

1. Introduction

Rill erosion is a process of soil scouring by concentrated flow and the transportation of detached particles in the water flow downstream [1,2]. Rills are small channels with steep sides formed by channelized surface water, which runs quicker in rills than the overland flow, transporting sediments downslope [3,4]. Once soil incision starts on hillslopes, rills become deeper and wider over time [5]. Moreover, rills collect runoff and sediments from inter-rill areas, which gradually develop into ephemeral or permanent gullies and irreversibly destroy hillslopes [2,6,7]. Therefore, rill erosion causes more erosion than splash and sheet erosion [8,9], especially in agricultural areas and degraded landscapes.

Rill erosion, with its concentrated water flow, is the main source of sediments and the primary mechanism for erosion at the hillslope scale [4,10], especially on long and steep slopes [11,12]. This form of erosion is of particular concern worldwide, since it can lead to substantial soil loss. Intense erosion reduces agricultural productivity and degrades water quality through the supply of sediments and pollutants to water bodies. There is, therefore, a need for studies that clarify the dynamics of rill erosion [5], since previous research has indicated that the evolution of parameters to describe the influence of rill erosion is controversial [13]. This need is increasingly pressing, since the intensity and extent of soil erosion are expected to increase due to climate change stressors (e.g., increasing temperatures, changes in precipitation patterns, and ongoing desertification) [14]. On one hand, more frequent and heavier rainstorms will result in increased surface runoff, which will move higher amounts of sediments, thus noticeably increasing erosion rates. On the other hand, drought will progressively lead to increasing degradation of soil quality, e.g., reducing water storage, losing vegetation cover, and breaking down soil structure. Moreover, human actions will continue to transform the landscape (e.g., by deforestation, fraudulent fires, and intensive agriculture), exacerbating the risk and impacts of erosion [15]. In particular, the loss of vegetation cover is thought to be the most severe factor of soil erosion: vegetation shades soil from detachment and enhances water infiltration [16,17] and makes land less vulnerable to erosion. In addition to the direct impacts on soil health and quality, rill erosion will affect several ecosystem services. For instance, soil loss reduces its fertility, impacting agricultural production and, as a consequence, food security. Rill erosion leads to a decline in the quality of water bodies (lakes, rivers, and reservoirs), where transported contaminants are supplied by eroded particles, which sometimes even partially or completely fill their storage capacity.

Therefore, rill erosion is a factor of soil degradation, which depends on many non-homogeneous factors, and has a huge impact on ecosystem components. This short review proposes a state-of-the-art overview of rill erosion based on a review of literature studies. More specifically, after giving an outline of the theory of rill erosion (erosion forms, factors, and physics), methods for measuring and monitoring, as well as techniques to control and mitigate erosion, are illustrated. Moreover, the most common tools to model rill erosion are presented. Finally, practical recommendations and future research needs to evaluate and tackle rill erosion are given.

2. Theoretical Approach to Rill Erosion

2.1. Factors of Rill Erosion

According to [18], soil erosion due to water appears under several forms:

- splash erosion, caused by the impact of raindrops on the soil surface, which lifts and displaces soil particles from their natural position, especially in bare areas (without or with scarce vegetation cover) and in loose soils
- sheet erosion, which uniformly removes the soil's surface layer, especially at slow flow rates and on hillslopes with a gentle slope
- inter-rill erosion, which removes particles in areas between rills, and is particularly influenced by the slope and land cover
- rill erosion, which is due to concentrated and channelized flow
- gully erosion, when rills increase in size, forming deep and large channels by continuous water flow
- piping erosion, a form of underground erosion where water erodes soil beneath the surface, leading to the land's collapse and the formation of cavities.

Specifically dealing with rill erosion, the mean rates are in a wide range (10 to even 40 tons per hectare per year, [19]). This means that many environments, if not protected, may be exposed to intolerable rill erosion rates. Soil loss tolerance is not a single and universal value but is determined by various factors, including soil type, depth, climate, land use, and the desired level of long-term productivity. A limit of 6 tons per hectare per year for the agricultural areas, which generally show higher erosion compared to forestland, is reported by [20,21]. The USDA-NRCS methodology sets five levels of permissible erosion rates at 2.5, 5.0, 7.5, 10, and 12.5 t per hectare per year. In this regard, [22], who proposed a method to establish a quantitative basis for soil erosion tolerance, defined these limits as a function of a soil's productivity, its vulnerability to productivity losses from erosion, an allowable reduction in productivity, and a planning horizon. More recently, [23] reviewed the concept of tolerable soil loss and summarized available definitions and recommended values, which are linked to the rate of soil formation. Finally, [24] suggested a range between 1 ton per hectare per year for shallow sandy soils and 5 tons per hectare per year for deep, well-developed soils in Europe. The same authors noted that some European studies adopt values ranging from 0.3 to 2 tons per hectare per year.

A combination of specific environmental factors influences rill formation and morphological development of the rill network (Figure 1), which makes rill erosion a site-specific process. According to [25], the factors that drive rill erosion are direct (i.e., rainfall characteristics and soil properties) and indirect (topography, vegetation cover and land use) (Figure 1). Among rainfall characteristics, its amount and duration (driving its intensity), and the resulting water flow of surface runoff are critical in shaping the extent of rill erosion. In particular, the volume and velocity of runoff determine the energy available to erode the soil. Therefore, the distribution of rainfall, both spatially and temporally, plays a role in the development of rill networks. Rainfall regime variations are expected in future climate change scenarios, especially regarding their intensity, with more intense but less frequent events that will increase the energy available for erosion. Moreover, the temporal distribution of rainfall will shift, with rainfall concentrated in a few extreme events that will cause more erosion compared to more evenly distributed rains. Moreover, the forecasted higher temperatures will lead to increased evaporation (making drier soils and thus more vulnerable to detachment) and to decreased soil moisture (resulting in lower cohesion between particles and therefore to increased rill erodibility) [14]. Drier soils due to the effects of climate change will also lead to a noticeable or full reduction of vegetative cover, with a dramatic influence on rill erosion rates.

Soil properties, including texture, structure, and organic matter content, significantly affect the soil's resistance to erosion, determining the soil erodibility. Generally speaking, soils with higher fine particles (since clayey soils are cohesive) and coarse particles (medium to large sand, which are hardly removed and displaced) tend to resist erosion better, while silt and fine sand are more vulnerable to erosion [26]. Compact soils with high organic matter and stability of aggregates are more resistant to rill erosion, while loose soils, poor in organic matter and with a weak structure, are more prone to erosion [18]. However, excessive compaction often reduces infiltration and increases runoff, thus promoting all erosion forms.

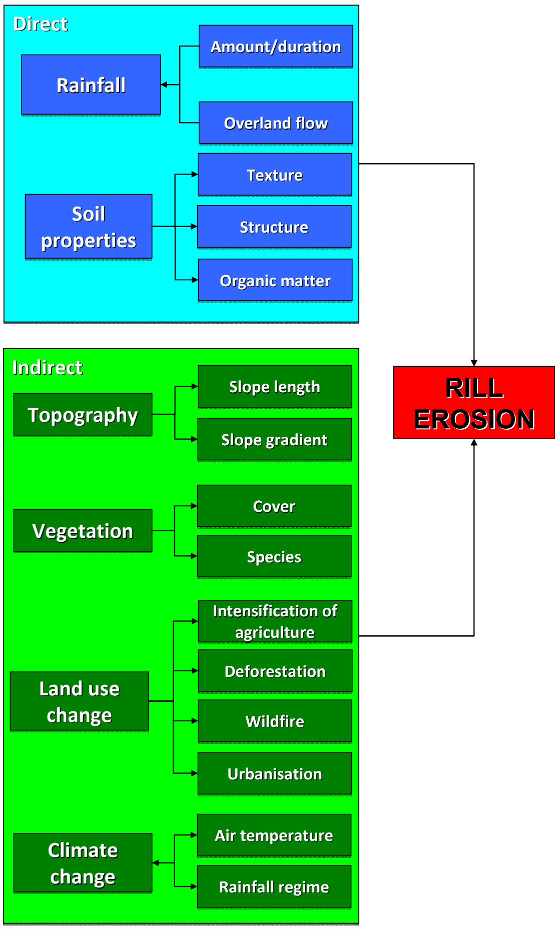

Figure 1. Main factors controlling rill erosion.

Slope gradient and length are part of topography and determine the accumulation and velocity of the water flow. Steeper slopes promote faster runoff, increasing the potential for rill formation and intensifying erosion. According to [27], a slope threshold of 18% determines significant differences in hydraulic variables and sediment transport in rills. Beyond this value, rills show different hydraulic and sediment behaviour. Refs. [28,29] identified a slope of 18% that discriminates 'gentle' and 'steep' slopes in terms of differences in hydraulic (flow depth, velocity, Reynolds number, Froude number) and sediment transport variables (flow transport capacity, actual sediment load) [27]. Vegetation cover plays an essential protective role by reducing the impact of rainfall on the soil surface and slowing down runoff. The presence of plants with deep root systems can also bind soil particles, making the soil less susceptible to erosion, and absorb part of the rainfall with the epigeous apparatus, thus reducing water flow velocity. Areas with sparse or poorly managed vegetation (such as overgrazing or deforestation) are more vulnerable to rill erosion, which is also enhanced by drought, causing the loss of vegetation cover and biomass. Soil can also be protected by vegetal residues left on the soil surface (e.g., agricultural and forest residues). These residues act as a ground cover that buffers raindrop impact, retains part of the rainwater, and slows overland flow [30]. Thousands of studies have acknowledged the importance of soil protection with living vegetation and vegetal residues in reducing soil erosion in croplands and forests [31]. Regarding the impact of climate change, through increasing temperatures, changes in precipitation patterns and vegetation cover will significantly alter all erosion processes. Similarly, droughts can degrade soil quality by reducing the soil's ability to retain water, further intensifying rill erosion (Figure 2).

The effects of climate change (increase in mean air temperature and alteration in rainfall patterns) will severely affect rill erosion. In more detail, as temperature and residue decomposition increase, soil structure will decay, which reduces the share of rainfall that infiltrates and increases runoff. This could potentially increase rill erosion. In contrast, the higher evapotranspiration due to the temperature increase will increase the water loss from soil and plants, thus reducing runoff and, as a consequence, rill erosion. Moreover, in sites where rainfall decreases, soil sealing/crusting is expected to increase, and soil water content and infiltration decrease (leading to higher rill erosion). Where rainfall increases, the water input to the soil is higher, which again results in increased surface runoff and higher detachment of soil particles due to erosion. However, more water input may result in higher infiltration and water storage, which means less surface runoff (Figure 2).

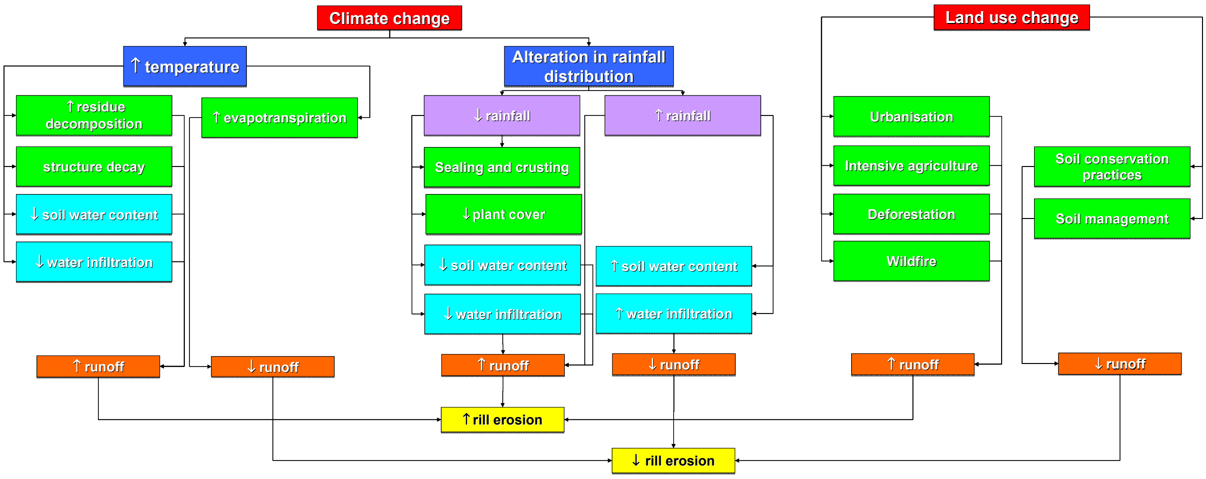

Figure 2. Mechanisms of action of climate and land use changes on rill erosion.

Finally, in addition to climate, land use is a main driver of rill erosion. Land use changes and human activities, such as intensive agriculture and deforestation, but also wildfire and urbanization, will accelerate natural erosion. In general, forest soils show a low rill erodibility, which dramatically increases in croplands. Specifically, the removal of vegetation for new agricultural areas will drastically increase soil loss. Agricultural practices, such as tillage, can significantly affect soil structure, generally breaking up aggregates, which makes soil more prone to erosion. In contrast, soil conservation practices can help reduce rill formation by preserving soil structure, as it will be further discussed below (Figure 2).

2.2. Processes of Rill Erosion

The most important variable driving the physics of rill erosion is the flow discharge, depending on its velocity and cross-sectional area of the rill. However, other hydraulic variables have been proposed as drivers of rill erosion (Table 1).

Estimation of flow velocity can be carried out according to two approaches [27]. A first approach ('Flow regime-based') uses empirical equations based on the characteristics of the flow itself. The second ('Flow resistance law-based') focuses on the resistance of rill bed and banks to water's drag force, using flow resistance laws, such as Darcy-Weisbach's equation. This flow resistance is influenced by three types of flow resistance:

(i) 'granular' resistance (due to the size and arrangement of sediments in the rill bed);
(ii) 'morphological' resistance (associated with irregularities in the bed, such as step-like structures or items—plant roots, gravel or the edges of large rocks extending from the rill bed—that can also alter rill channel morphology and influence flow);
(iii) 'sediment transport' resistance (related to the flow's capacity to transport solid particles).

The tight association of the weight of sediments eroded by a rill with flow discharge makes it also essential to precisely estimate the cross-sectional area of the rill. This estimation requires proper measurements of rill morphology. In this regard, techniques such as low-altitude photogrammetry to obtain Digital Terrain Models (DTM) are suggested for high-precision estimations of rill morphology (namely, shape and size). Rills exhibit a variety of cross-sectional shapes, including 'V-shaped', 'U-shaped', and 'box-shaped' forms. The depth and width of rills increase with their length, and, in some cases, rills become irregular and asymmetric [1].

Table 1. Main hydraulic parameters with equations proposed as drivers of rill erosion (source: [1], modified), showing that rill erosion increases as each input variable in the equations increases.

Parameter (Measuring Unit)	Equation	Variable Description (Measuring Units)	Reference
V = mean flow velocity (m/s)	$V = \alpha V_s$	α = correction factor V_s = surface flow velocity (m/s)	[32]
Fr = Froude number (dimensionless)	$Fr = V/\sqrt{(gR)}$	g = gravity acceleration (m/s^2) R = rill flow depth (m)	[33]
Re = Reynolds number (dimensionless)	$Re = VR/\nu$	R = hydraulic radius (m) ν = viscosity coefficient of rill flow (m^2/s)	[33]
τ = shear stress (Pa)	$\tau = \rho gRS$	ρ = water density (kg/m^3) S = sine value of slope gradients (dimensionless)	[34]
u* = shear velocity (cm/s)	$u^* = \sqrt{(\tau/\rho)}$	Dimensionless	[35]
ω = stream power (W/m^2)	$\omega = \rho gRSV$	Dimensionless	[36]
U = unit stream power (m/s^2)	$U = VS$	Dimensionless	[37]

Following Hewlett's theory [38], surface runoff, which is the dominant factor of rill erosion, is generated when rainfall exceeds the infiltration capacity of the soil. In rills, kinetic energy of water concentrates, and the flow increases its drag force on the soil matrix, eroding its surface. A rill starts developing when a minimum runoff rate is reached and the soil has a certain erodibility. Rills are initially shallow, but they quickly deepen and widen over time, generally merging into a network of interconnected channels. Controlled experiments reveal that soil cohesion, hydraulic shear stress, and flow concentration control where and how rills initiate [6]. After detachment of particles and their entrapment in the concentrated flow, sediments are carried by water and deposited in other areas. Particle deposition is another undesired effect of overall rill erosion (that results in off-site soil loss and degradation), which can affect water quality and the functioning of reservoirs. As a matter of fact, sedimentation can result in detrimental effects such as watercourse clogging and degradation of aquatic habitats [18] as well as nutrient enrichment that can lead to problems such as eutrophication [39].

During rill erosion, concentrated surface runoff forms small channels, or rills, which are highly effective at transporting a wide range of materials from agricultural and urban landscapes into water bodies. This process is a significant mechanism for the off-site movement of nutrients like nitrogen and phosphorus, contributing to eutrophication in lakes and rivers [40]. Similarly, pesticides and other agrochemicals, which are often adsorbed to soil particles, are readily detached and carried along with the eroded sediment, posing a threat to aquatic ecosystems and drinking water sources [41]. The transport of pharmaceuticals and their metabolites, while less studied than that of traditional pollutants, is also facilitated by rill erosion, as these compounds can be mobilized from biosolids, manure, or wastewater effluent applied to land, thereby contributing to pharmaceutical contamination in surface waters [42,43]. Thus, rill erosion acts as a crucial link between terrestrial pollution sources and aquatic environments, highlighting the need for effective soil and water conservation practices.

3. Measuring and Monitoring Rill Erosion

Rill erosion can be directly and indirectly measured [6]. Direct measures can be made both in the laboratory and in the field. In a laboratory (that is, under monitored conditions), controlled experiments help isolate individual factors of rill erosion, but are often unrealistic due to the boundary conditions. In the field, real-world observations show how and to what extent complex rill patterns evolve over time and in space, but it is difficult to obtain data with high precision. Indirect methods are based on the measurements of rill morphology (shape and size), from which the weight of eroded sediments is estimated. In this regard, rill measurement techniques include traditional and innovative techniques. Traditional techniques are manual measurements and photography, while innovative techniques consist of SfM photogrammetry and 3D laser scanners. The latter techniques have greatly improved the precision of Digital Terrain Models (DTM), allowing for detailed measurements of rill geometry. Moreover, these tools are particularly useful in detecting small rills and in difficult-to-reach environments, such as mountainous areas [1]. The latter authors have reported a list of tools to measure rill erosion (Table 2).

Table 2. Main tools to measure rill erosion with advantages and limitations (source: [1]).

Tool	Advantages	Limitations
Tape/Ruler	- Low costs - Easy operation	- Unsuitable for measuring cross-sections - Low precision
Profiles	- Useful for delimiting cross-sections	- Great field labour - Difficult to reproduce measurements
Total station	High temporal resolutions	- Need for data interpolation - Not available in areas with poor satellite coverage
Differential Global Positioning Systems (dGPS)	- Quick and easy - Fair under unfavorable weather	Not available in areas with poor satellite coverage
Total Laser Scanning (TLS)	- High-precision - Unsuitable in areas with dense vegetation	- Reduction in sampling density with a large incidence angle - Expensive and not portable
Photogrammetry	- High resolution - Time and labour-efficient	- Time-consuming - Need for professional pre-knowledge - Suggested for small plots or laboratories
Unmanned Aerial Vehicles (UAV)	- Portable and possible to be equipped with various sensors (e.g., RGB digital cameras, LIDAR, multispectral, thermal, multi-sensor fusion) - Need for flight pre-planning	- Susceptible to weather conditions

4. Mitigating Rill Erosion

Soil conservation techniques have been extensively studied to control or limit rill erosion. These practices aim at reducing surface runoff and sediment loss by improving the soil properties and supporting vegetation [44,45]. To cite the most common practices, rill erosion could be reduced, for instance, by techniques based on:

- soil preparation:
    - contour farming, by tillage and planting along contour lines to slow runoff
    - terracing, by constructing stepped levels on slopes to reduce flow velocity
    - no-till farming, minimal soil disturbance to preserve structure and reduce rill formation
    - subsoiling/ripping, deep tillage to break compaction, improving infiltration
- vegetation action:
    - strip crops, alternating crops in strips to disrupt flow
    - cover crops, where vegetation grows during off-season to protect soil
    - grassed waterways, using vegetated channels to convey runoff and stabilize flow paths
    - vegetative buffer strips, strips of grass/trees at field edges to trap sediment
- dead vegetative cover
    - crop residues
    - mulching (applying straw, leaves, wood chips, or synthetic cover to protect soil surface)
- construction of small structures
    - contour bunds/ridging, small embankments along contours to retain water and sediments
    - check dams, small barriers placed in rills to slow and trap sediment
    - stone bunds/rock walls, which are a traditional practice in drylands to reduce slope length and flow energy.

Vegetation-based measures use plants to protect the soil. These techniques are highly effective under low-intensity rainfall in lands with a gentle slope. Under these conditions, grasses, cover crops, and crop residue can significantly reduce runoff and soil loss by increasing infiltration and providing a physical barrier against raindrop impact. For moderate rainfall and slopes, a dense vegetation cover can still be very effective, but the increased runoff velocity may start to overpower less dense or weaker vegetation, leading to rill formation. The lowest effectiveness is found after high-intensity rainfall and/or steep slope, since the high energy of runoff can create rills even through vegetation. These measures may slow but cannot entirely prevent erosion under extreme conditions [46].

Structural measures modify the physical landscape to control water flow and are particularly important for steeper slopes and areas with high erosion potential. In more detail, in these conditions, rill and gully formation is highly likely without structural measures like bench terraces or check dams. They are the primary defense against catastrophic erosion in these conditions. Under low-intensity rainfall and on gentle slopes, measures like contour farming can reduce the speed of runoff, preventing the formation of even small rills. Contour farming and terracing are crucial for breaking up the slope and slowing concentrated water flow, significantly reducing rill formation and sediment transport in sites exposed to moderate rainfalls and with mild slopes [47].

Tillage practices aim at minimizing soil disturbance and protecting the surface. A moderate effectiveness of tillage is in areas characterized by low-intensity rainfall and a gentle slope. Under these conditions, conservation tillage, such as no-till or reduced tillage, leaves crop residue on the surface, which helps prevent minor erosion by protecting the soil from raindrop impact. However, in the case of moderate rainfall and slopes, while conservation tillage is beneficial, it may not be enough on its own to prevent rill formation as flow velocity increases. This means that tillage should be combined with other measures like contour farming. Tillage practices alone are insufficient to tackle the erosive power of high-velocity runoff in sites with high-intensity rainfall and on steep slopes [48,49]. Moreover, it should be borne in mind that intensive tillage practices, such as conventional tillage (e.g., using moldboard ploughs), are considered harmful, since they severely disrupt soil structure and lead to intense soil erosion and other negative effects (for instance, loss of soil organic matter, reduced soil biodiversity, and increased production costs). Conversely, practices like no-till and minimum tillage are less harmful and generally beneficial for soil health and the environment. Examples of conservation tillage are no-tillage, minimum-tillage, and strip-tillage. These techniques result in improved soil health, reduced erosion, enhanced water conservation, and increased biodiversity [50,51].

Although the effectiveness of these techniques depends on several factors, such as soil slope and type, rainfall intensity, and land maintenance [13,52], research has demonstrated that almost all can reduce soil detachment due to overland flow. Most studies, although not specifically focusing on rill erosion, measured the effectiveness of these techniques—typically reported as per cent reduction in soil loss compared to untreated conditions [53,54]—in terms of reduction in total soil loss [55,56]. The variability of this effectiveness, ranging from 20% to even 90% of reduction in total erosion in untreated lands, is large [57,58]. Combined techniques (e.g., mulching + contour farming) often yield additive benefits to the effectiveness of individual actions.

These techniques are specifically based on the reduction in the sediment paths, profile aggradation or construction of barriers for the flows of water and sediments. Other techniques consist of: (i) addition of substrates rich in organic matter to soil (e.g., polyacrylamide and biochar) [59,60]; and (ii) inoculation of bacteria to improve the biochemical properties of soil [61,62]. Most soil conservation techniques enhance vegetation growth, which, in turn, reinforces the soil surface by the root systems and improves the physical properties of the treated soils (e.g., hydraulic conductivity, aggregate stability, and porosity [63–65]. Enhanced vegetative growth also reduces soil erosion forms through interception, that is, catching raindrops on the leaves and stems of plants. This avoids the full energy of the falling raindrop from being expended on the soil surface.

Several authors stressed the need to control rill erosion by reducing the soil detachment capacity in the flow paths. In this regard, the reduction in soil detachment is often associated with the actions of plant roots having different characteristics among species [66–68]. Many of the aforementioned techniques are able to reduce the soil erodibility by modifying key soil properties, e.g., increasing the bulk density and reducing the stability of aggregates [54]. The implementation of these soil conservation techniques has implications for land management, consisting in (i) the evaluation of the erosion risk to identify the sites and areas to treat, (ii) modeling the expected results of these actions by proper erosion models to get an indication of the reduction in the rill erosion rates, and (iii) to control *ex post* the effectiveness of the implemented actions compared to the untreated sites [69].

5. Modeling Rill Erosion

Reliable predictions of rill erosion depend on various factors and input parameters of the models. Different approaches have been undertaken for erosion estimation by hydrologists and modelers. These approaches can be associated with two model types [6]: ‘empirical’ and ‘process-based’ models.

The empirical models rely on observed data and statistical relationships to predict erosion rates. These models are commonly used in areas where detailed field data is available, but their applicability can be limited in different sites. In contrast, the process-based models attempt to simulate the physical processes governing erosion (e.g., water runoff, sediment transport, and soil detachment). These models that use physically-based equations with different complexities offer more flexibility, which allows their adaptation to many environments. Their main constraint is the requirement of detailed input data, which can sometimes be difficult to obtain in some sites (the so-called 'data-poor environments').

The most common empirical erosion model is the Universal Soil Loss Equation (USLE, [21]) with their modifications and updates (constituting the 'USLE-family' models). The USLE-family models predict soil erosion based on data related to precipitation, land morphology and management and soil properties, and land management, but do not specifically predict rill erosion. Among the process-based models, the Water Erosion Prediction Project (WEPP, [70]) is well known. WEPP integrates rainfall, soil, and slope properties to predict erosion rates (with a specific focus on the rill form) over time [71] and provides a direct estimation of rill erosion through a dedicated component.

The use of rill erosion prediction models must take into account some constraints and problems. First, the prediction capacity is variable across different conditions, which makes the application of existing models under varying climate conditions and land uses hard and challenging. In general, most models have been developed to simulate erosion on agricultural lands, but these tools are not always suitable for predicting erosion in forests or other natural ecosystems. This happens because not all models are able to reproduce the complex interactions among different soil types, vegetation species and cover, and land management practices.

Second, all models simulate the evolution of rills over time, but the spatial and temporal variability of rills negatively affect the prediction accuracy. In particular, often the models fail to reproduce the highly dynamic variability in the physical characteristics of the soil and the hydraulic properties of the flow. This variability is hard to implement into the models—especially in the empirical type—to obtain more precise results. For instance, some existing models are not sufficiently robust to simulate the dynamic transition of rills into larger-scale erosive processes, such as gully and channel erosion [1]. Some developers embedded relatively novel tools in the models, such as SfM photogrammetry and DTM for real-time erosion mapping and monitoring, which sometimes improved the model's prediction capacity under dynamic conditions [18].

Third, rill erosion models often fail with scaling up from plot experiments to real hillslopes or landscapes due to the spatial variability in soil properties, variable patterns in vegetation, topography, and flow conditions [6], and unrealistic boundary conditions found in plot experiments. According to [15], this model issue is again linked to the limited capacity of static erosion models to account for the dynamic variability and complexity of interactions among physical, biological, and climatic factors that govern rill erosion.

Fourth and finally, the lack of universally used models for accurate predictions across different environmental contexts and climatic regions is evident. Dozens of models (almost all including a rill estimation component) have been developed and validated in almost all environmental conditions. Table 3 reports the most used erosion models with applicability in their rill form.

Table 3. Overview of the most used erosion models with applicability in their rill form.

Model	Authors	Input Parameters	Output	Key Features	Strengths	Limitations
WEPP (Water Erosion Prediction Project)	[70]	High	- Sediment yield - Rill depth - Rill flow hydraulics	- Simulation of rill/interrill erosion - Infiltration - Plant effects	- Very detailed - Widely validated	- Complex - Data requirements
EUROSEM (European Soil Erosion Model)	[72]	Moderate	- Soil loss - Runoff	- Rill detachment by flow - Rainfall impact - Based on sediment transport capacity and deposition	- Suitable for small catchments - Validated in Europe	No dynamic feedback
Hairsine–Rose Model	[73]	High	- Sediment flux - Layer changes	- Selective detachment by flow - Erosion-deposition processes	- Detailed - Layer-specific modeling	- Unsuitable for field-scale
RillGrow Model	[74]	Low–Moderate	- Rill patterns over time	- Simulates rill pattern development	- Captures rill erosion dynamics	- Low quantitative data
KINEROS2	[75]	High	- Runoff - Sediment transport	- Kinematic runoff with rill/interrill dynamics	- Field/watershed scale	- Steep learning curve
RUSLE2 (Revised Universal Soil Loss Equation 2)	[76]	Low	Soil loss	- Based on long-term plot data, factors in rill/interrill ratio	- Easy to use - Policy-friendly	- Generalized assumptions - Use for land management

6. Practical Recommendations and Future Research Needs

Given the global threats of rill erosion due to climate and land use changes, there is a pressing need for:

(i) effective land management practices to limit these impacts;
(ii) more reliable models to predict these rates;
(iii) improvements in tools for monitoring and measuring rill erosion;
(iv) adopting an integrated approach to the environmental issues associated with rill erosion;
(v) sharing standardized measurement and analytical methods in experimental activities to ensure the comparability of data and consistent interpretation of results.

About the first need, research should better understand how different vegetation types and agroforestry practices influence rill erosion to develop or improve, when existing, land management practices that reduce erosion while maintaining land productivity [25]. Land management strategies must prioritize sites where rill erosion rates are the highest, such as the longest and steepest hillslopes [54]. The soil conservation techniques must be environmentally and economically sustainable to avoid damage to treated ecosystems and to be applicable on large areas. More research is also required to assess how soil conservation practices perform under climate and land use changes.

For the second need, a fair compromise between the accuracy and computational complexity of process-based models on one side, and the easy use but low precision of empirical models on the other side, is still lacking. In this regard, hybrid models may be a viable solution, as they combine empirical relationships with process-based simulations to offer a more practical solution for accurately predicting the spatial variability and temporal dynamics of rill erosion. Moreover, integrating land use and climate change into prediction models is essential for understanding the impacts of human and natural activities on rill erosion. The effects of these stressors on rill erosion are depicted in Figure 2, showing that all drivers of this process are sensitive. Unfortunately, there are large uncertainties in the predictions due to the difficulty in accurately modeling extreme rainfall events, ecological responses of vegetation, and effects of agricultural practices [14]. At present, many models are not able to simulate those changes, which may result in dramatic underestimations of rill erosion rates in future projections and scenarios.

To address the third need, it is necessary to integrate the results of experiments and field measurements—preferably with improved measurement techniques to obtain more precise data—as data for parameterizing the variables governing rill erosion. Specific attention should be paid to parameters related to rill geometry, flow resistance, and the effects of soil properties on the formation and evolution of rills [6]. Efficient monitoring and measurement of these variables allow a better identification of the threshold conditions triggering rill erosion and areas where rill formation is likely to occur [25]. It is, therefore, essential to have an integrated approach that combines field measurements, advanced detection techniques, and numerical modeling for a deeper understanding of rill formation and control [1]. Both literature and markets propose promising tools to collect, process, and share data about rill erosion:

- Unmanned Aerial Vehicle (UAV) platforms (e.g., drones for rill erosion mapping) and sensors (e.g., RGB and thermal cameras, multispectral sensors, LiDAR);
- ground equipment (e.g., Real-Time Kinematic Global Navigation Satellite System—RTK GNSS, differential Global Positioning Systems—GPS, Terrestrial Laser Scanners—TLS, total station, robotic theodolites);
- software, such as tools for photogrammetry (e.g., high-accuracy SfM processing, orthomosaic & Digital Elevation Models—DEM generation, fast SfM processing, open-source point cloud analysis (e.g., rill depth, volume differences)) and data analysis and modeling platforms (e.g., MATLAB/Python, Google Earth Engine—GEE, cloud platforms for large-scale monitoring using satellite data);
- specialized tools for rill detection, such as erosion and rill development simulators, automated rill detection algorithms, Digital Surface Models-Digital Elevation Models (DSM-DEM) subtraction methods to detect micro-topographic rill changes.

Concerning the fourth and final need, in line with [15], there is a request for a more integrated research approach. This approach should bring rill erosion, specifically dealing with soil science, together with ecology, climatology, hydrology, and social sciences to fully understand the complexity and multifaceted issues of this process. More precisely, since the connections among soil properties, flow characteristics, and land management on one side, and land productivity and social conditions of farmers are tight and interrelated, the adoption of sustainable agroforestry practices and rational land use plans requires a careful evaluation of the socio-economic impacts of soil erosion and its countermeasures. In this regard, governments must support policies that promote soil conservation and sustainable land management with incentives for farmers adopting sustainable practices, mitigating the erosion problem at the local scale.

7. Concluding Remarks

This review has highlighted how rill erosion is a complex, multifaceted, and highly dynamic process, since many ecosystem components (soil, vegetation, water) influence the erosion rates, even within a given site. These rates are highly dynamic and largely variable from point to point under the pressure of environmental stressors (climate, land morphology, and management). This high complexity and variability require proper understanding, which must be based on three approaches: experimentation in the laboratory (to explore the interactions among drivers), monitoring in the field (to measure the natural variability), and modeling using numerical tools (to predict the expected rates). More research is needed to consider the effects of climate change scenarios on future rill erosion paths as well as their incorporation into prediction tools.

Understanding both rill erosion processes and their drivers is imperative for developing effective soil conservation techniques. The choice of these techniques must not only depend on soil characteristics and climate patterns in a given site but should also consider socio-economic factors, such as land ownership, agricultural and forestry practices, and policy guidelines. The protection of agroforestry lands intensely affected by rill erosion is crucial to limit soil degradation and adverse effects on land productivity and population health.

Funding

This research received no external funding.

Conflicts of Interest

The author has no relevant financial or non-financial interests to disclose.

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