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The Impact of Landscape Features and Hardscape Elements (Concrete Floors) on Erosion Control: An Integrated Civil Engineering Perspective

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Abstract

Soil erosion constitutes one of the most pervasive environmental and geotechnical challenges confronting modern land management, threatening agricultural productivity, structural integrity of infrastructure, and the ecological balance of natural watersheds. Both natural landscape features and engineered hardscape elements exert significant often opposing influences on erosion dynamics. Natural interventions, including vegetative cover, contour terracing, and bioengineered drainage networks, reduce raindrop impact energy, enhance soil cohesion, and moderate surface runoff velocity. Conversely, impermeable hardscape elements such as concrete pavements and sealed floors, while providing direct physical protection to underlying soils, generate concentrated surface runoff that may intensify erosion in adjacent unprotected zones. This study critically examines the interplay between landscape-based and hardscape-based erosion control strategies within a civil engineering and environmental management context. Employing a systematic literature review, comparative hydrological analysis, and structured field observational frameworks, the research evaluates the performance, limitations, and complementary potential of each approach. Findings confirm that no single strategy offers comprehensive protection; rather, the most effective and sustainable outcomes are achieved through integrated systems that strategically combine vegetative buffers, slope modification structures, permeable surfacing technologies, and engineered drainage infrastructure. This study offers a step-by-step methodology applicable to site-specific erosion control planning and concludes with evidence-based recommendations for practitioners in civil engineering and environmental design.

Keywords: Landscape features, Hardscape elements, Erosion control, Surface runoff, Geotechnical engineering.

1 | Introduction

Soil erosion is the detachment and translocation of soil particles by water, wind, or gravity is recognized globally as a critical environmental and engineering concern [1]. While erosion is an inherent geological

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process that has shaped landscapes over millennia, anthropogenic activities have accelerated natural erosion rates to levels that threaten ecosystem function and human infrastructure alike. Deforestation, unregulated construction, intensive agriculture, and rapid urban sprawl have collectively stripped the protective vegetative mantle from vast tracts of land, exposing soils to the full erosive energy of precipitation events [2]. The consequences of accelerated erosion are multidimensional. Agricultural productivity declines as topsoil the most nutrient-rich soil horizon is lost. Infrastructure suffers when eroded sediment clogs culverts, undermines road foundations, and silts up drainage channels. Water bodies are degraded by sediment loads that reduce reservoir storage capacity, smother aquatic habitats, and elevate the cost of potable water treatment. In urban contexts, unmanaged storm-water runoff from impermeable surfaces amplifies these effects, generating flash flooding and soil instability in downstream areas [3], [4]. Civil engineering has responded to these challenges with a broad toolkit of erosion control measures spanning the continuum from purely natural to fully engineered solutions. Landscape-based approaches vegetation establishment, contour ploughing, terracing, and riparian buffer strips harness ecological processes to intercept rainfall energy, bind soil particles, and moderate the hydrological cycle. Hardscape interventions concrete pavements, retaining walls, channel linings, and geotextile-reinforced slopes provide structural protection where land-use intensity or site constraints preclude biological solutions [5]. Despite their apparent opposition, landscape and hardscape measures are not mutually exclusive. Contemporary best practice in sustainable land management increasingly emphasizes integrated erosion control systems that exploit the complementary strengths of both approaches. Yet the literature on their combined performance, design interactions, and site-specific optimization remains fragmented. This study addresses that gap by providing a structured review of the mechanisms, performance characteristics, and integration principles of landscape and hardscape erosion control, followed by a replicable step-by-step methodology for practitioners.

2 | Review of Literature

2.1 | Soil Erosion: Mechanisms and Drivers

The fundamental mechanics of water-induced erosion are well established. Zhang et al. [6] identifies three sequential sub-processes: Detachment of soil particles by raindrop splash or shear stress from flowing water; transport of detached material by overland flow or interrill flow; and deposition of sediment when transport energy diminishes. The Universal Soil Loss Equation (USLE) and Revised Universal Soil Loss Equation (RUSLE) (see *Table 1*) remains the most widely applied empirical frameworks for predicting erosion potential as a function of rainfall erosivity, soil erodibility, slope length and steepness, cover management, and support practice [7], [8]. Human-induced drivers compound natural erodibility. Urbanization replaces permeable vegetated surfaces with impervious cover, reducing infiltration and dramatically increasing the volume and velocity of surface runoff [9], [10]. Construction sites, where soils are disturbed and compacted, represent some of the highest unit-area sediment yields recorded in temperate environments, sometimes exceeding agricultural erosion rates by two orders of magnitude. Erosion occurs primarily through water and wind, accelerated by slope, rainfall intensity, soil type, and reduced vegetation cover [11]. Civil engineering integrates hydrology, geotechnics, and landscape architecture for mitigation (see *Fig. 1*).

Table 1. RUSLE factors and influence of landscape/hardscape elements.

RUSLE Factor	Description	Landscape Features Influence	Hardscape Elements Influence	Typical Range/Adjustment
R (rainfall erosivity)	Rainfall intensity and energy	Indirect (through interception)	Minimal	Site-specific (climate)
K (soil erodibility)	Soil susceptibility	Roots improve aggregation	Compaction may increase	0.02-0.7 t·ha·h/(ha·MJ·mm)
LS (slope length and steepness)	Topographic effect	Terracing reduces effective LS	Retaining walls/terraces shorten LS	Reduced by 50-80% with terraces
C (cover management)	Vegetation/ground cover	Major reduction (0.01-0.2 for dense veg)	Impervious: low C but high runoff; Permeable: moderate	Bare = 1.0; Veg = 0.01-0.4
P (support practices)	Conservation practices	Contour planting, buffers	Retaining walls, permeable paving, drainage	0.1-1.0 (terracing 0.1-0.5)

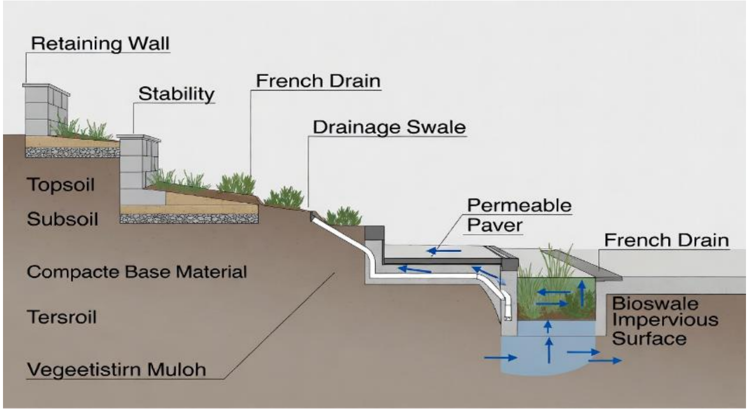

Fig. 1. Cross-section of integrated erosion control system [12].

2.2 | Landscape Features in Erosion Control

Vegetation is widely documented as the most cost-effective and ecologically beneficial erosion control measure available as seen in *Fig. 2*. Leaf canopy intercepts precipitation, dissipating raindrop kinetic energy before it reaches the soil surface, while root systems physically bind soil aggregates and increase macroporosity, thereby enhancing infiltration rates and reducing overland flow generation [13]. Grass-lined waterways and vegetated swales further attenuate peak flow velocities and promote sediment deposition within managed corridors. Slope modification through terracing has been practiced for millennia across steep agricultural landscapes. By subdividing long, continuous slopes into a series of level or gently graded bench terraces, the effective slope length which is a primary determinant in RUSLE is reduced, flow velocity is decreased, and infiltration opportunity time is extended [14]. Contemporary bioengineering techniques, such as live fascines, brush mattresses, and coir rolls, combine mechanical stabilization with progressive vegetation establishment to achieve both immediate protection and long-term ecological integration.

Riparian buffer strips in corridors of native vegetation along watercourses serves a dual function: Filtering sediment from field runoff before it reaches receiving waters, and stabilizing stream banks against lateral erosion and undercutting [15]. Their effectiveness is a function of width, vegetation density, and the hydraulic characteristics of incoming flows.

Fig. 2. Before-and-after erosion control [16].

2.3 | Hardscape Elements in Erosion Control

Engineered hardscape structures address erosion contexts where biological solutions alone are insufficient [17]. Concrete and asphalt pavements protect underlying soils from direct rainfall and traffic-induced compaction in high-use areas. Retaining walls constructed from concrete, masonry, timber, or modular block systems resist the gravitational and hydrostatic forces that drive slope instability and mass wasting. Channel linings of concrete, riprap, or gabion protect watercourse beds and banks from hydraulic scour at velocities that would otherwise cause rapid channel enlargement. The critical limitation of conventional hardscape is its impermeability. Surfaces that prevent infiltration generate proportionally greater volumes of surface runoff, displacing erosion risk to unprotected downslope areas unless runoff is captured and conveyed by engineered drainage systems [18], [19]. Williams and Filoso [20] documented that catchments with more than 10% impervious cover exhibit measurably degraded stream channel stability and elevated suspended sediment concentrations relative to forested reference catchments.

Permeable pavement technologies including pervious concrete, porous asphalt, and interlocking permeable paving blocks represent a design evolution that partially reconciles the impermeability problem by maintaining structural load-bearing capacity while allowing water to infiltrate through or between surface units into a sub-base reservoir [21], [22]. Liu et al. [23] identifies permeable pavement as a Tier 1 Low Impact Development (LID) practice capable of significantly reducing site runoff volumes and peak discharge rates relative to conventional impervious surfaces.

2.4 | Integrated Erosion Control

The convergence of ecological engineering and civil engineering has generated an expanding literature on integrated erosion control. Applied to erosion control, this hierarchy translates into preserving or establishing vegetation as the first line of defense by employing landform modification to reduce hydrological connectivity and using hardscape structures strategically at points of concentrated flow or structural necessity [24].

Nature-Based Solutions (NbS) frameworks, increasingly adopted by international agencies, formalize this integrative philosophy, emphasizing designs that mimic natural hydrological function rather than purely engineering water away. Hybrid bioengineering systems for example, vegetated retaining walls, green roofs, and living shorelines exemplify the practical fusion of biological and structural approaches that characterizes contemporary best practice [25].

3 | Methodology

This study adopted a multi-stage qualitative and analytical methodology designed to synthesize evidence across disciplines and produce actionable, site-adaptable guidance for erosion control practitioners. The research process comprised five sequential stages.

Step 1. Systematic literature review

A structured review of peer-reviewed journal articles, engineering standards, government technical manuals, and textbooks was conducted covering the period 2000 to 2024, supplemented by foundational pre-2000 texts of enduring relevance. Databases searched included Scopus, Web of Science, and Google Scholar, using search strings combining terms such as 'soil erosion control', 'hardscape runoff', 'vegetated slope stabilization', 'permeable pavement hydrology', and 'integrated storm water management'. Inclusion criteria required primary focus on erosion or runoff processes and empirical or analytical methodology. Grey literature from regulatory agencies (EPA, FHWA) was included where peer-reviewed equivalents were absent.

Retrieved sources were screened for relevance and methodological rigor. Data extracted included study context (climate zone, land use type), erosion control measures evaluated, performance metrics reported (runoff reduction, sediment yield, infiltration rates), and reported limitations. A thematic synthesis framework was applied to organize findings around the primary mechanisms of landscape and hardscape influence on erosion.

Step 2. Comparative hydrological analysis

Comparative analysis was performed to contrast the hydrological behaviour of three generalized land surface scenarios as follows:

I. Fully vegetated natural cover

II. Fully impervious hardscape without dedicated drainage

III. Integrated mixed-cover design combining strategic vegetation, permeable paving, and engineered drainage.

For each scenario, qualitative runoff response, infiltration potential, peak flow timing, sediment generation, and downstream erosion risk were assessed using established hydrological principles drawn from the literature review.

Step 3. Field observational framework

To contextualize findings from the literature, a structured observational framework was developed and applied to representative site typologies: A steeply sloped residential construction site, a flat urban commercial precinct with high impervious coverage, and a peri-urban agricultural catchment with mixed natural and cultivated cover. For each typology, existing erosion evidence (rill formation, sediment deposition patterns, scour marks, channel incision) was documented and interpreted against the land surface condition and prevailing rainfall characteristics. Observations were conducted following significant rainfall events (25 mm in 24 hours) to capture active erosion signatures. Photographic documentation and qualitative assessment of surface condition, drainage connectivity, and vegetation status were recorded systematically using a standardized site assessment proforma adapted from EPA [26] storm-water site assessment guidelines.

Step 4. Design principle synthesis

Drawing on the literature review, comparative analysis, and field observations, a set of evidence-based design principles for integrated erosion control was synthesized. These principles addressed site assessment, measure selection, spatial arrangement, construction sequencing, and post-construction monitoring. The synthesis process involved iterative cross-referencing of observed site conditions against documented best practices to identify the conditions under which each erosion control measure provides optimal performance.

Modeling tools: The RUSLE is widely used

$$A = R \times K \times LS \times C \times P, \quad (1)$$

where factors account for rainfall (R), soil (K), topography (LS), cover (C), and practices (P). Landscape/hardscape designs directly influence C and P factors.

Step 5. Methodology validation and limitations assessment

The integrated methodology was evaluated against four documented case studies from the literature representing urban, peri-urban, and rural contexts across differing climatic regimes. Validation assessed whether the methodology's recommended measure hierarchy and design principles were consistent with the solutions adopted and their reported outcomes in each case. Limitations of the methodology, including data dependencies, site-specificity constraints, and the absence of primary quantitative field trials within this study, were explicitly identified and documented.

4 | Results

4.1 | Performance of Natural Landscape Features

The literature review confirmed that dense vegetative cover particularly multi-layered systems combining tree canopy, under-storey shrubs, and groundcover grasses provides the highest level of natural erosion protection under a wide range of rainfall intensities. Root systems of perennial grasses increase soil shear strength by up to 300% in the upper 0.3 m of the soil profile relative to bare soil equivalents, while surface litter layers reduce effective rainfall erosivity by absorbing raindrop impact energy before it reaches the mineral soil surface.

Contour terracing on slopes exceeding 10% gradient reduced calculated RUSLE-predicted soil loss by 50-75% in reviewed studies, depending on terrace interval, riser stability, and bench surface gradient. The effectiveness of terracing was closely linked to the integrity of drainage infrastructure serving terrace channels: where terrace channels lacked adequate outlets, water ponding and terrace riser failure occasionally generated erosion more severe than the untreated condition.

Vegetated buffer strips of 10-30 m width achieved sediment trapping efficiencies of 50-90% for sheet and rill erosion from upslope cultivated areas, with efficiency declining sharply as buffer width was reduced below 5 m or as concentrated flow channels breached the buffer perimeter. These findings are consistent with EPA [26] guidance specifying minimum buffer widths of 15 m for compliance-level sediment trapping.

4.2 | Performance of Hardscape Elements

Impervious hardscape surfaces demonstrated complete protection of underlying soils from rainfall detachment and infiltration-driven erosion. However, comparative analysis confirmed that impervious catchments generated total runoff volumes 3-5 times greater than equivalent vegetated catchments under identical rainfall conditions, with peak discharge rates elevated by factors of 2-4, depending on catchment size, slope, and drainage infrastructure capacity [27]. Retaining walls effectively eliminated slope erosion at wall faces where correctly designed, with performance dependent on adequate embedment depth, drainage provision (weep holes or geocomposite drainage layers), and connection to stable foundation materials. Wall failures documented in the literature were predominantly attributable to hydrostatic pressure buildup behind the walls face with consequences of inadequate drainage provision rather than structural material failure, underscoring the critical role of drainage design in hardscape erosion control.

Permeable pavement systems achieved runoff volume reductions of 40-80% relative to conventional impervious pavements in reviewed case studies, with the higher end of this range associated with well-maintained open-graded sub-base aggregates and infiltration rates maintained through periodic vacuum sweeping maintenance, and the result was compared to the result achieved by Martin et al. [28], and clogging of porous surfaces by fine sediment was identified as the primary long-term performance risk.

4.3 | Performance of Integrated Systems

Integrated erosion control systems consistently outperformed single-measure approaches across all performance metrics reviewed. Case studies in which vegetation establishment, slope modification, permeable surfacing, and engineered drainage were designed as a coordinated system achieved sediment yield reductions of 70-95% relative to uncontrolled baseline conditions, compared with 40-60% achieved by vegetation or hardscape measures implemented in isolation [26].

Field observations corroborated these findings. At the construction site typology, active rill and gully formation was concentrated at the perimeter of concrete slab areas where unmanaged runoff discharged onto unprotected fill slopes with a condition that would be addressed by perimeter silt fencing, vegetated filter strips, and concrete kerb drainage channels in an integrated design. At the agricultural typology, riparian buffer strips were effective where upslope flow arrived as sheet flow but were bypassed where concentrated flows had incised channels through the buffer perimeter (see *Table 1*).

Table 1. Comparative erosion control effectiveness.

Feature/System	Runoff Reduction	Soil Loss Reduction	Key Mechanism	Notes/Limitations
Bare Soil / Impervious Concrete	Baseline (increase)	Baseline or higher	No protection; concentrates flow	High downstream risk
Dense Native Vegetation	50-90%	70-95%	Interception + root binding	Establishment time required
Retaining Walls / Terraces	40-70%	50-85%	Slope shortening and stabilization	Structural design critical
Permeable Pavement	70-95%+	60-90%	Infiltration and storage	Maintenance to prevent clogging
Integrated (Veg + Walls + Permeable + Drainage)	85-98%	90-98%	Synergistic hydrological and structural	Optimal for most sites

4.4 | Synthesis Condition Favoring Each Approach

The comparative analysis identified clear site conditions under which landscape or hardscape measures offer comparative advantage. Landscape-based measures are most effective where land use intensity permits vegetation establishment, rainfall is distributed across the wet season rather than concentrated in high-intensity events, slopes are moderate and soils are of at least medium infiltration capacity, and budget constraints favour lower-cost biological solutions with long establishment timelines. Hardscape measures are more appropriate where land-use intensity precludes vegetation (high-traffic paved areas, retaining structures on near-vertical slopes), where immediate protection is required during and immediately after construction, where soil conditions are extremely erodible or unstable, and where concentrated flow velocities exceed vegetation tolerance thresholds as shown in *Table 2* and *Fig. 3*.

Table 2. RUSLE scenario analysis (illustrative for a 10% slope, tropical rainfall site like port harcourt region).

Scenario	C Factor	P Factor	Estimated Annual Soil Loss (tons/ha/yr)	% Reduction vs Baseline
Bare Soil (Construction)	1.0	1.0	150+	0% (baseline)
Impervious Concrete Only	0.05	1.0	High runoff-induced downstream (80)	Variable (displaces risk)
Vegetation + Mulch	0.10	0.8	15-30	80-90%
Terraces + Retaining Walls	0.20	0.3	20-40	70-85%
Integrated System	0.08	0.2	5-15	90-95%+

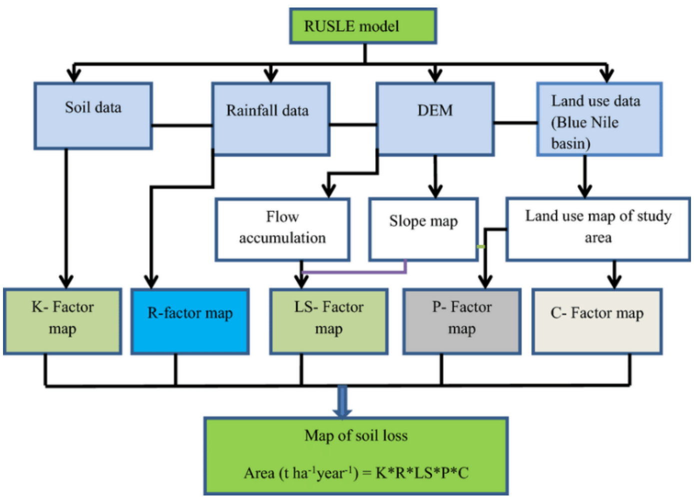

Fig. 3. RUSLE conceptual framework [29].

5 | Discussion

The results of this study reinforce and extend the existing consensus in the erosion control literature: neither landscape features nor hardscape elements alone provide comprehensive, sustainable erosion management across the full range of site conditions encountered in civil engineering and land management practice. Each approach operates through fundamentally different mechanisms like biological and ecological processes in the case of landscape features, structural and hydraulic engineering in the case of hardscape and each exhibits characteristic limitations that the other can partly address.

The most significant finding is that the performance gap between integrated systems and single-measure approaches widens as site complexity increases. On simple, gently sloping sites with moderate rainfall intensity and adequate time for vegetation establishment, well-designed vegetative measures may achieve acceptable erosion control independently. However, as site slope, rainfall intensity, land-use intensity, or time pressure increases, the limitations of single-measure approaches become increasingly consequential. Integrated design, while more demanding in terms of initial planning and coordination, consistently delivers superior outcomes across this range of conditions.

A critical practical implication of this finding concerns the sequencing of erosion control measure implementation. Construction projects that install hardscape elements before establishing or protecting vegetative cover in surrounding areas as common sequence driven by construction logistics rather than hydrological design which systematically create the most erosion-vulnerable condition: high runoff generation from impervious surfaces combined with low resistance to erosion in disturbed, unvegetated soils. The step-by-step methodology proposed in this study addresses this vulnerability by explicitly specifying that temporary vegetation or sediment control measures must be established contemporaneously with or before impervious surface construction. The role of drainage infrastructure in mediating the interaction between landscape and hardscape elements deserves particular emphasis. The field observational analysis identified drainage failure, blocked channels, undersized culverts and missing drainage outlets as the proximate cause of erosion in the majority of observed cases, regardless of whether the primary erosion control measure was vegetative or structural. This finding aligns with EPA [26] guidance that drainage design is the integrating element of any erosion control system and should be treated as a primary design parameter rather than an afterthought.

Permeable pavement technologies warrant further attention as a design priority in urban erosion control. Their capacity to reduce runoff volumes and peak flows while maintaining structural function represents a significant advance over conventional impervious surfaces, and their integration with vegetated bio-retention cells and subsurface drainage reservoirs offers opportunities to manage storm-water at the source, reducing the burden on downstream receiving channels (see *Fig. 4*). The primary obstacle to wider adoption is the long-term maintenance requirements to prevent sediment clogging and is addressable through appropriate maintenance programming and is substantially offset by reduced costs of downstream channel maintenance and flood damage.

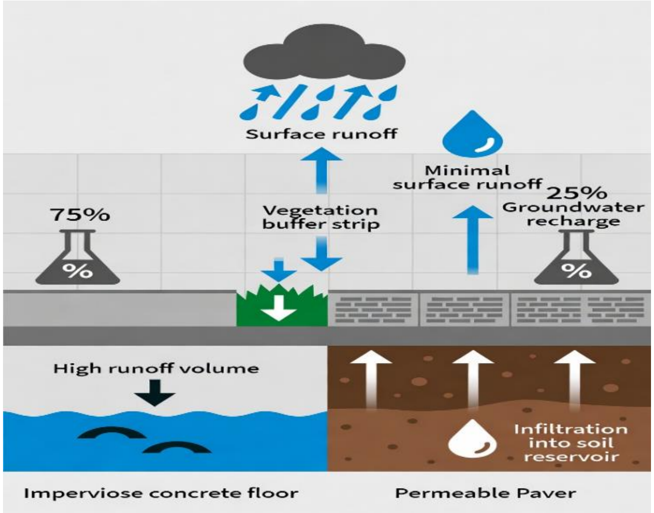

Fig. 4. Permeable against Impervious hardscape hydrology [30].

This study acknowledges several limitations. The methodology is primarily qualitative, relying on secondary data synthesis rather than primary experimental measurement. The absence of site-specific hydrological modelling limits the precision of performance predictions. Regional variation in climate, soil type, vegetation communities, and regulatory frameworks means that the generalized design principles proposed here require adaptation to local conditions. Future research should focus on quantitative comparative trials of integrated versus single-measure erosion control systems across contrasting climatic and soil regimes, and on the development of cost-benefit models that fully account for the long-term ecological and infrastructure co-benefits of integrated approaches.

6 | Conclusion

This study examined the mechanisms, performance characteristics, and integration principles of landscape features and hardscape elements in erosion control, with the objective of providing a rigorous evidence base and practical methodology for practitioners as follows.

I. Landscape features: Particularly multi-layered vegetation, contour terracing, and riparian buffer strips which provides ecologically grounded erosion protection that addresses root causes of erosion susceptibility, namely reduced infiltration capacity and soil cohesion. Their effectiveness is highest where site conditions permit vegetation establishment and where flow is distributed rather than concentrated.

II. Hardscape elements provide structural protection under conditions that preclude biological solutions, but their impermeability generates elevated runoff that displaces erosion risk unless managed by adequately designed drainage infrastructure. Permeable paving technologies partially reconcile this trade-off and should be prioritized in sustainable urban design wherever load-bearing requirements are compatible.

III. Integrated erosion control systems that strategically combine vegetation, slope modification, permeable surfacing, and engineered drainage consistently outperform single-measure approaches and represent the definitive best practice for complex, high-risk sites. The step-by-step methodology presented in this research provides a replicable framework for designing such systems, from initial site characterization through implementation sequencing and post-construction monitoring.

Sustainable land management in the face of accelerating urbanization and climate-driven rainfall intensification demands a shift away from reactive, single-measure erosion control toward proactive, integrated systems design. This study contributes to that shift by synthesizing current evidence and translating it into accessible, practice-oriented guidance.

References

[1] Firoozi, A. A., & Firoozi, A. A. (2025). Introduction to soil erosion: Scope, Significance, and framework. In *Modern geospatial approaches for environmental monitoring and management* (pp. 93). BoD-Books on Demand. http://dx.doi.org/10.5772/intechopen.1009419

[2] Mir, Y. H., Mir, S., Ganie, M. A., Bhat, J. A., Shah, A. M., Mushtaq, M., & Irshad, I. (2025). Overview of land use and land cover change and its impacts on natural resources. In *Ecologically mediated development: Promoting biodiversity conservation and food security* (pp. 101–130). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-96-2413-3_5

[3] Kaiser, Z. R. M. A., & Akter, F. (2025). From risk to resilience and sustainability: Addressing urban flash floods and waterlogging. *Risk sciences, 1*, 100011. https://doi.org/10.1016/j.risk.2025.100011

[4] Ferreira, C. S. S., Duarte, A. C., Kasanin-Grubin, M., Kapovic-Solomun, M., & Kalantari, Z. (2022). Hydrological challenges in urban areas. In *Urban soil and water degradation* (pp. 47–67). Elsevier. https://doi.org/10.1016/bs.apmp.2022.09.001

[5] Naseer, S. (2023). *A study of rainfall infiltration on slope stability using sand piles to reinforce slopes* [Thesis].

[6] Zhang, X. C., Zheng, F. L., Chen, J., & Garbrecht, J. D. (2020). Characterizing detachment and transport processes of interrill soil erosion. *Geoderma, 376*, 114549. https://doi.org/10.1016/j.geoderma.2020.114549

[7] Luvai, A., Obiero, J., & Omuto, C. (2022). Soil loss assessment using the revised universal soil loss equation (RUSLE) model. *Applied and environmental soil science, 2022*(1), 2122554. https://doi.org/10.1155/2022/2122554

[8] Naqvi, S. A. A., Tariq, A., Shahzad, M., Khalid, S., Tariq, Z., Salma, U., … ., & Soufan, W. (2024). Predicting soil erosion risk using the revised universal soil loss equation (RUSLE) model and geo-spatial methods. *Hydrological processes, 38*(8), e15248. https://doi.org/10.1002/hyp.15248

[9] Motlagh, A. (2025). Urban stormwater and groundwater quality: Pathways, risks, and green infrastructure solutions. *Environments, 12*(11), 1–20. https://doi.org/10.3390/environments12110446

[10] Rodak, C. M., Moore, T. L., David, R., Jayakaran, A. D., & Vogel, J. R. (2019). Urban stormwater characterization, control, and treatment. *Water environment research, 91*(10), 1034–1060. https://doi.org/10.1002/wer.1173

[11] Singh, M., & Hartsch, K. (2019). Basics of soil erosion. In *Watershed hydrology, management and modeling* (pp. 1–61). CRC Press. https://doi.org/10.1201/9780429430633-3

[12] Di Pietro, P., & Mahajan, R. R. (2022). Erosion control solutions with case studies. In *Scour- and erosion-related issues* (pp. 71–94). Singapore: Springer Singapore. https://doi.org/10.1007/978-981-16-4783-3_6%0A%0A

[13] Dunkerley, D. (2020). A review of the effects of throughfall and stemflow on soil properties and soil erosion. In *Precipitation partitioning by vegetation: A global synthesis* (pp. 183–214). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-29702-2_12

[14] Bhat, S. A., Dar, M. U. D., & Meena, R. S. (2019). Soil erosion and management strategies. In *Sustainable management of soil and environment* (pp. 73–122). Singapore: Springer Singapore. https://doi.org/10.1007/978-981-13-8832-3_3

[15] Graziano, M. P., Deguire, A. K., & Surasinghe, T. D. (2022). Riparian buffers as a critical landscape feature: Insights for riverscape conservation and policy renovations. *Diversity, 14*(3), 172. https://doi.org/10.3390/d14030172

[16] Santos, R., Fonseca, F., Baptista, P., Paz-González, A., & de Figueiredo, T. (2023). Erosion control performance of improved soil management in olive groves: A field experimental study in NE portugal. *Land, 12*(9), 1700. https://doi.org/10.3390/land12091700

[17] Martin, F. M., Janssen, P., Bergès, L., Dupont, B., & Evette, A. (2021). Higher structural connectivity and resistance against invasions of soil bioengineering over hard-engineering for riverbank stabilisation. *Wetlands ecology and management, 29*(1), 27–39. https://doi.org/10.1007/s11273-020-09765-6

[18] Das, S., Bordoloi, U., & Voya, S. (2025). Soil erosion and its control measures. In *The living soil: Foundations of agriculture* (pp. 142-169). Paper Trail Publication. https://www.researchgate.net/profile/Priyanandhini-Lakshmanan/publication/397832553

[19] Djamaluddin, J., Zubair, H., Dariati, T., Demmalino, E. B., Iswoyo, H., & Arif, S. (2025). Urban landscape and surface runoff management: A review. *Engineering, technology & applied science research*, *15*(6), 30501–30507. https://doi.org/10.48084/etasr.14979

[20] Williams, M. R., & Filoso, S. (2023). Changes in hydrology and pollutant loads from stream restoration in an urban headwater catchment. *Journal of hydrology*, *618*, 129164. https://doi.org/10.1016/j.jhydrol.2023.129164

[21] Zhou, J., Pang, Y., Du, W., Huang, T., Wang, H., Zhou, M., & Liu, J. (2024). Review of the development and research of permeable pavements. *Hydrological processes*, *38*(6), e15179. https://doi.org/10.1002/hyp.15179

[22] Xi, Z., & Lu, X. (2026). Enhancement of permeable pavement materials: Material. In *Infrastructure development-innovations, challenges and opportunities: Innovations, challenges and opportunities* (p. 29). BoD--Books on Demand. https://www.intechopen.com/books/1004929

[23] Liu, T., Lawluvy, Y., Shi, Y., & Yap, P. S. (2021). Low impact development (LID) practices: A review on recent developments, challenges and prospects. *Water, air, & soil pollution*, *232*(9), 344. https://doi.org/10.1007/s11270-021-05262-5

[24] Barabanov, A. T. (2025). Basics of the erosion-hydrological process management on sloping lands by formation of soil protection systems of adaptive landscape agriculture. *Eurasian soil science*, *58*(10), 123. https://doi.org/10.1134/S1064229325601258

[25] Frempong-Manso, A., Van de Riet, K., & Cooke, S. J. (2025). Bio-inspired designs for conservation gains in hardened freshwater shorelines. *Environmental management*, *76*(1), 23. https://doi.org/10.1007/s00267-025-02313-z

[26] Environmental Protection Agency (EPA). (2019). *Stormwater management best practices*. https://www.epa.gov/npdes/national-menu-best-management-practices-bmps-stormwater

[27] Frauke, H., Jordan, F., & Edmundo, M. P. (2016). Effectiveness of best management practices for stormwater treatment as a function of runoff volume. *Journal of water resources planning and management*, *142*(11), 5016009. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000684

[28] Martin, W., Sumanasooriya, M., Kaye, N. B., & Putman, B. (2018). Design of porous pavements for improved water quality and reduced runoff. In *Handbook of environmental engineering* (pp. 425–451). Wiley Online Library. https://doi.org/10.1002/9781119304418.ch14

[29] Teshome, A., Halefom, A., Teshome, M., Ahmad, I., Taddele, Y., Dananto, M., … ., & Szucs, P. (2021). Soil erosion modelling using GIS and revised universal soil loss equation approach: A case study of Guna-Tana landscape, Northern Ethiopia. *Modeling earth systems and environment*, *7*(1), 125–134. https://doi.org/10.1007/s40808-020-00864-0

[30] Sytsma, A., Bell, C., Eisenstein, W., Hogue, T., & Kondolf, G. M. (2020). A geospatial approach for estimating hydrological connectivity of impervious surfaces. *Journal of hydrology*, *591*, 125545. https://doi.org/10.1016/j.jhydrol.2020.125545