International Journal of
Environmental Sciences & Natural Resources
ISSN: 2572-1119

Juniper PUBLISHERS key to the Researchers

Mini Review
Volume 35 Issue 2 - May 2025
DOI: 10.19080/IJESNR.2025.35.556412

Int J Environ Sci Nat Res

Soil and Water Bioengineering for Natural Hazard Mitigation and Ecological Restoration: A Sustainable Nature-Based Solution

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Submission: April 14, 2025; **Published:** May 06, 2025

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Abstract

Soil and Water Bioengineering (SWB) is an environmentally friendly approach that integrates biological and engineering techniques applied to manage natural hazards and restore degraded ecosystems. Instead of using concrete or heavy machinery, SWB relies on vegetation, natural materials and ecological processes. This method helps to reduce disaster risks, improves soil quality, enhances water retention and increases biodiversity. SWB techniques, such as vegetative slope stabilization and erosion control, are cost-effective and adaptable to different landscapes. As a nature-based solution, SWB plays a key role in promoting sustainable land management, restoring ecological balance, and building resilience against climate-related hazards. This mini review aims to provide an overview of SWB as a sustainable, nature-based approach that integrates ecological and engineering principles to mitigate natural hazards and restore degraded ecosystems.

Keywords: Soil; Water bioengineering; Ecosystem; Biodiversity; Sustainable environmental management; Biodegradable materials; Wildlife habitats; Geotechnical engineering

Introduction

Soil and Water Bioengineering (SWB) is an innovative approach combining ecological principles with engineering techniques to address natural hazards like erosion, landslides, and floods while promoting ecosystem restoration [1]. Unlike conventional methods, SWB uses vegetation, biodegradable materials, and natural processes to enhance slope stability, improve hydrological regulation, and restore biodiversity [2]. SWB stabilizes soil, prevents erosion, and improves water quality and availability through plant materials like grasses, shrubs and trees, combined with structural elements such as geotextiles [3]. It is increasingly emerge as a sustainable alternative to traditional engineering solutions, which can disrupt ecosystems and require high maintenance [4]. SWB supports ecological restoration by rehabilitating degraded lands, improving soil fertility, enhancing wildlife habitats and contributing to carbon sequestration. Techniques like riparian zone restoration and wetland recovery help improve water quality and biodiversity [5,6]. This approach is gaining recognition as a crucial strategy for disaster risk reduction, restoration and sustainable environmental management, particularly in vulnerable regions [7]. This mini review highlights an overview of the scientific principles, practical applications, and long-term benefits of SWB for both hazard mitigation and ecological restoration.

Methodology

The methodology for this study involves conducting a desk study review of prior research on SWB using scientific databases such as Scopus, Google Scholar, Web of Science, and Science Direct. Relevant peer-reviewed articles, reports and case studies was identified from these databases to understand the effectiveness, applications, and challenges of SWB techniques in hazard mitigation and ecological restoration.

SWB Applications in Hazard Mitigation & Restoration

A. Erosion control

SWB is a useful method to minimize soil erosion and protect land from damage during heavy rain and landslides. It uses techniques such as live staking, brush layering, coir logs and grass planting to reduce surface runoff, stabilize soil and prevent sediment loss [8-10]. Live staking involves inserting woody cuttings from plants like willow and poplar into slopes, which stabilize the soil through root growth [8]. Brush layering places branches horizontally on slopes, helping trap sediment and promote vegetation growth [9]. Coir logs and geotextiles, made from biodegradable materials, reduce surface runoff and allow native plants to take root [10].

B. Slope Stabilization & Landslide Mitigation

In areas prone to landslides, SWB helps stabilize slopes and prevent erosion. Techniques such as using rooted cuttings from plants like willow and bamboo, combining geotextiles with vegetation, and planting on terraced slopes enhance the soil's strength. Vegetated gabions-rocks filled with soil and plants provide structural support and boost biodiversity [11]. Live crib walls, made of interlocking wooden structures filled with soil and plants, reinforce steep slopes [12]. Additionally, terracing with vegetation reduces the slope angle, preventing mass wasting like landslides [13].

C. Riverbank & Coastal Protection

SWB used for protecting riverbanks and coastlines from erosion and flooding. Techniques such as vegetated gabions, live fascines, afforestation and mangrove restoration dissipate wave energy, reduce scour and improve habitat connectivity. Willow spilling, where live willow branches are woven into riverbanks, helps reduce soil erosion and supports wildlife habitats [14]. Restoring mangroves and wetlands provides natural buffers against storm surges and tidal erosion [15].

D. Flood Mitigation

SWB techniques are adopted to reduce flood risks by controlling water flow and improving water quality. Methods like constructed wetlands, riparian buffers, and vegetated swales slow down water flow, increase water absorption, and filter out pollutants. Constructed wetlands help filter water and recharge groundwater [16], while riparian buffers, which are vegetated zones along rivers, reduce flood peaks and enhance biodiversity [17].

E. Ecological Restoration

In ecological restoration, SWB promotes the recovery of ecosystems by improving soil quality and biodiversity. Techniques such as planting native species, using soil bioengineering structures like log crib walls and introducing soil microbes help restore ecosystems. Native species planting enhances resilience by supporting local wildlife [18], while soil microbe inoculation improves soil fertility and plant growth [19]. The major applications of SWB techniques are presented below (Figure 1).

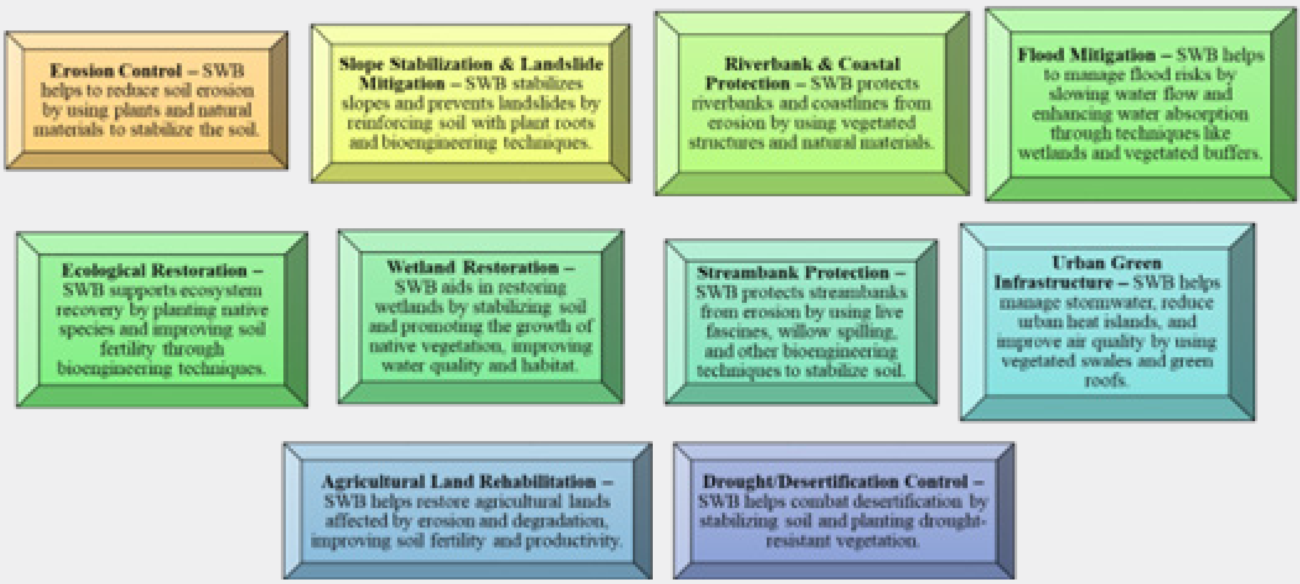

Figure 1: Applications of Soil and Water Bioengineering (SWB).

Advantages over Conventional Methods

SWB provides several ecological and functional advantages over conventional engineering methods. It uses renewable, biodegradable materials, making it more sustainable [1]. SWB is also more cost-effective, with lower long-term costs compared to concrete structures [2]. It provides climate resilience by adapting to changing environmental conditions [20]. It supports biodiversity by providing habitats for pollinators, birds and aquatic life [21]. Additionally, SWB offers multifunctional benefits,

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including carbon storage, habitat creation and aesthetic value. The increasing frequency of climate-related disasters [22] and land degradation [23] highlight the need for innovative solutions like SWB. Conventional "gray infrastructure" methods, such as concrete revetments and gabion walls, have limitations, including ecological disruption, higher failure rates under extreme weather, and higher lifecycle costs. Bioengineering methods are more effective in preserving biodiversity, with traditional stabilization methods reducing riparian biodiversity by 38-72% compared to bioengineered alternatives [24]. Bioengineered systems also have lower failure rates under extreme rainfall [25] and offer significant cost savings over conventional methods [26]. SWB leverages living plant materials to provide engineering functions while enhancing ecological value, making it a more sustainable and resilient solution.

Challenges & Future Perspectives

Despite its numerous advantages, SWB faces several challenges. One key limitation is the slow establishment of vegetation, which may require several years to achieve effective slope stabilization [4]. The successful implementation of SWB also demands site-specific designs and interdisciplinary expertise in hydrology, ecology, and geotechnical engineering [7]. Additionally, institutional barriers such as inadequate policy frameworks and limited financial support often hinder its adoption compared to conventional engineering solutions [27]. Long-term monitoring is essential to evaluate the performance and sustainability of SWB interventions. Future directions include enhancing resilience to extreme climatic events, fostering community participation to strengthen local ownership, and integrating SWB with conventional engineering techniques where appropriate.

Global Case Studies on SWB

In Europe's Alps, brush mattresses and live crib walls have been used for avalanche and landslide control. In the Himalayas, vetiver grass plantations have been implemented for slope stabilization. In the USA, willow wattles are used for riverbank restoration in the Pacific Northwest. Future research should focus on hybrid solutions (combining bioengineering with minimal hard structures) [11], long-term performance monitoring [1], and community-based implementation for wider adoption [27]. In London, UK, stormwater runoff from roads has become a major issue [28]. To tackle this, the city has introduced rain gardens, bioswales, and permeable pavements. Permeable pavements, made from materials like porous concrete, allow water to soak into the ground, reducing runoff and costing up to 50% less than traditional pavement [28]. Bioswales help filter stormwater and recharge groundwater. Rain gardens absorb about 30% more water than regular lawns and can also reduce flood risk when placed upstream in the same catchment area [28].

Soil and Water Bioengineering in Nepal

There is limited knowledge about how climate hazards affect livelihood resources and vulnerable groups in Nepal's mountainous regions, where adaptive capacity remains low due to poor access to information, services, and assets [29]. One promising yet underutilized approach is SWB, which uses locally available materials and vegetation to stabilize slopes and restore ecosystems. In Nepal, SWB practices have been implemented to a limited extent, primarily to address erosion control and flood risk management in the fragile hill and mountain regions. The primary soil bioengineering techniques used in Nepal include brush layering, palisades, live check dams, fascines, and vegetative stone pitching [30]. These techniques use locally available materials and vegetation to provide both structural support and ecological benefits, making them cost-effective and environmentally friendly solutions for land restoration and slope management. In the Siwalik foothills, techniques such as vegetative check dams and wire net check dams combined with plantation have proven effective in stabilizing streambanks and mitigating riverbank erosion [31]. Similarly, in the Midlands region, the application of check dams and vegetative measures has led to a significant reduction in gully head retreat (ranging from 14% to 73%) on degraded sloping lands [32]. These examples underscore the potential of SWB in enhancing slope stability, restoring ecosystems, improved community resilience and providing socio-economic benefits to local communities. Considering the increasing environmental degradation and vulnerability to hydro-climatic hazards across Nepal's ecological belts-from the flood-affected Terai to the erosion-prone hills and Himalayan regions, there is an urgent need to adopt SWB techniques. Since, implementing site-specific SWB interventions along this altitudinal gradient can support integrated watershed management, enhance resilience to climate-induced hazards, disaster risk reduction, and sustainable land use planning at both local and national scales.

Conclusion

SWB is a sustainable and cost-effective approach that combines ecological principles with engineering techniques to mitigate natural hazards such as erosion, landslides, and floods. By utilizing natural materials like plants and biodegradable structures, SWB improves slope stability, restores biodiversity, and promotes ecological restoration. This approach not only contributes to disaster risk reduction and environmental management but also provides resilient, long-term solutions for natural resource management, particularly in vulnerable areas. Through its integration of nature-based solutions, SWB offers a holistic approach to enhancing ecosystem health and reducing the impacts of natural disasters.

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