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The role of soil and forest characteristics in planning hydraulic-forestry and bioengineering works: Lessons from the Italian experience

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Abstract
Soil plays a crucial role in hydraulic-forestry and bioengineering works, influencing the design, construction, and implementation of measures aimed at mitigating land degradation and promoting environmental restoration. These systems involve various intensive and extensive interventions designed to address the causes and effects of land instability, particularly in hilly and mountainous torrent basins. A key objective is to create favourable conditions for vegetation re-establishment. Recent advancements have emphasized the use of natural engineering techniques, soil and water bioengineering, and nature-based solutions over traditional masonry structures. These innovative approaches not only restore damaged areas but also focus on preventing future degradation by addressing underlying causes, often related to soil properties and management practices. This review provides an overview of recent developments in Italy, showcasing practical examples of solutions that leverage soil knowledge and mapping, and the use of decision support systems and Geographic Information Systems (GIS). The meta-analysis identifies key soil properties influencing hydrological behavior, which must be considered when assessing hydraulic and geological risk in forested areas and when planning bioengineering or nature-based interventions.
Keywords: *Soil hydrology, climate change, geomorphological risk, NBS, GIS, DSS.*

Introduction

Changes in land use and the reduced maintenance of watersheds, in addition to the effects of climate change, have significantly increased hydraulic and geological risk. Referring to the floods of March 2025 and November 2023 in Tuscany, as well as the one in May 2023 in Emilia-Romagna, recent studies by the University of Florence on watersheds affected by floods have found that hydraulic risk has more than tenfold increased due to land transformations and the effects of climate change (Preti, 2024). The increase in hazard levels, estimated at 20-30%, is solely attributable to the reduction in retention and slowing capacity within the minor hydraulic network and hillside terracing ("equivalent diffuse expansion-lamination basin", Preti, 2020). When also considering the effects of climate change, this increase exceeds 50%, meaning that rainfall events that can have catastrophic consequences now occur more frequently, with a shorter return period. Traditional engineering responses tend to favor masonry structures and pay little attention to the nature of the soils where interventions take place. This approach is now considered obsolete and must be replaced by one that prioritizes Nature-Based Solutions (NBS, Preti al, 2022) and new digital technologies. Through an interdisciplinary engineering and pedological approach, this short review aims to highlight the role of the soil's physical-hydrological properties and condition in selecting the forest-hydraulics and bioengineering works, also leveraging GIS systems and multi-criteria analysis.

Forest watershed management, forest-hydraulics and bioengineering works

Forest-hydraulics and bioengineering works constitute

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a set of structural and non-structural interventions aimed at managing and mitigating hydrogeological instability, particularly in hilly and mountainous areas. These interventions seek to counteract the causes of instability and restore favorable conditions for vegetation regeneration through the sizing, construction, and application of both intensive and extensive works, to eliminate the causes or mitigate the effects of land degradation occurring in torrential basins (hilly and mountainous), thus fostering conditions for vegetation recovery (Puglisi, 1996). Historically, forest-hydraulics setups were regulated by the Ministerial Decree of August 20, 1912, which recommended the use of local natural materials, such as stone and timber, and the minimization of masonry costs (Hofmann, 2011). This approach was based on the enhancement of available resources and simplicity, as already highlighted by Leonardo da Vinci in the fifteenth century, who had proposed the use of willow trees to stabilize slopes. Over time, this sector has evolved towards innovative solutions, which today include techniques such as natural engineering and NBS. These methodologies emphasize the use of living materials to stabilize the terrain and on the integration of green infrastructure with natural processes, fostering a sustainable balance between human interventions and the environment. In forest-hydraulics and bioengineering works, priority is given to the zero-option approach (non-intervention unless necessary, in the case of natural processes) or to renaturalization/requalification before structural interventions. If such interventions are inevitable, they will be executed using "green" works rather than conventional "gray" ones, considering technical limitations and professional ethics. All this while fully respecting the "Do No Significant Harm (DNSH) principle", ensuring that interventions do not cause significant environmental damage. European and national strategies and programs, also supported by the "Recovery Plan/ PNRR" and the "Nature Restoration Law", are now aligned in this direction. With the issuance of "DPCM 27/09/2021", criteria and methods were defined for identifying funding priorities for hydraulic and geological risk mitigation interventions in Italy. Among the proposed interventions, priority will be given to so-called "integrated" interventions, which combine ecosystem and biodiversity protection with hydraulic and geological risk mitigation. From the preliminary design phase, projects should consider the "maximum applicability" of biongineering. If, for technical reasons, the project cannot adopt such solutions, a specific report must provide detailed justifications (Art. 3, BURC. Special August 19, 2002, Campania Region). The Legislative Decree No. 34 of 2018, which contains the Consolidated Law on Forests and Forestry Supply Chains, regulates a number of matters, including forest-hydraulics interventions and works of both intensive and extensive nature, recognizing their role in improving the functional efficiency of watersheds. Extensive works typically include afforestation, reforestation, and other activities resulting from forest management practices. The Tuscan Forestry Law (L.R. No. 39/2000) also reaffirms the stabilizing function of forests. The significance of these interventions lies in their ability to solve complex land management issues, combining local actions with long-term strategies to create sustainable solutions for hydraulic and geological risk mitigation.

Hilly and mountain watershed management

Forests represent a significant and distinctive element of the Italian mountainous territories, both in terms of surface area (35% of the territory) and function, with approximately 40% of forests serving a primary protective role, either directly or indirectly (Iovino, 2017). Nationally, around 65% of forested areas are located above 500 meters in elevation. About 87% of the forest macrocategory is subject to hydrogeological restrictions under Royal Decree Law No. 3267/1923, while 23% is affected by instability phenomena, including 3.3% impacted by landslides and soil slippages. The interaction between forests and the water cycle varies across different forest environments, depending on climatic conditions, spatial and temporal scales of analysis (Iovino et al., 2009). These relationships can be assessed in spatial terms, at both forest stand and watershed scales, and in temporal terms, for individual events or on a seasonal or annual basis, in response to natural (e.g., extreme weather events) or human-induced (e.g., wildfires, grazing, forestry operations) changes. The hydrological role of forests has been a subject of debate for the past two centuries. While extensive literature acknowledges the positive impact of forests on hydrology, there is no unanimous consensus on the magnitude and limitations of this effect (Iovino et al., 2009; Puglisi, 1996; Vazken, 2004; Bathurst et al., 2020). The protective function of forests consists of:

- reducing surface runoff, which is a primary component of flood discharge and a major factor in determining the frequency of extreme rainfall events with catastrophic consequences;
- increasing concentration time, thereby enhancing

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the ability of watersheds to attenuate flood peaks;
- decreasing surface soil erosion rates and mitigating the risk of shallow landslides and associated sediment transport.

The key factors behind these processes are high water consumption by vegetation and soils in good hydrological condition, which exhibit high infiltration capacity, well-drained upper horizons, and good water storage potential (Preti et al., 2011; Iovino, 2017). The impact of tree cover on flood regulation is most significant in watersheds up to 10 km², with broader forest cover and steeper slopes (concentration times ~1 hour) where it results in peak flow reductions of up to 30%. However, this effect diminishes in hundreds-of-km² watersheds, where interception losses are less significant, and becomes negligible in thousands-of-km² basins (Giacomin and Trucchi, 1992; Puglisi, 1996; Preti et al., 2011; Bathurst et al., 2021). The root system of forest cover plays a crucial role in stabilizing slopes by creating preferential flow pathways that enhance subsurface water drainage and strengthen soil geomechanically, improving slope stability regardless of soil water content (Arnone et al., 2017). These factors contribute to reducing the risk of shallow landslides (Piussi and Puglisi, 2012; Preti, 2013). In particular, root reinforcement has a more significant stabilizing effect than the biomass-induced surcharge. However, mature coniferous stands, coppice stands, and aged broadleaf high forests that have lost their ability to produce root suckers experience root degradation after logging. Thus, logging initially leads to a temporary improvement, due to reduced aboveground loading, but ultimately results in greater slope instability compared to pre-harvest conditions (Preti et al., 2025).

Soil properties and hydraulic and geological risks in forests

Soil is not merely the upper layer affected by cultivation or other surficial processes but includes the entire thickness of the outermost part of the Earth's crust, located between unaltered rock or sediment and the atmosphere. This thickness is far from homogeneous and is differentiated into horizons or layers with highly diverse characteristics, where transitions between two horizons can be abrupt, completely altering the soil's hydrology. This can occur due to pedogenetic processes or the successive deposition of sediments, as in the case of colluvial soils. Below is an analysis of soil properties that may influence land susceptibility to runoff, soil erosion, and slope instability.

Water retention capacity. Soil water capacity is the parameter most frequently considered in models for landslide risk assessment (Wicki et al., 2020). It is widely acknowledged that the water retention capacity of soil varies significantly, ranging from more than 300 mm to less than 50 mm, depending on the type of soil and the characteristics of its surface and subsurface layers. A decrease in the soil's storage capacity directly correlates with a shorter time needed to reach water saturation and initiate runoff, thereby proportionately reducing the time of water concentration (Meisina and Scarabelli, 2007). This factor is critically important, as the reduced interval between a significant rainfall event and the peak flow of watercourses draining the soils diminishes the ability to prevent and mitigate flooding or even to adequately warn the population of imminent risk.

Water infiltration and hydraulic conductivity. *Wa*ter infiltration into the soil is a complex process that depends on various factors, primarily the surface conditions of the soil, such as roughness, the presence of stones and organic matter cover, hydrophobicity, the presence of cracks and fissures, soil moisture, as well as the site's morphology and the depth of the water table. However, it mainly depends on soil porosity, as well as hydraulic conductivity (Costantini et al., 2016). The presence of interconnected macropores linked to the surface allows water to infiltrate and percolate into deeper layers. Susceptibility to surface crusting, surface and deep compaction, increase the risk of reduced rainfall penetration into the soil, leading to greater surface runoff. High susceptibility to crusting is often found in soils with low organic matter content. These soils are typically poorly structured, with weak and unstable aggregates. Such characteristics make them particularly vulnerable to structural degradation caused by the passage of heavy machinery, such as those used for logging and deforestation (Cambi et al., 2015). Tree roots breathe and require oxygen. Soil compaction due to human or heavy machinery traffic leads to asphyxia conditions, which promote the onset and spread of root pathogens, manifested by rot that undermines root stability. Compaction, especially in wet soil conditions, causes permanent damage to soil structure, which is difficult and time-consuming to remediate.

Rootability. A recent study analyzed the evolution of root systems in relation to slope stabilization using multi-approach monitoring methodologies (Giachi et

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al., 2024). Trees have a root system with highly variable size and geometry, depending on several factors such as species, plant age, health status, forest density, morphology, climate, but most importantly, soil characteristics. The soil's ability to support root growth (rootable mass or rootability) is particularly relevant (Costantini & Priori, 2023; Priori et al., 2021). This soil property can be limited by various factors, such as reduced depth due to the presence of compact and impenetrable surface sediments or rock, hardened soil horizons, a shallow water table, or layers with a mineralogical composition dominated by dynamic clays. Larger trees growing in shallow soils or in soils with restricted rooting depth may be more susceptible to uprooting and toppling. In forest environments, many tree-fall events are linked to the failure of root systems, which can occur due to pathogen attacks or because the root system is too small to support the mechanical stresses of a large tree. A mature, large tree requires a deep and widespread root system. The distribution of roots in the soil is determined by the specific characteristics of the tree species but is primarily influenced by the soil's physical-hydrological properties and its mana-gement. The risk of tree collapse increases when, as the tree grows in weight and age, the root system becomes insufficient to ensure stability. This phenomenon is more common in soils with limited rootable mass and in aged, unmanaged forest stands (Ho et al., 2012). As previously mentioned, there are conflicting opinions regarding the role of herbaceous and tree cover in landslide risk. The relationship between soil and vegetation is undoubtedly complex and cannot be oversimplified. In the case of the landslides that occurred in Sarno, Campania, in 1998, land management had significant interaction with the type of forest cover. The chestnut forests in that area played a crucial role in risk mitigation. Their funda-mental stabilizing effect appears to be attributed to the dense root network, which envelops and holds the soil even at considerable depths. Many landslide triggers occurred precisely where new forest roads were opened, disrupting the continuity of the root systems (Terribile et al., 2007). In other situations, however, such as during the disaster in Versilia in June 1996, the presence of aging forests on slopes near watercourses, which had been unmanaged for many years, contributed to instability. The significant accumulation of necromass, along with numerous fallen trees and overturned stumps, increased soil weight, weakened slope stability, and obstructed water flow. Thus, the mere presence of a forest is not always a guarantee of reduced landslide risk. Following the catastrophic events in Giampilieri (Sicily) in 2009, as well as across the Messina area, studies advised the Sicilian Region to promote the planting of suitable shrub species instead of trees. Shrubs were deemed preferable as they are lighter, spread and grow more quickly, and are more resistant to drought (Costantini et al., 2015).

Presence of compact horizons and discontinui-ties in the soil profile. Tree root development is strongly influenced by the nature of deep soil horizons. In forest soils, there are often horizons or layers that absorb water well, overlying others that slow down or prevent deep drainage, promoting sub-horizontal water movement. In such cases, the risk of landslides is significantly high, especially when the boundaries between horizons are abrupt. This risk is further exacerbated in sloping lands. An often-overlooked aspect of soil mana-gement is deep compaction. In addition to surface compaction caused by the use of heavy machinery for logging activities, naturally compact horizons may be present in the soil profile. These can include conso-lidated sediments, but also pedogenetic layers such as fragipan, or horizons cemented by salts, such as petrocalcic layers, found at varying depths but often within one meter from the surface. These compact horizons reduce water retention capacity and hydraulic conductivity (Costantini, 2021), hinder deep water drainage, and increase the risk of water stagnation in the overlying horizons. Consequently, they promote surface runoff, rill and gully erosion, and slope instability. In this regard, the soils of the Portofino Regional Park (Genoa) represent a striking example. The park features approximately 80 km of marked trails and dozens of mountain bike tracks, varying in slope and level of difficulty. The heavy use of trails, particularly by mountain bikes, has led to significant soil erosion, sometimes even in less steep sections. Many of the park's soils have high erodibility and are therefore easily removed by running water when not protected by vegetation, leaf litter, twigs, and dead branches, as is the case along trails and especially bike tracks (Scopesi et al., 2013). Additio-nally, many soils in the park are shallow, meaning that soil loss often exposes the underlying rocky or stony substrate, with negative consequences for both forest vegetation and trail accessibility. A particular note-worthy case is that of the park's most significant soil,

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known as "Monte Pollone." Unlike other soils in the park, this is an ancient relict paleosol (a Cutanic Acrisol), dating back at least to the Middle or Lower Pleistocene (several hundred thousand years ago), covering about thirty hectares on the ancient, originally roughly flat surface overlooking the famous Abbey of San Fruttuoso (Rellini et al., 2017). This soil has exceptional cultural significance, as it is extremely rare even on a European scale and provides evidence of environmental conditions different from those of today. Soils of this type and in this specific morphological position often preserve archaeological artifacts from various periods, including the Paleolithic. Monte Pollone soil is deeper than the other park soils, finer textured, and less stony, making it more suitable for recreational use, particularly cycling. However, these same characteristics make it highly susceptible to concentrated water erosion. Moreover, its fine texture makes it especially prone to compaction, further increasing erosion risk (Costantini, 2024). Based on scientific findings and expert recommendations demonstrating the link between cycling activity and increased erosion risk, along with the loss of an important environmental resource, the park administration recently decided to prohibit bicycle access within the park (https://www.parcoportofino.it/hh/index.php).

Andic soils. In many soils derived from volcanic effusions, pedogenesis leads to the formation of certain amorphous minerals such as allophane, imogolite, ferrihydrite, or aluminum-humus compounds. These colloidal clay minerals impart distinctive properties to the soil, known as andic properties. From a physical-hydrological perspective, these soils exhibit high porosity and low bulk density, high water retention capacity and hydraulic conductivity, low cohesion, high thixotropy, and significant vertical and lateral variability in soil properties. Some studies suggest a direct relationship between flow-type mass movements and andic soils (Scognamiglio et al., 2019; Vingiani et al., 2015). Andic soils can also be prone to liquefaction, a phenomenon that drastically reduces their stability during intense rainfall events. This aspect is particularly crucial in the design of forest-hydraulics interventions, as it necessitates a detailed assessment of soil conditions to prevent potential collapses. It is a key factor in determining soil susceptibility to landslide initiation, especially in soils with a northern exposure. Moreover, it is particularly relevant that soils with certain andic properties are also found in non-volcanic areas, where they characterize forested landscapes with a high landslide risk (Iamarino and Terribile, 2008). These soils have mostly developed on layers of aeolian deposits of various origins, which are present across all regions of Italy at different altitudes, including mountainous areas and slope morphologies. (Costantini et al., 2018).

Forest watershed management

The selection and management of the soil's vegetative cover should always be appropriately tuned according to the environmental characteristics, particularly the soil's physical-hydrological properties. Forest management aimed at its role in hydrogeological protection must control numerous risks such as soil water erosion, superficial gravitational instabilities, debris flows, toe erosion-induced landslides, the production/retention of woody debris and boulders, flood runoff, windthrows, and tree overturning. Forest uses cause hydrological and erosive alterations whose impacts must be contained (Cambi et al., 205). The structure of uneven-aged stands, as found in coppice management with steering and in thinned stands, ensures a more effective action in soil protection and positive regulation of the water cycle, compared to the contemporary overstory provided by a simple coppice or a stand subject to clear cutting, which cause periodic and complete soil denudation. It is therefore necessary to careful planning the maximum harvestable area that does not increase the hydraulic and geological risks of a given watershed. In this sense, the aphorism "no more forest, but a better forest" (Hofmann and Preti, 2019) is well understood.

Soil mapping in hydraulic-forest setups

The use of soil mapping, multicriteria analysis, and GIS has become a fundamental pillar in the planning of hydraulic-forest setup. In the Campania Region, where, as previously mentioned, there are territories with a high risk of rapid debris flows, an interesting multicriteria analysis and risk cartography was carried out (Terribile et al., 2007, 2011). In these studies, the potential susceptibility to the initiation and propagation of rapid debris flows in the Campania Region was estimated based on a multicriteria analysis that considered soil type, altitude, slope inclination, land use, and the presence of roads. Another noticeable application of the combination of tools such as GIS and multicriteria analysis is the identification of the most suitable areas for the con-

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struction of hydraulic structures, such as hilly reservoirs for flood attenuation. A recent study by Papini et al. (2024) developed a model for the optimal location of small hilly reservoirs in Tuscany, using multicriteria analysis to evaluate factors such as slope, land use, and geological characteristics. This approach allowed for the identification of sites that not only mitigate hydraulic and geological risks but also optimize the use of water resources for agricultural and forestry purposes. In a case study carried out in the municipality of San Casciano in Val di Pesa (Florence district), the multicriteria analysis led to the creation of a suitability map for the construction of hilly ponds, taking into account parameters such as the upstream catchment area, soil texture, and vegetation cover.

Conclusions

Hydraulic-forest works are an indispensable tool for the prevention of hydrogeological instability and the sustainable management of natural resources. Thanks to the integration of innovative techniques such as bioengineering and nature-based solutions, these interventions can ensure greater resilience of the territory. However, as with the choice of forest type and its management, it is essential that all restoration works, whether localized or extensive, consider the nature of the soils where they are carried out. The physical-hydrological properties of the soil, by interacting decisively with the area's geomorphological processes, the climate, the forest type, and its management, determine the erosive processes, the travel times, and the flow volumes of watercourses, whose estimation forms the basis for the choice, sizing, and positioning of restoration structures. In addition, the hydraulic forestry works must always guarantee the maintenance of soils in good hydrological condition, without impairing their capability of accepting and regulating the runoff of rain. Even a few extra hours before a flood wave can provide the possibility of warning populations in time of imminent danger and potentially saving lives. The interactions among forests, soils, climate, and geomorphology are certainly complex and spatially variables. Adequately considering them in the planning of remedial interventions requires the use of multicriteria analysis and IT tools such as GIS, databases, and decision support systems. Research by authors such as Terribile et al. (2007, 2011), Scopesi et al. (2013), Wicki et al. (2020), Papini et al. (2024), and Giachi et al. (2024) provide concrete examples of how the application of multicriteria analysis, soil cartography, and GIS techniques are improving the effectiveness and sustainability of these interventions. In the future, the increasingly widespread use of advanced technological tools and the adoption of nature-based solutions, tailored according to soil nature, will continue to play a significant role in territorial management and in the prevention of hydrogeological instability of the forest watersheds.

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