

DRY-STONE TERRACES FOR AGROHYDROLOGICAL RESILIENCE

TERRASSES EN PIERRE SÈCHE POUR UNE RÉSISTANCE AGROHYDROLOGIQUE

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ABSTRACT

Across Mediterranean and mid-mountain regions, dry-stone terraced landscapes historically functioned as integrated agrohydrological systems combining runoff regulation, soil conservation, gravity-based irrigation, drainage management, and microclimate adaptation. In a context of increasing climatic instability, prolonged droughts, violent rainfall events, erosion processes, and growing tensions surrounding water resources, their rehabilitation deserves renewed attention within contemporary irrigation and territorial adaptation strategies.

Based on field observations, restoration works, professional training activities, and territorial interactions developed in southern France, this paper proposes to reinterpret dry-stone terraces as distributed agrohydrological infrastructures operating across plot, landscape, and watershed scales. Particular attention is given to the Domaine du Paternel vineyard in Cassis, where restoration works conducted before winter rainfall periods allowed the rehabilitation of nearly ten breaches representing approximately 80 linear meters of dry-stone retaining walls.

The paper examines how these systems may contribute simultaneously to runoff attenuation, distributed infiltration, soil conservation, biodiversity support, vegetation hydration, and agricultural resilience. By articulating practical experience with historical agronomic knowledge and contemporary hydrological approaches, this contribution highlights the relevance of terraced systems within current reflections concerning regenerative hydrology, Nature-Based Solutions, conservation agriculture, and climate adaptation.

The paper finally argues for the development of operational indicators capable of translating the multifunctionality of terraced systems into measurable hydrological, ecological, agricultural, and socio-economic values supporting future rehabilitation strategies.

Keywords: dry-stone terraces; soil conservation; Runoff attenuation; Nature-Based Solutions, climate adaptation.

RESUME

A travers les régions méditerranéennes et de moyenne montagne, historiquement, les paysages de terrasses en pierre sèche ont joué un rôle intégré, combinant régulation de ruissellement, conservation des sols, irrigation gravitaire, gestion du drainage et adaptation au microclimat. Face à une instabilité climatique croissante, des sécheresses prolongées, des événements de fortes précipitations, l'érosion et les tensions accrues relevant des ressources en eau, leur réhabilitation mérite une attention renouvelée dans le cadre des stratégies contemporaines d'irrigation et d'adaptation au territoire.

Sur la base des observations de terrain, des travaux de restauration, des activités de formation professionnelle et des interactions territoriales menées au sud de la France, cet article propose de réinterpréter les terrasses en pierres sèches comme des infrastructures agrohydrologiques distribuées

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fonctionnant à l'échelle de la parcelle, du paysage et du bassin versant. Une attention particulière est accordée au vignoble du Domaine du Paternel à Cassis, où des travaux de restauration menés avant les périodes de précipitations hivernales ont permis la remise en état de près de dix brèches représentant environ 80 mètres linéaires de murs de soutènement en pierres sèches.

Cet article examine la manière dont ces systèmes peuvent contribuer simultanément à l'atténuation du ruissellement, à l'infiltration diffuse, à la conservation des sols, au maintien de la biodiversité, à l'hydratation de la végétation et à la résistance agricole. En associant l'expérience pratique aux connaissances agronomiques historiques et aux approches hydrologiques contemporaines, cette contribution met l'accent sur la pertinence des systèmes en terrasses dans le cadre des réflexions actuelles sur l'hydrologie régénérative, les solutions fondées sur la nature, l'agriculture de conservation et l'adaptation au changement climatique

Enfin, cet article discute en faveur d'élaboration des indicateurs opérationnels capables de traduire la multifonctionnalité des systèmes en terrasses en valeurs hydrologiques, écologiques, agricoles et socio-économiques mesurables, afin de soutenir les stratégies futures de réhabilitation.

Mots-clés : Terrasses en pierres sèches; Conservation des sols; Atténuation du ruissellement; Solutions fondées sur la nature; Adaptation au changement climatique.

1. INTRODUCTION

1.1 *Climate change and water-resource pressures*

Climate change is progressively transforming hydrological conditions in many agricultural regions of the world. Mediterranean territories are particularly exposed to alternating periods of prolonged drought and violent rainfall events, increasing runoff concentration, erosion processes, wildfire risks, and pressure on water resources.

In parallel, irrigation needs are expected to increase as rainfed agricultural systems become less stable and seasonal water availability more irregular. Under these conditions, strategies capable of slowing runoff, improving infiltration, preserving soil moisture, and supporting groundwater recharge become increasingly important for both agricultural production and territorial resilience.

These challenges concern not only Mediterranean mountain areas but also many cultivated territories structured by slopes, valley bottoms, drainage networks, and increasingly artificialized landscapes exposed to hydrological instability.

1.2 *Why revisit terraced systems today?*

Terraced agricultural systems historically emerged precisely within constrained environments characterized by climatic irregularity, limited soils, runoff concentration, drainage constraints, and strong exposure effects.

Far from functioning solely as erosion-control structures, these systems organized water circulation, infiltration, drainage, agricultural production, and microclimatic adaptation within coherent territorial infrastructures.

In many respects, the hydrological instability associated with climate change progressively recreates conditions for which these systems had originally been designed. Their rehabilitation therefore deserves renewed attention within current reflections concerning water-resource preservation, irrigation resilience, climate adaptation, and multifunctional territorial infrastructures.

1.3 Objectives and positioning of the paper

This paper proposes to reinterpret dry-stone terraces as distributed agrohydrological infrastructures operating simultaneously across plot, landscape, and watershed scales.

Based on field observations, restoration activities, and territorial interactions developed in southern France, the objective is not to provide quantitative hydrological modelling, but rather to explore how terraced systems may contribute to contemporary reflections concerning runoff attenuation, distributed infiltration, soil conservation, biodiversity support, vegetation hydration, and long-term water resilience.

2. TERRACED SYSTEMS AS HISTORICAL AGROHYDROLOGICAL INFRASTRUCTURES

2.1 Historical agronomic knowledge and water management

Historical terraced systems should not be understood solely as vernacular architectural features. They constituted operational agrohydrological infrastructures developed to sustain agricultural production under environmentally constrained conditions characterized by climatic irregularity, runoff concentration, poor soils, erosion risks, and limited water availability.

This dimension appears clearly in the *Mémento de l'agronome* (1984), which dedicates extensive sections to soil and water conservation systems adapted to agricultural regions exposed to hydrological instability and fragile pedoclimatic conditions. The document presents numerous hydraulic and agronomic arrangements combining dry-stone structures, infiltration devices, drainage organization, vegetative systems, ditches, and agricultural practices adapted to local environmental conditions. These approaches already integrated relationships between runoff management, soil conservation, infiltration capacity, slope organization, agricultural production, and long-term land fertility within coherent cultivated systems.

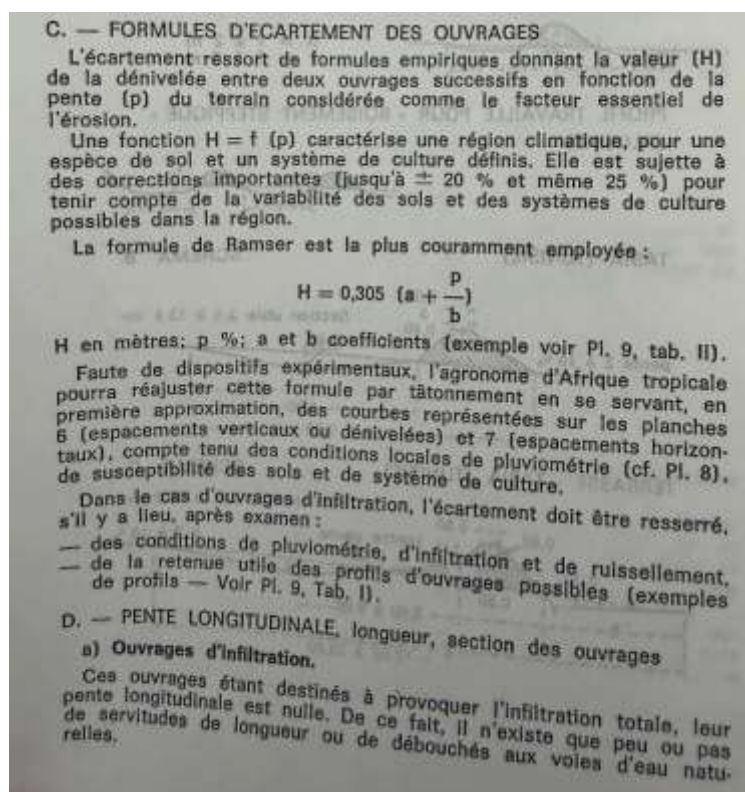


Figure 1. Extract from the *Mémento de l'agronome* (1984) presenting the Ramser empirical formula

The agronomic approaches presented in the *Mémento de l'agronome*, including the Ramser formula used to determine the spacing of soil and water conservation structures according to slope, runoff conditions, infiltration capacity, cropping systems, and local environmental constraints, already reflected a broad systemic understanding of cultivated landscapes.

These approaches integrated hydraulic organization, agricultural practices, vegetation management, drainage systems, soil conservation, and adaptation to pedoclimatic conditions within coherent production systems. Contemporary hydrological research does not fundamentally invalidate these historical principles, but rather extends them through multi-scale analyses involving hydrological connectivity, watershed processes, ecological interactions, and climate-resilience modelling.

Recent studies further emphasize that the quantitative hydrological effects of distributed landscape infrastructures remain insufficiently documented across the diversity of territorial configurations and agricultural systems currently concerned by climate adaptation challenges (Reverdy et al., 2025). In this perspective, revisiting historical agronomic frameworks may provide valuable insights for current reflections concerning regenerative hydrology, Nature-Based Solutions, and territorial adaptation strategies.

2.2 *Terraced systems and gravity-based hydraulic organization*

Field observations also show that terraced systems frequently integrated sophisticated hydraulic arrangements combining runoff interception, drainage regulation, and gravity-based water circulation. In Corsica, former cultivated landscapes combined dry-stone retaining walls, drainage structures, and small gravity-fed channels locally referred to as *canaletti*, organized to redistribute runoff and spring water between cultivated plots.

Monastic terraced gardens further illustrate how altitude, exposure, hydraulic organization, and thermal inertia created differentiated microclimates allowing the cultivation of diverse species, including citrus trees and avocados.

Exposure itself historically played a major role in agricultural organization. Viticultural landscapes on the Rhône hillsides or in Alsace illustrate how sunlight exposure, drainage capacity, thermal accumulation, and air circulation were integrated into agricultural design long before the emergence of contemporary agroecological frameworks.

Terraced systems were not limited to steep mountain slopes. Numerous retaining structures were also developed on softer reliefs, valley bottoms, and agricultural edges where walls organized runoff circulation, stabilized paths, protected drainage canals, and structured cultivated lands.

2.3 *Multifunctionality of terraced agricultural landscapes*

Taken together, these observations suggest that terraced systems historically operated as multifunctional territorial infrastructures linking agricultural production, hydrological regulation, climatic adaptation, ecological interactions, and landscape organization.

Recent studies further underline that terraced agricultural systems should not be considered solely as cultural landscape features or erosion-control structures. Their rehabilitation increasingly appears as a strategic component of watershed management and climate adaptation. Research conducted on Mediterranean terraced landscapes highlights the importance of maintaining these distributed infrastructures in order to preserve hydrological regulation, slope stability, soil conservation and agroecological functions across cultivated catchments (Preti et al., 2021).

Their multifunctionality did not result from the juxtaposition of independent functions but from the integration of water circulation, soil conservation, vegetation management, agricultural practices, and topographical adaptation within coherent agrohydrological systems.

These historical dynamics provide an important framework for understanding why terraced systems may once again become relevant under current climatic conditions.

Recent works by Rizzo et al. further emphasize that Mediterranean terraced landscapes should not only be considered as cultural heritage features, but also as multifunctional territorial systems combining agricultural production, ecological regulation, hydraulic organization, and social resilience within evolving rural environments.

3. HYDROLOGICAL AND ECOLOGICAL FUNCTIONS UNDER CLIMATE STRESS

3.1 Runoff regulation and erosion limitation

Research conducted by Tarolli et al. (2014) demonstrated that terrace abandonment increases hydrological connectivity, accelerates runoff concentration, and amplifies erosion processes within Mediterranean catchments.

Field observations developed during restoration works similarly indicate that breaches in retaining walls generate preferential flow paths accelerating sediment transfers toward roads, drainage ditches, downstream rivers, and coastal environments.

Conversely, rehabilitated terraces contribute to slowing runoff circulation and restoring more distributed hydrological functioning. Water remains longer within soils and cultivated systems before reaching downstream hydraulic networks.

3.2 Distributed infiltration and water-resource preservation

At the plot scale, dry-stone walls stabilize soils and regulate localized drainage conditions. At the landscape scale, terrace networks, forest edges, agricultural paths, and drainage channels create hydraulic continuities capable of redistributing runoff flows within cultivated territories.

At the watershed scale, these distributed infrastructures may contribute to diffuse infiltration processes and temporary soil-water storage likely to support aquifer recharge and more resilient water availability for agricultural systems.

These observations resonate strongly with principles currently promoted within regenerative hydrology, particularly the need to slow, spread, infiltrate, and temporarily store water within landscapes rather than evacuating it rapidly downstream.

The same dynamics also present important compatibilities with conservation agriculture approaches seeking to preserve soil structure, maintain infiltration capacities, reduce erosion, and sustain long-term soil fertility (Alletto and Bustillo, 2023).

3.3 Biodiversity, thermal buffering and ecological regulation

Beyond hydrological functions alone, terraced systems also generate important ecological effects. Dry-stone walls create refuges favorable to insects, reptiles, spontaneous vegetation, and auxiliary species interacting with cultivated systems.

The biodiversity hosted within stone structures may contribute to broader ecological balances capable of moderating certain parasitic pressures within agricultural parcels. The thermal inertia of stone walls further creates buffered microhabitats protecting living organisms during both intense heat and strong frost events. Under increasing climatic instability, such thermal regulation may become increasingly important for maintaining biodiversity continuity and ecological resilience within agricultural landscapes.

3.4 Vegetation hydration and wildfire resilience

Another important dimension concerns vegetation hydration and wildfire resilience. In many Mediterranean regions, former terraced systems progressively recolonized by forest vegetation continue to influence hydrological functioning even after agricultural abandonment. Measurements conducted in the Sainte-Baume massif suggest that forest productivity remains approximately 20% higher on former terraced systems than on non-terraced reference areas, even where retaining walls are partially degraded (Vennetier et al., 2018).

These observations suggest that terraced systems may continue to support soil moisture conservation, vegetation hydration, and localized humidity dynamics over long periods.

By contributing to active vegetation cycles and evapotranspiration processes, such systems may also indirectly participate in broader water-cycle regulation and long-term preservation of water resources. Terraced agricultural systems therefore appear increasingly relevant not only for erosion control but also for integrated responses to climatic instability, biodiversity erosion, water scarcity, and territorial resilience.

4. FIELD OBSERVATIONS AND OPERATIONAL LESSONS

4.1 *Domaine du Paternel: context and restoration process*

The Domaine du Paternel vineyard, located in Cassis near the Parc national des Calanques, provides an illustrative example of the contemporary relevance of terraced systems within highly constrained Mediterranean environments combining viticulture, steep slopes, forest interfaces, tourism pressure, and increasing climatic instability.

Following intense rainfall events, several breaches in retaining walls generated concentrated runoff and mudflows affecting cultivated areas and threatening downstream spaces.

According to the vineyard manager, considerable working time is required every year to anticipate rainfall events, organize water circulation, limit erosion, avoid wall collapses, and prevent runoff concentration capable of damaging both agricultural infrastructure and cultivated soils.

The restoration and training-action sessions organized between late October and early December therefore played an important preventive role before the main winter rainfall periods. During approximately one month and a half, nearly ten breaches were restored from foundation to coping level, representing around 80 linear meters of rehabilitated dry-stone walls.

The restoration work illustrated in Figure 2 was completed during a four-day advanced training session involving seven vineyard employees supervised by a professional dry-stone wall builder and an agronomist specialized in the rehabilitation of dry-stone agroecological infrastructures. The intervention focused on the reconstruction of a major breach using a buttress and shoulder reinforcement built according to dry-stone construction principles.

Beyond restoring the structural stability of the retaining wall, the intervention re-established the hydraulic continuity and anti-erosive functioning of the terraced system while improving safe tractor circulation on the upper terrace.

The broader landscape surrounding the Domaine du Paternel reflects the historical interdependence between limestone resources, terraced viticulture, forested upper slopes, and downstream coastal environments within the Cassis watershed. This territorial continuity remains symbolically expressed through the phrase displayed at the entrance of the town: "Cassis, la pierre, la vigne, la mer".



Figure 2. Rehabilitation of a dry-stone terrace breach at Domaine du Paternel (Cassis, France)

4.2 Hydraulic and agronomic observations

Beyond hydraulic considerations, the experience also highlighted practical agronomic dimensions sometimes neglected in contemporary discussions. Maintained retaining walls improve tractor safety and create more secure working conditions for agricultural workers operating on terraced slopes.

The vineyard manager also emphasized that attempts to maximize plantation density too close to retaining walls frequently become counterproductive. Historically, approximately 2.20 meters were intentionally left without vine rows near terrace edges. This space facilitated circulation and mechanical weeding while limiting competition for water on the warmest and most draining portions of the terrace strongly influenced by the thermal inertia of the wall itself. Attempts to cultivate too close to retaining walls often generated lower yields, increased water stress, and more difficult working conditions.

4.3 Circularity, material sobriety and operational efficiency

Another major lesson concerns operational efficiency and material circularity. In steep agricultural environments where logistics already generate significant technical and financial constraints, dry-stone restoration considerably simplifies maintenance operations. Most repair materials are already available on site and can be directly reintegrated into reconstructed walls.

Unlike concrete retaining structures requiring imported materials, water, cement, heavy machinery, and complex logistics, dry-stone rehabilitation largely relies on reuse and local resource mobilization.

This technical sobriety significantly reduces intervention times, transport constraints, and external material dependency while maintaining highly durable construction methods adapted to sloping agricultural territories.

The Domaine du Paternel experience therefore illustrates how terraced systems simultaneously connect agricultural production, runoff regulation, labor organization, ecological adaptation, material circularity, and territorial resilience.

5. TOWARD OPERATIONAL FRAMEWORKS FOR TERRITORIAL ADAPTATION

5.1 *Emerging territorial dynamics*

Recent territorial dynamics observed in southern France suggest growing interest in terraced systems within broader reflections concerning water management, agricultural revitalization, wildfire prevention, erosion control, and territorial adaptation. Municipalities confronted with increasing climatic pressures progressively recognize that former terraced landscapes may simultaneously represent hydraulic infrastructures, agricultural reserves, ecological transition tools, and landscape assets.

These evolving dynamics also resonate with recent reflections developed by Rizzo et al. concerning the need to reconnect terrace rehabilitation policies with contemporary territorial functions, including agricultural revitalization, landscape management, ecological continuity, and climate adaptation.

5.2 *Nature-Based Solutions and regenerative hydrology*

Contemporary frameworks associated with Nature-Based Solutions increasingly emphasize distributed approaches to runoff attenuation, infiltration enhancement, biodiversity support, and territorial resilience. The IUCN (2016) defines Nature-Based Solutions as actions protecting, sustainably managing, and restoring ecosystems while simultaneously addressing societal challenges.

Within this perspective, terraced systems may be interpreted as historical forms of multifunctional landscape infrastructures capable of contributing simultaneously to water regulation, agricultural adaptation, biodiversity support, and climate resilience.

Recent hydrological studies further emphasize the importance of slowing and conserving water within catchments rather than rapidly evacuating runoff downstream (Lalonde et al., 2024; Reverdy et al., 2025). Recent frameworks proposed by Rizzo et al. for the sustainable maintenance of runoff management structures also highlight the importance of preserving small-scale hydraulic elements capable of regulating hydrological processes across agricultural landscapes.

5.3 *Toward measurable indicators and investment frameworks*

Despite these potential contributions, terraced systems remain insufficiently integrated into operational frameworks associated with water policies, ecosystem-service evaluation, territorial investment strategies, or climate-adaptation planning.

One major challenge therefore concerns the development of measurable indicators capable of evaluating runoff reduction, infiltration dynamics, erosion limitation, biodiversity support, avoided damages, vegetation hydration, and broader territorial benefits associated with terrace rehabilitation.

Such approaches could progressively support the emergence of investment frameworks capable of integrating the multifunctional value of terraced systems within contemporary adaptation strategies.

6. CONCLUSION

Terraced agricultural systems should not be considered solely as remnants of historical landscapes disconnected from present-day environmental challenges. Field observations, restoration experiences, and territorial interactions presented in this study suggest that these systems continue to support a set of interconnected functions linking water regulation, soil conservation, vegetation hydration, biodiversity support, agricultural adaptation, and territorial resilience.

Developed over centuries in response to climatic variability, topographic constraints, and limited soil resources, dry-stone terraces illustrate how agricultural landscapes were historically designed to manage water circulation, infiltration, drainage, and land productivity at multiple spatial scales. Their underlying principles show strong compatibilities with contemporary approaches associated with regenerative hydrology, conservation agriculture, and Nature-Based Solutions.

Historical agronomic knowledge already provided operational frameworks for organizing the relationships between water, soil, vegetation, and agricultural production within cultivated landscapes. Approaches such as the Ramser formula should therefore not be viewed as obsolete empirical methods, but rather as early attempts to optimize hydrological functioning according to local environmental conditions. Contemporary hydrological sciences now offer opportunities to reinterpret and evaluate these principles through multi-scale analyses integrating hydrological connectivity, distributed water storage, ecosystem functioning, and climate resilience.

At the same time, significant knowledge gaps remain concerning the quantitative contribution of terraced systems to groundwater recharge, runoff attenuation, irrigation resilience, biodiversity regulation, wildfire mitigation, and the preservation of water quality at watershed scale. Developing measurable indicators capable of translating these functions into hydrological, ecological, agricultural, and socio-economic values appears essential for informing public policies, territorial planning, and future investment strategies.

Beyond their heritage value, dry-stone terraces may therefore be regarded as living agrohydrological infrastructures whose rehabilitation could contribute simultaneously to agricultural production, water security, ecosystem resilience, and climate adaptation. The challenge today is less to reinvent the principles that shaped these systems than to quantify, update, and integrate them into contemporary territorial strategies capable of addressing the growing pressures exerted by climate change on water resources, agricultural systems, and rural landscapes.

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